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Atmospheric forcing of decadal Baltic Sea level variability in the last 200 years: A statistical analysis

(Vom Department Geowissenschaften der Universität Hamburg als Dissertation angenommene Arbeit)

Authoress:

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Atmospheric forcing of decadal Baltic Sea level variability in the last 200 years: A statistical analysis

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Birgit Hünicke

130 pages with 32 figures and 3 tables

Abstract

This study aims at the estimation of the impact of different atmospheric factors on the past sea-level variations (up to 200 years) in the Baltic Sea by statistically analysing the relationship between Baltic Sea level records and observational and proxy-based reconstructed climatic data sets. The focus lies on the identification and possible quantification of the contribution of sea-level pressure (wind), air-temperature and precipitation to the low-frequency (decadal and multi-decadal) variability of Baltic Sea level.

It is known that the wind forcing is the main factor explaining average Baltic Sea level variability at inter-annual to decadal timescales, especially in wintertime. In this thesis it is statistically estimated to what extent other regional climate factors contribute to the spatially heterogeneous Baltic Sea level variations around the isostatic trend at multi-decadal timescales. Although the statistical analysis cannot be completely conclusive, as the potential climate drivers are all statistically interrelated to some degree, the results indicate that precipitation should be taken into account as an explanatory variable for sea-level variations. On the one hand it has been detected that the amplitude of the annual cycle of Baltic Sea level has increased throughout the 20th century and precipitation seems to be the only factor among those analysed (wind through SLP field, barometric effect, temperature and precipitation) that can account for this evolution. On the other hand, precipitation increases the ability to hindcast inter-annual variations of sea level in some regions and seasons, especially in the Southern Baltic in summertime. The mechanism by which precipitation exerts its influence on Baltic Sea level is not ascertained in this statistical analysis due to the lack of long salinity time series. This result, however, represents a working hypothesis that can be confirmed or disproved by long simulations of the Baltic Sea system – ocean, atmosphere and land.

Der atmosphärische Antrieb der dekadischen Variabilität von Ostseewasserstand in den letzten 200 Jahren: eine statistische Analyse

Zusammenfassung

In der vorliegenden Arbeit wird durch statistische Analyse der Beziehung von Wasserstandsdaten und Klimadaten (Beobachtungen und auf Proxydaten basierende Rekonstruktionen) der Einfluss verschiedener atmosphärischer Faktoren auf die Wasserstandsschwankungen der Ostsee in den letzten 200 Jahren untersucht. Das Hauptaugenmerk liegt auf der Identifikation und der möglichen Quantifizierung des Beitrags von Bodenluftdruck (Wind), Lufttemperatur und Niederschlag auf die dekadische bis multi-dekadische Variabilität von Wasserstand in der Ostsee. Es ist bekannt, dass der Wind als treibende Kraft den Hauptfaktor für die mittleren Wasserstandsschwankungen in der Ostsee darstellt. In der vorliegenden Dissertation wurde statistisch untersucht, in welchem Maße andere regionale Klimafaktoren zu den räumlich verschiedenen Wasserstandsvariationen um den isostatischen Trend auf multidekadischen Zeitskalen beitragen können. Auch wenn eine statistische Analyse keine endgültige Beantwortung dieser Fragestellung liefern kann, da die untersuchten Klimafaktoren miteinander in Beziehung stehen, so konnte mit Niederschlag ein Faktor identifiziert werden, der einen signifikanten Beitrag zur Erklärung der Wasserstandsschwankungen in der Ostsee liefern kann. Einerseits konnte nachgewiesen werden, dass die Amplitude im Jahreszyklus von Ostseewasserstand innerhalb des 20. Jahrhunderts angestiegen ist und Niederschlag statistisch gesehen der einzige der untersuchten Faktoren (Wind durch das Bodenluftdruckfeld, barometrischer Effekt, Lufttemperatur, Niederschlag) ist, der diese Entwicklung erklären kann. Andererseits erhöht Niederschlag die Fähigkeit von Nachvorhersagen („Hindcasts“) von Wasserstandsschwankungen in bestimmten Regionen und Jahreszeiten auf interannualen Zeitskalen. Der Mechanismus, durch den der Einfluss von Niederschlag auf den Ostseewasserstand beschrieben werden kann, konnte aufgrund fehlender Langzeitreihen (z.B. von Salzgehalt) nicht näher untersucht werden. Dennoch zeigt das erzielte Ergebnis neue Aspekte auf und liefert eine neue Arbeitshypothese, welche bei zukünftigen Langzeitsimulationen des Ostseesystems – Ozean, Atmosphäre und Land – geprüft werden sollte.

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Contents

List of papers

This thesis is based on the following peer-reviewed journal articles:

Hünicke, B. and Zorita, E. 2006.

Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century.

Tellus 58A (1), 141-153, doi: 10.1111/j.1600-0870.2006.00157.

Hünicke, B. and Zorita, E. 2008

Trends in the amplitude of Baltic Sea level annual cycle.

Tellus 60A (1), 154-164, doi: 10.1111/j.1600-0870.2007.00277.x.

Hünicke, B., Luterbacher, J., Pauling, A. and Zorita, E. 2008.

Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years.

Tellus 60A (2), 384-393, doi: 10.1111/j.1600-0870.2007.00298.x.

1 Introduction

1.1 Global and regional sea-level variations

Together with temperature near the surface, sea-level variations are arguably one of the variables in the climate system that most directly influences coastal environments. In the past, global climate variations have been usually accompanied by variations in global sea-level. For instance, the range of global sea-level variations between glacial and interglacial states in the Pleistocene are believed to be of the order of 140 m (Jansen et al., IPCC, 2007). These variations obviously exert a considerable imprint on the Earth surface and on all processes that take place on it. At these long time scales (about 100 thousand years), they are caused mainly by the build-up and disappearance of the continental ice-sheets in the Northern Hemisphere, with contributions from variations in ice volume in Antarctica. Climate projections for the end of the 21st century under different scenarios of atmospheric greenhouse gases foresee increases in the global sea level in the range 18-59 cm with respect to the 1980-1999 mean (Meehl et al, IPCC, 2007). About three-fourths of this projected increase will be mainly caused by the thermal expansion of the oceanic water column. But rising temperatures could also cause additional, albeit much more uncertain, contributions of the melting from glaciers, Greenland and West Antarctic ice-sheets. At longer timescales, of the order of several centuries, and with undiminished build-up of atmospheric concentrations of anthropogenic greenhouse gases, the Greenland ice-sheet will considerably diminish, causing a sea-level rise of potentially several meters.

A global average of sea-level rise, however, ensconces considerable regional variations that may be caused by other processes that operate at regional and local scales. Even the observed thermal expansion of the water column in the past few decades, which can be now measured with greater precision by satellite altimetry (Bindoff, IPCC 2007; Munk, 2002, Church and White, 2006), shows large regional heterogeneity, and some ocean areas even show a small or even falling sea level in the past decades due to the regional heterogeneity of the heat flux into the ocean, which is superimposed by decadal natural variability of temperature, precipitation and ocean currents (Fig. 1.1).

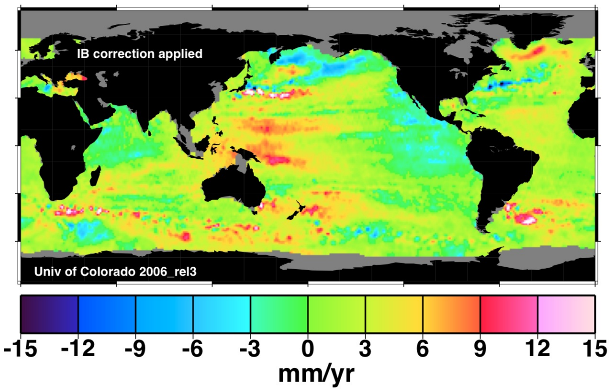


Fig. 1.1 *Local trends in sea level, calculated with a least-squares fit from 10-day and 1-degree resolution grids in the period, delivered by the TOPEX/Poseidon and Jason satellite observation platforms in the period 1992 to 2005, and provided by the University of Boulder (http://sealevel.colorado.edu). A trend, bias, annual, and semi-annual terms are fit simultaneously. Please note that these trends have been determined for only a fourteen-year period, and reflect the impact of decadal scale climate variability on the regional distribution of sea level rise (Leuliette et al., 2004).*

Additionally, in coastal regions, numerous local processes may confound the global signal. Apart from the geological processes of uplift and subsidence of the Earth outer layer (Peltier, 1998), other climate factors may considerably affect sea level, in particular in regions with complex coastal topography. For instance, to mention a few of these processes, changes in the direction or strength of the mean wind may influence the mean coastal currents or cause the pile-up of water masses against coast lines; changes in precipitation and river run-off concentrated in coastal areas may change the mean water salinity, and therefore density, also affecting sea level in these coastal areas.

The understanding of the local and regional processes that affect mean sea-level variations, which may themselves be affected by present and future climate change, is important for a better estimation of the global sea-level change- i.e. these local variations can be considered as noise that has to be filtered out to estimate a global signal. The present estimations of sea-level rise in the 20th century (Cavanes et al., 2001; Cazenave and Nerem, 2004) are affected by a controversy that originates in the limited sampling of long coastal sea-level records, which may be influenced by unknown long-term trends of regional origin (Holgate, 2007). But the understanding of the processes responsible for regional sea-level variations is also important because anthropogenic climate change may affect these local processes directly, and local sea-level variations might be, for the region of interest, more important than the global warming signal. Also, coastal zones are generally very sensitive to any external forcing, so climate changes are therefore likely to have the greatest impact and be experienced first in the coastal zone, whereas spatio-temporal buffering in the oceans may delay evidence of climate change for decades or even centuries (Sündermann et al., 2001).

As an illustrative example, we might consider sea-level variations in the Mediterranean Sea. It is believed that inter-annual to decadal variations of sea level in the Mediterranean Sea are modulated by *North Atlantic Oscillation* (NAO) (Tsimplis and Josey, 2001), the sea-level-pressure sea-saw between Azores and Iceland, which controls the strength of the westerly winds over the North Atlantic and many other aspects of the North Atlantic climate and adjacent regions. Air-pressure variations associated to changes in the phase of the NAO modulate Mediterranean Sea level. If, as many climate simulations seems to indicate, the NAO should intensify under anthropogenic climate change – i.e. the Azores High and the Icelandic Low become more intense - this will tend to lower Mediterranean sea level, although the global warming signal will tend to produce the opposite effect. The question then arises as to what extent might be the magnitude of the contribution of the NAO relative to the direct expansion of the water column caused by increasing water temperatures in this region. Therefore, a more accurate projection of future sea-level change in the Mediterranean region requires an understanding and quantification of the relationship between the NAO and sea level in this region.

The Baltic Sea is another, perhaps more complex, example of this situation. It is a semi-enclosed sea connected to the North Atlantic ocean (Fig. 1.2), and that is strongly influenced by the atmosphere in the North Atlantic European sector and by the fresh water fluxes from surrounding land areas. Furthermore, the vertical position of land surface in this area is still reacting to the melting of the Scandinavian Ice Sheet from its maximum attained about 20000 years ago. The Baltic Sea is, therefore, a clear example of a complex coupled ocean-atmosphere-land system, in which sea-level variations at inter-annual and longer timescales are not completely understood.

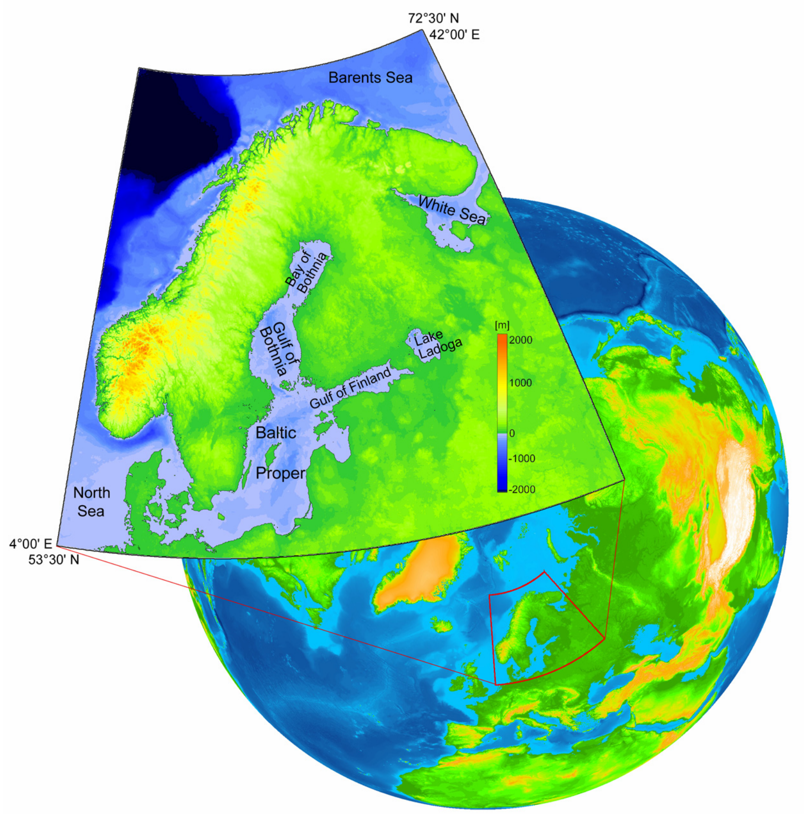


Fig. 1.2 *The location of the Baltic Sea Basin and the Baltic Sea area. Digital Elevation Model (REM). Data: ETOPO2 (NDGC, 2001), adapted from Rosentau et al., 2007.*

One important factor for the inter-annual sea-level variations in the Baltic Sea is, as in the case of the Mediterranean Sea, the NAO. In the case of the Baltic Sea, however, it is the modulation of the intensity of the westerly winds associated with the NAO phase that causes variations in sea level: stronger westerlies causes sea-level rise in the whole Baltic Sea coastal stations. The physical mechanism is related to the inflow of water masses from the North Sea as response to wind stress and to the hydrodynamical response to the wind forcing. However, inter-annual and decadal sea-level variations along the whole Baltic coast cannot be explained solely by the NAO. The statistical link between the NAO and Baltic Sea level is regionally very heterogeneous. For instance, the correlation in wintertime between the NAO index and sea level in the Gulf of Bothnia might reach 0.8 in recent decades but it attains only values around 0.3 in Warnemünde in the Southern Baltic Sea. Fig. 1.3 shows the correlation between the winter mean of the NAO index and the winter mean Baltic Sea level in the period 1900 to 1998.

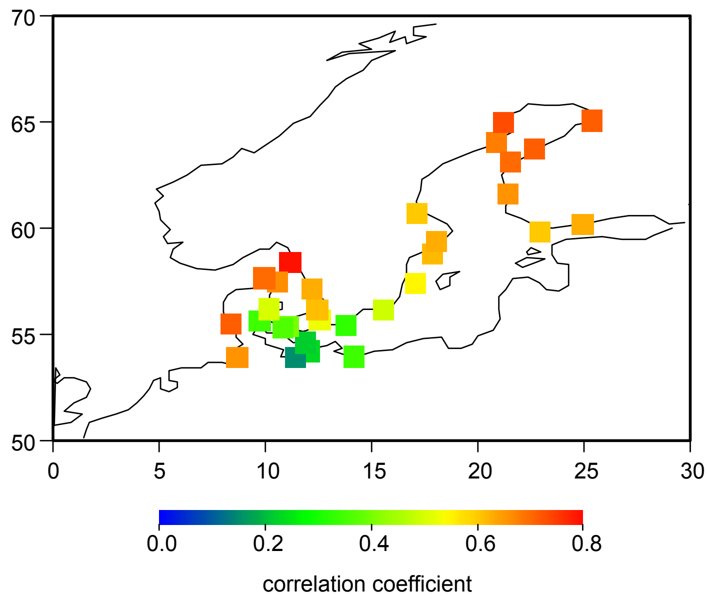


Fig. 1.3 *Correlation between the winter mean (December-January-February) of the NAO index and the winter mean (linearly detrended) Baltic Sea level in the period 1900 to 1998.*

This correlation is even not homogeneous in time (Hünicke and Zorita, 2006). When calculated in moving windows of 21-years, the correlation with the NAO can be as low as 0.3 for stations in the Northern Baltic. Therefore, it is reasonable to assume that although the NAO plays a predominant role as a whole for the Baltic Sea, other processes might have to be invoked for a full explanation of sea-level variations, especially at multi-year and decadal timescales, which are the relevant timescales in the context of anthropogenic climate change caused by increased concentrations of greenhouse gases in the atmosphere. Once the role of these processes is better understood from the analysis of the observational record, climate simulations with coupled global and atmospheric regional climate models for future periods can be better interpreted in terms of changes in Baltic Sea level, a process denoted by the term *downscaling*.

1.2 Downscaling

Present global climate models (General Circulation Models, GCMs) have a horizontal spatial resolution in the range of 3 to 4 degrees. Due to the coarse spatial scales resolved in current GCMs, the processes which might influence the Baltic Sea level variations cannot be properly represented. Climate information finer than the separation of a few model grid points have to be parameterized with semi-empirical bulk formulas. The Baltic Sea itself is only very schematically represented in global climate models. In some of them, for instance the finite-difference HadCM3 climate model of the Hadley Centre for Climate Prediction (Gordon et al., 2001), the Baltic Sea is a closed basin. In the versions of the ECHAM model of the Max-Planck Institute for Meteorology with a horizontal resolution of T30 (about 3.75x3.75 degrees) (e.g. Legutke and Voss, 1999; Röckner et al., 1999) the connection between the Baltic Sea and the North Sea is about 700 km wide. Higher resolutions are not able to resolve the narrow connection between the North Sea and the Baltic Sea. Since the exchange of water masses between the North Sea and the Baltic Sea is strongly topography dependent (Gustafsson and Andersson, 2001) a reasonable emulation of the effect of wind-stress and density gradients on the inflow of water masses from the 'model North Sea' into the 'model Baltic Sea' cannot be expected. Precipitation also shows large regional heterogeneities due to the presence of mountain ranges in the Scandinavian Peninsula which cannot be captured in a low-resolution atmosphere model, and which would give rise to an unrealistic river run-off. The ocean circulation of the Baltic Sea can be only very coarsely represented in a global climate model by a few grid-cells. Therefore, the different basins of the Baltic Sea and the exchange of water masses between them are non-existent in a global climate model. Consequently, it is reasonable to assume that the interpretation of the output of simulations with global climate models for estimation of climate-induced changes in Baltic Sea level rise requires the application of downscaling techniques to transfer the large-scale results produced by global climate models onto regional and local scales.

One strategy to interpret the results of global climate models is *dynamical downscaling*, by which a regional climate model, with a higher-resolution grid, is nested in the coarse resolution grid of the global model. The regional model covers the regional domain of interest and accepts the boundary conditions simulated by the global model at the boundaries of its domain. Regional models can be, however, as complex or still more complex than global models, and require a similar amount of computer time to simulate a prescribed time period. Dynamical downscaling has been more frequently applied in recent times thanks to the increase in computer power but the Baltic Sea still pose serious problems on its own in this regard. The main reason is that in the Baltic Sea region the atmosphere, land and ocean strongly interact, and these components and their exchanges of energy and matter have to be realistically modelled. Therefore, an atmospheric regional model – the most common tool used in dynamical downscaling- is not enough for the Baltic Sea, and a regional ocean model and a realistic soil model, all coupled, are additionally required. To date only two regional models of the Baltic region with these characteristics exists, the model BALTIMOS developed at the Max-Planck-Institute for Metereology (e.g. Lehman et al., 2004) and the Rossby Centre Atmosphere Ocean model RCAO (Döscher et al., 2002). However, to my knowledge no long simulations with the coupled models covering the 20th century yet exist.

The second strategy, on which this work is based, is *statistical downscaling*. Therefore we use the knowledge of the possible influence of large-scale factors -e.g. sea-level-pressure (SLP), spatially averaged air-temperature and spatially averaged precipitation, among others- on Baltic Sea level from the analysis of the observational records and assume that the empirical-statistical functions that describe this influence will remain unchanged in a future climate. Thereby, the large-scale changes simulated by global climate models can be interpreted in terms of possible changes in sea level. It has to be kept in mind, however, that these estimations comprise only the partial contribution of some selected large-scale regional predictors to the total potential change, and that there are other regional factors, such as the isostatic contribution to relative sea-level changes (see Section 1.3) or substantial changes in the sea-ice cover, and global sea-level rise, which have to be considered for an estimation of the total regional sea-level rise.

1.3 The Baltic Sea level

The Baltic Sea is a semi-enclosed basin, located between Scandinavia and mainland Northern Europe and connected to the North Atlantic through the narrow and shallow Danish straits (up to 16km wide and about 18m deep) (Fig. 1.2). With a total area of 415.000 km² and a volume of 21.700 km³ (including the Kattegat) it is one of the largest brackish seas in the world. The drainage area (Fig. 1.4) covers 1.74 million km² (BACC, 2008). The Baltic Sea can be divided into a number of different areas: the Baltic Proper, the Gulf of Bothnia, the Gulf of Finland and the Gulf of Riga. Between the Gulf of Finland and the Gulf of Riga there is no significant threshold to prevent the changing of their deep water and therefore they belong in geographical sense to the Baltic Proper. For oceanographers, the Baltic area begins from the Skagerrak and the Kattegat, the Skagen reef and continues to Marstrand. The water exchange between the Baltic Sea and the open ocean is hampered by the large and shallow entrance area, consisting of the Kattegat and the narrow straits of Öresund and the Belt Sea. Compared to the Danish strait, the connections between the different main basins of the Baltic Sea are wide and deep and allow much faster water exchange, which is mainly forced by density differences (Winsor et al., 2001).

The complex bathymetry of the Baltic Sea (the different basins are connected through narrow straits) strongly influences currents and mixing processes. These processes compose the physical transport system of the Baltic Sea, which may in principle explain the distribution of sea-salt if the freshwater supply is known (Stigebrandt, 2001). The Baltic Sea salinity is controlled by river runoff, net precipitation and water exchange through the North Sea (Meier, 2006). Fresh water excess, mainly from river discharge, can be described - in addition to a mean west wind component (Meier and Kauker, 2003) - as one of the main factors which drive the large-scale circulation.

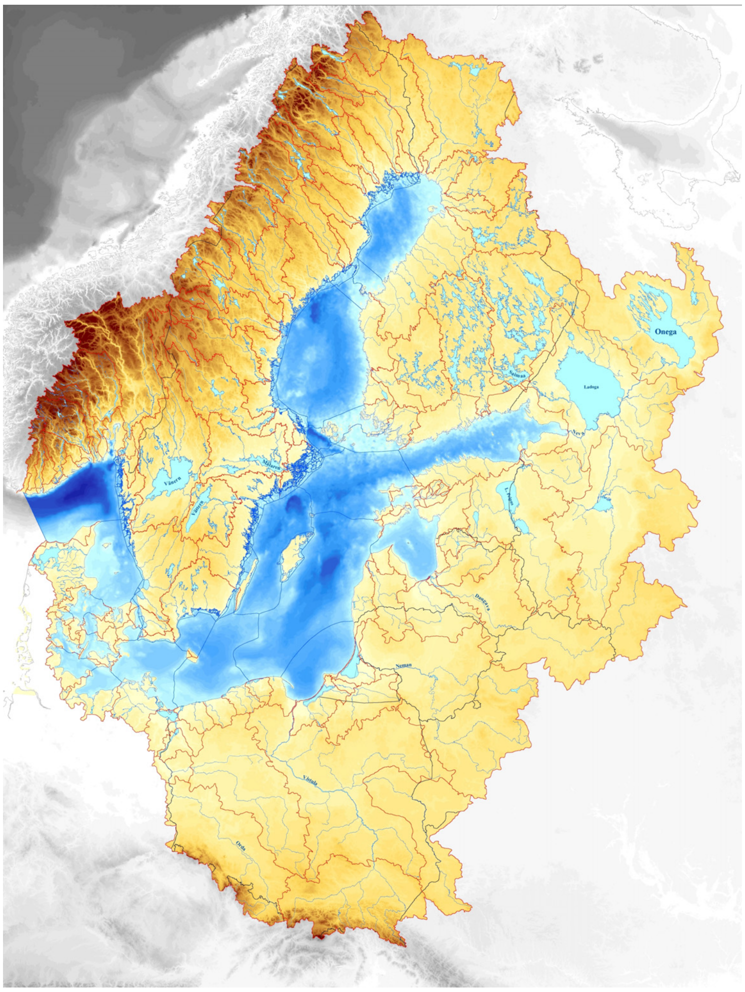


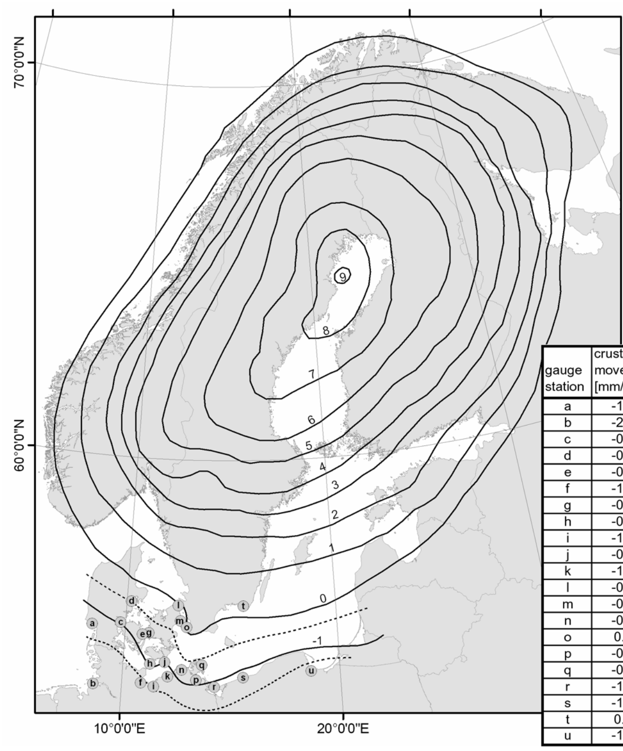
Fig. 1.4 *The drainage area of the Baltic Sea. Source: Swedish Meteorological and Hydrological Institute (SMHI).*

Due to the salinity gradient, the inflow causes higher water level in the Baltic Sea than in the Kattegat. The salinity decreases from almost oceanic values in the Kattegat to almost freshwater to the Gulf of Finland and Bay of Bothnia. For the 20th century, the average salinity amounts to only 7.4 psu (Janssen et al., 1999). This relatively small number can be explained by the limited water exchange with the world ocean and a relatively large freshwater supply (around 16.000 m^3 /s).

An up-to-date overview about the latest scientific findings in regional climate research on the Baltic Sea basin, including also a detailed oceanographic characteristic, is provided by the *BALTEX Assessment of Climate Change for the Baltic Sea Basin* (BACC, 2008), which offers a review of published knowledge for the geophysical (atmosphere, ocean, sea ice) as well as the ecological (terrestrial and marine) dimension. The focus of this report (with an overall format similar to the IPCC reports) lies in the assessment of ongoing climate variations in the Baltic Sea basin including climate changes in the recent past, climate projections up until 2100 using the most sophisticated regional climate models available and an assessment on terrestrial, freshwater and marine ecosystems. The comprehensive BACC report shows that progress on the understanding of sea-level variability and its climate drivers has been recently made, but it is still far from complete. The present study contributes to filling this gap.

Sea-level in the Baltic has varied considerably along the Holocene. In this epoch it has experienced periods of isolation from open ocean areas and its coastlines have markedly changed. It can be considered that a 'modern' form of the Baltic Sea with permanent connection to the North Sea was established around 7000 years BP when, due to the early Holocene global sea-level rise, marine water masses transgressed into the Baltic Sea Basin and led to one of the most dramatic environmental changes in the post-glacial history of the Baltic Sea –the Littorina trangression (e.g. Rössler, 2006). Sea level was at this time located about 7 to 10 meters lower than today. In the subsequent millennia relative sea level has still experienced variations of the order of several meters, with a time evolution that is still not completely reconstructed (Lampe, 2005). Associated with this evolution were strong salinity changes (e.g. Emeis et al., 2003).

In modern periods, i.e in the last few centuries, relative Baltic Sea level is still strongly influenced by the isostatic rebound of the Earth outer solid layers after the melting of the Scandinavian glacial ice-sheet and the flow of solid subsurface material towards the regions that once supported the weight of the ice masses (Peltier, 1998). This is reflected in a land uplift of about 5 mm/year in the Central Baltic, 9 mm/year in the Northern Baltic, and a downward movement of about 1 mm/year in parts of the Southern Baltic Sea. (Ekman, 1996; Milne et al., 2001; Rosentau et al., 2007, see Fig. 1.5).



gauge station	crustal movement [mm/yr]	observation time
a	-1.11	1889 - 1997
b	-2.54	1843 - 2000
c	-0.96	1889 - 1996
d	-0.48	1888 - 1996
e	-0.78	1896 - 1996
f	-1.67	1826 - 1995
g	-0.67	1897 - 1996
h	-0.96	1882 - 2003
i	-1.41	1848 - 2003
j	-0.97	1898 - 1996
k	-1.21	1855 - 2003
l	-0.04	1898 - 1996
m	-0.31	1889 - 1996
n	-0.72	1863 - 2003
o	0.02	1929 - 1997
p	-0.90	1847 - 2003
q	-0.64	1882 - 2003
r	-1.11	1811 - 1997
s	-1.16	1816 - 1999
t	0.11	1887 - 1997
u	-1.75	1886 - 1997

Fig. 1.5 *Map of vertical crustal movement relative to the sea level (mm/year). Synthesis of Ekman´s (1996) data from Fennoscandian glacio-isostatic uplift region and new data gauge measurements from the Southern Baltic Sea (Rosentau et al., 2007).*

These values are however difficult to estimate exactly as the observed gauge records are contaminated by climatic-induced trends and the satellite-based records have a limited length. But the overall picture indicates that sea-level rise will potentially be more relevant for the

Southern Baltic coasts than for the Northern regions, where the isostatic land uplift should overwhelm the climate-related sea-level rise. The rate of sea-level rise in the Eastern North Atlantic in the last 15 years estimated from satellite altimetry (TOPography EXperiment (TOPEX)/ Poseidon and Jason) indicates values of the order of 2-3 mm/year (Fig. 1.1, Leuliette et al., 2004).

The mean surface salinity shows a marked gradient from about 20 psu in the Kattegat region, diminishing to roughly 5 psu in the Gulf of Bothnia (Gustafsson and Andersson, 2001; Winsor et al., 2001; Meier, 2006b). This is mainly caused by the input of fresh water from river discharge. Ekman and Mäkinen (1996) found a sea surface height difference from the inner part of Gulf of Bothnia and the Skagerrak of the order of 35 to 40 cm and a steep sea level gradient in the border zone between the Skagerrak and the Kattegat, reaching 2 cm per 10 km, reflecting the salinity front between the brackish Baltic Sea water and the saline North Sea water. Partly due to this salinity gradient and partly due to a mean west wind component (about 1 to 2m/s averaged over the Baltic area; Meier and Kauker, 2003), the observed mean sea surface height (SSH) increases from the Kattegat to the Gulf of Finland and Bay of Bothnia by about 25 and 32m, respectively (Meier et al., 2004).

However, the information available about the evolution of salinity in the Baltic Sea in the 20th century is very fragmentary. Only very few surface salinity timeseries for the first half of the 20th century exist, with considerable gaps. Information about the evolution of salinity in the deeper layers is still more fragmentary. Therefore, although salinity timeseries would yield very useful information for the analysis of long sea-level time series, this is in practical terms not viable.

Another local factor that might have a strong local influence on sea level is the presence of sea-ice. In wintertime, part of the Baltic Sea surface is covered by sea-ice, in particular the Gulf of Bothnia and Gulf of Finland (Jevrejeva et al., 2004; Omstedt and Chen, 2001). The southern Baltic Sea is, however, seldom covered by sea-ice (Håkansson et al., 1995). Although from the physical point of view sea-ice should be considered in trying to analyse the variability of Baltic Sea level, this knowledge would be of limited use in the framework of downscaling simulations with global climate models. Due to the unrealistic connection between the North Sea and the Baltic Sea in these models, the simulated mean water temperature contains a large systematic error. For instance, in the ECHAM models, where this connection is too wide, water temperatures in the 'model' Baltic Sea are too warm and sea-ice cover is therefore unrealistic. Since sea-ice formation is a strongly non-linear process and the simple consideration of temperature anomalies from a control run is not a satisfactory solution; sea-ice cover would strongly depend on the size of this systematic error. For this reason, I have not considered sea-ice data in the analysis of the Baltic Sea level variability. Nevertheless, as explained in Hünicke and Zorita (2008), the influence of sea-ice in the very long observational sea-level record in Kronstadt (Gulf of Finland) does not seem to be strong. However, this will be not always the case for other stations located in the Northern Baltic, and sea-ice should be kept in mind as a potential important factor. In my opinion, in view of the scarcity of long sea ice observations, the best way to handle the factor sea-ice is by Regional Ocean modelling and not by statistical analysis.

Sea level in the Baltic Sea can be also modulated by anthropogenic activities that are not directly related to global climate. These are the regulation of river run-off from dams (Matthäus and Schinke, 1999; Schinke and Matthäus, 1998) and other coastal construction activities that might influence locally sea-level measurements. The quantification of the effect of these additional factors to Baltic Sea level is quite difficult, as the information of river run-off into the Baltic, for long timescales, is not satisfactory.

The general strategy applied in this thesis has been to consider the variations of sea level around an estimated linear long-term trend, i.e. the sea-level records and the climate records (essentially temperature) have been linearly detrended. This procedure admittedly also removes the long-term climate signal in the sea-level records, but this is necessary to enable the statistical analysis to be possible. The underlying assumption is that the relationships between sea level and regional climate at decadal timescales around this long-term trend can be also applied to centennial timescales. This assumption appears reasonable but cannot be completely ascertained.

1.4 Implications of sea-level variations in the Baltic Sea environment

Although the objective of this thesis does not lie in the analysis of the possible impacts of sea-level rise on the ecological and economic systems along the Baltic coast, a particular reasons that further motivates the study of sea-level variations in the Baltic Sea is related to the impacts of sea-level variations on Baltic sea ecosystems, as sea level might modulate coastal erosion, salt-water inflows and stratification.

From the human perspective, changes in sea level, in particular rapid changes or changes in frequency of sea-level extremes (Suursaar and Sooäär, 2007), require adaptation measures to protect the coastal infrastructures and economic environment or otherwise profound changes in the land-use in the coastal zone. For some areas in the Baltic Sea, especially those where the isostatic land uplift is smaller (i.e. in the Southern Baltic coast) sea-level rise might arguably pose more serious ecological and economic problems than future temperature rise. In other areas, where the land-uplift reaches values of 5 mm/year or more, the probability of severe impacts of sea-level rise seem small, unless catastrophic global sea-level rise is brought about by collapse of polar ice sheets. The most immediate effects of mean sea-level rise and storm surges (as example for the Baltic Sea see Baerens and Hupfer, 1999; for the North Sea Langenberg et al., 1999; Kauker and Langenberg, 2000) would probably be manifested in an increase in the erosion rate in parts of the coast, especially in sandy and silty shores.

Meier et al. (2004) applied regional climate scenarios to discuss the potential risk of extreme increase of sea level at four study sides in the Baltic Sea (Helsinki, Stockholm, Greifswald, St. Petersburg), pointing out the relevance for long-term planning especially in the eastern and southern Baltic Sea region. Similar findings are presented by Schmidt-Thome et al. (2006), who applied a decision support frame for climate impacts on sea level and river run-off on Stockholm in Sweden and Gdansk in Poland.

The shores are also an important part of the aquatic ecosystems. Avian and amphibious species use the shores for regular feeding and in their reproductive stages of their life cycles. Rapid changes in the shoreline would certainly have some disruptive consequences, which, however, are difficult to quantify under the present uncertainties in future sea-level rise (Kont et al., 1997).

Some concern has also been expressed regarding changes in salinity in the Baltic Sea. Most aquatic species can only live within certain ranges in salinity concentrations. As the horizontal salinity gradients in the Baltic Sea are large, relatively small imbalances in the water budget in the Baltic Sea could give rise to relative large displacements in the habitats of aquatic species. Projections for future climates (Meehl et al., IPCC 2007) indicate that annual precipitation at high latitudes will tend to increase with the consequent lowering of Baltic Sea salinity. However, Baltic Sea salinity is also influenced by irregular water inflows from the North Sea, which, in turn, are modulated by the wind forcing and the zonal pressure gradient between the Baltic Sea and the North Sea. Simulations under certain climate scenarios of the state of the Baltic Sea for the future (Meier and Kauker, 2003; Meier et al., 2006) show that although Baltic salinity will indeed decrease, the magnitude of this change will remain moderate. However, a possible future salinity decrease could have large impacts on species distributions, growth and reproduction of organism, as marine species with lower salinity limits might restricted to the more southern areas. An example is the cod, a key species in the Baltic proper, which is already affected by the salinity decrease during the past decades. The cod regulates as a top predator in the pelagic food chain the sprat and herring stocks (Meier et al., 2006b).

For the estimation of these impacts, however, a realistic simulation of Baltic Sea level is important, and to achieve this, all potentially relevant processes should be analysed and considered.

1.5 Thesis Objective

The objective of this thesis originates from a collaboration of geoscientists, biologists, climate researchers and archaeologists within the German Science Foundation (DFG) project SINCOS "Sinking Coasts: Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea" (Harff et al., 2005). A description of this project from a sciencejournalism perspective was published in *Science* (Curry et al., 2006). The general target of this Research Unit is the development of a model of relationships between the geosystem, ecosystem, climate and socio economic system for sinking coasts and tideless seas to be established as an example for the southern Baltic since the Atlanticum (since 8000 calendar years BP) by investigating the cause and effect relation between driving forces (climatic and geological processes) and the response of the natural and social environment in the coastal areas of a transgressive sea. Climate and geo-system form a complex of driving forces that influences, on the one hand, the eco-system and, on the other hand, together with the geo-system, drives the development patterns of human society. The feedback of society to the eco-system, climate and geo-system has to be particularly regarded for prognostic scenarios.

This thesis contributes to the SINCOS subproject ‘climate’, which aims at the estimation of the climatic influence on the recent past and future sea level changes in the Baltic Sea with the help of statistical methods and simulations with state-of-the-art climate models.

> *The presented work concentrates on the recent past sea level changes by statistically analysing the relationship between sea level and climatic data sets in the observational record, but using also climate reconstructions of the recent past centuries.*

In this thesis the variability and long-term change of Baltic Sea level is conceptionally decomposed in two groups of factors. One factor is the average North Atlantic Sea level variations, which determine the reference level from which the regional Baltic Sea level might deviate. These large-scale oceanic factors are driven by thermal expansion of the water column caused by atmospheric and lateral oceanic heat fluxes and by dynamical oceanic contributions. The second group of factors, which is the focus of the present thesis, comprise the atmospheric regional forcing – wind, temperature, precipitation, among others. The main objective of this thesis is the identification and, if possible, quantification of the contribution of these atmospheric large-scale climatic factors to the low-frequency (decadal and longer) variability of sea level in the Baltic Sea.

The analysis consists of a statistical analysis of observational climatic and sea-level records and also of longer proxy-based reconstructions of sea-level-pressure, temperature and precipitation in the last centuries. Only very seldom can the statistical analysis alone provide clear-cut answers in climate research, as climatically relevant processes are deeply entangled and often the data quality is not satisfactory. On the other hand, atmosphere and ocean modelling incorporate a more comprehensive range of physical processes than a statistical approach might be able to analyse. However, models are not perfect and the conclusions derived from modelling are also subject to uncertainties.

> *This study should be considered as complementary to long-term simulations of the state of the Baltic Sea for the past centuries.*

I have posed and tried to answer the following research questions:

- The wind forcing is the main factor explaining average Baltic sea-level variability at interannual and decadal timescales, especially in wintertime. Are there other regional climate factors that also contribute to
    - the average sea level,
    - the spatial sea-level variations within the Baltic Sea and
    - Baltic Sea level variability in other seasons?
- Baltic Sea level records show large trends mainly due to the isostatic post-glacial rebound. Is it possible to identify the underlying influence of regional climate factors by analysing the *amplitude* of annual cycle of sea level, which is not affected by the isostasy?
- Is the influence of regional climate factors at interannual and multidecadal timescales different? Can the strong signature of wind-stress forcing on sea level also be identified at multidecadal timescales or do other climate factors become dominant?

1.6 Thesis Outline

The thesis is based on three main Sections, Chapter 2 to 4, two of which have been published, while the third is accepted for publication. Each of this main Sections aim at answering a part of the *Research Questions* presented in the previous Section. Due to this structure, each Chapter can be read largely independently from the others; it also implies some recurrence of the contents, as each Chapter contains its own introduction, description of datasets and methods, discussion and conclusions. In the following a very brief overview about the context of these main Chapters is given:

- **Chapter 2**

  This Chapter aims at the investigation of Baltic Sea level variations in the 20th century on decadal timescales. Baltic Sea level variations at interannual to decadal timescales are generally believed to be caused essentially by variations in the atmospheric circulation, in particular by the NAO. Numerous of previous studies investigated this link so far, but most of these studies focused either on limited regions or used (statistical) methods which filtered out the more local sea-level variability. Therefore, I used a different approach based on regression analysis applied to each gauge station separately. This Chapter has been published in *Tellus A* (Hünicke and Zorita, 2006).

- **Chapter 3**

  One of the difficulties to identify the influence of climate factors on Baltic Sea level is the presence of the strong isostatic sea-level trend. In this Chapter I pursue the strategy of considering changes in the amplitude of the sea-level annual cycle in the Baltic Sea, which in theory should not be affected by geological processes. The Baltic Sea level undergoes a relatively marked annual cycle, with maxima in wintertime and minima in early spring. In this Chapter, I estimate the trends in the differences between minima and maxima – the amplitude of the annual cycle, establish its statistical significance with robust methods and analyse the possible physical mechanisms that might give rise to the widening sea-level annual cycle. This Chapter is published in *Tellus A* (Hünicke and Zorita, 2008).

- **Chapter 4**

The relevant timescales in the context of anthropogenic climate change are multi-decadal and centennial. The question arises as to whether the relationships between the regional climate factors and sea level that have been identified at inter-annual timescales can be extrapolated to longer timescales. For this purpose I analyse long tide-gauge sea-level records in the Baltic Sea, spanning almost 200 years, together with reconstructions of sea-level-pressure, temperature and precipitation, also covering the last 200 years. This Chapter is published in *Tellus A* (Hünicke et al., 2008).

- **Chapter 5**

In this concluding Chapter the main findings and suggested further research activities are presented. Furthermore, as a continuation and outlook of this thesis, an estimation of regional climate change by statistical means is presented by applying the statistical transfer functions (developed in this thesis) to the corresponding output of global climate simulations. The (preliminary) findings of this statistical downscaling are then compared to dynamical downscaling results (taken from the literature) and their possible future consequences are briefly discussed.

2 Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century[1]

ABSTRACT

It is known that inter-annual Baltic Sea level variations in the 20th century can be partially, but not totally, explained by the wind forcing linked to the North Atlantic Oscillation (NAO) and other atmospheric circulation patterns. Using regression analysis linking sea-level variations (as predictand) and sea-level-pressure (SLP), precipitation and air-temperature (included stepwise as predictors) it is investigated to what extent precipitation and temperature variations can also contribute to explain Baltic sea-level variability, in addition to sea-level-pressure. In wintertime, their additional contribution is small compared to that of sea-level-pressure (of the order of additional 15% of variance), but it is statistically significant and their inclusion as predictors help explain past deviations in the evolution of sea level, with higher than normal temperatures and precipitation values linked to a positive contribution to sea level anomalies. In summer, temperature and precipitation explain a substantial part of the sea-level variability except in the Kattegat region. In summer positive sea-level anomalies are linked to higher than normal rainfall but to lower than normal temperatures, suggesting that the

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[1] Hünicke, B. and Zorita, E. 2006. Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century. *Tellus* **58A**, 141-153, doi: 10.1111/j.1600-0870.2006.00157.x.

statistical link between sea level and temperature may artificially arise by the observed negative correlation between temperature and rainfall. For some stations, temperature and precipitation can explain, in addition to the variance explained by sea-level pressure alone, 35% of the total variability. Since part of influence of temperature and precipitation might be already contained in sea-level-pressure, this value represents a lower limit for the influence of these additional factors on sea-level variability. However, recent trends of winter sea level in the last 20 years cannot be described by a linear model with any of the predictors used in this study.

2.1 Introduction

One of the major concerns associated with expected global climate changes are future sea-level variations (IPCC, 2001), since they may have a strong impact on coastal ecosystems and human societies. Future changes of sea level on a global scale are believed to be brought about mainly by warming, and the corresponding expansion of the water column and, on somewhat longer time scales, by melting of the Greenland ice-sheet and land-glaciers. The projections for future sea-level rise based on thermal expansion of the water column simulated by different coupled ocean-atmosphere models, together with estimations of Greenland ice-sheet melting and land-glacier melting, lie within the range of 11-77 cm (IPCC, 2001). On the other hand, at regional scale the projections derived from these models may differ substantially, as at these scales sea-level rise is determined largely by the heat up-take by the ocean, changes in salinity and changes in wind driven ocean circulation. On regional scales, like coastal seas with complex boundary lines such as the Baltic Sea, other additional climatic factors may contribute to a further modulation of the climate signal on regional sea-level change in the future. Therefore, a detailed understanding of the physical factors that contribute to the observed variability of sea level is necessary for a complete assessment of possible future sea-level changes. Since the relevant timescales for anthropogenic climate change are decadal and longer, such an analysis should extend beyond the short time scales of inter annual variations.

Baltic Sea level variations at inter-annual to decadal timescales are generally believed to be caused essentially by variations in wind forcing, in particular (although not exclusive) by the North Atlantic Oscillation, the sea-level pressure sea-saw that pervades the inter-annual climate variability in the North-Atlantic European sector . Numerous of previous studies investigated this link so far, either through the analysis of observational data (e.g. Heyen, et al., 1996; Johansson et al., 2001; Andersson, 2002; Omstedt et al., 2004, Yan et al., 2004; Jevrejeva et al., 2005) or output of model simulations (e.g. Samuelsson and Stigebrandt, 1996; Meier et al., 2004).

Most of these studies focused on limited regions of the Baltic Sea. For instance Ekman (e.g. 2003 and references therein) and Andersson (2002) based their studies on the 200-year long Stockholm sea level record, pointing out that the winter climate, in particular wind, plays the central role for the Baltic Sea level variations. Omstedt et al. (2004) used the Stockholm sea level dataset to investigate the climate variations and trends of relevant Baltic Sea time series on different timescales. Their result support the hypothesis that the long-term climate change is mostly related to changes in the atmospheric circulation. Johansson et al. (2001) studied the trends in sea level variability in the northern Baltic Sea (Finnish Coast) over the past 100 years and could confirm a significant link with the NAO air pressure index in all the observed 13 stations.

On the other hand, Heyen et al. (1996) adopted a larger-scale perspective and used a multivariate statistical technique, canonical correlation analysis, to identify the atmospheric patterns responsible for variations in the modes of sea-level variability, finding a strong connection between the anomalies of large-scale sea-level air-pressure and the sea-level variability patterns in winter. Although they investigated the role of precipitation, they found no statistical link between these variable and leading spatial modes of sea-level variations.

As pointed out, the role of the NAO is prevalent at inter-annual time scales in the winter half year, but the influence of the NAO, as measured by a linear correlation coefficient, is not so strong in other seasons. Also, the correlation between the NAO and Baltic Sea level, even in wintertime, has not been constant over time and has undergone considerable decadal variations in the last two centuries (Andersson, 2002; Jevrejeva et al., 2005). Additionally, there exist regional differences in the spatial correlation between the NAO index and the Baltic Sea level (as illustrated later in this study). This varying strength of the NAO influence indicates that, superimposed on the NAO, other climate factors may be also modulating sea-level variations. The interest in identifying the role of these other factors lies in their possible influence within a future climate change. Although their influence within the present climate may be smaller than that of the NAO, large temperature or precipitation changes in the future may impinge a stronger fingerprint on Baltic Sea level changes.

In this paper we set out to investigate the influence of these other possible climate forcing on sea-level variations in the Baltic Sea by the analysis of the observational record. We focus on temperature and precipitation as the components with the highest data availability, assuming that they include - due to their relation to other water balance components like river run-off- a high amount of climate information. Due to lack of data, we do not consider in our analysis other factors that may be physically relevant (e.g. evaporation), but we keep in mind the need to include these factors in analysis of regional climate simulations of sea level.

One major problem in this endeavour is that in the present climate record the influence of these factors may be small in comparison with the influence of the NAO and other atmospheric modes. Another serious hurdle is that the NAO is also strongly correlated with these other forcings (e.g. winter-temperature or rainfall) (Hurrell, 1995), so that statistically it is difficult to disentangle their influence from that of the wind forcing associated with the NAO. The final goal in this study cannot be, therefore, the exact quantification of their influence (since part of it is already contained in the NAO indices and other atmospheric circulation modes) but to estimate their possible additional contribution, i.e. non-related to the NAO or to the SLP field in general. This additional influence would set a lower limit for their real influence on sea-level variations. A quantitative separation of the different contributions to sea-level variations, and the estimation of their possible non-linear interaction, can only be reached by numerical experiments with a realistic Baltic Sea ocean model, in which the variations of several forcing factors can be artificially suppressed.

The strategy in this study is the application of statistical regression models, in which Baltic Sea level is the predictand, and sea-level-pressure (as indicator of the geostrophic wind and therefore primary forcing of sea level variations), precipitation and temperature are the predictors. Time series of SLP, air-temperature and rainfall have a good coverage in the 20th century in the North Atlantic–European sector, allowing for a robust statistical analysis. This cannot be accomplished with wind time series. The analysis starts with sea-level-pressure as single predictor, thus yielding an estimation of its total skill in driving sea-level variations, and subsequently including step-wise the other two factors, thereby estimating the improvement in predictive skill. By analysing individual gauge stations separately possible regional differences are taken into account.

In this analysis we focus on the summer (June-August) and winter (December-February) seasons.

2.2 Data sets

Seasonal means of the following data sets were used.

2.2.1 Baltic Sea level data

We used data from 30 tide gauge stations in the Baltic Sea Region (Fig. 2.1) from the Permanent Service for Mean Sea Level. From this data set, the Revised Local Reverence (RLR) variant was used in the period 1900 to 1998. The selection of stations was based on the data availability, requiring that at least 75% of the months during the winter season (December-January-February) were covered.

The observation records contain a trend which is caused by postglacial land uplift and eustatic sea level change. At the time scales of our analysis (100 years) this trend can be assumed to be linear. To eliminate this influence we subtracted the long term linear trend from all time series. Only seasonal means were considered. In case of longer time scales (e.g. 200 years and longer) a more sophisticated filtering of postglacial rebound based on evaluation of a geological model would become necessary (Peltier, 1998).

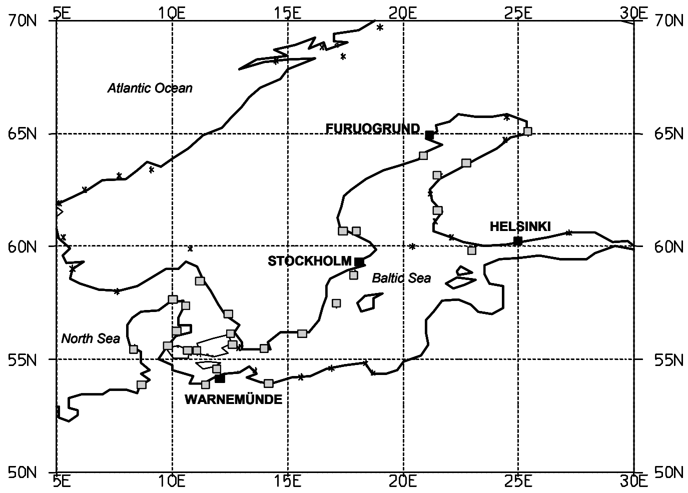

Fig. 2.1 *The location of the sea-level gauges.*

2.2.2 Climatic data sets

The following climatic data sets were used in this analysis:

- gridded (5-degree latitude-longitude) North Hemisphere monthly mean sea-level-pressure (SLP) from the National Centre for Atmospheric Research (NCAR, Trenberth and Paolino, 1980) in the geographical window 70W to 40E and 15N to 85 gridded (2.5x3.75 degrees latitude-longitude) monthly precipitation totals from the Climate Research Unit (CRU) (Hulme et al., 1998) in the geographical window 11.25E to 26.25E and 52.5 N to 62.5 N,

- gridded (5-degree latitude-longitude) monthly means of near-surface air temperature (Jones and Moberg, 1999) in the geographical window 10E to 30E and 50N to 65N and

- monthly values of sea level air pressure data from south-west Iceland and Gibraltar (Jones et al., 1997), obtained from the website of the CRU, Norwich.

The period of analysis usually extended from 1900 to 1998, except when precipitation was included in the analyses. In this case, due to the limitation of the precipitation data set, the analysis was limited to 1900-1996.

Furthermore, for some tests, we used monthly water temperature at different depths for 23 Baltic Sea locations, obtained from the Swedish Meteorological and Hydrological Institute and reporting between 1960 and 1996 (Zorita and Laine, 2000).

2.3 Relationship between Baltic Sea level and SLP

As stated before, a number of studies have established the link between atmospheric circulation and Baltic sea-level variations at inter-annual time scales, especially in wintertime. As a recapitulation of the results obtained in these studies, Fig. 2.2 shows the correlation pattern between the NAO index (from CRU) and sea-level variations in the period 1900-1998 for the winter (DJF) and summer (JJA) season.

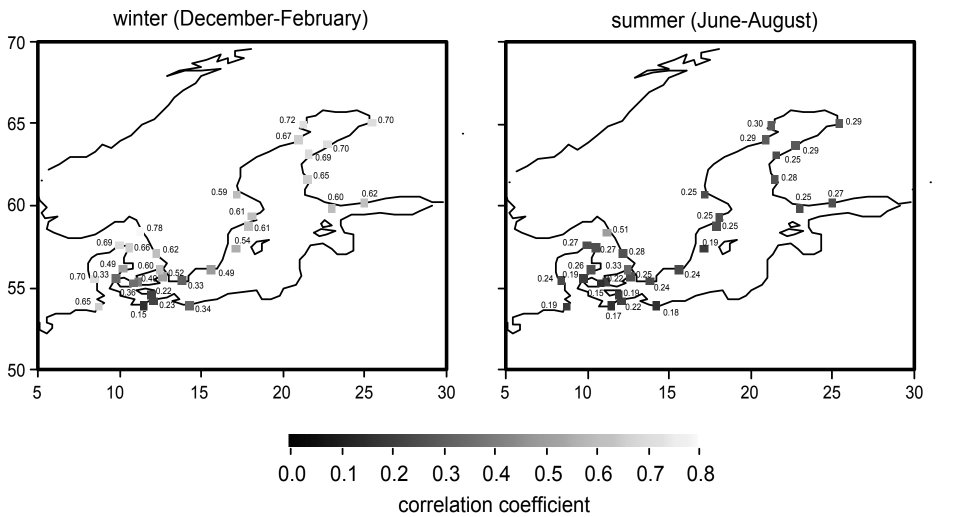

Fig. 2.2 *Correlation between the seasonal means of the North Atlantic Oscillation index and seasonal mean (linearly detrended) Baltic Sea level, 1900-1998.*

The correlations range between 0.1 and 0.8, but they are predominately weaker in summer (0.2-0.5) than in winter (0.1-0.8) and weaker for the Southern Baltic Sea. The relationship between NAO and Baltic Sea level has also undergone strong variations in time. Fig. 2.3 depicts the correlation coefficient between this winter NAO index and winter sea level in four Baltic Sea stations (Stockholm, Furuogrund, Helsinki and Warnemünde) in 21-year moving windows. It is shown that there exist strong decadal variations in correlations between the NAO and sea level. The correlations may get low as 0.25, although in recent decades the correlation has been as high as 0.8. In Warnemünde, the correlation with the NAO has even been negative for some periods.

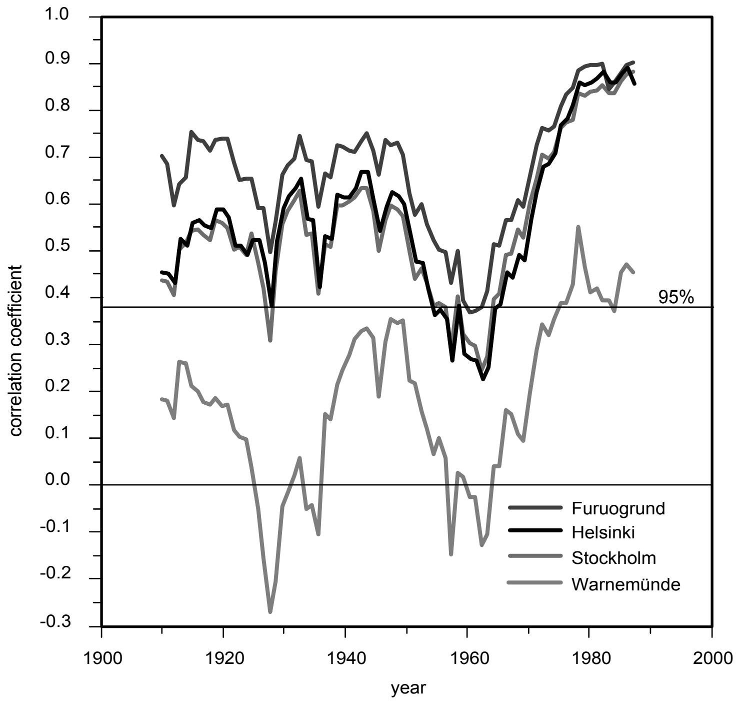

Fig. 2.3 *Moving correlation (21-year window) between winter (DJF) mean Baltic sea-level and the winter NAO index for four selected stations, 1900-1998. The two-sided 95% significance level is indicated.*

As some authors have used other definitions of winter months to calculate these correlations, for the sake of comparison we also carried out a similar analysis using the winter mean sea level for the month January, February and March, which shows, on average, a 0.3-0.4 higher correlation than in December to February (not shown). Noteworthy is the fact that all correlations tend to increase around 1965, up to a correlation coefficient of 0.9 (see also Andersson, 2002). This would be consistent with a stronger variability of the NAO in recent decades, measured by the standard deviation of the NAO index in 21-year moving windows (Fig. 2.4). As the variations of the NAO index have become larger, the NAO influence, all other factors remaining equal, is probably larger, thereby increasing the correlations between sea-level and NAO index.

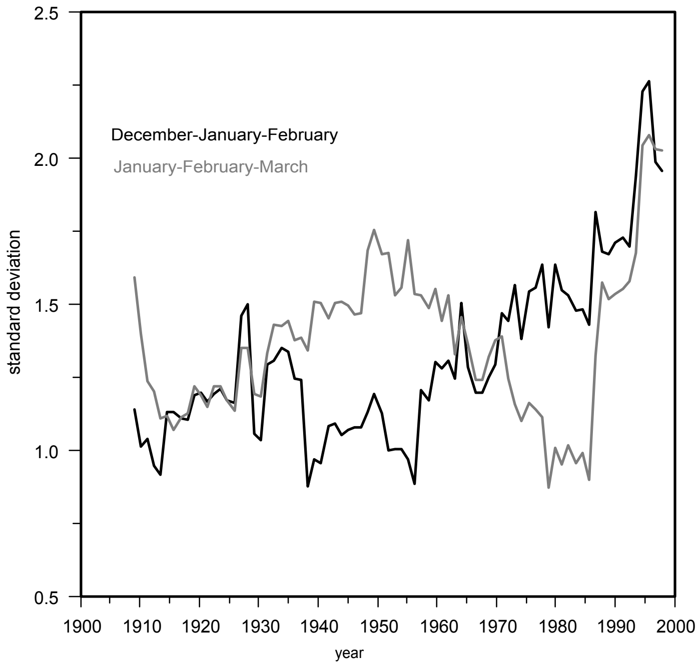

Fig. 2.4 *Comparison between the moving standard deviations (21-year window) of two different winter mean NAO indices, December-February and January-March.*

The physical link between the NAO index and sea-level variations in the Baltic Sea is further illustrated in Fig. 2.5: This figure shows the correlation pattern between sea-level, again exemplary for the four stations, and the SLP field in the North Atlantic sector in wintertime. The SLP pattern closely resembles the NAO pattern, albeit with some variations among the sea-level stations. The correlation pattern is again weaker for Warnemünde. The generally accepted interpretation of this correlation pattern is that stronger westerly winds are causally linked to higher than normal sea-level in all the Baltic Sea.

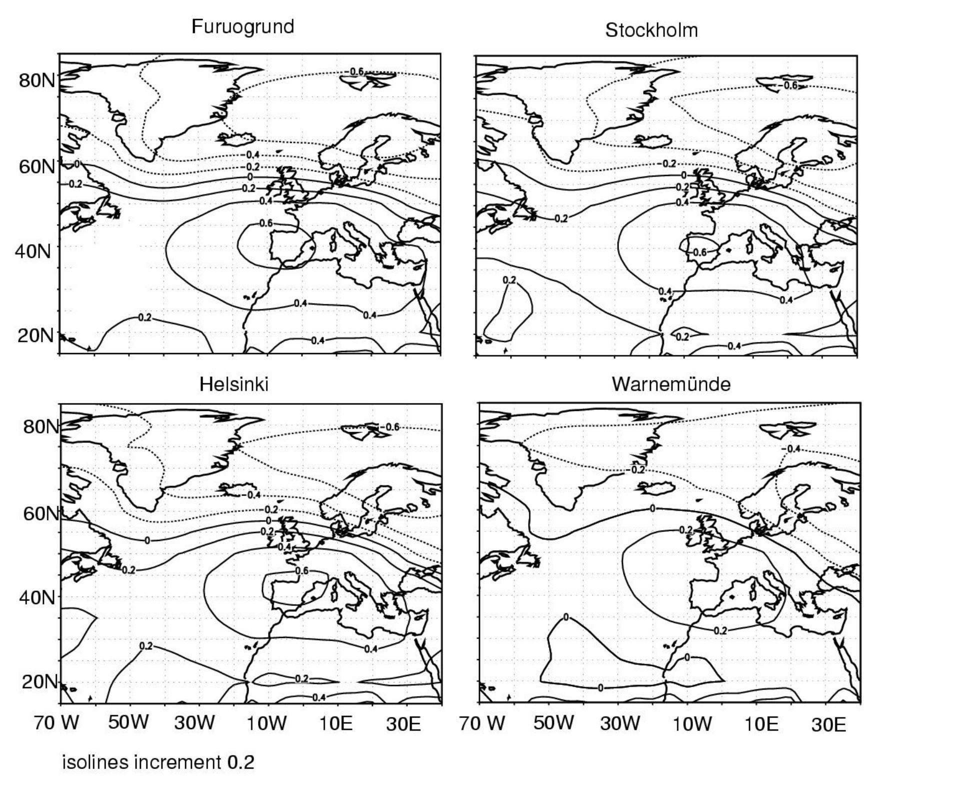

Fig. 2.5 *Correlation patterns between sea-level variations in four selected stations in the Baltic Sea and the SLP in winter (December-February), 1900-1998.*

In the following regression analysis we focus in more detail on these four stations that should be representative of the behaviour of Baltic sea-level: Furuogrund (north), Stockholm (west), Helsinki (east) and Warnemünde (south).

2.4 Statistical Regression Analysis

2.4.1 Winter season

To estimate the amount of variability in sea level which can be explained by the atmospheric circulation (and not only by the NAO) a simple linear regression model between sea level and the time series of the leading Principal Components (PCs) of the SLP field in the North Atlantic-West European sector has been set up for each station. The period 1960-1998 was used as calibration of these statistical models and the period 1900-1959 was reserved for their validation. The number of leading PCs used in the regression model was set by maximizing the amount of inter-annual explained variance in the validation. This was done to take into account all possible relevant predictors, but the calculation of the PCs and the estimation of the values of the regression parameters was always strictly performed in the calibration period. The number of PCs varied between 3 and 5.

$$SL(t)=\sum_{k=1}^{N_{eof}^{S}} a_k^S \, pc_k^S(t)+SLR^S(t) \; , \qquad (2.1)$$

where $pc_k^S(t)$ are the time series of the k^{th} PC and a_k^S are the regression coefficients of the leading N_{eof}^S , whereby the super index S stands for SLP. The first sum in the r.h.s. in eq.(2.1) represents the part of sea-level variations that can be linearly described by the evolution of the SLP field. The second term in the r.h.s of eq.(2.1) is SLR^S , i.e. the Baltic Sea level residuals that cannot be linearly described by the SLP field. For the calculation of the PCs of SLP and the estimation of the regression coefficients, only data in the period 1960 to 1998 have been used. Once these coefficients have been estimated by Least Mean Square-Error, the time series associated with the leading PCs have been determined for the whole period 1900-1998 by projecting the SLP anomalies (deviations from the 1960-1998 mean) onto the SLP eigenvectors. Equation (2.1) (without the term SLR) is used to reconstruct the sea-level time series in the whole period 1900 to 1998. Thus, the comparison between sea-level reconstruction and observations outside the calibration period 1960-1998 is an independent test of the skill of the statistical model. The results, smoothed with an 11-year running mean, are shown for four stations in Fig. 2.6 (left column).

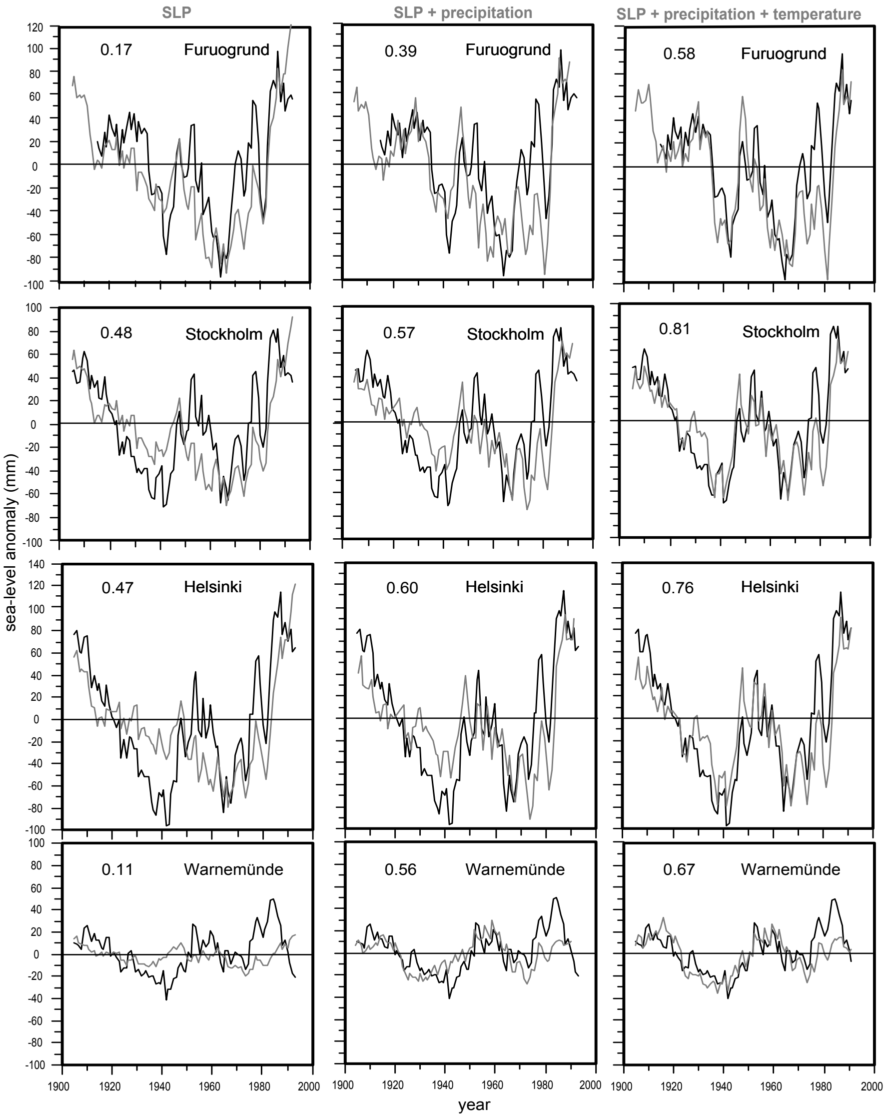

Fig. 2.6 *Winter (December-February) sea-level anomalies in four stations in the Baltic Sea (11-year Gaussian mean), observed (black) and reconstructed (grey) from the SLP field (left column), SLP and precipitation (middle column) and SLP, precipitation and temperature (right column).The regression model was calibrated in the period 1960-1990. The number in the left upper corner in each panel indicates the explained variance (Brier Skill Score, see text) in the validation period in the 11-year-mean smoothed timeseries. Note the different scales in the y-axes.*

For a measure of the variance explained by the model, the reduction of error (RE), sometimes also denoted as the Brier skill score (von Storch and Zwiers, 1999), was used. It is defined as

$$RE = 1 - \frac{\sum_t (o_t - p_t)^2}{\sum_t o_t^2} \quad , \tag{2.2}$$

where o_t are the observed anomalies and p_t the predicted anomalies at time t, relative to the mean of the calibration period. The sum extends over the validation period. The RE may take values between 1 (perfect prediction) and -∞. A value of zero indicates a skill equal to climatology (simply taking as prediction the value of the mean in the calibration period), and negative values indicate a skill worse than climatology. One advantage of using the RE as a measure of explained variance is that it takes into account changes in the mean between the calibration and the validation period, whereas the correlation between reconstructions and observations in the validation period does not. The variances explained by the SLP field in the validation period at decadal timescales are also indicated in Fig. 2.6.

The information contained in the SLP is indeed capable of reconstructing much of the past sea-level variations, but some clear deficiencies still remain. For instance, in all four stations the SLP field is unable to replicate the sea-level broad minimum around 1940 and also underestimates the sea-level maximum around 1950. The sea-level maxima around 1980 are also missed by the reconstruction, even though they lie within the calibration period. In Furuogrund, the maximum around 1930 cannot be explained by SLP and this is indeed the main reason for the low value of the explained variance compared to Stockholm and Helsinki. Clear limitations in this simple statistical model are especially obvious for Warnemünde, located in the Southern Baltic Sea and one of the stations with a weak statistical linkage with the NAO.

Thus, there seems to be a non-negligible amount of sea-level variability that cannot be explained linearly from the SLP field, and therefore from geostrophic wind forcing. Can the inclusion of other climate variables in the statistical model lead to an improvement of the explained variance?

To answer this question, the statistical model eq.(2.1) was augmented to include winter precipitation as a predictor. This is technically done in the same way as for SLP, namely through the PCs of the precipitation field in the Baltic Sea area. The idea behind including precipitation is that although much of the information about precipitation variations is, to be sure, already contained in the SLP field since the NAO index is positively correlated with average rainfall in wintertime, perhaps other local processes may cause precipitation variations that are not directly linked to the dynamics implied by the large-scale SLP field.

The model in eq.(2.1) is thus rewritten:

$$SL(t)=\sum_{k=1}^{N_{eof}^{S}} a_k^S\, pc_k^S(t)+\sum_{m=1}^{N_{eof}^{P}} b_m^P\, pc_m^P(t)+SLR^{SP}(t)\ , \qquad (2.3)$$

where the new term, with additional regression coefficients, corresponds to the PCs of precipitation. Both predictors, SLP and precipitation, stand on equal footing, i.e. no hierarchical regression has been performed, and therefore the regression coefficients in eq.(2.3) a_k^S may now be different as in eq.(2.1). However, a relevant result of eq.(2.3) would be if the augmented model could explain additional sea-level variability in a validation period, i.e. independent from the calibration. Model 2 is again calibrated for the period 1960-1998 and applied to reconstruct the sea-level variations in 1900-1998. Fig. 2.6 (middle column) shows the results of this reconstruction, together with the recalculated explained variances at decadal timescales in the validation period.

The reconstructions improved, in general, for all four stations. The minimum in 1940 and the maxima around 1950 come closer to the observed values; both lie outside the calibration period and thus the artificial skill is not caused by artificial statistical overfitting. This improvement shows that precipitation, or a variable related to it but not linearly to SLP, is also influencing sea-level variations.

As a logical step, the reconstruction model has been further augmented with the inclusion of air-temperature as a predictor. The rational here is that air-temperature is playing the role of an imperfect surrogate of water temperature and this may influence sea-level by the expansion of the water column. Clearly, the statistical reconstructions would have, in principle, more chances to be improved by using water temperatures, not only at the surface but also at various depths.

As a previous step to verify the usability of air-temperature data for our analysis, we calculated lag-correlations between winter sea-surface temperature anomalies and mean water temperature anomalies in 20-50 m depth, for 23 Baltic Sea locations, in the period 1960-1996. The correlations tend to be high, with values around 0.9 to 1, which are achieved at lag zero. The one-month lag correlations were also high and, except for very few exceptions, they were smaller than the simultaneous correlations. On the other hand, the sea surface temperature lags the air temperature by just a few days (Matthäus, 1996), so that it can be assumed that the air-temperature can be used in statistical sense as a representative of the temperature of the water column, at least up to intermediate depths. Unfortunately, the water temperature series are not as long as air-temperature timeseries, so that they are not as useful in this analysis as air-temperature. Furthermore, there is also a tactical reason for using air-temperature instead of water temperature as predictor in the statistical model. Such model can be applied to the output of a three-dimensional climate model to estimate future changes in Baltic sea-level. Water temperatures could not be used as predictor, since climate models do not realistically represent the Baltic Sea due to their coarse spatial resolution.

The third statistical regressions model reads:

$$SL(t)=\sum_{k=1}^{N_{eof}^{S}} a_k^S\, pc_k^S(t)+\sum_{m=1}^{N_{eof}^{P}} b_m^P\, pc_m^P(t)+\sum_{i=1}^{N_{eof}^{T}} c_i^T\, pc_i^T(t)+SLR^{SPT}(t)\ , \qquad (2.4)$$

where again the new regression coefficients correspond to the PCs of the air-temperature field in the Baltic Sea region. As in the case of precipitation, the SLP field already contains some of the information conveyed by the temperature field, since in wintertime the NAO is responsible for part of the inter-annual temperature variability in the Scandinavian region (Hurrell, 1995). However, at longer timescales, other factors such as variations in external forcing, solar variability and volcanic effects (Stott et al., 2000) or variations in the sea-surface temperature in the North Atlantic linked to the meridional overturning circulation may potentially also relevant.

The sea-level reconstructions using SLP, precipitation and air-temperature as predictors are shown in Fig. 2.6 (right column). Again, the reconstructions using air-temperature as an additional predictor show some improvements, also in the validation period. The minima around 1940 and maxima around 1950 are almost perfectly replicated in all stations. However, the fit to the observations is still not complete. Ironically, the biggest problem occurs in the calibration period, around 1975, when the match with observations should be theoretically better. Especially disturbing is the mismatch in the last decades of the 20^{th} century in Warnemünde and Furuogrund. Fig. 2.6 (right column) strongly indicates that some other factor remains responsible for much of the upward trend in sea-level in the 80's in these stations and the sea-level decay thereafter.

Some hints about the physical link between temperature and precipitation and the part of the sea-level variations that are not described by SLP, i.e. the residuals in the regression model 1, are given by the correlations between those residuals and both additional predictors. These correlation patterns (Fig. 2.7) are not the same for all four stations, indicating that indeed the influence of precipitation and/or temperature has some spatial variability. In the case of precipitation (Fig. 2.7a), the correlation patterns support the idea that higher rainfall is conductive to higher sea-level. This relationship is in general weaker in the northern stations and stronger in Warnemünde. A quantitative estimation of the influence of rainfall is much more difficult due to the role of evaporation and infiltration, which has not been considered here. Higher temperatures are also linked to higher sea-level residuals, suggesting that the mechanism linking both could involve the expansion of the water column (Fig. 2.7b). Assuming a level of decadal variability of water temperature of 1 K through a layer of about 50 m, the linear sea-level increase would be of the order of 10 mm, which agrees with the magnitude of the additional contribution to sea-level variations in Fig. 2.6. However, the relationship may be potentially more complicated, as for instance for Warnemünde, higher sea-level residuals are associated with higher temperatures in the Southern Baltic and lower temperatures in the northern Baltic.

Fig. 2.8 takes a closer look onto all 30 stations. Figure 2.8a shows the fraction of inter-annual variance (not decadal as in Fig. 2.6) in the validation period (1900-1959) that can be explained by SLP alone and additionally, the stepwise included predictors, temperature and precipitation. To estimate the level of significance of the additional explained variance, the temperature and precipitation PCs were replaced by synthetic Gaussian white noise.

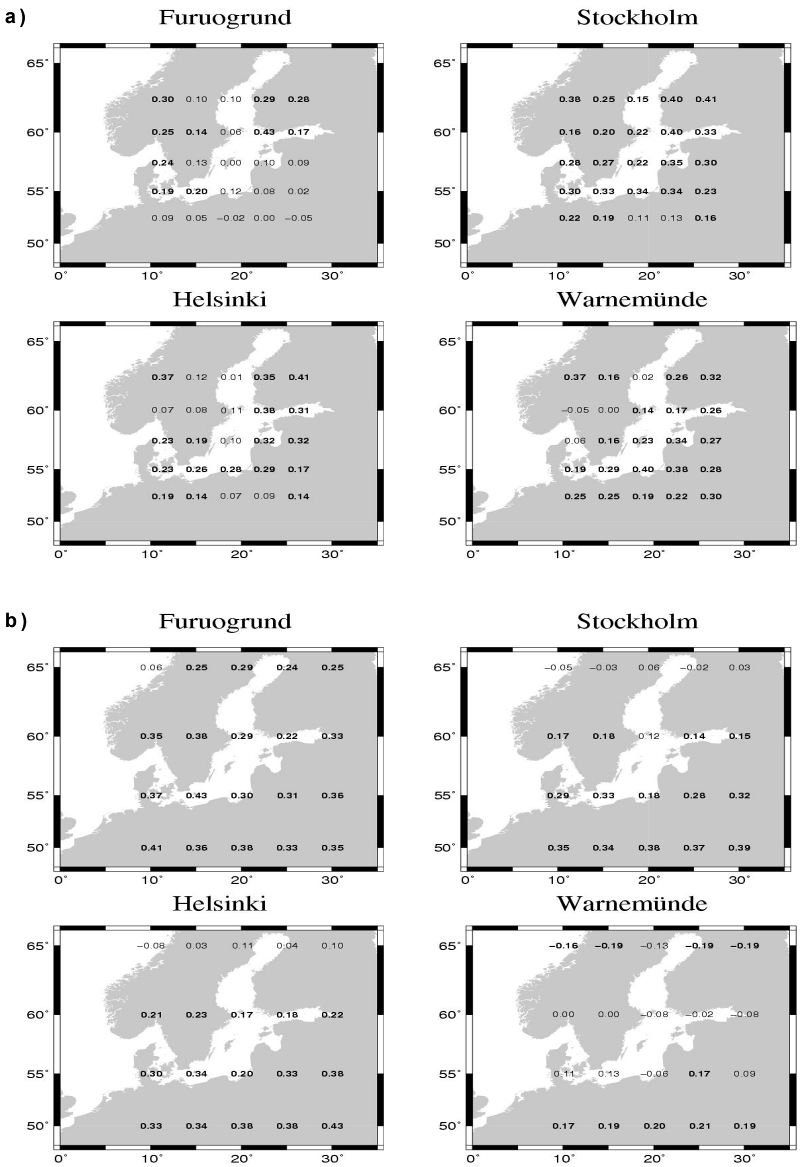

Fig. 2.7 *Correlation patterns between (a) sea-level residuals (eq.1) (part of the sea-level not linearly explained by SLP) and precipitation and (b) sea-level residuals and temperature in winter, 1900-1996. The 95% significance level is 0.14. Significant values are bold-typed.*

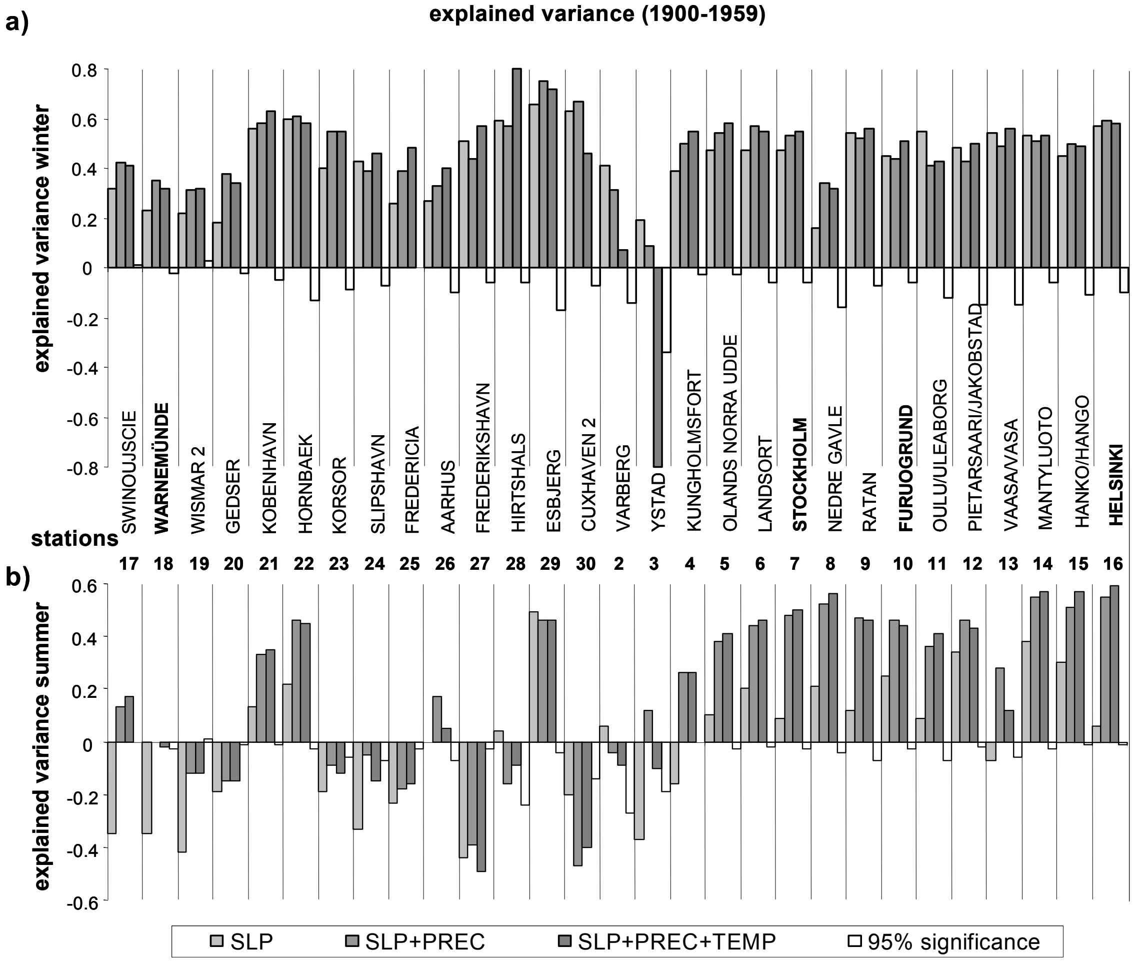

Fig. 2.8 Fraction of inter-annual variance (Reduction of Error or Brier Skill Score, see text) in the validation period (1900-1959) in (a) winter and (b) summer that can be explained by SLP, by SLP and the additional predictor precipitation (SLP+PREC) and by SLP, precipitation and air-temperature (SLP+PREC+TEMP) for 29 stations. The 95% significance level was estimated by using synthetic Monte Carlo predictors (Gaussian white noise) instead of the real temperature and precipitation predictors. The ordering of stations is geographically clockwise, starting in the Southwest.

The leading seasonal PCs used as predictors were expected to have low autocorrelations from one winter to the following (or from one summer to the following). Therefore the choice of white, instead of red, noise to estimate the level of significance seems justified. To ascertain that this was the case, the one-year-lag autocorrelations of all PCs employed were calculated. The magnitude of all autocorrelations was lower than 0.15 and therefore statistically non-significant at the 95% level, hence justifying the use of red noise in this calculation. In any case, the use of synthetic red-noise with these low autocorrelations changed very slightly the significance levels.

The synthetic explained variances were calculated in 100 realizations with these Monte Carlo predictors and reordered in decreasing values. The 95% significance level for each station was given by the 5th explained variance. Since in reality the distribution characteristics and the spectra of the sea-level data change from station to station, the level of significance is also station-dependent. Also, the level of significance may be negative, since the mean in the calibration and validation periods in the observations may be different.

Fig. 2.8a shows that the additional influence of temperature and precipitation, albeit small compared to that of SLP, is significant for almost all stations. Geographically, stations located in the Gulf of Bothnia tend to show smaller additional explained variance than those located in the south, as it was already exemplified in Fig. 2.6, but the case shown there (Warnemünde) is one of the most clear examples. Additionally, temperature seems to be a more important factor in the area close to Stockholm and Hanko in the Central Part of the Baltic, whereas south of this line precipitation is a more relevant factor. However, the available sea-level data set is under-represented in the South-Eastern Baltic Sea and this description should be completed with a more detailed analysis of this part of the coast.

In summary, both precipitation and temperature contribute to the improvement in the reconstructions of sea-level variations, but interestingly their relative contribution is not the same for all stations. As stated before, the influence of sea-level pressure is, in general, less in the Southern and high in the Northern stations. To test if these conclusions depend on the order in which the predictors (precipitation and temperature) have been included in the model, a similar calculation has been carried out with the ordering of precipitation and temperature interchanged, resulting in very similar results.

2.4.2 Summer season

A parallel analysis of the relationships between sea-level, SLP, temperature and precipitation was also carried out for the summer season. The results are briefly described in this Section.

The reconstruction of sea-level based on the statistical models of eq.(2.1) (predictor only SLP), eq.(2.3) (predictor SLP and precipitation) and eq.(2.4) (SLP, precipitation and temperature) are shown in Fig. 2.9. The most important discrepancies between sea-level observations and reconstructions from the SLP field alone (Fig. 2.9, left column) are the minima around 1910 and 1940 and the increasing sea-level 1980 onwards, peaking in the early 1990s.

The inclusion of precipitation as predictor considerably improves the reconstruction (Fig. 2.9, middle column). The minima around 1910, occurring outside the calibration period and therefore again an independent confirmation of the model, are now almost perfectly reproduced in all four stations. Also quite relevant is the match in the last two decades of the 20^{th} century. The remarkable improvement of the reconstruction model using SLP and precipitation as predictors leaves little room for further improvements when air-temperature is included (Fig. 2.9, right column). Actually, the reconstructions show almost no improvement with respect to the previous case. The explained variances, based on the 11-year Gaussian mean, show even a decrease for Warnemünde, Stockholm and Furuogrund.

The relevance of temperature and precipitation in summer, compared to the winter season, is clearly illustrated in Fig. 2.8b. The variance additionally explained by these two variables is much more clearly detected for most of the stations in the Baltic Sea. Exceptions are the stations located in the Kattegat region and the Southern Baltic, but in general the additional explained variance is larger than the variance explained by the SLP alone. These results justify a further analysis of regression models in which each one of the three predictors is used in isolation (Fig. 2.10). The variance that can be explained by precipitation or temperature in isolation is often larger than the variance explained by SLP alone, which in some cases, as in the Southern Baltic, is even negative. For instance, in these stations the inclusion of SLP as predictor is counter-productive, and precipitation or temperature in isolation produces a model with better skill than with all three predictors.

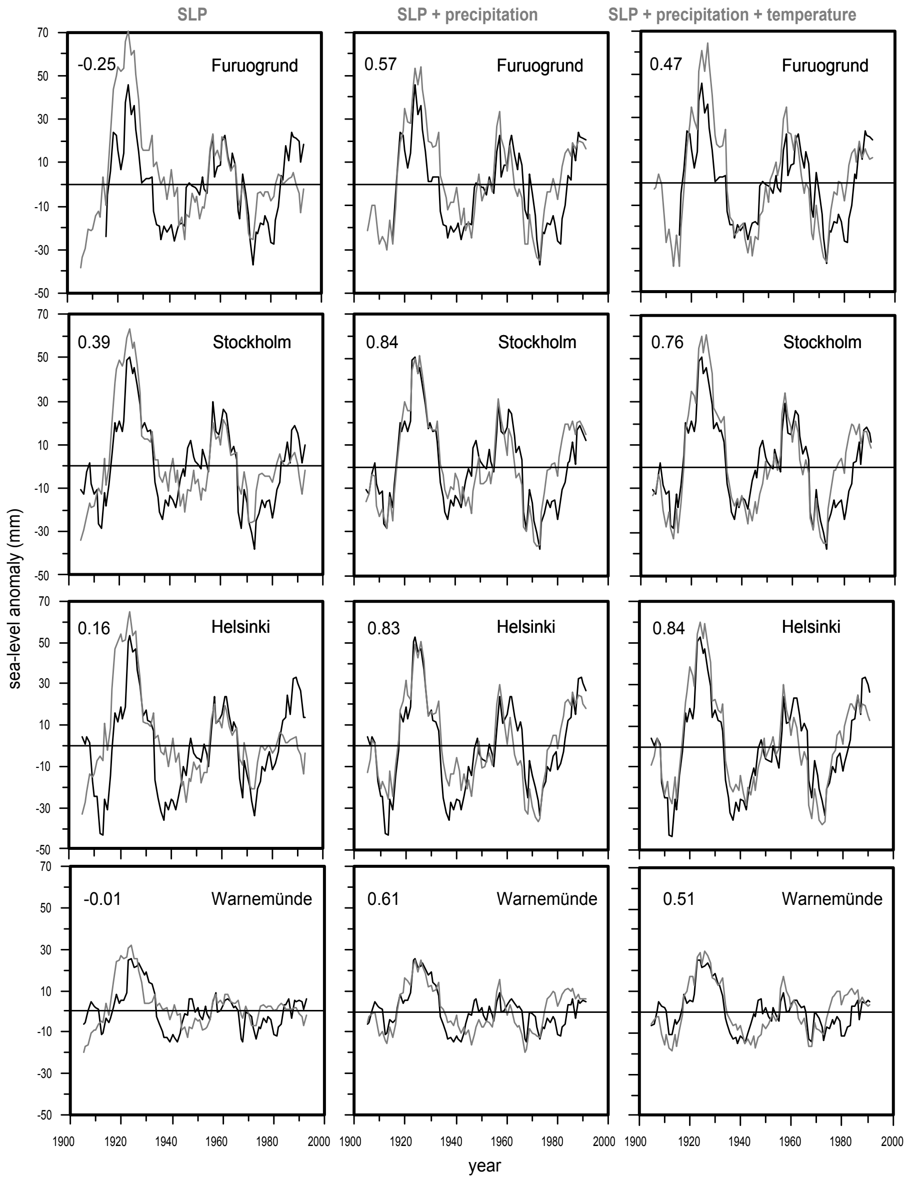

Fig. 2.9 *Summer (June-August) sea-level anomalies in four stations in the Baltic Sea (11-year Gaussian mean), observed (black) and reconstructed (grey) from the SLP field (left column), SLP and precipitation (middle column) and SLP, precipitation and temperature (right column). The regression model was calibrated in the period 1960-1990. The number in the left upper corner in each panel indicates the explained variance (Brier Skill Score, see text) in the validation period (11-year Gaussian mean).*

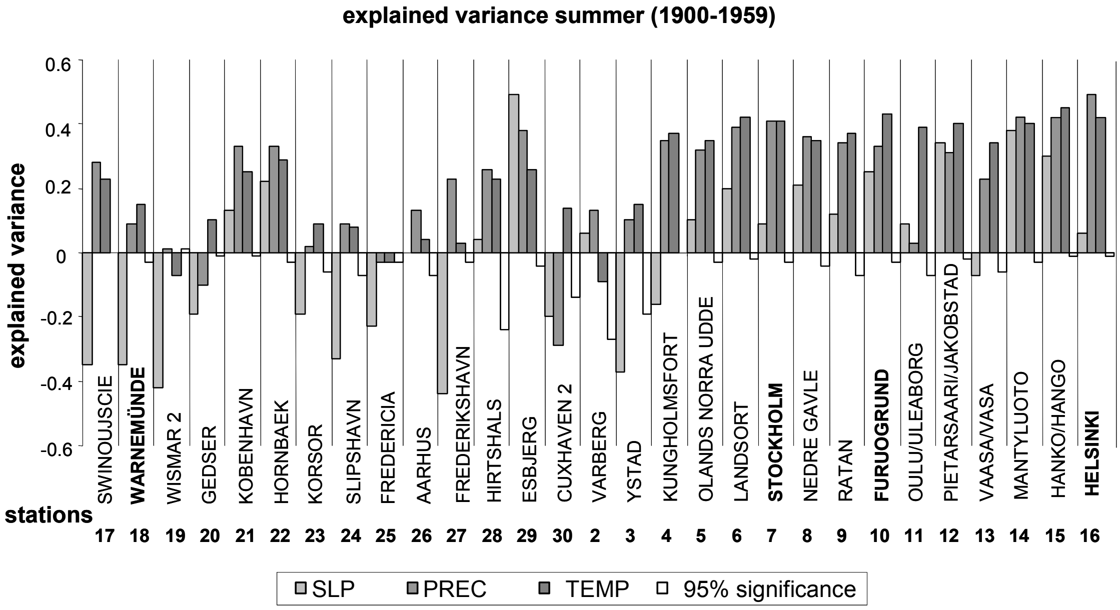

Fig. 2.10 *Fraction of inter-annual variance of sea-level in the validation period (1900-1959) in summer that can be explained by SLP, by precipitation (PREC) and by air-temperature (TEMP), each one as isolated predictor. The level of significance has been estimated as in Fig. 2.8.*

Fig. 2.10 indicates that precipitation and temperature have similar levels of skill to predict sea-level variations, so that the question arise which variable is actually physically connected to sea-level variability. Here, statistical analysis can only offer some preliminary clues about the real answer.

The correlation patterns between the sea-level and temperature in summer (Fig. 2.11a) clearly show a sign of the correlation (negative for all four stations) that is not compatible with the hypothetical effect of the water column expansion. Therefore this link could be, if at all, mediated by other indirect mechanisms. The link to precipitation, on the other hand, is stronger and compatible with the direct influence of rainfall on sea-level, as indicated by the correlations between sea-level and precipitation (Fig. 2.11b). This conclusion is also verified if the correlation is calculated between the sea-level residuals (of a statistical model with only SLP as predictor) and temperature or precipitation (not shown).

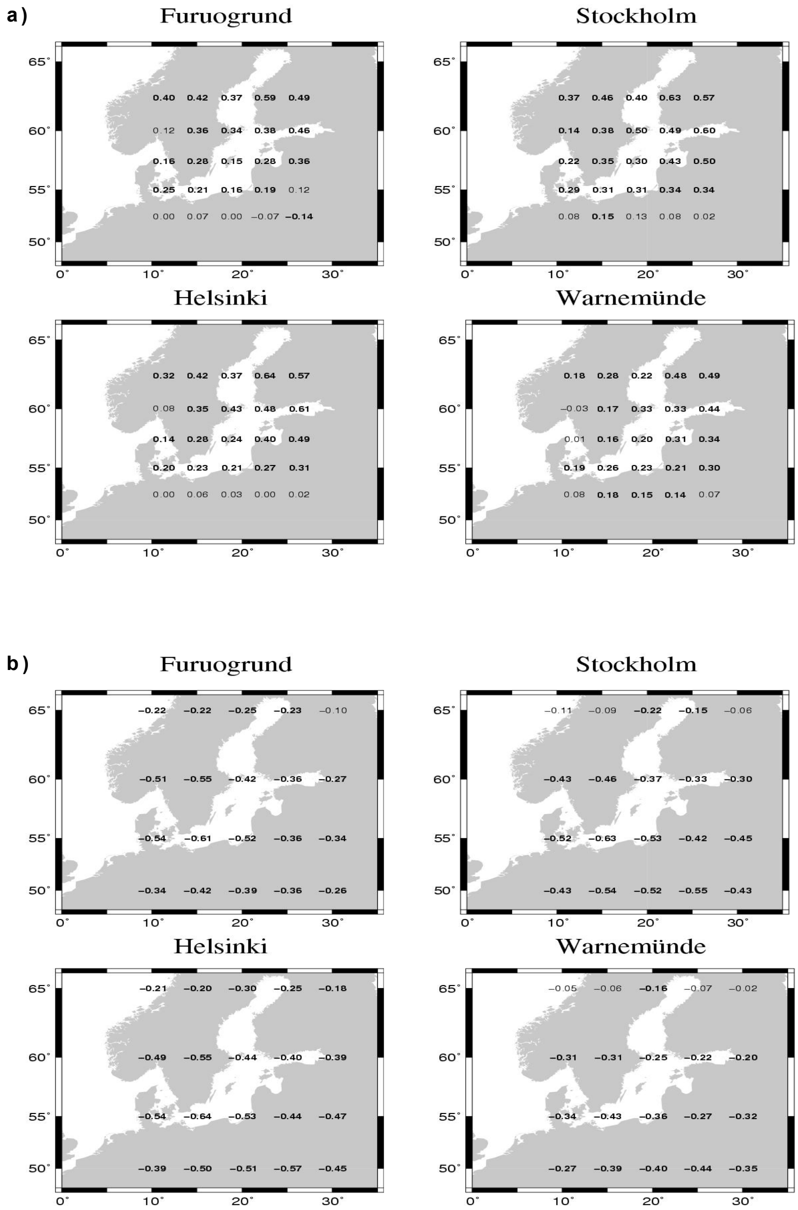

Fig. 2.11 *Correlation patterns between (a) sea-level and precipitation and (b) sea-level and air-temperature in summer, 1900-1996. The 95% significance level is 0.14. Statistically significant correlations are bold-typed.*

If this interpretation is accepted, the link between temperature and sea-level arises artificially, through an indirect correlation to another factor. This factor could be precipitation, as temperature and precipitation in the Baltic Sea region are indeed negatively correlated at inter-annual and decadal time scales. The latter relationship is clearly illustrated in Fig. 2.12.

In summary, although SLP is also able to explain a certain amount of sea-level variability in summer, the amount of variance explained by SLP alone is much smaller than in winter. This is consistent with the already known smaller correlation between the NAO and sea-level in the summer season.

The influence of precipitation and/or temperature seems to be much more considerable for most stations than in wintertime (except in the Kattegat region). Both variables taken in isolation represent in general a better predictor for sea level than SLP.

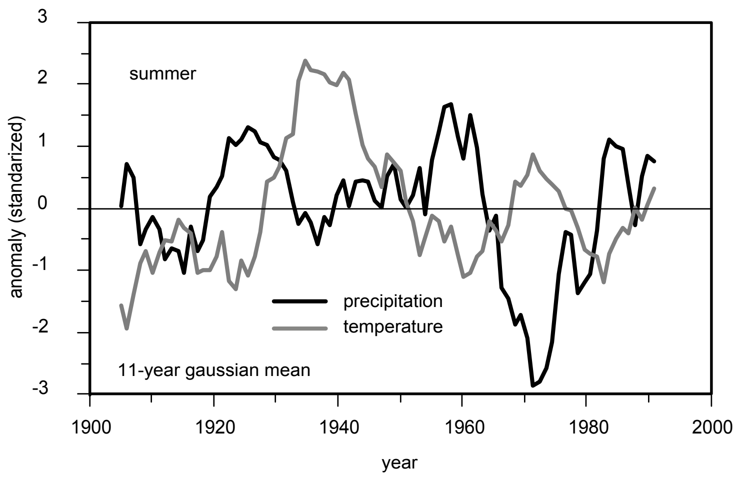

Fig. 2.12 *Summer mean temperature and precipitation anomalies in the Baltic Sea region (see Section 2.2 for details), smoothed with an 11-year Gaussian mean filter, and standardized to unit standard deviation.*

Which one of these two is the most important factor for sea-level variability is difficult to ascertain on statistical grounds alone. However, sea-level is positively correlated with precipitation and negatively correlated with temperature, suggesting that the driving role is played by rainfall. Although a statistical analysis alone cannot rule out completely a physical influence of temperature on sea-level, a mechanism directly linking negative temperature anomalies with higher sea-level in summer is not obvious.

2.5 Discussion and outlook

A series of simple statistical models linking sea-level in the Baltic Sea and SLP, precipitation and air-temperature, introduced step-wise as predictors, show that in wintertime precipitation and air-temperature contribute to determine an additional part of the part of sea-level variability that cannot be linearly explained by SLP (thus by the forcing of the geostrophic wind). In most stations, this additional explaining power of models containing temperature and precipitation as predictors is small (of the order of 15 % of the total inter-annual sea-level variance) but it is unlikely to arise by chance, and the inclusion of these predictors helps achieve a better fit to observed sea-level variations in a validation period. It should be noted, however, that part of the signal conveyed of the predictor SLP may also contain the possible effect of the other two variables, since in wintertime SLP is strongly positively correlated to temperature and to precipitation anomalies.

The identification of the influence of temperature and precipitation on sea-level seems to stand in contradiction to the conclusions obtained by Heyen et al. (1996), who found that precipitation has a little impact on Baltic Sea level variations. They used a statistical method (canonical correlation analysis with previous principal components filtering) that tends to identify the modes of sea-level variations that are present in all or a majority of a station network, thereby filtering out the sea-level variability that has a more local character. By setting up a linear regression model for each station separately, the statistical model is freed from this constrain and it is reasonable to expect that it can identify weaker signals and signals that are not so coherent spatially.

In the summer season the influence of precipitation and temperature variations on sea-level is much stronger than in wintertime and for many stations this influence is stronger than that of the SLP alone. For instance, in Helsinki in summertime, the inclusion of precipitation allows the regression model to explain an additional 35% of the total inter-annual variance. This may be caused by the smaller variability of the SLP field (and therefore also of the wind) in summer than in winter, thus allowing the other factors to gain in relative importance. If these results are to be applied for estimations of future sea-level changes in the Baltic Sea in a future climate, the observational evidence thus indicates that regional precipitation and temperature changes in summertime have to be taken into account. In this respect it would be important to disentangle the separate effect of temperature and precipitation. In the observational record both variables are negatively correlated. But this relationship may not be extrapolated into the future, since their mean changes will not necessarily be opposite to each other. Therefore, it seems desirable to achieve a quantification of their effect in the past century, possibly by modelling studies.

A simple reasoning indicates that temperature is unlikely to be a driving factor of sea-level variations in summer, since in general it is negatively correlated to sea-level. This can be speculatively explained by the fact that in summer the stratification of the Baltic Sea hinders the spread of heat-flux into the water column, and therefore the effect of water expansion remains constrained to a relatively shallow layer.

The geographical distribution of the additionally explained variance tends to be larger in the Southern stations, both in winter and in summer; although in summer this additional variance is spatially distributed in a slightly more homogeneous way. This is consistent with the higher correlations with the NAO found in the Northern stations and also with the fact that in summer the correlation with the NAO is geographically more homogeneous than in winter (Fig. 2.2).

The results presented here, therefore, indicate that additional forcing factors cannot be neglected and need to be, at least in principle, taken into account in the estimation of future, and also of past, sea-level variations. The statistical reconstruction model using all three variables constitutes a transfer function between a large-scale climate field and a local climate variable, such as sea-level. In this sense, this transfer function can be applied to the output of an atmosphere-ocean climate model, such as those used in the prediction of the effects of anthropogenic greenhouse forcing in the 21st century. Numerical simulations with a Baltic Sea ocean model driven by future climate scenarios also constitute a much more complicated transfer function for the estimation of future changes in the Baltic Sea (Meier et al., 2004). The output of the global climate models could indicate that changes in air-temperature in the Baltic-Sea area may be as large as to overcome the expected changes in the NAO in a future climate, and thus become a dominant factor in determining future sea-level trends in the Baltic Sea. This will be investigated in forthcoming studies.

Acknowledgments

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3 Trends in the amplitude of Baltic Sea level annual cycle[2]

ABSTRACT

Baltic Sea tide gauge data and climatic data sets are statistically analysed to investigate the centennial trends in the amplitude of the annual cycle of Baltic sea-level. In almost all gauge stations analysed, an increase of the amplitude (winter-spring sea-level) is detected. These trends are not large compared to the decadal variations of the annual cycle, but they are statistically significant. The magnitude of the trends is almost spatially uniform, with exception of the Skagerrak area. Since inter-annual and decadal variability of sea-level displays a clear spatial pattern, the mechanism responsible for the trends in the annual cycle seem to be not regional, but affect the Baltic Sea basin as a whole.

Several hypotheses are proposed to explain these centennial trends on the winter minus spring sea level: wind (through the SLP field), the barometric effect, temperature and precipitation. By elimination of three of the working hypothesis, seasonal Baltic precipitation remains a plausible candidate. For the other three, either the sign or magnitude of the trend makes them unlikely the sole explanation.

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[2] Hünicke, B. and Zorita, E. Trends in the amplitude of Baltic Sea level annual cycle. *Tellus* **60A** (1), 154-164, doi: 10.1111/j.1600-0870.2007.00277.x.

3.1 Introduction

According to simulations with global climate models, anthropogenic climate change in the next decades will be likely associated with a general increase of sea-level. Most estimations of global sea-level rise in the 21st century, due to the thermal expansion, melting of land glaciers and of the Greenland ice-sheet lie within the range of 18-59 cm (IPCC, 2007). The observed long-term global sea-level rise in the 20th century has been estimated in the range of 1-2 mm/year, but this figure conceals large regional variations due to a number of different processes that may also give rise to long-term trends in regional sea-level. In the open ocean the penetration of heat into the deeper layers depends on the mean ocean circulation and on the processes of deep water formation. In coastal regions and semi-enclosed seas atmospheric circulation patterns, rainfall, sea-ice and other causes may result in deviations from the global sea-level trends. For instance, sea-level in the Mediterranean shows a negative-trend in the last decades, possibly due to trends in the intensity of atmospheric sea-level-pressure (SLP) patterns, such as the North Atlantic Oscillation (NAO) (Yan et al., 2004). These regional processes may continue to be active in the next decades, so that an understanding of the regional sea-level variations at decadal, multi-decadal and centennial time-scales is relevant for more accurate predictions of regional sea-level trends.

The Baltic Sea is one of the regions were multiple factors are likely to contribute to long-term sea-level trends. The isostatic adjustment from the melting of the Scandinavian ice-sheet in the early Holocene causes a current negative sea-level trend in the northern Baltic coast. Furthermore, the Baltic Sea is strongly exposed to the influence of North Atlantic atmospheric circulation patterns, which drive wind, rainfall and temperature, all factors that directly or indirectly may influence the long-term behaviour of Baltic-Sea level. Focusing on the Baltic Sea, the influence on sea-level by factors external to the Baltic Sea may even be strongly station-dependent. Jevrejeva et al. (2005) found the NAO exerts a strong influence on winter sea-level variability at inter-annual time-scales in the central and northern gauge stations, but that this influence is much weaker in the southern Baltic Sea. Therefore, trends in the NAO index, as envisaged in many global climate models (Stephenson et al. 2006) could induce differences in the spatial pattern of sea-level rise in the Baltic.

In a recent study, Hünicke and Zorita (2006) put forward an estimation of the relative importance of temperature and precipitation in modulating long-term (decadal) variations of Baltic Sea level in the past century, by analysing time series of sea-level-temperature, precipitation and sea-level-pressure. The main result of that study suggested that sea-level variations in winter and summer are influenced by quite different factors and thus its evolution in a future climate may be also potentially different. In winter, the widely held view that Baltic sea-level variations are indeed mostly modulated by the westerly winds, possibly with additional smaller contributions from temperature (via expansion of the water column) and precipitation (through increased fresh water run-off into the Baltic Sea) was confirmed. However, precipitation seemed to be an important factor for sea-level variations in summer.

The question arises as to whether the results of this analysis conducted for inter-annual time-scales, can be extrapolated to longer time-scales and therefore become relevant in the context of future anthropogenic climate change. Chen and Omstedt (2005) studied the long-term record of sea-level in Stockholm in the period 1873-1995 and found that the long-term trend, once the isostatic adjustment has been removed from the record, depends on the season. They concluded that all months in the calendar year, except June and August, display a positive sea-level trend, whereas June and August show a negative trend that they interpret, for the latter month, as due to a negative long-term trend in Baltic precipitation. These authors warn, however, that a detailed analysis of the hydrological budget may be necessary to ascertain this conclusion. They also found that the link between trends in air temperature and the positive trends in sea-level for some months of the calendar year may be suggestive, but difficult to prove. For Stockholm, different processes seem, therefore, to be responsible for the different trends through the calendar year. The question arises whether these processes may possibly react differently to regional climate changes brought about by an increase in atmospheric greenhouse trace gases, thus giving rise to different seasonal long- trends in Baltic Sea level.

Baltic Sea level shows a mean annual cycle that usually peaks in the winter months and attains its minimum in early spring. The annual cycle amplitude in sea-level has been found to have increased in the 20th century in the North Sea and Baltic Sea (Plag and Tsimplis, 1999), especially in the last decades, a result that coincides with the analysis of Ekman and Stigebrandt (1990) for Stockholm. This increase is, however, superimposed upon large decadal variations, which these authors interpret in general as a result of decadal variations in the strength of the atmospheric circulation and the resulting changes in wind-stress. As the annual cycle has underdone the strongest variations in the last decades of the 20th century Plag and Tsimplis (1999) raise the question of the influence of anthropogenic climate forcing. However, the response of the atmospheric circulation, and in particular, of the NAO to anthropogenic greenhouse forcing, is still much debated (Stephenson et al., 2006).

The focus of this study lies on the investigation of the centennial trends in the amplitude of the annual cycle of Baltic sea-level and their possible physical origins. Section 3.2 presents the data (observational records) used in this study. Section 3.3 examines the existing trends in the amplitude (winter-spring sea level) of the annual cycle of Baltic Sea level and their statistical significance by using different trend estimators and significance tests (parametric and non-parametric). In Section 3.4, possible causes for the trend in the amplitude are investigated by statistically analysing several hypothetical factors: the wind stress forcing (closely associated with the NAO, but also other SLP patterns), the pressure difference between the Baltic Sea and the North Atlantic Region (due to the barometric effect), the temperature (due to thermal expansion through the water column) and precipitation (including a discussion of the role of fresh water balance and salinity). Section 3.5 presents a discussion of the results and some conclusions.

3.2 Data sets

3.2.1 Baltic Sea level observations

For analyses in the 20th century we used data from 30 Baltic Sea tide gauge stations from the Revised Local Reference (RLR) dataset of the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003). For some of the analysis back to 1800, the four longest sea level records from stations situated along the Baltic Coast, Kolobrzeg (from 1815 to 1999; PSMSL, before 1951 provided by Technische Universität Dresden), Swinoujscie (from 1815 to 1997; PSMSL), Stockholm (from 1801 to 2000; Ekman, 2003) and Kronstadt (from 1840 to 1993; Bogdanov et al., 2000 were selected (Fig. 3.1).

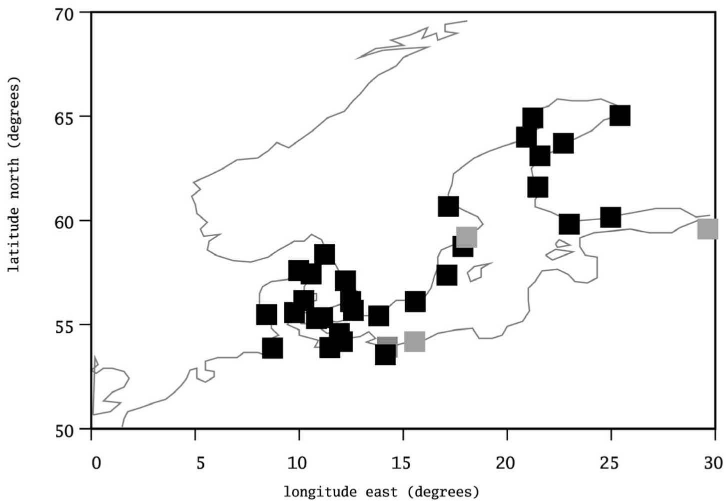

Fig. 3.1 *Sketch of the Baltic Sea, showing the location of the sea-level gauges. (The grey squares indicating the four longest available sea-level records.)*

Missing values in two of the time series (Kolobrzeg from 1940 to 1950; Swinoujscie from 1945 to 1950) were not filled-in.

3.2.2 Climatic data sets

The following gridded climatic data sets were used:

- 5°x5° monthly mean sea-level-pressure (SLP) from the National Centre for Atmospheric Research (NCAR, Trenberth and Paolino, 1980) for the region 70W to 40E and 15N to 85N,
- 2.5°x3.75° monthly precipitation totals from the Climate Research Unit (CRU) (Hulme et al., 1998) for the region 1.25E to 26.25E and 52.5 N to 62.5 N,

- 5°x5° monthly means of near-surface air temperature (Jones and Moberg, 1999) for the region 10E to 30E and 50N to 65N.

Furthermore, as for the calculation of the NAO-index, monthly values of sea level air pressure data from south-west Iceland and Gibraltar (Jones et al., 1997), obtained from the website of the Climatic Research Unit of the University of East Anglia, UK, were used.

3.3 Trends in the amplitude of the annual cycle of Baltic Sea level

For illustration purposes, the seasonal cycle of monthly mean sea-level in selected gauge-stations in the Baltic Sea in two different periods, 1900-1930 and 1970-1998, are shown in Fig. 3.2.

Sea level attains a well defined minimum in early spring and a relatively flat maximum in winter. The shape of the annual cycle agrees with the one shown by Chen and Omstedt (2005) for Stockholm. Sea level has decreased from the beginning of the 20th century for all months, except in the station located in the southern Baltic. These long-term trends are mostly due to the isostatic adjustment as a consequence of the last deglaciation. However, no large changes in the shape of the annual cycle can be discerned Fig. 3.2. If present, those shifts in the annual cycle have probably been small. In this study it will be assumed that the shape of the annual cycle has remained essentially unchanged.

Similar conclusions can be drawn for the equivalent calculations with four longer sea-level records, namely Kolobrzeg, Swinoujscie, Stockholm and Kronstadt. Fig. 3.3 shows the annual cycles in these four gauge stations in the periods 1850-1880 and 1950-1980.

The influence of the isostatic adjustment in each gauge station in the period 1900-1998 can be roughly subtracted by linearly detrending the sea-level records as, at this time scale, the isostatic adjustment can be assumed to be approximately linear. However, linearly detrending will also subtract other possible long-term trends due to other climate processes. Although the influence of isostasy on sea-level cannot be statistically separated from long-term trends in climate factors that may also be influencing sea-level, it is reasonable to assume that the trend *difference* between any two seasons of the year has to be related to factors different from isostasy. For instance, the trend in the sea-level difference between winter and the following early spring, i.e., the trend in the amplitude of the annual cycle, is very probably unrelated to isostasy, as the influence of isostasy at time-scales of a few months is negligible. This fact is exploited to identify the influence of long-term climate forcings on Baltic Sea level. In the following, spring will be denoted as the months from March to May and winter as the months from November to January. Seasonal means, as defined within these seasons, of sea-level will be considered.

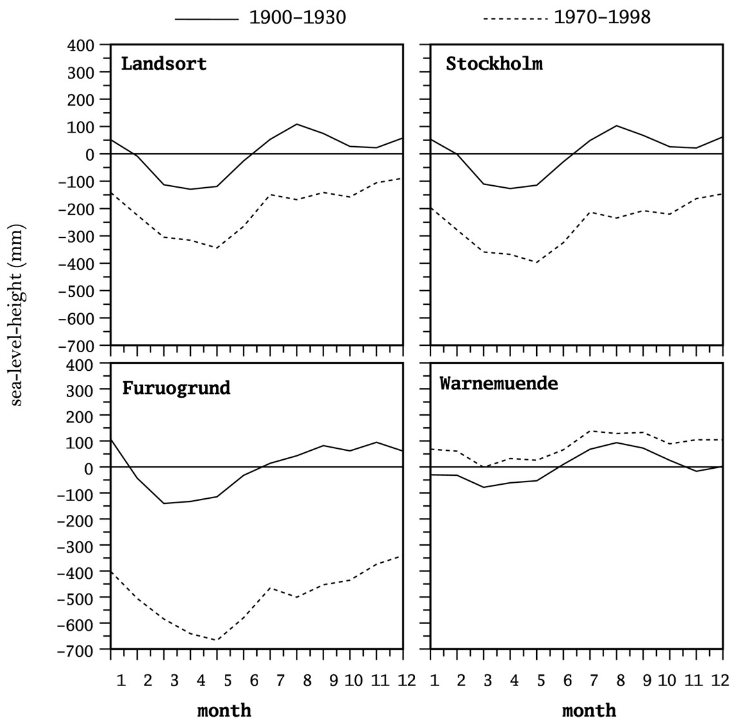

Fig. 3.2 *Sea-level annual cycle derived from monthly means averaged in two different periods in the 20th century (1900 to 1930 solid line, 1970 to 1998 dashed line) in four selected stations in the Baltic Sea.*

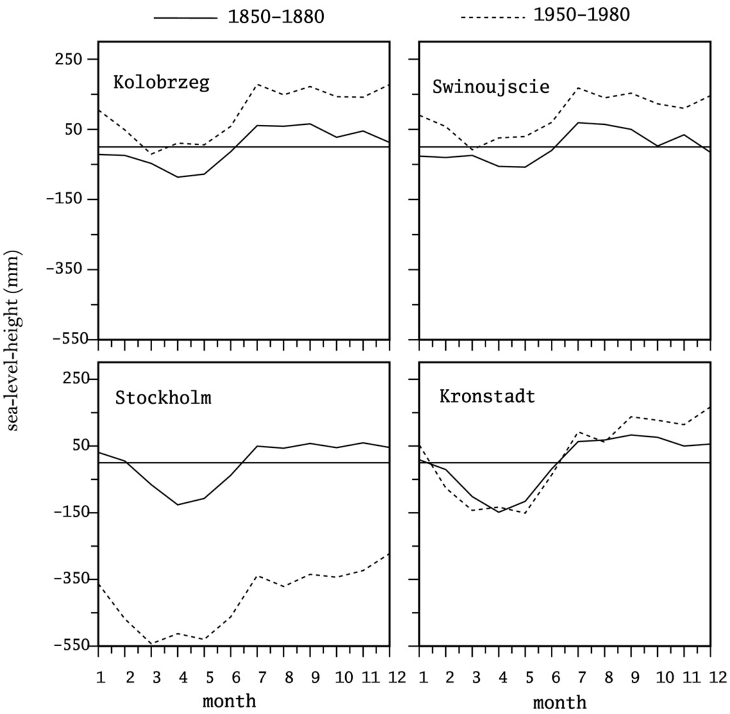

Fig. 3.3 *Sea-level annual cycle derived from monthly means in four selected stations in the Baltic Sea, averaged in one period in the 19th century (1850 to 1880 solid line) and one period in the 20th century (1950 to 1980 dashed line).*

The estimation of linear trends and of their statistical significance by the usual method of a linear fit by least-square-error minimization might be too strongly dependent on the assumptions of independence of the error terms and normality of the data. The independence of the error terms in a linear regression with timeseries is usually addressed by testing for the presence of lag-1 autocorrelation in the residuals resulting from the linear fit. A usual test for this goal is the *Durbin-Watson test* (Durbin and Watson, 1950). In all following trend estimations, the Durbin-Watson test was applied and only in two cases was the resulting Durbin-Watson statistics outside the range that would indicate the presence of auto correlated residuals. These two cases were for sea-level differences in Vaasa and Esbjerg, where the Durbin-Watson statistics indicated a slight positive autocorrelation of the residuals of the linear fit.

The dependence of trend estimation on the normal distribution of the data was addressed by estimating the sea-level trends, in addition to the more usual method of linear fit, by a non-parametric method, the *Theil-Sen method* (Sen, 1968). The Theil-Sen trend estimator is defined as

$$\beta = m\left\{\frac{x(t_i)-x(t_j)}{t_i-t_j}, i \neq j\right\}, \tag{3.1}$$

where m is the median of the ratios (x(i)-x(j))/(i-j) for i=/j, where x is the variable of interest (e.g. sea-level) and i and j comprise all possible time-steps.

Fig. 3.4 shows the linear trends for winter (November-January) minus previous spring (March-May) sea-level in the period 1900-1998 for the Baltic sea-level gauges, estimated by linear regression and by the Theil-Sen method.

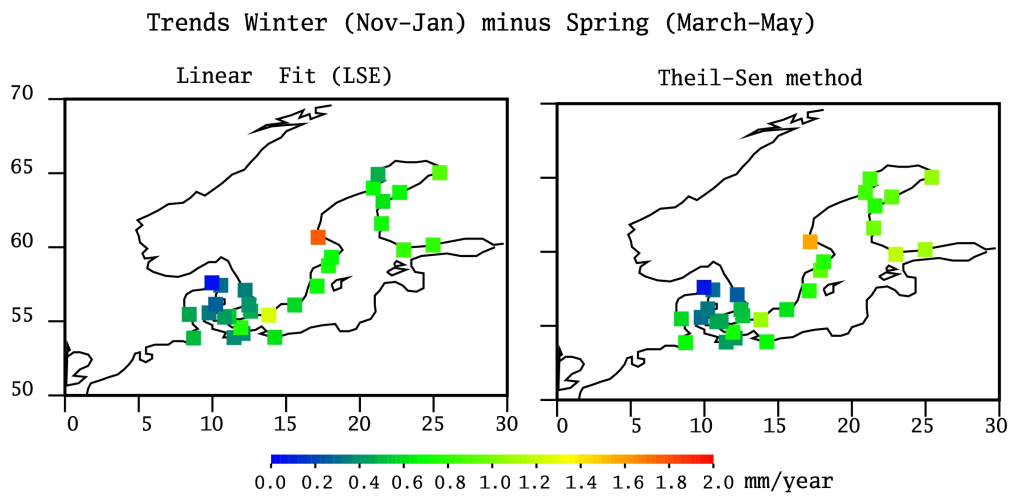

Fig. 3.4 *Trends in the amplitude of the sea-level annual cycle winter minus spring in the Baltic Sea estimated in the 20th century by a least-square-error linear fit and by the non-parametric Theil-Sen method.*

The magnitudes of the estimated trends are very similar using both methods. All trends are found to be positive, i.e. winter sea-level has risen relative to spring sea-level in all stations in this data set. This result agrees with the trend analysis of Chen and Omstedt (2005) for Stockholm, who found the strongest positive trends in the winter months, whereas in spring and summer these trends were weak or even negative. Similar findings were obtained by Plag and Tsimplis (1999) in a larger set of North Sea and Baltic Sea stations. In the present analysis the largest trend difference are found in the Gulf of Bothnia, in the Gulf of Finland and in the Baltic proper (of the order of 0.8-1 mm/year), whereas in the western Baltic the trend differences are smaller (of the order of 0.2-0.4 mm/year). It is remarkable that the trends in the southern Baltic, for instance in Warnemünde, are of similar magnitude as in the Gulf of Bothnia and in the Gulf of Finland, although the inter-annual and decadal variability of sea-level in the southern Baltic is much smaller than in the Northern regions.

Although the trend is positive for all stations, its magnitude is not large compared to the decadal variations. Fig. 3.5 shows the smoothed timeseries of the winter-minus-spring sea-level for these four selected stations in the period 1900-1998. The decadal variations are also coherent in these four stations, although the magnitude of these variations is smaller for the station Warnemünde, located in the southern Baltic coast.

To identify the individual stations that present trends in the winter-minus-spring sea-level that are individually statistically significant, two tests have been applied to each station separately: the Mann-Kendall test and a permutation test. The *Mann-Kendall test* is a standard non-parametric test for presence of trends in timeseries, based on the comparison of all possible pairs of data in a timeseries (Mann, 1945). The number of positive versus the number of negative differences of time-ordered pairs can be compared to the results expected in a truly trendless series and levels of statistical significance in the observed values can be derived.

The *permutation test* is based on the reasoning that, under the hypothesis that the series are trendless, a probability distribution of the sample trend can be obtained by random permutation of the elements of the timeseries (Effron and Tibshirani, 1993). For each station separately, synthetic timeseries are constructed by reshuffling at random the original timeseries and the linear trend is calculated by linear regression. This exercise is repeated

1000 times. The 90% significance level is estimated to be the 900th largest trend of these 1000 cases.

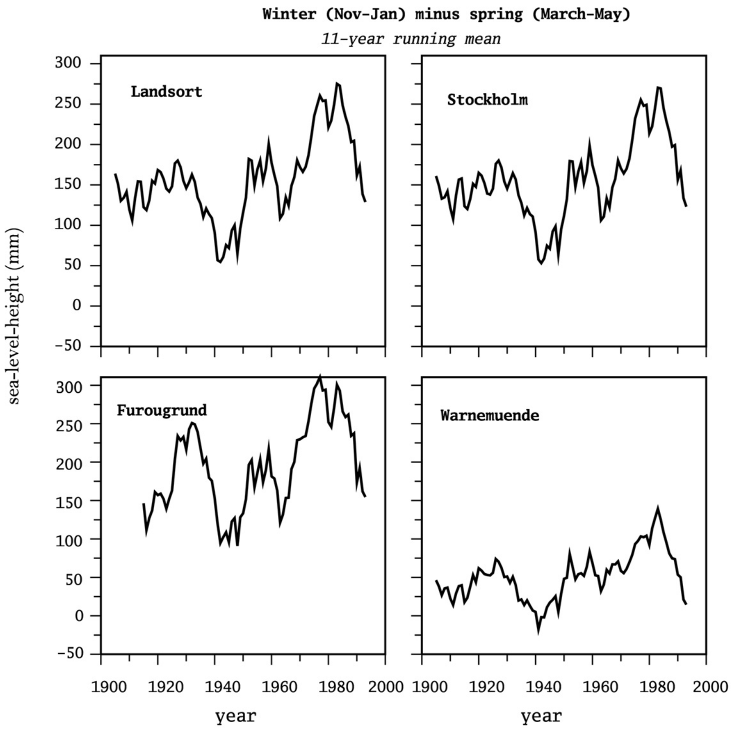

Fig. 3.5 *Decadally smoothed timeseries of winter-minus spring sea-level in four selected stations in the Baltic Sea in the 20th century.*

Fig. 3.6 shows the stations that, according to the Mann-Kendall and the permutation test, have a statistically significant (at the 90% level) long-term trend in their winter-minus-spring difference.

In general both tests detect statistically significant trends in all areas sampled by the original station set. The levels of significance are in general slightly above or below the 90% level, perhaps due to the slightly different ratios between long-term trend and inter-annual variability. But it seems that no spatial clustering of the statistically significant trends occurs, apart from the unavoidable irregular location of the available stations. It seems, therefore, that centennial trends are really present in the amplitude of the annual cycle in the Baltic Sea. The sampling in the southern Baltic is however poor, but as the trend in Warnemünde is of the same order of magnitude as in the northern stations, it is reasonable to assume that this phenomenon has occurred in the whole Baltic Sea.

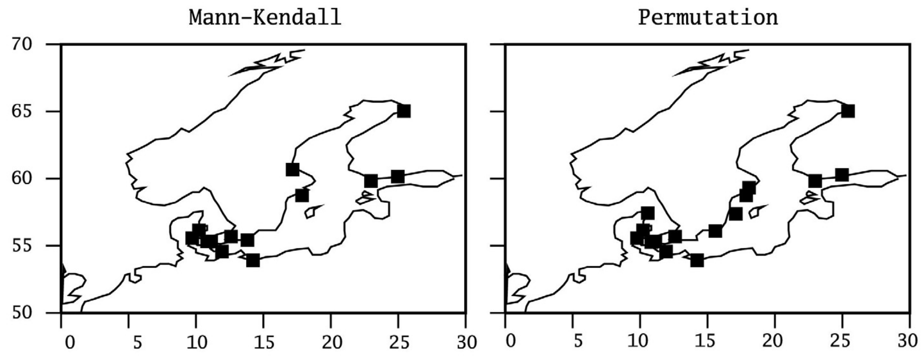

Fig. 3.6 *Stations with statistically significant trends in the 20th century winter-minus-spring sea-level. Significance was tested with the Mann-Kendall test and with a permutation test.*

The widening of the sea-level annual cycle can also be observed in longer records of Baltic sea-level that cover a large part of the 19th century. Fig. 3.7 depicts the linear trend in the sea-level difference winter-minus-spring for four of these long sea-level records, calculated for 100-year moving windows.

The linear trends are almost always positive, with the exception of the 100-year period centered in 1900 for Stockholm and Kronstadt. In the 19th century, the magnitude of the trends shows larger difference among these four stations. It is also noteworthy that the magnitude of the trend in the 20th century (the last value in the curves in Fig. 3.7) is the highest for Kronstadt and Stockholm records, but not for Kolobrzeg and Swinoujscie. It is also remarkable that in the 20th century the four linear trends evolve in a coherent way and attain similar absolute values.

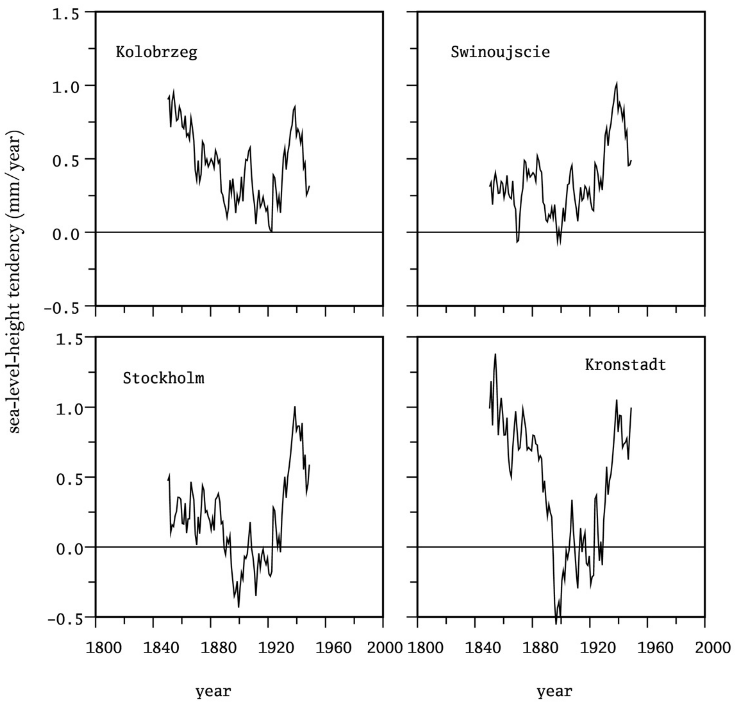

Fig. 3.7 *Linear trends in the winter-minus-spring sea-level estimated by linear fit in moving 100-year windows in four selected stations in the Baltic Sea in the 19th and 20th century. The abscissa of each data-point indicates the centre of the 100-year window. Sea-level data of Kronstadt before 1840 were not used for this analysis.*

3.4 Possible causes for the increasing amplitude of the annual cycle

The question arises about which factor - or factors- are responsible for the long-term trend in the amplitude of the annual cycle. To answer this question, several hypotheses have been put forward and their plausibility has been statistically analysed.

3.4.1 Factor 1 - wind stress forcing

It is well known that the winter sea-level variations in parts of the Baltic Sea at interannual to decadal timescales are mostly modulated by the westerly winds over the Baltic Sea region. At long timescales the intensity of the westerly winds is closely associated to the NAO, although the influence of the NAO is much stronger in the North and rather weak in the southern Baltic Sea (Jevrejeva et al., 2005; Hünicke and Zorita, 2006). In general, a positive trend in the NAO-index in winter would lead to a positive trend in winter sea-level and therefore could explain the more positive trend in wintertime relative to spring. In spring, SLP is known to have a much weaker influence on sea-level and consequently will not to be included, at a first step, in this hypothesis. The winter NAO-index shows a negative trend in the period 1900-1998 for the months November-January. The seasonal November-January mean NAO index, standardized to standard deviation unity in the period 1900-1998, shows a trend of -0.006 $year^{-1}$ +-0.005 (95% confidence interval) in the period 1900-1998. This figure amounts to a mean decrease in 100 years of roughly one half of the inter-annual standard deviation. This trend should, in principle, tend to lower sea-level in the winter months if the sign of the relationship between the NAO index and sea-level can be extended to centennial timescales.

Although the NAO is the dominant SLP large-scale pattern over the North Atlantic, the NAO explains, on average, only 32% of the total variability of sea-level at inter-annual time-scales (Kauker and Meier, 2003). Therefore, it could be argued that the remaining SLP variability patterns should also be taken into account to clearly rule out that SLP is responsible for the sea-level winter trend. The statistical extraction of the 'non-NAO part' from the SLP field is not straightforward, but we can use regression analysis - linking sea-level variations as predictor and sea-level pressure as predictand (Chen and Omstedt, 2005; Hünicke, and Zorita, 2006) - to test if there is a positive trend detectable in the reconstructed sea-level which is caused by the SLP field (including the NAO). Formally, the statistical model reads:

$$SL(t) = \sum_{i=1,N} a_i \, pc_i\left(t\right) + SLR\ (t)\,, \qquad (3.2)$$

where pc_i are the i^{th} principal component (PCs), resulting from an Empirical Orthogonal Function (EOF) analysis of the SLP field in the North-Atlantic European region (see Section 3.2), a_i is the corresponding regression coefficient, N the number of PCs included in the regression and SLR are the sea-level residuals.

The SLP data have been detrended prior to the calculation of the PCs. Therefore, the statistical model should capture only the inter-annual relationship between sea-level and SLP. Once the regression parameters have been estimated by least-mean-square error minimization, the model is applied with the non-detrended SLP anomalies to estimate the possible contribution of SLP to the sea-level winter trend in each of the stations. This contribution is also found to be negative for all stations, with values varying between -0.01 and -0.1 mm/year, and therefore, the SLP field as a whole, and not only the NAO, is unlikely to explain a positive trend in winter sea-level, again provided that the relationship between wind-stress (here represented by the SLP gradients) and sea-level at inter-annual time-scales can be extrapolated to the centennial trends.

Another mechanism that could potentially link wind-stress and Baltic sea-level at long time-scales can be derived from the relationship between wind speed and salinity, as discussed by Meier (2005) who used a Baltic Sea model to estimate the age of water masses in the Baltic Sea, finding that increased wind-stress is associated, in general, with lower average salinity. The mean horizontal gradient of salinity in the Baltic is one important driver for the mean sea-level elevation (Ekman and Mäkinen, 1996) and therefore a plausible reasoning could be that modifications of the salinity field by the wind forcing could also affect long-term sea-level changes. At inter-annual time-scales there is also an empirical negative link between the NAO index and Baltic Sea salinity (Zorita and Laine, 2000), which the latter authors tentatively ascribed to higher precipitation in the Baltic Sea area in winters with stronger NAO index. This question is further discussed in Section 3.4.4 in relation with precipitation changes. This notwithstanding, the sign of the link between wind forcing and sea-level within the Meier (2005) mechanism would be the same as with the direct wind-stress forcing on sea-level height, and therefore the negative long-term trend in the NAO index could not contribute to the increasing relative sea-levels in wintertime.

3.4.2 Factor 2 – pressure difference between Baltic Sea and North Atlantic Region

Another reasonable explanation for trend in the winter-minus-spring sea-level is the barometric effect, due to trends in the pressure differences between the Baltic Sea and the North Atlantic Region. To test this hypothesis, sea level pressure differences between the Baltic Sea Region (10E to 30E and 50N to 65N) and the North Atlantic Area (30W to 10E and 50N to 65N) were calculated. In the spring season a negative trend value of -0.009 mb/year was obtained. Assuming a complete equilibrium of sea-level to the air-pressure differences, this would result in a positive sea-level trend in spring of 0.09 mm/year. In the winter season, a positive value in the air-pressure difference between the Baltic and the North Sea of 0.006 mb/year was found, which should correspond to a negative Baltic Sea level trend of -0.06 mm/year. Thus, the difference of the winter and spring barometric gradients would produce a difference between winter and spring sea-level of the order of + 0.15 mm/year. The sign of these barometric trends contribute to the explanation of the observed winter-minus-spring sea-level trends, but the barometric effect is too small to explain these trends. Only the stations located in the Skagerrak area display such small trends, but these stations are likely the ones less affected by the pressure seasaw between the Baltic and the North Sea. Plag and Tsimplis (1999) also concluded that the influence of the barometric effect is not strong enough to explain the variations of annual cycle of sea-level in the North Sea and Baltic Sea.

3.4.3 Factor 3 -Temperature

Sea level can be affected by temperature directly due to thermal expansion of the water column. For instance, Stigebrandt (2001) estimated an amplitude of 2cm for the sea-level variations in the Baltic Sea associated with seasonal cooling and warming. Hünicke and Zorita (2006) estimated the magnitude of the additional contribution of air-temperature to the amplitude of decadal winter sea level variations of the order of 1 cm. An increasing sea-level in winter relative to spring could possibly be traced back to different long-term trends in winter and spring water temperatures in the Baltic Sea. Century-long time series of water temperature are not available, and to test this hypothesis we have to rely on trends in the observed air-temperature in the Baltic Sea region. At these long time-scales, air temperature should be closely coupled to water temperature, but the absolute magnitude of the water temperature trends would remain uncertain. As we are analysing seasonal means, the link between air-temperature and water temperature can be considered simultaneous.

Fig. 3.8 shows the evolution of the average air-temperature in the Baltic-Sea region smoothed by an 11-year running mean filter for the winter and spring seasons, for the period 1900 to 1998.

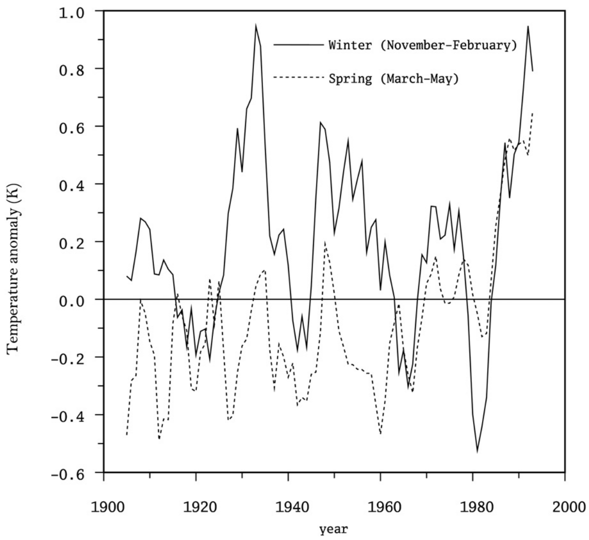

Fig. 3.8 *Decadally smoothed winter (solid line) and spring (dashed line) averaged air-temperature in the Baltic Sea region in the 20th century.*

In both seasons a positive trend was obtained, whereby the value for the spring (0.7 ±0.5 K/century, 95% confidence interval) is higher than for the winter season (0.2 ±0.6 K/century). If these trends, or at least their relative magnitude, also apply for the water column in the Baltic Sea, temperature is likely not responsible for the difference in the trend in the amplitude of the sea-level seasonal cycle. The sign of the difference in trends indicates that this effect cannot theoretically contribute (smaller trend in winter), and also the order of magnitude of the implied sea-level trends due to water column expansion is too small to explain a large part of the observed trend in the amplitude of the sea-level annual cycle.

Assuming that the trend in air-temperature is communicated entirely to the water column, and assuming that in winter the warming penetrates down to 100 m and in spring only down to 20 meters, the implied sea-level trends would amount to 0.03 mm/year and 0.06 mm/year for spring and winter, respectively (the effect in winter is larger although the temperature trend is smaller because of the larger assumed heat penetration). Their difference is an order of magnitude smaller than the observed trend in sea-level seasonal differences. Only if the spring warmth would reach much deeper levels in the water column could this effect become relevant. As the water temperatures have likely not completely realized the trend in air-temperature, these calculations are probably an upper bound for this effect.

Note that in the statistical analysis of the sea-level trends in Stockholm by Chen and Omstedt (2005), these authors also consider it unlikely that temperature trends could be responsible for the different trends in sea-level across the calendar year at this station. Note also that the positive trend in winter air-temperature is mainly due to the sharp increase in the last 15 years of the 20th century. The long-term trend of winter temperature in the period 1900-1980 is actually negative. As shown before, the amplification of sea-level annual cycle can be also observed in the mid-20th century relative to the mid 19th century (Fig. 3.3), when temperature increases were possibly less rapid than in the last 15 years of the 20th century.

3.4.4 Factor 4 - Precipitation

Hünicke and Zorita (2006) found precipitation to explain a part of the decadal variability of Baltic sea-level variations in summertime in the 20th century. According to that analysis, higher than normal precipitation is linked to higher than normal sea-level in summertime, but they did not analyse precipitation trends in other seasons, e.g. trends in the spring precipitation. However, if this link is also present in spring and maintained at centennial time-scales, a negative trend in spring precipitation could explain a more positive sea-level trend in winter with respect to spring, thus contributing to the explanation of the widening winter-minus-spring sea-level difference. Fig. 3.9 depicts the spatially averaged spring and winter precipitation timeseries, smoothed with an 11 year running mean, for the period 1900 to 1996. It can be seen that spring precipitation in the Baltic Sea shows indeed a slight positive trend in the 20th century (1.4 ±4 mm/month per century, 95% confidence interval), whereas in the winter months the trend is also positive but much larger (5 ±4 mm/month per century).

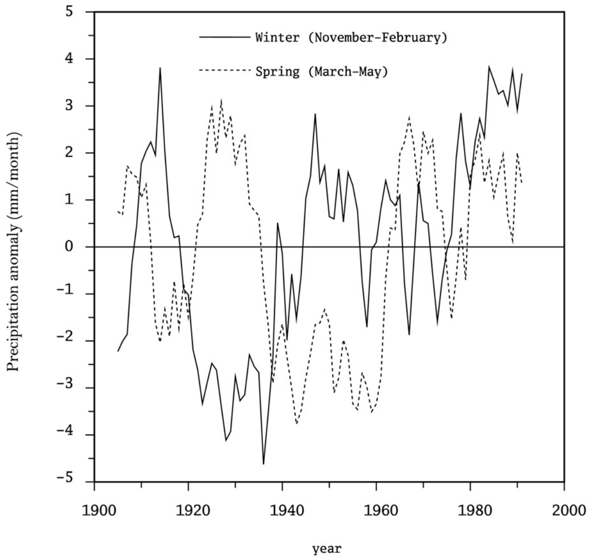

Fig. 3.9 *Decadally smoothed winter (solid line) and spring (dashed line) averaged precipitation in the Baltic Sea region in the 20th century.*

Therefore, the trend in winter precipitation is statistically significant whereas spring precipitation can be considered as trendless in practical terms. The difference in trends in winter and spring precipitation could in principle explain the increasing difference between winter and spring sea-level observed in the last 100 years.

However, a number of uncertainties remain before the role of precipitation can be completely ascertained. For instance, trends in evaporation or soil infiltration in the Baltic Sea are difficult to include in the analysis due to the lack of data. Also, precipitation in winter may fall in the form of snow over land and may not be readily available to fully contribute to a rise in sea-level. The precipitation trend in the autumn months (September-November) is also relatively large and positive (4 mm/month per century) so that actually it is precipitation in the whole winter half year that shows a positive trend, which is larger than in the summer half year. Overall, based on the sign of its seasonal trends, precipitation cannot be ruled out as the main contribution to the seasonal sea-level trends, but a quantification of its effect is almost impossible by statistical means alone.

Although this analysis has focused on the centennial sea-level trends, the decadal variability of the Baltic precipitation in spring and winter shown in Fig. 3.9 shows one remarkable aspect. Both time series seem to be anti-correlated, although there is no a priori reason to think that winter (November- January) and spring (March-May) precipitation should be linked in any way. The timing of the highest deviations between both, around 1930 and around 1950, coincide also with two maxima in the amplitude of the annual cycle (Fig. 3.2). Although this timing may be just a coincidence, it could support the role of precipitation in long-term variations of Baltic sea-level.

The mechanisms by which long-term trends in precipitation, and in general fresh water balance, can affect long-term trends in sea-level may be quite entangled. Sea-level will be affected by the net balance between North Sea inflow, from precipitation and run-off on one side and evaporation and outflow on the other side. Precipitation and run-off trends probably have the same sign. However, any imbalance between inflow and outflow longer than a few weeks will tend to cancel, so that it is difficult to substantiate that precipitation can directly affect the whole fresh-water volume in the Baltic Sea. However, precipitation also affect salinity, and therefore water density. Changed salinity gradients could also affect sea-level changes, in the same way as the mean sea-level gradient is affected by the mean salinity gradient (Ekman and Mäkinen, 1996). The direct magnitude of the influence of long-term salinity trends on sea-level is difficult to ascertain, as available salinity timeseries are not long enough, and the few available salinity timeseries are not seasonally resolved. To produce a trend in the amplitude of the annual cycle of sea-level of 1 mm/year, salinity should display a difference of about 0.01 psu/year in its seasonal long-term trends, assuming that these trends are communicated to the upper 100 meters and that salinity in the North Sea remains constant. In view of the lack of observational data, it would be interesting to see if such trends in seasonal salinity are found in simulations of evolution of the Baltic Sea in the 20th century.

3.5 Discussion and conclusions

The existence of centennial trends in the amplitude of the annual cycle (winter minus spring) has been detected. These trends are not large compared to the decadal variations of the annual cycle, but they are statistically significant. The magnitude of the trends is almost uniform in the station data set analysed here, with the exception of the Skagerrak area. This is remarkable, as the inter-annual and decadal variability of sea-level displays a clear spatial pattern, with higher values in the Gulf of Bothnia and in the Gulf of Finland (Meier, 2006). This aspect suggests that the mechanisms responsible for the trends in the annual cycle are not regional, but affect the Baltic Sea basin as a whole.

In the present analysis several hypotheses have been proposed as mechanisms to explain the centennial trends in the winter-minus-spring sea-level: the effect of wind (through the SLP field), temperature, barometric effect and precipitation. By elimination of three of these hypotheses precipitation appears to be a plausible candidate. For the other three either the sign or the magnitude of the trend make them too problematic to be considered as a sole explanation. However, the barometric effect was found to contribute potentially to the trend in the sea-level annual cycle.

Previous studies had already underlined the importance of wind forcing to the changes in the amplitude of the annual cycle sea-level variations in the Baltic Sea. Ekman (1999) investigated the connection between variations in the North Atlantic Oscillation (NAO) index and the Baltic Sea level, using the sea level time series of Stockholm, since 1825. The main conclusion of this study was that the winter climate, in particular wind, plays the central role for the Baltic Sea level variations. Ekman (1999) also discussed shortly the causes of the long-term variations in the sea-level annual cycle, concluding that this is also due to long-term changes in the wind conditions. At first glance, these conclusions might seem to stand in contradiction to the results presented here. But this study was focused on one or a limited region of the Baltic Sea, whereas our results are based on the analysis of 30 Baltic Sea level stations situated around the Baltic Coast, yielding information about the spatial structure of the long-term trends.

As illustrated in Hünicke and Zorita (2006), the correlation between the winter NAO index and winter (DJF) sea level variations in the period 1900 to 1998 range between 0.1 and 0.8 and shows a spatial heterogeneous pattern with a strong north-south gradient with much weaker values for the Southern Baltic Coast. If changes in the wind climate were to be responsible for the trends in the amplitude of the annual cycle, and the relationship between wind and sea-level has the same spatial structure at interannual as at centennial timescales, the spatial pattern of the trends in the amplitude of sea-level annual cycle would be also spatially heterogeneous, with higher values in the north and lower values in the south. However, as shown in the present study, the trend differences in the amplitude of sea-level annual cycle winter (NDJ) minus spring (MAM) in the Baltic Sea estimated in the 20th century (Fig. 3.4) show a quite homogeneous pattern with (significant) trends of similar magnitudes in the southern Baltic Sea as in the Gulf of Bothnia and the Gulf of Finland. Therefore, we conclude that the explanation involving wind forcing as main mechanism would not be consistent with similar levels of the trends in the northern and in the southern stations.

It has to be kept in mind, however, that the list of possible mechanism is not closed by the four hypotheses considered here, and that if further mechanisms can be proposed, the role of precipitation may appear less certain. For instance, the Baltic drainage basin has been subject to non-negligible construction of dams and other hydrological public infrastructures, which may possibly have had an influence on the timing of the river discharge into the Baltic Sea. This could also influence the amplitude of the annual cycle of sea-level, depending on whether this infrastructure is utilized for the generation of electricity or for artificial irrigation or for water for public consumption, as these needs dictate different timing of the largest release of stored water. Other mechanism that could affect trends in the annual cycle are shifts in the main discharge due to shifts in the melting season, as temperatures in the region also display discernible trends in the 20th century.

An interesting aspect is whether the detected trends in 20th precipitation can continue into the future, potentially modulating also the trends in the sea-level annual cycle. Simulations with global climate models (Giorgi and Bi, 2005) driven by different scenarios of anthropogenic greenhouse gas forcing and anthropogenic tropospheric aerosols indicate that dry-season (November-April) precipitation will likely increase in Northern Europe, whereas wet season (May-October) precipitation will likely undergo a slight reduction. Although the definitions of the rainfall seasons in Giorgi and Bi (2005) do not exactly match the definition adopted in this study for the extrema of the sea-level annual cycle, the simulated trends in the dry (winter) season are consistent with the trends observed in the 20th century. If a causal link between rainfall trends and greenhouse gas forcing can be established, the difference between winter and spring sea-level in the Baltic Sea may continue increasing in the next decades. However, it is noted that the trend in the sea-level annual cycle at the end of the 20th century is not unprecedented for all of the stations. Two stations located in the southern Baltic display larger centennial trends in the 19th century. The 20th century trends seem to be more coherent in space and time than in the 19th century.

The analysis presented here should be understood as complementary to modelling studies. Simulations with a regional model of the Baltic Sea (Meier and Kauker, 2003) can help to falsify or confirm these hypotheses.

Acknowledgments

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4 Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years[3]

ABSTRACT

Decadal sea-level variations in selected stations located in the southwestern, central and eastern Baltic Sea are found to be less coherent in the 19th century than in the 20th century. The effect of the North Atlantic sea-level-pressure (SLP), precipitation and air-temperature in the 19th and 20th centuries from gridded climate reconstructions, and their relationship to Baltic sea-level, are statistically analysed to explain this difference. The influence of these factors on sea-level varies geographically. In the central and eastern Baltic, sea-level variations are well described by SLP alone, whereas in the southern Baltic Sea area-averaged precipitation better explains the decadal sea-level variations. The evolution of precipitation in the 19th century could explain the different behaviour of the southern Baltic stations; however, the physical mechanism for this relationship remains unclear. The effect of temperature variations is either already contained in the SLP field or is less important for decadal sea-level variations than the other two factors.

[3] Hünicke, B., Luterbacher, J., Pauling, A. and Zorita, E. Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years. *Tellus* **60A** (2), 384-393, doi: 10.1111/j.1600-0870.2007.00298.x.

4.1 Introduction

Estimations of future global sea-level from simulations with coarse-resolution global climate models mostly depend on large-scale processes, such as the heat-flux into the ocean, on changes in the ocean circulation and on the rate of melting of land-ice masses (IPCC, 2007). In regions with complex coastlines, sea-level changes may additionally depend on other regional factors which are not properly represented in global models. The Baltic Sea, located between Scandinavia and mainland Northern Europe, and connected to the North Atlantic by the narrow and shallow Danish straits (up to 16 km wide and about 18m deep) is a suitable example of this. In wintertime, inter-annual sea-level variations at its northern and eastern boundaries are influenced by the westerly winds, related to the sea-level-pressure (SLP) pattern of the North Atlantic Oscillation (NAO) (Andersson, 2002). Stronger westerlies in periods with a positive NAO phase cause comparatively higher sea-level in some areas of the Baltic Sea. However, some studies indicate that the connection between individual Baltic stations and SLP may be heterogeneous in time and in space. For instance, the correlation between the winter NAO index and winter sea-level in the 20th century ranges spatially between 0.1 and 0.8 (Hünicke and Zorita, 2006). Jevrejeva et al. (2005) found that the moving correlation between winter mean sea-level and the NAO varied between zero and 0.6 in Wismar (southwestern Baltic Sea) in the period 1860-1980. They concluded that processes other than wind-stress forcing are important for sea-level variability. Previous studies have suggested that precipitation and temperature may also contribute to sea-level variations (Chen and Omstedt, 2005; Hünicke and Zorita, 2006), thus modulating the correlations between sea-level and the NAO. The question arises as to whether these local processes might also significantly influence sea-level variability at low-frequencies, i.e. multi-decadal, so that their contribution should be considered for future sea-level projections at local scales.

Here, we present a statistical analysis of the relationships between Baltic sea-level and large-scale atmospheric forcing in the past 200 years, using long gauge-records and gridded climate reconstructions of SLP, air-temperature and precipitation covering the European land area (Luterbacher et al., 2002, 2004; Pauling et al., 2006). We aim at confirming the heterogeneous regional response of sea-level to large-scale forcing at multi-decadal timescales and at identifying possible factors for this behaviour.

Previous statistical analysis (Heyen et al., 1996), using canonical correlation analysis, considered the relationship between SLP patterns and patterns of sea-level anomalies in the Baltic Sea. However, this approach may preclude the identification of a spatially heterogeneous response of sea-level to the SLP forcing, as canonical correlation yields in this case coherent patterns of co-variations, i.e. the variability shared by set of stations that is also connected to the variations in some atmospheric SLP patterns. In this study, we consider each gauge station individually to ascertain whether the effect of large-scale factors may also vary regionally. Our approach is based on statistical regression methods to hindcast sea-level variations and on an examination of the skill of the different predictors. The statistical models are calibrated in the 20th century and validated in the 19th century. However, the method is also tested when interchanging validation and calibration periods and also with calibration and validation periods entirely within the 20th century. The gridded climate reconstructions did not make use of any sea-level information; therefore this analysis consequently can potentially support the quality of the climate reconstructions.

The analysis is restricted to the winter season. In this season the variability of the atmospheric forcing is largest, making it easier to understand the effect of those individual forcings on sea-level variations above other, more local, processes or measurement noise. For instance, as stated before, the role of the NAO on winter sea-level in part of the Baltic Sea is well established, and yet the reason for the low and erratic correlation between this leading mode of atmospheric winter variability and sea-level in the Southern Baltic is not clear. It is intended, however, to extend this type of analysis for other seasons in future work. The processes responsible for regional winter sea-level variations for high-latitude semi-enclosed seas are complex, as sea-ice, precipitation and/or run-off might effect sea-level in some regions more strongly than in others. In this study the predictors considered are restricted to those for which long observations or reconstructions are available and which are potentially well simulated by coarse resolution models, so that conclusions may be applied to the output of General Circulation Model (GCM) simulations. In practice, the predictors are SLP (an indicator of geostrophic wind), area-averaged precipitation and air-temperature.

This work is structured as follows: Section 4.2 presents the data (observational records and reconstructions) used in this study. Section 4.3 examines the relationship between Baltic Sea level and the large-scale gridded climate fields. The role of the different climate forcings that might effect Baltic sea-level is statistically explored by constructing linear regression models in which these forcings are treated as individual predictors. The statistical models are presented and their application and skill discussed. Section 4.4 presents a discussion of the results and some conclusions.

4.2 Data sets

In this study we focus on winter season which is defined here as the mean of the month December, January, February (DJF). As we are interested in variability at decadal and longer timescales, all timeseries were smoothed with an 11-year running mean filter.

4.2.1 Baltic Sea level observations

We examined winter means of four of the longest time series of sea level (up to 200 years long) from coastal observation stations situated along the Baltic Coast (Fig. 4.1), obtained from different sources: the data collection of the Permanent Service for Mean Sea level (PSMSL; Woodworth and Player, 2003) and (documented) sea level records of historical importance, which are not included in the PSMSL dataset (Bogdanov et al., 2000; Ekman, 2003). As stated by the PSMSL, this is ‘either because the data are not available in the monthly and annual mean format used by the PSMSL, or because they are not true Mean Sea Level (MSL) or even Mean Tide Level (MTL) as such (based perhaps on irregular observations of high and low waters rather than on continuous observations by a 'tide gauge' or 'tide pole' as now understood)’. Nevertheless, the existence of several previous studies, which used these long historical time series for their analyses (beside the original publications) should stand for a verification of the data quality (e.g. Andersson, 2002, Omstedt et al., 2004; Chen and Omstedt, 2005; Jevrejeva et al., 2005).

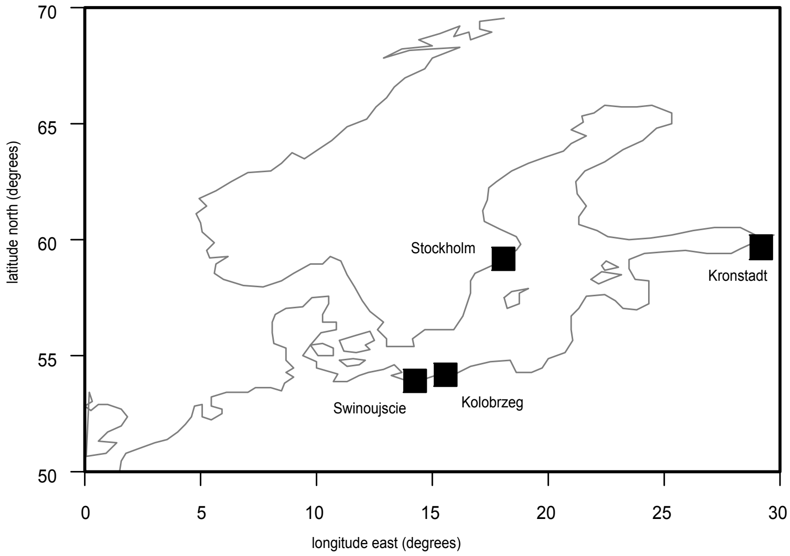

Fig. 4.1 *Sketch of the Baltic Sea, showing the location of the four sea-level gauges used in this study.*

Also, we used (undocumented) sea level data provided by the Technische Universität Dresden, which was compiled in the frame of the German Science Foundation Project 'Sinking Coasts' (SINCOS). Detailed information about the sea level data (time period used, data source, missing values) are given in Table 4.1.

Table 4.1 *Schematic description of the sea level data sets.*

Location	Years	Data source
Kolobrzeg	1816-1999	PSMSL, before 1951 TU Dresden
Swinoujscie	1811-1996	PSMSL
Stockholm	1801-2000	Ekman, 2003
Kronstadt	1841-1993	Bogdanov et al., 2000

Missing values in two of the time series (Kolobrzeg 1940 to 1950; Swinoujscie 1945 to 1950) were not interpolated or replaced by the climatological means. We did not use the entire available Kronstadt time series (1777 to 1993) due to frequently missing data in the beginning and because it appears from the original reference that sea level data maybe considered unreliable before 1841. This is also quite clear by a simple visual inspection of the time series. The values prior to this date appear unreasonably large (higher sea-level). Also in the originally Stockholm dataset (1774 to 2000) the beginning missing values are frequent and only from 1825 onwards is the series complete. For the largest gap in 1812 to 1824, reconstructions of the missing mean sea level values (by transformation of monthly mean sea levels from the station Copenhagen) are available from the original reference (Ekman, 2003). We decided to include these reconstructions in our analysis, but for the discussion of our results these caveats should be kept in mind.

The trend in the sea level records, caused by a combination of post-glacial land uplift and eustatic sea level change, is assumed to be linear and is eliminated by statistically estimating the individual linear trend by a linear least-mean-square fit and subtracting it from the record. This procedure also eliminates the linear trends that may be caused by eustatic sea-level change and by the long-term trends in the regional climate forcing (see Chen and Omstedt, 2005 for discussion). These trends, which have different physical origins, cannot be separated by statistical methods alone and this analysis is, therefore, restricted to variations around the overall long-term linear trend.

4.2.2 Climate Reconstructions

We used gridded reconstructions of monthly sea-level pressure and temperature and seasonal precipitation as large-scale fields for winter over the 1800 to 2000 period. Detailed information about references, grid resolution and the geographical area which was considered for each of the climate reconstruction fields are given in Table 4.2.

The climate reconstructions coincide with corresponding observations in their calibration period (1901 to 1990 for SLP, 1901 to 1995 for temperature and 1901 to 1983 for precipitation): monthly SLP prepared by NCEP (National Centres for Environmental Prediction) (Trenberth and Paolino, 1980), precipitation and temperature fields by Mitchell and Jones (2005) (for more details see original references).

Table 4.2 *Schematic description of the climate reconstructions.*

Climate field	Grid resolution	Geographical region	Data source
sea level pressure	5.0°x5.0°	30°W-40°E; 30°-70°N	Luterbacher et al., 2002
precipitation	0.5°x0.5°	11°-26°E; 52-62°N	Pauling et al., 2006
temperature	0.5°x0.5°	10°-30°E; 50°-65°N	Luterbacher et al., 2004

The geographical distributions of the climate reconstruction considered for this study were selected based on the climate data sets used by Hünicke and Zorita (2006).

An important aspect of these climate reconstructions is that they are not simple spatial interpolation of available long-instrumental and indirect (documentary, proxy-based) climate data. The reconstruction method is based on principal component (PC) regression, in which a statistical regression model uses a set of long time series of local climate data as predictors and the leading PCs of the target field (temperature or precipitation or SLP) as predictands. The regression model is calibrated in a period in which both predictor and predictand overlap (1901 to 1960 for SLP and temperature, 1901 to 1956 for precipitation), and verified with the corresponding data in the second part of the 20th century. The PCs of the target field are also calculated in this calibration period. The regression model is then used to reconstruct the PCs of the target field using the long predictor's time series, under the assumption of being stationary in the statistical relationships. The gridded target field is reconstructed by linearly combining the reconstructed PCs with their corresponding spatial eigenvectors calculated in the calibration period. The final product, although presented as gridded field, is essentially a linear combination of these constant spatial eigenvectors, the linear combination changing through time. Therefore, the effective average spatial resolution is given by the typical spatial scales of these constant eigenvectors. As the PCs of the target fields are calculated in the European land area, the effective resolution of the reconstructed fields will not change over a relatively small area such as the Baltic Sea. Consequently regional differences in the skill of the predictor to explain sea-level variations cannot be ascribed to regional differences in the quality of the climate reconstructions or to regional differences in the spatial resolution of the reconstructions. More details about data and methods can be found in the original references.

4.3 Relationship between Baltic Sea level and large-scale gridded climate fields

Fig. 4.2 displays four (linearly detrended and standardized to unit variance) decadally smoothed sea-level records from the southwestern, central and eastern Baltic Sea covering the past 200 years (see Fig. 4.1 for the location of these stations).

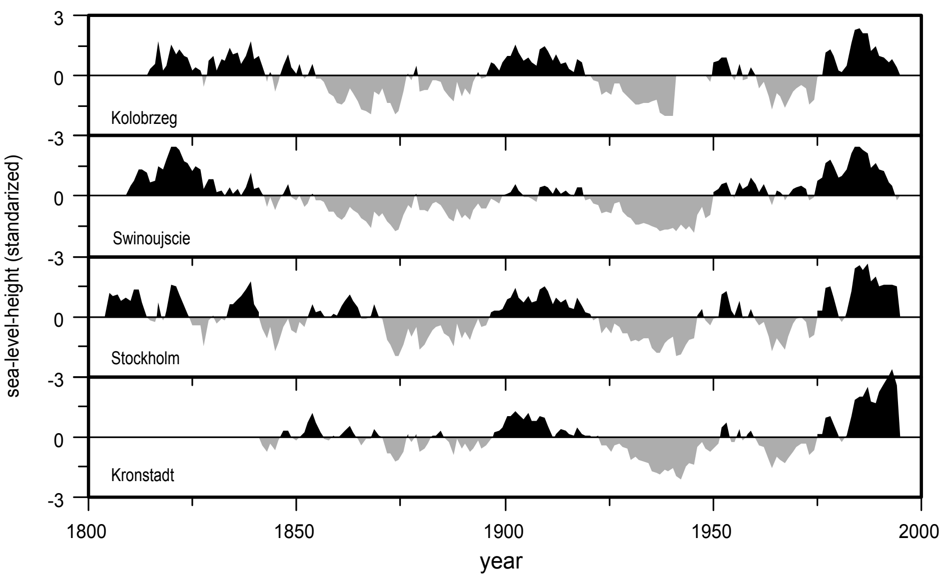

Fig. 4.2 *Relative winter mean (December-February) sea-level height at four stations in the Baltic Sea in years 1800-2000: deviations from the 1900-1999 mean, linearly detrended, smoothed by a 11-year running-mean and standardized to unit standard deviation.*

Considering these four stations, several sub-periods can be identified in which sea-level is spatially coherent and other periods in which there are differences among the stations. The most similar behaviour is displayed by the Stockholm and Kronstadt sea-level time series for the entire period. For these stations the sub-periods with positive and negative sea-level anomalies match almost perfectly. The relative magnitude of the anomalies (the series have been standardized) is also very similar. For the southern stations, some periods of deviation can be found. In the earlier 19th century the southern stations show sustained positive sea-level deviations, whereas Stockholm and Kronstadt are more erratical.

Around 1850-1875, the southern stations display large negative anomalies, whereas sea-level in Kronstadt and Stockholm remained closer to its long-term mean. Around 1900-1925 Swinoujscie remains near the long-term mean sea-level, whereas the other three stations show clear positive anomalies. In 1950-1975 the anomalies at Swinoujscie are again near zero, whereas at the other stations they are negative and large. Overall, the agreement between the four stations is larger in the 20th century than in the 19th century. When decadally smoothed, the inter-station correlation exceeds 0.85 for all station pairs in the 20th century, but in the 19th century the correlations between the southern stations and the rest falls to about 0.5.

Deficiencies in data quality and changing measurements methods could be invoked to explain part or all of these differences in the 19th century, especially in the earlier decades. However, on the one hand, the similar behaviour of the sea level timeseries of the two southern Baltic stations point to a good data quality as both stations are located relatively nearby and therefore a similar behaviour of the sea-level variations in these stations might seem logical. This would support the validity of the inter-station correlations. On the other hand, it cannot be ruled out that this similar behaviour could also possibly be a result of interpolation processes during the recording or/and post-processing. As we do not have access to original raw data, this question cannot be answered in the present analysis, but it certainly has to be considered as a possibility in the interpretation of the final results.

A view of the possible external atmospheric forcings that may give rise to this behaviour is presented in Fig. 4.3, showing the timeseries of the leading SLP PC in this area, (which is related to the NAO index), the timeseries of the averaged precipitation and the timeseries of averaged temperature (the latter linearly detrended over the whole period).

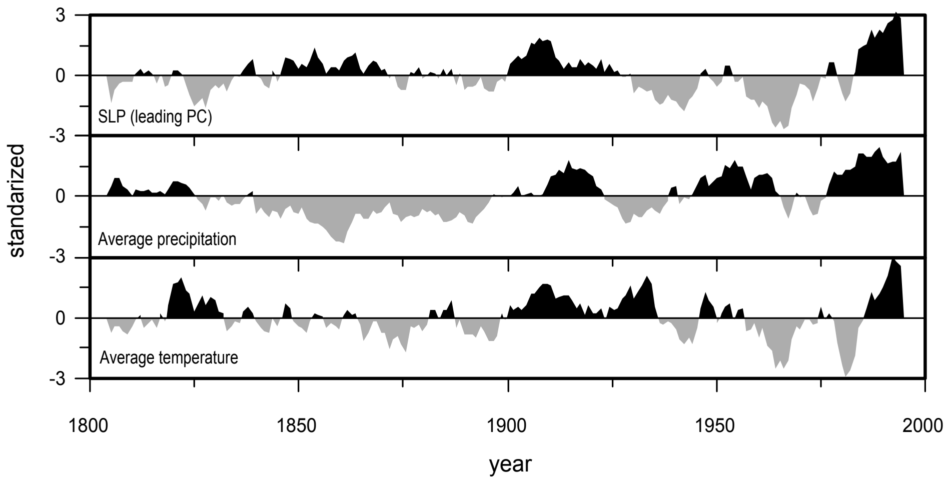

__Fig. 4.3__ Timeseries of the leading winter SLP principal component in the North Atlantic-European sector, timeseries of the area averaged precipitation and timeseries of the area averaged temperature in the Baltic Sea region: deviations from the 1900-1999 mean, smoothed by a 11-year running mean and standardized to unit standard deviation (after linearly detrending temperature). The original data stem from European climate reconstructions, see Section 4.2.2 for references.

Again, periods can be identified where the decadal variations of these three potential forcings deviate from each other. In the 19th century precipitation shows a prolonged period of negative sign between 1850 and 1900 that is not matched by the SLP PC or by the averaged air temperature. Temperature and SLP in the 19th show little coherence and even periods of opposite sign of their anomalies - a significant feature taking into account that originally the 20th century positive correlation between the NAO and Scandinavian temperature constituted one of the defining features of the NAO. However, the leading PC of SLP and Baltic air-temperature anomalies, albeit more coherent in the 20th than in the 19th century, also show deviant behaviour around 1930. Overall, for the 20th century, a calculation of the mutual correlations between the leading SLP PC, precipitation and temperature was performed with smoothed timeseries (11-year running mean filter) and with unsmoothed (inter-annual) timeseries. Thereby, the statistical significance was estimated by Monte Carlo simulations emulating the same degree of smoothing. The results show that the leading SLP PC is more closely related to temperature than to precipitation. The correlation coefficient between SLP and temperature is 0.77 in the 20th century (smoothed and inter-annual, both statistically significant at the 95% level), whereas between SLP and precipitation it is 0.46 and 0.36, respectively (only the former being statistically significant at 95% level). Temperature and precipitation indicate weaker relationships, with correlations of 0.24 and 0.26, both not statistically significant.

The role of these different climate forcings that might effect Baltic sea-level is statistically explored in the following by constructing linear regression models in which these forcings are treated as individual predictors, and not in combination. Combinations of predictors have not been considered here, as our goal is to disentangle the effect of the individual predictors. As they may be inter-correlated, it would not be straight forward to interpret the results if a combination of predictors had been used simultaneously.

Although one of the immediate forcings for sea-level variations in the Baltic is the surface wind, long observations over the ocean covering the 19th century do not exist. However, at decadal timescales and at mid-latitudes, surface wind is closely related to SLP gradients through the geostrophic relation. SLP gradients also influence sea-level through the inverse barometric effect (Ponte, 1994). SLP is therefore considered here as the first predictor in a regression equation to estimate sea-level at one station (sl). The SLP field is first decomposed in its PCs to avoid co-linearity and the resulting instability of the regression. The regression model reads:

$$sl(t) = \sum_{i=1,N} a_i \, pc_i(t) + SLR(t), \qquad (4.1)$$

where pc_i is the i^{th} PC, a_i is the corresponding regression coefficient, N the number of PCs included in the regression and SLR are the sea-level residuals. The parameters a_i were calibrated in part of 200-year period by ordinary least-square error minimization and the resulting regression model is validated in the remaining part of this period. To estimate sea-level variations outside the calibration period, the SLP anomalies relative to the calibration mean are projected onto the spatial eigenvector of loadings from the PC analysis previously calculated in the calibration period. The cut-off number N=3 of PCs included in the regression was the one yielding the best model skill in the validation period. The skill of the regression was evaluated by the Reduction of Error (RE) statistics (von Storch and Zwiers, 1999) and by the correlation coefficient between observations and estimations, both evaluated in the validation period. The RE is defined as

$$RE = 1 - \frac{\sum_t (est(t) - obs(t))^2}{\sum_t \left(obs(t) - \overline{obs}\right)^2}, \tag{4.2}$$

where $est(t)$, $obs(t)$ refer to the estimated and observed values at time t, and $\overline{obs}$ is the mean value of the observations estimated in the calibration period. RE values range between -∞ to unity (perfect ‘prediction’). A value of zero indicates a skill equal to that of climatology (simply taking as prediction the value of the mean in the calibration period), whereas negative values indicate a skill worse than the simple climatological mean. An advantage of using the RE as a measure of explained variance is that it takes into account changes in the mean between the calibration and the validation period, whereas the correlation between reconstructions and observations in the validation period does not. Note that this analysis represents an evaluation of the skill of the predictors. Therefore, confidence intervals for the sea-level estimations are not considered.

A summary of the skill of the regression models using different predictors, and using two different calibration periods, can be found in Table 4.3.

In the following these results are explained in a more detailed way, illustrated with corresponding plots of the resulting timeseries for the case with the calibration period 1900-1999. Fig. 4.4 shows the results for the four Baltic Sea stations when the calibration period is 1900-1999. The sea-level estimations are compared with observations. For the stations Stockholm and Kronstadt, the model skill is high (validation RE =0.35 and 0.60) with significant correlations of 0.59 and 0.85, respectively. This confirms the relevance of SLP for sea-level variations also at longer timescales and in the 19th century. Only very short periods of disagreement can be found where estimations and observations deviate (for Stockholm around 1850, for Kronstadt around 1960 and 1970), indicating that SLP is sufficient to accurately determine decadal sea-level variations in this station. A second important consideration of this agreement is that, as SLP does not contain prior information from sea-level and was not focused on the Baltic Sea in particular, the sea-level data in Kronstadt and the SLP reconstructions are very likely to be accurate. As stated in Section 4.2, the accuracy of the SLP reconstructions is very likely to apply to the whole Baltic Sea area, as they are based on the large-scale PCs of the European-wide SLP.

Table 4.3 *Reduction of Error (RE) statistic and correlations (r) as an evaluation of the skill of the predictors SLP, precipitation (Prec) and temperature (Temp) to reconstruct sea-level. The analysis period is split in a calibration period (CAL) and a validation period (VAL). Correlations significant at the 95% level (taking into account the degree of smoothing) are bold-typed.*

RE	**CAL 1900-1999**	**VAL 1801-1900**	**CAL 1801-1900**	**VAL 1900-1999**
predictor*	**SLP / Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**
Kolobrzeg	0.67/ 0.48/ 0.08	0.01/- 0.51/ -0.14	0.21/ 0.43/ 0.03	-0.74/ 0.05/ -0.01
Swinoujscie	0.51/ 0.41/ 0.02	0.12/ -0.14/ 0.02	0.27/ 0.55/ 0.50	-0.98/ -0.54/ -0.34
Stockholm	0.85/ 0.53/ 0.25	0.35/ -0.87/ -1.12	0.37/ 0.23/ -0.01	0.67/ 0.27/ 0.08
Kronstadt	0.90/ 0.40/ 0.35	0.60/ -9.00/ -7.00	0.66/ 0.02/ 0.20	0.79/ -0.13/ -0.15
r	**CAL 1900-1999**	**VAL 1801-1900**	**CAL 1801-1900**	**VAL 1900-1999**
predictor*	**SLP / Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**
Kolobrzeg	**0.82**/ **0.70**/ 0.29	0.26/ **0.68**/ 0.19	**0.56**/ **0.68**/ 0.19	-0.21/ **0.70**/ 0.29
Swinoujscie	**0.72**/ **0.64**/ 0.13	0.37/ **0.76**/ 0.22	**0.57**/ **0.76**/ 0.22	-0.17/ **0.64**/ 0.13
Stockholm	**0.92/ 0.73/ 0.50**	**0.59/ 0.48**/ 0.00	**0.61/ 0.48**/ -0.01	**0.89/ 0.73/ 0.50**
Kronstadt	**0.96/ 0.63/ 0.60**	**0.85**/ -0.20/ 0.46	**0.85**/ 0.20/ 0.46	**0.91**/ -0.63/ **0.60**

*leading SLP PCs/ area-averaged precipitation/ area-averaged temperature

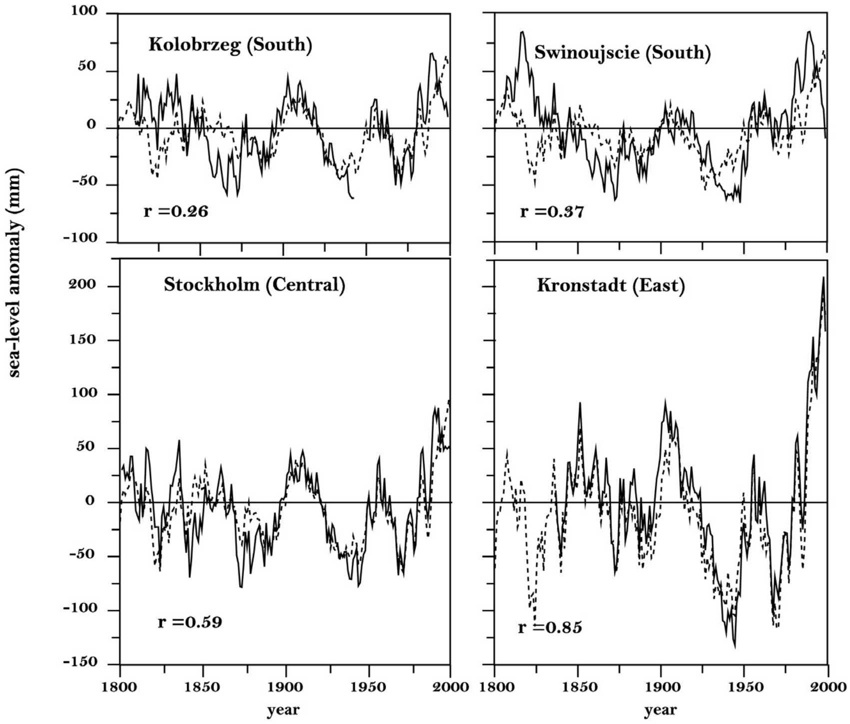

Fig. 4.4 *Decadally smoothed and linearly detrended observed (solid lines) sea-level and reconstructed (dashed lines) sea-level deviations from the 1900-1999 mean, using the SLP field as predictor. Figures within the panel indicate the decadal correlation between observations and reconstructions in the 19th century. The regression model was calibrated in 1900-1999. Note that for Kronstadt the data prior to 1941, although available, have not been used in the analysis.*

In contrast, the calibration skill for the southern stations, Kolobrzeg and Swinoujscie, is considerably lower, and the validation skill is poor (RE= 0.01 and 0.12) with non-statistically significant correlations of 0.26 and 0.37, respectively. Observations and estimations are clearly not correlated at decadal timescales in the first half of the 19th century. As the estimations for Stockholm and Kronstadt are much better, this mismatch in the southern Baltic is likely not caused by a poor SLP reconstruction in the 19th century. These results confirm that decadal SLP is not an adequate large-scale predictor for all stations in the Baltic Sea, and that other forcings are required to explain the decadal variations in this area. When calibration and validation period are interchanged (Table 4.3), essentially the same conclusions can be reached. SLP remains a good predictor for Stockholm and Kronstadt, whereas its skill for the southern stations Kolobrzeg and Swinoujscie remains poor.

We now explore if precipitation is a skilful predictor for sea-level in stations Kolobrzeg and Swinoujscie. Different mechanisms could give rise to a physical link between precipitation and Baltic sea-level. Precipitation is closely related to the fresh-water balance of the Baltic Sea (in- and outflows, river run-off and net precipitation). Spatially averaged precipitation should also be related to run-off into the Baltic, although not to evaporation. As the southern Baltic Sea does not freeze during normal winters (with the exception of sheltered areas) (Håkansson et al., 1995), an unlagged relation between winter precipitation and winter sea-level could be assumed, and spatially averaged winter precipitation can be considered as a sole predictor. On the other hand, precipitation influences salinity, and therefore water density, which in turn is related to sea-level. Actually, the mean climatological spatial distribution of salinity is, in part, responsible for the mean sea-level gradient in the Baltic-Sea (Ekman and Mäkinen, 1996). This is discussed further in Section 4.4.

Fig. 4.5 shows that using 1900-1999 as the calibration period, the correlation in the validation period of winter precipitation for Kolobrzeg and Swinoujscie, though not perfect, has increased relative to the SLP, with correlations of 0.68 and 0.76, respectively, which are now statistically significant. The RE values, however, are still of a negative sign. The combination of a high verification correlation but a negative verification RE likely indicates a change in the long-term mean value of the 19th and of the 20th century that is not captured by the precipitation as predictor. In other words, the variations around the changed mean value in the 19th century are relatively well reproduced (high correlation), but the absolute error is still large compared to the typical deviations of the 19th values relative to the 20th mean. Precipitation does not seem able to describe the long-term variations in change in the mean value of sea-level. This question is further discussed in Section 4.4. Nevertheless, as in the case of SLP, the reasonable skill of precipitation for the southern Baltic stations at decadal timescales supports the validity of the winter precipitation reconstructions in the 19th century (Pauling et al., 2006) in this region and at this decadal timescale.

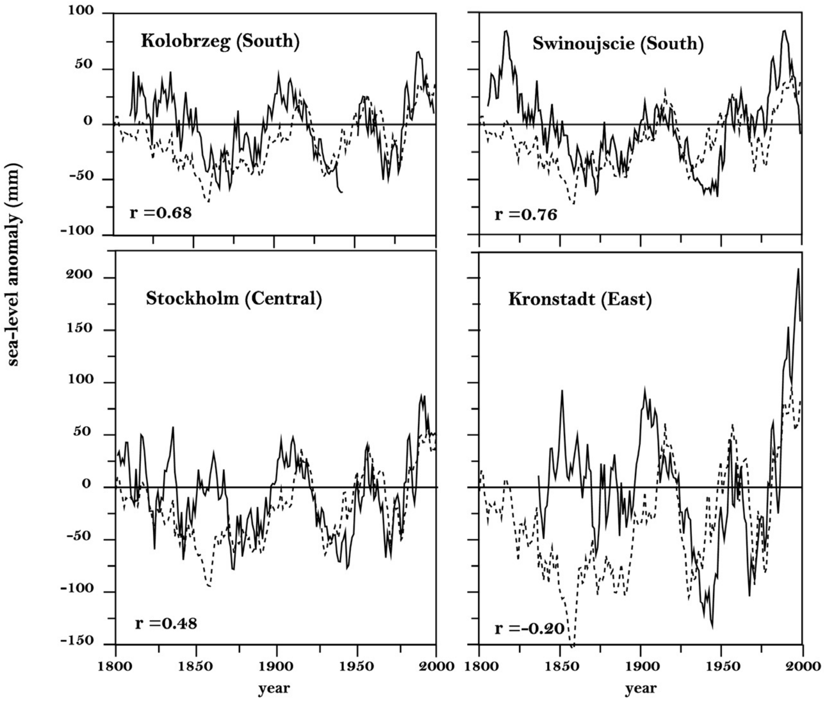

Fig. 4.5 *Decadally smoothed and linearly detrended observed (solid lines) sea-level and reconstructed (dashed lines) sea-level (deviations from the 1900-1999 mean), using area-averaged precipitation as predictor. Figures within the panel indicate the (decadal) correlation between observations and reconstructions in the 19th century.*

It is noteworthy to mention that precipitation is a much poorer predictor for the sea-level variations in Kronstadt and Stockholm than for the southern stations (Table 4.3). The RE and correlation statistics are lower for these stations than for the southern stations, in particular for Kronstadt, where SLP was an excellent predictor.

This picture of the role of precipitation is essentially the same when the calibration and validation period are exchanged (Table 4.3). The correlations between observations and estimations in the validation period (now the 20th century) remain high for the southern stations, but it is also high for Stockholm, albeit it is negative for Kronstadt. The RE statistics hover around the value of zero for all four stations. Therefore, it appears that precipitation is indeed a good predictor for the decadal variations of sea-level in the southern stations, regardless of the calibration and validation period, but that the very slow variations of sea-level which affect the changes in mean value between the 19th century and the 20th century are not well captured by this predictor.

Winter air-temperature was also used as a sole predictor, with both representations of temperature (Baltic Sea area-averaged temperature and PC representation of the temperature field). The rationale for this analysis is that water temperature, which is affected by air-temperature, may modulate the expansion of the water column and thus also sea-level. Note that we are analysing seasonal December-February means, as the vertical mixing is greater than in summer, and therefore it is reasonable to assume that variations in air-temperature have had enough time to penetrate into deeper layers. The statistical model with temperature as a sole predictor did not show any improvement relative to the SLP-only model (Table 4.3). The validation correlations between observations and estimations remain in general non-statistically significant. The exception is for Kronstadt and Stockholm in the 20th century, when the connection between air-temperature and the SLP field, through the NAO, is strong (Hurrell, 1995). Therefore, it seems that these correlations are brought about by the indirect correlation of sea-level and temperature with the NAO. To ascertain this result, air-temperature was used in combination with SLP as predictors, to check whether the skill of the regression models increased significantly relative to the models with SLP alone (not shown). This was not the case.

4.4 Discussion and conclusions

Our study showed that decadal sea-level variations in the Baltic Sea may be regionally homogeneous, also at timescales longer than inter-annual, and it statistically explored the possible role of atmospheric forcings in this spatial heterogeneity. It was found that SLP shows large prediction skill for the station Kronstadt, and somewhat smaller but still high for Stockholm, thereby supporting the dominant role of the atmospheric circulation for these stations, found by previous studies, also at decadal timescales. At these scales the role of other factors, such as for instance sea-ice, which in principle should be an important factor for Kronstadt, seems to be minor or already statistically embedded in the SLP field. The good agreement between observations and reconstructions regardless of the choice of calibration and validation periods, either 1800-1899 (for some stations, a somewhat later start) or 1900-1999, indicates that the quality of the sea-level observations in Kronstadt and Stockholm and of the SLP reconstructions is also good, as the SLP reconstructions did not make use of any sea-level information and were not even aimed at the Baltic Sea area in particular.

For the southern Baltic stations the skill of SLP at decadal timescales is lower than for Kronstadt and Stockholm, a feature already recognized for inter-annual timescales by previous studies that indicated a low correlation between the NAO and sea-level in the Southern Baltic Sea. For these stations, area-averaged winter precipitation shows a larger skill than SLP in describing decadal sea-level variations. However, precipitation is not the sole factor that can explain sea-level variations in these stations. On the one hand, its skill measured by the Reduction of Error statistics, which is sensitive to long-term differences of the mean value between the calibration and validation periods, remain unsatisfactory, indicating that another underlying factor is playing a role for slow variations in this region. An alternative explanation, for instance that the linear detrending of the original sea-level data to substract the eustatic contribution is a too simplistic approach, seems unlikely as in these stations this eustatic contribution is clearly smaller than in Stockholm.

The mechanism by which precipitation may be affecting sea-level more strongly in the southern stations remains unclear. At decadal timescales, changes in the water balance brought about by changes in area average precipitation are affecting all stations in roughly the same manner (provided the mean water circulation is not affected by the additional fresh-water inflow). However, the effect of the wind forcing on sea-level is clearly much stronger in Kronstadt and in Stockholm, so that perhaps changes in the overall water balance of the Baltic may be only detected in areas where the effect of the wind is small enough. This explanation, however, remains problematic, as, at decadal timescales, any changes in the water inflow should be equilibrated by corresponding changes in the outflow.

Decadal changes in the spatial distribution of salinity in periods with high or low average precipitation could in principle affect sea-level, as, although the total volume on the Baltic may remain constant at these timescales, salinity affects the water density. Unfortunately, long timeseries of salinity, even for the surface, spanning the whole 20^{th} century are scarce and their quality for their earlier periods is questionable. From the modelling study of Meier and Kauker (2003), the volume-average salinity in the Baltic Basin is 7.4 ‰, with decadal variations of the order of 1 ‰. Thereby, half of the decadal variability of average salinity is caused by the decadal variations in the accumulated freshwater inflow (Meier and Kauker, 2003). Considering as a rough estimate a mean depth of the Baltic Sea of 200 m , and assuming that the salinity in the North Sea remains constant, these decadal salinity variations would be linked to variations of average sea-level of 20 cm, which is the right order of magnitude. Therefore, in areas where sea-level is not so strongly affected by the wind forcing, as in the Southern Baltic, the effect of salinity could in theory explain a non-negligible part of the decadal variations of sea-level. Nevertheless, a reasonable explanation could also be that sea level changes are caused by changes in the currents brought about by local salinity changes. Probably the best way to disentangle this question is by analysing simulations of the Baltic Sea, driven by observed forcings in the 20^{th} century, as all these mechanisms should be well represented, with only minor uncertainties, in the Baltic Sea ocean models (Meier, 2006).

Finally, an alternative explanation for the behaviour in the southern stations may be unresolved problems with data quality. An additional advantage of the modelling approach is that data-quality issues in the southern stations could be better assessed than with the statistical analysis alone. If modelling results and observations clearly disagree in this region, the joint analysis of both data sets may offer some clues (periods, magnitude and timescales of disagreement) about possible observational errors.

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5 Conclusions and Outlook

In the introduction to this thesis I posed a set of research questions. In this concluding Section I try to present how this work has contributed to clarify those questions and suggesting further research activities. Furthermore, as a possible continuation and outlook of this thesis, an estimation of regional climate change by statistical means is presented by applying the statistical transfer functions developed in this thesis to the corresponding output of global climate simulations. The preliminary findings of this statistical downscaling are then compared to dynamical downscaling results (taken from the literature) and their possible future consequences are briefly discussed.

5.1 Conclusions

In this thesis the influence of atmospheric forcing of decadal Baltic Sea level variability in the last 200 years was statistically analysed. The strategy of this work was based on *statistically downscaling*. Therefore, I used the knowledge of the possible influence of large-scale factors on Baltic Sea level from the analysis of the observational records under the assumption that the empirical-statistical functions describing this influence, remains unchanged in a future climate. The focus lied on the identification and possible quantification of the contribution of *sea-level pressure (as an indicator of geostrophic wind), temperature* and *precipitation* to the low-frequency (decadal and longer) variability of Baltic Sea level. For this purpose different approaches were used: The influence of temperature and precipitation on decadal Baltic Sea level variations was analysed in the 20^{th} century for the winter and summer season by using statistical regression models. Trends in the amplitude of the Baltic Sea level annual cycle were studied and the regional differences in winter sea-level variations in the Baltic Sea were investigated for the past 200 years. Thereby, the considered climate forcings were restricted to those for which long term observations or reconstructions are available and which are potentially well simulated by coarse resolution models. In the following the main findings of this study are presented by briefly answering the research questions set up in the introduction Section.

- *The wind forcing is the main factor explaining average Baltic sea-level variability at interannual and decadal timescales, especially in wintertime. Are there other regional climate factors that also contribute to*
    - *the average sea-level,*
    - *the spatial sea-level variations within the Baltic Sea and*
    - *Baltic Sea level variability in other seasons?*

Yes, there are other regional climate factors that contribute to Baltic Sea level and in this thesis it is statistically estimated to what extent these other regional climate factors contribute to the spatially heterogeneous Baltic Sea level variations around the isostatic trend. Although the statistical analysis is not fully conclusive, as the potential climate drivers are all statistically interrelated to some degree, the results indicate that precipitation should be taken into account as an explanatory variable for sea-level variations.

Using regression analysis linking sea-level variations (as predictand) and sea-level pressure (SLP), precipitation and air-temperature (including stepwise as predictors), it was investigated to what extent precipitation and temperature variations can also contribute to explain decadal Baltic Sea level variability in the 20th century, in addition to SLP. Data of 30 tide gauge station were analysed, spanning the whole Baltic Sea Region, by applying the regression models to each sea-level station separately. This approach differs from previous studies as it does not filter out the more local sea-level as it was done by Heyen et al. (1996). It was found, that in wintertime the additional contribution of precipitation and temperature on decadal timescales in the 20th century is small compared to that of SLP (of the order of additional 15% of variance), but it is statistically significant and their inclusion as predictors help to explain past deviations in the evolution of sea level, with higher than normal temperatures and precipitation values linked to a positive contribution to sea level anomalies. In summer, temperature and precipitation explain a substantial part of the sea-level variability except in the Kattegat region. Thereby, positive summer sea-level anomalies are linked to higher than normal precipitation but to lower than normal temperatures, suggesting that the statistical link between sea-level and temperature may artificially arise by the observed negative correlation between temperature and precipitation. For some stations, temperature and precipitation could explain, in addition to the variance explained by sea-level pressure alone, 35% of the total variability. The geographical distribution of the additionally explained variance tends to be larger in the southern stations, both in winter and summer, although in summer it is distributed slightly more homogeneously. This is consistent with the higher correlation of the NAO found in the northern stations and also with the fact that in summer the correlation with the NAO is geographically more homogeneous than in winter. Nevertheless, it has to keep in mind that part of influence of temperature and precipitation might be already contained in sea-level-pressure. Therefore, the values can just represent an upper limit for the influence of these additional factors on sea-level variability.

- *Baltic Sea level records show large trends mainly due to the isostatic post-glacial rebound. Is it possible to identify the underlying influence of regional climate factors by analysing the amplitude of annual cycle of sea-level, which is not affected by the isostasy?*

Yes, it is possible. In this thesis it could be detected that the amplitude of the annual cycle of Baltic Sea level (winter-spring sea level) has increased through the 20th century. Again timeseries of 30 Baltic gauge stations were analysed and an increase in nearly all stations could be detected. These centennial trends are not large compared to the decadal variations of the annual cycle, but they are statistically significant. Interestingly, the magnitude of the trends is almost spatially uniform. Since interannual and decadal variability of sea level display a clear spatial pattern, the mechanism responsible for the trends in the annual cycle seem to be not local, but affect the Baltic Sea basin as a whole. Possible causes for the detected trend in the amplitude were investigated by statistically analysing several hypothetical factors: the wind stress forcing (closely associated to with the NAO, but also other SLP patterns), the pressure difference between the Baltic Sea and the North Atlantic

Region (due to the barometric effect), the temperature (due to thermal expansion of the water column) and precipitation. Precipitation seems to be the only factor among those analysed that can account for the increasing centennial trend in the amplitude of the Baltic Sea level annual cycle. For some of the analysis back to 1800, the four longest sea-level records from stations situated along the Baltic Coast were used. It was found that the two stations located in the Southern Baltic display larger centennial trends in the 19th century. The 20th century trend seems to be more coherent in space and time than in the 19th century.

- *Is the influence of regional climate factors different at interannual and multidecadal timescales? Can the strong signature of wind-stress forcing on sea-level also be identified at multidecadal timescales or do other climate factors become dominant?*

Long-gauge sea level records and gridded climate reconstructions were analysed to answer this question, whereby the analysis was restricted to the winter season. It was found that selected stations in the southwestern, central and eastern Baltic Sea behave less coherent in the 19th century than in the 20th century. To explain this difference, the effect of SLP, precipitation and air-temperature in the 19th and 20th century and their relationship to Baltic Sea level was statistically analysed. It was found that the influence of these factors on sea-level varies geographically. In the central and eastern Baltic Sea, sea-level variations are well described by SLP alone, whereas in the southern Baltic Sea area-averaged precipitation better explains the multi-decadal sea-level variations. A possible explanation for this different behaviour could be may find in the evolution of precipitation in the 19th century.

Summarising all these results, it can be concluded that precipitation should be taken into account as an explanatory variable for sea-level variations. On the one hand it has been detected that the amplitude of the annual cycle of Baltic Sea level has increased along the 20th century and precipitation seems to be the only factor among those analysed that can account for this evolution. On the other hand, precipitation increases the ability to hindcast inter-annual variations of sea-level in some regions and seasons, especially in the Southern Baltic in summertime. Nevertheless, it has to keep in mind that the statistical analysis cannot be completely conclusive, as the potential climate drivers are all statistically interrelated to some degree.

The mechanism by which precipitation exerts its influence on Baltic Sea level cannot be ascertain in this statistical analysis due to the lack of long salinity time series. This result, however, represents an interesting working hypothesis that can be confirmed or disproved by long simulations of the Baltic Sea system - ocean, atmosphere and land. Most climate simulations with global and regional climate models project an increase of annual precipitation in a future climate driven by anthropogenic greenhouse gas emissions, although the magnitude of the increase is uncertain. Therefore precipitation changes may indeed play a role in the future evolution of Baltic Sea level, in particular in areas where the isostatic land-uplift is smaller.

As a by-product of this analysis that can be of some interest for researchers working on reconstructions of recent past climate and recent sea-level, it could be confirmed that the long observational timeseries of sea level in Kronstadt (located in the Gulf of Finland) and Stockholm do not suffer from major inaccuracies- at least the multi-decadal variations around the isostatic trend- as their behaviour in the past 200 years agrees very well with what can be expected from solely independent reconstructions of the sea-level-pressure in Europe in this period.

5.2 Outlook

The establishing of the statistical relationship between sea level and climatic data sets in the observational record allows the application of the statistical regression models to the output of global climate model simulations. Therefore the statistical relationship has to represent real physical links between the predictors and sea-level, something that can only be proven by simulations with realistic models. As already pointed out in the introduction of this thesis, a statistical analysis alone cannot provide clear-cut answers in climate research, as climatically relevant processes are deeply entangled. Atmosphere and ocean modelling incorporate a more comprehensive range of physical processes than a statistical approach might be able to analyse. Therefore it has to be kept in mind that the results of this thesis should be understood as complementary to modelling studies. Future research activities include the plan to consider and prove the findings of the statistical downscaling presented in this thesis in simulations with the regional Baltic Sea model of the Rossby Centre Ocean model (RCO), a regional coupled ice-ocean model (e.g. Meier et al. 2004).

However, as a continuation of this thesis, an estimation of regional climate change by statistical means is presented by applying the statistical transfer functions (developed in this thesis) to the corresponding output of global climate simulations under the following two assumptions:

- The statistical relationship represents real physical links between the predictors and the sea-level.
- The statistical model remains valid in the future.

Although the global climate models do not realistically represent the Baltic Sea due to the coarse spatial resolution (about 350 km), all predictors are represented in the climate model by several grid-points and therefore have, from this point of view, a large-scale character. Within the usual framework of climate predictions for future decades it can be assumed that these predictors are potentially well simulated by the climate models. Therefore, the output of the statistical model, when driven by the fields simulated by the climate model, gives an estimation of their consequences of past and future climate variations for Baltic Sea level. Here, I present just an example of how such estimation would look like. A few GCM climate simulations for future climate under certain scenarios of greenhouse trace gas concentrations were used to quantify the contribution of the large-scale climate changes to past and future Baltic sea-level changes.

The results are presented in Fig. 5.6 for two Baltic Sea stations, Kronstadt and Kolobrzeg (Southern Baltic Sea), as an illustration. Based on the findings of this thesis, SLP was used as a predictor for the station Kronstadt and mean averaged precipitation for the station in the Southern Baltic Sea. The models were calibrated with observations. For the estimations, the predictors were taken from (ensemble) climate simulations with different global climate models (ECHO-G, HadCM3 and ECHAM4/ OPYC3) driven by IPCC Special Report on Emission Scenarios (SRES) future scenarios of anthropogenic radiation forcings A2 and B2.

This was conducted to illustrate the uncertainties. The A2 scenario assumes a more rapid increase in emission of the major anthropogenic greenhouse gases compared to the B2 scenario.

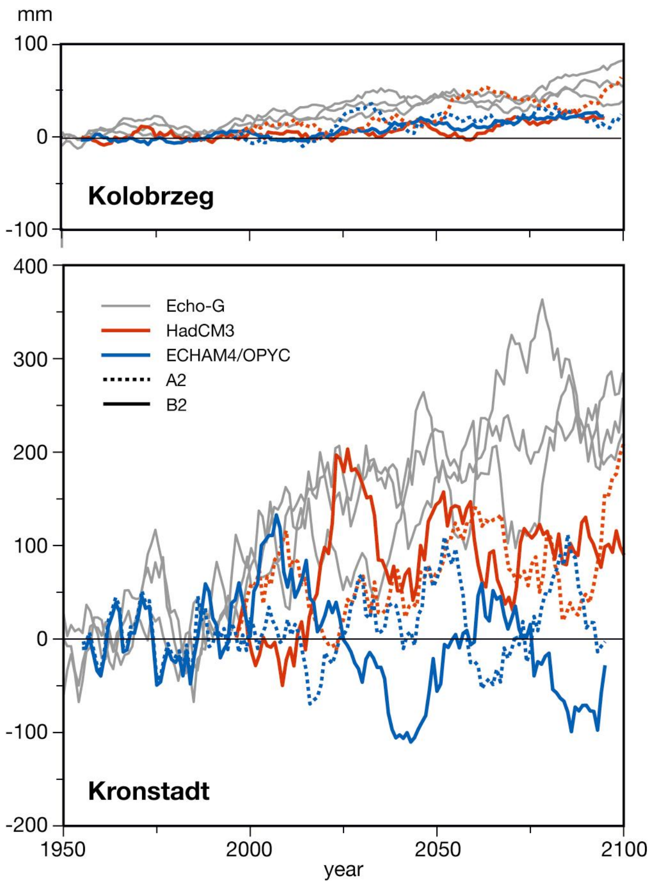

Fig. 5.6 *Estimations of the contribution of SLP (lower panel) and precipitation (upper panel) changes to future winter sea-level change for two stations in the Baltic Sea, based on regression between observed sea-level and the predictors. For the estimations, the predictors were taken from (ensemble) climate simulations with the global climate models ECHO-G, HadCM3 and ECHAM4/ OPYC3 driven by IPCC SRES future scenarios of anthropogenic radiation forcing A2 and B2. Time series are smoothed by an 11-year low-pass filter. Upper panel: for the southern sea-level station Kolobrzeg, based on regression models with observed Baltic winter rainfall as predictor. Lower panel: for the sea-level station Kronstadt, based on regression models with observed Baltic winter SLP as predictor.*

The ensemble simulation with the climate model ECHO-G under future scenario B2 shows that the trend in sea-level rise caused by these regional factors is much larger than the past variability and might be of the order of 1 mm/year. Simulated changes in the SLP can contribute to changes in sea-level in Kronstadt with an average trend of the order of 2 mm/year, respectively, in the 21st century, provided that the linear statistical model remains valid under this rather strong intensification of the meridional atmospheric pressure gradient. For the stations in the Southern Baltic Sea, the estimated changes brought about by simulated changes in precipitation are of the order of 0.5 mm/year and therefore smaller. Both of the factors, SLP and precipitation, contribute to an upward trend of sea-level.

In contrast, the simulations with the HadCM3 and ECHAM4/ OPYC3 climate model under future scenario B2 and A2 show a noisier, but tentatively positive signal on sea-level changes, whereas the rainfall contribution is more similar and positive.

These (preliminary) findings qualitatively agree with the results of a regional dynamical modelling approach by Meier et al. (2004). They used the Rossby Centre Atmosphere Ocean Model (RCAO), driven by the global models HadAM3H and ECHAM4/OPYC3 under future scenarios A2 and B2 (to characterise the uncertainties stemming from the large scale forcing and from the future external climate forcing) and combined a range of simulated global eustatic sea-level rises with the impact of simulated regional wind changes for the Baltic Sea area. They found the same sign in the sea-level trend as in the present study, but their maximum of about 50 cm in winter mean sea-level rise for the eastern and southern Baltic coast is much higher than our findings.

According to the BACC assessment report, precipitation increased in the 2nd half of the 20th century and a general increase in precipitation is projected for the Baltic Sea basin, except for the southernmost areas in summer.

A more thorough analysis using the output of all global climate models used in the Fourth IPCC Assessment report, which is now available online, is planned for the future.

List of Abbreviations

Abbreviation	Explanation
BACC	BALTEX Assessment of Climate Change for the Baltic Sea Basin
BALTEX	The Baltic Sea Experiment
BALTIMOS	BALTEX Integral Model System
CRU	Climate Research Unit
DEM	Digital Elevation Model
DFG	Deutsche ForschungsGemeinschaft
DJF	(December-January-February)
ECHAM	General circulation climate model from the Max-Planck Institute, Hamburg
EOF	Empirical Orthogonal Function
GCM	Global Circulation Model
HadCM3	Global climate model from the Hadley Centre, UK
IMPRS	International Max Planck Research School on Earth System Modelling
IPCC	Intergovernmental Panel on Climate Change
JJA	(June-July-August)
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration

Abbreviation	Explanation
NCAR	National Centre for Atmospheric Research
NCCR Climate	Swiss Climate Research
NCEP	National Centres for Environmental Prediction
NDJ	(November-December-January)
MAM	(March-April-May)
MSL	Mean Sea Level
MTL	Mean Tide Level
PC	Principal Component
PSMSL	Permanent Service for Mean Sea Level
psu	practical salinity units
RCAO	Rossby Centre Atmosphere Ocean model
RE	Reduction of Error
RLR	Revised Local Reference
SINCOS project	Sinking Coasts
SLP	Sea Level Pressure
SOAP project	Simulations, Observations and Palaeodata: climate variability over the last 500 years
SRES	Special Report on Emission Scenarios
SMHI	Swedish Meteorological and Hydrological Institute
SSH	Sea Surface Hight
TOPEX	TOPography EXperiment

List of Figures

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