8 Data gaps, uncertainties and future needs

This chapter gives an overview of uncertainties in general and those related to the climate change indicators in this report in particular. The main purpose is to show the gaps in observed trends and projections and the need for further improvements in monitoring (*in situ* and satellites) and modelling of future climate change.

8.1 Introduction

Need to address uncertainty

Decision making should take into account the rate of climate change, its impacts and the availability and effectiveness of measures to mitigate global climate change and adapt to the impacts. Actions are needed to adapt to current and projected climate change even with substantial mitigation measures in place. Ignoring uncertainty increases the risk of inappropriate action to tackle the challenge of climate change and its impacts on the environment, the economy and human well-being. Decision makers also need to take into account the precautionary principle according to which absence of full scientific certainty should not be used as a reason to postpone measures where there is a risk of serious or irreversible harm to public health or the environment. They can also take advantage of 'no-regret measures' and profit from 'win-win situations'. For example, in the transport sector, measures leading to a more efficient use of energy reduce greenhouse gas emissions and can have positive effects on the economy and health. Other examples are multiple benefits from protection of wetlands for biodiversity and flood protection, establishing mixed forests for biodiversity and increasing resilience of forests to changing environmental conditions, and greening urbanisation to improve local climate and human health.

Main types of uncertainty

Three basic types of uncertainty can be distinguished.

1. **Incomplete knowledge**
   Lack of understanding of the physical, chemical and biological processes, and attribution of climate change to anthropogenic and natural factors are all sources of uncertainty, as is attribution of impacts to climatic or non-climatic drivers. There may be still unknown processes in the Earth's systems. However the physical processes in the atmosphere and its interaction with land and sea surface are reasonably well understood. This is shown by the fact that climate models are able to reproduce the past and present climate rather well. However, there remain uncertainties in the understanding of the climate system, of which the last IPCC report (IPCC, 2007) gives a good overview, including impacts of cloud cover on the energy balance of the atmosphere, which implies uncertainty in climate sensitivity, a key variable in climate change modelling.

   Another process-related uncertainty for climate impact analysis is related to the 'double attribution': the attribution of climate change to anthropogenic activities and the attribution of observed changes in the environment to climate change impacts. The former attribution is approached indirectly by running models with and without anthropogenic forcing and comparing the results with observations. The latter type occurs especially in systems that are intensively managed or affected by human activities. Generally, this type of attribution is approached by analysing the consistency of observed indicator changes with observed climate change, taking into account understanding of the climate-dependency of the indicator, e.g. derived from controlled experiments or model analysis. Increase in crop yield for example may be caused by a combination of higher temperatures, CO_2 fertilisation, growth of new crop varieties and/or improved management. Responses in systems with high levels of complexity like biological, social or economic systems are very difficult to assess. Climate impacts can either be increased by other, non-climatic factors, or compensated by adaptation of the system, or internally compensated until a critical level of resilience is exceeded. Sensitivity analysis with computer models can support a better understanding of these systems by analysing the different combinations of drivers.

2. **Insufficient observed trends**
There may be high confidence in the understanding of particular processes of climate change and impacts. But if there are insufficient observation data and trends, assessments can often only give qualitative information which is of limited value for mitigation and adaptation strategies. There have been far more observation data available in recent years that clearly demonstrate that the climate system reacts very sensitively to changes in forcing, and small changes are already leading to significant impacts on nature and human well-being (see also Chapter 2).

   However in cases where data are still too limited for appropriate modelling and assessments, confidence in the findings is usually low. Data may be completely missing or have insufficient spatial or temporal resolution or coverage. Time-series can be too short for detecting trends and understanding causal links with either anthropogenic climate change or natural variability. For instance, the question of whether the frequency and intensity of hurricanes and floods is changing due to anthropogenic climate change or as part of natural variability is still unresolved. This is partly because the time-series of the observed trends are still too short and partly because the variability of these events is much higher than the trend in climate change. Scarcity in terms of temporal and spatial coverage of data describing the so-called lower boundary conditions of the climate system, like sea surface temperature, ice and snow cover, and permafrost, still limit the reliability of climate modelling (GCOS, 2003). Observed data and trends for many of the impact indicators presented in this report often lack the appropriate spatial and temporal scale.

3. **Uncertainty in future socio-economic developments**
The most important sources of uncertainty are human behaviour, evolution of political systems, demographic, technological and socio-economic developments. Policies to control greenhouse gas emissions affect the rate and intensity of future climate warming. For projections of climate change and impacts, the unpredictable component of the anthropogenic forcing is handled by using ensembles of potential futures based on different storylines of socio-economic development leading to a set of emission scenarios, such as the ones presented in the last IPCC reports (IPCC, 2001; 2007). These scenarios are used to analyse the influence of human activities on the climate system in an 'if — then' mode: if emissions increase or decrease to a certain degree then the anthropogenic impacts on the climate system will change in a certain way. The IPCC scenarios describe a range of such possible futures (Nakićenović *et al.*, 2000) (see also Chapter 4).

Several decades of climate research and the series of IPCC reports allow a first comparison of early projections with observations over the past 20 years. The results show that there is increasing evidence that emissions of greenhouse gases and increases in temperatures tend to be underestimated in projections. Even 'business as usual' or 'worst case' scenarios projected lower emissions and rises in temperatures in the past 20 years than the actual measurements in the same period show (IPCC, 2007). Underestimation of economic growth, energy demand and the carbon intensity of energy supply might be one of the reasons.

The projected range of temperature increase to the end of the 21st century has only changed slightly, from 1.4–5.8 °C in the third IPCC assessment report (IPCC, 2001) to 1.1–6.4 °C with a best estimate of 1.8–4.0 °C in the fourth assessment report (IPCC, 2007). This is the current best available framework for decision makers when they consider options for climate policy measures.

The scenarios for the climate change impacts and vulnerability indicators presented in this report are based mainly on these global IPCC scenarios and contain spatially detailed European information for only few indicators. They are also incomplete and differ between indicators. Regular interaction is needed between the climate modelling community and the user community that is analysing impacts, vulnerability and adaptation in order to develop high-resolution, tailor-made climate change scenarios for the regional and local level. It would be useful if European research projects were to adopt the same contrasting set of climate scenarios for global development, such as those used by IPCC, and make use of regional climate projections as soon as they become available.

Data and scenario requirements for adaptation planning

The need for regional assessments for better understanding of climate change and impacts requires analysis at higher spatial resolutions (e.g. more detailed than the currently available 50 x 50 km scale), including seasonal changes over the year (IPCC, 2007). To adequately support decisions on adaptation measures, more precise information at a regional and local level is required. Unfortunately, uncertainty in projections of future climate increases from the global to the regional and the local level because other factors like topography and other environmental conditions are important at such more detailed scales. Planning for winter tourism for example requires very detailed information on local climate, especially on changes in temperatures and snow-fall during winter, to analyse the cost-effectiveness of managing ski resorts and the environmental impacts of running these facilities. Taking climate change impacts into account for flood protection measures requires very detailed information on changes in precipitation frequency and intensity for appropriate planning of dams and dikes.

However, in the absence of definite information, stakeholders have to make decisions under uncertainty and (possibly) increasing information over time, aiming for no-regret measures. Preparation for the future does not require fully accurate prediction, but rather a foundation of knowledge upon which to base action, a capacity to learn from experience, close attention to what is going on in the present, and healthy and resilient institutions that can effectively respond or adapt to change in a timely manner.

8.2 Gaps in observations and uncertainties in projections

The number of indicators and the quality of the underlying information in terms of pan-European coverage for describing climate change impacts have been significantly increased since the last EEA climate change indicator report 2004. New indicators have been developed, especially for systems like ecosystems, biodiversity, forestry and agriculture (Table 8.1). Others have been dropped or incorporated in other indicators either because they have not been considered to be important for the communication of climate change impacts (e.g. greenhouse gas concentration) or because they have been replaced by a more Europe-wide view (e.g. plant species distribution in mountains).

Most of the indicators are based on studies published in reviewed papers. This means that it has not been possible to create a standard set of emission scenarios and climate model runs for the impact assessments. Table 8.2 gives an overview of the emission scenarios and climate models used for impact analysis for each indicator. In most cases, emission scenario A1B, A2, B1 or B2 are used as input for the climate models (see Box 4.1 in Chapter 4). For climate data, different versions of the Hadley Centre model (Had) or the ECHAM model from the Max Planck Institute for Meteorology (MPI-M)) have mostly been used. In some cases, regional climate (e.g. REMO) and weather models such as Hirham have been applied for a more detailed regional projection of future climate. The use of different emission scenarios and climate models leads to different results for future changes in temperature and precipitation. These changes vary over the seasons and also across European regions.

Because different scenarios have been presented in this report it is useful to understand how these results can be compared across the different indicators. An overview of all models and scenarios used in this report is therefore presented in Figure 8.1.

The uncertainties in climate projections (2071–2100 average value) for winter (December–February, DJF) and summer (June–August, JJA), for northern and southern Europe, are shown in Figure 8.1. The graphs show a clear relationship between temperature and precipitation increases in the north European winter (Figure 8.1a). Almost all models project higher temperatures and lower precipitation for the summer in southern Europe (Figure 8.1d). There are also clear indications of higher temperatures in north European summers (Figure 8.1b) and south European winters for all models (Figure. 8.1c) while models project different changes in precipitation (either small increases or decreases). Because of the uncertainty in projected precipitation in these cases the uncertainty in the impact indicators presented in this report, that are linked to precipitation and water supply/demand, such as floods, droughts, irrigation demand and crop growth, is high.

The current state in terms of uncertainties and data needs are summarised below for each indicator category presented in this report.

Atmosphere and climate

Atmospheric routine measurements have taken place for many decades. Data availability is in general therefore relatively good compared with other indicators, although it also differs among the climate indicators and among regions. At the global

Table 8.1 Major changes in indicators 2004–2008

Sector	New indicator in 2008	Replaced or removed indicator from 2004 report
Atmosphere and climate	Storms and storm surges in Europe	
	Air pollution by ozone	
		Greenhouse gas concentrations
Cryosphere	Greenland ice sheet	
	Mountain permafrost	
Water quantity, river floods and droughts	River floods (number of events)	
	River flow drought	
Freshwater quality and biodiversity	Water temperature	
	Lake and river ice cover	
	Freshwater biodiversity and water quality	
Terrestrial ecosystems and biodiversity	Distribution of animal species	Bird survival
	Animal phenology	
	Species-ecosystem relationships	
Soil	Soil organic carbon	Terrestrial carbon uptake *
	Soil erosion by water	
	Water retention	
Agriculture and forestry	Growing season for agricultural crops	
	Timing of the cycle of agricultural crops (agrophenology)	
	Crop-yield variability	Crop yield losses in 2003
	Water requirement	
	Forest growth	
	Forest fire danger	
Human health	Water- and food-borne diseases	
Economic sectors	Normalised losses from river flood disasters	
	Coastal areas	
	Public water supply and drinking water management	
	Agriculture and forestry (crop yield)	
	Biodiversity and ecosystem goods and services	
	Energy	
	Tourism and recreation	
	Health	
	Costs of climate change for society	

Note: * from section 'Terrestrial ecosystems and biodiversity'.

level, major gaps in coverage are identified mainly for Africa, the oceans and the polar regions (GCOS, 2003). For Europe there is still lack of data for regional and local assessments at the appropriate spatial resolution and quality. More detailed and quantitative, tailor-made information is especially needed for regional climate impact assessments and the development of cost-effective adaptation strategies. Climate reanalysis at global and regional level (see Box 5.2) is a tool to create data sets from land and oceans (surface to the upper layers of atmosphere) for periods up to 50 years and can thus improve study of climate and climate variability.

For adaptation particularly, information on extreme events is most important, but changes in storms and storm surges in relation to climate change are still uncertain since time-series of observed data are too short to understand the contributions of natural

Table 8.2 Emission scenarios and climate models used for impact studies

Indicator		IPCC SRES Scenario	Climate model	Remark
5.2	**Atmosphere and climate**			
5.2.2	Global and European temperature	A1B	*	21 climate models
5.2.3	European precipitation	A1B	*	21 climate models
5.2.4	Temperature extremes in Europe	A2	Hirham4 + HadCM3	
5.2.5	Precipitation extremes in Europe	A1B	Echam4	
5.2.6	Storms and storm surges in Europe	A2, B2	ECHAM4 + (HadAM3H)	
5.2.7	Air pollution by ozone	A2, B2	RegCM (climate) + CHIMERE (air quality)	JRC analysis
5.3	**Cryosphere**			
5.3.2	Glaciers	B2	HadCM3 & Echam4	Alps: sensitivity study
5.3.3	Snow cover	A1B, B1, A2	REMO; RCM-H-A2 (multi-model)	
5.3.4	Greenland ice sheet	---	---	
5.3.5	Arctic sea ice	*	*	13 IPCC AR4 climate models
5.3.6	Mountain permafrost	A1B, A2, B1	REMO	
5.4	**Marine biodiversity and ecosystems**			
5.4.2	Sea-level rise	*	*	Different scenarios and models
5.4.3	Sea surface temperature	A1B	*	Different models
5.4.4	Marine phenology	---	---	
5.4.5	Northward movement of marine species	---	---	
5.5	**Water quantity, river floods and droughts**			
5.5.2	River flow	A2	HIRHAM + HadAM3H	JRC analysis
5.5.3	River floods	A2	HIRHAM + HadAM3H	JRC analysis
5.5.4	River flow drought	A2	HIRHAM + HadAM3H	JRC analysis
5.6	**Freshwater quality and biodiversity**			
5.6.2	Water temperature	*	*	Different scenarios and models, 50–70 % of air temperature increase
5.6.3	Lake and river ice cover	A2	RCM	JRC analysis
5.6.4	Freshwater biodiversity and water quality	A2	---	
5.7	**Terrestrial ecosystems and biodiversity**			
5.7.2	Distribution of plant species	A2	HadCM2	
5.7.3	Plant phenology	---	---	
5.7.4	Distribution of animal species	A2	HadCM3	
5.7.5	Animal phenology	---	---	
5.7.6	Species-ecosystem relationship	A2	HadCM3	
5.8	**Soil**			
5.8.2	Soil organic carbon	A2	HadCM3	JRC analysis
5.8.3	Soil erosion by water	---	---	
5.8.4	Water retention	A2	ECHAM5/T106L31	JRC analysis
5.9	**Agriculture and forestry**			
5.9.2	Growing season for agricultural crops	---	---	
5.9.3	Timing of the cycle of agricultural crops (agrophenology)	---	---	
5.9.4	Crop-yield variability	---	---	
5.9.5	Water requirement	---	---	
5.9.6	Forest growth	A1B	NCAR-CCM3	
5.9.7	Forest fire danger	A2	Hirham4+DMI	
5.10	**Human health**			
5.10.2	Heat and health	A2	Normalised per °C	JRC PESETA project
5.10.3	Vector-borne diseases	Various	Normalised per °C and rainfall (mm)	IPCC model ensemble
5.10.4	Water- and food-borne diseases	Various	Normalised per °C	IPCC model ensemble
7	**Economic consequences of climate change**			
7.2	Direct losses from weather disasters	---	---	
7.3	Normalised losses from river flood disasters	A2, B2	HadAM3H, HIRHAM	JRC PESETA project
7.4	Coastal areas	A2	ECHAM4	JRC PESETA project

Table 8.2 Emission scenarios and climate models used for impact studies (cont.)

Indicator		IPCC SRES Scenario	Climate model	Remark
7.5	Public water supply and drinking water management	A2	ECHAM4, HadCM3	WaterGAP model
7.6	Agriculture and forestry	A2	HadCM3/ HIRHAM ECHAM4/RCA3	JRC PESETA project
7.7	Biodiversity and ecosystem goods and services	---	---	
7.8	Energy	A1B, B2	ECHAM4, HadCM3	WaterGAP model
7.9	Tourism and recreation	A2	HadCM3/ HIRHAM	JRC PESETA project
7.10	Health	SRES A2, B2	---	JRC PESETA project
7.11	Costs of climate change for society	Various	---	IPCC 2007

Note: --- projection based on observed sensitivity to climate change and expected qualitative trends in climate.

* combined assessment based on multiple scenarios and/or climate models mostly based on IPCC SRES.

variability and anthropogenic forcing. Sufficient data for better analysis of changes in the frequency and intensity of other extreme events like heat waves and heavy rain falls are still lacking, in parts of Europe and in terms of the length of the observed time-series.

Cryosphere

Ice and snow cover have been monitored directly for at least a century, the last decades also from space. Measuring techniques and coverage have gradually improved. Particularly important are changes in mass balances of ice-sheets and glaciers which are the key information for assessing water availability and changes in sea level. Changes in the extent and duration of snow-cover and sea-ice are also important due to the feedback mechanisms in the global climate system created by their change (albedo effect).

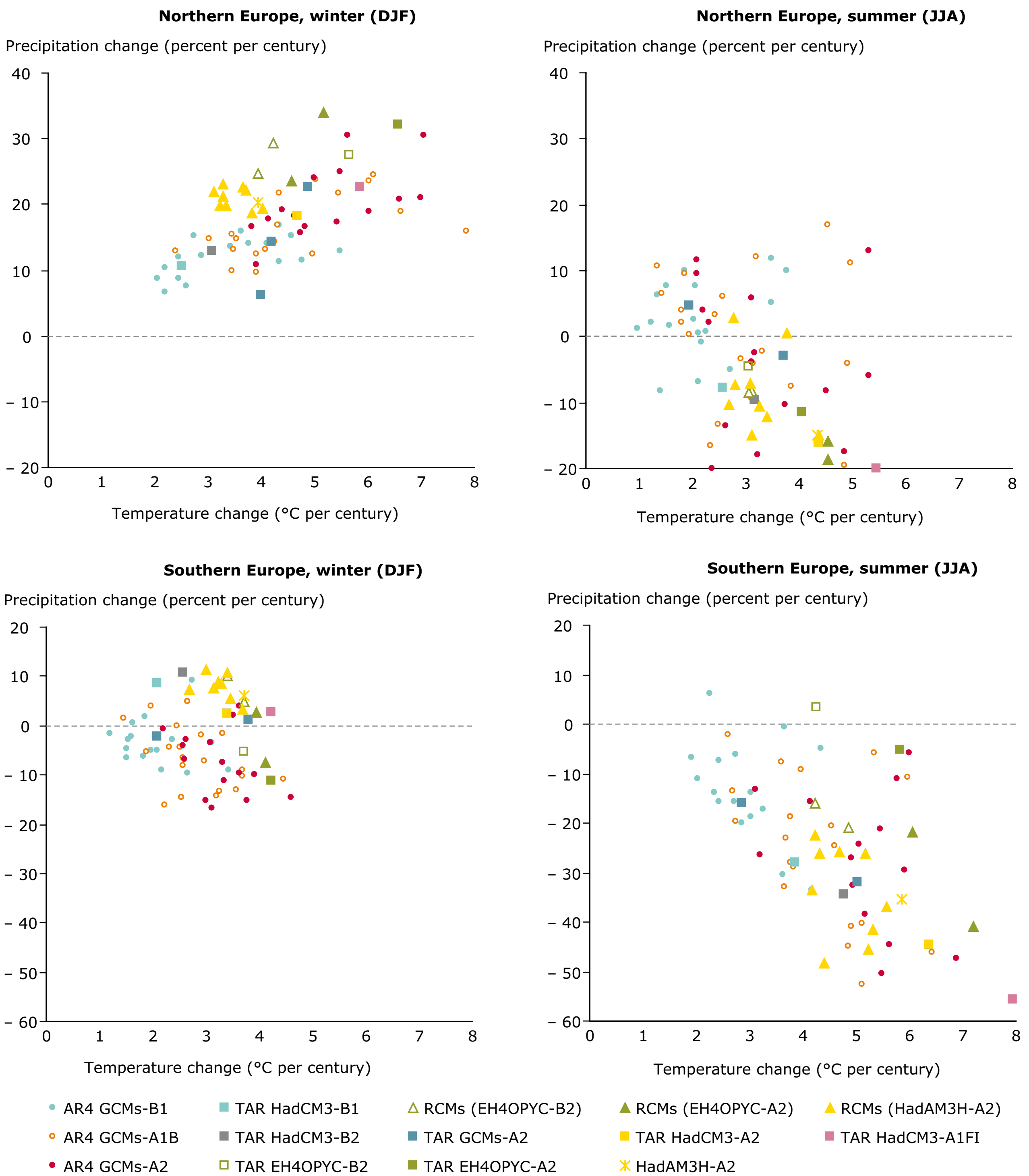
The evidence for these changes is robust for the selected mountain glaciers that are monitored intensively. But the majority of glaciers are not, and especially for the Greenland ice sheet, uncertainty in changes in mass-balances is still high. There is more and more evidence that melting rates for the Greenland ice sheet and Arctic sea ice are accelerating rapidly, with an unknown risk of reaching tipping points. Monitoring and research activities in Greenland have only recently been stepped up, and in time understanding may improve. Melting of permafrost has been observed, but data and knowledge for quantitative assessments are still rather poor due to too short time-series.

Marine biodiversity and ecosystems

Observations of both sea-level change and sea surface temperature are made using a network of ground-based stations and by satellites. The land-based observations of sea level are less accurate and are affected by vertical movements of the earths crust (sometimes called isostatic rebound), and cover only few points in space. Observations of sea surface temperature are made in a network of ocean based stations, and similarly have low spatial resolution, but both parameters have been measured for more than a century. The satellite observations of both sea surface elevation and sea surface temperature are more accurate and are temporally and spatially comprehensive, but have only been made for a relatively short period. By combining the two types of measurements, accurate time series of historical changes in mean sea level and sea surface temperature have been compiled. Projections of both sea-level change and sea surface temperature are, however, highly uncertain because some of the most important physical processes involved are poorly understood. In the case of sea-level change the processes include the internal ice-dynamics of the Greenland and Antarctic ice sheets, changes in the thermal structure of the oceans, and changes in the vertical movement of land. Sea surface temperature is affected by changes in ocean heat content and large-scale ocean circulation, and because the physical processes are poorly understood they are subject to intense scientific investigation and debate.

In the marine biological environment, observations have been made that indicate that marine organisms are changing their seasonality and southerly species are moving northward which in some cases can have serious ramifications for the entire marine foodweb. The studies that have been done at the planktonic level (the bottom of the marine food web) are primarily made by the Sir Alistair Hardy Foundation for Ocean Science using the Continuous Plankton Recorder. These observations are the only ones that have been made for a long enough time-period (observations were started in 1958) and that cover a

Figure 8.1 Comparison of scenarios of air temperature and precipitation applied in impact studies described in this report



Note: Data are from the PRUDENCE project (http://prudence.dmi.dk/index.html.). Results are split between northern (a,b) and southern Europe (c,d), winter (December–February, DJF) and summer (June–August, JJA). Projections are for the last 30 years of the 21st century relative to simulated present-day climate under different SRES scenarios of greenhouse gas and aerosol emissions. Projections from global climate models (GCMs) were reported in the IPCC Third (TAR) and Fourth (AR4) Assessment Reports. Outputs from two TAR GCMs (HadAM3H and EH4OPYC) were dynamically downscaled in the FP5 PRUDENCE project using regional climate models (RCMs — triangular symbols). Other TAR GCM projections (square symbols) were selected as scenarios in various FP5 and FP6 impact studies (e.g. ATEAM, ACCELERATES, ALARM). Recent AR4 multi-model ensemble GCM projections (small circles) are shown for comparison. Definitions of northern Europe differ slightly: for the AR4 GCMs, 48.0°N–75.0°N, 10.0°W–40.0°E (data from Isaac Held, personal communication); for the TAR GCMs, 47.5°N–67.5°N, 10.0°W–40.0°E (data from Ruosteenoja *et al.*, 2003); for the RCMs, 47.5°N–75.0°N, 15°W–35°E.

Source: Carter and Fronzek, 2008.

sufficiently large area (the North East Atlantic and North Sea) to document that large-scale changes are occurring. The bottom of the marine foodweb will also be first to be impacted by changes in ocean acidification; however the rate at which oceans will become acidified is uncertain. Satellite observation of ocean colour is a promising new monitoring technology, but can not yet show large scale changes in chlorophyll concentrations because time series availability is currently too short (10 years). There is also a shortage of ground observations available to interpret the causes of changes observed from space. Observations have been made of some species of fish moving northward, but analysing community changes is an area of emerging research. Because both the changes in the physical oceanographic environment and marine biological response to the physical changes are poorly understood, it is not possible to make projections for changes in marine biodiversity and ecosystems. A more systematic evaluation of changes in marine ecosystems is needed in terms of coverage of European seas and comparability of methods used.

Water quantity

The assessment of changes in water quantity and especially floods is linked to quantification of trends in mean and extreme precipitation which are still uncertain, especially for summer rainfall. Small differences in projected precipitation can lead to very large differences in water quantity, especially in areas with low annual precipitation (see Figure 8.1). In some areas of Europe, river discharge is also linked to changes in the mass balances of snow and ice. Water extraction as well as water management across catchments and changes in land use and management also make it very difficult to attribute changes in average water discharge, floods and droughts to climate-change forcing.

Monitoring networks for river discharge and groundwater levels are relatively dense and deliver robust numbers on average water flows. But due to non-climatic factors, uncertainties in climate-change-induced impacts are rather high. For projections, uncertainties in climate models further increase uncertainties in projected changes in water quantities. In particular, projections of changes in floods and droughts require much more detailed information on regional changes in precipitation and land management. Reliable information on quantities is the key information for appropriate water management and flood protection.
A pan-European view on river discharges and changes is still missing but will be implemented in the Water Information System for Europe (WISE) in the near future.

Water quality

There are already many observations of marked changes in water temperature, ice coverage, and stratification in European rivers and lakes that can be attributed mainly to higher air temperatures. Some long-term observations clearly describe the changes and these are supported by a growing set of shorter-term observations (30–50 years) that provide additional evidence of changes in the temperature regimes of rivers and lakes.

European freshwaters and their biodiversity, which plays an important role for water quality, are already affected by many human pressures related to land use, pollution with nutrients and hazardous substances, and acid deposition. Because of difficulties of disentangling the effects of climatic factors from other pressures, there is limited empirical evidence to demonstrate unequivocally the impact of climate change on water quality and freshwater ecology. On the other hand, there are many indications that freshwaters that are already under stress from human activities are highly susceptible to climate change impacts.

Changes in oxygen content and stratification of lakes which can be attributed to climate change are derived from national and local research and monitoring activities. It is obvious that especially higher temperatures and subsequent lower oxygen content will increase pressure on freshwater ecosystems, especially if nutrient and pollutant loads are already high, but quantification of these processes is still highly uncertain. European water quality is regularly monitored and reported as part of the Water Framework Directive and data are available via WISE.

Terrestrial ecosystems and biodiversity

Phenology and diversity of plants and animals show significant changes, but observed trends are still rather fragmentary in terms of European coverage and number of observed species. A fundamental problem is the different sensitivity of individual species to changes in temperature, precipitation, humidity and other climate variables. Using the observed distribution of species in relation to current climate conditions allows projections of the natural habitat of these species under future climates. However, these take no account of the individual resilience and adaptation capacity of the species, positive and negative impacts of management and risk of disconnection of predator — prey relations in the food web. The impact of climate change on the number of individuals per species (abundance), which is also very important for genetic variety and consequently for survival, so far was considered only to a very limited extent. Monitoring of biodiversity is based partly on regular screening of plants and species in protected areas. Most of the pan-European information is based on temporary research projects, voluntary networks and the activities of NGOs.

There is more information on observed changes in phenology, based mainly on voluntary observation networks than for changes in distribution. However there are only very general projections on phenological changes, based mainly on interpretations of changes in temperatures. More efforts are needed to improve monitoring, especially in areas where data sampling is still rather poor or data exist but are not accessible. A more systematic and harmonised observation of species and their abundance across Europe is needed to improve the still very fragmented knowledge of climate change impacts on ecosystems and biodiversity.

Soil

Climate is a key factor of soil development that controls the main soil-forming processes and directly or indirectly affects major soil threats in the EU. Wind soil erosion is triggered mainly by wind speed combined with droughts. Changes in heavy rainfalls and the loss of vegetation cover increase the risk of water erosion. However, the amounts of soil material removed by the erosion are quantified only for small areas. There is only information available on erosion risks and not on the real soil loss. Uncertainties concerning total soil loss and the impact of climate change in relation to human management are very high.

Soils are the biggest reservoir of carbon on earth. Under constant environmental conditions the rate of carbon accumulation in soil is balanced by the loss of carbon due to decomposition of dead vegetation remains and mineralisation of humus. This balance results in storage of carbon in soils over long periods. Higher temperature and less precipitation increase the rates of decomposition/mineralisation and accelerate the release of CO_2 from soils into the atmosphere. Decay of peat also leads to significant emissions of CH_4 and N_2O into the atmosphere. The amount of these GHG emissions from soils can be much higher than reductions through mitigation measures and can therefore seriously accelerate global warming. The magnitude of the carbon turnover in soils on the EU scale is insufficiently understood, making assessment and quantification of the effect of climate change on soils and evaluation of feedback of soil impact on climate uncertain.

Biodiversity of soil organisms is very complex and still poorly monitored. The organisms are very important for processes such as the decomposition of organic matter and for ecosystem stability. But there are only very few data about species that are winners or losers under changing climate and the impacts these changes may have on ecosystem functioning.

A better understanding of soil processes under climate change would need more information on trends in extreme weather events, more detailed data on carbon storage and in-depth understanding of soil processes under changing climate.

Agriculture and forestry

The agriculture and forestry sectors are affected by climate change and non-climatic impacts. Both sectors are clearly dominated by management, and it is therefore difficult to attribute specific trends from field observations uniquely to a changing climate.

Nevertheless, direct observations and model-based reconstructions allow the identification of specific climate-related impacts on plant growth. Also very extensive experiments e.g. FACE (free-air CO_2 enrichment experiments) are being performed to investigate the impacts of climate change on crop and tree species, including interactions with increasing atmospheric CO_2 concentrations and the impacts of management. Results are then extrapolated using models to simulate the physiological response of plants to changing conditions. There is still significant lack of knowledge and data on the individual responses of species to climate change and the subsequent changes in competition in forests and grasslands, also because the responses of species depend on age and time of exposure. More precise analyses and projections for agriculture and forestry would further require more detailed information on management for each site and forest stand. Projections of fire risks are rather robust but projections of the impacts of other extreme events like storms are very uncertain. There is a big gap in information on the possible changes in pressures from pests and diseases on crops and forests under a changing climate.

Pan-European assessments will certainly be more precise and accurate when specific local conditions and physiological constrains of crops, trees and pests are fully taken into account. But lack of knowledge on physiological responses of individual plant species to climate change and still inaccurate projections of future climate at the regional level make projections rather uncertain, especially in areas where precipitation is the limiting factor for agriculture and forestry. Projections for areas where temperatures are the limiting factor are expected to deliver more robust results.

Human health

Climate change impacts on human health include direct impacts due mainly to heat waves, storms and floods, and indirect impacts by vector-, water-, and food-borne diseases. Positive impacts include a lower risk of deaths from low temperatures. Quantification of the direct impacts of temperature has been attempted in several studies; quantification of the other extreme events and indirect impacts lacks empirical studies. A review of the health impact assessments of climate change has been made in the context of the fourth assessment report of the IPCC (WG II, chapter 8: human health; Confalonieri *et al.*, 2007). Several research needs have also been identified in the cCASHh and EDEN projects. Regarding projections, few assessments of the potential future health impacts of climate change have been made. They stress various limitations and rarely quantify the health impacts. Methods and tools to assess 'unpredictable' events, e.g. unknown and new pathogen agents and transmission modes, are needed. There is also a need for integrated approaches through international networks and research combining vector biology and ecology, microbiology, hosts, vectors and pathogens genetics, epidemiology, medical and social sciences, including economics. There are many data gaps at the appropriate spatial and temporal resolution, needed for proper climate change related decision making. An example is the lack of information on vector competence under a changing climate of many arthropod species (insects, ticks), competence of many vertebrate (rodents, bats, other wild mammals, birds) species and an understanding of the genetic, biological and ecological basis of vector/host distribution and their transmission competence for bacteria, viruses and parasites.

An important source of uncertainty is the extent to which adaptation actions, such as preventive measures and appropriate changes in health systems, will be implemented and effective over the next few decades (Confalonieri *et al.*, 2007; Campbell-Lendrum *et al.* 2007; McMichael *et al.*, 2004). Furthermore analysis is needed of effective combinations of climate change mitigation and adaptation actions to reduce cardio-respiratory diseases.

Economy

Economic effects of climate change include direct impacts of extreme events like storms, floods, heat waves, and indirect impacts via changes in ecosystem services for agriculture, forestry, biodiversity and ecosystem goods and services, tourism, energy and water, and human health. Changes in temperature are also affecting energy demand, leading to less heating in winter and more cooling in summer. The economic effects of climate change vary across Europe and depend to a large extent on the resilience of societies and their capability to adapt to the changes.

For more comprehensive economic assessments of increasing damage costs, more integrated data and studies across all sectors are needed on the specific contribution of anthropogenic climate change, and of social change and economic developments (e.g. increases in wealth and infrastructure). Only limited data on the costs of adaptation are available and much more information on good practices at the local, regional and national levels is needed. In addition, assessment methodologies need to be significantly improved to capture the variety and complexity of economic effects linked to climate change, with a particular focus on the valuation of ecosystems.

8.3 Future needs

To address the data gaps identified above (Section 8.2) a sustained integrated monitoring and observation system for Europe should be considered. Integration should take place across the main climate system elements, including atmospheric, oceanographic, terrestrial, cryospheric and biological observations. It should be sustained to be able to produce sufficiently long and accurate data of all key system elements from both *in situ* and satellite sources.

There are many efforts to improve climate-change related data availability in Europe which are also linked to global activities. For improving understanding of the climate system, the Global Climate Observing System (GCOS) network identified a data set as described in Table 8.3. requiring long-term time-series on atmospheric, marine and terrestrial processes with appropriate temporal and spatial resolution (GCOS, 2003). Most of these are also part of EEA's indicators on climate change impacts, such as near-surface atmospheric conditions, sea surface temperature, ice and snow cover, and permafrost.

The EU 'Global Monitoring for Environment and Security' (GMES) Programme (EC, 2004) aims to strengthen monitoring capacity in Europe and the world by making data available as 'services' from 2008 onwards. The combination of satellite and ground-based information to services and the envisaged long-term funding of the services will significantly improve the availability of data on changes in the environment. Many of the services developed will also improve the availability of essential climate variables. For example information in 'Service marine' will include sea surface temperatures and salinity, 'Service land monitoring' will provide information on land-cover changes, and 'Service atmosphere' will monitor greenhouse gas concentrations, aerosols and radiation. The services will be extended stepwise over the coming years and will be fully established by 2013. GMES is also contributing to the global activities currently coordinated and streamlined in the Global Observation System of the Systems (GEOSS) programme (GEOSS, 2005). Another important programme aimed at monitoring is the Data User Element (DUE) of the European Space Agency (ESA) which include global and regional data on land cover (GlobCover), ocean colour (GlobColour), carbon (GlobCarbon), cryosphere (GlobIce, GlobSnow, Permafrost), and other climate-relevant data.

European research projects are improving our understanding of processes and impacts and enhancing data availability. However there is normally lack in continuity of funding. Consequently, measurements performed in these projects only cover short time-periods and/or small areas which often limits the value of the information for climate change assessments. Some projects are funded for implementing GMES monitoring services such as MERSEA and MyOcean for marine, Geoland-1 and Geoland-2 for land and GEMS and MACC for atmosphere services. These projects will be transferred into a long-term operational programme from 2013 onwards.

Climate-related projects (see Box 8.1 for further details), such as PRUDENCE, and ENSEMBLES, are improving the availability of regional projections of climate change. Other ongoing or already completed projects deal with specific sectors, like ACCELERATES for agriculture and ALARM for biodiversity or EUROLIMPACS and CLIME for freshwater ecosystems. Some projects focus on regions, like CIRCE for the Mediterranean area, or investigate climate change impacts and their social and economic impacts, like ATEAM on vulnerability of ecosystem services in Europe. cCASHh has focused on understanding the adaptation needs for human health and ADAM is focused on adaptation and mitigation strategies for supporting European climate policy, and PESETA deals with projections of economic impacts of climate change in different sectors and regions like coastal systems, energy demand, human health, agriculture, tourism, and floods. The EuroHEAT project analysed the effectiveness of early warning and public health action and the MicroDYS project analysed disasters, relevant not only for Europe but globally. A more comprehensive overview on climate change related research activities can be found in EC, 2005; EC, 2006a; 2006b; 2006c; EC, 2007a, 2007b.

Table 8.3 Essential climate variables as required by UNFCCC for detecting and modelling climate change

Domain	Essential climate variables	
Atmospheric (over land, sea and ice)	**Surface:**	Air temperature, precipitation, air pressure, surface radiation budget, wind speed and direction, water vapour.
	Upper-air:	Earth radiation budget (including solar irradiance), upper-air temperature (including MSU — microwave sounding unit — radiances), wind speed and direction, water vapour, cloud properties.
	Composition:	Carbon dioxide, methane, ozone, other long-lived greenhouse gases, aerosol properties.
Oceanic	**Surface:**	Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, current, ocean colour (for biological activity), carbon dioxide partial pressure.
	Sub-surface:	Temperature, salinity, current, nutrients, carbon, ocean tracers, phytoplankton.
Terrestrial	River discharge, water use, ground water, lake levels, snow cover, glaciers and ice caps, permafrost and seasonally-frozen ground, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), biomass, fire disturbance.	

Source: GCOS, 2003.

There are also many activities at the national and regional level, including both public and non-governmental research and monitoring programmes (e.g. transboundary projects of the Interreg Programme).

The monitoring activities and results of this research will further help to understand, and maybe reduce, the uncertainties related to lack of data and knowledge about climate change and its impacts, and will therefore improve the basis for decision making. In summary, from the perspective of climate change impacts and adaptation, future efforts should aim mainly at:

- better data and better models for projections for the coming decades (in addition to models for the period up to 2100) in terms of spatial density, quality and length of time-series (including historic data) for detecting environmental changes due to climate change;
- improved information on extreme events, especially needed for adaptation;
- improved, timely and free public access to data and tools through metadata description, standardisation, harmonisation, improved architecture and infrastructure for data management including distributed data centres and portals for standardised access;
- research to advance understanding of the linkages between the behaviour of vulnerable systems, climatic changes, and non-climatic drivers and positive and negative feedbacks.

Planned research programmes at both the national and the European level will result in a rapidly increasing amount of data and information on climate change impacts, vulnerability and adaptation. A European clearing house on climate change impacts, vulnerability and adaptation can make this information widely available to potential users across Europe. The information can include data on observed and projected climatic changes, information on vulnerable systems, indicators, tools for impacts assessments, and good practice adaptation measures. Such a Clearing House should be developed and made consistent with the existing European environmental data centres that are currently managed by EEA (on climate change, water, land use, biodiversity and air) and JRC (forestry and soil) other existing information platforms such as the European Community Biodiversity Clearinghouse Mechanism (hosted by EEA) and the WHO Climate, Environment and Health action and Information system (CEHAIS). Such a system can also effectively provide important European information to international organisations such as UNFCCC.

Box 8.1 European climate change impacts and adaptation research

Various research projects of the European Commission focus on climate change impacts in Europe or on providing the basis for assessing them. Fewer projects as yet address adaptation issues. The projects aim at better understanding of the functioning of the Earth system, the origin and impacts of climate change and predicting its future evolution, to guide and support the EU's international commitments and EU policies, and to provide a basis for effective mitigation and adaptation measures. Most FP6 projects have not yet been finalised, but some intermediate results could be used for this report. The following are important pan-European projects funded within the EU Research Framework (FP5 and FP6) and European Regional Development Fund (Interreg) Programmes and the GMES initiative.

ADAGIO (Adaptation of Agriculture in European Regions at Environmental Risk under Climate Change; FP6). ADAGIO will evaluate and disseminate potential adaptation measures to climatic change in agriculture, considering three main vulnerable regions of Europe (south Europe and the Mediterranean area, middle Europe and eastern Europe) in cooperation with 11 partners. Compared with the many-fold potential impacts of climate change on agro-ecosystems, potential adaptation measures are even more complex because of the high number of options available through the human factor. New policies must therefore be adopted under climate change conditions considering all potential and realistic adaptation measures.

ADAM (Adaptation and Mitigation Strategies: supporting European climate policy; FP6).The project will lead to a better understanding of the synergies, trade-offs and conflicts that exist between adaptation and mitigation policies at multiple scales. ADAM will support EU policy development in the next stage of the development of the Kyoto Protocol, in particular negotiations around a post-2012 global climate policy regime, and will inform the emergence of new adaptation strategies for Europe.

Box 8.1 European climate change impacts and adaptation research (cont.)

ACCELERATES (Assessing Climate Change Effects on Land use and Ecosystems; from Regional Analysis to The European Scale; FP5). This project has constructed regional and Europe-wide geo-referenced databases, developed models that represent biophysical and socio-economic processes of agro-ecosystems on the European scale and advanced methodologies at fine spatial and temporal resolutions. In the project, adaptive responses to climate change of agro-ecosystems were analysed, using integrated models.

AMICA (Adaptation and Mitigation — an Integrated Climate Policy Approach; Interreg IIIC). AMICA is a completely new approach to environmental policy designed to combine long-term climate protection with short- and medium-term adaptation measures on the local level as a means to improve coherence of decisions and allocation of financial means.

ASTRA (Developing Policies & Adaptation Strategies to Climate Change in the Baltic Sea Region; Interreg IIIB). The main objective is to assess regional impacts of continuing global climate change and develop strategies and policies for climate change adaptation. The project will address threats arising from climate change in the BSR, such as extreme temperatures, droughts, forest fires, storm surges, winter storms and floods. In order to elaborate adaptation and mitigation strategies it is essential to involve regional and local spatial planners and stakeholders.

ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling; FP5). ATEAM's primary objective was to assess the vulnerability of human sectors relying on ecosystem services with respect to global change. We consider vulnerability to be a function of potential impacts and adaptive capacity to global change. Multiple, internally-consistent scenarios of potential impacts and vulnerabilities of the agriculture and forestry sectors, carbon storage, water, nature conservation and mountain tourism in the 21st century were mapped for Europe at a regional scale for four time slices (1990, 2020, 2050, 2080).

BRANCH (Biodiversity Requires Adaption in Northwest Europe under a CHanging climate; Interreg IIIB). Biodiversity must adapt to climate change. For many habitats and species, this will be difficult because the landscape across Europe is fragmented and past decisions limit the opportunities for adaptation. Spatial planners must act now to create a landscape and coastline that can withstand the effects of climate change. BRANCH provides the guidance and evidence to take action. It has brought together planners policy makers and scientists from England, France and the Netherlands, to show how spatial planning could help biodiversity to adapt to climate change.

CIRCE (Climate Change and Impacts Research: the Mediterranean Environment; FP6). The project will predict and quantify the physical impacts of climate change and evaluate the consequences of climate change for the society and economy of the populations in the Mediterranean area. Adaptation and mitigation strategies will be identified in collaboration with regional stakeholders.

CIRCLE (Climate Impact Research for a Larger Europe; FP6). Climate impact analysis and adaptation response must be informed by a coherent body of research and it is CIRCLE's prime objective to contribute to such efforts by networking and aligning national research programmes in the 19 CIRCLE partner countries. Implementation of a European Research Area (ERA) for climate change is CIRCLE's final goal.

CASHh (Climate change and adaptation strategies for human health; FP5). The project assessed the impacts of climate change water, food and vector boren diseases, as well as the consequences for health of floods and heat-waves. It came up with a set of recommendations for adaptation action in Europe.

ClimChAlp (Climate Change, Impacts and Adaptation Strategies in the Alpine Space; Interreg III B). The ClimChAlp project aims at supporting the political decisions regarding protection and natural disasters prevention due to climate change in the Alps. Climate change poses a serious challenge to social and economic development. The Alps are particularly sensitive to climate change, and recent warming has been roughly three times the global average. Climate models project changes in the coming decades, including a reduction in snow cover at low altitudes, receding glaciers and melting permafrost at higher altitudes.

CLIME (Climate and Lake Impacts in Europe; FP5). The central aim of CLIME was to develop a suite of methods and models that can be used to manage lakes and catchments under future as well as current climatic conditions. The most up-to-date regional climate scenarios, and existing catchment and lake models were used in CLIME to address issues that are central to the implementation of the Water Framework Directive. CLIME took advantage of automatic water quality monitoring systems already deployed on many of our target lakes. CLIME had a socio-economic component which paid particular attention to two water quality issues that are likely to become increasingly important.

EDEN (Emerging Diseases in a changing European eNvironment; FP6). This integrated project aims to identify and catalogue those European ecosystems and environmental conditions which can influence the spatial and temporal distribution and dynamics of human pathogenic agents. The project develops and co-coordinates a set of generic methods, tools and skills such as predictive models, early warning and monitoring tools which can be used by decision makers for risk assessment, decision support for intervention and public health policies.

Box 8.1 European climate change impacts and adaptation research (cont.)

ENSEMBLES (Ensemble-based predictions of climate changes and their impacts; FP6). This project aims to develop an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, global and regional Earth System models developed in Europe, validated against quality-controlled, high-resolution gridded datasets for Europe. Eventually, the outputs of the ensemble prediction system are intended to be used for a range of impacts analyses, including agriculture, health, food security, energy, water resources, insurance and weather risk management.

ESPACE (European Spatial Planning — Adapting to Climate Events). Recognising the vital role of spatial planning in enabling society to adapt to climate change, the ESPACE project aims to change the philosophy and practice of spatial planning. ESPACE has focused on managing climate change impacts on spatial planning for water management, including: flooding — coastal, estuarine and riverine; water resources and water quality.

EUROLIMPACS (Evaluating the Impacts of global change on European Freshwater Ecosystems; FP6). Euro-limpacs is a project designed to assess the effects of future global change on Europe's freshwater ecosystems. The research programme is relevant to the EU Water Framework Directive and other European and international directives and protocols and supports the EU's charter on Sustainable Development. The four main areas of investigation in Euro-limpacs are: stressors of aquatic ecosystem change, the impact of climate change on different temporal scales, tools for ecosystem management and cross-cutting themes.

GEMS (Global and regional Earth-system (Atmosphere) Monitoring using Satellite and *in situ* data; GMES initiative). GEMS is developing comprehensive monitoring and forecasting systems for trace atmospheric constituents important for climate and air quality. The systems will provide the basis for value-added data and information services to be developed as part of Europe's Global Monitoring for Environment and Security (GMES) initiative. The GEMS project will create a new European operational system for operational global monitoring of atmospheric chemistry and dynamics and an operational system to produce improved medium-range and short-range air-chemistry forecasts, through much improved exploitation of satellite data.

MACIS (Minimisation of and Adaptation to Climate change Impacts on BiodiverSity; FP6). MACIS summarises what is already know about the impacts of climate change on biodiversity and develops methods to assess the potential impacts in the future. In joint co- operation with policy makers and stakeholders MACIS shows what can be done to stop biodiversity loss. Specifically, MACIS develops methods to identify habitats at greatest risks and to identify all habitats that buffer against negative impacts. Together with policy makers and stakeholders MACIS and the closely linked projects COCONUT and ALARM identify policy options to stop biodiversity loss due to climate and land-use change.

MERSEA (Marine Environment and Security for the European Area; GMES initiative). MERSEA aims to develop by 2008 a European system for operational monitoring and forecasting the ocean physics, bio-geochemistry and ecosystems on global and regional scales. This ocean monitoring system is envisioned as an operational network that systematically acquires data (earth observation from satellites, *in situ* from ocean observing networks, and surface forcing fields from numerical weather prediction agencies) and disseminates information to serve the various user needs. The prediction time scales of interest extend from days to months. This integrated system will be the Ocean component of GMES ('Global Monitoring for Environment and Security').

MICRODIS (Integrated Health Social and Economic Impacts of Extreme Events: Evidence, Methods and Tools; FP6). This project has the overall goal to strengthen preparedness, mitigation and prevention strategies in order to reduce the health, social and economic impacts of extreme events on communities. The main objectives and goals are to strengthen the scientific and empirical foundation on the relationship between extreme events and their health, social and economic impacts, to develop and integrate concepts, methods, tools and databases towards a common global approach, and to improve human resources and coping capacity in Asia and Europe though training and knowledge sharing.

NeWater (New Approaches to Adaptive Water Management under Uncertainty; FP6). NeWater identifies key elements of current water management regimes and investigates their interdependence. The project recognises the value of highly integrated solutions and advocates integrated water resource management (IWRM) concepts. However, NeWater is based on the hypothesis that IWRM cannot be realised unless current water management regimes undergo a transition towards more adaptive water management. Research is therefore focused on transformation processes of these elements in the transition to adaptive integrated water resources management.

PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis; FP6). PESETA aims to make a multi-sectoral assessment of the impacts of climate change in Europe for the 2011–2040 and 2071–2100 time horizons, focusing on the impacts of climate change on coastal systems, energy demand, human health, agriculture, tourism, and floods. The emphasis is on the economic costs of climate change in Europe based on physical impact assessment and state-of-art high-resolution climate scenarios.

Box 8.1 European climate change impacts and adaptation research (cont.)

PRUDENCE ('Prediction of regional scenarios and uncertainties for defining European climate change risks and effects'; FP5). Prudence used several regional models to assess climate change at spatial scales between 30–50 km. The project developed scenarios for the variability of climate change with levels of confidence for the period 2071–2100, providing a quantitative basis for assessing the risks arising from changes in regional weather and climate in different parts of Europe. Future changes in extreme events such as drought, flooding and wind storms were estimated and a robust estimation of the likelihood and magnitude of such changes provided.

SCENES (Water Scenarios for Europe and for Neighbouring States; FP6). SCENES is a 4-year project developing and analysing a set of comprehensive scenarios of Europe's freshwater futures up to 2025, covering all of 'Greater' Europe reaching to the Caucasus and Ural Mountains, and including the Mediterranean rim countries of north Africa and the near East. These scenarios will provide a reference point for long-term strategic planning of European water resource development, alert policymakers and stakeholders about emerging problems, and allow river basin managers to test regional and local water plans against uncertainties and surprises which are inherently imbedded in a longer term strategic planning process.

WATCH (Water and Global Change; FP6). This project will bring together the hydrological, water resources and climate communities to analyse, quantify and predict the components of the current and future global water cycles and related water resources states; evaluate their uncertainties and clarify the overall vulnerability of global water resources related to the main societal and economic sectors.