1 Introduction and Summary

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In this introductory chapter, we describe the mission and the organisational structure of BACC, the "BALTEX Assessment of Climate Change in the Baltic Sea Basin" (www.baltex-research.eu/BACC/). Short introductions of the specifics of the Baltic Sea Basin, in terms of geological history, climate, marine and terrestrial ecosystems as well as some aspects of the economic condition, are provided. The different assessments of instationarities in the observational record are reviewed, and the concept of "climate change scenarios" is worked out. Finally, the key findings of the four main Chaps. 2 to 5 are summarised.

1.1 The BACC Approach

1.1.1 General Background – The Global Context

In the last two decades the concept of anthropogenic climate change, mainly related to the release of greenhouse gases, has been firmly established, in particular through the three[1] assessment reports by the Intergovernmental Panel Climate Change IPCC (Houghton et al. 1990, 1992, 1996, 2001). This insight is based on remarkable advances in science and technology related to climate studies. Important progress has been made, for example with respect to the climate archives, correcting data, making data available through data centres, process understanding and modelling. The result of these efforts is an increased understanding of the key aspects of climate dynamics and of climate change on the global scale. These efforts culminated in the famous assertion of the IPCC, according to which the hypothesis that recent climate change is entirely due to natural causes can be rejected with very little risk (global detection), and its conclusion that the elevated greenhouse gas concentrations are the best single explanatory factor. These findings refer mostly to variables and phenomena linked to the thermal climate regime, e.g. temperature itself, number of frost days, ice and snow.

The situation is less clear when regional scales (less than $107\,\mathrm{km}^2$) are considered. For smaller scales, the weather noise is getting larger, so that the detection of systematic changes becomes difficult or even impossible. In general, very few efforts have been made. For the Baltic Sea Basin no rigorous detection studies have been carried out; however, under the influence of this assessment finding, efforts have now been launched do deal with such questions.

1.1.2 Climate Change Definition

In this book we address the problem of "climate change", which is unfortunately differently understood in different quarters (e.g. Bärring 1993; Pielke 2004). The problem is that "inconstancy" (Mitchell et al. 1966) is an inherent property of the climate system. Some use the term "climate change" to refer to "all forms of climatic inconstancy, regardless of their statistical nature (or physical causes)" (Mitchell et al. 1966). Also, the Intergovernmental Panel on Climate Change (IPCC) defines climate change broadly as "any change in climate over time whether due to natural variability or as a result of human activity." In contrast, the United Nation's Framework Convention on Climate Change (UNFCCC) defines climate change as "a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and that is in addition to natural climate variability over comparable time periods". Obviously, it is rather important which definition is used, in particular when communicating with the public and the media (Bärring 1993; Pielke 2004).

BACC has decided to essentially follow the IPCC-definition, and to add explicitly "anthropogenic" to the term "climate change" when human causes are attributable, and to refer to "climate variability" when referring to variations not related to anthropogenic influences.

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[1] The editorial deadline for his book was in 2006 prior to the publication of the 4th IPCC Assessment Report, which is therefore not referenced throughout this book. Statements in this book made with reference to the 3rd IPCC Report are consistent with the assessment of the 4th IPCC report.

1.1.3 The BACC Initiative and the HELCOM link

The purpose of the BACC assessment is to provide the scientific community with an assessment of ongoing climate variations in the Baltic Sea Basin. An important element is the comparison with the historical past, whenever possible, to provide a framework for the severity and unusualness of the variations, whether it may be seen as climate variability or should be seen as anthropogenic climate change. Also, changes in relevant environmental systems due to climate variations are assessed – such as hydrological, oceanographic and biological changes. The latter studies also take account of, and attempt to differentiate, the impacts of changes in other driving factors that co-vary with climate *sensu stricto*, including atmospheric CO_2 concentrations but also acidification, pollution loads, nutrient deposition, land use change and other factors.

The overall format is similar to the IPCC process, with author groups for the individual chapters, an overall summary for policymakers, and a review process. The review process has been organised by the former chair of the BALTEX Science Steering Group, Professor Hartmut Graßl, Hamburg.

Altogether, the BACC team comprises more than 80 scientists from 13 nations, most of them based in the countries around the Baltic Sea, spanning a spectrum of disciplines from meteorology, oceanography and atmospheric chemistry to ecology, limnology and human geography. Each of the Chaps. 1 to 5 has one or more "lead authors", who had the responsibility of organising the work of their assessment groups, consisting of contributors from almost all countries in the Baltic Sea Basin. These groups had the task of considering all relevant published work in their assessment, not only in English but also as far as possible in all of the many languages of the region.

When the BACC initiative was well underway, a contact with the Helsinki Commission, or HELCOM, was established[2]. It turned out that HELCOM was in need for a climatic assessment of the Baltic Sea area. It was agreed that the BACC report may become a basis for HELCOM's assessment of climate change – which eventually became true: the findings of the BACC report were summarized and put in context in the "HELCOM Thematic Assessment in 2007: Climate Change in the Baltic Sea Area" (Baltic Sea Environment Proceedings No. 111)[3]. This Thematic Assessment was formally adopted at the annual Meeting of the Helsinki Commission by the representatives of the Baltic Sea coastal countries in March 2007. It was announced that this assessment will serve as a background document to the HELCOM Baltic Sea Action Plan to further reduce pollution to the sea and restore its good ecological status, "which is slated to be adopted at the HELCOM Ministerial Meeting in November 2007".

1.2 The Baltic Sea – Geological History and Specifics

In the following a very brief introduction into the specifics of the Baltic Sea Basin is provided; for further details, refer to the Annexes.

1.2.1 Geological History of the Baltic Sea

Since the last deglaciation of the Baltic Sea Basin, which ended 11,000–10,000 cal yr BP, the Baltic Sea has undergone many very different phases. The nature of these phases was determined by a gradually melting Scandinavian Ice Sheet, the glacio-isostatic uplift within the basin, the changing geographic position of the controlling sills, the varying depths and widths of the thresholds between the Baltic Sea and the land surface of the Baltic Sea Basin, and the changing climate. During these phases, salinity varied greatly as did the water exchange with the North Sea.

In the first phase, at the end of the glaciation and during the Younger Dryas, the *Baltic Ice Lake* (BIL) located in front of the last receding ice sheet was formed. It was repeatedly blocked from the ocean, and at least twice, the damming failed at the location of Billingen, with dramatic consequences. The final drainage of the BIL was a turning point in the late geologic development of the Baltic Sea: a warmer climate, a rapidly retreating ice sheet and direct contact with the saline sea in the west characterised the starting point for the *Yoldia Sea* stage, which would last approximately

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[2] HELCOM is assessing and dealing with environmental conditions of the Baltic Sea from all sources of pollution through intergovernmental co-operation between Denmark, Estonia, the European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden. HELCOM is the governing body of the "Convention on the Protection of the Marine Environment of the Baltic Sea Area" – more usually known as the Helsinki Convention.

[3] www.helcom.fi/stc/files/Publications/Proceedings/bsep111.pdf

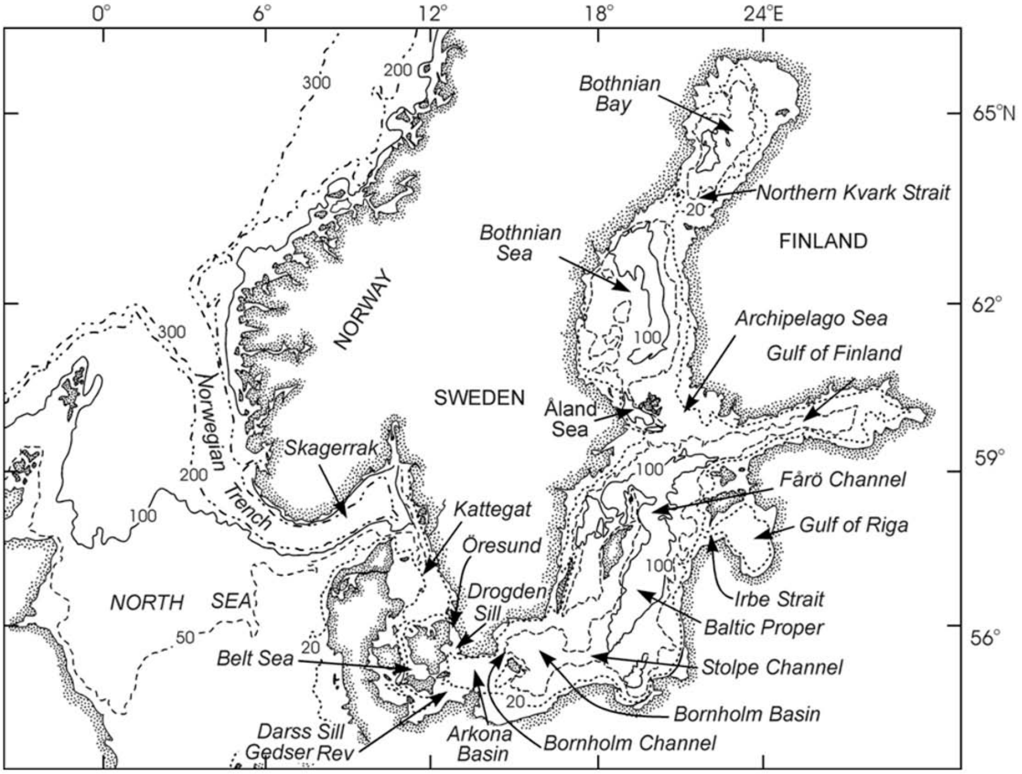

Fig. 1.1. The Baltic Sea-North Sea region with depth contours indicated (from Omstedt et al. 2004a)

900 years, followed by the *Ancylus Lake* transgression, which started around 10,700 cal yr BP. The *Ancylus* transgression ended abruptly with a sudden lowering of the Baltic water level at ca. 10,200 cal yr BP.

A rapid spread of saline influence throughout the Baltic Sea Basin occurred between 9,000–8,500 cal yr BP. The phase of the *Littorina Sea* is reflected in increased organic content in the sediments. With the increased saline influence, aquatic primary productivity clearly increased in the Baltic Sea. During 8,500–7,500 cal yr BP the first and possibly most significant *Littorina* transgression set in. The extent of this and the next two transgressions was of the order of at least 10 m in the inlet areas, with a large increase in water depth at all critical sills. This allowed a significant flux of saline water into the Baltic Sea. The increasing salinity, in combination with the warmer climate of the mid-Holocene, induced a rather different aquatic environment. In terms of richness and diversity of life, and therefore also primary productivity, the biological culmination of the Baltic Sea was possibly reached during the period 7,500–6,000 cal yr BP. The high productivity, in combination with increased stratification due to high salinities in the bottom water, caused anoxic conditions in the deeper parts of the Baltic Sea.

A last turning point in Baltic Sea development took place after about 6,000 cal yr BP: the transgression came to an end almost everywhere along the Baltic Sea coast line. Due to uplift, a renewed regression occurred, which went along with shallower sills and a reduced flux of marine water into the basin. Baltic sediments suggest that since then salinities in the Baltic Sea have decreased.

1.2.2 Oceanographic Characteristics

The Baltic Sea is one of the largest brackish seas in the world[4]. It is a semi-enclosed basin with a total area of 415,000 km^2 and a volume of 21,700 km^2 (including Kattegat; Fig. 1.1). The Baltic Sea is highly dynamic and strongly influenced by large-scale atmospheric circulation, hydrological processes in the catchment area and by the restricted

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[4] A detailed description of the Baltic Sea is given in Annex 1

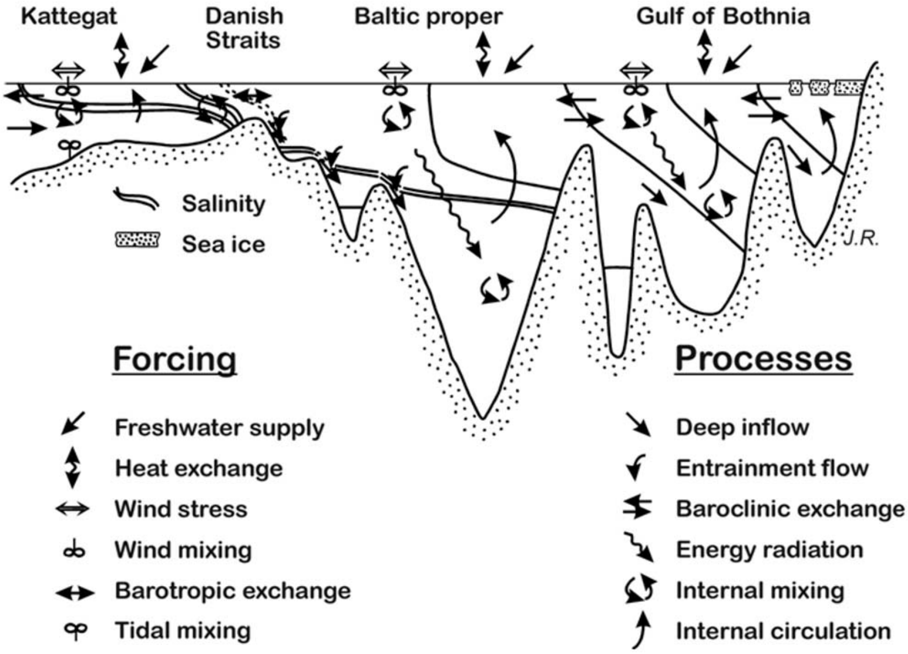

Fig. 1.2. Conceptual model of the Baltic Sea. On the left are processes that force the exchange and mixing and on the right processes that distribute the properties within the Baltic Sea (from Winsor et al. 2001)

water exchange due to its narrow entrance area. It can be divided into a number of different areas; the Kattegat, the Belt Sea, the Öresund, the Baltic Proper, the Bothnian Bay, the Bothnian Sea, the Gulf of Finland and the Gulf of Riga. The Baltic Proper includes the sill areas at its entrance, the shallow Arkona Basin, the Bornholm Basin and the waters up to the Åland and Archipelago Seas.

The complex bathymetry of the Baltic Sea, with its narrow straits connecting the different basins, strongly influences currents and mixing processes (Fig. 1.2). The inflow of freshwater, mainly from rivers into the Baltic Sea, can be described as the engine which drives the large-scale circulation. This inflow generally causes a higher water level in the Baltic Sea than in the Kattegat. The differences in water level force the brackish surface water out of the Baltic Sea. On its way towards the Skagerrak, the brackish water becomes increasingly saline, since the surface water becomes mixed with underlying water and fronts. As compensation for the water entrained into the surface currents, dense bottom water originating from the Skagerrak and Kattegat flows into the Baltic Sea and fills the deeps.

The large scale circulation of the Baltic Sea is due to a non-linear interaction between the estuarine circulation and the exchange with the North Sea. Figure 1.3 represents a conceptual description of the long-term mean circulation (see also Annex 1). Added to the estuarine circulation are large fluctuations, caused by changing winds and water level variations. These influence the water exchange with the North Sea and between the sub-basins, as well as transport and mixing of water within the various sub-regions of the Baltic Sea.

The Baltic Sea has a positive water balance. The major water balance components are inflows and outflows at the entrance area, river runoff and net precipitation. Changes in water storage also need to be considered. Minor terms in the long-term budget are volume change by groundwater inflow, thermal expansion, salt contraction, land uplift and ice export.

The salt balance is maintained by an outflow of low saline water in the surface layer, and a variable inflow of higher saline water at depth. This pattern leads to a permanent stratification of the central Baltic Sea water body, consisting of an upper layer of brackish water with salinities of about

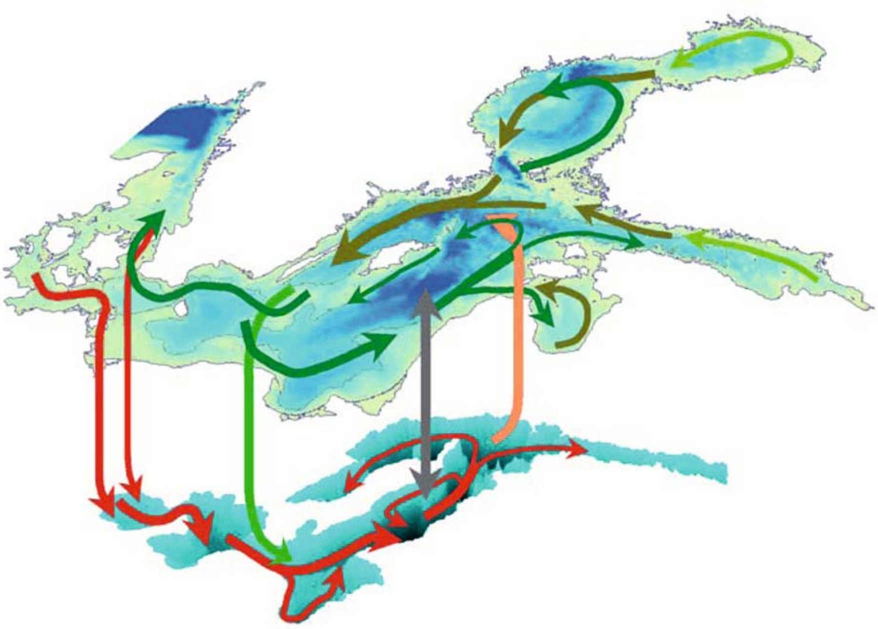

Fig. 1.3. Conceptual model of the Baltic Sea mean circulation. Deep layer circulation below the halocline is given in the lower part of the figure (by courtesy of J. Elken, for details see also Annex 1.1)

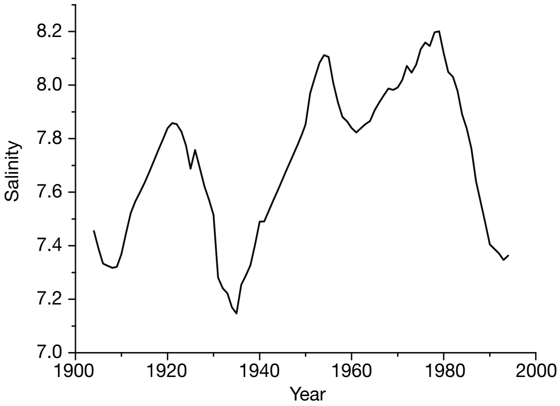

Fig. 1.4. Baltic Sea mean salinity (psu) averaged vertically and horizontally and presented as 5 years running means (from Winsor et al. 2001, 2003)

6–8 and a more saline deep water layer of about 10–14[5]. Figure 1.4 illustrates the long-term Baltic Sea mean salinity of 7.7 and its rather slow variation with an amplitude of 0.5 and a time scale of about 30 years.

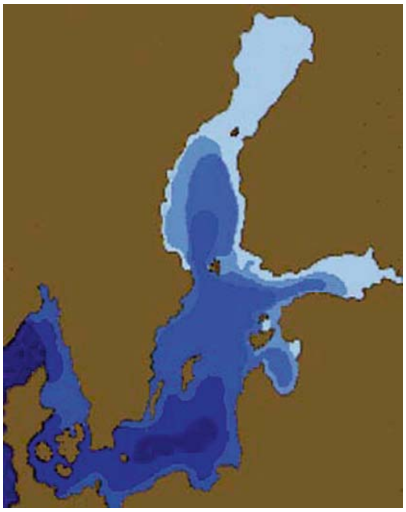

Fig. 1.5. The maximum ice extent in mild, average, severe, and extremely severe winters is marked analogously with darker colours for the more severe ice winters (redrawn from Seinä and Palosuo 1996, see also Fig. 2.59)

The temperature undergoes a characteristic annual cycle. During spring, a thermocline develops, separating the warm upper layer from the cold intermediate water. This thermocline restricts vertical exchange within the upper layer until late autumn. Sea ice is formed every year, with a long-

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[5] The salinity is given according to the Practical Salinity Unit (psu) defined as a pure ratio without dimensions or units. This is standard since 1981 when UNESCO adopted the scale.

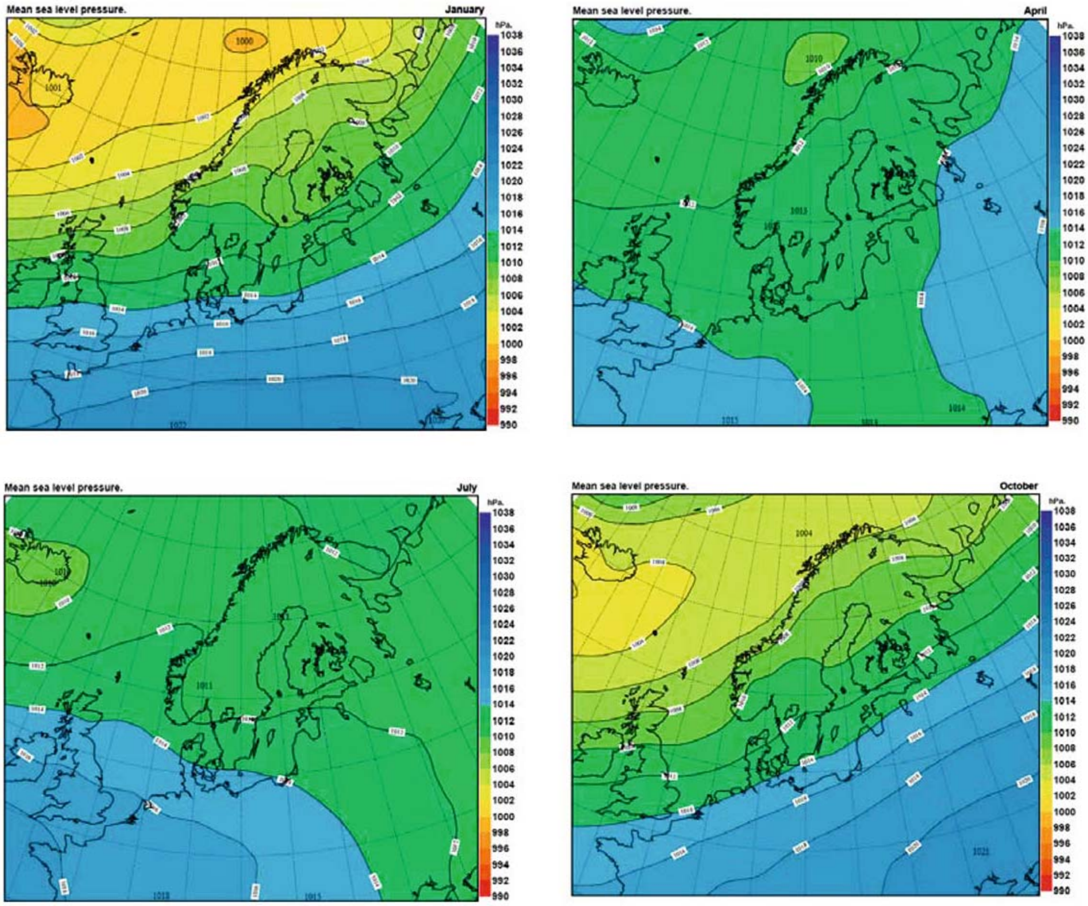

Fig. 1.6. Mean monthly patterns of sea level air pressure during 1979 to 2001 for January, April, July and October (*from top left to bottom right*). The maps were kindly provided by Per W. Kållberg, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden, and are extracted from the ERA-40 re-analysis data set (Uppala et al. 2005)

term average maximum coverage of about half of the surface area and with large inter-annual variations (Fig. 1.5).

On average, the Baltic Sea is almost in thermodynamic equilibrium with the atmosphere. The dominating fluxes, with respect to annual means, are the sensible heat, the latent heat, the net long wave radiation, the solar radiation to the open water and the heat flux between water and ice. Minor terms, in relation to long term means, are heat fluxes associated with the differences between inflows and outflows, river runoff and precipitation.

1.2.3 Climate Characteristics

The climate of the Baltic Sea is strongly influenced by the large scale atmospheric pressure systems that govern the air flow over the region: The Icelandic Low, the Azores High and the winter high/summer low over Russia. The westerly winds bring, despite the shelter provided by the Scandinavian Mountains, humid and mild air into the Baltic Sea Basin. The climate in the southwestern and southern parts of the basin is maritime, and in the eastern and northern parts of the basin it is sub-arctic. The long-term mean circulation patterns are illustrated in Fig. 1.6. Westerly winds dominate the picture, but the circulation pattern shows a distinct annual cycle, with strong westerlies during autumn and winter conditions. The atmospheric circulation is described in more detail in Annexes 1.2 and 7.

The mean near-surface air temperature of the Baltic Sea Basin is, on average, several degrees

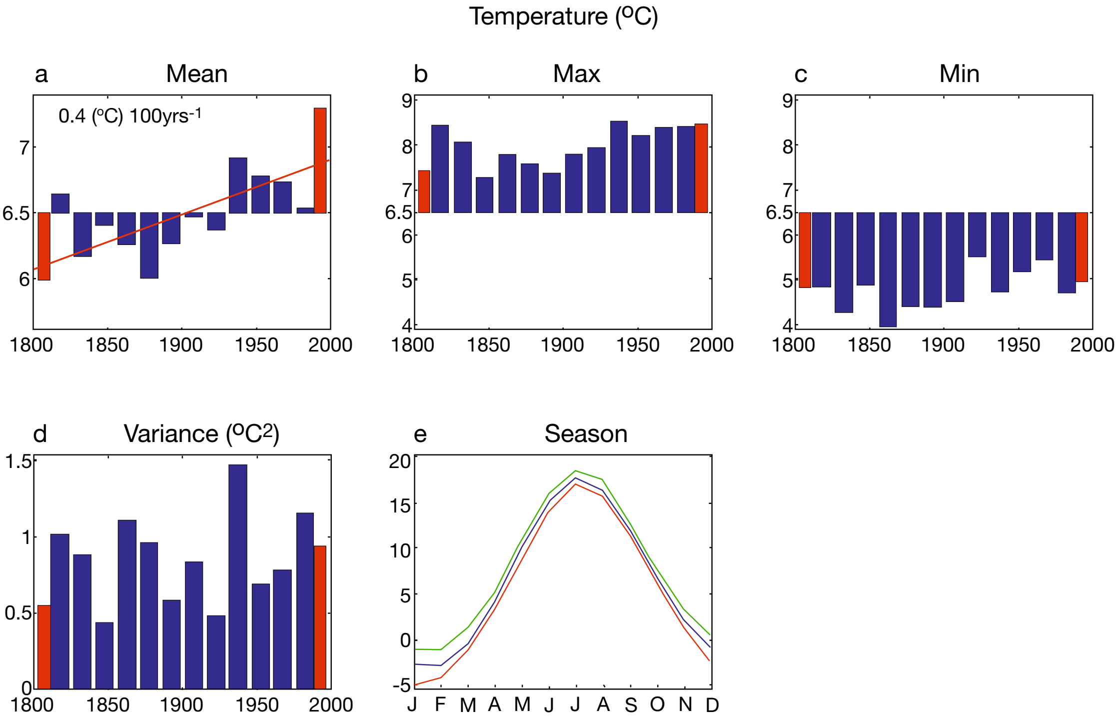

Fig. 1.7. Climate statistics of the Stockholm mean annual air temperature for individual sub-periods during 1800 to 2000. (**a**) Sub-period mean values and trend, (**b**) maximum, (**c**) minimum, and (**d**) variance of individual annual means within each sub-period. The sub-period lengths used are 15 years (*blue bars*) and 10 years (*red bars*). (**e**) shows the mean, maximum and minimum seasonal cycle based on sub-period values (from Omstedt et al. 2004b)

higher than that of other areas located at the same latitudes. The reason is that warm ocean currents bring heat through the Gulf Stream and the North Atlantic Drift to high latitudes along the European coast. The distribution of surface air temperatures is closely linked to the land-sea distribution and the general atmospheric circulation.

The climate variability and trends evident in 200 years of Stockholm temperature records are illustrated in Fig. 1.7. The mean temperature for the whole period is 6.5 °C, and the mean temperatures for sub-periods show a clear positive trend, with the last decade standing out as unusually warm. The increase in the mean sub-period temperature starts at the beginning of the 20th century, as did the increase in maximum air temperatures. However, high maximum temperatures were also recorded at the beginning of the 19th century. The sub-period minimum temperatures were lowest in the mid 19th century. No clear trend can be discerned in either the maximum or minimum temperatures or in their variance. The statistical trend is drawn as a linear trend over the whole period, but closer inspection indicates that the 19th and 20th centuries behaved differently.

The magnitude of the Stockholm annual air temperature cycle (defined as the difference between the summer and the winter seasonal temperatures, Tsw) appear in Fig. 1.8. For a large index, we would expect a more continental climate influence, while a smaller index would indicate a stronger maritime influence. The mean magnitude of the annual cycle is 18.6 °C, with a decreasing trend over the entire period. The figure indicates that in the 19th century up to 1850, the magnitude of the annual cycle was larger; thereafter, the amplitude was below average with particularly low values at around 1900 and at the end of the 20th century.

The annual temperature cycles for some selected stations in the Baltic Sea Basin are illustrated in Fig. 1.9. The annual mean surface air temperature differs by more than 10 °C in the area. The coldest regions are north-east Finland, and the most maritime region is in the south-western part (Northern Germany and Denmark).

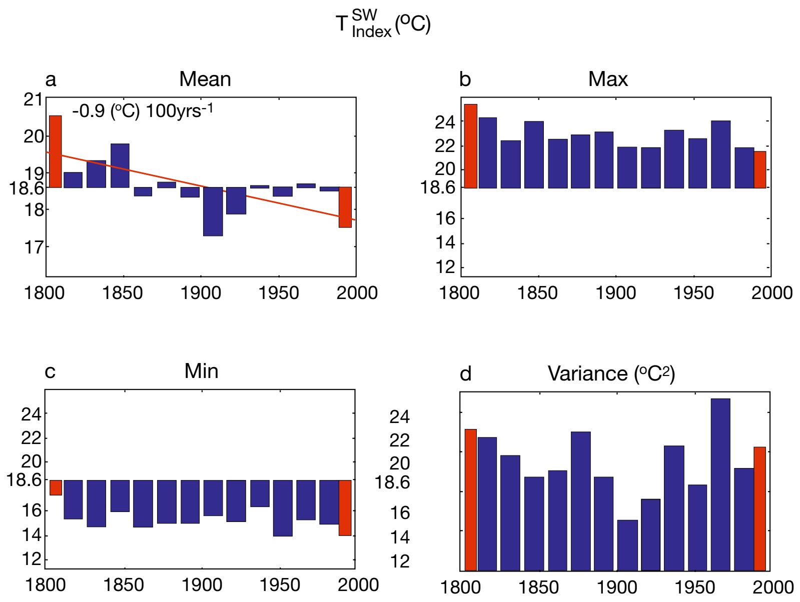

Fig. 1.8. Climate statistics of the magnitude of the seasonal Stockholm air temperature cycle, Tsw index, for individual sub-periods during 1800 to 2000. (**a**) Mean magnitude and trend, (**b**) maximum, (**c**) minimum, and (**d**) variance of the annual cycle within each sub-period. The sub-period lengths used are 15 years (*blue bars*) and 10 years (*red bars*) (from Omstedt et al. 2004b)

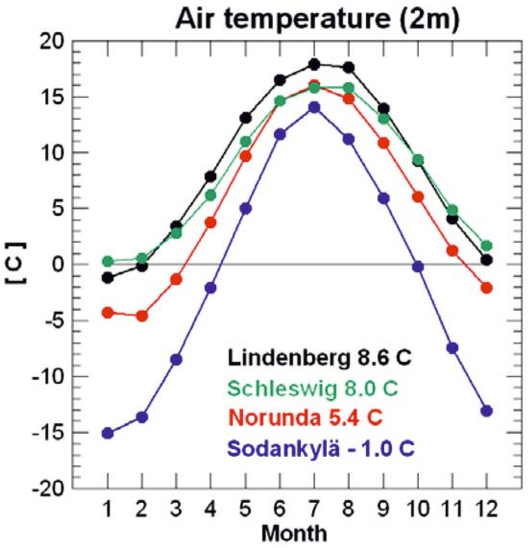

Fig. 1.9. Mean annual cycle of surface air temperature, T_a (°C) for the period 1961 to 1990 at Sodankylä (northern Finland, *blue*), Norunda (mid-Sweden, *red*), Lindenberg (eastern Germany, *black*) and Schleswig (northern Germany, *green*). The station name is plotted together with the long-term annual mean value of T_a. Except for Schleswig, data were provided by the respective station managers in the context of CEOP, the Coordinated Enhanced Observing Period of GEWEX, see also www.gewex.com/ceop. Data for Schleswig are taken from Miętus (1998) (by courtesy of Hans-Jörg Isemer, see also Annex 1.2)

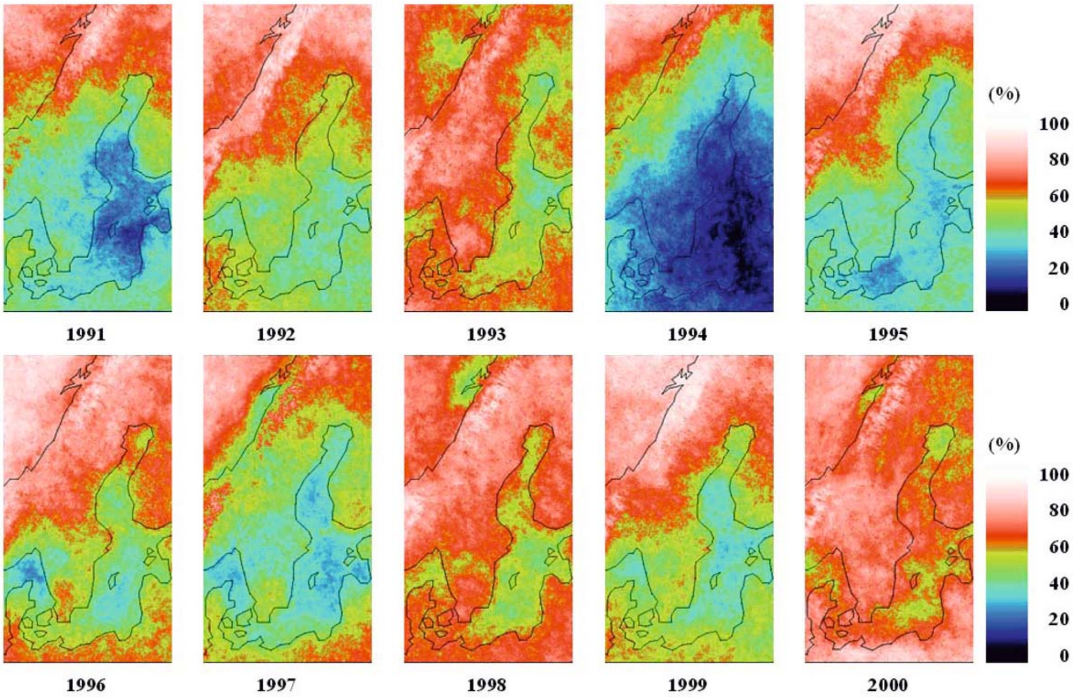

Fig. 1.10. Cloud frequencies over Scandinavia and the Baltic Sea for July during 1991 to 2000 (from Karlsson 2001, see also Annex 1.2 and Karlsson 2003)

Cloudiness, precipitation and humidity all show distinct annual cycles, with large regional variability. This is illustrated by the cloud climate as determined from satellite data, shown in Fig. 1.10. The cloud frequencies in July show large variations from year to year. Also, there is a high degree of regional variability, with high cloud frequencies in the north and low cloud frequencies above the Baltic Sea. The cloud climate reflects the mean atmospheric circulation, the land-sea distribution and the topography.

1.2.4 Terrestrial Ecological Characteristics

The Baltic Sea Basin comprises watersheds draining the Fennoscandian Alps in the west and north, the Erz, Sudetes and western Carpathian Mountains in the south, uplands along the Finnish-Russian border and the central Russian Highlands in the east. The basin spans some 20 degrees of latitude, and climate types range from alpine to maritime to sub-arctic. The Baltic Sea Basin can be divided roughly into a south-eastern temperate part and a northern boreal part, as shown in Fig. 1.11. In the south-eastern part, characterised by a cultivated landscape, the river water runs into the Gulf of Riga and the Baltic Proper. The northern boreal part is characterised by coniferous forest and peat. The natural vegetation is mainly broadleaved deciduous forest in the lowland areas of the southeast and conifer-dominated boreal forest in northern parts. Cold climate lands and tundra occur in the mountainous areas and in the sub-arctic far north of the catchments region. Wetlands and lakes are a significant feature of the boreal and sub-arctic zones.

Extensive changes in land use have taken place during last centuries, paralleled by a considerable increase in the number of people living in the Baltic Sea Basin. Industrialisation and growing cities have changed the landscape, and much of the forest has been converted to farmland. Only in the northern parts does forest still dominate the landscape. Approximately half of the total catchment area consists today of forest, most of the remainder being agricultural land.

Many plant species are temperature sensitive and cold-limit range boundaries can be correlated to the minimum temperature. The main reason is assumed to be the result of ice formation in plant tissue leading to death. Some other plants are more correlated with growing season heat sums.

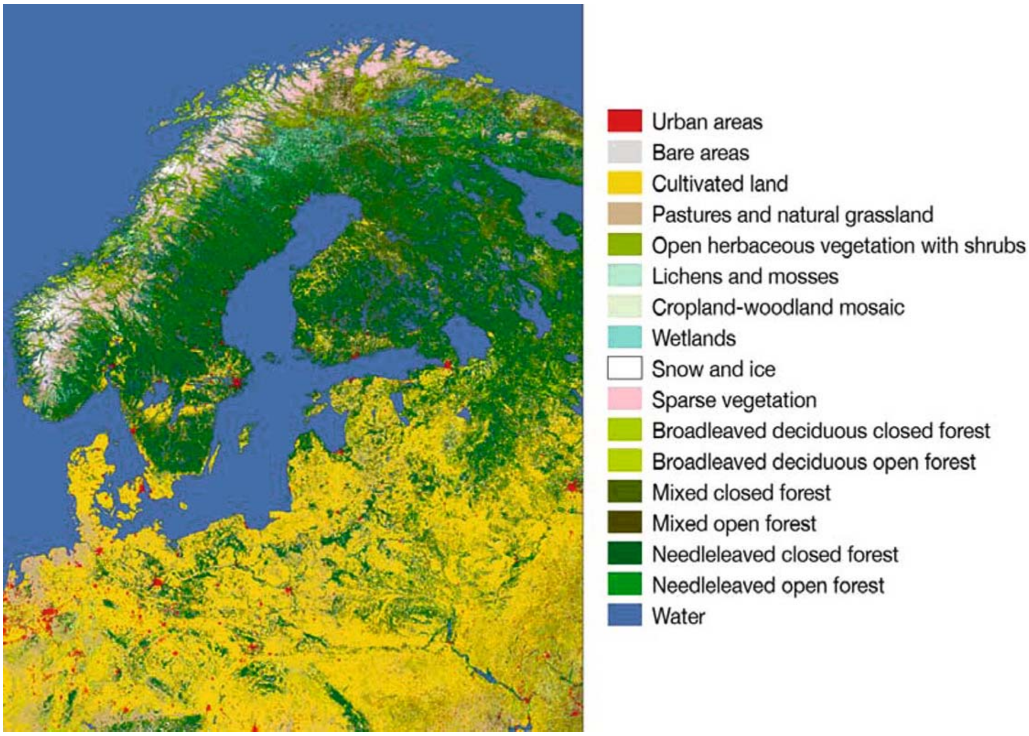

Fig. 1.11. Land cover of the Baltic Sea Basin and surroundings areas (adapted from Ledwith 2002 and the Global Land Cover 2000 database, European Commission, Joint Research Centre 2003; www.gem.jrc.it/glc2000, page visited 26 Feb 2007)

However, at southern or low-altitude range boundaries, temperature relationships are more varied and less well understood.

The most important processes in terms of the overall control of the ecosystem are the physiological processes underlying net primary production, photosynthesis, respiration, stomatal regulation and carbon allocation in plants. Several factors such as temperature, light, soil nutrient concentration, soil water content and atmospheric gases influence these processes; see further discussion in Annex 3.2.

1.2.5 Marine Ecological Characteristics

The Baltic Sea is a large transition area between limnic and marine conditions. Plants and animals are a mix of marine and limnic species together with some genuinely brackish water forms (the Baltic Sea lacks endemics at species level, due to its geological youth). The brackish water affects biodiversity in a profound way due to osmotic stress on plants and animals. Generally, poverty of species number, i.e. low biodiversity, is a common characteristic of brackish waters. The lowest number of species is not in mid salinities, but displaced close to freshwater (Remane and Schlieper 1971). In the Baltic Sea, the area with lowest number of species is between 5–7 psu, which currently is found north of Gotland (cf. Fig. 1.12). Marine representatives of the Baltic fauna and flora have mostly invaded the area since the end of the last freshwater stage (cf. Annex 2: *The Late Quaternary Development of the Baltic Sea*). Baltic Sea salinity ranges from almost freshwater (the largest single source of freshwater is the River Neva in the Gulf of Finland) to about 25–30 psu. Following this, the number of marine species declines from south to north and east (Fig. 1.12). Marine species also are (submergent according to stratification) more common in deep water due to higher salinity there. Also, due to the stratification of the water and the lack of effective mixing and ventilation, large areas of the bottom are anoxic, covered with hydrogen sulphide and devoid of metazoan life. These zones have been called "the benthic deserts" (Zmudzinski 1978).

Besides distribution, also growth of many marine species, even key species, is influenced negatively by low salinity (rule of size diminution).

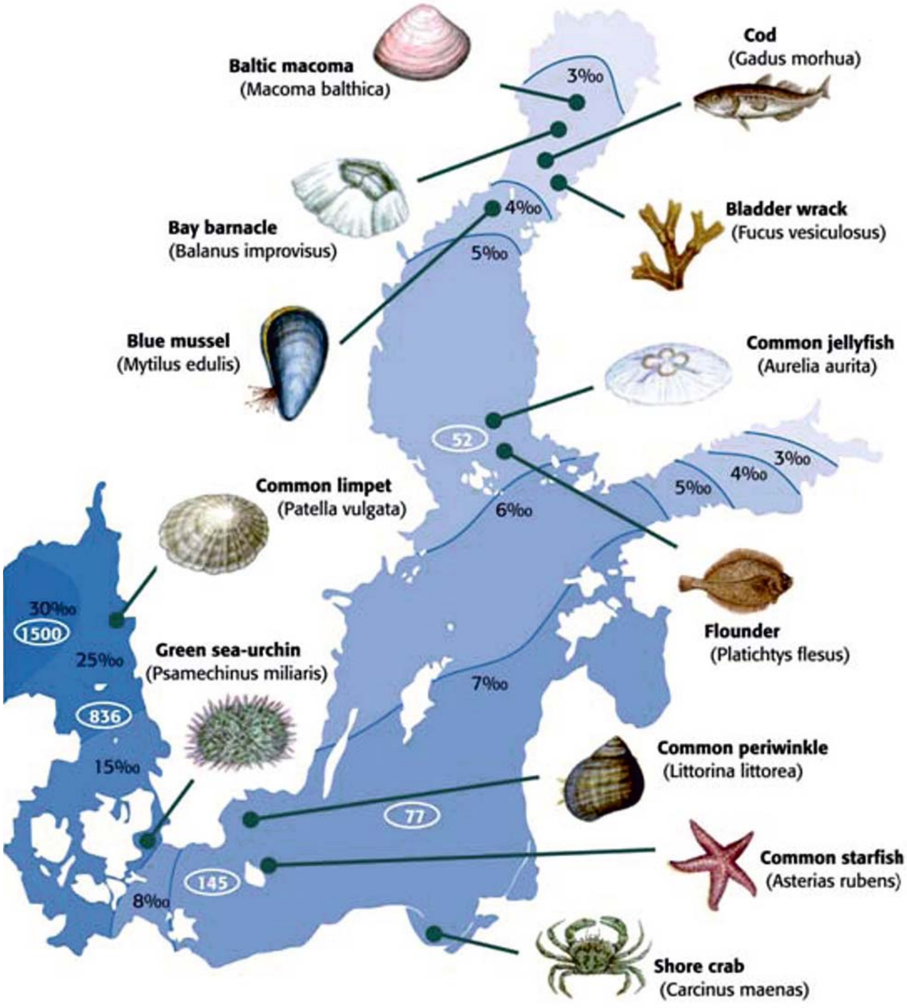

Fig. 1.12. Illustration of how salinity affects biodiversity in the Baltic Sea. The numbers in circles indicate the number of marine macrofauna species found in the area (Figure by Prof. B-O Jansson, Stockholm Marine Research Centre, Stockholm University)

Known examples of reduction in size are the mussels, *Mytilus edulis* and *Mya arenaria*, and the Baltic herring, or streamling, *Clupea harengus membras*.

The Baltic Sea ecosystem is also a transition area between sub-Arctic conditions in the Bothnian Bay to a boreal environment in the central and southern parts of the Baltic Sea. Some of the marine species are Arctic in origin, such as the bivalves *Astarte borealis* and *Macoma calcarea.* They are found in the central and southern half of the Baltic Sea, in the Belt Sea and Kattegat but only sporadically on the Norwegian coasts. In addition to the impoverished fauna of the Arctic and the North Sea, there is a special group of animals in the Baltic Sea, the glacial relicts (Segerstråle 1966). These arrived in North European waters shortly after the last glaciation. The glacial relicts are often, but not exclusively, closely related to forms living in the Arctic Ocean. Examples of originally Arctic marine species, which are found as glacial relicts in the larger North European lakes and in the Baltic Sea are crustaceans, such as *Mysis relicta*, *Saduria entomon*, and *Monoporeia affinis*, and the fish *Myoxocephalus quadricornis*; freshwater relicts are also found, such as the copepod *Limnocalanus macrurus* and the whitefish *Coregonus lavaretus.* These are found in relatively cool deep water, or in the benthos, which makes them particularly vulnerable to deep water anoxia. Freshwater species, naturally, have entered the Baltic Sea via river mouths. They continue to do so, and many of them are confined to littoral and shallow water, such as the perch, roach and pike, which thrive among the reef beds, but also can be very numerous among truly marine flora, e.g. in the bladder wrack. A description of basic structure and function of this mosaic mixture of species can be found in the Annex 3: *Ecosystem Description.*

Anthropogenic impact is changing the Baltic Sea, not only through contaminants, which have caused reproduction disorders in some key species, such as seals and the white tailed eagle, but also due to eutrophication, which has contributed to anoxia, dead bottoms and disrupted deep water food chains, and has caused local disappearance of bladder wrack, and increased blooms of cyanobacteria in the surface layer of the open water. So far, these influences have not caused any species extinctions, but they have considerably changed species distribution patterns, especially in the coastal areas and deep basins (Leppäkoski and Olenin 2001). On the other hand, the Baltic Sea is a relatively young sea, thus having many vacant niches, and immigrant species arrive with surprising frequency. The first great wave of non-native species came after the building of the inland waterway systems at the end of the 18th to the beginning of the 19th centuries, which connected ultimately Pontocaspian brackish water areas with the Baltic Sea, e.g. bringing in the hydrozoan *Cordylophora caspia* and the zebra mussel *Dreissena polymorpha* (Olenin 2002). The most recent wave of immigration appeared after the collapse of the Soviet Union and the subsequent increase in sea traffic (e.g. the arrival of the Pontocaspian cladoceran *Cercopagis pengoi*). The "original" low biodiversity of the Baltic Sea is thus disappearing rapidly.

Some species occupy several different habitats during their lifetimes; e.g. the Baltic herring spawns in the littoral, often next to freshwater outlets; it feeds in the pelagial in the summer and while young, but on the bottom during winter and when it has grown larger. Finally, it may even turn predator of other fish. A striking example of species utilising widely different habitats during their lives are the Arctic waterfowl, which overwinter in the Southern Baltic Sea Basin and Northern Europe, and migrate through the Baltic Sea twice a year in millions, making spectacular sights. In environmental management of the Baltic Sea, one must therefore be able to cover a species during the entire life cycle and in every habitat it will use during its lifetime, taking into account the extreme mobility of some species.

1.3 Trends, Jumps and Oscillations – the Problem of Detecting Anthropogenic Climate Change and Attributing it to Causes

People perceive climate not as something stationary – they even think it *should* be stationary – and the deviation from this assumed stationarity is taken as evidence for climate change, in most cases as adverse anthropogenic climate change[6]. This is related to a duality of the term "climate". One meaning is the geophysically defined statistics of weather, which are objectively described by observations and – within limits – by dynamical models. This "geophysical construct" is what this assessment report is about. However, the alternative meaning of a "social construct" refers to what people think about climate, how they perceive it[7]. For the definition of climate policy, it may be questioned whether the key driver is the social construct or the geophysical construct of climate.

This Assessment Report of Climate Change for the Baltic Sea Basin emphasises the need for a rigorous discrimination between long-term systematic changes, related to anthropogenic drivers (foremost greenhouse gas emissions, but also aerosol emissions or land-use change), and natural variations at shorter time-scales, related to internal climate dynamics and to identify the most probable causes of the systematic changes. The

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[6] The complaints that weather is less predictable than it was in the old days seem to be part of our culture (e.g. Rebetez 1996). An interesting episode in the history of ideas occurred during the 19th and early 20th century, when scientists, and to some extent the public and policymakers, were discussing whether ongoing events were an expression of systematic change or natural variability (e.g. Williamson 1770; Brückner 1890; Stehr et al. 1996; Pfister and Brändli 1999, Kincer 1933, Callendar 1938). In those days, those who claimed that the trends and clustering of extreme events were man-made seem to have been more successful in their arguments.

[7] Thus, there are – even if just emerging – efforts to describe these perceptions scientifically and to understand the social implications of our views of climate and of climate change. Examples of such studies dealing with this social construct are Glacken (1967); Kempton et al. (1995); Kempton and Craig (1993); von Storch and Stehr (2000) and Bray and von Storch (1999).

technical terms are “detection” and “attribution” (Hasselmann 1993; Zwiers 1999; IDAG 2005). For changes on the global and continental scales, a large body of literature has come into being in the last few years; also in the IPCC Assessment Reports this issue plays an important if not dominant role. These efforts led to the famous statement in the Third Assessment Report (Houghton et al. 1996): “The balance of evidence suggests that there is a discernible human influence on global climate.” However, for specific regions and impact variables, successful detection has rarely been claimed.

With respect to the Baltic Sea Basin, no formal detection and attribution studies appear to have been carried out so far. It seems that – at least at present – a methodically sound detection of anthropogenic climate change signals in the Baltic Sea Basin due to increased greenhouse gas concentrations has not been achieved (see Chap. 2). This is probably due to the unfavourable signal-to-noise ratio of anthropogenic signals (whose existence on the global scale is well established, at least in terms of air temperature, see IPCC Assessment mentioned above) and natural variability (as for instance related to the NAO). Instead, many studies have attempted to detect trends in recent decades, and sometimes claims are made that such trends are due to global climate change when they are “statistically significant” (see also Sect. 1.3.3).

1.3.1 The Concepts of Formal Detection and Attribution

Detection is formally a statistical test dealing with the null hypothesis that the recent changes of climate are within the limits of natural variations. Usually, the variable considered is the change during the past few, say two or three, decades. This change can take the form of a trend during that time. The test has to be done in a very large multi-dimensional space (spanned by very many locations and variables). Scenarios prepared with climate models help to sort out those dimensions along which a favourable sign-to-noise ratio is expected for changes related to elevated greenhouse gas and aerosol concentrations. We have already mentioned that the regional signal-to-noise ratios at the present level of anthropogenic climate change are seemingly too small for a successful detection. Another requirement is the availability of enough observational data to determine the distribution of natural variations. This is probably not such a severe limitation for Baltic Sea Basin studies, where several data series extending for more than 100 or even 200 years exist (see Chap. 2). Also, climate model simulations may over or under estimate the level of natural variability.

Attribution is formally a statistical fit based on the assumption that the “signal” of climate change is made up additively of contributions of different influences. Each influence is a function of quantifiable forcings, e.g. the concentration of greenhouse gas concentrations. Then, given the time-dependent forcings, a best mix of contributions to the observed change is determined. The coefficients in this fit are subjected to a statistical test – however having the desired outcome as the null-hypothesis and not as an alternative hypothesis. Thus, a successful attribution, in this formal sense, is a less powerful argument than a successful detection, which would feature the desired outcome as an alternative hypothesis.

Usually, attribution makes sense only after a successful detection. In some cases, however, this is not possible, for instance because of insufficient observational data for determining the level of natural variability. Using attribution in cases where the signal-to-noise ratio is insufficient for a formal detection, one can at least determine to what extent the recent changes are consistent with the hypothesis of anthropogenic forcing. Most claims of ongoing regional anthropogenic climate change are based on such reasoning.

Chapter 2 (see summary in Sect. 1.5.1) reports on a number of such studies. With regard to ecological change (Chaps. 4 and 5, Sects. 1.5.3 and 1.5.4) such efforts have rarely been done; in that academic environment it has been common to relate the emergence of signals to elevated levels of greenhouse gases and anthropogenic aerosols without an adequate statistical analysis.

1.3.2 Homogeneity of Data

An obvious requirement for a meaningful statistical analysis of observational data with respect to their temporal development, the existence of break points, jumps, regime shifts, cycles or stochastic characteristics, is that the data are quality-controlled and *homogeneous* (see also Annex 5). Quality control means ensuring that the data are observed at the ascribed location and time or that they are recorded using prescribed protocols and instruments. It happens, for instance, that log books of ships list incorrect locations, for instance far inland. The quality control of data is a time-consuming task.

The same is true for homogenisation (e.g. Alexandersson 1986; Alexandersson and Moberg 1997; Jones 1995; see Annex 5). A time series is considered homogeneous when it represents the unchanged informational value throughout the observational record. Homogeneity may be compromised by updating old instruments by more accurate ones, by replacing observers, by moving the location of the instrument or the time of the recording, by changing the environment of the instrument (in particular, changing land-uses, for example urbanisation). For instance, when the main weather station of Hamburg was relocated from the harbour area to the airport, the number of reported storms abruptly decreased.

For laymen, it is generally difficult to assess whether meteorological and oceanographic data are of sufficient quality and whether they are homogeneous. There are examples in the literature where significant but false conclusions were drawn from in-homogeneities in data sets. Corrections for in-homogeneities in data sets have started in the meteorological research community but other disciplines such as hydrology, oceanography and ecology have only just recognised the problem. This indicates that many time series in the Baltic Sea Basin may still lack quality and homogeneity controls.

1.3.3 Stationarity of Data – Trends, Oscillations and Jumps

Climate change is expected to emerge in terms of trends or regime shifts, or a blending of jumps and trends (Corti and Palmer 1999). What we subjectively see from data depends much on what we are expecting and on our scientific training. Figure 1.13 illustrates a time series presented as normalised data and as original data. In the figure the same time series is interpreted in three different ways. Obviously, the data is very noisy and the subjective approach doesn't lead anywhere. The original dataset illustrates how the maximum annual ice extent in the Baltic Sea has varied from 1720 up to now. This time series is one of the important data sources for the understanding of the climate in the Baltic Sea and is further discussed in Chap. 2.3.3.

Figures 1.4 and 1.14 provide examples of time series illustrating the methodical problem. The Baltic Sea mean salinity exhibits large variations on long time scales (Fig. 1.4; Winsor et al. 2001, 2003), so that statements of systematic increases or decreases may be derived when limited segments of many years are considered. However, the time series extending across the entire last century indicates that speaking about a long-term trend makes little sense. In particular, the development during the last few decades appears to be inconsistent with the earlier development. Figure 1.14 shows an index of storm frequency for Southern Sweden (Lund; Bärring and von Storch 2004). Again, when limited segments are considered, trends are found, but overall the time series are remarkably stationary. One can certainly not find evidence of a systematically elevated level of storminess in recent decades from this analysis. Both cases tell the same story, namely that short time series are usually insufficient to inform about anthropogenic climate change. They can be used only if other information about the spectrum of natural variability is available (e.g. from extended model simulations).

The above arguments demonstrate that **rigorous statistical analysis is required**. A key concept in the statistical assessment of changing climate is that of stationarity, i.e. the assumption that the statistical parameters such as mean, dispersion, auto-covariance and characteristic patterns are not time-dependent. Detection then refers to rejecting the null hypothesis of stationarity.

In statistical thinking, a time series is a limited random sample of a stochastic process; in principle there may be any number of realisations of this process (von Storch and Zwiers 2002), even if we have only one such realisation available. We may then again, in principle, estimate for each time the statistical parameters across the ensemble of realisations. If they do not depend on time, then the process is stationary. The assumption of ergodicity[8], together with stationarity, allows us to derive estimates from one available time series across time instead of from several samples at the same time across the ensemble.

Examples for non-stationary behaviour in geophysical time series are the diurnal and the annual cycles: The ensemble mean of temperature

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[8] Ergodicity is a formally difficult concept. It describes the fact that the trajectory (given by the time series) "will eventually visit all parts of the phase space and that sampling in time is equivalent to sampling different paths through phase space. Without this assumption about the operation of our physical system, the study of the climate would be all but impossible" (von Storch and Zwiers 2002).

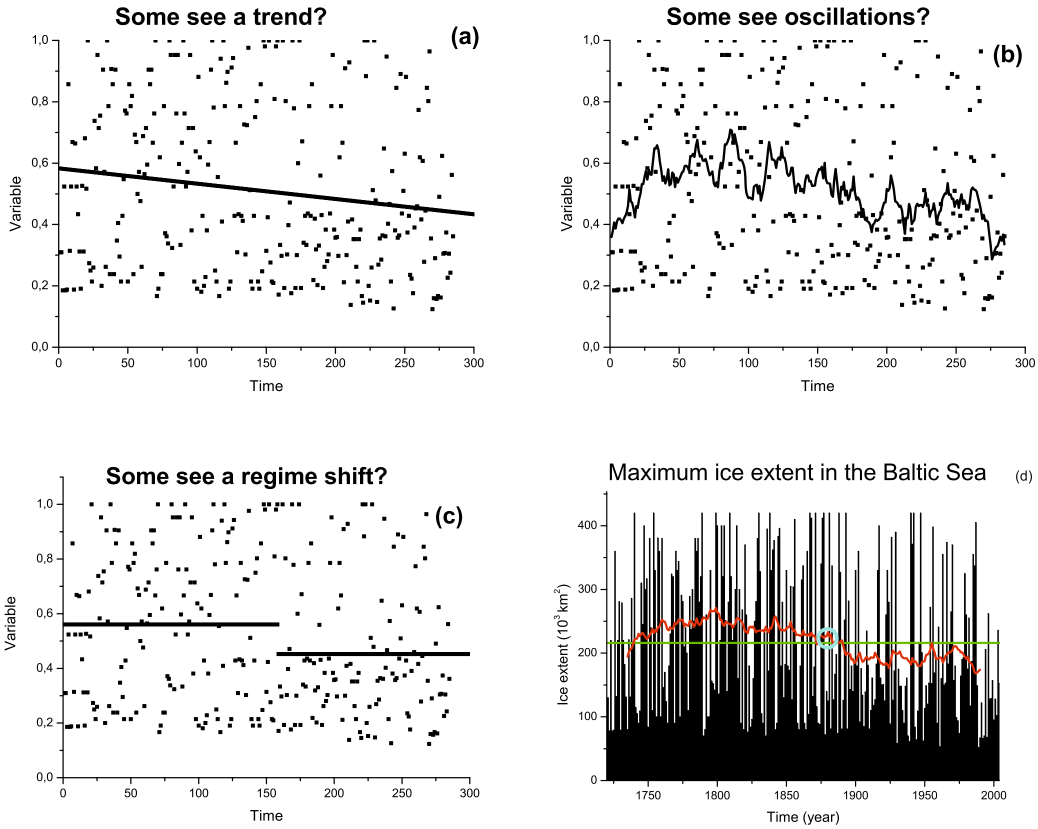

Fig. 1.13. Climate change can be detected by trends, oscillations and jumps or regime shifts. In this figure the same data sets is used and normalised (Figs. **a**–**c**). The original data set is illustrated in Fig. (**d**), for details see Omstedt and Chen (2001)

at 6:00 in the morning is markedly different from the ensemble mean at 18:00 in the evening. Time series with phase-fixed cycles are not stationary; they may represent cyclo-stationary[9] processes, however. But there may be quasi-periodic behaviour, with variable phases, periods and amplitudes, which are not in conflict with the concept of stationarity. Examples are autoregressive processes of the 2$^{\text{nd}}$ order with little damping (von Storch and Zwiers 2002). Similarly, jumps and break points do not contradict stationarity, as long as the time between these events is random.

Thus, for a break point, a jump or a regime shift to qualify as evidence for climate change, it needs to be markedly different from previous such events. If such events have not happened for a very long time, then it would be good evidence – as long as such events are not related to inhomogeneities in the data gathering process.

One may assume that anthropogenic climate change emerges as a mixture of jumps and trends; in scenarios it takes a form something like slowly increasing trends, but in local variables jumps also may be possible. Therefore, much emphasis is on the **detection of trends**. The key question is whether the most recent trend, during the period when we expect the anthropogenic signal to be strongest, is larger than previously recorded trends. If the time evolution has not been monitored for a long enough time to derive an appropriate distribution of past trends, then formal detection studies cannot be done.

Therefore, many studies adopt to the concept of *significance of trends*, i.e., testing the null hypoth-

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[9] Cyclo-stationary processes are instationary processes, which have parameters, such as the mean or the variance, which depend cyclically on time. The weather is considered cyclo-stationary, with two main cycles, the annual and diurnal cycle. Minor cycles are related to atmospheric tides (see also von Storch and Zwiers 2002).

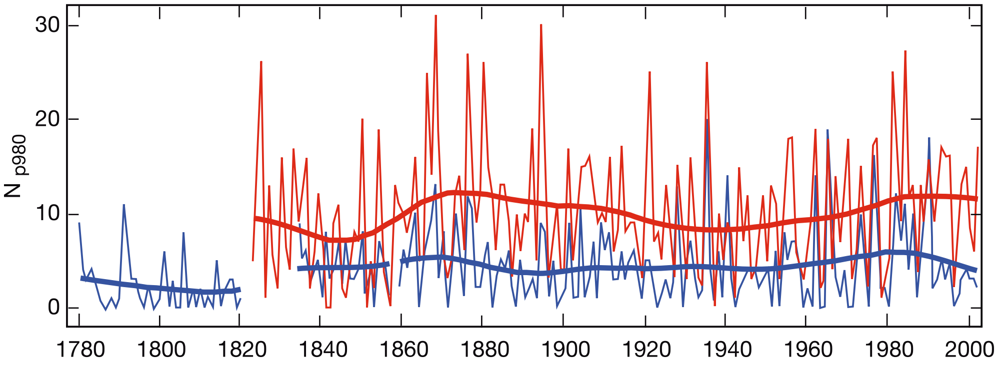

Fig. 1.14. Frequency of daily low pressure readings for Lund (*blue*) and Stockholm (*red*) (Bärring and von Storch 2004). The thin lines show annual variations and the smooth thick lines (Gaussian filter, $\sigma = 3$) show variations at the decadal time-scale

esis of "no trend". However, testing the null hypothesis of no trend is a difficult issue. There are well-established tests in the literature, for instance the Mann-Kendall test, and they are often used in a cookbook recipe like manner. Unfortunately the meaning of the term "trend" used in everyday language is different from the meaning of the same term in statistical analysis. In everyday language it refers to something ongoing for the foreseeable future, whereas the statistical analysis is asking if the trend within a fixed time interval [1, T] could be generated by noise. In the statistical concept, the evolution outside the fixed time interval is not considered.

Instead, as the thought experiment goes, one assumes to have a number of time series over the fixed interval [1, T] generated by the same unknown, these underlying stochastic process with no trend[10]. However, each of these realisations will have a trend, i.e., a linear (or nonlinear) fit to the data from time 1 to time T, simply because of random variations. One determines the distribution of trends within [1, T], associated with realisations of the no-trend random process. If the actual trend, which has to be assessed, is larger than a pre-selected high percentile of this distribution, the null hypothesis of no trend in [1, T] is rejected with a given risk. Obviously, the whole argument does not deal with the question whether we have a trend continuing into the future or not.

A standard method for performing such a test is the Mann-Kendall test. However, this test (and other similar ones) operates with an assumption which is in most cases not fulfilled by geophysical data – that of no serial correlation. If the data are auto correlated, even if only weakly, due to memory, trends or cycles, then the test no longer rejects a correct null hypothesis as rarely as stipulated. The test simply becomes wrong (Kulkarni and von Storch 1995, see Annex 8). It is probable that many claims of the detection of "statistically significant" trends are based on this invalid application of the Mann-Kendall and other similar tests. The same is true for tests of break points.

The proper way to circumvent this problem is to simulate the distribution under a null-hypothesis which explicitly incorporates serial correlation in the data. An alternative is to "prewhiten" the time series before conducting the test (Kulkarni and von Storch 1995). However, these approaches are not commonly used in the present assessment of climate change.

1.4 Scenarios of Future Climate Change

1.4.1 Scenarios – Purpose and Construction

Scenarios are descriptions of possible futures – of different plausible futures. Scenarios are not predictions but "storyboards", a series of alternative visions of futures, which are possible, plausible, internally consistent but not necessarily probable (e.g. Schwartz 1991; Tol 2007). The purpose of scenarios is to confront stakeholders and policymakers with possible future conditions so that they can analyse the availability and usefulness of options to confront the unknown future. Scenar-

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[10] More precisely, it is the same concept already used to define stationarity: The process is generating a limited series for the times 1 to T. Then, for each time in this interval, one can define statistical parameters such as the mean, standard deviation and so on. If a linear function is fitted to these parameters in the interval [1, T], and the assumption of no trend is valid, then the slope is zero.

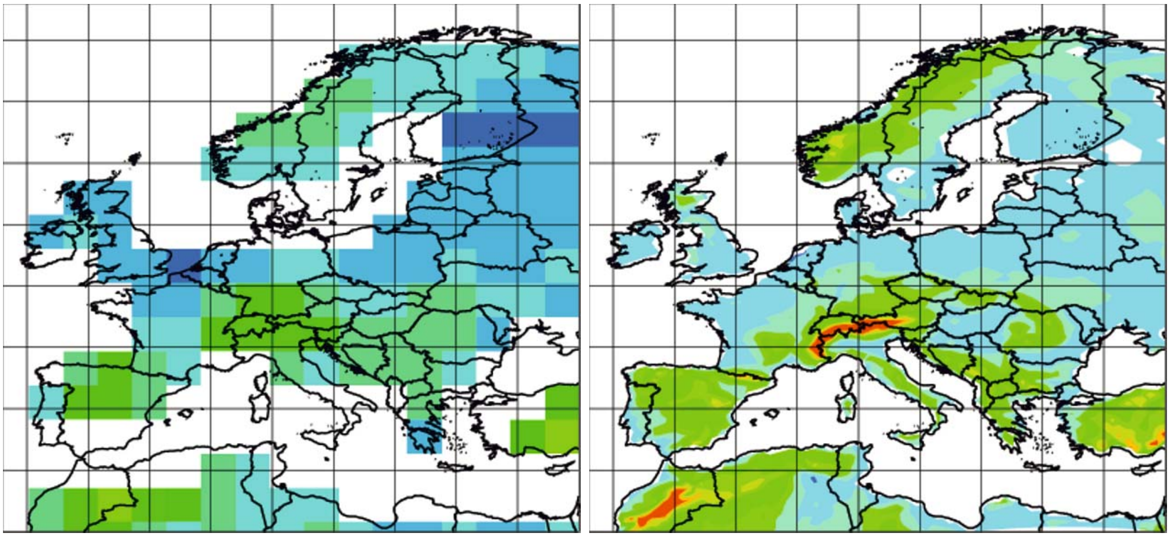

Fig. 1.15. Some typical atmospheric model grid resolutions with corresponding land masks. *Left:* T42 used in global models, *right:* 50 km grid used in regional models (by courtesy of Ole Bøssing-Christensen, Danish Meteorological Institute)

ios allow implementing measures now to avoid unwanted futures; they also may be used to increase chances for the emergence of favourable futures.

In daily life, we frequently operate with scenarios. For instance, when planning in spring for a children's birthday party next summer, we consider the scenarios of an outdoor party on a sunny day or an indoor party on a rainy day. Both scenarios are possible, plausible and internally consistent. Planning for a snowy day, on the other hand, is not considered, as this would be an inconsistent scenario.

In climate research, scenarios have been used widely since the introduction of the IPCC process at the end of the 1980s (Houghton et al. 1990, 1992, 1996, 2001). These scenarios are built in a series of steps. This series begins with *scenarios of emissions* of radiatively active substances, i.e., greenhouse gases, such as carbon dioxide or methane, and aerosols. These scenarios depend on a variety of developments unrelated to climate itself, in particular on population growth, efficiency of energy use and technological development. Many of these factors are unpredictable; therefore, a variety of sometimes ad-hoc assumptions enter these scenarios (Tol 2007).

In the next steps, the construction of scenarios is less ad-hoc, as they essentially process the emissions scenarios. The first step is to transform the emissions into atmospheric concentrations, which are then fed into global climate models[11]. Thus, possible, plausible and internally consistent future emissions are used to derive estimates of possible, plausible and internally consistent future climate, i.e., seasonal means, ranges of variability,

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[11] There are different types of **climate models** (cf. McGuffie and Henderson-Sellers 1997; Crowley and North 1991; von Storch and Flöser 2001; Müller and von Storch 2005). In their simplest form they are energy balance models, which describe in a rather schematic way the flux and fate of energy entering the atmosphere as solar radiation and leaving it as long and short wave radiation. These models are meant to be conceptual tools of minimum complexity for describing the fundamental aspects of the thermodynamic engine "climate system". At the other end of the range of complexity are the highly complex tools containing as many processes and details as is can be processed on a contemporary computer. Being limited by the computational resources, these models grow in complexity in time – simply because the computers continually become more powerful. Such models are supposed to approximate the complexity of the real system. They simulate a sequence of hourly, or even more frequently sampled, weather, with very many atmospheric, oceanic and cryospheric variables – such as temperature, salinity, wind speed, cloud water content, upwelling, ice thickness etc. From these multiple time series, the required statistics (= climate) are derived. Thus, working with simulated data is similar to working with observed data. The only, and significant, difference is that one can perform experiments with climate models, which is not possible with the real world. However, present day climate models are coarse, and several processes related to the water and energy cycles are not well understood or described in these models. Direct observations are therefore the main source for the understanding of the climate.

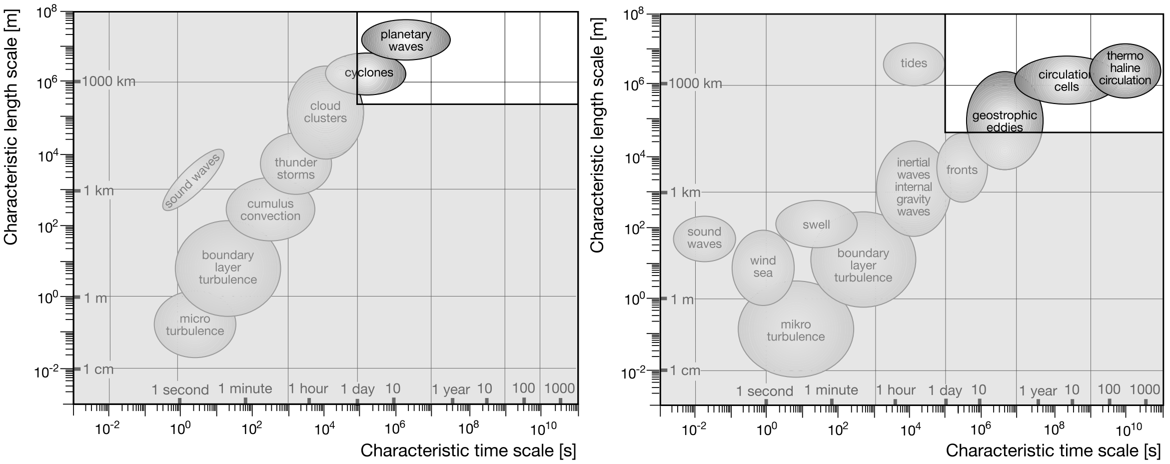

Fig. 1.16. Spatial and temporal scales of some major processes in the atmosphere (*left*) and in the ocean (*right*). In the figures the grey area represents sub-grid scales in common global models, while the visible parts in the upper right corners represent the processes which climate models often aim to resolve (redrawn from Müller and von Storch 2004)

spectra, or spatial patterns. These are the *global climate change scenarios*. Effects of changes in climate forcing factors such as solar radiation, volcano eruptions or land use are often not considered in these scenarios. Instead, the scenarios try to envision what will happen in the future depending only on anthropogenic changes. We may thus call them *anthropogenic climate change scenarios*.

Global climate models are supposed to describe climate dynamics on spatial scales[12] of, say, 1000 km and more. They do not resolve the key geographical features of the Baltic Sea Basin. For instance, in the global models, the Baltic Sea is not connected to the North Sea through narrow sills; instead, the Baltic Sea is something like an extension of the North Sea with a broad link. In addition, the Scandinavian mountain range is shallow (Fig. 1.15). Therefore, in a second step, possible future changes of regional scale climatic features are derived using regional climate models[13]. These models are based on the concept of "downscaling", according to which smaller scale weather statistics (regional climate) are the result of a dynamical interplay of larger-scale weather (continental and global climate) and specific regional characteristics physiographic detail (von Storch 1995, 1999). There are two approaches for downscaling. One is empirical or statistical downscaling, which employs statistically fitted links between variables representative for the large large-scale weather state or weather statistics, and locally or regionally significant variables (see Chap. 3.4). The alternative is dynamical downscaling, which employs a regional climate model (see Chap. 3.5). Such regional models are subject to the large-scale

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[12] "**Scales**" is a fundamental concept in climate science. The term refers to typical lengths or typical durations of phenomena or processes. Scales necessarily refer only to orders of magnitude. Global scales refer to several thousand kilometres and more; the continental scale to a few thousand kilometres and more and regional scales to a hundred kilometres and more. The Baltic Sea is a regional feature of the global climate system. When constructing climate models the equations can only be solved within a limited resolution. Dynamic features larger than the grid domain then need to be prescribed, while features below about ten times the grid size need to be parameterised. Typical processes that need to be parameterised in climate models are indicated in Fig. 1.16.

[13] Regional climate models are built in the same way as global climate models - with the only and significant difference that they are set up on a limited domain with time-variable lateral boundary conditions. Mathematically, this is not a well-posed problem, i.e., there is not always one and only one solution satisfying both the ruling differential equations and the boundary constraints. By including a "sponge-zone" along the lateral boundaries, within which the internal solution and the externally given boundary conditions are nudged, it is practically ensured that there is a solution, and that instabilities are avoided. The present day regional climate models only downscale the global models and they thus do not send the information back to the global scale. This implies that they are strongly controlled by the global climate model. The advantage of regional climate models is that they provide an increased horizontal resolution. Therefore, they can simulate the regional details that are often needed in many impact studies.

state simulated by the global models along the lateral boundaries and sometimes in the interior. With horizontal grid sizes of typically 10 to 50 km, such models resolve features with minimum scales of some tens to a few hundred kilometres. They also simulate the emergence of rare events, such as strong rainfall episodes and strong windstorms.

Methodologically, the *anthropogenic* climate change scenarios are *conditional predictions*. After the emissions scenarios are given, no further ad-hoc decisions are required. Significant assumptions are only required for the design of the emission scenarios. These assumptions refer to socio-economic processes, which lead to emissions.

When dealing with regional or local scenarios, one has to keep in mind that not only global climate changes, but also that regional and local climate conditions change, for example due to changing regional and local land use – which may or may not be on a scale comparable to global changes. When assessing impacts of climate change, these have to be compared to the influence of changing usage of the local and regional environment given by another set of scenarios (e.g. Grossmann 2005, 2006; Bray et al. 2003) – e.g. land use, but also the release of anthropogenic substances.

1.4.2 Emission Scenarios

A number of emission scenarios have been published as an "IPCC Special Report on Emissions Scenarios" (SRES; www.grida.no/climate/ipcc/emission) prepared by economists and other social scientists for the Third Assessment Report of the IPCC. They utilise scenarios of greenhouse gas and aerosol emissions or of changing land use:

(A1) a world of rapid economic growth and rapid introduction of new and more efficient technology,
(A2) a very heterogeneous world with an emphasis on family values and local traditions,
(B1) a world of "dematerialisation" and introduction of clean technologies,
(B2) a world with an emphasis on local solutions to economic and environmental sustainability.

The scenarios do not anticipate any specific mitigation policies for avoiding climate change. The authors emphasise that "no explicit judgments have been made by the SRES team as to their desirability or probability".

The **Scenarios A2 and B2** are widely used. Therefore, we explain the socio-economic background of these scenarios in more detail (for a summary for the other two scenarios, refer to Müller and von Storch 2004): SRES describes the A2-scenario as follows: "… characterised by lower trade flows, relatively slow capital stock turnover, and slower technological change. The world "consolidates" into a series of economic regions. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. Economic growth is uneven and the income gap between now-industrialised and developing parts of the world does not narrow.

People, ideas, and capital are less mobile so that technology diffuses more slowly. International disparities in productivity, and hence income per capita, are largely maintained or increased in absolute terms. With the emphasis on family and community life, fertility rates decline relatively slowly, which makes the population the largest among the storylines (15 billion by 2100). Technological change is more heterogeneous. Regions with abundant energy and mineral resources evolve more resource-intensive economies, while those poor in resources place a very high priority on minimizing import dependence through technological innovation to improve resource efficiency and make use of substitute inputs. Energy use per unit of GDP declines with a pace of 0.5 to 0.7% per year.

Social and political structures diversify; some regions move toward stronger welfare systems and reduced income inequality, while others move toward "leaner" government and more heterogeneous income distributions. With substantial food requirements, agricultural productivity is one of the main focus areas for innovation and research, development efforts, and environmental concerns. Global environmental concerns are relatively weak."

In B2, there is "… increased concern for environmental and social sustainability. Increasingly, government policies and business strategies at the national and local levels are influenced by environmentally aware citizens, with a trend toward local self-reliance and stronger communities. Human welfare, equality, and environmental protection all have high priority, and they are addressed through community-based social solutions in addition to technical solutions. Education and welfare programs are pursued widely, which reduces mortality and fertility. The population reaches about

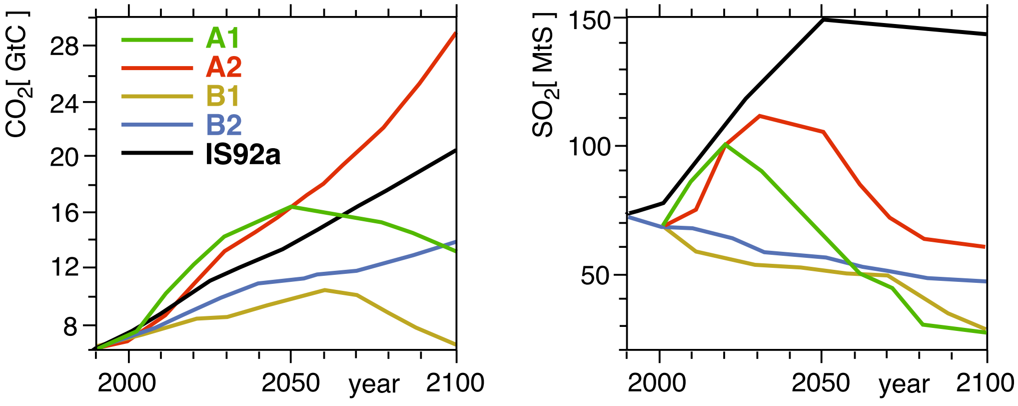

Fig. 1.17. Scenarios of possible, plausible, internally consistent but not necessarily probable future emissions of carbon dioxide (a representative of greenhouse gases; in gigatons) and of sulfur dioxide (a representative of anthropogenic aerosols; in megatons). A1, B1, A2 and B2 are provided by SRES, IS92a is a scenario used in the Second Assessment Report of the IPCC in 1995 (Nakićenović and Swart 2000)

10 billion people by 2100. Income per capita grows at an intermediate rate. The high educational levels promote both development and environmental protection. Environmental protection is one of the few truly international common priorities. However, strategies to address global environmental challenges are not of a central priority and are thus less successful compared to local and regional environmental response strategies. The governments have difficulty designing and implementing agreements that combine global environmental protection. Land-use management becomes better integrated at the local level. Urban and transport infrastructure is a particular focus of community innovation, and contributes to a low level of car dependence and less urban sprawl. An emphasis on food self-reliance contributes to a shift in dietary patterns toward local products, with relatively low meat consumption in countries with high population densities. Energy systems differ from region to region. The need to use energy and other resources more efficiently spurs the development of less carbon-intensive technology in some regions. Although globally the energy system remains predominantly hydrocarbon-based, a gradual transition occurs away from the current share of fossil resources in world energy supply."

Expected emissions of greenhouse gases and aerosols into the atmosphere are derived from these assumptions and descriptions. Figure 1.17 shows the expected SRES scenarios for carbon dioxide (a representative of greenhouse gases; in gigatons per year) and sulfur dioxide (a representative of anthropogenic aerosols; in megatons sulfur). The SRES scenarios are not unanimously accepted by the economic community. Some researchers find the scenarios internally inconsistent. A documentation of the various points raised is provided by the Select Committee of Economic Affairs of the House of Lords in London (2005). A key critique is that the expectation of economic growth in different parts of the world is based on market exchange ranges (MER) and not on purchasing power parity (PPP). Another aspect is the implicit assumption in the SRES scenarios that the difference in income between developing and developed countries will significantly shrink until the end of this century (Tol 2006, 2007). These assumptions, the argument is, lead to an exaggeration of expected future emissions.

1.4.3 Scenarios of *Anthropogenic* Global Climate Change

The emission scenarios are first transformed into scenarios of atmospheric loadings of greenhouse gases and aerosols. Then, the global climate models derive from these concentrations – without any other externally set specifications – sequences of hourly weather, typically for one hundred years. A large number of relevant variables are calculated for the troposphere, the lower stratosphere and the oceans, but also at the different boundaries of land, air, ocean and sea ice – such as air temperature, soil temperature, sea surface temperature, precipitation, salinity, sea ice coverage or wind speed. Global climate models are subject to some degree of systematic error, so-called

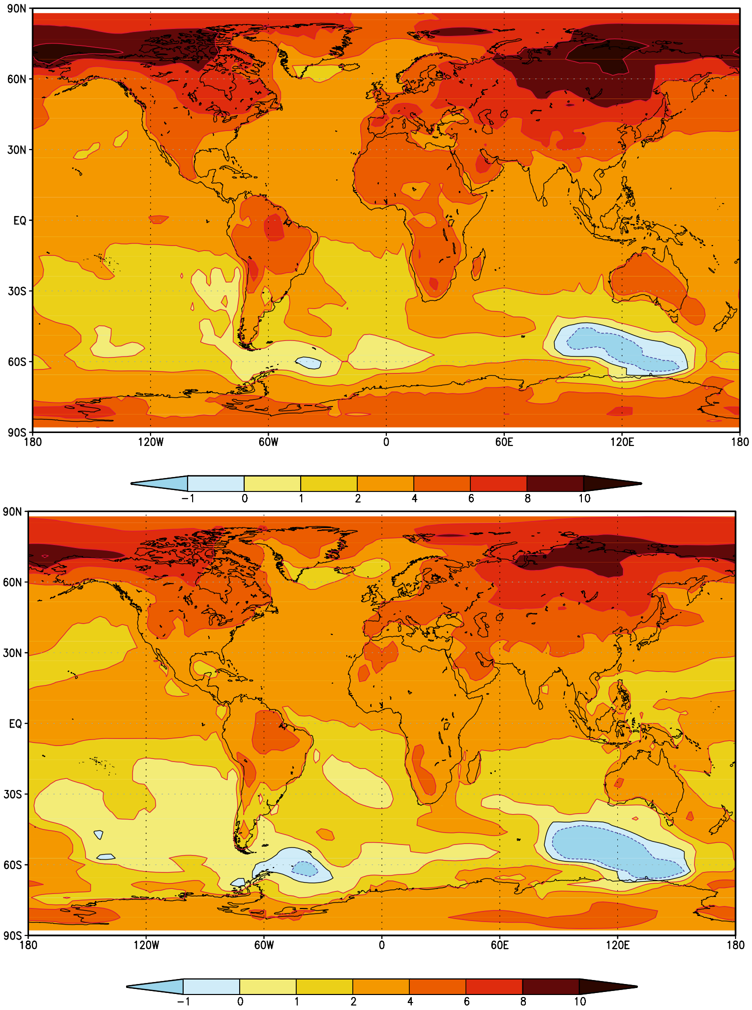

Fig. 1.18. Global scenarios of the winter surface air temperature change (in K) at the end of the 21st century as determined with a global climate model forced with A2 (*top*) and B2 (*bottom*) emissions (by courtesy of Martin Stendel, Danish Meteorological Institute)

biases. This error can be regionally large and is, for example, too large to permit determination of the expected climate change only from a simulation with elevated greenhouse gas concentrations. Instead, the climate change is determined by comparing the statistics of a "scenario simulation" with plausible elevated anthropogenic greenhouse gas and aerosol levels with the statistics of a "control run", which is supposed to represent present conditions with contemporary atmospheric greenhouse gas and aerosol levels. The difference between the control run and present climate conditions provide us with a measure of the quality of the climate simulation. If this difference is large compared to the scenario change, the climate simulation should be interpreted with care.

Figure 1.18 shows as an example of the expected change of winter air temperature for the last 30 years of the 21st century in the scenario A2 and in the scenario B2. This change is given as the difference between the 30 year mean in the scenario run and that of the control run. The air temperature rises almost everywhere; the increase is larger in the higher-concentration scenario A2 than in the lower-concentration B2. Temperatures over land rise faster than over the oceans, which are thermally more inert than land. In Arctic regions, the increase is particularly strong – this is related to the partial melting of permafrost and sea ice.

In Chap. 3.3, global climate change scenarios are discussed in some detail with respect to the Baltic Sea Basin.

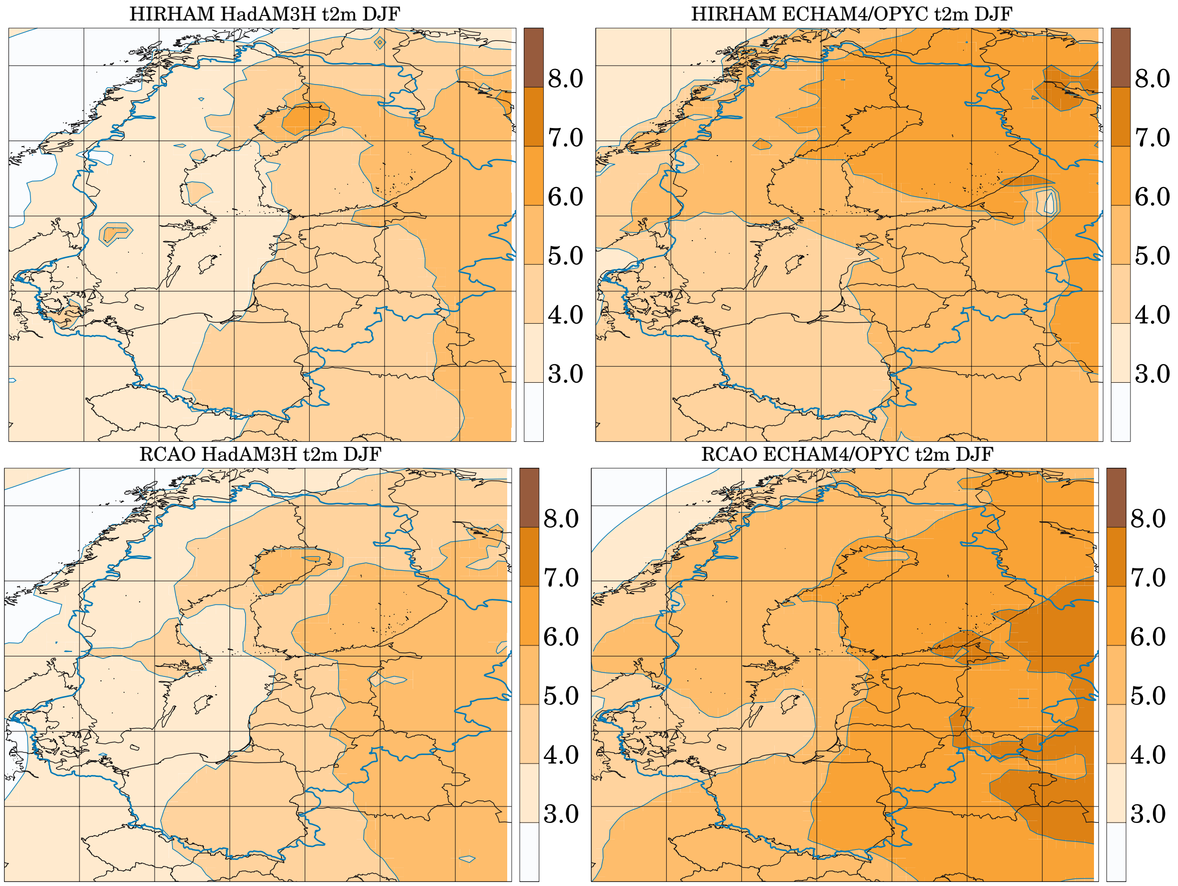

Fig. 1.19. Surface air temperature change (in K) for winter (DJF) between the periods 1961–1990 and 2071–2100 according to the SRES A2 scenario. Plots on the left used HadAM3H as boundary conditions; plots on the right used ECHAM4/OPYC3 as boundaries. For each season the upper row is the DMI regional model HIRHAM and the lower row is the SMHI model RCAO. Note that the ECHAM4/OPYC3 scenario simulations used as boundaries are different for the two downscaling experiments. The Baltic Sea Basin is indicated by the thick pale contour. – For further details see Chap. 3.5

1.4.4 Regional Anthropogenic Climate Change

A number of projects, as e.g. PRUDENCE (Christensen et al. 2002), have used regional climate models (RCM) to derive regional climate change scenarios for Central and Northern Europe. The results have been used to evaluate different sources of uncertainties in the scenarios. Chapter 3.5 (see also Sect. 1.5.2) of this assessment summarises the main and robust results of these studies.

A major result was that the regional models generally return rather similar scenarios for seasonal averages and larger areas when forced by the same global climate change scenario (Déqué et al. 2005). For higher order statistics like daily temperatures, daily rainfall or maximum daily wind speed, the choice of the regional model has an effect (Kjellström et al. 2007; Beniston et al. 2007; Rockel and Woth 2007). Thus, the choice of the regional climate model is of minor relevance when mean changes for larger areas are needed. When different driving global climate change scenarios are used – by using different emission scenarios or different global climate models – the differences become larger (e.g. Woth 2005; Déqué et al. 2005).

If higher levels of anthropogenic forcing are applied, then on average the regional changes become stronger, even if not necessarily in a statistically significant manner. This lack of significance is related to the fact that the signal-to-noise ratio of systematic change and weather noise gets smaller if the considered spatial scales are reduced. In all regional climate change scenarios, a warming is obtained in the entire Baltic Sea Basin and for all seasons (Christensen and Christensen 2003). The warming is most pronounced in the northern and eastern parts of the basin during winter, together with a dramatic reduction in the snow cover, and to the south in summer. Precipitation increases in winter and decreases in southern areas in summer in many scenarios. In general, the projected changes also increase with greenhouse gas emissions.

As an example, the expected changes of winter (DJF) mean temperatures are shown in Fig. 1.19 (see also Chap. 3.5). The different model configurations (two global models, two regional models) indicate that when the snow cover retreats to the north and to the east, the climate in the Baltic Sea Basin undergoes large changes. A common feature in all regional downscaling experiments is the stronger increase in wintertime temperatures compared to summertime temperatures in the northern and eastern part of the Baltic Sea Basin (e.g. Giorgi et al. 1992; Jones et al. 1997; Christensen et al. 2001; Déqué et al. 2005; Räisänen et al. 2004). For further discussion, refer to Chap. 3.5.

Frequency distributions tend to become broader with respect to summer rainfall (Christensen and Christensen 2003), North Sea winter wind speeds (Woth 2005) and continental summer daily temperatures (Kjellström 2004). On the other hand, frequency distributions of daily temperatures become narrower in eastern and northern Europe during winter (Kjellström 2004).

1.5 Ongoing Change and Projections for the Baltic Sea Basin – A Summary

The following provides a summary of the main findings which are presented and discussed in Chaps. 2 to 5 of this book. No specific references are given – they are all listed in the detailed account of the following chapters.

Many of the conclusions depend on the time period studied. A frequent deficiency of contemporary literature is the lack of discrimination between climate variability and anthropogenic climate change. Also, only a few long time series have been quality controlled and are homogeneous. Here, we repeat the main and most robust findings.

When considering the ecological state of the Baltic Sea Basin, assessments of anthropogenic climate change need to distinguish between effects caused by factors such as nutrient and contaminant discharges, eutrophication, over-fishing, land use change, and air pollution. At present no regional studies for the Baltic Sea Basin have been found that can attribute robustly recent trends in climate to increased greenhouse gases. The observed changes in the thermal conditions are, however consistent with the global signals, which have been attributed reliably to human causes, and consistent with the projections available for the region.

1.5.1 Recent Climate Change in the Baltic Sea Basin

The variability of the large scale atmospheric circulation has a strong influence on the surface climate (temperature, precipitation, wind speed, etc.) of the Baltic Sea Basin. During the 200 years studied, the 19th and 20th centuries' climates differ in several ways. Towards the end of the 19th century, the Little Ice Age ended in the region, and during the period 1871–2004 there were significant positive trends in the mean temperature for the northern and southern Baltic Sea Basin, being 0.10 °C/decade on the average north of 60° N and 0.07 °C/decade on the average south of 60° N. With regard to annual mean temperatures, there was an early 20th century warming that culminated in the 1930s. This was followed by a cooling that ended in the 1960s and then another warming until the present. The warming is characterised by a pattern where mean daily minimum temperatures have increased more than mean daily maximum temperatures. Spring is the season showing the strongest warming. The number of cold nights has decreased and the number of warm days has increased, with the strongest change during the winter season.

The variability in **atmospheric circulation** has a strong influence on the surface climate in northern Europe. From about the 1960s until the 1990s, westerly airflow intensified during wintertime. This increased frequency of maritime air masses contributed to higher wintertime temperatures and enhanced precipitation at regions exposed to westerlies, especially during the 1990s. On a centennial timescale it can be seen that relationships between large scale atmospheric circulation and surface climate elements show strong temporal variability.

Over the latter part of the 20th century, on average, northern Europe has become wetter. The increase in **precipitation** is not spatially uniform. Within the Baltic Sea Basin, the largest increases have occurred in Sweden and on the eastern coast of the Baltic Sea. Seasonally, the largest increases have occurred in winter and spring. Changes in summer are characterised by increases in the northern and decreases in the southern parts of the Baltic Sea Basin. In wintertime, there is an indication that the number of heavy precipitation events has increased.

Characteristics of **cloudiness and solar radiation** show remarkable inter-annual and inter-decadal variability in the Baltic Sea Basin. A decrease in cloudiness and an increase in sunshine duration was observed in the south (Poland) while opposite trends were revealed in the north (Estonia). In the 1990s, all these trends changed their sign. Long-term observations in Estonia show that an improvement in air quality (i.e. a decrease in the aerosol emissions to the atmosphere) reversed the decreasing trend in atmospheric transparency and direct radiation during the 1990s. Presently, atmospheric transparency is at the same level as in the 1930s.

Centennial time series from southern Scandinavia reveal no long-term trend in **storminess** indices. There was a temporary increase in the 1980s–1990s. In the Baltic Sea Basin, different data sources give slightly different results with respect to trends and variations in the extreme wind climate, especially concerning small-scale extreme winds. At the same time, there are indications of increasing impact from extreme wind events. But this increasing impact results from a complex interaction between climate and development trends that increase the exposure to damage and/or the vulnerability of nature and society.

The inter-annual variability in **river water inflow** is considerable, but no statistically significant trend can be found in the annual time series for the period 1921–1998.

The analysis of the long-term dynamics of the **dates of the start and ending of ice events and the duration of ice coverage** for the rivers of the Russian part of the Baltic Sea Basin showed a stable positive trend from the middle of the 20th century to its end.

As to the maximal **ice cover thickness**, a negative tendency has been established for all Polish and Russian lakes studied. In Finland, both decreasing and increasing trends can be found in the maximum ice thickness time series.

A recent decrease in **snow cover duration and water equivalent** has been observed in the southern parts of all the Fennoscandian countries, while the opposite trend prevails in the north. Changes of **snow depth** are quite similar, i.e. a decrease in the southwestern regions and an increase in the north-eastern regions.

During the 20th century, the Baltic Sea **mean salinity** decreased during the 1980s and 1990s, but similar decreases had also appeared earlier in the century. No long-term trend was found for the 20th century.

There are indications of a sea level rise in the 20th century compared to the 19th century.

A climate warming can be detected from the time series of the maximum **annual extent of sea ice and the length of the ice season** in the Baltic Sea. On the basis of the ice extent, the shift towards a warmer climate took place in the latter half of the 19th century. This gradual shift has been identified as the ending of the Little Ice Age in the Baltic Sea Basin.

Coastal damages appearing in various regions of the southern Baltic Sea generally result from a combination of strong storms, sea-level rise and the decreasing trend in ice cover in the winter, i.e. at times when the most intensive storms occur.

1.5.2 Perspectives for Future Climate Change in the Baltic Sea Basin

Projections of future climate change have been constructed with a series of dynamical models of the regional climate system. Most of these models simulate only the atmosphere and prescribe sea surface temperature and sea ice conditions; in this respect, the model used by the Swedish Meteorological and Hydrological Institute (SMHI) is significantly more sophisticated and an improvement over most other models as it includes a dynamical model of the Baltic Sea itself and regional lakes.

The skill of these models has been demonstrated by their ability to reconstruct the main characteristics of the recent climate. However, the reproduction of recent climate is not perfect, in particular with respect to regional water and energy balances. Also, even a perfect performance with present conditions would be no proof that the models can do a realistic job in describing possible future climate conditions. There is, however, no alternative to the model-based approach (cf. Müller and von Storch 2004), but it is prudent to closely monitor the changing climate conditions closely and to compare these changes with the projections provided by the various models. Also, when the simulated changes are comparable or smaller than the model biases, scenarios should be considered with care. One such example is precipitation over the Baltic Sea Basin, where the differences between present day simulations and observed precipitation are often larger than the simulated regional manifestation of global climate change.

Increasing greenhouse gas concentrations are expected to lead to a substantial warming of the global climate during this century. Cubasch et al. (2001) estimated the annual globally averaged warming from 1990 to 2100 to be in the range of 1.4 to 5.8 °C. This range in temperature change takes into account differences between climate models and a range of anthropogenic emissions scenarios, but it excludes other uncertainties (for example, in natural variability or in the carbon cycle) and should not be interpreted as giving the absolute lowest and highest possible changes in the global mean temperature during the period considered.

Projected future warming in the Baltic Sea Basin generally exceeds the global mean warming in global climate model (GCM) simulations. Looking at the annual mean from an ensemble of 20 GCM simulations, regional warming over the Baltic Sea Basin would be 0.9 °C higher than global mean warming, or some 50% larger in relative terms. In the northern areas of the basin, the largest simulated warming is generally in winter; further south the seasonal cycle of warming is less clear. However, the relative uncertainty in the regional warming is larger than that in the global mean warming. Taking the northern areas of the basin as an example, the warming from the late 20th century to the late 21st century could range from as low as 1 °C in summer (lowest scenario for summer) to as high as 10 °C in winter (highest scenario for winter). The simulated warming would generally be accompanied by an increase in precipitation in the Baltic Sea Basin, except for in the southernmost areas in summer. The uncertainty for precipitation change is, however, larger than that for temperature change, and the coarse resolution of GCMs does not resolve small-scale variations of precipitation change that are induced by the regional topography and land cover.

A more geographically detailed assessment of future anthropogenic climate change in the Baltic Sea Basin requires the use of statistical or dynamical downscaling methods. Yet, as only a limited number of GCM simulations have been downscaled by regional climate models (RCMs) or statistical downscaling methods, the range of results derived from those downscaling experiments does not fully reflect the range of uncertainties in the GCM projections. Accepting this, the range of results from available downscaling studies is presented below as it gives an indication of plausible future changes. All values refer to changes projected for the late 21st century, represented here as differences in climate between the years 1961–1990 and 2071–2100. All references to “northern” and “southern” areas of the Baltic Sea Basin are defined by the subregions shown in Fig. 3.12 (Chap. 3).

Consistent with GCM studies, all available downscaling studies also indicate increases in **temperature** during all seasons for every subregion of the Baltic Sea Basin. Combined results show a projected warming of the mean annual temperature by some 3 to 5 °C for the total basin. Seasonally, the largest part of this warming would occur in the northern areas of the Baltic Sea Basin during winter months and in the southern areas during summer months. Corresponding changes in temperatures would be 4 to 6 °C in winter and 3 to 5 °C in summer, as estimated from a matrix of regional climate model experiments. As noted above, these ranges most probably underestimate the real uncertainty. The diurnal temperature range – the difference between daily maximum and minimum temperature – would also decrease, most strongly in autumn and winter months. Such levels of warming would lead to a lengthening of the growing season, defined here as the continuous period when daily mean temperature exceeds 5 °C. An example from one RCM indicates that the growing season length could increase by as much as 20 to 50 days for northern areas and 30 to 90 days for southern areas by the late 21st century. The range depends on which of the different emissions scenarios is used.

Projected changes in **precipitation** from downscaling studies also depend both on differences in greenhouse gas emissions scenarios and differences between climate models. Moreover, precipitation results are more sensitive than temperature results to the statistical uncertainty in determining climatological means from a limited number of simulated years, particularly at regional scales. Seasonally, winters are projected to become wetter in most of the Baltic Sea Basin and summers to become drier in southern areas for many scenarios. Northern areas could generally expect winter precipitation increases of some 25 to 75% while the projected summer changes lie between −5 and 35%. Southern areas could expect increases ranging from some 20 to 70% during winter while summer changes would be negative, showing decreases of as much as 45%. Taken together, these changes lead to a projected increase in annual precipitation for the entire basin. In broad terms, these results are consistent with GCM studies of precipitation change, although the projected summer decrease in the southern areas of the basin tends to be larger and extend further north in the available RCM studies than in most reported GCMs. This difference reflects the fact that the few GCM simulations that have been downscaled by RCMs also show this pattern of precipitation change.

Projected changes in **wind** differ widely between various climate models. Differences in the circulation patterns of the driving GCMs are particularly important for the modelled outcome of this variable. From the RCM results presented here, only those driven by the ECHAM4/OPYC3 GCM show statistically significant changes for projected future climate scenarios. For mean daily windspeed over land areas, this would amount to a mean increase of some 8% on an annual basis and a maximum mean seasonal increase of up to 12% during winter. The corresponding mean seasonal increase over the Baltic Sea in winter, when a decrease in ice cover would enhance near-surface winds, would be up to 18%. For RCMs driven by the HadAM3H GCM, the changes are small and not statistically significant. Modelled changes in extreme wind generally follow the same pattern as for the mean wind; however, the spatial resolution of both GCMs and RCMs is far too coarse to accurately represent the fine scales of extreme wind. As the downscaled projections differ widely, there is no robust signal to be seen in the RCM results. Looking at projected changes in large-scale atmospheric circulation from numerous GCMs, and thereby changes in wind, they indicate that an increase in windiness for the Baltic Sea Basin would be somewhat more likely than a decrease. However, the magnitude of such a change is still highly uncertain and it may take a long time before greenhouse gas (GHG) induced changes in windiness, if ever, will emerge from background natural variability. It can be noted, moreover, that ECHAM4/OPYC3 is one of the GCMs that gives higher values for changes in wind.

Hydrological studies show that increases in mean annual **river flow** from the northernmost catchments would occur together with decreases in the southernmost catchments. Seasonally, summer river flows would tend to decrease, while winter flows would tend to increase by as much as 50%. The southernmost catchments would be affected by the combination of both decreased summer precipitation and increased evapotranspiration. Oceanographic studies show that the mean annual sea surface temperatures could increase by some 2 to 4 °C by the end of the 21st century. **Ice** extent in the sea would then decrease by some 50 to 80%. The average **salinity** of the Baltic Sea is projected to decrease between 8 and 50%. However, it should be noted that these oceanographic findings are based upon only four regional scenario simulations using two emissions scenarios and two global models.

1.5.3 Changing Terrestrial Ecosystems

The changing climate and other associated environmental and anthropogenic changes may be expected to affect the structure and functioning of ecosystems and threaten the services they provide to society. We assess the potential impacts of the changing environment on terrestrial and freshwater ecosystems of the Baltic Sea Basin, aiming to evaluate the hypotheses:

- that climate change and other associated environmental change over recent decades has affected the ecosystems and their services; and
- that ongoing climate change will cause (further) changes in the ecosystems and their services over the remainder of the 21st century.

In order to highlight the most compelling and societally-relevant aspects of ecosystem change, the analysis focuses on:

- processes and indicators of particular diagnostic value for the attribution of ecosystem changes to identifiable forcing factors; for example, changes in phenology, species distributions and the seasonality of physical, chemical and biological phases in lakes;
- ecosystems and functions of sectorial relevance; for example, productivity and carbon storage in forests; and
- uncertainty associated with ecological complexity and limitations to process understanding; for example, regarding stress responses to changing climatic extremes.

Significant changes in climate, including increasing temperatures and changing precipitation patterns, have occurred over the Baltic Sea Basin in recent decades (Chap. 2). Other associated changes include the continuously rising atmospheric CO_2 concentrations, and increases in deposition loads of atmospheric pollutants, including nitrogen compounds and other acidifying pollutants. A variety of ecosystem impacts of these changes have been identified (hypothesis 1), including the following:

An advancement of spring phenological phases such as budburst and leaf expansion is apparent for many plant species, likely reflecting increasing mean temperatures. Many species also show delayed autumn phases, but trends are less consistent. Phenological trends are stronger in northern Europe than for Europe as a whole, possibly reflecting stronger climate warming.

Species distributional shifts tracking isothermal migration are apparent for both plant and animal species. Possibly related changes include weaker migratory behaviour, for example in some bird species. Treeline advance has been observed in the Fennoscandian mountain range.

Increased growth and vigour of vegetation at high northern latitudes generally is apparent from satellite observations and can be attributed to increased growing season warmth and an extended growing season. Other observations, such as tree ring data, support the existence of a positive growth trend. The magnitude of the trend within the Baltic Sea basin is representative for high latitude areas in Eurasia, and strong compared with similar latitudes in North America.

Physiological stress related to the combined effects of atmospheric pollutants and extreme weather events such as spring frosts and drought are a possible explanation for late 20th-century dieback in boreal and temperate forests.

Degradation of discontinuous permafrost in the subarctic north may be causing a shift towards a greater representation of wet habitats in tundra. Possible consequences include an increased release of methane through (anaerobic) decomposition, which would accelerate greenhouse forcing.

Climate-related changes in lakes including higher water temperatures, advancement of ice break-up, lower water levels and increased influxes of dissolved organic matter from land have consequences for lake ecosystems, including dominance shifts in phytoplankton communities, higher summer algal biomass, and shifts in trophic state.

Climate scenarios described in Chap. 3 consistently point to increased temperatures throughout the Baltic Sea Basin by the end of the 21st century compared with the present. Precipitation scenarios are more variable but generally point to increased precipitation in winter, with southern areas experiencing decreased rainfall in summer. Combined with the effect of higher temperatures on evapotranspiration, this suggests that ecosystems of the temperate zone may face increasingly unfavourable water budgets during the growing season in the future. Potential impacts of these and other associated environmental changes (hypothesis 2) include the following:

Extrapolation of recent phytophenological trends suggests that extension of the vegetation period by 2–6 weeks, depending on the climate scenario, is likely over much of the Baltic Sea Basin.

Further changes in the distributions of some species may be expected, but for many species, lags associated with population and community processes, dispersal limitations etc. are likely. Wholesale biome shifts, such as the northward displacement of the temperate-boreal forest boundary, will be slow compared to the rate of isotherm migration. Natural and semi-natural vegetation of the future may be of a transient character, e.g. aging conifer stands with an increased representation of broadleaved trees in the younger age classes. Changes may be especially marked in subarctic and alpine areas, with forest invading areas that are currently tundra. Increased local richness is likely as species associated with the forest extend their ranges northward and upslope.

Modelling studies generally point to increasing ecosystem production and carbon storage capacity throughout the region of the Baltic Sea Basin in the next 50–100 years, in conjunction with a longer growing season, increased atmospheric CO_2 concentrations and the stimulation of mineralisation processes in warmer soils. However, increased autumn and winter temperatures may be detrimental to hardening processes in trees, increasing susceptibility to spring frost damage. Growing season drought stress may reduce or inhibit production enhancement in temperate parts of the region.

The potential impact of climatic change on the incidence of pest and pathogen outbreaks affecting vegetation is still largely open. It seems reasonable to assume that harmful insects and fungi from central and southern Europe may expand into the Baltic Sea Basin in the warming climate. Warmer water temperatures combined with longer stratified and ice-free periods in lakes may be expected to accelerate eutrophication, increasing phytoplankton production and shifting the phytoplankton community structure towards species with higher temperature optima, including cyanobacteria. Shallow lakes and lake littoral zones may be particularly sensitive to climate warming. Increasing influxes of humic substances in runoff from boreal catchments would steepen light attenuation, with negative impacts on periphyton and benthic communities in lakes. Coldwater fish species may be extirpated from much of their present range while cool- and warm-water species expand northwards.

Uncertainties associated with the assessment of future ecosystem changes are substantial and include uncertainties due to understanding of the biological phenomena being modelled or projected, including system-internal feedbacks and complexity, as well as variation among climate and greenhouse gas emission scenarios on which the assessments are based. The most important source of uncertainty with regard to many impacts is the future development in non-climatic, anthropogenic drivers of ecosystem dynamics including deposition of atmospheric pollutants, land use changes, changes in forest management and agricultural practices, changes in human populations, markets and international trade, and technological development.

1.5.4 Changing Marine Ecosystems

The Baltic Sea is not a steady state system and external drivers acting on different time scales force major changes in the marine ecosystem structure and function. Postglacial isostatic and eustatic processes have shaped the Baltic Sea's coastline, topography, basic chemistry and sedimentary environment on millennium scales (see Annex 2). Climate variability acts on all time scales and, at least over the last 150 years, overlaps with human activities in the drainage basin and the coastal zone, leading to considerable changes in the biogeochemistry of this semi-enclosed sea. Thus, the emerging impacts of anthropogenic climate change (Chap. 2) cannot be separated at this time from natural variability and from other anthropogenic influences.

Studies of past and present ecosystem changes have demonstrated the sensitivity of the marine ecosystem to **temperature** variations. For instance, Northern Baltic annual peaks of the most abundant cladoceran species were found to co-vary with surface water temperature. The higher temperatures during the 1990s were associated with a shift in dominance within the open sea copepod community from *Pseudocalanus* sp. to *Acartia* spp. Increased production and survival rates of sprat and herring populations during the last 5–10 years co-varied with high temperatures and high NAO indices. In the earlier warming period in Fennoscandia between 1870–1940, many range shifts in birds were observed, regarding both the northern and southern borders as well as spring and autumn migration. Furthermore, extreme winter temperatures have long been documented to influence water bird mortality in the Baltic Sea, and winter conditions in the Baltic Sea Basin are known to determine the range of land birds as well as water birds. Spring migration has generally occurred earlier in recent years, although there is a high variation between and within species.

Also, past changes in **salinity** have been associated with marked changes of the ecosystem. An increase in salinity during the first half of the century resulted in a spread of several marine species (e.g. mesozooplankton, barnacles, jellyfish, larvaceans) towards the northern and eastern parts of the Baltic Sea. Correspondingly, the decrease in salinity after the late 1970s in the northern Baltic Sea was reflected in a biomass decline of the large neritic copepod species and an increase of the freshwater cladoceran species. In the deep basins of the open Baltic Sea, the decrease in salinity resulted in reduced standing stocks of *Pseudocalanus elongatus*, an important player in the pelagic food web. In contrast, temperature-sensitive species increased their population sizes. A retreat towards the south has been found in benthic fauna, e.g. *Scoloplos armiger*. The decrease in herring and sprat growth has been related to a salinity-mediated change in the copepod community. The cod, a top predator in the pelagic food chain and a key species in the Baltic Proper which usually regulates the sprat and herring stocks, has seen a decrease. This decrease and the climatically enhanced sprat reproductive success have induced a switch from cod-domination to sprat-domination.

Eutrophication is a phenomenon of the recent past; still it has been documented to change the biota. Several monitoring programmes have been targeted to follow it since the 1970s, mainly because it poses a direct threat to health (toxic algal blooms) and biota (anoxic bottoms develop hydrogen sulphide). Changes of phytoplankton biomass and species composition reflect eutrophication and climatic changes simultaneously. A further twist emerges from the fact that eutrophication itself may be promoted directly by climatic factors, such as runoff and rainfall. There is some evidence that increased primary production has led to an increase of biomass at higher trophic levels (e.g. zooplankton and fish). This trend has been especially clear in benthos. Above the halocline, macrofauna biomass in the 1990s was about five-fold compared with conditions in the 1920s–30s. The deep basins of the Baltic Sea are frequently exposed to hypoxia and anoxia, which results in periodic extinction and recolonisation of bottom fauna.

Anthropogenic climate change **scenarios** for the Baltic Sea Basin (see Chap. 3) describe an increase in temperature, especially during wintertime, and an increase in rainfall in the northern part of the runoff area. The consequence of increasing precipitation is twofold. Increasing precipitation results in a decrease in salinity and in an increase of nutrient leakage and associated eutrophication (see also Sect. 1.5.3).

Projected **increased temperatures**, especially during winter months, will lead to changes in growth and reproduction parameters for fauna and flora, many of which are of boreal origin, i.e., adapted to low temperatures. The following changes are considered possible:

- Increased temperatures stimulate pelagic bacteria growth more than primary production, thus the ratio between bacteria biomass to phytoplankton is expected to increase with increasing temperature in eutrophic waters.
- Diatom spring blooms are subject to species change when winters become milder. Furthermore, it has been suggested that the diatom bloom itself may disappear after milder winters and be replaced by dinoflagellates.
- Increasing summertime temperatures may enhance cyanobacterial blooms.
- Elevated winter temperatures may prevent convection in late winter and early spring with the result that nutrients are not mixed into the upper euphotic zone.

Modelling studies describe the extinction of southern subpopulations of the Baltic ringed seal as a probable effect of expected diminishing **ice** cover suitable for breeding. The grey seal, however, has been shown to have the capability of breeding extensively on land, even in the Baltic Sea Basin.

Expected decreases of **salinity** of the Baltic Sea will modify its ecology in several ways. The most important changes will probably be seen in species distributions (both horizontal and vertical), though growth and reproduction are also likely to be affected. The lower limit of approximate salinity tolerance is 2 psu for *Praunus flexuosus*, *Neomysis vulgaris* and *Gammarus locusta* and 3 psu for *Corophium volutator*; for *Palaemon adspersus* and *Idotea baltica* it is 5.5 psu; for *Pontoporeia femorata* and *Harmothoe sarsi* it is 6 psu; for *Pygospio elegans* and *Laomedea lovéni* it is 7 psu; and for *Terebellides strömii* and *Fabricia sabella* it is 7.5 psu. Thus, along the complete range of Baltic Sea surface salinity we can expect decreases of species number due to changes in species distributions (see also Fig. 1.12).

A decrease of marine fauna is expected to occur first in the northern Baltic Sea surface area, because of the expected intensified rainfall in the northern part of the watershed. In the western Baltic Sea the common starfish (*Asterias rubens*) and common shore crab (*Carcinus maenas*) are among the species expected to decrease if salinity decreases.

We are likely to meet a reversed situation as compared to changes in the 1950s when salinity was rising. Some of this expected trend has already been documented as species like cod, which need a certain level of salinity during a certain life stage, display low reproductive success in the Baltic Sea. Cod eggs need a minimum salinity of 11.5 psu for buoyancy, which they usually find in the halocline regions of the deep Baltic Sea basins. Due to low salinity but also low oxygen concentrations in the deep water, cod eggs are frequently exposed to lethal oxygen conditions in the layer where they are neutrally buoyant.

Finally, decreasing salinity enables all freshwater species to enlarge their distributions in the Baltic Sea. Because of its ecological and evolutionary history, the Baltic Sea predominantly receives species originating from both the adjacent inland waters and the oceanic coasts but also from remote seas. Most of the recent invaders in the Baltic Sea originate from warmer climates. In conditions of increasing water temperature, not only spontaneously spreading European invaders but also exotics from warmer regions of the world can be expected to become established in the Baltic Sea.

Two target species, known to cause severe changes in invaded ecosystems, most likely will spread with climatic warming. The zebra mussel *Dreissena polymorpha* may penetrate to the Gulf of Bothnia. The North American jelly comb *Mnemiopsis leidyi*, which recently invaded the Black and Caspian Seas, may invade the Baltic Sea and cause changes its pelagic system.

In addition, the combination of decreasing salinity and increasing temperature will clearly reduce the general fitness of native benthic species and their adaptability to cope with other stressors, e.g. low oxygen or chemical pollution.

Accelerated **eutrophication** is an expected consequence of anthropogenic climate change in the Baltic Sea due to freshwater runoff determining most of the nutrient load entering it, especially in the near coastal areas.

Eutrophication is expected to enhance the production and biodiversity in the ecosystem up to a certain point, after which a collapse will appear due to several mechanisms such as chemical (anoxia) and biotic interactions (competition, predation, exploitation). After this, a new ecological balance will develop, which will be characterised by low biodiversity and high variability due to episodic outbursts of dominant species. Some effects of eutrophication are clear and predictable, such as the general increase of primary production, but other effects, such as species-specific interactions are extremely hard to predict because of the nonlinearity and complexity of the marine ecosystem. In Chap. 5, a variety of possible effects and ongoing changes are discussed.

1.6 References

Alexandersson H (1986) A homogeneity test applied to precipitation data. J Climatol 6:661–675

Alexandersson H, A Moberg (1997) Homogenization of Swedish temperature data. Part I: A homogeneity test for linear trends. Int J Climatol 17:25–34

Bärring L (1993) Climate – change or variation? Climatic Change 25:1–13

Bärring L, von Storch H (2004) Scandinavian storminess since about 1800. Geophys Res Lett 31 L20202 doi:101029/2004GL020441:1–4

Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, Goyette S, Halsnæs K, Holt T, Jylhä K, Koffi B, Palutikof J, Schöll R, Semmler T, Woth K (2007) Future extreme events in European climate: An exploration of regional climate model projections. Climatic Change 81:71–95

Bray D, von Storch H (1999) Climate Science. An empirical example of postnormal science. Bull Am Met Soc 80:439–456

Bray D, Hagner C, Grossmann I (2003) Grey, Green, Big Blue: Three regional development scenarios addressing the future of Schleswig–Holstein. GKSS-Report 2003/25, GKSS Research Center, Geesthacht, Germany

Brückner E (1890) Klimaschwankungen seit 1700 nebst Bemerkungen über die Klimaschwankungen der Diluvialzeit (Climate variations since 1700 and remarks on climate variations during diluvial time). Geographische Abhandlungen. Hrsg. von Prof Dr. A. Penck in Wien. Wien and Olmütz, E.D. Hölzel (in German)

Callendar GS (1938) The artificial production of carbon dioxide and its influence on temperature. Q J Roy Met Soc 64:223–239

Christensen JH, Christensen OB (2003) Severe summertime flooding in Europe. Nature 421:805–806

Christensen JH, Räisänen J, Iversen T, Bjørge D, Christensen OB, Rummukainen M (2001) A synthesis of regional climate change simulations – A Scandinavian perspective. Geophys Res Lett 28:1003–1006

Christensen JH, Carter T, Giorgi F (2002) PRUDENCE employs new methods to assess european climate change. EOS 83:147

Corti S, Molteni F, Palmer TN (1999) Signature of recent climate change in frequencies of natural atmospheric circulation regimes. Nature 398:799–802

Crowley TJ, North GR (1991) Paleoclimatology. Oxford University Press, New York

Cubasch U, Meehl GA, Boer GJ, Stouffer RJ, Dix M, Noda A, Senior CA, Raper S, Yap KS (2001) Projections of future climate change. In: IPCC Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge New York, pp. 525–582

Déqué M, Jones RG, Wild M, Giorgi F, Christensen JH, Hassell DC, Vidale PL, Rockel B, Jacob D, Kjellström E, de Castro M, Kucharski F, van den Hurk B (2005) Global high resolution versus Limited Area Model climate change projections over Europe: Quantifying confidence level from PRUDENCE results. Clim Dyn 25,6:653–670

Giorgi F, Marinucci M, Visconti G (1992) A 2 × CO_2 climate change scenario over Europe generated using a Limited Area Model nested in a general circulation model 2. Climate change scenario. J Geophys Res 97:10011–10028

Glacken CJ (1967) Traces on the Rhodian Shore. University of California Press

Grossmann I (2006) Three scenarios of the greater Hamburg region. Futures 38,1:31–49

Grossmann I (2005) Future Perspectives for the Lower Elbe Region 2000-2030: Climate Trends and Globalisation. PhD thesis, Hamburg University

Hasselmann K (1993) Optimal fingerprints for the detection of time dependent climate change. J Clim 6: 1957–1971

Houghton JT, Jenkins GJ, Ephraums JJ (eds) (1990) Climate Change. The IPCC scientific assessment. Cambridge University Press

Houghton JT, Callander BA, Varney SK (eds) (1992) Climate Change 1992. Cambridge University Press

Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds) (1996) Climate Change 1995. The Science of Climate Change. Cambridge University Press, Cambridge New York

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (2001) Climate Change 2001: The Scientific Basis. Cambridge University Press, Cambridge New York

House of Lords, Select Committee on Economic Affairs (2005) The Economics of Climate Change. Volume I: Report 2nd Report of Session 2005–06. Authority of the House of Lords, London, UK; The Stationery Office Limited, HL Paper 12-I (www.publications.parliament.uk/pa/ld/ldeconaf.htm)

IDAG (2005) Detecting and attributing external influences on the climate system. A review of recent advances. J Clim 18:1291–1314

Jones PD (1995) The Instrumental Data Record: Its accuracy and use in attempts to identify the "CO_2 Signal". In: von Storch H, Navarra A (eds) Analysis of Climate Variability: Applications of statistical techniques. Springer, Berlin Heidelberg New York, pp. 53–76

Jones RG, Murphy JM, Noguer M, Keen AB (1997) Simulation of climate change over Europe using a nested regional-climate model 2. Comparison of driving and regional model responses to a doubling of carbon dioxide. Q J Roy Met Soc 123:265-292

Karlsson KG (2001) A NOAA AVHRR cloud climatology over Scandinavia covering the period 1991–2000. SMHI Reports Meteorology and Climatology No 97

Karlsson KG (2003) A 10 year cloud climatology over Scandinavia derived from NOAA advanced very high resolution radiometer imagery. Int J Climatol 23:1023–1044

Kempton W, Craig PP (1993) European perspectives on Global Climate Change. Environment 35: 16–45

Kempton W, Boster JS, Hartley JA (1995) Environmental values in American Culture. MIT Press, Cambridge London

Kincer JB (1933) Is our climate changing? A study of long-term temperature trends. Mon Wea Rev 61:251–259

Kjellström E (2004) Recent and future signatures of climate change in Europe. Ambio 23:193–198

Kjellström E, Bärring L, Jacob D, Jones R, Lenderink G, Schär C (2007) Modelling daily temperature extremes: Recent climate and future changes over Europe. Climatic Change 81:249–265

Kulkarni A, von Storch H (1995) Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall-test of trends. Met Zeitschrift 4 NF:82–85

Ledwith M (2002) Land cover classification using SPOT Vegetation 10-day composite images – Baltic Sea Catchment basin. GLC2000 Meeting, Ispra, Italy, April 18–22

Leppäkoski E, Olenin S (2001) The meltdown of biogeographical peculiarities of the Baltic Sea: The interaction of natural and manmade processes. Ambio 30 4-5:202-209

McGuffie K, Henderson-Sellers A (1997) A climate modelling primer, 2nd ed. Wiley & Sons, Chichester, Great Britain

Miętus M (ed) (1998) The Climate of the Baltic Sea Basin. Marine Meteorology and Related Oceanographic Activities. Report No. 41. WMO/TD-No. 933. World Meteorological Organization, Geneva

Mitchell JM Jr, Dzerdzeevskii B, Flohn H, Hofmeyr WL, Lamb HH, Rao KN, Wallén CC (1966) Climatic Change. WMO Technical Note No 79, World Meteorological Organization, Geneva

Müller P, von Storch H (2004) Computer Modelling in Atmospheric and Oceanic Sciences: Building knowledge. Springer, Berlin Heidelberg New York

Nakićenović N, Swart R (eds) (2000) Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge New York

Olenin S (2002) Black Sea–Baltic Sea invasion corridors. In: Briand F (ed) Alien marine organisms introduced by ships in the Mediterranean and Black Seas. CIESM Workshops Monograph. Comission Internationale pour l'Exploration Scientifique de la mer Mediterranee, Monaco, pp. 29–33

Omstedt A, D Chen (2001) Influence of atmospheric circulation on the maximum ice extent in the Baltic Sea. J Geophys Res 106:4493–4500

Omstedt A, Elken J, Lehmann A, Piechura J (2004a) Knowledge of the Baltic Sea Physics gained during the BALTEX and related programmes. Progr Oceanogr 63:1–28

Omstedt A, Pettersen C, Rodhe J, Winsor P (2004b) Baltic Sea climate: 200 yr of data on air temperature, sea level variations, ice cover, and atmospheric circulation. Clim Res 25:205–216

Pfister C, Brändli D (1999) Rodungen im Gebirge – Überschwemmungen im Vorland: Ein Deutungsmuster macht Karriere (Uprooting in mountain areas – Flooding in the foreland: The career of an interpretation pattern). In: Sieferle RP, Greunigener H (eds) Natur-Bilder. Wahrnehmungen von Natur und Umwelt in der Geschichte. Campus, Frankfurt New York, pp. 9–18 (in German)

Pielke R jr (2004) What is climate change? Issues in Science and Technology Summer 2004, pp. 1–4

Räisänen J, Hansson U, Ullerstig A, Döscher R, Graham LP, Jones C, Meier HEM, Samuelsson P, 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

Rebetez M (1996) Public expectation as an element of human perception of climate change. Climatic Change 32:495–509

Remane A, Schlieper C (1971) Biology of Brackish Water. E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller), Stuttgart

Rockel B, Woth K (2007) Extremes of near-surface wind speed over Europe and their future changes as estimated from an ensemble of RCM simulations. Climatic Change 81:267–280

Schwartz P (1991) The art of the long view. John Wiley & Sons

Segerstråle SG (1966) Adaptational problems involved in the history of the glacial relicts of Eurasian and North America. Rev Roum Biol- Zoologie: 11:59-66

Seinä A, Palosuo E (1996) The classification of the maximum annual extent of ice cover in the Baltic Sea 1720-1995. Meri Report Series of the Finnish Institute of Marine Research 20:79–91

Stehr N, von Storch H, Flügel M (1996) The 19th century discussion of climate variability and climate change: Analogies for present day debate? World Res Rev 7:589–604

Tol RSJ (2006) Exchange rates and climate change: An application of FUND. Climatic Change 75: 59–80

Tol RSJ (2007) Economic scenarios for global change. Proceedings IV, GKSS School on Environmental Research. Springer, Berlin Heidelberg New York (in press)

Uppala SM, Kållberg PW, Simmons AJ, Andrae U, da Costa Bechtold, V, Fiorino M, Gibson, JK, Haseler J, Hernandez, A, Kelly GA, Li X, Onogi K, Saarinen S, Sokka N, Allan RP, Andersson E, Arpe K, Balmaseda MA, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Caires S, Chevallier F, Dethof A, Dragosavac M, Fisher M, Fuentes M, Hagemann S, Hólm E, Hoskins BJ, Isaksen L, Janssen PAEM, Jenne R, McNally AP, Mahfouf JF, Morcrette JJ, Rayner NA, Saunders RW, Simon P, Sterl A, Trenberth KE, Untch A, Vasiljevic D, Viterbo P, Woollen J (2005) The ERA-40 re-analysis. Q J Roy Met Soc 131:2961-3012.doi:10.1256/qj.04.176

von Storch H (1995) Inconsistencies at the interface of climate impact studies and global climate research. Meteorol Zeitschrift 4 NF, pp. 72–80

von Storch H (1999) The global and regional climate system. In: von Storch H, Flöser G (eds) Anthropogenic Climate Change. Springer, Berlin Heidelberg New York, pp. 3–36

von Storch H, Flöser G (eds) (2001) Models in Environmental Research. Proceedings of the Second GKSS School on Environmental Research. Springer, Berlin Heidelberg New York

von Storch H, Stehr N (2000) Climate change in perspective. Our concerns about global warming have an age-old resonance. Nature 405:615

von Storch H, Zwiers FW (2002) Statistical Analysis in Climate Research. Cambridge University Press, Cambridge New York

Williamson H (1770) An attempt to account for the change of climate which has been observed in the Middle Colonies in North America. Trans Am Phil Soc 1:272

Winsor P, Rodhe J, Omstedt A (2001) Baltic Sea ocean climate: An analysis of 100 yr of hydrographic data with focus on the freshwater budget. Clim Res 18:5–15

Winsor P, Rodhe J, Omstedt A (2003) Erratum: Baltic Sea ocean climate: an analysis of 100 yr of hydrographical data with focus on the freshwater budget. Clim Res 25:183

Woth K (2005) Projections of North Sea storm surge extremes in a warmer climate: How important are the RCM driving GCM and the chosen scenario? Geophys Res Lett:32 L22708 doi: 101029/2005GL023762

Zmudzinski L (1978) The evolution of macrobenthic deserts in the Baltic Sea. 11th Conference of Baltic Oceanographers, vol. 2. Rostock, pp. 780–794

Zwiers FW (1999) The detection of climate change. In: von Storch H, Flöser G (eds) Anthropogenic Climate Change. Springer, Berlin Heidelberg New York, pp. 163–209