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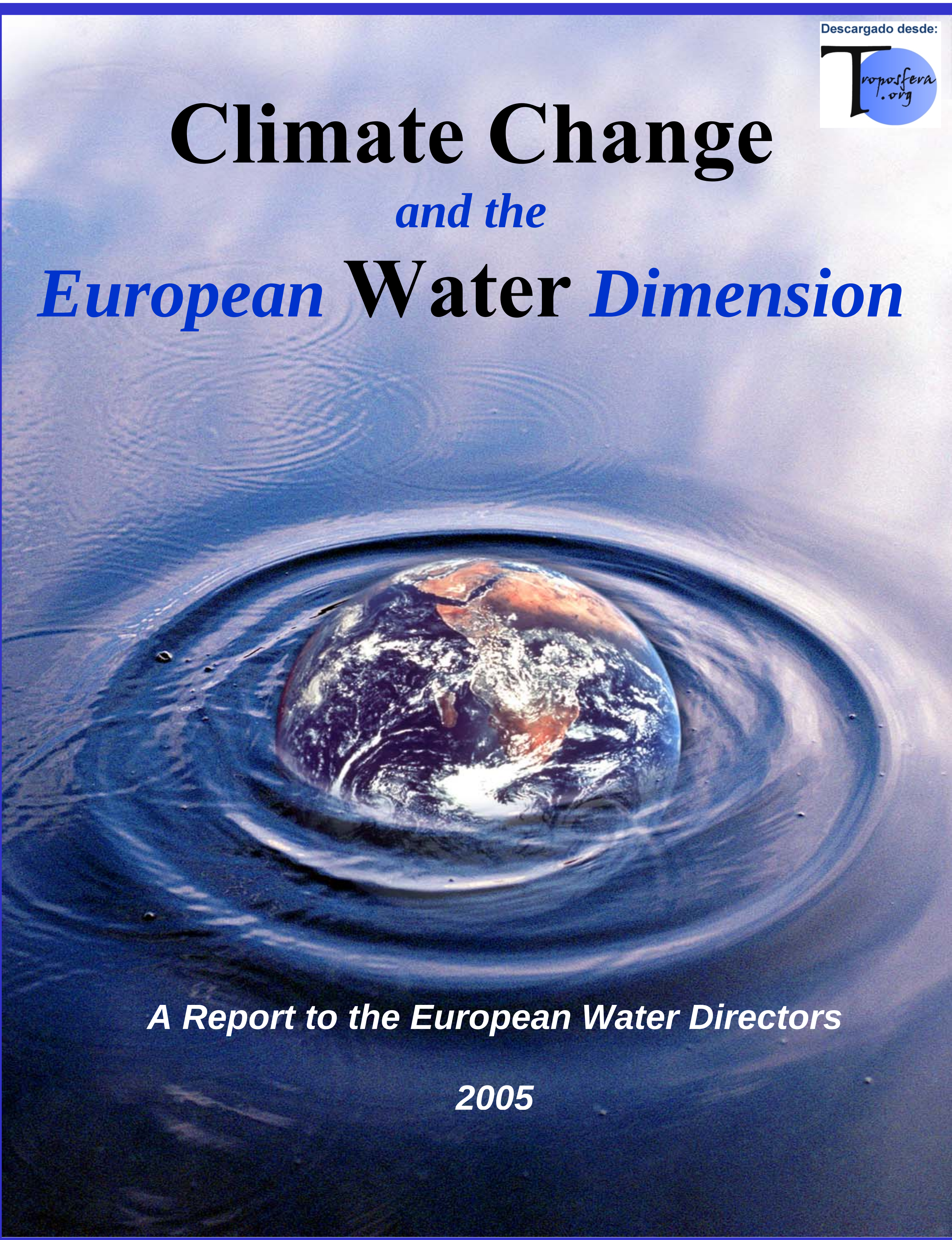
Institute for Environment and Sustainability

Climate Change
and the
European Water *Dimension*



A Report to the European Water Directors

2005

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PREFACE

The Intergovernmental Panel on Climate Change (IPCC) published in 2001 an assessment document on the global and regional evidence for and the potential impacts of climate change. The IPCC said ..*"there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."* To the question is the Earth warming, the answer is a scientifically unequivocal *YES*. Science is also clear that increasing greenhouse gas concentrations in the atmosphere are the most direct driver of the warming of the planet.

In 2004, two important reports appeared. The European Environment Agency (EEA) published its report on *"Impacts of Europe's Changing Climate, an Indicator-Based Assessment",* updated the information and findings reported by the IPCC at the European scale. On water, it states *"….therefore, water availability will change over Europe in the coming decades."* In October 2004 the Arctic Council under the work of the Arctic Climate Impact Assessment published its report *"Impacts of a Warming Climate*". They conclude that climate warming in the Arctic region will dramatically impact the land, flora, fauna, mammals and indigenous people of the region. They additionally point out that the Northwest Passage is likely to be open again in the warming seas at least during the summer months.

With this new report on *"Climate Change and the European Water Dimension* (JRC, 2004) the Joint Research Centre of the European Commission contributes to the focused evaluation of the possible impact of climate change on water resources and quality in the *European* inland and marine/coastal waters. It is obvious that in many aspects we do not have sufficient information to be absolutely confident of some conclusions, but it is, in our opinion, necessary to make an effort at assessment now by compiling and evaluating existing scientific knowledge. In any case we dare to say that the evidence of change is already overwhelming and it may be critical that we act now to secure these natural resources for the future. I hope that this report serves as a useful input to further discussions and decisions taken in respect to the sustainable utilization and management of European water bodies being exposed to substantial pressures arising from the climate change phenomenon.

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BACKGROUND AND RECOMMENDATIONS

The European Water Directors (WDs), consisting of the Water Directors from the European Members States (EU25-MS), and the associated countries of Iceland, Norway, Switzerland, Romania and Bulgaria, guide the strategic development and implementation of water issues for the EU. They provide strategic guidance to the common implementation strategy of the Water Framework Directive, the European Marine Strategy, and initiate discussions and actions on issues such as river basin management, flood protection and management, drought management, and now climate change.

The WDs acknowledge that the reality of climate change is recognised internationally and the Kyoto protocol is designed to commit countries to progressive reductions of greenhouse gases. However, even if it is assumed that the Kyoto Protocol commitments are respected, this still presumes significant changes in climate, average temperatures, precipitation patterns and river hydrology. How much climate change (i.e., temperature rise) will or is likely to occur before 'dangerous' climate change exerts its influence? (Note February 2005 Conference in Exeter, UK on *Avoiding Dangerous Climate Change*[1]) Climate change will have a major impact on water resources in Europe that in turn may require changes in the way that Europeans manage and protect these resources. And of course climate change and viability are and will continue to impact the wider environment worldwide (Note the 2004 Arctic Council Report on the climate change and impacts in the Arctic).

The WDs asked 'to what extent have the Commission, Member States, marine and river basin commissions, and others developed detailed predictions concerning the possible consequences of climate change? Where these forecasts/predictions exist, have they been developed on the basis of common scenarios? Do we know enough about the possible impacts of climate change at the European scale to act?

In the light of the information needed to address these questions set out above, the WDs concluded that there existed a serious need to improve the knowledge base for Water Directors? They asked how should this be done? And to what extent and how should this be co-ordinated?

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[1] Note in Editing: *Avoiding Dangerous Climate Change* – Exeter (UK) Conference, February 6, 2005: Although the initial trigger for this conference to consider was the need to define precisely what constituted "dangerous climate change," the scientists ended up instead detailing "critical thresholds that we should aim not to cross". Questions asked were why is the climate warming happening, how we know about it, and what we can do about it were central to the conference. The impact of continued rapid increases of levels of greenhouses gases in the atmosphere will be world-changing, one might say, but in a bad way. But just how bad? How fast will they happen? And what are our best choices for mitigating the worst of it?
(see http://www.worldchanging.com/archives/002062.html)

At the 2003 Rome Informal Meeting of the Water Directors, they requested that the JRC coordinate the preparation of a scientific document on climate change emphasizing Europe and the dimension of the water resource implications of a climate changed world. The JRC accepted the challenge and sought the collaboration of more than 40 scientists from Europe and within the JRC to draft a scientific synthesis of what we know or think we know about climate change and its impacts on water resources at the European scale. This report, which increases the knowledge base on climate change, would then be used,, along with other recently issued reports by the EEA (2004) and the Arctic Council (2004) to address the question whether existing EU water policy and anticipated evolution of water policy could accommodate the protection of European water resources in a climate-changed world. The draft outline of the report now titled *Climate Change and the European Water Dimension* was approved at the Water Directors Meeting in Rome. The Report is a scientific synthsis, not a concensus document, of many but not all dimensions of the climate change phenomena in the water sector.

The Report is organized into six chapters progressing from the global to European perspectives of climate change, initially based on the IPCC 2001 report but updated with new published information, potential aquatic impacts in different aquatic sectors and case studies. Specifically, *Chapters I and II* present the global and European perspective on climate change predictions, scenarios and impacts. *Chapter III* summarizes the hydrological cycle and the compartments and flows most sensitive to climate change impacts. *Chapter IV* provides a summary of the global and regional indicators of climate variability such as the North Atlantic Oscillation, and then proceeds to provide analyses of real and potential climate change impacts on lakes, coastal and marine systems, and Mediterranean lagoons (as an example of an especially sensitive aquatic ecosystem). *Chapter V* is a series of sub-chapters addressing some of the major challenges in climate change scenarios such as floods, droughts, changing ecological status and the WFD, and water in agriculture. *Chapter VI* provides a series of case studies highlighting the reality of climate change and variability as witnessed for four lakes in Europe, the Venice lagoon, and the Ebro and Po River Basins. Further chapters address the issues of water-borne and vector-borne disease likely exacerbated by climate change. The last part of *Chapter VI* introduce the potential implications of climate change as a perturber of the global Hg cycle and to mobilization of persistent organic chemicals such as dioxins and PCBs as a result of floods and general temperature increases.

The Key Points of this Report are presented at the beginning of each Chapter to provide additional clarity in grasping the information and knowledge. The chapters document rising temperatures, sea level rise, intensification of the hydrologic cycle, the competing needs of different water sectors exacerbated by climate-induced change, the warming of large lakes and the global ocean including the Mediterranean Sea, ecosystems at risk and the potential for indirect effects hardly imagined today.

It is beyond the scope of this report to make specific recommendations to the policy makers how they might address the climate-induced changes in the water sector. However surrounding the release of the report and discussions at the Amsterdam Water Directors Meeting in December 2004 and over numerous coffees, some suggestions for discussion were raised.

In the area of adaptation, there is a need to:

- Identify and detect signals of climate change in inland and coastal waters.
- Develop indicators sensitive to climate variability and climate change of the impacts on inland and coastal waters.

- Provide relevant input to EU water policy makers on the impacts to the water sector (agriculture, urban centres, industrial and energy sectors, civil protection, spatial planning) under climate change scenarios.
- Perform economic analyses of the costs of adapting to climate change in the water sector and analysis of the externalities of environmental systems under climate change impacts.
- Most importantly, to develop and apply regional climate change models at the sub-regional and river basin scale to Asses potential response of land and water systems, and mitigation strategies with associated costs.

Specifically in the water sector, to

- Quantify at the European and river basin scale the impacts of climate change on *water quality* of surface water and GW, and water classification for river basin management by coupling river basin – coastal zone models in a climate changed world.
- Quantify at the European and river basin scale the impacts of climate change on *water quantity*, its spatial-temporal distribution including extreme events such as floods and droughts, and availability of surface and GW under different scenarios and uses, and the associated costs of adaptation.
- Evaluate the effectiveness of different protection measures in trans-national river basins with hydrological models as a response to possible increase in extreme events.
- Evaluate the impacts of climate change on the re-mobilization, redistribution and emission of contaminants (chemical and microbiological) as a result of warming and extreme events.
- Establish long term monitoring at the pan-European scale of marine and coastal systems using earth observing satellites and other tools of those parameters sensitive or indicative of climate change (SST, sea level rise, biomass, primary productivity, carbon cycles, wind fields, trophic state).

We hope the Report contributes to the European discussions on climate change, its impacts and policy implications. The policy makers of Europe and worldwide have their hands full in coming years and decades, as the climate warms, as water resources become too spatially intensive or scarce, as ecological systems undergo serious and perhaps irreversible changes. Our policy makers will need considered input from all elements of society to address the important issues facing sustainable water use.

As a final word, I wish to acknowledge all the co-authors of this Report for their willingness to contribute their time, knowledge and experience to an 'extra' activity of importance. Without the many co-authors, the preparationof this Report would not have been possible.

The Editor

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Chapter I. Observations of Global Climate Change and its impact on the hydrological cycle

Key Points

- **Average global temperature over land surfaces has risen by 0.6 ± 0.2°C in the period from 1861 to 2000. This temperature increase is unprecedented within the past millenium.**
- **Observations show a non-uniform increase of about 2% in global land precipitation since the beginning of the 20th century. More extreme precipitation events are observed.**
- **Direct and indirect effects of aerosols appear to exert an important, but not fully understood, influence on radiative forcing and on the hydrological cycle.**
- **The projected temperature increases over the 21st century for the full set of scenarios developed by the IPCC for the TAR were in the range 1.4 to 5.8^{0}C.**
- **According to model predictions, precipitation at high latitudes will increase both summer and winter. Mean precipitation at subtropical latitudes will decrease while precipitation in most tropical areas will increase.**
- **Projected sea level rises are in the range 0.09 to 0.88 m over the period from 1990 to 2100, however feedbacks and non-linear effects may lead to an accelerated collapse of ice sheets and thus larger sea level rises.**

Chapter I. Observations of Global Climate Change and its impact on the hydrological cycle

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) in 1988. The IPCC has involved a large number of leading scientific experts in its efforts to assess scientific information on climate change and its impacts. The assessment reports published by this panel can be considered as an expression of the state of the art of the science in this field, and the following introduction to global climate change is thus largely based on the work of the IPCC, particularly its third assessment report (TAR), that was published in 2001 [Houghton *et al., 2001*].

I.A. The Temperature Record of the Earth

Last 140 years

Global temperature changes within approximately the last one and a half century can be estimated based on reported surface temperature measurements; for recent years also observations from satellites are available. An analysis of thermometer data on a global scale led the IPCC to the conclusion, that the average global temperature over land surfaces has risen by 0.6 ± 0.2°C in the period from 1861 to 2000. The warming (see Fig. I.1) has mainly taken place in the periods from 1910 to 1945 and from 1976 to 2000. The ten warmest years in the series have occurred after 1980, seven of them have occurred in the 1990's.

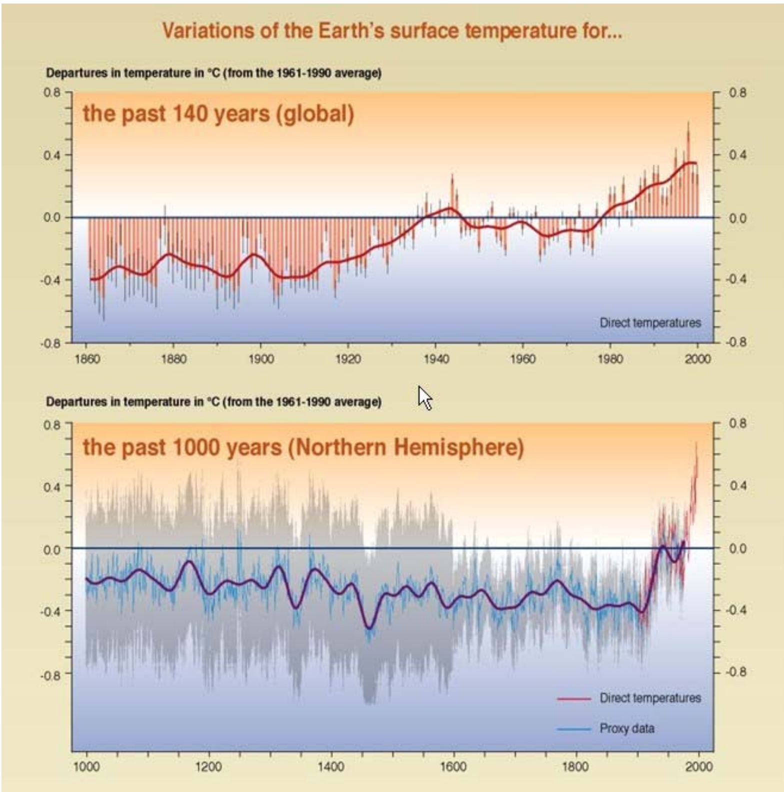

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Fig. I.1. Temperature changes in the past 140 years and in the past millennium (IPCC 2001)

Changes in the diurnal variation of temperature in recent decades have also been analysed: Observations from 1950 to 1993 show an increase in maximum daily temperature of approximately 0.1°C per decade while the increase in the minimum daily temperature is approximately 0.2°C per decade. Thus the diurnal temperature variations have decreased. One of the reasons for this may be an increase in cloud cover, since clouds reduce the diurnal variations in temperature by reducing both warming during the day and cooling in the night. Also aerosols may play a role, as will be discussed later.

Variations in sea surface temperatures (SSTs) have been analysed based on *in situ* measurements as well as, for the most recent years, satellite observations. The global average SST shows a trend quite similar to that of the land surface temperature up to 1976, but the increasing trend seen after 1976 is somewhat less pronounced than for the land surface temperatures.

The temperature changes in the lowest 8 kms of the atmosphere since the late 1950's have been evaluated based on balloon soundings; the overall temperature increases were found to be similar to those of the surface of approximately 0.1 ^{0}C per decade. However, since 1979, both balloon and satellite observations of the lower atmosphere have shown significantly slower rates of temperature increase than at the surface. One of the reasons for this difference may be the depletion of the stratospheric ozone layer, leading to a cooling of the lower stratosphere.

The observed inter-annual fluctuations of surface temperatures are significantly influenced by large-scale natural oscillations in the climate system, of which the most important is known as the El Niño-Southern Oscillation (ENSO). These phenomena and their possible interaction with global warming will be discussed later.

Last 1000 years

In order to judge whether the temperature rise during the last 140 years is likely to be part of the natural variability of climate, temperature records over much longer time scales must be constructed. The last 1000 years, where the astronomical conditions of the Earth have been close to the present situation, are of particular importance for assessing the relevant background variability. Reports of instrumental temperature observations for this period are scarce, so other means of evaluating temperature variations have to be used, typically based on the fact that many physical, chemical or biological processes depend strongly on temperature, and these processes sometimes leave 'proxies' for temperature change.

Tree rings are an example of a high-resolution proxy climate indicator, since their width and density are related to climate and allow the reconstruction of warm season and annual temperatures several centuries or more into the past. However, tree ring growth is influenced by other factors than temperature and thus it appears that tree ring data are most useful when other types of proxy information about temperatures supplement them.

Marine corals are another temperature proxy that has allowed us to reconstruct past variations in climate in tropical and sub-tropical oceans with annual or seasonal time resolution. Climatic variations are reflected in the chemical and isotopic characteristics of the coral skeleton as well as in density and fluorescence.

Also ice cores from polar or mountain regions provide possibility for assessing temperature changes in the past, since they in various ways reflect temperature variations, e.g. by their isotopic composition.

The temperature record over the last 1000 years (Figure I.1) has been constructed using a combination of temperature measurements and proxies. It shows that the temperature increase in the last 140 years is unprecedented within this time span.

I.B. Precipitation

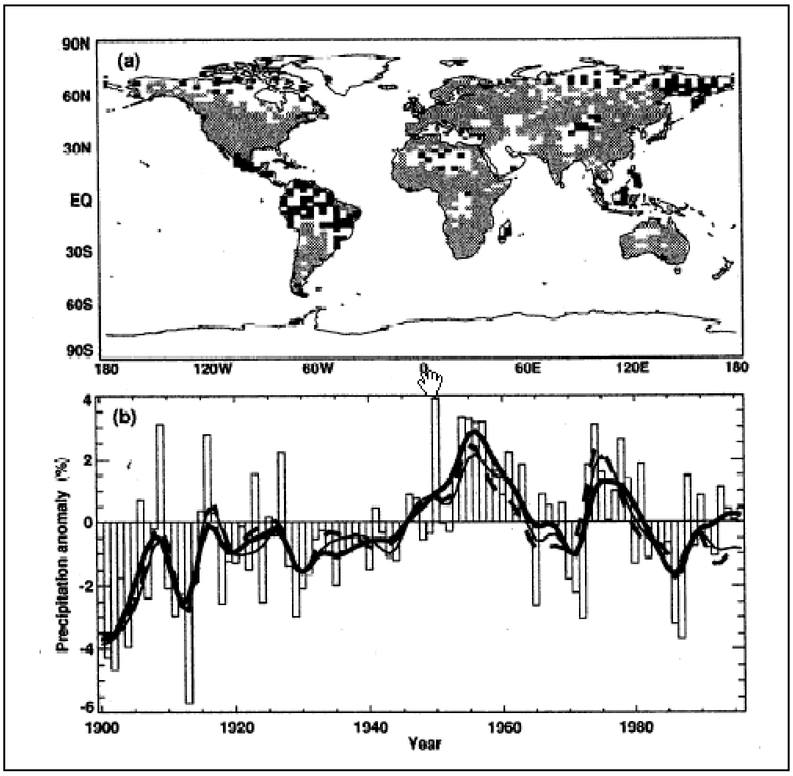
Intuitively we expect that evaporation would increase with increasing temperatures, and, in fact, all atmospheric general circulation models predict enhanced evaporation of water. Also an increase in atmospheric moisture has been predicted by models and confirmed by many observations.

Increased evaporation must obviously be balanced by increased precipitation. Also the observation that atmospheric moisture is increasing leads to the expectation that precipitation will increase. Increased evaporation means also that more latent heat will be released in the atmosphere, and this may lead to more intense storms. The overall result would be an intensification of the hydrological cycle with increased precipitation at a global scale, but concentrated in more intense events. This possible trend towards more extreme weather events will be discussed later.

Precipitation is measured at a large number at stations within Europe and globally. Analysis of observations shows an increase of about 2% in global land precipitation since the beginning of the 20th century. This increase, however, is neither temporally nor spatially uniform (see Figure I.2). The observed increase in the annual precipitation for the zones between 30^{0}N to 85^{0}N is between 7 and 12% while the increase in the Southern Hemisphere between 0^0 S and 55^{0}S is about 2%. The increase observed in the Northern Hemisphere is likely to be biased because the data have not been corrected for the fact that an increasing fraction of the precipitation is in liquid rather than frozen form, again due to increasing temperature. However, this bias is expected to be small, and the increasing trend is significant, although it is unsteady, e.g. interrupted by drought years in some areas. The trend towards increasing precipitation has been confirmed by analyses of data from the United States that show increasing streamflows.

A clearly increasing precipitation trend over the 20th century has been reported for Northern Europe, while the tendency for Southern Europe and the Mediterranean Area in general has been towards less precipitation. Significant increases in precipitation over the 20th century have been found also for USA and Canada and parts of the former USSR. China has experienced a slightly negative trend in precipitation over the last 50 years, but with large geographical variations. The TAR concludes that the present increase in precipitation over the middle and high northern latitudes will continue at a rate between 0.5 and 1% per decade, except for over Eastern Asia.

In contrast to the significant increases in precipitation in the mid- and high northern latitudes, the trends observed in the tropics and sub-tropics show a more complex picture; e.g. a decrease in precipitation in the northern sub-tropics. The effects of aerosols on the hydrological cycle will be discussed later.



Fugure I.2. (a) Maximum grid coverage in dataset. Black boxes do not have five years of data per decade from 1900 to 1996. (b). Observed terrestrial precipitation 1900-1996 (% deviation from 1961-1990 mean). The increasing trend is pronounced only in the first half of the century. (Hulme *et al.*, 1998).

I.C. Snow/ice cover

Increasing temperatures will naturally be associated with melting of ice on mountains and in Polar Regions. It is also expected that a larger part of the precipitation will be liquid water rather than snow. This tendency may be counteracted by increasing precipitation as well as by changes in atmospheric or ocean circulation patterns. There are important feedbacks between changes in snow and ice cover and climate change. These feedbacks include the influence of snow and ice cover on surface albedo and the influence of melt/freeze processes on sea surface salinity and deep-water formation.

Of particular relevance to climate change is the sea-ice cover in the Arctic and around the Antarctic; these areas cover about 5% of the global surface. Satellite observations over the period 1978 to 1996 showed a decrease in sea-ice extent in the Northern Hemisphere of –2.8±0.3% per decade. The coverage of earlier data is incomplete, but they suggest that the decline in Arctic ice-cover was not pronounced during the first half of the 20th century. The recent decrease in ice-cover is consistent with observed Arctic temperature changes. Recent observations have also indicated a reduction in the thickness of the Arctic sea-ice. In the Antarctic, five ice shelves have retreated during the last century; recently (1995) the collapse of the Prince Gustav and parts of the Larsen ice shelves were reported. However, satellite observations during the last decades show that after an initial decrease in the mid-1970's, the Antarctic sea-ice extent has remained stable or even slightly increased.

Permafrost regions represent an issue with a potentially strong bearing on global climate change. Permafrost, defined as soil or rock material that remains frozen throughout two or more consecutive years, underlies almost 25% of the land surface in the Northern Hemisphere. Above the permafrost is a thin layer, called the active layer that experiences seasonal freezing and thawing. Thawing of permafrost may contribute directly to global warming by release of greenhouse gases, especially CO_2 and CH_4 and indirectly influence radiation balance and surface hydrology by causing changes in vegetation. Systematic monitoring of permafrost areas has begun only recently.

The recession of glaciers is among the most spectacular evidence of climate change. Systematic observations of glaciers started only about 100 years ago, but there is a wealth of earlier written information as well as pictures, that allow us to reconstruct the length records of some glaciers over longer periods. Glacier length does not reflect short-term fluctuations in temperature; the response time of glaciers to temperature changes has been found to be in the range of 10 and 70 years. Glacier records provide a useful supplement to temperature records because they are often found in areas where temperature observations are scarce and at higher altitudes than those where meteorological stations typically are placed.

The general trend found at mid- and high latitudes as well as tropical and subtropical regions is that of retreat. In a few regions (Norway, New Zealand) the opposite trend is currently observed for several glaciers; this appears to be explained by increases in precipitation and, in the case of New Zealand, to conditions with little warming during the last decades. Interestingly, the recent trend of tropical glaciers is found to be that of increasing retreat, while temperature observations in the tropics by satellites and radiosondes show a lack of warming in the last decades. This apparent discrepancy has been explained by the fact that temperature increases may be occurring in the tropics but most noticeably at high altitudes,

I.D. Sea level rise

There are two reasons for expecting that global warming will lead to higher sea levels. i.) the melting of land-ice and snow leading to increased water input to the oceans (melting of sea-ice, whose weight is already supported by the oceans, does not increase the sea level). ii.) the density of water decreases with increasing temperatures, thus thermal expansion of the oceans takes place. The heating of the oceans is a slow process due to their large heat capacity; the thermal expansion of the oceans is thus expected to continue for many centuries even after climate had been stabilised. The processes that influence the uptake of heat in the oceans have a key role in climate change: the faster heat is taken up by the oceans, the faster will occur the thermal expansion of the oceans, but slower will be the rise in atmospheric temperature. The thermal expansion of the oceans, which is not uniformly distributed, appears to be the most important cause of rising sea level. The phenomena leading to sea level rise are counteracted by the effect of increasing precipitation in the Arctic and Antarctic regions.

The clearest evidence of ocean warming comes from observations in the North Atlantic. The TAR reports only one published global analysis of heat uptake by the oceans, which indicate an average of 0.5 W/m^2 during the period 1955-1995, half of this occurring in the upper 300 m, leading to an estimated warming of 0.7^0C per century. This corresponds to a sea level rise of 0.55 mm/year. All in all, the observational evidence suggest that the sea level rise caused by thermal expansion is about 1 mm/year for recent decades, in reasonable agreement with the predictions of Atmosphere-Ocean General Circulation Models (AOCGMs) of 0.7 to 1.1 mm/year over a similar period. The model simulations suggest that the ocean rise due to thermal expansion over the 20th century is 0.3 to 0.7 mm/year.

The available measurements only allow us to establish a mass balance for the rate of change of a very small part of the more than 160 000 glaciers in the world. Thus the input of water to the sea resulting from the retreat of glaciers must be estimated based on a number of assumptions and approximations. The different approaches that have been applied have lead to estimates of the contribution of glacier and ice caps to sea level rise over the last century in the range of 0.2 to 0.4 mm/year.

The ice sheets of Greenland and the Antarctic contain enough water to raise sea levels by 70 m, so fractional changes in these ice masses are of obvious importance. The precipitation falling on the Arctic and Antarctic ice sheets is approximately balanced by loss of ice due to melting and calving. The temperatures in the Antarctic are so low that melting practically does not take place, while melting is of significant importance in Greenland. The response time of ice discharge to climate change is sufficiently long (100 to 10000 years) that it is likely that ice sheets now are still adjusting to their past history. For the 21st century it is expected by the IPCC that surface mass balance changes will dominate the volume response of both ice sheets (there is, however, considerable disagreement about this, as discussed below). Land movements also influence sea levels; for this reason some places experience decreasing sea level.

I.E. Climate Extremes

Changes in the mean value of climate variables such as temperature or precipitation may also be associated with a change in their distribution, thus leading to either more or less occurrence of extreme events; e.g. floods, droughts, very warm and very cold spells.

Several studies have addressed the variability of global temperatures. The observations give little evidence of an increase in inter-annual temperature variations over the past few decades, but there is evidence suggesting that intra-annual temperature variations have widely decreased. It has been found that much of the warming in the mid- and high latitudes in the 20th century has been during the cold season, consistent with higher yearly minimum temperatures and a tendency towards a narrower yearly temperature range. Some regional studies have also shown decreasing diurnal temperature variations because of increasing night-temperatures. The dramatic floods of central and Eastern Europe in August 2002, and the subsequent severe drought and high temperatures of summer 2003 emphasize the extreme in climatic variations.

As mentioned earlier, it may be expected that the increased release of latent heat would lead to the occurrence of more intense precipitation events and analyses of precipitation data show such a widespread tendency. Since the mid- and high latitude land areas have experienced increasing precipitation during the last half of the 20th century the question arises if this has been associated with more extreme precipitation events. The observations show such a tendency, although not uniform, with a larger percentage of the precipitation falling into the upper five percentiles and a 4% increase in the annual maximum five day precipitation in total.

The observations show little evidence of a long-term trend for tropical storms, but inter-decadal variations are large. Recent increases in the extra-tropical cyclone frequency and intensity in the Northern Hemisphere have been observed, but the available information does not allow us to determine whether a long-term trend exists. Although the long term pattern may be elusive, the population of the Florida and Gulf of Mexico coasts would likely argue for a peak in hurricane activity in 2004.

I.F. Radiative Forcing Agents and Global Warming

At equilibrium, the energy flow of the outgoing, long-wavelength radiation must equal that of the ingoing, short-wavelength radiation from the sun. This equilibrium can be perturbed, by changes in the incident solar radiation, in the albedo of the Earth surface, in the concentration of absorbing gases in the atmosphere, or by the absorption and reflection of radiation by aerosols and clouds. Such perturbations of the radiative balance have the potential to cause changes in the surface temperature in order to re-establish equilibrium.

Greenhouse gases are gases that absorb long wavelength (infrared) radiation. In the atmosphere, they absorb part of the outgoing infrared radiation and re-emit it in all directions, including downwards towards the surface of the Earth. The emission of infrared radiation from an object increases with temperature. Thus to compensate for the reduction of the outgoing radiation caused by greenhouse gases in the atmosphere, a warming of the Earth's surface and part of the atmosphere must take place in order to establish a radiative equilibrium. In other words, greenhouse gases trap heat in the atmosphere. The heating effect of greenhouse gases is related to the fact that there is a negative temperature gradient in the lower atmosphere; the heat-trapping efficiency of a given greenhouse gas concentration increases with decreasing temperatures along this gradient. Greenhouse warming is an important naturally occurring phenomenon with water vapour being the main natural greenhouse gas. This causes a rise in the natural average temperature of the Earth from -19^0C in an atmosphere without infrared absorption to the actual of $+14^0$C.

The consequence of increasing concentrations of greenhouse gases in the atmosphere is a radiative imbalance, which provides a driving force for heating the Earth and its atmosphere. This radiative imbalance can, in principle, be measured at the top of the atmosphere as the difference between incoming and outgoing radiation.

The concept of 'radiative forcing' is used by the IPCC to gauge the strengths of perturbations, and is defined in the following way: "The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent (say a change in greenhouse gas concentrations) is the change in net (down minus up) irradiance (solar plus long-wave; in Wm^{-2}) at the tropospause, after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperature and state held fixed at the unperturbed values".

The TAR report provides the most authoritative assessment of radiative forcing with the next IPCC report to be completed in 2007. Since the TAR was published a number of climate scientists have produced additional interpretations and variations of the IPCC analysis. Of particular interest is the comprehensive modeling study from the NASA Goddard Institute (Hansen *et al.*, 2002) that infers that the planet is now out of radiative balance by 0.5 to 1 W/m^2 and that additional global warming of about 0.5 ^{0}C is already "in the pipeline".

Other causes
Other causes of climate change include: deforestation and other changes in land-use that enhance surface albedo. The largest effect is believed to be at high latitudes, where snow-covered fields with high albedo have replaced snow-covered forest with lower albedo. Warming due to increasing solar irradiance change has been taking place mainly in the first half of the 20th century. Other mechanisms by which emissions from the sun may influence climate have been proposed, but the IPCC has not found that they have a sufficiently rigorous scientific basis. Stratospheric aerosols from explosive volcanic eruptions (e.g. Pinatubo) in lead to cooling that lasts a few years.

I.G. Global Greenhouse Gas Emissions

The majority of the important greenhouse gases are compounds that are chemically inert or only slowly degraded by chemical reactions in the atmosphere. These gases tend to become well mixed in the atmosphere because of their long residence times. The most important example of such a greenhouse gas is CO_2.

The concentration of CO_2 in the atmosphere remained stable at 280±10 ppmV for several thousand years until the beginning of the Industrial Era in the middle of the18th century. Since then CO_2 concentrations have been steadily increasing to reach a level of 367 ppmV in 1999. The Mauna Loa record depicts an 18.8% increase in the mean annual CO2 concentration, from 315.98 ppmv in 1959 to 375.64 ppmv in 2003 (Figure I.3). The 1997-98 increase in the annual growth rate of 2.87 ppmv represents the largest single yearly jump since the Mauna record began in 1958 Three quarters of the present atmospheric increase is caused by fossil fuel burning while the last quarter is caused by land use changes (mainly deforestation). These emissions are partially compensated by

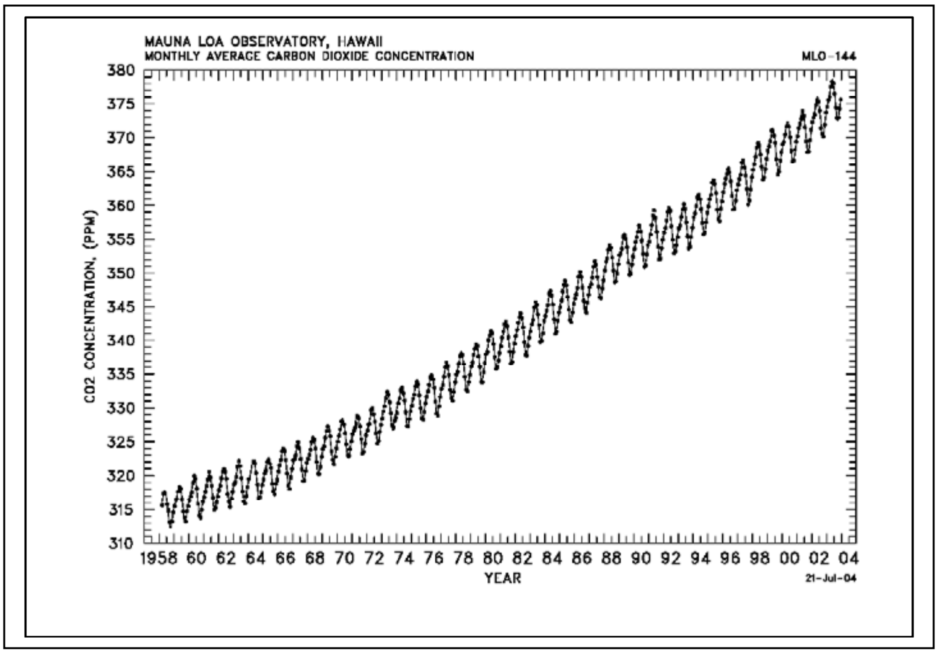


Figure I.3. CO_2 Concentrations at Mauno Loa since 1958 (through Nov., 2004). (74Hhttp://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm).

uptake of CO_2 by the oceans and by a terrestrial sink. CO_2 is soluble in water, and while it is essentially unreactive, the gas phase dissolved CO_2 becomes chemically reactive when it forms carbonate and bicarbonate ions; this favours the uptake in water. Land and ocean fluxes of CO_2 can be separated based on atmospheric measurements. For the 1980's and the 1990's such measurements showed a net uptake of CO_2 both by land and oceans, thus implying that the CO_2 release caused by land use changes are compensated by a net residual sink. Among the likely reasons for this sink is the 'fertiliser' effect of increased CO_2 and increased nitrogen (NOx, nitrate) deposition from the atmosphere. The residual terrestrial sink was estimated for the 1980'ies to be of the same magnitude as oceanic uptake.

Other greenhouse gases with relatively long atmospheric lifetimes are those covered by the Kyoto Protocol, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), as well as those listed in the Montreal Protocol and its amendments, the chlorofluorocarbons (CFCs), the hydrofluorocarbons (HFCs) and the halons. Methane derives partially from natural sources (e.g. wetlands and termites) but the anthropogenically-controlled sources provide a larger contribution (most important are rice agriculture, energy and ruminants). Methane is the second most important greenhouse gas, and its lifetime in the troposphere is determined by its reaction with the OH radical. Also N_2O comes both from natural and anthropogenic sources, agricultural soils being the most important anthropogenic source. The halogen-containing greenhouse gases are mainly of industrial origin.

The estimated total radiative forcing due to these well-mixed greenhouse gases is 2.36 Wm^{-2}, of which 1.46 Wm^{-2} from CO_2, 0.48 Wm^{-2} from methane, 0.34 Wm^{-2} from halocarbons and 0.15 Wm^{-2} from N_2O.

Ozone is the third most important greenhouse gas with respect to radiative forcing, and differs from the others by having a relatively short atmospheric lifetime (3-6 weeks above the boundary layer, less within the boundary layer) and thus being less

	CO_2 (Carbon Dioxide)	CH_4 (Methane)	N_2O (Nitrous Oxide)	CFC-11 (Chlorofluoro-carbon-11)	HFC-23 (Hydrofluoro-carbon-23)	CF_4 (Perfluoro-methane)
Pre-industrial concentration	~ 280 ppm	~ 0.70 ppm	~ 270 ppb	zero	zero	40 ppt
Concentration in 1998	365 ppm	1.745 ppm	314 ppb	268 ppt	14 ppt	80 ppt
Rate of concentration change, 1990-1999	1.5 ppm/year	7.0 ppb/year	0.8 ppb/year	-1.4 ppt/year	0.55 ppt/year	1 ppt/year
Atmospheric lifetime	5 to 200 yr	12 yr	114 yr	45 yr	260 yr	>50,000 yr

Table I.1 Examples of Greenhouse gases influenced by human activities (IPCC 2001)

uniformly distributed in the atmosphere than the long-lived greenhouse gases. It is not directly emitted but derives from photochemical reactions in the atmosphere, involving nitrogen oxides (NO_x) in combination with CH_4, CO or volatile organic compounds, the other source is influx of stratospheric air. The main sinks of tropospheric ozone are photochemical destruction in the atmosphere and deposition to the surface (mainly to vegetation). Ozone concentrations can be strongly influenced by anthropogenic emissions, but it is not straightforward to construct a historical record of atmospheric ozone concentrations. Based on evaluation of ozone surface measurements from the 19^{th} and early 20^{th} century ozone concentrations in Northern Hemisphere have approximately doubled since the pre-industrial era. The estimated radiative forcing due to tropospheric ozone is 0.35 Wm^{-2}. In addition to its direct effect, ozone has an indirect effect on some greenhouse gases (particularly methane) because it influences the tropospheric OH radical concentration and thus the oxidation rates of many gases.

Stratospheric ozone can influence climate both by absorbing incoming short-wavelength radiation and by absorbing the outgoing infrared radiation. The estimated overall radiative forcing caused by the depletion of the stratospheric ozone layer that has taken place is –0.15 Wm^{-2}.

I.H. Global warming and the hydrological cycle

Feedbacks between the atmospheric hydrological cycle and global warming have been extensively studied and discussed within the scientific community. A basic reason for expecting an impact of global warming on water in the atmosphere is that a warmer atmosphere can contain more water vapour. However, global warming may in many ways influence the evaporation, transport and precipitation of water, e.g. via atmospheric and oceanic processes. Feedbacks can be established, because water is itself an important greenhouse gas and also clouds have an influence on the radiative balance of the Earth. Current models predict that the water vapour feedback approximately doubles the global warming compared to what it would be for fixed water vapour concentrations.

Trends in water vapour concentrations in the lower troposphere have been investigated based on analysis of surface measurements and observations from weather balloons and satellites. The IPCC TAR concludes that water vapour concentrations in the Northern Hemisphere have likely increased several per cent per decade since the early 1970's, while changes in the Southern Hemisphere have not yet been assessed. Also the cloud cover over mid- and high latitude continental areas in the Northern Hemisphere appears to have increased by about 2% since the beginning of the 20^{th} century.

Greenhouse gases exercise radiative forcing much more efficiently at the low temperatures in the upper troposphere than at the close-to-surface temperatures in the boundary layer, and, in fact, models indicate that increases in water vapour in the region above the boundary layer (i.e. in the free troposphere) is the main reason for strong feedback effects. However, the water vapour feedback in the upper troposphere is more complex than in the boundary layer, where relative humidity tends to remain fixed, and thus water vapour concentrations increase with temperature. In the upper troposphere, a variety of dynamical and microphysical processes influence water vapour. Observational evidence for this region is ambiguous. Satellite observations have shown a statistically significant increasing trend of water vapour in the upper troposphere in a zone around equator (10^0N to 10^0S) for the period 1980 to 1997. Positive as well as negative trends were found for other latitudes but none of them were statistically significant.

Clouds have a cooling effect on the surface of the Earth by reflecting incoming short wavelength radiation (albedo effect), but they also absorb outgoing long-wavelength radiation and thereby contribute to greenhouse warming. The balance between the radiative cooling and warming influences of clouds depend on several factors, such as their liquid water content, cloud droplet (or crystal) equivalent radius and phase (liquid or ice). Clouds in the boundary layer are particularly important in this context, because their albedo effect is not compensated for by a significant greenhouse effect. It is clear that global warming caused by radiative forcing of greenhouse gases will, in turn, have an impact on clouds and thus lead to a change in cloud radiative forcing. However, the understanding of this feedback remains still very uncertain; and models even disagree about the sign of the expected net change in cloud radiative forcing e.g. associated with a doubling of CO_2 in the atmosphere.

Climate Sensitivity

A quantitative estimate of the warming for a given radiative forcing is expressed by the climate sensitivity, which is defined by the IPCC as the ratio between the rise in global surface temperature, ΔT_s for a given radiative forcing, ΔF:

$$\Delta T_s / \Delta F = \lambda.$$

The climate sensitivity depends on the feedbacks, mainly related to the hydrological components such as water vapour, ice albedo, lapse rate, clouds (see below). These feedback effects can be of considerably larger magnitude than the initial forcing. In addition to these physical feedbacks, there are biogeochemical feedbacks such as the influence of increased CO_2 concentrations on the uptake of CO_2 by vegetation. The climate sensitivity, defined as the equilibrium response of global surface temperature to a doubling of the CO_2 concentration, estimated by applying different AOCGMs, lies in the range of 1.5 to 4.5^0C. Recent studies of climate sensitivity point to a most likely value of around 3°C (see e.g. Kerr, 2004). The uncertainty on the climate sensitivity makes an important contribution to the overall uncertainty on projections of future climate change.

Aerosols, climate and the hydrological cycle

Aerosols can influence the radiative balance of the Earth directly by scattering of incoming sunlight as well as by absorption of radiation. In addition they exhibit indirect effects on climate through their interaction with clouds. The estimates of the effects of aerosols represent some of the main uncertainties in the present understanding of climate change (Figure I.4).

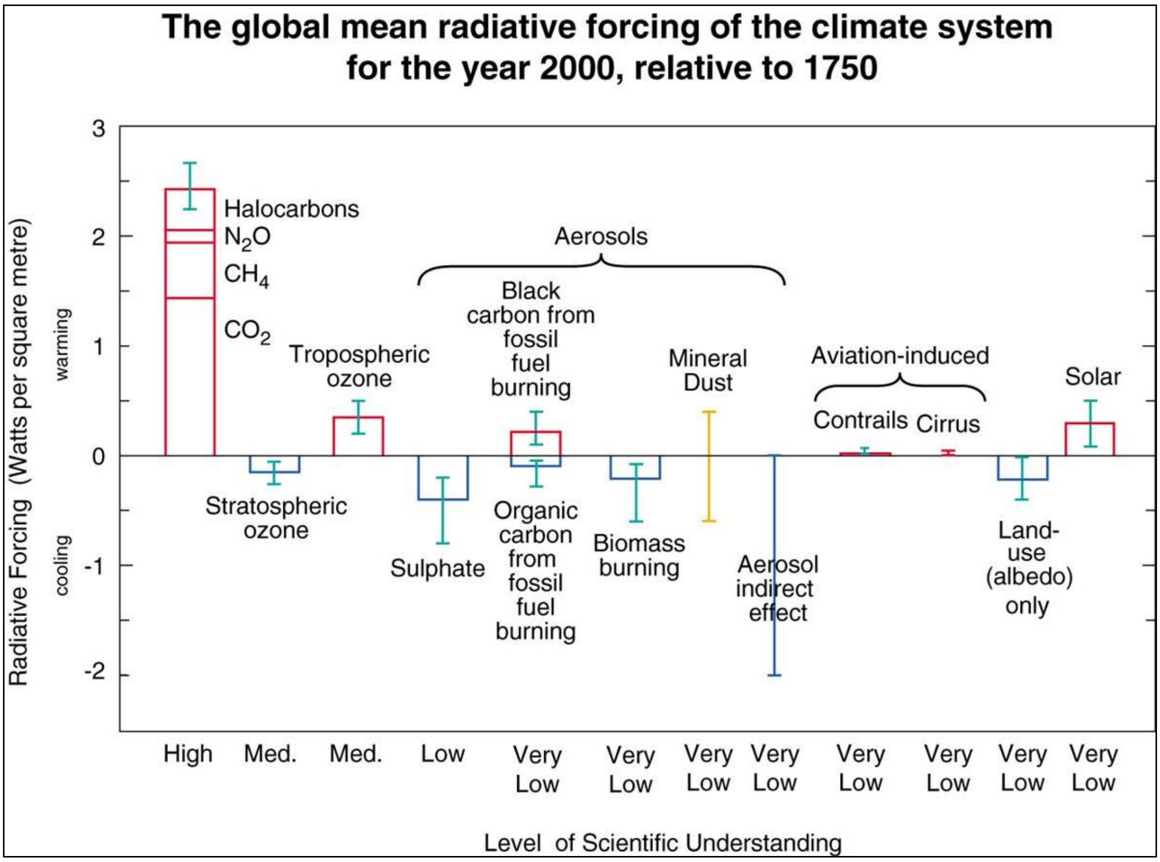


Figure. I.4. Radiative forcings and their uncertainties according to the IPCC (2001)

The climate impact of aerosols depend on their chemical composition and their size distribution, which has a strong influence on their atmospheric life times as well as their capacity to scatter light. The most important influence comes from aerosols in the accumulation mode, i.e. between 0.1 and 1 µm mass median diameters; smaller particles coagulate rapidly and deposition or formation of cloud droplets efficiently removes larger particles. Accumulation mode aerosol has atmospheric lifetimes up to several weeks.

Atmospheric aerosols are directly emitted (primary aerosols) as well as formed by gas to particle conversion following chemical reactions in the atmosphere (so-called secondary aerosols). Particles are modified in the atmosphere by physical as well as chemical mechanisms (coagulation, condensation, cloud processing, etc.). Important sources of primary aerosol are soil dust, sea salt, industrial dust and carbonaceous aerosols (organic and black carbon) as well as primary biogenic aerosol. Black carbon aerosols from fossil fuel or biomass burning are of particular relevance because of their capacity to absorb light and thus contribute to heating of the atmosphere. Secondary aerosol frequently derives from oxidation of sulphur dioxide or natural organic sulphur compounds (such as DMS) to sulphuric acid, from the oxidation of natural and anthropogenically emitted volatile organic compounds (VOCs such as terpenes, aromatics) as well as from the formation of ammonium nitrate following the oxidation of NO_x to nitric acid. Volcanoes are an important source of primary dust aerosol as well as sulphur dioxide in the atmosphere.

The direct radiative forcing caused by anthropogenic aerosol has been estimated using models that simulate the global distribution of particles as well as their optical properties. There are large uncertainties involved in such models, both related to their concentrations and to their optical properties. Validation of model simulations has been performed through comparison with observations, e.g. surface measurements of particle concentrations and composition as well as estimates of atmospheric optical depths and total aerosol reflectivity based on satellite observations. Direct forcing by anthropogenic aerosols is estimated to be –0.4 Wm^{-2} for sulphate, -0.2 Wm^{-2} for aerosols from biomass burning, –0.1 Wm^{-2} for fossil fuel organic carbon and +0.2 Wm^{-2} for fossil fuel black carbon aerosols. The uncertainties on these numbers are illustrated in Figure I.4. Other estimates have recently been presented by NASA scientists (Hansen, 2002, Hansen and Sato, 2001) who calculates a net forcing (including indirect effects) of black carbon of 1 ±0.5 W m^2 and of -0.6 to -1.0 W m^{-2} for sulphate aerosol.

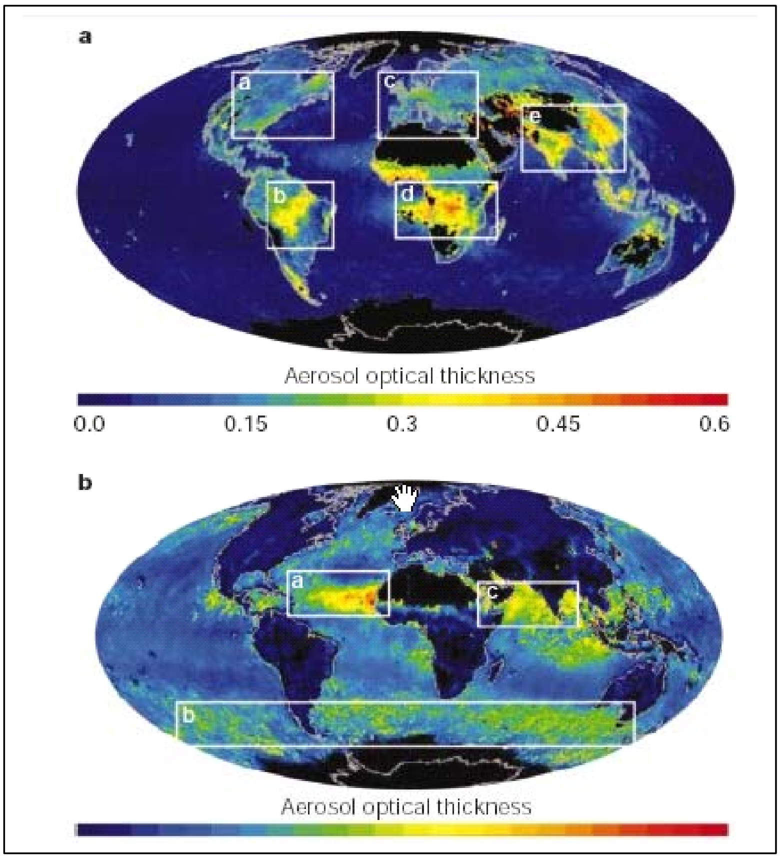


Figure I.5. Aerosol optical thickness (AOT) derived from satellite observations (Kaufman et al., 2002).

(a). Distribution of fine AOT, showing fine particles from pollution (a, c and e) and vegetation (b and d).

(b). Distribution of coarse AOT from dust (a), salt particles (b) and desert dust (c).

There are two indirect effects of aerosols on clouds that can lead to radiative forcing. The first indirect effect is due to an increase in droplet number in clouds caused by an increase in the concentration of cloud condensation nuclei leading to an enhanced reflectivity of these clouds and thus to a negative radiative forcing. The hypothesis of this effect is supported by experimental evidence, e.g. satellite observations of reflectivity and cloud drop concentrations in polluted vs. clean air. The second indirect effect is related to the hypothesis that the influence of aerosols also will reduce the precipitation efficiency of clouds and this, in turn, will lead to more persistent clouds and thus increase cloud albedo. There is clear experimental evidence for the influence of aerosols on the precipitation efficiency of clouds, e. g. based on satellite observations of the impact of forest fires (Rosenfeld, 1999), urban and industrial air pollution (Rosenfeld, 2000) and desert dust (Rosenfeld *et al.*, 2001) on rainfall. All in all, the indirect effect of aerosols on clouds is potentially very important but at the moment their magnitude is highly uncertain.

A semi-direct effect of absorbing aerosols on clouds, suggested by model studies, is due to the fact that a warming of the atmosphere may cause evaporation of clouds (e.g. Hansen *et al.* 1999).

Several important studies on the effect of aerosols on climate and, particularly, on the hydrological cycle, have been published after the TAR. A major finding was that of the so-called "Asian Brown Cloud" during the INDOEX experiment, which is a brown haze covering most of the Arabian Sea, Bay of Bengal and the South Asian region in the period between November and April (and possibly longer) (Ramanathan *et al.* 2001). Anthropogenic sources were found to contribute about 80% to the aerosols in this 'cloud', which has a high content of absorbing, black carbon aerosol. This leads to a large negative forcing at the surface (-20 ± 4 W m^{-2}), about an order of magnitude larger than the positive forcings by greenhouse gases, and to a strong heating of the atmosphere. The resulting reduced ocean heating is likely to lead to a reduction in the precipitation. In fact, as pointed out by Ramanathan *et al.* (Current Science 2002), a pronounced decrease in precipitation in the tropics has taken place since the 1950s (Hulme *et al.,* 1998), contrary to predictions by models that do not include aerosol effects. Model calculations indicated that the perturbations caused by the 'cloud' have an important influence on tropical rainfall patterns.

Another recent example of the importance of black carbon aerosol in regional climate change comes from the model simulation study by Menon *et al*. (2002) of the influence of aerosols on precipitation and temperature changes in China. It was found, that the observed trend towards increased summer floods in South China, increased drought in North China and moderate cooling in China and India (contrary to the global trend) were comparable to the effects of aerosols simulated by a global climate model.

Andreae *et al*. (2004) show that the influence of smoke from Amazon forest fires suppresses the onset of precipitation from 1.5 kilometres above cloud base in pristine clouds to more than 5 kilometres in polluted clouds. This means invigorating of updrafts which causes intense thunderstorms, large hail and increased likelihood that cloud tops may penetrate into the stratosphere, which may give profound impacts on the climate system

Satellite observations of aerosol optical depths (Kaufman *et al.*, 2002) show that phenomena like the "Asian Brown Cloud" are found in and downwind of all inhabited areas of the world; thus emphasizing the importance of improving the understanding of the impact of anthropogenic absorbing aerosols on regional climate change (see Figure I.5).

I.I. Future projections

Large efforts have been made in recent years to construct reliable global climate models and several Atmosphere-Ocean General Circulation Models (AOCGM) are now available. Regional climate models with higher spatial resolution supplement these global models, having a relatively coarse resolution of hundreds of kilometres or more. Not all of the forcings discussed above were included in the models used for the TAR projections; in most cases only well-mixed greenhouse gases and the direct effect of sulphate aerosols were considered. Models, used for the simulation of future global climate change scenarios in the TAR, were evaluated against observations; i.e. their ability to simulate present and past climates was tested and it was concluded that they provide credible simulations of climate, at least down to sub-continental scales and over temporal scales from seasonal to decadal.

The projection of future climate changes requires not only an understanding of the physical (and possibly biogeochemical) aspects but also predictions of future emissions scenarios. The IPCC has defined a number of scenarios for the world economic and demographical development, grouped into different storylines and scenario families, that differs e.g. by the rate of economic growth, use of non-fossil energy sources and population growth. The TAR has compared the results of these different scenarios. The variations caused by choice of scenario were found to be of the same order as those caused by the choice of model.

The TAR concentrates particularly on two scenarios from the IPCC Special Report of Emission Scenarios (SRES), A2 and B2, that differ with respect to population growth rates (A2 has the highest population growth rate) and socio-economic development. A2 represents a scenario with relatively high greenhouse gas emissions while B2 has relatively low emissions. For the global average surface air temperature (SAT), applying the A2 scenario, the models predict an increase of 1.1^{0}C with a range from 0.5 to 1.7^{0}C for the difference between average 1961-1990 and average 2021 to 2050. For the B2 scenario, the mean is 1.2^{0}C with a range from 0.5 to 1.4^{0}C. If the 1961-1990 average is compared to the average global surface temperature at the end of the century, the differences become somewhat more pronounced: A2 gives a mean value of 3.0^{0}C with a range of 1.3 to 4.5^{0}C while B2 gives a mean of 2.2^{0}C with a range of 0.9 to 3.4^{0}C. The projected temperature increases over the 21st century (1990 to 2100) have been calculated for the full set of scenarios described in the SRES, using a simplified procedure compared to the full AOCGM runs; the global average surface temperature increases predicted were in range 1.4 to 5.8^{0}C in 2050.

Inclusion of sulphate aerosols in the models lead to a slower warming in interval up to the mean mid-21st century; e.g. for one of the typical scenarios (IS92a) the average temperature increase goes down from 1.6 to 1.3^{0}C when sulphate aerosols are included. Since fossil fuel burning is a source of sulphate aerosol, the inclusion of such aerosol tend to mitigate the greenhouse warming caused by use of these fuels and thus make alternative scenarios less favourable in the short run. However, since the removal of CO_2 from the atmosphere is much slower than the deposition of aerosols, at longer time scales the warming caused by the accumulated CO_2 dominates over the cooling by the sulphate aerosols, and the scenarios with high fossil fuel consumption becomes the most unfavourable.

The projected warming is not uniformly distributed: the land warms faster than the sea and the strongest warming is expected at high latitudes.

The IPCC has been criticised by US scientists for paying too much attention to unrealistically high CO_2 emission scenarios (e.g. Hansen and Sato, 2001, Hansen *et al.*, 2001). These scientists also emphasise the relatively large contribution that non-CO_2 greenhouse gases and absorbing aerosols have given to global warming in recent decades and propose to pay more attention to the benefits that may be obtained by reduction of methane emissions and air pollution (ozone and absorbing aerosols).

After the TAR, a detailed study of projected radiative forcings due to ozone changes in the troposphere and the lower stratosphere in the 21st century has been published (Gauss *et al*., 2003). This study, based on a modified SRES emission scenario, considered to be an upper limit for ozone precursor emissions, analysed the results of 11 chemical transport models and used them as input for radiative forcing calculations. The estimated radiative forcings from 2000 to 2100 due to the increasing tropospheric ozone and the recovery of ozone in the stratosphere were in the range from 0.40 to 0.78 $W.m^{-2}$ with an average of 0.56 $W.m^{-2}$. The combined forcings of all the well-mixed greenhouse gases in the same scenario is exactly 10 times as much.

Precipitation:
The predicted changes in precipitation in the 21st century are pretty much in line with the changes that have been found in the 20th century. Globally water vapour and precipitation are expected to increase, although not with a uniform distribution of the precipitation (Figure I.6.). According to the modelling results, precipitation at high latitudes will increase both summer and winter. Mean precipitation at subtropical latitudes will decrease while precipitation in most tropical areas will increase. In spite of the projected global increase in precipitation, decreases in soil moisture are expected in mid-continental areas, because an increased potential evaporation is not balanced by precipitation.

Sea level rise:
Projected changes in sea level over the 21st century have been calculated using the full set of SRES emission scenarios and seven AOGCMs. For each of the scenarios the mean value of the model was calculated, this gave estimated sea level rises of 0.09 to 0.88 m over the period from 1990 to 2100. The mean value of this projected rise corresponds to a rate of between two to four times the rate over the 20th century. The main cause of this rise is thermal expansion and melting of glaciers (0.11 to 0.43 m and 0.01 to 0.23 m, respectively). The thermal expansion is expected to accelerate through the 21st century. The contribution from Greenland (-0.02 to 0.09 m) and the Antarctic (-0.17 to 0.02 m) are relatively small and could even be negative. Rising sea levels will cause more frequent extreme high water levels; this tendency may be further enhanced if the frequency or intensity of storms increases as a result of global warming.

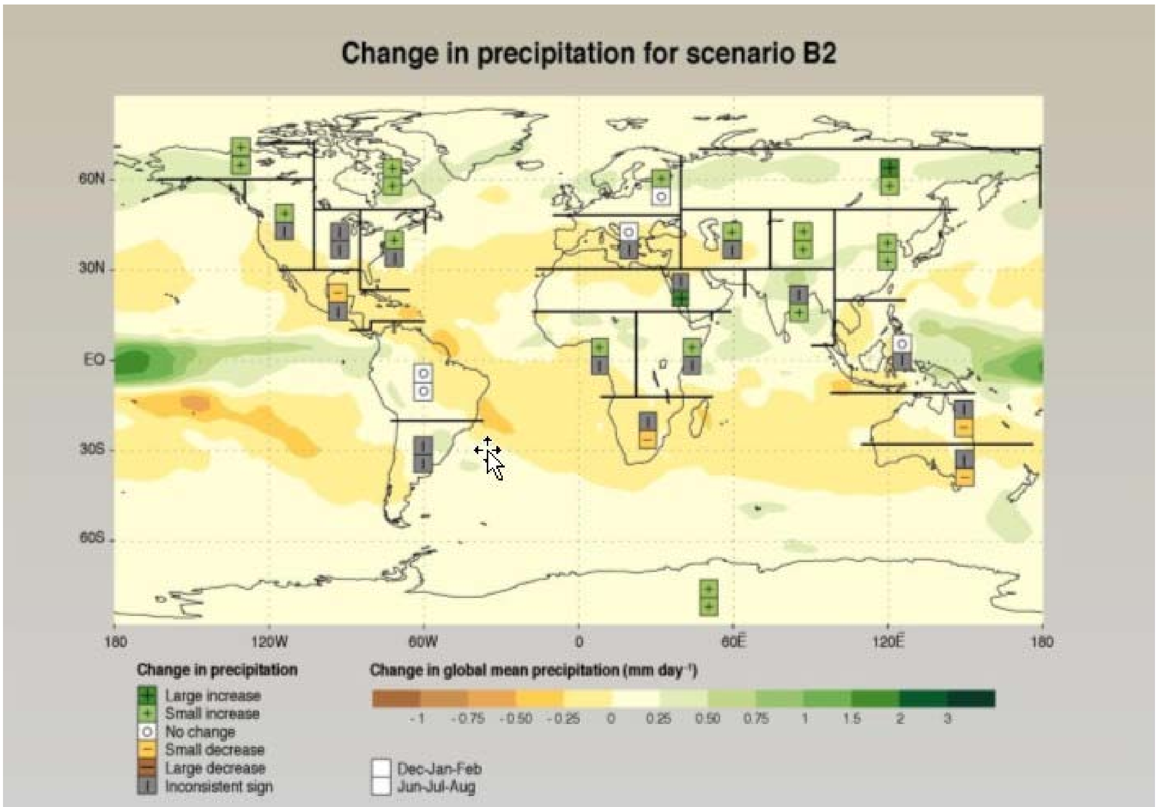


Figure I.6. Projected changes in precipitation for a medium level emission scenario (IPCC 2001)

The estimate made in the TAR Arctic and Antarctic ice sheets takes only snowfall, sublimation and melting into account. The NASA scientist James Hansen (Hansen, 2003 and references therein) argues that there are non-linear processes and feedbacks that may lead to an accelerated, much faster collapse of ice sheets. This prediction is supported by paleoclimate data: it seems that the sea-level during the previous (Eemian) interglacial period was 5-6 meters higher than today. In order to reach the temperatures of the Eemian period an additional average global warming of only about 1 ^{0}C is needed. Paleoclimatic evidence shows also that deglaciation can be rapid: deglaciation after the last ice age gave about 1 m sea level rise every 20 years for several centuries. An additional contribution to the melting of Greenland and Antarctic ice sheets may come from warming due to increased surface absorption of sunlight because of deposition of black carbon particles (Hansen, 2004).

Extreme Events
Model simulations suggest that the frequency of some extreme events will increase over the 21st century, while in other cases the frequency of extremes may be reduced (e.g. the number of frost days). Table I.2 summarises the findings.

I.J. Interannual climate oscillations

Global climate is influenced by large-scale natural oscillations. The strongest of these natural fluctuations is the El Niño-Southern Oscillation (ENSO). This phenomenon is related to a change in the ocean-atmosphere system over the tropical Pacific, which normally is characterised by a situation where the trade winds push warm surface water towards the west Pacific causing a gradient in the sea surface level across the Pacific and upwelling of cold water at the east side of the ocean. ENSO is associated with a relaxation of the trade winds that stops the upwelling of cold water and leads to unusually high temperatures in the tropical Pacific. This eventually leads to changes in the atmospheric circulation that extend to influence the weather around the globe. The opposite phase of ENSO is called La Niña and leads to unusually low temperatures in the tropical Pacific. ENSO occurs irregularly with two to seven years intervals and its most intense phase lasts around one year. Extreme temperature events have been observed during the 1997/98 El Niño event.

Other mechanisms leading to interannual oscillations of climate are known; the North Atlantic Oscillation and the Arctic Oscillation are particularly important for climate variations in Europe. These oscillations have longer time scales than ENSO. There is growing understanding of the role of these oscillations and global climate models are now starting to reproduce variations that resemble ENSO.

Current models show little change or a small increase in the intensity over the next hundred years. However, as the ‘baselines’ for variables such as temperature and precipitation changes with global warming, also an El Niño event of normal intensity is likely to lead to greater extremes.

Confidence in the observed changes (latter half of the 20th century)	***Changes in phenomenon***	***Confidence in the projected changes (during the 21 century)***
Likely	**Higher maximum temperatures and more hot days over nearly all land areas**	Very likely
Very likely	**Higher maximum temperatures, fewer cold days and frost days over nearly all land areas**	Very likely
Very likely	**Reduced diurnal temperature range over most land areas**	Very likely
Likely, over many areas	**Increase of heat index[a] over land areas**	Very likely, over most areas
Likely, over many Northern Hemisphere mid- to high-latitude land areas	**More intense precipitation events**	Very likely, over many areas
Not observed in the few analyses available	**Increase in tropical cyclone peak wind intensities**	Likely, over some areas
Insufficient data for assessment	**Increase in tropical cyclone mean and peak precipitation intensities**	Likely, over some areas

a) Heat index: A combination of temperature and humidity that measures effects on human comfort.

Table I.2. Estimates of confidence in observed and projected changes in extreme weather and climate events (IPCC, 2001)

Northern Hemisphere thermohaline circulation (THC)

THC is the circulation in the Atlantic of warm surface water flowing northwards and cold saline water flowing southwards at depth. This 'conveyor belt' has an important influence on the temperature of the surface water in the North Atlantic and causes warming of the atmosphere that contributes to give the relatively mild winters in Western Europe. This circulation is driven by density differences that are caused by temperature and salinity differences. Changes in the buoyancies of surface waters can have an important impact on this mechanism, and such changes can in several ways be caused by the effects of global warming, e.g., by changes in precipitation and melting of sea-ice. Most models show a weakening of the THC, however none of them predict a complete shutdown within the 21s^{t} century. All models predict that the increased greenhouse warming over Europe will more than compensate for the reduced heat transport by the THC.

Chapter II. Climate Change at the European scale

Key Points

- **The average increase in the observed annual mean temperature across the European continent is 0.8^{0}C. The temperatures during the winter season have in general increased more than during the summer.**

- **The summer of 2003 was very likely the hottest summer and the last 30 years appear to have had the warmest climate within the last five centuries.**

- **Aerosols and ozone appear to exert an important influence on radiative forcing in the Mediterranean basin.**

- **Annual precipitation over Northern Europe has increased by between 10 and 40% in the last century while the Mediterranean basin has experienced up to 20% reduction in precipitation.**

- **Heat waves as well as intense precipitation events, especially in winter, will become more frequent throughout Europe. Risk of drought is likely to increase in central and southern Europe.**

Chapter II. Climate Change at the European scale

The observed and expected impacts of climate change vary significantly at the regional European scale, e.g. from reduced precipitation in the Mediterranean basin to increased precipitation at higher latitudes. Also the socio-economic impacts of a certain climatic trend can depend strongly on where in the European region it is observed; increasing temperatures, for example, may give advantages for agriculture at locations where it is temperature limited (at high latitudes) while a temperature rise may have adverse effects at more southern latitudes.

Regional climate change is discussed in the TAR. One of the contributions to this discussion within the TAR was a detailed assessment of potential effects and adaptations for Climate Change in Europe performed within the EC project ***ACACIA***. The literature that has appeared after the TAR has paid particular interest to climate change in the Mediterranean region and the impact of aerosols on climate records.

II.1. Temperature Trends

Temperature variations were analysed in the ACACIA study: The average increase in the observed annual mean temperature across the continent is 0.8^0C, with the strongest increases observed over Northwestern Russia and the Iberian Peninsula. The temperatures during the winter season have in general increased more than during the summer. Also an increase in SSTs over the 20^{th} century has been observed. A tendency towards a warmer climate is reflected by changes in biological indicators, such as the length of the growing season and the lengthening of the ice-free season lakes. Nocturnal temperatures have increased more than daytime values, and there is some evidence from European observations that this is associated with increased cloudiness.

Many areas in Europe have experienced an unusually hot summer in the year 2003. An analysis of reconstructed surface temperature fields in Europe back to 1500 (Luterbacher *et al*., 2004) showed that the summer of 2003 was very likely **the** hottest summer and that the last 30 years appear to have the warmest climate within these last five centuries (Figure II.1).

Projected global temperature changes were simulated within ACACIA based on four different SRES global emission scenarios combined with a range of climate sensitivities (from 1.5 to 4.5^0C) reflecting the uncertainties on this parameter. The resulting temperature changes in 2055 compared to the average temperature in the period 1961 to 1990 lie between 0.97 and 2.64^0C. Aerosol effects were not included.
Future changes in the temperatures in Europe were calculated using five different Global Circulation Models (GCMs) adapted to estimate the European warming under the conditions of the four global scenarios. The results indicated that annual temperatures would rise at a rate of between 0.1 and 0.4 ^{0}C per year, which may be compared to the present temperature increase in Europe (since the mid-1970'ies) of about 0.2^0C per decade. The largest increases are projected for Northeast Europe (Finland, Western Russia, 0.15-0.6^0C per decade) in the winter months and for Southern Europe in the summer months (0.2-0.6^0C per decade). The smallest temperature increases are expected along the Atlantic coastline. The best agreement among the models is found for southern Europe in the winter while the largest disagreements are found in the same region in the summer.

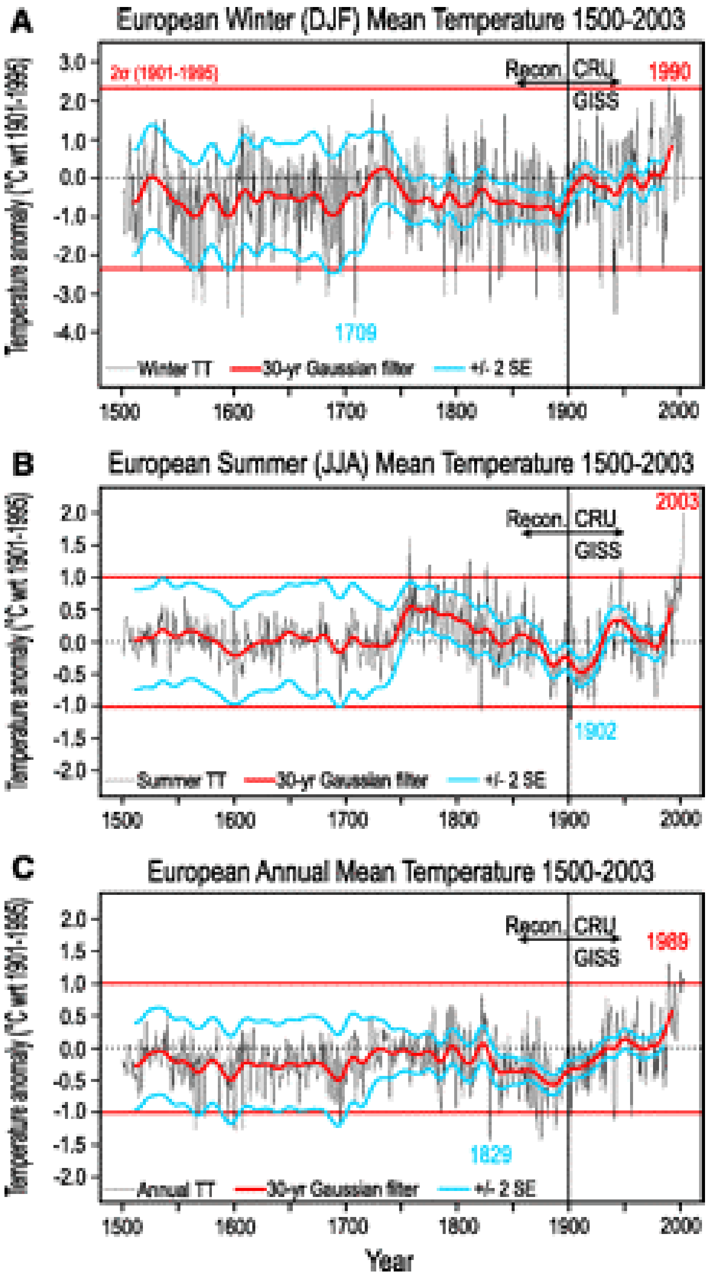


Figure.II.1. Winter (A), summer (B) and annual (C) averaged–mean temperature anomalies (relative to the 1901 to 1995 average) over the period from 1500 to 2003, over the land area 25°W to 40°E and 35°N to 70°N (thin black line). The figure is reproduced from Luterbacher *et al.* (2004), where the sources of the data are described. Blue lines show ±2 standard errors while the red horizontal lines are the ±2 standard deviations for the period 1901-1995. The thick red line is a 30-year Gaussian low-pass filtered time series. Coldest years are denoted in blue, warmest years in red. Possible inhomogeneities in the instrumental data before the mid-19th century cannot be fully excluded (e.g. caused by insufficient radiation protection)

Aerosols and climate change in the Mediterranean

The impact of reflecting as well as absorbing aerosols on climate was not included in the model simulations that for the basis of the discussion of the European regional scenarios in the TAR. As mentioned in Part A, recent observations have indicated that high aerosol levels may cause a substantial impact on climate in several parts of the world. Within Europe, it appears that particularly the Mediterranean basin is subject to the influence of aerosols: several studies indicate that aerosol radiative forcing over the summertime Mediterranean is among the highest in the world. Studies have shown (Lelieveld *et al*., 2002) that the Mediterranean area has become a global air pollution 'crossroads' with transport of polluted air masses from west and eastern European from the north in the boundary layer, Asian (and to a lesser extent North American) pollution in the mid-troposphere and Asian Pollution in the upper troposphere. Although southerly winds are uncommon in the summer, also transport of Saharan dust can be important in some episodes [MINATROC].

An observed radiative forcing at the surface of about 18 $W.m^{-2}$ was 2.7x higher than at the top-of-the-atmosphere fording, thus implying a large absorption of solar radiation within the atmosphere due to absorbing aerosols, particularly black carbon, and water vapour (Ramanathan *et al*., 2001). The result is cooling of the surface and heating of the atmosphere; it seems likely that the warming tendency, which is mainly in the lowest 4 kilometers of the atmosphere, is exported to northern Africa with the prevailing winds during the summer, and impacting the Mediterranean Sea region

The inputs of polluted air to the Mediterranean do also contribute to elevated levels of ozone that has been found to contribute significantly to radiative forcing in the area during the summer (e.g. Hauglustaine and Brasseur, 2001).

Precipitation

The observed changes in precipitation rates over Europe in the 20th century follow the general hemispheric trend of increasing precipitation at mid- and high latitudes and decreasing precipitation in the subtropics. The observations showed a strong decadal variation in drought frequency. The variations projected for scenarios including man-made forcings have been compared to the variations found in a model simulation over 1400 years with no anthropogenic changes. This analysis showed that the anthropogenic influence on projected temperature changes tend to be more significantly different from natural variations than the anthropogenic influence on precipitation changes.

Northern Europe

Annual precipitation over Northern Europe has increased by between 10 and 40% in the last century; the strongest increases are found in Scandinavia and Western Russia. The changes in Central Europe are less pronounced and include both increases (in the western part) and decreases (in the eastern part). The projected precipitation in the 21st century was evaluated within the ACACIA project in the modeling exercise mentioned above. It was found that the trend towards increasing precipitation in Northern Europe would continue at a rate of 1 to 2% per decade. An increasing trend is expected for the winter as well as the summer season. The projected changes for Central Europe (e.g. France and Germany) are small or ambiguous.

Southern Europe

Most of the Mediterranean basin has experienced up to 20% reduction of precipitation in some areas during the last century. The projections for the 21st century show further decreases in precipitation over Southern Europe, but not by more than, at most, about 1%. Contrary to Northern Europe, there is a marked difference between the seasons: apart from the Balkans and Turkey, Southern Europe can expect more precipitation in the winter while in the summer precipitation is projected to decrease by up to 5% per decade. The previously mentioned effects of aerosol pollution over the Mediterranean, implying cooling of the sea-surface and heating of the atmosphere, are likely to cause reduced summer precipitation in the region. These aerosol-driven changes are not included in the TAR evaluation of European climate change.

Storms and other extreme weather events

The intensification of the hydrological cycle is likely to cause more intense storms and other extreme weather events, but the available studies regarding Europe appear to give a rather fragmented and incomplete picture of this tendency. An analysis of maximum 1-day precipitation records in the Nordic countries showed a maximum in the 1930s and an increasing trend in the 1980s and 1990s. Daily precipitation intensities have been found to increase in recent decades in the UK in the winter, but not in other seasons. Also storminess over the North Atlantic has increased in recent decades, but storm intensities are not larger than in the beginning of the 20th century. The TAR does not explicitly quantified the risk of extreme weather events in their projections of future climate scenarios, but it is concluded that it is likely that summer heat waves as well as intense precipitation events, especially in winter, will become more frequent throughout Europe, especially in winter. Risk of drought is likely to increase in central and southern Europe. Also gale frequencies may increase. Flood hazard is projected to increase in much of Europe, except where snowmelt peaks have been reduced.

Mountain regions
Temperature increases in mountain zones will result in an upward shift of biotic and cryospheric zones that is likely to lead to a perturbation of their sensitive ecosystems. The most spectacular effect of temperature rises in areas at high elevation is the melting of glaciers, but also tree line rises and changes in vegetation have been observed. Observations in the Swedish Scandes have shown tree line rises of up to 150-165 m (Kullman, 2001) and saplings of mountain birch, spruce and pine have recently become established 500-700 m over their current tree limits (Kullman, 2004). The upward migration of tree species is projected to continue, but there are some uncertainty regarding how fast this will take place and how far it will go. The TAR concludes that the redistribution of species caused by climate change in mountain regions will cause a risk of extinction in some cases.

Projected changes for mountain regions suggest that the European Alps are likely to have slightly warmer winters with more precipitation than previously while the summer climate may become much warmer and drier than today (Beniston, 1995). It seems likely that alpine climate change will lead to changes in timing and amount of run-off in European river basins and that floods and droughts will become more frequent.

II.2. Impacts in European Coastal Areas

Sea level rise
The sea level rise predicted under the scenarios considered in the TAR for European regional climate change is in the range between 13 and 68 cm by the 2050s, mainly due to thermal expansion of the oceans. This estimate does not include the effects of vertical land-movements that are adjustments after the last glaciation nor effects of oceanic circulation, which will cause some differences in relative sea-level change across Europe. Regional values, e.g. at European Coasts, can be 50% higher or lower (UKCIP02, 2003). Sea level rise of 0.5 to 2m are expected after the climate system will be in equilibrium with a CO_2 concentration of 560 ppmV (twice the pre-industrial concentration), but this will happen over several hundreds of years.

As mentioned earlier, the predictions by the IPCC are ‘conservative’ in the sense that they consider only snowfall, sublimation and melting and do not incorporate nonlinear processes and feedbacks that, according to other studies, may enhance deglaciation very significantly and possibly cause sea level rises of several meters over a century (Hansen, 2003). If these, more pessimistic, predictions are correct, sea-level rise may well become the globally most important climate change-related problem. A rising sea level possibly combined with more frequent storms and associated surges are likely to cause enhanced coastal erosion (see Section IV.C). Whether the effects of the recent tsunamis in the Indian Ocean were exacerbated by sea level rise is unlikely.

Chapter III. The Hydrologic Cycle

Key Points

- The "hydrologic cycle" comprises nature's method of replenishing, redistributing and purifying the world's natural water resources.
- Increases in temperature may lead to increased evaporation, and changes in precipitation patterns and regimes.
- Global average precipitation is predicted to rise, but this increase is likely to be regional. Winter and spring precipitation may increase in Northern Europe and summer precipitation will decrease, although southern, central and Eastern Europe may experience reduced precipitation.
- The incidence of extreme precipitation events is predicted to increase, which suggests implications not only for increased contamination resulting from run-off but also decreased groundwater recharge and increased incidence of flooding. Duration, intensity and frequency of drought spells might also increase.
- Changes in precipitation patterns might influence availability of surface water resources, leading to increased exploitation of groundwater. Exploitation beyond a sustainable level may adversely impact wetlands and coastal ecosystems.

Chapter III. The Hydrologic Cycle

III.1. INTRODUCTION

Water covers 70% of the Earth's surface, and is present in the atmosphere and the crust; it also comprises a large part of all living matter. Water is the only natural resource that exists naturally in three forms: liquid, solid (snow, ice) and gas (clouds). Unlike most mineral resources, it is renewable it exists in an endless cycle, moving between its gaseous, liquid and solid forms. This "hydrologic cycle" comprises nature's method of replenishing, redistributing and purifying the world's natural water resources.

By hydrologic cycle we mean the circulation (and transformation) of water between the earth and the atmosphere through different pathways (Figure III.1). Being a cycle, it has no specific beginning or ending. Rather, liquid water from the Earth's surface, particularly the oceans, is either evaporated into a gaseous form and enters

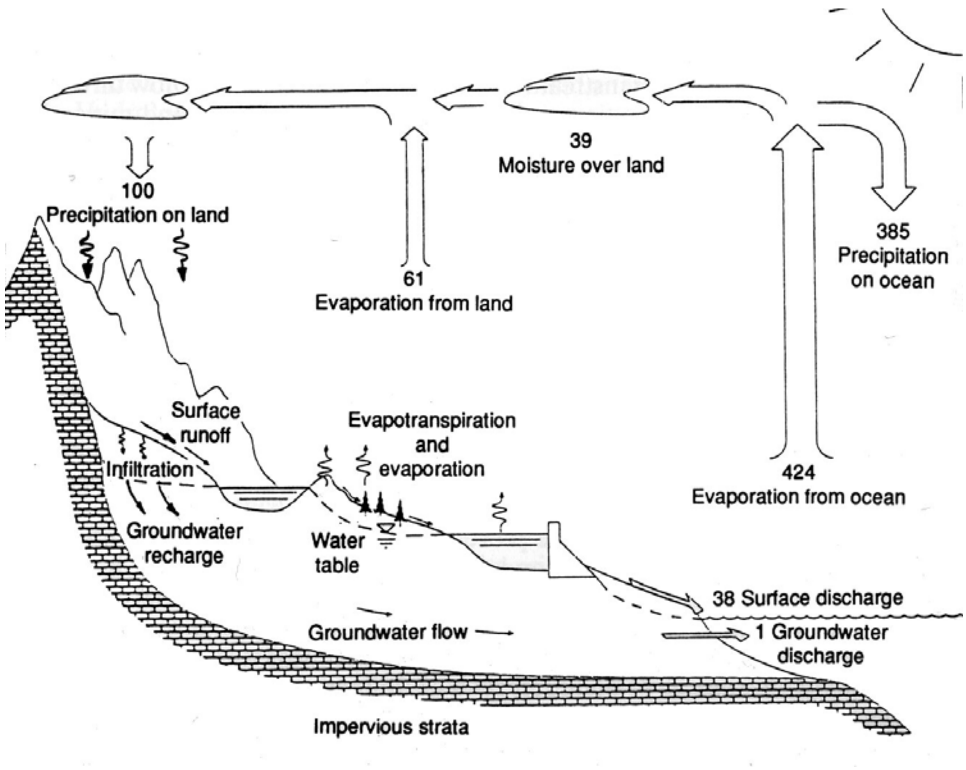


Figure III.1. The hydrologic cycle, with annual volumes of flow given in its units relative to the annual precipitation on the land surface. Because of its negligible magnitude compared to other components, aerosol has been removed from the cycle (Maidment, 1993; with permission).

the atmosphere as water vapor (clouds) or is dispersed in the atmosphere through aerosols. The atmospheric moisture is eventually returned to the Earth's surface in the form of rain, snow or hail. Approximately 100,000 km^3 (about 20% of the total global annual precipitation) falls onto the land surface of the continents. Except for that portion evaporated or transpired directly back into the atmosphere, and the portion moved directly into the atmosphere through aerosols, most of the water reaching the land surface in the form of rain, snow or hail will eventually find its way back to the oceans via transport in streams, rivers, lakes, reservoirs, wetlands and groundwater bodies, to begin its cycle anew.

Approximately 42,000 km^3 of precipitation flows each year to the oceans through the world's rivers. Some of the precipitation will seep down into the Earth's surface and become groundwater. Some of it will be taken up by plants and subsequently released in gaseous form back into the atmosphere via transpiration. A substantial quantity of water is returned to the atmosphere in this manner, thereby short-circuiting the full hydrologic cycle. It is estimated, for example, that a hectare of corn can transpire about 30-40 m^3 of water into the atmosphere each day. Nevertheless, because of their enormous surface area, the most important source of water in the atmosphere is evaporation from the oceans, which comprises nearly 90% of the total global evaporation. Indeed, more water evaporates from the oceans than is directly precipitated back, thus creating the driving force for the hydrologic cycle.

III.2. HYDROLOGIC CYCLE COMPONENTS AND CLIMATE CHANGE

Geographical Distribution of Resources

The magnitude of each component of the hydrologic cycle in a region or country is determined by a number of factors, including the amount of water received from precipitation, inflow and outflow in rivers and aquifers (this factor is particularly important in transnational water bodies) and the amount lost by evaporation and evapotranspiration (influenced to a large extent by local land use/land cover). Human activities also greatly affect individual components of the hydrological cycle, through actions such as water abstraction from ground and surface water bodies, through irrigation, and morphological changes. Methods for calculating the availability of freshwater resources vary considerably from country to country, making comparison difficult. Rees and Cole (1997) have developed a method of estimating the renewable freshwater resources across the EU. The method uses data from hydrometric (river gauging) networks, supplemented by an empirical freshwater balance model that relates runoff to precipitation and potential evaporation. Freshwater resources vary considerably across the European Region: annual runoff ranges from over 3000 mm in western Norway, to 100 mm over large areas of Eastern Europe, and to less than 25 mm in inland Spain (figure III.3). The average annual runoff for the member countries of the European Environment Agency (EEA, 1998) is estimated to be about 3100 km^3 per year. This is equivalent to 4500 m^3 per capita per year for a population of 680 million (Stanners and Bourdeau, 1995). The population of the WHO European Region is some 870 million, but figures for total runoff are not available. Specific processes govern the generation of each individual component in the hydrologic cycle. The following paragraphs offer a description of each component, and how each could be possibly affected by climate change.

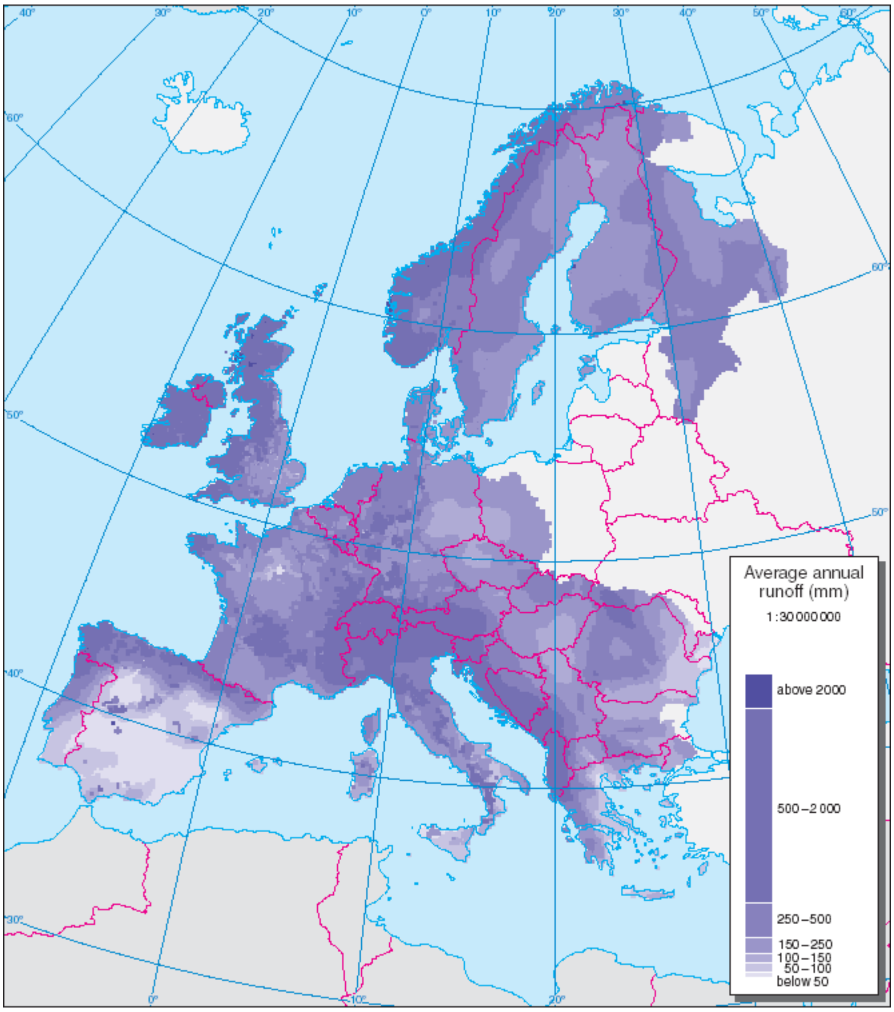


Figure III.2. Long-term average annual runoff in the European Union and nearby areas (EEA, 1998).

Precipitation

Precipitation is the primary mechanism for transporting water from the atmosphere to the surface of the earth. Dominant variables in precipitation dynamics are temperature, density and pressure. The starting point for precipitation formation is atmospheric moisture content, expressed as the *mixing ratio* (ratio between mass of water vapor and mass of dry air) or *specific humidity* (ratio between water vapor mass and total mass). Clouds form when air becomes supersaturated with water vapor, i.e. when moisture content is higher that corresponding to saturation vapor pressure. Supersaturation is associated with the rapid cooling of ascending air masses, where water vapor condenses forming hydrometeors. Aerosol particles in turn act as *seeds* for the formation of water droplets, which fall to the ground when their weights exceed the carrying capacity of atmospheric currents. Because of atmospheric circulation, water vapor can move over large distances; thus precipitation, in any of its forms (rain, hail, snow, sleet, and freezing rain), happens at locations that are different from those where atmospheric water vapor was generated. For a complete review on precipitation processes and related atmospheric dynamics see Smith (1993). Precipitation is characterized by a high variability in space and time. Striking differences can be observed in precipitation intensity even at small space and time ranges, sometimes giving birth to extreme occurrences of high precipitation (floods) or no precipitation (droughts). For a review of methods for rainfall point and spatial measurement, estimates, prediction and modeling see Smith (1993).

Precipitation and climate change
Annual precipitation trends in the 20th century included enhanced precipitation (10 to 50%) in the northern half of Europe. By contrast, the region stretching from the Mediterranean Sea through central Europe into the European part of the Russian Federation and Ukraine experienced decreases in precipitation by as much as 20% in some areas (Figure III.3).

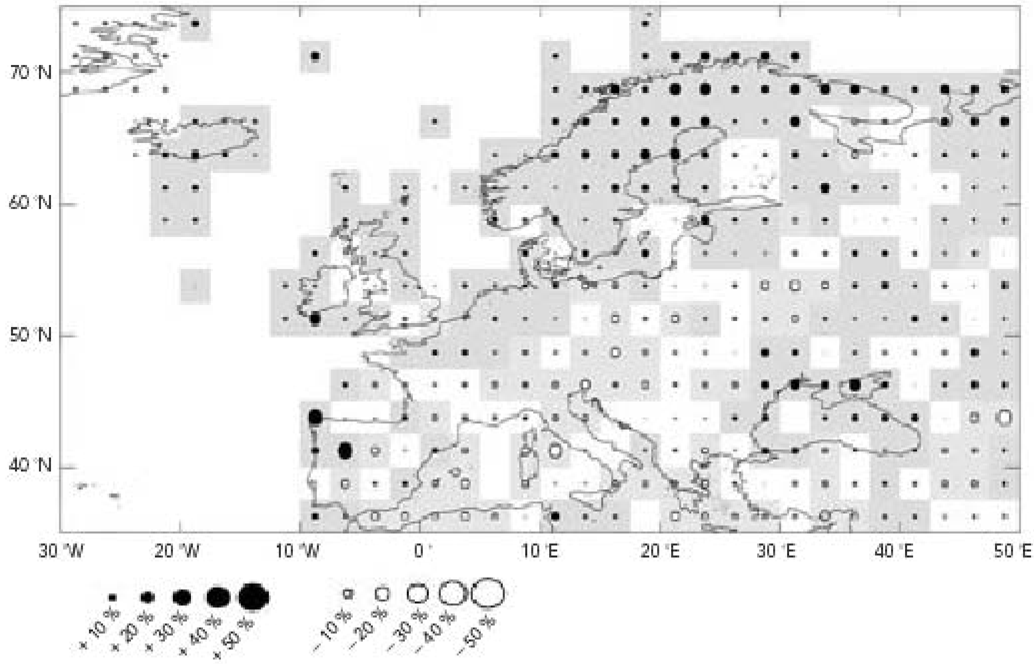


Figure III.3. Annual precipitation trends in Europe for the period 1900-1999. Black represents an increase; white represents a decrease (EEA, 2004).

Predictions of climate change are subject to large uncertainty. Changes in global precipitations are influenced by changes in global mean temperatures. Even where the likely global trend appears to be clear, the response in individual regions may vary substantially. Thus, although global temperatures are predicted to increase by 1 to 3.5 °C by the year 2100 (Nicholls *et al*., 1996) the actual rise in individual areas will differ significantly, and some regions may even become cooler. Increasing temperatures mean also that a smaller proportion of precipitation may fall as snow. In areas where snowfall currently is marginal, snow may cease to occur altogether, with significant implications for hydrological regimes (e.g. spring river flows where snowmelt plays a significant role).

Global average precipitation is predicted to rise, but this increase is also likely to be regional. It is predicted that winter and spring precipitation will increase in Europe and summer precipitation will decrease, although the Mediterranean region and central and eastern Europe are expected to experience overall reduced precipitation (Kovats *et al*., 2000; see also Figure III.4). Recent scenarios for the UK, derived from HadCM2 experiments, indicate an increase in the relative variability of seasonal and annual rainfall totals resulting from global warming (Hulme and Jenkins, 1998). Although global mean precipitation is primarily constrained by the energy budget, the heaviest rainfalls are likely to occur when effectively all the moisture in a volume of

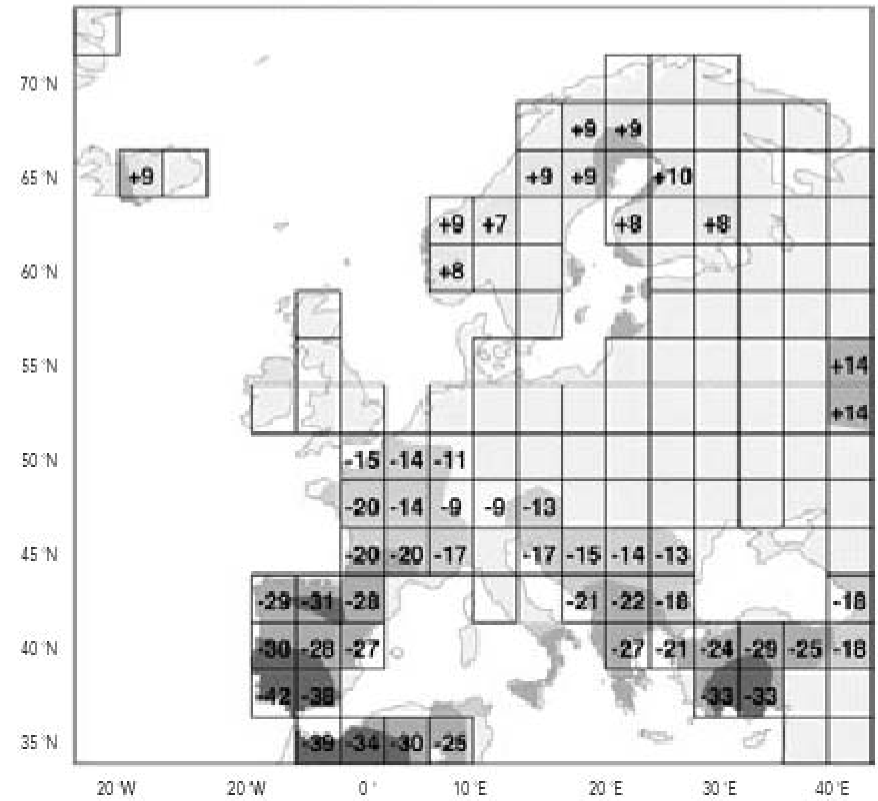


Figure III.4. Projected change in summer precipitation (%) in Europe up to 2080, relative to average precipitation in the period 1961-1990 (based on intermediate ACACIA scenario; EEA, 2004).

air is precipitated out, thus suggesting that the intensity of these events will increase with the availability of moisture. Therefore the incidence of heavy precipitation and drought events is also predicted to increase, which suggests implications not only for increased contamination resulting from run-off but also decreased groundwater recharge and an increased incidence of flooding. Moreover, changing precipitation rates affect rates of chemical weathering of silicate rocks, and hence ultimately the carbon dioxide content of the atmosphere.

Among the anthropogenic factors for climate change are anthropogenic carbon dioxide and aerosols of various origins. Such changes could have a large impact on the hydrologic cycle. For example, sulphate aerosols from volcanic and anthropogenic sources in the stratosphere and in the troposphere may increase the scattering of sunlight away from space, either directly or via effects on clouds. Aerosols can also produce direct tropospheric heating, with similar effects to CO_2 on the hydrologic cycle. Aerosols can also influence precipitations. Already in 1968 Warner (1968) deduced that aerosol emissions from sugar cane fires were affecting precipitation by examining rainfall records from Western Australia. Aerosol-induced precipitation suppression has been observed both with in situ measurements (Ferek *et al.*, 2000), and in satellite observations (Rosenfeld, 2000) showing that the effect does in fact occur in the atmosphere. If precipitation is suppressed, water that would have been removed from the atmosphere remains aloft and can be transported to other locations before it is deposited to the surface. The same is true for the energy associated with such water—the latent heat released on condensation in clouds and the energy required for evaporation of water from the surface. The redistribution of water and latent heat due to precipitation suppression may have the potential to influence circulation patterns.

Evaporation and evapotranspiration

Evaporation occurs when water is converted to water vapor. Whether occurring from a liquid surface, from soil or from plants (in the latter case it is called transpiration, defined as soil water reaching the atmosphere through plants), driving mechanisms for evaporation are similar, and rates are controlled by the energy available at the evaporating surface (radiation), air temperature, humidity and wind speed. The physics of evaporation and transpiration rely on surface exchange processes, as driven by latent heat flux, water molecule migration between water and air, saturated water content of air (which in turn is influenced by removal action of air currents) and sensible heat flux. At non-limiting water availability conditions, evaporation rates are controlled by surface radiation balance. Plant stomatal resistance also controls transpiration. In particular, in agricultural crops or forested areas transpiration from canopy and evaporation from underlying soil surface occur simultaneously, and there is no easy way to calculate each contribution separately, so that the two processes are condensed into a single one named evapotranspiration.

Evapotranspiration has always been difficult to measure, especially on an ecosystem or watershed spatial scale. Methods have been developed to measure evapotranspiration at the leaf level, the tree level, and the stand level. At the stand level, instruments mounted on a tower above the canopy are routinely used to measure humidity and wind velocities at high frequency, with water fluxes out of the forest canopy calculated by the eddy covariance method. Several general methods are available for measurement of evaporation/evapotranspiration (e.g. evaporation pans, water balance at lysimeter scale, water balance at watershed or water-body scale). For a complete review, see Shuttleworth (1993) and references therein.

On the other side, estimates of crop evapotranspiration usually follow a two-step procedure: i) estimation of potential evapotranspiration ET_0; ii) adjustment through appropriate coefficient for specific crop, management practices and actual water availability to obtain actual evapotranspiration ET_a. Although a large number of more or less empirical methods have been developed over the last 50 years to estimate ET_0, none of then has proved to be universally valid. Choice of one method over the other depends on data availability and type of application. Among the most popular methods are: Blaney-Criddle (1950); radiation - e.g. Priestley-Taylor (1972) equation, or Turc (1967) equation; Penman-Monteith (Penman, 1948; Monteith, 1965); Hargreaves (1974) and pan evaporation. For a comparison among the different methods see again Shuttleworth, 1993. Crop coefficients and other correction procedures to derive ET_a from ET_0 can be derived for a large number of commercial crops from Doorenbos and Pruitt (1977). Large-scale evapotranspiration can also be estimated with the aid of remote sensing measurements, adopting an energy balance calculation approach (Bastiaanssen *et al*., 1998a; 1998b).

Evaporation and climate change

Over the entire land surface of the globe, rainfall averages around 750 mm per year, of which some two thirds is returned to the atmosphere as evapotranspiration, making evapotranspiration the largest single component of the terrestrial hydrological cycle (Baumgartner and Reichel, 1975). In Figure III.5 the annual potential evapotranspiration for Europe is presented. The actual rate of evaporation is constrained by water availability; due to an increase in evaporative demand as a result increased temperatures, a decrease in actual evapotranspiration might correspond in those areas with scarce soil moisture (arid and semi-arid areas); in other words it could happen that a reduction in summer soil water could lead to a reduction in the rate of evaporation from a catchment despite a temperature driven increase in evaporative demands. In areas with sufficient available moisture (regions in northern Europe), increases in temperature would lead to increases in evaporation and evapotranspiration: water in the atmosphere can affect the radiation balance of the planet through water vapor greenhouse and cloud greenhouse effects and through reflection of sunlight by clouds and ice. Arnell (1996) estimated for a sample of UK catchments that the rate of actual evaporation would increase by a smaller percentage than the atmospheric demand for evaporation, with the greatest difference in the "driest" catchments, where water limitations are greatest.

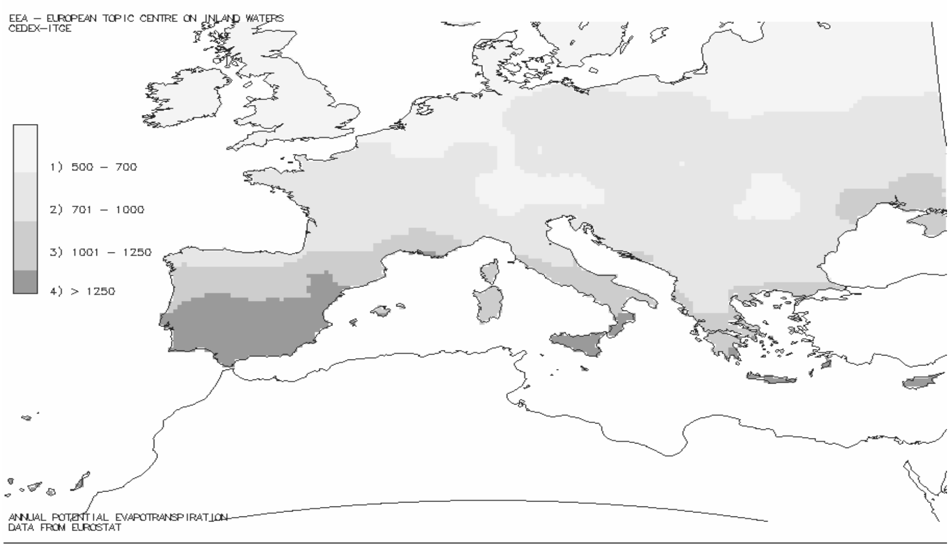


Figure III.5. Annual potential evapotranspiration map for Europe (EEA, 1996).

Runoff and river discharge
Runoff is the movement water over land, and consists of that portion of precipitation that is not evaporated, transpired, or infiltrated in the soil. The magnitude of runoff after a precipitation event is determined chiefly by the soil characteristics and soil conditions prior to the precipitation event: precipitation on saturated soil is likely to produce a greater runoff than the same event on the same soil under dry conditions. Soil cover also plays a role, as intercept of water by vegetation can delay runoff or decrease it. Water flowing over land can be trapped in small irregularities on the ground (depression storage), or trickle to form networks, thus routing from small streams to larger channels to sea. High-intensity precipitation events or long-duration/low-intensity precipitation (but also snowmelt or dam and levees operation) can cause excess runoff, which in turn can lead to flooding. The study of runoff and channel routing processes is of fundamental importance for protection of human settlements and infrastructures.

Peak discharge originating from excess runoff can be calculated with a variety of methods. For small to medium size watersheds the most widely used methods are: the rational method (see Pilgrim and Cordery, 1993, and references therein, for a description of the method), the U.S. Soil Conservation Service method (see Singh, 1982, for a review of main procedures and subsequent developments), and the regional flood frequency methods (see Stedinger *et al*., 1993 for a review). Fread (1993) provides a review of channel flow routing.

Runoff, river discharges and climate change

Average annual runoff in Europe varies widely, from less than 25 mm in southeast Spain to more than 3000 mm on the west coast of Norway. Predictions of the effect of climate change on river flow are uncertain, and the results of different models are highly variable. Arnell and Reynard (1996), for example, modeled river flows in the United Kingdom under various climate change scenarios and found that, under all scenarios, the concentration of flow increased in winter. All models predict that monthly flow would change by a greater percentage than annual flow. However, different catchment areas would respond differently to the same scenario; progressive change would be small compared with variability over a short time scale, but that it would be noticeable on a decade-to-decade basis.

As a consequence of increased precipitation intensities, peak runoff is subject to increase, thus increasing the occurrence of flood events. As a general trend, because runoff is more directly dependent on precipitation rather than on temperature increase, runoff in higher-latitude areas (e.g. Rhine and Danube) would decrease in the spring (as a result of less precipitation falling as snow in the winter, leading to less snow melting in the spring) and increase in the winter. In mild temperature climates, annual runoff would remain constant, but display a more extreme seasonal cycle. Catchments with considerable groundwater would display changes in summer flows that are largely a function of the change not in summer rainfall but in rainfall during the winter recharge season. In arid and semi-arid regions runoff would be most immediately linked to precipitation, and a given percentage change in rainfall would produce a considerably larger percentage change in runoff. Projected changes in annual water runoff by the year 2050 are presented in figure III.6.

Infiltration, Deep Percolation and Groundwater Flow

Infiltration is the process by which water enters the soil, moving from the surface to lower soil horizons. Some of the water entering continues to flow close to the surface (subsurface runoff), to resurface at some distance or to flow into a stream, while some moves to greater depths (deep percolation) eventually reaching a groundwater body (aquifer). Infiltration rates are governed by soil water characteristics (soil water content, water retention characteristics, and hydraulic conductivity). Water flow in saturated soils is governed by Darcy's law (Darcy, 1856). Unsaturated flow is described by Richards' equation (Richards, 1931). For a complete review on infiltration and soil water movement see Rawls *et al*. (1993).

Aquifers are subterraneous porous medium formations that store and transport large masses of water. Two soil layers can be distinguished below ground level: in the one nearest the surface gaps between soil particles are filled with both air and water (unsaturated zone). Below this layer is the saturated zone, where the gaps are filled with water. The boundary between these two layers is called water table. As the amount of water in the aquifer increases or decreases, the water table rises or falls accordingly. When the entire area below the ground is saturated, flooding occurs because all subsequent precipitation is forced to remain on the surface. Aquifers are distinguished in unconfined (when only the bottom is confined by an layer of impervious material, so that the aquifer is in contact with the atmosphere through the unsaturated zone) and confined (when the aquifer has impervious layers both at the bottom and at the surface). Both types of aquifer have a recharge area (where water infiltrates the ground surface to reach the aquifer) and a discharge area (sea, river, lake). The movement of water in the aquifer is driven by porous matrix characteristics such as porosity, hydraulic conductivity, permeability, transmissivity and storativity (see Smith and Wheatcraft, 1993, for a description of aquifer hydraulic characteristics and corresponding methods for measurement or estimate). Such characteristics may or may not be uniform throughout the entire water body, and anisotropy may exist. For a review of groundwater hydrology see Smith and Wheatcraft (1993).

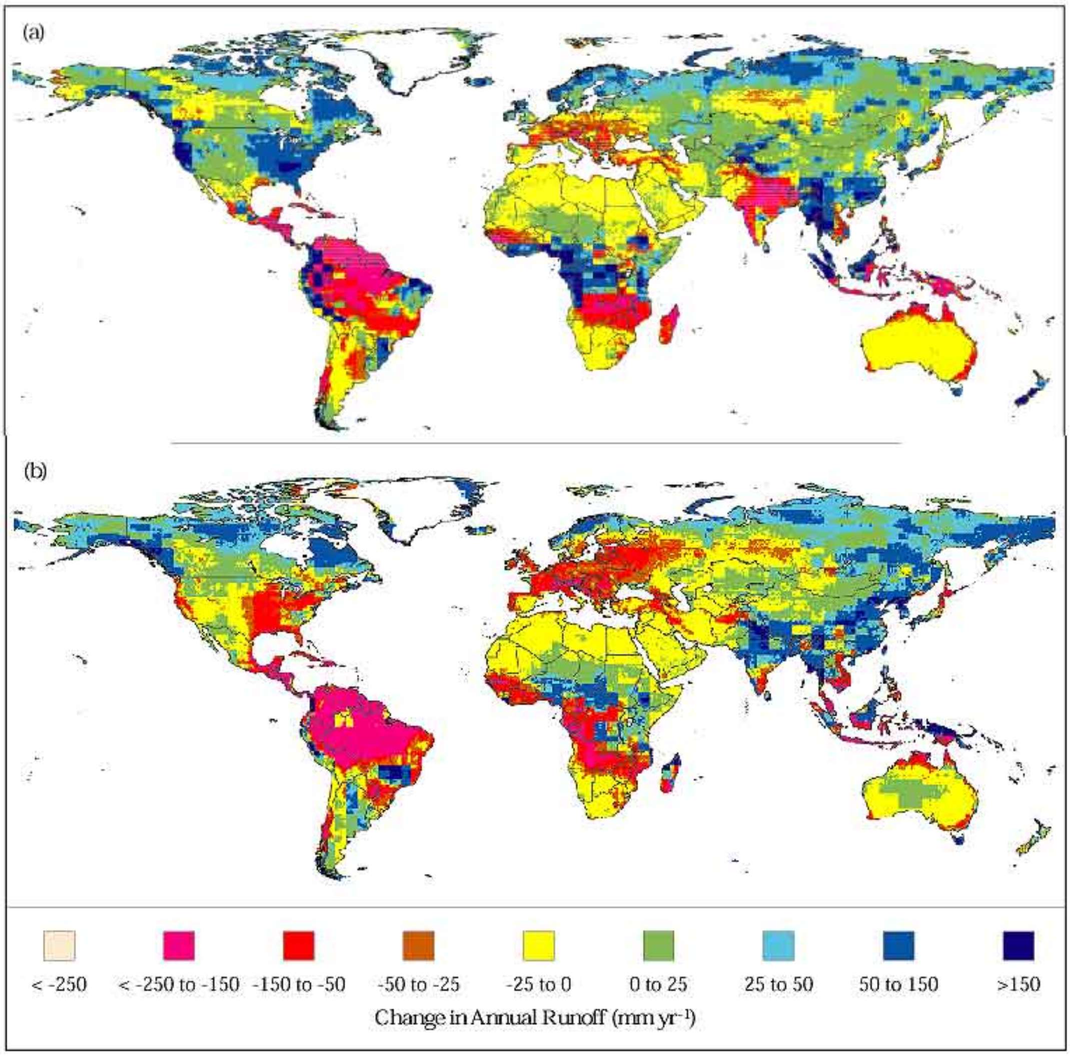
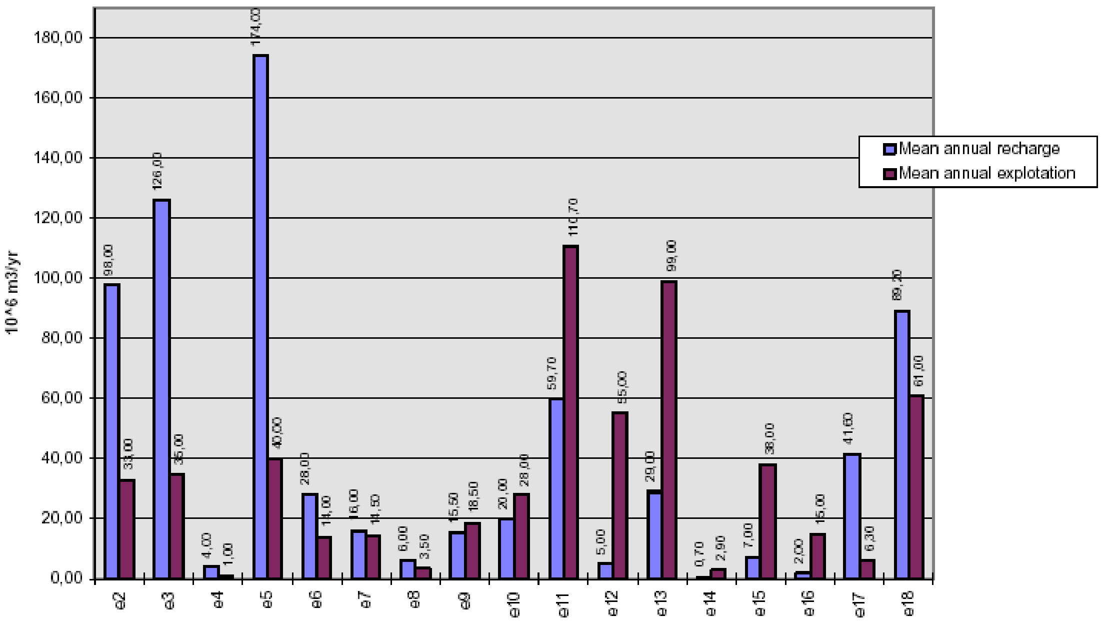


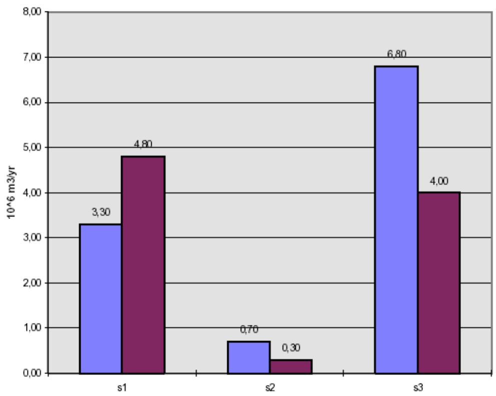
Figure III.6. Projected changes in average annual water runoff by 2050, relative to average runoff for 1961-1990, calculated using as inputs climate projections from (a) HadCM2 ensemble mean and (b) HadCM3 (IPCC, 2001).

Groundwater flow and climate change

Cooper *et al*. (1995) found that the effect of various climate change scenarios on aquifer recharge depended on the aquifer type, and that a scenario incorporating high evaporation produced the greatest change in hydrological regime of aquifers. As recharge to the aquifer only occurs when there is no soil moisture deficit, thus mostly the winter months, higher temperatures mean that evapotranspiration from the soil and vegetation continues later into the fall season leading to a delay in the start of aquifer seasonal recharge. Similarly the end of the recharge period would come earlier in the spring. Arnell (2003) finds that average annual recharge in UK aquifers is expected to fall by 5% to 15%. However, there is as yet no firm information on how recharge would change in a dry period. The UK Environment Agency guidance implies that it should be taken as falling by the same amount as the average annual recharge. Thus, a significant risk exists that in a dry year aquifer recharge may fall by even more than the annual average.

On a more general view, more of concern is the coupling of climate change and anthropogenic activities. Aquifers usually recharge slowly, and current abstraction levels may not be sustainable under future climate change scenarios. In some areas of southern Europe aquifers are already overexploited (see Figure III.7). In many cases, determining whether over-exploitation would occur is difficult. It is often thought of as being a relatively straightforward question of water taken out of the aquifer and water filtering back into it. Difficulties in estimating long-term recharge confound this simple approach. Changes in precipitation patterns may influence surface water resources availability, leading to increasing exploitation of groundwater bodies. Exploitation beyond a sustainable level can affect the environment (lowering of the water table can lead to loss of wetlands and can affect river ecosystems) and reduce the future availability of the resource. When aquifers near the coast are over-exploited, salt water may intrude, thus reducing water quality in the aquifer.





Aquifer list

e2: Ayamonte-Huelva; e3: Campo de Montiel; e4: Mancha Real-Pegajalar; e5: Sevilla-Carmona; e6: Aljarafe; e7: Rota-Sanlucar-Chipiona; e8: El Saltador; e9: Campo de Nijar; e10: Andarax-Almeria; e11: Campo de Dalias; e12: Ascoy-Sopalmo; e13: Guadalentin; e14: Cresta del Gallo; e15: Jumilla Villena; e16: Sierra de Crevillente; e17: Bloque de Gaia; e18: Camp de Tarragona; s1: Muravera; August; s2: Rio Su Canoni-Portovesme; s3: Santa Lucia.

Figure III.7. Aquifer exploitation in Spain (top) and Sardinia, Italy (bottom) (EEA, 1996).

III.3. CONCLUDING REMARKS

There is evidence in historic records of an increase across Europe in annual surface air temperature of about 0.8°C during the 20th century (IPCC, 2001). Higher temperatures potentially lead to higher evaporation and evapotranspiration. Annual precipitation trends for the period 1900–2000 show a contrasting picture between northern Europe (10–50 % wetter) and southern Europe (up to 20 % drier). Changes have been greatest in winter in most parts of Europe. Projections for Europe show a 1–2 % increase per decade in annual precipitation in northern Europe and an up to 1 % per decade decrease in southern Europe (in summer, decreases of 5% per decade may occur) (EEA, 2004). Higher temperatures affect precipitation patterns as well, even in those cases in which total annual rainfall may not display significant changes. A higher frequency of weather extremes is likely to be observed (torrential rains, leading to floods; dry periods, leading to droughts).

River discharges (being a function of precipitation and watershed characteristics, among other factors) will in turn be affected; soil, in fact, acts as a storage buffer: in winter and spring, increasing precipitation normally generates higher discharges because the buffer is full and evaporation is low; during the summer, storage is reduced by evaporation and transpiration, and the soil must be refilled before runoff begins. As a consequence of increased precipitation intensities, peak runoff is subject to increase, thus increasing the occurrence of flood events.

Groundwater recharge is also dependent on precipitation and soil moisture conditions. Aquifers usually recharge slowly and mostly during the winter season. Shortening of the wet season across Europe might negatively affect recharge rates. Moreover, future reduced surface water availability during the dry season might induce over-exploitation of groundwater resources, thus further deteriorating the status of some aquifers.

There is a need for advancement in our capability to describe the interaction in time and space between physical processes governing climate and the various components of the hydrologic cycle. On a short time scale individual components of the hydrological cycle are much more variable than climatic factors. Seasonal to inter-annual variability in precipitations and temperatures accounts for some of the shifts in hydrological characteristics in European river basins. However, accurate predictions about the consequences of climate change on individual components of the hydrologic cycle at European, regional or local scale are difficult to obtain because of the bias introduced by anthropogenic factors (changes in land-use patterns and the drainage conditions of rivers, increases in the proportion of impermeable areas) (Beniston *et al.*, 1994). There is a strong want for further research, aiming at decoupling the effects of human activities (e.g. increased population, expansion of irrigated land, industrial growth) and climate change on the hydrological cycle, to avoid in the future catastrophic synergies and interactions.

Chapter IV.A. Proxy Indicators of Aquatic Forcing

Key Points

- **Time-averaged proxy indicators like the North Atlantic Oscillation (NAO) index, El Niňo Southern Oscillation (ENSO) index or Gulf Stream index quantify complex atmospheric circulation patterns in simple indices.**
- **A positive NAO index is associated with strong westerly winds and wet winters in Northern Europe, whereas drier conditions occurr over much of Central and Southern Europe. The NAO has had a strong influence on winter temperatures across Western, Northern and Central Europe during recent decades.**
- **Recent studies have recognised a distinct influence of the ENSO on spring precipitation in Western Europe and autumn precipitation in the Western Mediterranean countries.**
- **Annual variability in the latitudinal position of the Gulf Stream is associated with variability in wind speed around Britain.**
- **Due to the non-stationary character of the relationships between climate indices and lake state variables, long-term predictions are not practical.**

Chapter IV.A. Proxy indicators of Climate Forcing

IV.A. Introduction

Consequences of climate variability for hydrology, ecology, and economy during the last decades were often studied using proxy indicators for complex meteorological, atmospheric, and/or oceanographic phenomena. The use of simple time-averaged proxies reduces by definition complex space and time variability into simple measures and allows researchers of different disciplines to link their work to climate forcing in a straightforward manner. Proxies with relevance for European climate include the indices for large-scale climatic patterns such as the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO), the El Nino Southern Oscillation (ENSO), the Gulf Stream Position, and several more regional indices.

As there are several ways to define the spatial structure of specific climate patterns, usually several indices, i.e. proxies do exist for the description of the temporal dynamics of a climate pattern. Most often these indices are either derived from simple pressure differences between relevant locations or from principal component time series of the leading eigenvector of sea level pressures. However, different indices for one climatic pattern are usually highly correlated, and hence will not be presented and discussed in the following overview.

The best-known circulation pattern with respect to European climate is the NAO representing a large-scale fluctuation in the air pressure difference between the Azores High and the Iceland Low. It dominates much of the atmospheric behaviour over the North Atlantic, and is known to influence air temperature and precipitation over large areas of the Northern Hemisphere (Hurrell 1995, IPCC 2001). The NAO fluctuates between positive index values, and a negative index values. The positive (negative) phase is characterised with higher (lower) than normal surface pressures near the Azores combined with anomalously low (high) pressure throughout the Arctic and sub-Arctic. As a consequence, the prevailing westerly winds across the North Atlantic are strengthened and moved northwards during a positive phase of the NAO, whereas the westerly winds are weakened during a negative phase of the NAO. The NAO is closely related to the Arctic Oscillation (AO) and may be (Thompson et al. 2003)– but this is still somewhat controversial (Hurrell et al. 2003) a smaller-scale manifestation of the latter. Figures IV.A.1a,b).

Despite its presence throughout the year, the influence of the NOA on Europe is strongest during winter (Figure IV.A.2). The regional pattern of NAO influences in Europe is as follows: a positive NAO index is associated with enhanced storminess from Southern Greenland across Iceland into northern Europe, and a modest decrease in activity towards southern Europe. Wetter winters in high positive NAO years have been recorded in Northern Europe, whereas drier conditions in high NAO years occurred over much of central and southern Europe, the Mediterranean and parts of the Middle East. As a consequence, in the Mediterranean and the Middle East, river run-off (e.g., the Rhone, Ebro, Euphrates Rivers (Cullen and deMenocal 2000; Lloret *et al*. 2001)) and water levels (e.g., the Caspian Sea (Rodionov 1994)) were lower during high positive NAO phases, whereas river runoff in Irish and Welsh rivers (Kiely 1999; Bradley and Ormerod 2001) and into the Baltic Sea was higher (Hänninen et al. 2000). However, Spring flood discharges in the Warta and Bug rivers in Poland were negatively related to the NAO Index, probably as a result of decreased winter snow cover in high NAO years (Kaczmarek 2003).

The NAO has displayed a strong influence on winter temperature across western, northern and central Europe during the recent decades. As a consequence, there

- *A combination of a stronger than usual subtropical high pressure center and a deeper than normal Icelandic low.*
- *The increased pressure difference results in more and stronger winter storms crossing the Atlantic Ocean on a more northerly track.*
- *This may result in warm and wet winters in Northern Europe and in cold and dry winters in the Mediterranean and North Africa*

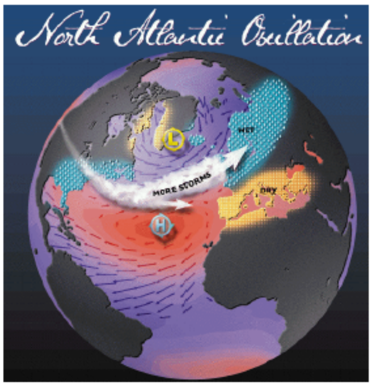


Figure IV.A.1 (a). Postive NAO Index

- *The negative NAO index phase shows a weak subtropical high and a weak Icelandic low.*
- *The reduced pressure gradient results in fewer and weaker winter storms crossing on a more west-east pathway.*
- *They bring moist air into the Mediterranean and North Africa and cold dry air to northern Europe*

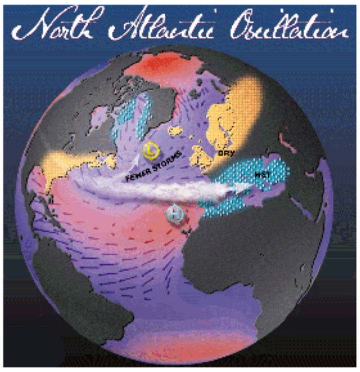


Figure IV.A.1 (b). Negative NAO Index

was a strong response of physical (Livingstone 1999; Livingstone 2000; Livingstone and Dokulil 2001; Gerten and Adrian 2001), chemical , and biological characteristics of lakes to inter-annual NAO variability in these regions. For example, in Lake Constance, Straile (2000) demonstrated that the influence of the NAO on local meteorology is transferred via its impact on lake physics and temperature-controlled herbivore population dynamics and finally to phytoplankton phenology (Figure IV.A.3). For several parameters, i.e., ice break up (Livingstone 2000), water temperature (Livingstone and Dokulil 2001), timing of the clear-water phase (Straile 2002), these responses seem to be synchronised over rather large areas. However, the coherent response pattern to NAO variability may be modified by e.g., geography (Livingstone and Dokulil 2001), morphology (Gerten and Adrian 2001) and trophic status of lakes (Livingstone 1997).

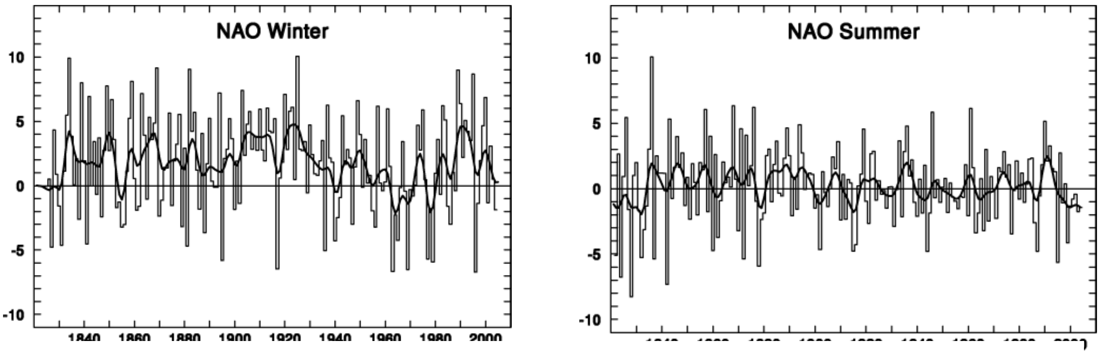


Figure IV.A.2 NAO - North Atlantic Oscillation
Data runs up to October 2004 (Source: http://www.cru.uea.ac.uk/cru/climon/data/nao/)

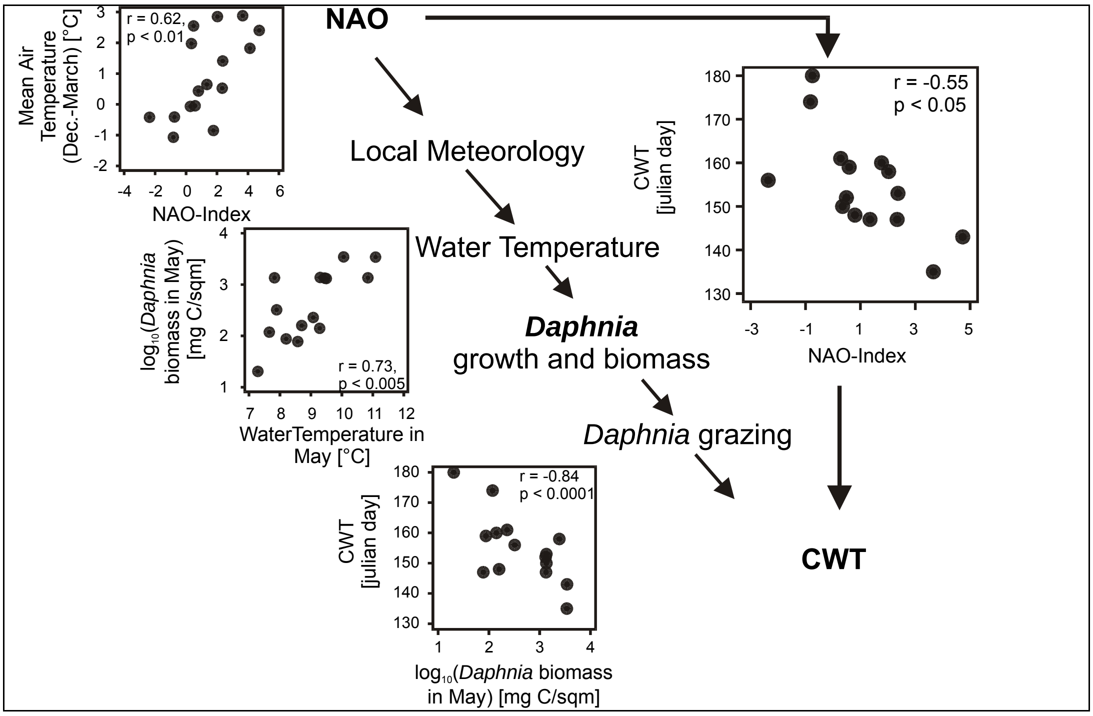


Figure IV.A.3. Cascading influence of the NAO from local meteorology towards food-web interactions in Lake Constance (from Straile et al 2003)

The ENSO is the most important global circulation pattern with serious influences in the Southern hemisphere, but also in Northern America. ENSO results from a cyclic warming and cooling of the surface ocean of the central and eastern Pacific. Warming anomalies (El Nino events) and cooling anomalies (La Nina events) have severe consequences for world climate. Indices describing ENSO variability are based on pressure differences (e.g. the Southern Oscillation index is based on pressure differences between Tahiti and Darwin) or anomalies in sea surface temperatures (e.g., NINO3, NINO4, Nino3.4). Positive SOI values indicate La Nina events, and negative values reflect El Nino events. While the teleconnection patterns of ENSO to the tropics and to some extra-tropical areas around the Pacific are well documented and shown to be strong, the influence of ENSO on European climate appears to be weaker and was, until recently, less studied (Moron and Ward 1998). Van Loon and Madden (1981) have noted a decrease in temperature and precipitation in Scandinavia during winters of El Nino conditions. Also, El Nino years are related to an increase of days with cyclonic circulation types (Großwetterlagen) in England (Wilby 1993) and Germany (Fraedrich 1994). During recent years the ENSO teleconnection patterns to Europe have received more attention and several studies recognize a distinct ENSO influence on European climate (Rodó et al. 1997; Van Oldenborgh *et al*. 2000; Mariotti *et al*. 2002; Merkel and Latif 2002; Lloyd-Hughes and Saunders 2002; Knippertz *et al*. 2003; Moron and Plaut 2003; Matyasovszky 2003; Greatbatch *et al*. 2004).

Spring (MAM) precipitation in distinct European regions is significantly related to the NINO3 Index with a lag of three months. Strongest positive correlations occur over Southern England, northern France, the Low Countries and Germany, whereas in Eastern Spain negative correlations occur during spring (Van Oldenborgh *et al*. 2000). In addition, western Mediterranean rainfall in autumn is shown to be negatively related to the Nino3.4 index in autumn (Mariotti et al. 2002). That is in this region the sign of the relationship between ENSO and precipitation changes from autumns towards spring. Studies regarding the influence of ENSO on lakes and rivers in Europe are scarce. For example, Rodó et al (1997) have showed the ENSO influence on the water level dynamics of Lake Gallocanta, Spain. Price *et al*. (1998) found evidence for an influence of ENSO on precipitation in Israel and water level variability of Lake Kinneret during the last quarter of the 20th century.

The position of the Gulf stream is related both to the NAO (Taylor and Stephens 1998) and – with a lag of approximately two years - to ENSO (Taylor *et al.* 1998). Annual variability in the latitude of the Gulf Stream is associated with variability in wind speed around Britain. Due to this relationship an influence of the Gulf Stream position on lakes in the British lakes District and throughout northern Europe has been suggested. For example, reduced wind speed during years with a more northerly position of the Gulf stream is associated with less mixing and lower chlorophyll *a* concentration in Esthwaite Water (George 2002). Likewise, in Lake Windermere the thermocline depth is higher when the Gulf Stream is in a more northerly position (George and Taylor 1995). However, observations relating impacts of the Gulf Stream variations to lakes' physics and biology are restricted up to now to Great Britain.

The use of regional climate indices for a better understanding and prediction of climate effects on lakes is under-explored at present. Circulation patterns such as the Scandinavian (Eurasia-1) and the East Atlantic/West Russia (Eurasia-2) pattern were proposed by Barnston and Livezey (1987). However they are seldom used as a tool to link changing lake and river variables to climate variability. Nevertheless, there seems to be a large potential in using regional indices and/or frequencies of circulations types such as the Großwetterlagen (Gerstengarbe *et al*. 1999) or the Lamb circulation types (Lamb 1972). Recently, Blenckner and Chen (2003) used a set of regional circulation indices established for Scandinavia and showed that these indices can indeed explain a larger part of interannual variability in limnological variables such as the Lake Erken duration of ice cover, timing of ice-break-up and phytoplankton spring bloom than the NAO (Blenckner and Chen 2003).

Although variability in state variables measured from a variety of river and lake systems all over Europe were successfully linked to climate proxies during the recent years, it is important to note that this success may be only temporary. That is, established relationships may break down if time series were continued, because the ealier-observed influences were non-stationary. For example, the effect of ENSO on weather patterns in Europe and the Middle East is not robust on inter-decadel time scales. The relationship between ENSO and Lake Kinneret water level is only apparent during the last three decades (Price *et al*. 1998). This is in line, with a shift in the relationship of the ENSO – Red Sea coral record during the 1970s, which was attributed to non-stationarity in the ENSO teleconecction pattern (Rimbu et al. 2003). Also in Europe non-stationarity between ENSO and precipitation has been recorded (Mariotti et al. 2002; Knippertz et al. 2003). It is quite possible that not only ENSO, but also the NAO influence may be non-stationary. For example, the impact of NAO on ice-break up in certain regions varies over time (Livingstone 2000; Straile *et al*. 2003) (Figure IV.A.4). Significant relationships between the NAO and ice-break up in Lakes Baikal/Russia and San Murezzan/Switzerland do not exist in a period from the 1980s to the 1960s, but are only evident when more recent years were included. Hence, the relationship between climate indices and lake state variables should not be used to predict changes in state variables. Rather, their great value is due to the fact that they may allow insights into the mechanisms of climate and meteorological forcing of freshwater systems.

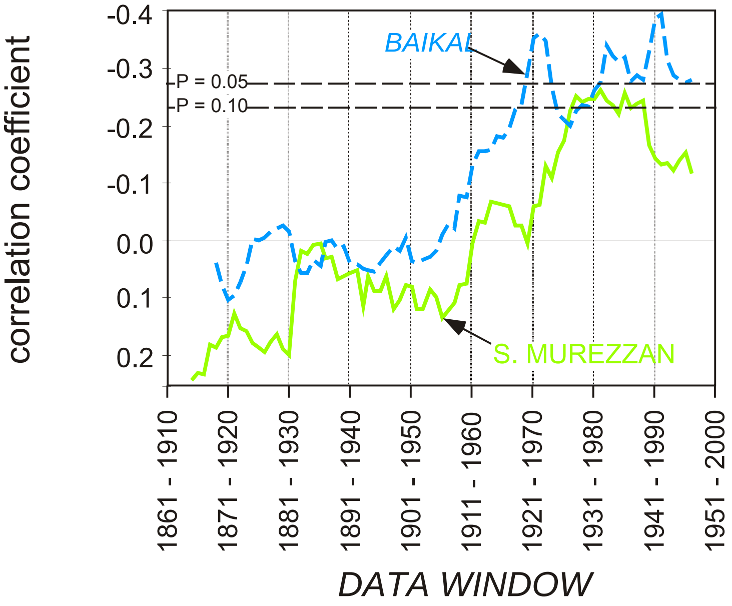


Figure IV.A.4. Running correlation of a 50 years time window between ice-break-up data from the lakes Baikal and San Murrezan and the NAO Index (modified from (Straile *et al*. 2003))

Climate Change
and the
European Water Dimension

Chapter IV.B. The Impact of Climate Change on Lakes in Europe

Key Points

- **Response of lakes to climate forcing is most coherent for physical parameters: there is a high probability for earlier ice-out, increase of lake temperatures, and stronger thermal stratification in a warmer future.**

- **Anticipated changes in the chemical regime of lakes (e.g. accelerated eutrophication, increase in water colour, and decrease in oxygen availability) are less coherent and depend strongly on lake type and local conditions.**

- **Because of complex interactions, biological changes induced by climate change are inherently unpredictable. Small variations in climate can have dramatic effects on biota, especially in extreme habitats where many species, living at the limit of their capabilities, will perish**

- **Lakes in the arctic, sub arctic, and alpine regions are particularly sensitive to climate change. At the same time, these are the areas where the highest and most rapid temperature increase is expected.**

Chapter IV. B. The Impact of Climate Change on Lakes in Europe

IV. B.1. Introduction

If present trends continue, climatologists predict that the concentration of CO_2 in the atmosphere will have doubled by the year 2050 (McCarthy *et al*., 2001). This increase will have a profound effect on the global climate and influence the seasonal dynamics of lakes throughout Europe. To date, there have been relatively few European studies on the impact of climate change on the dynamics of lakes. In North America, there have been a number of such studies that also highlight the geographic variation in the projected responses. These include studies on the potential effects of climate change on the Laurentian Great Lakes (Magnuson *et al*., 1997), the lakes of the Arctic and Sub arctic (Rouse *et al*., 1997) and the mountain lakes of the Pacific coast (Melack *et al*, 1997). Recently the Arctic Council (2004) published its report on *"Impacts of a Warming Climate*" also emphasizing the dramatic changes occurring now in Arctic lakes.

In this review, potential effects of climate change on lakes in Europe are summarized. European lakes have recently been the subject of intensive study in several projects funded by the European Union (**EUROLAKES, MANTRA-East, CLIME, EMERGE, PHYTOPLANKTON ON-LINE, ECOFRAME, HMLS**). This review focuses especially on the products of the RTD FP5 project CLIME (*Climate Impacts on European Lakes*) that started in 2003 and is due to end in 2005 and is mainly based on data collected within this project and the foregoing project REFLECT from three European regions: the Northern Region, the Atlantic Region and the Alpine Region. Climate impact on lakes and reservoirs located in the Mediterranean region and in Central and Eastern Europe are analyzed basing on published data.

In the review, our analysis of the impact of climate change is based on the output of two contrasting Regional Climate Models (Räisänen *et al*., 2004) and an analysis of the long-term changes recorded in a number of intensively studied lakes. Particular attention is paid to the effects of the more extreme inter-annual variations in the weather and the indirect as well as the direct effects of these climatic perturbations. A number of investigators have already examined the effects of global warming on water quantity (Boorman, 1997; Arnell, 1999) but very little attention has, hitherto, been paid to the effects on water quality. The review includes a number of case studies (Ch.VI.A) that illustrate some of the variations observed in four key lakes listed as Primary Sites in the CLIME project (*www.water.hut.fi/clime*). These lakes have been the subject of intensive study for more than 50 years and the observed variations provide a good indication of the sensitivity of these lakes to the changing climate.

IV.B.2. The Distribution of Lakes in Europe

Lakes are distributed unevenly in Europe. Norway, Finland and Sweden have numerous lakes accounting for approximately 5-10 per cent of the surface area of their repective countries (Table IV.B.1). A large number of lakes can also be found in Baltic countries, in northern parts of Poland and Germany, in Denmark, Ireland and in the northern and western parts of the United Kingdom. In Central Europe most natural lakes are situated in mountain regions, the ones at high altitude being relatively small and the ones in the valleys being the largest, examples being Lake Geneva, Lake Constance, Lake Garda and Lake Maggiore in the Alps. Mountainous Switzerland is especially rich in lakes. Generally, the percentage of lakes in the landcover decreases from north to south and remains below 0.5% in several southern countries in Europe like Bulgaria, Slovenia, Macedonia, France, Spain, and Portugal. In these areas man-made lakes such as reservoirs and ponds occur more frequently than natural lakes. In Spain, for instance, there are more than 1,000 large reservoirs. Also in Belgium, The Netherlands, Southern England, Slovakia, and the central parts of Germany there are generally few natural lakes. As lakes can be used for water supply, irrigation and several other purposes, the relative importance of each lake is reciprocally related to the occurrence of lakes in a particular area.

Table IV.B.1. Percentage of the total area of lakes and reservoirs in the total country area. Data on CORINE landcover (unit 512 “lakes”) from the EEA database, country areas from UN database if not indicated otherwise

Country	Percentage of lakes in landcover
Sweden	9[1]
Finland	8.72
Norway	4.65[2]
Estonia	4.38
Switzerland	3.99[3]
Ireland	1.80
Lithuania	1.66
Latvia	1.59
Albania	1.40
The Netherlands	1.28
Hungary	1.20
Poland	1.20
United Kingdom	0.89
Germany	0.84
Denmark	0.82
Romania	0.64
Czech Republic	0.63
Greece	0.59
Italy	0.57
Austria	0.49
Bulgaria	0.47
Spain	0.39
Belgium	0.35
Bosnia and Herzegovina	0.35
Portugal	0.32
Slovakia	0.32
Macedonia	0.31
France	0.28
Luxembourg	0.15
Slovenia	0.13

[1] http://www.internat.naturvardsverket.se
[2] http://www.ssb.no/english/yearbook/2002/tab/t-010101-022.html
[3] Aggregated airphoto-based estimate together with rivers after Waser et al. (2000)

Lakes, which the following numbers demonstrate, dominate the landscape of Northern Europe: 65,000 lakes in Norway, 95,700 lakes in Sweden and 187,888 lakes in Finland (Henriksen *et al*., 1998). The number of lakes counted in each country depends on the lower size limit set to separate ponds from lakes. The given numbers refer to water bodies bigger than 500 m^2. In Finland, for example, the number decreases to 56,000 for lakes bigger than 1 ha, and only 309 lakes exceed the size of 10 km^2. The main reason for this high density of lakes is the relatively young landscape formed after the last ice age, 10,000 years ago. The most common lake types are small and shallow lakes (<0.1 km^2). Some of the largest are Vänern and Vättern in Sweden and Inari, Saimaa and Päijänne in Finland. All trophic levels are represented. However, geographically, more eutrophic lakes occur in the south of Sweden while oligotrophic lakes can be found in the north and at high altitudes. In the boreal landscape, most of the lakes contain high concentrations of humic substances that give the water a yellow-brown colour (Keskitalo and Eloranta, 1999). Because of generally low carbonate content, northern lakes are prone to acidification. Some of these are naturally acidic, whereby a high number of lakes are still influenced by anthropogenic acidification and are, therefore, frequently limed. Most of the lakes are ice-covered during winter. The lakes range by mixing types from cold monomictic lakes in sub arctic areas having a short ice-free period in summer, to dimictic lakes in the southern parts of the countries. In Northern Europe, lakes are an important source for drinking water. The Baltic countries, Northern Poland (Mazurian Lake District), Northern Germany and Denmark have a large variety of shallow lowland lakes with ice-cover duration from one to five months.

Lakes in maritime areas in Western Europe usually do not freeze in winter. In the UK most of the larger lakes are situated in mountainous areas but a few are located in the lowlands and in marshy areas near the coast. Many of these lakes are used to supply water to large conurbations whilst others are important sites for water-based recreation and tourism. The most important natural lakes are those located in North Wales, the English Lake District and the North of Scotland. In Ireland, most of the larger lakes are situated in the south and the west but one large lake (Lough Neagh) is located north of the border between the Republic and Northern Ireland.

Lakes in the Perialpine Region are mainly of the ‘alpine lake’ type. Although this term is widely accepted and used as a descriptor for a specific lake type around the globe, a precise definition is not available. Depending on their origin and elevation, three main categories of alpine lakes can be distinguished with several types in each one (Dokulil, 2004):

- high alpine lakes – high altitude, above the tree-line,
- alpine lakes – glacial valley or fjord-type lakes,
- pre- or subalpine lakes – at lower elevations in the Perialpine Lowlands.

According to Meybeck (1995) lakes in the Alps cover approximately 3.440 km^2. Small lakes of less than 0.1 km^2 in size are most abundant. By far the largest lakes in the region are Lac Leman (581 km^2) and Lake Constance (593 km^2). Most lakes are deep and therefore stratify during summer. Freezing during winter largely depends on lake size and elevation (Dokulil 2004). By mixing regimes the lakes are either dimictic when they freeze or warm monomictic if they mix throughout the winter. Lakes at higher elevations are cold-monomictic and ice-covered for the greater part of the year (Eckel, 1955). One of the major differences of alpine lakes to other deglaciated lake regions is the much greater lake depth in the Alps resulting from glacial scour. The maximum to mean depth ratio of 0.46 is very similar to the world average and characteristic for deep lakes (Dokulil, 2004). Several lakes in the region are characterised by metalimnetic (i.e., located at the lower boundary of the mixed surface layer) populations of the cyanobacterium *Planktothrix rubescens.*

Mountain lakes can be found in most of Mediterranean countries like Italy, France, Spain, Albania, and Greece where they should be allocated to alpine rather than to Mediterranean types.

The most important Italian lake district is located in northern Italy and includes the deep sub alpine lakes and some small-medium Insubrian lakes, which together make up more than 80% of the total volume of lakes in Italy (Premazzi *et al*., 2003). One of the most important hydrodynamic features in the great lakes (i.e. Como, Garda, Maggiore) is their specific holo-oligomixis. The rainfall regime in this area is typical of the Alpine Region with the precipitation maximum between May and November. Approximately 70-75% of the annual precipitation volume is concentrated to this period. The climate is of continental type.

The Central Italian lakes belong to the Middle Thyrrenian Climatic District, and occupy the highest part of the volcanic area characterised by a maritime climate with generally mild winters and hot summers (Ambrosetti and Barbanti, 2002). The lakes in this region are of different origin: volcanic crater lakes (like Lake Bolsena), alluvial lakes (like Lake Trasimeno) or coastal (like Lake Lesina and Lake Varano in Puglia). The Latium lakes (Bolsena, Bracciano, Nemi, Vico) have some hydrodynamic features characteristic of lakes in an oceanic climate. As a consequence of this, the thermocline in these lakes develops much deeper than in the northern district, though not as deep as in lakes with a really oceanic climate (Pompilio *et al*., 1996).

Greek lakes can be divided into three categories: warm monomictic deep lakes, warm monomictic shallow lakes, and dimictic shallow lakes (Zacharias, 2002).

Spanish lakes range by their salinity level from freshwater to hypersaline lakes and by their permanency from ephemeral, filled with water for less than one month, to deep stratified permanent lakes. Temporary lakes with increased salt content are characteristic of endorheic basins (without outflow) in semi-arid and arid climate zones while permanent lakes are located at higher altitudes and in carstic areas.

Besides natural lakes, there are about 4000 large dams in the Mediterranean region (Table IV.B.2). The top five countries in terms of the number of dams are Spain, with 1,196 large dams, or just under one third of the Mediterranean total, Turkey (625), France (569), and Italy (524) (Haas, 2002).

Table IV.B.2. Number of large dams* in Mediterranean countries (Haas, 2002)

Region, country	Number of large dams in 2000	Percentage of dams in the region
North Mediterranean		
Albania	306	7.8
Bosnia-Herzegovina	25	0.6
Croatia	29	0.7
Spain	1196	30.6
France	569	14.5
Greece	46	1.2
Italy	524	13.4
Malta	-	-
Monaco	-	-
Portugal	103	2.6
Slovenia	30	0.8
Yugoslavia	69	1.8
East Mediterranean		
Cyprus	52	1.3
Israel	?	?
Jordan	5	0.1
Lebanon	5	0.1
Syria	41	1.0
Palestinian authority territories	?	?
Turkey	625	16.0
South Mediterranean		
Algeria	107	2.7
Egypt	6	0.2
Libya	12	0.3
Morocco	92	2.4
Tunisia	72	1.8
Total	3914	100

*15 m or more high (from the foundation). If dams are between 5-15 metres and have a reservoir volume of more than 3 million cubic metres they are also classified as large dams (Dams and Development, 2000).

IV.B.3. Climatic Variations within the Regions

The climate of Europe is dominated by a westerly flow of cyclonic depressions that are sometimes blocked by stationary areas of high pressure. Although southern areas enjoy long periods of cloudless skies during summer, European weather can change rapidly, with significant differences from year to year.

The climate in Northern Europe ranges from temperate to arctic and from wet to dry. Scandinavia contains some of the cloudiest regions in the world with considerable cloudiness throughout the year. In a belt along the Scandinavian western, northwestern and northern coasts, the number of clear days averages 25 to 35 days a year, while the high mountain regions of the Scandinavian Peninsula experience an average of 35-45 clear days a year (European Daylighting Atlas, 1996).

The climate in the Atlantic Region is wet and relatively mild. Many of the larger lakes are situated near the coast so are either free of ice or only covered with ice for a few days a year. Precipitation gradients in the Atlantic Region are typically very steep and there is often a strong altitude (orographic) component to the rainfall. In the UK and Ireland, the most striking meteorological contrast is between the wet west and the dry east. These differences are most pronounced in winter where the average rainfall recorded between 1961 and 1990 ranged from more than 500 mm in the west to less than 200 mm in the east. Another important factor modulating the weather conditions experienced in the region is the trajectory of the Gulf Stream in the Atlantic. The warm water of the Gulf Stream reduces the severity of the winters experienced along the western seaboard whilst the position of its north wall influences the trajectory of storms in the western approaches (Taylor, 1996).

The coastal climate in Northern France, Flanders and the lowlands of Belgium, the entire territory of The Netherlands, and the lowlands of the Northern Germany shows greater contrasts of temperature than the climate in Britain. Further east and south, in the uplands of eastern Belgium, Luxembourg and Central Germany, the distance from the sea and the sporadic occurrence of continental influences or modifications due to the relief in the neighborhood of mountain slopes, cause more pronounced annual ranges of temperature, mainly on account of the progressive lowering of winter temperatures. Winters are dry and relatively severe, and the absence of snowfall is unusual. The shortness of the intermediate seasons, autumn and spring, causes the transition to be more abrupt, and the contrasts of temperature more noticeable.

The continental influence increases eastwards in the Northern Alpine Fore-land from the Swiss part eastwards to the Austrian part. The climate of the Northern Alpine Fore-land is in all parts mainly governed by the influence of the Alps. This is especially the case during northerly flow due to the upwind effects which are not so much a function of the relative difference in height but rather a function of the distance, windwards of the base of the Alps (Wallén, 1977). The mean annual cloud cover is as low as about 50% over the south slope of the Alps, but it amounts to 65% over the north slope (European Daylighting Atlas, 1996).

The inner alpine regions are dry and have sunny valleys, and the scanty precipitation is rather uniformly distributed over the year. Valleys, which are oriented from west to east, receive considerably less precipitation, whereas the north south valleys may receive abundant rainfall due to hill effects with northwesterly flow.

The Mediterranean climate has a typical seasonal rhythm strongly marked with respect to temperature, precipitation and weather in general. Hot dry summers from mid-May to mid-September and rainy, rather changeable, winters from November to mid-March are separated by short autumn and spring seasons of rapid change in weather conditions.

Due to climatic reasons, water scarcity is a general concern in many Mediterranean countries. Broader variations in water resource availability across the Mediterranean region, corresponds **to three geographic groupings** (Margat and Vallé, 2000):

Group 1*:* Mainly Northern Mediterranean countries (Portugal, Spain, France and Monaco, Italy, Bosnia-Herzegovina, Croatia, Slovenia, F.R. of Yugoslavia, Albania, Greece). Generally rich in water (above 3000 m^3/year/cap) where total water demand is stable, or even decreasing, without quantity shortage problems (except for short periods of time, or drought cycles for localized areas), but having to face water quality degradation and meet the increasing needs of environmental protection and restoration.

Group 2**:** Western Mediterranean and Middle East countries (Turkey, Cyprus, Syria, Lebanon, Israel, Palestinian territories of Gaza and the West Bank, Jordan) have overall excess resources (1000 to 3000 m^3/year/cap), but due to increasing demands these countries are more sensitive to short term or structural shortages. The average annual amount of precipitation e.g. in Cyprus is about 500 mm. The records available over the period 1917-2000 demonstrate a slight decrease in the precipitation since 1971 (Pashiardis, 2002). Negative correlation found between interannual variability of the North Atlantic Oscillation (NAO) indices and the Turkish precipitation (Türkes, 2002) indicate that the NAO is one of the major atmospheric sources for the year-to-year and quasi-decadal variability of the precipitation conditions in the Eastern Mediterranean Basin.

Group 3: Countries from North Africa, the Middle East, or islands (Egypt, Libya, Tunisia, Algeria, Morocco, Malta) have limited water resources (less than 1000 m^3/year/cap) that are already overexploited or are becoming so where demographic growth is strong.

At present, countries in the north Mediterranean receive about 72% of regional precipitation compared to 23% for countries in the east and 5% for countries in the south.

IV.B.4. The Climate Change Scenarios for Lakes

In this review, conclusions are based on an ensemble of climate change scenarios produced by the Swedish Rossby Centre as a contribution to the PRUDENCE (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) project (Räisänen *et al*., 2004). Simulations using two driving global models (HadAM3H and ECHAM4/OPYC3) and two IPCC SRES emission scenarios (A2 and B2) resulted in four realizations of climate change from 1961–1990 to 2071–2100.

According to the latest climate change scenarios (Räisänen et al., 2004), the warming in Northern Europe will be largest in winter or late autumn. In Central and Southern Europe, the warming peaks in summer when it locally reaches 6 to 10˚C. The four simulations in general agree that the amount of precipitation will generally increase in Northern Europe especially in winter and decrease in Southern and Central Europe in summer. A large increase in the lowest minimum temperatures in northern, Central and Eastern Europe, are expected, most likely due to reduced snow cover. Extreme daily precipitation increases even in most of those areas where the mean annual precipitation decreases.

The regional scenarios suggest that the mean annual air temperature in Sweden will increase by about 4°C within the next 100 years, depending on the ensemble of emission scenarios and general circulation models (2071-2100, see for details Räisänen *et al*. 2004). This is over 40 per cent more than the mean global change. The mean winter temperature is expected to rise by 3-5°C. The temperature rise in summer is expected to be somewhat lower 2 - 3°C (Räisänen *et al*., 2004).

An application of the climate scenarios combined with a physical lake model on a lake in middle Sweden predicted that the lake will be totally ice free 2 years out of 10 (Blenckner *et al*., 2002). Additionally, the stratification period in summer will be longer and more distinct, which is likely to favour cyanobacterial blooms. In warmer climate the thermocline will develop earlier in spring and disappear later in autumn. Higher lake temperatures may greatly affect drinking water quality in terms of taste, odour and colour (Sweden's, 2001).

Model simulations reveal a general increase in the precipitation in Northern Europe with a large increase in winter precipitation. The greatest increases in both precipitation and net precipitation-evaporation difference (approximate measure of water availability) are foreseen along the Atlantic coast and in Northern Scandinavia. A slight decline is predicted in southeastern Sweden, however. The predicted changes in precipitation vary in a larger range, which illustrates the uncertainties involved in impact studies.

The estimated changes in water supply largely conform to the changes in precipitation-evaporation: increased water supply in the north, but no clear change or decrease in the south. One important conclusion to date is that the characteristic spring flood of today will be more irregular and less intense, on average. This is because the snow period will be shorter and the snow depth less due to the warming effect. However, the water supply is expected to increase in winter and also in autumn as a result of heavier precipitation. Accordingly, the risk of flooding will diminish in spring but increase in late summer and autumn, particularly in the north (Sweden's, 2001).

A preliminary simulation of the regional climate scenarios indicates a clear increase in surface water temperature in the North in spring and late summer and one month shorter ice cover period compared to today's climate. This will have implications for the mixing regime, as dimictic lakes become monomictic with wide consequences for nutrient and phytoplankton dynamics. The increase in surface water temperature in summer implies an increase in summer stratification length with alterations in the composition of summer phytoplankton blooms (unpublished results).

The scenarios (Räisänen *et al*., 2004) indicate that climate change may have a dramatic impact on the Swedish environment. The rapid changes predicted in these scenarios include a rise in mean temperature of about 0.4°C per 10-year period. Precipitation is also forecast to rise by up to 2 per cent per decade. The climate zones determining the range of the various biomes may move north by 50 to 80 kilometres a decade (Sweden's, 2001).

In the Alpine region, future temperature change will exert a significant influence on the hydrological cycle because temperature regulates how much of the precipitation falls as rain or snow. Higher temperatures in winter reduce the amount of spring snowmelt, raise the evaporation, and hence reduce run-off in spring. Temperature increase leads to an expansion of the vegetation period and increases transpiration reducing discharge. On the other hand, glacial melting is enhanced leading to greater discharge during summer. In general temperatures will increase in most areas of Austria while precipitation will decrease.

Similar to northern Europe, the Mediterranean region will warm at a rate of between 0.1 and 0.4ºC/decade (Haas, 2002). Projections point to more precipitation in the winter and less in summer over the region as a whole, while mean annual precipitation is expected to decline south of 45°N. The general tendency would be that northern parts of the Mediterranean would become wetter, and the southern parts drier, thus amplifying current rainfall differences and water scarcity. The IPCC (2001) nonetheless acknowledges that the regional averages also mask important basin-specific and temporal problems with distribution. Because the general circulation models used to assess global and regional variations do not have sufficient resolution and accuracy as yet to assess local effects, or changes in a particular basin, (the interactive influences of the Sahara, Atlantic and Mediterranean are also particularly difficult to model), the analysis can be only directional and indicative of the trends.

Table IV.B.3. Projected first order impacts of climate change on Mediterranean hydrological systems (Haas, 2002)

Aspect	Representative Impacts
More variability and extreme weather events: o More frequent and intense storms o Increased number of days of heavy rainfall events and torrential downpours o More frequent and longer lasting droughts spells o Greater seasonal and year-to-year variation in precipitation, especially in semi-arid areas in the southern and eastern portions of the region	• Higher surface runoff with less chance for infiltration • Increased variability in river flows through the year • More frequent and higher floods, especially over northern parts of the Mediterranean basin • Increased erosion from intense storms and sediment in runoff (in conjunction with effects of drought making soils erosion-prone) • Lower groundwater recharge rates associated with drought
Wetter winters and dryer summers o More precipitation in winter, less in summer over the Mediterranean region as a whole, with variability in basins o Earlier snowmelt (e.g. shifting to Jan, Feb, Mar) o More winter precipitation falling as rain (in mountainous and colder climate regions)	o Shift in normal season of peak flows in rivers from spring to winter, especially in basins with mountains in the upper catchments o Runoff in a particular basin may increase or decrease on average, but the seasonal distribution will change o Lower groundwater recharge rates where infiltration is less, and in dry summers o Less efficient rainwater infiltration feeding inland and coastal water tables and fragmentation of fresh water aquifers
Hotter summers and heat waves o Warming trend greater in summer than in winter o Hotter and longer summers, o Heat waves becoming the norm.	o Increased soil evaporation, plant evapo-transpiration o Dryer and more erosion-prone soils o Acceleration of desertification effects o Multiple impacts such as increasing water needs in human, agriculture and natural systems

IV.B.5 PHYSICS

Thermal characteristics
In northern Europe, four regional climate simulations were made within the PRUDENCE project (Räisänen *et al*., 2004). In Southern and Central Europe, the winter-summer contrast in warming is reversed from that in the north. A large increase in summer temperatures occurs especially in the southwestern parts of the European continent, where the warming locally exceeds 10ºC. Such a large warming may have adverse consequences, even without the accompanying decrease in precipitation discussed elsewhere. The most pronounced increases in the air temperatures will be recorded during the summer with the more extreme conditions being recorded in the southeast of the UK and in Ireland. The responses of the lakes to the projected increases will vary from site to site and season to season.

Long distance climatic forcing affects several thermal parameters such as the onset, timing and duration of thermal stratification, heat content (Ambrosetti and Brabanti, 2002a,b), extent of mixing, or duration and break-up date of ice-cover, to name a few. Changes in the freeze-thaw cycle of lakes at high latitudes and altitudes are often used as proxy indicators of regional changes in the weather (Magnuson *et al*., 2000). The European Topic Centre on Air and Climate Change selected changes in duration of lake ice and lake temperature from among a list of climate change state indicators (Erhard *et al*., 2002). Both indicators fulfil most of the criteria on indicativeness, sensitivity, representativeness, comparability, accessibility, and data quality.

Ice duration
A long-term trend towards shorter periods of ice cover due to a later freezing and an earlier ice break-up has been reported for lakes around the Northern Hemisphere (Palecki and Barry, 1986; Kuusisto, 1987; Assel and Robertson, 1995; Livingstone, 1997; Magnuson *et al*., 2000; Assel *et al*., 2003). Additionally, year-to-year variability in ice break-up dates in Northern Europe are related to climatic (NAO and regional atmospheric indices) variation (Weyhenmeyer *et al*., 1999; Blenckner and Chen 2003) in a complex manner. The trend toan earlier ice-out increases the ice-free period and lake temperatures in spring (Blenckner *et al*. 2002). A further increase in climatic warming could imply that dimictic lakes may become warm monomictic (Blenckner *et al*., 2002).

In the arctic, sub arctic, and alpine regions freshwater systems are particularly sensitive to climate change, and most climate change scenarios indicate that the highest and most rapid temperature increases will occur in these regions (McCarthy *et al*., 2001; Arctic Council, 2004). The biggest changes will occur in lakes, which previously were permanently ice-covered become temporarily ice-free (Psenner 2003), and also in lakes which totally loose their winter ice-cover. Ohlendorf *et al*. (2000) concluded from their observations on a remote high alpine lake that the mere occurrence of ice cover is more important than the duration to preserve climate signals. Historical observations from a high alpine lake in Switzerland indicate that the date of ice break-up occurred 12 days earlier in 1990 than 150 years ago. As a result of reduced ice duration, effects of UV radiation became more pronounced in some high alpine lakes in the last century (Psenner and Schmidt, 1992).

Very few records of ice-cover are available for the Atlantic lakes. There are, however, records of a progressive reduction in ice cover at Loch Leven in Scotland and

Windermere in the English Lake District (George, 2000a). In the future, only a few lakes in the more mountainous areas of the Atlantic Region will freeze every year and even here there will be a marked reduction in the duration of ice-cover.

Temperature

One of the most important physical parameters in any lacustrine system is lake temperature, because it reflects meteorological forcing immediately and sensitively (Dokulil, 2000). In temperate region the highest **surface water temperatures** in winter will be recorded in deep lakes that retain heat and the lowest temperatures in shallower lakes that loose heat to the atmosphere. In ice-covered lakes the signals of climatic forcing are mostly reflected in ice-cover duration and less pronounced in water temperature. However, winter temperature controls whether it predominantly snows or rains in winter, and this is crucially important for winter light conditions and gas regime of ice-covered lakes.

Long-term measurements in the English Lake District demonstrate that the winter temperature of the larger lakes has increased by at least 0.6 ^{o}C over the last forty years. Much of this warming can be related to year-to-year variations in the NAO (George *et al*, 2000), an effect described in some detail by Livingstone (2000) and Straile *et al* (2003).

Comparing a relatively cold period in Sweden, 1982 to 1988, with the warm period 1989 to 1995, surface water temperatures in May in Sweden's largest lakes increased by 0.6 to 4.7 °C (Weyhenmeyer 2001). Significant increasing trends in the water temperature in April and May since the 1950s have been reported also for shallow lakes in the Baltic countries (Nõges & Järvet, in press).

Despite the often-pronounced geomorphological differences of lakes in alpine regions, their physical parameters show still a high degree of synchrony (Dokulil and Teubner, 2002). For lakes in the Northern Perialpine Area a high degree of spatial coherence in lake surface temperature among deep lakes has been established. Correlations of the lake surface temperature with air temperature, and with seasonal indices of the NAO suggest that lake surface temperature in winter and spring is related to large-scale atmospheric processes occurring over the North Atlantic (Livingstone and Dokulil, 2001).

Deep alpine lakes orographically situated in more remote, narrow valleys show generally clear trends of **deep water warming**, like several others in the Perialpine Region north and south of the Alps (Blanc *et al*., 1990; Livingstone, 1993,1997; Ambrosetti and Brabanti, 1999). Hypolimnetic temperatures are correlated to climate signals with a time lag of about one year. Reduced winter cooling can result in the persistence of small temperature gradients that may resist complete mixing (Straile *et al*., 2003). Mixing in turn can determine the trophic status of lakes (Salmaso *et al*., 2003), and thus might have essential implications for the assessment of ecological status over time relative to the Water Framework Directive.

Stratification

Thermal stratification, resulting from heating by the sun, is the most important physical process in the lake’s annual cycle and dominates most aspects of lake structure in summer. Thus, the most important weather-related effects in summer will be those associated with the increase in the water temperature and the enhanced physical stability of thermally stratified lakes. The effects of the increased temperature will be most pronounced in shallow, isothermal lakes and the effects of the change in stability in moderately deep lakes that are also relatively productive.

The responses of thermally stratified lakes to changes in the flux of heat and the intensity of wind mixing are quite complex (Reynolds, 1984; Rouen *et al*., 2001).

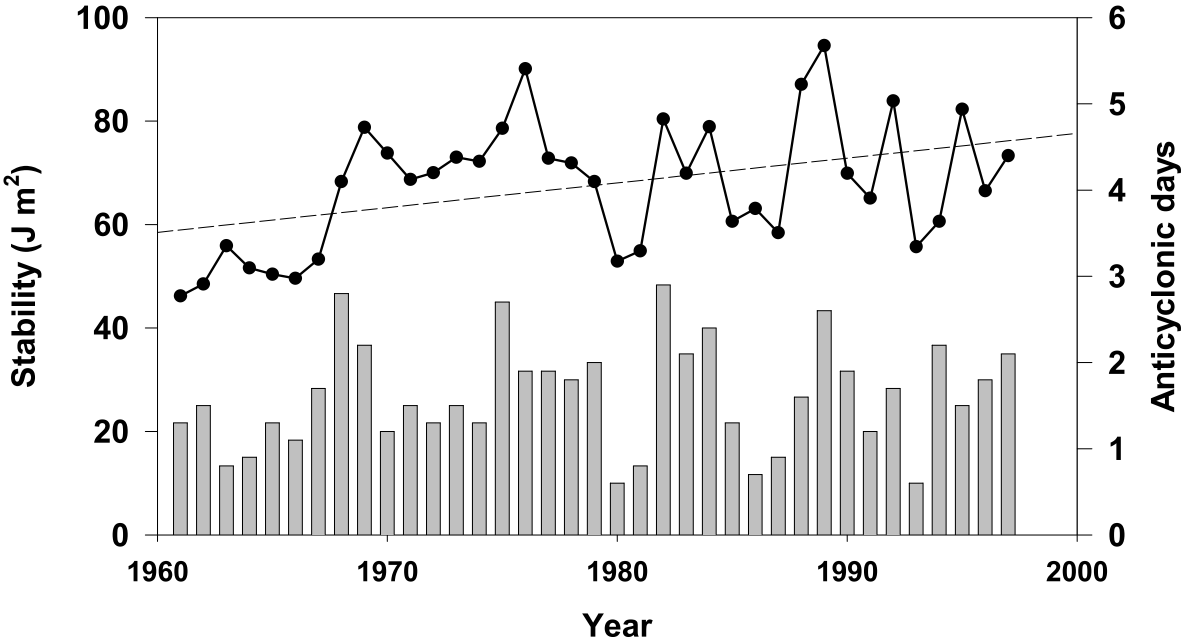


Figure IV.B.1. Long-term variation in the summer stability of Esthwaite Water.

Many of the seasonal changes recorded in the Atlantic Region are closely correlated with seasonal variations in the synoptic weather patterns (Lamb, 1972). Figure IV.B.1 shows the long-term variation in the summer stability of Esthwaite Water, a small thermally stratified lake in the English Lake District, in relation to the frequency of 'anticyclonic' days. In the forty-year period shown, there was a 15% increase in the number of calm summer days and the trend line fitted to the stability measurements is statistically significant at the 95% level. The scenarios produced by the United Kingdom Climate Impacts Programme (UKCIP, 2002) suggest that this trend will continue into the foreseeable future with the summer reductions in wind speed being most pronounced in the east of Ireland and the north of the UK.

Memory and Sensitivity of Lakes

The length of the period for how long the climate signal can be observed depends on the lake morphometry. Gerten and Adrian (2001) found circulating polymictic lakes to be least influenced by the winter effects of the NAO, with an effect lasting only into early spring. In contrast, in a deep dimictic lake with stable summer stratification, the NAO signal persisted in the hypolimnion until the following winter. In high NAO years, hypolimnetic temperatures in this lake were up to 2ºC higher than in low NAO years. In very deep lakes that do not circulate fully each winter, a positive NAO phase may contribute to multi-annual deep water warming.

Historical data sets of deep-water temperatures in Italian lakes reveal that a marked increase in the heat of the whole water mass is occurring, with evident changes in their vertical structure. In particular, there has been a reduction in the depths reached by the winter mixing over the last 40 years and, consequently, the deeper layers are progressively less affected by seasonal variations. The deep hypolimnion of lakes contains a “climatic memory” (represented by variations in the caloric content) from which is revealed thermal variations on a relatively long time scale, comparable with that of the ongoing climatic changes (Ambrosetti *et al.*, 2003).

The climatic memories of deep Italian sub alpine lakes are represented in Figure IV.B.2. The complete circulation in deep lakes will become more and more difficult to achieve in the future, with major repercussion for lake hydrodynamics and turnover. More energy is presently required than for the past mixing events and without the possibility of re-establishing the initial thermal conditions (Ambrosetti and Barbanti, 1999).

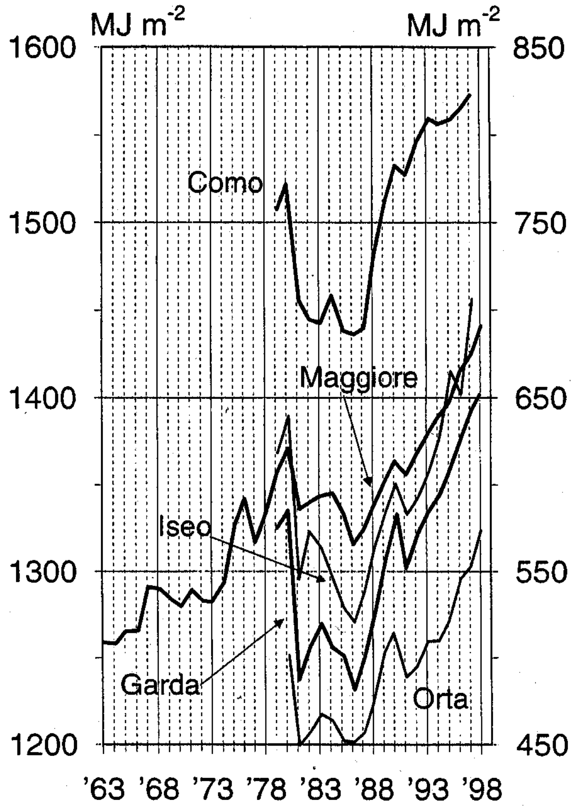


Figure IV.B.2. Trends of the heat content in five deep Italian lakes. Values for Lake Orta on the right axis (from Ambrosetti and Barbanti, 1999)

Direct and Indirect Effects of Temperature Changes

The direct effect of the projected increases in the winter temperatures on the dynamics of lakes in the Atlantic Region is likely to be quite small. There will, however, be significant indirect effects on the flux of nutrients and the growth of plankton much later in the year.

The biological effects of the increased surface temperatures and enhanced stability in summer depend on the physical characteristics of the individual lakes and, in particular, their maximum depth. The very high surface temperatures recoded in shallow lakes may well change the geographic distribution of some cold water species but most planktonic organisms have a cosmopolitan distribution. Most of these species already thrive at temperatures that are very much higher than those predicted by the climate models (UKCIP, 2002). Deep, thermally stratified lakes also provide spatial refuges for organisms that cannot tolerate high temperatures so the direct effects of the projected increases in temperature may be quite small. The annual abundance and long-term survival of these organisms may, however, be compromised if there is a 'mismatch' between their seasonal dynamics and a key resource (George and Harris, 1985).

IV.B.6. Hydrology

All four scenarios used in the simulations within the PRUDENCE project (Räisänen *et al.,* 2004) agree on a general increase in winter precipitation in Northern and Central Europe. They also agree on a general and in some areas large (up to 70%) decrease in summer precipitation in Central and Southern Europe, and of a smaller decrease in summer precipitation north to Central Scandinavia. The climate change scenarios suggest that that there will be a significant increase in winter rainfall throughout the Atlantic Region and a corresponding decrease in the summer rainfall. In winter, some areas in eastern UK that are currently rather dry will thus become much wetter. The most pronounced summer reductions are projected to occur in the south of Ireland and the UK where there may be a 30% reduction in the rainfall within the next twenty years.

Changes in water richness affect lakes in two principal ways: by changing the water residence time and/or changing the water level. The rate of water renewal affects nutrient dynamics and has a critical effect on eutrophication (Dillon, 1975; Vollenweider, 1975) while changes in the water level, especially in shallow lakes, affect the strength of sediment resuspension, light conditions, and the areas of macrophyte colonisation (Nõges and Nõges, 1999).

Residence time

The residence time of a lake is expressed as an annual average, which takes no account of the short-term fluctuations in the rainfall. The effects of the projected changes in the weather will, however, be critically dependent on the seasonal distribution of the rainfall and the frequency of extremes. George and Hurley (2003)

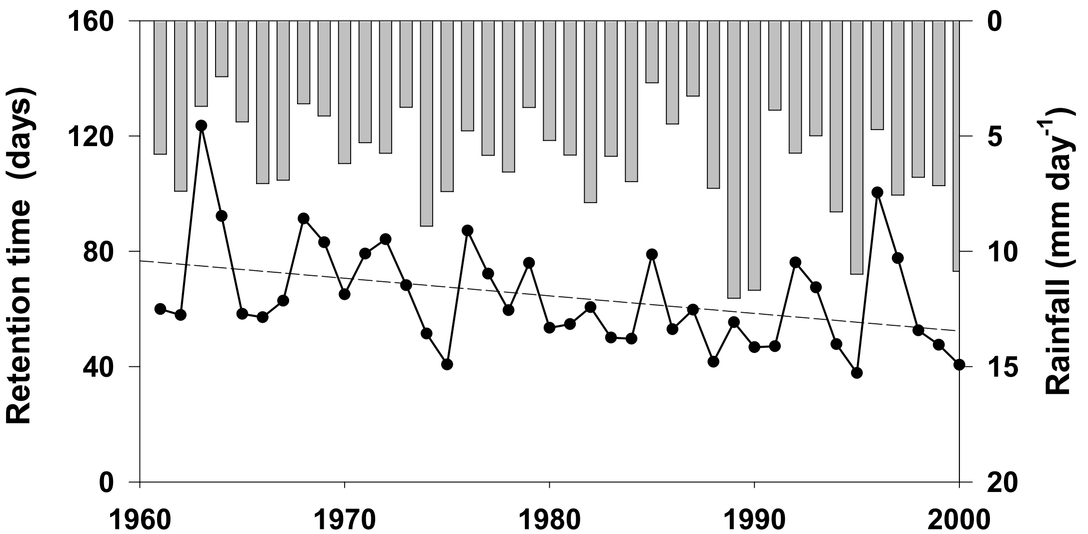


Figure IV.B.3. Winter residence time of Esthwaite Water (UK)

have recently described a method that can be used to 'hindcast' the seasonal variation in the residence time of a lake. Using this system, some lakes are classified as 'one season' lakes which respond very quickly to changes in the rainfall whilst others are 'multi-season' lakes that are influenced by the changes recorded over months or even years. In UK the most pronounced changes will thus be recorded in the 'wet' west during the winter and the dry 'east' during the summer.

Figure IV.B.3 shows the effect that historical variations in the rainfall have had on the winter residence time of Esthwaite Water, a lake with an average annual residence time of 92 days. The results show that the winter residence time of this lake has decreased progressively over the past 40 years with the rate of decline averaging 0.5 days a year. Lakes with long residence times are less sensitive to the effects of changes in the rainfall since the effects of heavy winter rains may then counter the impact of summer droughts. An increase in the water residence time in a warmer climate due to higher evaporation and decreased stream outflow will also increase the retention of chemical constituents, and intensify the nutrient cycle.

To summarize, in deep perialpine lakes (north and south of the Alps) climate changes are having a double and contrasting impact on the renewal times of lake waters. In summer, an increase in the thickness of the mixo-limnion accelerates the renewal time, as a greater volume of water is involved. In winter, the need for more mixing energy to trigger a complete vertical mixing, or a deeper mixing, reduces the volume of the water mass involved in the renewal.

Water level

Because of the intimate hydrological link between river discharge and lake level, changes in run-off will ultimately influence lake level characteristics. Increasing trends in heavy rainfalls (Osborne and Hulme, 2002; Matulla *et al*., 2004) will affect lake levels and increase the flood risk.

Climate change has introduced another level of uncertainty to the management of most dams. The safety of large dams is affected by changes in the magnitude or frequency of extreme precipitation events. One of the first studied in this area concluded that the discharge of the 50-year flood on the River Severn in the United Kingdom might increase by approximately 20% by 2050 (Tedd, 2000). There is concern whether existing spillways of large dams can accommodate such floods in the future.

In the flat landscapes in Estonia, N-W Russia, South Finland and North Germany where the outflow from lakes is often limited by the small slope of rivers, changes in precipitation result in large seasonal and interannual fluctuations of the water level. Changes in water levels, particularly in shallow lakes, may change the mean water column irradiance (Behrendt and Stellmacher, 1987) and shift areas of sediment erosion, transportation, and accumulation (Bengtsson et al. 1990). The large surface area to mean depth ratio makes the shallow lakes, especially large ones, highly susceptible to climatic influences (Magnusson *et al*. 1990). The responses of phyto- and zooplankton communities to altered environmental conditions may be complex (Weyhenmeyer *et al*. 1999; Nõges and Nõges, 1999; Irigoien et al. 2000; Gerten and Adrian 2000; Straile 2000; Straile and Adrian 2000). Generally, shorter residence time and higher water levels in lakes will contribute to the improvement of all common water quality parameters in these temperate lakes.

Lake levels in semi-arid and arid areas reflect a sensitive balance between water inflow and evaporation. Increasing temperature and prolonged droughts decrease the water level in these lakes and shift them from a permanent status to a semi-permanent or temporary status. Shallow lakes may totally dry out or remain ephemeral, filled with water only for short periods during sporadic rainfalls.

Temperature-related increases in evaporation from water surfaces, and in evapo-transpiration from soils and vegetation in the catchment areas will have an impact on water demand-supply balances. In arid and semi arid regions the evapo-transpiration potential (ETp) will exceed annual precipitation, and precipitation/ETp ratios may fall as low as 0.25, presenting implications for how both evaporation and storage is managed. At present, evaporation from surface water bodies alone is estimated to be about 5% of available water supply in the dry climate areas (Dams and development, 2000). Longer-term temperature rises will influence water demand and need to be taken into account in demand forecasts. While industrial and household water demand is sensitive to temperature in certain circumstances, agriculture demand (evapo-transpiration) and natural evaporation will be most critically affected as conditions become hotter and drier.

IV.B.7. Optical Properties of Lakes

Climate change may affect the light conditions in lakes and optical properties of water in five major ways:

1. by shortening the ice-cover duration and decreasing the thickness of snow on the ice;
2. by increasing the leaching of dissolved organic matter from soils;
3. by increasing phytoplankton primary production and biomass;
4. by intensifying the resuspension of bottom sediments in shallow lakes through decreasing water levels and increased storminess.
5. by increasing sediment transport from the watershed;

A reduction in the spatial and temporal extent of lake and stream ice cover as a result of warmer winters can decrease light attenuation, which is a major limiting factor for production in boreal aquatic systems (McCarthy et al., 2001). However, the other four processes decrease water transparency and light availability for plants and phytoplankton.

Ice and snow cover in high alpine lakes can be one or more meters thick effectively blocking all light from the lakes. Without light, photosynthesis is no longer possible, turning the entire water body into a heterotrophic system. After ice break-off, these lakes transit to extremely bright light conditions within a very short period of time. The higher altitude the lake, the stronger is the shortwave UV radiation (UVB, 280-320 nm). At an elevation of 3000 m, UVB is approximately 50% higher than at sea level. In addition, ozone depletion in the stratosphere has increased UVB radiation by 10% since 1970, which penetrates deeply into high alpine lakes because of the lack of humic acids and other dissolved organic compounds (Psenner, 2003).

Milder winters contribute to under-ice light conditions in lakes also in Northern and Central Europe where more frequent thaw periods melt the reflecting snow-cover and make the ice more transparent.

In most of the lakes in the Atlantic Region the optical characteristics of water are primarily determined by the concentration of phytoplankton in suspension (see the remote sensing studies of George (1997) in the English Lake District). Some shallow lakes may, however, contain high concentrations of suspended sediment whilst a few lakes situated in upland areas are strongly coloured by dissolved humic compounds.

The available evidence suggests that the projected changes in climate will reduce the transparency of most lakes in the region but the factors responsible for this change will vary from lake to lake. In deep lakes that are moderately productive the key factor will be the quantitative and qualitative changes in the seasonal composition of the phytoplankton. Seasonal and interannual changes in the composition of the phytoplankton will also influence the transparency of shallow lakes but here the overall effect will be complicated by the periodic resuspension of the bottom sediments. The wind speed scenarios currently available for the Atlantic region suggest that wind speeds will tend to increase in winter and decrease during the summer. These changes could well lead to a general reduction in the transparency of the lakes with more sediment being brought into suspension during the winter and more algal blooms appearing during the summer.

Intensified rainfall events result in higher erosion and, consequently, in higher sediment content in runoff water. In clay-rich areas the increase in water turbidity in lakes and reservoirs may last for weeks after a heavy rainfall event affecting the light conditions, gas regime, and primary productivity of these water bodies (Hargreaves, 1999).

Sedimentation exacerbated by climate change and desertification is becoming a major issue, in particular, in reservoirs. In its 2002 State of the Environment Report, the United Nations Environment Programme (UNEP) singled it out as a significant, emerging issue for many regions of the world, where sediment reduces storage capacity, reducing the reliability of water supply and power generation, and reducing flood control effectiveness (Haas, 2002).

The present annual loss of storage in existing reservoirs is estimated at 0.5 to 1.0 percent globally (Dams and Reservoirs, 2003) though the “best guess” is 2% annually in some Mediterranean countries. At a 1.0 percent loss rate there will be a 25 percent reduction in the existing freshwater storage capacity (6,000 km^3 of surface storage provided by large dams at present) globally in the next 25-50 years (Dams and development, 2000). And it will occur mainly in countries that are water stressed and most vulnerable to climate change effects. In particular, rates of sediment yield from large catchments with high induced erosion rates, such as prevalent in arid and semi-arid southern and eastern parts of the Mediterranean, as well as parts of semi-arid or drought prone Northern Mediterranean countries (e.g. parts of Southern Spain and Italy) are projected to increase from the combine effects of elevated temperatures that would affect soil retention characteristics, cycles of drought, land use change – and more concentrated, intense rainfall and flood events.

IV.B.7. Lake Chemistry

Signals of climatic and weather impacts cascade and weaken coherence among lakes from physical and hydrological variables, via chemical to biological parameters.

Nutrients
Climate-induced changes of nutrient dynamics in lakes may be divided into two groups:

1. alterations in **catchment processes** (leaching, runoff, retention) that affect the external loading of nutrients, and water residence time;
2. **in-lake changes** because of changed water column stability in stratified lakes, changed sediment resuspension rate in shallow lakes and in littoral areas of deeper lakes leading to alterations in nutrient cycles.

Most of the processes in nutrient cycles are biologically mediated and thus temperature-dependent.

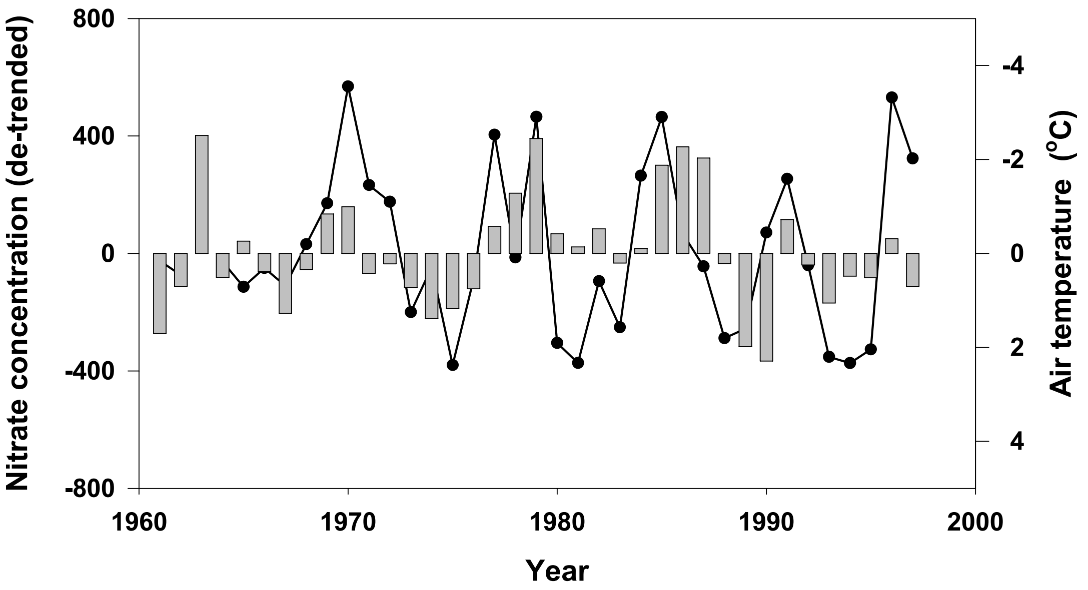


Figure IV.B.4. De-trended winter nitrate data for Blelham Tarn

Catchment processes

Melting of glaciers and loss of soil permafrost in catchments of high alpine and sub arctic lakes as a result of climate warming causes dramatic changes in chemistry and biota of these lakes. For example, a temperature increase by two degrees that melted the permafrost and left Lake Schwarzensee, a remote high alpine lake in Austria, ice-free for two months in summer, changed totally the regime of the lake. Conductivity and silica doubled, the lake became warmer and hence more productive, and pH dramatically increased (Psenner and Schmidt, 1992).

One of the simplest measures of this catchment effect is the concentration of nutrients measured in the lakes during the winter when the biological uptake rate is very low (Sutcliffe *et al*, 1982). Year-to-year variation in winter air temperature has been found to influence the nitrate concentration in lakes in the English Lake District, as warm winters lead to a reduced nitrate concentration in the water (George *et al*., 2004). (Figure IV.B.4) shows the result of de-trending the winter nitrate data for Blelham Tarn, a small lake in the Windermere catchment. Once the long-term 'anthropogenic' trend has been removed, the residual variation is clearly related to the short-term variations in the air temperature.

Very similar interannual variations in the winter concentration of dissolved reactive phosphorus have also been detected in de-trended time-series from the English lakes. The most pronounced effects are detected in lakes with relatively short residence times. The most likely explanation for this trend is the effect that heavy rain has on the routing of drainage in the catchment. The first step in the transfer of dissolved reactive P (DRP) in the drainage system is the dissolution of phosphorus from the superficial layers of the soil. If the rainfall is light, much of the dissolved phosphorus is adsorbed as the water passes through the soil (Sharpley and Sayers, 1979). In contrast, heavy rain increases the proportion of water reaching the lake as overland flow, which contains higher concentrations of DRP (McDiffet *et al.,* 1989).

In Lake Erken (Sweden) the hypolimnetic phosphorus concentration increased during the 1990s. It was concluded that the increase in water residence time was the main factor causing strong internal eutrophication, illustrating the potential sensitivity to climate change of lakes with a long water residence time.

Weather-related effects on the flux of nutrients are more difficult to detect in summer since the concentrations reaching the lakes are rapidly depleted by the growth of phytoplankton.

Changes in the water richness predicted for the Mediterranean Region adversely affect water quality in summer and winter (Haas, 2002). More frequent high river flows in winter may improve water quality because of dilution effect. Still the intensified runoff **increases pollution loading** from catchments. More intense precipitation and frequent torrential downpours would be primarily responsible for soil erosion, leaching of agricultural chemicals, and runoff of urban and livestock wastes and nutrients into water bodies that will accelerate eutrophication of lakes and reservoirs.

Lower flows (either from climate change or increased abstraction, or both) coupled with increasing volumes of effluent discharges into watercourses from growing populations, agriculture activity (pesticides and fertilizers) and industrial activities will result in **increased concentrations** of pollutants including nutrients in water courses.

In-lake processes

In thermally stratified lakes, the internal recycling of nutrients is strongly influenced by the entrainment of nutrients across the seasonal thermocline. This process is particularly important in more productive lakes where large concentrations of DRP accumulate in the anoxic hypolimnion. In a warmer world, most lakes in the Atlantic Region will stratify earlier in the year and will tend to accumulate higher concentrations of decaying matter in the hypolimnion. Oxygen concentrations at depth are therefore likely to fall, which can enhance the nutrient release from the sediment.

In terms of phosphorus, an earlier timing of ice break-up, as found in a Swedish lake (Lake Erken), prolonged the P-limitation period for phytoplankton during the mixing period, but increased the nutrient availability in summer due to a probably enhanced bacterial activity at warmer water temperatures in combination with the prolonged mineralization period (Blenckner *et al.,* 2002). In general, the nutrient turnover might be enhanced in a warmer climate (Hamilton *et al*., 2001), leading to enhanced internal eutrophication.

In contrast, earlier onset and longer duration of thermal stratification in small sharply stratified lakes may result in strong epilimnetic phosphorus depletion during summer. Phosphorus taken up by algae during the spring bloom will settle out when the bloom ceases. Further the established thermocline isolates the nutrient-rich hypolimnion from the nutrient-depleted epilimnion. During summer, metalimnetic maxima of blue-green algae (Konopka, 1981) and photosynthesizing bacteria often occur in this type of lake while the transparent epilimnion allows sufficient light penetration to this depth. Strong algal blooms may reoccur during autumn when the thermocline is eroded and deeper mixing returns hypolimnetic phosphorus back to the surface layer.

Deep water warming observed in peri-alpine and alpine lakes may lead to less upward mixing of nutrients, which accumulated in the hypolimnion during the previous stratification period. In this way, climate variability influences both the causes and symptoms of trophic changes in lakes (Straile et al., 2003).

Very little is known about the way in which year-to-year variations in the weather influence the flux of nutrients from the shallow littoral and the bottom sediments of shallow lakes. Day to day variations in the wind speed are known to influence the transfer of nutrients from the bottom sediments and short-lived, thermally induced currents may also increase the rate at which nutrients are transported from the littoral zone into the open-water (George, 2000). Large internal phosphorus loading may occur when wind-induced resuspension reaches deeper, anoxic sediments with high P concentration in pore-water. In shallow Lake Võrtsjärv the daily release of SRP ($45.2*10^3$ kg) during the storm exceeded the annual external phosphorus load to the lake (Nõges and Kisand, 1999).

Salinity

Higher evaporation rates may increase lake water salinity levels in endorheic basins of semi-arid and arid regions. Lower flows in rivers as they enter the Mediterranean, coupled with sea level rise would accelerate saltwater intrusion into estuaries and coastal aquifers (Haas, 2002).

Plyas in Spain are mainly small closed-basin saline lakes, which respond to changes in precipitation/evaporation balance with changes in lake depth and salinity. These changes are, in their turn, reflected in changes in biota, lithology and geochemistry.

IV.B.8. Dissolved Gas Regime

Most of the lakes in the boreal region are supersaturated with CO_2 in relation to the atmosphere. Here, the pCO_2 is closely related to the DOC concentration in lakes, which, in turn, is often regulated by the catchment characteristics (Sobek *et al.* 2003). In a future climate precipitation will direct the discharge of DOC into the lakes and, thereby, on pCO_2. Most boreal lakes are, therefore, net sources of greenhouse gases (GHG) such as CO_2 and methane.

A study in Finland (Juutinen *et al.* 2001) analysed the methane fluxes in relation to temperature and water level changes. Seasonal methane flux dynamics were found to affect changes in lake water level, which directly responds to variations in precipitation. Additionally, methane fluxes were highest during spring flood, illustrating the strong climate feedback mechanisms in boreal lakes.

Even a productive lake such as Esthwaite Water in the English Lake District is a source of CO_2 to the atmosphere over a year despite substantial under-saturation during much of the summer (Talling, 1976; Maberly, 1996). High concentrations of CO_2 in lakes is input of CO_2-rich water from streams and rivers (Cole and Caraco, 2001) and the heterotrophic breakdown of terrestrial organic carbon within the lake (del Giorgio and Peters, 1994).

The emission of GHG from reservoirs due to rotting vegetation and carbon inflows from the catchment is a recently identified ecosystem impact (of climate) of storage dams. Reservoirs interrupt the downstream flow of organic carbon, leading to emissions of GHG that contribute to climate change (Dams and Development, 2000). A first estimate suggests that the gross emissions from reservoirs may account for 1 to 28% of the global warming potential of GHG emissions (St. Louis *et al*., in press).

The projected increase in the atmospheric concentration of CO_2 will not have a major effect on the dynamics of lakes since they do not rely on the atmosphere as their primary carbon source. However, it has been recurrently shown that doubling of atmospheric CO_2 concentration expected during a time-span of about one hundred years (McCarthy *et al*., 2001) may strongly impact the structure and functioning of terrestrial ecosystems (Lincoln, 1993, Agrell *et al*., 2000). Recent work has demonstrated that changes in stoichiometric elemental ratios in terrestrial and aquatic primary production can substantially impact the structure and functioning of aquatic food webs. Tuchman et al. (2002) showed that nutritional quality of foliage and leaf litter from plants grown under elevated pCO_2 is lower for aquatic decomposers and insects because of higher levels of structural compounds and lower N:C ratio. Larval craneflies (*Tipula abdominalis*) fed elevated CO_2-grown leaves grew 12 times slower than their ambient fed counterparts. Changes in leaf litter composition may affect ecosystem functioning in streams but also and small lakes located in woodland.

In addition, plankton experiments (Urabe et al., 2003) showed that increased partial pressure of carbon dioxide (pCO_2) stimulated algal growth but reduced algal P:C ratio. When feeding on algae grown under high pCO_2, growth of *Daphnia*, an important planktonic herbivore, decreased regardless of algal abundance. Thus, high pCO_2-raised algae were poor food for *Daphnia*. Both results suggest that, in freshwater ecosystems with low nutrient supplies, increased CO_2 may reduce energy and mass transfer efficiency to higher trophic levels by decreasing nutritional quality of the plant biomass.

Elevated temperatures reduce the solubility of CO_2 in water leading to chemical calcite precipitation in hard waters. Of much greater importance, however is the biogenic de-calcification due to rising pH-values as a consequence of enhanced photosynthesis (Dokulil *et al.,* 1993; Schröder *et al*., 1983).

In summer, lower dissolved oxygen levels can be expected in lakes due to higher water temperatures. Incomplete mixing in spring can result in near-bottom oxygen depletion (Livingstone, 1997; Livingstone and Imboden, 1996). Increased water column stability and a longer period of thermal stratification in summer will further exacerbate oxygen availability in the hypolimnia of stratified lakes. In winter, on the contrary, a reduction in the spatial and temporal extent of lake and stream ice cover in boreal region can reduce winter anoxia that typically occurs in shallow lakes (McCarthy *et al*., 2001).

IV.B.9. Coloured Dissolved Organic Carbon (CDOM)

In recent years, the colour of water has increased in streams and lakes throughout the UK (Evans and Monteich, 2001). An increase in concentrations of coloured dissolved organic carbon (CDOM) has been observed in the UK lakes and also in Central Europe. Model predictions for a South Bohemian river (Hejzlar *et al.,* 2003) suggested a 7% increase in CDOM concentration under the scenarios of possible future climate change related to doubled CO_2 concentration in the atmosphere.

There is clear evidence that this is a consequence of the changing climate. Mitchel and McDonald (1992) have shown experimentally that the drying and re-wetting of peat has a major effect on the amount of coloured dissolved organic carbon (CDOM) released from upland soils. The timing of the release is strongly influenced by the hydrological characteristics of the catchment. In the Atlantic Region, the most serious water colour problems are thus likely to occur in the ‘dry’ eastern areas where they will be closely correlated with the frequency of extreme weather events.

Transport of DOM to freshwaters represents a significant carbon flux from the soils global carbon pool to the hydrosphere (Freeman et al., 2001). Increased CDOM input would be beneficial for heterotrophic organisms, but at the same time it also affects the quality of water resources (Vik and Eikebrokk, 1989), reduces light penetration, including that of damaging UV-B radiation (Schindler and Curtis, 1997), changes the vertical distribution of solar heating (Schindler *et al*., 1996), and in this way accelerates the effects of global climate warming on the thermal structures of lakes.

IV.B.10. BIOLOGY

Small variations in climate can have dramatic effects on environmentally sensitive high latitude and high altitude lakes. In these extreme habitats, whether shallow or deep, many species are living at the limit of their capabilities and will respond immediately to changes in ice regime. Big changes can be predicted also in other extreme environments like, e.g., temporary lakes in the Mediterranean area or shallow soda lakes in Austria (Kirschner *et al*., 2002). Seasonal systems that presently can cope with occasional or periodic drought will experience additional stress that some species might not be able to survive (Brock and van Vierssen, 1992). Changes in lake permanence cause temporal habitat fragmentation (Thomas, 2003) that has drastic consequences to the biota. Most of the species die out and will be replaced by species, which have special adaptations to tolerate intermediate dry periods.

Microcosm experiments (Petchey *et al*., 1999) showed that extinction risk in warming environments depends on trophic position. Warming (+2ºC per week during 7 weeks) significantly increased primary production, directly through increased temperature-dependent physiological rates and indirectly through changes in trophic structure. Warming greatly increased herbivore and predator extinction frequencies but had little effect on the composition of producers and bacterivores leaving the latters over-represented in warmed communities.

Phytoplankton

Climate impacts on phytoplankton via catchment and lake processes are conceptually summarised in Figure IV.B.5. In general, effects of global warming on phytoplankton dynamics seem to be not fundamentally different in different regions of the world (Gerten and Adrian, 2002). **In winter**, the most important weather-related effects are those connected with light conditions: for ice-covered lakes biggest changes are projected in ice duration while in ice-free lakes light conditions depend mostly on the interannual variations in the intensity of wind-induced mixing. **In summer**, the most important weather-related effects are those associated with the projected increases in the water temperature and the enhanced physical stability of the water column in stratified lakes.

Timing of spring bloom

In winter ice-covered lakes the timing of the phytoplankton spring bloom is mainly triggered by light availability, controlled by the ice characteristics and the snow on the ice. Therefore, strong relationships between the timing and the winter climate were found in North European lakes (Weyhenmeyer *et al.* 1999). The timing of ice break-up and duration of the overturn control light climate and the transport of the nutrients from hypolimnion to epilimnion (Kilman *et al.* 1996). In spring, the water column is commonly dominated by diatoms, that typically favour high nutrient conditions, low light and low temperature. Generally, large, heavily silicified species, such as

Aulacoseira spp. favour the changed conditions during spring overturn (Lund 1966, Round *et al.* 1990). These diatom blooms can collapse for a variety of reasons, but thermal stratification and sedimentation usually accelerates their rate of decline. Once the diatoms have departed, a variety of small flagellates then tend to dominate the plankton. These small forms have high rates of growth but can only survive if the water column is periodically mixed by the wind.

In lakes which do not freeze in winter, the timing of the spring bloom is mainly dependent on light and turbulence, two factors influenced by climatic variation and change. Lund (1950) and Talling (1971) detailed the influence of stratification and spring rains on the timing and magnitude of spring diatom blooms. A critical factor is the time the growing cells spend in the illuminated and dark portion of a mixed water column. Phytoplankton suspended in 'dark' water cannot grow because their respiratory losses are greater than their gross rate of carbon fixation.

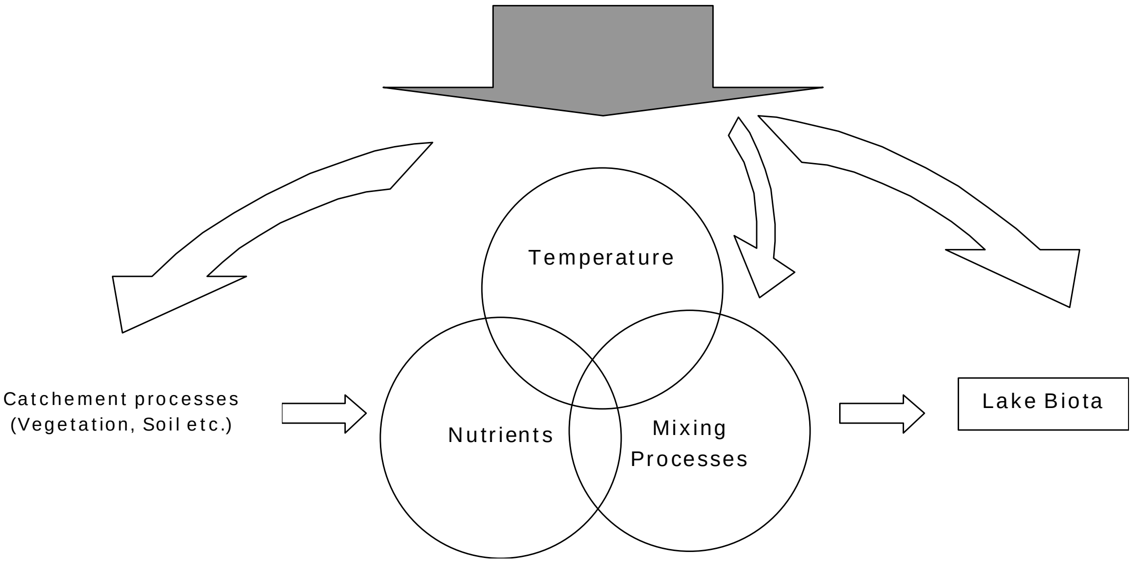


Figure IV.B.5. Conceptual diagram of climate impacts on catchment and lake processes, and their relations (Modified by Dokulil from Anderson, 2000)

The magnitude of the bloom may be differently related to climatic factors. The loss of ice cover or less snow on the ice might change and/or increase the algae population during winter (Pettersson, 1990; Adrian *et al*., 1995). Thus, the nutrient availability might be lower for the actual spring bloom, leading to a reduced algae peak (Pettersson 1990). Cloud conditions in spring, the mixing regime, and the timing of the onset of stratification strongly affect the magnitude of the phytoplankton spring peak (Gaedke *et al*., 1998a,b) and the annual primary production alpine lakes (Goldman *et al*., 1989). In extreme mild winters in Europe (i.e. 1989 and 1990) an coherent increase in cyanobacterial biomass was found in a number of European lakes (Weyhenmeyer *et al*., 2002).

Overwintering

Relatively small differences in the overwintering stocks of some algae can have a major effect on their growth rate later in the year. For many slow-growing species of phytoplankton, their growth rate in early summer is strongly influence by the number of cells that overwinter in the open water (Heaney and Canter, 1989). Wet winters invariably reduce the size of this spring inoculum, which may then influence the seasonal succession of phytoplankton later in the year. Also the overwintering success of resting stages, for example of *Gloeotrichia echinulata*, a dominant summer blooming species in Lake Erken (Pettersson *et al*., 1993; Tymowski and Duthie, 2000), might be strongly influenced.

Temperature effects
Most planktonic species can survive and grow at temperatures well in excess of those predicted for a warmer world. Hawkes (1969) has examined the temperature tolerance of different groups of algae and suggested that diatoms grow best at temperatures below 25 C and blue-green algae at temperatures above 30 ^{0} C. There are, however, notable exceptions, such as the diatom *Acnanthes marginulata*, which can tolerate temperatures up to 41 C (Patrick, 1969) and the blue-green alga *Oscillatoria rubescens* that is commonly described as a cold-water form. In physiological terms, most groups of algae photosynthesise most efficiently at temperatures of around 25 ^{0}C. The rate of carbon fixation could therefore increase with increasing temperature, but factors other than temperature usually limit net production in most lakes.

If the climate becomes warmer, with warmer winters, the composition of phytoplankton might be totally changed, as observed in 1989 from only one extremely mild winter (Weyhenmeyer *et al*., 2002). In addition to the direct (in terms of no time lag) response, the outbreak of blooms in the summer period can also be influenced by the warmer winter period (Hallegraeff, 1993; Guess *et al*., 2000).

Density and viscosity of water directly influence the ability of phytoplankton organisms to remain in suspension. Viscosity decreases by about 50% from 0°C to 25°C. Consequently sinking rates of phytoplankton double over this range. Any prolonged rise of water temperature will therefore result in higher loss rates due to sinking or selective growth of species which can more easily compensate sinking such as cyanobacteria, increasing the risk of algal bloom formation and the appearance of toxic species (Dokulil, 2000, 2003).

Another temperature-related phenomenon is the change in species distribution areas. The tropical bloom-forming cyanobacterium *Cylindrospermopsis raciborskii* is causing increasing concern because of its potential toxicity and invasive behavior at mid-latitudes (Neilan *et al*., 2003; Briand *et al*., 2004). This species has recently been identified in several temperate areas in Hungary, Germany, France, and Portugal. It is suggested that the colonization of mid-latitudes by *C. raciborskii* may result from a combination of its ability to tolerate a rather wide range of climatic conditions and climate warming, which provides this species with better environmental conditions for its growth.

Mixing vs. stability
In general, increasing mixing depth increases the proportion of abiotic light attenuation within the mixed layer, leading to a decrease of phytoplankton production averaged over the mixed layer (Huisman *et al*., 1999; Diehl, 2002). Windy and rainy periods (and the NAO) also affect the mixing depth and therefore lead to a lower phytoplankton biomass compared to calm and sunny periods (Arvola *et al.* 2002).

Warm water and longer periods of stratification can promote a dominance of potentially toxic cyanobacteria (George and Harris, 1985; George et al., 1990; Hyenstrand *et al.,* 1998). Additionally, large cyanobacteria colonies (besides other phytoplankton groups) are resistant against grazing by zooplankton, leading to a dominance of cyanobacteria in the last stages of the stratification. Figure IV.B.6 shows the results of a long-term study of the factors influencing the growth of the blue-green alga *Aphanizomenon* in Esthwaite Water (George *et al*., 1990). The solid line shows the de-trended and smoothed summer abundance of the species and the vertical bars are a simple measure of water column stability. Algal blooms of this kind are commonly regarded as a symptom of eutrophication. Here, the key factor influencing the appearance of these summer blooms was the quasi-cyclical variation in the intensity of wind mixing. In a warmer climate-changed world, algal blooms of this kind will appear much earlier in the year and may also be more persistent if the trend towards lower summer wind speeds is sustained in the Atlantic Region.

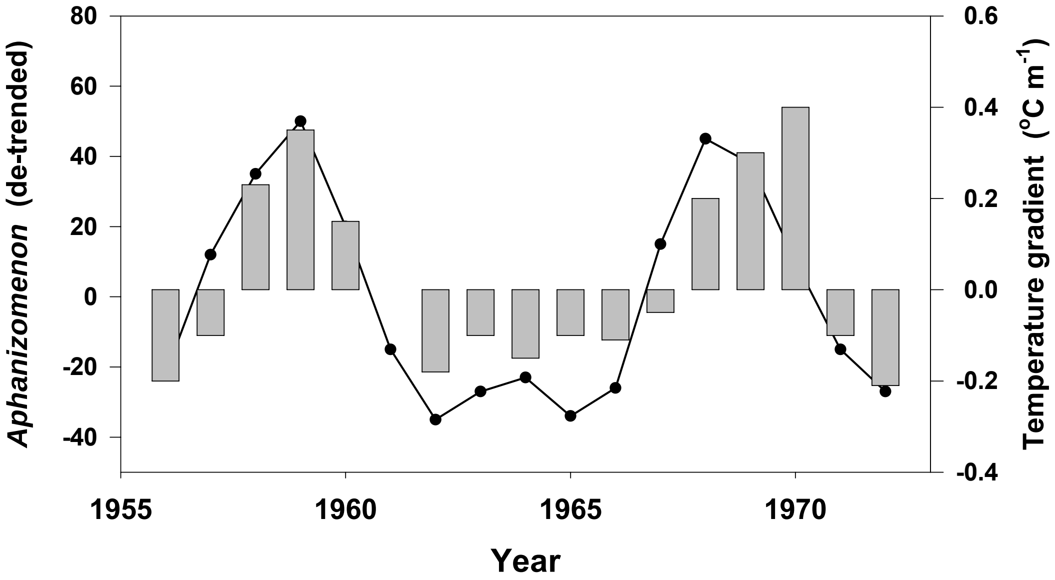


Figure IV.B.6. Factors influencing blue-green algae growth in Esthwaite Water, UK (George *et al.*, 1990)

Besides direct effects on phytoplankton growth conditions, climate change may alter the cascading top-down relations in the food chain (Scheffer *et al*., 2001). In a warmer world the biggest increase in phytoplankton biomass due to released grazing control can be expected in arctic lakes (Flanagan *et al*., 2003).

Macrophytes
An littoral zone experiment under different temperature regimes in Finland showed that, during warmer conditions, macrophytes emerged earlier and developed faster, which led to a two-fold higher above ground biomass. Additionally, an increase in filamentous green algae in the littoral zone was recorded (Kankaala *et al.* 2000).

Very little is known about how macrophytes will be impacted by climatic change in alpine lakes. From the few observations of temperature effects on submerged plants it can be concluded that increase in water temperature will generally affect growth and decay of plant material. Moreover, invasive plants will be favoured and already endangered species might be lost (Dokulil *et al*., 1993).

Zooplankton
The combined effects of predation and the availability of food regulate the zooplankton populations that dominate the open water communities of lakes. Most weather-related effects are mediated by changes in the quantity and quality of food (George *et al*, 1990). The consequences of a sustained change in the fish community on the open water food-web are more difficult to predict but could include

increased predation from some species like perch and roach that currently produce strong year classes in very warm years (Sarvala and Heliminen, 1996). One 'food supply' effect that has a major effect on the dynamics of planktonic herbivores is the episodic growth of edible algae. In most lakes, such species are only abundant for a few weeks in the year and there is typically a clear correlation between the appearance of strong cohorts of grazers and the seasonal dynamics of these edible forms (George and Reynolds, 1997). Warmer surface water can reduce the nutritional value of edible phytoplankton, but it also may shift primary production toward green algae and cyanobacteria, which are less favoured by secondary consumers (McCarthy *et al*., 2001).

Zooplankton that graze on phytoplankton as a food resource, appear shortly after the phytoplankton spring bloom. Since the phytoplankton spring bloom shifted as a result of warmer winters, in some Swedish lakes the zooplankton biomass peak shifted as well, occurring earlier after warm winters. This is reflected by a higher zooplankton biomass in May after warm winters in the large Swedish lakes (Weyhenmeyer, 2001).

Increased water temperatures can have negative impacts on zooplankton because of enhanced metabolic requirements and adverse effects on development and growth (Dokulil *et al*., 1993). In Lake Constance for example, the interannual variability of *Daphnia* growth rate is closely related to water temperature and hence to climate signals. This correlation is due to physiological response of *Daphnia* egg development and growth rates to increased water temperatures and is not mediated by better food supply (Gaedke *et al*., 1998; Straile, 2000).

In temperate lakes, asynchronous cycles in surface water temperatures and incident ultraviolet (UV) radiation expose aquatic organisms to damaging UV radiation at different temperatures. The enzyme systems that repair UV-induced DNA damage are temperature dependent, and thus potentially less effective at repairing DNA damage at lower temperatures (MacFadyen *et al*., 2004). The important implication is that aquatic organisms that depend heavily on DNA repair processes may be less able to survive high UV exposure in low temperature environments. Photoprotection may be more effective under the low temperature, high UV conditions such as are found in early spring or at high elevations. In high alpine lakes zooplankton is pigmented and deep living to avoid exposure to high doses of UVB radiation (Praptokardiyo, 1979).

Zoobenthos

The response of freshwater benthos to climatic changes is not well documented in the perialpine region. Fossil remains have mainly been used by Lotter et al. (1997) to reconstruct the recent past environmental conditions in alpine lakes. Similar circumstantial evidence comes from a high mountain lake in Spain where fossil chironomids indicate recent warming (Granados and Toro, 2000).

Fish

Thermal stress is defined as any temperature change that produces a significant disturbance in the normal functions of a freshwater fish and thus decreases the probability of survival. According to Alabaster & Lloyd (1980), an increase in water temperature from about 0°C to 2°C in winter at the time of reproduction would severely affect spawning of *Coregonus* sp. and burbot (*Lota lota*). Summer temperature of 20 to 21°C is the upper permissible temperature for salmonids of the genus *Salmo*. Coregonids can withstand a rise of temperature of 5 to 6°C but the maximum for the summer months should not exceed 22 to 23°C. For many cyprinids, the permissible increase of temperature is about 6°C above the natural ambient values, with an upper limit of 30°C during the warmest season. An increase in temperature might first suppress the populations of burbot, salmonids, and coregonids and favour the preponderance of cyprinid species.

With climate change, the greatest losses in cold-water species would occur in the southern borders of a species' natural range, where the minimum temperatures are closest to thermal tolerances. Many species are particularly temperature-sensitive during spawning. An EPA study based on modelling of thermal conditions in lakes assuming a doubling of CO_2 levels, found that the region faces a 50 to 100% potential loss of habitat for brown, brook, and rainbow trout, cold-water species that are highly valued by anglers.

The projected increases in winter temperature could adversely affect the spawning and embryonic development of a number of fish species in the Atlantic Region. The eggs and embryos of most fish tolerate a much narrower range of temperatures than their juveniles and adults (Elliott, 1981). The most temperature sensitive fish in the region are the whitefishes (*Coregonus lavaretus*) and the charr (*Salvelinus alpinus*). These species are often called 'glacial relicts ' and are assumed to be land-locked remnants of species that at one time migrated freely to and from the sea. The current geographical distribution of these species is clearly influenced by temperature (Wheeler, 1977; Maitland, 1977). Most of the lakes in which they thrive today are cool, deep basins in the more mountainous areas of the U.K. Both species have an upper thermal limit of 8°C for their egg stage so many of these populations could be endangered by the predicted increases in winter temperature.

The spawning performance of trout and salmon populations in the Atlantic Region should not be adversely affected by the projected increases in winter temperature. Increased spring temperatures could, however, stimulate early emergence when the larvae would be smaller in size and might not be able to find enough food to survive.

The response of fish to warmer winters in Sweden's largest lakes Vänern, Vättern and Mälaren is complex and not yet completely analysed. One study shows that autumn spawners such as vendance (Coregonus albula) have difficulties in adapting to warmer temperatures. The catch of vendance drastically decreased when lake ice breakup was very early in the year (Nyberg *et al*. 2001).

The impact of global warming on freshwater fish will vary seasonally. The additional temperature may provide growth benefits in winter, but may threaten fish populations living towards the upper end of their thermal tolerance zone in (late) summer (Morgan *et al*., 2001). Simulated global warming had little effect on the growth and physiology of rainbow trout (*Oncorhynchus mykiss*) fed to satiation over much of the summer. However, in late summer, when ambient water temperature was at its highest, the addition of 2°C caused a marked inhibition of appetite and growth, although this impact was not exacerbated by a reduction in food availability. In winter, a change of temperature of +2°C stimulated metabolism, appetite and growth by approximately 30 to 60%.

To a certain extent fish can acclimate to higher temperature. Rainbow trout exposed to + 2°C had a slightly (0.2-1.0°C) but significantly higher lethal temperature than those exposed to ambient temperature (Morgan *et al*., 2001).

The potential effect of climate change on average runoff in tundra regions is highly uncertain (McCarthy *et al*., 2001), but if water levels decrease, connections between tundra lakes could be severed. This would result in changes in community structure and possibly elimination of seasonal migrants to shallow, ice-covered winterkill lakes. In temperate region, on the contrary, the risk of winter fish-kills is smaller in warmer winters. In response to higher temperatures, northern boreal populations of cyprinid and percid fish species are expected to increase at the expense of coldwater, salmonid species (Lehtonen, 1996). Shallow lakes would be most susceptible to these changes because of their lack of thermal stratification. Total freshwater fish production is expected to increase, but with the projected changes in the composition of fish fauna, the recreational and commercial value of catches will decrease (Lehtonen, 1996).

IV.B.10. Ecosystem response of lakes

In conclusion, different species as well as physical and chemical properties react differently because of their different interactions in the foodweb. However, some changes might be relevant on a species level, but all these single effects may weigh differently in the lake ecosystem as a whole. Petchy *et al*. (1999) conducted microcosm experiments to control species composition and rates of environmental change. They suggested that ecosystem responses are not as clear as studies of single trophic levels indicate. Complex responses generated in entire food webs greatly complicate inferences based on single functional groups. Here, the consideration of more general ecological concepts is needed in order to understand and synthesize climatic effects on lake ecosystems. The strength of food web interactions is characterized by many weak and few strong interactions (McCann *et al*., 1998). Weak links in particular act to dampen oscillations between consumers and resources (McCann *et al*., 1998) and presumably also environmental stressors, as climate extremes. This means that not all responses at a specific trophic level are propagated to lower trophic levels or have significant impacts on ecosystem processes (Pace *et al*., 1999). Additionally, a prolongation due to food web interactions is possible as the signal of winter climate can be detected in the clear water phase in early summer (Straile and Adrian, 2000) or in the summer phytoplankton composition and biomass (Weyhenmeyer, 2001; Blenckner *et al*., 2002). A system approach is necessary to examine the cascading effects in response to climatic change and variability. The magnitude of a climate-driven response of an autotrophic organism is not necessarily mediated or cascaded to the heterotrophic species, or vice versa. The potential for misleading inferences has been highlighted (Harrington *et al*., 1999). Furthermore, the non-linearity in the response to environmental variables (including climate) of animal and plants should be remembered (May, 1986; Mysterud *et al.,* 2001), as smooth changes can be interrupted by drastic switches to a contrasting state of the ecosystem function (Scheffer *et al*., 2001).

Chapter IV.C. Impact of Climate Change on Coastal Systems

Key Points

- **Global warming is responsible for a rise in sea level of 1-2 mm/yr with a subsequent increase in coastal erosion, flooding, salinization of estuaries and land aquifers.**

- **An intensification of the hydrological cycle has impacts on the water and salinity budget of coastal systems, coastal shape and productivity (eutrophication) leading to loss of habitats.**

- **Global sea surface temperature has warmed by a mean of 0.6°C resulting in a re-distribution and loss of marine organisms, higher frequency of anomalous and toxic bloom events, and enhancement of hypoxia at depth**

- **The response of coastal systems to climate forces varies regionally and is tightly coupled to human activities on land emphasizing the importance of downscaling models and statistics for proper assessment.**

- **All forces act simultaneously and at different time scales in the coastal area, requiring long-term and synoptic data records to extract signals of natural variability from climate change trends.**

Chapter IV.C. Impact of Climate Change on Coastal Systems

IV.C.1. Introduction

Coastal zones, including the continental margin, extend from the coastline to the 200 m bathymetric line and occupy at most 8% of the ocean surface and only 0.5 % of its volume. Nevertheless, coastal zones include some of the most productive and valuable habitats of the biosphere, including estuaries, mangroves, lagoons, rocky shores, sandy beaches, and seagrass meadows. About 90% of the fish catch originates from the coastal zones that account for 25% of the ocean primary production. A large part of this carbon production is exported to the open ocean influencing the carbon cycle of the ocean as a whole.

In addition, the coastal zones represent a wealth of biodiversity and provide a large variety of natural resources and services that have been continuously exploited by human population. Nearly 40 to 50% of the human population lives within 100 km from the coastline including some of the world's largest cities. The impact of human activities on the variability of the coastal systems is considerable, usually observed as negative trends (i.e. decline, degradation) with respect to marine resources, standing stocks and coastal landscape. Differentiating the effect of climate change from direct anthropogenic activities is very difficult. The latter, in general, reduces the resilience property of the coastal system, which then becomes more vulnerable to stresses due to climate variability.

Coastal zones are transitional areas in which processes are controlled by complex interactions and fluxes of material between land, ocean and atmospheric systems. As a result, coastal zones are among the most changeable environments on Earth. Natural factors that are expected to have the largest impact on coastal systems are temperature changes, sea-level rise, increasing greenhouse gases in the atmosphere, availability of water from precipitation and river runoff, wind patterns, and storminess. In all cases, however, these natural forces are not acting individually on a specific compartment of the coastal systems, but are interconnected in many ways and often associated with a human signature of some sort.

Driven by economic interests, the issues and problems related to coastal degradation and scarcity of marine resources have been receiving an increasing level of national and international attention over the last 20 years. Regional Conventions for the protection of the marine environment and coastal areas were created under the auspices of the United Nations (UNEP) to provide the legal framework for regional Action Plans, expressing thus political concerns of governments to assess and monitor the main factors influencing the marine environmental quality. In 1996, the European Commission implemented a multi-years Demonstration Programme on Integrated Coastal Zone Management (ICZM) to identify and promote mitigation strategies in response to a continuous degradation of the coastal environments. As a result, EU Member States are committed since 2002 to develop strategies for ICZM, including a number of rules and good practices that were identified in this Demonstration Programme.

Compliance to these agreements, conventions, laws, and the achievement of their challenging goals require a sound scientific understanding of how the coastal systems respond to a broad spectrum of phenomena including its susceptibility to a increasing human pressure, as well as to steady global climate change. The Joint Global Ocean Flux Study (JGOFS) was established in 1988 as a core project of the International Geosphere-Biosphere Programme (IGBP) to assess and understand the processes controlling, regional to global and seasonal to inter-annual fluxes of carbon between the atmosphere and the ocean, and their sensitivity to climate changes. The role and the complexity of the continental margins on the marine biogeochemical cycles was quickly highlighted, calling for the launch of two other IGBP core projects, the Global Ocean Ecosystem Dynamics (GLOBEC) in 1995, and the Land-Ocean Interactions in the Coastal Zone (LOICZ) in 1993. Both projects consider global change in the broad sense, encompassing the gradual processes of climate change, as well as shorter-term changes resulting from anthropogenic pressures. The numerous studies conducted thus far in the frame of LOICZ and its European counterpart, the ELOISE cluster (Murray *et al*. 2001), have contributed to substantial knowledge on climate change science, addressing both coastal ecosystems and coastal hydrology and their complex interplay between atmosphere, ocean, and land systems.

In this chapter, the contribution of recent scientific results to our increasing knowledge and understanding of the coastal system are presented and to what extent changes in the various compartments of that system could reflect or be indicative of a climate change. The chapter is divided into sections addressing climate impact on the hydrography and chemistry of the coastal system, the carbon pool and budget, potential shifts in the coastal ecosystem, and changes in coastal habitats.

IV.C.2. Hydrography

Coastal systems encompass a wide range of environmental conditions over short spatial gradients, particularly with respect to salinity content and chemical speciation controlled in many ways by the hydrologic cycle. Hence, any climatic disturbances affecting the sea level, the rate of precipitation, freshwater runoff, and evaporation, will have direct consequences on the geochemistry of coastal waters.

Global warming is responsible for a general increase in sea level due to thermal expansion of the water on the one hand, and melting of glaciers and polar ice caps, on the other hand. According to IPCC (2001), the sea level is rising at 1 to 2mm/yr on average, threatening most coastal regions and causing major problems just at the time when rapid coastal development is taking place. Sea level, however, appears to be rising at different rate depending on the oceanic regions (Figure IV.C.1), interfering with other processes such as tides, evaporation, or even various tectonic processes (e.g. seismic disturbance and volcanic action) that may lead to crustal motions along the coastline.

During the last 2 centuries, sea level has increased significantly in the Baltic with a clear shift in the rate of change at the end of the 19th century from 1.8 cm/century to 9.9 cm/100 yrs (Omstedt *et al*. 2004). This is correlated with a decrease in the probability of ice occurrence, particularly in the southern Baltic, and a tendency for shorter ice periods (Jevrejeva *et al.* 2004).

The progression of sea level is different for the Mediterranean Sea where a shift is observed at several tide gauge stations from an increasing trend (ca. 1.2-1.5 $mm.yr^{-1}$) before 1960 to a decreasing trend (ca. -1.3 $mm.yr^{-1}$) after 1960 (Tsimplis and Baker 2000). Recent data indicate another trend reversal around 1995 with a rapid rising of sea level, up to 20 $mm.yr^{-1}$ in the eastern Mediterranean (Figure IV.C.2.), as observed from field measurements as well as satellite altimetry (Cazenave *et al*. 2001;Tsimplis and Rixen 2002). Whether the sudden rise in sea level since the mid-1990's represents a long-term trend or an inter-annual/decadal fluctuation is still an open question. According to Cazenave *et al.* (2001), however, the rate of sea level rise in the Alboran and Aegean Sea estimated at the end of the 1990's, is the highest value of the past 30 to 40 years, and would correlate with a continuous increase in sea surface temperature over the basin.

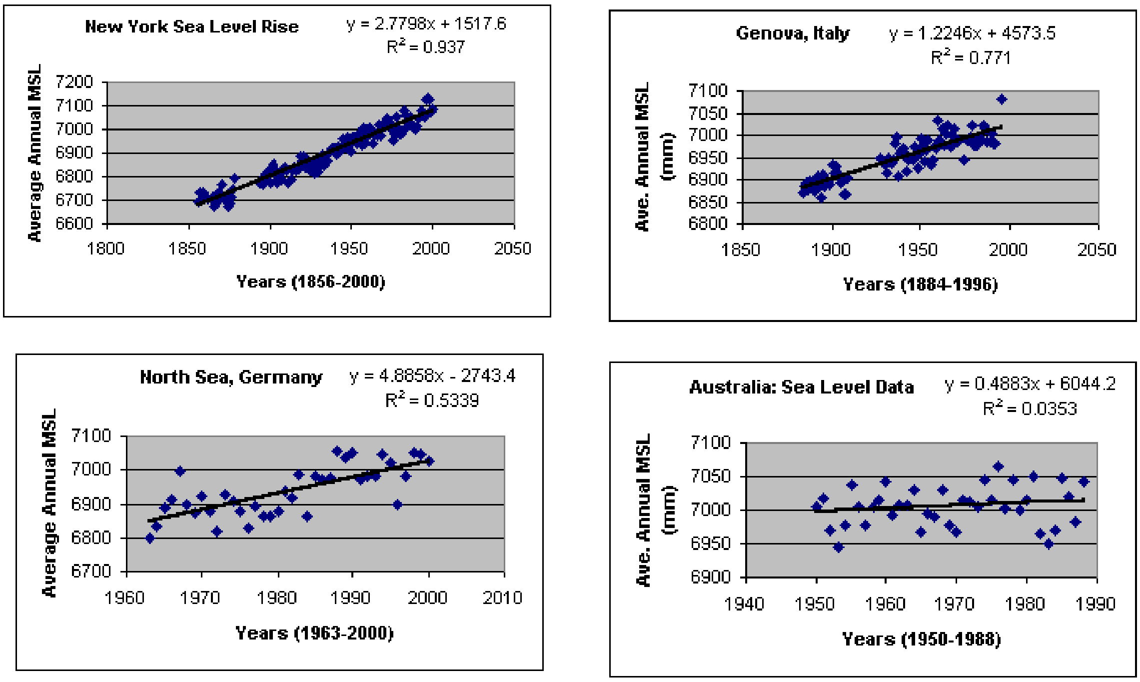


Figure IV.C.1. Average sea level rise (mean sea level MSL, in mm) from tidal gauges collected at different coastal locations around the world.
(Source: Richmond and Barker,
http://ecosystems.wcp.muohio.edu/studentresearch/climatechange02/sealevel/sealevel.htm).

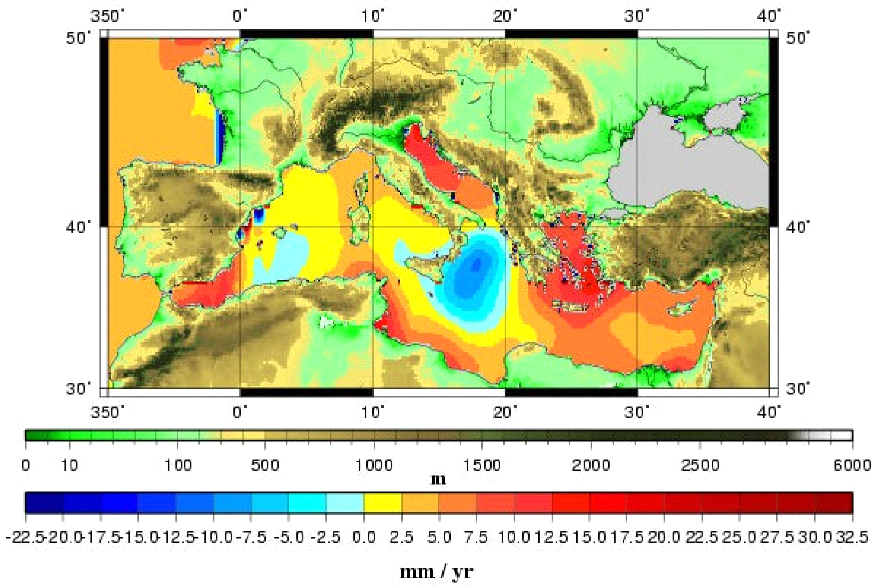


Figure IV.C.2. Rates of sea level change in the Mediterranean Sea as computed with Topex-Poseidon altimeter data between Jan. 1993 and Feb. 2004. *(Source: LEGOS/CNES, Toulouse. A. Cazenave, with permission)*

Sea level rise is partially due to expansion of seawater volume with increasing temperature. The Mediterranean Sea being almost totally landlocked, and with restricted exchange of water with the Atlantic ocean has often been compared to a miniature model of the worlds oceans, where environmental changes occurring at large scale can be effectively measured and monitored. In terms of climatic warming the Mediterranean Sea is probably one of the first places where such effect has been measured.

Change in surface temperature (SST) conditions has been analyzed using NOAA AVHRR satellite data covering the Mediterranean Sea for the period January 1982 to December 2000 (L. Nykjaer, JRC, pers. comm.). Figure IV.C.3 shows the trend of SST from best linear fit through the dataset. An increasing SST trend is evident over the entire basin with the eastern Mediterranean Sea showing an increase of 0.12 °C.year^{-1}, and about 0.1 °C.year^{-1} for the western basin. The spatial resolution of the satellite data (4 km) additionally reveals non-homogeneous patterns of the SST trend especially in the eastern basin. These patterns are linked to mesoscale circulation and changes in water mass distribution. Temperature increases may exceed 3-4°C at mesoscale resolution over the 19-year period, with consequences to sea level rise, ecosystem functioning, eutrophication, physical circulation, biodiversity and marine resource distribution.

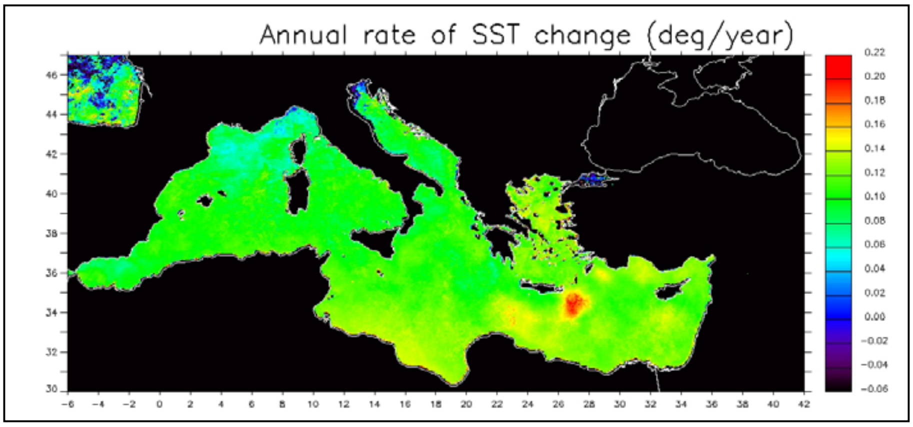


Figure IV.C.3. Annual rate of SST change for the Mediterranean Sea for the period 1982-2000. (from L. Nykjaer, JRC Ispra, personal communication).

In addition to an increase in the volume of water, the impacts of a sea level rise include coastal flooding and erosion, as well as landward intrusion of salt water with subsequent changes in the chemical characteristics of near-shore aquifers and coastal lakes, subsequently affecting the ecosystem community structures. Coastal wetlands are likely to be most vulnerable to the effects of sea level rise (Figure IV.C.4). All these effects will be further exacerbated by an increasing vulnerability to storms and waves.

However, the impact of sea level rise onto these habitats can be to some extent mitigated by changes in hydrologic cycle and intensification of precipitation on land leading to larger sediment delivery from the catchment basin, and subsequent accretion in low-lying areas and deltaic environment. A complete assessment of sea level effects on the coastal systems must therefore take into account changes in the hydrologic cycle over land.

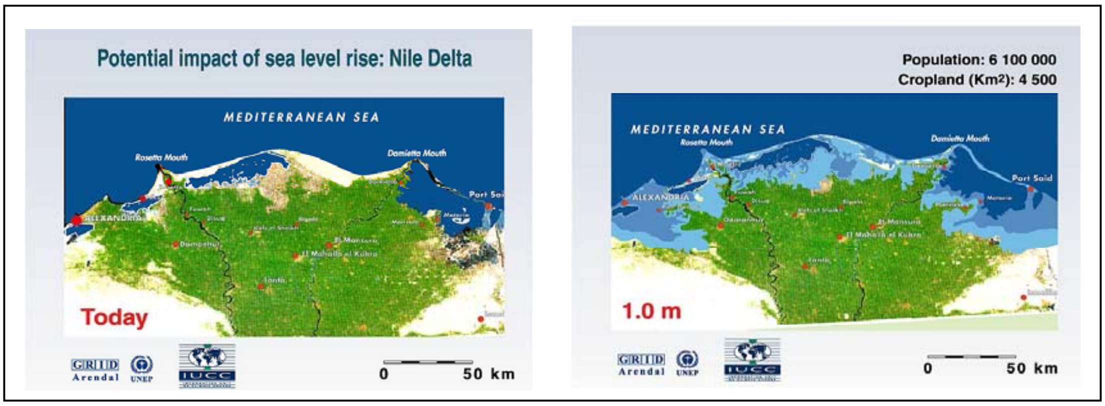


Figure IV.C.4. ***Potential impact of sea level rise on the Nile Delta.*** *Assuming an extreme sea level rise of 1.0 m over the next century, the impact on Egypt's economy would be very serious, with destruction of the protective sand belt and inundation of valuable agricultural land. Sea level rise effect has accelerated in this area since the construction of the Aswan dam. (Sources: Otto Simonett, UNEP/GRID Geneva; Prof. G. Sestini, Florence; Remote Sensing Centre, Cairo; DIERCKE Weltwirschaftsatlas).*

Under a scenario of doubling CO_2, climate models are converging towards an intensification of the hydrologic cycle with increase in precipitation intensity, up to 1% per decade in the 20th century over the northern mid- and high latitudes, whereas other areas in southern mid-latitudes are experiencing drier conditions (IPCC 2001). However, the low levels of confidence still associated with model results and future trends would tend to indicate more complexity in the interactions between climate and the water cycle, acting differently at regional and seasonal scales. It is also recognized that changes in the hydrologic cycle would emerge as extreme events in time, either floods or droughts at specific periods of the year.

Increased rainfall with subsequent increase in freshwater runoff would enhance the stratification of the water column in estuaries and adjacent coastal waters, leading to a reduction in oxygen concentration at depth, often exacerbated by an excess of organic matter in the upper layers. For example, observations revealed that the levels of precipitation and river flow have been increasing over the Mississippi River watershed during the last 100 years (Baldwin and Lall 1999), and are responsible for a significant change in the physical structure and productivity of the Gulf of Mexico (Donner *et al.* 2002). Similarly, winter precipitation has substantially increased over Northern Europe, multiplying flooding events along river basins and increasing runoff of freshwater into the North Sea (see Box # 1).

On the contrary, an analysis of hydrological data in the Baltic Sea over 100 years (Winsor *et al*. 2001; Rodhe and Winsor 2003) showed no significant long-term trends in river runoff and salinity although large fluctuations are observed on a time scale of few years, as well as several decades. In this area, the effect of an increasing precipitation rate may be compensated by an increase in evaporation due to global warming, resulting in little change in net precipitation (Rutgersson *et al*. 2002).

Box # 1: The North Sea

The North Sea is a large (ca. 7.105 km2) semi-enclosed, epi-continental sea located between mainland Europe (from Norway in the north to France in the south) and the British Isles forming its western boundary. The water budget and circulation in the North Sea is driven by a combination of tides, wind, and density gradients, leading to a cyclonic circulation with Atlantic salt water entering from the north (Norwegian Sea) along the British coast, and warmer waters from the Channel flowing along the French/Dutch/Belgian coasts. In addition, it receives low-salinity water from the Baltic through the Kattegat and the Skagerrak.

Climate variability has strong influence on the hydrodynamics and hydrology of the North Sea and the way such a coastal system will respond to future climate change is of major concern to the ca. 190 million people living in the adjacent countries. The North Sea originates from a major climatic change that occurred 12.000 years ago causing post-glacial sea level rise of at a speed of 80 $cm.century^{-1}$. The trend is still persisting today although at much lower speed. In the western North Sea, Woodworth and Player (2003) have recorded changes in sea level that varies from 1.1 to 2.4 $mm.yr^{-1}$ depending on the location along the coast of Britain.

In northern Europe, sea level is positively related to higher North Atlantic Oscillation (NAO) index, particularly for the winter season (Yan *et al.* 2004). This large-scale atmospheric circulation pattern is also responsible for an intensification of the westerly winds over the North Atlantic and the North Sea as observed during the last 40 years (Figure IV.C.5, Siegismund and Schrum 2001), with a possible consequence of an increase in the North Sea salt content resulting from an intensification of the water exchange with the North Atlantic (Schrum 2001). Coincidentally, the present-day climate conditions acting simultaneously on the tides, wind-driven circulation, and on the meridional density distribution in the N.-E Atlantic Ocean are most favourable to the renewal of water masses in the North Sea (Blaas *et al.* 2001).

Related climatological phenomena occurring in northern countries include increased precipitation and, consequently, higher river discharge, and increased storm events, acting on the hydrography of the coastal systems at different scales. Discharges of the Rhine river vary strongly on an annual and inter-annual time scale but a positive trend is observed since 1950 with an increase of the discharge by 4.4 m^3s^{-1} per year (de Jonge and de Jong 2002) which would be responsible for a 10% increase of suspended material in the adjacent coastal area. Similarly, an increase in freshwater runoff from the Schelde River has also been observed over the last 10 years (Struyf *et al.* 2004), particularly over the winter season in correlation with a larger increase in rainfall during that period of the year.

The total catchment area of the North Sea is about 8.4 10^5 km^2 with a total input of about 300 to 350 km3 of freshwater distributed through major rivers, e.g. Thames, Rhine, Meuse, Elbe, and melt water from Scandinavia (Ducrotoy *et al.* 2000). In spite a major dry periods during the last 20 years, a large part of the Thames catchment has experienced an increasing rate of flood events also related to winter precipitation increase. A global climate scenario would indicate an increase of 15-25 % of the Thames runoff by 2050 (http://firma.cfpm.org/regions/regThames.htm).

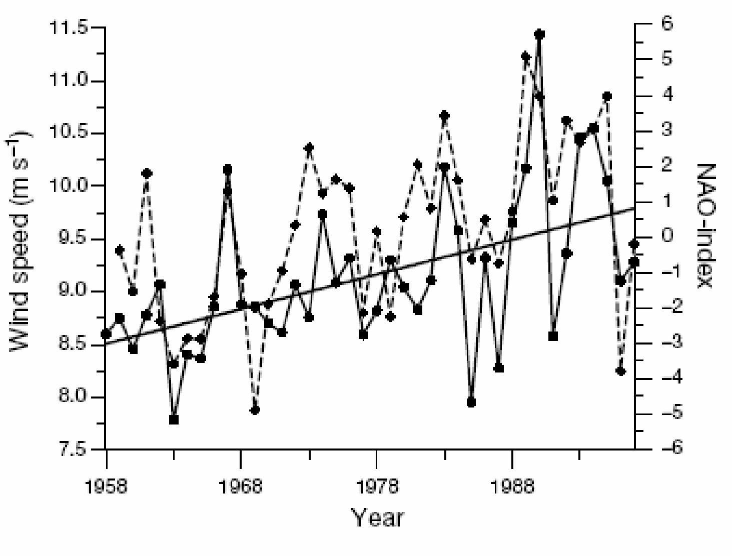


Figure IV.C.5. Time series of winter mean wind speed (December to March) over the North Sea for 1958 to 1997, derived from NCEP re-analysis (solid line), and the winter NAO index (dashed line). *The trends for both time series are calculated by linear regression. (Source: Siegismund and Schrum, 2001)*

The combined effect of climate change on the precipitation / river runoff on the one hand, and the intensification of North Atlantic input, on the other hand, could explain that no trends in salinity have been observed over 120 years in the North Sea (Laane *et al.* 1996).

In opposition to the northern regions, the latest IPCC report (2001) indicates that the Southern mid-latitudes, including the Mediterranean regions, are already experiencing decreases in precipitation and stream flow. Future projection of this trend will reduce drastically water supplies in these areas, affecting considerably the population and economy of the Mediterranean countries (Trigo *et al.* 2004). As for higher precipitation in the north, seasonal trends to lower stream flow is linked to an increasing NAO index, which can be felt as far as the Middle East (Cullen et al. 2002). In addition, differences in sea surface temperature across the Pacific resulting from an unusually-long cold phase of ENSO (La Niña) would have triggered the 1998-2002 drought seasonal period over the southern United States, merging its effect with the positive anomaly of the NAO index to propagate the drought in the western Europe –Mediterranean regions (Hoerling and Kumar 2003; Pal *et al*. 2004).

IV.C.3. Nutrients- Eutrophication

Changes in the water cycle and river discharges have multiple effects on the nutrient composition of coastal waters. Of major importance to the entire ecosystem, the process of eutrophication represents the biogeochemical response to heavy nutrient loading (Cloern 2001), and is typically a regional issue, which occurs worldwide. It reflects both natural processes affecting the hydrological cycle in the catchment basin, but also human modifications of nutrient delivery due to agricultural practices (systematic use of fertilizers) and pollution from urban areas. Under increased precipitation and run-off in northern latitudes, heavy water discharges would decrease the residence time in the main estuarine channels, transferring nutrients and organic material more rapidly to the coastal waters. Accordingly, the total dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) loadings can be scaled directly to functions of the population density and runoff magnitude (Smith et al. 2003). This provides global estimates of the present DIN and DIP fluxes to coastal waters that have doubled or even tripled during the past several decades (Mackenzie *et al.* 2002, Smith *et al.* 2003). Future projection adopting business-as-usual scenarios with sustained perturbation on land from human activities and from increasing global temperature will maintain the trends in the same direction with increasing delivery of reactive nitrogen and phosphorus to the global coastal margins (Mackenzie *et al*. 2002). At regional scales, observations are giving some credit to the global model results. The export of nitrate by the Mississippi river to the Gulf of Mexico has tripled since the 1950s, owing to an increase in agricultural fertilizer application and hydrological changes (Donner *et al.* 2002, Justic *et al.* 2003).

The combination of meteorological forcing and human activities has not only changed the load of material to the coastal systems, but also the chemical speciation and elemental stoichiometry of the water. Unlike N and P, silica (Si) is little affected by human pollution and results mostly from the weathering or dissolution of silicate minerals. Consequently, the Si to N and Si to P ratios are significantly decreasing in coastal waters, even though higher precipitation and runoff must enhance the erosion of rock minerals and Si loads in the aquatic system. In coastal waters, the lack of Si with respect to other macronutrients would affect the phytoplankton assemblage and the entire ecosystem.

On the other hand, the loading ratio of DIN and DIP remain relatively stable over time in spite of having very different chemical transformation pathways. Using a data set of 165 globally-distributed sites, Smith *et al.* (2003) describe the tight coupling between DIN and DIP with a loading ratio of 18:1, very close to Meybeck's (1982) observations made several decades earlier on a much smaller data set, although the concentration of these nutrients were three times less. Note that the DIN:DIP ratio is also very close to the well-known Redfield ratio of 16:1 for oceanic waters published earlier (Redfield 1958). Anomalies from this ratio occur systematically on regional and temporal scales according to the dominant chemical and ecological processes (nitrification, denitrification, mineralization, uptake) controlling the nutrient cycling. For example, the riverine N:P ratio for the East China Sea is 111 (Chen *et al*. 2003), much different than the average ratio of 16. This 'excess nitrate' still remains, although at lower values, in the adjacent coastal waters, making the ecosystem P-limited rather N-limited. Inversely, higher runoff increases both the delivery of nutrients in coastal waters and the water column stratification, thereby increasing the probability of a sub-surface oxygen-depleted layer and favoring denitrification processes with the release of N_2O into the atmosphere and a decrease in the N:P ratio. Over an extended area on the Indian continental shelf, Naqvi et al. (2000) observed an intensification of the denitrification process resulting from increasing runoff of nutrients from land and water stratification, producing anoxic conditions in coastal sub-layers, and reducing considerably the N:P ratio when compared with the value of 16 (i.e. Redfield ratio) observed in oxygenated waters. Although anthropogenic nutrient inputs are mostly responsible for this situation, the influence of climatic factors such as an intensification of the summer monsoon due to global warming can be significant (Naqvi *et al.* 2000).

According to Seitzinger and Kroese (1998), ca. 21 $TgN.yr^{-1}$ is exported from rivers to estuaries and coastal zones, i.e. twice the value estimated earlier by Meybeck (1982). Inputs to the enclosed and semi-enclosed European Seas account for 12% ($2.5TgN.yr^{-1}$) of the world river N export. A large part (75%) of this N input results from anthropogenic activities and as expected displays a significant north-south gradient with 4 to 10 times greater inputs in the coastal oceans of the northern hemisphere (Seitzinger and Kroese 1998). Such an excess of nitrogen stimulates microbial processes such as nitrification and denitrification in the coastal margins, which contribute to 33% of the total greenhouse gas N_2O emission from aquatic environments.

IV.C.4. Atmospheric Inputs

Another source of inorganic nutrients, and particularly iron, is found in the mineral dust transported from semi-arid and arid continental regions to the ocean via the atmosphere, as demonstrated by Duce and Tindale (1991) from a network of aerosol sampling stations. Iron availability is very important to support phytoplankton growth and biomass in different parts of the world ocean (Boyd *et al*. 2000, Bishop et al. 2002) and in coastal systems. According to Prospero *et al.* (1989), 50 % of the dust material is lost within 500km distance, suggesting a potentially large impact on the coastal ecosystem (see below). Two major systems are transporting hundreds of millions of tons of dust derived from mineral soil annually. The African Sahara and Sahel systems affect the Mediterranean basin (Figure IV.C.6), and Europe and transport dust material across the tropical Atlantic to the American continent. The Gobi and Takla Makan system occurs in Northwest Asia and transports dust across Korea, Japan and the North Pacific up to North America.

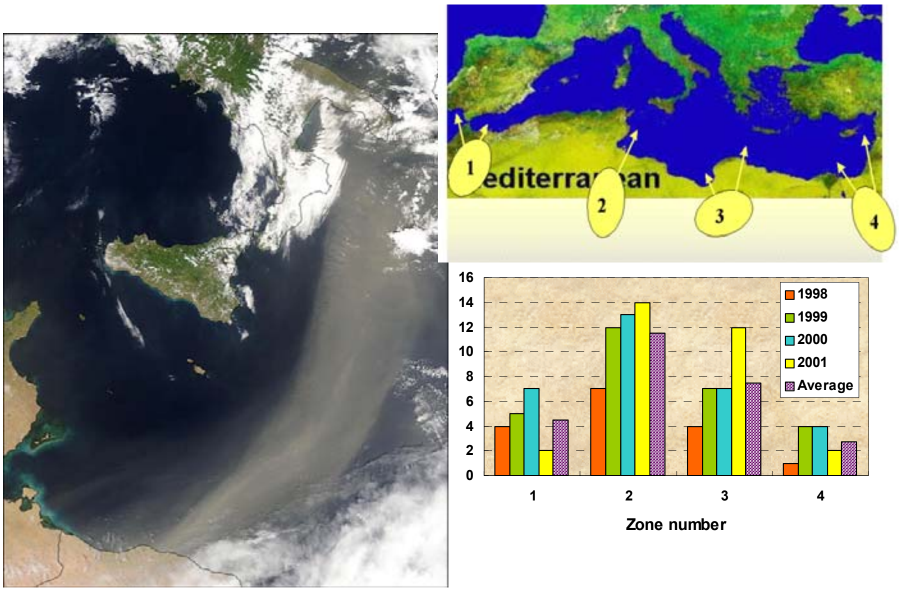


Figure IV.C.6. (Left) Massive dust flow from Africa to Italy. MODIS-Terra image acquired on May 04, 2004. *(Source:NASA Earth Observatory; http://earthobservatory.nasa.gov/NaturalHazards/ natural_hazards_v2.php3?img_id=12108) (Right) Main point sources of Saharan dust particles in the Mediterranean Sea and repartition of dust events per source for the 1998-2001periods (Source: Martiny and Hoepffner, 2003).*

Dust storms have always occurred as a natural phenomenon. Global warming, i.e. drier climate, and higher winds, changes in land-use practices have modified the dust input in the oceans and, thus, the controlling role of iron and other nutrients in plankton blooms (de Baar and La Roche 2002). In turn, an intensification of atmospheric dust storms will act to reflect more sun light away from the Earth's surface, causing a cooling effect. The variability of exported dust from North Africa is coupled with the NAO index, with greater flux during positive NAO anomalies, suggesting that climate rather than change in land-use is a major forcing factor in dust transport (Moulin *et al.* 1997).

In Asia, after a long period of stability or negative trend in the dust event frequencies, recent observations showed an upsurge of heavy dust events during the last 3-4 years, with a monthly peak in March-April (Kurosaki and Mikami 2003). The reason for such an outbreak in dust storms is still under investigation, although greater importance is given to a change in climate (Sugimoto *et al*. 2003).

Atmospheric inputs of nutrients to the coastal system and the ocean at large can take place through dry and wet (i.e. rain) deposition, and is not restricted to iron and other trace elements. As for river runoff, the atmospheric input of macro-nutrients have increased by a factor of at least two above natural levels due to human activity and climate change (Cornell *et al.* 1995). According to Guerzoni et al (1999), the atmospheric input of inorganic nitrogen represents 60% of the total nitrogen entering the Mediterranean from continental origin, 66% of that flux is through wet deposition. Bio-available dissolved organic nitrogen (e.g. urea) is also an important constituent observed in marine rainwater samples and contributes to enhanced marine primary production (Cornell *et al.* 1995, 2001; Bishop *et al.* 2002).

Transport via the atmosphere is also recognized as an important route for reactive P (Garrison *et al*. 2003). Unlike N compounds which have dominant anthropogenic sources (urban pollution), the aerosol P content is of continental / natural origin (e.g rock and soil) as it often correlates with the calcite content (Herut *et al.* 1999). Regional differences in the aerosol content of bio-available macro-nutrients contribute to a change in the N:P ratio in coastal waters with possible shift from a nitrogen-limited ecosystem to a phosphorus-limited one, such as is observed in the Eastern Mediterranean (Herut *et al.* 1999, Kouvarakis *et al.* 2001).

IV.C.5. Upwelling

Sites of coastal upwellings are of economical importance due to high productivity sustaining large biodiversity and valuable fish resources. Upwelling events are driven by along shore wind stress inducing offshore transport of surface waters, replaced then by deeper cold water enriched in macronutrients, iron and inorganic carbon. Coastal upwellings are especially intense along the eastern boundary currents. Four main systems are commonly differentiated, contributing to 80-90% of the total new production: Northwest Africa-Iberia, Southwest Africa-Benguela, Peru-Chile, and California-Oregon. A direct link to meteorological forcing would expose upwellings to higher sensitivity to climate disturbances. Warming is associated with a stronger pressure gradient between land and ocean, which in turn, reinforce alongshore geostrophic wind, hence coastal upwelling. Bakun (1990) highlighted a possible mechanism whereby global greenhouse warming could accelerate coastal upwelling through multi-decadal intensification of the alongshore wind stress observed at all upwelling sites (Figure IV.C.7).

Several lines of evidence (Schwing and Mendelssohn 1997; Snyder et al. 2003) have now confirmed Bakun's hypothesis showing an increasing strength of the seasonal upwelling in the California Current system over the last 30 years, and an extension of the phenomena through late fall. The ecological consequences of higher upwelling strength are still uncertain. Primary productivity would be significantly stimulated, galvanizing then the rest of the food chain. In the South African Benguela system, Verheye (2000) measured a 100-fold increase in zooplankton numerical abundance as a long-term biological response to intensified coastal upwelling. Higher productivity in the upper layers could, however, have a negative impact on part of the ecosystem and contribute to the development of low-oxygen (hypoxia) sub-layers with drastic perturbations within demersal and benthic organisms (Grantham et al. 2004).

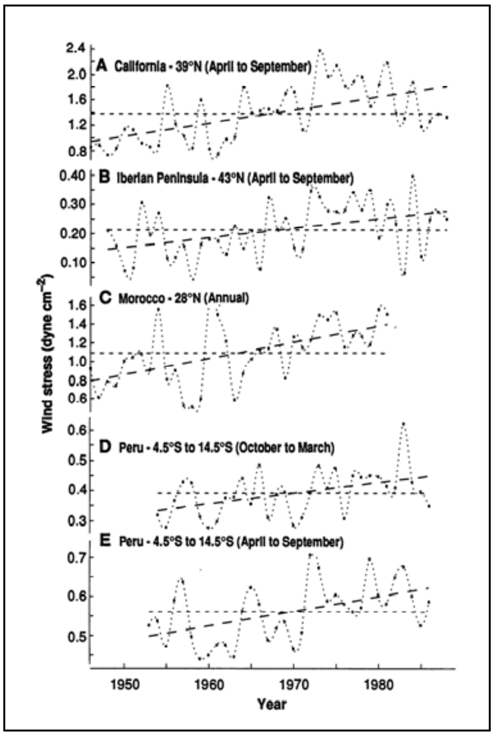


Figure IV.C.7. Within-year averages of monthly estimates of along-shore wind stress off different upwelling sites: A. California. B. Iberian Peninsula. C. Morocco. D and E Peru. Short dashes indicate the long-term mean for each series. Longer dashes indicate the linear trend fitted by the method of least squares. (Source: Bakun (1990) Reprinted from Science, with permission).

IV.C. 6. Carbon biomass and productivity

The coastal system represents undoubtedly the largest reservoir of particulate organic carbon resulting from both local high productivity rates and large inputs of terrestrial organic material via river runoff. In addition, the coastal waters in general represent also a large pool of inorganic carbon from continuous exchange with the atmosphere, river runoff and upwelling of deep oceanic waters. A large part of the coastal carbon is recycled within the water column, while another part becomes buried and eventually recycled in the sediment, or exported into the sub-layers of the open ocean, involving complex interactions between various processes which are sensitive to environmental forcing, but often neglected in global ocean models, or in terrestrial ecosystem models, and consequently poorly represented in global scenarios of climate change.

Coastal carbon pool

The carbon cycle in marine coastal waters involves two major processes: i) an inorganic long-term cycle driven by water alkalinity and the formation of calcium carbonate and ii) an organic short-term cycle with the formation of organic material through photosynthesis.

Chemical weathering of rock material on land provides dissolved inorganic carbon to the water system, further transported into the ocean as alkalinity (mainly HCO_3^-,

CO_2^{2-}). In turn, the alkalinity is a key element controlling the $CaCO_3$ saturation state of marine waters, through the chemical reaction:

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \qquad (1)$$

The formation of calcium carbonate can also be mediated through the metabolism of various organisms as they build their exoskeletons and shells (e.g. corals, coccolithophorids). Note that, in reaction 1, the production of one mole of carbonate releases one mole of CO_2 in marine waters, 60% of which is out-gassed back to the atmosphere (Ware *et al*. 1991). Accordingly, the contribution of coral reefs to atmospheric CO_2 has been estimated to be 0.02 – 0.08 Gt $C.yr^{-1}$ (i.e. 0.4 to 1.4% of the rate of anthropogenic production from fossil fuel combustion; Ware *et al.* 1991). Nevertheless, the calcite-carbon production is estimated at 0.4 to 1.4 Gt $CaCO_3$-C as an annual sediment flux from the mixed layer (Sundquist 1985). This flux is highly depending on temperature and pressure, and, as a result, coastal tropical waters represent the largest pool of $CaCO_3$-C. Occasionally, a significant carbonate flux can be observed in northern latitudes following blooms of coccolithophorids (Brown and Yoder 1994). In that case, the calcification process is directly coupled with the production of organic matter through photosynthesis. The resulting effect on the carbon flux and the drawdown of atmospheric CO_2 depends on the ratio of both processes. In the North Sea, blooms of *Emiliana huxleyi* have shown to represent a net sink of carbon (Buitenhuis *et al.* 2001).

The short-term-cycling production of organic carbon, so-called primary production, derives from the light-driven fixation of inorganic carbon, i.e. photosynthesis, by the phytoplankton cells and other marine plants such as seaweeds and seagrasses following the reaction:

$$nCO_2 + 2nH_2O \rightarrow (CH_2O)n + nH_2O + O_2 \qquad (2)$$

A global estimate of the coastal primary production may be averaged to 8 $GtCyr^{-1}$, which represents ca. 20% of the total oceanic primary production (Liu et al. 2000). Satellite ocean colour provides slightly higher estimates, ca. 12.4 $GtCyr^{-1}$ corresponding to 24% of the global ocean production (Mélin and Hoepffner 2004). Per unit area, however, the coastal systems generate at least twice as much photosynthetic carbon than the open ocean systems, ca. 0.8-0.85 $gC.m^{-2}.d^{-1}$ (Mélin and Hoepffner 2004), with maxima observed within upwelling systems, 1.0 to 1.5 $gC.m^{-2}.d^{-1}$ (ca. 0.04-0.06 $GtC.yr^{-1}$) in the Moroccan and Mauritanian shelf waters (Hoepffner *et al.* 1999), and in the vicinity of river plumes. Primary production in the ocean is by far the major process controlling the flux of atmospheric CO_2, contributing to a net sink of 2 $PgC.yr^{-1}$.

Both inorganic and organic carbon cycles are affected by environmental forcing, hence climate change. Future climate scenario (IPCC 2001) predicts an increase of water pCO_2, in response to an increase in atmospheric CO_2. As a result, the pH of surface water will decrease, acting directly on a decrease of calcification rate (reaction 1). With expected conditions by the year 2100, the ratio of calcification: photosynthesis for coccolithophores species could be reduced by 23 to 50% (Riebesell et al. 2000). On the other hand, observations have shown an increasing abundance of coccolithophore blooms in specific areas, e.g. the Bering Sea (Napp and Hunt 2001) presumably reflecting changes in water physics and chemistry (increasing temperature and alkalinity) due to climate anomalies. Such a climate link has been recently challenged (Merico *et al.* 2003). Coccolihtophorids, as other species belonging to the Haptophytes group (e.g. *Phaeocystis*) are important for their role in the sulfur cycle and the production of dimethyl sulphide (DMS) which is ventilated to the atmosphere and contribute to the formation of clouds, providing thus a feedback mechanism to global warming.

The production of organic carbon from phytoplankton photosynthesis (reaction 2) is enhanced, by an increase of atmospheric CO_2 and water pCO_2. In addition, the fixation of inorganic carbon by algae is intimately coupled to the nutrient cycle and light. Assuming that coastal water is not limited with inorganic carbon, any change in climate directly affecting nutrient inputs and illumination will either stimulate or inhibit primary production, and the growth of phytoplankton. It is commonly recognized that organic production in most coastal systems is N-limited. In other words, a moderate enrichment of coastal waters with nutrient, particularly N, from higher river runoff and atmospheric deposition could sustain an optimal productivity of the ecosystem with an efficient transfer of energy between all trophic levels up to fish species of economical interests.

A recent study in Danish waters (Figure IV.C.8) showed that climate change could have a significant impact of primary production through increases in nutrient loads, as well as increases in the mean temperature in the growing season.

In contrast, some model simulations in the North Sea demonstrated that a 50% reduction in the loads of N and P from river runoff reduces the primary production by 10 to 30% in the southern North Sea (Skogen *et al.* 2004). In other marine areas, the loads of atmospheric N, which have continuously increased over the past three decades from anthropogenic pollution (Paerl and Whitall 1999), represent a large nutrient input in the marine system and can account for all measured new production in the eastern Mediterranean Sea (Kouvarakis et al. 2001; Mace et al. 2003), driving the area into a P-limited system. Increasing precipitation will also increase the availability of rainwater DON to phytoplankton growth (Seitzinger and Sanders 1999).

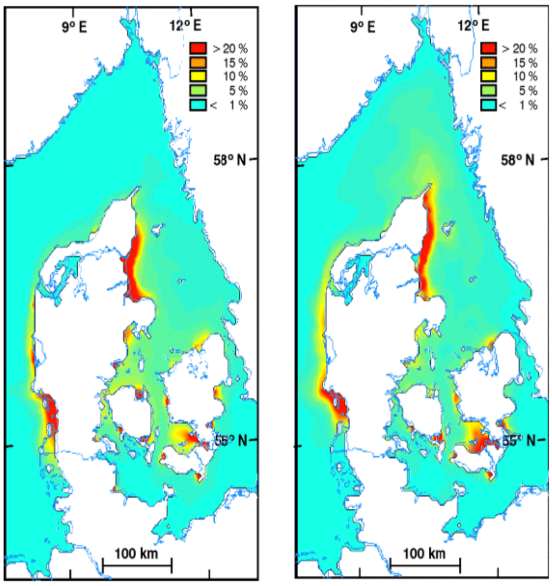


Figure IV.C.8. ***Average changes in winter concentrations (Jan. & Feb.) of inorganic N (left) and daily primary production (right)during the growth period (Mar.to Sept.) in Danish coastal waters in response to a simulated 50% increase in runoff from Danish rivers.*** *As part of the Danish national research programme DECO (1997-2000), a eutrophication module has been coupled to a 3D hydrodynamic "Farvandsmodel" to analyse the sensitivity of Danish coastal waters to changes in climatic parameters on the basis of year-2075 scenario simulated by global climate modes.(Source: K. Edelvang et al. 2001, with permission) .*

An excessive and imbalanced concentration of nutrients can alter significantly the ecosystem. Increasing N and P with respect to Si in river-dominated coastal systems will reduce the growth of the Diatoms population in time and space, rapidly substituted by other non-Si demanding species usually less efficient in the vertical export flux of carbon and in the transfer of energy along the classic food web phytoplankton-zooplankton-fish. Moreover, non-Diatom blooms are often associated with toxic or harmful species (see box #2), which have proliferated during the past two decades due to a combination of mild winters, appropriate nutrient ratios, higher stratification, and possibly exposure to UV radiation. In contrast, neither N nor Si seems to be limiting the phytoplankton growth rate in the North Adriatic, which may be more sensitive to changes in light and temperature (Bernardi-Aubry *et al.* 2004). Nitrogen fixers such as *Trichodesmium* are mainly distributed in subtropical and tropical areas where the combination of warm temperature and stratification is favorable to their growth. This community has also a strong iron requirement and could therefore benefit from global warming, subsequent land desertification and an intensification of dust events. Lenes et al. (2001) observed a 100-fold increase in *Trichodesmium* biomass at the West Florida shelf after a major Saharian dust event.

Box #2: Harmful Algal Blooms (HABs)

Over the last several decades, the world coastal environment has encountered an increasing and problematic situation of anomalous phytoplankton blooms (AABs). The term 'anomalous' is used here to differentiate these blooms with those occurring regularly following well-known seasonal processes (e.g. spring blooms, seasonal upwellings). In addition, AABs are very often associated with harmful or negative consequences (i.e., HABs) on the surrounding ecosystem, or even toxic material causing mass mortalities of marine organisms, as well as affecting human health through contaminated shellfish and fish populations.

The increasing frequency of these blooms and their socio-economical impacts have lead to the development of important regional and national programmes such as EUROHAB (Granéli et al. 1999) in Europe and ECOHAB in the United States to investigate on possible causes that have triggered such an upsurge of HABs events threatening today most coastal systems, and to better understand the dynamics and trophic interactions of these blooming species. In response to the globalization of the phenomena, international efforts have been initiated (GEOHAB 2001; EU-US HAB 2003) to coordinate scientific progress made locally and develop common approaches to evaluate the impact of HABs.

HABs have been classified within two groups on the basis of their noxiousness and geographical distribution: the toxin producers mainly occurring in open coastal systems which may lead to harmful impact even at low density; and high-biomass producers which tend to develop in enclosed or semi-enclosed seas obstructing light penetration and depleting oxygen in subjacent layers. The initiation, growth and maintenance of these blooms are still under studies with possible explanations around man-induced pollution effects and/or climate shifts. The hemispheric differences in the distribution of some toxic species (Figure IV.C.9) would support the role of anthropogenic pollution and increase of nutrient loadings in the northern coastal zone through rivers and atmospheric deposition.

Cyanobacterial blooms have been present in the Baltic Sea during the summer periods for thousand years as documented from fossil records of cyanobacterial pigments (Bianchi *et al*. 2000). Since the early 1960's, the occurrence of these blooms has significantly increased, extending to the Baltic proper and Gulf of Finland (Finni et al. 2001; Poutanen and Nikkilä 2001), presumably in response to anthropogenic eutrophication of the coastal waters. However, the fact that cyanobacteria populations could be part of the natural system indicates that optimal physical and meterological conditions are also required for their growth. Peperzak (2003) showed the importance of increasing temperature and stratification in doubling the growth rate of harmful algae, concluding that the risk of HABs due to climate change scenarios as suggested by IPCC (2001) will rather increase than decrease. Belgrano *et al*. (1999) related the occurrence of toxic phytoplankton blooms in the Skagerrak to changes in the phase of the NAO, suggesting an important role of climate forces in HABs formation.

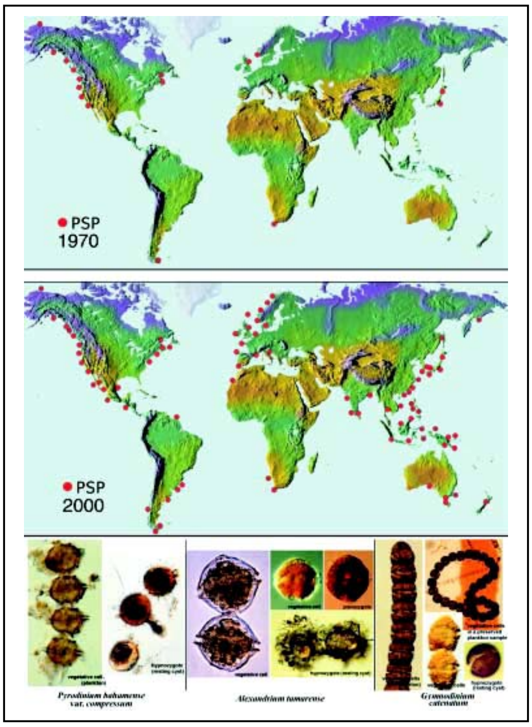


Figure IV.C.9. Global maps of the distribution of organisms associated with the production of the toxic syndrome Paralytic Shellfish Poisoning (PSP). The increasing occurrence of this toxic material from 1970 (upper panel) to 2000 (lower panel) indicates a stronger impact in the northern hemisphere, and polluted coastal areas. (Source: GEOHAB Science Plan. http://www.jhu.edu/~scor/GEOHAB_2001.pdf).

Increasing nutrients, higher productivity and increased stratification due to freshwater inflow have also lead to a drastic decrease in the oxygen content of the water column, establishing a hypoxic or even anoxic subsurface layer causing mass mortalities in the benthic and demersal communities. The combination of N fertilizer applications, land-use changes and increase in runoff on the Mississippi river basin has lead to the occurrence and extension of a low oxygen 'dead zone' in the Gulf of Mexico bottom waters which can extend as far as 130 km offshore (Rabalais *et al.* 1996; Turner and Rabalais 1991)

Eutrophication is also a widespread problem in European coastal waters, favoring the occurrence of hypoxic conditions in sensitive areas such as enclosed or semi-enclosed seas. Permanent anoxic conditions are well-known in the Black Sea. In other regions such as the Baltic, the frequency of anoxic periods has been increasing (Figure IV.C.10) as a result of eutrophication, as well as a reduction in the intrusion events of dense water through the Danish Straits (von Bodungen *et al.* 2000), that would be required to ventilate the Baltic deep waters. On the contrary, no significant trends of hypoxia are observed in the North Sea and the Mediterranean, although recurrent near-shore local events can be observed along the Aegean Sea and in the North Adriatic (Ærtebjerg and Carstensen 2004).

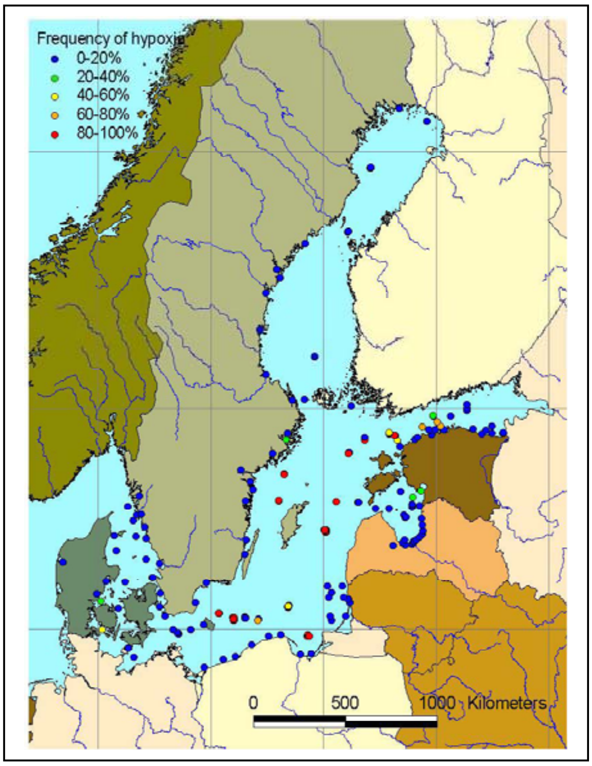


***Figure IV.C.10*. Mean frequency of hypoxia (<2 ml/l) at stations in the Baltic Sea over the period 1995-2002**.
(Source: Data from HELCOM and EEA member countries. Ærtebjerg and Carstensen 2004; http://themes.eea.eu.int/Specific_media/water/indicators/WEU15%2C2004.05/WEU15_HypoxiaTCM_260404.pdf)

In addition to organic and inorganic carbon locally produced in marine waters, the coastal system is receiving a large quantity of carbon from rivers. Within the river catchment, atmospheric CO_2 is consumed by organic matter formation and chemical weathering, and is transported by rivers as particulate (POC) and dissolved (DOC) organic carbon, and dissolved inorganic carbon (DIC). Current estimate of the total riverine carbon flux is 0.8-0.9 $PgC.yr^{-1}$ (Liu *et al.* 2000; McKee 2003), of which half is in the form of organic carbon. This flux of organic material also includes significant amount of organic nitrogen and phosphorus. Riverine carbon transits first through estuaries where it experiences significant biological and physical transformations. The impact of higher rainfall and runoff to the coastal zone will vary according to the type of estuary and human activities upstream. Increasing water quality due to a dilution effect and a reduction of the water residence time in the upper estuary have been observed in the Schelde estuary (Struyf *et al.* 2004) following a threefold increase in yearly discharge between 1996 and 2000 due to winter rainfall.

Source vs sink of carbon
Coastal waters have a limited capacity to retain organic and inorganic carbon that are either produced locally or discharged from external reservoirs. Although a major part of this carbon is recycled within the water column, the so-called 'continental shelf pump' (Tsunogai *et al.* 1999) represents a sink of carbon that has been recognized only recently as an important component of the global carbon cycle. Before the Industrial Revolution, the exchange flux of CO_2 between the ocean and atmosphere was assumed to be in equilibrium. The coastal zone receiving additional organic and inorganic carbon from rivers was then considered as a net source of carbon to the

atmosphere (Liu et al. 2000). With increasing atmospheric CO_2, coastal waters, now under-saturated with respect to CO_2, has turned into a net carbon sink. In an attempt to include the continental shelf pump into a global circulation model, Yool and Fasham (2001) estimated a net uptake of 0.6Gt $C.yr^{-1}$ imputable to the continental shelf pump. Even in river-dominated coastal systems like the East China Sea, Tsunogai *et al.* (1999) have estimated a mean air-to-sea flux per unit area of 35 $gC.m^{-2}.yr^{-1}$. In comparison, the Baltic Sea absorbs 11 $gC.m^{-2}.yr^{-1}$ (Thomas and Schneider 1999). High biological activity stimulated by increasing input of nutrients, on the one hand, and the decoupling in time and space of the production and respiration processes, on the other hand, have been highlighted by Thomas *et al.* (2004) as main controlling factors of the water pCO_2 in the North Sea, characterized by a net sink of 8.5 $TgC.yr^{-1}$, most of it being exported to the North Atlantic Ocean.

Frankignoulle and Borges (2001) estimated an annual sink of ca. 90 to 170 Mt C for the European continental shelves with, however, a large variability in time and space depending on the physical conditions (temperature, stratification) and the duration of the phytoplankton growing season. According to the authors, situations of pCO_2 super-saturation in coastal waters (i.e. source of atmospheric CO_2) can occur, for example, in winter time with low productivity, in direct influence by rivers with supersaturated water, in period and/or areas of intense vertical mixing and sediment re-suspension. In the well-mixed English Channel, CO_2 under-saturation only occurs from May to July when light is optimal for primary production (Frankignoulle and Borges 2001). Under global warming and increased stratification, the under-saturation period may increase due to enhanced primary production in the upper layer.

As important as the seasonal cycle to identify the continental margins as sink or source of CO_2, the spatial distance from the coast contributes to the debate on the trophic status of the coastal system. According to Gattuso *et al.* (1998, also in Frankignoulle and Borges 2001), proximal coastal areas directly under the influence of terrestrial inputs may often be considered as net heterotrophic systems with a net efflux of CO_2 to the atmosphere. On the contrary, distal continental shelves are autotrophic systems, acting as a net sink of CO_2. The impact of climate change on the carbon budget of coastal systems will thus depend on the regional manifestations of the dominant forces (e.g. higher runoff, intensification of the wind field).

Large inputs of POC and high turbidity commonly set upper estuaries upstream of the turbidity maximum zone (TMZ) where freshwater meets seawater, as net heterotrophic ecosystems with mineralization of POC, resulting in CO_2-supersaturated waters. Frankignoulle *et al.* (1998) showed that European estuaries emit 30 to 60 $MtC.yr^{-1}$ to the atmosphere, representing a CO_2 source equivalent to 5-10% of anthropogenic emissions for Western Europe. On the other hand, the outer estuaries, downstream the TMZ, higher inorganic nutrients from POC mineralization and less turbidity favour the production of organic matter through photosynthesis, making the area as a net sink for atmospheric CO_2. Körtzinger (2003) measured a net sink of CO_2 of 0.014 $PgC.yr^{-1}$ in association with the most external zone of the front created by the Amazon River plume in the Tropical Atlantic Ocean.

IV.C.7. Coastal biodiversity and Ecosystem Shifts

Since 1856, the global mean temperature has warmed by a mean of 0.6°C (IPCC 2001). There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. Key questions for biologists and ecologists are:

(1) Are we already observing a response of ecosystems to climate warming?
(2) What could be the consequences for ecosystems, exploited resources and biogeochemical cycles?

Effects of both global warming and the increase in CO_2 concentration on ecosystems have just started to emerge in the scientific literature and many aspects of this influence are still poorly understood (Hughes 2000). Such effects may influence organisms in a direct way by acting on the physiology, e.g. photosynthesis (Keeling *et al.* 1996; Myneni *et al.* 1997) or on the species phenology (e.g. seasonal cycle; Crick *et al.* 1997; McCleery and Perrins 1998). It may also influence biological systems in indirect ways by modifying abiotic factors involved in interspecific relationships between organisms (Pounds 2001). This, in turn, may affect the spatial distribution of species and modify the whole community at the ecosystem level.

Long-term datasets are essential to identify relationships between climate fluctuations and both changes in species abundance and biodiversity and changes in the structure and functioning of both aquatic and terrestrial ecosystems. These datasets should also encompass a large range of regions in order to appreciate the spatial variability in the response of ecosystems to climate change. Such datasets are unfortunately rare. For the marine pelagic environment, the Continuous Plankton Recorder (CPR) survey is the only plankton-monitoring programme that allows examination of the long-term changes of more than 400 plankton species or taxa over many regions in the North Atlantic Ocean and its adjacent seas. The CPR programme is operated by a high-speed plankton recorder that is towed (about 20 km h^{-1}) behind voluntary merchant ships at a depth of approximately 6-7m (Warner and Hays 1994; Reid *et al.* 2003).

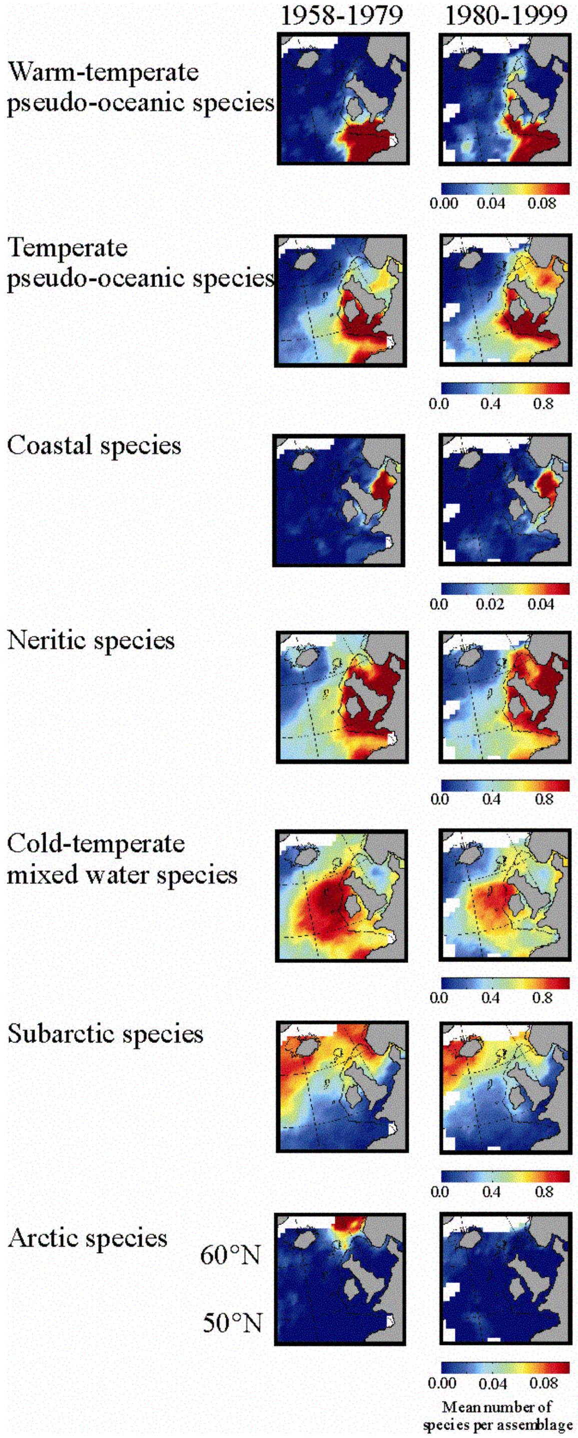
Results from the CPR survey have shown that major changes have taken place in the biodiversity of plankton over the last few decades mainly in the northeastern part of the North Atlantic Ocean, including the North Sea.

Using species assemblage indicators of calanoid copepods (Beaugrand *et al.* 2002a; Beaugrand *et al.* 2002b) have recently reported substantial changes during the period 1960-1999 in the spatial distribution of calanoid copepod assemblages at an ocean basin scale and have provided evidence that this might have been influenced by the combined effect of the climatic warming of the Northern Hemisphere and the North Atlantic Oscillation. Maps of the mean number of species present in an area for all species assemblages (Figure *IV.C.11*) demonstrate that major biogeographical shifts for all species assemblages have taken place since the early 1980s to the southwest of the British Isles and from the mid 1980s in the North Sea.

The mean number of warm-temperate, temperate pseudo-oceanic species increased by about 10° of latitude. In contrast, the mean number of cold-temperate mixed water, sub arctic and arctic species have decreased towards the north. All the biological assemblages show consistent long-term changes, including neritic species assemblages that seem to have also slightly moved northwards.

These changes have been correlated to the Northern Hemisphere Temperature (NHT) anomalies and to a lesser extent to the winter NAO index. These biogeographical modifications paralleled a northward extension of the ranges of many warm-water fishes in the same region (Quero *et al.* 1998; Stebbing *et al*. 2002).

Figure IV.C.11. Long-term changes in the spatial distribution of the calanoid copepod species assemblages around the United Kingdom. *Note the northward movement of the warm-water species associated to a decrease in the mean number of cold-water species. Redrawn from Beaugrand et al. (2002).*



These results indicate a shift of marine pelagic ecosystems towards a warmer dynamic regime in the northeastern North Atlantic. In terrestrial ecosystems in western Europe, similar changes in spatial distribution and phenology have been detected for many species of plants (Fitter and Fitter 2002), butterflies (Parmesan *et al*. 1999), amphibians (Beebee 1995) and birds (Thomas and Lennon 1999), all attributed to climate warming. West of the mid-Atlantic ridge, especially in the Labrador Sea, the trend was opposite and the number of both subarctic and arctic species has increased while the number of warm-water oceanic species has decreased. This result indicates a possible move of northwest Atlantic ecosystems towards a colder-biological dynamic regime. The opposite results found in the eastern and western side of the North Atlantic indicate that the response of the biosphere to climate change may exhibit complex behaviour. This kind of response is mediated through complex regional interactions with existing hydro-climatic channels such as the NAO. Indeed, the inverse response of ecosystems to climatic features on the two sides of the North Atlantic Ocean is consistent with the spatially heterogeneous nature of the climatic manifestations induced by this dominant mode of atmospheric variability (Dickson *et al*. 1996; Drinkwater 1996).

These large-scale biogeographical changes have deeply impacted the diversity of calanoid copepods in the North Sea (Beaugrand 2003; 2004). Calanoid copepod diversity has increased in that region due to an increase in warm-water species (Figure IV.C.11). These modifications seem to be a response of pelagic ecosystems to an augmentation in sea surface temperature positively correlated to Northern Hemisphere Temperature anomalies and may have a strong impact for the functioning of the ecosystems, biogeochemical cycles and exploited resources (Figure IV.C.12). Using a plankton index indicator of the quality and quantity of prey available for larval cod survival in the North Sea, Beaugrand *et al*. (2003) showed that long-term changes in the index paralleled changes in cod recruitment at age 1 and therefore larval cod survival (Figure IV.C.12). The index revealed a clear distinction between the periods 1963-1983 and both the periods 1984-1999 and 1958-1962 (Figure IV.C.12). The period 1963-1983 ('Gadoid Outburst', Cushing 1984) was characterized by high abundance of prey for larval cod (positive anomalies in the biomass of calanoid copepods, in the abundance of *C. finmarchicus*, euphausiids and *Pseudocalanus* spp.) and a high mean size of calanoid copepods. Larval cod survival decreased from the mid-1980s, coincident with unfavourable changes in the plankton ecosystem, compared to the earlier period 1963-1983. The change in the quality and quantity of plankton prey was related negatively to fluctuations in sea surface temperature. Increasing sea temperature may have had a double negative impact on larval cod survival in the North Sea.

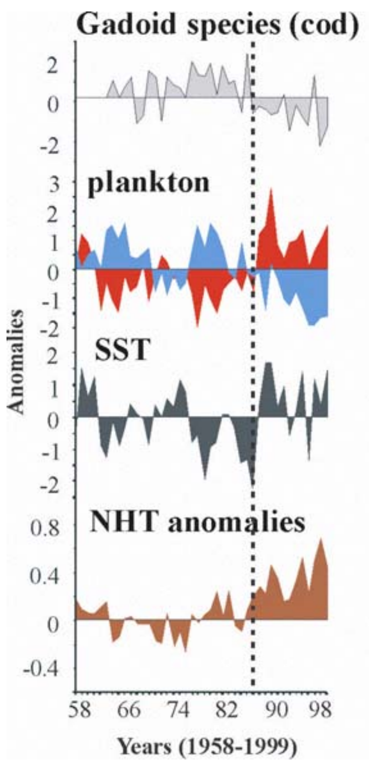


Figure IV.C.12. The regime shift in the North Sea. Long-term changes in fish abundance in relation to year-to-year changes in calanoid copepod composition and hydro-meteorological forcing. a. Long-term changes in gadoid recruitment (especially cod). b. Long-term changes in calanoid copepod species composition (in red: warm-water copepod calanoid species; in blue: cold-water calanoid copepod species). c. Changes in hydrological variables (sea surface temperature). d. Changes in large-scale hydro-climatic forcing (Northern Hemisphere Temperature anomalies). From Beaugrand (2004).

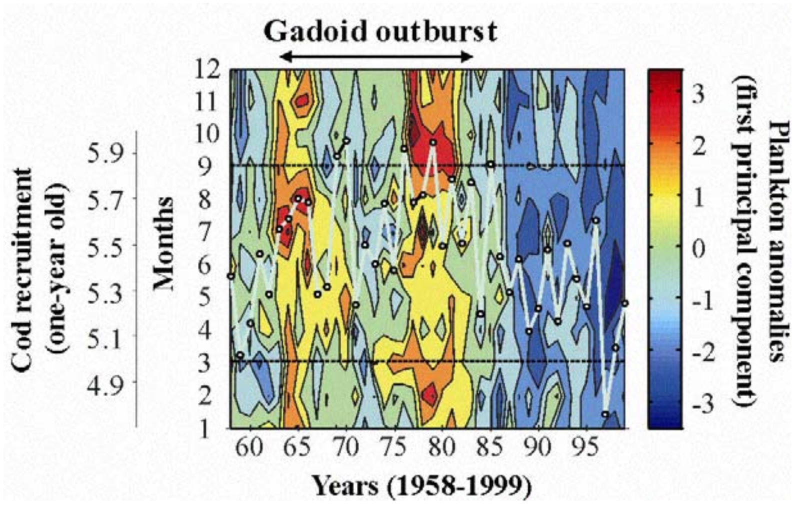


Figure IV.C.13. Long-term monthly changes (1958-1999) in the plankton index. A negative anomaly in the index indicates a low value for Calanus finmarchicus, euphausiids, mean size of calanoid copepods with the exception of C. helgolandicus (opposite pattern) and Pseudo-calanus spp. (no relationship). *A positive anomaly indicates a high abundance of preys (and preys of suitable size). Cod recruitment (in decimal logarithm) in the North Sea (curve in white) is superimposed. The period of the Gadoid Outburst (Cushing 1984) is also indicated. Modified from Beaugrand et al. (2003).*

Temperature increases metabolic rate and therefore increases the energy demand. Temperature rises decreases the quality and the quantity of prey available for larvae (so the energetic supply). Temperature rise may have therefore augmented the energetic unbalance of larval cod that may have resulted in increasing larval mortality (the hypotheses of size specific survival or growth dependent mortality). These results provide evidence that changes in the plankton ecosystem are the probable cause of the increased recruitment during the period 1963-1983, which was called the “Gadoid Outburst”.

IV.C.8. Habitats

The coastal marine system is organized as a succession of spatial units, each of them having its own characteristics and where the organisms are adapted to a specific range of environmental conditions. Estuaries, salt-marshes, lagoons, rocky shores, seagrass meadows, sandy beaches, all these units or habitats are often very productive, and in the same time, very vulnerable to changes in the external forcing which are issued from land, atmosphere and ocean and interact in the coastal zone at overlapping scales. Coastal lagoons around Europe are already experiencing drastic and irreversible changes (see part B and part E of the Report) in their ecosystems reacting to both climatic trends and increasing human pressure. Seagrass beds are another example of marine habitats under climate change threats, particularly vulnerable to increase in storminess.

Seagrass meadows
Seagrasses are vascular plants, typically configured like their terrestrial counterparts with a system of leaves, flowers and roots. Originally deriving from land and/or freshwater

system, their physiology and internal structure have been modified to sustain an optimal growth rate in a saline environment. No more than 60 species, organized in 12 genera, are obligate halophytes, distributed worldwide except for Antarctica. Seagrasses occur as large meadows concentrated within a narrow coastal band, limited off-shore by the available sunlight at the bottom for photosynthesis, and on-shore by the species tolerance to turbulence and wave action.

In addition to be highly productive (ca. 0.6 Gt $C.yr^{-1}$; Duarte and Chiscano 1999), seagrass meadows provide habitat for a wide variety of organisms, as well as nursery ground for many fish species, and shrimps. An entire ecosystem is preserved within the seagrass beds owing to the accumulation of detritus and the regeneration of nutrients at the bottom layer by anaerobic bacteria in the sediment. Seagrass leaves are also an important food source for several large-sized consumers such as sea turtles, birds and dugongs. However, a large fraction of their photosynthetic production remains unused and subject to low decomposition rate (Cebriàn and Duarte 1997). As a result, seagrass beds represent efficient carbon storage, ca. 15% of the carbon storage in the ocean (Duarte and Chiscano 1999). In addition, seagrass beds play a significant role in stabilizing the bottom sediment, preventing thus from coastal erosion, and improve the water quality by filtering and retaining suspended matter in the water column.

Climate change expressions such as level rise, increase in atmospheric CO_2 and UV-B radiations, global warming, intensification of storm events, all can affect seagrass distribution, productivity, and community composition at various degree (Short and Neckles 1999). Single effects can be beneficial (e.g. increase CO_2 and inorganic nutrient availability for photosynthesis) or detrimental (e.g. increasing turbidity and reduction of light penetration) to the development of seagrass meadows. The net effect combining all forcing factors are still difficult to assess, although a global decline of seagrass populations is becoming more and more factual as a result of climate change (Short and Neckles 1999) and direct human disturbance (Duarte 2002).

In early 30's, 90% of the North Atlantic eelgrass population (*Zostera marina*) was destroyed possibly by an epidemic infection due to some organisms. According to Rasmussen (1977), however, increased temperature in the North Atlantic relative to other ocean basins and the Mediterranean Sea is at the origin of the seagrass decline, becoming then more sensitive to organisms attacks such as bacteria, fungus and other species. Significant biomass recovery in affected areas (e.g. Danish Coastal waters) took place 30 years after, in early 60's, and is still experiencing a positive trend in spite of a strong inter-annual variability (Frederiksen *et al*. 2004). On the contrary, eelgrass biomass, in areas unaffected by the 'wasting disease', shows a negative long-term trend over the entire time-series (starting in the mid-50's; Frederiksen *et al.* 2004).

The physiological responses of seagrass species to different levels of physical gradients are flexible, tolerating in most cases moderate changes over reasonable adaptative time scales. For example, the single effect of an increase of a few degrees Celsius in water temperature over the next century as a result of global warming would likely have little effect on seagrass growth and distribution. On the other hand, global warming is expected to intensify extreme weather events in different parts of the world, causing dramatic consequences on seagrass population through storms, wave actions, re-suspension of sediment in the water column, as well as sudden pulses of freshwater water runoff. After such events, the re-colonization can take several tens of years, or even centuries, particularly with species having less successful sexual reproduction such as *Posidonia oceanica* (Balestri and Cinelli 2003).

Changes in the amount and quality of light have also important implications for seagrass habitats. Sea level rise and higher water column turbidity reduce the available light to the bottom modifying thus the offshore limit of plant growth to shallower depths. According to Short and Neckels (1999), a scenario of 50cm sea level rise over the next century would cause a 30-40% reduction in seagrass growth as result of 50% reduction in light availability. The propagation of marine waters on-shore may compensate that loss and provide new opportunities for the plants to extend shoreward, assuming that progression is not perturbed by specific infrastructures. The penetration of light can also be reduced through increasing turbidity resulting from sediment re-suspension or eutrophication of the water column above. In the latter process, phytoplankton and epiphytes organisms on seagrass leaves are acting as strong competitors for the use of macronutrients and inorganic carbon, reducing by as much their availability to the growth of seagrass plants.

As the light penetrates into the water column, its quality is modified with higher penetration at lower wavelengths, in the blue and UV part of the spectrum. Accordingly, seagrass beds are expected to be very sensitive to the highly penetrating UV-B radiations that are increasing as a result of a reduction in the stratospheric ozone. The impact of these radiations on the physiology of the plants is similar to those reported for phytoplankton, i.e. bleaching of the photosynthetic pigments and damaging the cellular DNA pool (Häder 1997; Helbling *et al.* 2001). The net effect of UV-B radiations on seagrass plants remains, however, difficult to assess because of the ability of some species to produce UV-B blocking compounds (Short and Neckles 1999) and the protective role of epiphytes organisms on the plant surface to filter UV-B radiations (Brandt and Koch 2003).

Conclusion

There is no doubt that the concerted scientific efforts conducted over the last decade through international and European programmes have led to significant progress in our understanding of the coastal system and ecosystem processes. A signal of change is reflected in the various components of the system, ranging from its physical structure, hydrography and water circulation, to the nutrient and carbon cycle and organisms physiology. Some causes and indirect impacts have been thoroughly analyzed, owing to joint actions of multidisciplinary teams.

However, the coastal system is complex and operates through multiple and non-linear interactions between all its components, as well as each component reacting and providing feedbacks to external forces. In addition, the reactions of the coastal biota and elemental cycles on meteorological variations and increasing anthropogenic pressure encompass a wide variety of spatial and temporal scales. Under such situation, assessing the effect of climate change, extricating the natural variability of the system from human-induced changes, still represents a formidable challenge which remain to be constantly addressed to develop and improve integrated management tools that would protect as much as possible the coastal environment and its invaluable resources.

Coastal eutrophication is, for example, a process that has been extensively studied worldwide. Nevertheless, questions are still open on e.g., the contribution of groundwater seepages to the coastal inorganic and organic loads; how does the benthic community interact with the nutrient cycles and changes in elemental stoichiometry? Although some climate change impacts have been identified on the several components of the system, further attention needs to be given to response mechanisms that would allow more confidence in predictive scenario.

Scientific programmes continue to provide data and information for application in modeling and monitoring. However the complexity of coastal systems requires that each coastal element be studied and managed as a distinct unit. Taking this into consideration, the IPCC global prediction using large-scale models may not be totally relevant to assess the regional vulnerability and sensitivity of the coastal systems. Recent activities on dynamical downscaling have shown encouraging performance to understand the complex interactions in coastal systems under global warming scenario (Vichi *et al*. 2003). In addition to modelling, there is also a need to further develop an observational strategy to detect the effect of climate change on each of the coastal units. Identification of proxies and climate-sensitive keystone species having large impact on the rest of the community needs to be achieved in timely manner in order to develop appropriate monitoring programmes. The initiative of establishing an international Global Ocean Observing System (GOOS) and particularly its coastal module (UNESCO 2003) would be largely beneficial to improve the capacity to detect and predict the effect of global climate change on coastal systems, unravelling thus the problem of sovereignties associated with access to critical margins.

Chapter IV.D. Future of Mediterranean Coastal Lagoons

Key Points

- **Lagoon ecosystems are fragile due to water from from developed areas, their shallowness and low water volume to surface area ratio. As a consequence there is a high probability that coastal lagoons will be the first to react to consequences of changes in climatic trends, especially in rainfall.**

- **Temperature increases in coastal lagoons will influence organism metabolism and niche distribution, affect species interactions and distribution, modify structure of the food web and biogeochemical cycles (e.g. N, C), and change ecological processes, especially primary production and decomposition.**

- **Changes in precipitation patterns will have important consequences for the water balance of coastal ecosystems, increased nutrient transport from the watershed to the coastal lagoon and sediment transport both from land-side and sea-side.**

- **Sea level rise (SLR) will increase water depth in the lagoon, alter water circulation and salinity, affect solid transport and erosion-sedimentation equilibrium, erode the lagoon barriers, and increase ingression of salt water into inland coastal areas.**

- **Quantification of impacts of climate change on coastal lagoons will require the identification of a suitable set of indicators and an integrated modelling approach (watershed-lagoon) with scenario and socio-economic analysis.**

IV.D.1. Introduction

Coastal lagoons are inland water bodies separated from the Sea by littoral arrows and sand barriers connected by one or more inlets. They have shallow waters, few meters depth, and a salinity that varies from fresh water to hypersaline depending on their water balance (Kjerfve, 1994). River mouths can play a crucial role in lagoon formation with their sediment contribution. Morpho-dynamics of tidal lagoons is controlled by long-term (net) sediment fluxes between littoral and tidal channels as well as between channels and shallows (intertidal shoals and salt marshes). Coastal lagoons are common along the Atlantic and Mediterranean coasts of Southern Europe, as well as along the south-eastern Baltic coast. Several fjords along the Danish coast can be considered to some extent as lagoons, as they have restricted mouths and slow water exchange with the Baltic Sea. In many coastal areas, especially in Netherlands, lagoons have decreased or almost disappeared as a consequence of land reclamation and coastal protection programmes. Mediterranean coastal lagoons are microtidal or non tidal, whilst along the Atlantic coast they are mesotidal (de Wit *et al*., 2001). Coastal lagoons play a key role as spawning grounds for fish and shellfish, see Figures IV.D.1-2; for this reason, such areas are also extensively exploited for aquaculture, especially for mollusc farming. Moreover, they are often important for bird reproduction and rest areas, and they present a rich and specific biodiversity, both for fauna and flora.

Figure IV.D.1: Ria Formosa-Clam culture (bivalve hand collection, 5000 tons/y)
(Photo courtesy of Dr. Falcao, IPIMAR, Portugal)

Figure IV.D.2: Traditional fishing system in Mar Menor (Murcia, Spain*).*
(Photo courtesy of Dr. Martinez, Murcia University)

In addition, coastal lagoons are well suited for human settlement with a strong commercial/recreational vocation, in particular connected to ports, and play a relevant role for economic, social and cultural development, see for instance the Venice lagoon (Lasserre, 1979). Therefore lagoons are subjected to strong anthropogenic pressures, as they receive freshwater inputs, rich in organic and mineral nutrients derived from urban, agricultural and/or industrial effluents including pollutants and finally domestic sewage. In addition, port use and management, aquaculture and fishing are responsible of internal perturbations (pollution, sediment dredging, removal of indigenous species, changes in food web structure, etc.). Finally Mediterranean coastal lagoons are subjected to tourism pressures mainly during the summer season, Figure IV.D.3. As far as the aquatic ecosystem is concerned, the latter pressure is mainly responsible for an increase in freshwater demand and delivery of wastewater that can outstretch water treatment plant capacity. Furthermore, the aquatic activities related to the port and to tourism (*e.g.* ship) can increase the concentration of some pollutants (*e.g.* petrol, oil, organometallic compounds used as antifouling biocide such as organotin compounds - TPT, TBT and their derivatives-, heavy metals and endocrine disruptors).

Figure IV.D.3: Tourism is one of the anthropogenic pressures affecting the Mar Menor lagoon *(Photo courtesy of Dr. Martinez, Murcia University).*

In the last decade, a general model has been proposed considering pristine coastal lagoons as dominated by extensive meadows of seagrass species, which are assumed to take advantages of nutrient supply from sediment (de Wit et al., 2001; Schramm and Nienhuis, 1996, Castel *et al*., 1996, Hemminga, 1998). These communities are naturally productive and, to a certain extent, resistant and resilient. However, an increasing nutrient input is thought to favour in a first phase phytoplankton and epiphytic microalgae, and later floating ephemeral macroalgae. In the later stages of this succession, when internal equilibria undergo a short circuit, the imbalance of phosphorus to nitrogen ratio can favour cyanobacteria and/or picoplankton species. Macroalgal blooms have been recognised as one of the most catastrophic symptoms of community degeneration (Morand and Briand, 1996, Valiela *et al*., 1997, Flindt *et al*., 1999). These changes have been particularly severe in the Mediterranean coastal lagoons with summer events of anoxia and dystrophy (Sfriso *et al.,* 1992, Chapelle *et al.*, 2001, Viaroli et *al.,* 2001,), see Figures IV.D.4-5. More recently, harmful algal blooms (HABs) and bacterial contamination have become a growing concern not only for aquaculture and tourism exploitation but also for the natural planktonic communities (*e.g.* change in the trophic relations, nutrient uptake).

Figure IV.D.4: Thau lagoon during a dystrophic episode (malaïgue). In August 1997, nearly one third of the annual oyster annual production was lost.

Figure IV.D.5: The Sacca di Goro lagoon during a bloom of Cladophora (upper panel) and during a dystrophic crises (lower panel) in which water takes on the typical white colour *(in the background the water has a typical blue colour. On the left a mussel farm is affected by the white tide)*

The recent evolution of Mediterranean coastal lagoons has been sudden and drastic. The non-linear response of the natural ecosystems to stress is a known concept in ecology and the coastal ecosystems including lagoons are not exceptions. For example, at low perturbation levels, seagrass communities are resistant, but when a certain threshold is exceeded, dramatic non-linear changes occur. Non-linear behaviour and unpredictability of coastal ecosystems is one of the major research topics in coastal lagoons (de Wit *et al*., 2001, Cadée *et al*., 2001, Herman *et al*., 2001). Due to these characteristics, and specially due to the fact that lagoon ecosystems are fragile because they receive water draining directly from highly inhabited areas, and because of their shallow water and low water volume compared to the adjacent sea, there is a high probability that, among Mediterranean marine ecosystem, Mediterranean coastal lagoons will be the first to react to consequences of changes in climatic trends. Trends may include temperature elevation, precipitation distribution patterns, weather extremes, sea level raise (SLR) and UVB radiation (UVBR: 280-320 nm,) increase. However, it may be difficult to distinguish between these and already existing anthropogenic and climate change effects. Assessments are further hampered by lack of historical time series, the Venice lagoon being probably the only Mediterranean lagoon where this analysis has been attempted (Camuffo and Sturaro, 2004, Day *et al*., 1999).

IV.D.2 Major Drivers of Change in Mediterranean Coastal Lagoons

The main changes of climatic conditions in Europe and in the Mediterranean area specifically have been summarised in the IPCC (Intergovernmental Panel on Climate Change) reports (IPCC, 2001).

Temperature
The report foresees an annual temperature increase at a rate of between 0.2 and 0.6°C per decade over the Mediterranean arc with an increase in the frequency of hot summers and a decrease in the cold winters (1/10 in 1961-1990).

Precipitation
The general pattern for southern Europe in annual precipitation is a small decrease (maximum –1% per decade) with a marked contrast between winter and summer patterns of precipitation change. The Mediterranean area will become wetter in the winter season (between +1 and +4% per decade) and drier in summer (drying of as much as –5% per decade).

Weather extremes
Climate change scenarios do not explicitly quantify changes in daily weather extremes. However, it is very likely that frequencies and intensities of summer heat waves will increase throughout Southern Europe; and that intense precipitation events will increase in frequency, especially in winter, and that summer drought risk will increase in southern Europe; it is also possible that gale frequencies will increase.

UVB radiation
The accumulation of CFCs and other chlorinated and brominated compounds has depleted the stratospheric ozone layer with consequent increases in ultraviolet-B radiation (UVBR: 280-320 nm) at the Earth's surface.

Sea level
Estimates of Global-mean sea level rises by the 2050s are around 13–68 cm. These estimates make no allowance for natural vertical land movements. Owing to tectonic adjustments following the last glaciation, and the different pattern of average atmospheric pressure change, there are likely to be regional differences across Europe in the natural rates of relative sea-level change.

IV.D.3. Expected effects related to changes in environmental factors

Temperature increase in coastal lagoons would

- *influence organism metabolism and niche distribution*
- *affect species interactions and distribution*
- *modify structure of food web and biogeochemical cycles (e.g. N, C)*
- *change ecological processes, especially primary production and decomposition*

Temperature increase may have different effects. Species are adapted to specific ranges of temperature. Temperatures exceeding these ranges will influence life cycles, nutrient uptakes, growth rates, cellular division (*e.g.* heterotrophic bacteria, phytoplankton), predation rates (*e.g.* ciliates, copepods), reproduction and recruitment processes (*e.g.* zooplankton, mollusc), habitat colonization (*e.g.* seagrasses) and finally the production (*e.g.* primary and secondary). Temperature effects may include changes in ecosystem communities. For example, species adapted to warmer temperatures - e.g. exotic species migrating from the Red Sea or imported with commercial species - will take advantage from temperature rise, whilst indigenous species will be out-competed. Species that are unable to migrate or compete for resources may face an extinction risk.

Changes in community composition (*e.g.* food web) can alter energy transfer and biogeochemical cycling (Viaroli *et al.*, 1996). In turn, alteration of biogeochemical processes can affect water quality and species adaptation/survival. Expected increase in metabolism rates may also increase mineralization rates of organic matter, which in turn may enhance nutrient availability and intensify the oxygen disequilibrium already existing in Mediterranean coastal lagoons. A greater availability of mineral nutrients is expected to favour spring macroalgal blooms followed by an accentuation of summer dystrophic crises and harmful microalgal blooms in the colder periods.

As far as commercial species are concerned (e.g., clams, oysters, mussels), increase of water temperature and its duration will have effects on metabolism and recruitment, increase of pathogen diffusion (Troussellier *et al*., 1998), risk of harmful microalgal blooms that affect commercial value, increase of oxygen demand and sulphide production.

Changes in precipitation patterns have important consequences for

- *water balance of coastal ecosystems*
- *dissolved nutrient transport from the watershed to the coastal lagoon*
- *solid transport both from land-side and sea-side*

Increases or decreases in precipitation and runoff may respectively increase the risk of coastal flooding or drought. Increase of extreme events, namely flooding/drought alternance like in Southern Europe in 2000-2003 can alter salinity and nutrient balances within lagoons. Prolonged flooding determines submersion in the subsident areas of the watershed and a decrease of salinity in the lagoon. This will affect marine, and to a lesser extent brackish species. Salinity changes will influence seagrasses, changing seed germination, propagule formation, growth and photosynthetic rates (Short and Neckles, 1999). Many commercial species (e.g. clams) may be negatively influenced. Prolonged drought causes a decrease in freshwater discharge. On the landside, it causes increased costs (e.g. for irrigation) and decreased vegetal production (as in 2003). In the lagoon side, less freshwater discharge causes a decrease in nutrient discharge, which in turn lower phytoplankton production and biomass with effects on clam and mussels crops. For example in the

Po River Delta lagoons, the long drought from spring to late summer 2003 caused an estimated loss of about 50% of the current mussel crop, and an almost total loss of recruitment.

Sea level rise (SLR) would

- *increase water depth in the lagoon*
- *alter water circulation*
- *affect solid transport and erosion-sedimentation equilibria*
- *increase ingression of salt water into inland coastal areas*

Sea-level rise will gradually inundate coastal lagoons and surrounding lands. Coastal lagoons could potentially migrate inland with rising sea levels; however, most of the Mediterranean coast is obstructed by human development, therefore they face the risk of annihilation. Even a limited increase can submerge part of sandy barriers separating lagoons and sea. The first consequence may be an increase of the hydrodynamic exchange with the sea. It may happen that for some lagoons, submergence will only displace the equilibrium between accretion (sedimentation accumulation) and SLR rates, leading to the maintenance of the same volumetric capacity (Nichols and Boon, 1994). If the relative rate of sea level rise is accelerated, or for lagoon with small barriers, accretion may not be sufficient to maintain equilibrium with SLR, certain lagoons may disappear. Overall, these processes are influent on coastal lagoon persistence.

Most of the coastal lagoons and their watershed in the Mediterranean area are influenced by sea eustatism and are subjected to a natural subsidence that has been accelerated by marshland reclamation and, especially, by groundwater and natural gas extraction. For example, in the Po River Delta, areas below the sea level can be found up to 40 km inland (Gambolati *et al*., 2002). The cost of maintaining these areas dry (by means of pumps) increase with SLR and therefore substantial changes in coastal land use (e.g reclaimed land for agriculture returns to wetland) can be expected. Changes in sea level and increasing episodes of extremely high riverine discharge can cause persistent flooding of the subsidence areas. Flooding persistence associated with temperature raise and different land use may allow the development of human pathogens that were commonly found until the 1950's, among these malaria, Mediterranean fever, etc. Still and warm water are a suitable environment for several harmful phytoplankton and cyanobacterial species producing toxins with acute and chronic effects also on humans. Finally, floods, by covering the land near the lagoon, can cause the dissolution of buried pollutants.

Freshwater inland resources can be contaminated due to the intrusion of saline water, both underground and on surface, increasing drought problems (e.g. experienced in 2003 in the southern region of the Venice lagoon), both for human use and agriculture production.

The protection adopted to defend the coastline from SLR could by itself be a cause of alteration of a natural equilibrium, as they necessarily modify the water flow and/or the tidal regime. Sea barriers, even if partially mobile as proposed in the case of Venice, defend the coasts from inundation and flooding, but may lead to a complete "artificialisation" of the lagoons and loss of the natural dynamics of the system.

UVBR increase

UVBR has been demonstrated to have deleterious effects on numerous planktonic organisms and processes (Mostajir *et al*., 1999, Worrest, 1989), and can penetrate lagoon water masses due to their shallow depth. However, to our knowledge no study has been maded to explore potential effects of UVBR increase in shallow lagoons. In marine algae, phanerogams and phytoplankton, photosyntehsis can be inhibited by UVBR (Smith *et al*., 1992). Furthermore, UVBR enhances phytoplankton and bacterial mortality particularly in the top 5 m of the water column, where there is little attenuation (Boelen *et al*., 2002).

It has been also demonstrated that enhanced UVBR can change the structure and dynamics of the pelagic food web (Mostjir *et al*., 1999). As a consequence, the ecosystem develops toward a microbial food web (smaller organisms, less productive) in preference to an herbivorous food web (larger organisms, much more productive). This food web change can have broad implications for aquaculture in lagoons.

IV.D.4. Expected long-term effects related to climate changes that are super-imposed on direct human alterations

Human activities within watersheds and in coastal lagoon systems have direct impact on the quantity and quality of the waters delivered to adjacent seas or ocean. An increased variety of land uses has contributed to increased changes in watershed structure and hydrographic networks. Overall, these alterations influence coastal lagoons and nearshore coastal waters through spatial dependent and time-lagged processes that control the delivery of nutrients and pollutants (Borum, 1996, Turner *et al*., 1997, Valiela *et al*., 1997, Vitousek *et al.*, 1997, Carpenter, *et al*, 1998, Holland *et al*., 2004).

Losses of goods and services.
Seagrass communities, and to a lesser extent microphytobenthic systems, support high secondary production that is not only of commercial interest. Biotic equilibria, especially those depending upon seagrass processes, are responsible for invaluable ecosystem functions and services such as carbon dioxide and nutrient sinks, sediment oxygenation and stability, recovery of redox buffers, etc. Climate change may indirectly add further stress, degrading and threatening their ecological sustainability. In the long term, losses of non-commercial goods and services can determine also economic losses, e.g. fishery decline, touristic attractiveness, etc.

Impact of aquaculture:
Aquaculture development affects local ecosystems, where wastewater from fish or mollusc farming can pollute the aquatic environment. The exploitation of benthic organisms (e.g., clams) can also cause sediment reworking and alteration. In warm water, not only the development risk of human pathogens increases, but also water quality undergoes deterioration. Accelerated microbial decomposition of aquaculture wastes can cause lowering of oxygen concentrations and perhaps induce stress to cultivated organisms as well as natural species. Higher temperatures may allow higher incidences of disease, especially if the organisms in the region are under stress.

Increasing eutrophication.
The interaction between eutrophication and climate change can potentially determine shifts in community structure and enhance the risk of harmful algal blooms, the risk of increase in the frequency and severity of anoxic crises with subsequent mortality of commercial species.

Increasing unpredictability.
Coastal lagoons are recognised as highly unpredictable environments. There is evidence that within certain thresholds, marine communities and ecosystems are

resilient to environmental changes and can buffer against external stresses. However, resilience and buffering capacities do not follow linear behaviour, but rather undergo sudden and exponential responses. Therefore, an increasing stress – e.g., by physical and chemical stressors – can result in rapid and irreversible deterioration of the aquatic ecosystems.

Deterioration and losses of marginal ecosystems that buffer against perturbations and protect lagoons

Coastal lagoons are not unique and homogeneous ecosystems, but rather made up of a mosaic of subsystems. The marginal/littoral subunits usually work as a buffering system. For instance, the littoral reed (*Phragmites australis*) marshes are sinks for particulate materials and traps for dissolved nutrient and contaminants. Moreover, they are suitable habitats for a number of waterfowl species. An increase in flooding frequencies and/or an increase in storms frequency can determine a die-off of the reed as well as an erosion of reed marshes with the subsequent decrease in protection for the whole lagoon.

Impact derived from hazardous activities

The primary impacts of climate changes in coastal lagoons can trigger other impacts such as damage to wastewater works, landfills etc. Where hazardous waste landfills are close to the coastal lagoon, pollutants can migrate from the landfills to the lagoon, because of frequent flooding events and water-table changes. As sea-level rise accelerates, these impacts may become more severe, depending on individual site characteristics and protection strategies.

The impact of climate change in coastal lagoons is difficult to predict in quantitative terms since several factors have opposing effects. For example, temperature increase may increase primary production but UVBR may increase mortality. The outcome of both effects is difficult to assess based on present knowledge. It may not be, a priori, excluded that some positive consequences arise, e.g. increase of primary production leading to increase in exploitable resource biomass in lagoon ecosystems. However, the duration of these effects is difficult to assess. Furthermore, the establishment of a new ecological equilibrium in these fragile ecosystems is uncertain.

Chapter V.A. Climate Change and Extreme Events - Floods

Key Points

- **The main driver of floods and droughts is extreme precipitation linked to regional soil moisture and atmospheric temperature.**
- **Changes in extreme climate are likely to have a greater impact on society than changes in mean climate.**
- **Flood magnitude and frequency are likely (a 66-90% probability) to increase in most regions of Europe.**
- **Expected climate change will intensify the hydrological cycle causing dislocations and high costs in agriculture and urban areas.**
- **The European summer climate will affect the incidence of heatwaves and droughts in the future.**
- **Today's climate models are not yet adequate at predicting extreme climate events in local areas such as flooding in a given river basin, but climate change analysis on water resources needs to be done at the river basin scale.**
- **With a rising likelihood of extreme weather conditions and resulting floods and droughts, the areas prone to these risks should be carefully mapped.**

Chapter V.A. Climate Change and Extreme Events: Floods[2]

V.A.1. Introduction

The aim of this document is to provide a synthesis of what is currently known about possible climate changes in Europe and how these will affect the occurrence of extreme flood and drought events. Furthermore, known gaps and questions are defined. The document is intended as a basis to evaluate the link of climate change with water policies. Other aspects, such as adaptation and reduction, also are approached in the document.

Main drivers for Flood and Drought Events
The main driver for flood and drought events is extreme precipitation. Furthermore, increasing ambient air temperatures will increase heat stress and potential evaporation, which will change soil moisture availability and therefore directly influence the occurrence of droughts. Also, changing soil moisture conditions will affect the initial conditions for flood events: precipitation on drier soils can be buffered because of the increased soil water storage potential. A further driver for flood and drought events is the increased vulnerability to natural disasters due to growing urban population, environmental degradation and a lack of planning, land management and preparedness.

Current Knowledge of Expected Climate Changes in Europe
Schnur (2002) states that *"changes in extreme climate, such as hot spells, droughts or floods, potentially have a much greater impact on society than changes in mean climate, such as summertime temperature averaged over several decades".* The Third Assessment Report on Climate Change (IPCC, 2001) states that *"it is very likely (a 90-99% chance) that precipitation has increased by 0.5 to 1.0 % per decade in the 20th century over most mid- and high latitudes of the Northern Hemisphere continents"* and that *"in the mid- and high latitudes of the Northern Hemisphere over the latter half of the 20th century, it is likely (a 66-90% chance) that there has been a 2-4% increase in the frequency of heavy precipitation events"* As a consequence, it has been concluded (IPCC-McCarthy *et al*, 2001) that: *"flood magnitude and frequency are likely (a 66-90% probability) to increase in most regions, and low flows are likely to decrease in many regions."*

Palmer & Räisänen (2002) and Milly *et al*. (2002) concluded that the risk of extreme precipitation and flooding would increase in the future because of rising levels of atmospheric carbon dioxide. These conclusions are based on climate models that are run using a rate of net greenhouse gas increase that is twice the current observed value. Palmer and Räisänen (2002) find that in the winter over Europe, the probability of extremely high seasonal precipitation increases by about two to five times over the course of the next 50 to 100 years (Figure V.A.1). These changes appear because, in general, the climate models produce more precipitation in those regions when the greenhouse effect is enhanced. According to the authors, the "increase in CO2 [used in their models] is somewhat faster than is anticipated for the 21st century, but can be justified from the neglect of other anthropogenic greenhouse gases."

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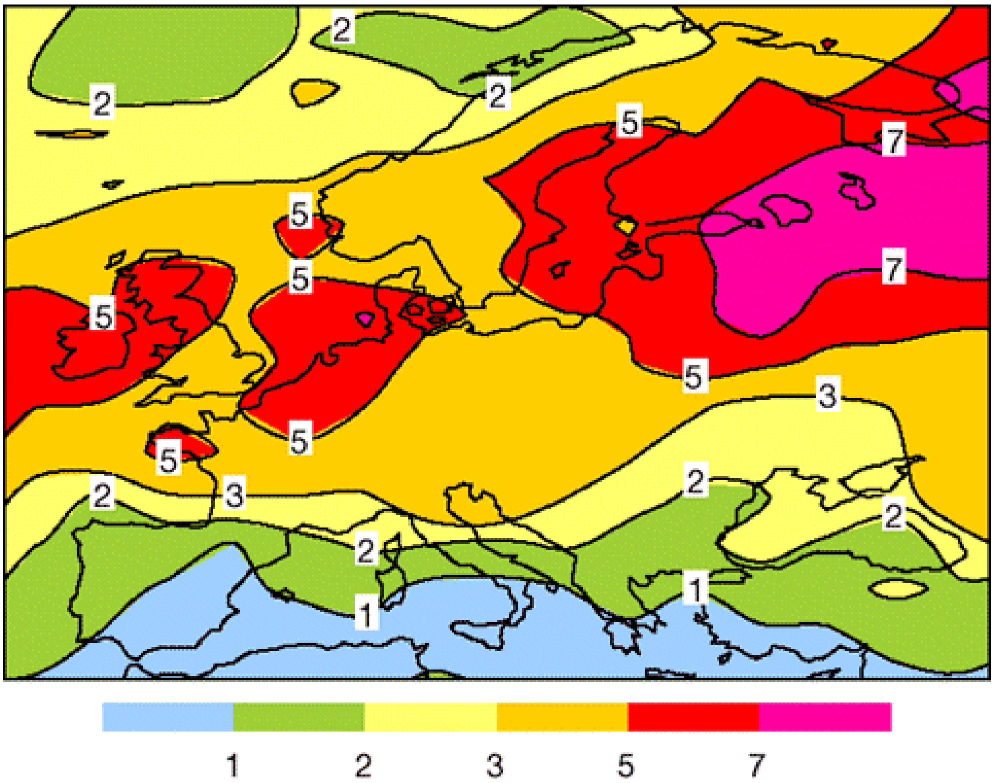

Figure V.A.1. A map showing the number of times more likely it is that a European winter will be extremely wet in 50 to 100 years, compared with today. ***Source: Palmer and Räisänen (2002).***

Milly *et al*. (2002) examined the historical occurrence of hundred-year floods on large-scale river basins around the world and then used climate models to assess whether the observed behavior was related to an enhanced greenhouse effect, as well as to surmise what we may expect in the future. As for the historical record, they found that a greater frequency of hundred-year floods occurred in the latter half of their record than in the early half. The trend they found in hundred-year flood occurrence over the 20th century was 1.99×10^{-4} events per year, which means a trend that results in one extra hundred-year flood every 5,000 years! They have identified this trend in climate models run with 20th-century conditions, but also found that this trend will continue, and perhaps even grow into the future (using models incorporating rates of greenhouse enhancement that are about twice the current observed values).

Vellinga and Van Verseveld (2000) conclude that *"as concentrations of greenhouse gases in the atmosphere continue to rise, it is likely that there will be an increase in the intensity of rainstorms, river floods, droughts, and other extreme weather events."*

The World Water Council (2003) states that *"the expected climatic change during the 21st century will further intensify the hydrological cycle, with rainy seasons becoming shorter and more intense in some regions, while droughts in other areas will grow longer in duration, which could endanger species and crops and lead to drops in food production globally. The risk of more frequent, and possibly more brutal, storms, extreme weather events will increase". "Economic losses from weather and flood catastrophes have increased ten-fold over the past 50 years, partially the result of rapid climate changes. These rapid climate changes are seen in more intense rainy seasons, longer dry seasons, stronger storms, shifts in rainfall and rising sea levels. More disastrous floods and droughts have been the most visible manifestation of these changes."*

It is realized that adaptation to climate change – that is the *'ability ... to adjust to climate changes (including climate variability and extremes) to moderate potential damages….or to cope with consequences'* (IPCC, 2001) – should be a key issue. Possible adaptation options can be taken in populated areas that involve the planning of settlements and their infrastructure, placement of industrial facilities etc. in a manner to reduce the negative effects of events and to forecast and minimize potential damages.

V.A.3. Main expected effects for extreme floods and droughts

"(Monthly) Runoff tends to increase in northern Europe, and decrease in the south. Percentage increases are up to 25% and decreases may be as great as 50%" (Arnell, 1999). "*Low flows tend to be reduced in maritime parts of Europe, as summer flows decline, but may increase* (in winter) *in more continental parts of Europe"* This is because of a shift of snowfall to rainfall and increased snowmelt during winters in these continental areas, which have now low winter runoff.

"During summer months, Southern Europe is expected to become drier while Northern Europe will probably get wetter" (Vellinga and Van Verseveld, 2000).

"Flood magnitude and frequency are likely (a 66-90% probability) to increase in most regions, and low flows are likely to decrease in many regions" (IPCC-McCarthy *et al*, 2001).

Palmer and Räisänen (2002) find that in the winter over Europe, the probability of extremely high seasonal precipitation increases by about two to five times over the course of the next 50 to 100 years.

Simulations by Schar *et al.* (2004) suggested that, towards the end of this century, every second summer in Europe could be as hot and dry as the summer of 2003. They write: *"The European summer climate might experience a profound increase in year-to-year variability in response to greenhouse forcing. Such an increase might be able to explain the unusual European summer of 2003, and would strongly affect the incidence of heatwaves and droughts in the future."*

In addition to the direct effects, increased heat stress and lower soil moisture availability will increase the demand for water resources in summer, leading higher rates of water abstraction from stream flows and groundwater that in turn might decrease low flows and lower the groundwater table.

Known gaps and questions
Schnur (2002) stated that today's climate models are not good at predicting extreme climate events in local areas, such as flooding in a given river basin, because they are limited in their resolution to a coarse grid size of about 200 kilometres. For the average river basin, climate-change simulations would need a much higher resolution of tens of kilometres, but this will not be available for quite some time.

Burlando (2004) goes even further and states that climate change analysis on water resources needs to be done at the catchment scale, preferably at sizes of 1km2 or even smaller, which is the scale where weather variability and landscape variability reaches manageable proportions.

Until these high-resolution climate change simulations are available, downscaling methods need to be applied to produce the proper spatial resolution needed for extreme flood modeling. Downscaling methods available are Regional Climate Models (using the GCM's as boundary conditions), statistical downscaling and stochastic downscaling. No clear consensus exists on which methodology to apply, although stochastic downscaling (Burlando et al. 1999) might be the least problematic. Arnell (1999) on the contrary, advises to not use downscaling at all.

Menzell and Schwandt (2004) also state the importance of further downscaling research, both to improve spatial as well as temporal resolution. They mention that it is not clear if the prediction of increased rainfall by global circulation models at large scales means increased extreme rainfall amounts at small scales leading to floods.

Furthermore, computational resources in climate research need to be improved to allow the calculation of much larger ensembles that are needed for more reliable estimates of extreme events, particularly for very rare events. Multi-model ensembles of the size used by Palmer and Räisänen (2002) are available only for future changes in CO_2 concentration. Similar model integrations will be needed for a more complete picture of the factors contributing to climate change, such as other greenhouse gases and sulphate aerosols, including any uncertainties attached to these agents.

A quantitative prediction of the frequency, location, extent, and intensity of highly intensive local rainfall has so far only been possible to a very limited degree, even in short-term weather forecasting (Bronstert, 2003). Methods of analyzing spatial and temporal precipitation frequency on small scale must be further developed.

The significance of the observed changes in the frequency of western weather conditions in parts of Europe over long time periods is not yet known (Bronstert, 2003). There is a strong correlation between this circulation type and the occurrence probability of regional or local precipitation in Central Europe. It would be desirable to trace large-scale weather conditions well into the past and to correlate them with proxy sources, such as biological indicators.

Hydrologists have not yet been able to distinguish the influence of climate change on flooding in relation to other anthropogenic interferences or in relation to the natural variability of the meteorological and area-specific meteorological conditions. For such analysis the further development of process-oriented hydrological models coupled with meteorological and hydraulic simulation tools is necessary (Bronstert, 2003).

Climatic change influence on land cover may become a more important factor influencing the frequency and severity of floods in Europe should be taken into account (Bronstert, 2003).

With a rising likelihood of extreme weather conditions and resulting floods and droughts it would be important to map the areas prone to these kind of risks (flooding, forest fire, water shortage, storm damage, etc. risks) and to assess the number of people (urban-rural population), building stock, industries etc. located in such areas at European level. This information is also needed for setting up regional prevention plans and would also need to be fed into the spatial planning processes in order to take these risks into account in the future land use planning.

Further research is needed to build up scenarios for the prevention and reduction of natural hazards to prepare a better adaptation to climate change effects. Spatial planning methods have to be investigated to understand the relations between the spatial influences and the environmental disasters. New models of spatial development have to be established.

Chapter V.B. Climate Change and European Droughts

Key Points

- **Droughts are a natural and recurrent feature of the European climate occurring in both high and low rainfall areas, and in any season.**

- **The impacts depend on the severity, duration and spatial extent of the rainfall deficit, but also on the environmental and socio-economic vulnerability of the affected region.**

- **Europe's vulnerability to drought is increasing due to increased demand for water in some sectors and regions, and the impact of climate change.**

- **Total economic cost (primarily from agriculture) of the 2003 drought was approximately US$13 billion, and in general higher than for floods.**

- **The increased integration of water resource systems at the regional level, with the optimal exploitation of both surface and groundwater sources, has significantly increased capabilities to withstand the impact of within-year drought episodes.**

- ***A Pan-European Drought Forecasting and Monitoring System*: Reducing the economic, social and environmental impact of future droughts will require reliable and useable information (through forecasting and monitoring) to be provided to policy makers, water managers and citizens.**

Chapter V.B. Climate Change and European Droughts

This chapter originated as a Discussion Document sponsored by the EurAqua Network of European Freshwater Research Organizations. A large number of individuals from across Europe have contributed text, data, and photographs and then commented upon the original document.

V.B.1. Introduction

This chapter considers Europe's susceptibility to drought, how the range of problems experienced during 2003 may be exacerbated as a consequence of climate change, and how resilience to future drought stress can be strengthened. In particular, consideration of drought severity under future climate change scenarios is warranted in view of:

- The possible future increases in drought frequency and severity across Europe
- The severity of the drought which affected much of Europe during 2003,
- The low priority given to droughts in many European policies.
- The increased potential for collaboration on water issues at European level,
- Recent advances in the scientific understanding of droughts,
- The better preparedness and mitigation approaches now being used in other advanced countries

The purpose of this chapter is to highlight the threat of droughts and emphasize the need to improve drought mitigation measures at all levels if future impacts of climate change are to be managed.

V.B.2. Europe's Vulnerability to Drought

Droughts are a natural and recurrent feature of the European climate (EEA, 2001) occurring in both high and low rainfall areas, and in any season. They develop slowly, can persist for years over very wide areas, and have major economic, social and environmental consequences. Drought is one of the major weather related disasters and recent events have demonstrated Europe's continuing vulnerability to this natural hazard. The impacts depend on the severity, duration and spatial extent of the rainfall deficit but also, and to a large extent, on the environmental and socio-economic vulnerability of the affected region. Many parts of Europe suffer water stress, and, as was seen in 2003, it is these areas that are most vulnerable to drought. Climate change modeling (Arnell, 1999) using a range of climate scenarios, has predicted that droughts are likely to increase in frequency and intensity across most of Western Europe.

Notwithstanding the severe impact of major droughts on the fabric of society, the institutional frameworks to cope with droughts at European level are poorly developed (Vogt and Somma, 2000). There is a growing need for drought to feature more strongly on the political agenda since:

- Droughts are a major threat to the economic and social well being of European citizens.
- Europe's vulnerability to drought is increasing due to increased demand for water in some sectors and regions, and the impact of climate change
- While drought planning in some member states is at an advanced level, and compares favorably with practices elsewhere in the world, the extent and effectiveness of drought management procedures is highly variable between

member states. Moreover some agencies take a reactive “crisis management” approach to droughts, rather than a proactive risk management approach.

- At a European scale the approach to drought lags behind other industrialized countries, with no coordinated European drought forecasting, monitoring and mitigation network, or commitment to European scale drought research and best practice to reduce vulnerability.

What is the economic cost of droughts to Europe?

Drought affects all sectors of society in very complex and interactive ways and therefore its economic cost is difficult to quantify. Typically, published data on the economic cost of a drought is based upon one sector, in one area, and in one year. In addition, economic losses in a drought-affected area can result in improved demand in another area – so the scale at which losses are calculated can be important. For example, while the total volume of some French agricultural products fell by up to 60% in 2003, the total value of production was largely unaffected. The reduced production forced prices up – financial losses in drought-affected areas were matched by higher profits in the less affected areas.

Planning for future droughts requires good data, and the capability to interpret it appropriately. However, there is no established methodology to quantify the economic, social and environmental costs of droughts. Notably the UN Economic Commission for Latin America and the Caribbean (ECLAC) has done some work to develop such methodologies. The EC Humanitarian Office (ECHO) has also sponsored studies on how these methodologies might be developed (CRED, 1997). These improved methods are essential if reliable estimates are to be made of the economic costs of climate induced changes in European drought severity. Even with these serious difficulties, it is apparent from Table V.B.1 that droughts have a major economic impact upon Europe.

Box 1

Economic costs of droughts compared to floods

Munich Re has estimated the total economic cost (primarily from agricultural data) of the 2003 drought as approximately US$13 billion. This is comparable to their estimate of US$13.5 billion for the August 2002 floods. This is consistent with a recent study by the US National Drought Mitigation Centre (1998) which summarized the socio-economic impact of droughts - comparing the warning time, duration, frequency, fatalities, costs and losses and the spatial extent with similar figures for floods and hurricanes. The costs of the worst recent drought in the USA (1988-89, $39-40 billion) were on average more than twice the costs of the worst flood (1993, Mississippi valley, $15-28 billion).

Table V.B.1 Minimum economic cost of recent major drought events in Europe
(from Munich Re[3], EEA, COPA-COGECA and other sources)

Period	Region / Countries affected	Economic costs (€ billion)
1976-77	**Western Europe** Cost of building damage due to land subsidence in London alone estimated at € 800 million	
1981- 82	**Iberian Peninsula** (Portugal, Spain, Southern France, Corsica, Italy)	> 5.0
1988- 91	**Mediterranean Region** (Portugal, Spain, Southern France, Italy, Albania, Greece)	> 2.1
1992- 94	**Eastern Europe** (Germany, Denmark, Poland, Lithuania, Hungary, Yugoslavia, Ukraine, Moldova)	> 1.1
1992- 95	**Spain**	> 3.7
2000	**Central Europe** (Romania, Hungary, Poland, Bulgaria, Greece, Yugoslavia, Czech Rep, Turkey, Germany)	> 0.5
2003	**Europe** (Romania, Hungary, Poland, Bulgaria, Greece, Yugoslavia, Czech Rep, Austria, Switzerland, Italy, Germany, Belgium, Denmark, Netherlands, Norway, UK, France, Spain, Portugal)	> 13.0

What causes European droughts?
Droughts are complex phenomena, the result of a combination of meteorological conditions (low rainfall and high temperatures), land surface conditions (land use, soil moisture conditions), and water use practices. Northern and southern European droughts tend to be caused by different meteorological conditions, and land use and water resource management practices. The common problems range from the need for more effective drought forecasting and monitoring, to the development of holistic drought mitigation strategies. Three general types of drought may be recognized: meteorological droughts – defined on the basis of rainfall deficiency; hydrological droughts – where accumulated shortfalls in river flows or groundwater replenishment are of primary importance; and agricultural droughts where the availability of soil water through the growing season is the critical factor. During lengthy droughts, all three categories may combine to increase water stress.

High temperatures are not a necessary component of drought conditions, dry winters can lead to water resources stress in the following summer. But high temperatures were certainly influential in 2003, and may be expected to assume a greater importance in a warming world.

V.B.3. Climate and climate variability

For Europe, the dominant influence upon climate variability is the global atmospheric circulation pattern and, in particular the tracks followed by rain-bearing Atlantic frontal systems. When intense high-pressure systems develop and persist over continental Europe is when major droughts occur; normal rain bearing storms are blocked/diverted to either lower or higher latitudes.

[3] Munich RE : NatCat Database of European droughts, heat waves and forest fires (1976-2003)

Large, global scale climatic drivers cause droughts. As a result droughts affect large areas and tend to continue for several seasons – causing "clusters" of drought years. Ultimately these systems can produce exceptionally protracted rainfall deficiencies such as occurred over much of western Europe during the late nineteenth and early twentieth century (Figure V.B.1) (Thomsen, 1993). There have been no close recent parallels to drought episodes of such duration but the 1975/76 drought was of unprecedented intensity over parts of Europe (from western Germany to the English Midlands) (Doorkamp et al., 1980) resulting in substantial agricultural and industrial losses and environmental stress. However, the event was perceived, at the time, to be extremely rare – with return periods exceeding 100 years in many regions. As a consequence, it did not provide a sufficiently strong stimulus for the development of cross-sectoral coping strategies appropriate for the potential increases in drought magnitude as global warming intensifies.

These periods of drought (and indeed floods at the other end of the flow regime) show clear patterns, alternating between drought-rich and drought-poor times. See for example, in Figure V.B.1, the drought period of the 1880-1900's replaced by wetter conditions around 1915. These sequences occur due to natural climate variability. Currently there is no statistically significant signal in this historical data to suggest a trend towards an increased frequency or magnitude of extremes. Natural variability (at all time scales) will also change with global warming over the next century, but there is much uncertainty associated with aspects of current climate change scenarios.

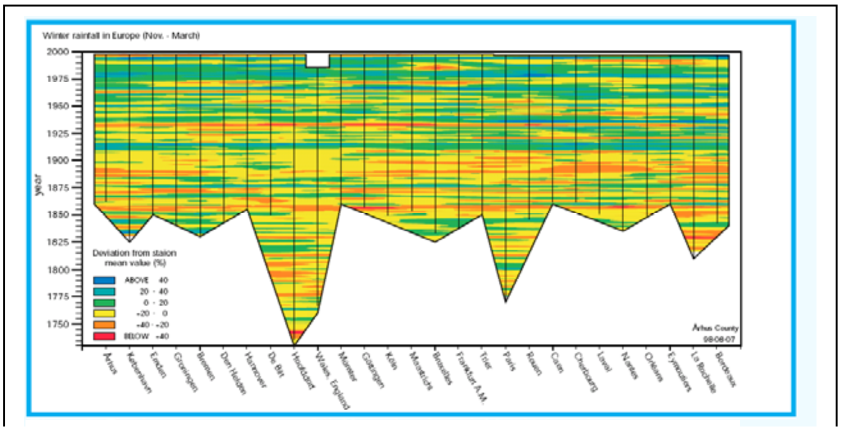

Figure V.B.1. The derivation of winter rainfall (November through March)

V.B.4. Water and Drought Management

Reservoirs, rivers and aquifers are sustained not by rainfall directly but by that proportion which remains after evaporative demands have been met. Evaporation losses are concentrated in the summer half-year and impose a strong seasonality on river flows and groundwater replenishment. On average around three-quarters of Europe's rainfall is lost to evaporation, the proportion increasing to >90% in the driest regions. Thus, variability in river flows and groundwater replenishment is normally much greater than for rainfall, with many parts of Europe being vulnerable to even small decreases in rainfall. Evaporation losses mean that relatively minor rainfall deficiencies can translate into large deficiencies in runoff and aquifer replenishment. Adequate river flow and groundwater monitoring networks are therefore essential to assess any climate-induced changes in drought episodes.

Water resource systems adapt over time to the normal range of climatic variability. This adaptation reflects not only regional rainfall patterns but also contrasts in land use and, particularly, geology that largely determines the amount of natural water storage available in groundwater and soils. Where countries are underlain by permeable rock strata a dominant proportion of their water needs are commonly met from groundwater. In other areas spring and summer flows are maintained by water held as snow and ice. Both these types of storage provide a buffer that can greatly reduce national vulnerability to short-term droughts. However, where several dry winters cluster together, this buffering capacity may be reduced and severe drought conditions may develop.

Poor water and land management practices, together with inadequacies in infrastructure, demand management, governance structures, legislative frameworks and regulatory mechanisms can increase the adverse impacts of rainfall deficiencies. This is particularly the case in regions that are already water stressed, and in extreme cases this can lead to self-perpetuating drought conditions. Poor adaptation to drought may reflect a limited understanding of how patterns of water availability, water use and land use can increase or moderate drought vulnerability. Poor monitoring or reporting capabilities can prevent the timely introduction of mitigation measures. Possibly most importantly - an absence of political will may mean that unsustainable water use practices are never addressed. In a changing climate, the need for optimal and adaptive water management practices will be inescapable.

The increased integration of water resource systems at the regional level, with the optimal exploitation of both surface and groundwater sources, has significantly increased capabilities to withstand the impact of within-year drought episodes. However, in the longer term, demand management initiatives now offer greater scope for ensuring that limited water resources are used in a sustainable way.

Policies measures are needed which encourage “soft” demand management approaches, rather than “hard” infrastructure supply side approaches. These will need to be tuned to local and national circumstances, and fit within a suitable pan-European framework. Measures could include the use of economic instruments, water-reuse and recycling, increased efficiency of domestic, agricultural and industrial water use – supported by strong public education programmes.

Figure V.B.2. Example of field irrigation.

We must recognize that climate change, as well as constituting an increasing threat, has the potential to contribute to an enhanced resilience to droughts across Europe. An increased frequency of wet winters would generally be beneficial for water resources and Europe needs to be able to develop water management strategies that capitalize most effectively on such opportunities, and exploit them in flexible drought mitigation strategies.

V.B.5. Climate change and droughts

Global warming is predicted to cause significant changes to the world's climate, but uncertainties remain about the precise nature of these changes. This is particularly true with regard to possible changes at a regional level and to extremes, such as prolonged periods of low rainfall. It is precisely the changes in these climate extremes that will have a direct impact on the frequency and severity (in space and time) of drought episodes across Europe.

The latest climate change scenarios from the various groups modeling the global climate response to increased concentrations of greenhouse suggest significant summer drying across many parts of Europe, particularly in the Mediterranean basin with more hot days and heat waves very likely across most land areas (IPCC, 2001). These scenarios also suggest decreases in rainfall in some areas for spring and autumn and an increased variability in the amount of winter rainfall. Combining these patterns of change leads to an assertion that over the next 100 years Europe is likely to suffer more frequent **meteorological drought** conditions, especially in the south. Furthermore, the scenarios mean that these events might manifest themselves either as short but extreme single season droughts (such as the hot summer of 2003) or longer-term, multi-season droughts, and they might be local or widespread in nature. A comprehensive framework for reducing Europe's vulnerability to droughts is essential in preparing for conditions of increasing drought frequency and severity

With generally elevated temperatures (scenarios suggest that summer temperatures might be, on average, anything between 2 and 6ºC higher than the present day) these rainfall deficits are likely to be accompanied by higher evaporative demand leading also to the potential for severe **hydrological drought**. Despite the uncertainty surrounding these climate scenarios it is vital that water resource planners across Europe begin to think about their potential vulnerability to changes in climate as described above. For example, in the UK the water industry have been addressing the issue of incorporating climate change scenarios into their long-term water resource plans, including some specific low probability but high consequence extreme scenarios. The current method evaluates the climate change impacts using reference scenarios developed by the UK Climate Impact Programme, known as the UKCIP02 scenarios. These scenarios are applied using a simple perturbation method whereby the observed series of climatic inputs to a hydrological model are changed proportionally according to the UKCIP02 monthly factors.

However, more sophisticated techniques are now available which express climatic changes simulated by Global Climate Models (GCMs) at hydrologically appropriate time and space scales. These techniques include statistical and dynamic methods such as the use of output from Regional Climate Model (RCMs). There remains much uncertainty surrounding future climate change scenarios. These uncertainties may be derived from assumptions about the future socio-economic trends leading to certain greenhouse gas emissions pathways, through to uncertainties in how local-scale, high intensity, short duration rainfall events might change. While it is true to say that many of the GCMs are converging in terms of their predictions for global average temperature change, there remain serious discrepancies (in terms of direction of potential change as well as the magnitude) in the scenarios of change in extreme rainfall events. Hence, the choice of GCM within a climate change impact assessment is thought to be the largest single source of uncertainty (Jenkins and Lowe, 2003, Prudhome *et al*., 2003, Reynard and Young, 2003). Future analysis of climate change impacts should therefore use the output from a range of GCMs (IPCC, 2001).

European researchers are leading in the development of improved understanding of the processes that drive such large-scale climate systems. This improved understanding will underpin a more reliable forecasting of the frequency and persistence of future European droughts ((Wilby *et al*., 2005). However, considerable challenges remain if policy makers and water managers are to be furnished with effective tools to counteract the threat of drought. Greater reconciliation is required between existing scenario outputs and directly monitored hydrological behaviour at the basin and catchment scale. As yet there is little compelling evidence of changes in the frequency and magnitude of low flow episodes in those areas of Europe where flow patterns a little affected by man's activities (Hisdal *et al*., 2001). It is important therefore that monitoring programmes are maintained to provide the ground-truth and process understanding that will help inform the development of future generations of sub-regional climate models.

V.B.6. Impacts of drought – Lessons from 2003

The 2003 drought was a stark reminder of Europe's vulnerability to drought, demonstrating clearly what can happen when an exceptional rainfall deficiency is combined with extended heat-wave conditions. In parts of Europe summer temperatures were 4-7 °C higher than the seasonal average.

The diversity and far reaching effects of the 2003 drought are illustrated in the following selected examples. The impacts in Italy were particularly severe, with the country on the brink of a national emergency. The tragic effects of "la canicule" (extreme heat wave) of 2003 have left a profound social and political impression upon the people of France.

European **Agriculture** was particularly badly affected, with farm lobby groups in the EU estimating losses of €11 billion. Typical agricultural production losses are shown in Table V.B.2 (COPA COGECA 2003).

Table V.B.2. Impact of the summer 2003 heat wave and droungt on Agriculture and forestry in 5 countries.

For example, the reduced production of green fodder required :

- importing this bulky commodity from as far away as the Ukraine,
- the early slaughtering of cattle,
- reduced carry over of feed for livestock for 2004

EU cereal production was 23 mio tonnes below that of 2002, requiring imports and depletion of carry over stocks.

In addition to the direct economic costs, the increased water demands of agriculture (and particularly irrigated agriculture) played a very significant role in making drought conditions worse.

Evacuation from forest fires at Massif des Maures near Vidauban, France

Die-back of trees attributed to the 2003 drought

Forestry stocks can be adversely affected by both fire and die-back. In 2003, exceptionally dry conditions and high temperatures resulted in over 25,000 reported heath and forest fires, extending from Portugal (losses in excess of €1 billion) to Ireland and Finland. In total, 650,000 ha of EU forests were destroyed by fire. In Switzerland widespread dieback was attributed to the drought, with trees becoming susceptible to attack from a variety of pests. The reduced yields of many forestry crops grown for biomass will affect energy production for many years to come.

Tourism is of vital importance to many of Europe's less developed regions. During the summer of 2003, the number of tourists visiting Spain from northern European countries fell by over 800,000 as people chose to stay at home to enjoy warm and sunny local conditions. Droughts also reduce snowfall in mountain areas, affect recreational on lakes and rivers, damage landscapes, and affect water supplies to tourist resorts.

Many European rivers are essential sources of water for navigation, water supplies, hydroelectricity and cooling waters, recreation and maintaining ecosystems. The 2003 drought caused rivers such as the Danube, Rhine and Po to drop to their lowest levels in more than a century. **Navigation** was restricted on many rivers, with individual river ports on the Danube reporting losses of several millions of Euros. **Thermal and nuclear power** plants were closed because of either a lack of water for cooling systems, or restrictions on discharging heated waters. **Hydropower** production was affected in Norway, France and Germany. Power cuts occurred in Italy, France and Germany – with knock-on losses across many other industrial sectors.

In 2003 the seasonal decline in **groundwater resources** was exceptionally steep with groundwater levels reaching 100- year record lows. Drying up of boreholes, springs and wetlands, and restrictions on water use and abstractions was common across much of Europe. In eastern Austria, the drought has prompted the construction of additional **domestic and industrial water supply** networks at a cost of €40 million. In the Netherlands, **salt water intrusion** has been estimated to increase the agricultural costs of drought by 10% and the need to maintain freshwater flows in the main rivers (especially the Rhine) to limit saltwater encroachment restricts abstractions from rivers for other users – a change in the management policy is under consideration as part of the Netherlands Drought Plan (ARCADIS, 2003).

Rivers, lakes and wetlands make a major contribution to the quality of life in Europe; they are also important to the maintenance of **biodiversity**. However, during the 2003 drought, terrestrial, freshwater and coastal ecosystems were all put under exceptional stress, with increased risk of biodiversity loss (AVEC, 2003). **Fish** kills due to high temperature and increased pollution loads and low flows were reported as far north as Scotland, while eutrophication affected many southern lakes and rivers. In the 2003 crisis, emergency exemptions from environmental legislation (e.g. on discharging heated water from power stations) were taken at the expense of the environment. Across much of Europe, the summer of 2003 was the warmest on record (in a series extending back over 240 years). The associated **heat stress** is estimated to have contributed to the deaths of more than 30,000 people. The exceptionally dry soil conditions and clay shrinkage caused **structural damage to buildings** and increased leakage from water supply pipes. In southern England, insurance claims for building subsidence have been estimated to increase by €400 million in 2003 due to the exceptionally dry soil conditions.

Most climate change predictions indicate that there will be an increase in climate variability. The climate will alternate more rapidly between increased extremes. In these scenarios drought impacts described above will be more frequent and more extreme, and in some areas, will last longer.

V.B.7. A European Framework for Drought Mitigation

While the 2003 drought set a number of records, Europe has experienced more extreme drought conditions and the tendency for dry years to form clusters increases the magnitude of the drought threat. For example, any repetition of the sustained rainfall deficiencies that were a feature of a 25-year period beginning in the 1880s would, with present demand levels, represent a very severe challenge to water management throughout much of Europe. Longer-term (last 1000+ years) climate information suggests that droughts of even greater severity, spatial extent and duration have occurred. Thus, on the grounds of climate variability alone, there is a need for pan-European drought mitigation strategies; this need will become more compelling as climate change causes increased temperatures and changes in rainfall patterns.

A recent succession of severe and extensive droughts has led to a fundamental reappraisal of drought mitigation strategies in the USA, Australia and South Africa. The 2002 drought in the USA in particular stimulated many water conservation and demand management initiatives. Similarly, the recent drought in Australia has led to a wide-ranging approach to ameliorating drought impacts and reducing long-term pressures on water resources at national and state level. In the same way, Europe should view 2003 as a wake-up call. The 2003 drought should be the catalyst for actions aimed at reducing drought impacts across all relevant sectors.

Policy framework

Despite its profound effects, drought receives scant attention in many areas of European policy. In respect to agricultural policy, droughts are rarely mentioned – and yet droughts have major impacts, both direct (water stress in all plants, reduced water for irrigation, increased water pumping / transportation costs) and indirect (soil erosion and desertification).

The Common Agricultural Policy supports water intensive practices in regions with high water stress and high vulnerability to future droughts. The social and economic fabric of these regions is now almost entirely dependent upon unsustainable water systems. .

Figure V.B.4. In Thessaly, Greece irrigated cotton crops failed as rivers dried up.

In European forest policy, water is considered in terms of mitigating flooding and acid rain, with isolated references to optimizing recharge. There is inadequate consideration of the impacts of drought upon forest health, reduced biomass production (for building and energy), or the high water consumption of some energy crop species (esp. *Eucalyptus globulus* in Mediterranean areas). Despite impacts on water supplies for hydropower and the restrictions on both abstractions and discharges of cooling water, and increased consumer electricity demands during hot weather – drought is not mentioned in European energy policies. Similarly European transport navigation policy makes no reference to low flow conditions. Similarly, health policies make few provisions for reduced water supplies and deteriorating water quality. Drought is one criterion for exemption to the requirements of the Water Framework Directive – an increasingly likely situation. It makes no provision for managing biodiversity protection during severe droughts.

In contrast to internal policy, drought is addressed as a real issue in EU development policies. Drought is seen as a threat to sustainable development, a humanitarian issue and a driver of mass migration and political instability. The inadequacies of Europe's internal drought policies, planning and operations reduce the EU's authority in influencing drought related initiatives at international level.

During a protracted European drought, political and policy initiatives would need to be soundly based to ensure that trans-boundary mitigation measures are effective and equitable, and to preserve cohesion and avoid real damage to the social and economic fabric of the EU. There are currently very few mechanisms in place to coordinate transboundary preparedness and mitigation measures for prolonged drought situations. These will be needed if the challenges of future climates are to be met. The optimum framework for developing and implementing comprehensive drought mitigation measures needs to be found. The very wide cross-sectoral impact and feedbacks of droughts suggests that the issue should be addressed at an explicit European policy level. This should be supported by actions to achieve greater coherence between European policies for all sectors affected by, or contributing to, drought.

Best practice in drought preparedness and mitigation

A number of recent studies, research projects and workshops have examined a wide range of issues related to droughts at European level. They include studies of current European drought management methods and future scenarios using climate change predictions. Many of these studies concluded that while in some member states drought planning is of world standard, in some member states this is not the case, and certainly, at European scale there are some conspicuous deficiencies. At European scale the EU lags behind other industrialized countries in policy, planning and operational aspects. These deficiencies in turn affect the competitiveness of European industry.

In the USA, a national Drought Policy sets the framework within which individual states develop and implement Drought Plans. There are integrated US national drought forecasting and monitoring activities that provide real time information to states for local enhancement, and to sector interests for enhancement for specific sectoral applications.

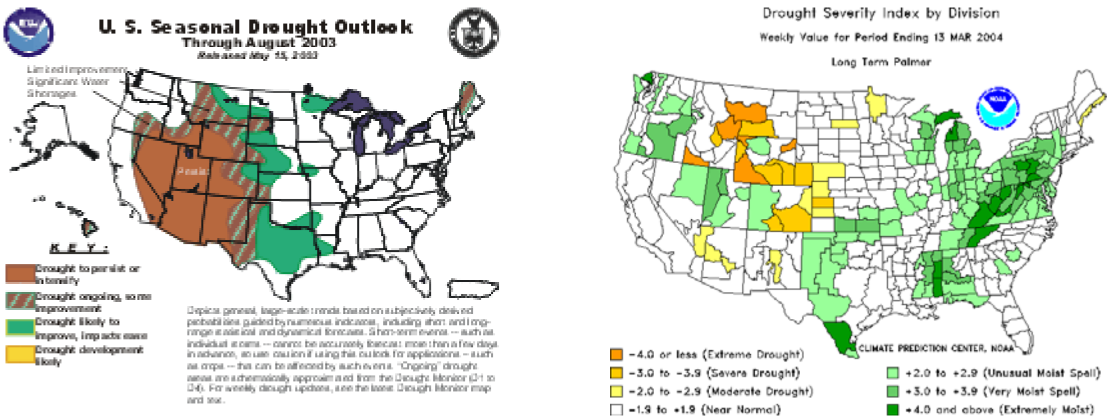

Figure V.B.5. On-line products from US National Drought Monitoring Centre
http://www.drought.unl.edu/dm/current.html

This process has produced a significant improvement in drought preparedness through benchmarking and sharing of best practices at state level. At national level, improved drought related analysis and response tools have been developed, spurred on by more informed demands from the states and different sectors. Similar national Drought Policies have recently been adopted in Australia and South Africa, with responsibility for development and implementation of Drought Plans at state level.

Pan-European forecasting and monitoring

Reducing the economic, social and environmental impact of future droughts will require reliable and useable information (through forecasting and monitoring) to be provided to policy makers, water managers and citizens. Research projects within the EU's 4th and 5th Framework Programmes have developed and demonstrated operational, real-time drought monitoring across the EU. Prototype communication tools have delivered this information through open access web portals. Several southern European web portals currently provide a range of information on conditions relating to, or affected by, drought extent and severity. These actions on drought forecasting, monitoring and mitigation in the Mediterranean region need to be developed, improved and extended to other parts of Europe. The establishment, in 2004, of a European Drought Centre – a virtual centre of expert groups and organizations working in drought research or management – is a very welcome initiative. Much can be gained by capitalizing on and adapting international best practice approaches to minimize drought impacts and by the development of more generic decision support systems. Coordinated action is required to bring these resources together, share expertise and strengthen Europe's resilience to future droughts at the level of citizens, the river basin, nationally and at EU level.

Drought mitigation and the involvement of citizens
A framework for European drought mitigation must set out to change the focus from crisis management, to risk management. In order to meet the climate driven challenges of the future, greater emphasis will need to be placed upon stakeholder participatory methods in planning and decision making with respect to water resources. Measures are required to enable and encourage citizens' to adopt "drought aware" lifestyles. Such measures need to affect a wide range of citizens' water use decisions (purchasing, home, work, leisure). Education has a primary role to play in establishing a foundation to build equitable and sustainable strategies for combating drought stress. Web based information portals, such as a European Drought Network, should provide citizens with a basis for making informed decisions based upon the best available information.

V.B.8. Preparing for Future European droughts

The strengthening Europe's resilience to future droughts will require major investments in monitoring, research, technology transfer and education. Research is required to underpin the development of improved understanding of the complex inter-relationships between physical, social, economic and political processes which contribute to policy, technical and non-technical measures which reduce Europe's vulnerability to droughts. Actions to prepare for future droughts should include:

Policy Research

- Studies to develop a policy framework for European drought mitigation. A clear definition and methodology for estimating economic, social and environmental cost of droughts is required.

Physical Sciences

- Research to improve the accuracy of climate models, and in particular, predictions of the spatial extent, severity and duration of drought events in the medium and long term.
- Improved understanding of drought processes, feedbacks, interactions and impacts.
- Research on drought tolerant crops, non-conventional water resources and more efficient irrigation technologies. Integrated water resource management systems which deliver conjunctive surface and groundwater abstractions, and preserve ecosystems during droughts.

Risk Management Approaches

- Process, statistical and operational systems research to develop improved criteria and tools to identify the onset of droughts, leading to systems which "trigger" different levels of response.
- Research into the risk management aspects of drought management
- Improve the linkages between European policymakers, operational water management agencies and researchers to ensure current operational best practice is shared.
- Methodologies to assess the cost effectiveness of different uses of water in different EU regions should be extended to imported agricultural products, especially from developing countries.

Technologies

- Research into the integration of all available instruments (technologies, systems, policies) to improve water efficiency in industrial, domestic and agricultural water use, including desalination.

- Measures are required to improve the quality, spatial coverage and accessibility of meteorological, hydrological, water use, social and economic data, including the use of remote sensing methods.

V.B.9. Conclusion

This chapter has sought to raise the profile of droughts as a major and immediate natural disaster threatening Europe. It has examined the range and scale of impacts experienced during the 2003 drought, summarized the latest information on how climate change is likely to affect drought severity, and considered how Europe should prepare for these changes. The deficiencies of current European policies in respect to droughts have been highlighted, and a call is made for better policy integration around a specific framework for European drought mitigation. This drought framework should be founded upon a risk management approach, embedded within comprehensive Integrated Water Resource Management. It recommends that such a framework should emphasize demand management, by informing and involving European citizens. The chapter highlights several areas where Europe is lagging behind other industrialized nations in drought forecasting, monitoring and mitigation and points to ways forward. It concludes by mapping out the areas where improvements to drought mitigation are needed in order to better mitigate future European droughts.

Recent research projects related to European droughts

ARIDE
Assessment of the Regional Impact of Droughts in Europe
http://www.hydrology.uni-freiburg.de/forsch/aride/navigation/about/about.htm

ASTHyDA
Analysis, Synthesis and Transfer of Knowledge and Tools on Hydrological Droughts Assessment through a European Network
http://www.geofysikk.uio.no/drought/

AVEC
Integrated Assessment of Vulnerable Ecosystems under Global Change
A workshop on Vulnerability of European ecosystems facing an increased drought risk
Held in Samos, Greece, 10 - 12 April 2003
http://www.pik-potsdam.de/avec/avec_droughts.html

CLIMAGRImed
Mediterranean Component of the FAO CLIMAGRI project
http://www.fao.org/sd/climagrimed/c_4_01.html

FRIEND
Flow Regimes from International Experimental Network Data
A contribution to the UNESCO International Hydrological Programme (IHP)
http://www.nwl.ac.uk/ih/www/research/bfriend.html

MICE
Modelling the Impacts of Climate Extremes
http://www.cru.uea.ac.uk/cru/projects/mice/

MITCH
Mitigation of Climate Induced Natural Hazards
http://www.mitch-ec.net/default.htm

WAM-ME
Water resources management under drought conditions: criteria and tools for conjunctive use of conventional and marginal waters in Mediterranean regions.
http://www.dica.unict.it/users/fvaglias/Wam-meWeb/index.htm

DSS-DROUGHT
A Decision Support System for Mitigation of Drought Impacts in Mediterranean Region – particularly in relation to management of irrigation systems.
http://www.medaqua.org/forum/DSS-DROUGHT.html

MEDROPLAN
Mediterranean Drought Preparedness and Mitigation Planning
http://www.iamz.ciheam.org

Other Useful References / Links to droughts

Australia's National Drought Policy. Dept of Agriculture, Fisheries and Forestry. http://www.affa.gov.au/content/output.cfm?&OBJECTID=D2C48F86-BA1A-11A1-A2200060B0A06258

COPA-COGECA (2003). Assessment of the impact of the heat wave and drought of the summer 2003 on agriculture and forestry. Committee of Agricultural Organisations in the European Union / General Confederation of Agricultural Co-operatives in the European Union. Fact Sheet. 14p. http://www.copa-cogeca.be/pdf/pocc_03_78i4_1e.pdf

EurAqua (1996). A review of European flood and drought mitigation measures. 6th EurAqua Science and Technological Review, Rome October 1996.

European Environment Agency (2004). Mapping the impacts of recent natural disasters and technological accidents in Europe. Environmental issue report No.35. European Environment Agency, Copenhagen. http://reports.eea.eu.int/environmental_issue_report_2004_35/en

Glinni, A.F., Sivakumar, M.V.K., and Wilhite, D.A. (2001). Drought management and preparedness – WMO perspective. Paper presented at the MITCH (Mitigation of Climate Induced Natural Hazards) Workshop, 12-13 December 2001. WL Delft Hydraulics, Delft, The Netherlands. 15p. http://www.mitch-ec.net/papers/glinni.pdf

Lehner, B and Dill, P. (2001). Eurowasser: Europe's droughts today and in the future. Chpt 7 p7-1 to 7-16, in : EuroWasser - Model-based assessment of European water resources and hydrology in the face of global change. Kassel World Water Series 5. http://www.usf.uni-kassel.de/usf/archiv/dokumente/kwws/kwws.5.en.htm

Rossi, G., Cancelliere, A., Pereira, L., and Oweis, T. (eds) (2003). *Tools for Drought Mitigation in Mediterranean Region*, Kluwer.

SEDEMED Hydrometeorological monitoring systems and drought bulletins for use by environmental public institutions, administrations and universities
www.uirsicilia.it/progetti/sedemed/intro_sedemed.html

UNEP, 2003. Impacts of summer 2003 heat wave in Europe. DEWA/Europe/GRID- Geneva. http://www.grid.unep.ch/activities/earlywarning/preview/appl/climatic/images/heatwave_en.pdf

USA National Drought Monitoring Centre. http://drought.unl.edu/dm/

USA National Drought Mitigation Centre. http://drought.unl.edu/

Chapter V.C. Climate Change, Ecological Status and the WFD

Key Points

- **At the time scale of the programs of measures foreseen under the Water Framework Directive, considerable change in climate can be expected.**
- **Climate change effects on aquatic ecosystems cannot be mitigated at the level of the river basins, but only at global scale.**
- **Reference conditions, the basis of ecological classification in the Water Framework Directive, are likely to change with climate and therefore cannot be considered as static.**
- **Adaptation of the classification scales could be allowed by adjusting reference conditions to accommodate effects of climate change that cannot reasonably be mitigated.**
- **Climate change effects on aquatic ecosystems are not fully understood, and in many cases inherently unpredictable. Long-term monitoring of minimally impacted sites is highly important to measure and understand climate change effects on reference conditions**

Chapter V .C. Climate Change, Ecological Status and the Water Framework Directive

V.C.1. Introduction

The Water Framework Directive (2000/60/EC; WFD) creates a legislative framework to manage, use, protect, and restore surface water and groundwater resources in the European Union. The WFD approaches water management at the scale of major river catchments (river basins), which in many cases include several countries. The WFD requires the establisment of a 'river basin management plan' (RBMP) for each of the river basins. The RBMP is a detailed account of how the environmental objectives (i.e. good ecological status of natural water bodies and good ecological potential of heavily modified and artificial water bodies) are to be achieved by 2015. For those countries that can demonstrate that this is not feasible without disproportionate economic and social costs, the Directive allows the possibility for a delay until 2030. This sets a time scale for restoration of the water bodies during which a considerable change in climate can be expected. Although it is stated that "… *this Directive should provide mechanisms to address obstacles to progress in improving water status when these fall outside the scope of Community water legislation, with a view to developing appropriate Community strategies for overcoming them"* (WFD, Article 47), climate change and its possible impact on water bodies has been left out of the scope of the WFD; the term "climate" does not appear in the text of the Directive.

The WFD defines ecological status as *"… an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters …".* (WFD, Article 2: 21). The assessment of the ecological status in the WFD requires classification of water bodies in five quality classes using a Ecological Quality Ratio (EQR), which is a ratio between reference conditions and measured status of the biological quality elements. Reference conditions should equal almost natural conditions. As shown elsewhere in this report, the anticipated effects of the climate change will affect most of the physical, chemical and biological parameters of water bodies used for ecological quality assessment. Although in some cases, climate change may bring a relief to environmental problems and help to achieve the restoration goals set by the Directive (e.g. in areas with a prospected increase in precipitation), often pressures to aquatic ecosystems will increase as a result of climate change. As a consequence, these effects cannot be mitigated in the context of the river basin management plan.

In this chapter we discuss the conceptual impacts of the climate change on the process and requirements of the ecological status assessment in the WFD. Using some examples we consider the various steps in the classification and assessment where the CC effects should be considered. We argue that reference conditions cannot be considered as static but will change as a consequence of climate change impacts on physical and chemical conditions of water bodies. The review of the river basin characterization every 6 years, as required by the WFD, will also include re-evaluation of reference conditions. As a consequence the restoration targets (i.e. the good ecological status) will also need to be evaluated periodically.

V.C.2. WFD implementation and adaptation to climate change

Although the influence of human activities on climate represents an adverse environmental impact, the management of that impact is global rather than only a European-scale issue. In the background paper evaluating the REFCOND guidance Owen et al. (2002) wrote:*"The benefits of recording global impacts through the Directive's classification scheme are likely to be outweighed by the increased complexity of determining the relative significance of these pressures."* Although the underlying causes of human effects on climate are beyond the scope of river basin planning, the river basin management plans can be used as an istrument to mitigate adverse effects of climate impact. However, there will be adverse effects of human-induced climate change that cannot be avoided, even with co-ordinated action at a European level. As a consequence, classification scales and therefore the river basin management plans need to be adapted taking into account the effects of climate change.

Typology and type specific reference conditions of water bodies
Depending on geographic region, catchment geology and size, water bodies obtain naturally different chemical and physical features and offer different habitats for biota. Water bodies located in areas of fertile soils with rich mineral composition show naturally higher nutrient concentrations and higher productivity compared, e.g. to water bodies in silicious catchments. Trophic scales like that worked out by the OECD (1982) are useful tools for describing these differences but do not allow distinguishing between natural and anthropogenic eutrophication. To enable the distinction between natural variability and anthropogenically caused changes, the WFD introduced the requirement to work out a detailed typology of water bodies and to specify type specific reference conditions (RC) that could serve as the basis for water quality assessment. As the principle issues for the WFD implementation related to typology of water bodies, Owen et al. (2001) pointed out the following questions:

- how much natural variation can be accommodated within types?
- how can we differentiate between natural variation and impact?
- should we update the natural range of values to accommodate "natural" changes, such as climate change?

The factors used to build up the typology are summarised in Table V.C.1. Several of the typology factors suggested by the WFD are actually climatic variables (mean air temperature, precipitation), have an intimate linkage to them (altitude, latitude, longitude, river flow, water level, lake mixing) or may be influenced by climate in a longer perspective (morphometric characteristics).

As a result of climate change, water bodies, especially those located near the boundary of the type characteristics, may change in type. The most probable changes, already observed in some cases, are the changes in lake mixing type. In warmer climate cold monomictic lakes may stratify in summer and become dimictic (Sorvari, 2001). The disappearance of ice-cover will cause a continuous mixing in winter turning previously dimictic lakes into warm monomictic lakes. Higher stability of the water column may prevent full mixing of deep lakes changing them from holomictic to meromictic (Ambrosetti *et al*., 2003). Decrease in precipitation often accompanied by increased summer temperatures in the future climate scenarios for warm regions will consistently change river discharges, increase evaporation and cause a shift from permanent to temporary water bodies. All these changes will have a major impact on the ecosystems of these water bodies.

The quality class boundaries within the WFD are set in relation to the reference conditions. Six principal methods were suggested by the REFCOND Working Group (REFCOND, 2003) for setting type-specific reference conditions (Figure V.C. 1). Four of them, based on using spatial networks, modelling, curve fitting, and expert judgement, are able to consider also climate change impacts, while methods based on paleo-ecology and historical data are more static.

It is also possible to consider the RC as a *flexible*, *non-static* reference, capable of responding to natural changes. The concept of a flexible RC could be the appropriate way to incorporate irriversible large-scale anthropogenic impacts (e.g. climate change, species extinctions and introduction) in the WFD assessment systems. This could be based on periodical monitoring of a set of reference sites and adjusting the values of reference conditions taking into account long-term natural processes (de Wilde *et al*., 2002), together with the effects of climate change. If RC are not updated in these circumstances a deterioration in status would be recorded under the classification scheme.

Table V.C.1. Obligatory and optional factors for characterisation of surface water body types given in Annex II of the WFD. Factors sensitive to climate variability/climate change are marked in red colour

	Rivers	Lakes
Obligatory factors	**altitude latitude longitude geology size**	**altitude latitude longitude depth geology size**
Optional factors	**distance from river source energy of flow mean water width mean water depth mean water slope form and shape of main river bed river flow category valley shape transport of solids acid neutralising capacity mean substratum composition chloride air temperature range mean air temperature precipitation**	**mean water depth lake shape residence time mean air temperature air temperature range mixing characteristics acid neutralising capacity background nutrient status mean substratum composition water level fluctuation**

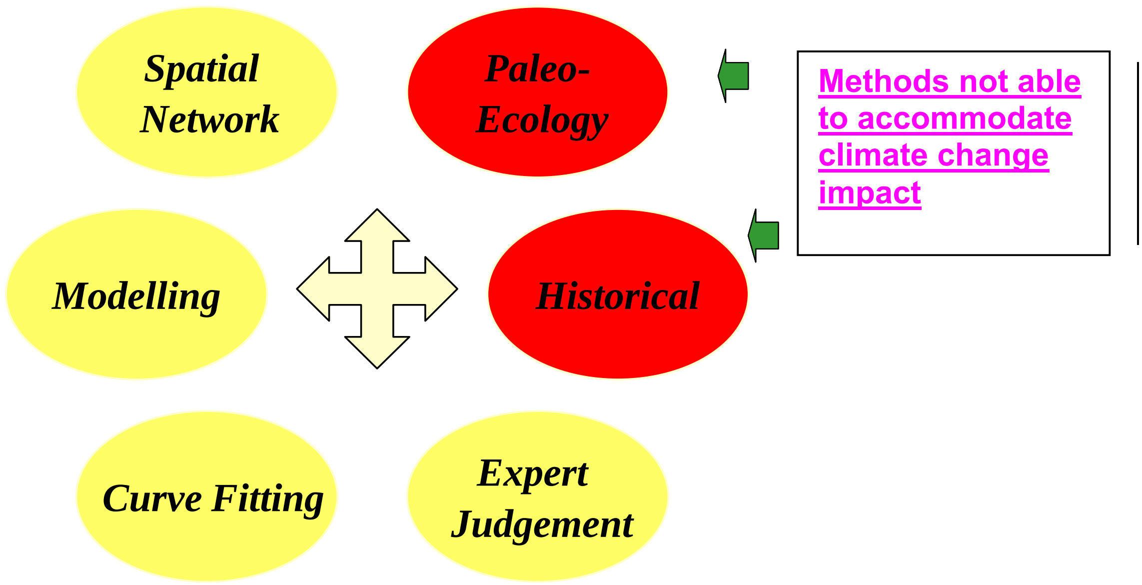

Figure V.C.1. Methods to establish reference conditions (from REFCOND guidance, 2003).

There are several ways to make the Reference Conditions flexible. Natural variation can be included within the RC by relating the latter to the natural causes of variability. In this case the procedure of setting reference conditions should include a multivariate analysis, which, instead of a single RC value would yield a table or a nomogramm showing the relationship of the quality parameter to the most important natural factors. Irriversible effects of human-induced climate change can be taken into account in a similar way as the natural causes of variability.

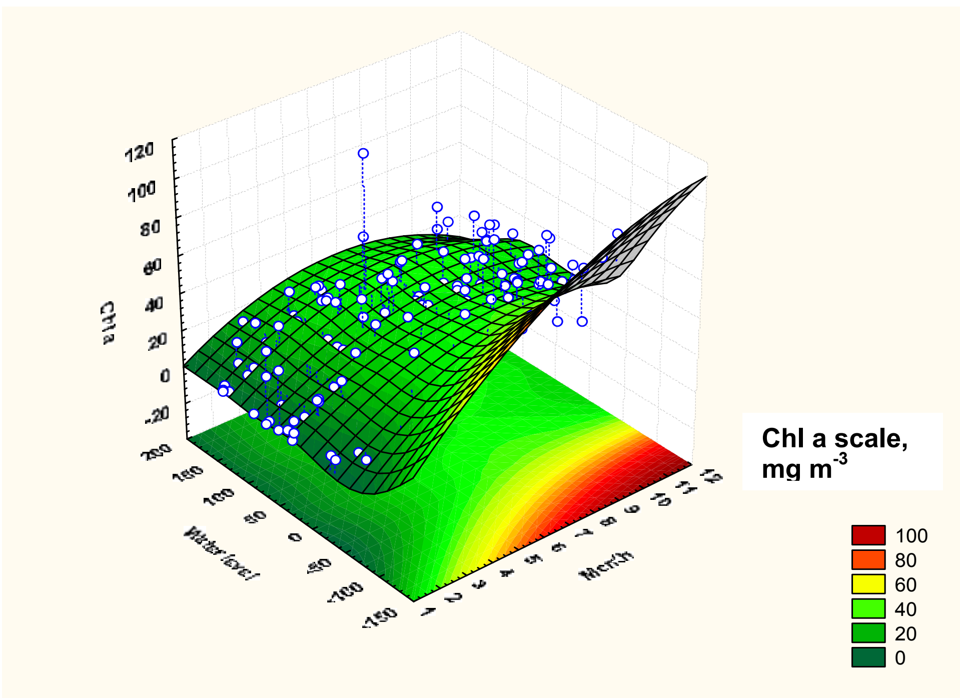

Figure V.C.2. Long-term distribution of chlorophyll *a* in L. Võrtsjärv as a function of water level and season. Points show actual monthly values during the period 1982-1998.

An example of this kind of relationships is given in Figure V.C.2. Chlorophyll concentration in the large shallow Lake Võrtsjärv (see Case Study) shows a marked seasonal variation. Water level in this lake carries the signal of the North Atlantic Oscillation and is the main driving factor in the ecosystem. Dropping of the water level below a certain threshold (-50 cm on the relative scale) results in an enormous increase of chlorophyll. The reasons for this increase are the improvement of light conditions (as the water layer becomes thinner), and stronger resuspension of the surface sediment. Resuspension has a dual effect on chlorophyll concentration: it has a direct effect by stirring up the microbenthic algae living on the sediment surface and the planktonic algae already settled out, but also an indirect effect by releasing the nutrients from the sediment to the water layer where they support new algal production. Including this natural variability already to RC of this lake substantially decreased the variability in ecological quality estimates and allowed chlorophyll values measured in different seasons to be used for quality assessment purposes. This method can most easily be used for working out site specific RC for water bodies which have a long investigation record. At the moment, a similar system of flexible RC has been applied on the 5th largest lake in Europe, the transboundary Lake Peipsi shared between Estonia and Russia (Nõges and Nõges, 2003).

Climate Change sets new requirements to the monitoring process.
The methods currently used to monitor and model water bodies were developed when weather patterns were different from those experienced today. Most are based on a deterministic rather than a probabilistic approach and do not properly represent the ‘cascade of uncertainty’ associated with recent climate-change scenarios (CLIME, 2001). The future surveillance monitoring must be capable of detecting long-term changes in the water environment. For example, long-term climate changes and land cover changes could affect the condition of aquatic plants and animals in surface waters by increasing the frequency of droughts and floods. Information on such changes will be needed to avoid wrongly attributing their affects to other pressures.

Climate change effects on aquatic ecosystems are not fully understood, and in many cases inherently unpredictable. Long-term monitoring of minimally impacted sites is highly important to measure and understand climate change effects on reference conditions. To advance our understanding of ecosystem responses to climate change, basic ecological research, especially sensitivity analyses at site-specific or sub-regional scales would still be needed. Direct extrapolation of observed species distributions in relation to present climate as a means for projecting future responses is inappropriate; such projections must include consideration of physiological tolerances, competition, and dispersal mechanisms (Halpina 1997). There is an urgent need to develop modelling tools to analyse and understand regional climatic changes, the underlying changes within these catchment systems, and the hydrochemical and ecological behaviour occurring in aquatic ecosystems. Better knowledge of these mechanisms would help to work out methods of mitigating the impacts of environmental change across Europe.

V.C.3. European Research Projects Addressing Climate Change Impact on Implementation of the WFD

In order to support the implementation of the Water Framework Directive, the European Commission has established a cluster on Integrated Catchment Water Modelling (CatchMod). The objective of this cluster is the development of common harmonised modelling tools and methodologies for the integrated management of water at river basin scales based on scenarios of climate change and other expected environmental and socio-economic changes. There are eleven projects integrated to the CatchMod cluster at the moment (Blind, 2004).

Climate impact is specifically analysed within the project CLIME (Climate and Lake Impacts in Europe; EVK1- CT- 2002 - 00121). The CLIME project aims to assess the direct and indirect effects of changes in the weather on the dynamics of lakes. Particular attention is paid to water quality variables that are used as diagnostic elements in the Water Framework Directive. Many water quality problems that were once thought to be due to local factors are now known to be influenced by variations in the weather that operate on a global scale. If present trends continue, changes in the weather will have a major effect on the dynamics of lakes throughout Europe. In winter, the most pervasive effects are those associated with the North Atlantic Oscillation but some important summer effects are related to the north-south movements of the Gulf Stream in the Atlantic.

Another research programme especially relevant to the EU Water Framework Directive is the EURO - LIMPACS (http://www.eurolimpacs.ucl.ac.uk/) project funded by the EU and designed to assess the effects of future global change on Europe's freshwater ecosystems. The work program will include the direct impacts of climate change as well as its interactions with hydromorphology, eutrophication, acidification, and toxic substances. Some of the key hypotheses checked within this project are:

1. Global change may cause hydromorphological deterioration of a water body through intensification of land-use or through a more variable discharge regime that results in habitat modifications and losses;
2. Alternatively, global change may cause significant improvement if, for example, human disturbances are withdrawn from floodplains due to more frequent flood events or as a result of floods that generate a near-natural habitat structure.
3. Increased temperature will interact with continued high nutrient loading to lakes that will increase the severity of eutrophication symptoms to an extent greater than that expected from natural fluctuations in climate.
4. Predicted prolonged low-flow periods for stream and floodplain systems will increase denitrification and sedimentation rates and that increased winter flows will enhance the deposition of sediment-associated nutrients and nitrogen removal rates.
5. The impact of climate change on acidification recovery is dependent on hydrological and hydrochemical processes at the catchment scale.
6. Future climate change will influence the distribution patterns and mobility of organic pollutants and toxic metals (e.g., lead, cadmium, mercury) in freshwater systems and lead to changes in the uptake and accumulation of these substances in freshwater food chains. The cycling and fate of both organic and inorganic pollutants is intrinsically linked to the C cycle and trophic status. Climate change influenced eutrophication will alter the biogeochemical cycles and bioavailability of these contaminants.

Chapter V.D. Climate Change and Water Use in Agriculture

Key Points

- **Agriculture, as one of the main water users in Europe, uses ca. 38% of the abstracted water with large regional differences - 50 to 80 % in southern Europe, < 5% in northern Europe.**
- **Climate change will affect agricultural crops *directly* via changes in CO_2, temperature, and precipitation and *indirectly* via soil processes, weeds, pests and diseases with difficult to predict positive and negative effects.**
- **Climate warming will cause a general northward expansion of crop species, cultivars and management practices.**
- **Agriculture, therefore, is the most vulnerable human activity under unfavourable climatic conditions. In Europe, this is particularly true for the northern (temperature-limited) and southern (moisture-limited) regions.**
- **The large amount of water used for irrigation in the southern European countries is critical. The already existing water scarcity will be aggravated, including an increased competition with other sectors.**
- **Possible mitigation strategies include short-term adjustments that aim at optimising production without introducing major system changes (e.g., use of different cultivars, improved irrigation techniques, reducing water losses) and long-term adaptations where heavier structural changes will take place (e.g., change of farming systems and land use types).**

Chapter V.D. Climate Change and Water Use in Agriculture

V.D.1. Introduction

Agriculture is one of the economic activities that largely depend on climatic and weather conditions. From the climate point of view, day length, incoming radiation, temperature and water availability are the most important factors determining the yield of agricultural crops. Over the centuries a delicate balance has emerged between climatic conditions and agricultural practices, resulting in a large variety of agricultural activities and cropping patterns across Europe (see, for example, Olesen and Bindi, 2002). Terrain form and soil type are other important natural factors in this balance.

Modern cultivation techniques (including irrigation) could alleviate some of the natural limitations and agricultural policies (national and EU) have largely shaped the cultivation patterns in Europe over the last century. However, climate and weather conditions remain a basic boundary condition for the cultivation of agricultural crops. Water availability is certainly among the most important factors in this respect. It is strongly varying across the European continent, with pronounced gradients in both North-South and East-West direction.

Agriculture is one of the main water users, especially in southern and eastern Europe. While the expansion of the irrigated areas, mainly in the Mediterranean, has raised concern about the overuse and depletion of water resources in the past, possible changes in climate and weather patterns as a consequence of increasing levels of greenhouse gases in the atmosphere are at the focus of the discussion in recent years. It is expected that climate change will lead to major shifts in the spatial and temporal patterns of precipitation and temperature across Europe, including a higher frequency of pronounced dry and wet periods leading to drought and flood events (McCarthy *et al*., 2001; Lehner *et al*., 2001). Flood hazard is likely to increase generally across the continent while the risk of water shortage is projected to increase particularly in southern and eastern Europe. In general, climate change is likely to exaggerate the water resource differences between northern and southern Europe (Parry, 2000)

As a consequence, the already existing pressures on water resources and their management in Europe are likely to increase over the next decades. This situation calls for long-term planning and pro-active management in order to ensure a sustainable use of water resources across Europe (Vogt and Somma 2000).

The purpose of this chapter is to review the present situation, the trends and current and future critical areas with respect to agriculture and water use in Europe. However, it should be noted that agricultural water use might not be seen isolated from domestic and industrial withdrawals, which in many areas of Europe are the largest consumers of water. It is the total of all withdrawals that finally determines whether a region is or will be under water stress (Lehner et al. 2001).

V.D.2. European Agricultural Regions

Kostrowicki (1991) divided Europe into five major agricultural regions based on environmental and socio-economic factors. Olesen and Bindi (2002) further subdivided these regions to arrive at the eight agricultural regions as shown in Figure V.D.1.

Regions 1 to 5 represent mainly a market-oriented agriculture, which has been heavily influenced by the EU Common Agricultural Policy (CAP). While in region 1 (Scandinavia) climate and soil conditions are the limiting factors, which allow only for a small fraction of the land to be cultivated, region 2 (British Isles) is characterised by the wet conditions along the Atlantic coast, resulting in a dominance of grasslands and extensive cattle breeding. Region 3 (Western Europe) is mainly characterised by small-scale, mixed or large-scale intensive arable and lifestock farming. Region 4 (Mediterranean) offers a broad range of agricultural patterns due to largely variable environmental, technological and socio-economic conditions. This region is characterized by a market-oriented agriculture of crops, fruit trees, grapes and olives, including considerable areas of traditional agriculture. In the Alpine region (5) both market-oriented and transitional forms of agriculture from extensive mixed to market-oriented farming occur. Regions 6 and 7 (North Eastern and South Eastern Europe), which encompass many of the New Member States, include market-based and traditional as well as socialised agriculture with root crops and cereals as the main products. Here the share of socialised agriculture has been rapidly diminishing since the political changes of the late 1980s, with a strong trend towards a market-based agriculture of the West-European type. Yields in these two regions are, however, low due to the still low production intensity. Region 8 (Eastern), which is the European part of the former USSR, is dominated by large-scale socialised agriculture with a trend to a more quality-oriented agriculture (Olesen and Bindi, 2002; Parry, 2000; Kostrowicki, 1991).

In North European countries (Regions 1 and 2) low temperatures are a major limiting factor for agriculture. Climatic constraints limiting crop production include the length of the growing season, late spring and early autumn soil frost and incoming solar radiation. In addition, wet conditions along the Atlantic coast limit the extent of cereal cultivation in these areas, which are mostly dedicated to pasture. In the Mediterranean (Region 4), to the contrary, cereal cultivation is mainly limited by hot and dry weather conditions, which are more favourable for the cultivation of permanent crops such as olives and grapes.

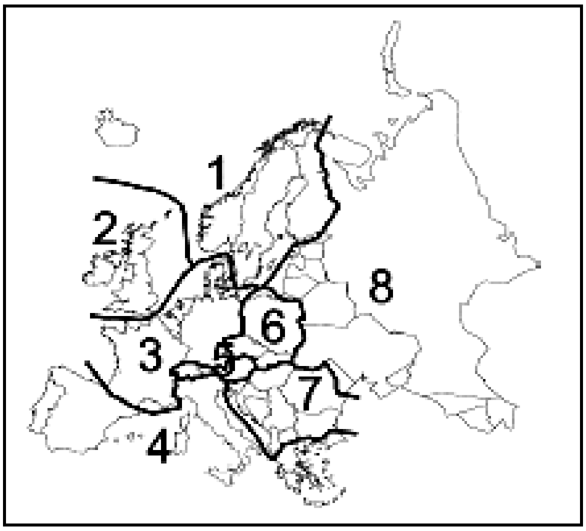

Figure V.D.1. Major Agricultural Regions in Europe (Olesen & Bindi, 2002)

From a climatic point of view, the most productive regions of Europe are located in central Europe including Southeast England, Northern France, Benelux, Germany and Poland (mainly Regions 3 and 6). Considering the total agricultural area and its share of the total land surface, the most important agricultural regions of Europe are the British Isles, Western Europe, the Mediterranean, the North Eastern and the

South Eastern regions (see Table V.D.1). At the same time, the Mediterranean and South Eastern regions represent the areas with the highest proportion of irrigated agriculture as well as with the largest rural population shares. Table V.D.1 gives an overview on land use and population statistics for the different regions distinguished above.

Table V.D.1: Land Use and population in different regions of Europe based on FAO statistics from 1998 (land use) and 1995 (population).

Region	Agricultural Area			Population		
	Mill. ha	% of Land	% Irrigated	Total (Mill.)	Rural (%)	Rural (Mill.)
1. Nordic	6.6	6	5	19	25	4.8
2. British Isles	21.9	70	0	62	13	8.1
3. Western	53.4	52	7	171	17	29.1
4. Mediterranean	58.1	56	14	118	33	38.9
5. Alpine	5.0	40	1	15	37	5.6
6. North Eastern	22.7	57	1	49	36	17.6
7. South Eastern	44.0	57	10	72	42	30.2
8. Eastern	286.9	16	3	173	27	46.7

Source: adapted from Olesen and Bindi 2002

V.D.3. European Agriculture and Water Use

In Europe, large amounts of water are abstracted from both surface and groundwater stocks for households, industry and agriculture every year. For Europe as a whole (including New Member States and Accession Countries) some 38% of the abstracted water is used for agricultural purposes, while domestic uses, industry and energy production account for 18%, 11%, and 33%, respectively (EEA WQ2, numbers based on New Cronos Eurostat-OECD JQ2002) [4].

However, large differences exist across the continent. In Malta, Cyprus and Turkey, for example, almost 80% of the abstracted water is used for agriculture, and in the southwestern countries (Portugal, Spain, France, Italy, Greece) still about 46% of the abstracted water is used for this purpose. In the central and northern countries (Austria, Belgium, Denmark, Germany, Ireland, Luxembourg, Netherlands, UK, and Scandinavia), to the contrary, agricultural use of the abstracted water is limited to less than 5%, while more than 50% of the abstracted water goes into energy production (a non-consumptive use).

By far the largest part of the water used in agriculture is used for irrigation. This percentage approaches 100% in the southern European countries, which at the same time have the largest share of irrigated land in Europe (74% of the total irrigated area). During the 1990s a slight decrease in water used for irrigation has

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1 All numbers in this chapter are to be viewed as approximate. Figures change slightly from publication to publication due to varying regional references and data sources. While they give a good indication of the order of magnitude, absolute values may change depending on the regional grouping of countries and the statistical sources.

been observed in southwestern countries. This trend can be explained by the use of more efficient irrigation methods and the influence of the 1992 CAP reform on crop production. In the southern countries as a whole, however, there was an increase in water allocation to irrigation in the 1990s, mostly due to activities in Cyprus, Spain and Turkey. Southern countries use ca. three times more water per unit of irrigated land than other parts of Europe. Over the same period, the amount of water used for irrigation has largely decreased in the central Accession Countries, mainly due to the deterioration and non-use of irrigation systems (in total a decrease of more than 70% of the water abstracted for agricultural and industrial uses has been observed). This trend could, however, be reversed with the progressive integration of their economies into the EU and the resulting development of more intensive agricultural practices. (EEA, 2003; EEA WQ2; EEA WQ02a).

In 1999, the average allocation of water for irrigation was around 5600 m^3/ha/year for Europe and around 7200 m^3/ha/year for Southern countries (EEA WQ02a). For EU 15, between 1990 and 2000, the irrigated area increased by about 14.5%, with large regional differences (e.g., 28.8% for France, Greece and Spain) (EEA, IRENA Indicator Fact Sheet on Water Use Intensity). The large amount of water dedicated to irrigation in the southern countries is problematic since most of these countries have been classified as water stressed, and face problems associated with groundwater over-abstraction such as aquifer depletion and salt-water intrusion (EEA, 2003; EEA WQ03b).

V.D.4. Potential Climate Change Impacts on European Agriculture

Climate change will impact directly on agriculture by the alteration of meteorological conditions, which is the major driving force of crop production, and indirectly since agriculture is competing with other sectors for water allocation. The involved processes are manifold and it is difficult to make generalised conclusions on the combined effects of the increases in CO_2 and temperature and the changing precipitation patterns (Fuhrer, 2003). In addition, climate change is expected to have impacts on agriculture by affecting soil processes (e.g., oxidation of soil OM), which in turn might affect negatively or positively agricultural production. While, for example, an increase in CO_2 will have positive effects on the water use efficiency and productivity of many crops, accelerated plant development will increase total crop water consumption. Increasing temperature will have negative effects due to a generally higher evaporative demand, the higher frequency of heat waves, and possible increases in competition with weeds. At the same time pest and diseases may spread more widely (Fuhrer, 2003; Olesen and Bindi, 2002; Iglesias et al., 2000).

The projected climate change based on GCM calculations can be summarised as follows. It is expected that annual average temperatures will increase between 0.1 and 0.4°C per decade, with the largest increase in southern Europe (Spain, Italy and Greece) and in northeastern Europe (Finland), while the lowest increases are expected along the Atlantic coast (Kundzewicz *et al*., 2001). It is further expected that summer warm-up will be twice as fast in southern Europe than in northern Europe and that precipitation will increase between 1 and 2 percent per decade in northern Europe while it will decrease by less than one percent per decade in southern Europe. At the same time seasonal differences will increase throughout Europe. Most of the continent will get wetter in winter, while during summer wetting is expected in northern Europe (+2% per decade) and drying is expected in the South (-5% per decade). The reduction of precipitation in southern Europe is expected to have severe effects, e.g. more frequent droughts, with considerable impacts on agriculture and water resources (EEA, 2004). Finally, a rise of the mean sea level between 13 and 68 cm is projected by 2050.

Presently agriculture is the dominant user of abstracted water in southern countries. Under climate change conditions, it is expected that irrigation water demand will further increase in those areas, aggravating the competition with other sectors whose demand is also projected to increase (Parry, 2000). In addition, an expected lowering of the groundwater table will make irrigation more expensive, which, in turn might have to be limited to cash crops. In parallel, a general increase in agricultural and domestic water requirements is projected, putting additional pressure on the groundwater resources. Extreme weather events such as heat waves will impact on peak irrigation requirements (see, for example, Beniston 2004 for a discussion of the 2003 heat wave). As the evaporative demand will increase due to higher temperatures, it is expected that capillary rise will increase the salinisation of soils, having a major impact on irrigation management. Salinisation might also occur in coastal aquifers due to sea level rise and aquifer depletion, causing salt-water intrusion.

Döll (2002) used a global irrigation model at 0.5° by 0.5° resolution to evaluate the change in irrigation requirements under climate change scenarios as calculated by two Global Circulation Models (GCMs). For Europe she predicted an increase in net irrigation requirements of about 6% for the 2020s, and of about 9% for the 2070s as compared to the baseline scenario (1961-1990), including large regional differences. While a drop of net irrigation requirements from 771 mm/year to 701 mm/year in the 2020s is predicted for in western Spain, irrigation requirements are predicted to increase in southeast England from 77 to 120 mm/year.

Lehner *et al.* (2001) predicted an increase of water withdrawal from 415 km^3/year in 1995 to 660 km^3/year in the years around 2070 (63% increase), with the irrigation abstraction increasing from 142 to 146 km^3/year (less than 3% increase). In general, one could have expected larger changes, especially in the southern countries, where irrigation is important. However, the expected improvements in water use efficiency are larger than the expected decrease in water availability due to climate change. The result could be an overall decrease of water withdrawn for irrigation. At the same time many unknown factors such as changes in the irrigated areas; changes in crop varieties and their regional distribution could heavily influence the results of such predictions.

Fischer *et al.* (2002) evaluated the impact of several climate change scenarios on environmental constraints to crop production. They considered soil constraints such as soil depth, fertility, texture, drainage, and salinity/sodicity. Climate constraints included the length of cold spells and dry spells. The evolution of severe environmental constraints from the baseline scenario (1961-1990) to the HaDCM3 scenario (2080s) is summarised in Table V.D.2.

Table V.D.2 shows that climate change will introduce a drop in the areas affected by severe conditions for rain-fed crops in Northern Europe by 7%, while there is an increase in the areas affected by severe constraints in the South. Table V.D.2 clearly illustrates that in Northern Europe “too cold” constraints will disappear, while there is an increase of the constraints due to “poor soil”, which can partly be explained by the disappearance of cold conditions as a limiting factor. For the Southern regions, there is an increase in the area affected by the “too dry” condition.

Table V.D.2: Percentage area affected by different environmental constraints for rain-fed crop production for the baseline scenario (BL) and for the climate change scenario HaDCM3-A1FI (CC).

Region	Total Area 10^6 ha	Area with constraints (%)		Too cold (%)		Too dry **(%)**		Too wet **(%)**		Poor soils **(%)**	
		BL	CC	BL	CC	BL	CC	BL	CC	BL	CC
Northern Europe	173	45.2	38.3	18.0	0.5	0.0	0.0	0.0	0.4	24.6	32.9
Southern Europe	132	44.1	45.5	0.7	0.0	0.2	2.4	0.0	0.0	23.1	22.6
Eastern Europe	171	18.0	18.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0	15.0
Western Europe	110	28.9	28.9	0.6	0.0	0.0	0.0	0.0	0.0	18.1	18.1

Table adapted from Fisher *et al*. (2002). Note: "Columns are mutually exclusive and the order in which constraints are listed defines a priority ranking for areas where multiple severe constraints apply. For instance land with very poor soil conditions in the artic region is shown as "too cold" and is not listed as having severe soil constraints."

Agricultural production is radiation dependent and is strongly affected by changes in the temperature and precipitation regimes. Agriculture, therefore, is the most vulnerable human activity under unfavourable climatic conditions. In Europe, this is particularly true for the northern (temperature-limited) and southern (moisture-limited) regions. It is expected that in middle and higher latitudes higher temperatures will lead to an increase of the length of the growing season, earlier spring planting, faster maturation and earlier harvesting. In addition, milder winters will allow for the cultivation of more productive cultivars of winter and annual crops, and the cultivation of perennial crops will increase. In southern latitudes, however, the actual cultivars might not be adapted to the predicted higher temperatures. With temperatures exceeding the temperature range for optimum growth, a reduction in net growth and yield is expected in this region.

Climate warming will cause a general northward expansion of crop species, cultivars and management practices. For Finland, for example, Carter *et al*. (1996) predicted a northern shift of 120 to 150 km of the area suitable for the cultivation of spring cereals for each degree of increase in mean annual temperature. In the Mediterranean region, however, a general reduction in cereal yields is expected due to drier conditions. At the same time, the area of seed crop cultivation (e.g., oil seed rape, sunflower) is expected to expand northward with an increased productivity. Similar northward shifts are expected for vegetables and permanent crops (Perry, 2000).

V.D.5. Adaptation Strategies

Strategies to adapt to climate change should not be seen as individual remedies since agriculture is competing for water allocation with other sectors affected by climate change. Parry (2000) distinguishes between short adjustments that aim at optimising production without introducing major system changes, and long-term adaptations where heavier structural changes will take place to alleviate the adverse effects of climate change. Suggested adjustments include changes in planting strategies and the use of more appropriate cultivars: long season cultivars might increase yield potential, while late cultivars might be used to prevent destruction due to heat waves and drought during the summer. However, the use of more extended growing season crops might increase seasonal irrigation requirements (Rosenzweig and Hillel, 1998). In addition, with faster crop growth, farmers might tend to go for multiple cropping, also increasing water requirements.

Management practices, such as conservation tillage, drip and trickle irrigation, and irrigation scheduling are among the short-term possibilities for preserving soil moisture. Improving irrigation efficiency is a key component of combating potentially increased water requirements. It will involve reducing water losses from storage and distribution systems, proper maintenance of irrigation systems, optimising irrigation scheduling, and using water conservative techniques such as drip irrigation (Rosenzweig and Hillel, 1998). Promoting such strategies will be crucial since these practices, besides preserving soil moisture, will allow farmers to reduce the cost of production.

Long-term changes include the change of land use to adapt to the new climate in order to stabilise production and to avoid strong inter-annual variability in yields. This could be achieved through the substitution of existing crops with crops with a lower productivity but more stable yields (e.g., wheat replaced by pasture). For areas with increased water stress, it has further been recommended to use less water consuming and more heat resistant crops. Other measures mentioned, for example, by Perry (2000) include the change in farming systems since many farms are specialised in arable farming and, therefore, are tightly linked to local soil and climate conditions.

Chapter VI.A. Case Study on Specific Lakes

Key Points

- **Lake Mondsee: an increase in spring water temperature leading to an earlier onset of thermal stratification, a longer stratified period during summer, higher summer surface temperatures, and a trend of rising deep-water temperature. a high degree of synchrony in timing of physical and chemical parameters has been established.**
- **Esthwaite Water: The chlorophyll concentrations measured in the lake are substantially lower if the winter is wet. When the winter is cold, appreciable numbers of *Daphnia* survive in the open water. When the winter is mild, , the *Daphnia* cannot ingest enough food to survive and the *Eudiaptomus* then dominate. Relatively small changes in the winter water temperature can have a significant effect on the long-term dynamics of a key planktonic species. The historical variations in the winter characteristics show that this lake is very sensitive to year-to-year variations in the weather. These weather-related variations influence the physical, chemical and biological characteristics of the lake.**
- **Lake Erken: In eutrophic lakes with long water residence times, eutrophication problems might become serious in a warmer future climate. 1970's and 1980's data showed that earlier ice-out and higher temperatures in May lead to increased phosphorus concentration and phytoplankton biomass in summer, and an overall doubling with climate scenarios.**
- **Lake Võrtsjärv: In non-stratified shallow lakes the changes of the lake depth affect the average illumination of the mixed water column, resuspension intensity, nutrient release from sediments, and denitrification rate. These factors control the growth and composition of phytoplankton that is the first link of the pelagic food web. Cold winters characterised by low water level cause several winter fish-kills. In warmer and wetter climate the probability of both the summer blue-green blooms and winter fish-kills should decrease.**

Chapter VI.A. Case study: Lake Mondsee, Austria

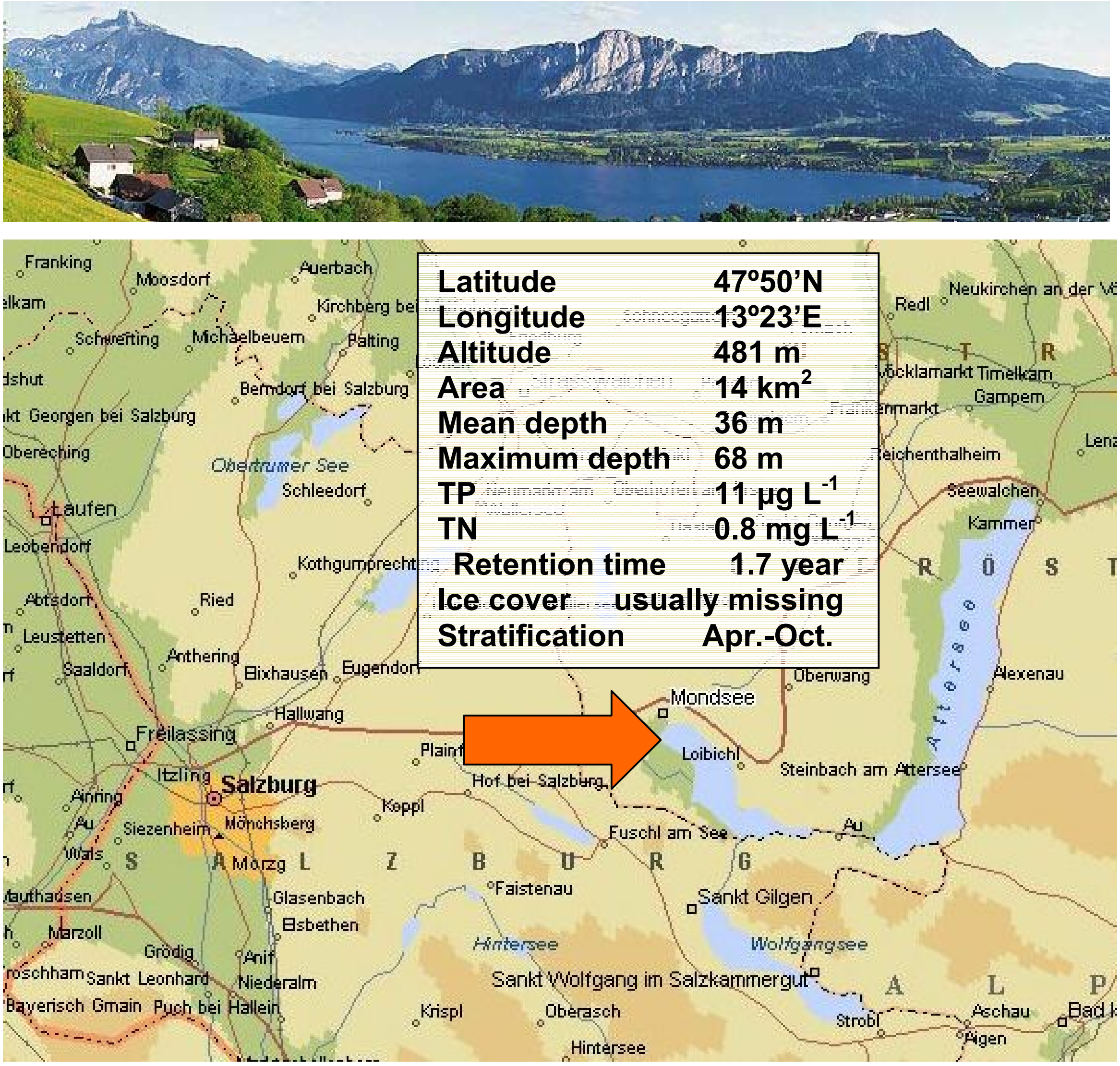


Fig. VI.A.1 General view, location and general characteristics of Lake Mondsee

► **Deep oligo-mesotrophic lake expressing climate-related changes in the thermal regime typical to alpine and prealpine lakes.**

VI.A.1. Limnology of Lake Mondsee

The alpine lake Mondsee is situated in the Austrian lake region 'Salzkammergut' 25 km east of the city of Salzburg, embedded between high limestone mountains and softer Flysch formations at the edge of the alpine ridge. The watershed consists mainly of alpine meadows, forest or grassland with little agriculture, industry, and urbanisation.

In the rare cases of complete ice-cover the lake is dimictic having full mixing in spring and fall (Dokulil, 2004); however, in most years, mixing occurs throughout the winter as typical to warm monomictic lakes. Thermal stratification usually lasts from end of April to mid-October. Summer lake surface temperatures are commonly well above 20°C resulting in considerable recreational pressure during touristic season.

Data availability and investigations

Regular surface lake temperatures are available from the hydrological lake level station as far back as 1909 (Hydrographisches Zentralbüro, 1964). The lake chemistry and biota have been irregularly monitored since the mid-1950s (Findenegg, 1959, 1965, 1969, 1973; Danecker, 1969). More regular measurements with monthly intervals started in 1968 (Schwarz and Jagsch, 1998). Intensive sampling began in with weekly intervals between 1982 and 1984, and biweekly intervals since then (Dokulil, 1993; Dokulil and Skolaut, 1991; Dokulil and Teubner, 2001). Climate impacts on Mondsee have previously been analysed and published by Dokulil (2000), Livingstone and Dokulil (2001) and Dokulil and Teubner (2002).

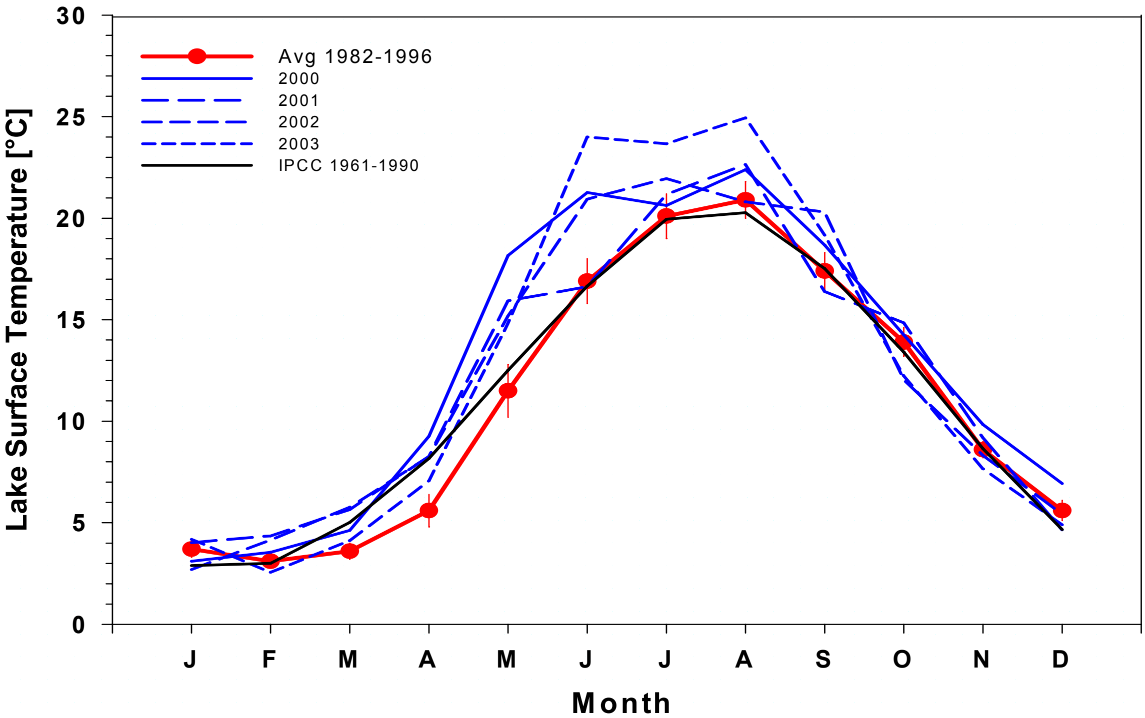


Figure VI.A.2. Lake Surface Temperature by Season and time.

These studies have documented an **increase in spring water temperature** (Figure VI.A.2) leading to *an* ***earlier onset of thermal stratification****, a* ***longer stratified period*** *during summer,* ***higher summer surface temperatures****, and a trend of* ***rising deep-water temperature****. Among the lakes analysed so far in the Salzkammergut region, a high degree of synchrony (coherence) in timing of physical and chemical parameters has been established.* **Changes in run-off conditions may alter the residence time and the in-lake concentrations in the near future**.

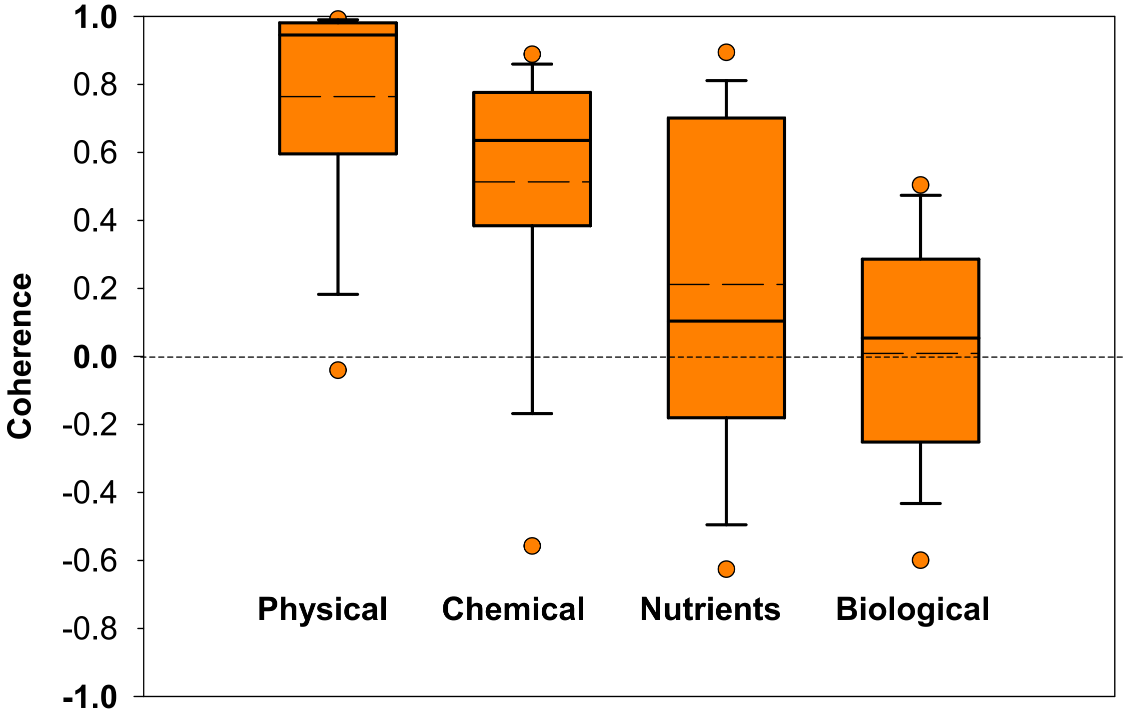


Figure VI.A.3. Spatial coherence measured as Spearman correlation coefficients for groups of variables between alpine lakes in the Salzkammergut region of Austria (see also Dokulil and Teubner, 2002).

Case Study: Esthwaite Water, Cumbria, UK

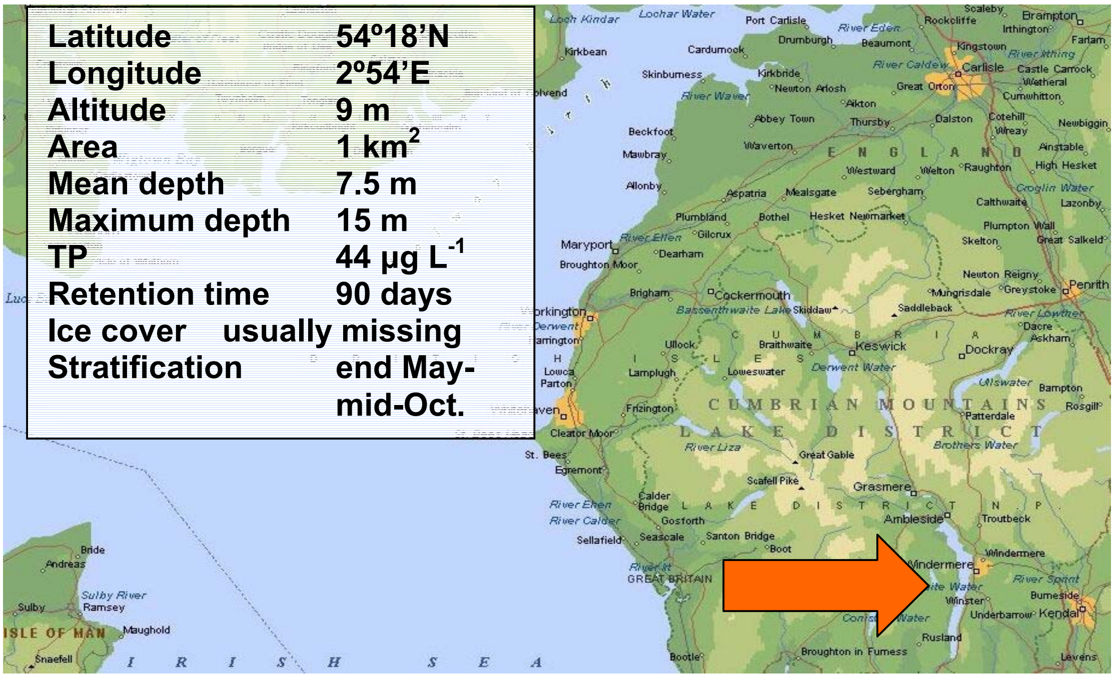


Figure VI.A.4. General view, location and general characteristics of Esthwaite Water

► **Eutrophic lake in which increased flushing rate in wet and mild winters tends to wash out slower growing phytoplankton that, in turn, causes changes in the food chain.**

VI.A.2. Limnology of Esthwaite Water

Esthwaite Water is one of the most productive lakes in the English Lake District. The lake is situated in a sheltered valley and remains thermally stratified in summer with large seasonal variations in the depth of wind mixing. The concentration of nutrients entering the lake from the catchment has always been high but increased steadily from the 1960s to 1980s due to anthropogenic nutrient loading. Dense blooms of blue-green algae have, however, been observed in the lake at regular intervals since the early 1950s with the highest concentrations being recorded during warm, calm summers (George *et al*., 1990). The crustacean plankton of Esthwaite Water that consists of relatively few species belonging to a small number of genera is typical of many large lakes. The winter and spring plankton is dominated by the calanoid copepod *Eudiaptomus gracilis* and the summer plankton by the cladoceran *Daphnia hyalina* var *galeata*.

Weather conditions in the English Lake District

The climate of the English Lake District is mild but very wet. Winter air temperatures occasionally fall below -10^{o}C but only the smaller lakes freeze over in a typical winter. There is a strong altitude-related component both in the temperature regime and in rainfall. The latter ranges from less than 4 mm a day near the coast to more than 10 mm a day in the mountains. Winter weather conditions in the area are strongly influenced by the North Atlantic Oscillation (see Chapter IV.A). When the North Atlantic Oscillation Index (NAOI) is positive, the area is exposed to a prevailing westerly air flow and the air temperature is higher and there is more rain. In contrast, strong negative values of the NAOI are associated with easterly winds, lower air temperatures and much dryer conditions.

Esthwaite Water is one of the most intensively studies lakes in the English Lake District. It was the site used by Mortimer (1941, 1942) for his classic studies on the seasonal dynamics of iron and phosphorus and has since been used for pioneering studies on the spatial distribution of phytoplankton (George and Heaney, 1978) and the aquatic applications of airborne remote sensing (George and Allen, 1997). In this Case Study, weather-related factors that influenced the winter dynamics of the lake between the mid 1950's and the late 1990's are described. This period includes several mild winters and one winter that was the coldest on record.

The winter characteristics of the lake

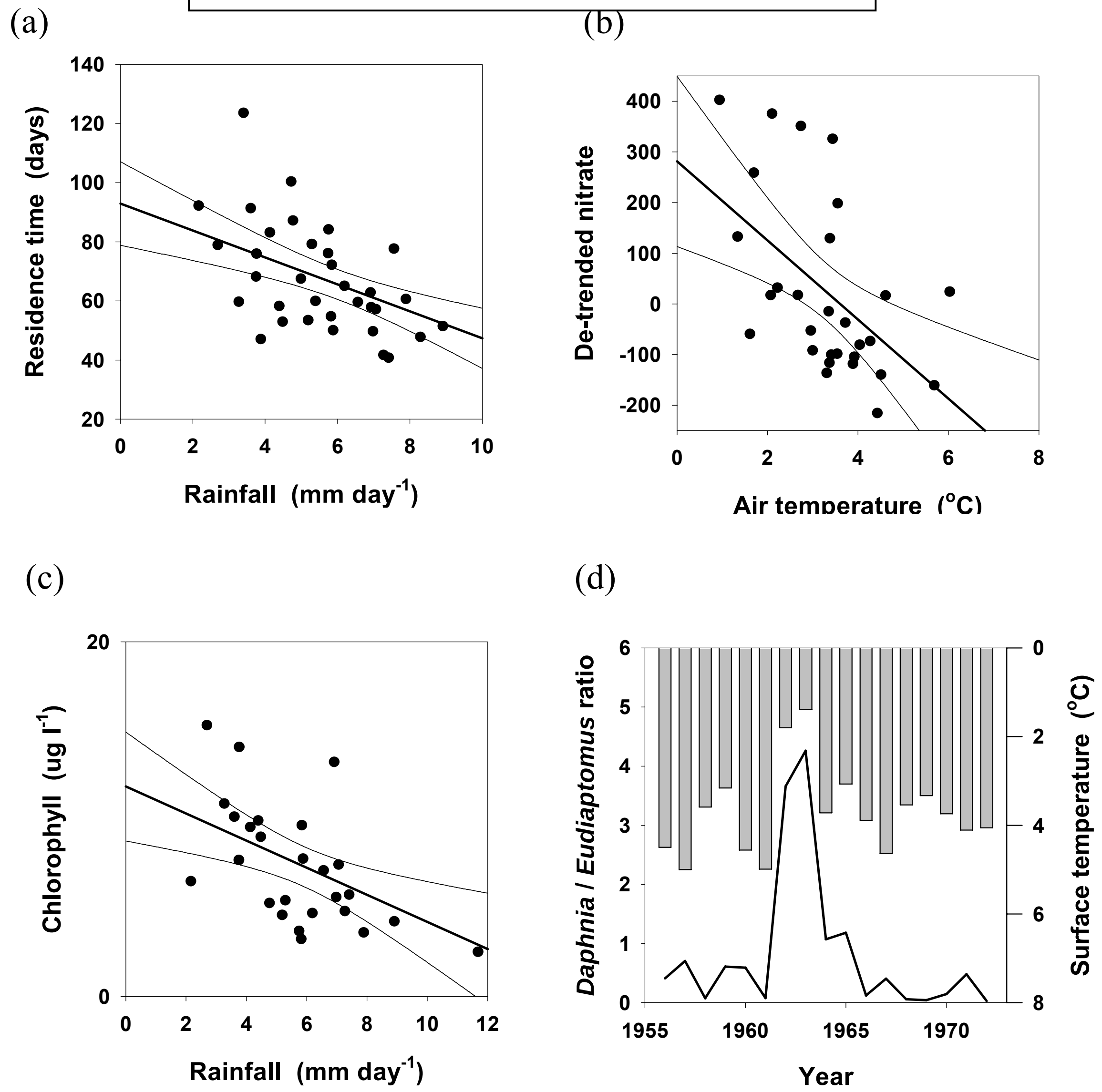


Figure VI.A.5 (a) The inter-annual variation in the residence time of the lake in relation the average rainfall. (b) The inter-annual variation in de-trended concentration of nitrate in relation the average air temperature. (c) The inter-annual variation in the chlorophyll concentration in relation the average rainfall. (d) The inter-annual variability in relative abundance of Daphnia and Eudiatoptomus in relation to the water temperature.

Since Esthwaite Water has a relatively short residence time, the year-to-year variations in the flushing rate are quite pronounced (Figure VI.A.5). The method used to estimate the residence time was that described by George and Hurley (2003). This is based on the amount of rain falling on the catchment in the first ten weeks of each year, a time when the lake is particularly sensitive to interannual variations in the rainfall. Since winters in the area are projected to become wetter in the coming decades the residence time of the lake will continue to decrease and have a major effect on its winter chemistry and biology. In Esthwaite Water, as in other lakes in the area, the quantity of nitrate leached from the catchment decreases during mild winters (Figure VI.A.5). The factors responsible for this trend have been discussed by George (2000b) and appear to match those reported by Monteith *et al*. (2000) in a number of upland sites.

The chlorophyll concentrations measured in the lake are substantially lower if the winter is wet i.e. a greater proportion of the slow growing winter crop of phytoplankton is flushed out of the lakes (Figure VI.A.5). These losses are likely to increase in the coming decades and could have a major effect on the subsequent growth of the spring phytoplankton.

Analyses have shown that cold winters favour the survival and growth of the cladoceran herbivore *Daphnia hyaline* var *lacustris. Daphnia* is a filter feeder that requires a relatively high food concentration whilst the calanoid *Eudiaptomus* can survive in much less productive environments. **When the winter is cold, appreciable numbers of *Daphnia* survive in the open water even when their supply of food from the phytoplankton is very low. When the winter is mild, however, the *Daphnia* cannot ingest enough food to survive and the *Eudiaptomus* then dominate the micro-crustacean community** (see more details in George & Hewitt, 1999). Here, the important point is that relatively small changes in the winter water temperature can have a significant effect on the long-term dynamics of a key planktonic species.

VI.A.2. Conclusions

The historical variations in the winter characteristics of Esthwaite Water show that this lake is very sensitive to year-to-year variations in the weather. These weather-related variations influence the physical, chemical and biological characteristics of the lake. In some cases, the changes are modulated by a single climatic variable while in others the lake responds to the combined effects of the prevailing wind, sun and rain.

Case Study: Lake Erken, Sweden

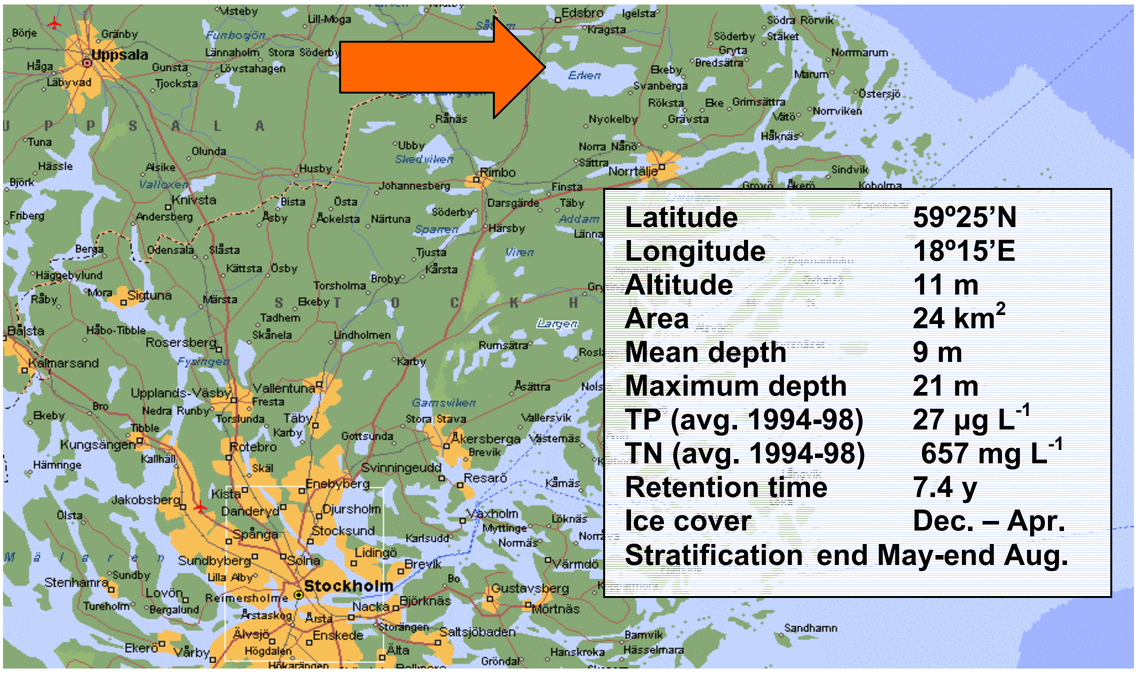


Figure VI.A.6 General view, location and general characteristics of Lake Erken

► **Mesotrophic lake with a rather long residence time in which temperature-related and internal processes such as longer ice-free period and enhanced bacterial mineralisation, increase nutrient availability and phytoplankton productivity in mild years.**

VI.A.3. Limnology of Lake Erken

Lake Erken is a mesotrophic lake in eastern Sweden 10 km north of Norrtälje and 70 km northeast of Stockholm. Granites and gneisses dominate the bedrock of the area, while the overlaying soils are rich in calcareous material. The lake is stratified during summer and winter (dimictic) and has a relatively small inflow of humic matter from the catchment. The mean Secchi depth is 4.5 m and the theoretical lake water retention time 7.4 years. The catchment area (140 km^2) consists of 70% forest, 10% agricultural land and 20% lakes. The lake is always ice-covered in winter. The ice break-up occurs between March and early May Dominant phytoplankton species are: *Stephanodiscus hantschii* var. *pusillus*, *Asterionella formosa, Chrysochromulina parva, Rhodomonas lacustris*, and *Gloeotrichia echinulata*. The latter causes water blooms in the lake in July and August (Pettersson *et al*., 1993).

VI.A.2. Data availability and investigations

The ice break-up has been registered since 1954. Also water samples have been taken since 1954 with more intensive sampling both in the 1970s and from 1993 onwards. Thus, at least 20 years of data from Lake Erken are available. Climate impacts on Erken have previously been analysed by Weyhenmeyer *et al*. (1999), Blenckner *et al*. (2002) and Pettersson and Grust (2002). These analysis indicate that this mesoeutrophic lake is a very good ecosystem to analyse climatic impacts on lake processes, as the land use in the small catchment has not been change over time. This unique study environment offers therefore the possibility to analyse direct and indirect effects on climatic change, as the observed changes are not due to changes in the catchment.

Observed changes

The studies so far performed document a **one month earlier ice break-up** during the later period, compared with the 1960s, and a **decrease of springtime snow cover**. These changes, in turn, can explain a **shift in the timing of the spring phytoplankton bloom**, which now occurs one month earlier than in the 1960s and 1970s. Additionally, warmer winters seem to **shift the phytoplankton species composition** towards diatom dominance. A longer ice-free period at present has led to an **increase in water temperature**, especially in May, which may stimulate bacterial activity (Goedkoop and Törnblom, 1996). The resulting enhanced remineralization of nutrients combined with the longer ice-free period has **enhanced the availability of nutrients to algae**. Indeed, a significantly higher summer phytoplankton biomass has occurred during the late 1990s (Blenckner *et al*., 2002) (Figure VI.A.7).

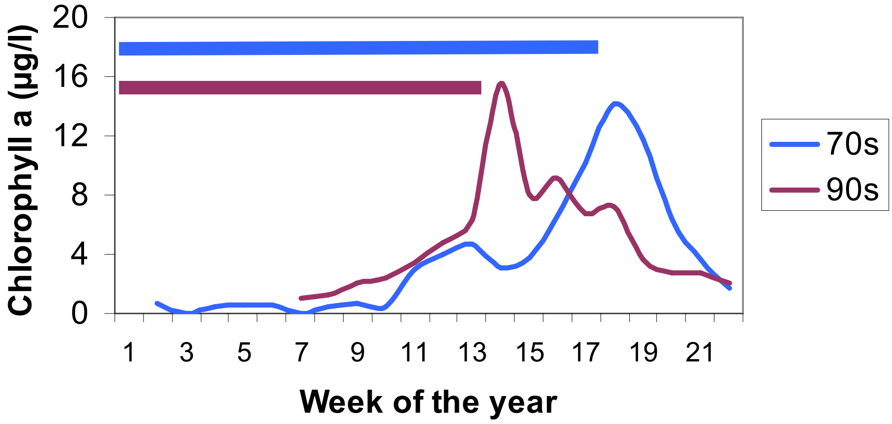
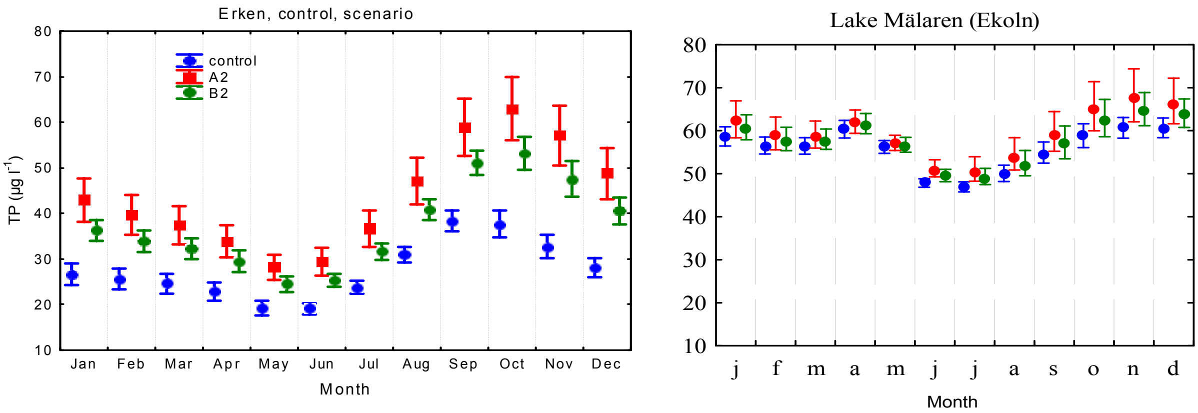


Figure VI.A.7 The comparison of phytoplankton biomass (Chl a, lines) and the ice cover periods (bars) between the 70s (blue) and 90s (brown) in Lake Erken.

Modelling
To analyse this process further, a physical lake model and a mechanistic phosphorus model were combined with two emission scenarios generated by a regional climate model (RCM) in three sites in central Sweden – Lake Erken and two basins of Lake Mälaren (Galten and Ekoln). In the phosphorus model water mixing, mineralization, diffusion and biological uptake are temperature dependent.



FigureVI.A.8. Mean, maximum and minimum values of predicted total phosphorus (TP) concentration (µg/l) in Lake Erken and in the Ekoln basin of Lake Mälaren for the three climate emission scenarios *(control 1960-1990; A2 - 2070-2100; B2, - 2070-2100).*

In the simulations, Lake Erken was much more sensitive to climate warming than the two basins of Lake Mälaren (Figure VI.A.8), and the reason was shown to be the much longer water residence time in Lake Erken (seven years), stressing the importance of internal processes. In Galten and Ekoln the water residence times are less than one year, and the effects of water temperature changes are small. In Lake Erken the concentration of epilimnetic, dissolved phosphorus almost doubles in spring and autumn in the scenarios. Long-term datasets from Lake Erken from the 1970's and 1980's showed that earlier ice-breaks and higher temperatures in May led to increased phosphorus concentration and phytoplankton biomass in summer (Blenckner et al., 2002). Since the lake is mostly phosphorus-limited, this means that the phytoplankton production is almost doubled in the future scenarios. The implication would be that **in Lake Erken, and in other eutrophic lakes with long water residence times, eutrophication problems might become serious in a warmer future climate.** Water managers may need to take action today in order to maintain good water quality in these lakes.

Case study: Lake Võrtsjärv, Estonia

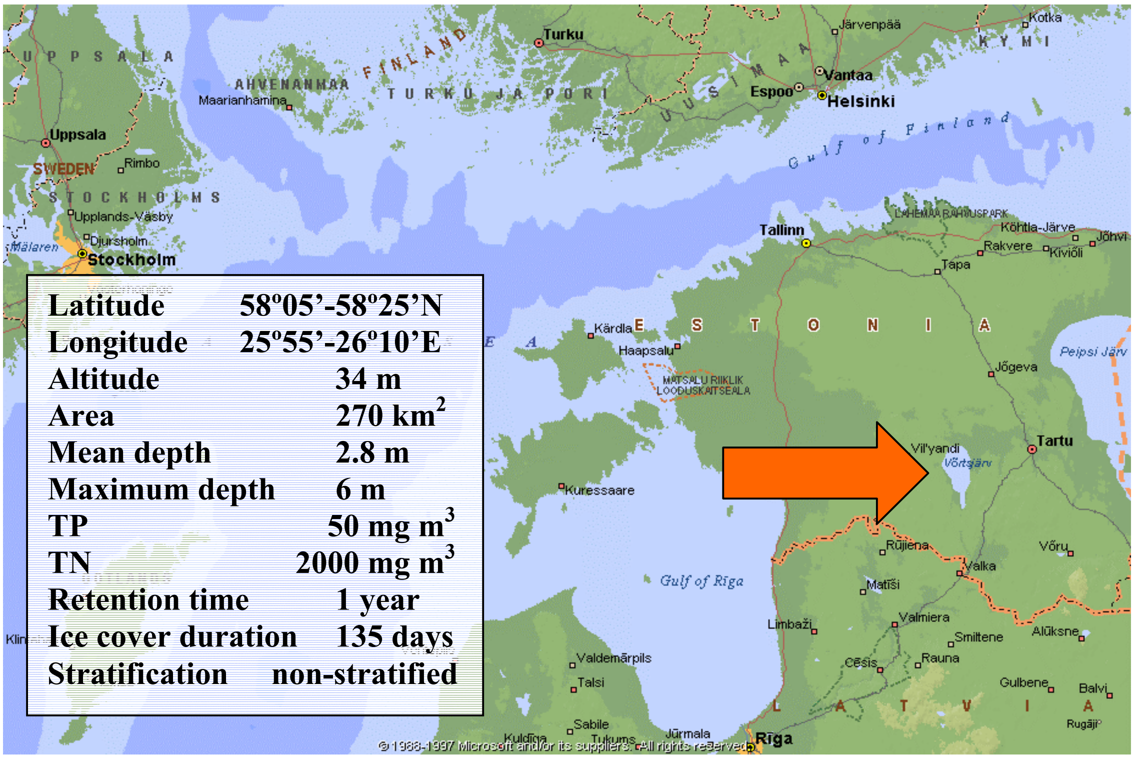


Figure VI.A.9 General view, location and general characteristics of Lake Võrtsjärv

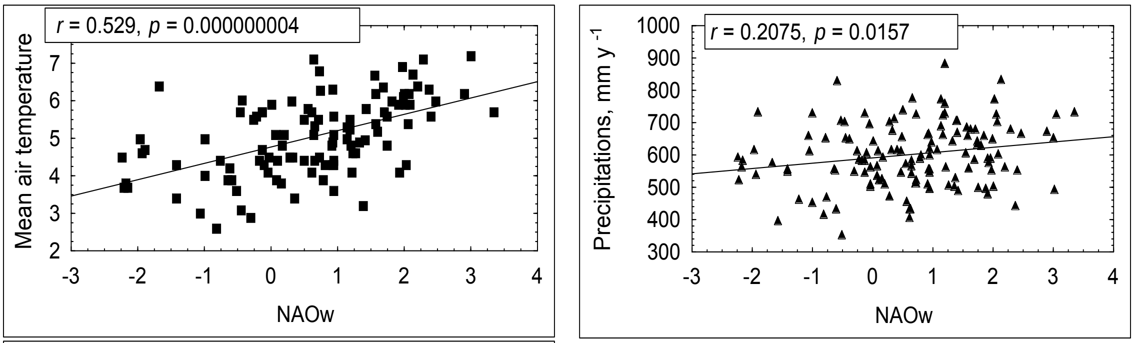
► **Large shallow ecosystem, which chemical and biological parameters strongly depend on the fluctuating water level determined by the amount of precipitation.**

VI.A.4. Limnolofy of Lake Võrtsjärv

Lake Võrtsjärv (Figure VI.A.9) is a large shallow non-stratified eutrophic lake is located in Central Estonia. The mean annual amplitude of water level fluctuations in this lake is 1.4 m, and the maximum range is 3.2 m. The latter corresponds to 1.4-times difference in the lake area, 2.4-times difference in the mean depth and three-times difference in lake volume (Nõges and Nõges 1999). Thus, changing water level is considered to be the leading factor controlling the ecosystem dynamics of Lake Võrtsjärv, first of all through phytoplankton (Nõges *et al*., 2003).

Data availability and investigations
Climatic and hydrological data series for L. Võrtsjärv basin reach back up to more than 100 years. Air temperature has been measured since 1894, precipitations since 1866, water level since1923, ice-on and ice-off dates since 1924, and water temperature since 1947 by Estonian Institute of Hydrology and Meteorology. Data on water chemistry and biota have been collected since 1960s at Võrtsjärv Limnological Station, the main centre of freshwater research in Estonia.

North Atlantic Oscillation and lake water level
In Estonia the western airflow from the Atlantic during positive NAO remarkably increases air temperature and the amount of precipitation in winter (Tomingas and Jaagus 1999). **In high-NAO years the ice cover on Lake Võrtsjärv has a shorter duration**



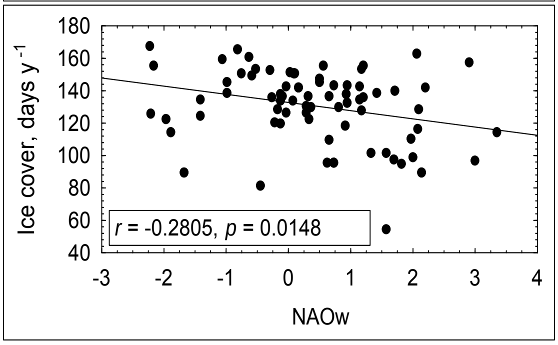
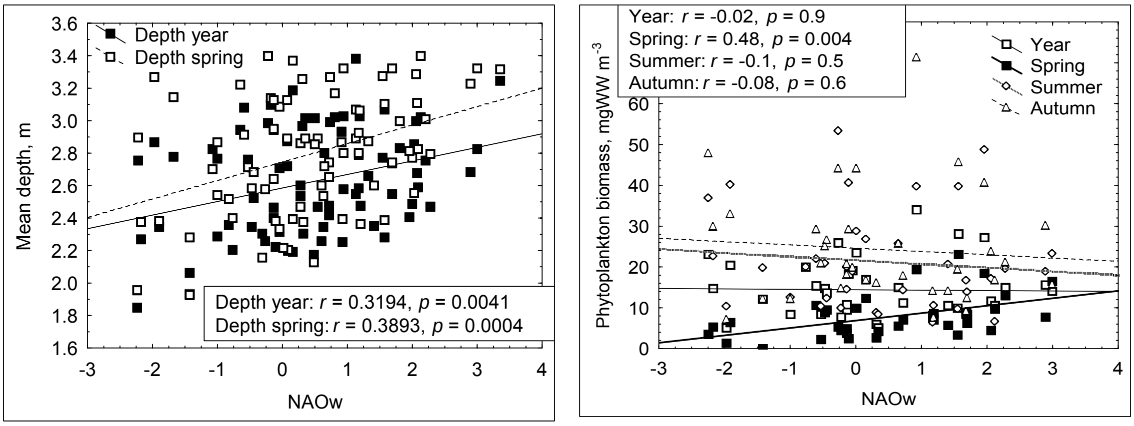


Figure VI.A.10. Correlation of the yearly average amount of precipitations in Estonia, air temperature in central Estonia and duration of ice cover on L. Võrtsjärv with North Atlantic Oscillation Index in winter (NAOw)

while the yearly average air temperature and the amount of precipitations in the vicinity of the lake are higher (Figure VI.A.10). **Because of flat lanscape and restricted outflow, the increased amount of precipitation is directly reflected in lake's water level** that remains high for several months after the flood. In this way the water level in spring determines the water level throughout the whole year.

The effect of changing water level on the ecosystem
Phytoplankton biomass is higher in the springs after high-NAO winters but during the other seasons the relation is rather opposite. **In summer, and autumn phytoplankton biomass is inversely related with the depth** (FigureVI.A.11). This phenomenon has been explained by the reverse relationship between average light intensity and water depth in polymictic water column bringing about light limitation and worse growth conditions to phytoplankton (Nõges and Nõges 1999). Weaker resuspension in deeper water releases less phosphorus from the bottom sediments while lower denitrification rate keeps nitrogen concentration high (FigureVI.A.12). Consequently, **in a warmer world the N/P ratio in Lake Võrtsjärv would probably be higher and potentially toxic N_2-fixing cyanobacteria (blue-green algae) will have less chance to develop** (Figure VI.A.13), thus the risk of toxic water blooms will be reduced.



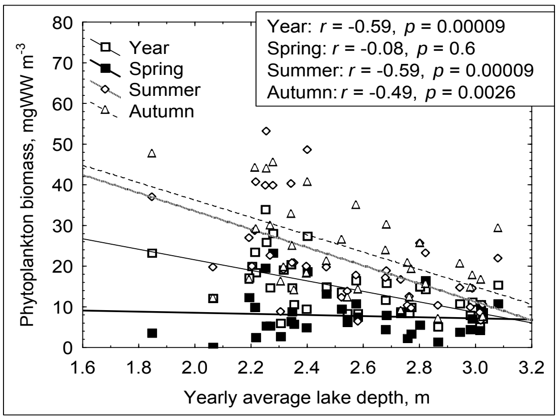


Figure VI.A.11. Correlation of the lake depth, and phytoplankton biomass in L. Võrtsjärv with North Atlantic Oscillation Index in winter (NAOw), and the relation of phytoplankton biomass with lake depth

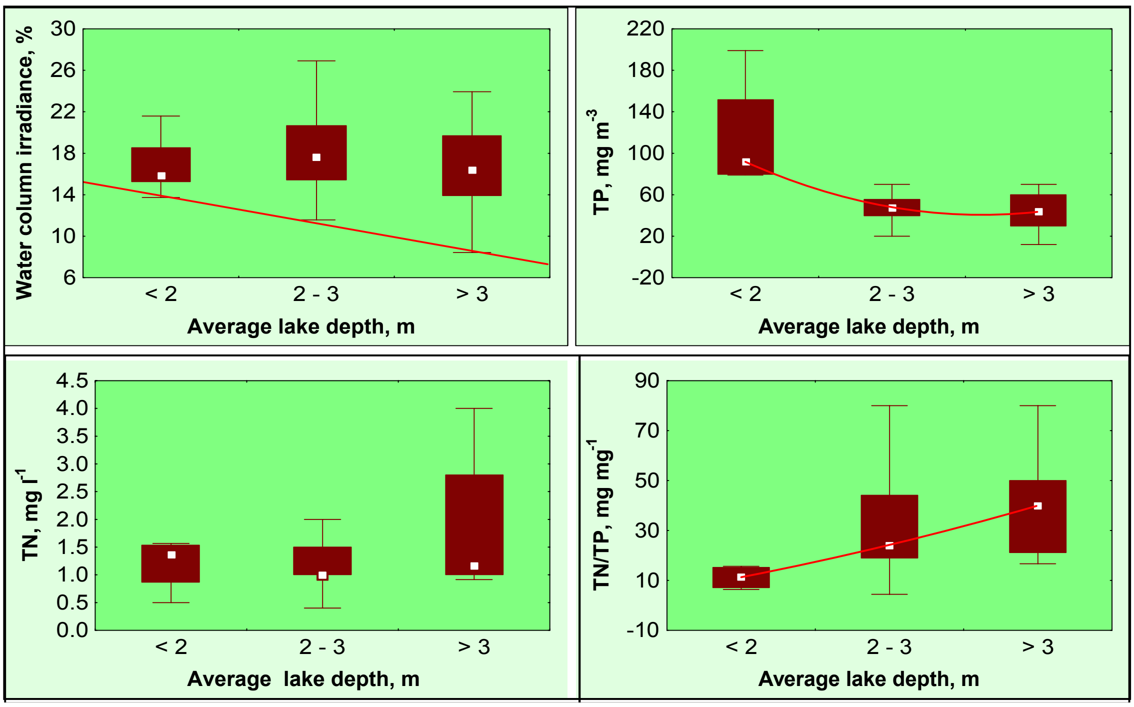


Figure VI.A.12. Relationship between the mean depth and concentration of total nitrogen (TN), total phosphorus (TP), TN/TP mass ratio and average irradiance of the water column in L. Võrtsjärv (Nõges *et al*. 2003).

Several winter fish-kills have been documented in Lake Võrtsjärv during the last century (in 1939, 1948, 1967, 1969, 1978, 1987, 1996). One reason for these fish-kills is the depletion of oxygen in low-water years during late winter when the under-ice oxygen concentration dropped faster due to smaller amount dissolved in the smaller volume of water. **The warmer and wetter climate bringing about higher water level in Lake Võrtsjärv would decrease the risk of fish-kills in the lake** (Figure VI.A.13).

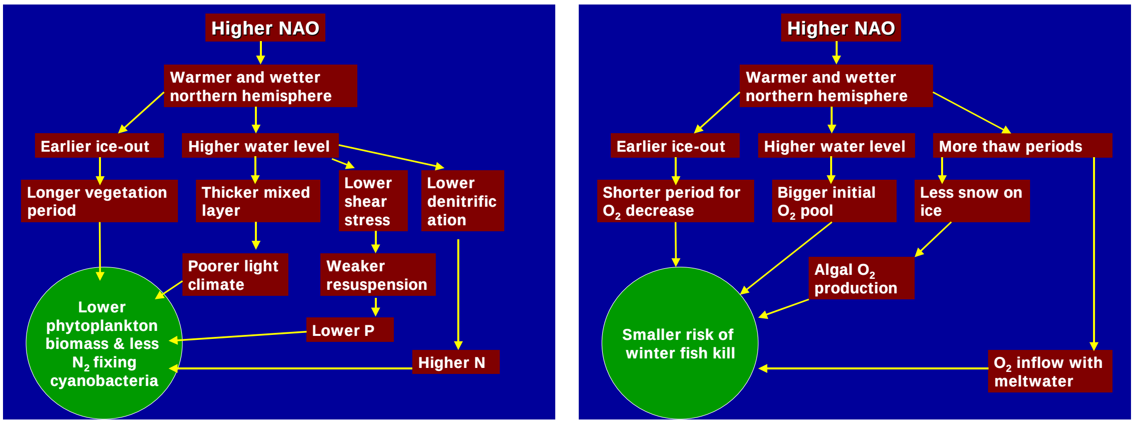


Figure VI.A.13. Consequences of global warming on phytoplankton and fish-kills in Lake Võrtsjärv.

Conclusion

In non-stratified shallow lakes the changes of the lake depth affect the average illumination of the mixed water column, resuspension intensity, nutrient release from sediments, and denitrification rate. These factors are important as they control the growth and composition of phytoplankton that is the first link of the pelagic food web. Cold winters often characterised by low water level have caused several winter fish-kills in the lake. In warmer and wetter climate the probability of both the summer blue-green blooms and winter fish-kills are supposed to decrease in L. Võrtsjärv.

Acknowledgements

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Chapter VI.B. Climate Change and the Venice Lagoon

Key Points

- **The Venice lagoon is the largest coastal wetland in the Mediterranean with a distinctive tidal regime, ecology, and cultural heritage. The uniqueness of Venice lies in the *mix* of issues.**

- **Throughout Venice's long history the activities of man have regulated its environment and adapted to changing conditions – it is one of the longest surviving examples of "sustainable development". Long data series exist and it is possible to measure effects of climate change.**

- **Conditions in Venice, and the lagoon, are a function of its exchanges with the Adriatic Sea, pollution sources, ecology and morphology within the lagoon, the influence from the drainage basin, and physical changes that affect hydrodynamics.**

- **Sea level and the associated frequency of flooding are increasing, most markedly since the mid 20th century. This results mostly from human-induced subsidence and physical changes to the lagoon that reduces its resistance to incoming tides and strengthened currents.**

Chapter VI.B. Climate Change and the Venice Lagoon

VI.B.1. Why Venice? A historical insight

The Lagoon of Venice, the largest in the Mediterranean region, is a compendium of almost all the problems facing these environments: the unique characteristic of Venice is mainly to have survived in spite of the co-presence of all of them. For over five centuries the continuous intervention of man has allowed Venice to be preserved along with the "lagoon status" of the environment around it, overcoming the "natural changes" occurring during this period. Meanwhile, other tidal lagoons of the Adriatic Sea were "naturally" silted from the sediments carried by the rivers (or eroded by the greater relative force of the sea, and transformed from wetlands into a marine bay).

In the Venice lagoon, huge engineering works, starting in the 15th century, were able to divert most of the river outlets from the lagoon to the sea and so maintained the "water wall" around the city, essential for defence reasons, and for Venice's strategic economic role as a city-port. The last big and very expensive public works undertaken by the Venetian Republic was the building of the sea defences (*Murazzi*) along the coastal strip, at the end of the 18th century, completed only two years before surrendering to Napoleon's Army. More recently, the long jetties built between the late 19th and early 20th centuries determined the current form of the three inlets. To facilitate Venice's economic development, a large industrial area at the lagoon margin was created (*Marghera*); beginning in about 1910, deep canals were also dug through the lagoon to connect the new port to the inlets, and artificial islands were constructed for further industrial growth. Fish farms have also been developed in the north and south of the lagoon, closing areas of the lagoon to tidal expansion. A few decades ago, the Venice international airport was built on reclaimed land on the lagoon's margin. Other land has also been reclaimed to facilitate extension of the industrial zone, housing development and agriculture.

In recent years, after the great flooding event of 1966, the future of Venice received much attention, following decades of neglect as regards urban maintenance. Many scientific and technical institutions have produced countless reports. Since 1973 the Italian Government has supported large environmental and socio-economic programmes and is presently launching a 4-billion € programme (to be concluded in 2012) mainly addressing safeguarding the city from sea level rise. The efforts of the Italian State were addressed not only to reinforce the old sea defences or to implement other new essential works in the lagoon, the city and in the drainage basin, but also to strengthen the research infrastructure and to sustain its activity.

VI.B. 2. Brief Description

The lagoon of Venice, with a surface area of about 550 square km, of which 418 square km are open to the tides of the Upper Adriatic (the widest tidal range in the Mediterranean), is the largest Mediterranean lagoon. The sea and the lagoon are connected through three inlets: Lido, Malamocco and Chioggia. The coastal barrier stretches for a total of about 60 km. About 78% of the lagoon surface is submerged by water, which are crossed by a dense network of channels of varying depth. The lagoon is subjected to heavy anthropogenic pressure, which increased greatly during the last century, following large scale urban, industrial and agricultural development.

The "closed lagoon"

The part of the lagoon not subjected to the tide ("closed lagoon") includes all of the fish farms with their internal islands, along with mud flats and salt marshes. Typical of the lagoons of the Upper Adriatic, fish farms are separated from the open lagoon by embankments that block them from the ebb and flow of the tide. They are shallow basins of salt and brackish water and they make up special environments that have been equipped for fish breeding and sometimes hunting. Within their confines are water areas, artificial and natural channels, salt marshes and structures for regulation of salt and fresh water flow.

The "open lagoon" and water flows

The currents and the sea level in the Venice Lagoon are driven mainly by two different forcing functions. The first one is tidal forcing, which is strictly periodic and deterministic, so that it can be predicted with certainty. The second kind of forcing are non–periodic functions, such as wind and atmospheric pressure (Gacic *et al*., 2004). The meteorological component is the main factor of the frequent flooding of Venice.

The average daily volume of water that enters the lagoon from the sea is about 400 million m^3. The volume of water exchanged with each tidal cycle is about 350 million m^3 during spring tide and 175 million m^3 during neap tide (http://www.salve.it). The maximum water flow in one inlet can exceed 12000 m^3/s, more than the volume of the River Po in full flow (Bianchi *et al*., 2004).

Man-induced changes over the past century have increased the amounts of water exchanged with the sea through the inlets (due to their reconfiguration and construction of jetties) *and* reduced the lagoon's resistance to incoming tides as a result of loss of extensive areas of saltmarsh and the excavation of the principal navigation channels. Consequently currents are stronger and erosion rates high.

The water contribution of the drainage basin

Moreover 900 million m^3 of fresh water flow into the lagoon every year through the 2,515 km of the hydrographic network. The yearly quantity of rainwater from the drainage basin is 1.4 km^3 (588 mm) and directly into the lagoon, 0.3 km^3. The annual quantity of nutrients from the drainage basin is estimated to be 7000 tons of N and 1500 tons of P. The average concentration of nutrients at the mouths of the rivers is about 10 mg/l of N and 1 mg/l P (http://www.salve.it).

A number of ecosystems

The Lagoon of Venice is a fragile and complex environment in the transition between fresh and sea water, composed of a continuous series of ecotones, in which the anthropogenic impact increased over the course of many centuries. Moving from sea to land, specific fauna and flora characterize different ecosystems. Along the coastal dunes and the wooded areas behind the dunes live amphibians, reptiles, birds, and mammals, which adapt well to medium to high daytime temperatures. The fish species along the external areas of the lagoon are typical of a marine environment. Areas of the littoral strips have different levels of plant colonisation: in the wet areas behind the dunes, pond vegetation can be found. Patches of wind-breaking vegetation can interrupt sand vegetation.

The Venice lagoon is one of only two tidal coastal wetlands in the Mediterranean region; it is also characterised by a transitional Mediterranean/Atlantic climate system. Consequently, the salt marshes ("barene") represent some unique features, exposed during low tides and flooded by high tides. Their characteristic vegetation is composed of several halophytic species that survive within a narrow range relative to water level. Together with the associated mudflats, they are also an essential habitat for many bird species (breeding, feeding, over-wintering etc.).

Concerning the flora of the lagoon bed, there are four species of eelgrass native to the lagoon. Until recently, eelgrass was an important element of lagoon bed vegetation. Vast meadows of eelgrass covered the lagoon beds, consolidating them with its complex system of roots. The growth of this plant has now greatly diminished, and algae (in some cases invasive, exotic species) have spread throughout the lagoon.

For fisheries the Northern lagoon basin (with a good presence of salt marshes) and the freshwater inlets attract large numbers of juveniles of many fish species, as well as the role of salt marsh creeks and sea-grass meadows in supporting the endangered species included in the Habitat and Species Directive (92/43/EEC). The lagoon acts as a fish nursery for an important part of the fish present in the North Adriatic Sea (Mainardi *et al*., 2004).

Some interesting transitional environments such as swamps, wetland meadows and woods, and backwaters that were once part of the lagoon are now reclaimed lands. The clay quarries in the inland territory behind the lagoon have been spontaneously re-colonised by the fauna which once lived in these original transitional environments: small molluscs, insects, reptiles, and amphibians. During the migratory season, birds find a needed temporary habitat and feeding grounds in these areas.

These environments are the only areas where fresh fluvial waters and brackish waters meet in the lagoon. Almost all of the coot and the ducks in the lagoon region are concentrated in fish farm areas during the winter months and during the migratory season. The reed bed environments offer nesting areas for numerous species. Plants adapted for fresh water environments grow around waterways and swamps. Typical plants that can be found in these areas are the common reed and the cattail. Following the waterways, the reeds make their way into the lagoon along the channels. In the northern part of the lagoon, fresh water marsh vegetation thrive in brackish water environments which are rich in species that can adapt and live in brackish habitat.

VI.B.3 Measurable Climate Change Effects

Sea level rise

Venice is considered the world test-case city for sea level rise (SLR). Even if the journalistic description is occasionally exaggerated, the frequency of flooding increased dramatically in the second half of last century, both due to land subsidence and SLR. The present natural subsidence is limited to less than 0.4 mm/yr, while in the period 1950-1970 the actual rate of subsidence was as high as 7 mm/yr due to freshwater extraction from wells for industrial use. Since 1896, of the 23 cm of relative sea level loss, approximately 12 cm is attributed to anthropogenic land subsidence.

Figure VI.B.1 shows the mean sea level of Venice and Trieste (Pirazzoli and Taroni, 1999) where good agreement is observed in the initial and in the final part of the period Carbognin and Taroni (1996). In the period between 1920 and 1970 the strong extraction of underground water caused Venice to sink giving an apparent SLR signal. The presence of long historical data series and the use of state-of-the art techniques (as InSAR Satellite Interferometer), allows distinguishing between different causes of relative sea level rise.

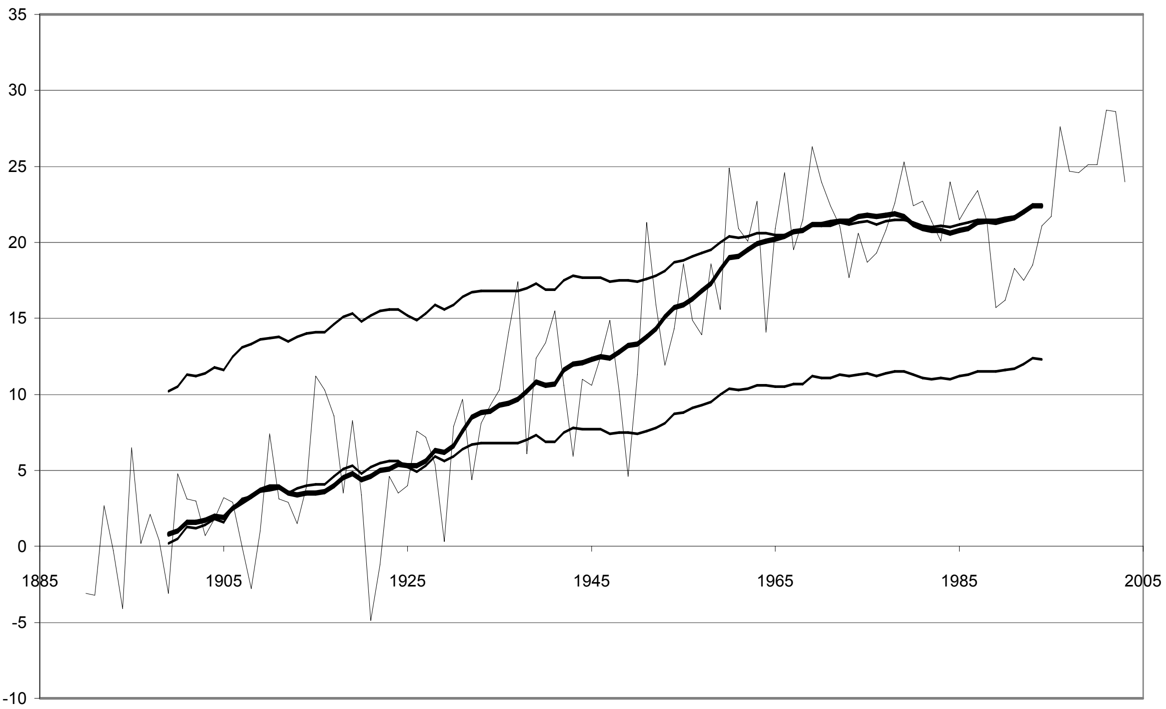


Figure VI.B.1: Yearly sea level in Venice (wiggling). Thin, smooth line refers to Trieste (drawn twice), 19-year moving average. The other smooth line gives the same average for Venice.

Meteorological and oceanographic data

Flooding frequency in Venice is not just related to rising relative sea level (due to subsidence and eustacy), but also to meteorological features. The main components of flood tides are winds (bora and sirocco, especially) and atmospheric pressure. The astronomic tide component is marginal.

The lagoon of Venice, besides the presence of a long time-series of meteorological data, is well equipped to study micro-climatic variation, as it has more than 80 measuring stations, most of them connected for real-time data collection .The Oceanographic Platform "Acqua Alta" situated 12 nautical miles off the coast of Venice in the Northern Adriatic Sea is a valuable component of the network and is operated by the ISMAR-CNR (Institute for Marine Science of the Italian National Research Council) and is the home of the JRC's COAST project.

For example, Figure VI.B.2 shows the declining trend of bora wind at Tessera in the last decades (Pirazzoli abd Tomasin, 1999), whereas in Figure VI.B.3 the opposite trend may be observed for atmospheric pressure (Cocheo and Amuffo, 2002), which exerts the well-known "inverted barometer effect" on the sea.

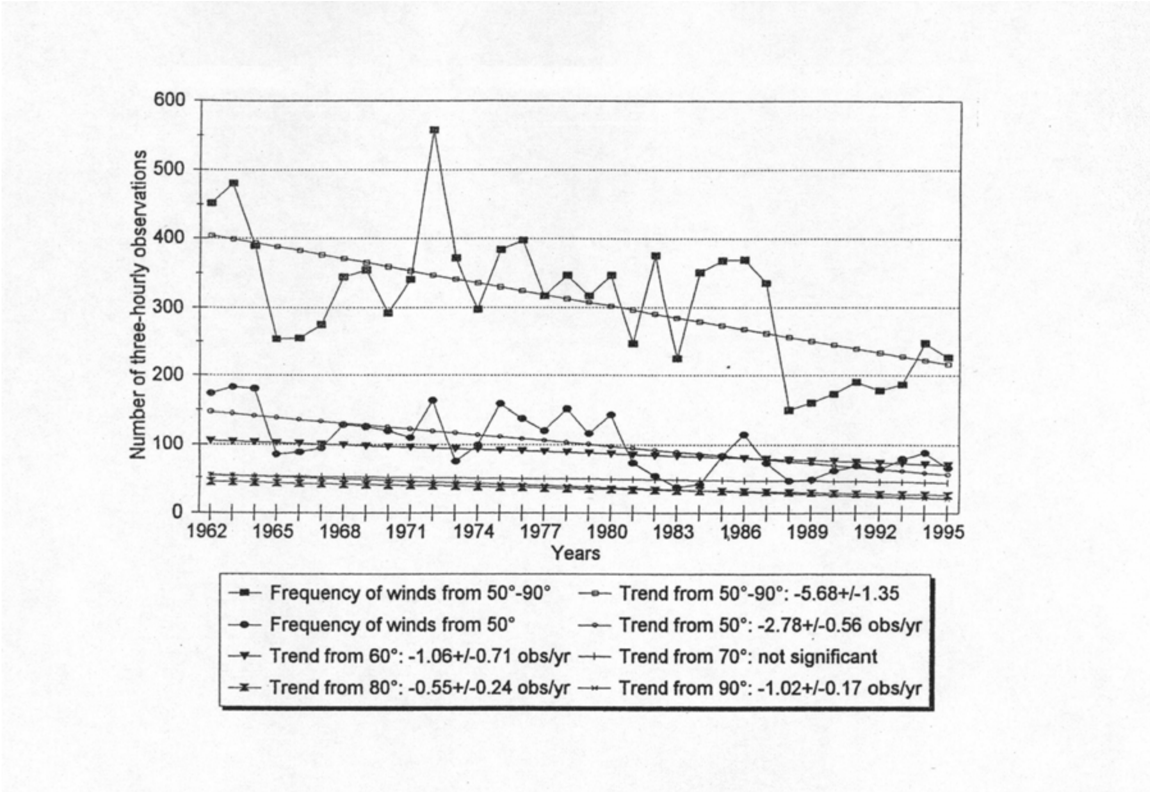


Figure VI.B.2: Frequency of "bora" wind at Tessera airport.

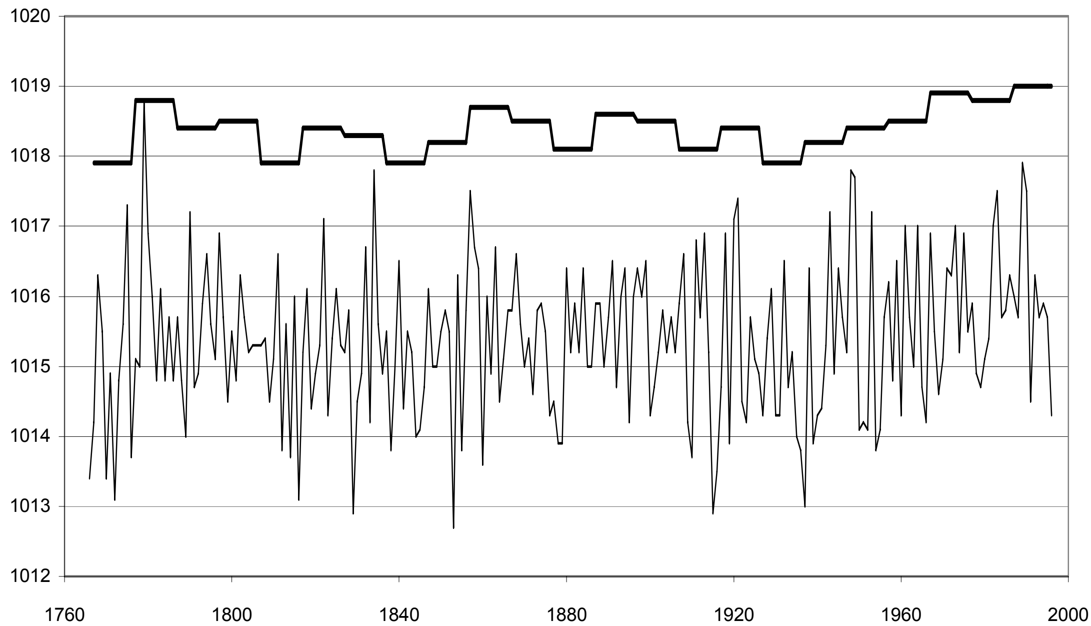


Figure VI.B.3: Lower: mean yearly pressure in Padua (hPa). Upper: ten-year average (increased by 3 units).

Remote sensing and satellite images

Remote sensing techniques are used daily for a number of purposes and updated techniques are applied, merging information coming from instruments passing over the lagoon at different altitudes and carrying different sensors (planes, balloons, satellites). Morphological changes due to the combined effect of vegetation distribution and tidal forces (both subjected to climate change) have been extensively studied in the last years. The presence of many reference points on the lagoon surface makes the Venice site very valuable for satellite analysis and calibration, (e.g. NASA projects MODIS and SeaWifs).

Biomarkers and bioindicators

In the last years, several research campaigns were carried out with the aim of evaluating the environmental health of the Lagoon by means of the biomarker approach applied to marine bivalves (Livingstone et al., 1995, Nasci et al., 2002). Several studies have shown how the biological response can be affected not only by chemical pollutants but also by a number of natural stressors such as temperature, salinity, hypoxia, food availability and the reproductive cycle of the sentinel organism (Nasci et al., 2000). The expected effects of climate change related to changes in environmental factors may be measured also through biological tools already developed

Impact mitigation

For the comprehensive defence of Venice and of the inhabited areas of the lagoon from high tides, including extreme events, the “MOSE system” has been created. The system includes mobile flood barriers constructed at the lagoon inlets in order to isolate the lagoon from the sea in the case of tides higher than the pre-established height, the so-called “complementary measures”. These engineering works increase the friction in the canals at the lagoon inlets with the scope of diminishing the level of the most frequent tides, and strengthening local defences by “raising up” lagoon banks and public pedestrian areas in the lowest lying areas.

The long-term effect of this intervention has been the focus of much scientific and public concern and discussion, involving both social and natural sciences. The detailed environmental and economic evaluation of the measures, also in terms of technical effectiveness will certainly characterise the scientific (and possibly the political) debate in the coming years.

Conclusion

The Venice lagoon can be considered as an early sentinel of global changes, due to the existence of both anthropogenic and natural characteristics and pressures that typify coastal lagoons. The availability of large data-sets, of a highly experienced scientific community and significant international interest guarantee a fast and reliable transfer of knowledge to other sites and a proper evaluation of general information concerning global change and possible suitable mitigation measures.

Chapter VI.C. Climate Change and Water Resources in the Ebro River Basin

Key Points

- **Model output indicates that air temperature might increase (2-3°C) and precipitation reduced (5-20%) for most of Spain, and for the Ebro watershed. Increased temperature will increase evaporative losses, crop water demands, and an overall increase in water resource demand from all sectors (civil, agricultural, industrial).**

- **There is likely to be a higher frequency of extreme events (dry periods/droughts, torrential rains/floods).**

- **Runoff will likely decrease, pointing to a more efficient management of water resources and runoff regulation for flood protection.**

- **Reduced flows will result in diminished diluting power in the Ebro and saline water might further advance. The tenuous ecosystem in the river and its delta might be endangered, leading to disappearance of endemic species.**

- **Subsidence of the delta due to reduced sediment deposition coupled with global sea level rise of 0.2-0.82 m by the year 2100 could be a threat to the existence to the wetlands and the delta system.**

- **It is difficult to decouple pressures and impacts of climate change from anthropogenic activities (e.g. increased population, expansion of irrigated land, industrial growth). It is important to distinguish natural fluctuations from the effects of anthropogenic activities.**

Chapter VI.C. Climate Change and Water Resources in the Ebro River Basin

VI.C.1. Introduction

The Ebro River is located in North-Eastern Spain and flows into the western Mediterranean Sea (Figure VI.C.1). It is the largest Spanish fluvial system, with a drainage basin of 85530 km^2, and one of the largest contributors of freshwater in the Mediterranean. Catchment characteristics are highly heterogeneous in terms of geology, topography, climatology (mean annual precipitation varies from 2000 mm in the Pyrenees to less than 400 mm in the arid interior), and land use. Water flow in the catchment is regulated by 187 reservoirs, with a total water storage capacity of approximately $6837 \cdot 10^6$ m^3 (about 57% of the total mean annual runoff) (Comín, 1999; Batalla *et al*., 2004). Diverted water is used for agricultural irrigation, electricity production and domestic consumption. Monthly water discharge is quite irregular, with a significant decrease during last century attributed mainly to increased water use for human activities (Figure VI.C.2). The river ends at the Ebro delta, covering an area of about 320 km^2 of sedimentary material with wetlands and coastal lagoons, which are valuables in terms of natural resources and related economic activities.

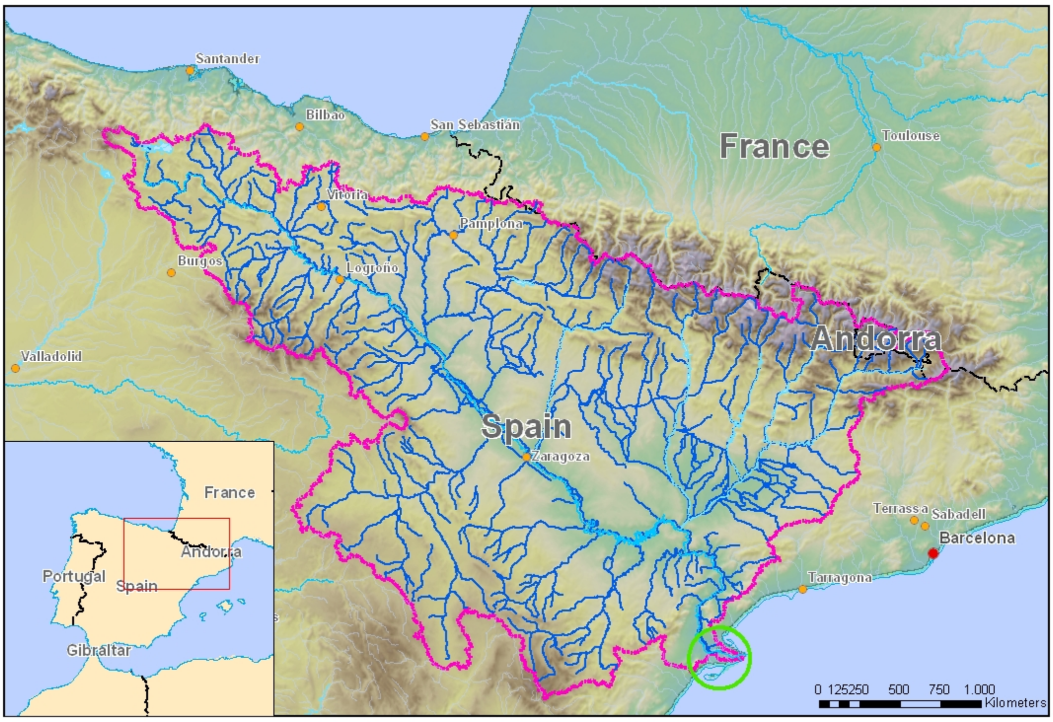


Figure VI.C.1. Ebro watershed and its delta.

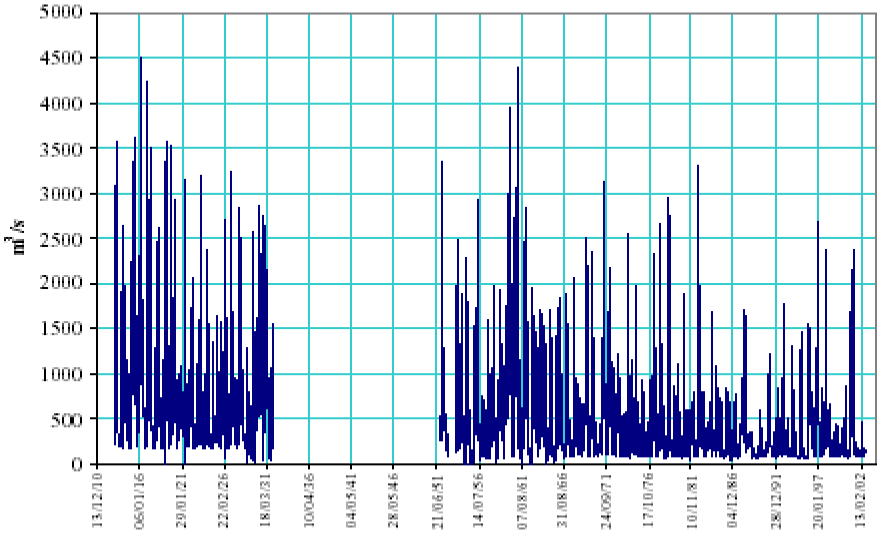


Figure VI.C.2. Daily flows in Ebro river from 1913 to 2001 (PHN, 2000).

There is increasing evidence that global climate is changing and most of the warming observed since pre-industrial era is attributable to human activities (IPCC, 2001). Observed changes in sea level, snow cover, ice extent and precipitation patterns are consistent with the current scenario of higher temperatures. Based on current trends it is reasonable to assume that the global hydrologic cycle will be accelerated, with greater event variability and extremes.

Impacts of climate change can be evaluated using three different approaches; in order of increasing prediction uncertainty those are:

- analysis of changes recorded in the current geophysical record;
- analysis of changes predicted from Global Circulation Models (GCMs);
- analysis of changes determined from various assumed scenarios of the impact of global climate change.

All three approaches have been adopted for the Ebro river basin.

The three factors of global climate change that could most impact the hydrology of the Ebro watershed are: increasing air temperature, changes in precipitation (leading to variations in annual runoff), and sea level rise. Findings from the various studies, highlighting the effects of climate change on some components of its hydrologic cycle, as well as on the ecological status of the river and its delta area, are summarized in the following paragraphs. Some of the problems arising when trying to assess and quantify the effects of climate change are also presented.

VI.C.2. Climate Change Impacts

Temperatures

According to IPCC (2001), global mean temperature has increased by about 0.6°C over the past 100 years. Globally the 1990s were the warmest decade on record, and 1998 the warmest year. It is likely that the increase in temperature in the 20th century was the largest of any century during the past 1000 years. There is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities. Based on predictions from seven GCMs, IPCC (2001) reports that there is a potential for increases in average air temperature by the year 2100, ranging from +2 to +4.2 °C,. Under IPCC emission scenarios, global average temperature are projected to rise by 1.4°C to 5.8°C between 1990 and 2100, leading to projected further decrease of glaciers, ice-caps and extent of sea ice. Temperature increase in Europe is consistent with the global trend, although natural variations are larger (Figure VI.C.3).

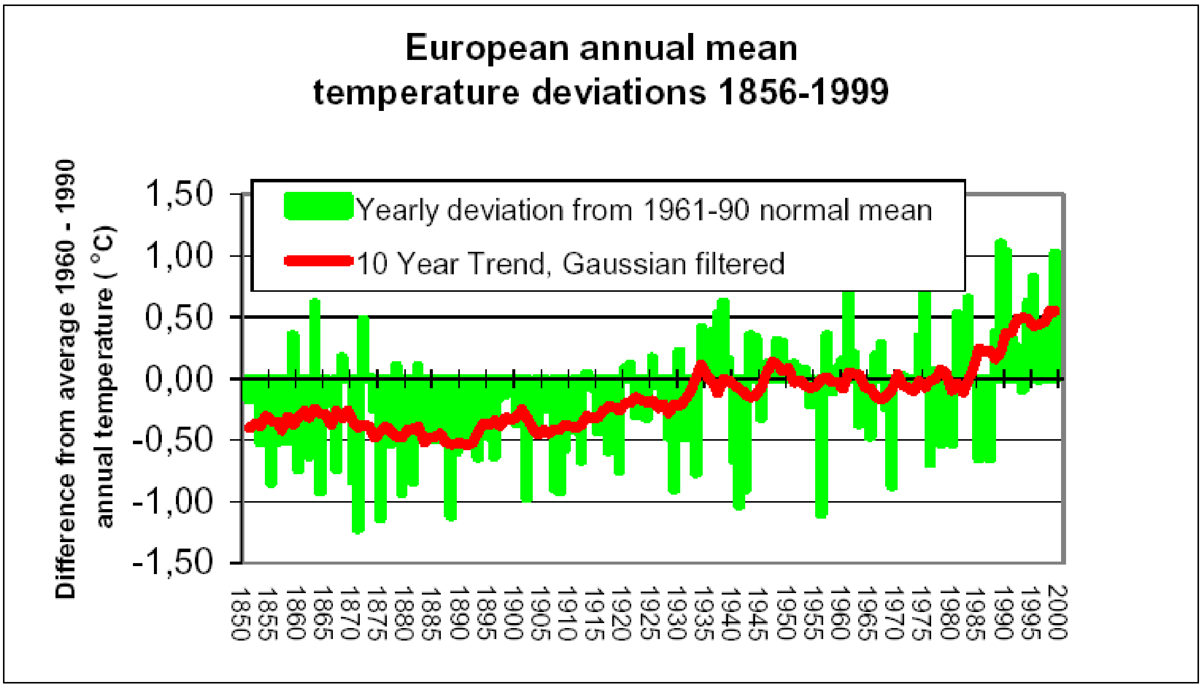


Figure VI.C.3. Annual mean-temperature deviations in Europe (CRU, 2000).

Results from the IMAGE model (Alcamo *et al.*, 1996) show a projected temperature increase between 2 and 3 °C for most of Spain, and in particular for the Ebro watershed (Figure VI.C.4). This is in agreement with projections from other studies.

Increased average temperature in the watershed will result in higher evaporation losses, higher crop water requirements, and an overall increase in water resource demand from all sectors (civil, agricultural, industrial). However, on the basis of current knowledge, it is difficult to decouple pressures and impacts of increased water demand due to climate change from those due to further development of human activities (e.g. increased population, expansion of irrigated land, industrial growth). For example, Ludwig *et al*. (2004) investigated the effect of recorded increased temperatures on the hydrology of the Têt River (Southern France) and concluded that, with increasing temperatures, humidity of Mediterranean origin becomes more important for the hydroclimatic functioning of the watershed leading to a downstream shift of precipitation in the basin and an increase of flood discharge especially in the lower reaches.

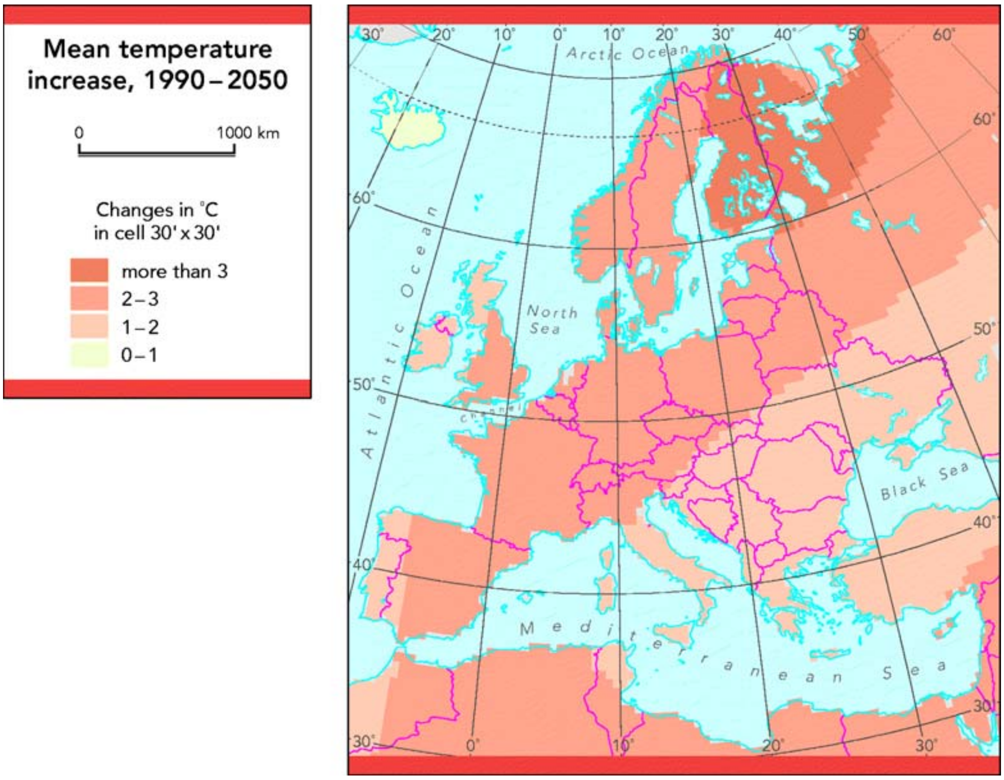


Figure VI.C.4. Mean temperature increase across Europe (Alcamo *et al.*, 1996).

Precipitation and river flows

The statistical analysis of rain intensity during the period 1940-2000 using data from 2150 meteorological stations in the Ebro basin, applying the non parametric Mann-Kendall trend test, does not yield a significant trend (PHN, 2000). Studies analyzing precipitation series across Europe indicate that, for all locations in Spain, no significant trend exists (Klein Tank *et al.*, 2002, Figure VI.C.5). In light of such findings, it is difficult to derive meaningful projections for future precipitation trends in the Ebro watershed.

GCM simulations and climate change scenarios estimate air temperature increases and precipitation reductions, accompanied by a significant change in precipitation patterns, with a higher frequency of extreme events (dry periods, torrential rains). Possible reductions from 5% to 20% have been foreseen (PHN, 2000; 2003), in agreement with prediction from international models. However, the impacts of changes in precipitation in the Ebro river basin are difficult to assess due to the heterogeneity of the watershed. For example, Batalla *et al.* (2004) divide the Ebro river basin into four main climatic zones:

- the Atlantic headwaters, 23% runoff, 900 mm/year;
- the west–central Pyrenees, 31% runoff, 950 mm/year;
- the eastern Pyrenees, 41% runoff, 800 mm/year;
- and the southern Mediterranean zone, 5% runoff, 500 mm/year.

Mean average precipitation is ~ 670 mm/year (PNH, 2000) and results from different contributions from each of the four zones. Considering such a subdivision, projections presented by IPCC (2001) for the year 2050, using the coupled model of the Hadley Centre, foresee a reduction between 0 and 25 mm/year for the main part of the Ebro watershed with the exception of the Pyrenees where reductions of up to 25-150 mm/year may be expected.

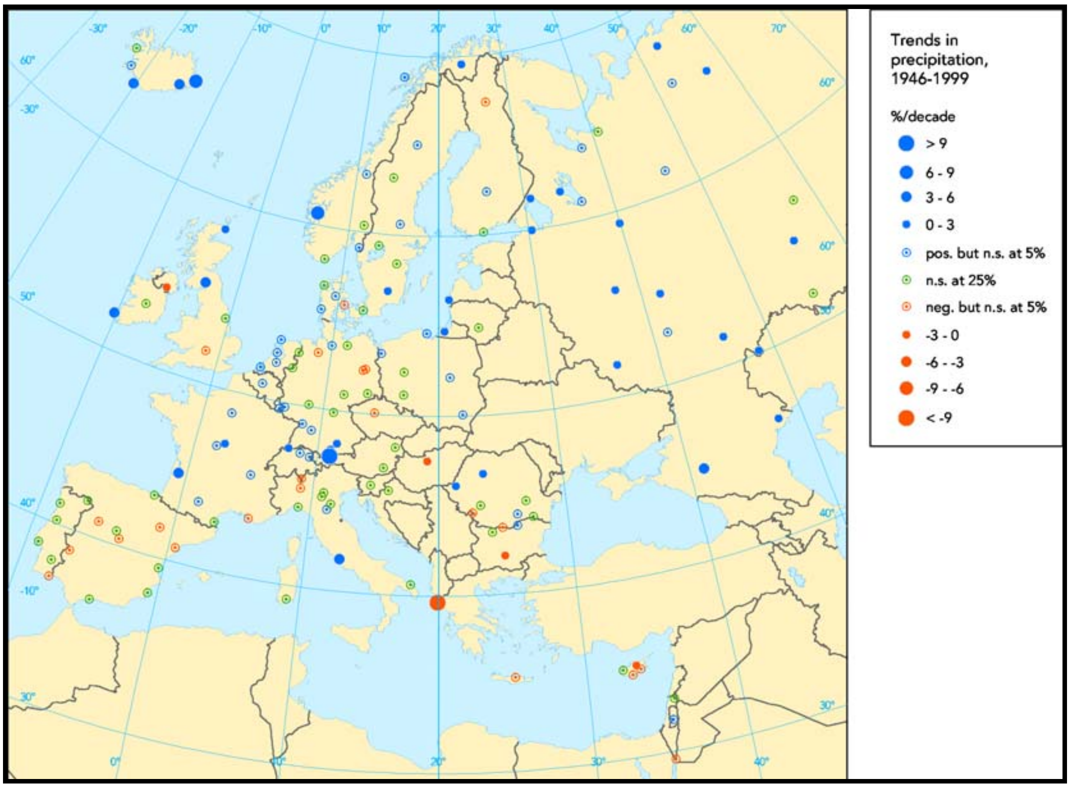


Figure VI.C.5. Precipitation trends across Europe (Klein Tank *et al.*, 2002).

Accepting such uncertainties in assessing the actual magnitude of precipitation reduction, the decrease in river runoff for the Ebro basin is likely to be ~ 0-12% of the mean annual runoff by the year 2050. However, because the Pyrenees contributes about 70% of the total water runoff, it is doubtful whether higher decreases of river runoff should be considered. Moreover, changes in precipitation patterns will in turn affect runoff patterns, thus urging more efficient management of water resources for domestic, agricultural, and industrial use, and runoff regulation for flood protection, especially in large river basins such as the Ebro. The occurrence and magnitude of drought events might also increase, giving in turn rise to further deterioration of the watershed (exacerbating erosion), depletion of overexploited freshwater resources and decline in surface and groundwater quality.

One must bear in mind that, other than increasing air temperature and decreasing precipitation due to climate change, river flows and water quality may be affected also by anthropogenic factors, such as increased water abstraction from the Ebro, changes in water demand patterns, growing pressure from farming and agricultural activities (increasing discharge of nutrient and pesticides), change in agricultural practice and land cover, and industrial development. In the attempt to assess long-term effects of climate change, and separate those from the effects of anthropogenic activities, significant water savings could result from the improvements to the irrigation infrastructure being planned for the Ebro catchment, thus compensating for increased demands linked to climate change-driven increasing temperature (PHN, 2000). However, research is needed to test this assertion.

A further reduction in the Ebro flow might endanger the already tenuous equilibrium between species in the river and its delta. In particular, concern exists about the protection of the endangered fresh water mussel *Margaritifera auricularia* (exclusively found in the Ebro) and ephemeroptera *Ephoron virgo* (very rare in many of the large rivers of Europe). In particular, the survival of the mussel is dependent upon many factors including an appropriate substrate and an adequate flow regime. In addition, the presence of certain fish species is necessary to transport the larval stages of the mollusk upstream for development and recruitment of new adults. No general agreement exists on whether new flow regimes fostered by climate change are compatible with survival of the mussel in the main river channel.

Reduced flows will result in a diminished diluting power in the Ebro. Thus freshwater quality could decrease as a consequence of decreasing flow and/or increasing discharges from agricultural fields and from treatment plants in the Ebro River. Decreased flows would also lead to increasing salt wedge at the river delta. Such effect could be compensated by accurately gauging releases of freshwater from upstream dams. However, no consensus exists on the estimate of appropriate releases. Current knowledge supports the idea that there will be a further increase in salinity in winter and spring months and an increase in phosphorous (from agricultural fields) as a consequence of the decrease in spring flows, fostering an increase of primary production (phytoplankton or macroalgae) in the lower reaches of the river.

Increased salinity in the spring may affect survival of some macroinvertebrates, especially the clam *Margaritifera* and the ephemeroptera *Ephoron*. The effects on fish fauna may be even more dramatic: the native species are adapted to the fluctuations of the river hydrology, while the invasive species are more adapted to constant flow and eutrophic waters; a switch towards latter conditions may cause the definite disappearance of the today much reduced native fish populations. In summary, climate-change-driven decreasing flows in the Ebro River will have a further detrimental effect on the ecological status of the lower part of the watershed.

Transport of dissolved organic matter (DOM) from terrestrial ecosystems to freshwater and, eventually to coastal waters is also an important factor in maintaining the equilibrium of coastal ecosystems. Hejzlar *et al*. (2003) have investigated the effects of climate change on the concentration of DOM. They report a negative correlation between DOM concentration and temperature in well drained soils, whereas in poorly drained soils, DOM concentration tends to increase independent of temperature. Scenarios of possible future climate change related to double atmospheric CO_2 concentration suggests an increase in DOM concentration of about 7%, resulting from a complex of not yet well understood processes.

The productivity of the coastal waters in the region of the Ebro is closely linked to both the total flow volume of water discharged into the sea and the amount of particulate matter and DOM. In general, it is suggested that decreasing flow in the river would have an impact on the productivity of the contiguous coastal areas. Satellite images of chlorophyll a biomass in the Mediterranean Sea show how areas of high productivity overlap with the run-off of the main rivers: the Rhone, the Ebro, the Po and the Evros. In particular the area overlapping with the wide continental shelf off the Ebro River mouth has large populations of foraging seabirds, whether or not associated with industrial fishing vessels (Abelló *et al.* 2003), and is one of the main spawning areas of small pelagics in the western Mediterranean.

Sea level rise

The deltaic body of the Ebro River has developed its present 50 km of sandy shoreline over the last five centuries. The main morphological features are two sandy spits that protrude to form lagoon areas. The delta is a biologically rich and diverse environment (waterfowls, fisheries, vegetation), and supports a large economic system based on tourism, agriculture, hunting, fishing and aquaculture. The existence of the delta area is dependent of the steady supply of sediments (mainly sand) from the river. After centuries of growth, the trend in sediment deposition at the delta area over the last hundred years has reversed, due to the construction of several dams regimenting the flow, so that dynamic equilibrium between river deposition and wave transport has shifted towards prevailing sea wave erosion.

The geological evidence for the past 10,000 to 20,000 years indicates that major temporal and spatial variation occurs in relative sea level change (e.g. figure VI.C.6, Pirazzoli, 1991) on time-scales of the order of a few thousand years. Potential global rise of sea level has been predicted by the IPCC (2001) to range between 0.2 and 0.82 m by the year 2100. It is generally recognized that the synergistic effects of subsidence of the delta, due to reduced sediment deposition, coupled with sea level rise, could be a major threat to the continued, long-term existence of the unique habitat present in the Ebro delta and, in the end, to the existence of the delta system itself. On one hand saline water wedging would be enhanced; on the other hand decreased freshwater and solid discharge and increased nutrient concentration would lead to chemical pollution, increased eutrophication, water salinity and temperature increase, finally affecting the species composition of the various microenvironments of the delta area (macrophites, benthos, fish, etc.).

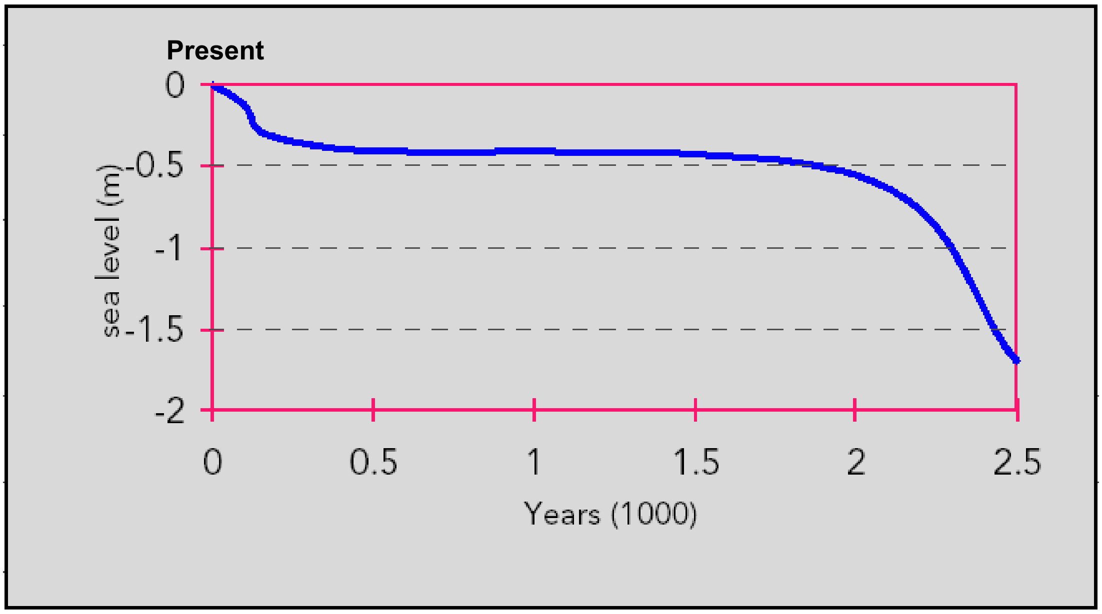


Figure VI.C.6. Average sea level change in the past 2500 years (Pirazzoli, 1991).

Survival of large wetland areas would also be threatened. Those are areas where the vertical growth range of vegetation is very small, so that even slight increases in water level would have the potential of flooding or even sweeping away vegetation, leading to the complete disappearance of marsh ecosystems (Sănchez-Arcilla *et al*., 1996).

Assessment of potential impacts of climate changes in the Mediterranean region, based on several case studies, have been carried out by UNEP/MAP and include drought, floods, changed soil erosion, desertification, storms, coastal erosion, seawater temperature and salinity currents together with sea level rise and biodiversity reduction. Recent paleoclimatic data collected in geologically stable areas, combined with archaeological or historical evidence, indicate that sea level increase for the next century (2100) could be limited to 30 cm, taking into account the pace of anthropogenic enhancement of sea level rise. Such a scenario is compatible with the lower limit range indicated by the IPCC. In the Ebro in particular, the study foresees increased coastal erosion, reshaping of coastline, loss and flooding of wetlands, and reduced fisheries yield.

Sea-level rise and possible changes in the frequency and/or intensity of extreme events, such as temperature and precipitation extremes, cyclones, and storm surges, represent consequences of climate change that are of most concern to coastal zones. Except for sea-level rise itself, there currently is little understanding of the possible interaction of different aspects of climate change in the coastal zone. Other possible changes in climate could be costly. In The Netherlands, the costs of protection against an adverse 10% change in the direction and intensity of storms may be worse than the costs of a 60-cm rise in sea level (Peerbolte *et al*., 1991; IPCC 2001).

Conclusions

Although the physical impact of climate change in all of its dimensions can be better predicted with the constant improvement of the accuracy of models, data obtained on the Mediterranean spatial scale and particularly for the Ebro catchment have still a high uncertainty to properly quantify the future impacts. This is also enhanced if considered in conjunction with other threats posed by human activity (UNEP/EEA, 2000). We conclude that further multi-disciplinary research is still needed to assess the major environmental problems that may arise in the Ebro watershed from increased temperatures, changing precipitation patterns (increasing in turn the frequency of floods and drought events, and acceleration of erosion and desertification), sea level rise, and other threats that originate from climate change, and to distinguish natural fluctuations from the effects of anthropogenic activities.

Chapter VI.C. Climate Change and Nutrient Dynamics in the Po River Basin

Key Points

- **Effects of nutrient reduction in the coastal sea are non-linear and related to a dynamic interaction of chemical, physical and biological processes acting on different temporal and spatial scales in the atmospheric, water and soil ecosystems.**

- **Changes in catchment level nutrient dynamics may impact water quality in the coastal zone. Warmer temperatures are expected to increase primary production, accelerate nutrient cycling and organic matter decomposition leading to an increase of marine vegetation growth.**

- **The contribution of diffuse sources is higher (69%) than point sources (31%) for N, whereas point sources contribute with 62% of the total and diffuse sources with the remaining 38% for P.**

- **Climate changes may lead to significant variations in natural conditions in the Po River watershed producing effects on major driving forces related to eutrophication in the coastal zone.**

Chapter VI.C. The Effects of Climate Change on Nutrient Dynamics in the Po River Basin

VI.C.1 Introduction

Eutrophication in the Northern Adriatic is one of the major negative feedbacks originating from the rapid socio-economic development that has occurred in the Po region over the last decades. Nutrients released at river catchment level are carried to the Adriatic Sea by several important rivers and of these the Po makes the largest contribution. In order to mitigate eutrophication a reduction of the impact of anthropogenic sources in the catchment is needed, however, it is well known that the effects of nutrient reduction are non-linear and related to a dynamic interaction of chemical, physical and biological processes acting on different temporal and spatial scales in the atmospheric, water and soil ecosystems (Pirrone *et al*., 2005). Among the external forces that can affect the nutrient cycle, climate change may play an important role in the overall water cycle and affect pollutant transport pathways on a river catchment - coastal zone continuum scale. Changes in temperature and precipitation since the beginning of the 20th century yield a global surface temperature change of +0.6 ±0.2°C, with the sea surface temperature rise about half that of the mean land-surface air temperature rise, a continued decrease in snow cover and the extent of land-ice all suggest that global warming is a major driving force that should be considered in long-term trend analyses of environmental pressures acting at local to global scales. Since the 1960s the extent of snow cover has decreased by about 10% and similarly the annual duration of lake and river ice has decreased by about two weeks at mid- to high latitudes in the Northern Hemisphere. The annual land precipitation has increased in the middle and high latitudes of the Northern Hemisphere whilst it has decreased over the sub-tropics, showing a strong relationship with annual stream flow. Recent studies suggest that significant differences between regional patterns are primarily related to various phases of atmospheric-oceanic oscillations such as the NOA and the ENSO (Avila *et al*., 1996; IPCC, 1996; IPCC, 2001a).

Thus changes in catchment level nutrient dynamics may impact water quality in the coastal zone. Warmer temperatures are expected to increase primary production, accelerate nutrient cycling and organic matter decomposition leading to an increase of terrestrial and marine vegetation growth. The foreseen contrasting trends in precipitation due to changes in catchment hydrology will have a contrasting effect on terrestrial vegetation and a significant impact on nutrient cycling, leading to an increase in winter nutrient inputs and a summer decrease. Therefore in order to identify optimal management strategies aimed at the reduction of CZ eutrophication, there is a strong need to promote integrated catchment-coastal zone continuum research to evaluate the effects on the nutrients cycle of the major driving forces related to climate change.

VI.C.2. The Nutrient Cycle and the Climate Change

A preliminary assessment of the relative contributions of the major driving forces related to climate change on nutrient dynamics in the Po catchment-North Adriatic Sea continuum has been performed adopting the Driver-Pressure-State-Impact-Response (DPSIR) approach. In the DPSIR analysis, major driving forces included both human and pseudo-natural drivers (not properly natural because they are of anthropogenic origin) (see Table VI.C.1). The nutrient loads (i.e. environmental

Pressures) deriving from these Drivers are reported (see Table VI.C.2) (ABP, 1999) in terms of “Potential” and “Effective” loads for both nitrogen and phosphorous. Table-2 suggests that the contribution of diffuse sources is higher (69%) than point sources (31%) for nitrogen, whereas for phosphorous point sources contribute with 62% of the total and diffuse sources with the remaining 38%.

Table-VI.C1: Drivers affecting the nutrients transport pathways related to anthropogenic and natural forces.

	Drivers	Catchment	Coastal zone
Human activities	Agriculture	+	
	Livestock	+	
	Industry	+	
	Population	+	+
	Tourism		+
Socio-economic framework and governance	Legislation	+	+
	Institutions	+	+
	Policies	+	+
Natural Conditions	Climate	+	+

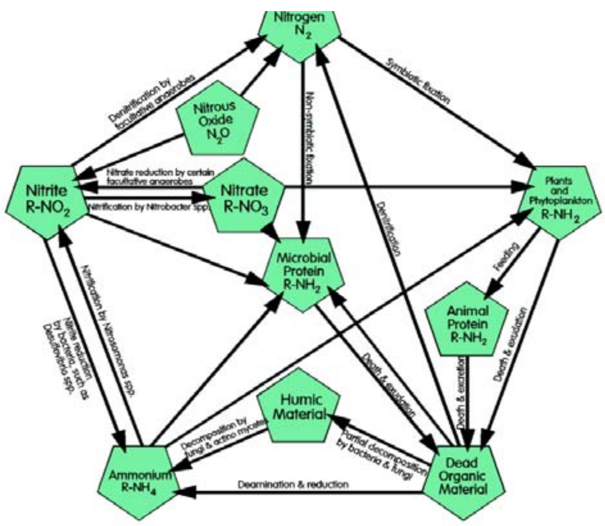
Table-VI.C.2: Potential and effective nutrient loads in the Po catchment estimated for diffuse and point sources (from ABP, 1999).

Source	Sector	Nitrogen *t/y*	Nitrogen *%*	Phosphorus *t/y*	Phosphorus *%*
		Potential Loads			
Point	Civil	78000	11	10000	6
	Indstrial	25000	4	1000	1
Diffuse	Livestock	260000	39	50000	33
	Agriculture	310000	46	90000	60
	Total	**673000**	**100**	**151000**	**100**
		Effective Loads			
Point	Civil	61000	23	6000	56
	Industrial	22000	8	700	6
Diffuse	Livestock	105000	40	2100	20
	Agriculture	60000	23	1200	11
	Superficial runoff	15000	6	750	7
	Total	**263000**	**100**	**10750**	**100**

Nutrient drivers

It is well known that Nitrogen (N) and Phosphorous (P) are present in the environment and that their inorganic forms are ‘reactive’ and therefore potential pollutants when in excess or in the wrong place (Hatch *et al*., 2002). Nitrogen is an essential nutrient to both plants and animals, it is found in different organic and inorganic forms, and its biogeochemical cycle occurs in the soil, water and atmospheric compartments. Water is the main carrier of N but the atmosphere is the major source and the cycle is soil based. Anthropogenic activities interact with the natural N cycle by introducing inorganic fertilizers and spreading manure. Waste water also increases N input to the catchment. Meanwhile, atmospheric nitrogen reaches the soil through atmospheric scavenging by precipitation and it is transformed into inorganic forms. Other natural inputs of N are related to chemical and biological transformations of organic material. The major chemical and physical processes that occur in the nitrogen cycle include denitrification, volatilization, runoff and leaching (Figure-VI.C.7). Bacterial activity (denitrification) transforms nitrates present in soil to gaseous nitrogen (N2) which is released to the atmosphere; similarly, urea fertilizers and manures emit gaseous nitrogen to the atmosphere (volatilization); both processes have a strong effect on soil fertility. The runoff process is an important transport mechanism that carries nitrogen loads to rivers, lakes and the sea; while leaching is

Figure-VI.C.7: The nitrogen cycle (from: Edwards & Alken-Murray Corporation, http://www.alken-murray.com/Phosphorous.html).



the main carrier of nutrients to groundwater.

Like nitrogen, phosphorous is one of the most important mineral nutrients for biological systems, but unlike nitrogen, is found in sedimentary rocks and not in the atmosphere (Leinweber *et al*., 2002). Phosphate rocks are eroded resulting in a phosphorous supply available to plants and then to animals. Through plant or animal tissue and faeces, phosphorous is returned to water and soil in organic forms. Phosphorous in the soil is dissolved in water. Much phosphorous is lost at the bottom of oceans. The main pathways involved in the P cycle are similar to those of the nitrogen cycle although the chemical, physical and biological processes are different. Manure, fertilizers and detergents are the main factors that can influence the phosphorous cycle. Therefore, the major drivers are agriculture, livestock and demography, whereas tile drainage, groundwater and runoff are the major pathways to be considered when evaluating the effects of climate change.

Table-VI.C.3: Selected physiographic characteristics and socio-economic indicators of Po Catchment (after Pirrone et al., 2005).

General data	
Drainage area (Italy 96%, Swiss and France 4%)	73,760 km^2
Length of the river	652 km
Minimum annual discharge (Pontelagoscuro)	275 m^3/s
Maximum annual discharge (Pontelagoscuro)	10,300 m^3/s
Average annual discharge (Pontelagoscuro)	1,510 m^3/s
Average altitude	740 m a.s.l.
Delta area	380 km^2
Municipalities	3,251
Inhabitants	15,764,600
Density (min – max)	25 - 1,478 inhab./km²
Employed industry	3,171,000
Employed tertiary	2,791,000
Cultivated area	31,000 km^2
Cows	4,188,000 heads
Pigs	5,232,000 heads
Water resource uses	
Area with irrigation use	1.5 x 10^4 km^2
Diverted flow rate	1,850 m^3/s

Modeling the nutrient pathways in the Po Catchment

To estimate the effect of climate-change-related pressure factors on nutrient transport pathways at catchment scale, a multi-compartment steady-state model was used (Algieri et al., 2003; Pirrone et al., 2005). Point and diffuse sources were considered in assessing the relative contribution of different nutrient transport pathways within the catchment and to the CZ. Key socio-economic indicators (Table-VI.C.3) were used in the model, each sub-catchment was characterized using GIS developed for the Po catchment, and the final nutrient amount was referred to the Pontelagoscuro outlet station (the reference station). For each sub-basin, and for the total catchment, the relative contribution of each transport pathway was estimated for both nitrogen and phosphorous (see Table-VI.C.4). Our preliminary modelling results show that a large contribution is from diffuse sources, whereas WWTPs and urban systems represent a significant pathway for phosphorus load discharged to the Po catchment and transported to the North Adriatic CZ. Nitrogen is mostly generated by agricultural activities (groundwater and tile drainage accounting for more than 60%), but WWTPs and urban systems represent a

Table-VI.C.4: Relative contributions of selected transport pathways of nutrients loads in the Po basin assuming the 2001 as reference year (Pirrone et al., 2005).

Pathway	**Nitrogen**		**Phosphorous**	
	t/y	*%*	*t/y*	*%*
Atmospheric deposition	1350	0.5	61	0.6
Tile drainage	67212	25.6	1496	14.4
Groundwater	95830	36.4	862	8.3
Overland flow	4536	1.7	445	4.3
Erosion	958	0.4	835	8.0
WWTP	68992	26.2	3677	35.4
Urban systems	24091	9.2	3010	29.0
Total	**262 969**		**10 386**	

Table-VI.C.5: Scenario for the Mediterranean system (IPCC, 2001). Indicators of observed (2000) and predicted (2025, 2050, 2100) changes.

Indicator	**2000**	**2025**	**2050**	**2100**
Global mean temperature (change from 1961-1990 average, *°C*)	0.2	0.4–1.1	0.8–2.6	1.4–5.8
Continental precipitation (change *mm day*$^{-1}$)	0	-0.25		
Heavy precipitation events		Increased	Increased	Increased
Frequency and severity of drought		Increased	Increased	Increased
Snow cover area (since 1960)	-10%	Decreased	Decreased	Decreased
Growing season (days per decade)	1 to 4		Lengthened	Lengthened

significant contribution (35% of the total). Phosphorus is released primarily by WWTPs and urban systems (64%), but the erosion, tile drainage and groundwater pathways are significant (31%). The modelling process shows, as expected, the strong dependence of nutrient fluxes on the water balance.

Table-VI.C.6: Assumptions adopted for the A, B, C scenarios for modelling nutrients dynamics in the Po Catchment.

Scenario	Hypothesis	2025	2050	2100
A	Variation of Continental precipitation. [*mm day*$^{-1}$]	-0,25	-0,35	-0,50
B	Heavy precipitation events: % Increase in number of days with storm water events.	+15 %	+30%	+50%
C	Variation of maximum Groundwater recharge value. [*mm*]	1500	1000	700

The selected scenarios hereafter analysed were based on IPCC scenarios (IPCC, 2001) assuming a doubling of atmospheric CO_2 by 2030. These scenarios were based on the projection of selected key parameters including temperature, precipitation, wind, air humidity, soil moisture as suggested in IPCC (2001) and detailed in Table-VI.C.5 and Table-VI.C.6.

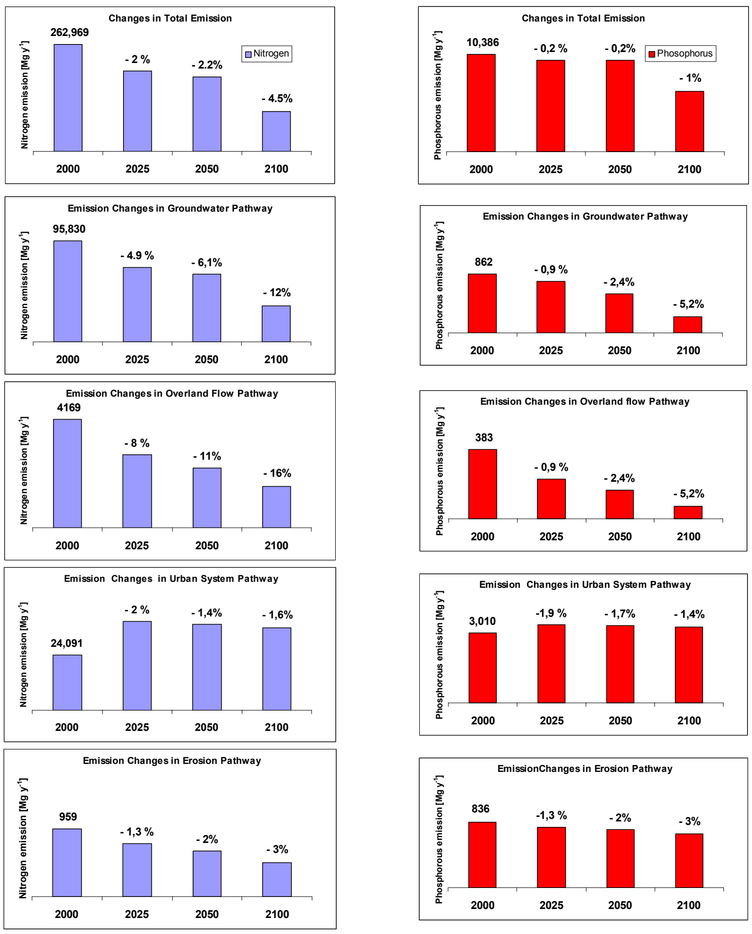


Figure-VI.C.8: Effects of precipitation changes on nutrients emission assuming the 2001 as reference year.

Scenario A

Projected total emission (in 2100) of nitrogen and phosphorus show a 4.5% and 1% reduction, respectively. Although the overall N and P projected reductions are small their relative variation for each transport pathway can be substantial.

Transport by the overland flow and groundwater pathways show a relevant decrease for both nutrients with a decrease in precipitation, this effect is primarily caused by a reduction of runoff into rivers affecting the nitrogen mobility within the soil. Meanwhile, the urban system pathway shows an increase of both N and P emissions related to changes in their inputs from urban areas, for which the contribution derives from a wide array of sources *e.g.,* households, industrial indirect discharge, traffic, paved and unpaved areas, these were estimated separately and later lumped in the same category. An opposite behaviour of nutrients emission pathways is expected with changes in water balance.

Scenario B

The major outcome of this scenario is that heavy precipitation events do not result in significant variation of nutrient loadings with total N and P loading varying by 2%

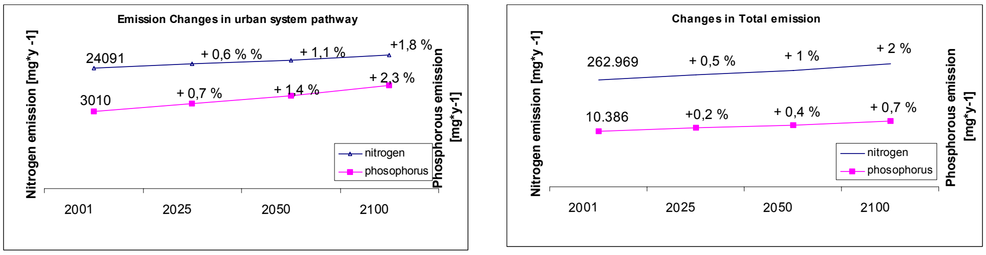


Figure-VI.C.9: Effects of heavy precipitation events change on nutrients emission assuming the 2001 as reference year.

and 0.7%, respectively (Figure-VI.C.9). Assuming a constant precipitation, the observed variations are due only to changes in the number of precipitation events; it is important to point out that the influence of relevant processes such as *e.g.,* erosion, leaching and overland flow, was not considered in this preliminary analysis. Among the possible pathways, the urban system exerts a considerable effect on the nutrient load changes, variations of +1.8% for N and +2,3 % for P are expected primarily due to the direct relationship between the number of storms events and nutrient emissions.

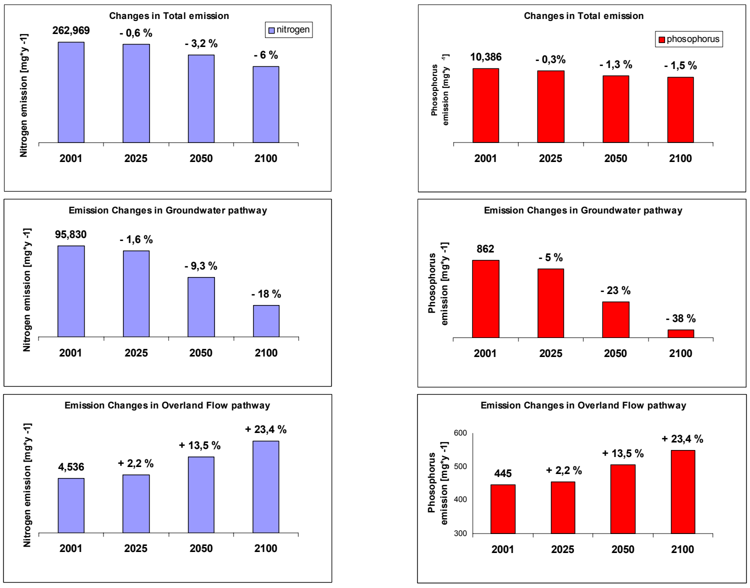


Figure-VI.C.10: Effects of groundwater recharge changes or nutrients emission assuming the 2001 as reference year.

Scenario C

This scenario is aimed at the evaluation of nutrient emission changes with the maximum groundwater recharge (see Table-VI.C.6.) This scenario highlights some "indirect effects" of climate change involving water resources. The total emission of nutrients shows a small decrease expected for the year 2100 (Figure-VI.C.10). A step-by-step analysis shows that high reductions in N (18%) and P (28%) are expected with changes in the groundwater pathway, whereas increases of 23% in N load and 23% in P load are expected to occur with changes in overland flow. The decrease of emissions within the groundwater pathway is related to the reduction of ground water volumes, while the increase of emissions in overland flow is due to the change of water dynamics through the soil.

VI.C.3 Final remarks

In order to identify optimal strategies to reduce eutrophication in the NA Coastal Zone there is a strong need to improve our understanding of the long-term effects of Climate Change in combination with projected changes in socio economic indicators. Our preliminary evaluation for the Po Catchment-NA coastal zone continuum suggests that climate changes may lead to significant variations in natural conditions producing effects on major driving forces related to eutrophication (see Table-VI.C.7). One of the major effects of Climate Change at the Po catchment scale is a significant variation in the water balance due to the reduction of precipitation. Thus, as a consequence, the natural system will likely be altered, with a reduction of water resources and the increase in water demand for both human consumption and productive activities, especially agriculture the major high water consumption economic activity in the Po Basin. Moreover, changes in natural conditions, as the increase of extreme events, will likely modify the terrestrial system and exacerbate environmental problems caused by habitat loss leading to a reduction of biodiversity (animal species extinction). Meanwhile, in the North Adriatic Sea the effects of climate change combined with socio-economic development could seriously alter natural conditions not only in terms of eutrophication but also in terms of habitat destruction biodiversity loss, coastal erosion and loss of wetland areas.

Table-VI.C.7: Main factors and consequences adopted in the assessment of climate change effects on the Po River-North Adriatic system (data based on the scenario assessment for the Mediterranean system)

	Climate change effects		
	Catchment		**Coastal Zone**
Agricultural effects			
Average crop yields	• Increase	Coastal shorelines	• Increased erosion of shorelines
Extreme low and high temperatures	• Reduced frost damage. • Increased heat stress damage to crops and livestock	Coastal wetlands	• Permanent inundation • Loss of wetland habitat • Increase of flood risk • Salt intrusion • Change in river discharge
Incomes and prices	• Food prices increase.		
Water supply	• Peak river flow shifts.	Habitat	• Loss of biodiversity • Increase of algal blooms • Increase in net primary productivity • Change in ecological parameters • Introduction of new species
Water quality	• Degraded by higher temperatures; • Changes by water flow volume changes. • Increase in saltwater intrusion.		
Water demand	• Increase of demand.	Water quality	• Change of trophic conditions
Extreme events	• Increased flood damage. Increased drought frequency. • Increased flood damage. increased drought frequency		
Terrestrial ecosystems			
Habitat	• Increase in net primary productivity. • Increase in frequency of ecosystem disturbance. • Loss of habitats. • Increase of fire risk	Economic activity	Reduction of tourists hosted
Biodiversity	• Shifts in ranges of plant and animals. • Extinction of species.		
Ice environments			
Glaciers	• Retreat of glaciers, Decreased sea-ice extent • Substantial loss of ice volume from glaciers. • Ground subsidence leading to infrastructure damage.		

Chapter VI.D. Climate Change and the Mercury Biogeochemical Cycle

Key Points

- **Natural sources (volcanoes, surface waters, soil and vegetation) contribute ~2700 tonnes.year^{-1} of Hg released to the global atmosphere, whereas the contribution from major industrial sources account for ~2250 tonnes.year^{-1}.**

- **Mercury emissions in Europe and North America contribute < 25% to the global atmospheric emissions, whereas Asia accounts for about 40% of global total. The majority of the emissions originate from combustion of fossil fuels, particularly in Asia. Combustion of coal is and will remain the main source of energy in the near Asian future.**

- **Climate change may impact the global Hg cycle via primary effects (increase in air and sea temperatures, wind speeds and variation in precipitation patterns), and secondary effects (related to an increase in O_3 concentration and aerosol loading, to a decrease of sea ice cover in the Arctic and changes in plant growth regimes). All these primary and secondary effects act on difference time scales and influence the atmospheric residence time of mercury and ultimately its dynamics from local to regional and global scale.**

- **Hg in European soils especially from deposition over the centuries raises the possibility that Hg emissions from soils will increase due to soil OM oxidation releasing it into surface and coastal waters. This increased Hg load has the capacity to contaminate aquatic food webs beyond any new emission sources.**

Chapter VI.D. Climate Change and the Mercury Biogeochemical Cycle

VI.D.1. Background

During the 80's and part of 90's most research on atmospheric mercury has focused on sources and deposition to terrestrial watersheds and freshwater lakes. The recent advances in automated techniques for the accurate measurement of gaseous oxidised mercury species, at the concentrations typically encountered in the atmosphere, have had a major impact on the study of mercury cycling in the environment. The use of these instruments at contaminated sites and in remote locations has produced not only more, but also more reliable data with greater time resolution in the last 3-4 years than in all the time atmospheric mercury has been studied (EC 2001; UNEP 2002 and references herein).

It is well known that mercury is released to the environment from a multitude of **natural and anthropogenic sources**. Once released to soil, water and atmospheric ecosystems it can be re-distributed in the environment through a complex combination of chemical, physical and biological processes that can act with different time scales. Recent estimate indicate that natural sources (volcanoes, surface waters, soil and vegetation) contribute with 2700 tonnes of mercury released annually to the global atmosphere, whereas the contribution from major industrial sources account for 2250 tonnes per year (Pirrone *et al*. 1996; Pirrone *et al*. 2001; Pacyna *et al*. 2003). Mercury emissions in Europe and North America contribute less than 25% to the global atmospheric emissions, where Asia account for about 40% of global total. The majority of the emissions originate from combustion of fossil fuels, particularly in the Asian countries including China, India, and South and North Korea. Combustion of coal is and will remain in the near future as the main source of energy in these countries. The emissions from stationary combustion of fossil fuels (especially coal) and incineration of waste materials accounts for approximately 70% of the total quantified atmospheric emissions from significant anthropogenic sources. As combustion of fossil fuels is increasing in order to meet the growing energy demands of both developing and developed nations, mercury emissions can be expected to increase accordingly in the absence of the deployment of control technologies or the use of alternative energy sources.

Once released to the atmosphere, mercury and its compounds can be transported over long distances before being removed by particle dry deposition and wet scavenging by precipitation. The temporal and spatial scales of mercury transport in the atmosphere and its transfer to aquatic and terrestrial receptors depends primarily on the chemical and physical forms of mercury that drive their interactions with other atmospheric contaminants and with surface marine waters as well. Gaseous elemental mercury (Hg^0) is relatively inert to chemical reactions with other atmospheric constituents, and is only sparingly soluble in pure water. Therefore, once released to the atmosphere, mercury can be dispersed and transported for long distances over hemispheric and global scales before being deposited to terrestrial and aquatic receptors. The concentration of Hg^0 in ambient air is mainly determined by the background concentration of around 1.5-1.8 ng m^{-3} in the Northern Hemisphere and 0.9 – 1.5 ng m^{-3} in the Southern Hemisphere (see Table VI.D.I). Oxidised mercury (Hg(II)) and mercury bound to particulate matter (Hg(p)) are typically present in concentrations less than 1 % of the Hg^0 (see Table VI.D.I for details).

Table VI.D.1 - Typical concentrations of Hg species in the planetary boundary layer.

Species	Conc Range	Location	References
Hg^0 (ng m^{-3})	0.5 – 1.2 1.1 – 1.8 0.8 – 2.2 1.5 – 15 0.1 – 1.4 0.1 – 1.1 1.7 – 4.1	Atlantic air, southern hemisphere Atlantic air, continental background, northern hemisphere Mediterranean air* Continental air, urbanized, industrial Arctic* Antarctica* United States	UNEP, 2002 Wängberg *et al.,* 2001; EC, 2001 Sprovieri *et al.,* 2003; Pirrone *et al.,* 2001; 2003a Sprovieri *et al.,* 2000 Sprovieri *et al.*, 2002*;* Ebinghaus *et al.,* 2002 Keeler *et al.,* 1995 Landis *et al., 2002*
Hg(II) (pg m^{-3})	< 30 up to 40 5 – > 50 up to 200	Background air marine and continental (1) near sources Antarctica and Arctic (1)	Sprovieri *et al.,* 2003; Pirrone *et al.,* 2001; 2003 Wängberg *et al.*, 2003 Sprovieri *et al.,* 2002
Hg(p) (ng m^{-3})	0.1 – 5 0.1 – 25 5 - >50	Background air Marine (Mediterranean air) (1) Continental background, higher near sources. Antarctica and Arctic (1)	Sprovieri *et al.,* 2003; Pirrone *et al.*, 2001; 2003 Wängberg *et al.,* 2003 Sprovieri *et al.,* 2002
CH_3HgX	0.1 – 10	Background air	Lee *et al*., 2003
$(CH_3)_2Hg$	< 5 -30	Background air Marine polar air	
Hg(II) in precipitation (ng L^{-1})	1 – 20	Background / marine locations	Wängberg *et al.,* 2001 Keeler *et al.,* 1995

(*) Sampling time of 5 minutes, whereas the average concentrations reported in the table are related to the whole study period.
(1) Sampling time of 2 hours, whereas the average concentrations reported in the table are related to the whole study period.

Atmospheric deposition to marine waters **is driven primary by particle dry** deposition and wet scavenging by precipitation mechanisms. Generally, the relative contribution of wet deposition accounts for about two thirds of the overall mercury budget entering to the marine system compared to particle dry deposition. However, in warm and dry region (i.e., Mediterranean) dry deposition was found to account for nearly 50% of the total flux. Gas exchange of gaseous mercury between the top water microlayer and the atmosphere is considered the major mechanisms driving gaseous mercury from the seawater to the air (e.g., Pirrone *et al*. 2001; Pirrone *et al*. 2003).

Once released to marine waters, it undergoes a number of chemical and physical transformations. Hg^0 is found in the mixed layer and in deeper waters of the ocean with concentrations generally ranging from 0.01 to 0.5 pM (e.g., Horvat *et al*. 2000). Gas exchange via Hg reduction and volatilization is the major loss term for marine Hg. Due to the low solubility of Hg^0 in water, almost all the aqueous mercury is present as Hg(II) in the inorganic form and organic methylmercury. Mercury levels in fish constitute a long-standing health hazard and this environmental problem relates predominantly to the conversion of inorganic Hg in neurotoxic monomethylmercury (MMHg) and dimethylmercury (DMHg) (e.g., IARC, 1994). MMHg is about 100 times more toxic than inorganic Hg and has been found to be mutagenic under experimental conditions. Anthropogenic activities presumably increased the surface water marine Hg concentration by a factor three, an increase which resulted amongst others in elevated Hg concentrations in marine fishes (e.g., Amyot *et al*. 1997; Horvat *et al.* 2001). It is currently thought that most of the methylated Hg found in the water column and the biota of the marine waters is generated by *in-situ* production, though the reaction mechanisms are not yet clearly understood (e.g., Mason *et al*. 2002; Hintelman *et al*. 1997).

Variations in the regional and global mercury cycle between atmospheric, marine and terrestrial ecosystems over time can occur due to changes in emissions of mercury and other atmospheric contaminants (e.g., NO_x, SO_2) as well as to climate change. The **effects driven by climate change** on the global mercury cycle can be classified as primary and secondary effects. Primary effects account for an increase in air and sea temperatures, wind speeds and variation in precipitation patterns, whereas secondary effects are related to an increase in O_3 concentration and aerosol loading, to a decrease of sea ice cover in the Arctic and changes in plant growth regimes. All these primary and secondary effects may act with difference time scales and influence the atmospheric residence time of mercury and ultimately its dynamics from local to regional and global scale.

VI.D.2. The Lifetime of $Hg^0_{(g)}$ in the Planetary Boundary Layer

The lifetime of elemental mercury is determined by the reactions which convert $Hg^0_{(g)}$ to $Hg(II)_{(g)}$ which is much more readily scavenged and deposits much more rapidly than $Hg^0_{(g)}$. The major atmospheric oxidants of $Hg^0_{(g)}$ are O_3 and OH in the continental boundary layer and Br and other reactive halogen species in the Marine Boundary Layer (MBL). There are exceptions to these generalisations however, it is known that in the Arctic halogens are important in so-called Mercury Depletion Events (MDEs), these are nonetheless seen at coastal sites and thus not far removed from the MBL. The other known exception is the Mediterranean Sea region, where very high O_3 concentrations are seen, particularly during the summertime (when air quality

Table VI.D.2.– Mercury depletion (%) as a function of relative humidity (rh) and *O_3 concentration (*O_3 concentrations were derived from IPCC (2001) WG-1 scenarios*).*

	O_3 concentration		
% $Hg^0_{(g)}$ depletion after 7 days	**30 ppb**	**60 ppb**	**80 ppb**
10% r.h.	12.5	18	21
40% r.h.	19.5	28	33
70% r.h.	24	34	40

standards are often exceeded) and OH proves to be a major $Hg^0_{(g)}$ oxidant even in the MBL. The impact of increasing O_3 concentrations in the atmosphere, including the boundary layer seen in some IPCC modelling scenarios, would therefore have an influence on the atmospheric oxidation rate of $Hg^0_{(g)}$, which in turn would influence Hg deposition both in terms of dry and wet deposition. The nature of this influence is not however entirely clear. Over the land Hg oxidation would certainly occur more rapidly, although both relative humidity (which influences OH concentration) and O_3 concentration play a part as seen in Table VI.D.II. The figures reported in Table VI.D.2 were obtained using a version of the Chemical Balance Model-IV (CMB-IV) to which atmospheric Hg chemistry has been added.

Due to its relative involatility, $Hg(II)_{(g)}$ produced in the atmosphere is readily scavenged by rain and also by particulate matter. If O_3 and particulate matter concentrations increase, the probability is that continental air would contain more oxidised $Hg(II)_{(g)}$ and Hg associated with particulates than previously, especially if the air were humid. Deposition of Hg would therefore occur closer to sources, or would occur where dryer continental air meets more humid air. Thus there is the possibility that Hg deposition would increase substantially in coastal areas. Hg sources located near coasts could provide much more local contamination than has so far been the case.

The **cycling of Hg in the MBL** is not yet entirely understood, certainly $Hg^0_{(g)}$ is oxidised quite rapidly under conditions favouring the release of reactive halogen compounds from sea salt aerosols, and it has been suggested that changes in global wind fields as a result of climate change would alter the distribution of the acid gases which promote halogen activation and also tend to result in higher production rates of sea salt aerosol. This would increase the rate of $Hg^0_{(g)}$ oxidation in the MBL. Interestingly though a concurrent increase of the boundary layer O_3 concentration would actually contrast this increase because higher O_3 would produce higher HO_2 which is the primary sink for active Br compounds in the MBL. To test this hypothesis the AMCOTS box model (Hedgecock and Pirrone 2001; 2003) which has already been used to study the lifetime of $Hg^0_{(g)}$ in the MBL has been run with higher than usual O_3 concentrations (as suggested in IPCC (2001) WG-1 scenarios). Using typical seasonal cloud cover and air temperature values for the three latitudes used, increasing the initial O_3 concentration in the model, actually results in less $Hg^0_{(g)}$ depletion in most instances.

The fact that in spite of rapid oxidation in the MBL the background $Hg^0_{(g)}$ concentration, at least hemispherically, points to an extremely dynamic exchange of Hg between the MBL and marine waters. Unfortunately not all the processes that regulate this exchange are at all well understood, but the perturbation of the processes that contribute could result in an imbalance, leading to far greater Hg input into coastal and marine waters.

Many studies during the 90's have indicated an atmospheric lifetime of Hg^0 of around one year, based on mass balance considerations. Field measurements in the Arctic and Antarctic during polar spring have, however, shown that under these specific conditions Hg^0 can behave as a reactive gas with a lifetime of minutes to hours during MDEs (e.g. Schroeder *et al.,* 1998, Ebinghaus *et al.,* 2002). These MDEs occur only during a limited time of a few weeks and are not representative of the overall behaviour of atmospheric Hg^0. Recent modeling and several Arctic field studies suggest that atmospheric Hg has the shortest **lifetime** when air temperatures are low and sunlight and deliquescent aerosol particles are plentiful (Hedgecock and Pirrone, 2004). Thus the modeled lifetime for a clear sky condition is actually shorter at mid-latitudes and high latitudes than near the Equator, and for given latitude and time of year, cooler temperatures enhance the rate of Hg^0 oxidation. Under typical summer conditions (for a given latitude) and cloudiness, the lifetime (τ) of Hg^0 in the MBL is calculated to be around 10 days at all latitudes between the Equator and 60° N. This value is much shorter than the generally accepted atmospheric residence time for Hg^0 of a year or more. Given the relatively stable background concentrations of Hg^0 which have been measured, continual replenishment of Hg^0 must take place, suggesting a '*multi-hop*' mechanism for the distribution of Hg, as originally suggested by Mackay *et al.* (1995), rather than solely aeolian transport with little or no chemical transformation between source and receptor.

Primary effects

The effects of **increased air temperature** are not obvious, but higher temperatures favour ozone production, increase the oxidation rate of Hg^0 to more soluble forms, and may alter the partitioning between the gas and particulate phases which would effect deposition patterns over time and spatial scales.

An **increase of seas temperature** may cause significant increase of elemental Hg emission rates from the seas that would lead to increase of Hg re-cycling between the atmosphere and, possible impacts on coastal zones. Increase in seas temperature may cause significant changes in biological activity of the oceans that would lead to changes in the rate and spatial distribution of Hg methylation and therefore Hg redistribution between the biotic and abiotic marine systems.

Changes in precipitation patterns as an increase in precipitation frequency and intensity would cause an increase in Hg deposition (input) to marine waters. Higher frequencies of extreme events that tend to result in increased run-off rather than the water being absorbed by the soil would tend to increase Hg loadings transported to rivers and thus seas.

Secondary effects

Higher O3 concentration: it would determine higher rates of Hg oxidation in the atmosphere, thus more local dry and wet deposition rates to surface waters.

Increased average wind speeds: it would cause higher sea salt aerosol production, possibly higher levels of reactive inorganic Br compounds, and increase in Hg oxidation that would increase deposition fluxes.

Less sea ice and snow cover in the Arctic: with greater areas of ocean exposed MDEs could become more frequent, if more bare land is uncovered the almost direct re-emission of Hg from the snow could be reduced increasing the Hg loading to the Arctic ecosystem.

Increases aerosol loading: gaseous Hg^0 is not generally readily scavenged by aerosol particles, with the exception of black carbon, in fact activated charcoal is a useful adsorbent for $Hg^0_{(g)}$. Oxidised Hg compounds however are extremely prone to scavenging both by dry and deliquesced aerosol particles due to their involatility and usually high solubility. Should atmospheric oxidation rates of Hg increase, see above, and at the same time aerosol loading increases the atmospheric concentration of Hg associated with atmospheric particles would be expected to increase significantly. The transport of oxidised Hg compounds on particles depositing to water bodies could become the major pathway for water-soluble Hg compounds to reach aquatic environments. Washout of particles by precipitation would also introduce these oxidised compounds directly to water bodies, and also indirectly via run-off.

One aspect of increased aerosol loading which may have particular consequences for the marine environment is the increased production of sea salt particles resulting from changes in global wind fields (Sander et al., 2003). An increase in sea salt aerosol, would increase the concentration of reactive halogen (particularly Br) in the MBL, accelerating $Hg^0_{(g)}$ oxidation. If combined with an increase in acid gases, or their precursors, from anthropogenic emissions which are necessary to acidify sea salt particles and initiate halogen activation, the effect on the oxidation rate of $Hg^0_{(g)}$ in the MBL would be noticeable. Using the box model AMCOTS Hedgecock and Pirrone (2004) suggest that a decrease of liquid water content (LWC) (due to deliquesced sea salt particles) would reduce the rate of Hg^0 depletion. Increases in sea salt loading increase oxidation and decrease $Hg^0_{(g)}$ residence time. The fall off seen in Figure VI.D.1 as LWC increases is because under the model conditions for the remote MBL the concentrations of acid gases were not high enough to titrate the sea salt aerosol alkalinity. If the acid gas concentration is increased in the model the fall-off in $Hg^0_{(g)}$ depletion is not seen. Increases in LWC beyond 300% showed a more rapid initial effect on Hg^0 depletion, which then diminished. This was due to more rapid halogen activation, followed by a more rapid decline in the concentrations of active halogen compounds.

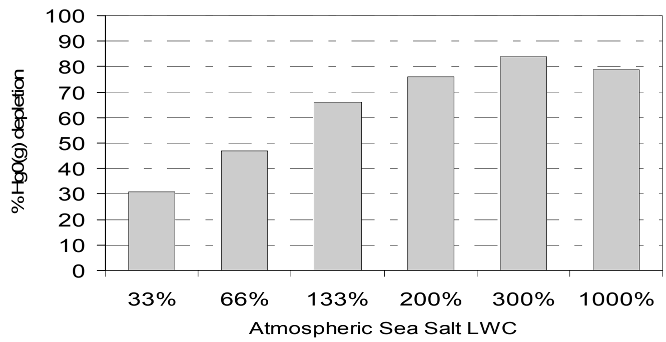


Figure VI.D.1 – Modeled Hg^0 depletion rate (%) with LWC of sea salt aerosol.

Changes in plant growth regimes: evapotranspiration rates would change increasing where biological growth occurs faster. Most Hg in leaves comes from the atmosphere, changes in uptake from the atmosphere, but the dynamics of Hg release from leaf litter are not really understood.

The occurrence of Hg in European soils especially from anthropogenic emissions and deposition over the centuries raises the distinct possibility that Hg emissions from soils will increase. One scenario under consideration is, in a warmer and drier environment under climate change, Hg emissions will increase due to soil OM oxidation releasing it into surface and coastal waters. This increased Hg load has the capacity to contaminate aquatic food webs beyond any new emission sources. This is just one of the possible feedbacks in a climate-changed world.

Climate Change
and the
European Water Dimension

Chapter VI.E. Climate Change and Waterborne and Vector-Borne Diseases

Key Points

- **Extreme weather events and changes in weather conditions increase the frequency of heavy rainfall events, with associated flooding and increased temperature, with a concomitant increase in waterborne and vector-borne infections.**

- **There is increasing evidence that global warming might lead to an increase of infectious disease outbreaks, particularly in developing countries.**

- **Changes in the distribution and abundance of disease vectors and reservoirs are likely to be amongst the most important and immediate effects of climate change.**

- **Climate-based models are probably not sufficient to predict future changes in transmission of vector-borne disease and their geographic distribution.**

- **Rapid molecular methods for detection of infectious agents and a new group of models that combines information from climate, epidemiology and human behavior need to be developed.**

VI.E. Climate change and waterborne and vector-borne diseases

VI.E.1. Introduction

Climate can influence the emergence and transmission of infectious agents and the specific mechanisms underlying the linkages between climate and infectious diseases vary widely. Many diseases are clearly sensitive to changes in humidity, temperature, precipitation and ultraviolet radiation intensity (Rose *et al*., 2001). Among them are some of our planet's greatest killers, such as malaria and cholera; others (e.g. Lyme disease, hantavirus, Dengue fever), although less deadly, are still dangerously debilitating. A first step is thus to define which characteristics make a disease or pathogen "climate sensitive". Climate change can influence the epidemiology of infectious diseases by affecting the replication and movement of disease agents and vectors or can influence transmission dynamics indirectly through its effects on ecology or human behavior. As global temperatures continue to rise, there are growing concerns that climate change may produce serious adverse health effects. From 1889 to 1990, the global average temperature rose by 0.4-0.8°C (Patz *et al*., 2001) and there is a nine out to ten chance that global average temperatures will rise 4-7°C by 2100, with longer and hotter summers and milder winters. However, to date, it is unclear to which extent climate change affect public health through waterborne infectious diseases.

VI.E.2. Waterborne Diseases

Both water quality and quantity can be affected by ecological changes and waterborne diseases (e.g. cholera, leptospirosis, schistosomiasis, giardiasis, criptosporidiosis, human enteric viruses induced diseases, campylobacteriosis) are or are suspected to be associated with weather-related components. Pathogen concentration in surface waters may rise due to drought or increased precipitation leading to enhanced runoff of pathogens with manure from the land. Coastal and oceanic waters are known to harbor and transport pathogenic microorganisms and to influence indirectly their distribution and disease patterns. El-Nino-Southern Oscillation (ENSO) has been proposed to influence cholera outbreaks (Colwell, 1996) and has been associated with dynamics of the disease (Pascual *et al.*, 2000). ENSO has also been associated with levels of diarrheal disease in Peru' (Checkley *et al*., 2000). As a consequence of higher temperatures the geographic range of many Vibrio spp. would be expected to increase with warming water. For a review of the potential El Nino associated health effects (Kovats *et al.*, 2003).

Heavy rainfall mainly causes storm water overflow thereby increasing pathogen concentration in surface waters. Extreme precipitation also causes flooding of urban and rural areas with wastewater contaminated by fecal pollution. Outbreaks are not limited to countries with poor sanitation systems. In developed nations, heavy rains overburden water treatment facilities and sewage systems: with spillovers of raw sewage and animals waste from farms, high level of enteric pathogens are released into local water supplies. More than half of the waterborne diseases outbreaks in the US in the past 50 years have been preceded by heavy rainfall (Patz, 2004). With climate predictions suggesting a greater intensity of storms and average precipitation, waterborne diseases are likely to increase. Floodwaters and storm waters can carry 1000 times the normal amount of disease-bearing microorganisms (Ford *et al*., 1998) and have been associated to high incidence of gastrointestinal disease. In a longitudinal cohort study, the rates of gastrointestinal illness during a severe flooding were investigated (Wade *et al*., 2004) and an increase in the incidence of gastrointestinal symptoms during the flood was observed with excess among people with high susceptibility to infectious gastrointestinal illness. An analysis of the relationship between precipitation and waterborne diseases, based on the US EPA waterborne disease database (548 reports outbreaks from 1948-1994) and precipitation data from the National Climatic Data Centre, showed that there was a statistically significant association between the two with outbreaks due to surface water contamination having the strongest association with extreme precipitation during the month of the outbreak (Curriero *et al*., 2001). An example of a rather severe outbreak is the *E. coli* O157:H7 outbreak following heavy rainfall and flooding in Walkerton, Canada, which cost 6 lives and had 65 hospital admissions (Anonymous, 2000). For developing countries outbreaks of leptospirosis, hepatits E, malaria and diarroheal diseases following floods have also been described. Hunter (2003) gives a concise review of the epidemiology of waterborne disease outbreaks associated with climate change or extreme whether events by dividing the impact of climate in three major groups: heavy rainfall events, flooding and increased temperature. Even the increased flow rate of rivers will cause more resuspension of pathogenic microorganisms accumulated in sediments, shorter residence times and therefore less inactivation of pathogens. In case of ground waters, contamination originates from manure on the land or from wastewater leaking from sewage pipes or septic tanks. Due to increased water flow rates, transport of pathogens is faster requiring larger protection zones. Moreover, increased urbanization continues to alter watersheds and freshwater flows, resulting in contamination from both point sources (factory and sewage treatment discharge plant) and non point sources (microbe-contaminated runoff from farmlands).

The role of water quality in outbreaks is often overlooked and underreported; some waterborne diseases such as salmonellosis, campylobacteriosis and giardiasis may cause only mild discomfort in healthy individuals. Many do not seek medical attention, dismissing the symptoms as food poisoning or stomach flu. The link between climate-mediated water contamination and outbreaks is easy to miss. A two-month lag is typical between heavy rainfall and the detection of groundwater contamination. One month usually passes before dirtied water causes widespread illness (Diaz, 1996). Quantifying the real threat of waterborne disease is thus difficult due to the fact that many cases, typically gastroenteritis, go unreported: symptoms usually do not last long and are self limiting in healthy people (Bernasconi, 2004). However gastrointestinal illnesses can be chronic and even fatal in children, the elderly, pregnant women and immuno-compromised people such as transplanted, people affected by AIDS (acquired immune deficiency syndrome) or diabetes or undergoing chemotherapy. Waterborne pathogens can even cause extended illnesses, such as hepatitis, that last several months even in healthy people and they are often associated with other serious conditions including hepatic, lymphatic, neurologic, endocrinologic diseases (ASM, 1998) and even increased cancer risk (e.g. *Helicobater pylory* and MALT lymphoma). Even more concern is due to the emergence or re-emergence of new pathogens, antibiotic resistant strains and a larger susceptible population (Gerba et al., 1996). For example, cclimate change can influence the potential for *Legionella*, an emerging pathogen, to colonize water and air conditioning systems (Rose *et al*., 2001), either directly due to increased temperatures or indirectly (nutrients, association with free living amoebas, such as *Acanthamoeba*).

Climate change may have effects on different environments and thus on associated diseases: wetlands (encephalitis, malaria, schistosomiasis), permanent water (filariasis, malaria, schistosomiasis, onchocerciasis), sea surface temperature, height (cholera). Mosquito borne diseases are more influenced by ambient conditions than diseases transmitted directly from human to human. In fact, climate changes:

- influence distribution and growth rate of vectors,
- alter the geographic distribution of pests
- temperature plays a determinant role in vector development, cutting the time necessary to develop from egg to adult and fastening the generation turn over (Kiska, 2000).

However, temperature affects also pathogen development within the vector (Bouma et al., 1994): incubation period decreases and disease reproduces faster inside the pest carrier.

VI.E. Vector-Borne Diseases

Mosquitoes are among the first organisms to extend their range as climate change make new areas more accessible (Lindsay, 1996). The transmission of infectious diseases may rise as temperature grows warmer and insects migrate northward. As a consequence, diseases that are typically restricted to tropical and subtropical regions could become more common in northward areas. In North America, malaria and dengue fever are already among the new arrivals; Lyme disease already affects northern US regions (http://www.ccah.cpha.ca). Malaria has already appeared in Canada: during hot, humid period in 1990, locally transmitted malaria occurred in Toronto as well as in the northeastern (New York, New Jersey) and north central (Michigan) United States. It is estimated that 300-500 million people suffer from malaria every year (WHO, 1993), while over 2 billion people are considered at risk from contracting disease (Epstein, 2000) with a predicted 3°C rise in global temperature, an additional 50-80 million cases of malaria will occur each year.

Since 1970 the height at which freezing occurs (the freezing isotherm) has climbed approximately 160m within the tropical belts, equivalent to almost 1°C warming (Diaz and Graham 1996). Insects and insect borne diseases are now being reported at high elevation in east and central Africa, Latin America and Asia. Malaria is nowadays detected in highland urban centers like Nairobi, and rural highlands in Papua New Guinea (Epstein *et al*., 1998).

Dengue fever is a tropical disease caused by Arbovirus and transmitted by the bite of an infected mosquito (genus *Aedes*). There is no vaccine and the disease becomes increasingly fatal with successive infections. (Breslin, 1994). Outbreaks have so far been restricted to Central America but warming trends due to climate change would increase the range and frequency of dengue fever in North America. However concern arises because, although specific vector are involved in transmission of malaria and dengue fever, even local mosquitoes can become potential vectors and the cost of mosquito eradication would dramatically increase to control the spread of disease.

Table VI.E.1. Waterborne pathogens and related health risk

Health risk	Pathogen
Arthritis	Campylobacter, Salmonella, Giardia
Aseptic meningitis	Coxsackievirus, new Enterovirus type 68 to 71
Cancer, peptic ulcer	Helicobacter pylori
Cholera	Vibrio cholerae
Diarrhea and gastroenteritis	Enterovirus, Norwalk virus, calicivirus, rotavirus, E. coli O157 Criptosporidium, Salmonella, Giardia
Heart disease	Coxsackievirus B, Legionella pneumophila
Diabetes	Coxsackievirus B
Kidney failure	Hepatitis A virus, Legionella pneumophila
Liver failure	Hepatitis E virus
Wound infection	Vibrio

Currently, the level of understanding of the linkages between water diseases and climate is lower than that for vector-borne diseases. Although the doomsday scenario in the thriller film *The Day After Tomorrow* may be far from reality, it is clear that climate is changing, challenging the health sector and the whole of human society. An interdisciplinary analysis, and integrated prevention planning are mandatory. Mathematical modeling of infectious diseases, (e.g. waterborne, vector-borne) in relation to climate is at the first stage to identify the key environmental and climate parameters associated with disease variability. Furthermore, how many potential pathogens are sharing this planet with us, awaiting the right conditions for their chance at stardom by becoming an emerging infectious disease?

Chapter VI.F.1 Climate Change, Extreme Events and POPs – an example

Key Points

- **The mobilisation, distribution and fate of chemical pollutants and pathogens through floodwaters are a source of public concern.**
- **In the 2002 Elbe flood, no significant increase was measured in levels of PCDDs/Fs and PCBs in river and floodplain sediments after the flood with few exceptions. Concentrations of trace metals, hydrocarbons, PAHs, organochloro-pesticides, and PCBs exceeded German guidelines only in a few isolated cases, without distinct threats to human health.**
- **The 2002 flooding event did not result in a large-scale contamination of the areas affected by the floodwaters. The relatively high contamination levels found in the floodplains represent the historic dimension of repeated flood events in upstream industrial regions.**
- **Floods have the capacity to re-mobilize and re-distribute large amounts of contaminants; increased incidence or severity of floods has the potential to cause widespread contamination.**

Chapter VI.F. Climate Change, Extreme Events, Dioxins and the 2002 Flood in the River Elbe

Chapter VI.F.1. Introduction

Press and radio reporting during the late summer of 2002 was dominated by flooding of the Rivers Elbe, Danube and Moldau catchments. Devastating damage of private property, infrastructure, industrial and commercial enterprises and cultural monuments, together with numerous fatalities, especially in the Elbe catchment, eclipsed all flood damages ever experienced in central Europe.

Heavy floods are periodic natural phenomena as the climatic history of central Europe shows. Their recurrence is foreseeable and consequently preventive measures against floods have always been part of the human settlement history along rivers. But the extent of damages caused by floods is rising as function of urbanisation of the river catchments and even without any change of climatic factors, urban areas are continuously moving towards a higher flood risk.

Several determining factors are known: Settlement areas on former floodplains increase the amount of “economic damage” through floods, even though the flood intensity remains the same. Straightening (channelling) of river courses and dikes separate the river from its floodplains and alluvial forests, which before, acted as natural buffers that temporarily absorbed floodwaters and flattened the flood peaks. Overall, it is estimated that only 20% of Europe’s floodplains remain functional.

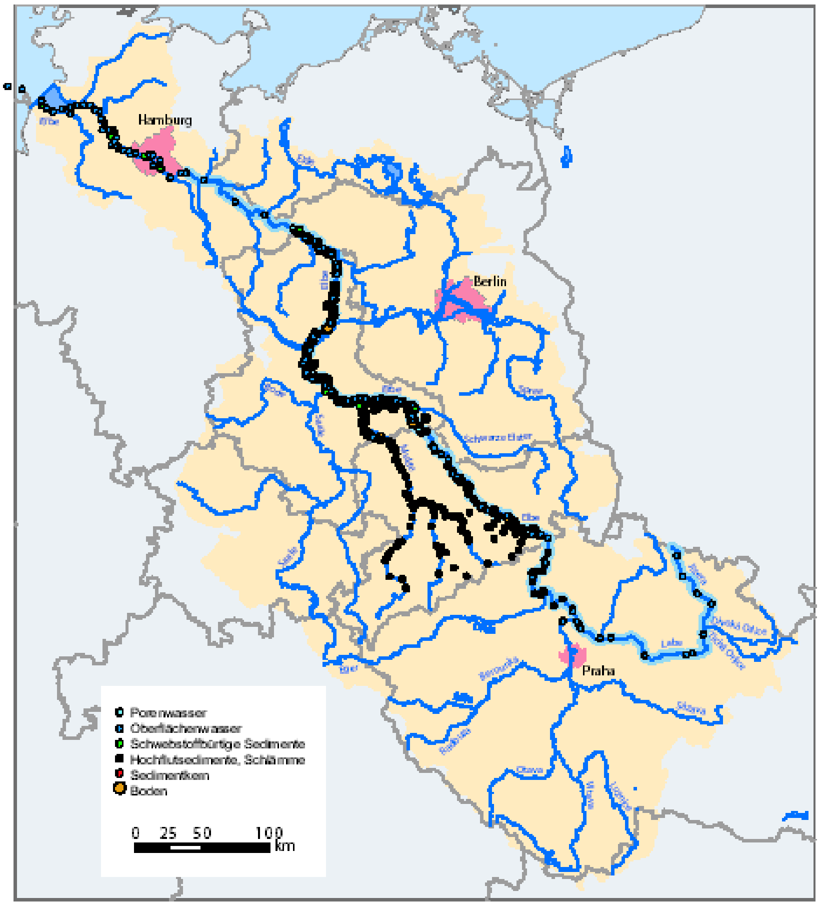
In addition the water storage capacity in soils of the river catchments has decreased as a result of surface sealing in urban areas, deforestation, and soil compaction on agricultural land. Consequently a given amount of precipitation moves comparatively faster and at increasing floodwater levels through the river catchment of an urban area. On top of these physical changes of the catchment properties, an increase of intensity of precipitation has been observed in the recent years and is being discussed in the context of climate change.

Besides various aspects of increasing physical damages related to floods the mobilisation, distribution and fate of chemical pollutants and pathogens through floodwaters have received public concern in the recent years. Past observations of fish kills in floodwaters, caused by mobilization of anoxic sediments and the related decrease of dissolved oxygen in the water, have demonstrated that large water flow does not necessarily result in a dilution of pollutants. In contrast the complex dynamics of sedimentation and re-suspension in riverbeds typically result in a “first flush” of sediment born pollutants during flood events.

In addition, flooding of urban areas, especially behind broken dikes, affects industrial sites, mining areas, sewage sludge plants, and waste deposits, and may result in additional pollutant releases from terrestrial sources. The mobilisation of pollutants during the Elbe flood in 2002 was addressed in the frame of an a issued by the German federal ministry of Education and Research (Bundesministerium fuer Bildung und Forschung - BMBF) involving various research institutes and federal institutions in Germany and Czech Republic. The objective of this project[5] was the determination of pollutants in water, soil, river sediment and floodwater sediments combined with an assessment of related threats to the environment and human health.

[5] The final report can be downloaded from http://www.ufz.de/data/HWEnd1333.pdf

Figure VI.F.1. Elbe and Mulde catchment affected by the flood in 2002



VI.F.2 Release of Chemicals during the 2002 event

The survey revealed no significant increases in levels of chemical pollution in river and floodplain sediments after the flood with few exceptions on a local scale, mainly along River Mulde. Concentrations of trace metals, hydrocarbons, PAHs, organochloro-pesticides, and PCBs exceeded German guidelines only in a few isolated cases, without distinct threats to human health.

Polychlorinated Dioxins and Furans (PCDD/Fs) and Mercury contamination in soils behind dikes that broke in 2002 were, on average, typical of urban contamination levels indicating minor re-mobilization through the floodwaters. The investigated playgrounds and agricultural areas showed contamination levels far below German guidelines. Only a few pasture areas slightly exceeded the recommended maximum level of PCDD/F contamination for this type of land use. Contrary observations were made in the floodplain soils regularly affected by floodwaters, where Mercury and particularly PCDD/Fs levels significantly exceeded German guidelines especially downstream of the inlets of Rivers Mulde and Saale.

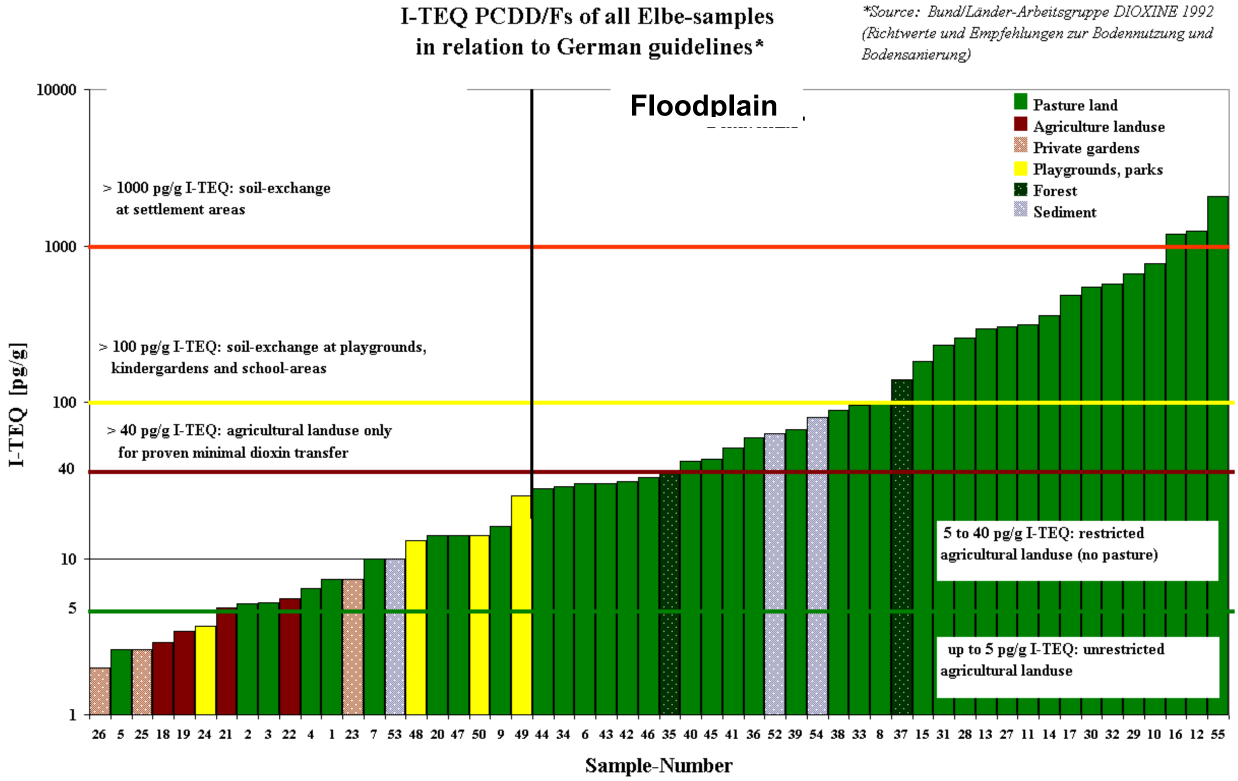


Figure VI.F.2 Overview on the I-TEQ from PCDD/Fs for flooded soils in relation to land use and the related German guideline values.

The elevated concentrations in the floodplains represent a memory of historic floods and cannot be attributed to the flooding in 2002. Metallurgic processing in the past released significant quantities of PCDD/Fs into the Mulde and Saale catchment. The PCDD/F congener pattern Elbe downstream the inlet of the two tributaries changes significantly and shows a high similarity with the pattern found in the vicinity of the old industrial installations there. A similar pattern can be observed in the harbour sediments of Hamburg as well.

Concern has risen due to the fact that slag heaps from former Uranium mining in the Mulde catchment were affected by erosion due to the high intensity of precipitation. However, the post-flood concentrations of ^{238}U and ^{226}Ra in the sediments of Freiberger Mulde were in the range of the typical geogenic background of this region. The sediments of the Zwickauer Mulde, historically contaminated at a higher level, showed a significant decrease when compared to past campaigns. Except for local problems around the Lenkteich and the Plohnbach, where erosion of contaminated sediments has lead to a local-scale mobilisation of radionuclides, no flood related contamination was observed.

Release of pathogens during the 2002 event

The threat arising from potential contact with pathogenic microorganisms present in the muddy residues from the floodwaters in urban areas, especially in buildings and playgrounds, was another aspect of the project.

Among the species identified through the cultivation on selective media, were *Enterococcus, Enterobacter, Wollbachia, Neisseria, Rickettsia, Legianella, Citrocacter* and *E.Coli*. Although the colony counts as such were not alarming, a remarkable resistance against antibiotics was observed. The isolated pathogens from more than 50 % of the samples showed no effect from the treatment with *Ampicillin, Erythromycin* and *Gentamycin*. Interestingly, the isolates from the river water itself revealed a much lower resistance. This indicates that the river was not the source of contamination. Obviously the pathogens were initially released from terrestrial sources such as sewage treatment plants or farms and entered the river subsequently.

VI.F.3 Conclusion

Concerning chemical pollution, the 2002 flooding event did not result in a large-scale contamination of the areas affected by the floodwaters. The relatively high contamination levels found in the floodplains represent the historic dimension of repeated flood events in industrial regions. However, flooding in other European river basins may yield a different result.

In contrast to chemical pollution, the presence of pathogenic microorganisms in flooded urban areas revealed a significant effect attributable to the flood event. In addition, resistance of many of these pathogens against antibiotics was observed, which potentially multiplies the related human health risk. The observed resistance is most probably due to the adaptation of pathogens present in wastewater treatment plants and agricultural applications where various anti-microbial pharmaceuticals are present.

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Chapter VI.F.2 Climate Change and Global Persistent Organic Chemicals

Key Points

- **The atmosphere is the 'conduit' through which POPs can move from atmospheric emission sources via deposition to terrestrial and aquatic ecosystems, several processes accelerated by climate warmng.**
- **A net transfer of POPs from warm source/usage areas to colder remote regions (i.e. a global re-distribution) is documented. Repeated temperature-controlled air-surface exchange provides the key mechanism for this so-called 'cold condensation' process. Furthermore, 'global fractionation' may occur, whereby different POPs travel different distances from a common source area.**
- **Temperature is an important driver to the global cycling of POPs through its influence on emissions from primary and secondary sources, gas-particle distributions, reaction rates, air-surface exchange (inland and marine waters, vegetation, soils, snow/ice) and global transport.**
- ***'Inter-annual variations of POP air concentrations from the Great Lakes region and the Arctic have been strongly associated with atmospheric low-frequency fluctuations, notably the North Atlantic Oscillation (NAO), the El-Nino-Southern Oscillation (ENSO) and the Pacific North American (PNA) pattern. This suggests interactions between climate variation and the global distribution of POPs…." Ma et al., 2004.***

Climate Change and Global POPs

VI.F.4. Persistent Organic Pollutants (POPs)

POPs are described in the UNECE Convention on Long-Range Transboundary Air Pollution (CLRTAP) as '…organic compounds that: i). possess toxic characteristics; ii). are persistent; iii). are liable to bioaccumulate; iv). are prone to long-range atmospheric transport (LRAT) and deposition; and v). can result in adverse environmental and human health effects at locations near and far from their sources'. They represent a small percentage of the chemicals of commerce, and many are already strictly regulated or not currently in production. International agreements to reduce or eliminate POPs are designed to reduce the risks to regional and global environments (www.unece.org/env/lrtap). On May 2001, 151 Governments adopted the Stockholm Convention on POPs, targeting the 12 chemicals/groups listed in Table 1. The Convention contains provision for other compound classes with similar properties to become the subject of the Convention and international controls in the future. Examples of such "new or candidate POPs" include the polychlorinated naphthalenes (PCNs) and polybrominated diphenyl ethers (PBDEs). The 2001 Stockholm Convention became legally binding on May 17 2004 (http://www.pops.int/documents/press/pr2-04SC.pdf) (UNECE, 1998; UNEP, 1998).

VI.F.5. The role of the atmosphere and the global re-distribution of POPs

The atmosphere is the 'conduit' through which POPs can move from atmospheric emission sources via deposition to terrestrial and aquatic ecosystems (Klecka *et al*., 2000). Indeed, the combination of POP semi-volatility and persistence means that they can undergo Long Range Atmospheric Transport (LRAT), moving from source regions to more remote locations, so that they have been detected in biota from regions of the world where they were neither used nor produced. Their global transport and distribution is extremely complex (see Figure VI.F.3). For example, it is influenced by:

- the location of primary (i.e. fresh/new) emission/source areas;
- an array of emission and atmospheric transport and fate processes;
- the potential for repeated air-surface exchange;
- the physico-chemical properties of the substance in question.

These vary spatially and temporally, and ultimately influence the global fate/sinks of POPs and their entry into food chains.

The complexity of the processes leading to the releases of POPs and the environmental systems in which POPs circulate cause considerable gaps in our understanding of their environmental fate and global budget. In many cases, knowledge of the spatial and temporal pattern of primary emissions of POPs over the last decades is poorly known. Uncertainty over the sources impedes the interpretation of measured concentrations, because: i). it is difficult to determine whether a certain concentration in the environment represents a recent or local signal or whether it is the residue of a long-lasting emission/degradation processes; ii). understanding of the pathways and sinks in the environment is incomplete. For example, the importance of export to the deep ocean has only recently been studied quantitatively.

The process of POP transfer to remote regions occurs in three stages. First, the chemical is emitted to the atmosphere in source regions (e.g. by combustion, incineration, pesticide spraying, volatilisation from pesticide treated soils or landfills).

Second, the chemical is transported (often over 10s – 100s – 1000s of km) through the atmosphere to a more remote region (Beyer et al., 2000; Ikonomou et al., 2002; Wania, 2003; Wania and Dugani, 2003). The chemical must be sufficiently persistent in the atmosphere to survive this long journey. Third, dry (gaseous or particulate) or wet deposition of the chemical to the more remote region can occur. Importantly, on being deposited to an environmental compartment (soil, vegetation, water bodies, snow/ice) POPs might be re-emitted (i.e. a secondary emission of 'old'/previously deposited POP).

It has been hypothesised that a net transfer of POPs from warm source/usage areas to colder remote regions via LRAT (i.e. a global re-distribution) is occurring (Wania and Mackay, 1993; 1995; 1996; Jones and de Voogt, 1999; Wania and Su, 2004). Repeated temperature-controlled air-surface exchange provides the key mechanism for this so-called 'cold condensation' process. Furthermore, 'global fractionation' may occur, whereby different POPs travel different distances from a common source area. The extent of fractionation would be dependent on compound physical-chemical properties - notably vapour pressure and air-surface partitioning. Compounds with higher volatility will undergo LRAT and condense in colder (polar) regions, while less volatile compounds will be deposited closer to the source area. This could happen either in one single event of release followed by deposition, or alternatively in a series of 'hops' through repeated air-surface exchange influenced by changes in temperature (the 'grasshopper effect') (Wania and Mackay, 1996). Fractionation does not necessarily lead to a net increase of POPs in polar regions (i.e. cold condensation) – it could arise simply following a single primary emission pulse, where different compounds undergo LRAT, deposition and loss processes to slightly different extents.

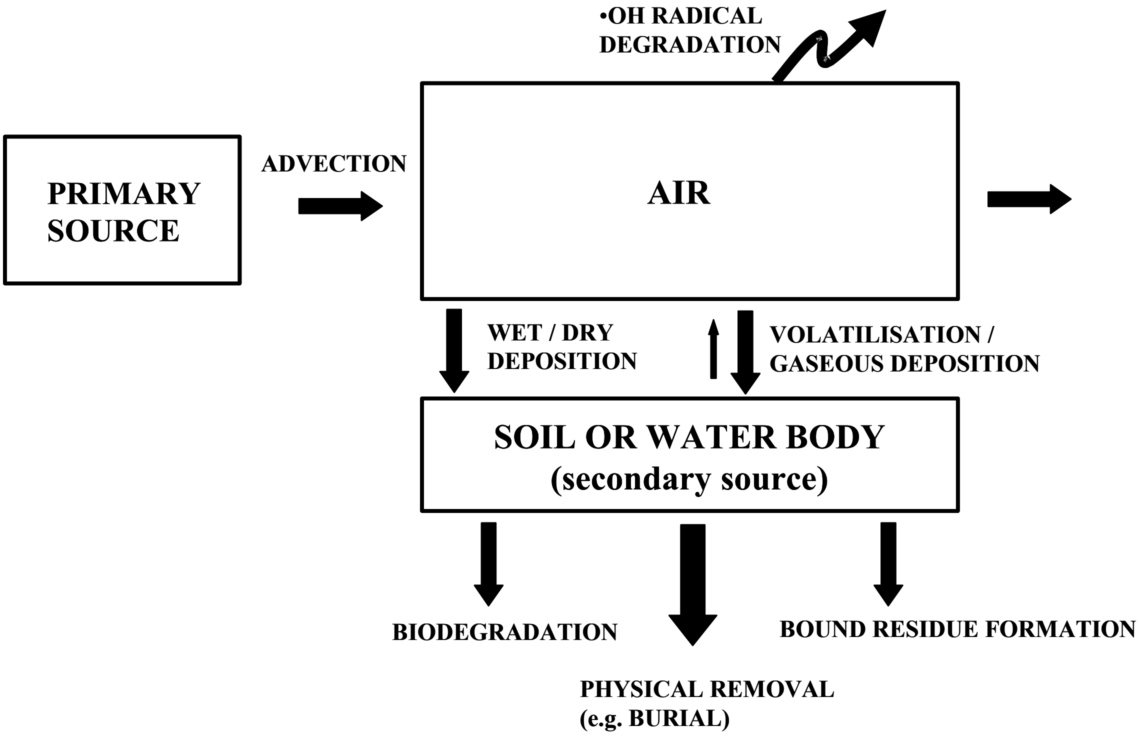
This general concept of a temperature-driven re-cycling and re-distribution of POPs has provided the motivation for numerous studies designed to look for evidence of global cold condensation and fractionation. There is no doubt that fractionation and cold condensation do occur (Wania and Mackay, 1996; Ockenden *et al*., 1998; Meijer *et al*., 2003a; Jaward *et al*., 2004a), but it appears that these processes exert a relatively minor influence on the global mass balance of POPs (Meijer *et al*., 2003b; Wania and Su, 2004). This is likely because a number of other key factors influence the global cycling and atmospheric distribution of POPs, and these can confound or lessen the importance of the cold condensation/fractionation processes. Key among them are:

- The potential for ongoing (often diffusive) primary sources of POPs, even now, long after many POPs have been regulated and banned (e.g. Jaward *et al*., 2004b);
- The patterns of atmospheric circulation and air mass origin (e.g. Cortes *et al.,* 2000);
- The capacity of environmental compartments to store or degrade POPs. This is intimately linked to the amounts and forms of organic matter in those compartments (e.g. Meijer *et al*., 2003b);
- The timescales required for large-scale re-cycling and exchange to occur.

All these issues need to be borne in mind when considering the potential impacts of underlying climate changes on the global cycling of POPs.

VI.F.6. The potential influences of climate change on POPs

Figure VI.F.3. Conceptual diagram of input and loss mechanisms controlling atmospheric concentrations of POPs (adapted from Sweetman and Jones, 2000).



The direct effects of temperature

As noted in the previous section, temperature is an important driver to the global cycling of POPs. Several important processes are temperature dependent, notably:

1. Emissions from some primary sources:
PCBs and PBDEs have been widely used in urban areas in many industrialised countries, and may be subject to diffusive emissions from their primary sources – PCBs from sealants, transformers, electronic equipment etc; PBDEs from fire-retarded fabrics and treated polyurethane foam, for example (Breivik *et al*., 2002a; 2002b; Prevedouros *et al*., 2004).

2. Emissions from secondary sources:
Emissions from the key environmental 'repositories' of soils, sediments, vegetation, water (inland and marine) are obviously influenced by temperature. Volatilisation rates of pesticides from soils are temperature dependent, although other factors also exert a strong influence, notably soil moisture status, organic matter content, depth of compound incorporation, and wind field and intensity.

3. Gas: particle partitioning and subsequent impacts on deposition processes:

POPs exist in the atmosphere in the gas phase and associated with particles. Their partitioning is controlled by temperature (Bidleman, 1988; Falconer and Bidleman, 1994) and can be quite different in different environments – the tropics compared to the Arctic, for example.

4. Reaction rates:
POPs are degraded in the environment, in the atmosphere by reactions with the hydroxyl radical, and in soils/sediments by microbially mediated processes (e.g., Anderson and Hites, 1996; Totten and Eisenreich 2000, Mandalakis *et al*., 2003).

Despite all these obvious examples of the influence of temperature on the emissions and environmental distributions of POPs, it must be remembered that regional or global increases in ambient temperatures attributed to underlying changes in climate are 'small' – averaging only 1-2 ^{0}C over time frames of decades or longer. These are unlikely to be sufficient – by themselves – to substantially impact global POPs cycles. After all, timeframes of decades are sufficient to see the 'rise and fall' of POP compound production/use/restrictions/bans, while reaction rates and environmental partitioning phenomena generally only increase by a factor of 2-3 for a 10 ^{0}C increase in temperature.

The role of air-surface exchange
As noted above, there is evidence that gas phase POPs can 'hop' between environmental surfaces and the atmosphere (Gouin *et al*., 2004). The clearest evidence for this comes from measurements of the diurnal cycling of atmospheric concentrations (highest in the day, lowest at night) that are positively correlated with temperature. However, such cycling is *not* observed in all studies, and appears to be a strong function of the underlying surface. The clearest evidence for such T-driven cycling comes from studies over vegetated surfaces - a peat bog in Minnesota and grassland in the UK, for example (Hornbuckle and Eisenreich, 1996; Lee *et al*., 1998) as well as urban areas (Brunciak *et al*., 2002; Dachs *et al*., 2002). In contrast, studies over the open ocean suggest that other factors control atmospheric concentrations over a typical 24-hour cycle (Jaward *et al.,* 2004c). When diurnal cycling has been observed, it is clearest where ambient temperatures show the largest diurnal amplitude and where the surface compartment undergoes large diurnal shifts in temperature. These observations are potentially important with respect to possible influences of climate change, because underlying changes that affect the nature and partitioning properties of environmental surfaces may impact the rate and magnitude of the air-surface exchange of POPs. Hence – it is hypothesised - increased desertification, changes in land use and vegetative cover, changes in the extent of the ice sheets, and changes in the rates of primary productivity in the oceans may all exert an influence on global POP cycling.

Vegetation:
Vegetation is a compartment that actively participates in air-surface exchange of POPs. The waxy surfaces of leaves can provide an important storage compartment for these compounds (Barber *et al*., 2004), are in intimate contact with the atmosphere, and can undergo substantial diurnal and seasonal changes in temperature. It is not a compartment with a particularly large capacity to store POPs, compared to soils or sediments for example, but it can:

- scavenge POPs from the atmosphere;
- enhance the rates of deposition to forested areas relative to adjacent clearings, and on vegetated areas relative to adjacent bare soil;
- store POPs in quantities which vary as a function of the plants lipid content;

- provide a surface where photolytic degradation of POPs may occur.

It has been estimated that coniferous forests have the largest storage capacity for POPs (of the different vegetation types), while tropical systems may be areas where photodegradation occurs most rapidly. Hence, changes in vegetative cover over the Earth's surface will alter the dynamics of POPs cycling.

Soils:
Soil is a major environmental reservoir/sink of POPs, either because of direct applications in urban or agricultural areas, or because all soils receive POPs as a result of accumulative atmospheric deposition. The soils' storage capacity for POPs is strongly influenced by the soil organic matter (SOM) content (and – to a lesser extent – type), while the degradation rates in soils are affected by the fertility, aerobic status, moisture content and temperature. The POPs content of global background soils are positively correlated to their SOM, suggesting: i). that compounds can 'hop' between locations until they find soils of higher SOM status, from where they are less likely to be re-emitted to atmosphere (Meijer *et al*., 2003; Gouin *et al*., 2004); *and/or* ii). Their rate of degradation in soils is inversely proportional to the SOM content, perhaps because higher SOM results in lower compound bioavailability. Figure VI.F4 shows how the capacity of surface soils to store an illustrative POP (PCB-153) has been estimated to vary globally and seasonally – as a function of SOM and temperature. It can vary over orders of magnitude with location and by about a factor of 10 seasonally.

Clearly, underlying climate change processes that result in a change in soil use and management, or a direct change in SOM content, can be expected to influence the storage capacity and turnover of POPs in this major environmental repository (see below). Rates of organic matter turnover in soils may also play an important part in their incorporation into SOM, and rates of degradation. POP half-lives in background soils are 'long' (perhaps decades); it may therefore be anticipated that underlying changes in soils - occurring over these timeframes as a result of climate change – may impact global POPs cycles.

Water bodies:
Oceans cover seventy percent of the world's surface. Some major 'enclosed' water bodies, such as the Baltic Sea, the North American Great Lakes, and the estuaries of the Atlantic Coast of the USA are areas of the world where the adverse effects of POPs have been most extensively reported. Water bodies are therefore of critical importance to the storage, processing and removal of POPs from the global cycle.

There is evidence that the air and open oceans are close to a state of dynamic equilibrium, with respect to many POPs that undergo air-water gas exchange (Jaward *et al*., 2004c; Wodarg *et al*., 2004). The storage capacity of the surface oceans is strongly influenced by the phytoplankton, with close coupling of the air-dissolved phase-phytoplankton system (Dachs *et al*., 2000). Ultimately, the surface oceans loose POPs to the deeper oceans in association with the C flux. Any factors that influence the rates of C removal to the deeper oceans, or the rates of primary productivity of the surface oceans, would potentially be major drivers influencing the air-surface exchange of POPs. Air-water exchange is enhanced by increases in biomass (i.e., eutrophication) and thus more eutrophic water bodies may 'capture' atmospheric gas phase POPs (Jeremiason *et al*., 2000, Dachs *et al*., 2000).

Snow/ice cover:
Snow and ice are efficient scavengers of POPs from the atmosphere, resulting in their deposition to polar and mountainous environments. On the other hand, snow

and ice have quite a low capacity to store POPs, so that an important aspect of POP cycling in these environments concerns the extent to which POPs in the snow/ice pack may be re-emitted to atmosphere, or percolate to soils and water bodies, particularly during snow melt (e.g., see Franz *et al*., 1997).

Influence of changing land use and surface cover

As shown in the previous section, the processes of deposition and re-emission are key to the global cycling of POPs, so any underlying changes in land use, or surface cover characteristics induced by climate change could have a potentially profound effect on such cycles. Other aspects of land use, and the link to hydrological cycles are also likely to be of importance. Examples include:

- Deforestation, and other changes to habitat type and distribution, especially underlying effects on soil organic carbon budgets. It seems that the organic matter-rich soils of the temperate northern hemisphere are particularly important environmental reservoirs/sinks of POPs, for example (Meijer *et al*., 2003b);
- Underlying changes to the hydrological cycle, such as flood frequency/ seasonality/ intensity. This could potentially impact POP cycling and distribution through sediment mobilisation, and delivery to floodplains, for example (Bergqvist *et al*., 2000).
- Both of the above examples could have an important effect by influencing the regional patterns of chemical usage – for example through the distribution of urban and agricultural areas, and the associated influence on the emissions of industrial chemicals, and the use of agrochemicals.

The role of air mass origin

Changes in both temperature and large-scale wind systems are associated with global atmospheric circulation patterns, while – as shown above - surface air temperatures influence atmospheric concentrations of POPs. However, the link between inter-annual changes in atmospheric POP concentrations and climate variability (e.g. Shindell *et al.,* 1999) has not been studied extensively. As Ma *et al* (2004) suggest, this may be due to the lack of continuous atmospheric POP measurements before the 1980s, and because any associations of climate fluctuations with air concentrations of POPs are difficult to discern while current (primary) emissions dominate annual cycles. However, utilising data obtained from two major POP air monitoring programmes established in North America during the 1990s, - the Canadian Northern Contaminants Program (NCP), and the Integrated Atmospheric Monitoring Network (IADN), Ma *et al* (2004) looked for evidence of relationships between air concentrations of hexachlorobenzene (HCB), the HCHs and PCBs between December 1990 and May 2000, and major Northern Hemisphere climate variables. They concluded that: *'Inter-annual variations of POP air concentrations from the Great Lakes region and the Arctic have been strongly associated with atmospheric low-frequency fluctuations, notably the North Atlantic Oscillation (NAO), the El-Nino-Southern Oscillation (ENSO) and the Pacific North American (PNA) pattern. This suggests interactions between climate variation and the global distribution of POPs. Atmospheric concentrations of HCHs, HCB and several lighter PCBs measured around the Great Lakes basin increased during the positive phases of NAO and ENSO in the spring. This implies that anomalous high air temperatures associated with NAO and ENSO enhance volatilisation of POPs from reservoirs on the Earth's surface accumulated in the past. These compounds are then available to transport from source regions to more pristine regions such as the Arctic under favourable flow patterns associated with global climate variations'.*

They also note that: *'Temperature is not the only parameter of climate variation that would affect the transport processes of compounds. For instance, changes in other climate parameters, e.g. wind intensity, ice cover over the Great Lakes, and quantity, quality, and spatial variation of rain and snow, associated with various climate patterns would also affect scavenging and deposition of organic pollutants'.*

The study by Ma *et al*. (2004) is important, because it is the first of its kind and clearly provides evidence for the potential scope and scale of underlying climate fluctuations to impact the distribution and cycling of atmospheric POPs.

VI.F.4. A brief case study of the Arctic – an illustration of potential complexities and inter-linking

Macdonald and co-workers (2003) present an excellent synthesis of the potential influences of global change on contaminant pathways to, within and from the Arctic. They state: *During the 1990s, a quiet revolution took place in the perception of the Arctic. Despite early evidence of cyclical change in northern biological populations and ice conditions, the general view among many western physical scientists throughout the 1960s to 1980s was that the Arctic was a relatively stable place. This view has been replaced by one of an Artic where major shifts can occur in a very short time, forced primarily by natural variation in the atmospheric pressure field associated with the 'Arctic Oscillation (AO)'.*

They go on to give examples, and to speculate, about the ways in which such large-scale atmospheric processes can potentially influence:

- Inputs of POPs/pesticides from the source regions of North America, Europe and Asia;
- Gas exchange, influenced by deposition and ice cover, in the North Pacific and Bering Sea, and in the Arctic Ocean (Jantunen and Bidleman, 1995);
- Inputs to the Arctic waters from Russian and Canadian riverine inputs;
- Releases from glacial ice mass loss and snow melt;
- Cycling of POPs within Arctic lake waters;
- The chemical partitioning and degradation of POPs in the Artic;

These physical and chemical changes may ultimately, in turn, be linked to key biological aspects, such as:

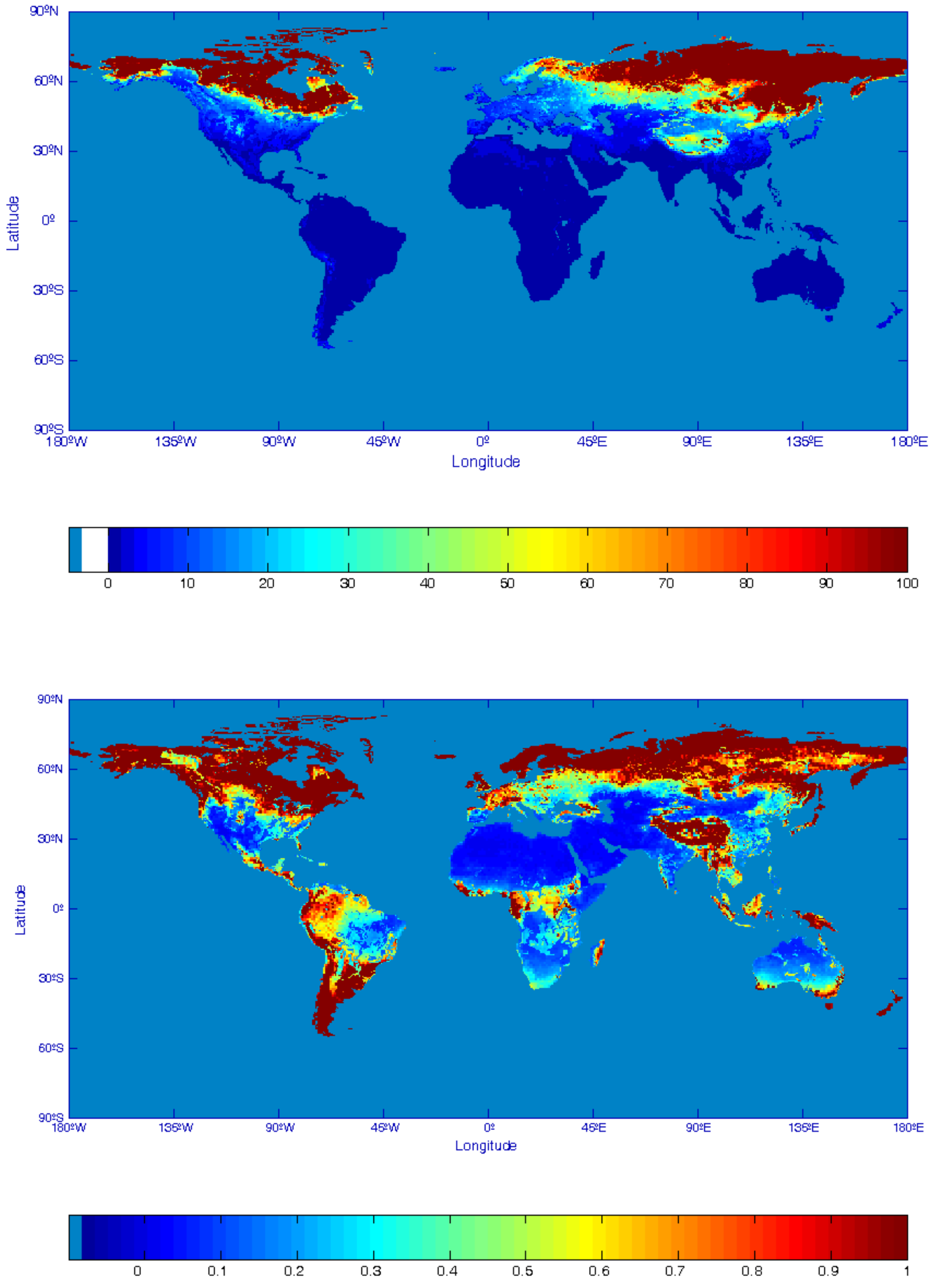
- Altering food web structure;
- Food deprivation or shifts in diet;
- Altered migration pathways and invading species, and even – it is argued –
- The link between organochlorine compounds, disease and epidemics in wildlife populations (Macdonald *et al*., 2003).

Table VI.F.1. Priority substances in the UNECE POPs protocol. Substances highlighted in bold are to be included in the UNEP global POPs convention.

Pesticides	Industrial products	Unintentional byproducts
Aldrin [1] **Chlordane** [1] Chlordecone [1] **DDT** [1,2] **Dieldrin** [1] **Endrin** [1] **Heptachlor** [1] **Hexachlorobenzene (HCB)** [1,3] Hexachlorocyclohexane (HCH) [1,2] **Mirex** [1] **Toxaphene** [1]	**Polychlorinated biphenyls (PCBs)** [1,2] Hexabromobiphenyl [1]	Polycyclic aromatic hydrocarbons (PAHs) [3] **Polychlorinated dibenzo-p-dioxins (PCDDs)** [3] **Polychlorinated dibenzofurans (PCDFs)** [3]

1. Substances scheduled for elimination
2. Substances scheduled for restrictions on use
3. Substances scheduled for emission reductions

Figure VI.F.4. Maximum Reservoir Capacity (MRC) for PCB-28, January (A) and July (B). Different scales are used in the two predictions.



$$MRC = \left[0.246 \times \rho \times f_{oc} \times K_{OA} + \frac{0.2RT}{H} \right] \times \frac{d}{AML}$$

where R is the gas law constant, T is the absolute temperature, f_{oc} is the fraction of organic carbon in the soil, ρ is the soil density (kg/l), H is the dimensionless Henry's law constant, d is the active soil depth (here 1 mm was considered), AML is the air mixing layer (1000 m).

Climate Change and the European Water Dimension

References by Section:

I. Global Climate Change and Water and II. European Regional Climate Change and Water

1. Andreae M.O., Rosenfeld D., Artaxo P., Costa A.A., Frank G.P., Longo K.M., Silva-Dias M.A.F., Smoking rain clouds over the Amazon, *Science*, 303, 1337-1342, 2004.
2. Beniston M., Ohmura A., Rotach M., Tschuck P. Wild M. and Marinucci M.R., Simulation of climate trends over the Alpine Region. In *Development of physically based modelling studies for application to regional studies of current and future climate. Final scientific report no. 4031-33250*, Swiss National Science Foundation, Bern, Switzerland, 1995.
3. Gauss M *et al.* (23 authors), Radiative forcing in the 21st century due to ozone changes in the troposphere and the lower stratosphere. J. Geophys. Res., 108, 10,1029/2002JD002624, 2003.
4. Hansen J., Can we defuse the global warming time bomb? http://naturalscience.com/ns/articles/01-16/ns_jeh.html, 2003.
5. Hansen J., A brighter future, *Climate Change*, 52, 435-440, 2002.
6. Hansen J. *et al.* (28 authors), Climate forcings in Goddard Institute for Space Studies SI2000 simulations, *J. Geophys. Res., 107,* 10.1029/2001JD001143, 2002.
7. Hansen J. and Nazarenko L., Soot climate forcing via snow and ice albedos, *Proc. Natl. Acad. Sci. USA*, 101, 423-428, 2004.
8. Hansen J. and Sato M., Trends of measured climate forcing agents, *Proc. Natl. Acad. Sci. USA*, 98, 14778-14783, 2001.
9. Hauglustaine D.A. and Brasseur G.P., Evolution of tropospheric ozone under anthropogenic activities and associated radiative forcing of climate, *J. Geophys. Res*., 106, 32337-32360, 2001.
10. Houghton J.T. *et al.*, *Climate Change 200. The scientific basis (Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change),* Cambridge University Press, Cambridge, 2001.
11. Hulme M. and Osborne T.J., Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations, *Geophys. Res. Lett.*, 25, 3379-3382, 1998.
12. Kaufman Y.J., Tanre D. and Boucher O., A satellite view of aerosols in the climate system, *Nature*, 215-223, 2002.
13. Kerr R.A., Three degrees of consensus, *Science*, 305, 932-934, 2004.
14. Kullman, L., 20th century climate warming trend and tree-limit rise in the southern Scandes of Sweden, *Ambio*, 30, 72-80, 2001
15. Lelieveld J. *et al.* (31 authors), Global air pollution crossroads over the Mediterranean, *Science*, 298, 794-799, 2002
16. Luterbacher J., Dietrich D., Xoplaki E., Grosjean M. and Wanner H., European seasonal and annual temperature variability, trends and extremes since 1500, *Science*, 303, 1499-1503, 2004.
17. McCarty J.J. *et al., Climate Change 2001. Impacts, Adaptation , and vulnerability (Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change)*, Cambridge University Press, Cambridge 2001.
18. Menon S., Hansen J., Nazarenko L. and Luo Y., Climate effects of black carbon aerosols in India and China, *Science*, 297, 2250-2253, 2002.
19. Nakicenovic N. *et al.*, *Emissions Scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, 2000.
20. Parry M. *et al.*, *Assessment of potential effects and adaptations for climate change in Europe. The Europe ACACIA project*, University of East Anglia, Norwich, UK, 2000.
21. Ramanathan V. *et al.* (40 authors), Indian Ocean Experiment: An integrated analysis of the climate forcing and effects of the great Indo-Asian haze, *J. Geophys. Res.,* 106, 28371-28398, 2001.

22. Ramanathan V., Crutzen P.J., Mitra A.P. and Sikka D., The Indian Ocean Experiment and the Asian Brown Cloud, *Current Science*, 83, 947-955, 2002
23. Rosenfeld D., Desert dust suppressing precipitation: A possible desertification feedback loop, *Proc. Natl. Acad. Sci. USA,* 98, 5975-5980, 2001.
24. Rosenfeld D., Suppression of Rain and Snow by urban and industrial air pollution, *Science*, 287, 1793-1796, 2000.
25. Rosenfeld D., TRMM observed first indirect evidence of smoke from forest fires inhibiting rainfall, *Geophys. Res. Lett.*, 26, 3105-3108, 1999.

III. The General Hydrologic cycle

1. Arnell, N.W., 1996. *Global Warming, River Flows and Water Resources*. John Wiley and Sons, Chichester, United Kingdom, 226 pp.
2. Arnell, N.W., 2003. *Effects of Climate Change on river flows and groundwater recharge: UKCIP02 Scenarios*, UKWIR.
3. Arnell, N.W., Reynard N.S., 1996. The effects of climate change due to global warming on river flows in Great Britain. *Journal of Hydrology*, **183**: 397–424.
4. Bastiaanssen, W.G.M., Menenti M., Feddes R.A., Holtslag A.A.M., 1998a. A remote sensing surface energy balance algorithm for land (SEBAL) 1. Formulation. *Journal of Hydrology*, **212-213**: 198-212.
5. Bastiaanssen, W.G.M., Menenti M., Feddes R.A., Holtslag A.A.M., 1998b. A remote sensing surface energy balance algorithm for land (SEBAL) 2. Validation. *Journal of Hydrology*, **212-213**: 213-229.
6. Baumgartner, A., Reichel E., 1975. *World Water Balance: Mean Annual Global, Continental and Maritime Precipitation, Evaporation and Run-off*. Elsevier, Amsterdam.
7. Beniston, M., Rebetez M., Giorgi F., Marinucci M.R., 1994. An analysis of regional climate change in Switzerland. *Theoretical and applied climatology*, **49**: 135–159.
8. Blaney, H.F., Criddle W.D., 1950. Determining water requirements in irrigated areas from climatological and irrigation data. *Soil Conservation Service Technical Paper 96*. Soil Conservation Service, U.S. Dept. of Agriculture, Washington, D.C..
9. Cooper, D.M., Wilkinson W.B., Arnell N.W., 1995. The effects of climate changes on aquifer storage and base fow. *Hydrol. Sci. J.*, **40**: 615-631.
10. Darcy, H., 1856. *Les fontaines publiques de la ville de Dijon*, Dalmont, Paris.
11. Doorenbos, J., Pruitt W.O., 1977. Crop water requirements. *FAO Irrigation and drainage paper 24,* Rome.
12. EEA (European Environment Agency), 1996. *Water resources problems in Southern Europe*. Topic report No 15/1996.
13. EEA (European Environment Agency), 1998. *Europe’s environment. The second assessment*. Amsterdam, Elsevier Science.
14. EEA (European Environment Agency), 2004. *Impacts of Europe's changing climate*. EEA, Copenhagen, 2004.
15. Ferek, R.J., Garrett T., Hobbs P.V., Strader S., Johnson D., Taylor J.P., Nielsen K., Ackerman A.S., Kogan Y., Liu Q.F., Albrecht B.A., Babb D., 2000. Drizzle suppression in ship tracks. *J. Atmos. Sci.*, **57**(16): 2707-2728.
16. Fread, D.L., 1993. Flow routing. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
17. Hargreaves, G.H., 1974. Estimation of potential and crop evapotranspiration. *Transactions of the ASAE*, **17**(4):701-704.
18. Hulme, M., Jenkins G., 1998. Climate Change Scenarios for the United Kingdom: Scientific Report. *UKCIP Technical Report No. 1*. Climatic Research Unit, University of East Anglia, Norwich, United Kingdom, 80 pp.
19. IPCC, 2001. *Third Assessment Report. Climate Change 2001*. Working Group II: Impacts, Adaptation and Vulnerability.
20. Kovats, S., Menne B., McMichael A., Bertollini R., Soskolne C. (eds.), 2000. *Climate change and stratospheric ozone depletion. Early effects on our health in Europe*. Copenhagen, WHO Regional Office for Europe (WHO Regional Publications, European Series, No. 88).
21. Maidment, D.R., 1993. Hydrology. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.

22. Monteith, J.L., 1965. Evaporation and Environment. *19th Symposia of the Society for Experimental Biology*, **19**:205-234. University Press, Cambridge.
23. Nicholls, N. et al., *Observed climate variability and change*. In: Houghton, J.T., Meira Filho L.G., Callender B.A., Harris N., Kattenberg A., Maskell K. (eds.), *Climate change 1995. The science of climate change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, Cambridge University Press, 1996, pp. 133–192.
24. Penman, H.L., 1948. Natural evaporation from open water, bare soil, and grass. *Proceedings of the Royal Society of London*, A**193**:120-146.
25. Pilgrim, D.H., Cordery I., 1993. Flood runoff. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
26. Priestley, C.H.B, Taylor R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, **100**(2): 81-92.
27. Rawls, W.J., Ahuja L.R., Brakensiek D.L., Shirmohammadi A., 1993. Infiltration and soil water movement. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
28. Rees, H.G., Cole G.A. (eds.) 1997. *Estimation of renewable water resources in the European Union.* EUROSTAT for the European Environment Agency, pp. 38–73.
29. Richards, L.A, 1931. Capillary conduction of liquids in porous mediums. *Physics*, **1**: 318-333.
30. Rosenfeld, D., 2000. Suppression of rain and snow by urban and industrial air pollution. *Science*, **287**: 1793-1796.
31. Shuttleworth, W.J., 1993. Evaporation. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
32. Singh, V.P. (ed.), 1982. *Modelling Components of Hydrologic Cycle*. Water Resour. Publ., Littleton, Colorado.
33. Smith, J.A., 1993. Precipitation. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
34. Smith, L., Wheatcraft S.J., 1993. Groundwater flow. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
35. Stanners, D., Bourdeau P. (eds.), 1995. *Europe's environment: the Dobrís assessment. An overview*. Copenhagen, European Environment Agency.
36. Stedinger, J.R., Vogel R.M., Foufoula-Georgiou E., 1993. Frequncy analysis of extremem events. In: *Handbook of Hydrology*, D.R. Maidment (ed.), McGraw-Hill.
37. Turc, L., 1967. Evaluation des besoins en eau d'irrigation, evapotranspiration potentielle, formule climatique simplifice et mise a jour. *Ann. Agron*., **12**: 13-49.
38. Warner, J., 1968. A reduction in rainfall associated with smoke from sugarcane fires - An inadvertent weather modification? *J. Appl. Meteor.*, **7**: 247-251.

IV. Climate Change and Aquatic Ecosystems

A. Proxy Indicators

1. Barnston, A.G. and R.E.Livezey 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon.Weather Rev. 155: 1083-1126.
2. Blenckner, T. and D.L.Chen 2003. Comparison of the impact of regional and North Atlantic atmospheric circulation on an aquatic ecosystem. Climate Research 23: 131-136.
3. Bradley, D.C. and S.J.Ormerod 2001. Community persistence among stream invertebrates tracks the North Atlantic Oscillation. J.Anim.Ecol. 70: 987-996.
4. Cullen, H.M. and P.B.deMenocal 2000. North Atlantic Influence on Tigris-Euphrates streamflow. Int.J.Climatol. 20: 853-863.
5. Fraedrich,K. 1994. An Enso Impact on Europe - A Review. Tellus 46A: 541-552.
6. George, D.G. 2002. Regional-scale influences on the long-term dynamics of lake plankton, p. 265-290. *In* [eds.], P.J.le B Williams, D.N.Thomas, and C.S.Reynolds Phytoplankton productivity: carbon assimilation in marine and freshwater ecosystems. Blackwell Science.
7. George,D.G. and A.H.Taylor 1995. UK lake plankton and the Gulf stream. Nature 378: 139.

8. Gerstengarbe,F.-W., P.C.Werner, and U.Rüge. 1999. Katalog der Großwetterlagen Europas (1881-1998) - nach Paul Hess und Helmuth Brezowsky.
9. Gerten, D. and R.Adrian 2001. Differences in the persistency of the North Atlantic Oscillation signal among lakes. Limnol.Oceanogr. 46: 448-455.
10. Greatbatch, R.J., J.Lu, and A.Peterson 2004. Nonstationary impact of ENSO on Euro-Atlantic winter climate. Geophys.Res.Lett. 31, Art. No. L02208: 1-4.
11. Hänninen, J., I.Vuorinen, and P.Hjelt 2000. Climatic factors in the Atlantic control the oceanographic and ecological changes in the Baltic Sea. Limnol.Oceanogr. 45: 703-710.
12. Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676-679.
13. Hurrell, J.W., Y.Kushnir, G.Ottersen, and M.Visbeck 2003. An overview of the North Atlantic Oscillation, p. 1-35. *In* [eds.], J.W.Hurrell, Y.Kushnir, G.Ottersen, and M.Visbeck The North Atlantic Oscillation: Climatic significance and environmental impact.
14. Kaczmarek, Z. 2003. The impact of climate variability on flood risk in Poland. Risk Analysis 23: 559-566.
15. Kiely, G. 1999. Climate change in Ireland from precipitation and streamflow observations. Adv.Water Res. 23: 141-151.
16. Knippertz, P., U.Ulbrich, F.Marques, and J.Corte-Real 2003. Decadal changes in the link between El Nino and springtime North Atlantic oscillation and European-North African rainfall. International Journal of Climatology 23: 1293-1311.
17. Lamb, H.H. 1972. British Isles Weather types and a register of daily sequence of circulation patterns, 1861-1971. Geophysical Memoir 112: 1-85.
18. Livingstone, D.M. 1997. An example of the simultaneous occurrence of climate-driven "sawtooth" deep-water warming/cooling episodes in several Swiss lakes. Verh.Internat.Verein.Limnol. 26: 822-826.
19. Livingstone, D.M. 1999. Ice break-up on southern Lake Baikal and its relationship to local and regional air temperatures in Siberia and to the North Atlantic Oscillation. Limnol.Oceanogr. 44: 1486-1497.
20. Livingstone, D.M. 2000. Large-scale climatic forcing detected in historical observations of lake ice break-up. Verh.Internat.Verein.Limnol. 27: 2775-2783.
21. Livingstone, D.M. and M.T.Dokulil 2001. Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperature and the North Atlantic Oscillation. Limnol.Oceanogr. 46: 1220-1227.
22. Lloret, J., J.Lleonart, I.Solé, and J.M.Fromentin 2001. Fluctuations of landings and environmental conditions in the north-western Mediterranean Sea. Fish.Oceanogr. 10: 33-50.
23. Lloyd-Hughes, B. and M.A.Saunders 2002. Seasonal prediction of European spring precipitation from El Nino-Southern Oscillation and local sea-surface temperatures. International Journal of Climatology 22: 1-14.
24. Mariotti, A., N.Zeng, and K.M.Lau 2002. Euro-Mediterranean rainfall and ENSO - a seasonally varying relationship. Geophysical Research Letters 29.
25. Matyasovszky, I. 2003. The relationship between NAO and temperature in Hungary and its nonlinear connection with ENSO. Theoretical and Applied Climatology 74: 69-75.
26. Merkel, U. and M.Latif 2002. A high resolution AGCM study of the El Nino impact on the North Atlantic/European sector. Geophysical Research Letters 29: 1291-doi:10.1029/2001GL013726.
27. Moron, V. and G.Plaut 2003. The impact of El Nino-southern oscillation upon weather regimes over Europe and the North Atlantic during boreal winter. International Journal of Climatology 23: 363-379.
28. Moron, V. and M.N.Ward 1998. ENSO teleconnections with climate variability in the European and African sectors. Weather 53: 287-295.
29. Price,C., L.Stone, A.Huppert, B.Rajagopalan, and P.Alpert 1998. A possible link between El Nino and precipitation in Israel. Geophysical Research Letters 25: 3963-3966.
30. Rimbu, N., G.Lohmann, T.Felis, and J.Patzold 2003. Shift in ENSO teleconnections recorded by a northern Red Sea coral. Journal of Climate 16: 1414-1422.

31. Rodionov, S.N. 1994. Global and regional climate interaction: the Caspian Sea experience. Kluwer.
32. Rodó, X., E.Baert, and F.A.Comin 1997. Variations in seasonal rainfall in Southern Europe during the present century: relationships with the North Atlantic Oscillation and the El Nino-Southern Oscillation. Clim.Dynamics 13: 275-284.
33. Stenseth, N.C., G.Ottersen, J.W.Hurrell, A.Mysterud, M.Lima, K.S.Chan, N.G.Yoccoz, and B.Adlandsvik 2003. Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Nino Southern Oscillation and beyond. Proceedings of the Royal Society of London Series B-Biological Sciences 270: 2087-2096.
34. Straile, D. 2000. Meteorological forcing of plankton dynamics in a large and deep continental European lake. Oecologia 122: 44-50.
35. Straile, D. 2002. North Atlantic Oscillation synchronizes food-web interactions in central European lakes. Proc.R.Soc.Lond.B 269: 391-395.
36. Straile, D., D.M.Livingstone, G.A.Weyhenmeyer, and D.G.George 2003. The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation, p. 263-279. *In* [eds.], J.W.Hurrell, Y.Kushnir, G.Ottersen, and M.Visbeck The North Atlantic Oscillation: Climatic significance and environmental impact.
37. Taylor, A.H., M.B.Jordan, and J.A.Stephens 1998. Gulf stream shifts following ENSO events. Nature 393: 638.
38. Taylor, A.H. and J.A.Stephens 1998. The north Atlantic Oscillation and the latitude of the Gulf stream. Tellus 50A: 134-142.
39. Thompson, D.W.J., S.Lee, and M.P.Baldwin 2003. Atmospheric processes governing the Northern Hemisphere annular mode/North Atlantic Oscillation, p. 81-112. *In* [eds.], J.W.Hurrell, Y.Kushnir, G.Ottersen, and M.Visbeck The North Atlantic Oscillation: Climatic significance and environmental impact.
40. Van Loon, H. and R.A.Madden 1981. The Southern Oscillation .1. Global Associations with Pressure and Temperature in Northern Winter. Monthly Weather Review 109: 1150-1162.
41. Van Oldenborgh, G.J., G.Burgers, and A.K.Tank 2000. On the El Nino teleconnection to spring precipitation in Europe. International Journal of Climatology 20: 565-574.
42. Wilby, R. 1993. Evidence of ENSO in the synoptic climate of the British Isles since 1880. Weather 48: 234-239.

IV.B. Lakes

1. Adrian, R., Deneke, R., Mischke, U., Stellmacher, R. & Lederer, P. (1995). A long-term study of the Heiligensee (1975-1992). Evidence for effects of climatic change on the dynamics of eutrophied lake ecosystems. Archiv fuer Hydrobiologie 133, 315-337.

2. Agrell, J., McDonald, E.P., Lindroth, R.L. 2000. Effects of CO2 and light on tree phytochemistry and insect performance. Oikos 88:259–272.

3. Alabaster, J.S. & Lloyd, R. 1980. Water quality criteria for freshwater fish. Butterworths. London and Boston.

4. Ambrosetti, W. & L. Brabanti, 1999. Deep water warming in lakes: an indicator of climatic change. J. Limnol.58: 1-9.
5. Ambrosetti, W. & L. Brabanti, 2002a. Physical limnology of Italian lakes. 1. Relationship between morphometry and heat content. J. Limnol 61: 147-157.

6. Ambrosetti, W. & L. Brabanti, 2002b. Physical limnology of Italian lakes. 1. Relationship between morphometric parameters, stability and Birgean work. J. Limnol 61: 159-167.

7. Ambrosetti, W., Brabanti, L. & Sala, N. 2003. Residence time and physical processes in lakes. J. Limnol.62: 1-15.

8. Anderson, N.J., 2000. Diatoms, temperature and climatic change. Eur. J. Phycol.35: 307-314.

9. Arctic Council, 2004. Impacts of a warming climate. Cambridge University Press, Cambridge, UK: 146 pp.

10. Arnell, N.W. 1999. The effect of climate change on hydrological regimes in Europe: a continental perspective. Glob. Env. Change 9: 5-23.

11. Arvola, L., Palomäki, A., Lehtinen, S. & Järvinen, M. 2002. Phytoplankton community structure and biomass in two basins of a boreal lake in relation to local weather conditions and the North Atlantic Oscillation. Verh. Internat. Verein. Limnol. 28: 700-704.

12. Assel, R. A. and D. M. Robertson 1995. Changes in winter air temperature near Lake Michigan, 1851-1993, as determined from regional ice records. Limnol. Oceanogr. 40: 165-176.

13. Assel, R., Cronk, K. and Norton, D. 2003. Recent trends in Laurentian Great Lakes ice cover. Climatic Change 57: 185-204.

14. Behrendt, H. & Stellmacher, R. 1987. Long-term changes in water quality parameters of a shallow eutrophic lake and their relations to meteorologic and hydrologic elements. - The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. 168: 535-544.

15. Bengtsson, L., T. Hellström, and L. Rakoczi. 1990. Redistribution of sediments in three Swedish lakes. Hydrobiologia **192:** 167-181.

16. Blanc, P., C. Corvi & F. Papin, 1990. Evolution physicochimique des eaux du Leman. Rapp. Comm. Int. prot. eaux Leman contre pollut., Campagne 1988: 23-43.

17. Blenckner, T. & Chen, D. 2003. Comparison of the impact of regional and North Atlantic atmospheric circulation on an aquatic ecosystem. Clim. Res.23: 131–136.

18. Blenckner, T., Omstedt, A. and Rummukainen, M. 2002. A Swedish case study of contemporary and possible future consequences of climate change on lake function, Aquatic Sciences 64, 171-184.

19. Boorman, D.B. & C.E.M. Sefton, 1997. Recognising the uncertainty in the quantification of the effects of climate change on hydrological response. Clim. Change 35: 415-434.

20. Briand, J.-F., Leboulanger, Ch., Humbert, J.-F., Bernard, C. & Dufour, Ph. 2004. Cylindrospermopsis raciborskii (Cyanobacteria) invasion at mid-latitudes: selection, wide physiological tolerance, or global warming? Journal of Phycology 40: 231-238.

21. Brock, T.C.M. & W. van Vierssen, 1992. Climate change and hydrophyte-dominated communities in inland wetland ecosystems. Wetlands Ecology and Management, 2, 37–49.

22. Cole J.J. & Caraco N.F. 2001. Carbon in catchments: connecting terrestrial carbon losses with aquatic metabolism. Mar Freshwater Res. 52: 101-110.

23. Dams and development. A new framework for decision-making, 2000. The report of the World Commission on Dams. Earthscan Publications Ltd, London and Sterling, 356 pp.

24. Dams and Reservoirs, 2003. DHI Water & Environment publication: http://www.dhi.dk/AreasOfInterest/Dams_&_Reservoirs.pdf

25. Diehl, S. 2002. Phytoplankton, light, and nutrients in a gradient of mixing depths: Theory. Ecology 832: 386-398.

26. Dillon, P.J. 1974. A critical review of Vollenweider's nutrient budget model and other related models. Water Resources Bulletin 10:969-989.

27. Dokulil, M.T., 2000. Die Bedeutung hydroklimatischer Ereignisse für die Dynamik des Phytoplanktons in einem alpinen Klarwassersee (Mondsee, Österreich). Gewässerökol. Norddt. 4: 87-93.

28. Dokulil, M.T., 2003. Algae as ecological bio-indicators. In: B.A. Markert, A.M. Breure, H.G. Zechmeister (eds.) Bioindicators and biomonitors, Elsevier Sci. Ltd., Amsterdam, 285-327.

29. Dokulil; M.T., 2004. European Alpine Lakes. In: P.E. O´Sullivan and C.S. Reynolds, *The Lakers Handbook*. Vol. 2, Blackwell Publ., Oxford, *in print*.

30. Dokulil, M.T. & K. Teubner, 2002.The spatial coherence of alpine lakes. Verh. Int. Ver. Limnol. 28: 1861-1864.

31. Dokulil, M.T., U.H. Humpesch, R. Schmidt & M. Pöckl, 1993, Limnologie: Auswirkungen geänderter Klimaverhältnisse auf die Ökologie von Oberflächenwässer in Österreich. In: Bestandsaufnahme - Anthropogene Klimaänderungen: Mögliche Auswirkungen auf Österreich - Mögliche Maßnahmen in Österreich. Dokumentation (Hg. Komm. Reinhaltung d. Luft d. Österr. Akad. Wiss.) 5.1-5.84. Verlag der Österr. Akad. Wiss., Wien.

32. Eckel, O., 1955. Statistisches zur Vereisung der Ostalpenseen. Wetter und Leben 7: 49-57.

33. Elliott, J.M. 1981. Some aspects of thermal stress on freshwater teleosts. In: A.D. Pickering (ed.) Stress and Fish, pp. 209-245. Academic Press, London.

34. Erhard, M., van Minnen, J. & Voigt, Th. 2002. Proposed set of climate change state and impact indicators in Europe. European Environment Agency, Technical Report No. XX, 19 pp.

35. European Daylighting Atlas. European Commission, Directorate General XII, 1996.

36. Evans, C.D. & Monteich, D.T. 2001. Chemical trends at lakes and streams in the UK Acid Waters Monitoring Network 1988-2000: evidence for recent recovery at a national scale. Hydrol. Earth Syst. Sci. 5: 283-297.

37. Flanagan, K.M., McCauley, E., Wrona, F. & Prowse, T. 2003. Climate change: the potential for latitudinal effects on algal biomass in aquatic ecosystems. Can. J. Fish. Aquat. Sci. 60: 635–639.

38. Freeman, C., Ostle, N. & Kang, H. 2001. An enzymatic ´latch´ on a global carbon store. Nature 409: 149.

39. Gaedke, U., D. Ollinger, P. Kirner & E. Bäuerle, 1998. The influence of weather conditions on the seasonal plankton development in a large and deep lake (L. Constance). III. The impact of water column stability on spring algal development. In: D.G. George, J.G. Jones, P. Punčochář, C.S. Reynolds & D.W. Sutcliffe (eds.), Management of lakes and reservoirs during global climate change. NATO ASI Series 2: Environment Vol. 42, Kluwer Acad. Press, Dordrecht, 71-84.

40. Gaedke, U., A. Seifried & R. Kümmerlin, 1998. The influence of weather conditions on the seasonal plankton development in a large and deep lake (L. Constance). I. The impact of irradiance, air temperature and wind on the algal spring development – an analysis based on long-term measurements. In: D.G. George, J.G. Jones, P. Punčochář, C.S. Reynolds & D.W. Sutcliffe (eds.), Management of lakes and reservoirs during global climate change. NATO ASI Series 2: Environment Vol. 42, Kluwer Acad. Press, Dordrecht, 39-55.

41. George, D.G., 1997. The airborne remote sensing of phytoplankton chlorophyll in the lakes and tarns of the English Lake District. International Journal of Remote Sensing 18: 1961-1975.

42. George, D.G., 2000a. The impact of regional-scale changes in the weather on the long-term dynamics of *Eudiaptomus* and *Daphnia* in Esthwaite Water, Cumbria. Freshwater Biology, 43, 111-121.

43. George, D.G., 2000b. Using Climate Indicators to monitor patterns of change in freshwater lakes and reservoirs. In: Water in the Celtic World (Ed. J.A.A. Jones, K. Gilman, A. Jigorel and J.Griffin), British Hydrological Society, Occasional Paper No. 11: 93-102.

44. George, D.G. & Harris, G.P., 1985. The effect of climate on long-term changes in the crustacean zooplankton biomass of Lake Windermere, UK, Nature 316: 536-539.

45. George, D.G. & Reynolds, C.S., 1997. Zooplankton-phytoplankton interactions: the case for refining methods, measurements and models. Aquatic Ecology 31: 59-71.

46. George, D. G. & Hurley, M.A., 2002. Using a continuous function for residence time to quantify the impact of climate change on the dynamics of thermally stratified lakes. J. Limnol., 62(Suppl. 1): 21-26.

47. George, D.G., Hewitt, D.P., Lund, J.W.G. & Smyly, W.J.P. 1990. The relative effects of enrichment and climate change on the long-term dynamics of Daphnia in Esthwaite water, Cumbria. Freshwater Biology 23: 55-70.

48. George, D.G., Talling, J.F. and Rigg, E. 2000. Factors influencing the temporal coherence of five lakes in the English Lake District, Freshwater Biology 43: 449-461.

49. George, D. G., Maberly, S. C. & Hewitt, D.P. 2004. The influence of the North Atlantic Oscillation on the physical, chemical and biological characteristics of four lakes in the English Lake District. Freshwater Biology 49(6): 760-774.

50. Gerten, D. & Adrian, R. 2000. Climate-driven changes in spring plankton dynamics and the sensitivity of shallow polymictic lakes to the North Atlantic Oscillation. Limnol Oceanogr 45:1058–1066.

51. Gerten, D. & Adrian, R. 2001. Differences in the persistency of the North Atlantic Oscillation signal among lakes. Limnol. Oceanogr. 46:448–455.

52. Gerten, D. & Adrian, R. 2002. Effects of climate warming, North Atlantic Oscillation, and El Niño-Southern Oscillation on thermal conditions and plankton dynamics in Northern Hemispheric lakes. The Scientific World Journal 2: 586-606.

53. Giorgio, del P.A. & Peters, R.H. 1994. Patterns in planktonic P:R ratios in lakes: Influence of lake trophy and dissolved organic carbon. Limnol Oceanogr 39: 772-787.

54. Goldman, C.R., A. Jassby & T. Powell, 1989. Inter-annual fluctuations in primary production: meteorological forcing at two subalpine lakes. Limnol. Oceanogr. 34: 310-323.

55. Granados, I. & M. Toro, 2000. Recent warming in a high mountain lake (Laguna Cimera, Central Spain) inferred by means of fossil chironomids. J. Limnol 59 (Suppl 1): 109-119.

56. Guess, S., Albrecht, D., Krambeck, H. J., Mueller-Navarra, D. C. & Mumm, H. (2000). Impact of weather on a lake ecosystem, assessed by cyclo-stationary MCCA of long-term observations. Ecology 81, 1720-1735.

57. Haas, L. 2002. Mediterranean water resources planning and climate change adaptation. *Water, wetlands and climate change. Building Linkages for their Integrated Management.* Mediterranean Regional Roundtable. Athens, Greece, December 10-11, 2002. Draft for Discussion. 62 pp.

58. Hallegraeff, G. M. 1993. A review of harmful algae blooms and their apparent global increase. Phycologia 32: 79-99.

59. Hamilton, D. P., Spillman, C., Prescott, K. L., Kratz, T. K. & Magnuson, J. J. 2001. Effects of atmospheric nutrient inputs on trophic status of Crystal Lake, Wisconsin. Verh. Int. Verein. Limnol. 28: 467-470.

60. Hargreaves, J.A. 1999. Control of Clay Turbidity in Ponds. SRAC Publication No. 460.

61. Harrington, R., I. Woiwood & Sparks, T. 1999. Climate change and trophic interactions. TREE 14: 146-150.

62. Hawkes, H.A., 1969. Ecological changes of applied significance from waste heat. In Krenkel & Parker (eds), Biological Aspects of Thermal Pollution, Vanderbilt University Press, 15-53.

63. Hejzlar, J., Dubrovský, M. Buchtele, J. & Růžička, M. 2003. The apparent and potential effects of climate change on the inferred concentration of dissolved organic matter in a temperate stream (the Malše River, South Bohemia). The Science of the Total Environment 310: 143-152.

64. Henriksen, A., Skjelkvåle, B.L., Mannio, J., Wilander, A., Harriman, R., Curtis, C., Jensen, J.P., Fjeld, E. & T. Moiseenko, 1998. Northern European Lake Survey - 1995: Finland, Norway, Sweden, Denmark, Russian Kola, Russian Karelia, Scotland and Wales. Ambio 27(2), 80-91.

65. Huisman, J., R. R. Jonker, C. Zonneveld & F.J. Weissing, 1999. Competition for light between phytoplankton species: experimental tests of mechanistic theory. Ecology 80: 211-222.

66. Hyenstrand, P., P. Blomqvist & K. Pettersson, 1998. Factors determining cyanobacterial success in aquatic systems - a literature review. Arch. Hydrobiol. Spec. Issues Advanc. Limnol. 51: 41-62.

67. Irigoien, X., R.P. Harris, R.N. Head, and D. Harbour. 2000. North Atlantic Oscillation and spring bloom phytoplankton composition in the English Channel. J. Plankton Res. 22: 2367-2371.

68. Juutinen, S., J. Alm, et al. 2001. Effects of spring flood and water level draw-down on methane dynamics in the littoral zone of boreal lakes. Freshwater Biology 46: 855-869.

69. Kankaala, P., A. Ojala, T. Tulonen, L. Arvola & J. Haapamäki, 2000. Response of littoral vegetation on climate warming in the boreal zone; an experimental simulation. Aquatic Ecology 34: 433-444.

70. Keskitalo, J. & Eloranta, P. (eds.). 1999. Limnology of humic waters. Backhuys Publishers, Leiden: 284 pp.

71. Kilman, S., E. C. Theriot & S. C. Fritz, 1996. Linking planktonic diatoms and climate change in the large lakes of the Yellowstone ecosystem using resource theory. Limnology and Oceanography 41: 1052-1062.

72. Kirschner, A.K.T., Eiler, A., Zechmeister, T.C., Velimirov, B., Herzig, A., Mach, R. & Farnleitner, A.H. 2002. Extremely productive microbial communities in shallow saline pools respond immediately to changing meteorological conditions. Environmental Microbiology 4: 546–555.

73. Konopka, A. 1981. Influence of temperature, oxygen, and pH on a metalimnetic population of Oscillatoria rubescens. Appl Environ Microbiol. 42: 102–108.

74. Kuusisto, E. 1987. An analysis of the longest ice observation series made on Finnish lakes. Fennica 17: 123-132.

75. Lamb, H.H. 1972. British Isles weather types and a register of the daily sequence of circulation patterns. Geophys. Mem: 16 (116), 85 pp.

76. Lehtonen, H., 1996: Potential effects of global warming on northern European freshwater fish and fisheries. Fisheries Management and Ecology, 3, 59–71.

77. Lincoln, D.E., Fajer, E.D. & Johnson, R.H. 1993. Plant–insect herbivore interactions in elevated CO2. Trends Ecol. Evol. 8:64–68.

78. Livingstone, D.M., 1993. Temporal structure in the deep-water of four Swiss lakes: a short-term climatic change indicator? Verh. Int Ver. Limnol 25: 75-81.

79. Livingstone, D.M., 1997. An example of the simultaneous occurrence of climate-driven 'sawtoth' deep-water warming/cooling episodes in several Swiss lakes. Verh. Int. Verien. Limnol. 26: 822-826.

80. Livingstone, D.M. 2000. Large-scale climatic forcing detected in historical observations of lake ice break-up. Verh. Internat. Verein. Limnol. 27: 2775-2783.

81. Livingstone, D.M. & D.M. Imboden, 1996. The prediction of hypolimnetic oxygen profiles: a plea for a deductive approach. Can. J. Fish. Aquat. Sci. 53: 924-932.

82. Livingstone, D.M. & M.T. Dokulil, 2001. Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperatures and to the North Atlantic Oscillation. Limnol. Oceanogr. 46: 1220-1227.

83. Lotter, A.F., H.J.B. Birks, W. Hofmann, & A. Marchetto, 1997. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. 1. Climate. J. Palaeolimnol. 18: 395-420.

84. Lund, J. W. G. 1966. The importance of turbulence in the periodicity of certain freshwater species of the genus Melosira. Bot. Zhurn. 51: 176-187.

85. Lund, J. W. G. 1950. Studies on Asterionella formosa Hass. 2. Nutrient depletion and the spring maximum Pt. 1 Observations on Windermere, Estwaite Water and Belham Tarn. Pt. 2 Discussion. J. Ecol. 38: 15-35.

86. Maberly, S.C. 1996. Diel, episodic and seasonal changes in pH and concentrations Of inorganic carbon in a productive English Lake, Esthwaite Water, Cumbria. Freshwater Biology: 35: 579—598.

87. MacFadyen, E.J., Williamson, C.E., Grad, G., Lowery, M., Jeffrey, W.H. & Mitchell, D.L. 2004. Molecular response to climate change: temperature dependence of UV-induced DNA damage and repair in the freshwater crustacean Daphnia pulicaria. Global Change Biology 10: 408-416.

88. Magnuson, J.J. 2000. Historical trends in lake and river ice cover in the Northern Hemisphere, Science 289: 1743-1746.

89. Magnuson, J.J., B.J. Benson, and T.K. Kratz. 1990. Temporal coherence in the limnology of a suite of lakes in Wisconsin, U.S.A. Freshwat. Biol. 23: 137-143.

90. Magnuson, J.J., K.E. Webster, R.A. Assel, C.J. Bowser, P.J.Dillon, J.D.Eaton, H.E. Evans, E.J. Fee, R.I. Hall, L.R. Mortsch, D.W. Schindler, and F.H.Quinn. 1997. Potential effacts of climate changes on aquatic ecosystems: Laurentian Great Lakes and Precambrian Shield Region, p. 7-53. *In* C.E. Cushing [ed.], Freshwater ecosystems and climate change in North America. A regional assessment. John Wiley & Sons.

91. Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart & V.S. Vuglinski, 2000. Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. Science 289: 1743-1746.

92. Maitland, P. S. 1977. The Hamlyn guide to freshwater fishes of Britain and Europe. Hamlyn Publishing Group Limited, New York, NY.

93. Margat, J. & Vallé, D. 2000. Mediterranean Vision on water, population and the environment for the 21st Century. Blue Plan, 66 pp.

94. Matulla, C., H. Formayer, P. Haas & H. Kromp-Kolb, 2004. Possible climate trends in Austria in the first half of the 21st century. Österr. Wasser- und Abfallwirtschaft 56: 1-9.

95. May, R. M. 1986. When two and two do not make four: nonlinear phenomena in ecology. Proc. R. Soc. Lond. B. 228: 241-266.

96. McCann, K., A. Hastings & Huxel, G. 1998. Weak trophic interactions and the balance of nature. Nature 395: 794-798.

97. McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J. & White, K.S. (eds.), 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

98. McDiffet W.F., Beidler A.W., Dominick T.F. & McCrea K.D. 1989. Nutrient concentration-stream discharge relationship during storm events in a first-order stream. Hydrobiol. 179: 97-102.

99. Melack, J.M., J. Dozier, C.R. Goldman, D. Greenland, A.M. Milner & R.J. Naiman. 1997. Effects of climate change on inland waters of the Pacific coastal mountains and western Great basin of North America. Hydrological Processes 11: 971-992.

100. Meybeck M., 1995. Global distribution of lakes: In: A. Lerman, D.M. Imboden and J.R. Gat (eds.) *Physics and chemistry of lakes*. 1-35, 2nd Edition, Springer-Verlag Berlin.

101. Mitchell, G.N. & A.T. McDonald, 1992. Discolouration of water by peat following induced drought and rainfall simulations. Wat. Res. 26: 321-326.

102. Morgan, I.J., McDonald, D.G. & Wood, C.M. 2001. The cost of living for freshwater fish in a warmer, more polluted world. Global Change Biology 7: 345- 355.

103. Mysterud, A., Stenseth, N.C., Yoccoz, N.G., Langvatn, R., and Steinheim, G. 2001. Nonlinear effects of large-scale climatic variability on wild and domestic herbivores. Nature 410: 1096-1099.

104. Neilan, B.A., Saker, M.L., Fastner, J., Törökné, A. & Burns, B.P. 2003. Phylogeography of the invasive cyanobacterium Cylindrospermopsis raciborskii. Molecular Ecology 12: 133-140.

105. Nõges, P. & A. Kisand, 1999. Forms and mobility of sediment phosphorus in shallow eutrophic Lake Võrtsjärv (Estonia). International Review of Hydrobiology 84: 255-270.

106. Nõges, T. & Nõges, P. 1999. The effect of extreme water level decrease on hydrochemistry and phytoplankton in a shallow eutrophic lake. – Hydrobiologia 409: 277-283.

107. Nyberg, P., Bergstrand, E., Degerman, E. & Enderlein, O. 2001. Recruitment of pelagic fish in an unstable climate: studies in Sweden's four largest lakes. Ambio 30: 559-564.

108. Ohlendorf, C., C. Bigler, G.-H. Goudsmit, G. Lemcke, D.M. Livingstone, A.F. Lotter, B. Müller & M. Sturm, 2000. Causes and effects of long periods of ice cover on a remote high Alpine lake. J. Limnol. 59 (Suppl. 1): 65-80.

109. Osborne, T.J. & M. Hulme, 2002. Evidence for trends in heavy rainfall events over the UK. Phil. Trans. R. Soc. Lond. A, 360: 1313-1325.

110. Pace, M. L., J. J. Cole, Carpenter, S. R. & Kitchell, J. F. 1999. Trophic cascades revealed in diverse ecosystems. TREE 14: 483-488.

111. Palecki, M. A. and R. G. Barry 1986. Freeze-up and break-up of lakes as an index of temperature changes during the transition season: A case study for Finland. J. Appl. Meteor.. 25: 893-902.

112. Pashiardis, S. 2002. Trends of precipitation in Cyprus: Rainfall analysis for agricultural planning. Proc. 1st Technical Workshop of the Mediterranean Component of CLIMAGRI Project on Climate Change and Agriculture, Rome, September 25-27, 2002.

113. Patrick, R. 1969. Some effects of temperature on freshwater algae. Biological Aspects of Thermal Pollution. Vanderbilt Univ. Press, Nashville, Term. 161-185.

114. Petchey, O. L., P. T. Mc Phearson, P. T., Casey, M. & Morin, P. J. 1999. Environmental warming alters food-web structure and ecosystem function. Nature 402: 69-72.

115. Pettersson, K. 1990. The spring development of phytoplankton in Lake Erken: species composition, biomass, primary production and nutrient conditions - a review. Hydrobiologia 191: 9-14.

116. Pettersson, K., Herlitz, E. & Istvanovics, V. (1993). The role of Gloeotrichia echinulata in the transfer of phosphorus from sediments to water in Lake Erken. Hydrobiologia 253, 123-129.

117. Pompilio, L., W. Ambrosetti & L. Barbanti. 1996. Morphometry and thermal stratification in Italian lakes. 1. Predictive models. Mem. Ist. ital. Idrobiol., 54: 1-29.

118. Praptokardiyo, K., 1979. Populationsdynamik und Produktion von *Cyclops abyssorum tatricus* (KOZMINSKI 1927) im Gossenköllesee (2413 m ü. NN, Kühtai, Tirol). PhD Thesis Abt. limnologie Innsbruck 15, 1-83.

119. Premazzi, G., Dalmiglio, A., Cardoso, A.C. & Chiaudani, G. 2003. Lake management in Italy: the implications of the Water Framework Directive. Lakes and Reservoirs:Research and management 8:41-59.

120. Psenner, R., 2003. Alpine lakes: Extreme ecosystems under the pressure of global change. EAWAG news 55: 12-14.

121. Psenner, R., R. Schmidt, 1992. Climate-driven pH control of remote alpine lakes and effects of acid deposition. Nature 356: 1-3.

122. Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P., Jones, C., Meier, H. E. M., Samuelsson, P. and Willén, U. 2004. European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. Clim. Dyn. 22, 13-31.

123. Reynolds, C.S. 1984 *The Ecology of Freshwater Phytoplankton*. Cambridge University Press, Cambridge.

124. Rouen, M A, George D.G & Hewitt D P. 2000. Using an automatic monitoring station to assess the impact of episodic mixing on the seasonal succession of phytoplankton. Verh. Internat. Verein. Limnol. 27: 2972-2976.

125. Round, F. E., R. M. Crawford & D. G. Mann (1990). The diatoms. Cambridge University Press, Cambridge.

126. Rouse, R.W., M.S. V. Douglas, R.E. Hecky, A.E. Hershey, G.W. Kling, L. Lesack, P. Marsh, M. McDonald, B.J. Nicholson, N.T. Roulet, and J.P. Smol. 1997. Effects of climate change on the freshwaters of Arctic and Subarctic North America. Hydrological Processes 11: 873-902.

127. Salmaso, N., R. Mosello, L. Garibaldi, F. Decet, M. C. Brizzio& P. Cordella, 2003. Vertical mixing as a determinant of trophic status in deep lakes: a case study from two lakes south of the Alps (Lake Garda and Lake Iseo). J. Limnol., 62(Suppl. 1): 33-41.

128. Sarvala, J., & Helminen, H. 1996. Year-class fluctuations of perch (*Perca fluviatilis*) in Lake Pyhajarvi, Southwest Finland, Ann. Zool. Fenn 33: 389-396.

129. Scheffer, M., D. Straile, E.H. Van Nes, & H. Hosper, 2001. Climatic warming causes regime shifts in lake food webs. Limnology and Oceanography. 46: 1780-1783.

130. Schindler, D.W. and P.J. Curtis, 1997. The role of DOC in protecting freshwaters subjected to climatic warming and acidification from UV exposure. Biogeochemistry, 36(1): 1–8.

131. Schindler, D.W., P.J. Curtis, B.R. Parker, and M.P. Stainton, 1996. Consequences of climate warming and lake acidification for UV- B penetration in North American boreal lakes. Nature, 379 (6567):705-708.

132. Schröder, H.G., H. Windolph & J. Schneider, 1983. Bilanzierung der biogenen Karbonatproduktion eines oligotrophen Sees (Attersee, Salzkammergut – Österreich). Arch. Hydrobiol. 97: 356-372.

133. Sharpley A.N. & Syers J.K. 1979. Phosphorus inputs into a stream draining an agricultural watershed: II. Amounts and relative significance of runoff types. Water, Air and Soil Pollut. 11: 417-428.

134. Sobek, S., G. Algesten, A.-K. Bergstöm, M. Jansson, L.J. Tranvik, 2003. The catchment and climate regulation of pCO2 in boreal lakes. Global Change Biology 9: 630-641.

135. St Louis, V., Kelly, C.A., Duchemin, E., Rudd, E.W.M. & Rosenberg, D.M. Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. BioScience (in press).

136. Straile, D. & Adrian, R. 2000. The North Atlantic Oscillation and plankton dynamics in two European lakes - two variations on a general theme. Global Change Biology **6:** 663-670.

137. Straile, D., 2000. Meteorological forcing of plankton dynamics in a large and deep continental European lake. Oecologia 122: 44-50.

138. Straile, D., D. Livingstone, G.A. Weyhenmeyer, & D.G. George, 2003a. The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation. In: J.W. Hurrell, Y. Kushnir, G. Ottersen & M. Visbeck (eds.) The North Atlantic Oscillation. Climatic significance and environmental impact. Geophysical Monograph 134: 263-279, American Geophysical Union, Washington.

139. Straile, D., K. Jöhnk & H. Rossknecht, 2003b. Complex effects of winter warming on the physicochemical characteristics of a deep lake. Limnol. Oceanogr. 48: 1432–1438.

140. Sutcliffe D.W.S., Carrick T.R., Heron J., Rigg E., Talling J.F., Woof C. & Lund, J.W.G. 1982. Long-term and seasonal changes in the chemical composition of precipitation and surface waters of lakes and tarns in the English Lake District. Freshwat. Biol 12: 451-506.

141. Sweden's third national communication on Climate Change Under the United Nations Framework Convention on Climate Change. 2001. Ministry of the Environment Sweden. Departementsserie 71.

142. Talling J.F. 1971. The underwater light climate as a controlling factor in the production ecology of freshwater phytoplankton. Mitt. Int. Verein. Limnol. 17: 214-243.

143. Talling J.F. 1976. The depletion of carbon dioxide from lake water by phytoplankton. Journal of Ecology 64: 79—121.

144. Taylor, A.H. 1996. North-south shifts of the Gulf Stream: ocean-atmosphere interactions in the North Atlantic. Int. J. Climatol. 16: 559-583.

145. Tedd P (ed), 2000, Dams 2000, proceedings of the biennial conference of the British Dams Society, University of Bath, 14-17 June, London, Thomas Telford Publishing.

146. Thomas, Ch. 2003. Climate change and habitat fragmentation. In: Green, R.E., Harley, M., Miles, L., Scharlemann, J., Watkinson, A. & Watts, O. (eds.), Global climate change and biodiversity. University of East Anglia, Norwich, 36 pp.

147. Tuchman, N.C., Wetzel, R.G., Rier, S.T., Wahtera, K.A. & Teeri, J.A. 2002. Elevated atmospheric CO2 lowers leaf litter nutritional quality for stream ecosystem food webs. Global Change Biology 8: 163-170.

148. Türkeş, M. 2002. Precipitation Anomalies in Turkey and Relationships with the North Atlantic Oscillation. Proc. 1st Technical Workshop of the Mediterranean Component of CLIMAGRI Project on Climate Change and Agriculture, Rome, September 25-27, 2002.

149. Tymowski, R. G. & Duthie, H. C. (2000). Life strategy and phosphorus relations of the cyanobacterium Gloeotrichia echinulata in an oligotrophic Precambrian Shield lake. Archiv fur Hydrobiologie. Stuttgart 148, 321-332.

150. UKCIP. 2002. Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

151. Urabe, J., Togari, J. & Elser, J.J. 2003. Stoichiometric impacts of increased carbon dioxide on a planktonic herbivore. Global Change Biology 9: 818-825.

152. Vik, E.A. & Eikebrokk, B. 1989. Coagulation process for removal of humic substances from drinking water. In: Suffet, I.H. & MacCarthy, P. (eds.), Aquatic humic substancies: Influence on fate and treatment of pollutants. American Chemical Society, Washington DC: 385-408.

153. Vollenweider RA. 1975. Input-output models with special reference to the phosphorus loading concept in limnology. Schweiz. Zeitschr. Hydrol. 37:53-84.

154. Wallén, C.C. 1977. Climates of Central and Southern Europe. In: Landsberg, H.E. (ed.) World Survey of Climatology, vol. 6, Elsevier: Amsterdam, Oxford, New York.

155. Waser, L., Zimmermann, N., Keller, M. & Schwarz, M. 2001: Rapid Assessment of Land Cover in the European Alps - Evaluation of MODIS Mod12 Data; - In: Belward, A.; Binaghi, E.; Brivio, P.A.; Lanzarone, G.A. Tosi, G. (eds), Int. Workshop on Geo-Spatial Knowledge Processing for Natural Resource Management, pp 376-381.

156. Weyhenmeyer, G. 2001. Warmer winters: Are planctonic algal populations in Sweden`s largest lakes affected? Ambio 30: 565-571.

157. Weyhenmeyer, G. A., R. Adrian, U. Gaedke, D.M. Livingstone & S.C. Maberly, 2002. Response of phytoplankton in European lakes to a change in the North Atlantic Oscillation. Verh. Internat. Verein. Limnol. 28: 1436-1439.

158. Weyhenmeyer, G., Blenckner, T, & Pettersson, K. 1999. Changes of the plankton spring outburst related to the North Atlantic Oscillation. Limnol. Oceanogr. 44:1788–1792.

159. Wheeler, A. 1978. Key to the fishes of northern Europe. Frederick Warne Ltd., London, England.

160. Zacharias, I., Bertachas, I., Skoulikidis, N & Koussouris, Th. 2002. Greek Lakes: Limnological overview. Lakes & Reservoirs: Research and Management 7: 55-62.

IV.C. Coastal Systems

1. de Baar, H.J.W., and La Roche, J. 2002. Trace metals in the oceans : evolution, biology and global change. In: G. Wefer, F. Lamy, F. Mantoura (eds). Marine Science frontiers for Europe. Springer-Verlag.
2. Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247: 198-201.
3. Baldwin, C.K., and Lall, U. 1999. Seasonality of streamflow: the upper Mississippi River. Water Resour. Res. 35(4): 1143-1154.
4. Beaugrand, G. 2003. Long-term changes in copepod abundance and diversity in the north-east Atlantic in relation to fluctuations in the hydro-climatic environment. - Fisheries Oceanography 12: 270-283.
5. Beaugrand, G. 2004. The North Sea regime shift: evidence, causes, mechanisms and consequences. - Progress in Oceanography 60: 245-262.
6. Beaugrand, G., Brander, K. M., Lindley, J. A., Souissi, S. and Reid, P. C. 2003. Plankton effect on cod recruitment in the North Sea. - Nature 426: 661-664.
7. Beaugrand, G., Ibañez, F., Lindley, J. A. and Reid, P. C. 2002. Diversity of calanoid copepods in the North Atlantic and adjacent seas: species associations and biogeography. - Marine Ecology Progress Series 232: 179-195.
8. Beaugrand, G., Reid, P. C., Ibañez, F., Lindley, J. A. and Edwards, M. 2002. Reorganisation of North Atlantic marine copepod biodiversity and climate. - Science 296: 1692-1694.
9. Beebee, T. J. C. 1995. Amphibian breeding and climate. - Nature 374: 219-220.
10. Belgrano, A., Lindhal, O., and Hernroth, B. 1999. North Atlantic Oscillation primary productivity and toxic phytoplankton in the Gullmar Fjord, Sweden (1985-1996). Porc. R. Soc. Lond. B 266: 425-430.
11. Bernardi-Aubry, F., Berton, A., Bastianini, M., Socal, G., and Acri, F. 2004. Phytoplankton succession in a coastal area of the NW Adriatic, over a 10-year sampling period (1990-1999). Cont. Shelf Res. 24:97-115.
12. Bianchi, T.S., Engelhaupt, E., Westman, P., Andrén, T., Rolff, C., and Elmgren, R. 2000. Cyanobacterial blooms in the Baltic Sea: natural or human-induced? Limnol. Oceanogr. 45:716-726.
13. Bishop, J.K.B., Davis, R.E., and Sherman, J.T. 2002. Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. Science 298: 817-821.

14. Blaas, M., Kerkhoven, D., and de Swart, H.E. 2001. Large-scale circulation and flushing characteristics of the North Sea under various climate forcings. Clim. Res. 18: 47-54.
15. Boyd, P.W. et al. 2000. A mesoscale phytoplankton bloom in the polar southern ocean stimulated by iron fertilization of waters. Nature 407:695-702.
16. Brown, C.W., and Yoder, J.A. 1994. Coccolithophorid blooms in the global ocean. J. Geophys. Res. 99(C4): 7467-7482.
17. Buitenhuis, E.T., van der Wal, P., and de Baar, H.J.W. 2001. Blooms of Emiliana huxleyi are sinks of atmospheric carbon dioxide: a field and mesocosm study derived simulation. Global Biogeochem. Cycles 15(3): 577-587.
18. Cazenave A., Cabanes,C., Do Minh, K., and Mangiarotti, S. 2001. recent sea level change in the Mediterranean Sea revealed by Topex/Poseidon satellite altimetry. Geophys. Res. Let. 28:1607-1610.
19. Chen, C.-T. A., Liu, K.-K., and Macdonald, R. 2003. Chapter 3: Continental margin exchanges. In, M.J.R. Fasham (Ed.) Ocean Biogeochemistry: the role of the ocean carbon cycle in global change. IGBP Series. Springer. p. 53-97.
20. Cloern, J.E. 2001. Our evolving conceptual model of coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210: 223-253.
21. Cornell, S., Mace, K., Coeppicus, S., Duce, R., Huebert, B., Jickells, T., and Zhuang, L.-Z. 2001. Organic nitrogen in Hawaiian rain and aerosol. J. Geophys. Res. 106(D8): 7973-7983.
22. Cornell, S., Rendell, A., and Jickells, T. 1995. Atmospheric inputs of dissolved organic nitrogen to the oceans. Nature 376: 243-246.
23. Crick, H. Q. P., Dudley, C., Glue, D. E. and Thomson, D. L. 1997. UK birds are laying eggs earlier. - Nature 388: 526.
24. Cullen, H.M., Kaplan, A., Arkin, P.A., and Demenocal, P.B. 2002. Impact of the North Atlantic Oscillation on middle eastern climate and streamflow. Climatic Change 55: 315-338.
25. Cushing, D. H. 1984. The gadoid outburst in the North Sea. - Journal du Conseil. Conseil International pour l'Exploration de la Mer 41: 159-166.
26. Dickson, R., Lazier, J., Meincke, J., Rhines, P. and Swift, J. 1996. Long-term coordinated changes in the convective activity of the North Atlantic. - Progress in Oceanography 38: 241-295.
27. Donner, S.D., Coe, M.T., Lenters, J.D., Twine, T.E., and Foley J.A. 2002. Modeling the impact of hydrological changes on nitrate transport in the Mississippi River Basin from 1955 to 1994. Global Biogeochem. Cycles 16 (3), 1043, 10.1029/2001GB001396.
28. Drinkwater, K. F. 1996. Atmospheric and oceanic variability in the Northwest Atlantic during the 1980s and Early 1990s. - Journal of Northwest Atlantic Fishery Science 18: 77-97.
29. Duce, R.A., and Tindale, N.W. 1991. Chemistry and biology of iron and other trace metals. Limnol. Oceanogr. 36:1715-1726.
30. Ducrotoy, J.-P., Elliott, M., and de Jonge, V.N. 2000. The North Sea. Marine Pollution Bulletin 41: 5-23.
31. EU-US HAB 2003. The EU-US Scientific initiative on Harmful Algal Blooms. Report from a Workshop jointly funded by the European Commission – Environment and Sustainable Development programme – and the US National Science Foundation (Trieste, Italy, Sept. 5-8, 2002).
32. Finni,T., Kononen, K., Olsonen, R., and Wallström, K. 2001. The history of cyanobacterial blooms in the Baltic Sea. Ambio 30:172-178.
33. Fitter, A. H. and Fitter, R. S. R. 2002. Rapid changes in flowering time in British plants. - Science 296: 1689-1691.
34. Frankignoulle, M., Abril, G., Borges, A., Bourge, I., Canon, C., Delille,B., Libert, E., and Théate, J.-M. 1998. Carbon dioxide emission from European Estuaries. Science 282: 434-436.
35. Frankignoulle, M., and Borges, A.V. 2001. European continental shelf as a significant sink for atmospheric carbon dioxide. Global Biogeochem. Cycles 15:569-576.
36. Garrison, V.H., Shinn, E.A., Foreman, W.T., Griffin, D.W., Holmes, C.W., Kellogg, C.A., Majewski, M.S., Richardson, L.L., Ritchie, K.B., and Smith, G.W. 2003. African and Asian dust: from desert soils to coral reefs. BioScience 53(5): 469-480.
37. Gattuso, J.-P, Frankignoulle, M., and Wollast, R. 1998. Carbon and carbonate metabolism in coastal aquatic ecosystems. Annu. Rev. Ecol. Syst. 29:405-433.

38. GEOHAB 2001. Global Ecology and Oceanography of Harmful Algal Blooms: Science Plan. P.M. Glibert, and G. Pitcher (eds). SCOR and IOC, Baltimore and Paris. 87pp.
39. Granéli E., Codd, G.A., Dale, B., Lipiatou, E., Maestrini, S.Y., and Rosenthal, H. 1999. EUROHAB. Science initiative. Harmful algal blooms in European marine and brackish waters. Energy, Environment and sustainable development. EUR 18592.
40. Grantham, B.A., Chan, F., Nielsen, K.J., Fox, D.S., Barth, J.A., Huyer, A., Lubchenco, J., and Menge, B.A. 2004. Upwelling-driven nearshore hypoxia signals ecosystem and oceanographic changes in the northeast Pacific. Nature 429: 749-754.
41. Guerzoni, S., Chester, R., Dulac, F., Herut, B., Loÿe-Pilot, M.-D., Measures, C., Migon, C., Molinari, E., Moulin, C., Rossini, P., Saydam, C., Soudine, A., and Ziveri, P. 1999. The role of atmospheric deposition in the biogeochemistry of the Mediterranean Sea. Prog. Oceanogr. 44: 147-190.
42. Herut, B., Krom, D., Pan, G., and Mortimer, R. 1999. Atmospheric input of nitrogen and phosphorus to the Southeast Mediterranean: sources, fluxes, and possible impact. Limnol. Oceanogr. 44: 1683-1692.
43. Hoepffner, N., Sturm, B., Finenko, Z., and Larkin D. 1999. Depth-integrated primary production in the eastern tropical and subtropiocal North Atlantic basin from ocean colour imagery. Int. J. Remote Sens. 20(7):1435-1456.
44. Hoerling, M., and Kumar, A. 2003. The perfect ocean for drought. Science 299: 691-694.
45. Hughes, L. 2000. Biological consequences of global warming: is the signal already apparent? - Trends in Ecology and Evolution 15: 56-61.
46. IPCC. 2001. Climate change 2001. The scientific basis. - Cambridge University Press.
47. Jevrejeva, S., Drabkin, V.V., Kostjukov, J., Lebedev, A.A., Leppäranta, M., Mironov, Ye.U., Schmelzer, N., and Sztobryn, M. 2004. Baltic Sea ice seasons in the twentieth century. Clim. Res. 25: 217-227.
48. De Jonge ,V.N., and de Jong, D.J. 2002. 'Global Change' Impact of interannual variation in water discharge as a driving factor to dredging and spoil disposal in the river Rhine system and of turbidity in the Wadden Sea. Estuarine, Coastal and Shelf Science 55: 969-991.
49. Justic, D., Turner, R.E., and Rabalais, N.N. 2003. Climatic influences on riverine nitrate flux: implications for coastal marine eutrophication and hypoxia. Estuaries 26(1):1-11.
50. Keeling, C. D., Chin, J. F. S. and Whorf, T. P. 1996. Increased activity of northern vegetation inferred from atmospheric CO2 measurements. - Nature 382: 146-149.
51. Körtzinger, A. 2003. A significant CO2 sink in the tropical Atlantic Ocean associated with the Amazon River plume. Geophys. Res. Let. 30 (24), 2287, doi:10.1029/2003GL018841.
52. Kouvarakis, G., Mihalopoulos, N., Tselepides, A., and Stavrakakis, S. 2001. On the importance of atmospheric inputs of inorganic nitrogen species on the productivity of the eastern Mediterranean Sea. Global Biogeochem. Cycles 0: 1-13.
53. Kurosaki, Y., and Mikami, M. 2003. Recent frequent dust events and their relation to surface wind in East Asia. Geophys. Res. Let. 30(14), 1736, doi:10.1029/2003GL017261.
54. Laane, R.W., Southward, P.M., Slinn, A.J., Allen, J., Groeneveld, G., de Vries, A. 1996. Changes and causes of variability in salinity and dissolved inorganic phosphate in the Irish Sea, English Channel, and Dutch coastal zone. ICES J. Mar. Sci. 53: 933-944.
55. Lenes, J.M., Darrow, B.P., Cattrall, C., Heil, C.A., Callahan, M., Vargo, G.A., Byrne, R.H., Prospero, J.M., Bates, D.E., Fanning, K.A., and Walsh, J.J. 2001. iron fertilization and the Trichodesmium response on the West Florida shelf. Limnol. Oceanogr. 46:1261-1277.
56. Liu, K.K., Chen, C.-T.A., Gao, S., Hall, J., Macdonald, R.W., Talaue-McManus, L., and Quinones, R. 2000. Exploring continental Margin carbon fluxes on a global scale. Eos, Transact., AGU 81: 641-644.
57. Mace, K.A., Kubilay, N., and Duce, R.A. 2003. Organic nitrogen in rain and aerosol in the eastern Mediterranean atmosphere: an association with atmospheric dust. J. Geophys. Res. 108(D10), 4320, doi:10.1029/2002JD002997.
58. Mackenzie, F.T., Ver, L.M., and Lerman, A. 2002. Century-scale nitrogen and phosphorus controls of the carbon cycle. Chem. Geol. 190: 13-32.
59. Martiny, N., and Hoepffner, N. 2003. definition of an empirical index for dust aerosol remote sensing over the Mediterranean Sea: application to SeaWiFS data. Report of the European Commission EUR 20663 EN.

60. McCleery, R. H. and Perrins, C. M. 1998. Temperature and egg-laying trends. - Nature 391: 30-31.
61. McKee, B.A. 2003. RiOMar: the transport, transformation and fate of carbon in river-dominated ocean margins. Report of the RiOMar community workshop, Tulane University, New Orleans, 1-3 Nov. 2001.
62. Mélin, F., and Hoepffner, N. 2004. Global marine primary production: a satellite view. Technical Report of the European Commission. EUR 21084 EN.
63. Merico, A., Tyrrell, T., Brown, C.W., Groom, S.B., and Miller, P.I. 2003. Analysis of satellite imagery for Emiliana huxleyi blooms in the Bering Sea before 1997. Geophys. Res. Let. 30(6), 1337, doi:10.1029/2002GL016648.
64. Meybeck, M. 1982. Carbon, nitrogen, and phosphorus transport by world rivers. Am. J. Sci. 282: 401-450.
65. Moulin, C., Lambert, C.E., Dulac, F., and Dayan, U. 1997. Control of atmospheric export of dust from North Africa by the North Atlantic Oscillation. Nature 387:691-694.
66. Murray, N, Barthel, K.-G, Barth, H., and Fragakis, C. 2001. Introduction: European Land-Ocean Interaction Studies: the ELOISE thematic network. – Cont. Shelf Res. 21 (18-19).
67. Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G. and Nemani, R. R. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. - Nature 386: 698-702.
68. Naqvi, S.W.A., Jayakumar, D.A., Narvekar, P.V., Naik, H., Sarma, V.V.S.S., D'Souza, W., Joseph, S., and George, M.D. 2000. Increased marine production of N2O due to intensifying anoxia on the Indian continental shelf. Nature 408:346-349.
69. Napp, J.M., and Hunt Jr., G.L. 2001. Anomalous conditions in the south-eastern Bering Sea 1997: linkages among climate, weather, ocean, and biology. Fish. Oceanogr. 10:61-68.
70. Omstedt, A., Pettersen, C., Rodhe, J., and Winsor, P. 2004. Blatic Sea Climate: 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation. Clim. Res. 25: 205-216.
71. Paerl, H.W., and Whithall, D.R. 1999. Anthropogenically-derived atmospheric nitrogen deposition, marine eutrophication and harmful algal bloom expansion: is there a link? Ambio 28:307-311.
72. Pal, J.S., Giorgi, F., and Bi, X. 2004. Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophys. Res. Let. 31: L13202, doi:10.1029/2004GL019836.
73. Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J. K., Thomas, C. D., Descimon, H., Huntley, B., Kaila, L., Kullberg, J., Tammaru, T., Tennent, W. J., Thomas, J. A. and Warren, M. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. - Nature 399: 579-583.
74. Peperzak, L. 2003. Climate change and harmful algal blooms in the North Sea. Acta Oecologica 24:S139-S144.
75. Pounds, J. A. 2001. Climate and amphibian declines. - Nature 410: 639-640.
76. Poutanen, E.-L., and Nikkilä, K. 2001. Carotenoid pigments as tracers of cyanobacterial blooms in recent and post-glacial sediments of the Baltic Sea. Ambio 30:179-183.
77. Prospero, J.M., Uematsu, M., and Savoie, D.L. 1989. Mineral aerosol transport to the Pacific Ocean. In: J.P. Riley, R. Chester, R.A. Duce (eds). Chemical oceanography, vol. 10. Academic Press. London.
78. Quero, J.-C., Du Buit, M.-H. and Vayne, J.-J. 1998. Les observations de poissons tropicaux et le réchauffement des eaux dans l'Atlantique européen. - Oceanologica Acta 21: 345-351.
79. Rabalais, N.N., Turner, R.E., Justic, D., Dortch, Q., Wiseman Jr., W.J., and Sen Gupta, B.K. 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries 19(2B):386-407.
80. Redfield, A.C. 1958. The biological control of chemical factors in the environment. Am. Sci. 46:205-221.
81. Reid, P. C., Colebrook, J. M., Matthews, J. B. L., Aiken, J., Barnard, R., Batten, S. D., Beaugrand, G., Buckland, C., Edwards, M., Finlayson, J., Gregory, L., Halliday, N., John, A. W. G., Johns, D., Johnson, A. D., Jonas, T., Lindley, J. A., Nyman, J., Pritchard, P., Richardson, A. J., Saxby, R. E., Sidey, J., Smith, M. A., Stevens, D. P., Tranter, P., Walne, A., Wootton, M., Wotton, C. O. M. and Wright, J. C. 2003. The Continuous Plankton Recorder: concepts and history, from plankton indicator to undulating recorders. - Progress in Oceanography 58: 117-173.

82. Riebesell, U., Zondervan, I., Rost, B., Tortell, P.D., Zeebe, R.E., and Morel, F.M.M. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. Nature 407:364-367.
83. Rohde, J., and Winsor, P. 2003. On the influence of the freshwater supply on the Baltic Sea mean salinity. Tellus 55A: 455-456.
84. Rutgersson, A., Omstedt, A. and Räisänen, J. 2002. Net precipitation over the Baltic Sea during present and future climate conditions. Clim. Res., 22, 27-39.
85. Schrum, C. 2001. Regionalization of climate change for the North Sea and Baltic Sea. Clim. Res. 18: 31-37.
86. Schwing, F.B., and Mendelssohn, R. 1997. Increased coastal upwelling in the California current system. J. Geophys. Res. 102: 3421-3438.
87. Seitzinger, S.P., and Kroeze, C. 1998. Global distribution of nitrous oxide production and N inputs in freswater and coastal marine ecosystems. Global Biogeochem. Cycles 12: 93-113.
88. Seitzinger, S.P., and Sanders, R.W. 1999. Atmospheric inputs of dissolved organic nitrogen stimulate estuarine bacteria and phytoplankton. Limnol. Oceanogr. 44:721-730.
89. Siegismund, F., and Schrum, C. 2001. Decadal changes in the wind forcing over the North Sea. Clim. Res. 18: 39-45.
90. Skogen, M.D., Soiland, H., and Svendsen, E. 2004. Effects of changing nutrient loads to the North Sea. J. Mar. Syst. 46:23-38.
91. Smith, S.V., Swaney, D.P., Talaue-McManus, L., Bartley, J.D., Sandhei, P.T., McLaughlin, J., Dupra, V.C., Crossland, C.J., Buddemeier, R.W., Maxwell, B.A., and Wulff, F. 2003. Humans, Hydrology, and the distribution of inorganic nutrient loading to the ocean. BioScience 53 (3): 235-245.
92. Snyder, M.A., Sloan, L.C., Diffenbaugh, N.S., and Bell, J.L. 2003. Future climate change and upwelling in the California Current. Geophys. Res. Let. 30, 1823,doi:10.1029/2003GL017647.
93. Stebbing, A. R. D., Turk, S. M. T., Wheeler, A. and Clarke, K. R. 2002. Immigration of southern fish species to south-west England linked to warming of the North Atlantic (1960-2001). - Journal of the Marine Biological Association of the U. K. 82: 177-180.
94. Struyf, E., van Damme, S., and Meire, P. 2004. Possible effects of climate change on estuarine nutrient fluxes: a case study in the highly nutrified Schelde estuary (Belgium, The Netherlands). Estuarine, Coastal and Shelf Science. doi:10.1016/j.ecss.2004.03.004.
95. Sugimoto, N., Uno, I., Nishikawa, M., Shimizu, A., Matsui, I., Dong, X., Chen, Y., and Quan, H. 2003. Record heavy Asian dust in Beijing in 2002: observations and model analysis of recent events. Geophys. Res. Let. 30(12), 1640,doi:10.1029/2002GL016349.
96. Sundquist, E.T. 1985. geological perspective on carbon dioxide and the carbon cycle. In: E.T. Sundquist, W.S. Broecker. The carbon cycle and atmopsheric CO_2: natural variations archean to present. Geophys. Monogr. Ser. Vol. 32. AGU, Washington, D.C.
97. Thomas, C. D. and Lennon, J. J. 1999. Birds extend their ranges northwards. - Nature 399: 213.
98. Thomas, H., Bozec, Y., Elkalay, K., and de Baar H.J.W. 2004. Enhanced open ocean storage of CO2 from shelf sea pumping. Science 304:1005-1008.
99. Thomas, H., and Schneider, B. 1999. The seasonal cycle of carbon dioxide in Baltic Sea surface waters. J. Mar. Syst. 22: 53-67.
100. Trigo, R.M., Pozo-Vasquez, D., Osborn, T.J., Castro-Diez, Y., Gamiz-Fortis, S., and Esteban-Parra, M.J. 2004. North Atlantic Oscillation influence on precipitation, river flow, and water resources in the Iberian Peninsula. Int. J. Climatol. 24: 925-944.
101. Tsimplis, M.N., and Baker, T.F. 2000. Sea level drop in the Mediterranean Sea: an indicator of deep water salinity and temperature changes ? Geophys. Res. Let. 27(12):1731-1734.
102. Tsimplis, M.N., and Rixen,M. 2002. Sea level in the Mediterranean Sea: the contribution of temperature and salinity changes. Geophys. Res. Let. 29(23), 2136, doi:10.1029/2002GL015870.
103. Tsunogai, S., Watanabe, S.,and Sato,T. 1999. Is there a “continetal shelf pump” for the absorption of atmospheric CO_2? Tellus B51: 701-712.
104. Turner, R.E., and Rabalais, N.N. 1991. Changes in the Mississippi River water quality this century. Implications for coastal food webs. BioScience 41:140-148.

105. UNESCO 2003. The integrated strategic design plan for the coastal ocean observations module of the Global Ocean Observing System. GOOS Report # 125, IOC Information Doc. Ser. n° 1183.
106. Verheye, H.M. 2000. Decadal-scale trends across several marine trophic levels in the southern Benguela upwelling system off South Africa. Ambio 29: 30-34.
107. Vichi, M., May, W., and Navarra, A. 2003. Response of a complex ecosystem model of the northern Adriatic Sea to a regional climate change scenario. Clim. Res. 24: 141-158.
108. Warner, A. J. and Hays, G. C. 1994. Sampling by the Continuous Plankton Recorder survey. - Progress in Oceanography 34: 237-256.
109. Winsor, P., Rodhe, J., and Omstedt, A. 2001. Baltic Sea ocean climate: an analysis of 100yr of hydrographic data with focus on the freshwater budget. Cim. Res. 18: 5-15.
110. Woodworth, P.L., and Player, R. 2003. The permanent service for mean sea level: an update to the 21st century. J. Coast. Res. 19:287-295.
111. Yan, Z., Tsimplis, M.N., and Woolf, D. 2004. Analysis of the relationship between the North Atlantic oscillation and sea-level changes in Northwest Europe. Int. J. Climatol. 24: 743-758.
112. Yool, A., and Fasham, M.J.R. 2001. An examination of the "continental shelf pump" in an open ocean general circulation model. Global Biogeochem. Cycles. 2000GB001359.

IV.D. Lagoons

1. Kjerfve B. 1994. *Coastal Lagoon Processes*, Elsevier Science Publishers, Amsterdam, xx + 577 p.
2. De Wit R., Stal L.J., Lomstein B.Aa., Herbert R.A., Van Gemerden H., Viaroli P., Ceccherelli V.U., Rodriguez-Valera F., Bartoli M., Giordani G., Azzoni R., Schaub B., Welsh D:T:, Donnelly A., Cifuentes A., Anton J., Finster K., Nielsen L.B., Underlien Pedersen A-E., Turi Neubauer A., Colangelo M., Heijs S.K., 2001. ROBUST: the role of buffering capacities in stabilising coastal lagoon ecosystems. Continental Shelf Research, 21: 2021-2041.
3. Lasserre, P., 1979. Coastal lagoons. Sanctuary ecosystems, cradles for culture, targets for economic growth. Nature and Resources (UNESCO) 15, 2–21.
4. Schramm W. and Nienhuis P.H. (eds), 1996. Marine benthic vegetation. Recent changes and the effect of eutrophication. Ecological Studies 123, Springer, Berlin
5. Castel, J., Caumette, P., Herbert, R.A., 1996. Eutrophication gradients in coastal lagoons as exemplified by the Bassin d'Arcachon and the Etang du Prévost. Hydrobiologia, 329: xi-xxx.
6. Hemminga, M.A., 1998. The root rhizome system of seagrasses: an asset and a burden. Journal of Sea Reearch 39, 183–196.
7. Morand, P., Briand, X., 1996. Excessive growth of macroalgae: a symptom of environmental disturbance. Botanica Marina, 39: 491-516
8. Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K., 1997. Macroalgal blooms in shallow estuaries: control and ecophysiological and ecosystem consequences. Limnology and Oceanography 42 (5), 1105–1118.
9. Flindt, M.R., Pardal, M.A., Lilleb_, A.I., Martins, I., Marques, J.C., 1999. Nutrient cycling and plant dynamics in estuaries: a brief review. Acta Oecologica 20, 237–248.
10. Sfriso, A., Pavoni, B., Marcomini, A., Orio, A.A., 1992. Macroalgae, nutrient cycles, and pollutants in the lagoon of Venice. Estuaries 15, 517–528.
11. Viaroli, P., Azzoni, R., Bartoli, M., Giordani, G. and Tajé, L. 2001, Evolution of the trophic conditions and dystrophic outbreaks in the Sacca di Goro lagoon (Northern Adriatic Sea). In F. M. Faranda, L. Guglielmo and G. Spezie (eds), *Structure and processes in the Mediterranean Ecosystems*. Chapter 56, 443-451. Springer-Verlag, Milano. Italia.
12. Chapelle, A., Lazure, P. and Souchu, P. 2001. Modélisation numérique des crises anoxiques (malaïgues) dans la lagune de Thau (France). *Oceanologica Acta* **24**, S87-S97
13. Cadée, N., Dronkers, J., Heip, C.H.R., Martin, J.-M., Nolan, C., 2001. European Land–Ocean Interaction Studies, Science Plan, Ecosystem Research Report 11. European Commission, Luxembourg

14. Herman, P.M.J., Middelburg, J.J., Heip, C.H.R., 2001. Benthic community structure and sediment processes on an intertidal flat: results from the ECOFLAT project. Continental Shelf Research 21.
15. Camuffo, D. and Sturaro, G., 2004. Use of proxy-documentary and instrumental data to assess the risk factors leading to sea flooding in Venice. *Global and Planetary Change* **40**, 93-103.
16. Day Jr., J. W., Rybczyk, J., Scarton, F., Rismondo, A., Are, D. and Lecconi, G., 1999. Soil accretionary dynamics, Sea-level raise and the survival of wetlands in Venice lagoon. A field modeling approach. *Estuarine, Coastal and Shelf Science* **49**, 607-628.
17. Intergovernamental Panel on Climate Change. Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability http://www.ipcc.ch/
18. Viaroli, P., Pugnetti, A., and Ferrari, I., 1992. *Ulva rigida* growth and decomposition processes and related effects on nitrogen and phosphorus cycles in a coastal lagoon (Sacca di Goro, Po River Delta), in G. Colombo, I. Ferrari, V. U. Ceccherelli and R. Rossi (eds.), *Marine eutrophication and population dynamics*. Olsen & Olsen, Fredensborg, pp 77-84.
19. Troussellier M., Bonnefont J-L., Courties C., Derrien A., Dupray E., Gauthier M., Gourmelon M., Joux F., Lebaron P., Martin Y. and Pommepuy M. 1998. Responses of enteric bacteria to environmental stresses in seawater. *Oceanol. Acta* **21**, 965-981.
20. Short, F. T. and Neckles, H. A., 1999. The effects of global climate change on seagrasses. *Aquatic Botany* **63**. 169-196.
21. Nichols M.N. and Boon J.D. 1994. Sediment transport process in coastal lagoons. pp: 157-219, In: *Coastal Lagoon Processes*, Kjerfve B. (ed.) Elsevier Science Publishers, Amsterdam.
22. Gambolati, G., Teatini, P and Gonella, M., 2002. GIS simulation of the inundation risk in the coastal lowlands of the Northern Adriatic Sea. *Mathematics and Computer Modelling* **35**, 963-972.
23. Mostajir B., Demers S., de Mora S., Belzile C., Chanut J-P., Gosselin M., Roy S., Villegas P.Z., Fauchot J. and Bouchard J. 1999. Experimental test of the effect of ultraviolet-B radiation in a planktonic community. *Limnol. Oceanogr*. **44**, 586-596.
24. Worrest, R.C. 1989. What are the effects of UV-B radiation on marine organisms? In: Schneider, T. et al. (Eds.),Atmospheric Ozone Research and its Policy Implications. Elsevier, Amsterdam, The Netherlands, pp.269-278.
25. Smith, R.C., Prezelin, B.B., Baker, K.S., Bidigare, R.R., Boucher, N.P., Coley, T., Karentz, D., MacIntyre, S., Matlick, H., Menzies, D., Ondrusek, M.,Wan, Z.,Waters, K.J., 1992. Ozone depletion: Ultraviolet radiation and phytoplankton biology in Antarctic waters. *Science* **255**, 952-959.
26. Boelen, P., Post, A. F., Veldhuis, M. J. W. Amd Buma, A. G. J., 2002. Diel patterns of UVBR-induced DNA damage in picoplankton size fractions from the Gulf of Aqaba, Red Sea. *Microbial Ecology* **44**, 164-174.
27. Borum J, 1996. Shallow waters and land/sea boundaries. In B. B. Jørgensen and K. Richardson (Eds), Eutrophication in Coastal Marine Ecosystems. *Coastal and Estuarine Studies* **52**: 179-203.
28. Turner RK, Adger WN, Lorenzoni I, 1997. Towards integrated modelling and analysis in coastal zones: principles and practices. LOICZ Reports & Studies, 11, 122 p.
29. Valiela I, Collins G, Kremer J, Lajtha K, Geist M, Seely B, Brawley J, Sham CH, 1997. Nitrogen loading from coastal watersheds to receiving estuaries: new method and application. *Ecological Application* **7**, 358-380.
30. Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG, 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecological Applications 7, 737-750.
31. Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley & V.H. Smith, 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 3: 559-568.
32. Holland, A.F., D.M. Sanger, C.P. Gawle, S.B. Lerberg, M.S. Santiago, G.H.M. Riekerk, L.E. Zimmerman & G.I. Scott, 2004. Linkages between tidal creek

ecosystems and the landscape and demographic attributes of their watershed. *Journal Experimental Marine Biology Ecology* **298**: 151-178.

V. Climate Change and Water Challenges

VA. Extreme Events – Floods

1. Arnell, N.W. (1999), The effect of climate change on hydrological regimes in Europe: a continental perspective. *Global Environmental Change* **9**, 5-23.
2. Bronstert, A. (2003), Floods and Climate Change: Interactions and Impacts. *Risk Analysis*, **23-3**, 545-557.
3. Burlando, P., E.M. Fraschini, And A. Kühne, (1999) Impact of climate change on river runoff in mountainous areas, in: P. Balabanis et al. (eds.) *RIBAMOD - River basin modelling, management and flood mitigation* concerted action, Luxembourg, pp. 251-268.
4. Burlando, P. (2004) Postgraduate course on water resources, ETH Zurich.
5. IPCC (2001), Third Assessment Report on Climate Change. IPCC. Cambridge Univ. Press.
6. McCarthy, J. J. et al. (eds.) (2001), Climate Change 2001: Impacts, Adaptation and Vulnerability. IPCC. Cambridge Univ. Press.
7. Menzel, L. , and D. Schwandt (2004) Hydrologische Modellierung von Klima- und Landnutzungsszenarien im Rheingebiet. Final report. German Research Network Natural Disasters (DFNK), Potsdam.
8. Milly, P.C.D., R. T. Wetherald, K. A. Dunne & T. L. Delworth (2002), Increasing Risk Of Great Floods In A Changing Climate. *Nature* **415**, 514–517
9. Palmer, Tim And Jouni Räisänen (2002), Quantifying The Risk Of Extreme Seasonal Precipitation Events In A Changing Climate. *Nature* **415**, 512 - 514
10. Schar, Christoph, Pier Luigi Vidale, Daniel Lüthi, Christoph Frei, Christian Häberli, Mark A. Liniger & Christof Appenzeller (2004), The role of increasing temperature variability in European summer heatwaves. *Nature* **427**, 332 - 336.
11. Schnur, Reiner (2002), Climate Science: The Investment Forecast. *Nature* **415**, 483 – 484.
12. Vellinga, P. & W.J. Van Verseveld (2000), Climate Change and Extreme Weather Events. *World Wide Fund for Nature,* Gland, Switzerland.

V. B. European Droughts

1. Arnell, N.W., (1999). The effect of climate change on hydrological regimes in Europe: a continental perspective. Global Environmental Change 9 (**1999**), 5-23.
2. Assessment of the Economic Impact of Natural and Man-Made Disasters - Expert Consultation on Methodologies. Held at Centre for Research on the Epidemiology of Disasters (CRED). 29 - 30 September **1997**. Brussels.
3. AVEC Concerted Action “Vulnerability of European ecosystems facing an increasing drought risk”. International Workshop held in Samos, Greece – April **2003**.
4. COPA COGECA **2003**: Assessment of the impact of the heat wave and drought of the summer 2003 on agriculture and forestry. http://www.copa-cogeca.be/pdf/pocc_03_78i4_1e.pdf.
5. Doorkamp, J.C., Gregory, K. J. and Burn, A.S. **1980**. Atlas of Drought in Britain. Institute of British Geographers. 86 pages.
6. EEA, **2001**: Sustainable water use in Europe. Part 3: Extreme hydrological events: floods and droughts (Environmental issue report No 21). Copenhagen: European Environment Agency.
7. Hisdal, H., Stahl, K., Tallaksen, M. and Demuth, S. (**2001**). Have streamflow droughts in Europe become more severe of frequent? Int. Jour. Climatol. 21, 317-333.
8. IPCC (**2001**) Climate Change 2001: The Science of Climate Change. Cambridge University Press: Cambridge.
9. Jenkins, G and Lowe, J. (**2003**) Handling uncertainties in the UKCIP02 scenarios of climate change. Hadley Centre. Technical Note 44.

10. Munich RE : NatCat Database of European droughts, heat waves and forest fires (1976-2003)
11. Netherlands Drought Study. Final Report Phase 1, March **2003**, Rijkwaterstaat RIZA, ARCADIS.
12. Prudhomme, C., Jakob, D., et al. (**2003**). Uncertainty and Climate Change Impact on the Flood Regime of Small UK Catchments. Jnl of Hydrology 277: 1-23.
13. Reynard, N. S. and A. R. Young (**2003**). A Review: Effects of climate change on river flows and groundwater recharge. Report to UKWIR / Environment Agency, CEH-Wallingford. 19pp.
14. Thomsen, R. **1993**. Future Droughts, Water Shortages in Parts of Western Europe. EOS Transactions, Vol. 74, No. 14, 161-165
15. Vogt, J.V. & Somma, F. (eds.) (**2000**). Drought and Drought Mitigation in Europe, Kluwer.
16. Wilby, R.L., Wedgbrow, C.S and Fox, H.R. (**2005**, in press). Seasonal Predictability of the summer hydrometeorology of the River Thames, Jour. Hydrology.16p.

V. C. Ecological Status and WFD

1. Ambrosetti, W., Brabanti, L. & Sala, N. 2003. Residence time and physical processes in lakes. J. Limnol.62: 1-15.
2. Blind, M. 2004. ICT Requirements for an 'evolutionary' development of WFD compliant River Basin Management Plans. In: Pahl, C., Schmidt, S. & Jakeman, T. (eds), iEMSs 2004 International Congress: "Complexity and Integrated Resources Management". International Environmental Modelling and Software Society. Osnabrueck, Germany, June 2004.
3. CLIME (Climate and lake impacts in Europe; EVK1- CT- 2002 - 00121) http://www.water.hut.fi/clime
4. Owen, R., Duncan, W. & Pollard, P. Definition and Establishment of Reference Conditions. Scottish Environment Protection Agency, http://www-rciws.slu.se/REFCOND/Eval_Definiti.pdf
5. de Wilde A.J., Knoben, R.A.E. & van Poppel, J.W.P.M. 2002. Setting Classboundaries for the classification of rivers and lakes in Europe. Final Report Project number 39534, Client Ministerie van Verkeer en Waterstaat. DG RWS - RIZA
6. Halpina, P. N. 1997. Global climate change and the natural-area protection: Management responses and research directions. Ecological Applications 7(3): 828–843.
7. OECD, 1982. Eutrophication of Waters, Monitoring, Assessment and Control. Organisation for Economic Co-operation and Development, Paris.
8. REFCOND, 2003. Rivers and Lakes – Typology, Reference Conditions and Classification Systems. Common Implementation Strategy for the Water Framework Directive (2000/60/EC). Guidance Document No 10. Produced by Working Group 2.3 – REFCOND. Office for Official Publications of the European Communities, Luxembourg, 2003, 87 pp.
9. Nõges, P. & T. Nõges 2003. Monitoring of large shallow transboundary Lake Peipsi (Estonia/Russia) and the indicators and criteria worked out for assessment of its ecological status. In Ruoppa, M., Heinonen, P., Pilke, A., Rekolainen, S., Toivonen, H., Vuoristo, H. (eds.) How to assess and monitor ecological quality in freshwaters. TemaNord 2003:547, 71-81.
10. Sorvari, S. 2001. Climate Impacts on Remote Subarctic Lakes in Finnish Lapland: Limnological and Palaeolimnological Assessment with a Particular Focus on Diatoms and Lake Saanajärvi. Academic dissertation in Hydrobiology University of Helsinki, Helsinki.

V.D. Agriculture

1. Beniston, M. 2004. The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model situations. *Geophysical Research Letters*, 31, L02202, doi: 10.1029/2003GL018857.

2. Carter, T.R., Saarikko, R.A., and Niemi, K.J., 1996. Assessing the risk and uncertainties of regional crop potential under a changing climate in Finland. Agricultural and Food Science in Finland, 3, 329-349.
3. McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Eds.). 2001. Climate Change 2001: Impacts Adaptation, and Vulnerability. Contribution of WG II to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge
4. Döll, P., 2002. Impact of climate change and variability on irrigation requirements: a global perspective. Climatic Change, 54: 269-293.
5. EEA. 2003. Europe's water: An indicator-based assessment. EEA Topic Report No. 1/2003, Copenhagen. (http://www.eea.eu.int).
6. EEA. 2004. Impacts of Europe's changing climate. An indicator-based assessment. EEA Report No. 2/2004, Luxembourg, 107 p. (http://www.eea.eu.int).
7. EEA WQ2. n.y. Indicator Fact Sheet: Water Use by Sectors (WQ2). (http://www.eea.eu.int).
8. EEA WQ02a. n.y. Indicator Fact Sheet: Mean Water Allocation for Irrigation in Europe (WQ02a). (http://www.eea.eu.int).
9. EEA WQ03b. n.y. Indicator Fact Sheet: Saltwater Intrusion (WQ03b). (http://www.eea.eu.int).
10. EEA. n.y. IRENA Indicator Fact Sheet on Water Use Intensity (IRENA Indicator 10). (http://www.eea.eu.int).
11. Fischer G., Shah M., and van Velthuizen, H., 2002. Climate change and agricultural vulnerability. International Institute for Applied Systems Analysis, Vienna.
12. Fuhrer, J. 2003. Agroecosystem responses to combinations of elevated CO_2, ozone and global climate change. *Agriculture, Ecosystems and Environment* 97, 1-20.
13. Iglesias, A., C. Rosenzweig, and D. Pereira. 2000. Agricultural impacts of climate change in Spain: developing tools for a spatial analysis. *Global Environmental Change* 10, 69-80.
14. Kostrowicki, J., 1991. Trends in the transformation of European agriculture. In: Land Use Change in Europe, Bouwer F.M., Thomas A.J., and Chadwick M.J. (ed.). The Geojournal Library Vol 18, Kluwer Academic Publishers, 21-47.
15. Kundzewicz, Z. W.; Parry, M. L.; Cramer, W.; Holten, J. I.; Kaczmarek, Z.; Martens, P.; Nicholls, R.; Öquist, M.; Rounsevell, M. D. A.; Szolgay, J. 2001. Europe (Chapter 13). In: Impacts, adaptation, and vulnerability. Contribution of Working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Ed.: McCarthy, J. J.; Canziani, O. F.; Leary, N. A.; Dokken, D. J.; White, K. S. Cambridge 2001. 641-692 p.
16. Lehner, B., T. Henrichs, P. Döll, and J. Alcamo. 2001. EuroWasser – Model-based assessment of European water resources and hydrology in the face of global change. Kassel World Water Series 5, Center for Environmental Systems Research, University of Kassel (http://www.usf.uni-kassel.de).
17. Olesen, J.E., and M. Bindi. 2002. Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy* 16, 239-262.
18. Parry, M.L. (Ed.). 2000. Assessment of potential effects and adaptations for climate change in Europe: The Europe ACACIA Project. Jackson Environment Institue, University of East Anglia, Norwich, UK, 320 pp.
19. Rosenzweig, C. and D. Hillel. 1998. Climate change and the global harvest. Potential impacts of the greenhouse effect on agriculture. Oxford University Press, Oxford
20. Seguin, B. 2003. Adaptation des systèmes de production agricole au changement climatique. *C.R. Geoscience* 335, 569-575.
21. Vogt, J.V. and F. Somma (Eds.) 2000. Drought and drought mitigation in Europe. Kluwer Academic Publishers. Dordrecht, Boston, London, 336 p.

VI. Case Studues

VI.A. Lakes

1. George D.G., 2000b. De-coupling natural and anthropogenic sources of variation in the lakes of the English Lake District. Verh. Internat. Ver. Limnol 27: 321-325.
2. George, D.G. & S.I. Heaney, 1978. Factors influencing the spatial distribution of phytoplankton in a small, productive lake. J.Ecol. 66: 133-155.
3. George, D.G., D.P. Hewitt, J.W.G. & W.J.P. Smyly, 1990. The relative effects of enrichment and climate change on the long-term dynamics of *Daphnia* in Esthwaite Water. Freshwater Biology 23: 55-70.
4. George, D.G. & C.M. Allen, 1994. Turbulent mixing processes in a small Cumbrian lake. In Physical mechanisms of transport and dispersion in the environment. (Ed: K. Beven, P.Chatwin and J. Millbank), Wiley, 3-15.
5. George, D.G. & M.A. Hurley, 2003. Using a continuous function for residence time to quantify the impact of climate change on the dynamics of thermally stratified lakes. J. Limnol. 62., Suppl 1: 21-26.
6. Monteith D.T., C.D. Evans, & B. Reynolds, 2000. Are temporal variations in the nitrate content of UK upland waters linked to the North Atlantic Oscillation? Hydrol. Process. 14: 1745-1749.
7. Mortimer, C.H. 1941-2. The exchange of dissolved substances between mud and water in lakes. J.Ecol. 29: 280-329; 30: 147-201.
8. Blenckner, T., Omstedt, A. and M. Rummukainen, 2002. A Swedish case study of contemporary and possible future consequences of climate change on a lake ecosystem. Aquatic Science, 64, 171-184
9. Goedkoop, W. and E. Törnblom. 1996. Seasonal fluctuations in benthic bacterial production and abundance in Lake Erken: The significance of major abiotic factors and sedimentation events. Arch. Hydrobiol. Spec. Issues Advanc. Limnol. 48: 197-205.
10. Pettersson K., and K. Grust, 2002. Seasonality of nutrients in Lake Erken - effects of weather conditions. Verh. Internat. Verein. Limnol 28: 731-734.
11. Pettersson, K., Herlitz, E. & Istvanovics, V. 1993. The role of Gloeotrichia echinulata in the transfer of phosphorus from sediments to water in Lake Erken. Hydrobiol. 128: 175-186.
12. Weyhenmeyer, G. A., T. Blenckner and K. Pettersson. 1999. Changes of the plankton spring outburst related to the North Atlantic Oscillation. Limnol. Oceanogr. 44: 1788-1792.
13. Danecker, E. (1969) Bedenklicher Zustand des Mondsees im Herbst 1968. *Österreichs Fischerei*, **22**, 25-31,
14. Dokulil, M.T. (1993) Long-term response of phytoplankton population dynamics to oligotrophication in Mondsee, Austria. *Verhandlungen der Internationalen Vereinigung für Limnologie*, **25,** 657-661.
15. Dokulil M.T. (2000) Die Bedeutung hydroklimatischer Ereignisse für die Dynamik des Phytoplanktons in einem alpinen Klarwassersee (Mondsee, Österreich). *Gewässerökologie Norddeutschlands*, **4**, 87-93.
16. Dokulil M.T. & Skolaut C. (1991) Aspects of phytoplankton seasonal succession in Mondsee, Austria, with particular reference to the ecology of *Dinobryon* EHRENB. *Verhandlungen der Internationalen Vereinigung für Limnologie*, **24, 968-973.**
17. Dokulil M.T. & Teubner K. (2000) Cyanobacterial dominance in lakes. *Hydrobiologia*, **438,** 1-12.
18. Dokulil M.T. & Teubner K. (2002) The spatial coherence of alpine lakes. *Verhandlungen der Internationalen Vereinigung für Limnologie*, **28**, 1861-1864.
19. Dokulil M.T. & Teubner K. (2003) Steady state phytoplankton assemblages during thermal stratification in deep alpine lakes. Do they occur? *Hydrobiologia*, **502,** 65-72.
20. Findenegg I. (1959) Das pflanzliche Plankton der Salzkammergutseen. *Österreichs Fischerei,* **5-6**, 32-35.
21. Findenegg I. (1965) Limnologische Unterschiede zwischen den österreichischen und ostschweizerischen Alpenseen und ihre Auswirkung auf das Phytoplankton. *Vierteljahrschrift der Naturforschenden Gesellschaft Zürich,* **110**, 289-300.
22. Findenegg I. (1969) Die Eutrophierung des Mondsees im Salzkammergut. *Wasser- und Abwasser-Forschung*, **4**, 139-144.
23. Findenegg I. (1973) Vorkommen und biologisches Verhalten der Blaualge *Oscillatoria rubescens* DC. in den österreichischen Alpenseen. *Carinthia II*, **163**, 317-330.

24. Hydrographisches Zentralbüro 1964. Die Wassertemperaturen in Österreich im Zeitraum 1901-1950. Hydrographischer Dienst in Österreich: Beitröge zur Hydrographie Österreichs, v. 37.
25. Livingstone D.M. & Dokulil M. T. (2001) Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperatures and to the North Atlantic Oscillation. *Limnology and Oceanography* **46,** 1220-1227.
26. Schwarz, K. & Jagsch, A. (1998) Die Seen Oberösterreichs. Gewässerschutzbericht 20 (CD-ROM), Amt der OÖ Landesregierung, Linz.**4.**
27. Nõges T. & Nõges P. 1999. The effect of extreme water level decrease on hydrochemistry and phytoplankton in a shallow eutrophic lake. *Hydrobiologia* 408/409: 277--283.
28. Nõges, T., Nõges, P, Laugaste, R. 2003b. Water level as the mediator between climate change and phytoplankton composition in a large shallow temperate lake Hydrobiologia 506 (1): 257-263.
29. Tomingas, O. & J. Jaagus, 1999. Large-scale fluctuations of atmospheric circulation and their influence on climatic variation in Estonia. Publicationes Instituti Geographici Universitatis Tartuensis 85: 106-121.

VI.B. Lagoons

1. Gačić M., Mancero Mosquera I., Kovačević V., Mazzoldi A., Cardin V., Arena F., Gelsi G., 2004: Temporal variations of water flow between the Venetian Lagoon and the open sea, Journal of Marine Systems, n. 1079 (in press).
2. Magistrato alle Acque web site http://www.salve.it
3. Bianchi F, Ravagnan E, Acri F, Bernardi_Aubry F, Boldrin A, Camatti E, Cassin D and Turchetto M, 2004. Seasonal fluxes of nutrients and suspended matter between the Venice Lagoon and the Adriatic Sea through the Lido inlet (years 2001-2002) in: CORILA Scientific Research and the Safeguarding of Venice. Research Programme 2001-2003 - 2002 results, P. Campostrini ed., CORILA 2004, ISBN 88-89405-00-7, pp. 417-425.
4. Mainardi, R. Fiorin, A. Franco, P. Franzoi, A. Granzotto, S. Malavasi, F. Pranovi, F. Riccato, M.Zucchetta, P. Torricelli, 2004. Seasonal Distribuution of fish fauna in the Venice lagoon shallow waters: preliminary results, in: CORILA Scientific Research and the Safeguarding of Venice. Research Programme 2001-2003 - 2002 results, P. Campostrini ed., CORILA 2004, ISBN 88-89405-00-7, pp. 437-447.
5. Pirazzoli, P. A. and Tomasin, A., 1999. L’evoluzione recente delle cause meteorologiche dell'acqua alta. Atti dell’Istituto Veneto di Scienze, Lettere ed Arti CLVII, 317-344.
6. Carbognin, L. and Taroni, G.,1996. Eustatismo a Venezia e Trieste nell'ultimo secolo. Atti dell’Istituto Veneto di Scienze, Lettere ed Arti CLIV, 281-298.
7. Cocheo, C. and Camuffo, D., 2002. Corrections of systematic errors and data homogenisation in the daily temperature Padova series (1725 – 1998). Climatic Change 53, 77-100.
8. Livingstone D R, Lemaire P, Matthews A, Peters L D, Porte C, Fitzpatrick P J, Förlin L, Nasci C, Fossato V, Wootton N, Goldfarb P, 1995: Assessment of the impacts from organic pollutants on goby (*Zosterisessor ophiocephalus*) and mussel (*Mytilus galloprovincialis*) from the Venice lagoon, Italy: biochemical studies. *Marine Environmental Research*, 39, 235-240
9. Nasci C, Nesto N, Monteduro R A, Da Ros L, 2002: Field application of biochemical markers and a physiological index in the mussel, *Mytilus galloprovincialis*: transplantation and biomonitoring studies in the lagoon of Venice (NE Italy). *Marine Environmental Research*, 54, 811-816
10. Nasci C, Da Ros L, Nesto N, Sperni L, Passarini F, Pavoni B, 2000: Biochemical and histochemical response to environmental contaminants in clam, *Tapes philipipinarum*, transplanted to different polluted areas of Venice lagoon, Italy. *Marine Environmental Research*, 50, 425-430

VI.C. River Basins

Ebro River Basin

1. Abelló, P., Arcos J.M., Gil de Sola L., 2003. Geographical patterns of seabird attendance to a research trawler along the Iberian Mediterranean coast. In: E. Mínguez, D. Oro, E. De Juana and A. Martínez-Abraín (Eds.), *Mediterranean Seabirds and Their Conservation*. Scientia Marina, **67**: 69-75.
2. Alcácer-Santos, C. 2004.Environment flow assessment for the Ebro delta in Spain. Improving links between wetland and catchment management
3. Alcamo, J., Kreileman G.J.J., Bollen J.C., van den Born G.J., Gerlagh R., Krol M.S., Toet A.M.C., de Vries H.J.M., 1996. Baseline scenarios of global environmental change. *Global Environ. Change*, **6**: 261-303.
4. Batalla, R.J.,Gomez C.M., Kondolf G.M., 2004. Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, **290**: 117-136.
5. Comin, F.A., 1999. Management of the Ebro river basin: Past, Present and Future. *Water Science and Technology*, **40**: 161-168.
6. CRU, 2000 (compiled for European Environment Agency by P. Jones, September 2000)
7. Hejzlar, J., Dubrovský M., Buchtele J., Růžička M., 2003. The apparent and potential effects of climate change on the inferred concentration of dissolved organic matter in a temperate stream (the Malše River, South Bohemia). *The Science of Total Environment*, **310**: 143-152.
8. IPCC, 2001. *Third Assessment Report*: *Climate Change*. Klein Tank, A.M.G., Wijngaard J.B., Können G.P., Böhm R., Demarée G., Gocheva A., Mileta M., Pashiardis S., Hejkrlik L., Kern-Hansen C., Heino R., Bessemoulin P., Müller-Westermeier G., Tzanakou M., Szalai S., Pálsdóttir T., Fitzgerald D., Rubin S., Capaldo M., Maugeri M., Leitass A., Bukantis A., Aberfeld R., van Engelen A.F.V., Forland E., Mietus M., Coelho F., Mares C., Razuvaev V., Nieplova E., Cegnar T., Antonio López J., Dahlström B., Moberg A., Kirchhofer W., Ceylan A., Pachaliuk O., Alexander L.V., Petrovic P., 2002. Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment**.** *International Journal of Climatology* , **22**(12): 1441-1453
9. Ludwig, W., Serrat P., Cesmat L., Garcia-Esteves J., 2004. Evaluating the impact of the recent temperature increase on the hydrology of the Têt River (Southern France). *Journal of Hydrology*, **289**: 204-221.
10. Peerbolte, E.B., J.G. de Ronde, L.P.M. de Vrees, M. Mann, G. Baarse, 1991. Impact of Sea-Level Rise on Society: A Case Study for the Netherlands. Delft Hydraulics and Rijkswaterstaat, Delft and The Hague, The Netherlands, 81 pp.
11. PHN (Plan Hidrológico Nacional).Vols. 1-5. Ministerio del Medio Ambiente, Madrid, septiembre 2000.
12. PHN (Plan Hidrológico Nacional). Climate change effects. Ministerio del Medio Ambiente, Madrid, febrero 2003.
13. Pirazzoli, P.A. (assisted by J. Pluet), 1991. *World Atlas of Holocene Sea Level Chanqes*, Elsevier Oceanography series vol. 58, Elsevier Science Publishers, 300 pp.
14. Sănchez-Arcilla A., Jiménez J.A., Stive M.J.F., Ibañez C., Pratt N., Day J.Q. Jr., Capobianco M., 1996. Impacts of sea-level rise on the Ebro Delta: a first approach. *Ocean and Coastal Management*, **30**(2-3): 197-216.
15. UNEP/EEA, 2000. *State and Pressures of the Marine and Coastal Mediterranean Environment*, United Nations Environment Programme (UNEP) and European Environment Agency (EEA), available on-line at: http://reports.eea.eu.int/medsea/en/medsea_en.pdf.

Po River Basin

1. ABP, Autorità di Bacino del Po, 1999. Inquinamento delle acque superficiali e sotterranee. Sottoprogetto 2.1. Parma.
2. Algieri A., Cinnirella S., Pirrone N., Trombino G., 2003. Estimate of Nutrient Emission from the Po catchment into the Northern Adriatic Sea. Proc. Conference on Southern

European Coastal Lagoons: The Influence of River Basin-Coastal Zone interactions. Ferrara, Italy. 10-12th Nov.
3. Avila A., Neal C., Terradas J., 1996. Climate change implications for streamflow and streamwater chemistry in a Mediterranean catchment. Journal of Hydrology, 177 (1-2): 99-116:
4. Banuri T., Weyant J., 2001. Climate change 2001: mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: 753 pp.
5. Brochier F., Ramieri E, 2001. Climate Change Impacts on the Mediterranean Coastal Zones. FEEM Working Paper, 27: 1-82. http://ssrn.com/abstract=277549.
6. Hatch D., Goulding K., Murphy D., 2002. Nitrogen. In: Agriculture, Hydrology and Water Quality, Haygarth P. and Jarvis S. (eds.). CABI Publishing.
7. IPCC, 1996. Climate Change 1995, the sciences of climate change [J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.)]. Contribution of Working Group I to the Second Assessment Report of IPCC, Cambridge University Press, Cambridge, UK.
8. IPCC, 2001a. Climate change 2001: impacts, adaptation, and vulnerability. [McCarthy J.J., Canziani O.F., Leary N.A., Dokken D.J., White K.S. (eds.)]Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: 1032 pp.
9. IPCC, 2001. Climate change 2001: the scientific basis. [Houghton J.T., Ding Y., Griggs D.J., Noguer M., van der Linden P.J., Dai X., Maskell K., Johnson C.A. (eds.)] Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: 881 pp.
10. Leinweber P., Turner B.L., Meissner R., 2002. Phosphorus. In: Agriculture, Hydrology and Water Quality, Haygarth P. and Jarvis S. (eds.). CABI Publishing.
11. Pirrone N., Trombino G., Cinnirella S., Algieri A., Bendoricchio G., Palmeri L., 2005. The DPSIR approach for integrated catchment-coastal zone management: preliminary application to the Po catchment-Adriatic Sea coastal zone system. *Regional Environmental Change* (in press).

VI.D. Mercury Cycle

1. Amyot, M., Gill, G.A., Morel, F.M.M. (1997) Production and loss of dissolved gaseous mercury in coastal sea water. *Environ. Sci. Technol.* **31**, 3606 - 3611.
2. Ebinghaus, R., Kock, H.H, Temme, C., Einax, J.W., Lowe, A.G., Richter, A., Burrows, J.P., Schroeder, W.H. 2002. Antarctic springtime depletion of atmospheric mercury. Environ. Sci. Technol. 36(6):1238-1244.
3. European Commission (2001) EU Ambient Air Pollution by Mercury (Hg) - Position Paper on Mercury. European Commission (Publisher), Office for Official Publications of the European Communities, Brussels, ISBN 92-894-2053-7.
4. Hedgecock, I., Pirrone, N., Sprovieri, F., Pesenti, E. (2003) Reactive Gaseous Mercury in the Marine Boundary Layer: Modeling and Experimental Evidence of its Formation in the Mediterranean. *Atmos. Environ.*, 37/S1, 41-50.
5. Hedgecock, I. M. and Pirrone, N. (2004) Chasing Quicksilver: Modeling the Atmospheric Lifetime of $Hg^0_{(g)}$ in the Marine Boundary Layer at Various Latitudes. *Environ. Sci. Techn.,* 38, 69 – 76.
6. Hintelmann, H.; Falter, R.; Ilgen, G.; Evans, R. D. (1997) Determination of artifactual formation of monomethylmercury in environmental samples using stable Hg(II) isotopes with ICP/MS detection: calculation of contents applying species specific isotope addition. *Fresenius J. Anal. Chem, 358*, 363-370.
7. Horvat, M., Kotnik, J., Fajon, V., Logar, M., Zvonaric, T., Pirrone, N. (2001) Speciation of Mercury in Waters of the Mediterranean Sea. In: Material and Geoenvironment, Hines, M., Horvat, M., Faganeli, J. (Editors). Proceedings of the *International Workshop on Mercury in the Northern Adriatic Sea*, May 13-15, 2001, Portoroz, Slovenia, Vol. 48, 241-252.
8. Horvat, M., Kotnik, J., Fajon, V., Logar, M., Zvonaric, T., Pirrone, N. (2003) Speciation of Mercury in Surface and Deep Seawater in the Mediterranean Sea. *Atmos. Environ.*, 37/S1, 93-108.

9. IARC (1994) Evolution of Carcinogenic Risk to Humans. Vol. 58. Mercury and Mercury Compounds. Lyon, France.
10. Lee, Y.H., Wängberg, I. and Munthe, J. (2003) Sampling and analysis of gas-phase methylmercury in ambient air. Sci. Total Environ. 304:107-113.
11. Keeler, G.J., Glinsorn, G. and Pirrone, N. (1995) Particulate Mercury in the Atmosphere: Its Significance, Transport, Transformation and Sources. *Water, Air and Soil Poll.*, 80, 159-168.
12. Landis, M. S.; Stevens, R. K.; Shaedlich, F.; Prestbo, E. M. *Environ. Sci. Technol.* **2002**, *26*, 3000-3009.
13. Mason, R. P.; Sheu, G.-R. (2002) Global Biogeochem. Cycles, 16, 1093, doi:10.10229/2001 GB001440.
14. Pirrone, N., Keeler, G.J. and Nriagu, J.O (1996) Regional Differences in Worldwide Emissions of Mercury to the Atmosphere. *Atmos. Environ.*, 30, 2981-2987.
15. Pirrone, N., Hedgecock, I., Forlano, L. (2000) The Role of the Ambient Aerosol in the Atmospheric Processing of Semi-Volatile Contaminants: A Parameterised Numerical Model (GASPAR). *J. Geophys. Res.*, 105, D8, 9773-9790.
16. Pirrone, N. (Guest Editor), Pacyna, J.M., Barth, H. (2001) Atmospheric Mercury Research in Europe Special Issue of Atmospheric Environment, Vol. 35 / 17 *Elsevier Science*, Amsterdam, Netherlands.
17. Pirrone, N., Ferrara, R., Hedgecock, I. M., Kallos. G., Mamane, Y., Munthe, J., Pacyna, J. M., Pytharoulis, I., Sprovieri, F., Voudouri, A., Wangberg, I. (2003) Dynamic Processes of Atmospheric Mercury Over the Mediterranean Region. *Atmos. Environ.*, 37/S1, 21-40.
18. Pirrone, N., Pacyna, J.M., Munthe, J., Barth, H. (2003) Dynamic Processes of Mercury and Other Atmospheric Contaminants in the Marine Boundary Layer of European Seas. Special Issue of Atmospheric Environment 37-S, 2977-3074, *Elsevier Science*, Amsterdam, Netherlands.
19. Pirrone, N. and K. Mahaffey (2004) Dynamics of Mercury Pollution on Regional and Global Scales. *Kluwer Academic Publishers*, Norwell, MA, USA (In press).
20. Sander, R., Cruzten, P.J., (1996): Model study indicating halogen activation and ozone destruction in polluted air masses transported to the sea. *J. Geophys. Res.*, Vol. 101, 9121- 9138.
21. Schroeder, W. H., Anlauf, K. G., Barrie, L. A., Lu, J. Y., Steffen, A., Schneeberger, D. R., Berg, T. (1998). *Nature*; Vol. 394, pp. 331-332.Sprovieri, F., Pirrone, N., Gardfeldt, K., Sommar, J. (2003) Atmospheric Mercury Speciation in the Marine Boundary Layer along 6000 km Cruise path over the Mediterranean Sea. *Atmos. Environ.*, 37/S1, 63-72.
22. Sprovieri, F. and Pirrone, N. (2000) A Preliminary Assessment of Mercury Levels in the Antarctic and Arctic Troposphere. *J. of Aeros. Sci.*, 31, 757-758.
23. Sprovieri, F., Pirrone, N., Hedgecock, I. M., Landis, M., Stevens, B, K. (2002) Intensive atmospheric mercury measurements at Terra Nova Bay in Antarctica during November and December 2000. *J. Geophys. Res.* 107, D23, 4722-4729.
24. Sprovieri, F., Pirrone, N., Gardfeldt, K., Sommar, J. (2003) Atmospheric Mercury Speciation in the Marine Boundary Layer along 6000 km Cruise path over the Mediterranean Sea. *Atmos. Environ.*, 37/S1, 63-72.
25. UNEP (2002) Global Mercury Assessment (GMS) report. United Nations Environment Programme, Geneva, Switzerland.

VI.E. Climate change and waterborne and vector-borne diseases

1. American Society for Microbiology, Office of Public Affairs. Microbial Pollutants in our nation's water :environmental and Public Health Issues. Washington, DC: American Society for Microbiology, 1998
2. Anonymous, (2000). Waterborne outbreak of gastroenteritis associated with contaminated municipal water supply, Walkerton, Ontario, May-June 2000, Canada Communicable Disease Report, 26: 170-173.
3. Bernasconi C, Ghiani M, Daverio E, Camozzi (2004). Molecular-based methodologies for the assessment of microbiological status of drimking and surface water. EUR 21085 EN

4. Bouma MJ, Sondrop HE, van der Kaay HJ. (1994). Climate change and predict epidemic malaria. Lancet, 343:1440
5. Breslin K (1994). Global climate change: beyond sunburn. Environmental Health Perspectives 102(5):440-443.
6. Checkley W, Epstein LD, Gilman RH, Figueroa D, Cama RI, Patz JA, Black RE (2000). Effect of El Nino and ambient temperature on hospital admissions for diarrhoeal diseases in Peruvian children. Lancet. Feb 5;355(9202):442-50.
7. CHPA Climate Change Site-Heath Effects, http://www.ccah.cpha.ca, November 1, 2000
8. Colwell RR (1996). Global climate and infectious disease: The cholera paradigm. Science, 274:2025-2031.
9. Curreiro F.C., Patz J. A., Rose J. B., Lele S. (2001). The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994, American Journal of Public Health, 91: 1194-1199.
10. Diaz HF, Graham NE (1996). Recent changes in tropical freezing heights and the role of sea surface temperature. Nature 383:152-155
11. Epstein PR, Diaz HF, Elias S, Grabherr G, graham NE, Martens WJM, Susskind EJ (1998). Biological and physical signs of climate change: focus on mosquitos-borne diseases. Bull American Metereol. Soc. 78:409-417
12. Epstein PR. (2000). Is global warming harmful to health? Sci Am.283(2):50-7.
13. Ford T, Trenbeth K, Easterling D, Rose J. (1998). Increased flooding and climate change : consequence for human health. Environmental and energy study institute.Washington DC ,202-628-1400
14. Gerba CP, Rose JB, Haas CN (1996). Sensitive populations: who is at greatest risk? Int. J. Food Microbiol. 30:113-123
15. Hunter P.R. (2003). Climate change and waterborne ad vector-borne diseases, Journal of Applied Microbiology, 94: S37-S46.
16. Kiska DL. Global climate change: an infectious disease perspective. Clinical microbiology newsletter (2000);22(11):81-86
17. Kovats R. S., Bouma M J., Hajat S., Worrall E., Haines A (2003). El Nino and health, Lancet, 362: 1481-1489,.
18. Lindsay SW, birley MH. (1996). Climate change and malaria transmission. Annals of tropical medicine and parasitology, 90(6):573-588
19. Pascual M, Rodo X, Ellner SP, Colwell R, Bouma MJ (2000). Cholera dynamics and El Nino-Southern Oscillation. Science. Sep 8;289(5485):1766-9.
20. Patz JA.Global warming. BMJ. 2004 May 29;328(7451):1269-70.
21. Patz JA, Mc Geehin MA et al (2001). The potential health impacts of climate variability and change for the United States: executive summary of the report of the health sector of the U S National Assessment. J. Environ. Health. Sep;64(2):20-8.
22. Rose JB, Huq A, Lipp EK (2001). Health climate and infectious diseases: a global perspective. Report from the American Association of Microbiologists. Washington DC
23. Wade T. J., Sandhu K., Levy D. Lee S., LeChevallier M.W., Katz L., Colford J. M. Jr (2004). Did a severe food in the Midwest cause an increase in the incidence of gastrointestinal symptoms?, American Journal of Epidemiology, 159: 398-405.
24. WHO. 1993. The situation of malaria and its control in the world: status and progress since 1992. Document CTD/MAL/MIP/WP/93.1

VI.F.1 Climate Change, Extreme Events and POPs – an example

Extreme Events: The 2002 Flood of the River Elbe

http://www.ufz.de/data/HWEnd1333.pdf

VI.F.2 Climate Change and Global Persistent Organic Chemicals

1. Anderson, P. N., Hites, R. A. (**1996**) OH radical reactions: The major removal pathway for polychlorinated biphenyls from the atmosphere. *Eniviron. Sci. Technol.* **30,** 1756-1763.

2. Bailey, R. E. (**2001**) Global hexacholobenzene emissions. *Chemosphere* **43,** 167-182.
3. Barber, J. L., Thomas, G. O., Kerstiens, G. and Jones, K. C. (**2004**). Current issues and uncertainties in the measurement and modelling of air-vegetation exchange and within-plant processing of POPs. Environ. Pollut. 128: 99-138.
4. Bergqvist, P. A., Strandberg, B., Ekelund, R., Rappe, C. and Granmo, A (**1998**). Temporal Monitoring of Organochlorine Compounds in Seawater by Semipermeable Membranes following a Flooding Episode in Western Europe. Environ. Sci. Technol., 32, 3887 -3892.
5. Beyer, A., Mackay, D., Matthies, M., Wania, F., Webster, E. (**2000**) Assessing long-range transport potential of persistent organic pollutants. *Environ. Sci. Technol.* **34,** 699-703.
6. Bidleman, T. F. (**1988**) Atmospheric processes. *Environ. Sci. Technol.* **22,** 361-367.
7. Breivik, K., Sweetman, A., Pacyna, J. M., Jones, K. C. (**2002a**) Towards a global historical emission inventory for selected PCB congeners - A mass balance approach 1. Global production and consumption. *Sci. Total Environ.* **290,** 181-198.
8. Breivik, K., Sweetman, A., Pacyna, J. M., Jones, K. C. (**2002b**) Towards a global historical emission inventory for selected PCB congeners - A mass balance approach 2. Emissions. *Sci. Total Environ.* **290,** 199-224.
9. Brunciak, P.A.; J. Dachs; C.L. Gigliotti; E.D. Nelson; S.J. Eisenreich. Atmospheric PCB dynamics and apparent degradation in the New Jersey coastal atmosphere. *Atmos. Environ*. **2001**, 35, 3325-3339.
10. Cortes, D. R., Basu, I., Sweet, C. W., Hites, R. A. (**2000**) Temporal trends in and influence of wind on PAH concentrations measured near the Great Lakes. *Environ. Sci. Technol.* **34,** 356-360.
11. Dachs, J.; S.J. Eisenreich; R.M. Hoff. Influence of eutrophication on air-water exchange, vertical fluxes and phytoplankton concentrations of POPs. *Environ. Sci. Tech*. **2000**, 34(6), 1095-1102.
12. Dachs, J.; T. R. Glenn; C. L. Gigliotti; P. Brunciak; E. D. Nelson; T. P. Franz; S. J. Eisenreich**.** Occurrence and diurnal variability of PAHs in the Baltimore and adjacent Chesapeake Bay atmosphere. *Atmos. Environ*., **2002**, 36/14, 2281-2295.
13. Falconer, R. L., Bidleman, T. F. (**1994**) Vapour pressures and predicted particle/gas distributions of polychlorinated biphenyl congeners as functions of temperature and ortho-chlorine substitution. *Atmos. Environ.* **28,** 547-554.
14. Franz, T.P.; D. Gregor; S.J. Eisenreich. "Snow deposition of atmospheric SOCs." J.E. Baker (Ed.), In Atmospheric Deposition of Contaminants in the Great Lakes and Coastal Waters. SETAC Press: Boca Raton, FL, **1997,** p. 73-108.
15. Gouin, T., Mackay, D., Jones, K. C., Harner, T., Meijer, S. N. (**2004**) Evidence for the "grasshopper" effect and fractionation during long-range atmospheric transport of organic contaminants. *Environ. Pollut.* **128,** 139-148.
16. Hornbuckle, K. C. and Eisenreich, S. J. (**1996**). Dynamics of gaseous semivolatile organic compounds in a terrestrial ecosystem - effects of diurnal and seasonal climate variations. *Atmos. Environ*. **30**, 3935-3945.
17. Ikonomou, M. G., Rayne, S., Addison, R. F. (**2002**) Exponential increase of brominated flame retardants, polybrominated diphenyl ethers, in the Canadian Arctic from 1981 to 2000. *Environ. Sci. Technol.* **36,** 1886-1892.
18. Jantunen, L and Bidleman, T. (**1995**). Reversal of the air-water gas exchnage direction of hexachlorocyclohexanes in the Bering and Chukchi Seas. *Environ. Sci. Technol.* **29**, 1081-1089.
19. Jaward, F. M., Meijer, S. N., Steinnes, E., Jones, K. C. (**2004a**) Further studies on the latitudinal and temporal trends of persistent organic pollutants in Norwegian and UK background air. *Environ. Sci. Technol.* **38**, 2523-2530.
20. Jaward, F. M., Farrar, N. J., Harner, T., Sweetman, A. J., Jones, K. C. (**2004b**) Passive air sampling of PCBs, PBDEs, and organochlorine pesticides across Europe. *Environ. Sci. Technol.* **38,** 34-41.
21. Jaward, F. M., Barber, J. L., Booij, K., Dachs, J., Lohmann, R. and Jones, K. C. (**2004c**). Evidence for dynamic air-water coupling of persistent organic pollutants over the open Atlantic Ocean. Environ. Sci. Technol. 38: 2617-2625.
22. Jeremiason, J.J.; S.J. Eisenreich; M.J. Paterson, D. Findlay; H.J. Kling; K. Beaty; R. Hecky., J. Elser. Biogeochemical cycling of atmospherically-derived PCBs in lakes of

variable trophic status: a paired lake experiment. *Limnol. Oceanogr*. **1999**, 44(3, Part 2), 889-902**.**

23. Jones, K. C. and de Voogt, P. (**1999**). Persistent organic pollutants (POPs): the state of science. Environ. Pollut. Special Issue, 100: 209-221.

24. Klecka, G., Boethling, B., Franklin, J., Graham, G., Grady, L., Howard, P., Kannan, K., Larson, R., Mackay, D., Muir, D., van de Meent, K. (**2000**). *Evaluation of persistence and long-range transport of organic chemicals in the environment*. SETAC Special Publication Series. Pensacola, Fl., USA.

25. Lee, R. G. M., Hung, H., Mackay, D., Jones, K. C. (**1998**). Measurement and modelling of the diurnal cycling of atmospheric PCBs and PAHs. Environ. Sci. Technol. 32: 2172-2179.

26. Li, Y. F. (**1999**) Global technical hexachlorocyclohexane usage and its contamination consequences in the environment: From 1948 to1997. *Sci. Total Environ.* **232,** 121-158.

27. Li, Y. F., Scholtz, M. T., van Heyst, B. J. (**2003**) Global gridded emission inventories of β-hexachlorocyclohexane. *Environ. Sci. Technol.* **37,** 3493-3498.

28. Ma, J., Hung, H. and Blanchard, P. (**2004**). Hoe do climate fluctuations affect persistent organic pollutant distribution in North America? Evidence from a decade of air monitoring? *Environ. Sci. Technol.* **38**, 2538-2543.

29. Macdonald, R. W., Harner, T., Fyfe, J., Loeng, H. and Weingartner, T. (2003). AMAP Assessment **2002**: the influence of global change on contaminant pathways to, within, and from the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

30. Meijer, S. N., Ockenden, W. A., Steinnes, E., Corrigan, B. P., Jones, K. C. (**2003a**) Spatial and temporal trends of POPs in Norwegian and UK background air: Implications for global cycling. *Environ. Sci. Technol.* **37,** 454-461.

31. Meijer, S. N., Ockenden, W. A., Sweetman, A., Breivik, K., Grimalt, J. O., Jones, K. C. (**2003b**) Global distribution and budget of PCBs and HCB in background surface soils: Implications for sources and environmental processes. *Environ. Sci. Technol.* **37,** 667-672.

32. Ockenden, W. A., Sweetman, A., Prest, H. F., Steinnes, E., Jones, K. C. (**1998b**) Toward an understanding of the global atmospheric distribution of persistent organic pollutants: The use of semipermeable membrane devices as time integrated passive samplers. *Environ. Sci. Technol.* **32,** 2795-2803.

33. Prevedouros, K., Jones, K. C. and Sweetman, A. J. (**2004**). Estimation of production, consumption and emissions of pentabrominated diphenyl ether (PeBDE) in Europe: 1970-2000. *Environ. Sci. Technol.* **38**, June issue.

34. Shindell, D. T., Miller, R. L.,Schmidt, G. A. and Pandolfo, L. (**1999**). Simulation of recent northern winter climate trends by greenhouse-gas forcing. *Nature*, **399**, 452-455.

35. Mandalakis, M. H. Berresheim, E. Stephanou. Direct evideince for destruction of PCBs by OH radical s in the subtropical atmosphere. *Enviro. Sci. Tech*., **2004**, 37, 542-547.

36. Sweetman, A. J., Jones, K. C. (**2000**) Declining PCB concentrations in the U. K. atmosphere: Evidence and possible causes. *Environ. Sci. Technol.* **34,** 863-869.

37. UNECE (**1998**) *Protocol on Persistent Organic Pollutants under the 1979 Convention on Long-Range Transboundary Air Pollution;* United Nations Economic Commission for Europe (ECE/EB.Air/60).

38. Totten, L.A.; S.J. Eisenreich Evidence for OH Radical Attack on PCBs During Tropospheric Transport. *Organohalogen Compounds*, **1999**, 43, 353-357.

39. UNEP (**1998**) *Preparation of an Internationally Legally Binding Instrument for Implementing International Action on Certain Persistent Organic Pollutants;* United Nations Environment Programme, UNEP/POPs/Inc.1/6.

40. Wania, F. (**2003**) Assessing the potential of persistent organic chemicals for long-range transport and accumulation in polar regions. *Environ. Sci. Technol.* **37,** 1344-1351.

41. Wania, F., Dugani, C. B. (**2003**) Assessing the long-range transport potential of polybrominated diphenyl ethers: A comparison of four multimedia models. *Environ. Toxicol. Chem.* **22,** 1252-1261.

42. Wania, F., Mackay, D. (**1993**) Global fractionation and cold condensation of low volatility organochlorine compounds in polar regions. *Ambio* **22,** 10-18.
43. Wania, F., Mackay, D. (**1995**) A global distribution model for persistent organic chemicals. *Sci. Total Environ.* **160/161,** 211-232.
44. Wania, F., Mackay, D. (**1996**) Tracking the distribution of persistent organic pollutants. *Environ. Sci. Technol.* **30,** 390A-396A.
45. Wania, F. and Su, Y. (**2004**). Quantifying the global fractionation of polychlorinated biphenyls. Ambio, 33, 161-168.
46. Wodarg, D., Komp, P. and McLachlan, M. S. (**2004**). A beseline study of polychlorinated biphenyl and hexachlorobenzene concentrations in the western Baltic Sea and Baltic Proper. *Marine Chem.* **87**, 23-36.

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