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The BACC Author Team

Assessment of Climate Change for the Baltic Sea Basin

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Preface

Climate change and its impact on our life, our environment and ecosystems in general, are in these days at the forefront of public concern and political attention. The Intergovernmental Panel on Climate Change (IPCC) reports have amply documented that anthropogenic climate change is an ongoing trend, which will continue into the future and may be associated with grave implications. Thus, one conclusion to be drawn is clear – the driver for this climate change should be curtailed to the extent socially responsible and sustainable. We need to strongly reduce the emissions of radiatively active gases into the atmosphere.

However, even the most optimistic emission reduction scenarios envision only a limited success in thwarting climate change. What is possible is to limit this change, but it can no longer be avoided altogether. Even if the challenging goal of a stabilization of global mean temperature at an upper limit of 2 °C above pre-industrial levels at the end of this century will be met, significant pressures on societies and ecosystems for adaptation will be the result. Thus, adaptation to recent, ongoing and possible future climate change is unavoidable.

The BACC initiative has dealt with these pressures for the region of the Baltic Sea Basin, which includes the Baltic Sea and its entire water catchment, covering almost 20% of the European continent. BACC has collected, reviewed and summarized the existing knowledge about recent, ongoing and possible futures regional climate change and its impact on marine and terrestrial ecosystems in this region. The acronym BACC stands for *BALTEX Assessment of Climate Change for the Baltic Sea Basin* and denotes an initiative within BALTEX (Baltic Sea Experiment), which is a Regional Hydrometeorology Project within the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program (WCRP).

The first chapter of the book places the initiative in context, clarifies a few key concepts and summarizes the key results; Chapters 2 to 5 document the knowledge about recent and ongoing changes in meteorological, oceanographical, hydrological and cryospherical variables, about scenarios of possible future climatic conditions, about changes in terrestrial and freshwater ecosystems, and about changes in marine ecosystems. A series of appendices provide background material relevant in this context.

Two remarkable aspects of the BACC initiative should be mentioned. The first is the acceptance of this report by the Helsinki Commission (HELCOM) as a basis for its intergovernmental management of the Baltic Sea environment. Based on this BACC report, HELCOM has compiled its own conclusions "Climate Change in the Baltic Sea Area – HELCOM Thematic Assessment in 2007". The second aspect is the fact that the BACC report was made possible by the voluntary effort of many individuals and institutions – without dedicated payment from scientific agencies, governments, NGOs, industries or other possibly vested interests. We think this adds significantly to the credibility of this effort, which we expect will be used as a blueprint for assessments of other regions in the world.

The success of BACC has convinced BALTEX that it would be worth to redo the effort in about five years time – assuming that significantly more knowledge has been generated, and that climate change has emerged even more clearly from the "sea of noise" of natural climate variability.

Hans von Storch (Chairman)

The BACC Author Team

The BACC Author Team consists of more than 80 scientists from 13 countries, covering various disciplines related to climate research and related impacts. Each chapter of the book is authored by one to four *lead authors* and several *contributing authors*. While the former established the overall conception, did much of the writing and are largely responsible for the assessment parts of the chapters, the latter contributed pieces of information of various extent to the contents of the book. In order to highlight the teamwork character of this book, both lead and contributing authors of each chapter are mentioned as an author group at the beginning of each chapter, rather than attributing individual section or text contributions to individual contributing authors. Lead authors are mentioned first followed by contributing authors, ordered alphabetically. The authors of annexes, by contrast, are named individually on top of each annex, section or sub-section within the annex part.

The following authors list firstly gives the lead authors of Chaps. 1 to 5, followed by an alphabetically ordered list of all other contributing and annex authors.

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An in-depth review of the main book chapters was conducted by several independent evaluators as part of the BACC process which improved the book material significantly. We highly appreciate this valuable contribution to BACC.

The BACC project benefited from countless comments by many scientists on earlier versions of the book's manuscript. The BACC Conference held at Göteborg University in May 2006, where a first version of the material had been presented for discussion to the scientific community and the interested public, was highly instrumental in fostering improvement of the BACC material and the BACC Author Team likes to express its gratitude to all who participated actively at the Conference and for all helpful comments received.

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The final shaping and editing of the huge BACC material according to the publisher's requirements turned out to be a major effort. The BALTEX Secretariat at GKSS Research Centre Geesthacht undertook to coordinate and perform this editing process and we would like to thank the Secretariat's staff Marcus Reckermann and Hans-Jörg Isemer, painstakingly supported by Silke Köppen, for skilfully coordinating and conducting this editing process. Numerous figures in this book needed to be redrawn or had to be graphically enhanced, which was excellently performed by Beate Gardeike (GKSS, Institute for Coastal Research). Parts of earlier versions of the manuscript needed major language editing and we like to appreciate the meticulous work by Susan Beddig, Hamburg. Last but not least, we thankfully highlight the major contribution by Sönke Rau who accurately established the print-ready book manuscript, thereby eliminating several errors and patiently adding all, even last-minute, changes to the manuscript.

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A.1 Physical System Description

A.1.1 Baltic Sea Oceanography

Jüri Elken, Wolfgang Matthäus

A.1.1.1 *General Features*

The Baltic Sea is an intracontinental dilution basin with a total area of 415,000 km^2 (including Kattegat). Water exchange with the North Sea is restricted by the narrow straits (Little Belt, Great Belt, Sound, with channel width 0.8, 16 and 4 km, respectively) and the shallow sills (Darss and Drogden Sills, with maximum depths of 18 and 8 m, respectively). While saline water enters the Baltic Sea in the southwestern strait area, the freshwater surplus is concentrated in the large gulfs located in the opposite northeastern part of the sea. This leads to the general estuarine gradients, both in salinity (Fig. A.1) and ecosystem variables. In the Baltic Proper, deep water exchange is restricted by submarine sills and channels connecting deep basins. Since the baroclinic Rossby deformation radius is small (1.3–7 km, Fennel et al. 1991), advection-diffusion dynamics of basins and connecting channels is rather complex.

Despite the relatively small depths (mean depth is about 55 m), the water column of the central Baltic Proper is permanently stratified (Fig. A.2). During winter, the permanent halocline (C, Fig. A.2) separates the less saline cold winter water (B) from the more saline and warmer deep water (D). In the shallow western area, there is a change between stratification and well-mixed conditions. The depth of the halocline increases from about 40 m in the Arkona Basin to 60–80 m in the eastern Gotland Basin. During summer, a seasonal thermocline develops at 25–30 m depth (A_2) separating the warm upper layer (A_1) from the cold intermediate water (A_3). During mild and normal winters, ice cover occupies 15–50% of the sea area in its northeastern part, but may extend to the whole sea during the infrequently occurring severe winters (Omstedt and Chen 2001).

The permanent halocline isolates the Baltic Proper deep layers to a great extent from the surface waters and their ventilation occurs mainly by lateral advection of transformed North Sea water. Frequent but weak inflows (10–20 km^3) interleave just beneath the permanent halocline and prevent stagnation there but they have little impact on the deep and bottom waters. Episodic inflows of larger volumes (100–250 km^3) of highly saline (17–25) and oxygenated water – termed major Baltic inflows (MBIs) – represent the only mechanism by which the Baltic Sea deep water is displaced and renewed to a significant degree (Matthäus and Franck 1992; Schinke and Matthäus 1998).

A total of 113 major inflows have been identified since 1880 excluding the periods of the two World Wars (Fig. A.3). All inflows have occurred between the end of August and the end of April. The seasonal frequency distribution of major inflows (Fig. A.3, top right corner) shows that such events are most frequent between October and February. They occur in clusters of several years, but some have been isolated events.

During the first three-quarters of the past century, MBIs were observed more or less regularly (Fig. A.3). Since the mid-1970s, their frequency and intensity has changed, and only a few major events have occurred since then. Oceanographic conditions in the central Baltic deep water changed drastically during this period which culminated between 1977 and 1992 in the most significant and serious stagnation period (Nehring and Matthäus 1991; Matthäus and Franck 1992; cf. also Fig. A.4). Moreover, the major inflows in January 1993 (Håkansson et al. 1993; Jakobsen 1995; Matthäus and Lass 1995) and January 2003 (Feistel et al. 2003) were only isolated events, and conditions in the central Baltic Sea deep water have soon started to stagnate again although in 1997 a small inflow (by the MBI index) led to an unusual increase of deep water temperature (Fig. A.4) after an exceptionally hot summer.

However, a similar stagnation period occurred earlier during 1920–1932 (cf. Fig. A.4). This natural variation is well described by the mean Baltic Sea salinity (Winsor et al. 2001, 2003) which is strongly related to the large-scale atmospheric variability and the accumulated freshwater inflow (Stigebrandt and Gustafsson 2003; Meier and Kauker 2003).

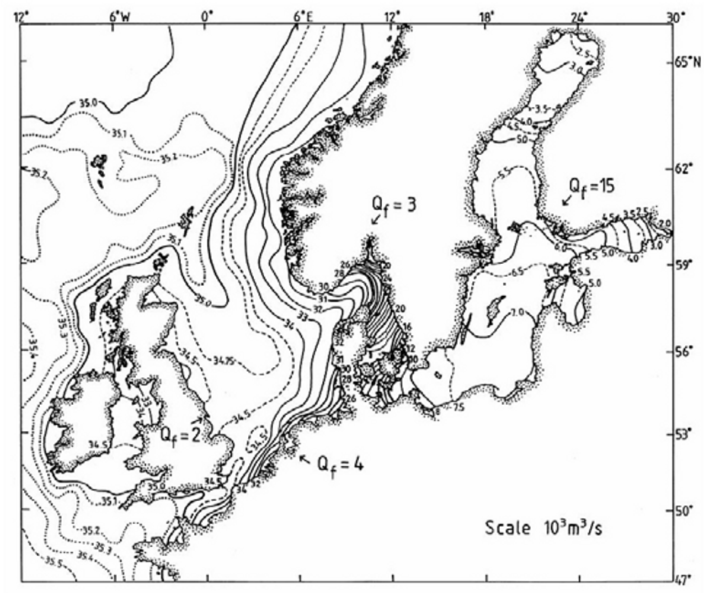

Fig. A.1. Surface salinity distribution. Also indicated is runoff, Qf, to the Baltic Sea (15,000 m^3 s^{-1}), to Kattegat and Skagerrak (3,000 m^3 s^{-1}), to the Danish, German, Dutch, and Belgian coasts (4,000 m^3 s^{-1}), and to the east coast of England (2,000 m^3 s^{-1}) (adapted from Rodhe 1998)

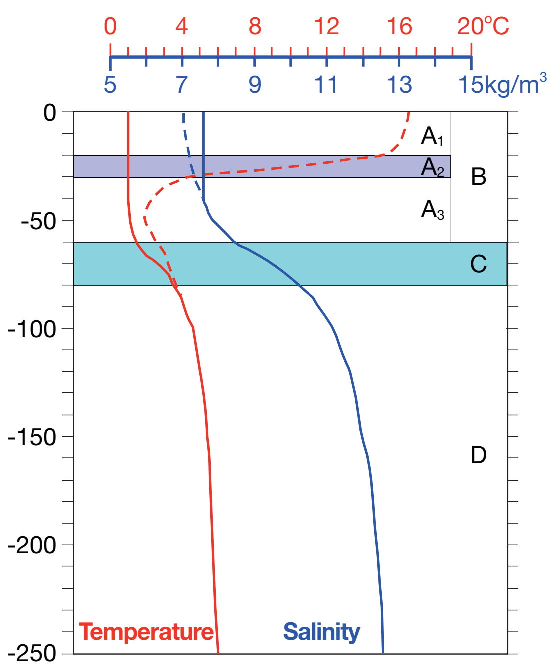

Fig. A.2. Typical thermohaline stratification in the central Baltic Sea during winter (*full line*) and summer (*partly hatched*)

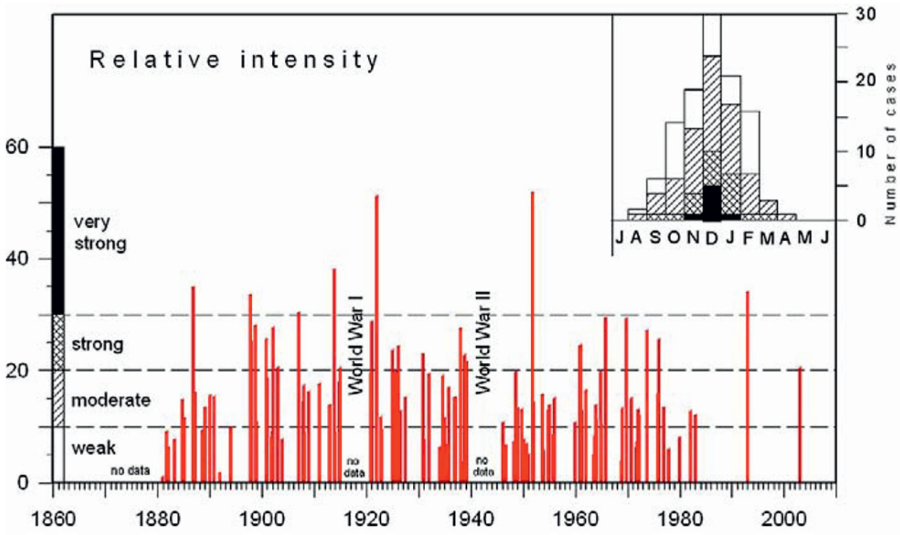

Fig. A.3. Major Baltic inflows (MBIs) between 1880 and 2005 and their seasonal distribution (*upper right*) shown in terms of their relative intensity (Matthäus and Franck 1992; Fischer and Matthäus 1996; supplemented and updated)

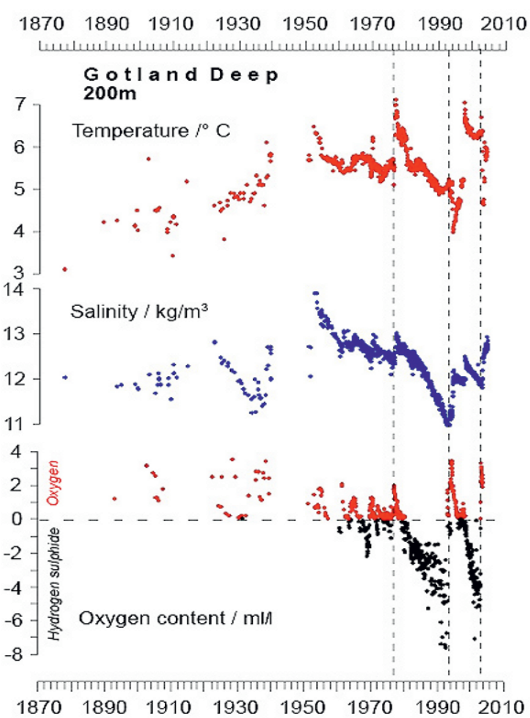

Fig. A.4. Long-term variation of temperature, salinity, oxygen and hydrogen sulphide (expressed in terms of negative oxygen equivalents) concentrations in the deep water of the central Baltic Sea (Gotland Deep)

A.1.1.2 *External Water Budget and Residence Time*

The average volume of the Baltic Sea – about 21,000 km^3 (excluding Kattegat and Belt Sea, e.g. HELCOM 2002) – is maintained by the external water budget, where dominating terms are water import by river discharge, inflowing North Sea water and net precipitation (precipitation minus evaporation), and export by outflowing Baltic Sea water. Volume change due to thermal expansion contributes some 10% (order of magnitude) of river discharge in the seasonal heating and cooling cycle (Stigebrandt 2001) but is small on the annual scales. Minor terms in the long-term budget are volume change by groundwater inflow (Peltonen 2001), salt contraction (Omstedt and Nohr 2004), land uplift and ice export (Omstedt and Rutgersson 2000). The water budget is closed by water storage variation due to the change of mean sea level, which is important on time scales of weeks and months (Lehmann and Hinrichsen 2001).

The major water budget components have recently been reviewed by Omstedt et al. (2004). Magnitudes of river discharge, net precipitation and resulting net outflow to the North Sea are well established (Table A.1) and various estimates differ mainly by the period involved in the study and the amount of data available. Regionally about 80% of the river runoff and 85% of the net precipitation enter the large gulfs (Gulfs of Bothnia, Finland and Riga), which thus represent the major source of freshwater input into the Baltic Sea and control the low salinity in the Baltic Sea surface water (Omstedt and Axell 2003).

Water exchange with the North Sea through the Sound and the Belt Sea (average flow ratio 3:8 according to Jakobsen and Trebuchet 2000) is highly variable in direction and magnitude ($\pm 100,000\,m^3\,s^{-1}$) even over short time periods (e.g. Mattson 1996; Jakobsen and Trebuchet 2000). During MBIs the accumulated volume may exceed 200 km^3 (50% of yearly river discharge) during a few weeks, e.g. in January 1993 (Håkansson et al. 1993; Matthäus and Lass 1995; Jakobsen 1995) and in January 2003 (Feistel et al. 2003; Piechura and Beszczynska-Möller 2004; Meier et al. 2004; Lehmann et al. 2004). In general, the water entering the Baltic Sea may flow out again within a short time, thus not affecting the conditions in the larger sea area.

According to modelled Lagrangian trajectories, only 6% of the Great Belt water and 32% of the Sound water remains after one year in the Baltic Sea (Döös et al. 2004). Therefore, summing up the individual inflow and outflow events, calculated from sea level difference along the straits without considering salinity, gives little information about water renewal in the sea. Flow in the straits is often separated according to its salinity and the term "inflow" usually covers the waters which form the deep layers below the primary halocline, i.e. waters entering the Arkona Basin with $S > 8$–9. This treatment also includes Baltic Sea water that is entrained to the inflow. The estimates of salinity-weighted inflows vary from 19,000 to $43,000\,m^3\,s^{-1}$ (Stigebrandt 1987; Kõuts and Omstedt 1993; Omstedt and Rutgersson 2000; Gustafsson 2001; Lehmann and Hinrichsen 2002; Meier and Kauker 2003; Omstedt and Nohr 2004) mainly depending on the methods/models used and how the salt fluxes are adjusted.

The above inflow estimates yield the Baltic Sea water residence times of 11 to 22 years. Stigebrandt and Gustafsson (2003) have argued that deep water entering from the Kattegat and Belt Sea is composed from the "true" Kattegat deep water and recirculated Baltic Proper surface water. Only Kattegat deep water, with mean inflow rate $5,000\,m^3\,s^{-1}$ contributes to the Baltic Sea water renewal, together with the freshwater supply, and the resulting residence time is 33 years. This latter estimate is consistent with the results from climatic scale runs with 3D models (Meier and Kauker 2003; Döös et al. 2004; Meier 2005).

A.1.1.3 *Processes and Patterns of Internal Water Cycle*

The water effectively recirculates in the Baltic Sea, even with the relatively impermeable halocline. This overturning circulation may be called Baltic haline conveyor belt (Döös et al. 2004), analogous to the Wold Ocean climatic water cycle. Understanding of the water cycle details is rapidly advancing in the present period due to the developments in high resolution measurements and 3D climatic scale modelling.

Calculation of water mass age, as refinement to the bulk residence time, has started only recently based on the method by Deleersnijder et al. (2001). By that, additional Eulerian tracer is embedded in the model to handle the age of seawater. It is defined as time elapsed since a water particle has left the source region that is kept constant in time. Meier (2005) investigated the spreading of

Table A.1. Water budget components of the Baltic Sea (Kattegat and Belt Sea excluded) according to Omstedt et al. (2004)

Water budget component	Long-term mean ($m^3\,s^{-1}$)	Interannual variability ($m^3\,s^{-1}$)
River discharge	14,000	$\pm 4,000$
Net precipitation	1,500	$\pm 1,000$
Volume change	0	$\pm 2,000$
Net outflow to the North Sea	15,500	$\pm 5,000$

surface water into the layers below by putting the constant source on the surface. Median ages of the bottom water between one year in the Bornholm Basin and 7 years in the northwestern Gotland Basin were found.

During 1903–1998 the oldest bottom water of about 11 years appeared at Landsort Deep. A secondary age maximum was calculated in the halocline of the deeper basins. In the eastern Gotland Basin, three stagnation periods (in the 1920/1930s, 1950/1960s, and 1980/1990s, cf. Fig. A.4) with residence times exceeding 8 years were found. Andrejev et al. (2004b) studied spreading of the Neva River water in the Gulf of Finland. The highest water ages (2 years) were found in the southeastern part of the Gulf. It takes around 5 years to renew 98% of the water masses of the Gulf of Finland.

Inflowing saline water (most frequently with salinity 12–16, but during MBIs up to 22–25), driven barotropically by along-strait sea level difference (e.g. Gustafsson and Andersson, 2001) is spread and transformed in the Baltic Proper in the cascade of deep sub-basins. This process is controlled by the flow regime in the connection areas (sills, deep channels) and depends on the "old" stratification of downstream basins relative to the variable density of new incoming water. Sinking water masses (levels determined by the buoyancy of the downstream basin) entrain ambient surface waters, reducing their salinity and increasing the flowrate (e.g. Stigebrandt 1987; Kõuts and Omstedt 1993). Saline water flowing to the Arkona Basin, the first in the basin sequence, forms a thin near-bottom dense water pool (Stigebrandt 1987) that leaks along the northern flanks as a baroclinic geostrophic boundary current to the Bornholm Strait and further on into the Bornholm Basin (Liljebladh and Stigebrandt 1996; Lass and Mohrholz 2003).

Starting from the Bornholm Basin, the basins work as buffers where incoming water may be trapped by the sill depth. Classical flow description in the buffering Bornholm Basin distinguishes three different modes of salt water intrusion (e.g. Grasshoff 1975): (1) regular inflow just below the primary halocline interleaving on the level of neutral buoyancy; (2) occasional inflow of saline water, sinking to the bottom and exchanging the Bornholm Basin deep water; (3) rather infrequent occasional (major) inflow of large amounts of saline water, filling the whole Bornholm Basin above Stolpe Sill level (60 m) and exchanging the Gotland Deep water. New observation techniques which have become available during the recent decade demonstrate the complex dynamics of the inflow process, which contains internal fronts with fine-scale intrusions, surface and subsurface eddies etc. The flow of higher-salinity water over the Stolpe Sill frequently has a splash-like nature (Piechura et al. 1997). Behind the sill, the deep layer often gets contracted, reflecting the internal hydraulic jump (hydraulically controlled transport over the sill). An example of a regular intruding water mass (identifiable by higher temperatures at 50–70 m depths) is given in Fig. A.6 (Zhurbas et al. 2004).

The response of the Southern Baltic Sea to the major inflow in January 2003 has been well documented (e.g. Piechura and Beszczynska-Möller 2004). The inflow water passed the western and southern slopes of the Bornholm Deep (as after the 1993 inflow, Jakobsen 1996) and detached in the cyclonic eddy into the central part. In the central and western parts of the Bornholm Deep, the usual layering of temperature became totally disrupted. Instead, chaotic distribution of patches of old-warm (> 10 °C) and new-cold (< 2 °C) water was clearly visible. By the end of April 2003, the new-cold water mass reached the Gdansk Deep,

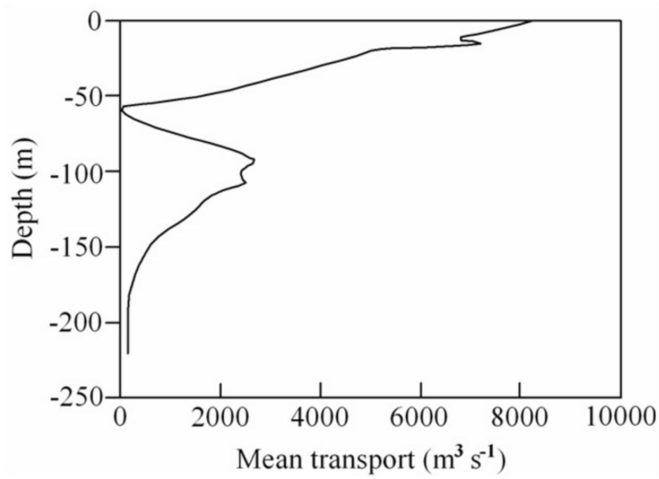

Fig. A.5. Total mean horizontally integrated transport ($m^3\,s^{-1}$) across a basin-wide section in the Eastern Gotland Basin between Gotland and Latvia for the period 1902–1998. Northward transports are counted positive. Results from RCO model, redrawn from Meier and Kauker (2003)

generating patchy small-scale intrusions there. After the 1993 inflow, a well-defined front of the intrusive region was found to be propagating north from the Stolpe Channel to the Gotland Deep with a speed of $2\,cm\,s^{-1}$ or more (Zhurbas and Paka 1997). A substantial horizontal intermittence of intrusion intensity, related to mesoscale eddies, was observed behind the front. Such intrusions survive several weeks and months before smearing out by diffusive processes, as recorded after the 2003 major inflow (Zhurbas and Paka 1997, 1999) but also during the stagnation period in the Gotland Deep (Elken et al. 1988; Kõuts et al. 1990; Elken 1996). As shown recently by Zhurbas et al. (2003, 2004), energetic eddies that accompany intruding larger deep water masses are generated by change of potential vorticity in the receiving basin.

Saline water passing the Stolpe Channel (although wind-dependent reversals may take place; e.g. Jakobsen 1996; Elken 1996; Golenko et al. 1999; Lehmann and Hinrichsen 2002) flows on average towards northeast along the eastern slope of the Hoburg Channel, making an occasional cyclonic loop along the slopes of Gdansk Basin. In the Eastern Gotland Basin, the flow forms a semi-enclosed cyclonic circulation cell, with a leakage towards the Northern Basin. This overall flow pattern is confirmed by observations (Elken 1996; Hagen and Feistel 2004; Zhurbas et al. 2004) as well as results from 3D models (Lehmann and Hinrichsen 2000; Lehmann et al. 2002; Döös et al. 2004). Gotland Deep receives saline water interleaving preferably at depths of 80–130 m (Elken 1996; Meier and Kauker 2003), with maximum northward flow across the basin reaching $2{,}500\,m^3\,s^{-1}$ around 100 m (Fig. A.5).

This ventilation depth range explains why hydrogen sulfide does not frequently appear at depths above 140–150 m, even during the long stagnation periods (e.g. HELCOM 1996, 2002). While short-term transport of intruding waters in the interior of the basins is mainly isopycnal, then diapycnal mixing (Stigebrandt et al. 2002) is an important stratification control mechanism on the longer time scales.

The Northern Basin is a region which splits into the two terminal areas of the saline water route – the entrance to the Gulf of Finland and the Western Gotland Basin. Due to the continuity requirements, the deep flow has to be converted into upward vertical advection. Since bidirectional diffusive mixing does not restore the high vertical gradients in the halocline, unidirectional upward entrainment has to be more effective in the terminal region than in other areas. Besides the ordinary "mixers" like wintertime convection and wind-driven turbulence (halocline erosion occurs at wind speeds above 14 m/s, Lass et al. 2003), wind waves reach highest significant heights in November (5 m) and December (9 m) due to the long fetch for dominating southwesterly winds

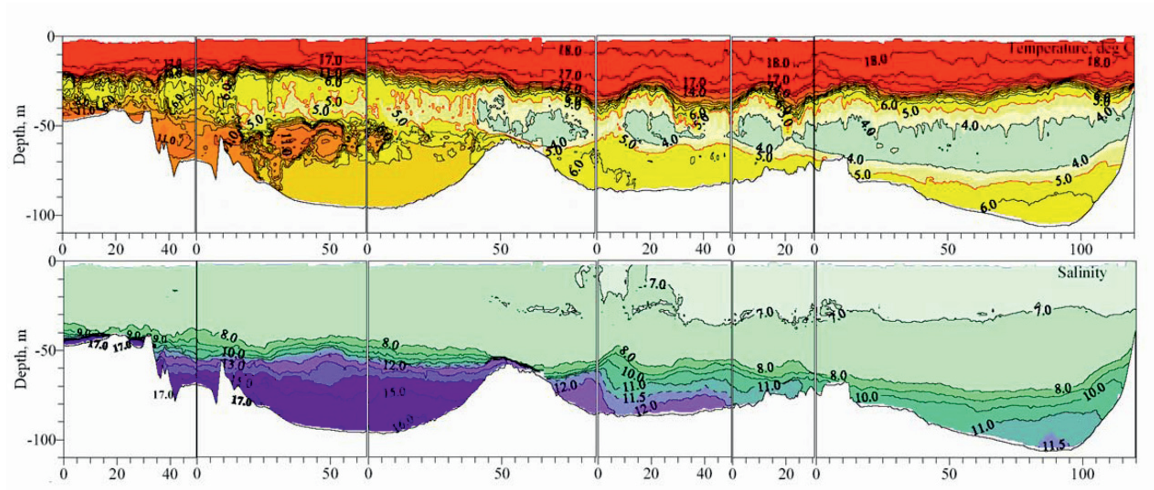

Fig. A.6. Temperature (*top*) and salinity (*bottom*) transect Bornholm Gate – Bornholm Deep – Stolpe Channel – Gdansk Deep in September 1999 (Zhurbas et al. 2004). Note the following features: (1) intruding warm water interleaving the Bornholm Deep at 50–70 m depths; (2) deep layer contraction (internal hydraulic jump) at the Stolpe Still followed by an eddy (halocline displacement) in the Stolpe Channel; (3) northward (cyclonic) deep water jet along the slope of Gdansk Basin

(Jönsson et al. 2003). Significant vertical advection (partly due to the seasonal deep flow reversal in the Gulf of Finland; Elken et al. 2003) coupled with stronger halocline erosion (because the vertical stability is less than in the upstream basins) leads to the highest seasonal amplitudes in the saline water (Matthäus 1984).

The Gulfs of Bothnia and Riga are topographically isolated from the saline water below the halocline and they receive only the Baltic Proper surface water. It is denser than the surface water of the gulfs and sinks behind the sills. During the summer, deep water spreading is similar to that of the Baltic Proper – cyclonic flow along the slopes (e.g. Marmefelt and Omstedt 1993; Omstedt et al. 1993; Håkansson et al. 1996; Lips et al. 1995; Raudsepp 2001; Lehmann et al. 2002) either on the bottom towards the greater depths ("major" inflows for the gulfs) or interleaving on the level of neutral buoyancy. However, during the late autumn before icing, the whole water column is usually mixed due to low haline vertical stability, leaving the horizontal gradients characteristic to the well-mixed estuary. The latter is also true for the eastern half of the Gulf of Finland (Alenius et al. 1998).

Motions of surface waters are strongly affected by variable wind forcing. Drift currents in the offshore areas are converted into up- and downwelling features in the coastal areas (Lehmann et al. 2002; Myrberg and Andrejev 2003) that are affected by Kelvin waves (Fennel and Strum 1992; Lass and Talpsepp 1993; Fennel and Seifert 1995) and topographic waves of different origin (Raudsepp 1998; Pizzaro and Shaffer 1998; Raudsepp et al. 2003). The water is laterally mixed by mesoscale eddies (Elken et al. 1994; Stigebrandt et al. 2002; Zhurbas et al. 2003) and inertial motions (e.g. Nerheim 2004).

Regular, basin-guided cyclonic flow cells are evident from observed surface salinity distributions (Rodhe 1998) and spreading patterns of juvenile freshwater originating from the spring maximum of discharge (Eilola and Stigebrandt 1998; Stipa et al. 1999), despite the sporadic nature of instantaneous currents. These flow patterns can be also seen from the model results (Lehmann et al. 2002; Stipa 2003; Andrejev et al. 2004a). In the converging flow areas, bi-directional currents feed quasipermanent but migrating and self-restoring salinity fronts (Pavelson 1988; Elken 1994; entrance to the Gulf of Finland: Pavelson et al. 1997; Gulf of Riga: Lilover et al. 1998) that are similar to the Kattegat–Skagerrak front controlling the major inflows to the Baltic Sea (e.g. Stigebrandt and Gustafsson 2003).

A schematic of the internal water cycle in the Baltic Sea is presented in Fig. A.7.

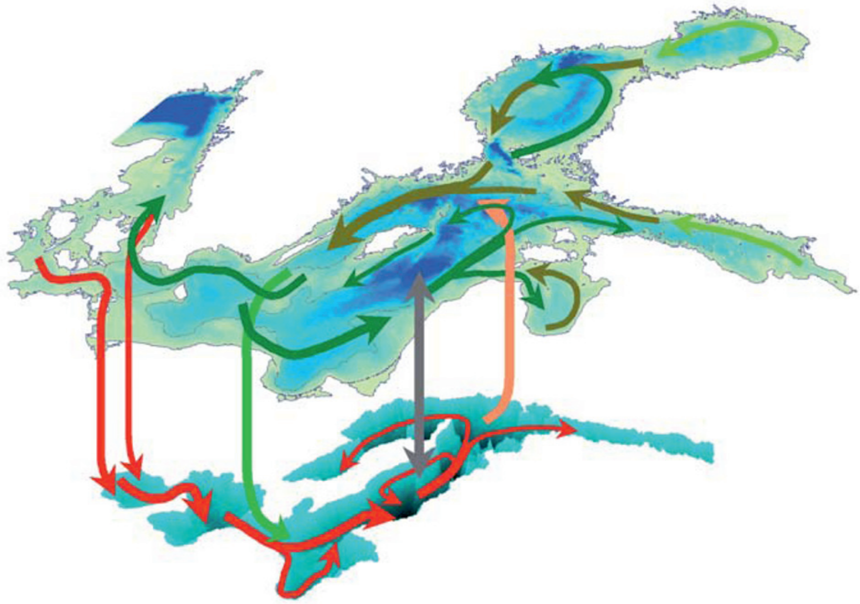

Fig. A.7. A schematic of the large-scale internal water cycle in the Baltic Sea. The deep layer below the halocline is given in the lower part of the figure. Green and red arrows denote the surface and bottom layer circulation, respectively. The light green and beige arrows show entrainment, the gray arrow denotes diffusion

A.1.2 Atmosphere

Hans-Jörg Isemer, Viivi Russak, Heikki Tuomenvirta

A.1.2.1 *Atmospheric Circulation*

The climate of the Baltic Sea Basin, located between the 50th and 70th northern parallels in the Eurasian continent's coastal zone, is embedded in the general atmospheric circulation system of the northern hemisphere, with its cyclonic circumpolar vortex providing for mean troposheric westerly air flow with annually varying intensity (e.g. Defant 1972). Strong westerly air flow provides for maritime, humid air mass transport in particular into the southwestern and southern parts of the basin, while in the east and north the maritime westerly air flow is weakend due to friction and drying processes providing for increasing continental climate conditions.

The following two climatic types according to Köppen's climate classification scheme dominate much of the Baltic Sea Basin: 1) Most of the middle and northern parts of the basin are dominated by the temperate coniferous-mixed forest zone, with cold, wet winters, where the mean temperature of the warmest month is not lower than 10 °C and that of the coldest month not higher than −3 °C, and where the rainfall is, on average, moderate in all seasons. 2) Much of the southwestern and southern region belongs to the marine west coast climate, where prevailing west winds constantly bring in moisture from the oceans, and the presence of a warm ocean current (the North Atlantic current system) provides for, in particular, moist and mild winters. Due to the influence of the warm ocean currents on parts of mid- and northern Europe, the mean temperature of the Baltic Sea Basin is, on average, several degrees higher than that of other areas located in the same latitudes. In addition to the two climate types mentioned above, the northeastern and eastern regions of the basin are influenced by the moderate sub-arctic continental climate.

Major air pressure systems known to affect the weather and circulation in the Baltic Sea Basin are the low-pressure system usually found near Iceland (Icelandic Low) and the high-pressure system in the Azores Island region (Azores High). Also, the continental anticyclone over Russia may influence climate and circulation in the basin. The position and strength of these systems vary on synoptic time scales, and any one of them can dominate

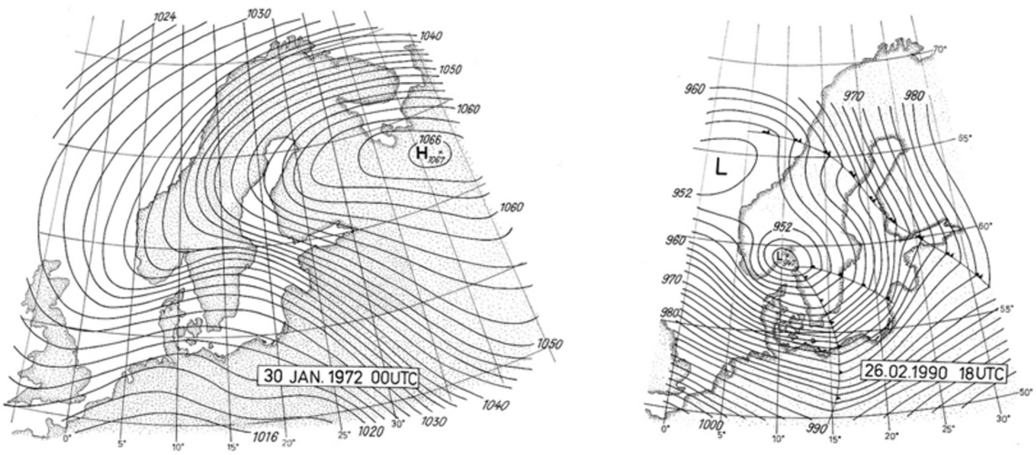

Fig. A.8. Examples of both a major continental anti-cyclone (*left*, core surface air pressure in excess of 1060 hPa) and a violent storm cyclone (*right*, less than 950 hPa at the centre) over the Baltic Sea Basin in winter (from Miętus 1998, with permission by WMO)

the weather for a period of days to weeks. These systems also dominate the long-term mean surface air pressure and related mean circulation patterns over northern Europe, showing a distinct annual cycle, see Chap. 1, Fig. 1.6. The following short description is largely based on Miętus (1998) and Uppala et. al (2005). The latter describe results of the ERA-40 re-analysis project for the period 1979 to 2001, which are used in Fig. 1.6.

In the cool season of the year, beginning in September, southwesterly air flow prevails, intensifying in October and becoming more cyclonic in November and December. The mean flow is especially intensive in January and in February, when the core pressure of the Icelandic Low is deepest and the anticyclone over Russia as well as the Azores High are well developed. The strongest mean horizontal air pressure gradient forms over the Baltic Sea Basin in this season. Note the pressure range in January (Fig. 1.6, Chap. 1), with mean surface air pressures of 1004 hPa and 1020 hPa in the far north and south of the basin, respectively.

A particular feature in winter (see again the January map) is the mean surface pressure trough forming leeward of the Scandinavian mountains along the main north–south axis of the Baltic Sea. In March the intensity of mean air flow over the Baltic Sea Basin decreases, becoming even weaker in April. The Azores High starts to stretch into parts of mid-Europe, and the mean flow over the southern Baltic Sea Basin becomes weakly anticyclonic. The mean pressure fields in April and May represent the weakest mean pressure gradients in the course of the year. During June and July, the direction of the mean air flow is northwesterly to westerly and is rather anticyclonic in character in the south, while in the north of the basin it is weak and hardly specified. Here, an extended but weak low pressure system extends over much of the area between Iceland and the White Sea, covering the northern Baltic Sea Basin as well. The summer months are therefore dominated by meridional weather patterns, in contrast to the winter months, with dominating zonal circulation patterns (e.g. Keevallik et al. 1999).

In September, the Icelandic Low deepens again and the mean pressure gradient starts to increase with the related mean air-flow becoming cyclonic again over much of the basin. Thus, the pressure gradient is rather strong, and the related air flow mostly cyclonic over much of the basin during October to March, with varying magnitude of the pressure gradient and both direction and strength of the flow. It is the Icelandic Low which dominates the basin during this period of the year, while during particularly May to August, especially the southern part of the basin is influenced by an extension of the Azores High with related anti-cyclonic mean flow patterns. The strength of the surface air pressure gradient between the Icelandic Low and the Azores High, the North Atlantic Oscillation (NAO) Index (see Annex 6), has frequently been used to characterise the circulation pattern and strength over northern Europe, and in particular the winter-time NAO has been shown to correlate with weather and climate in the basin (e.g. Busuicoc et al. 2001; Cheng and Hellström 1999; Jacobeit et al. 2001).

In summary, when westerly winds prevail, the weather may be warm and clear in much of, particularly, the northern part of the basin due to the 'föhn' phenomenon caused by the Scandinavian mountains. Despite the moderating effect of the ocean, the Asian continental climate also extends to the area at times, manifesting itself as severe cold in winter and extreme heat in summer. Since the area is located in the zone of prevailing westerlies where sub-tropical and polar air masses meet, weather types can change quite rapidly, particularly in winter. At synoptic time scales the individual air pressure and flow systems are drastically variable and both storm cyclones and major continental, sometimes long-lasting anticyclones may dominate the weather patterns in the region, see Fig. A.8.

A.1.2.2 *Surface Air Temperature*

The distribution of surface air temperature, T_a, is closely linked to the general climate and circulation regimes mentioned above. The general north–south gradient is modulated by the southwest/northeast contrast of maritime versus continental climate influences. In Fig. 1.9 (see Chap. 1), we show the annual cycle of T_a at four selected stations which form a transect from north to south through the basin. Mean annual T_a differs by more than 10 ˚C in the Baltic Sea Basin. The coldest regions are northeast Finland and the upper regions in the Scandinavian mountains, with mean annual surface air temperatures well below 0 ˚C (e.g. −1 ˚C in Sodankylä, and regions in northern Sweden and Finland with mean annual T_a even below −2 ˚C). These are also the regions with the largest amplitudes of the annual cycle (note the mean July minus January difference of about 29 ˚C at Sodankylä, Fig. 1.9). The "most maritime" region in the basin is the southwestern part (Northern Germany and Denmark) of the basin, which is less sheltered from the North Atlantic Ocean by the Scandinavian mountains, where mean monthly values of T_a exceed 0 ˚C throughout the year (Miętus 1998, exemplified by the station Schleswig in Fig. 1.9), but July mean temperatures are lower than in continental regions such as eastern Poland.

A.1.2.3 *Precipitation*

Precipitation in the Baltic Sea Basin shows both a distinct mean annual cycle and considerable regional variations. The latter are caused by the regionally varying circulation systems and the orographic influence of the land surface. As for clouds, precipitation patterns over the Baltic Sea may differ considerably compared to land areas of the basin.

Recent estimates of the annual mean precipitation for the entire Baltic Sea Basin (both land and sea) vary between 620 mm/y (based on the Climate Prediction Centre Merged Analysis of Precipitation (CMAP) climatology, see e.g. Xie and Arkin 1997) and 790 mm/y (based on the Global Precipitation Climatology Project (GPCP) climatology, see e.g. Huffman et al. 1997). Both estimates given for the Baltic Sea Basin are referenced and discussed by Arpe et al. (2005), who concluded that the CMAP data are significantly underestimated while the GPCP estimates are slightly overestimated.

Both climatologies use a blend of gridded rain gauge and satellite data. Earlier estimates based exclusively on rain gauge data are mostly within the above-given range, e.g. the 728 mm/y estimate of Kuusisto (1995), which is based on corrected direct observations. Re-analysis products such as NCEP (e.g. Ruprecht and Kahl 2003) and NCEP-RII (e.g. Roads et al. 2002) yield 730 mm/y and 640 mm/y, respectively; however, re-analysis products are known for several deficiencies which may cause significant biases in precipitation estimates (Ruprecht and Kahl 2003). Therefore, a reasonable current (i.e. for the recent 30 years) mean annual precipitation estimate is 750 mm/y for the entire Baltic Sea Basin, including land and sea.

Rutgersson et al. (2001) give various estimates of precipitation over the Baltic Sea. The SMHI (Swedish Meteorological and Hydrological Institute) 1 degree gridded data set on the one hand and estimates based on COADS (Comprehensive Ocean Atmosphere Data Set, see also Lindau 2002) on the other hand, which are based on totally different data sources, agree astonishingly well (600 and 606 mm/y, respectively) and exhibit a very similar annual cycle. Rutgersson et al. (2001) however present evidence that the SMHI data may underestimate precipitation, because of the neglect of the rain gauges' flow distortion and evaporation error correction. Based on the findings of Rubel and Hantel (1999, 2001), an annual

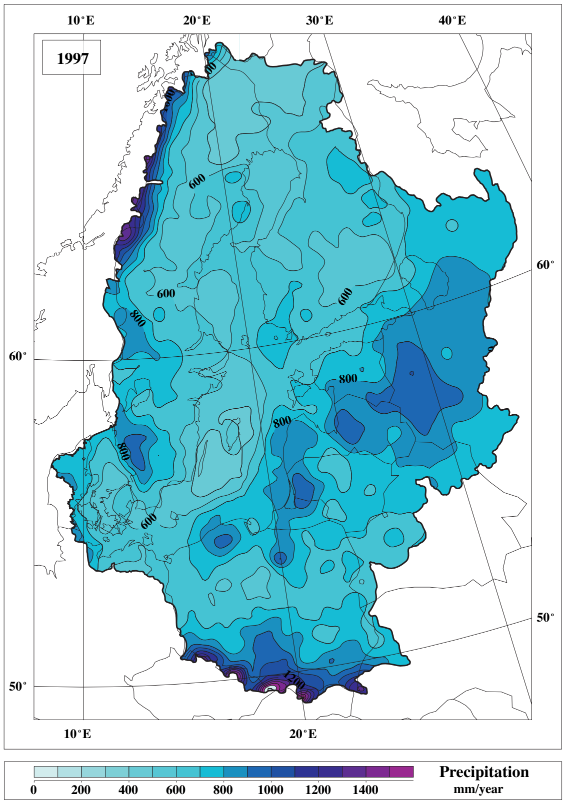

Fig. A.9. Annual precipitation field for the year 1997 in the Baltic Sea Basin (from Rubel and Hantel 2001)

mean correction factor may be in the range of +10 to +20% for stations in the Baltic Sea Basin, with, however, significant annual and monthly variation.

Applying the correction model proposed by Rubel and Hantel (2001) to the CRU (Climate Research Unite University, East Anglia) precipitation product, Jones and Ullerstig (2002) and Räisänen et al. (2003) quantified the correction effect to be about 19 % in the annual and up to 40% in the winter mean, respectively, for the entire land area of the Baltic Sea Basin (see also Sect. 3.3.2 and Fig. 3.6b). Combining the above findings would lead to a mean precipitation estimate over the Baltic Sea of between 600 and 660 mm/year. This estimate is distinctly lower than the combined land and sea estimates given above for the entire basin.

Regional variations of annual mean precipitation are large in the Baltic Sea Basin. The report by Miętus (1998), which is confined to the Baltic Sea and surrounding coastal regions, noted averages for 1961–1990 varying between 927 mm/y in Schleswig (Germany) and 433 mm/y in Oulu (Finland). Annual values in the mountain regions in Scandinavia and southern Poland may even exceed 1,500 mm/y. Rubel and Hantel (2001) have conducted the first objective analysis of a unique gauge data set for the Baltic Sea Basin defined on a 1/6 degree grid scale (roughly 18 km), which is, however, limited so far to a three-years period only.

The regional distribution for the year 1997 (Fig. A.9) is fairly typical, with maxima in the Scandinavian and Sudeten (South Poland) Mountains exceeding 1,500 mm/y, while minima with less than 600 mm/y occur in the northern and northeastern part of the basin as well as over the central Baltic Sea. Mean annual precipitation may vary even stronger, in particular in orographically structured regions, such as mountains. Tveito et al. (2001) found large spatial gradients in the average amount of precipitation in the Scandinavian mountains, ranging from more than 3,000 mm/y at windward sites to less than 500 mm/y in sheltered mountain valleys.

Mean monthly precipitation is highest during July and August, with up to 80 mm in August, and lowest during February to April, with less than

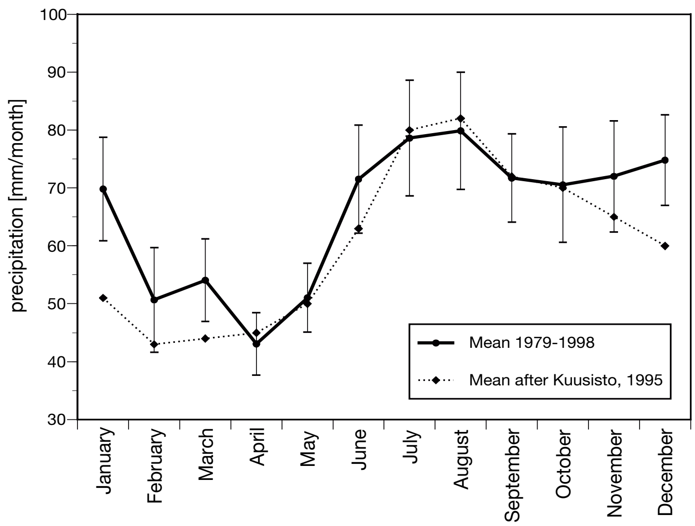

Fig. A.10. Annual cycle of precipitation calculated for the entire Baltic Sea Basin based on GPCP data (Huffman et al. 1997, *thick line*) and after Kuusisto (1995, *dotted line*), taken from Rubel and Hantel (2001). Vertical bars at the GPCP data indicate standard deviations of individual monthly values against the long-term monthly means

45 mm on average, see Fig. A.10. Figure A.10 also indicates inherent uncertainties even in our knowledge on long term means: While both data sets agree well during April to October, differences are noticeable during winter months, with difference peaks in December and January, which may be attributed at least partly to the different correction algorithms used for snow (Rubel and Hantel 2001). The interannual variability is large (Fig. A.10); the detailed analyses of Rubel and Hantel (2001), for example, yielded 646, 721 and 847 mm/y in the years 1996, 1997 and 1998, respectively.

A.1.2.4 *Clouds*

Changes and variability of clouds, as discussed in Sect. 2.2 of this book, relate almost entirely to total cloud cover, as "measured" by eye-observations at synoptic stations. As with many other parameters, information on mean annual and monthly cloud conditions is available either for individual stations (e.g. Keevallik and Russak 2001; Matuszko 2003) or only parts of the Baltic Sea Basin (e.g. Karlsson 2001; Raab and Vedin 1995).

Figure A.11 shows the annual cycle of total cloud cover at different stations across the basin and for the Baltic Proper. For much of the basin, in particular the eastern continental part and also for much of the Baltic Sea, a prominent annual cycle with highest cloud amounts during winter and lowest amounts during summer is clearly evident. Parts of the western and northern regions (mid- and northern Sweden and northern Finland in particular) exhibit a reduced or almost no annual cycle (e.g. at Haparanda and Östersund, Fig. A.11). Karlsson (1999, 2001), using NOAA AVHRR data over Scandinavia for 1991 to 2000, concluded that "with increasing distance from the central part of the Baltic Sea, the amplitude of the annual cycle of cloudiness decreases for inland stations in Scandinavia". This is mostly due to the fact that during summer months no or little convective clouds form over the Baltic Sea, in contrast to the surrounding land areas. Areas in the Swedish mountains even show slightly higher values in summer compared to winter. Karlsson (2001) showed distinct diurnal and inter-annual (Fig. 1.10, Chap. 1) variations of total cloudiness.

A.1.2.5 *Surface Global Radiation*

Global radiation, the solar radiation received by a unit horizontal surface, is usually measured at 1.5 to 2 m above the Earth's surface. Its variation in time and space depends largely on solar elevation and length of day, both linked to the geographical latitude of the site, and is considerably large in the Baltic Sea Basin. For example, in June, at 50° N, the sun is over the horizon for almost 16 hours per day, while in the north at 70° N the polar day

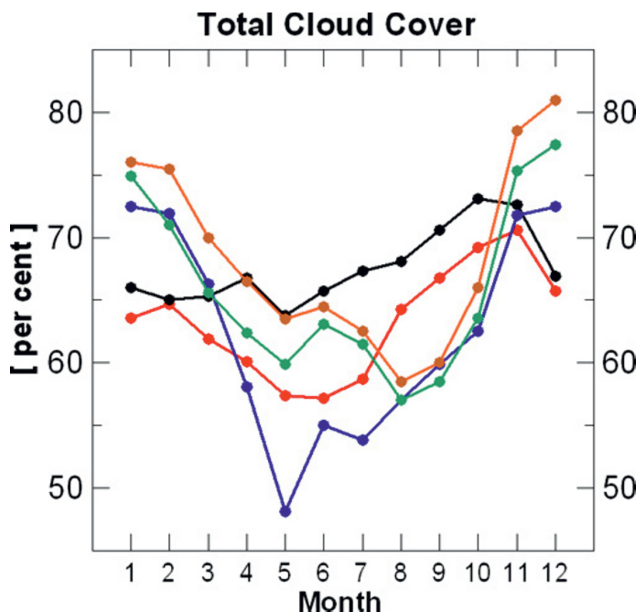

Fig. A.11. Mean annual cycle of total cloud cover (per cent) at various stations or regions in the Baltic Sea Basin. *Red:* Haparanda, northern Sweden; *black:* Östersund, mid-Sweden, both for 1951–2000 obtained from SMHI (H. Alexandersson, pers. comm.); *blue:* for the Baltic Proper based on ship data for 1980 to 1992 (data taken from Isemer and Rozwadowska 1999); *green:* Lindenberg, eastern Germany (52.2° N/14.1° E) for 1951–2003 obtained from German Weather Service DWD (F. Beyrich, pers. comm.); and *brown:* Cracow, southern Poland for 1906–2000, redrawn from Matuszko (2003)

exists in this time. In winter, when in the southern part of the basin the daylight lengths is about eight hours, the solar disk remains below the horizon in the northern Baltic Sea Basin for weeks.

Besides these regular diurnal and annual cycles, the amount and genera of clouds are major factors determining the variations of global radiation across the basin. Totals of global radiation during the warm season are higher in the coastal areas than in the hinterland. This is caused by less intensive formation and development of convective clouds over the sea and coastal region. Another factor influencing the distribution of clouds and, hence, global radiation is topography of the ground. Favourable conditions for cloud formation on slopes of mountain chains may result in a decrease of global radiation. On the other hand, on the elevated areas in mountains located higher than the height of low clouds, global radiation usually exceeds its value at lowland areas. The latter is more evident during winter months. In the cold half year, global radiation may increase, resulting from multiple reflection of solar radiation between the surface and the atmosphere (base of the clouds) in regions with snow cover. Due to the high albedo of snow, monthly totals of global radiation may increase by a factor of 1.4 to 1.8 (Tooming 2002). Global radiation may also be affected by atmospheric transparency. Direct and diffuse radiations are highly sensitive to changes in atmospheric turbidity. But due to their opposite dependencies on transparency, the increase in global radiation with increasing transparency is smaller. However, in highly polluted regions, totals of radiation may be noticeably smaller.

Unfortunately, long-term climatological solar radiation data for the Baltic Sea Basin are available only for a small number of locations and particularly few measurements are regularly made in the northern regions. In December, monthly mean global radiation flux density varies between less than 15 MJ/m^2 north of about 65° N to more than 90 MJ/m^2 in southern Poland with a rather strong orientation of isolines along latitudes. In June, the mean regional variation is between 550 and 750 MJ/m^2, with a much stronger variation according to the difference between Baltic Sea versus land surfaces, and also according to the mountain effect described above. Figure A.12 depicts 4 examples of annual cycles of global radiation flux densities at different locations in the Baltic Sea Basin.

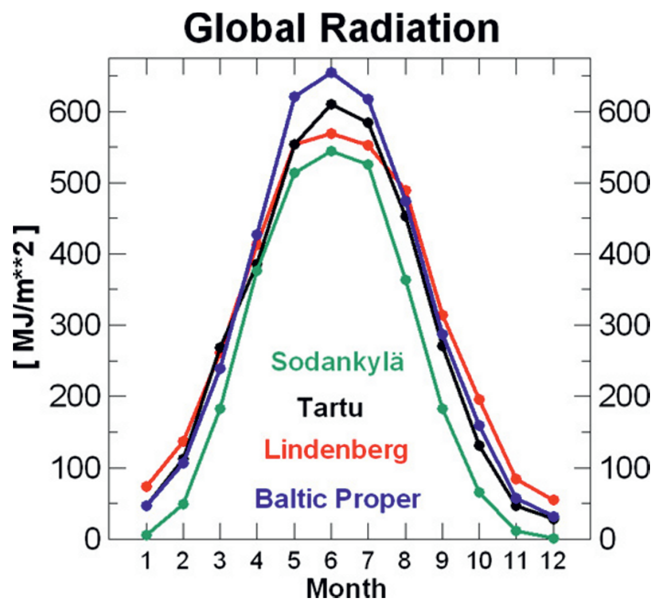

Fig. A.12. Average global radiation (MJ/m^2) at Sodankylä (northern Finland, 1971 to 2000), Tartu (Estonia, 1981 to 2000), Lindenberg (eastern Germany, 1981 to 2000) and at the surface of the Baltic Proper (1980 to 1992). The station data at Lindenberg, Tartu and Sodankylä are based on radiation measurements, while the Baltic Proper data set (taken from Rozwadowska and Isemer 1998) is based on parameterisations applied to cloud cover observations and humidity and air temperature measurements made aboard of voluntarily observing ships

The contribution of diffuse radiation depends on cloudiness, surface albedo and turbidity of the atmosphere. The mean annual percentage of diffuse radiation to global radiation at the surface increases from about 50% in the southern part of the basin to about 60–70% in the higher latitudes. This percentage of diffuse radiation varies seasonally: It is about 40–50% at 50–60° N in June, but may reach about 80–90% in December (European Solar Radiation Atlas, Palz and Greif 1996).

A.1.3 Hydrology and Land Surfaces

Esko Kuusisto, Valery Vuglinsky, Raino Heino, Lev Kitaev

A.1.3.1 *General Characteristics of the Baltic Sea Basin*

The drainage area of the Baltic Sea (in this section also referred to as 'Baltic Drainage' or simply 'Drainage'), which is the land surface region of the Baltic Sea Basin, covers 1.74 million km^2. It includes territories from altogether 14 countries, the largest areas belonging to Sweden (25.3%), Russia (19.0%), Poland (17.8%) and Finland (17.4%). Three countries – Latvia, Lithuania and Estonia – are completely within the Baltic Sea Basin, while only minor parts of Czech Republic, Germany, Norway, Slovakia and Ukraine drain towards the Baltic Sea.

The Baltic Sea Basin has about 80 lakes with a surface area larger than 100 km^2. The number of lakes larger than 1 km^2 totals almost 10,000; of them 4,300 are located in Sweden and 2,300 in Finland. The total area of all lakes in the Baltic Sea Basin is around 123,000 km^2 – one third of the area of the Baltic Sea – and their volume 2,100 km^3.

Forests cover about 54% of the Baltic Drainage. Agricultural land amounts to 26%, buildup land to 4% (ECE 1993). Wetlands are a hydrologically important feature of the Drainage; they still account for 20% of the total land area, although a considerable proportion of them have been drained and are today classified as forests or agricultural lands.

The climate varies considerably in the Baltic Drainage (see also Annex 1.2.2). Long, cold winters dominate in the north, mean annual temperatures being $-2 \ldots 0$ °C. In the southern part of the Drainage, thawing periods are frequent even in midwinter, annual mean temperatures reaching up to 9 °C. Precipitation is highest in the Scandes mountains, locally up to 2,000 mm/y, and exceed-

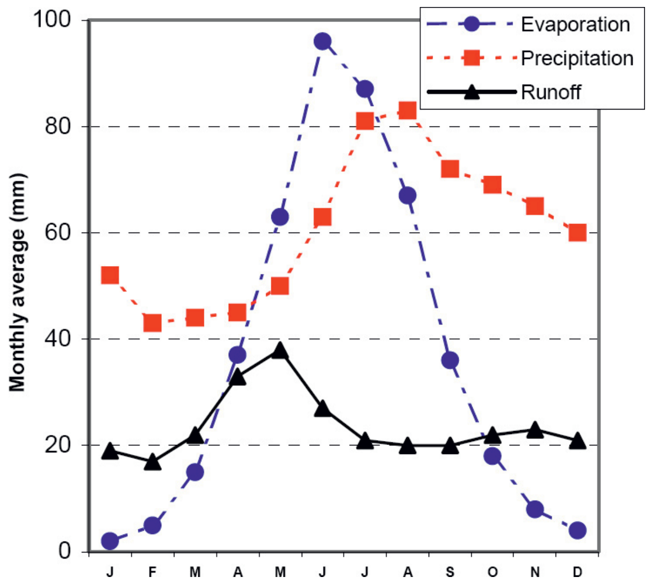

Fig. A.13. The average monthly water balance of the Baltic Drainage, as compiled by Kuusisto (1995) from various sources

ing 1,000 mm also in the Tatra mountains. Over most of the Drainage precipitation ranges between 500 and 750 mm/y. In the north, over 60% of precipitation arrives as snow, in the lowlands south of the Baltic Sea only 10–20%.

Figure A.13 shows the mean monthly values of the water balance components of the whole Baltic Drainage. The annual estimate of corrected precipitation is 728 mm, actual evaporation being 449 mm and runoff 279 mm. The rainiest month is August (82 mm), while evaporation is greatest in June (96 mm) and runoff in May (38 mm).

It is interesting to compare the evaporation from the Baltic Drainage with that of the Baltic Sea itself. In May, 74 mm evaporates from the drainage area, but the evaporation from the sea lingers near the annual minimum of 10 mm. In January, the cold land surface has a minimal vapor flux, while over 40 mm evaporates from the sea – more than in July. The energy required to maintain the total evaporation is about $2.5 \times 10^{21}\,\mathrm{J\,y^{-1}}$. Of this energy, 21% is consumed by evaporation from the Baltic Sea, and 5% by lake evaporation (Kuusisto 1995).

A.1.3.2 *River Basins*

The Baltic Sea can be divided into six subbasins (including the Danish Belts and Sound and the Kattegat). Accordingly, it is natural to divide the land part of the Baltic Sea Basin as shown in Fig. A.14. The Baltic Proper has the largest share of the total drainage area, one third, followed by the Gulf of Finland (24%). Even the smallest drainage subbasins have an area in excess of $100{,}000\,\mathrm{km}^2$.

The ten largest river basins draining into the Baltic Sea are given in Table A.2, with the characteristics of their mean runoff. These ten rivers account for 59% of the total Baltic Drainage. The next 10 basins have a total area of $251{,}000\,\mathrm{km}^2$, 14% of the total. Eight of these basins are in Sweden, two in Finland. The hundred largest basins cover about 86% of the Baltic Drainage. The remaining 14% or a quarter of a million square kilometers are divided into numerous small catchments along the coastal regions and on the Baltic Sea islands. The total area of the Baltic islands is almost $40{,}000\,\mathrm{km}^2$ and their number of the order of 200,000.

As to the mean annual flow, the ten largest river basins are not the top ten. The specific runoff is largest in the northwestern parts of the Baltic Drainage; therefore three rivers from that region, Ångermanälven, Luleälven and Indalsälven cover the positions 8–10, displacing Narva, Torne and Kymi rivers. The drainage area of Lule River is only $25{,}200\,\mathrm{km}^2$, but the specific runoff, $19.0\ \mathrm{l\,s^{-1}\,km^{-2}}$ leads to a mean annual flow of $486\,\mathrm{m^3\,s^{-1}}$.

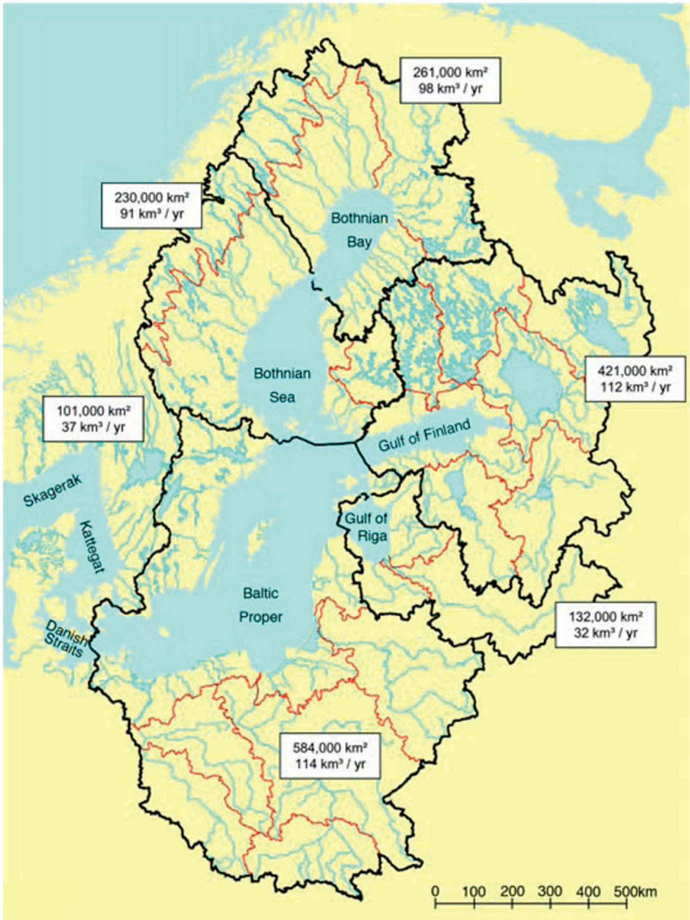

Fig. A.14. The subdivision of the Baltic Sea Basin, with areas and mean annual flows in 1950–1990 (from Bergström and Carlsson 1994)

Table A.2. The ten largest river basins of the Baltic Drainage. The runoff values refer to the period 1950–1990

River	Drainage area (km^2)	Mean annual flow ($m^3\,s^{-1}$)	Specific runoff ($l\,s^{-1}\,km^{-2}$)
Neva	281,000	2,460	8.8
Vistula	194,400	1,065	5.5
Odra	118,900	573	4.8
Neman	98,200	632	6.4
Daugava	87,900	659	7.5
Narva	56,200	403	7.2
Kemi	51,400	562	11.0
Göta	50,100	574	11.5
Torne	40,100	392	9.8
Kymi	37,200	338	9.1

A.1.3.3 *Lakes and Wetlands*

The total number of lakes in the Baltic Sea Basin might be almost 400,000, most of them in Sweden, Finland and Russia. Poland has some 9,300 lakes with surface areas over 1 ha; their total area is over 8,000 km^2. Estonia has about 1,200 lakes, the largest completely within Estonian territory is Võrtsjärv, 270 km^2. On the border of Estonia and Russia is the Lake Peipsi (3,555 km^2), the largest international lake in Europe. Lithuania has 2,850 lakes larger than 0.5 ha, covering 914 km^2.

Looking into individual river basins, the River Neva has by far the largest lake area, almost 50,000 km^2, including two largest lakes in Europe, Ladoga (18,130 km^2) and Onega (9890 km^2). As to the lake percentage, the basin of Motala Ström (Sweden) is number one (22.3%), followed by Kymijoki (18.9%) and Göta älv (18.6%).

In addition to natural lakes, there are thousands of man-made ponds and reservoirs in the Baltic Sea Basin. Most of them are small ponds in Poland and the Baltic States, but the largest reservoirs are in Sweden, with the exception of Narva Reservoir (200 km^2) on the Estonian-Russian border.

For centuries ago, all the countries around the Baltic Sea had large natural wetland areas. In Denmark, Germany, Latvia, Lithuania and Poland most of the wetlands have been drained for agricultural purposes. Estonia and particularly Finland still have rather large natural wetlands. In northern Sweden exploitation has had a relatively small impact on wetlands, while utilisation has been much more comprehensive farther south.

Even today the wetlands comprise one fifth of the Baltic Drainage. During the last few decades, the focus has changed from exploitation to conservation and preservation. Also the use of wetlands in water quality issues, such as the retention of nutrient leaching and cleaning of wastewater, has been increasingly recognised.

A.1.3.4 *Ice Regimes on Lakes and Rivers*

Ice regimes in the water bodies (rivers and lakes) of the Baltic Sea Basin are formed predominantly by the impact of Atlantic air masses producing a warming effect on the study area during the cold season. The Baltic Sea itself stores much heat in wintertime and also warms the adjacent areas. Therefore, the closer the water body to the sea coast, the later ice cover is formed and the earlier the ice break-up occurs.

In the north, rivers are typically frozen in the middle of October; rivers discharging to Lakes Ladoga and Onega are frozen in mid-November, and in southern and southeastern regions only late in December. In the rivers flowing towards the south-western coast of the Baltic Sea, permanent ice cover may not be formed during some warm winters. The duration of complete ice coverage in the rivers flowing in the northern extremity of the Baltic Sea Basin may last 180 to 200 days. Ice break-up in the rivers in the north usually occurs early in May; in the southeast of the area it happens late in March. Mean long-term maximum ice cover thickness on the rivers within the Baltic Sea Basin also differs greatly, depending on location. In the rivers discharging to the Gulf of Bothnia in the north it may be 90 to 100 cm thick; in other regions such as the southeast of the Baltic Sea Basin it is no thicker than 30–40 cm.

Changes in ice regimes in lakes within the study area are similar to those in the rivers. But ice on lakes is usually formed later than that on the rivers; ice break-up in lakes also occurs later.

On lakes in Poland (see e.g. Fig. 2.31), the ice cover is formed in mid-November at the earliest and in mid-February at the latest. A considerable diversity was observed in mean dates of the ice cover freeze-up depending on the lake depth. The ice cover formed earliest in the shallowest lakes (Lake Jeziorak – 12 December, Lake Lebsko – 19 December) and at the latest in the deeper lakes (Lake Hancza – 2 January, Lake Charzykowskie – 4 January). It is worth noting that the ice cover on Lake Studzieniczne froze up on the average 17 days earlier than on Lake Hancza, which is only 65 km away.

Ice characteristics of the Russian lakes differ greatly. This difference is mainly connected with the lakes' morphometry. The considerable influence of the lakes' morphometry is evident from the comparison of the ice characteristics of the lakes Ladoga and Onega. Mean ice cover duration, for example, of the shallower Lake Onega is 20 days longer, and ice cover is 5 cm thicker.

A.1.3.5 *Snow Cover*

Snowfalls occur every winter in the Baltic Sea Basin and seasonal snow cover is formed except in the southwestern regions. Typical durations of snow cover over most areas are between four and

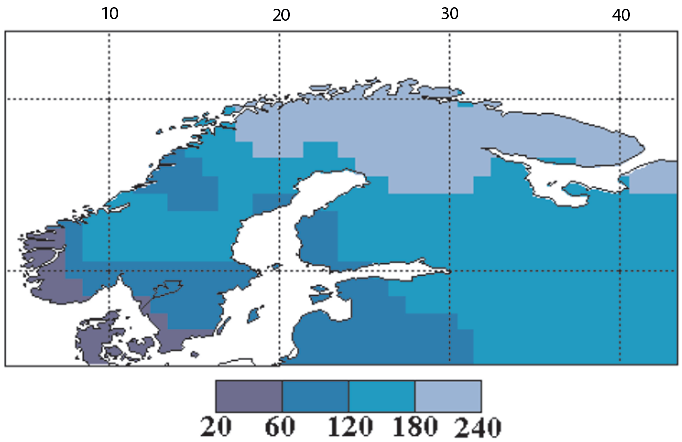

Fig. A.15. Mean regional variability of duration of snow cover (days) for the period 1936–2000 (from Kitaev et al. 2006)

six months (except for regions on the southern coast of the Baltic Sea). Snow cover is a regularly varying feature of the land areas. It affects the winter and spring climate in several ways, the two most important being (Kuusisto 2005):

- because of its high albedo, snow absorbs much less solar radiation than bare soil or vegetated surface;
- melting snow acts as a heat sink, keeping the ground temperature near 0 °C despite high daytime radiative fluxes.
- In the Baltic Sea Basin, 10–60% of annual precipitation occurs in form of snow. Snow is also the origin of a considerable proportion of runoff, its share of average annual runoff being typically higher than its share of annual precipitation. As to the floods, snowmelt is also a major agent almost all over the Baltic Sea Basin.

Although winter precipitation is quite evenly distributed, there are several factors that lead to significant regional variability of snow cover. The orographic gradient for solid precipitation tends to be larger than that for liquid precipitation, because the altitude of the cloud base is low in wintertime. A more important factor is the vertical temperature gradient; rain may fall at lower altitudes, while it snows on higher slopes. Wind redistributes snow particularly in open terrain, leading to extra accumulation in terrain depressions or on leeward sides of ridges or different obstacles. Finally, snow may melt at lower altitudes and on sunny slopes, while no melting occurs at higher sites or in shady places.

Snow Cover Season

The length of the snow cover season varies in the Baltic Sea Basin Basin within wide limits – from several days on average in the western part of the Scandinavian Peninsula to 7–8 months in the territories north of 65° N. Thus, the smooth increase in duration of snow cover from southwest to northeast goes along with the smooth decrease of mean air temperatures during the cold period – from about 0 °C in the west of the Scandinavian peninsula down to −10 °C in the north-eastern part of the eastern European plain (Fig. A.15). However, the correlation between the variation of the duration of the snow period and the air temperature, both at seasonal and at long-term levels, is not significant. In forests, the duration of snow cover is 10–30 days longer than on open ground. The difference depends mainly on the density of the forest canopy, which effectively reduces the rate of snowmelt, thus delaying the disappearance of snow cover (Kuusisto 1984; Kitaev et al. 2005a).

In Finland and north of the eastern European plain, the minimum average snow duration is around 100 days. In southwestern Sweden the duration increases from less than 50 days to more than 100 days within a distance of 100 kilometers; in Finland the gradient hardly reaches 30 d/100 km anywhere in the country. In forests, the duration of snow cover is 10–30 days longer than on open ground.

There are significant spatial differences in duration of snow cover in the territory of Estonia. Its lowest mean values, less than 80 days, are observed on the western coast of the West Estonian Archipelago, i.e. on the open coast of the Baltic Proper (Jaagus 1996, 1997; Tooming and Kadaja 1999, 2000a,b). The highest mean duration of snow cover, more than 130 days, is typical for north-eastern Estonia and for the uplands of southern Estonia. Generally, snow cover duration increases from west to east, similar to decreasing winter air temperature.

Over the territory of Latvia there are remarkable spatial differences in snow cover duration: in the western part of Latvia along the coast of the Baltic Sea and in the proximity of the Gulf of Riga the duration is 70–90 days; it increases to around 110 days moving away from the coast, and the longest snow duration, 114–134 days, is observed in the uplands of eastern Latvia (Draveniece 1998). In general, the duration of snow cover increases from west to east-southeast, following the descending winter air temperature isotherms.

Snow Accumulation

In southern Sweden, maximum snow depths are below 20 cm, and it is below 40 cm in southwestern Finland. Values exceeding 80 cm are reached everywhere north of the latitude 64° except along the coasts of the Gulf of Bothnia. In Finland and Russia the largest region with snow depth exceeding this value extends from Northern Karelia to south-eastern Lapland. The upper slopes of the Scandinavian mountains in Sweden typically have mean maximum snow depths of 100–130 cm, while in Finland one meter is generally exceeded only in the Kilpisjärvi area.

The smallest average maximum depths of snow cover in Poland are recorded in the western part of the country, at no more than 15 cm. The values grow towards the northeast to more than 30 cm; in the mountains they generally increase with altitude (depending strongly on the local topography). In the Tatra Mountains above the tree line, the average maximum seasonal snow depth exceeds 150 cm and 200 cm at summits (Falarz 2004).

The water equivalent of snow is a hydrologically much more important variable than the snow depth. Although weather conditions during the melting period vary considerably from year to year, the correlation coefficients between the maximum areal water equivalent of snow and the volume and peak of the spring flood are significant in almost all major river basins in Fennoscandia.

In Finland in the period 1961–75, the mean maximum water equivalent ranged from 80 to 140 mm in the southern part and from 140 to 200 mm in the northern part (Kuusisto 1984). Up to the latitude of 66° N, the values were 40–60 mm larger in the eastern part of Finland than on the western coast. The year-to-year variation of maximum water equivalent is highest in southwestern Finland, where the ratio between the high and low maximum water equivalent with a return period of 20 years was 4–5, according to data used by Kuusisto (1984). In northern Finland the corresponding value was 1.6–2.0.

In Sweden, about one quarter of the country has mean maximum water equivalent in excess of 200 mm, while the corresponding fraction in Finland is only around 5 per cent. On the other hand, roughly one quarter of Sweden has less than 80 mm of water bound in snow cover during the maximum accumulation; in Finland this fraction is also around 5 per cent. In Norway, the countrywide snow accumulation is still considerably more uneven than in Sweden. The variation of snow conditions from year to year is also quite large throughout Norway.

In western Estonia the mean maximum water equivalent on fields remains below 50 mm, exceeding 70 mm in upland areas, and 90 mm in the Haanja region (Tooming and Kadaja 2000b). The mean maximum water equivalent in Poland extends from below 30 mm in the west to above 75 mm in the north-eastern part of the country; it is above 100/200 mm in the highest part of the Sudeten/Carpathians, respectively (Sadowski 1980).

Extreme Snow Conditions

In Finland the official record snow depth, 190 cm, was measured at the Kilpisjärvi climatological station on April 30th, 1997. It is clear that this value is much lower than the true maximum in Finnish nature; accumulations of three to four meters are possible in narrow gorges in the fjells of Lapland above the tree line. Going further back in history, the snow cover of the winter of 1898–1899 was very probably much thicker than in any winter of the 20th century. Snow depths exceeding 150 cm were reported from several observation sites in northern Savolax.

In Karelia (Russia), the maximum measured snow depth was recorded in the winter of 1983/84, when the average snow depth in March reached 72 cm. Individual extreme measured values of snow depth in Karelia may reach 150 cm, which is more than twice the station standard deviation in this region. Both an increase in snow storage and in the number of winters with extreme snow depth conditions were observed during the last two decades (Kitaev et al. 2005b).

In Swedish lowlands, the highest official snow depth is the same, 190 cm, as the record for Finland as a whole. This value was measured at Degersjö in Ångermanland, only 20 km from the coast of the Gulf of Bothnia. Another coastal region in Sweden with severe snowstorms is northeast Uppland (Dahlström 1995). In the Swedish fjells, snow depths in excess of two metres have been measured at all climatological stations between the latitudes 62–68° N. The highest value, 327 cm, was observed at Kopparåsen, 15 km east of Riksgränsen, on the 28th of February in 1926. However, the variation of maximum snow depth is very high: There are winters when the maximum remains clearly below one meter even at the snowiest observations sites (Pershagen 1981).

Although the maximum snow depth of 77 cm as mean of route observation during the period 1962–2001 was recorded in Estonia on 20 December 1988 in the Haanja upland, the winter periods 1981/82 and 1965/66 can be considered as the snowiest, when the mean spatial (on the basis of land points of a 5 × 5 km grid) maximum water equivalent in February was 135.3 and 130.3 mm, respectively (Tooming and Kadaja 2006). In Latvia, with a background of average snow depth of 6–29 cm over the territory, a high value, 126 cm, was observed in Gureli, Vidzeme Upland in the third decade of March 1931. The variation of maximum snow depth is very high: almost half of all winters are warm and the others are colder than average or even severe. There are years in Latvia with a very thin snow cover: going further back in history such winters were 1948–1949, 1960–1961 and 1971–1972. In the winter of 1972–1973 the depth of transitional snow cover was only 3–8 cm.

The absolute maximum of snow cover depth in Poland was observed in Dolina Pięciu Stawów Polskich (Tatras, 1670 m a.s.l.; Falarz 2001). It was 503 cm on March 26th 1967. It is highly probable that the true maximum in highly located shielded valleys in the Tatras was much higher. Outside the mountains, the absolute maximum of snow cover depth was 85 (84) cm in Krakow (Suwałki) in February 1963 (1979). During the lowest-snow winter seasons, the maximum snow depth did not exceed 10 cm in the lowlands, with some western stations recording only 1–2 cm (Falarz 2004). In the winter season 1991/92 in Słubice no snow cover of at least 1 cm depth was observed.

The maximum snow cover duration in southwestern Poland (except for the mountains) reached 100 days, more than 140 days in the northeastern region and 230–260 days in the Tatra Mountains above the tree line. In southern and eastern Poland, these maxima were recorded in the winter of 1995/96, while in the rest of the country, these maxima occured in the season 1969/70. There are permanent snow patches in the Tatra Mountains. The shortest snow cover duration in western Poland was just a few days per winter season. Extremely short snow cover duration was observed in the winters of 1924/25, 1974/75 and 1988/89.

A.2 The Late Quaternary Development of the Baltic Sea

Svante Björck

A.2.1 Introduction

Since the last deglaciation of the Baltic Sea Basin, which began 15,000–17,000 cal yr BP (calibrated years Before Present) and ended 11,000–10,000 cal yr BP, the Baltic Sea Basin has undergone many very different phases. The nature of these phases was determined by a set of forcing factors: a gradually melting Scandinavian Ice Sheet ending up into an interglacial environment, the highly differential glacio-isostatic uplift within the basin (from 9 mm/yr to −1 mm/yr; Ekman 1996), changing the geographic position of the controlling sills (Fig. A.16), varying depths and widths of the thresholds between the sea and the Baltic basin, and climate change. These factors have caused large variations in salinity and water exchange with the outer ocean, rapid to gradual paleographic alterations with considerable changes of the north-south depth profile with time. For example, the area north of southern Finland-Stockholm has never experienced transgressions, or land submergence, while the development south of that latitude has been very complex. The different controlling factors are also responsible for highly variable sedimentation rates, both in time and space, and variations of the aquatic productivity as well as faunal and floral changes. The basic ideas in this article follow the lengthy, but less up-dated version of the Baltic Sea history (Björck 1995), a more complete reference list and, e.g., the

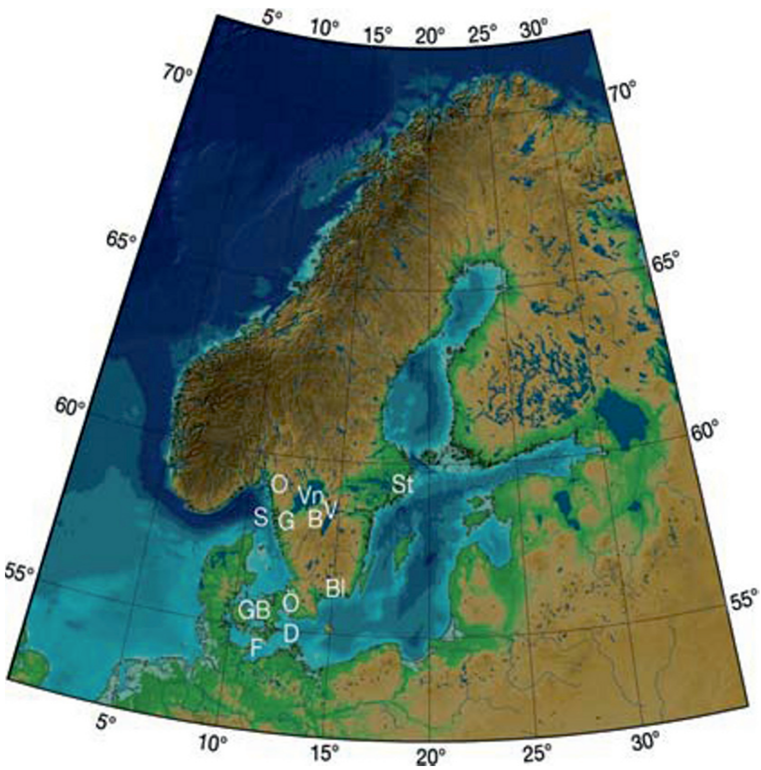

Fig. A.16. The Baltic Sea Basin, showing both land and submarine topography. The letters denote geographical names used in the text. B = Billingen, Bl =Blekinge, D = Darss sill, F = Fehmarn Belt, G = Göta Älv river valley, GB = Great Belt, O = Otteid/Steinselva strait, S = Skagerrak, St = Stockholm, V = Lake Vättern and Vn = Lake Vänern (by courtesy of Martin Jakobsson)

calendar year chronology of the different Baltic Sea phases can be found on the Internet[1]. Although I will focus on the postglacial history of the Baltic Sea in this restricted review, I think it is important to inform the reader about the preceding stages to the more modern Baltic Sea setting.

A.2.2 The Glacial to Late-Glacial Baltic Sea

Due to repetitive, more or less erosive, glaciations during the last glacial cycle, little detailed evidence exists about the glacial conditions in the Baltic before 15,000–14,000 cal yr BP. Based on lithostratigraphic correlations and a large set of OSL (optically stimulated luminescence) and ^{14}C dates, Houmark-Nielsen and Kjær (2003) have, however, indicated several 'embryonic' glacial stages of the Baltic Sea during MIS3 (Marine Isotope Stage 3 dated to about 25,000–60,000 cal yr BP). According to their model the dynamic behavior of the southwestern part of the Scandinavian Ice Sheet between about 40,000–17,000 cal yr BP, produced several proglacial Baltic Ice lakes before the last Baltic Ice Lake proper between about 15,000–11,600 cal yr BP (Björck 1995; Björck et al. 1996; Andrén et al. 1999). In-between glacial advances these proglacial stages have been dated to about 40,000–35,000 and 33,000–27,000 cal yr BP, but with changing configurations during these stages (Houmark-Nielsen and Kjær 2003). It is also postulated that the deep northwest–southeast trending Esrum-Alnarp valley, through Sjælland and Skåne, often functioned as the main connection between the Baltic Sea basin and the (glacio)marine waters of the Kattegatt-Skagerrak. After the final advance some time between 17,000–16,000 cal yr BP – the Öresund lobe (Kjær et al. 2003) – a rapid deglaciation of the southern Baltic Sea basin seems to have taken place (Björck 1995; Lundqvist and Wohlfarth 2001; Houmark-Nielsen and Kjær 2003).

A proglacial lake – the Baltic Ice Lake (BIL) – was developed in front of the receding ice sheet. Due to glacial in-filling of the Esrum-Alnarp val-

[1] www.geol.lu.se/personal/seb/Maps%20of%20the-%20Baltic.htm

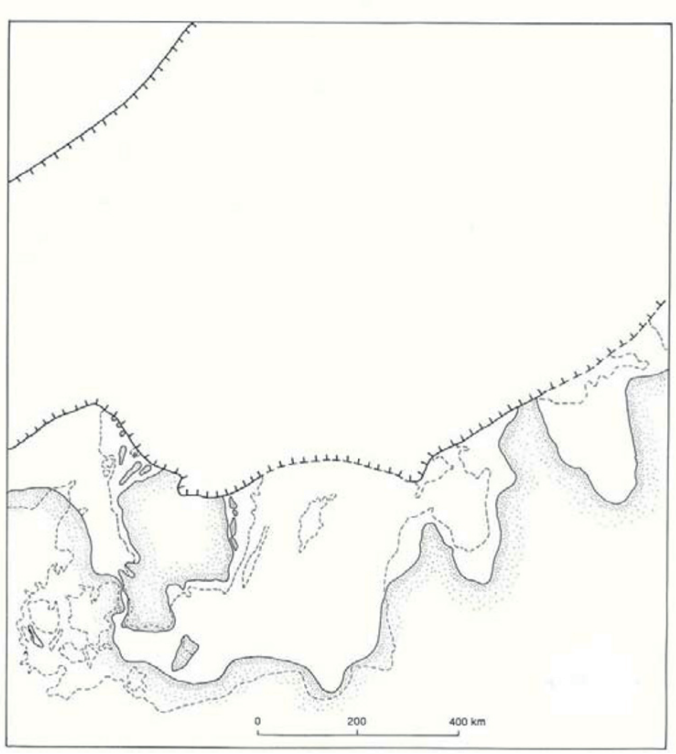

Fig. A.17. The configuration of the Baltic Ice Lake at about 14,000 cal yr BP. Note that the drainage through Öresund and that today's coast line is marked with a stiple line (from Björck 1995)

ley, the lowland in the Öresund region developed into the connecting channel between the Baltic Sea and the sea in the northwest. Glaciolacustrine sediments, e.g., varved clays, were laid down in the Baltic as the ice sheet retreated northwards.

At this early stage of the BIL global sea level was situated at −100 m (Lambeck and Chappell 2001); more than 2/3 of the last glacial maximum ice sheets still remained to be melted. Since the remaining rebound of the loading effect from the ice sheet was fairly small in the southernmost Baltic, the coast line was situated below today's sea level in southern Denmark, Germany and Poland. However, further north both the total and remaining unloading effect – glacial isostatic uplift – was larger than 100 m, and therefore the coast lines of Sweden and the Baltic republics were above today's sea level; the further north the higher.

As a consequence of the uplift the Öresund area, which was now the threshold of the BIL, emerged faster than the rising sea level. This gradual shallowing of the outlet increased the velocity of the out-flowing water and thus also the erosion of the sill area. As long as loose Quaternary deposits could be eroded, the erosion continued, and the present Öresund Strait was possibly shaped, with the island of Ven being an erosional remnant of a previous till-covered landscape. However, when the bedrock sill of flint-rich bedrock between Malmö and Copenhagen was exposed, erosion ceased. The consequence of this was that the continuing uplift made the threshold gradually shallower, until a critical water velocity was reached. At this stage, about 14,000 cal yr BP (Fig. A.17), the water level inside the threshold, i.e. the BIL level, had to rise to compensate for the decreased water depth of the sill. This caused the BIL to rise above sea level; a gradually higher water fall was created between the BIL level south of the threshold and sea level north of it. It also meant that coastal areas situated north of the Öresund isobase (isobases connect areas with the same uplift/shoreline) continued to emerge, while areas south of it submerged, the latter causing a transgression.

The melting Scandinavian Ice Sheet had a strong impact on the aquatic and sedimentary conditions in the Baltic; freshwater with a strong glacial influence produced clayey-silty sediments often of varved (annual layering) type and with-

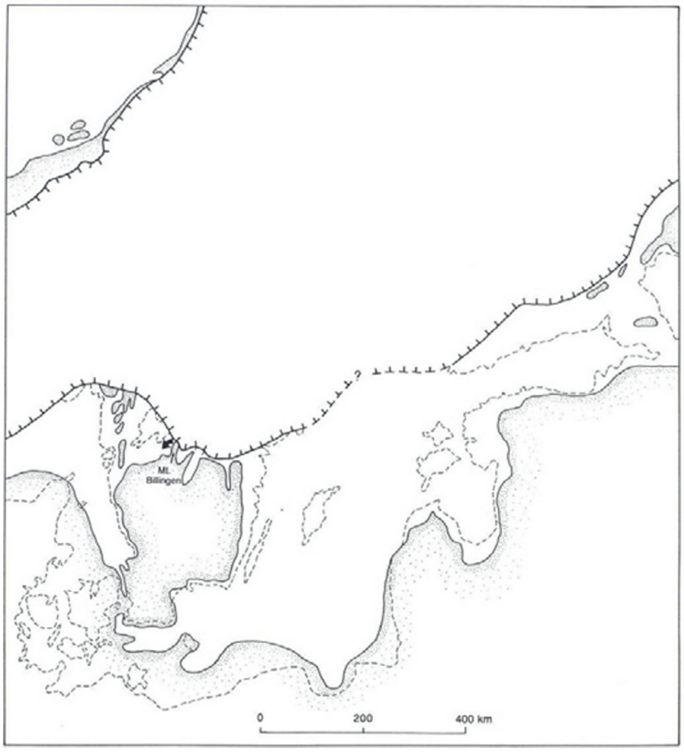

Fig. A.18. The configuration of the Baltic Ice Lake at about 13,000 cal yr BP. Note that it was drained north of Mt. Billingen and that Öresund was dry land. The arrow marks a possible subglacial drainage before Mt. Billingen was completely deglaciated (from Björck 1995)

out organic material. Diatoms are rarely found in these sediments and it is doubtful if any fauna at all existed in this glacial lake. As the melting continued northwards, an important watershed melted out of the retreating ice sheet: the Billingen bedrock ridge in south central Sweden between the two large lakes Vättern and Vänern. The Billingen area almost formed a 'wall' between the sea in the west and the up-dammed BIL in the east.

However, when the ice retreated to the northern tip of Billingen around 13,000 cal yr BP (Fig. A.18), the BIL was drained west, initially beneath the ice. We think the BIL was lowered some 10 m at this event, but any morphologic evidence about this drainage would have been destroyed by the ice. The effect of the sudden lowering was that Öresund was abandoned as the outflow and the BIL water flowed through the, at the time glaciomarine, Vänern basin and out into the Skagerrak through several different valleys/fiords. However, there is no evidence from sediments that saline water managed to penetrate into the Baltic, east of Billingen.

At about 12,800 cal yr BP the North Atlantic region experienced a fairly abrupt climatic change, the so-called Younger Dryas cooling. One effect of the lowered temperatures, especially in winter, was that the previously receding ice sheets of the region began to expand again, and the Scandinavian Ice Sheet advanced southwards to block Billingen again. This would have dramatic effects on the BIL: the water level would once again rise above sea level until Öresund began to function as the outlet (Fig. A.19). This quick transgression would have continued slowly in areas south of the sill, while the remaining Baltic coasts experienced regression, or emergence. The outlet/sill area was still rising quicker than the rising sea, which meant that the BIL rose more and more above sea level; the waterfall in Öresund became gradually higher. During this time the sediments in the Baltic were still very influenced by the glacial input, even in the southern Baltic.

At the end of the Younger Dryas cool period the ice sheet started to retreat again, and sometime between 11,700 and 11,600 cal yr BP a second, and very dramatic, drainage occurred at Billin-

Fig. A.19. The configuration of the Baltic Ice Lake just prior to the final drainage, 11,700–11,600 cal yr BP, which was to lower the Baltic by 25 m (from Andrén 2003a, by courtesy of Stockholm Marine Research Centre)

gen when the ice sheet receded north of the barrier. Since the Öresund threshold at this time had risen by about 25 m above sea level the water level within the Baltic Sea Basin fell by the same amount. It has been calculated that this drainage took 1–2 years and the main traces of it, huge sediment complexes of pebbles and boulders, can be found 5–7 km west of Billingen. As a consequence of the drainage, the coast around the Baltic emerged out of the water and 'fresh' coasts were suddenly exposed. Especially in the southern Baltic, large areas emerged and became land areas, which was of course also the case with the Öresund sill. A large land bridge between Skåne and Själland was established, which favoured a rapid northward plant and animal colonisation during the imminent Holocene interglacial period.

A.2.3 The Post Glacial Baltic Sea

The Yoldia Sea stage

Obviously the final drainage of the BIL at 11,600 cal yr BP was a turning point in the late geologic development of the Baltic Sea: a sudden paleogeographic change, a warmer climate, a rapidly retreating ice sheet and direct contact with the saline sea in the west, incl. Vänern. This is also the starting point for the next Baltic Sea stage, the *Yoldia Sea* stage, which would last for about 900 years.

The straits between Vänern and the Baltic were initially narrow, and saline water could not enter into the Baltic mainly due to the large amount of outflowing water. It would take 250 years (Andrén et al. 1999) until the straits had opened up enough to allow eastward penetration of salt water (Fig. A.20). This slightly brackish phase had its highest salinities in the low-lying areas between Vänern and Stockholm. However, brackish bottom-water also managed to penetrate down to the southern Baltic, creating periodically anoxic bottom conditions. Brackish conditions are shown by occurrences of foraminifera and the bivalve mollusk *Portlandia (Yoldia) arctica* as well as by the diatom flora of the sediments. This slightly saline phase only lasted for some 150 years until the straits between the marine water in Vänern and the Baltic became too shallow to allow saline inflow. Although the brackish conditions turned

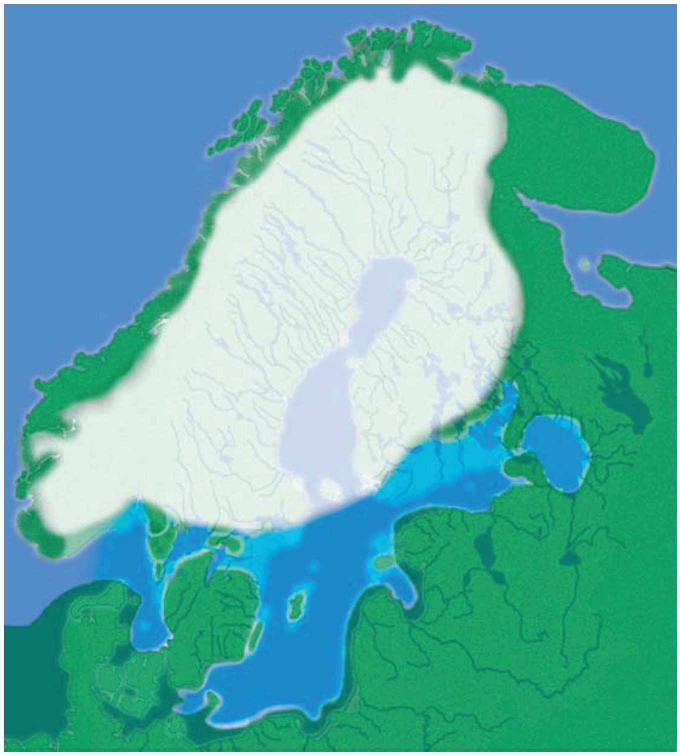

Fig. A.20. The configuration of the Yoldia Sea stage at 11,400–11,300 cal yr BP, when a short saline phase is about to start. Note the large paleogeographic changes between Figs. A.19 and A.20 with the huge land-bridge in the south and the Närke Strait in the north (from Andrén 2003b, by courtesy of Stockholm Marine Research Centre)

into freshwater the Baltic was still at level with the sea, and the sediments during the complete *Yoldia Sea* stage were characterized by low organic content. As a contrast the western part of Vänern was a fairly fauna-rich marine embayment (Fredén 1986).

Owing to the on-going and still rapid uplift in south central Sweden, the straits between Vänern and Skagerrak became gradually shallower, and even some of them even emerged above sea level. The outflowing water from the Baltic had to pass through Vänern and these straits, and in the end only two straits functioned: the Göta Älv strait, which today is the Göta Älv river valley between Vänern and Göteborg, and the Otteid/Steinselva strait at the Swedish–Norwegian border east of Idefjorden.

The Ancylus Lake stage

The gradual shallowing and narrowing of these straits resulted in increased water velocity in these outlets until a maximum was reached when they could not 'swallow' the amount of water entering the Baltic Sea Basin (including meltwater from the melting ice sheet); the water level inside the narrow straits had to rise to compensate for the decreasing outflow area in the straits. Similar to the up-damming of the Baltic Ice Lake, the water level had to rise in pace with the uplift of the sills/straits. South of the isobases for the outlet region this would result in a transgression, since the uplift here was smaller than the forced water level rise, while to the north the situation would be the opposite; a northwards increasing regression. This tilting effect is the onset of the *Ancylus Lake* transgression, which started around 10,700 cal yr BP.

The possibly already submerging coasts in the southernmost Baltic experienced an increased flooding, while the previously emerging coasts of southern Sweden and the northern Baltic republics now changed into submergence. This sudden submergence, or transgression, is witnessed by, e.g., drowned pine forests east of Skåne and tree-ring analyses show rapidly deteriorated living condi-

Fig. A.21. The configuration of the Ancylus Lake stage at about 10,300 cal yr BP at the culmination of the Ancylus transgression. Note the outlets west and southwest of Lake Vänern (from Andrén 2003c, by courtesy of Stockholm Marine Research Centre)

tions. The transgression is also clearly displayed by the *Ancylus* beach; a raised beach found in many places in, e.g., southeast Sweden, on the island of Gotland, and in Latvia/Estonia showing transgressive features.

The freshwater conditions with low primary productivity at the end of the *Yoldia Sea* and during the *Ancylus Lake*, named after the freshwater limpet *Ancylus fluviatilis*, resulted in good mixing of water without permanent stratification. The sediments of the *Ancylus Lake* are also poor in organic material, and the further north the more glacially influenced they are. The amount of the *Ancylus* transgression varies between areas/regions depending on the local uplift. The maximum transgression probably occurred outside the Polish coast and amounted to about 20 m, while a transgression of 10–12 m characterised the *Ancylus* coast in the southwest, Denmark–Sweden–Germany. The latter amount was probably also how much the *Ancylus Lake* was finally dammed-up above sea level. The transgressive phase of the *Ancylus Lake* lasted ca. 500 years, and was obviously governed by the possibility for the Baltic water to find an alternative outflow area. This meant that the transgression in the south continued as long as the constrained sills west of Vänern functioned as outlets (Fig. A.21).

From independent studies we know that the *Ancylus* transgression ended abruptly with a fairly sudden lowering of the Baltic water level at about 10,200 cal yr BP. The rate of the lowering, or regression, strongly implies that it is not only a gradual isostatic effect that shows up in the shore displacement curves, but rather a forced regression; the absolute water level fell. The most likely explanation for such a regression would be that the *Ancylus Lake* level fell due to a lowering of the base level. Since the base level was determined by the sills/outlets, it would mean that the sill(s) was eroded.

We do, however, also know that the sills west of Vänern consist of crystalline bedrock, and it is hardly possible for water to suddenly erode 10 m of hard bedrock. It has therefore been assumed that the water found a new outlet. Because of the transgression in the south, the most obvious threshold/outlet candidate should be situated in

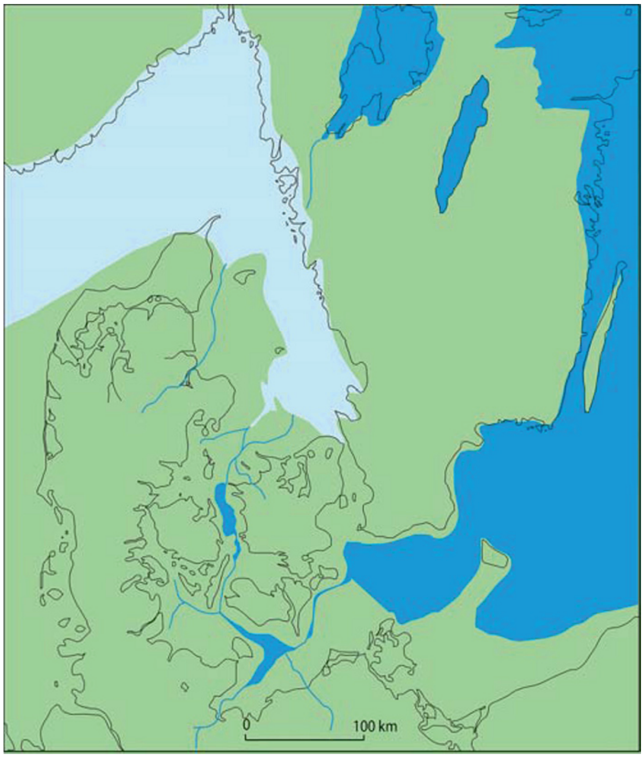

Fig. A.22. The configuration of the Ancylus Lake just prior to the first minor saline ingression at about 10,000 cal yr BP. In comparison with Fig. A.21, note the regressive shore line as a consequence of both isostatic uplift and the lowering caused by the Ancylus drainage. Also note that Lake Vänern was no longer a part of the Ancylus Lake (from Jensen et al. 2002)

low-lying areas of the Danish–German area, which is also characterized by lose Quaternary deposits. For a long time it has therefore been postulated that the water found its way over Darss Sill, into Mecklenburg Bay, over Fehmarn Belt and finally through the deep Great Belt, between the islands of Själland and Fyn, the so-called Dana River. Parts of the submarine morphology along this path have been interpreted to be a remnant of such an erosive event.

However, recent German and Danish studies (e.g. Bennike et al. 1998; Jensen et al. 1999; Lemke et al. 1999) partly contradict such a scenario, although Bennike et al. (2004) recently dated river deposits in the Great Belt channel to about 10,200 cal yr BP, surrounded by levée and lake sediments. In fact, a compromise between the rather dramatic picture of the Ancylus drainage presented by Björck (1995) and Novak and Björck (1998) and the calm Danish–German solution may be possible: an initial regression was caused by a few meters of erosion of the Darss Sill and possibly also in the Great Belt channel lowering the Baltic by up to 5 m. This was followed by a fairly calm fluvial phase; the gradient between the Kattegatt sea level and the *Ancylus Lake* level was only perhaps 5 m. As the region was now characterized by a rising sea level/base level this gradient decreased and conditions gradually became even calmer. We also know that the area outside the mouth of the Great Belt channel in Kattegatt at this time was not characterised by marine conditions, but was very influenced by freshwater (Bennike et al. 2004). Since the uplift of the area had more or less ceased, conditions were now controlled by the rapidly rising sea level (2–2.5 cm/yr). It would therefore last only 200–300 years before sea level was at level with the *Ancylus Lake*, i.e. at about 10,000 cal yr BP (Fig. A.22).

The transitional stage between the freshwater of the *Ancylus Lake* and the following brackish-marine *Littorina Sea* (named after the marine gastropod *Littorina littorea*), named the Early Littorina Sea by Andrén et al. (2000), is also partly an enigma. The first signs of marine influence have usually been seen in sediments with an age of about 9,000 cal yr BP, usually in the southern Baltic area. This is also in accordance with the time when we think that the Öresund Strait was flooded by the global marine transgression; at that time the sea level rise had exceeded the uplift rate in South Sweden. Therefore the younger limit of the *Ancylus Lake*, has often been set at about 8,500 cal yr BP, although geologists have been aware that the transition into the *Littorina Sea* is complex; the end of this transition stage has occasionally been named the Mastogloia Sea.

Lately, however, data from the Bornholm Basin and the archipelago of Blekinge in southeastern Sweden imply that the first saline influence may have occurred already at about 9,800 cal yr BP (Andrén et al. 2000; Berglund et al. 2005). This indicates that saline water from Kattegatt, through the Great Belt–Fehmarn–Mecklenburg–Darss channel, could occasionally penetrate into the Baltic fairly soon after the point in time when the rising sea level began to rise the Baltic level. However, this narrow and long outlet never did allow large amounts of salt water into the Baltic. It would take another 1,500 years before a real marine influence was felt inside the Baltic; then sea level had finally reached up to the Öresund threshold between Limhamn and Dragør and a wide outlet/inlet area was created.

The Littorina Sea

If we disregard some of the uncertainties about the initial outlet/inlet area during the Ancylus-Littorina transition, we can at least clearly document a rapid spread of saline influence throughout the Baltic basin around 8,500 cal yr BP. When the first clear signs of marine water appear, usually defining the onset of the *Littorina Sea* in the related sediments, this is also usually reflected in the sediment composition as an increased organic content. This implies that with the increased saline influence the aquatic primary productivity clearly increased in the Baltic. In the beginning of this phase salinities were very low in the north, but between 8,500–7,500 cal yr BP the first and possibly most significant *Littorina* transgression set in.

The reason that the southern Baltic, up to approximately the Stockholm–south Finland area, would experience transgressions during the forthcoming 2,500–3,000 years was that isostasy in this whole region was less rapid than the ongoing sea level rise. While the causes for most of the separate *Littorina* transgressions can possibly be related to sudden collapses of the Antarctic Ice Sheet and its huge ice shelves, the more or less steadily rising sea level until 6,000 cal yr BP was mainly an effect of the still melting North American ice sheets. At this point in time the last remnants of the Labrador Ice Sheet melted.

During the first three successive *Littorina* transgressions the water depths increased considerably (Berglund et al. 2005) in the, at the time, two functioning inlets, Öresund and Great Belt. The extent of these transgressions was in the order of at least 10 m in the inlet areas, with a large increase in water depth at any critical sill. In turn, this allowed a significant increase in the amount of inflowing saline water into the Baltic, with higher salinities as an important consequence. The increasing salinity, in combination with the warmer climate of the mid-Holocene, generated a fairly different aquatic environment, compared to before.

In terms of richness and diversity of life, and therefore also primary productivity, the biological culmination of the Baltic Sea was possibly reached between 7,500–6,000 cal yr BP (Fig. A.23). The high productivity, in combination with increased stratification due to high salinities in the bottom water, caused anoxic conditions in the deeper (> 100 m) parts of the Baltic Sea (Sohlenius et al. 2001), especially in the central and northern parts with its larger distance to ‘fresh’ oxygenated Atlantic water.

A turning point in the Baltic development can be seen after about 6,000 cal yr BP: the transgressive trend is broken around a large part of the Baltic coastline, although minor transgressions may have occurred until about 5,000 cal yr BP. While sea level had, generally speaking, ceased to rise, the uplift pattern in the Baltic area was complex. In the southernmost Baltic area the submergence continued, which meant that the transgression rate became less extensive than during peak Littorina time. In Sweden and along the coast from northern Lithuania and northwards uplift was still going on, which meant that the end of sea level rise resulted in a renewed regression. The regression caused shallower sills, which meant that a gradually less amount of marine water could enter the basin. Since the main sill areas, Öresund and Great Belt, are situated today around the isobase −0.4 mm/y (Ekman 1996), it implies that this shallowing ended perhaps a few hundred years ago. Since then the inlet areas have become slightly deeper, causing more inflow of Atlantic waters. Another consequence of the differential

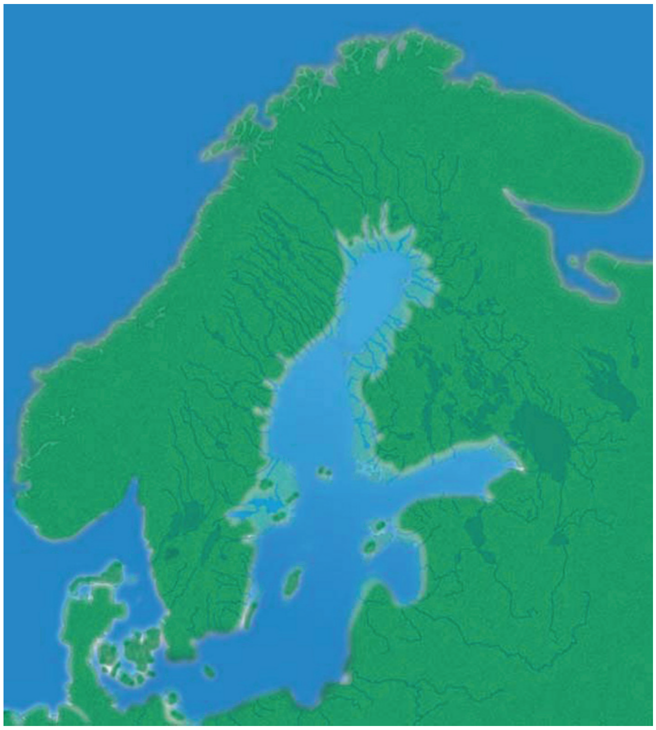

Fig. A.23. The Littorina Sea stage at about 7,000 cal yr BP. Note the wide straits in the south and the still much remaining uplift in the north, especially conspicuous in lowland areas (from Andrén 2004, by courtesy of Stockholm Marine Research Centre)

uplift is that a large part of the Baltic is rising, causing a shallowing effect, and a small part is sinking. If we are worried about a future reduced circulation/ventilation in the Baltic, it is fortunate, at least in the long-time perspective, that the deepest parts of the basin are situated in areas with fairly high uplift rates.

Generally speaking, the Baltic sediments tell us that since peak *Littorina* time, some 6,000 years ago, salinities in the Baltic Sea have gone down. Three possible reasons for this decline can be postulated: less inflow of Atlantic waters from Skagerrak/Kattegatt, and decreased summer temperatures and increased precipitation in most of the Baltic Sea Basin. All these three factors would by themselves have triggered reduced salinities, and it is very likely that they all are responsible for the long term trend.

According to several independent studies the last millennium of the Baltic Sea seems to have been characterised by at least two phases of high productivity and anoxic bottom conditions, the Medieval Warm Period and the last century, and one period with decreased productivity and oxygenated sediments, the Little Ice Age. Thus, the natural climatic variability seems to be a key player for the Baltic Sea and its often profound changes. Owing to the sudden appearance of the North American soft celled clam *Mya arenaria*, the youngest part of the Baltic Sea history have often been named the Mya Sea; it was thought to have been introduced in the bilges of European trade ships. However, Petersen et al. (1992) dated such clams in Danish coastal deposits and found that they predate Columbus' discovery of America by several hundreds of years. This would be additional evidence that Vikings discovered America before Columbus and that their ships brought this 'stranger' and newcomer into the Baltic Sea environment. This is a good example of how humans have been part of, and often were an important player of the natural environment. Today this is truer than ever.

Acknowledgment

With this article I would like to honor the friend and colleague Wolfram Lemke, who very sadly suddenly passed away when this article was being written.

A.3 Ecosystem Description

A.3.1 Marine Ecosystem

A.3.1.1 *The Seasonal Cycle of the Marine Ecosystems*

Maiju Lehtiniemi

The specific characteristics of the Baltic Sea, its shallowness, brackish water and partial ice cover during winter, form a rather unique environment for the biota living in the sea. In addition, changes in salinity from south (almost seawater salinity) to north and east (near freshwater salinity) regulate effectively the distribution of fauna and flora of low diversity. Permanent stratification, i.e. a halocline based on salinity differences between surface and deep water, prevails in most of the Baltic Sea affecting the distribution of fauna. Water exchange is restricted under the halocline, and thus bottom oxygen is often depleted, affecting animals living in benthic habitats (Matthäus 1995). The Baltic biota is a mixture of marine and freshwater species with some genuine brackish water species (Remane 1934). In addition to native species, the Baltic Sea hosts about 100 nonindigenous species, more than half of which have established reproducing populations (Leppäkoski et al. 2002). The ecosystem changes along latitudes and becomes simpler towards the north.

The location of the Baltic Sea at high latitudes affects the whole ecosystem through seasonality. Temperature and light conditions fluctuate along the seasons, which regulate primary production and the length of the growing period, which becomes much shorter from the southern to the northern Baltic Sea. Annual ice cover in the northern parts, which shows large year-to-year variations, requires special adaptations from all organisms.

Most of the invertebrates are specialised to live in either littoral, pelagic or benthic habitats, each of which forms a distinct environment. However, food chains often overlap and these interrelated food chains are part of the broader food web. Certain invertebrates, like mysid shrimps, utilise effectively different systems, enhancing the energy transfer between them. In addition, fish, birds and mammals migrate/move regularly between different subsystems utilising them as feeding, wintering or spawning habitats. Millions of Arctic birds (water birds, geese, divers) migrate through the Baltic Sea Basin twice a year on their migration between Siberia and Europe. Hundreds of thousands of them also overwinter in the Baltic Sea Basin, while most of the birds breeding in the Baltic Sea Basin, overwinter outside the area. Some of them, like Arctic Tern (*Sterna paradisaea* Pontoppidan), overwinter as far as on the Antarctic Ocean.

Spring Period – Intensive Primary Production and Reproduction

Primary production and growth increase rapidly during spring when enough light reaches the surface waters, in the northern parts after the ice break-up. Nutrients stored in the water column during winter are effectively utilised by the spring bloom, which is mainly dominated by chain forming diatoms and dinoflagellates (Edler 1979; Larsson et al. 1986). The highest biomasses are commonly reached after a weak thermocline has developed, which gives rise to a warmer well-lit surface layer. The development of thermal stratification prevents mixing with deeper water layers and thus suppresses cell losses from the euphotic layer and gives the phytoplankton better survival opportunities.

The spring bloom declines after most of the nitrate and phosphate are consumed from the water layer above the thermocline. After the bloom, most of the organic matter produced sinks out of the euphotic layer to the bottom because grazer numbers are still very low (Lignell et al. 1993). The most abundant species in the zooplankton community, which forms the next trophic level (Fig. A.24), are microprotozoans that have their maximum densities soon after the peak of the phytoplankton bloom (Kivi 1986; Johansson et al. 2004) and a few species of copepods and rotifers (Viitasalo et al. 1995; Möllmann et al. 2000).

The sedimenting organic material forms the main energy source for benthic secondary production (Kuparinen et al. 1984). The heterotrophic benthic community is coupled to the pelagic and littoral systems through the seasonal pulse of sedimenting organic material. Suspension feeders like barnacles (*Balanus improvisus* Darwin) and blue mussels (*Mytilus edulis* L.) on hard substrates or algae, and amphipods (*Monoporeia affinis* Lindström, *Pontoporeia femorata* Kröyer), isopods (*Saduria entomon* L.), bivalves (*Macoma balthica* L.) and polychaetes (e.g. *Harmothoe sarsi* Kinberg, *Marenzelleria viridis* Verrill, *Scoloplos armiger* O.F. Müller) in/on the sed-

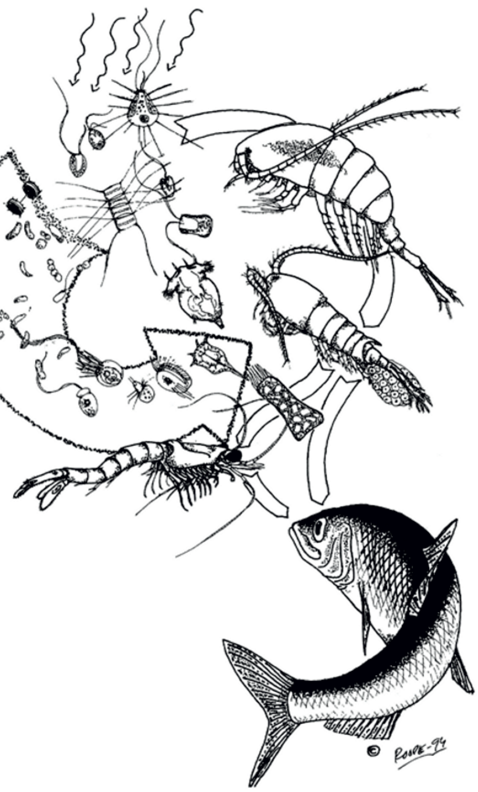

Fig. A.24. Baltic Sea pelagic food web, grazing chain on the right and microbial loop on the left. The grazing chain prevails mainly under turbulent nutrient-rich circumstances e.g. during bloom periods (Kiørboe 1993) while the microbial loop dominates during summer in stratified conditions (Uitto et al. 1997) (from Vuorinen 1994, figure by Juha Flinkman)

iment utilise the sinking organic material effectively. Mysid shrimps (*Mysis mixta* Lilljeborg, *M. relicta* Lovén), which are nektobenthic crustaceans, feed omnivorously on abundant phytoplankton and detritus and start to release their young after the spring bloom (Salemaa et al. 1986; Rudstam and Hansson 1990; Viherluoto et al. 2000). Also, many other invertebrates in the littoral (e.g. *Jaera* sp. and prawns) and benthic habitats (e.g. *M. affinis*) release their young after the spring bloom (Segerstråle 1950). Zooplanktivorous fish like Baltic herring (*Clupea harengus membras* L.) and sprat (*Sprattus sprattus* L.) increase their feeding, which concentrates mainly on large copepods (Fig. A.24; Möllmann et al. 2004). Salmon smolts (*Salmo salar* L.) migrate from spawning rivers to the coastal sea areas to feed on insects and invertebrates (Jutila and Toivonen 1985).

Spring is the most active spawning time for Baltic fish. Sprat and cod (*Gadus morhua* L.) live their whole life in the pelagial. They do not need coastal waters, even at spawning, because their eggs and larvae are buoyant and thus survive in the pelagial (Nissling and Westin 1991). Shallow coastal areas are, however, favoured spawning grounds of many littoral and pelagic fish species. For example herring, perch (*Perca fluviatilis* L.), roach (*Rutilus rutilus* Berg), pike (*Esox lucius* L.) and gobies (e.g. *Pomatochistus* spp.) lay eggs on gravel or among macroalgae and macrophytes, which start their active growing period after winter. The littoral zone provides fish larvae with shelter, a diverse food supply and, thus, a good start for future growth (Urho 2002). Littoral areas are characterised by clear zonation, which gradually changes from land to outer archipelagos and the pelagial.

In the northern Baltic, shallow bays with stands of *Phragmites australis* (Cav.) and Charophytes are dominated by limnic fauna, while outer areas with rocky shores covered with green and brown algal belts are inhabited by brackish and marine species of invertebrates and fish (Kautsky 1995; Munsterhjelm 1997). The southern and southeastern shores greatly differ, with sandy beaches turning into pelagial without the zone of archipelagos.

Early Summer Period – Secondary Production Increases

After the spring bloom phytoplankton production, which is at a low production stage, is maintained by recycling of ammonia and phosphate. The efficiency of the nutrient recycling is regulated by temperature, excretion of zooplankton and bacterial metabolism. The time of low primary production occurs in June–July but the timing varies spatially and between years. The dominant species are pico- and nanoplankton, which have a high turnover rate (Niemi 1975). At this time the main pathway for energy transfer from primary producers to top predators starts with the microbial loop (Fig. A.24; Azam et al. 1983; Uitto et al. 1997). It is a micro-food chain that works within (or along side) the classical food chain. In the microbial loop the smallest organisms, heterotrophic bacteria and picoplankton, use dissolved organic material (DOM) excreted by phytoplankton as carbon and energy sources. When these bacteria are later eaten by micrograzers such as flagellates and ciliates, the formerly "lost" carbon and energy are recycled back into the food web. After this the process continues up the classical food chain, energy is finally transferred up to fish, birds and seals.

Although each stage in the microbial food web involves consumption of organic matter, it also releases ammonium and phosphate into the water. These recycled nutrients can be taken up by algae, stimulating additional primary production (Azam et al. 1983). At this time zooplankton reproduces and biomass increases to its maximum regulating effectively primary production (Uitto et al. 1997). The zooplankton community is diverse, consisting of surface dwelling rotifers, cladocerans and copepod nauplii, and migrating copepods and larger cladocerans (Ackefors 1969; Viitasalo et al. 1995; Möllmann et al. 2000). Rotifers and cladocerans reproduce very rapidly, building up high densities due to parthenogenetic reproduction. Sinking organic matter is minimal, which increases intra- and interspecific competition among species of zoobenthos feeding on organic detritus (Lehtonen 1997). Mysids feed mainly on abundant zooplankton during their vertical migrations from the bottom to upper water column (Fig. A.24; Rudstam and Hansson 1990; Viherluoto et al. 2000).

Late Summer Period

During late summer, primary production again increases due to dinoflagellates (Kononen et al. 2003) and nitrogen-fixing cyanobacteria, which form large surface blooms all around the Baltic (Kuparinen et al. 1984; Kahru et al. 1994). Mass-occurrences are formed in warm water and calm weather conditions (Kononen et al. 1996). The optimum temperatures for cyanobacteria growth are higher than those of diatoms and green algae partly explaining their dominance during late summer (Robarts and Zohary 1987).

Organic matter produced by a cyanobacteria bloom is largely mineralised and consumed by zooplankton during the bloom's growth period, thus the sedimentation rate stays low (Kuparinen et al. 1984). The decaying bloom favours the growth of various bacteria, which may be consumed by ciliates, which further can be consumed by mesozooplankton (Engström-Öst et al. 2002). Thus, a decaying bloom may offer a good food source for the zooplankton community, although actively growing cyanobacteria are considered low quality food (Sellner et al. 1996).

The zooplankton community is still diverse, copepods and cladocerans being the dominant members. The most abundant species include surface dwelling cladocerans *Bosmina longispina* Leydig, *Podon spp.* and *Evadne nordmanni* Lovén and copepods *Acartia spp.* (mainly *A. bifilosa* Giesbrecht), *Eurytemora affinis* Poppe, neritic copepods *Pseudocalanus elongatus* Boeck, *Temora longicornis* Müller and *Centropages hamatus* Lilljeborg (Ackefors 1969; Viitasalo et al. 1995; Möllmann et al. 2000). Pelagic larvae of bivalves, gastropods and polychaetes also appear in the zooplankton community. The zooplanktivorous medusa *Aurelia aurita* L. is very abundant, although year-to-year variations are high. During the warm water period, a recent invasive predatory cladoceran *Cercopagis pengoi* Ostroumov, builds up dense populations rapidly by parthenogenetic reproduction. Herring, sprat and three-spined sticklebacks have included this cladoceran as a part of their diet (Gorokhova et al. 2004; Peltonen et al. 2004). Fishes have their most active growing period. Young–of–the–year fish have to attain a certain length to be able to survive over their first winter.

Autumn – Primary and Secondary Production Decline

After summer temperature decreases and the thermocline breaks down during autumnal turnover, mixing of the water column extends below the critical depth for net production. Primary as well as secondary production by zooplankton decrease due to water mixing, decreasing temperature and light intensity. Zooplankton biomass is partly reduced through intensive predation by Baltic herring, sprat and mysid shrimps (Hansson et al. 1990). Mysids and amphipods increase in the diet of herring, while sprat stays strictly zooplanktivorous (e.g. Möllmann et al. 2004).

Winter Period – Low Production and Activity

During winter, primary production is negligible in the water at the open sea areas, especially in the northern parts where ice cover prevents light penetration to the water. However, many species of phytoplankton, of which diatoms are dominant, occur in the ice (Ikävalko and Thomsen 1997). The biomass and species diversity of zooplankton are at their lowest. Rotifers and cladocerans winter mostly as resting eggs, which sink to the bottom, and copepods as different life stages or resting eggs (Viitasalo and Katajisto 1994; Werner and Auel 2004). However, rotifers and copepods are also found living in the ice as a part of the wintering community (Werner and Auel 2004). The zooplankton community is thus mainly formed of copepods with spatially varying dominant species and the appendicularian *Fritillaria borealis* Lohmann (Schneider 1990). During winter, copepods allocate energy mainly for maintenance, while reproduction starts later in spring. Mysids and amphipods overwinter as females carrying their young in the brood pouch (Segerstråle 1950, Salemaa et al. 1986). Fishes migrate to deeper areas also from the littoral habitats, which are characterised by perennial macrophytes (*Fucus vesiculosus* L., *Ascophyllum nodosum* (L.) Le Jolis, *Zostera marina* L.) that maintain visible canopies through winter. The activity level of fish during winter is usually low but species specific. Exceptionally active of the fish fauna is burbot (*Lota lota* Oken), which feeds actively and spawns during winter (Scott and Crossman 1973).

A.3.1.2 *External Input*

A.3.1.2.1 Atmospheric Load

Mikhail Sofiev

This section provides an overview of atmospheric input of anthropogenic pollutants into the Baltic Sea ecosystem. The atmospheric pathway is significant for two large groups of pollutants: nutrients (nitrogen oxide, ammonia and, to a much less extent, phosphorus), and toxic species, such as heavy metals (HMs) and persistent organic pollutants (POPs). Additionally, sulphur oxides contribute to acidification of the Baltic Sea Basin and tropospheric ozone adds to the load on vegetation.

The issues connected with availability and quality of modelled and measurement data are outlined in Annex 4.5.

Acidifying Compounds (Oxidised and Reduced Nitrogen, Sulphur Oxides)

According to the EMEP (European Monitoring and Evaluation Program) computations with the Lagrangian model (Bartnicki et al. 2002), the total deposition of the oxidised nitrogen onto the sea surface is fairly stable in time and amounts to 146 kton year^{-1} (see Table A.3), (Bartnicki et al. 2002, 2003, 2004; EMEP 2000, 2003, 2004, 2006). The corresponding value reported by the Eulerian model (Bartnicki et al. 2003, 2004, 2006) is 115–130 kton year^{-1}. The values for ammonium differ more strongly: 153 and 98 kton year^{-1}, respectively. Standard deviations of the values are about 10% for oxidised and 15% for reduced nitrogen for both models. A slight downward trend as visible but its absolute value is small.

The deposition of nitrogen oxides to the catchment area in 2002 (Bartnicki et al. 2004) was ~ 1.2 Mton N year^{-1}, with uneven distribution between the sub-basins (Table A.4).

To evaluate the load onto the ecosystems of the catchment area, more appropriate characteristics are the deposition density (Fig. A.25) and its exceedances over the critical load values for acidification (Fig. A.26) and nutrient nitrogen (Fig. A.27). The deposition density largely varies from south to north (about an order of magnitude for both sulphur and nitrogen compounds), also being subject to noticeable multi-annual variability. In some areas, the difference between the annual concentrations and depositions for two sequential years can be as much as 20–30% according to Bartnicki et al

Table A.3. Multi-annual deposition of pollutants onto the Baltic Sea surface (kton N year^{-1}). L denotes results from the EMEP Lagrangian, and E for the Eulerian model

	1996L	1997L	1998L	1999L	2000L	2000E	2001E	2002E	Aver.L	Aver.E
NO_x Kton N	140	138	158	150	145	147	128	113	146	129
NH_x Kton N	148	129	168	150	171	115	96	83	153	98
N total. Kton N	288	267	326	300	316	262	224	196	299	227

Table A.4. Total nitrogen deposition onto the Baltic Sea catchment in 2002

N total, Kton N/year	
Gulf of Bothnia Catchment	137
Gulf of Finland Catchment	164
Gulf of Riga Catchment	97
Baltic Proper Catchment	698
Belt Sea Catchment	54
Kattegat Catchment	83
Baltic Sea Catchment	1233

(2004, 2006). With regard to deposition variability, the precipitation amount and its distribution between the seasons plays one a major role.

For exceedances of acidification (Fig. A.26), the downward trend is stronger – mainly due to reduction of sulphur emission and, consequently, deposition during the last 20 years.

Comparison with HELCOM observations reveals some spatial tendencies in the models' quality, which can be used to adjust the above estimates or at least evaluate their uncertainty.

For the Lagrangian model, comparison with measurements shows a spatially stochastic pattern but with an indication that the model overstates the deposition values for all years. The computed wet deposition is higher than the measured one for 9 to 10 out of 14 HELCOM stations for both NO_x and NH_x. The extent of over-estimation varies but can be as much as a factor of 2 to 3 for some specific stations and years. Therefore, the overall load is probably also over-estimated.

For the Eulerian model, comparison for 2002 shows that for most of southern Baltic Sae stations (DK5, DK8, DE9, EE9, PL4, SE11) the concentrations of both oxidised and reduced nitrogen in precipitation are overstated by the model by 20–50%. Such over-estimation is not visible for northern stations, which are located in less polluted areas. There is no such tendency for concentrations in air, which generally demonstrate a good agreement with observed levels.

There can be two reasons for such a trend: spatially inhomogeneous quality of precipitation information and some nuances in parameterisation of scavenging. According to the EMEP status report 1/2004 (EMEP 2004), accumulated precipitation amount does not have a pronounced bias (although the difference for some stations can exceed a factor of 2). It is therefore possible to suggest that the Eulerian model over-estimates by $\sim 20\%$ the deposition onto the most-polluted sub-basins of the Baltic Sea (Kattegat, Belt Sea, Gulf of Riga, southern-most part of the Baltic Proper) and is on average unbiased for the other sub-basins. Due to comparatively small areas with such overestimation (Kattegat, Belt Sea and Gulf of Riga combined take $\sim 20\%$ of the total deposition onto the sea surface), the overall over-estimation can hardly be more than 5%. Comparison for 2001 leads to an even smaller number.

Within the scope of the EU project Baltic Sea System Study (BASYS) and a follow-up research, similar-type modelling assessments were made using a semi-independent Eulerian model HILATAR (Hongisto et al. 2003; Hongisto and Joffre 2005). This model, accepting the EMEP chemistry module, emission totals and, for part of the simulations, boundary conditions from the EMEP Lagrangian model, used a different advection method, meteorological data and own time variation of emission. The results appeared to be quite similar (Table A.5): mean total nitrogen de-

Table A.5. Results of a semi-independent model study within the BASYS project

	1993	1994	1995	1996	1997	1998	2000	2001	2002	Average
NO_x Kton N	175	169	150	144	139	179				159
NH_x Kton N	115	103	105	114	99	117				109
N total. Kton N	290	272	255	258	238	296	274	263	224	268

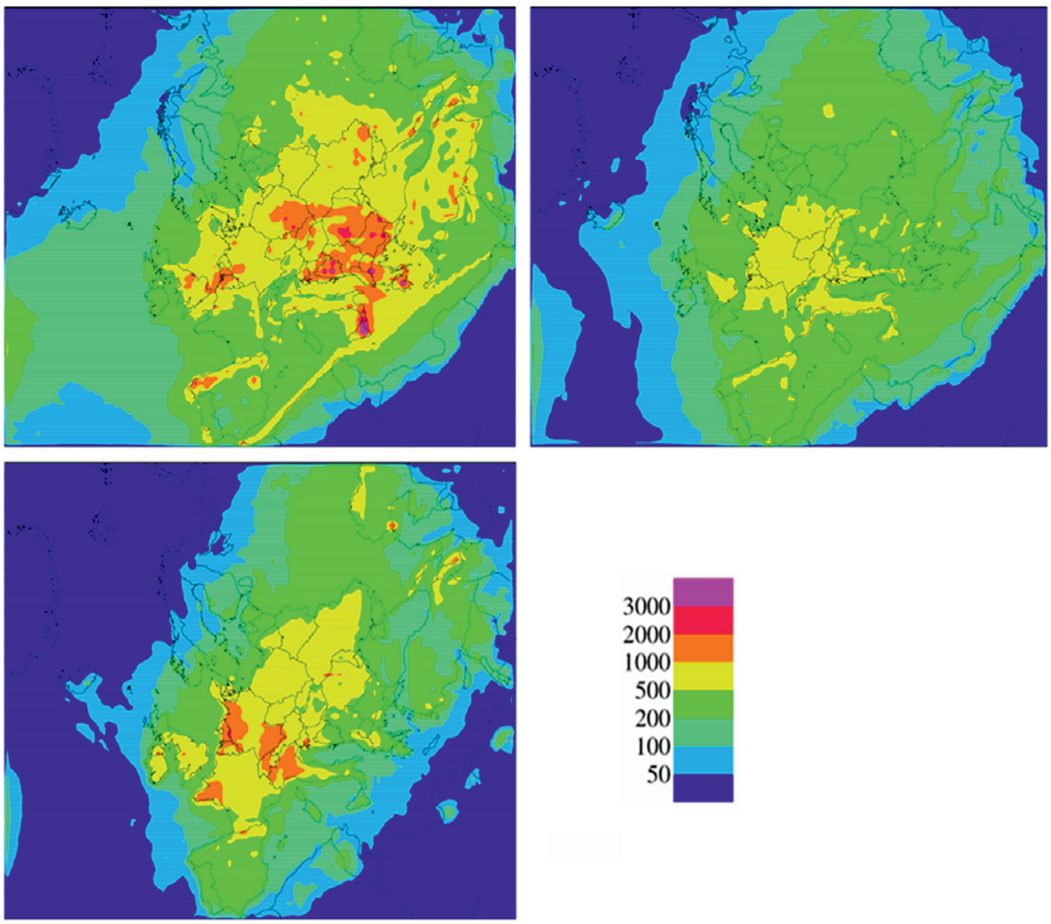

Fig. A.25. Map of total sulphur (*upper left*), oxidised nitrogen (*upper right*) and reduced nitrogen (*lower*) deposition in 2004. Unit is (mg S/N m^{-2} $year^{-1}$) (from EMEP 2006)

position of 263 ktons $year^{-1}$ for the period 1993–2002. The values are in between the results of the EMEP Eulerian and Lagrangian models, with NO_x load being almost exactly on the half-way and NH_x staying closer to the Eulerian model results.

Regarding the deposition density, the estimates for 1993–1998 showed practically the same mean value for sulphur oxides (for the Polish coastline, the HILATAR model showed about 1 g S m^{-2} $year^{-1}$) but somewhat higher nitrogen values (total nitrogen amounted to 1.2–1.4 g N m^{-2} $year^{-1}$). The standard deviations of the monthly deposition values were 30–40% with a tendency to grow towards the north. The comparison with measurements showed a limited overestimation of the NO_x wet deposition by HILATAR, while the ammonia fluxes are practically unbiased.

Another model-based estimate of Hertel et al. (2003) for 1999 resulted in slightly over 300 ktons N $year^{-1}$ of total nitrogen deposited onto

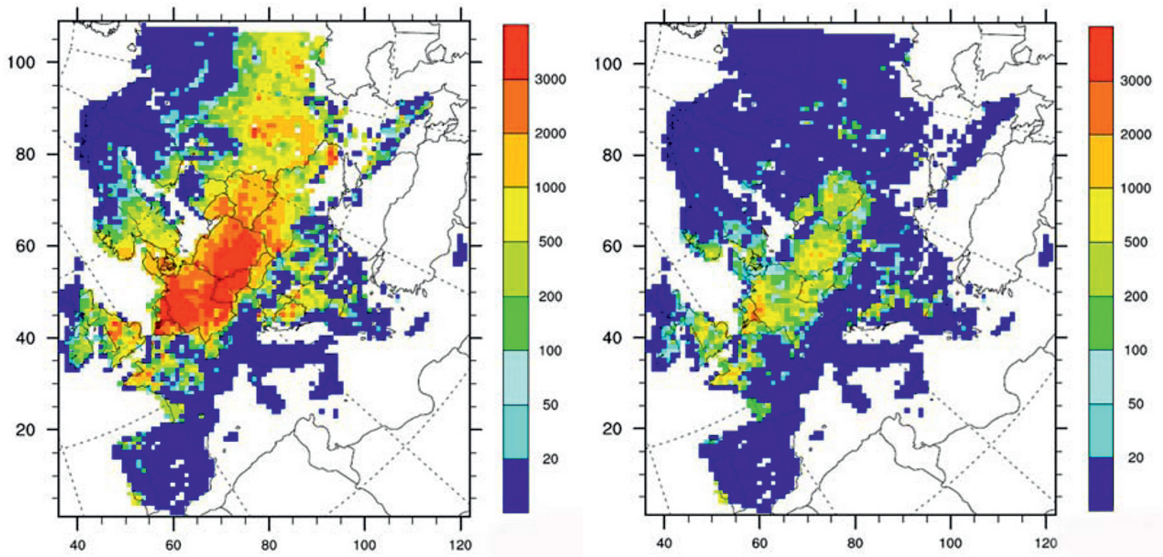

Fig. A.26. Maps of critical loads exceedances for acidification computed for 1990 (*left*) and 2004 (*right*). Unit is (equivalent ha^{-1} $year^{-1}$) (from EMEP 2006)

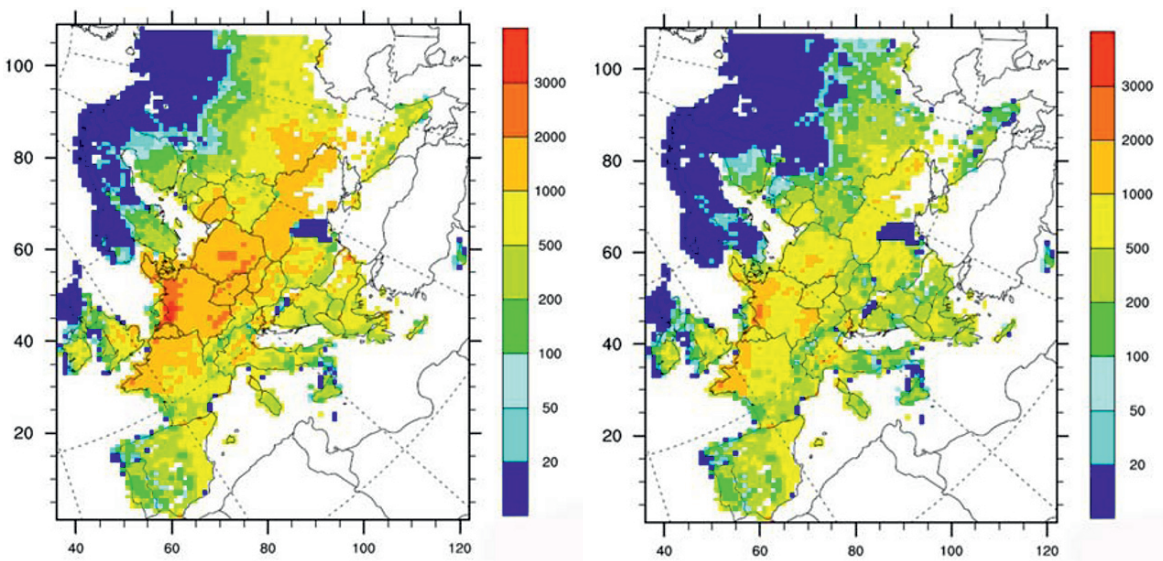

Fig. A.27. Maps of critical loads exceedance for nutrient nitrogen computed for 1990 (*left*) and 2004 (*right*). Unit is (equivalent ha^{-1} $year^{-1}$) (from EMEP 2006)

the sea surface. The results were obtained with the backward Lagrangian model, which is similar to the old EMEP model.

None of the long-term studies found a significant trend in nitrogen depositions, which allows consideration of some older works (with certain care due to still possible long-term trends and lower reliability of historical results). Thus, Dedkova et al. (1993) gave the preliminary values of total nitrogen deposition onto the sea surface as varying from 298 up to 343 ktons N $year^{-1}$. The load was computed for the period 1987–1991.

Another work of Lindfors et al. (1993) combined the extrapolated observations of wet deposition and model computations of dry deposition, resulting in over 400 ktons N $year^{-1}$ and

1.4–1.9 g N m^{-2} year^{-1} for total nitrogen deposition at the southern Baltic coast (average over 7 years 1980–1986). The total deposition onto the sea surface, however, can be challenged due to unclear representativeness of coastal deposition measurements offshore.

The deposition of 0.5 g N m^{-2} year^{-1} of oxidised nitrogen at the southern Baltic coast was also reported by MATCH model computations (Laurila et al. 2004). That work has also considered potential developments of the situation in the future climate and predicted small and irregular changes in the pattern – the difference of the deposition values computed for various emission and climate scenarios from the reference estimates was mainly within 10%.

Studies of Sofiev and Grigoryan (1996) and Sofiev et al. (1996) gave the values at the Polish coast of 0.6–0.7 mg N m^{-2} year^{-1} for oxidised and 0.5 mg N m^{-2} year^{-1} for reduced nitrogen. The estimates were computed by three different versions of an independent model for the period 1991–94 and appeared quite coherent.

It is seen that the results of the EMEP Lagrangian model and decade-old independent assessments are quite close to each other, while the Eulerian-model is closer to more modern applications.

The following can therefore be concluded:

(i) Annual total deposition of oxidised nitrogen onto the Baltic Sea surface is 125 ± 20 kton N year^{-1} (a standard deviation range); for ammonia this estimate is 100 ± 16 kton N year^{-1};

(ii) The deposition density varies from 0.5–0.6 g N m^{-2} year^{-1} at the southern coast down to about 0.05 g N m^{-2} year^{-1} in the north – for both oxidised and reduced nitrogen (though ammonia trend is more pronounced). For oxidised sulphur compounds the present-time values are $\sim$ 1 g S m^{-2} year^{-1} and 0.1 g S m^{-2} year^{-1}, respectively;

(iii) Inter-annual variability is comparatively small and has a standard deviation of 10–15%, thus accounting for the most of above uncertainty range;

(iv) No statistically significant trend for nitrogen oxides was observed by the above studies, while sulphur emission and deposition have strongly decreased;

Table A.6. A share of deposition obtained by each sub-basin of the Baltic Sea

	NO_x	NH_x
Belt Sea	8	14
Kattegat	8	10
Baltic Proper	58	54
Gulf of Riga	4	4
Gulf of Finland	6	4
Gulf of Botnia	16	13

(v) A large spatial gradient of depositions is noticed by all computations. The typical distribution of deposition to the sea sub-basins is presented in Table A.6

Tropospheric Ozone

There are several European models regularly computing the ozone level and its exceedance of the thresholds. The model formulations and their results were extensively compared with each other, which allowed to derive consensus-based assessments of the present ozone level and its importance for the Baltic Sea Basin (e.g. Roemer et al. 2003; Hass et al. 2003; Laurila et al. 2004; Zlatev et al. 2002).

It is generally agreed that a high ozone level during the vegetation season is not yet a matter of primary concern for the Baltic Sea ecosystems, except for the most southwestern areas (Germany and Denmark). It can, however, become more significant in future climate (Laurila et al. 2004). At present, the maximum value for the AOT-40 ozone index (Accumulated Ozone above the Threshold of 40 ppb) reaches 10 ppm-hours only in central Poland and in Germany, which is still several times lower than in the other parts of Europe. However, there are warnings of a possible change of the situation due to warmer climate and increasing emissions. In particular, this problem can become severe if strongly increasing amounts of ozone in other parts of the Northern Hemisphere will be advected towards the region (Derwent et al. 2002).

Toxic Species

Information about the toxic species is much less precise than that for nitrogen – both from observational and from modelling points of view. All data can be criticised for problems with quality and reli-

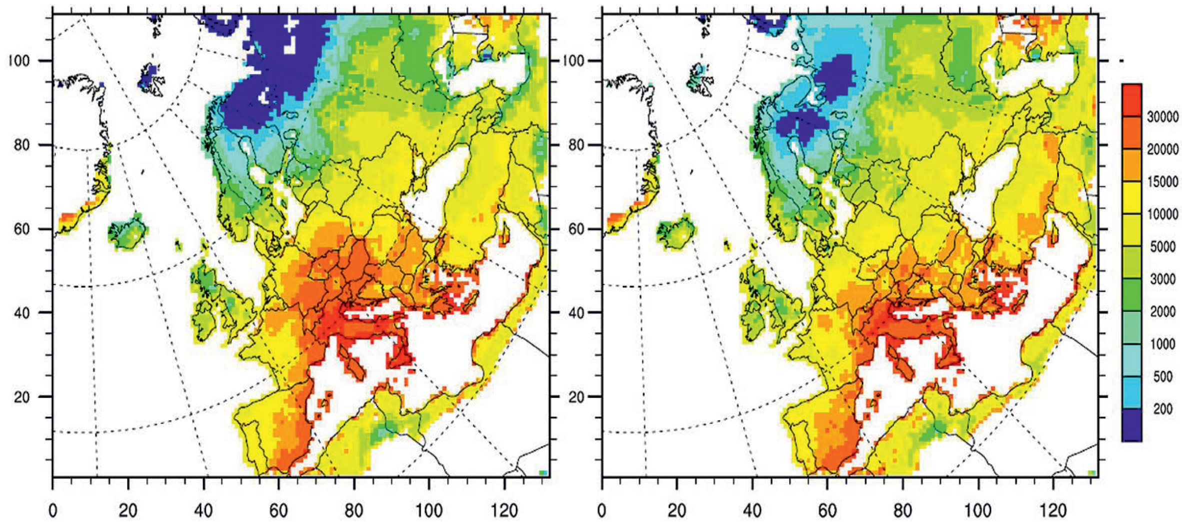

Fig. A.28. AOT-40 as computed by the EMEP model at the canopy level for the years 2000 (*left*) and 2004 (*right*). Note the new threshold of 5000 ppb-hours. Unit = ppb-hour (from EMEP 2006)

ability. and their mutual agreement usually leaves a large area for improvement. The emission of some toxic species is believed to have a strong reduction trend, so historical data cannot be taken into account without the trend correction. There is also an uncertainty in the absolute emission levels, especially for organic pollutants. As a result, historical and recent assessments based on models and measurements show large differences.

One of the ways to improve the load estimates by reducing at least the mean bias is to scale the modelled patterns with the relative bias of the wet deposition or concentration in precipitation. The resulting pattern would keep the simulated spatial distribution and simultaneously be non-biased (in average) from the available measurements. This method is crude and does not eliminate errors in observations and in spatial distributions of the load. However, the measurement-scaled patterns contain fewer problems than the original ones, which sometimes manifest a systematic deviation from observations by a factor of 3 to 10.

Trace Metals: Lead (Pb) and Cadmium (Cd)

Computations of EMEP for Lead (Pb) and Cadmium (Cd) (Bartnicki et al. 2002, 2003, 2004, 2005, 2006), as well as other comparatively recent results are summarised in Table A.7. Depositions of Pb and Cd onto the catchment area of the Baltic Sea are summarised in Table A.8

The deposition flux in the southern Baltic Sea coast is 0.5–1 mg Pb m^{-2} $year^{-1}$ in 2002 according to Bartnicki et al. (2004, Fig. A.29). The estimates for earlier years, such as Rodhe et al. (1980), HELCOM (1989, 1991, 1997), Duke et al. (1989), Schneider (1993) and Petersen and Krueger (1993) show that the total Pb deposition onto the sea surface ranges from 640 tons $year^{-1}$ (HELCOM 1997, a mean for 1991–1995 computed with emission data for 1990) up to 2400 tons for 1980. The respective deposition flux over the southern coast was about 2.5 mg Pb m^{-2} $year^{-1}$. Due to an uncertain but probably significant trend in Pb emission in the late 1980s and 1990s, these values are of little interest for modern load estimations, but still useful as indicators of uncertainties and past levels. More recent estimates of Sofiev et al. (2001) for 1998 were about 1 mg Pb m^{-2} $year^{-1}$. All results show a factor of 4 to 5 drop of fluxes towards the northern end of the Bothnian Bay.

As seen in Table A.7, there are large differences between the EMEP estimates and independent computations, with the model-measurement comparison favouring the latter ones. The EMEP heavy metal model demonstrated strong and systematic under-estimation of the concentration in precipitation and wet deposition. The recent simulations of Bartnicki et al. (2006), however,

Table A.7. Total deposition of Pb / Cd onto the Baltic Sea surface, tons year^{-1}

Pb/Cd			Measurements / model ratio	
Reference	Year	Total deposition	Range	comments
EMEP 2006	2004	235 / 5.7	?	only comp. charts provided
EMEP 2005	2003	134 / 7.0	1.5–5.7 / 1.6–5.8	comparison in precip.
EMEP 2004	2002	149 / 7.4	1.7–5.5 / 1.4–4.8	
EMEP 2003	2001	143 / 8.3	1.1–4.3 / 0.5–4.1	
Sofiev et al. 2001	1997–98	596, 680 / 9.0, 9.4	0.6–1.2 / 1.2–4.7	2 models; emission 1990
Schneider et al. 2000	1997–98	550 / 33, 18		Observ. extrap., 1/2 methods
HELCOM 1997	1990	640 / 27	0.5–4 / ?	mean 1991–95, compr. 1990

Table A.8. Total deposition of Pb / Cd onto the Baltic Sea Basin, in tons year^{-1}

	EMEP 2003	EMEP 2004
Gulf of Bothnia catchment	144 / 6.9	68 / 2.9
Gulf of Finland catchment	230 / 9.2	184 / 6.5
Gulf of Riga catchment	83 / 4.0	58 / 3.0
Baltic Proper catchment	757 / 52.4	573 / 38.9
Belt Sea catchment	12 / 0.7	18 / 0.8
Kattegat catchment	32 / 1.6	31 / 1.4
Baltic Sea total catchment	1,262 / 74.8	932 / 53.6

demonstrated a sharp increase of Pb (but not Cd) total deposition onto the sea surface in comparison with previous estimates (the input emission values have not changed much). The simulations were also performed retrospectively with a similar outcome: the new model version showed a significantly larger deposition of Pb but kept nearly the same Cd load.

The computations done within the of the EU BASYS project (Sofiev et al. 2001) agreed with the observations quite well and provided a load estimate close to the complementary observation-based assessment of Schneider et al. (2000). The BASYS values are also in good agreement with 640 tons Pb year^{-1} (HELCOM 1997), computed for 1991–95 with the same constant emission of 1990.

However, the simulations covered only 4 months during the years 1997 and 1998. These months included both winter and summer seasons, thus being representative for the whole period, but the extrapolation still increased uncertainty. Secondly, these simulations used the Pb emission data for 1990, thus missing a reduction during the 1990–1997 period. The significance of the latter limitation is unclear because the uncertainty in the absolute level of emission compares well with the reported trend. The validation of that model for 1990 by Sofiev et al. (1996) demonstrated $\sim$ 40% under-estimation of deposition values in comparison with available, albeit limited, observations.

To explain the above contradictions, one can consider the following:

- A systematic underestimation of the Pb emission, which was moderate in 1990 (a factor of $\sim$ 1.4), but practically doubled by 2002, due to an overestimated downward trend;
- Difficulties in the some EMEP heavy metal model versions, resulting in underestimations;
- Processes missing in the most of current models, such as re-suspension of particles after their deposition. This is very difficult to quantify but, according to Bartnicki et al. (2005), its contribution can mount up to 50% of total deposition to some sub-basins.

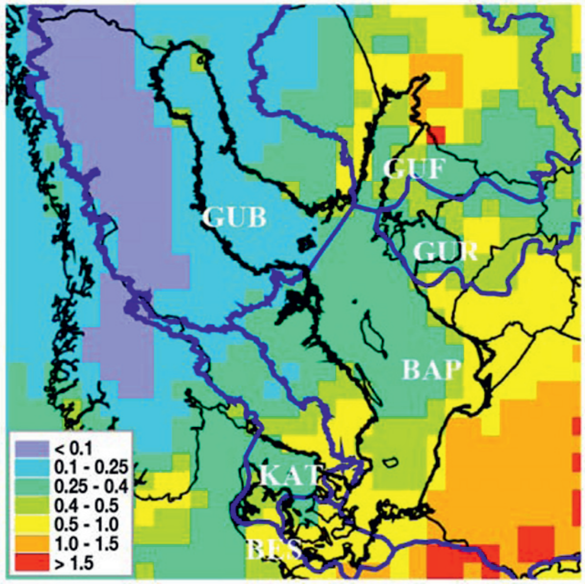

Fig. A.29. Spatial distribution of total lead deposition flux (kg km^{-2} year^{-1}) in the Baltic Sea Basin in 2002 with resolution 50 × 50 km^2 (adapted from Bartnicki et al. 2004)

Evaluation of these considerations requires further investigations.

Based on the above considerations, one can assume that current deposition of Pb onto the Baltic Sea surface accounts for at least 350–400 tons year^{-1} but the uncertainty is large and its origin is not fully clear. The Pb deposition flux at the southern coast does not exceed 1 mg Pb m^{-2} year^{-1}.

The case of Cd is similar to that of Pb: the under-estimation of the current models is a factor of a few times and the differences between the independent estimates are large (Tables A.7 and A.8). There is an agreement between almost all models, except for the old data of HELCOM (1997), for which the model-measurement comparison was not presented. All models show the total load onto the sea surface to be somewhat below 10 tons Cd year^{-1} and a factor of 2 to 3 of underestimation of the wet deposition or concentration in precipitation in comparison with observations. Scaling with this factor leads to the lower of the two observation-based estimates of Schneider et al. (2000).

It is therefore possible to suggest an uncertain emission as the main cause for the underestimation and conclude that the most probable deposition of Cd onto the Baltic Sea surface is about 20 tons year^{-1}. There was no strong trend in the reported Cd emission during last decade.

Mercury (Hg)

Persistent toxic pollutants constitute the most difficult and the most uncertain set of species. Their emission data are typically not very accurate and complete, nor is the knowledge on physical and chemical transformations in the environment. Therefore, the estimates given below only show an order of magnitude of the phenomena.

According to Bartnicki et al. (2004), Petersen et al. (2001) and Munthe et al. (2003), it is possible to suggest that the order of magnitude of Hg deposition onto the Baltic Sea surface is about 3 tons year^{-1}, but the input from the so-called "natural background", usually arbitrarily introduced into the models in order to meet the observations, can constitute over 50% of this value.

The wet deposition flux of all mercury species strongly varies over the region reaching its maximum in Germany – over 5 mg Hg m^{-2} year^{-1} – and falling below 0.1 µg Hg m^{-2} year^{-1} in the northern part of the region (Lee et al. 2001). The dry deposition flux could be a few times larger, mainly due to high dry deposition flux of the reactive Hg species. Munthe et al. (2003), to the contrary, suggested that dry deposition is about 3 to 6 µg Hg m^{-2} year^{-1} all over the region with practically no spatial trends. The estimates of Bartnicki et al. (2004) for the total deposition fluxes vary from over 15 to below 5 µg Hg m^{-2} year^{-1},

Table A.9. Example of the budget of HCH isomers fort the Baltic Sea, in tons year^{-1}

	POPCYCLING model		EMEP
	α–HCH	γ–HCH	γ–HCH
Bothnian Bay	1.7	0.4	
Bothnian Sea	4.3	1.9	−0.2
Gulf of Finland	1.1	0.5	−0.1
Gulf of Riga	−0.5	0.0	−0.08
Baltic Proper	7.5	5.3	−0.7
Danish Straits	0.5	0.4	−0.1
Kattegat	1.3	0.7	−0.08
Baltic Sea	16.0	9.2	−1.26

with a strong decrease from south to north. A possible explanation for the differences can again refer to the model formulations and, in particular, to treatment of the "background level". All three models agree well with the mean air concentrations of elemental mercury (the main observed Hg-related parameter), as well as the few available observations of reactive Hg components.

Persistent Organic Pollutants (POP)

For the persistent organic pollutants, a verified quantitative information for the Baltic Sea Basin is available only for α- and γ-isomers of hexachlorocyclohexane (HCH) and some polychlorinated biphenyls (PCB). Recent simulations, such as those of (Bartnicki et al. 2006), also provide lump estimates for dioxins/furans. The main sources of the information are: regional observations (e.g. HELCOM 1997) for HCH and PCB, the EU POPCYCLING project results (Breivik and Wania 2002) for α- and γ-HCH and the EMEP computations of Bartnicki et al. (2004, 2006) (Table A.9). The POPCYCLING project considered an actual emission development over 30 years (1970–2000) and computed the mean flows (Table A.9). The EMEP POP model was run over 12 years (1990–2002) to reach an equilibrium stage and then the last-year flux was taken as a result.

The HELCOM (1997) measurements of 7 PCB congeners suggest that the mean deposition flux at the Swedish west coast decreased from 0.9 to 0.6 μg PCB-sum m^{-2} year^{-1} during the period from 1980 to 1996. Corresponding values for sum of α– and γ–HCH do not show a clear trend, fluctuating between 1 and 4 μg HCH-sum m^{-2} year^{-1}.

Two of the above models disagree on the directions of the net air-surface flux. The EMEP POP model claimed that the region is a strong source of γ-HCH (Bartnicki et al. 2004): it estimated that between 3.2 to 4.5 tons of γ-HCH go into the air from the catchment area of the Baltic Sea. The POPCYCLING model showed that net volatilization occurs only from agricultural soils in the source areas: the Gulf of Riga for both isomers and the Danish Straits for Lindane. Forest soils are always a strong sink for HCHs and canopy and coastal water compartments are close to equilibrium with overlying air, still being net receptors of HCH. According to Breivik and Wania (2002b) these 30-years mean fluxes are also representative for the latest years, such as 1998–2000, with some correction towards equilibrium between deposition and evaporation.

Validation of both models against measurements was done in a different manner as well. The POPCYLING model was verified against observations in air, water, pine needles and sediments, with a general agreement to be within a factor of 2 to 5 (Breivik and Wania 2002a). The EMEP model output was compared only with concentrations in air (very good agreement – within a factor of 1.5 to 2) and in precipitation (strong underestimation by a factor of 3 to 12). Therefore, the results of the POPCYCLING model are probably more reliable, and they show that, on average, the Baltic Sea is a receptor of the HCH compounds. Over the catchment area of the Baltic Sea, only some agricultural fields serve as net emitters of HCH. Absolute levels are uncertain but do not exceed the values shown in Table A.9.

A.3.1.2.2 Aquaculture and Eutrophication

Marianne Holmer, Lars Håkanson

Aquaculture in the Baltic Sea is a relatively recent activity, which was initiated at larger scales in the late 1970s. In the Baltic Sea, the most important cultured species is rainbow trout, which is grown in net cages anchored to the sea floor in sheltered as well as open areas. Aquaculture is considered an important industry in the coastal zones around the world, supporting the growing demand for marine food products, but in the Baltic Sea marine aquaculture is from a global perspective of rather low importance because of unfavourable biological and economical conditions. Due to low salinities only a few species, such as rainbow trout and some brackish water species, such as pike and perch, are commercially attractive, and shellfish cultures are limited to the Swedish west coast and Danish waters. Whereas aquaculture production increased rapidly in the Baltic Sea during the 1980s, the production levelled out and even declined in most Baltic Sea countries, such as Denmark, Sweden and Finland, in the 1990s due to falling economical benefits caused by competitive imports of salmon, primarily from Norway and by environmental restrictions in some countries, such as Denmark (Håkanson et al. 1988; de Pauw et al. 1989; Mäkinen 1991). Total annual production was somewhat less than 57,000 tons in 2002 (Fig. A.30; FAO 2005).

The industry is now facing new challenges as new species have been successfully cultured under experimental conditions and market prices on fish and shellfish for consumption have increased so much that still more species have become attractive for cultivation. Aquaculture production in the Baltic Sea is expected to increase during the next decade, as several "new" countries in the Baltic Sea Basin are investing in aquaculture (e.g. Estonia), and established countries are expanding through culturing new species (e.g. cod, plaice and oyster) and increasing production of rainbow trout and blue mussels encouraged by increasing market prices. Nevertheless, the overall growth rate in aquaculture is expected to be lower than predicted for other parts of the EU, such as the Mediterranean, where fish farming is increasing very rapidly (GESAMP 2001).

Whereas shellfish culturing is considered to be neutral or even to reduce the eutrophication of the coastal zones (Petersen and Loo 2004), the intensive culturing of finfish on artificial feeds leads to a variety of environmental impacts, including the release of dissolved nutrients which may increase eutrophication of the Baltic Sea (Hall et al. 1990, 1992). Most of the nitrogen-containing waste products are released in the dissolved form (primarily through fish excretion) and may lead to eutrophication events in the water column, whereas the phosphorus compounds are primarily released as particles and settle in the vicinity of the fish farms, contributing to the "footprint" of the farms (Brooks and Mahnken 2003). A Danish survey shows that the release of waste nutrients per kilo produced fish has been reduced by 54% for N and 64% for P, and although the production of fish has been stable since the early 1990s, the total release of N and P has been reduced by 26% and 52% since 1987 (Havbrugsudvalget 2003). A similar trend can be expected for the Baltic Sea due to improvements of feed and feeding practices stimulated by increasing expenses and environmental regulations.

Due to high organic contents of the settling waste products the oxygen demand in the sediments increases and may impact the benthic fauna below the net cages (Håkanson and Boulion 2002). The organic loading of the sediments increases the bacterial activity and regeneration of nutrients back to the water column, and both direct release and regenerated nutrients may thus contribute to eutrophication (Hall et al. 1990, 1992). There have been quite a few environmental studies of single farms, which have been able to show benthic effects, and there are also several studies of water column parameters in the Baltic Sea (Wallin et al. 1992; Nordvarg and Håkanson 2002; Gyllenhammar 2004; Håkanson et al. 2004).

Most fish farms are placed at locations with rapid water renewal, and the nutrients released are diluted to low concentrations within hours of release. As the doubling rates of phytoplankton are in the order of days, blooms of phytoplankton caused by nutrient release from single farms have not been observed. The benthic effects are quite similar to observations from salmon farms, as the feeding practices and general management of the rainbow trout farms are similar to salmon farms (Hall et al. 1990, 1992; Holmer and Kristensen 1992; Brooks and Mahnken 2003), and estimates have shown that the overall nutrient release from fish farms will only decrease by 2% by shifting from rainbow trout to salmon culture, whereas the economical consequences probably will be much larger due to the low prices

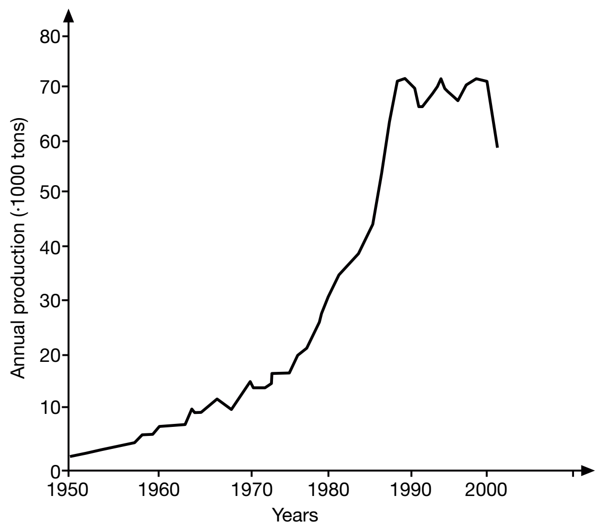

Fig. A.30. Production of rainbow trout (in MT × 1000) in the Baltic States during 1950–2002 (incl. freshwater production) (modified from FAO 2005)

on salmon (Aquaflow 2002). Most farms in the Baltic Sea are relatively small (100–1,000 tons annual production) compared to Atlantic farming (> 500 tons annually), and, as the local impacts among other factors are directly related to loading (Gyllenhammer and Håkanson 2005), local effects in the Baltic Sea are modest compared to the large farms in the Atlantic (Holmer and Kristensen 1992; Christensen et al. 2000).

A review to evaluate how emissions from fish cage farms cause eutrophication effects in coastal areas has just been published (Gyllenhammar and Håkanson 2005). The review focuses on four different scales, (i) the conditions at the site of the farm, (ii) the local scale related to the coastal area where the farm is situated, (iii) the regional scale encompassing many coastal areas, and (iv) the international scale including regional coastal areas (e.g. the Baltic Sea).

The aim was to evaluate the role of the fish farm emissions in a general way, but all selected examples were derived from the Baltic Sea. An important part of this evaluation concerned the method for defining the boundaries of a given coastal area. If this is done arbitrarily, one would obtain arbitrary results in the environmental impact analysis. In this work, the boundary lines between the coast and the sea are drawn using GIS methods (Geographical Information Systems) according to the topographical bottleneck method, which opens a way of determining many fundamental characteristics in the context of mass-balance calculations. In mass-balance modelling, the fluxes from the fish farm should be compared with other fluxes to, within and from coastal areas.

The study concluded that:

1. At the smallest scale (< 1 ha), one can conclude that the "footprint", expressing the impact areas of fish cage farms often corresponds to the size of a "football field" (50–100 m), if the annual fish production is low (about 50 tons).
2. At the local scale (1 ha to 100 km^2), there exists a simple load diagram (effect-load-sensitivity) to relate the environmental response and effects of a specific load from a fish cage farm. This makes it possible to obtain a first estimate of the maximum allowable fish production in a specific coastal area.
3. At the regional scale (100–10,000 km^2), it has been shown that it is possible to create negative nutrient fluxes, i.e. to use fish farming as a method to reduce the nutrient loading to the sea. The breaking point is to use more than about 1.3 g wild fish from the area per gram feed for the cultivated fish.
4. At the international scale ($> 10,000\,km^2$), related to the Baltic proper, the contribution from fish farms to the overall nutrient fluxes is very small. It has been estimated that, in 1989, fish farming accounted for 1.5% of the total phosphorus and 0.4% of total nitrogen loads to the Baltic Sea and Skagerrak (HELCOM 1993). A Danish study has estimated that marine

aquaculture in Denmark contributes with 0.4% and 1.3% of total Danish N and total P loading (including riverine load), respectively (Ærtebjerg et al. 2003). Of the direct point sources, marine aquaculture contributed with 9.2% and 8.1% N and P, respectively, but when the Danish nutrient release from marine aquaculture was compared with the total inputs to the Danish coastal waters from the Baltic Sea, Sweden and Germany it only accounted for 4‰ and 9‰ of the inputs of N and P, respectively (Ærtebjerg et al. 2003). Although the release of nutrients from marine aquaculture only has minor effects on the total budgets, it is important to note that it, together with other sources, contributes to the high loading of the Baltic Sea.

Due to the complexity of marine ecosystems, including spatial and temporal variabilities, complete studies using an ecosystem based approach to examine eutrophication effects of fish farming in the Baltic Sea are difficult and expensive to carry out. Håkanson (2005) used a modelling approach to demonstrate ecosystem effects of fish farm emission. The main questions in this study were: How would emissions of feed spill and faeces from a fish farm influence the production and biomass of key functional organisms and how long would such changes remain if the fish farm is closed down?

The work is based on a comprehensive lake ecosystem model, LakeWeb, which accounts for production, biomass, predation, abiotic/biotic interactions of nine key functional groups of organisms, phytoplankton, bacterioplankton, two types of zooplankton (herbivorous and predatory), two types of fish (prey and predatory), as well as zoobenthos, macrophytes and benthic algae. The LakeWeb model gives seasonal variations (the calculation time is one week), and it has been calibrated and critically tested using empirical data and regressions based on data from many lakes. These tests have demonstrated that the model can capture typical functional and structural patterns in lakes very well, lending credibility to the results, and the model suggests that fish farm emissions cause significant increases in the biomass of wild fish, without corresponding increases in algal volume.

Thus, it is concluded that the fish farm emissions influence the secondary production more markedly than primary production. Although this finding might seem to be a paradox, it is related to the fact that wild fish directly consume food spill and faeces from the fish farm, thereby creating a specific foodweb pathway. Similar findings have been done in the oligotrophic Mediterranean (Dempster et al. 2002), but remains to be validated for fish farms in the Baltic Sea, although many fish farmers support this hypothesis through observations of wild fish around their farms (K.M. Kjeldsen, pers. comm.).

The primary production in the Baltic Sea is limited by nutrients during summer, and phosphate is the typical limiting nutrient in the north, whereas nitrogen is argued to be limiting in the south (Elmgren 2001). Fish farming in the Baltic Sea may thus, due to the release of dissolved nitrogen directly through excretion of ammonium from the fish during summer and through the settling and regeneration of phosphorus, lead to a stimulation of the nutrient-limited primary producers. One important aspect when discussing mass-balances is that the nutrients released from fish farms are immediately bioavailable, whereas up to 50% of the nitrogen in the Baltic Sea is considered to be non-bioavailable, as it is bound in humus compounds (Elmgren 2001).

Increased water column chlorophyll-a concentrations and periphyton growth has been linked to fish farming activities in the Archipelago Sea in SW Finland (Honkanen and Helminen 2000). The study of the Archipelago Sea in Finland is one of the first to show an ecosystem effect on primary production under eutrophic conditions, and suggests that attached algae may be more sensitive indicators of nutrient release from fish farms. Although the nutrient release from fish farms in eutrophic regions is low compared to the other sources of nutrients as discussed above, the nutrients are released during the period, when the primary producers often are limited by the availability of nutrients, which may explain the eutrophication effects in the Finnish archipelago during summer. Most of the run-off from land occurs in the late autumn, winter and early spring (Håkanson and Boulion 2002).

In conclusion, fish farming in the Baltic Sea contributes to the general eutrophication, and although the overall contributions are low ($< 2\%$ of total load), calculations from Denmark show that fish farms account for up to 8–9% of the point sources. Whereas large investments have been done to reduce loads from point sources, only limited research has been undertaken to develop technology to reduce the environmental impacts of fish farms. The loss of nutrients can be minimized by capture of wild fish for feed production or by introduction of extractive cultures such as shellfish and macroalgae.

At the local scale, nutrient release should be compared with imports and exports from the area and the water residence time. If the water residence time is short, most nutrients will be exported to the coastal area, whereas most of the nutrients may be turned over within the area if the residence time is long. This may lead to increased primary and secondary production, in particular in periods with natural nutrient limitation in summer and autumn. Such increased production may result in enhanced settling of organic matter with risks of oxygen depletion events, in particular in stratified water bodies. The location of future aquaculture units has to be evaluated based on local conditions, such as nutrient limitation, water residence time and stratification.

A.3.1.3 *External Pressures*

A.3.1.3.1 Sea Traffic

Gerhard Dahlmann

Traffic and Navigational Situation

Shipping is steadily increasing in the Baltic Sea, reflecting intensifying international co-operation and economic prosperity. According to a more detailed statistical evaluation of the Baltic Sea shipping traffic, which was commissioned by Finland (Rytkönen et al. 2002), the sea-borne volume of transported goods is expected to roughly double by the year 2017.

Concerning ferry traffic and passenger transports the picture was a bit vague in the end of the 1990s because of the impact from the Belt-crossings and the abolition of duty free sales. Given data on the development during the last few years figures of ferry transport are still rising.

Around 2,000 sizeable ships are normally at sea at any time in the Baltic Sea. The Baltic Sea has some of the busiest shipping routes in the world (HELCOM 2005)

Generally, it is difficult to obtain a reliable up-to-date overview of ship traffic in the Baltic Sea. The situation is expected to change when a monitoring system for ships, based on AIS (Automatic Identification System) signals, which started in 2005, will be routinely explored. This will allow all the relevant statistics on shipping in the Baltic Sea to be stored at the HELCOM server in Denmark and displayed on the HELCOM website.

The AIS network is one of a package of 16 measures adopted by the extra-ordinary HELCOM meeting at ministerial level in Copenhagen in September 2001, known as the "Copenhagen Declaration". It includes incentives for IMO (International Maritime Organisation), such as enhancement of pilots, routing measures and introduction of traffic separation schemes, as well as regional and national activities, such as improved hydrographic services and use of Electronic Navigational Charts. The Copenhagen Declaration has to be seen as one of the most important milestones of the HELCOM work in the field of improving maritime safety and thus preventing pollution from ships.

Maritime shipping can clearly be regarded as one of the most environmentally friendly means of transportation. Nevertheless, steps to further enhance safety of navigation have to be considered, among them enforced use of AIS onboard ships and for monitoring systems in order to control traffic, improved availability of electronic data to be used for sophisticated ships' navigation systems in order to support ships' management, further needs of routing systems and traffic separation schemes in order to support ships' management and avoid as far as possible conflict situations.

Impacts from Maritime Shipping

In order to minimise detrimental impacts of maritime shipping to the environment of the Baltic Sea, energetic measures have been taken by HELCOM as well as by the IMO. The most important instruments for preventing marine pollution from ships are the world-wide applicable MARPOL Convention (International Convention for the Prevention of Pollution from Ships), and the Helsinki Convention, which reflects, with respect to shipping, MARPOL Regulations. These rules lead to a significant reduction of *inter alia* oil discharges form ships during operation and from oil tankers, discharge of sewage and waste and emissions from ships by reducing sulphur content of bunker fuel oil. A further international convention which has to be mentioned in this context is the Ballast Water Convention, aiming at the prevention of transfer of alien species through ships' ballast water (not yet in force).

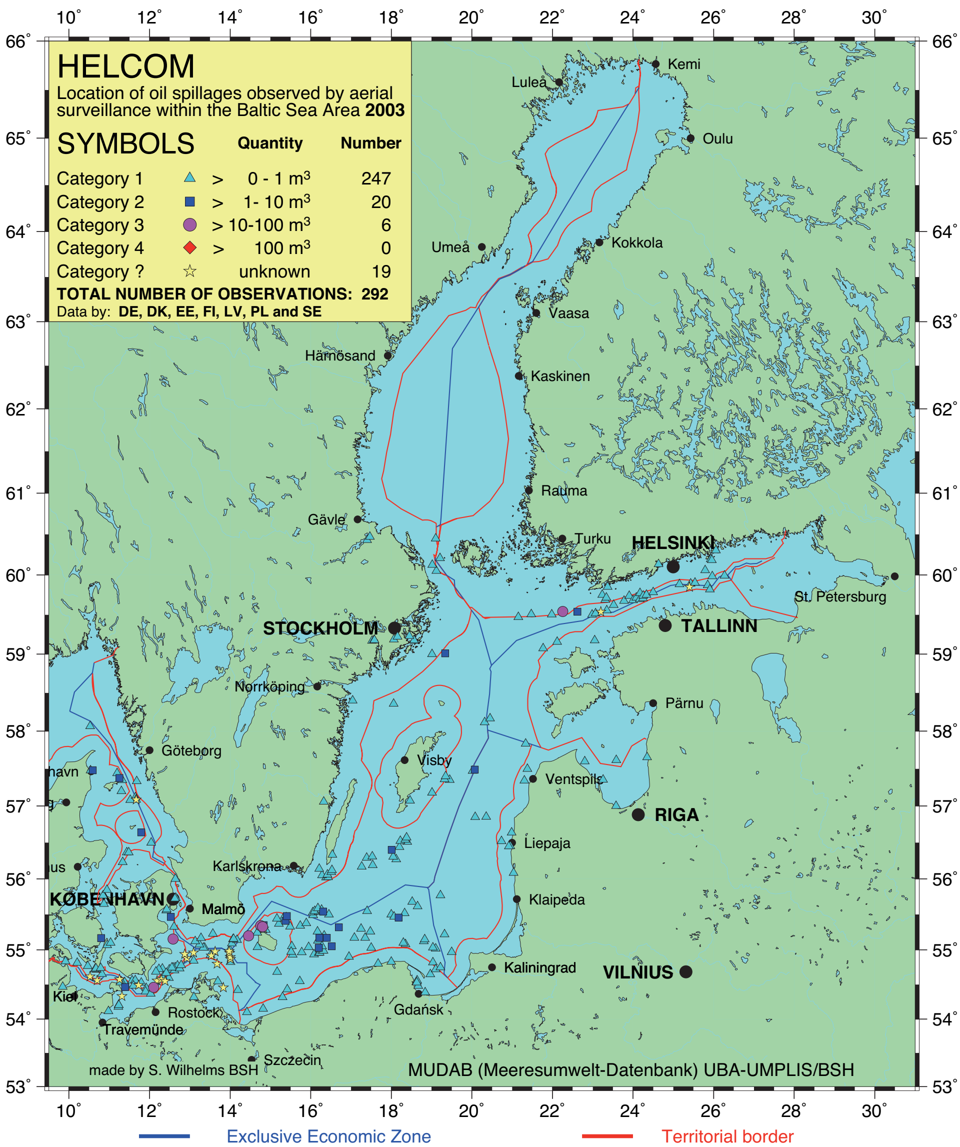

Fig. A.31. Location of oil spillages observed by aerial surveillance in 2003 (from HELCOM 2003b)

Oil Pollution

Oil is a serious threat to Baltic Sea ecosystems and wildlife. The most visible effect of oil spills is the oil contamination on the surface which causes smothing and death of birds and seals. As many of the chemicals in the oil spills are toxic, oil pollution causes serious accumulative effects, for example on plankton, fish and animals living on the seafloor, as it builds up in the ecosystems. Fauna and flora close to the shipping lanes are also negatively affected. In the Baltic Sea, where the average water temperature is only about 10 degrees, oil decomposes slowly due to the cold waters.

Illegal Discharges

About 10% of all the oil hydrocarbons in the Baltic Sea originate from intentional illegal discharges from the machinery spaces or cargo tanks of vessels sailing in the Baltic Sea.

During 1988 to 2001, surveillance aircraft detected an average of 400 illegal oil discharges per year in the Baltic Sea (HELCOM 2003a). In most cases, the amount of oil discharged is less than 1 cubic meter. Deliberate illegal oil discharges from ships are regularly observed within the Baltic Sea since 1988. As from 1999 the number of observed illegal oil discharges has decreased from ap-

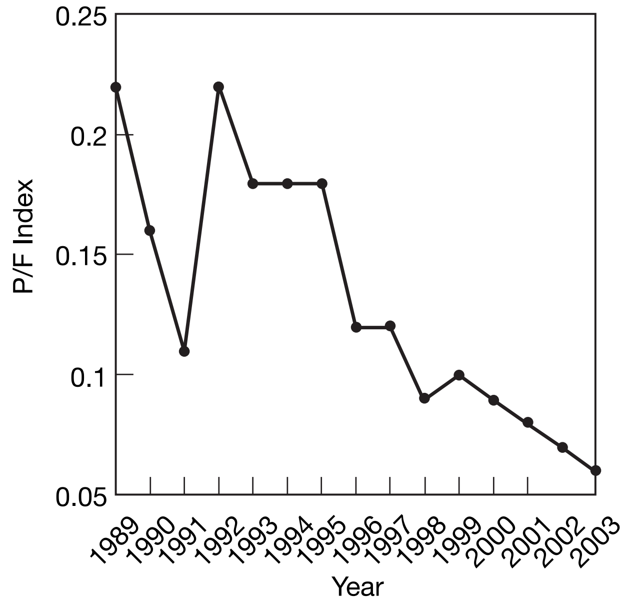

Fig. A.32. Annual number of detected oil slicks per flight hour (adapted from HELCOM 2003b)

Table A.10. Baltic Sea maritime traffic in 1995 (*second column from left*) and prognosis for 2017 (3rd *column from left*) (from Rytkönen et al. 2002)

Comodity	Volume in Baltic Sea (million tons)	Estimated future Volume in Baltic Sea (million tons)	Growth from 1995 to 2017
Break Bulk	29	82	186%
Dry Bulk	61	113	84%
General Cargo	22	64	186%
Liquid Bulk	1	2	84%
Oil	81	112	39%
Total	194	372	92%

proximately 500 to less than 300 in 2003. This trend is reflected also in a decrease in the number of observed oil discharges per flight hour.

Accidents

Increasing shipping traffic also means that ship accidents causing marine pollution become more probable. To reduce these risks, the Copenhagen Declaration will lead, besides the enhancement of maritime safety, *inter alia*, to improved emergency and response capacities and an improved network of places of refuge.

A.3.1.3.2 Tourism

Ralf Scheibe, Wilhelm Steingrube

Tourism is a comparatively recent social phenomenon. It developed very slowly at first, after the Industrial Revolution had radically changed all Western, Central and Middle European countries. Only after World War II did tourism start to become a mass phenomenon in the industrialised nations. Today it is one of the world's largest economic sectors (ranking fourth, according to www.world-tourism.org/facts/trends/economy.htm).

General development of tourism in the Baltic Sea Basin

Tourism developed properly in the 19th century. Its sudden rise was caused by the coincidence of several factors, e.g. the developments in the European transportation (steam boats, railways, road systems) and communication, and – decisively – the economic consequences of industrialisation which brought a certain economic wealth to new social groups and thus enabled them to travel. This new civic upper class immediately embraced the developing spas, for new scientific and medical insights confirmed their health benefits. In the course of the 19th century, the health interests of the bathers were soon joined by the economic interests of the local spa operators. However, this early form of tourism was restricted to relatively few spas and sea baths, and until the 20th century, the seaside repose remained a strict privilege of the upper social classes.

In Germany, this quickly changed when the national socialist system established the "Kraft durch Freude" movement and state-controlled recreation and holidays. Only the outbreak of the war in 1939 prevented the plans for mass tourism from being realised.

In the German Democratic Republic (GDR) of the 1970s and 80s, the state newly created a rising pressure on the southern Baltic Sea coast. As a result, that region had about 400,000 beds and 37 million overnight stays in 1989 – about 40% of the GDR's total volume (cf. Benthien 1996, p. 12). 1990 saw a huge slump in this sector caused by the reunification of Germany. The infrastructure of the East German socialistic tourism was not competitive, and new organisational and economic structures had to be built from scratch. Although the new infrastructure was quickly set up, tourism has failed to reach the pre-Unification volume. Today, the number of overnight stays in the German "Land" Mecklenburg-Vorpommern is about 22 million per year.

The development at the coasts of Poland, Lithuania, Latvia and Estonia took a similar course. But there, even more than in the GDR, the state installed large tourism infrastructures which were alien to the landscape and, today, create considerable utilisation problems.

The development of tourism in Scandinavia took a somewhat retarded and structurally different course. Although there, too, its early stage was shaped by the behaviour of the nobility, Scandinavian noblemen began already in the early 19th century to use their manors as summer residences, exhibiting a particular preference for waterside locations. As elsewhere, the assurgent civic circles imitated upper-class behaviour and looked for cheap summer lodgings in the countryside (Jäderholm and Steingrube 1996, p. 140 ff.). Thus, at an early time they already induced the beginning of the cabins and related facilities which are so typical of Scandinavia today.

Present and future situations in different tourism sectors

The present situation in the Baltic Sea Basin (cf. the up-to-date overview in Breitzmann 2004) is characterised by relative stability and can be summarised in the following points:

- Domestic tourism is dominant in all countries boardering the Baltic Sea, i.e. most of the tourists come from the respective country.
- The cabin holiday has become an integral part of life in the Scandinavian countries and, therefore, dominates domestic tourism. Because of the keen demand, domestic tourism is extending into the "dry" countryside. Otherwise, there is a clear local and regional trend: "to the water", i.e. especially to the seaside, but also to the lakes.
- In line with this trend, the southern Baltic Sea coast, with its typical sand beaches receives many bathing tourist.
- The intensively used areas are expanding continuously. On the whole, however, there is less of an addition in tourist numbers than a spatial redistribution:
  - The pattern of locally centralised facilities in old, long-standing sea baths is replaced by a scatter of resorts along the entire coastline.
  - Poland and the three Baltic states are slowly joining this market.
- The predominance of marine and other water-based activities creates a pronounced seasonality.
- Business tourism provides some counterbalance, but concentrates on the tourist centres and cities.
- The Baltic Sea is of increasing interest for cruise boat operators.

Medium-term trends:

- Domestic visitors will continue to dominate Baltic Sea Basin tourism;
- The pronounced seasonality will hardly abate, because the many efforts to extend the season will hardly have any quantitative effect.
- There are many current projects to diversify tourism. In rural regions, this will lead to the construction of a number of new facilities and to the provision of new visitor activities.
- In business tourism, the EU enlargement will cause an increase in travel volume and a shift into Poland and the Baltic States.
- The focus of the new developments will be on maritime tourism which may cause visible effects: creation of new marinas, more boat traffic, and an increasing number of "mini-cruises".
- Ferry traffic will further increase in spite of newly built or planned bridges.
- In the Baltic Sea Basin in general, there will be a slightly increasing travel volume caused by the recent opening of the borders to the new EU member states.
- There will be a net redistribution at the expense of the established destinations like Denmark, Schleswig-Holstein and Mecklenburg-Vorpommern, leading to more tourism in Poland and the Baltic States.

Environment, climate, and tourism – general observations

Of course there is an intimate interrelationship between tourism and the environment. On the one hand, the natural assets of a region are generally recognised as the basis of tourism; and on the other hand, (mass) tourism contributes to the destruction of its own basis.

Nature, however, is a wide term, and climate is usually understood to be a part of it. However, it makes sense to treat climate on its own. This is due to, in the global dimension of climatic effects, the atmosphere's high susceptibility to change, as compared to other environmental factors, and the special impact of climate on the different prerequisites and aspects of tourism. As a schematic, we thus yield the simple relation shown in Fig. A.33.

The largest, i.e. most intensively discussed intersection (A) is doubtlessly covered by those issues that deal with global climate change. It is not caused by specifically tourism-related activities, but rather by other human economic activities. Intersections B and C include all kinds of interactions between tourism and the environment, e.g. the waste problem in general, pollution caused by car traffic, as well as water supply and sewage treatment, or direct impacts on animals and plants (not only in reserves) that are caused directly by tourists. It must be emphasised that these interactions occur invariably in both directions.

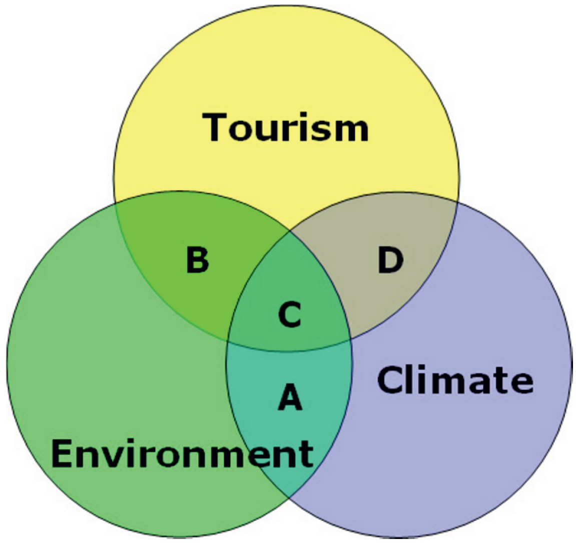

Fig. A.33. Tourism, Environment and Climate – Areas of Overlap

That tourism depends on the general natural and environmental conditions is self-evident. Tourism requires nature both in the form of the local natural assets, as a space of action for activities, and simply as a backdrop. "Beautiful scenery", "exotic nature" and similar attributes describe the predominantly desired framework for pleasant, successful holidays.

Trend sports, in particular, which play an increasingly important role in tourism, make use of natural areas that until recently were completely uninteresting for the leisure industry.

The opposite relationship – the impact of tourism on the environment – is easy to understand on a general level (Fig. A.34). The necessary physical infrastructure is the most obvious connection. It is also self-evident that leisure activities, the traffic they induce, and finally, the behaviour of the tourists themselves are always accompanied by environmental impacts. Equally easy to understand is the observation that tourism consumes resources like space, water, or energy.

The following, simple example gives an impression of the complexity that characterises this re-

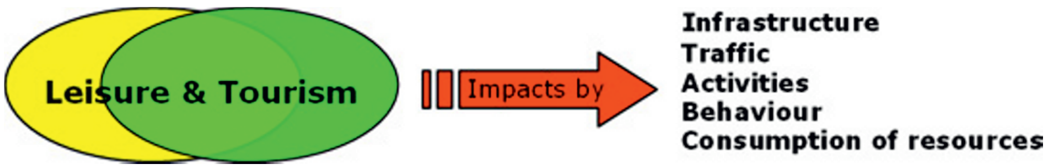

Fig. A.34. Environmental implications of leisure and tourism

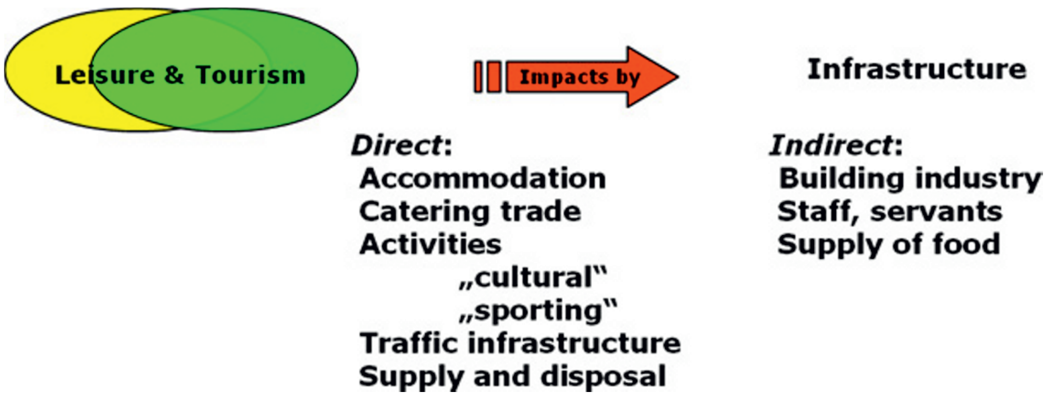

Fig. A.35. Infrastructure as a source of environmental impacts

lationship: To avoid tall hotel buildings that spoil the scenery, new projects are subject to recommendations or regulations that demand an architectural style in harmony with and typical of the scenery. But these buildings require, for the same number of beds, a floor space several times larger than do multi-storey hotels.

Admittedly, this rather general list of the most important environmentally relevant "pressure zones" needs to be spelled out in greater detail. Figure A.35 gives some examples for the environmental impacts created by tourism infrastructure, like lodging, catering trade, traffic infrastructure, as well as supply and waste facilities. But also the activities themselves – ranging from sports (swimming pools, bicycle lanes, golf courses, etc.) to culture (museums, theatres, etc.) – require a specific infrastructure.

These are the direct, immediately obvious environmental impacts. But we should not forget the indirect impacts:

- Tourism infrastructure requires a construction industry which, in turn, entails its own facilities, ranging from the gravel pit over the car pool to the business building.
- Many seasonal workers in tourism require additional lodgings and supply facilities.
- The gastronomic supply of the tourists implies a row of special production plants, ranging from fields or glasshouses to entire cattle herds and the meat-processing businesses.

Of course, many of the implications mentioned are desiderates of the economic policy of the respective country, and of course not every environmental impact is in itself destructive. The point here is rather to demonstrate the intimacy and complexity of these relationships.

Interactions between climate change and tourism

The central issue of this paper is part of intersection D (Fig. A.33), i.e. of the direct intersection between climate and tourism. It is not intended to separate it strictly from aspects which would be placed in its vicinity but still within intersection C.

The "First International Conference on Climate Change and Tourism" of the World Tourism Organization (WTO) in Djerba, Tunesia (1993) identified this subject area meanwhile as a sphere of problems too and focused on climate change related impacts on water resources, at coastal and island destinations, as well as mountain areas. The *Djerba Declaration on Climate Change and Tourism* recognises that climate change impacts are already occurring at some tourism destinations and the effects are expected to spread in the future[2]. Besides this, two other international meetings were held: at Milan (Italy) in 2003 on "Climate Change, the Environment and Tourism: The Interactions" and at Genoa (Italy) in 2004 on "Climate Change, the Environment and Tourism in Europe's Coastal Zones"[3].

In the context of climate and tourism we meet both directions of interdependencies: Consequences of climate change for tourism on the one hand, and the impact of tourism on climate change on the other hand.

Consequences of climate change for tourism

The climate, as well as the weather, crucially influences the choice of the holiday destination and duration. The decision pattern is shaped both by the objective opportunity to conduct certain activities (skiing, sailing, etc.) and by very subjective whims. Astonishingly, people often attach more importance to weather forecasts than to the actual weather (cf. Lohmann 2003, who also provides a comprehensive review of the literature). On the other hand, many tourists fail to catch up on the weather conditions in their holiday destination, or they do so only shortly before they set off (Hamilton and Lau 2004). Referring to selected European countries, Agnew and Palutikof (2001) conducted a study of climate impacts on the demand for tourism. In general, temperature is more strongly perceived and considered in the decision-making process than sunshine. Precipitation ranks only third. A certain "pleasant minimum temperature" should prevail, but the weather should also not be too warm. In general, an average temperature of 21 °C can be regarded as attractive for tourists. In all countries under investigation, a one-degree rise in temperature resulted in an increase of the number of domestic tourists by one to five percent.

Because the many existing studies are, for the greater part, not comparable, it became necessary to establish an independent index which is free especially of the interviewees' subjective influence. The Tourism Climate Index (TCI) fulfills this requirement. It combines seven weighted monthly averages as mean and maximum temperatures, humidity, sum of precipitation, sun hours and wind speed. The TCI is also an appropriate tool for estimating the attractiveness of a destination after climate change.

Scott and McBoyle (2001), who also provide a more detailed description of the TCI, attempted a forecast for selected North American cities, which may be quantified using the TCI in combination with models of climate change. They concluded that approximately from 2070, many Canadian and northern United States cities will be affected positively. As a contrast, cities located further to the south, which even today stands out with unpleasant summer TCIs, will become even less attractive. It is an obvious step to expect a similar development for Northern Europe and the Mediterranean.

The studies by Bigano et al. (2005) are also based on simulations, but this time using the Hamburg Tourism Model (HTM[4]), which predicts the development of demand patterns in tourism. These authors' predictions resemble those of Scott and McBoyle (2001): Tourism demand will double in colder regions and decrease by 20% in warmer countries. In some regions, visitor numbers will even drop to half their current level. There will be an increase, especially of international tourism, in the currently colder regions.

Besides the direct consequences of climate change, which can be immediately attributed to the respective climate elements, there are numerous indirect effects. These may be quite diverse, effects on e.g. terrestrial and marine ecosystems are covered in Chaps. 4 and 5 of this volume.

The most important effect for tourism, especially for infrastructure, is the expected rise of the sea level. Its particular consequences, though, appear to be less crucial than those of the general climate change (Bigano et al. 2005). At first glance, it seems to be a great advantage that the sea level will not rise unexpectedly and within a very brief time, but that this process will occur very slowly in the course of many years. This leaves ample opportunity to meet the effects with technical constructions (dykes, barrages, etc.).

[2] cf. www.world-tourism.org/sustainable/climate/final-report.pdf

[3] cf. www.e-clat.org; more scientific information is available via the very actual bibliography of "Climate, Tourism and Recreation" on www.fes.uwaterloo.ca/u/dj2scott/Documents/CTREC%20Bibliography_FINAL.pdf

[4] www.uni-hamburg.de/Wiss/FB/15/Sustainability/htm.htm

Tourism-relevant general impacts of a sea level rise are (after Sterr et al. 1999):

- *More available water surface.* Not all extremely low areas will be "defended" by dykes against the sea. This new water surface will be very attractive destinations for many people, i.e. these areas create additional tourism.
- *Increasing likelihood of (storm) flood events.* Its impact concentrates on coastal facilities like marinas, near-beach buildings, and the water vehicles themselves, even though the events appear (at present) to occur more often in the less tourism-relevant winter half year.
- *Loss of land in floods and enforced erosion.* This impact may extend to tourism-relevant areas, e.g. because buildings were erected in known flood-prone and erosion-endangered areas. Admittedly, most facilities are affected by sediment set free by erosion, the costs for the unsilting of harbour accesses would rise.
- *Penetration of seawater into surface- and groundwater bodies.* This may especially concern isolated water catchments on islands, where water consumption increases considerably during the main tourist season.
- *Biological changes in the coastal ecosystems.* For example, they might affect the number and distribution of fish species relevant for fishing, or, in combination with changes in water temperature and salinity, promote neozoa like the piddock which causes considerable damage to harbour infrastructure and coastal protection facilities.

Against the background of these results, we may expect the following trends in the Baltic Sea Basin: The summer tourism will profit from the expected climate change, because the climate will generally become more tourism-friendly. The TCI (Tourism Climate Index) will reach attractive levels even in the northern part of the Baltic Sea Basin, as well as the presently rather short tourist summer season will be extended. There will be negative impacts on the winter tourism. Especially in the more continental regions of Northern Europe, winter temperatures will rise while snow certainty decreases.

However, we should not forget that these changes will be much less effective than the socio-economic factors which define the general framework. The decision for the time and destination of a holiday depends crucially on income, education, and age. Especially the habits of younger holiday-makers (and, thus, their decision patterns) change very quickly. These factors entail a much less predictable risk than climate change (cf. Lise and Tol 2005).

Impact of tourism on climate

Tourism is not only a "victim" of climate change, but itself influences climate development. However, there is only one sector besides indirect effects translated through general pressure on the environment (resource consumption, waste, soil sealing, etc.) that directly affects the climate: tourism-based traffic. It produces considerable amounts of exhaust gases and thus greatly contributes to climate change.

For many years, the trend in tourism has been towards long-distance travel, which in turn causes an increase in flight traffic. Flight traffic is one of the strongest and most immediate sources of climate change. In the Baltic, however, long-distance traffic will increase "only" proportional to the general increase in long-distance travel. Because, on a global scale, the population size in this region is comparatively low, this cause of environmental pressure will be rather low-ranking. The increase in temperature could, under certain circumstances, even have a contrary effect. A certain – though probably rather small – fraction of the population in the Baltic Sea Basin will not travel to long-distance destinations but rather spend their holiday in the region itself. Thus, their contribution to the further increase of CO_2 emissions will be less than average. The present phase of cheap flight travel causes very sizeable new tourist streams. This form of tourism also occurs in the Baltic Sea Basin, which is both source area and destination. However, we can safely presume that the market will soon put an end to this phase and thus limit the present extreme emissions.

The primary form of tourism-related traffic in the Baltic Sea Basin is individual transport, i.e. car traffic. Even in the medium-term, it will not lose its predominant position.

In general, the tourism-based traffic in the Baltic Sea Basin will grow – as a continuing effect of the political opening of the East. Even in the medium-term, we will continue to sense that new source areas of travel traffic with an increased action range have entered the market. The population of Poland and the Baltic States still feel they have to catch up in terms of travel, and they will fulfil their desire as their economic wealth increases. On the other hand, these countries present new destinations which – lacking alternatives – aggressively promote tourism in their turn.

On a regional and local level, tourism- and leisure-based transport plays an especially important role. In Germany, 54% of the total traffic volume is caused by leisure traffic, which, in turn, includes a share of problematic individual traffic of more than 80% (UBA 2003, p. 19). Especially the rise of the trend sports is regularly linked to an increase in traffic volume. Among these particularly traffic-intensive leisure activities are diving, wind surfing, skiing, and climbing (Stettler 1998). Thus, in the medium-term tourism-based individual traffic will considerably contribute to the increase of CO_2 emissions.

Another source of increasing CO_2 emissions is the marine tourism. This form of tourism will gain even more importance in future. Not only will the number of private motor boats rise, but the already booming cruise market will continue to grow in the Baltic Sea as it does elsewhere. In addition, the river cruise market has been developing with a higher than average rate for several years. Thus, in the medium-term marine tourism will also create considerable emissions.

Conclusions

The traffic volume in the Baltic Sea Basin will continue to rise in the medium-term. This development is primarily still an effect of the political opening of the East and the consequent EU enlargement. All of the new EU member states place great hopes in the tourism sector.

As a result, we will witness shifts of the tourist destinations within the Baltic Sea Basin - at the southern Baltic Sea coast the shift will be from west to east, i.e. from Denmark and Germany to Poland and to some select seaside resorts in the Baltic States. Large cities such as Gdansk, Riga, and St. Petersburg are also attracting more tourists.

This development will lead to more traffic – predominantly individual traffic, but also ferry traffic – which can contribute considerably to climate-relevant emissions.

The trend towards marine tourism (more motor boats, more cruises) will also strongly increase emissions.

The remaining consequences are of a rather more general, ecological nature (consumption of space and resources, especially water, as well as waste disposal problems). However, they will occur predominantly as problems on the local and regional level – the total sum will hardly rise and could perhaps be balanced by infrastructural and technical counter-measures.

The opposite relationship – the impact of climate change on tourism in the Baltic Sea Basin – raises positive expectations. The probable change of the sea level will hardly have any negative effect. On the contrary, it might enhance the marine potential, and the rise in temperature will improve the natural basis for tourism. Consequently, the total volume of tourism will grow. But on the whole, the changes will lead to more domestic and less long-distance tourism, thus contributing to a reduction of the growth of climate-relevant emissions caused by tourism.

A.3.2 Terrestrial and Freshwater Ecosystems

Benjamin Smith, Thorsten Blenckner, Christoph Humborg, Seppo Kellomäki, Tiina Nõges, Peeter Nõges

A.3.2.1 *Catchment Area of the Baltic Sea*

The catchment area of the Baltic Sea (1,735,000 km^2), which constitutes the land surface region of the Baltic Sea Basin, comprises watersheds draining the Fennoscandian Alps in the west and north, the Erzgebirge, Sudetes and western Carpathians in the south, uplands along the Finnish-Russian border and the central Russian Highlands in the east. Politically, this includes most of Sweden, Finland, the Baltic States, Poland and part of Russia, Belarus, Ukraine and northern Germany (Fig. A.36). The Baltic Sea Basin spans some 20 degrees of latitude and climate types ranging from nemoral to alpine and subarctic. It can be roughly divided into a south-eastern part, draining into the Gulf of Riga and Baltic Proper, that is characterized by a cultivated landscape with a temperate climate and a northern boreal part characterized by coniferous forests and peat. The natural vegetation is mainly broadleaved deciduous (nemoral) forest in lowland areas of the temperate southeast, and conifer-dominated boreal forest (taiga) in northern Scandinavia. Cold-climate shrublands and tundra occur in mountainous areas and in the subarctic far north of the catchment region. Wetlands are a significant feature of the boreal and subarctic zones.

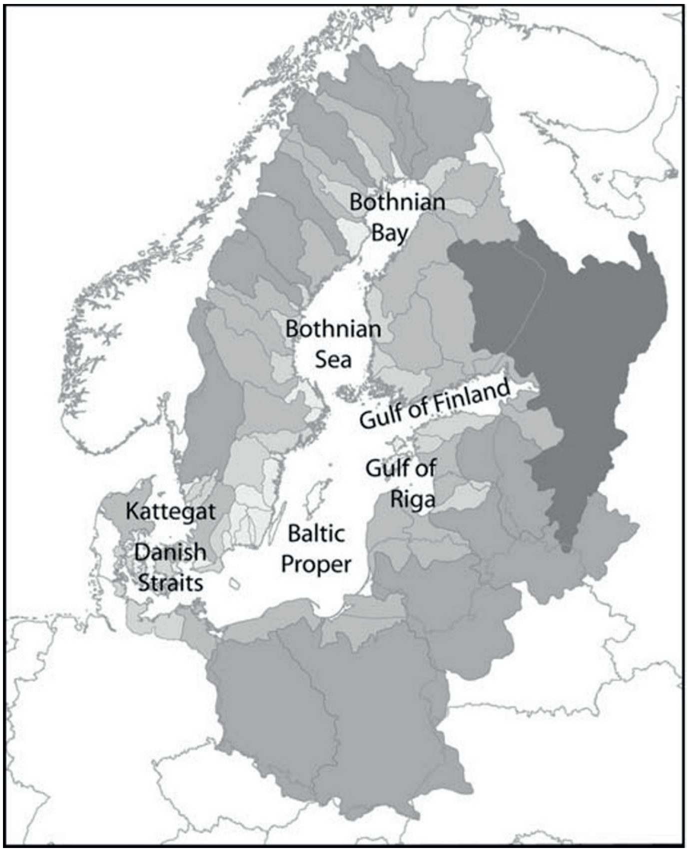

Fig. A.36. The Baltic Sea Basin showing sub-watershed drainage basins, national boundaries and the major basins of the Baltic Sea (source: UNEP/ GRID-Arendal, www.grida.no/baltic, page visited 26 February 2007)

Much of the nemoral forest zone has long been converted to agriculture (Ledwith 2002); only in northern parts of the Baltic Sea Basin (e.g. Sweden, Finland, north-western Russia) do forests still dominate the landscape. Approximately half of the total catchment area (about 8,200,000 km^2) consists of forest, most of the remainder being agricultural land (Chap. 1, Fig. 1.11). Most of the forests are managed, and forestry is mainly based on native tree species; particularly Norway Spruce (*Picea abies*) and Scots Pine (*Pinus sylvestris*). Especially in the temperate parts of the Baltic Sea Basin, the current tree species composition is determined by past land use and management activities rather than by natural factors. Areas of vegetation largely unaffected by direct human management are presumably of very limited extent, but some such areas occur in upland parts of northern Sweden and Finland.

A.3.2.2 *Climate and Terrestrial Ecosystems*

Climate control of large-scale vegetation patterns

Poleward or upper altitudinal range boundaries of many plant species and biomes correlate with isolines of absolute minimum temperature, and are assumed to be the result of ice formation in plant tissues leading to tissue and plant death, either directly or via secondary mechanisms such as dessication (Woodward 1987). Some range boundaries, including the alpine treeline in Scandinavia, are more closely correlated with growing season heat sums, rather than absolute minimum temperatures, which may suggest growth limitations associated with low temperatures and a short available period for carbon assimilation as possible limits to survival above treeline (Körner 1998; Grace et al. 2002). The mechanisms determining southern (warm) range limits are more varied and less well understood. For Norway spruce (*Picea abies*), limited snow cover and repeated freeze-thaw cycles have been suggested to interfere with the development and maintenance of winter-hardiness in seedlings, inhibiting natural regeneration of this species in oceanic climates (Dahl 1990; Sykes et al. 1996; Bradshaw et al. 2000). In many temperate tree species, the timing of budburst appears to be coupled to the duration and intensity of low temperatures in the winter. Budburst may thus be delayed by several weeks following a warm winter, protecting the frost-sensitive new shoots from damage by late frosts (Murray et al. 1989; Sykes et al. 1996). This chilling mechanism has been proposed to, for example, restrict the distribution of European beech (*Fagus sylvatica*) into the most oceanic climates (Sykes and Prentice 1995).

In reality, temperature is only one of several factors controlling large-scale distributions of tree species. Even if the seed dispersal of some species is able to keep up with climate change, local dominance shifts may be delayed by the long generation times of trees, competition with resident species, required changes in soil structure, hydrology, chemistry, litter depth, requirements for mycorrhizae and other factors (Sykes and Prentice 1996; Huntley 1991; Malanson and Cairns 1997).

Environmental control of ecosystem biogeochemistry

Climate affects biogeochemical cycling within ecosystems by modifying the rates and modes of individual ecosystem processes. The most important processes in terms of overall control of ecosystem functioning are the physiological processes underlying net primary production (NPP): photosynthesis, autotrophic (plant) respiration, stomatal regulation and carbon allocation in plants. Carbon assimilated in photosynthesis is eventually either respired or otherwise emitted (e.g. as biogenic volatile organic compounds) directly to the atmosphere, or fed into the soil organic matter pool as litter, root exudates, or residues from disturbance by fire. Productivity changes thus tend to propogate to litter and soil pools and impact decomposition processes. Productivity changes may also modify vegetation structure (e.g. leaf area index, LAI), changing the competitive balance among individuals and species, and leading to further structural changes and feedbacks on production. Changes in disturbance regimes, for example, damage due to wind storms and wildfires, can be a further consequence of changed vegetation structure.

The direct physiological effect of a temperature increase on plant carbon balance may be either positive or negative, depending on the relative kinetic stimulation of photosynthesis and plant respiration. However, NPP tends to be a constant proportion of GPP across biomes and climate types, which suggests that respiration rates are in the long term dependent on the supply of assimilates (i.e. net photosynthesis), and that acclimation to a temperature change may occur (Waring et al. 1998; Dewar et al. 1999).

Temperatures also affect annual productivity via growing season length. Phenological events such as budburst and leaf abscission in temperate and boreal plants are closely correlated with climate indices, particularly temperature sums (Kramer 1995; Badeck et al. 2004). Both temperature cues and photoperiod may determine growth cessation and the onset of hardening in the autumn. A uniform increase in average temperatures throughout the year implies that threshold temperatures for phenophase transitions in spring may be achieved a number of days earlier, while later autumn frosts may delay leaf abscission and winter hardening. However, many tree species require an extended period of cold temperatures (chilling) to initiate budburst and, in these species, warmer winter temperatures may delay the onset of growth even once normal spring temperatures have been achieved (Cannell 1989; Sykes et al. 1996). The effects of temperature changes on plant phenology may be expected to impact NPP particularly at high latitudes, where the growing season is shortest (Walker et al. 1995).

Soil nutrient status, particularly nitrogen availability, is considered to limit productivity in many temperate and boreal ecosystems (McGuire et al. 1995; Bergh et al. 1999; Hungate et al. 2003). Increased soil temperatures will tend to stimulate microbial activity and N-mineralisation rates, so long as soils remain moist, potentially releasing ecosystems from N-limitation (Melillo et al. 2002). This effect may be particularly important in the coldest boreal, arctic and alpine environments (Jonasson et al. 1999; Strömgren and Linder 2002).

Soil water deficits occasionally limit production, even in many mesic ecosystem types. Although water availability is not currently a major limiting factor for forest or agricultural production in the Baltic Sea Basin, it does occur, e.g. on well-drained soils in southern Sweden (Bergh et al. 1999). Increased temperatures lead to increased

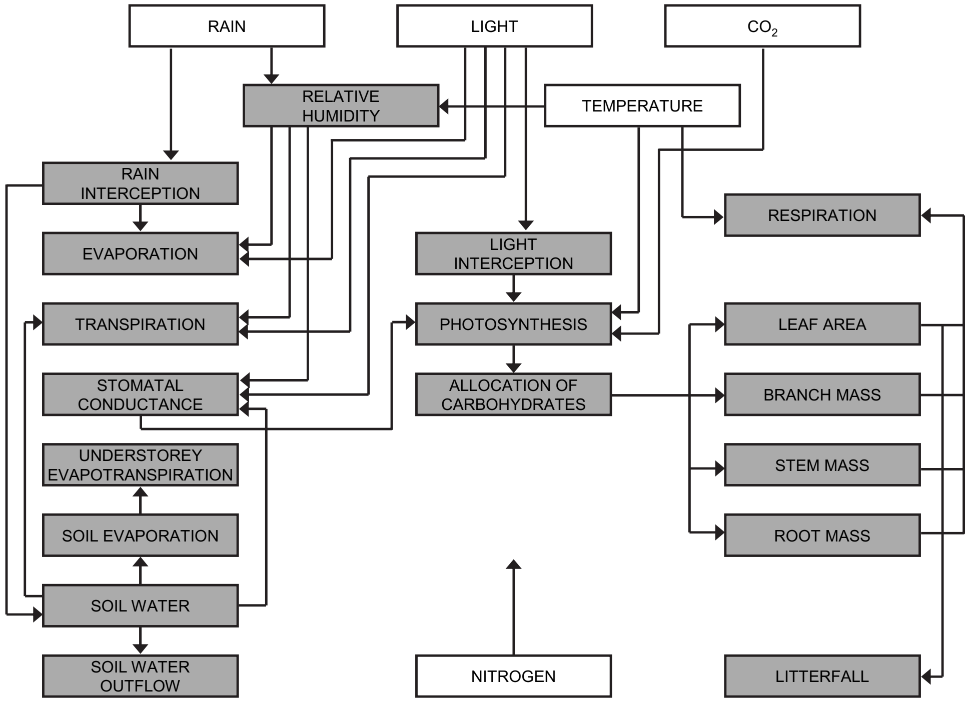

Fig. A.37. Conceptual diagram for the BIOMASS model (adapted from Freeman et al. 2005)

evaporative demand and depletion of soil water via increased evapotranspiration, while changes in precipitation patterns may exacerbate or ameliorate moisture deficits and effects on production.

Rising atmospheric carbon dioxide (CO_2) concentrations are one of the most certain aspects of global change. CO_2 is a plant resource, and it has long been assumed that increased ambient CO_2 levels would stimulate photosynthesis via reduced photorespiration and improve plant water budgets through reduced stomatal conductance, in both cases tending to augment net carbon uptake (Bazzaz 1990). Laboratory and field experiments exposing plants or whole ecosystems to elevated CO_2 levels confirm that production usually increases by 15–50% for a doubling of CO_2 above pre-industrial levels (Poorter and Navas 2003); for temperate forest ecosystems, the response across broad productivity gradients is rather conservative at a median of $23 \pm 2\%$ (Norby et al. 2005). However, it has been suggested that, in many ecosystems, negative biogeochemical feedbacks may inhibit plants from fully utilising the additional assimilates resulting from CO_2-fertilisation on multidecadal time scales (McGuire et al. 1995); reduced quality (lower N:C ratio) of the litter produced by CO_2-fertilised plants could lead to immobilisation of N by soil microbes, reducing plant N uptake and NPP (McGuire et al. 1995). To a certain extent, plants may compensate for nutrient limitations by an increased relative investment in below ground structures (roots) and functions (e.g. root exudates, investment in mycorrhizae, Lloyd and Farquhar 1996).

Overall responses of ecosystem biogeochemistry to environmental changes are characterised by the differential temporal signatures of many constituent processes. Short-term physiological responses, such as the direct response of net photosynthesis to a change in temperature, may be modified by longer-term changes in, for example, plant structure, population dynamics, vegetation species composition and soil organic matter stoichiometry (Shaver et al. 2000).

A.3.2.3 *Outline of the BIOMASS Forest Growth Model*

The BIOMASS model is based on sub-models describing radiation interception, canopy photosynthesis, phenology, allocation of photosynthates among plant organs, growth, litter fall and water balance, including nitrogen effects on processes (Fig. A.37; Freeman et al. 2005). BIOMASS simulates tree growth on a daily time step, which requires daily meteorological inputs of short-wave radiation, maximum and minimum air temperature, precipitation, and humidity of the air. Gross primary production is calculated from a radiation interception model requiring information on canopy architecture and a biochemically-based model of leaf photosynthesis by C_3 plants. Net primary production is obtained by subtracting the autotrophic respiration.

A.3.2.4 *Outline of the EFISCEN Forest Resource Model*

EFISCEN is a large-scale matrix model, which uses forest inventory data as input (Sallnäs 1990; Pussinen et al. 2001). EFISCEN can be used to compile information on forest resources in Europe and to produce projections of the possible future development of forests. The state of a forest is depicted in the model as an area distribution over age and volume classes in matrices. Growth is described as area changes to higher volume classes and ageing of forest is incorporated as a function of time up to the point of regeneration. The user defines the level of fellings and the model implements cuts according to predefined management regimes.

The basic input data include forest area, growing stock and increment by age classes, i.e. the data available from national forest inventories. European-wide data are compiled in the EFISCEN European Forest Resource Database (EEFR) at the European Forest Institute (Schelhaas et al. 1999). Country-level data consist of forest types, which are distinguished by region, owner class, site class and tree species, depending of the aggregation level of the provided data.

The current version of EFISCEN can be used to study the carbon balance of the whole forest sector. Stem-wood volumes are converted to carbon in the compartments stems, branches, leaves, and coarse and fine roots using dry wood density, carbon content and an age-dependent biomass distribution. Litter production is estimated using age-dependent turnover rates of each compartment and is used as input to a dynamic soil carbon module. A dynamic wood products model enables the flow of carbon to be followed further through processing and wood products up to the time point at which carbon is released back to the atmosphere. The EFISCEN version used in the calculations presented in Sect. 4.3.5 takes into account the impact of changes in temperature and precipitation on forest growth, and thus forest structure, carbon budget and fellings, as detailed by Pussinen et al. (2005).

A.3.2.5 *Climate Scenarios Used in SilviStrat Calculations*

Three climate scenarios were used in the SilviStrat project (Kellomäki and Leinonen 2005) to yield the predictions of change in forest growth presented in Sect. 4.3.5.

- *Current climate.* Temperature and precipitation values are based on monthly time series 1901–1995 and the CRU monthly climatology 1961–1990, with a spatial resolution of 0.5 degrees of latitude and longitude (Michell and Jones 2005). The warming trend in the interpolated monthly time series 1961–1990 was removed to generate 30 years of climate data with the typical interannual variability between years. From this sample, individual years were randomly drawn to generate the baseline climate ('current climate') for the simulation period of 110 years.
- *ECHAM4 climate.* Values for the period between 1990 and 2100 were used, taking the CRU monthly climatology 1961–1990 as a baseline. It was based on output from the ECHAM4-OPYC3 GCM (cf. Chap. 3) which is available as monthly means at a spatial resolution of $2.81 \times 2.76°$. The GCM simulation does not include the cooling effects of sulphate aerosols on climate.
- *HadCM2 climate.* The values were estimated for the period between 1990 and 2100 taking the CRU monthly climatology 1961–1990 as a baseline. It was based on output from the HadCM2 GCM (Chap. 3) at a spatial resolution of $2.5 \times 3.75°$. The GCM simulation includes the cooling effects of sulphate aerosols on climate.

Climate scenarios from both GCMs were based on the IS92a 'business as usual' emission scenario, which assumes a doubling of atmospheric CO_2 concentrations in the 21^{st} century. To generate monthly surface climate data, GCM results were downscaled to the sites by calculating the difference for each parameter between the time period 1990–2100 and the average values of the reference period 1931–1960 using monthly time steps. Spatial interpolation of GCM data on the sites was performed with the Delaunay triangulation. The time series of these anomalies were then added to the average values of baseline (CRU) data for the study sites.

A.4 Observational Data Used

A variety of data has been used for the description and analyses of the atmosphere, the ocean, the runoff from rivers, and the ecology of the Baltic Sea and its surrounding area. Below follows a short survey.

A.4.1 Atmosphere

Øyvind Nordli

Regular measurement with mercury in glass thermometers and barometers started at a few sites in the Baltic Sea Basin already in the 18th century. As standard instruments at the meteorological services they were much improved as time passed. Now, the mercury instruments have been replaced in large numbers by sensors for automatic registration. For long-term temperature trend analyses, the homogeneity of the series is a challenge for several reasons. Examples are improvements of the thermometers themselves, and also, a better sheltering from short wave radiation (Nordli et al. 1997).

As site measurements grew denser, reliable grid box mean values could be calculated. Advantage is taken of a work done by the Climate Research Unit (CRU) at the University of East Anglia (IPCC 2001, Chap. 2). For this study of the Baltic Sea Basin (see Chap. 2), a subset of the CRU data set with solely land stations is chosen. The dataset starts in 1851, but only data after 1870 are used in this book. The CRU data set includes many well homogenised series from the Nordic countries (Jones and Moberg 2003).

Glass barometers with mercury are of about the same age as the mercury thermometers. A challenge has been to keep the calibration of the instruments constant during transportation and also to keep them in good shape over long time spans. The readings of the barometers have to be adjusted to standard gravity and temperature. As standards, 45° latitude and 0 ˚C have been chosen, respectively. The pressure at station level is also adjusted to sea level. This operation may be challenging for mountain stations and stations situated in valleys where temperature inversions (temperature increase with height) tend to develop. Thanks to a network of radiosond stations also the height of distinct pressure surfaces, as for example the 500 hPa surface is mapped. During World War II, the sonds were much improved in an increasing number, and a global data network from the upper atmosphere was established.

The pressure data sets have undergone two very important procedures, namely reanalysis and gridding. This enables the study of circulation and circulation changes. Data sets often used for daily data are the ERA-40 (1957–2002) for Europe and a global data set from NCEP (1948–present).

The analyses of precipitation changes are based upon measurements by rain gauges. Precipitation has larger spatial variability than temperature and, in particular, pressure. This is often sought to be compensated by a denser network. During wind a main problem is that the gauges fail to catch all precipitation. The under-catch, which is largest under solid precipitation, is sometimes adjusted for by empirical formulae (see more in Annex 1.2.3).

Cloud cover is manually observed at the meteorological stations. The coverage of the sky is assessed in oktas, which has been standard since the 1st of January 1949. Solar radiation is also measured at some stations (see Annex 1.2.5); the length of reliable time series is now up to 40–50 years. For Europe as a whole they amount to about 300 (Kallis 1995).

A.4.2 Ocean

Philip Axe

A.4.2.1 *Hydrographic Characteristics*

Systematic temperature observations in the Baltic Sea extend back to measurements from lightships during the 1880's. Early observations of sea temperature were made using mercury thermometers and buckets. The invention of the reversing thermometer in 1874 made accurate (potentially better than 0.01 ˚C) in-situ measurements possible. These thermometers continued in use until very recently, though are now largely replaced by electronic ones offering better accuracy and ease of use. More detailed temperature profiles were obtained using bathythermographs – first mechanical, and later electronic. Claimed accuracies were better than 0.06 ˚C though Emery and Thomson (1997) suggest an accuracy of +/ − 0.1 ˚C is optimistic. Profiles (accurate to 0.002 ˚C) are now obtained by a combination of platinum resistance thermometers and thermistors mounted in a CTD (standing for 'Conductivity, Temperature and Depth'). The CTD is conventionally lowered through the water column, though can be towed behind vessels. Sea surface temperature is measured both by ships and from satellite borne radiometers.

Baltic Sea lightships also measured seawater density using an aerometer – a form of hydrometer. Knowing the sample temperature, it is possible to estimate the salinity. Salinity was also estimated from the chlorinity of seawater, determined by titration. Now salinity is determined by comparing the conductivity of a sample compared to the conductivity of a reference solution. This is done both for water samples, and *in situ* using the CTD. A modern CTD is accurate to about 0.005 psu (practical salinity unit). For more information on the salinity scale, see for example, UNESCO 1985.

Together with changes in salinity, oxygen content is used for identifying inflow events and for estimating seawater ventilation. The principle method of determination (Winkler titration) has not changed since 1889, and is capable of an accuracy of 1%.

A.4.2.2 *Sea Level Variability*

Harbour authorities have collected sea level data since at least the beginning of the eighteenth century. First measurements consisted of scratching the sea level on rocks, some of which are still apparent. Sea level observations in harbours were made by visual observation of a graduated staff, before being superseded by float gauges. Float gauges remain widely used. When well maintained and used in conjunction with a properly designed stilling well they are accurate. More recently, systems based on pressure gauges, acoustic time-of-flight and radar have been introduced. Pressure gauge systems require knowledge of the seawater density to calculate the height of the sea surface above the sensor. Acoustic and radar based systems measure the distance between sensor and sea surface from the time taken by a signal to return after reflection from the sea surface. Early acoustic systems had problems with changes in the speed of sound in air due to temperature changes. Acoustic and pressure gauge systems can suffer from sensor drift, requiring good datum control. When regularly checked, these systems are also capable of delivering high quality sea level data. Since 1991, the coastal observations have been augmented by satellite altimetry. These space-borne sensors provide sea level measurements over the offshore Baltic Sea.

The world's longest continuous sea level record is from Stockholm, starting in 1774 (Ekman 1988), while data from Kronstadt extend back to 1777 (Bogdanov et al. 2000). The Intergovernmental Oceanographic Commission's GLOSS programme (IOC 1997) have identified a set of 175 tide gauges with sea level records of at least 60 years suitable for climate research. Of these, 45 are located in the Baltic.

Sea level recorded at Landsort, Sweden (established 1886) is considered a good proxy for the volume of the Baltic Sea as a whole. The volume of barotropic exchanges through the Danish Straits can be estimated using sea level gradients in the Sound. These methods are now supplemented by current (and hydrographic) measurements from automatic stations in the straits.

Though sea state observations have been made from ships, long-term wave measurements were uncommon before the 1970's. Swedish measurements started in 1978 (B. Broman, pers. comm). Methods used have included upward looking echo sounders deployed near lighthouses (e.g. Almagrundet). Systems based on pressure transducers, as well as accelerometer buoys, are currently in use.

A.4.2.3 *Optical Properties*

A dataset consisting of more than 40,000 Secchi depth measurements, collected in the North and Baltic Seas between 1902 and 1999, was assembled by Aarup (2002). This data set is available from ICES (International Council for the Exploration of the Sea).

A.4.3 Runoff

Göran Lindström

Systematic runoff observations in the Baltic Sea Basin have been carried out since the early 1800s. The longest continuous data series is from the outlet of Lake Vänern, where observations started in 1807. Since around the mid-1800s, data is available from several other rivers, including Neva, Vistula, Neman, Daugava, Dalälven, Emajogi and Vuoksi.

Several systematic runoff datasets covering mainly the last fifty years have been collected. The BALTEX Hydrological Data Centre at SMHI in Norrköping has collected runoff data from the different national institutes. The database extends to the year 1950 and consists of data from over 200 river flow stations, most of them near the mouths of the rivers. The pan-Nordic dataset created in the CWE (Climate, Water and Energy, www.os.is/cwe) and CE (Climate and Energy, www.os.is/ce) Programmes consists of over 150 streamflow records with an average length of 84 years of daily data.

In addition, separate observation series from different countries have been utilised. These include runoff, water level and water temperature data. Some historical data concerning major floods before systematic observations started have also been available.

A.4.4 Marine Ecosystem Data

Ilppo Vuorinen, Joachim Dippner, Darius Daunys, Juha Flinkman, Antti Halkka, Friedrich W. Köster, Esa Lehikoinen, Brian R. MacKenzie, Christian Möllmann, Flemming Møhlenberg, Sergej Olenin, Doris Schiedek, Henrik Skov, Norbert Wasmund

Observational evidence used in Chap. 5 (*Climate-related marine ecosystem change*) is mainly, but not completely, based on long term monitoring data from various sources. Information on nutrients, contaminants and phytoplankton is exclusively based on data from the "Convention on the Protection of the Marine Environment of the Baltic Sea Area" – more usually known as the Helsinki Convention, or HELCOM[5]. HELCOM is also the source for most of the data used on zooplankton. Information on fish, fisheries and mammals rely on data from the International Council for the Exploration of the Sea, ICES[6] Bird data is based on a Pan-European monitoring programme established by the Royal Society for the Protection of Birds (RSPB[7]).

Below is a short summary of both HELCOM and ICES monitoring programmes based on these organisations' websites. In most cases also other, national data or data sets from different research projects have been used in Chap. 5. Their use is explained in Annex 4.4.3 below for sections of Chap. 5.

[5] www.helcom.fi

[6] www.ices.dk/ocean/

[7] www.rspb.org.uk/science/survey/2004/Europe.asp

A.4.4.1 *HELCOM*

HELCOM works to protect the marine environment 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. The Monitoring and Assessment Group (MONAS) looks after one of HELCOM's key tasks by assessing trends in threats to the marine environment[8], their impacts, the resulting state of the marine environment, and the effectiveness of adopted measures. MONAS aims to ensure that HELCOM's monitoring programmes[9] are efficiently used through horizontal co-ordination between HELCOM's five permanent working groups.

HELCOM's oldest monitoring program for physical, chemical and biological variables of the open sea started in 1979, followed in 1984 by the monitoring of radioactive substances in the Baltic Sea. Monitoring of inputs of nutrients and hazardous substances was initiated in 1998.

The HELCOM monitoring system consists of several complementary programmes:

- The Pollution Load Compilation[10] (PLC) programmes (PLC-Air and PLC-Water) quantify emissions of nutrients and hazardous substances to the air, discharges and losses to inland surface waters, and the resulting air and waterborne inputs to the sea.
- The COMBINE programme[11] quantifies the impacts of nutrients and hazardous substances in the marine environment, also examining trends in the various compartments of the marine environment (water, biota, sediment). The programme also assesses physical forcing.
- Monitoring of radioactive substances (MORS) quantifies the sources and inputs of artificial radionuclides, as well as the resulting trends in the various compartments of the marine environment (water, biota, sediment).

[8] www.helcom.fi/environment2/en_GB/cover/

[9] www.helcom.fi/groups/monas/en_GB/monas_monitoring/

[10] www.helcom.fi/groups/monas/en_GB/plcwaterguide/

[11] www.helcom.fi/groups/monas/CombineManual/en_GB/main/

- HELCOM also coordinates the surveillance of deliberate illegal oil spills around the Baltic Sea, and assesses the numbers and distribution of such spills on an annual basis.

A.4.4.2 *ICES*

ICES provides advice on the status of fish and shellfish stocks in the North Atlantic Ocean. Last year's advice can be found in the ICES Advice report series[12]. The information forming the basis of this advice is collected by marine scientists in the ICES 20 member countries. They collect data through sampling landings of fish at fish markets, sampling the amount of fish discarded from fishing boats and by targeted surveys with research vessels. The data is used by ICES Working Groups[13] to assess the status of fish and shellfish stocks. There also is a Working Group of Marine Mammal Ecology (WGMME), which has reported annual changes in marine mammal species since 2001.

This information is then collated into advice by the Advisory Committee on Fishery Management (ACFM). This Committee has representatives from each of the member countries and meets every year in summer and autumn. ICES advice covers over 135 separate fish and shellfish stocks. The advice for each stock usually includes:

- An estimate of historical trends in landings, spawning stock biomass, recruitment and fishing mortality rate;
- A description of the 'state of the stock' in relation to historical levels;
- The likely medium term development of the stock using different rates of fishing mortality;
- A short term forecast of spawning stock biomass and catch.

A.4.4.3 *Other Observational Data used in Chap. 5*

Nutrients, Contaminants (chemical pollution) and Phytoplankton

Information on sources and distribution of nutrients, contaminants (chemical pollution), and phytoplankton is exclusively based on HELCOM data, see Annex 4.4.1 above.

[12] www.ices.dk/products/icesadvice.asp
[13] www.ices.dk/iceswork/workinggroups.asp

Bacteria

Data and information on bacteria is based on research projects on both the Baltic Sea and other marine areas. Regular monitoring of bacteria biomass and production is carried out in the Bothnian Bay and the Bothnian Sea by the Umeå Marine Sciences Centre, Sweden.

Zooplankton

Zooplankton has been monitored in a variety of ways in the Baltic Sea. There is no comprehensive assessment of this data prior to 1979. However, after the commencement of HELCOM monitoring programs, the zooplankton has been a standard issue. A recently established working group under the leadership of Dr. Lutz Postel at the Baltic Sea Research Institute Warnemünde (IOW), has just made an assessment on the current status of zooplankton monitoring in the Baltic Sea.

Altogether, there are 122 regularly visited stations where vertical net samples are taken. The monitoring has been carried out once to several times per annum. Sampling gear consists of vertical Juday nets (Baltic States) and WP-2 nets, which is the HELCOM standard today. The mesh size is $100\,\mu$m. Hauls are usually taken separately from close to the bottom to halocline, halocline to thermocline, and thermocline to surface. Ship-of-opportunity techniques have been applied to zooplankton monitoring in the Baltic Sea since 1998, when the Finnish Institute for Marine Research (FIMR), in co-operation with the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) Plymouth and supported by the shipping company Transfennica Ltd, undertook Continuous Plankton Recorder (CPR) experiments.

After experimental and gear comparison studies conducted during 1998 to 2004, the Baltic Sea CPR survey is now operational on a route between Lübeck, Germany and Hamina, Finland on a monthly basis. Another one is just being set up by the Baltic Sea Regional Programme (BSRP), running across the Baltic Sea between Sweden and Poland.

Benthos

Quantitative methods to study bottom macrofauna in the Baltic Sea have been used since the early 1910s. Data used are referenced in Chap. 5. No ICES or HELCOM materials on bottom macrofauna in the Baltic Sea were used because they are not available in a form accessible for international use.

Fish

Only ICES data (see Annex 4.4.2 above) were used for fish and fisheries.

Marine Mammals

Until recently, marine mammal monitoring in the Baltic Sea was not well coordinated. An informal working group on grey seals has coordinated annual surveys since 1999. Ringed seal monitoring in the Bothnian Bay started in the 1970s and is now regularly performed by the Swedish Museum of Natural History, which also has the responsibility for Swedish harbor seal surveys. Lack of ice has caused problems for ringed seal surveys in the Gulf of Finland and Riga as aerial counts should preferably take place in peak melting season (end of April to beginning of May). Surveys in these areas have not been possible on an annual basis, and, in the Gulf of Finland, the border zone permission system has been additionally demanding.

Methodically sound data on ringed seal abundances in the Gulfs of Finland and Riga exist since the mid-1990s, and more limited data from the Archipelago Sea since 2001. A reliable trend estimate for the ringed seal exists currently only for the Bothnian Bay. Projected changes in ice climate are very challenging for ringed seal surveys in especially the southern breeding areas, as well timed aerial surveys of seals hauled on ice have been the standard method. Harbor porpoise abundances have been only sporadically estimated in the Baltic Sea. The extensive SCANS (1994) and SCANS II (2005) surveys (biology.st-andrews.ac.uk/scans2/) have only partial coverage, and the number of observed animals in transects is necessarily very small because of limited numbers.

Marine mammals data are based on information from the Working Group on Marine Mammal Ecolgy under the auspices of ICES[14], which has reviewed information on marine mammal species since 2001, and on advice on seal and harbor porpoise populations in the Baltic marine area (ICES 2005). There are also national monitoring data included in the analysis. An expert group on seals has also recently been established in HELCOM, and analysis initiated by this group will be available in the coming years.

Sea Birds

The Pan-European Common Bird Monitoring Project was launched in January 2002 by the European Bird Census Council[15]. Its main project goal is to use common birds as indicators of the general state of nature using scientific data on changes in breeding populations across Europe. It is a collection of national monitoring programs. In 2006, 20 countries reported monitoring results of 244 species. In this review published results of Swedish[16] and Finnish[17] monitoring programs and those directed to Baltic marine birds by Danish authorities were used. Phenological changes were described based on unpublished databases obtained from the Jurmo and Hanko bird stations (run by Turku Ornithological Society and Helsinki Ornithological Society Tringa, respectively) and phenology programs of ornithological societies of Turku and Kemi-Tornio (Xenus).

A.4.5 Observational and Model Data for Anthropogenic Input

Mikhail Sofiev

Two most important sources of information about the atmospheric pollution of the Baltic Sea Basin are the EMEP (European Monitoring and Evaluation Program) and HELCOM programmes, which provide regular assessments of concentration and deposition of several species over Europe and over the Baltic Sea Basin, respectively. Databases of these programmes contain both observations and model data (the latter ones are based on EMEP models). An advantage of these datasets is their internal consistency and long period of time covered.

However, the data quality strongly depends on considered species. Some of the species are comparatively well studied and there are both observational and model assessments of their input to the Baltic Sea, with uncertainties to be within a factor of 2 (first of all, oxidised nitrogen and ammonia). Some others are less known and available

[14] www.ices.dk/iceswork/wgdetailace.asp?wg=WGMME

[15] www.ebcc.info/

[16] www.biol.lu.se/zooekologi/birgmonitoring/Eng/index.htm

[17] www.fmnh.helsinki.fi/english/zoology/vertebrates/info/birds/index.htm

estimates have an uncertainty as large as a factor of 3 to 10 (most of toxic metals). Finally, some species are known poorly and the corresponding estimates are based on crude considerations showing an order of magnitude as the best or even serving only as indicators of presence of the effect (most of persistent multi-media pollutants). Therefore, the estimates from one source have to be cross-verified with (semi-) independent sources of information, such as dedicated scientific studies. Such studies are usually more concentrated on specific problems and processes and do not provide that universal and long-term datasets as the EMEP/HELCOM ones: they cover limited period of time, possibly only part of the sea, etc. Generalization of their output might lead to large uncertainties in the final estimates and thus has to be done with care.

Due to permanent development of all models, the estimates given by formally the same model in different years can vary significantly. For example, the nitrogen deposition onto the Baltic Sea surface estimated by Bartnicki et al. (2001) and Bartnicki et al. (2002) for the same year 1998 using the same EMEP Lagrangian model differ by as much as 36%. Similar concerns are valid for other modelling sources of information, although the corresponding long-term data are rarely available. Similar problems with observational data are discussed in Annex 5. Therefore, a special attention has to be paid to a synchronous consideration of model, observations and their mutual fitting. Should several estimates are available for the same period made by the same tool the chronologically last ones should be taken.

A.5 Data Homogeneity Issues

Raino Heino

In practice it is difficult to obtain long homogeneous data records. Various factors, such as changes in (i) instruments and their exposure, (ii) observation times and averaging methods, and (iii) observation sites and their environments, introduce inhomogeneities into the data.

The inhomogeneities of climatological time series may be in the form of (i) impulsive (or step-like) change of central tendency, (ii) progressive change (or trend) or (iii) some kind of oscillation. Most of the inhomogeneities fall typically in the first category of impulsive change (including changes in instrumentation, observers or averaging methods and station relocations) and typically alter the average value only, usually leaving the higher statistical moments unchanged. An inhomogeneity, however, may also contain changes in variability or in other distribution parameters. In practice, the inhomogeneity of a longer-term time series is usually a combination of many factors.

Climatic records, of course, contain variations that are due to several causative factors, such as variations in incoming solar radiation and changes in atmospheric transparency, which may take any of the above forms. Climatic records, at least those that are in their original form, are normally complex mixtures of both apparent and real variations. It is obvious that the apparent variations should be detected and eliminated before proceeding too far in the detection of real variations and their causes.

Several statistical methods to study the homogeneity can show whether any bias is included in the data records. However, these do not provide any indication of its location or cause. Information on the history of the measurements and stations is thus essential for a successful study of the data inhomogeneity. The importance of this "metadata" should also be emphasised.

A straightforward way to identify possible points of inhomogeneity in records is a careful study of the "methodological history" of the country in question (e.g. country-wide changes in instrumentation or times of observations and averaging methods). The background of each observing station should also be checked from station inspection reports or other relevant documents. Any changes in instrumentation or observing methods occurring at a particular station should be checked as a possible source of inhomogeneity.

Even if the observations were free of instrumental or observational inhomogeneities, the records may still show local step-like or progressive changes. Major, as well as some minor relocations of the stations, typically introduce severe inhomogeneities. In addition to horizontal moves, a station relocation often includes a change in elevation and environment. Information on station histories is of primary importance to the homogenisation process and can only be assessed station by station.

Progressive changes in the surroundings of the observation station also represent a frequent source of inhomogeneity. Many of them are connected with urbanisation and/or industrialisation and they include (i) increase in artificial heat (thermal pollution), (ii) increase in gases, smoke and dust (atmospheric pollution) and (iii) decrease in natural surfaces, evaporation and snow.

In addition to urban and industrial effects, there are many other obvious consequences of man's activities for local climates (e.g. de/reforestation, artificial lakes, etc.). Their detection and correction, however, are more difficult, because these, like real variations in climate, are generally trend-like. Apparent cyclic changes are also generally gradual and hidden amongst the real changes.

A.5.1 Homogeneity of Temperature Records

The "true" temperature of the air (i.e. the thermometer bulb in thermodynamic equilibrium with the surrounding air) cannot be measured realistically in free air because of the effect of direct, diffuse and reflected solar radiation as well as longwave radiation from the ground and surrounding objects. Thus, thermometers need to be sheltered from radiation disturbances as well as from rain and snow. However, any shelter introduces its own disturbing factors.

Although the first international meteorological congress (held in Vienna, 1873) took a somewhat pessimistic view concerning the achievement of uniform, reliable arrangements for temperature measurements, the majority of temperature observations have been made in sufficiently similar and uniform ways to guarantee reasonably comparable results in time and space. It is also noteworthy that the present regulations for temperature measurements do not differ much from the situation in the latter half of the 1800s.

Information on station relocations is of primary importance in estimating the homogeneity of temperature records at individual stations. A site change normally causes systematic changes in temperature. Parallel observations would help to estimate the corrections needed. Unfortunately such measurements have been more an exception than the rule. Therefore, comparisons between the new and old sites have to be made with other stations, which are usually quite distant. Thus the results of comparisons, at least in the case of individual years, cannot be wholly reliable.

A site change generally involves more than a geographical shift in location, however. In many cases, a change in height or a modification in the screen/shelter may also occur. In addition, although the station might have remained at the same location (according to the coordinates and height information), minor relocations of the thermometer or screen sometimes take place, and may have an even larger effect than a major relocation.

The effects of site changes on a record are usually found alongside urbanisation effects; the two sometimes counterbalancing each other, especially if the airport is situated near the sea or a large lake.

Considering that some of the longest-term (> 100 years) Baltic Sea Basin temperature records are combinations of town and airport records, correcting for station relocations to airports in the 1940 and 1950s was one of the major steps in the homogenisation process. In all cases the correction applied was negative on an annual basis, but for monthly means the corrections were more complicated. In addition, all these records contain one or two corrections due to relocations of earlier town sites.

Despite relocations to airports, some of the longer continuous observational records still come from towns. These records are thus expected to contain a local apparent trend attributable to the development rate of the town.

A.5.2 Homogeneity of Precipitation Records

Measurements of precipitation are highly dependent on the structure of the precipitation gauge and its exposure, and consequently introduce more complications than temperature measurements. The records of precipitation amounts are always underestimates of the real amounts and they can usually be expected to contain great inhomogeneities in both space and time. In addition, most of the random-type inhomogeneities are also negative, resulting from reduction in the catch (e.g. due to a leaking gauge, spilling of water).

Of particular concern is the measurement of snowfall from conventional gauges, where large errors are known to occur. When precipitation errors are expressed as a percentage of the true precipitation, they tend to be largest in windy high latitude climates.

The principal errors in measuring precipitation are due to the following three causes: (i) wetting, i.e. the loss when transferring precipitation from the gauge (ii) evaporation from the gauge and (iii) wind (aerodynamic) effects.

The first loss is an instrument error and can be estimated quite accurately for different amounts of precipitation. Until now, very few of such corrections (see e.g. Hantel and Rubel 2001 and Annex 1.2.3) have been applied to the Baltic Sea Basin precipitation data and thus changes in the wetting error are due only to gauge changes. Evaporation from the gauge depends on inter alia instrument design and material, location of the station and other meteorological parameters (e.g. air temperature, saturation deficit, wind). This error is not accounted for in the Baltic Sea Basin routine precipitation records, either. The largest errors in precipitation measurements are due to aerodynamic causes.

The effect of instrumental errors on the homogeneity of long-term precipitation records can be considerable for winter precipitation, although the magnitude of the error depends strongly on the amount of precipitation occurring in solid forms and on the openness of the observing site. Since this information was taken into account only very crudely, the corrections should be regarded as preliminary until more exact information is available (especially regarding the openness of each station).

Precipitation measurements are extremely dependent on the local exposure of the gauge, so any changes in measuring sites or their surroundings may introduce severe inhomogeneities into the data records. This section describes relocations to airports, other types of relocations and urbanisation.

A.5.3 Homogeneity of Other Climatic Records

Generally speaking, **air pressure** records are likely to have been made with sufficiently good instruments and exposures. Relocations of stations as well as environmental changes have no significant effect on pressure records, providing that the exact heights of the barometers (plus temperature data) are available. Specific points to note in the evaluation of the homogeneity of pressure records include (i) the date of introduction of the correction to standard gravity, and (ii) reduction to mean sea-level and information on the barometer height of each station.

Wind observations have been based on various wind vanes and anemometers. However, the most serious sources of inhomogeneities in long-term records arise from the relocation of observation sites or from environmental changes in the vicinity of stations. Routine wind observations measured about 10 m above the surface are very sensitive to local topography and obstacles. Any changes in these conditions should be checked as a possible break in data homogeneity.

Observations of total **cloudiness** are expected to contain serious inhomogeneities. A change in the estimation scales should also be noted when using the data. The considerable inhomogeneities that occur in individual records are due to the subjectivity of cloudiness observations as well as to the openness of the station.

It is also possible to study changes in cloudiness with the help of measurements of **sunshine** duration. Indeed, sunshine information provides a better indication of the incoming radiation to the surface than cloudiness, because the cloudiness observations do not discriminate between different types and thicknesses of cloud, which can have a large effect on the transmission of radiation. Compared with the other climatic elements, the inhomogeneities of sunshine duration data, however, are relatively small and the data since the 1960s are quite reliable.

The examples selected above are from atmospheric elements, but terrestrial and oceanographic elements contain similar types of inconsistencies.

A.6 Climate Models and Scenarios

Burkhardt Rockel

Climate models are based on mathematical equations that describe the physical behaviour and evolution of the atmosphere and ocean, including more or less complex parameterisations of physical processes. With these models, future climate can be predicted and past climate can be hindcasted to a certain precision. Besides the effect on the accuracy that lies in the concept of the model itself (e.g. numerical schemes, parameterisation of processes), there are factors which influence the results of the model simulations but cannot be predicted by the model on its own. These factors are called “external forcings” and can be of natural (e.g. changes in incident solar radiation due to variations in the activity of the sun, volcanic eruptions) or anthropogenic type.

The natural external forcings have been, at least to some extent, known for the past centuries and can be used in model simulations of the past climate. However, they are unknown for the future and can hardly be predicted. Anthropogenic external forcings are also unknown for future times, but they can at least be assessed by assumptions of different kinds of future behaviour of man. The Intergovernmental Panel on Climate Change (IPCC)

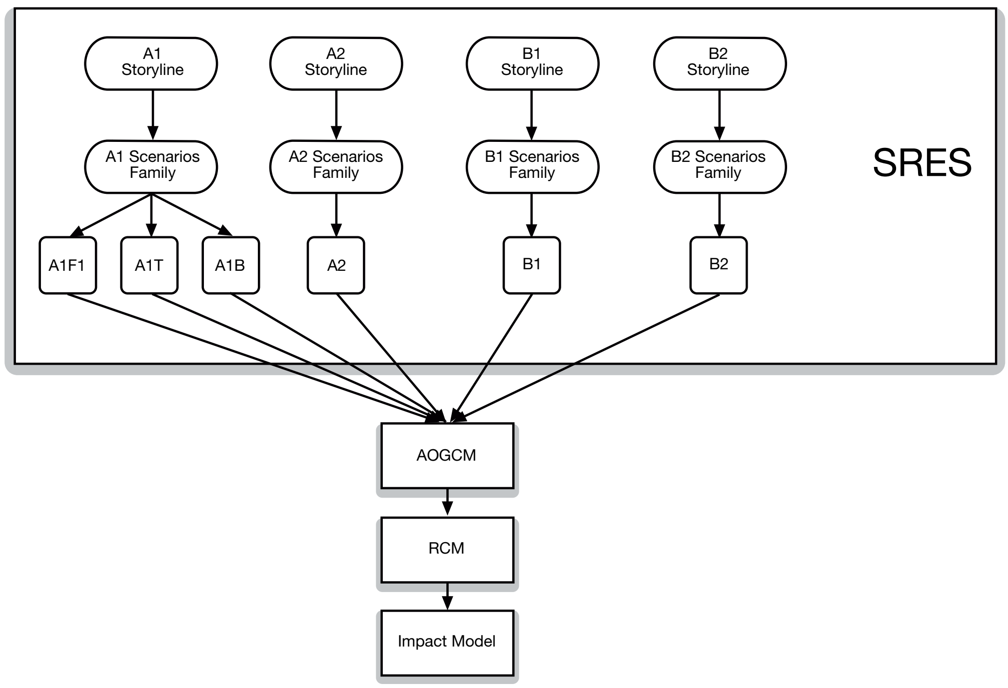

Fig. A.38. SRES scenarios and climate models

developed different kinds of qualitative assumptions, called story lines, for the future and deduced several quantitative future scenarios published in the Special Report on Emission Scenarios (SRES). Figure A.38 shows a schematic sketch for the relationship between story lines, scenarios, and climate models. In the following sections a concise overview is given on scenarios and climate models.

A.6.1 The SRES Emissions Scenarios

Emissions scenarios are plausible representations of the future development of emissions of greenhouse gases and aerosol precursors, based on coherent and internally consistent sets of assumptions about demographic, socio-economic, and technological changes in the future.

The SRES scenarios (Nakićenović and Swart 2000) were built around four narrative storylines, A1, A2, B1 and B2, each based on different assumptions about the factors that drive the development of human society in the 21st century. Several more detailed scenarios were formulated within each storyline. Six of these, commonly referred to as A1FI, A1T, A1B, A2, B1 and B2, were chosen by the IPCC as illustrative marker scenarios. In general, in the world described by the A storylines people strive after personal wealth rather than environmental quality. In the B storylines, by contrast, sustainable development is pursued.

A.6.1.1 *A1FI, A1T and A1B Scenarios*

The A1 storyline describes a world of very rapid economic growth and efficient international cooperation. Technological development is rapid and new innovations are distributed to developing countries faster than today. Increasing economical well-being leads to decreasing fertility in the developing world, and the global population declines to 7.1 billion in the year 2050 after peaking at about 8.7 billion after the year 2050. The A1FI, A1T and A1B illustrative scenarios describe alternative directions of technological change in the energy system, and are therefore quite different in terms of the greenhouse gas emissions. In A1FI, energy production remains highly dependent on fossil fuels throughout the century, whereas A1T represents a rapid migration toward non-fossil energy sources. A1B is intermediate between these extreme cases.

A.6.1.2 *A2 Scenario*

In the A2 storyline scenarios, the world is characterised by economical blocks that are more inclined to defend their own special interests than to co-operate with each other. As a result, economical growth is slower than in A1, particularly in the developing world. The distribution of new environmentally efficient technologies to the developing world is also slower. The global population increases continuously, reaching 15 billion in the year 2100.

Although the *per capita* economic growth is relatively slow, the increasing population and slow introduction of non-fossil energy sources lead to a large increase in global greenhouse gas emissions.

A.6.1.3 *B1 Scenario*

The B1 storyline is characterized by efficient international co-operation and rapid distribution of new technologies and by the same evolution of global population as A1. However, technological development is driven more strongly by environmental values than in the A1 and A2 storylines. Economical growth is slightly slower, and the gap between the developing and the industrialised world decreases more slowly than in A1, but the introduction of clean and resource-efficient technologies is faster. Furthermore, there is a rapid change in economic structures toward a service and information society. As a result of these changes, greenhouse gas emissions are reduced below the present-day level by the end of the 21^{st} century.

A.6.1.4 *B2 Scenario*

The B2 storyline scenarios share features from both A2 and B1. International co-operation is less efficient and the distribution of new technologies is slower than in A1 and B1. The global population increases continuously but less rapidly than in A2, reaching 10.4 billion in 2100. Like B1, the B2 scenario is also oriented towards environmental protection and social equity, but the development of environmentally friendly technologies proceeds more slowly than in B1. As a result, greenhouse gas emissions continue to grow throughout the 21^{st} century, although at a substantially slower rate than in the A2 and A1FI scenarios.

A.6.2 Climate Models

The behaviour of the climate system can be studied and simulated by using various types of climate models. The results represented in this assessment report are mainly based on simulations made with coupled atmosphere–ocean general circulations models (AOGCMs or GCMs, see also Chap. 3) and regional climate models (RCMs).

A.6.2.1 *Atmosphere–Ocean General Circulation Models (GCMs)*

GCMs are the most advanced tool developed for studying climate change on global and large regional scales. These models simulate the three-dimensional time evolution of atmospheric and oceanic conditions based upon physical laws expressed by mathematical equations. The submodels for the atmosphere and the ocean interact with each other and with separate model components simulating the sea ice and land surface conditions. The atmospheric components of the GCMs used for this assessment report typically have a horizontal resolution of about 300 km with some 10 to 30 levels in the vertical. The resolution of the ocean models is similar or somewhat better. Some but not all GCMs use so-called flux adjustments to artificially add or remove energy, freshwater and momentum at the atmosphere-ocean interface. Flux adjustments improve the simulation of present-day climate, but many modellers find them undesirable because of their unphysical nature. Although the adjustments are kept constant with time, they may also indirectly modify the simulated climate changes. However, there is little evidence of any systematic differences in climate change between flux-adjusted and non-flux-adjusted models. A list of global models referred to in this book is provided in Table 3.1.

A.6.2.2 *Regional Climate Models (RCMs)*

RCMs are used to simulate the climate in some area with a higher horizontal resolution (typically 20–50 km) than is computationally feasible in global GCMs. This allows a more detailed representation of the local physical geography, such as mountain ranges and the land-sea distribution, as well as a more detailed representation of weather systems. An RCM only covers a limited part of the world and is therefore dependent on boundary conditions provided by a global climate model. For this atmospheric quantities (typically temperature, wind, moisture and cloud water) and surface quantities (typically pressure, temperature, moisture, snow amount, sea ice and others) of the GCM are at first interpolated onto the RCM grid. These boundary data are then used in the RCM in mainly two ways. The most common one is

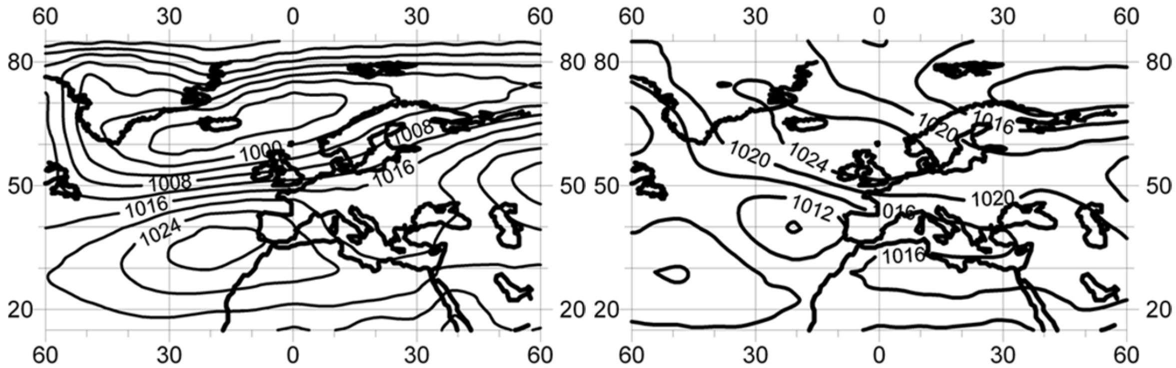

Fig. A.39. Mean sea level pressure SLP (hPa) in the North Atlantic – European sector (20° N to 80° N, 60° W to 60° E) during a positive (*left*, January 1995) and a negative (*right*, January 1963) phase of the NAO. SLP data from CRU (Jones 1997)

the lateral boundary formulation by Davis (1976), where a weighted mean of GCM and RCM data replaces the actual RCM data in a zone of typically 8–10 grid boxes at the lateral boundaries of the RCM area. This zone is called boundary or sponge zone. The weight for the GCM data decreases from 1 at the outermost grid boxes to 0 at the innermost of the boundary zone. The weight for the RCM is vice versa. Additional information of the GCM can be transferred to the RCM by the spectral nudging method (e.g. Waldron et al. 1996; von Storch et al. 2000; Miguez-Macho et al. 2004). In a first step GCM and RCM grid data are transferred into spectral data. The low wave numbers of the RCM data fields are then replaced by those of the GCM. In the last step the combined spectral data are transferred back into grid data. The surface height and land/sea mask of a RCM grid box are determined from high resolution observational data sets. A list of regional models referred to in this report is provided in Table 3.2 (Chap. 3)

GCMs and RCMs provide future assessments of quantities like temperature, wind, precipitation and so forth. However, they cannot describe the influence of these changes e.g. on the environment or the consequences for agriculture. This can be performed by impact models (e.g. crop models, hydrology models) which generally run on a local scale and take the quantities provides by the climate models as input.

A.7 North Atlantic Oscillation and Arctic Oscillation

Joanna Wibig

The North Atlantic Oscillation (NAO) is a leading mode of circulation variability over the North Atlantic mid-latitudes. At sea level it manifests itself as a large scale mass alternation between the Subtropical High and the Polar Low (Walker 1924; van Loon and Rogers 1978). Because in the Northern Hemisphere (NH) air flows counterclockwise around cyclones and clockwise around anticyclones, the high pressure gradient between the Icelandic Low and the Azores High results in strong westerly air flow over the eastern North Atlantic and Europe (Fig. A.39; January 1995). In the negative phase of the NAO, both pressure systems are weak and so are the westerlies. Complete reversal of the pressure pattern, with pressure near Iceland higher than in the vicinity of the Azores, sometimes occurs but is very rare. Such a situation is connected with easterly winds in the midlatitudes of the North Atlantic, blocking episodes and extremely severe winters in Europe (Fig. A.39, January 1963).

There is a great variety of concepts on how to measure the strength of the NAO. The two point normalized pressure difference is the one most often used. Rogers (1984) used the SLP series from Ponta Delgada at the Azores and Stykkisholmur or Akureyri at Iceland, Hurrell (1995) made use of Lisbon and Stykkisholmur (Fig. A.40). Jones et al. (1997) used series from Gibraltar and compiled records from the vicinity of Reykjavik and extended the NAOI record back to 1821.

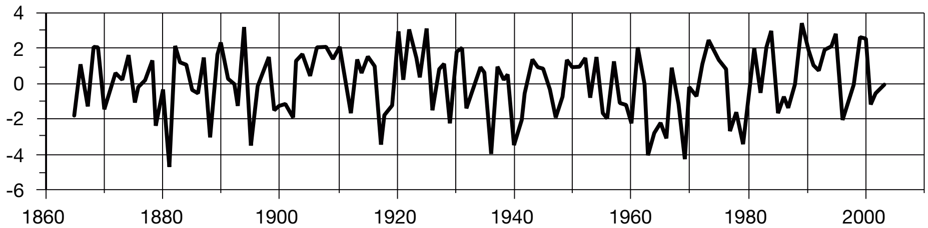

Fig. A.40. Winter (DJFM) index of the NAO based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland since 1864. The SLP anomalies at each station were normalized relative to the 120-year period 1864–1983. NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA, see Hurrell (1995)

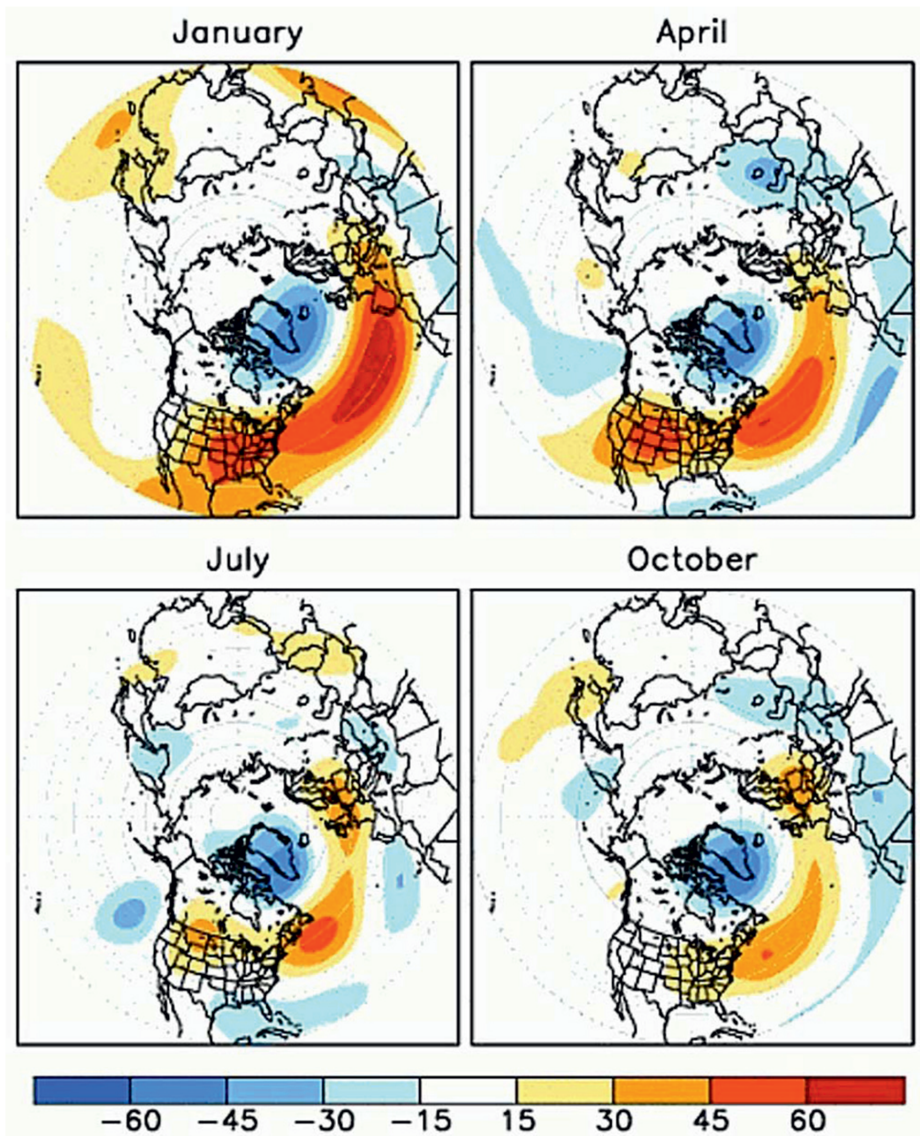

Fig. A.41. The monthly patterns of NAO presented as maps of correlation coefficients (×100) between principal component related to NAO and geopotential heights at the 500 hPa level (from www.cpc.ncep.noaa.gov/data/teledoc/; see also Bell 2007)

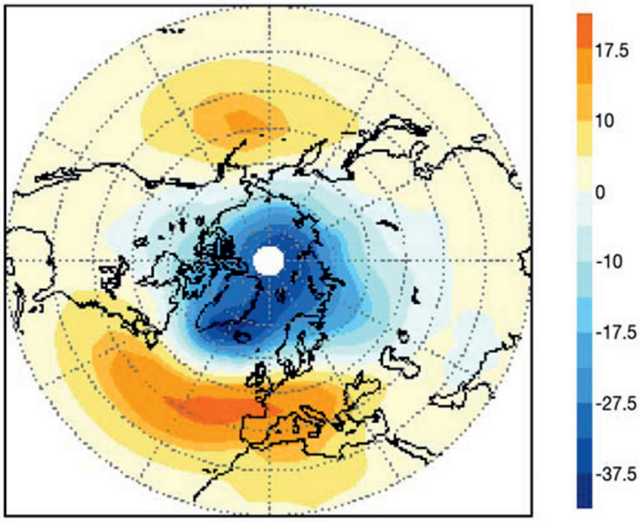

Fig. A.42. The surface signature of the Northern Hemisphere annular node (NAM). The NAM is defined here as the leading EOF of the Northern Hemisphere monthly mean 1000 hPa height anomalies. Units are m/std of the principal component time series (adapted from Thompson and Wallace 2000)

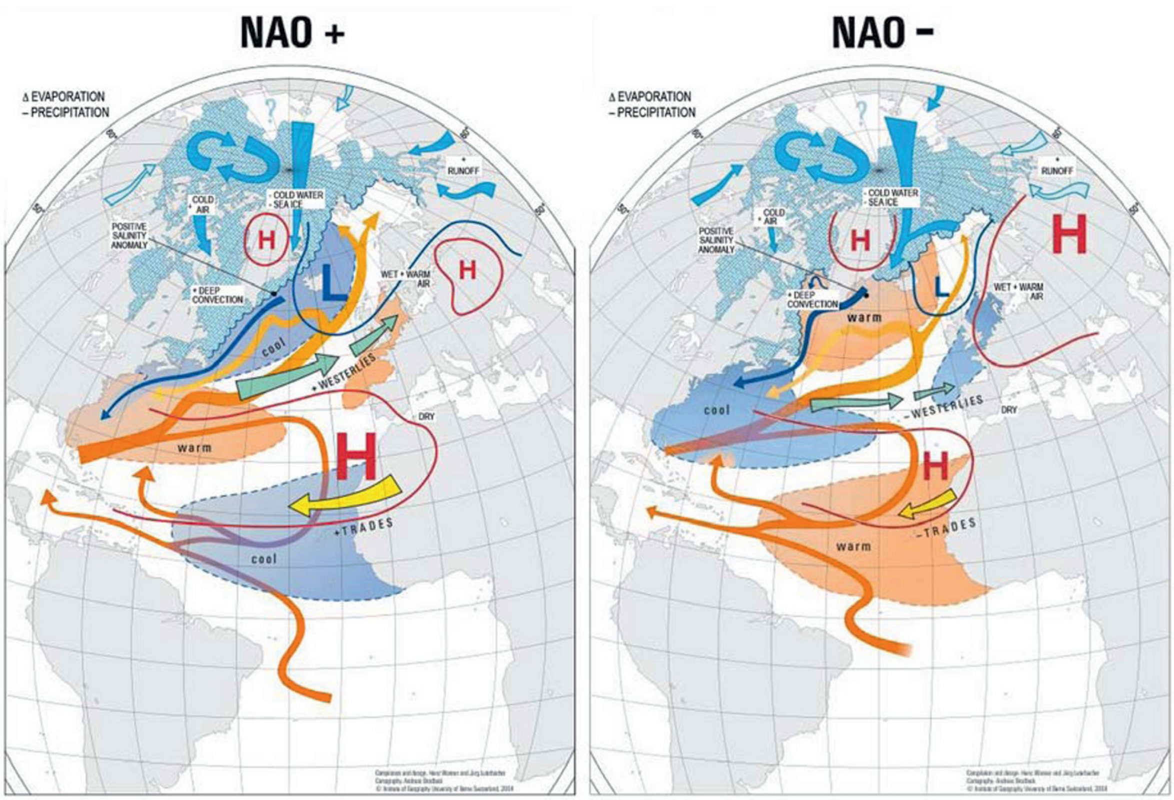

Fig. A.43. Weather conditions during positive (*left*) and negative (*right*) phase of the NAO (from Wanner et al. 2001)

The NAO can also be distinguished as an atmospheric teleconnection pattern. It is evident throughout the year in the NH, but its amplitude is largest during winter, when it accounts for about one-third of total SLP variance over the North Atlantic. A lot of different methods allow for identification of teleconnection patterns (Wallace and Gutzler 1981; Barnston and Livezey 1987). The NAO mode can be identified throughout the year, although its spatial pattern varies from season to season (Fig. A.41). It reveals the seasonal shift of the "centers of action", because the eigenvectors are constructed to explain maximum variance of pressure or geopotential height field.

Recently, another pattern, closely related to the NAO has been distinguished (Thompson and Wallace 1998, 2001). It is known as the Arctic Oscillation (AO) or Northern Hemisphere annular mode (NAM). AO is defined as a leading eigenvector of the monthly sea level pressure (SLP) field north of 20° N weighted by area (Fig. A.42). The spatial pattern of the AO in its positive phase has a strong low pressure center over the Arctic and a zonal high pressure band in the subtropics with two distinct centers, over the North Atlantic and the North Pacific. The spatial patterns of AO and NAO are very similar in the Atlantic sector. Some authors state that the NAO is a regional representation of the AO related with a more global pattern in the NH extratropics (Delworth and Dixon 2000). Others suggest that the NAO and AO represent the same phenomenon, for which different descriptions of dynamical processes are used (Wallace 2000).

The positive and negative phases of the NAO are associated with different spatial distributions of temperature and precipitation anomalies, not only across Europe, but across the whole NH extratropics.

The well developed Icelandic Low results in a flow of warm and wet air into north-western Europe whereas cold and relatively dry air comes to eastern Greenland. In the positive phase of the NAO in winter, temperature is above normal in all of Europe except its southern part, much of northern Eurasia and the central and western United States (US). The below normal temperature occurs in the northeastern part of the North America, southern Europe and northern Africa and over the Northern Pacific (Fig. A.43).

The NAO exerts a strong influence on winter precipitation also. In its positive phase above normal precipitation occurs in northern Europe and the eastern US, whereas a water deficit occurs in southern Europe, northern Africa and the northeastern part of North America. The storm track across the North Atlantic is shifted north. During the negative NAO phase, the storms wander more southerly along the Mediterranean region, bringing above normal precipitation to the Mediterranean area and Black Sea, whereas northern Europe then has precipitation below the average.

The NAO exhibits considerable seasonal and interannual variability, with prolonged periods of domination of positive or negative phases exerting a strong influence on different components of the ocean–atmosphere–sea-ice system: the localisation of warm and cool pools in the North Atlantic; the intensity of the subtropical and subpolar gyres, the Gulf Stream, the Mid-Atlantic and West Norwegian currents; the formation of sea-ice in the north (also in the Baltic Sea); runoff from big Siberian and Canadian rivers and the freshwater balance of the polar basin and many others (Wanner et al. 2001).

A.8 Statistical Background: Testing for Trends and Change Points (Jumps)

Hans von Storch, Anders Omstedt

A fundamental conceptual problem with trends and change points is that the statistical expression "a significant trend" or "a significant change point" is understood by some not as formally defined but by the everyday language meaning of the words "change point" and "trend" (Annex 8.1). There are well established procedures in the statistical literature to determine whether a given limited time series contains such instationarities as change points and trends. These tests almost always assume serially independent data, which for most physical and ecological environmental variables is not fulfilled (Annex 8.2). Therefore, pre-whitening and Monte Carlo methods need to be employed (Annex 8.3).

A.8.1 A Trend or a Change Point – a Property of a Random Process Generating Limited Time Series

Two key concepts in the description of non-stationary time series are jumps, or change points, and trends. Intuitively, these terms are quite clear, since they have a meaning in every day language. For instance, in the American Heritage Dictionary, the word "trend" is explained as "the general direction in which something tends to move" and "a general tendency or inclination", while a "change point" is explained as "a point of discontinuity, change, or cessation".

The meanings of the everyday language expressions imply changes beyond the range of recorded experience, in particular into the future. A trend means that we see the system of interest to have undergone systematic changes in the recent, documented past, and it is assumed that this tendency will continue for some time into the foreseeable future. It is often a trend "towards" something, e.g., higher prices or warmer temperatures. Similarly, if a development has a change point, then the new state will continue into the future, at least for some time. That is, in this language, the two terms contain a prediction of the foreseeable future.

The statistical definition of these terms is different, and the continuous blending of the two often causes difficulties in discussions about changing conditions.

In statistical thinking, a time series $X(t)$ of length T has a **trend** if

$$X(t) = \alpha t + n(t) \quad \text{with} \quad t = 0, \ldots T$$

is a valid description of $X(t)$; here α is a free parameter, t usually the time, and $n(t)$ a stationary random variable[18]. "Stationary" means that the random process generating $n(t)$ has the same properties for all considered t. Obviously, $X(t)$ is not stationary if $\alpha \neq 0$. Note that nothing is assumed about a state of $X(t)$ at times t prior to 0 or after T.

The time series $X(t)$ has a change point at time $t^\star$ if

$$\begin{aligned} X(t) &= \alpha_1 + n(t) \quad \text{for} \quad t < t^\star \quad \text{and} \\ X(t) &= \alpha_2 + n(t) \quad \text{for} \quad t \geq t^\star \end{aligned}$$

is a valid description[19]. Here, α_1 and α_2 are constants and $n(t)$ a stationary process. Again, nothing is implied for the state of X prior to 0 and after T.

The validity of the expressions for a trend or a change point is examined in the formalism of a statistical test, which features the properties "no trend" or "no change point" as null hypothesis and the properties "non-zero trend" or "existence of a change point at $t^\star$ with $0 < t^\star < T$" as alternative hypothesis.

To do so, an arithmetic expression $S(X,T)$ of the $T + 1$ data points $X(0)$ to $X(T)$ named "test statistics" is derived, which results in large numbers if the alternative hypothesis prevails and small numbers if the null hypothesis is a consistent description[20]. Then, the distribution of S is derived for the population of cases which satisfy the null hypothesis. If S_{95} is the 95%-ile of the distribution of S[21] then the null hypothesis is rejected if $S(X,T) > S_{95}$.

Rejecting the null hypothesis means to accept the alternative hypothesis. Note that the alternative hypothesis is not necessarily the negation of the null hypothesis. The latter is

$$X(t) = n(t)$$

so that the rejection would be

$$X(t) \neq n(t)$$

or "$X(t)$ is not a stationary process", which is not equivalent to either

$$\begin{aligned} X(t) &= \alpha t + n(t) \quad \text{or} \\ X(t) &= \alpha_1 + n(t) \quad \text{for} \quad t < t^\star \quad \text{and} \\ X(t) &= \alpha_2 + n(t) \quad \text{for} \quad t \geq t^\star \end{aligned}$$

It needs other arguments, preferably physical or ecological ones, to conclude that these specific alternative hypotheses are a rational choice. Also, the definition of S should be geared towards large values, when the specific alternative hypothesis is valid.

Rejection of the null hypothesis or acceptance of the alternative hypothesis does not imply that the trend or the state after the change point will continue beyond T. Instead it means that we assign the process, which has generated the finite time series the property described by the alternative hypothesis. Thus, if we would generate another limited time series, this would also have a trend, or a

[18] This is a linear trend in the mean. Clearly, one may construct also trends in the dispersion (variance) and other statistical parameters. Also, one may assume different forms of the trend, such as a cyclic $X(t) = sin(\alpha t/P) + n(t)$ or any other form.

[19] In principle this may be seen also as a "trend" with a step-function as trend. One could also define change points in terms of variability and other statistical properties.

[20] More precisely, S should attain numbers in a certain numerical range, when the data are inconsistent with the null hypothesis, and another range if they are consistent. For the sake of simpler language we assume that the former range contains small numbers, and the later large numbers.

[21] Or any other high percentile, which is subjectively chosen as sufficient to consider the data $X(0) \ldots X(T)$ to be inconsistent with null hypothesis.

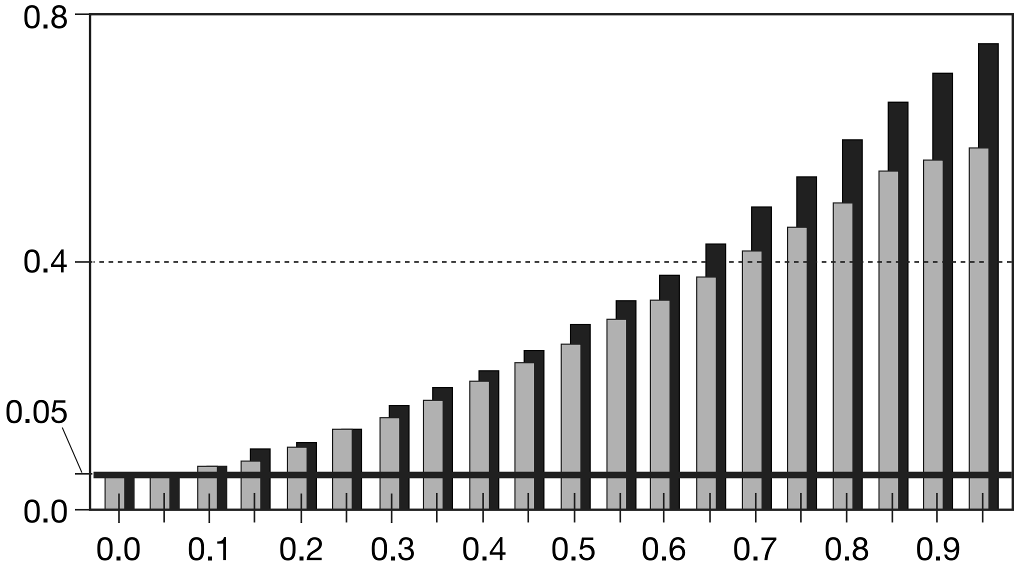

Fig. A.44. Rate of false rejections of the null hypothesis "Time series $X(1)\dots X(T)$" contains no change point" with $T = 100$ (*light*) and $T = 500$ (*black*), when $X(t) = n(t)$ is generated by a red noise process with a memory term l given by the horizontal axis (adapted from Busuioc and von Storch 1996)

change point, in the limited time $[0, T]$. The random process, or the "dice" we are rolling, is generating a sequence of $T+1$ numbers $X(0)\dots X(T)$. If we "roll the dice" again, then not the numbers $X(T+1)\dots X(2T)$ are generated but a completely independent sequence of $T+1$ numbers.

A.8.2 Serial Dependency and its Effect on the Accuracy of Conventional Tests

There are a number of conventional test statistics, and their distributions, given in the statistical literature. For instance the Pettit-test (Pettit 1979) is often used in meteorological quarters, while the Mann-Kendall text (Mann 1945; Sneyers 1975) is popular for detecting trends. Other non-parametric trend tests are the Cox and Stuart test, the Daniel test and others (refer to e.g. Conover 1971). Thus, it seems that the detection of change points and trends should not pose a methodical challenge as standard routines can be used – it seems.

However, while this may be true in many applications, it is not true in most climatic applications. The reason is that these standard approaches assume that there is no serial dependence among the $n(t)$, i.e., that $n(t)$ and $n(t+\Delta)$ are independent. Because of memory in the physical (or ecological) processes, this condition is hardly fulfilled.

Instead, the lag correlation

$$c(\Delta) = \frac{1}{t-\Delta}\sum_{t=0}^{T-\Delta} X'(t)X'(t+\Delta)$$

is in most cases not zero, even if small[22] The violation of the condition of serial independence makes the test to reject a correct null hypothesis more frequently than formally stipulated by the adopted percentile S_{95}[23].

Monte Carlo experiments, in which serially correlated data without a trend or without a change point are examined with the Mann-Kendall test (Kulkarni and von Storch 1995) and with the Pettit-test (Busuioc and von Storch 1996), give an impression of how serious the problem is.

For instance, if the serial correlation is related to a short term "red" memory, i.e.,

$$n(t+1) = \lambda n(t) + m(t)$$

with a constant "memory term" λ and a stationary $m(t)$[24], the rate of false rejections, which was

[22] X' represents the normalized series of X, centered and rescaled to variance one.

[23] The test becomes "liberal" – and thus plainly false.

[24] This "red noise" is a so-called autoregressive process of first order; it is equivalent to a first order differential equation with a linear damping and a random forcing; see also von Storch and Zwiers, 2002. If $\lambda = 0$ then there is no serial correlation and the noise is called "white"; $m(t)$ is assumed to be white noise.

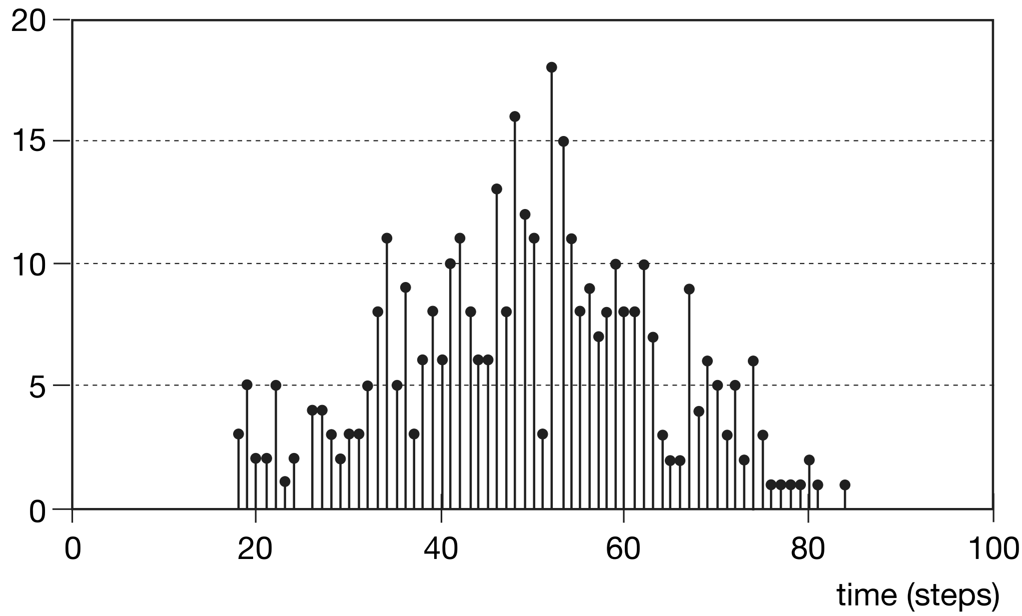

Fig. A.45. Frequency (in per mille) of false detections of a change point at the $t^\star$ values given at the horizontal axis. 1000 Monte Carlo cases have been evaluated, all generated by a linear trend overlaid with white noise ($\alpha = 0.005$; variance of noise = 1) (adapted from Busuioc and von Storch 1996)

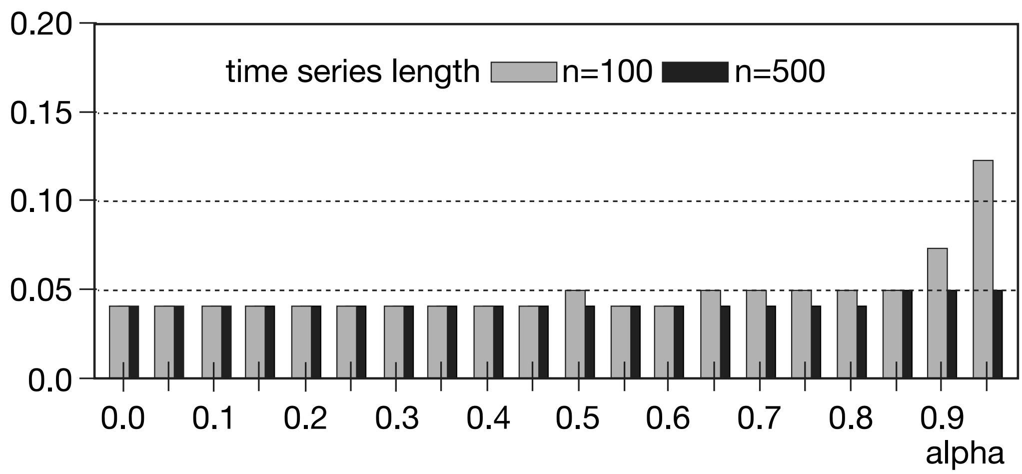

Fig. A.46. Rate of false rejections of the null hypothesis "Time series $X(1)\ldots X(T)$ contains no change point" with $T = 100$ (*light*) and $T = 500$ (*black*), when $X(t) = n(t)$ is generated by a red noise process with a memory term l given by the horizontal axis, when the Pettitt-test is applied to the pre-whitened, i.e., applied to $Y(t)$ instead of $X(t)$ (adapted from Busuioc and von Storch 1996)

stipulated to be 5%, of the Pettit-test dealing with the detection of change points, is markedly larger than 5% even for small $\lambda \geq 0.15$ (Fig. A.44).

For large λ, say 0.8, in more than 50% of applications of the Pettit test to a series without a change point and without other instationarities, the test indicates falsely that a change point is contained in the data. A similar demonstration was provided by Kulkarni and von Storch (1995) for the case of the Mann-Kendall test of linear trends (not shown).

When the serial correlation is related to a linear trend, similarly false assessments of the alternative hypothesis happen. Figure A.45 shows the result for 1,000 cases of series with a trend given by

$$X(t) = \alpha t + n(t)$$

(Busuioc and von Storch, 1996). These series all do not fulfil the null hypothesis of stationarity, but they are all free of a change point. The time series have a length of $T = 100$, and the diagrams display how often a $t^\star$ is falsely associated with a change point. They all cluster in the middle; for instance the mid point $t^\star = 50$ is chosen in 1.5% of all 1000 cases, while $t^\star$'s smaller than 40 or larger than 60 are picked at a rate of on average 0.5%. $t^\star$'s smaller than 20 and larger than 80 never appear. In total, a false change point is identified in 38% of all cases.

A.8.3 Pre-whitening and Monte Carlo Approaches to Overcome the Serial Dependency Problem

At least two possibilities exist to overcome the problems related to serial dependence. One is pre-whitening and the other is Monte Carlo simulations.

"Pre-whitening" means to try to filter out the serial dependence. The detail of the filter depends on what is known, or assumed, about the serial dependence. For instance, if the serial dependence originates from a linear trend, then a difference filter, i.e.,

$$Y(t) = X(t+1) - X(t)$$

would be appropriate. If the serial dependence may be described by an auto-regressive process with memory λ, then a suitable filter is

$$Y(t) = X(t+1) - \lambda X(t)$$

Figure A.46 shows as an example the frequency of false rejections of the null hypothesis of no change point for different values of λ, when $Y(t)$ is tested instead of $X(t)$. Figure A.44 has demonstrated that with increasing λ's this rejection rate grows well above the stipulated level (of 5%). Except for very large values of λ, the test operates as required.

Another possibility is to construct a large ensemble of limited time series $X(0) \ldots X(T)$ with the same statistical properties of the series to be tested – without the specific property the test is dealing with, i.e., without a change point or without a trend. Then, by construction each member of the ensemble fulfils the null hypothesis. Then, for each member the test statistic S is determined, and finally by polling all S-values, an empirical distribution of the test statistic is derived.

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Acronyms and Abbreviations

If an acronym or abbreviation is used once or twice only locally, it is not necessarily included in this list.

3D	Three-dimensional
ACCELERATES	Assessing Climate Change Effects on Land Use and Ecosystems – From Regional Analyses to the European Scale, EU-funded project
ACIA	Arctic Climate Impact Assessment
AIS	Automatic Identification System
AO	Arctic Oscillation
AOGCM	Coupled Atmosphere-Ocean General Circulation Model
AOT-40	Ozone Index: Accumulated Ozone above the Threshold of 40 ppb
a.s.l	above sea level
ATEAM	Advanced Terrestrial Ecosystem Analysis and Modelling, EU-funded project
BACC	BALTEX Assessment of Climate Change for the Baltic Sea Basin
BALTEX	Baltic Sea Experiment
Baltic States	Estonia, Latvia and Lithuania
BASYS	Baltic Sea System Study, EU-funded project
BIL	Baltic Ice Lake
BP	Before Present
BSH	Bundesamt für Seeschifffahrt und Hydrography, Germany
C	Carbon
cal yr BP	Calibrated Years Before Present
CAVM	Circumpolar Arctic Vegetation Map
CC	Cloud Cover
CCEP	Climate Change and Energy Production
CCIRG	UK Climate Change Impacts Review Group
Cd	Cadmium
CDD	Consecutive Duration of Dry Days with Precipitation less than 1 mm
CH_4	Methane
CMAP	Climate Prediction Centre Merged Analysis of Precipitation
CMIP2	Coupled Model Intercomparison Project, Phase 2
CO_2	Carbon Dioxide
${CO_3}^{2-}$	Carbonate
CI	Confidence Interval
CPR	Continuous Plankton Recorder
CRU	Climate Research Unit at the University of East Anglia
CTD	Oceanographic device to measure Conductivity, Temperature, Depth
Cu	Copper
CWP	Clear-Water Phase

DDT	Dichloro-Diphenyl-Trichloroethane (a synthetic pesticide)
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DJF	December–January–February
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
DSi	Dissolved Silicate
DTR	Daily Temperature Range
DWD	Deutscher Wetterdienst (German Weather Service)
ECA	European Climate Assessment & Dataset, EU-funded project
ECHAM	Global climate model developed by Max-Plank-Institute Hamburg, Germany
ECE	Economic Commission for Europe
ECMWF	European Centre for Medium-Range Weather Forecasts
EMEP	European Monitoring and Evaluation Program
EMHI	Estonian Meteorological and Hydrological Institute
ENSEMBLES	Ensemble-based Predictions of Climate Changes and their Impacts, EU-funded project
ENSO	El Niño / Southern Oscillation
ERA-15	ECMWF Re-analysis Dataset 1978–1994
ERA-40	ECMWF Re-analysis Dataset 1958–2001
EU	European Union
FAD	First Arrival Date
FAO	Food and Agricultural Organisation (UN)
FIMR	Finnish Institute of Marine Research
GCM	Global Climate Model or General Circulation Model
GDR	German Democratic Republic
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas
GIS	Geographical Information Systems
GISS	Goddard Institute for Space Studies
GPCP	Global Precipitation Climatology Project
GPP	Gross Primary Production
GPS	Global Positioning System
HCB	Hexa-Chloro-Benzene (a synthetic pesticide)
HCH	Beta-Benzene-Hexa-Chloride (a synthetic pesticide)
HCO_{3^-}	Hydrogen Carbonate
HELCOM	Baltic Marine Environment Protection Commission
HIRHAM	Regional climate model, based on HIRLAM and ECHAM
HIRLAM	High Resolution Limited Area Model
Hg	Mercury
H_2S	Hydrogen Sulfide

IBFSC	International Baltic Sea Fisheries Commission
ICES	International Council for the Exploration of the Sea
IDAG	International ad-hoc Detection and Attribution Group
ILMAVA	Effect of Climate Change on Energy Resources in Finland, Finnish project
IMO	International Maritime Organization
INTAS	The International Association for the Promotion of Co-operation with Scientists from the New Independent States of the Former Soviet Union
IOC	Intergovernmental Oceanographic Commission
IOW	Baltic Sea Research Institute Warnemünde, Germany
IPCC	Intergovernmental Panel on Climate Change
IPG	International Phenological Gardens
JJA	June–July–August
K	Potassium
LAI	Leaf Area Index
MAM	March–April–Mai
MARPOL	International Convention for the Prevention of Pollution from Ships
MBI	Major Baltic Inflow
MIB	Maximum Annual Ice Extent in the Baltic Sea
MICE	Modelling the Impact of Climate Extremes, EU-funded project
MMT	Mean Migration Time
N	Nitrogen
N_2	Molecular Nitrogen
N_2O	Nitrous Oxide
NAM	Northern Hemisphere Annular Mode
NAO	North Atlantic Oscillation
NAOw	Winter North Atlantic Oscillation
NCAR	National Centre of Atmospheric Research
NCEP	National Centres for Environmental Prediction
NDVI	Normalized Differenced Vegetation Index
NGO	Non-Governmental Organisation
NH	Northern Hemisphere
NH_{4+}	Ammonium
NO_{2-}	Nitrite
NO_{3-}	Nitrate
NO_x	Nitrogen Oxides
NPP	Net Primary Production
O_2	Molecular Oxygen
O_3	Ozone
P	Phosphorus
PAH	Polycyclic Aromatic Hydrocarbons (organic pollutants)
PAX	Baltic Sea Patchiness Experiment
Pb	Lead
PBDE	Polybrominated Diphenyl Ethers (organic pollutants)

PCB	Polychlorinated Biphenyls (organic pollutants)
PEN	Potential Excess Nitrogen
POP	Persistent Organic Pollutant
POPCYCLING	Environmental Cycling of Persistent Organic Pollutants in the Baltic Region, EU-funded project
POSITIVE	Phenological Observations and Satellite Data: Trends in the Vegetation Cycle in Europe, EU-funded project
ppb	parts per billion
ppm	parts per million
PRUDENCE	Predictions of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects, EU-funded project
psu	Practical Salinity Unit
q850	Absolute Humidity at 850 hPa
RACCS	Regionalisation of Anthropogenic Climate Change Simulations, EU-funded project
RCA	Regional Climate Atmosphere Model
RCAO	Regional Climate Atmosphere Ocean Model
RCM	Regional Climate Model
RCO	Regional Climate Baltic Sea Model
RegClim	Regional Climate Development under Global Warming, Nordic project
S	Sulphur
Si	Silicate
SILMU	Finnish Research Programme on Climate Change
SilviStrat	Silvicultural Response Strategies to Climatic Change in Management of European Forests, EU-funded project
SLP	Sea Level Air Pressure
SMHI	Swedish Meteorological and Hydrological Institute
${SO_4}^{2-}$	Sulphate
SON	September–October–November
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
STARDEX	Statistical and Regional Dynamical Downscaling of Extremes for European Regions, EU-funded project
SW	South-West
SWECLIM	Swedish Regional Climate Modelling Programme
TAR	Third Assessment Report
TBT	Tri-Butyl-Tin (an organic pollutant)
TCI	Tourism Climate Index
THC	Thermohaline Circulation
TIN	Total Inorganic Nitrogen
Tn	Daily Minimum Air Temperature
TOC	Total Organic Carbon
Tx	Daily Maximum Air Temperature

UK	United Kingdom
UKMO	United Kingdom Meteorological Office
UN	United Nations
UNFCCC	United Nation's Framework Convention on Climate Change
UN-ECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States
USSR	Union of Soviet Socialist Republics
UV	Ultraviolet
VASClimO	Variability Analysis of Surface Climate Observations, German research project
WASA	Waves and Storms in the North Atlantic, EU-funded project
WMO	World Meteorological Organisation
WWF	World Wide Fund for Nature
YOY	Young of the Year
Zn	Zinc