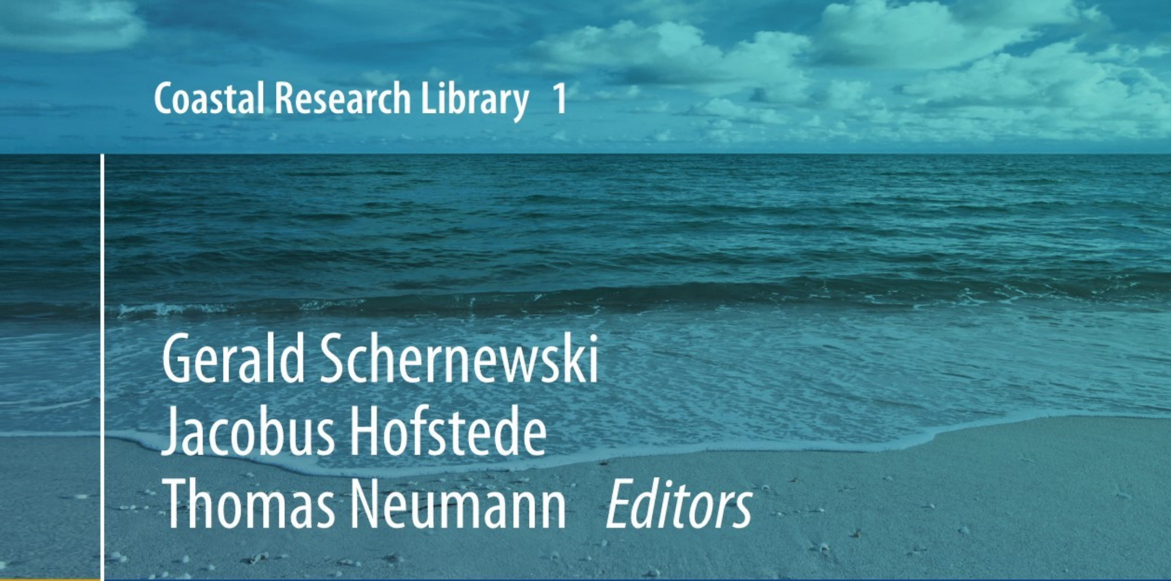

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Global Change and Baltic Coastal Zones

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Coastal Research Library

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Global Change and Baltic Coastal Zones

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Preface

According to the United Nations Framework Convention on Climate Change (UNFCCC), the term Climate Change means a climatic change attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods. According to IPCC (2007), eleven of the last 12 years (1995–2006) rank among the twelve warmest years since 1850. Observations of increases in global average air and ocean temperatures as well as widespread melting of snow and ice provide clear evidence of an ongoing global warming.

The impacts of Climate Change vary regionally. In Europe, especially the Mediterranean will be significantly affected. In this region, Climate Change is projected to increase heat waves and droughts during summer, reduce water availability and decrease crop productivity. The negative consequences in the Mediterranean are overwhelming and Climate Change is regarded as a major threat for the future. In the North Sea region, rising mean sea levels and storm surge water levels are seen as a major challenge resulting from Climate Change. In the Baltic Sea region, the effects as well as the perception and evaluation of the consequences are different. Here, people tend to look – as well – at the opportunities of Climate Change.

A changing climate is not the only challenge for the future. At the same time political, social, economic and agricultural transformation processes are ongoing in the world. These developments interact with Climate Change and both can be summarized under the label 'Global Change'. The strong geographical variability in Global Change calls for a regional focus, in this case the Baltic Sea region.

In the Baltic Sea region, Climate Change and ongoing transformation processes in economy and agriculture will have strong and multiple impacts. Numerous investigations on these topics have been conducted. During the last years the focus of activities shifted from analysis and evaluation of consequences via mitigation strategies towards adaptation approaches. This is well reflected in national initiatives and projects. The German 'KLIMZUG' funding activity, initiated in 2009, is one example. Background was the perception that an urgent demand for society, economy and politics exists to develop new and improved methods for adaptation. This initiative particularly stresses the regional aspect of adaptation by funding seven large regional projects. One of them is RADOST (Regional Adaptation Strategies for the German Baltic Coast). Similar large international projects, like BaltCICA

(Climate Change: Costs, Impacts and Adaptation in the Baltic Sea Region) or BALTADAPT (Baltic Sea Region Climate Change Adaptation Strategy) have their focus on pan-Baltic cooperation.

Adaptation strategies and measures are urgently needed but require a thorough and spatially differentiated understanding of underlying ecological, economic and social processes. The book addresses these changes, their consequences, practical challenges as well as adaptation options with a clear focus on the coastal zones of the Baltic Sea region.

Regardless of the strong spatial variability of Global Change, the resulting problems, challenges and, thus, possible solutions may show similarities for different regions in the world. In awareness of the fact that concrete adaptation measures and their implementation have to be tailor-made and fitted to the special situation

of a locality, an exchange of experiences in dealing with Global Change seems appropriate. Closer co-operation between scientific, administrative and political actors as well as different regions is required. Learning how the problems are addressed in different parts of the world, how different strategies and solutions look like and how basic approaches can be transferred to other regions are important educational issues today.

Against this background, the international summer-school 'Climate Change in the Baltic – From global problems to local adaptation' took place at the Leibniz-Institute for Baltic Sea Research between 6th and 17th of September 2010. 19 students and young scientists from 13 countries had the opportunity to exchange experiences and get an insight into activities in the Baltic Sea Region. Several lectures served as a basis for the articles of this book.

The participants of the summer-school 'Climate Change in the Baltic – From global problems to local adaptation' at Warnemünde beach

This book has been funded by the Federal Ministry for Education and Research within the KLIMZUG-project RADOST (Regional Adaptation Strategies for the German Baltic Coast; 01LR0807B). It received additional support from EUCC-The Coastal Union Germany and the European Regional Development Fund within the Baltic Sea Region Programme project BaltCICA (Climate Change: Costs, Impacts and Adaptation in the Baltic Sea Region) and BALTADAPT (Baltic Sea Region Climate Change Adaptation Strategy).

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Part I
Global Change – The Scientific Background

Chapter 1
Regionalisation of Climate Scenarios for the Western Baltic Sea

Ulf Gräwe and Hans Burchard

Abstract Global coupled climate models are generally capable of reproducing the observed trends in the globally averaged atmospheric temperature. However, the global models do not perform as well on regional scales. Here, we present results from two 140-year, high-resolution regional ocean model experiments for the Western Baltic Sea. The forcing is taken from a regional atmospheric model and a medium scale ocean model. The model runs with two greenhouse gas emission scenarios (each for 100 years), A1B and B1, for the period 2000–2100. A control run (C20) from 1960 to 2000 is used for validation. For both scenarios, the results show the expected warming, with an increase of 0.5–2.5 K at the sea surface and 0.7–2.8 K below 40 m. The simulations further indicate a decrease in salinity, a change in stratification, and an increase of the return period of storm surges.

1.1 Introduction

Climate Change and variability affect the coastal zone, the marine ecosystem, and fisheries in several ways. First temperature has a direct influence on metabolism and growth; see for example, Jobling (1996). Climate may also have secondary effects, affecting a species by changes in food availability, competitors, or predators. For the North Sea and Baltic Sea, there are several recent studies on the effects of Climate Change on the fish stock and plankton (Clark et al. 2003, Isla et al. 2008, Neumann 2010). Temperature and salinity changes may also act as proxies for other climate mechanisms such as circulation changes and changes in vertical mixing and stratification. For the Baltic Sea the episodic inflow of saline, oxygen rich North Sea water is an important climate variable (Omstedt et al. 2004, Meier 2007). In

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addition to the influence on the salinity, these inflows are also a source of nutrients and zooplankton (Feistel and Nausch 2008). Due to this highly variable environment, life in the Baltic Sea is highly adapted and often reaches its physiological limits (e.g. Feistel and Nausch 2008). Moreover, large scale variability in the atmospheric variables, and hence changes in local climate, might lead to significant changes in coastal erosion (Zhang et al. 2010, Meyer et al. 2008).

The Climate Changes projected to occur within the next 100 years, will have a considerable impact on the physical conditions of the Baltic Sea (BACC 2008). The projected warming is between 3 and 5 K, with a tendency towards a reduced salinity. To study the projected implications of Climate Change (Meier et al. 2004, Meier et al. 2006, Sanchez et al. 2004, Wang et al. 2008, Somot et al. 2008, van Roosmalen et al. 2010), a consistent scenario of future climate is needed. Such scenarios are produced by global coupled atmosphere-ocean circulation models. However, for shallow seas like the Western Baltic Sea, the present generation of such global models do not have the necessary resolution to properly resolve the complex topography. Typically, they also lack important shelf sea physical processes like turbulent mixing, overflows and fronts and a realistic description of the bathymetry and the coastline. Hence, there is an increasing need to use regional ocean model to provide valuable, high-resolution information to governments, stakeholders and coastal engineers (Holt et al. 2010, Brown et al. 2010, Melsom et al. 2009, Adlandsvik and Bentsen 2007).

This modelling study is embedded into a general framework for adaptation strategies for the German Baltic Coast, RAdOst (2009). The objective of RAdOst is the development of adaptation strategies for the Baltic Sea coastline of Germany through a dialogue between science, economists, policy-makers, and the public. Other important goals are to minimise the economic, social, and environmental harm and to capitalise on development opportunities brought about by Climate Change.

This paper uses dynamical downscaling to regionalise future global climate scenarios for the Western Baltic Sea. This is done by forcing a high-resolution regional ocean model with atmospheric forcing and open ocean lateral boundary description from a regionalised atmospheric and large-scale ocean model. The final spatial resolution of the model is approx. 1 km, which allows for a realistic description of topographic features like sills, sounds and coastlines. The forcing used in the present study are two greenhouse gas emission scenarios proposed by the Intergovernmental Panel on Climate Change (IPCC 2007), A1B and B1. The latter is the more optimistic of the two scenarios, with less greenhouse gas emissions. Because the simulations range from 1960 to 2100, no care has to be taken for the additional spinup in time slice experiments. These transient simulations are a novel feature in regionalised ocean climate modelling, because they do not rely on the assumption, that the underlying system has reached a steady state. This was also pointed out by Neumann (2010).

In this paper we are analysing the following model output data: 3-hourly sea level data, daily mean fields of temperature/salinity and weekly averaged potential energy anomaly.

1.2 Methods

1.2.1 The Forcing Scenarios

From the IPCC IPCC07, simulations of 20 Atmospheric-Ocean General Circulation Models (AOGCMs) are available. Ideally, these 20 AOGCMs are used to force 10 regional climate models (RCM) (Christensen and Christensen 2007, Jacob et al. 2007). This would give a total number of 200 possibilities for one realisation of one forcing scenario to span a sufficiently large ensemble of regional simulations. However, this is not yet feasible for a single working group. Therefore, only one combination of AOGCM and RCM is chosen to force the high-resolution ocean model.

The meteorological forcing chosen for our simulations was provided by the dynamic downscaling carried out with the CLM (CLM 2008), the climate version of the operational weather forecast model of the German Weather Service, used as the RCM for downscaling. The horizontal resolution of the CLM is about 18 km (this is high enough to capture the effect of land/sea transition) and the time resolution is taken as 3 h for all necessary meteorological variables (10 m wind, air temperature, dew point temperature, cloud cover, air pressure and precipitation). The global climate model is ECHAM5/MPI-OM of the Max-Planck-Institute for Meteorology in Hamburg, Germany (MPI 2008). The forcing data set covers the period from 1960 to 2100. It is splitted into the reference period (C20) covering the years 1960–1999 and the two greenhouse gas emission scenarios, A1B and B1 (2000–2100).

The oceanic boundary conditions are taken from the transient Modular Ocean Model, MOM-3.1 (Griffies et al. 2001) simulations of Neumann (2010). The model covers the entire Baltic Sea and parts of the North Sea and has a horizontal resolution of 3 nm and 77 vertical (geopotential) grid layers, with a near-surface resolution of 2 m, increasing with depth (Neumann 2010). For a validation of Baltic Sea simulations see Neumann (2000) and Janssen et al. (2004). The boundary conditions are provided with a temporal resolution of 4 h. At the boundaries, profiles of temperature and salinity are prescribed. Additionally, the sea surface elevation and the depth-averaged currents are given at the boundary points. Because the simulations of Neumann (2010) do not include the effect of sea level rise, it has to be added explicitly. Here we follow the projections of the IPCC, where the possible range for the A1B scenario is given as 21–50 cm and for the B1 scenario as 18–38 cm. In our experiments, we have chosen a sea level rise of 50 cm for the A1B scenario and of 25 cm for the B1 run. These values are linearly interpolated between 2000 and 2100.

1.2.2 The Regional Ocean Model

The General Estuarine Transport Model (GETM) (Burchard and Bolding 2002, Burchard et al. 2004), which has been used for the present numerical study, combines the advantages of a bottom-following coordinates with the turbulence module of the General Ocean Turbulence Model (GOTM) (Umlauf et al. 2006). GETM has been successfully applied to several coastal, shelf sea and limnic scenarios, for turbulent flows in the Wadden Sea (Stanev et al. 2007, Lettmann et al. 2009), for dynamics in the North Sea (Staneva et al. 2009), for estimating exchange and residence times the Willapa Bay in Washington State (Banas and Hickey 2005) and for a basin-exchange study in the Lake of Geneva (Umlauf and Lemmin 2005). Furthermore, GETM has recently shown its capabilities to simulate inflow events into the Baltic Sea (Burchard et al. 2005, 2009).

GETM is a three-dimensional free-surface primitive equation model using the Boussinesq and boundary layer approximations. Vertical mixing is parameterised by means of a two-equation $k - \varepsilon$ turbulence model coupled to an algebraic second-moment closure (Canuto et al. 2001) (see also Burchard and Bolding 2001) explicit horizontal mixing is neglected. For the discretisation, a high-resolution bathymetry (0.5 nm resolution) has been used as well as bottom- and surface-fitted vertical coordinates with 35 vertical layers and a horizontally homogeneous bottom layer thickness of 0.4 m, such that the flow can smoothly advect along the bed. Details of the model setup are explained in detail in Burchard et al. (2009). In contrast to the original settings, the time step was 15 s for the barotropic and 375 s for the baroclinic mode. These settings are close to the stability criterion, but allow for a fast time stepping. Additional, the Odra Lagoon (Fig. 1.1) was added to the computational domain.

To properly simulate the river discharge, five rivers are included in the model domain. The time series of river discharge are also taken from the simulations of Neumann (2010). The most important is the Odra (mean discharge 600 m^3s^{-1}), which directly discharges into the Odra lagoon (Fig. 1.1). For consistency, both ocean models use the same CLM atmospheric forcing on the same spatial grid. Due to the two open boundaries at which sea levels from the MOM Baltic Sea model Neumann (2010), were prescribed, the net flow through the Western Baltic Sea had to be fitted. This was done by adjusting the barotropic pressure difference between both open boundaries. Furthermore, to keep the water exchange through the Great Belt realistic, the bathymetry was deepened in the narrow channels (Fig. 1.1). The adjustment procedure, the changes in the bathymetry and more details of the model setup are explained in detail in Burchard et al. (2009). Although we used an ocean model with a wetting and drying algorithm, no changes in the coastline are considered. Especially the loss of land due to flooding is not taken into account. To keep the simulation computationally feasible, the whole domain (426 × 469 × 35 grid-points) was decomposed into 251 active sub domains (21 × 22 × 35 grid-points). The calculations were performed at one of the German supercomputers (22,000 cpu's (HLRN 2007)). At the supercomputing facility, 1 year of simulation took about 120 min of wallclock time.

1.2.3 Statistical Comparison

To validate climate simulations it is not possible to compare time series. Therefore, climate projections cannot reproduce single events rather than reproducing the

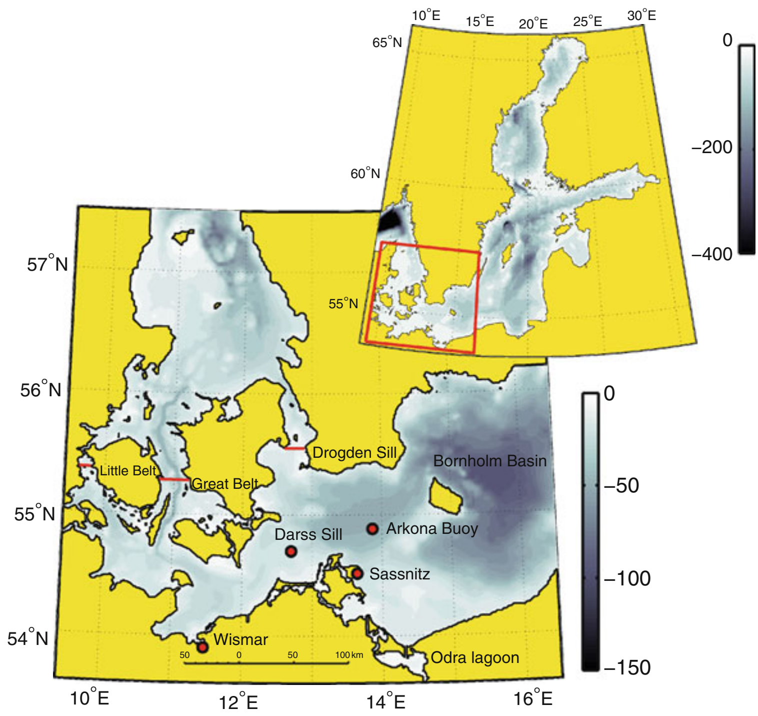

Fig. 1.1 Model domain and location of the Western Baltic Sea. The *grey shading* indicates the depth below mean sea level in m. *Upper panel*: a map of whole Baltic Sea showing the location of the model domain. The location of observation stations are denoted by the *dots*

long-term statistic. It is common to use 30 years to compute the appropriate statistics (Christensen et al. 1997). Because the observations of high-resolution time series of atmospheric forcing and temperature/salinity in the water only cover 14 years (Table 1.1), we have compared the statistic of 14-year slices and the full reference period. For both case no significant difference were visible. Thus, the limited lengths of observations are still challenging, but allow for a validation. Table 1.1 summarises the available observation data. The hourly sea level gauge data of Sassnitz and Wismar are converted to 3-hourly data by sampling every third point. Temperature/salinity and atmospheric forcing is measured hourly but for comparison with the control run, a daily average is computed.

Table 1.1 Summary of available observations stations (see also Fig. 1.1)

Station	Atmos. forcing	Gauge	Temperature/salinity
Wismar	–	1978–2004	–
Darss Sill buoy	1995–2009	–	1995–2009
Sassnitz	–	1978–2004	–

1.3 Validation

In the following section a validation of the atmospheric forcing and the simulation of the reference run (1970–2000) is given.

1.3.1 Atmospheric Forcing

In Fig. 1.2a, the comparison of the 2 m air temperature is shown, for which we have chosen the Darss Sill buoy (Fig. 1.1) for validation. At first, it is central in the model domain and quite representative for the whole German coast. Second this observation station offers time series spanning from 1995 to 2009. It is clearly visible that the CLM data show a cold bias of 1.3 K. However, the atmospheric model is able to reproduce the bimodal temperature distribution. Nevertheless, one has to keep the cold bias in mind to judge the outcome of the climate projection, especially if the GETM output is used in further impact studies.

In Fig. 1.2b, the probability density function (pdf) of the measured wind speed and the CLM wind speed is shown. The CLM dataset shows a slight overestimation of wind speed above 12 m s^{-1} and below 2 m s^{-1}. Because the CLM dataset tends to overestimate the extremes (low and high wind speed), there is an underestimation of moderate wind speeds of 5–12 m s^{-1}. However, one can conclude that the atmospheric model can reproduce the reference wind statistic.

For a detailed comparison of the CLM data and an inter-comparison of different RCA, the interested reader is referred to Jacobs et al. (2007).

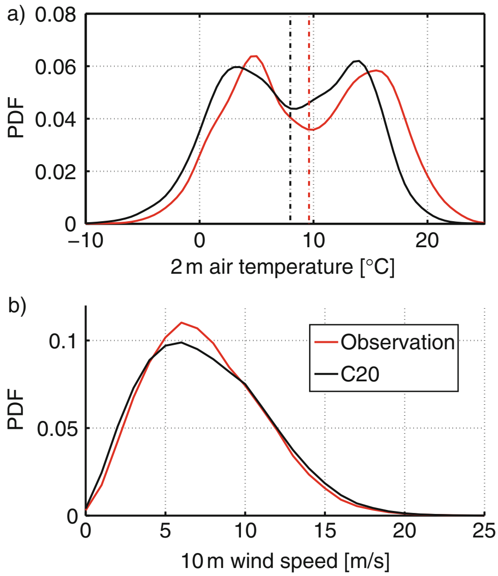

Fig. 1.2 Validation of CLM forcing at Darss Sill buoy, (**a**) pdf of 2 m air temperature. The *dashed lines* indicate the mean. (**b**) pdf of wind speed

1.3.2 Temperature and Salinity

To show that GETM can represent the present day statistic, Fig. 1.3a shows the pdf of bottom salinity at Darss Sill buoy. This station is quite important, because approx. 70% of the water exchange between the North Sea and the Baltic Sea goes over Darss Sill (Matthäus and Franck 1992). The comparison indicates that GETM can quite well estimate the salinity pdf. The occurrence of high salinities is only slightly overestimated. For the low salinity events, this is just reversed. Because the salinity within the Western Baltic Sea is mainly controlled by the boundaries, these minor deviations might be caused by the boundary conditions.

Looking on the statistics of the bottom temperature (Fig. 1.3b) reveals the impact of the cold bias in the CLM air temperature. The simulations show a cold bias of 0.9 K, which is slightly lower than for the air temperature (1.3 K). Having the cold bias in mind, it is difficult to judge the quality of the results.

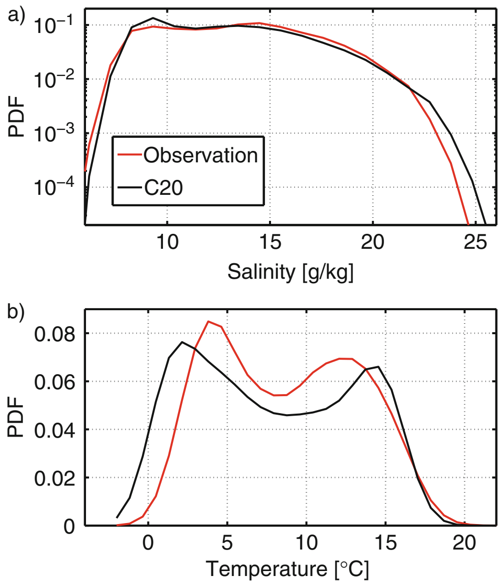

Fig. 1.3 Validation of the pdf of daily averaged (**a**) bottom salinity and (**b**) bottom temperature at Darss Sill buoy (19 m depth)

1.3.3 Sea Surface Elevation

A quantity, which is of great interest for coastal engineers and port authorities, is the occurrence of storm surges. Based on the return period of 10-year, 30-year, etc. surges, dykes and coastal protections have to be designed. In Fig. 1.4 we show the comparison of the pdf of sea surface elevation at two gauge stations Sassnitz and Wismar (Fig. 1.1). One has to note that Wismar is the more challenging, because topographic feature and local wind stress are modifying the surge. Looking onto the statistic of surges higher than 1 m, GETM slightly underestimates the probability of

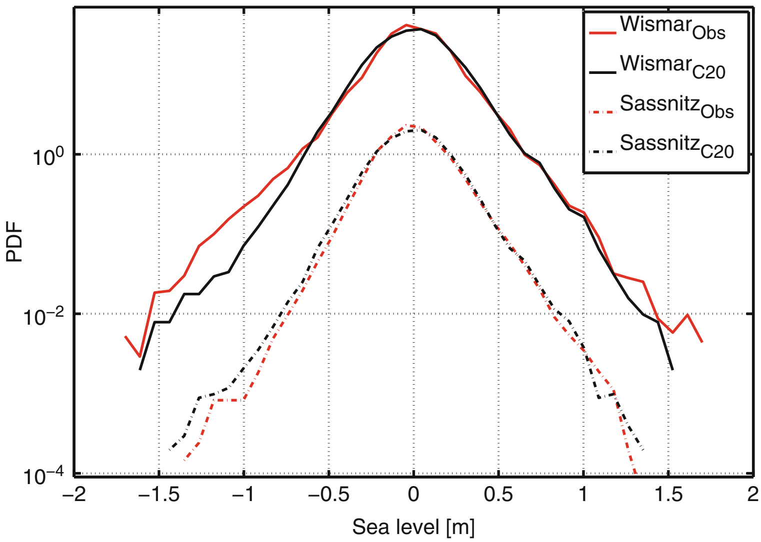

Fig. 1.4 Validation of the pdf of sea surface elevation at Wismar and Sassnitz. For better comparison, the Wismar gauge pdf is shifted upward

extremes. Further, GETM misses some of the extremes. This can be caused by the atmospheric forcing. The 18 km resolution of CLM is reasonably high; it still can be too coarse to reproduce the proper extreme wind statistic. Anyhow, GETM can reproduce the right side of the pdf of sea surface elevations for Wismar and Sassnitz. For extreme low water, GETM deviates from the observation. This might be caused by bathymetry and by the wetting/dry algorithm in GETM. Because Wismar is surrounded by much shallower water than Sassnitz, this effect is more pronounced. However, these low waters might be of interest for ship routing and fairways, but of minor importance in the context of Climate Change.

To have better comparison than by visual inspection, we performed a Wilcoxon rank sum test (Gibbons 1985). This test compares two time series and test the hypothesis if both do not have the same underlying distribution. As significance level, we have chosen the 5% level. Because we are interested in the high waters, only the distributions of the tails are compared. As tail, we define sea surface elevations greater than the 99 percentile of the observation time series (1978–2004). The 99 percentile for Sassnitz are 0.56 cm and 0.68 cm for Wismar (Table 1.4). The P-value of the Wilcoxon rank sum test indicates that the observed and simulated time series are drawn from the same distribution at the 5% significance level (37% for Sassnitz and 31% for Wismar).

1.4 Climate Projections for the Western Baltic Sea

In the following section, the impact of the projected climate-change on the Western Baltic Sea hydrodynamics is discussed. For visualising the results, some of the model state variables are used.

1.4.1 Atmospheric Forcing

To set the stage for showing the impact of Climate Change on the Baltic Sea in Fig. 1.5a annual mean time series of projected 2 m air temperature and standard deviation for the model domain (only above water points) is given. Here the increase by 2–3.5 K at the end of the century is visible. The standard deviation indicates a slight decrease in variability. Doing the same exercise for the wind speed revealed that the annual mean wind speed stays nearly constant in the next 100 years (not shown). More interestingly is, that the 99% quantile of the wind speed (strong wind events) (Fig. 1.5b) will slightly increase in the future. This might have implications on the occurrence of storm surges. The standard deviation does not indicate any significant trend.

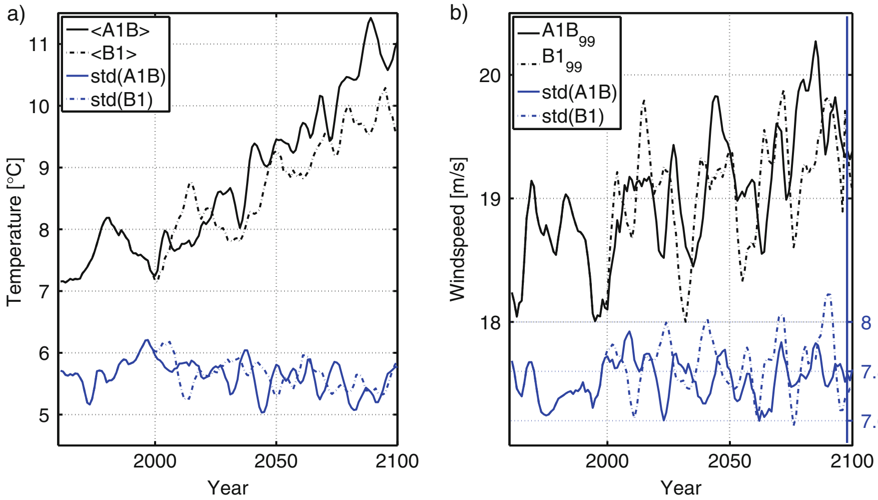

Fig. 1.5 (**a**) Projected annual 2 m air temperature over the western Baltic Sea and annual standard deviation and (**b**) projected annual 99% quantile of the wind speed and standard deviation of the annual wind speed. The data are smoothed by using a 5-year running mean

1.4.2 Sea Surface Temperature

Figure 1.6a shows the annual mean sea surface temperature (SST) for the control run (1970–2000). The average sea surface temperature along the German coast is approx. 8.5°C. Peak values of 9°C are reached in the Odra lagoon and around Wismar. The cooler water in the northeast of the domain is caused by coastal upwelling due to the prevailing westerly winds. The A1B scenario, Fig. 1.6b indicates an average increase of 0.9 K for the period 2020–2050 and 2.5 K for the period 2070–2100 (Fig. 1.6c). The highest warming can be seen in the Bornholm Sea and in the Arkona Basin. For the B1 scenario, the average increase for the period 2020–2050 is 0.5 K (Fig. 1.6d) and for the period 2070–2100 on average 1.7 K (Fig. 1.6d). In almost the same manner warming can be seen in the Bornholm Sea and in the

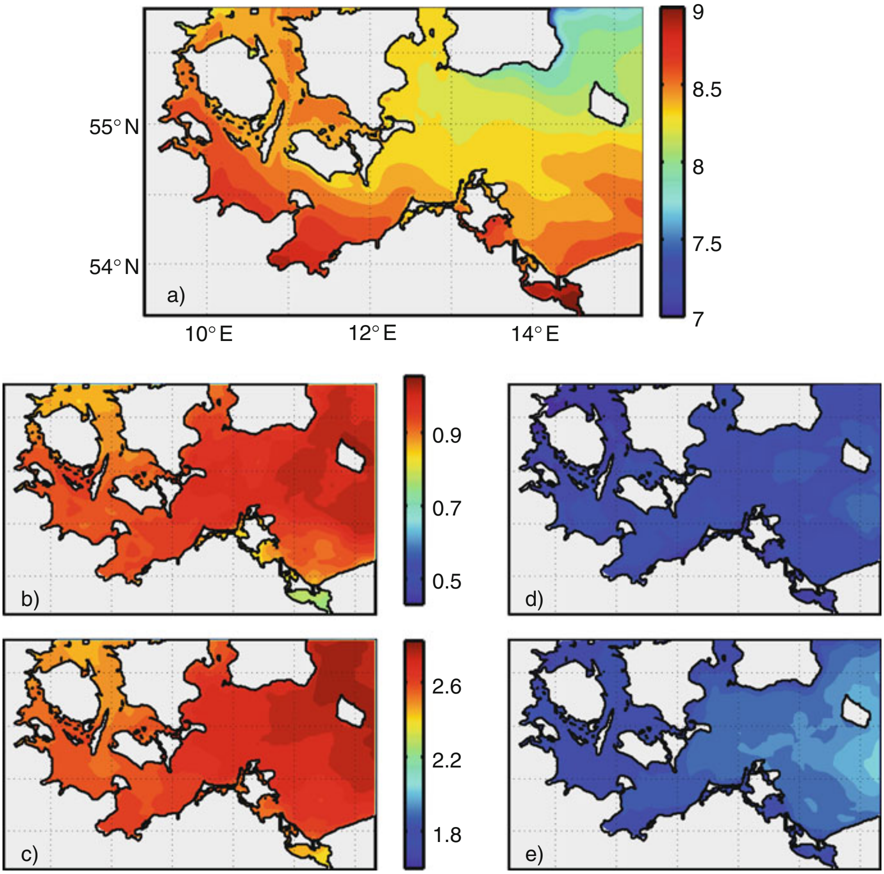

Fig. 1.6 (**a**) Annual mean sea surface temperature for the period 1970–2000. Projected changes in the annual mean sea surface temperature for (**b**) A1B 2020–2050, (**c**) A1B 2070–2100, (**d**) B1 2020–2050 and (**e**) B1 2070–2100. Note the different scales for 2020–2050 (**b**, **d**) and 2070–2100 (**c**, **e**)

Arkona Basin. A detailed description of the warming in relation to C20 is given in Table 1.2. The warming at the bottom (depth >40 m) is the strongest; however the values indicate that the whole water column is shifted towards higher temperatures.

Table 1.2 Summary of temperature changes for the SST, bottom temperature (depth > 40 m) and the whole water body

Station	A1B		B1	
	2020–2050	2070–2100	2020–2050	2070–2100
SST	+0.9 K	+2.5 K	+0.5 K	+1.7 K
Bottom temperature	+1.0 K	+2.8 K	+0.7 K	+2.0 K
Whole water body	+0.9 K	+2.7 K	+0.5 K	+1.8 K

1.4.3 Water Exchange

To compute the water exchange with the North Sea, the water transport Q_W through the cross-sections in the Little Belt, Great Belt and at Drogden Sill (Fig. 1.1) is calculated:

$$Q_W(t) = \int_A v(x,z,t)dA, \qquad (1)$$

where A is the area of the cross section and v the meridional velocity. To quantify the overall residual mass flow, the advective salt flux Q_S into the Baltic Sea has been calculated explicitly:

$$Q_S(t) = \int_A v(x,z,t)S(x,z,t)dA, \qquad (2)$$

Where S is the salinity. It is obvious, that $Q_S$should sum up to zero (if the salinity remains constant in the Baltic Sea), because there are no salt sources or sinks in the Baltic Sea. Therefore, to give Q_S a meaning, we compute the salt flux only for salinities exceeding a certain threshold. Thus, it is possible to quantify the inflow of saline North Sea water into the Baltic Sea.

The results are summarised in Table 1.3. The mean outflow Q_W during the reference period is approx. 15,000 m^3 s^{-1}, which is similar to the observed climatological one Feistel08. The values indicate a slight increase for the B1 scenario. However, this is caused by the increase in freshwater supply (Meier and Kauker 2003) and agrees with the decrease in salinity (Fig. 1.7). Moreover, an increase in variability in the second part of the century is visible.

A second quantity of interest is the salt flux Q_S into the Baltic Sea. This can be decomposed into two parts: first, the contribution due to the salinity difference,

Table 1.3 Summary of water exchange through the Little Belt, Great Belt and over Drogden Sill (Fig. 1.1). Positive values indicate a flux out of the Baltic Sea

	Period	A1B	B1
Q_W	1970–2000	14,900 ± 5,700 m^3 s^{-1}	14,900 ± 5,760 m^3 s^{-1}
Q_W	2020–2050	14,300 ± 5,000 m^3 s^{-1}	16,600 ± 5,710 m^3 s^{-1}
Q_W	2070–2100	14,800 ± 6,900 m^3 s^{-1}	17,300 ± 6,490 m^3 s^{-1}
$Q_{S>15}$	1970–2000	–355 ± 90 t s^{-1}	–355 ± 90 t s^{-1}
$Q_{S>15}$	2020–2050	–340 ± 75 t s^{-1}	–380 ± 70 t s^{-1}
$Q_{S>15}$	2070–2100	–360 ± 105 t s^{-1}	–380 ± 80 t s^{-1}
$Q_{S>20}$	1970–2000	–240 ± 100 t s^{-1}	–240 ± 100 t s^{-1}
$Q_{S>20}$	2020–2050	–180 ± 105 t s^{-1}	–310 ± 75 t s^{-1}
$Q_{S>20}$	2070–2100	–130 ± 80 t s^{-1}	–280 ± 85 t s^{-1}
$Q_{S>25}$	1970–2000	–10 ± 25 t s^{-1}	–10 ± 25 t s^{-1}
$Q_{S>25}$	2020–2050	–5 ± 10 t s^{-1}	–35 ± 30 t s^{-1}
$Q_{S>25}$	2070–2100	–0 ± 10 t s^{-1}	–29 ± 30 t s^{-1}

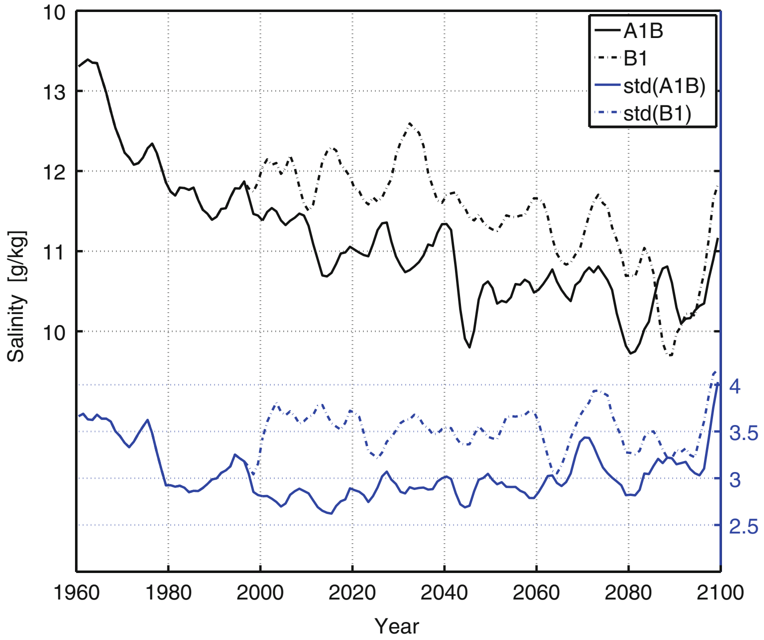

Fig. 1.7 Projected changes in annual mean bottom salinity and standard deviation for Darss Sill buoy. The data are smoothed by using a 5-year running mean

hence the baroclinic pressure gradient and the barotropic part, which is caused by sea level difference, between the North Sea and the Baltic Sea. Especially the later one is important for the deep-water exchange in the Baltic Sea. To characterise such inflow events, Matthäus and Franck (1992) used as indicator the bottom salinity at Darss Sill buoy. Salinities above 17 g kg^{-1}, during more than 5 days, define a major inflow event. It is not the intention of this paper to verify the findings of Matthäus and Franck (1992), rather than to give a broad description of the residual salt flux. Because we have the simulation data available, the flux is computed at Little Belt, Great Belt and at Drogden Sill transects (Fig. 1.1) for 3 thresholds, 15, 20, and 25 g kg^{-1}. For the calculation of Q_S we used transects of daily mean salinity and meridional velocity.

The results in Table 1.3 indicate, that there is an increase in Q_S into the Baltic Sea by medium inflow events, but also during major events (S >25 g kg^{-1}) for the B1 emission scenario. This would also explain the higher variability in the stratification in the Arkona Basin. The opposite is true for the A1B scenario. Here a decrease in salt flux for salinities >20 g kg^{-1} is visible, which again explains the lower variability at the Arkona buoy.

1.4.4 Bottom Salinity

The projected changes in the bottom salinity at Darss Sill buoy are given in Fig. 1.7.

For both scenarios, a decrease in salinity is visible, mainly caused by the increase in freshwater supply (Meier and Kauker 2003). These findings are in agreement with the results of Neumann (2010), with a decrease of approx 1.5 g kg^{-1} for the B1 scenario and 2 g kg^{-1} for the A1B scenario. In the time series of the standard deviation, no significant trend is visible, except that the B1 run shows a somewhat higher variability. Figure 1.7 further indicates that there are differences before and after 2000. At first the salinity is significant higher and second, the variability before 2000 is lower (especially 1980–2000). Here, a second control run might clarify these differences.

1.4.5 Stratification

Potential energy arguments have been found to be an excellent measure to study the competition of stratification and mixing. To quantify stratification, Simpson et al. 1977, considered changes in potential energy relative to the mixed condition and defined a scalar parameter ϕ, the potential energy anomaly,

$$\phi = \frac{1}{D}\int_{-H}^{\eta} (\overline{\rho} - \rho)\, gzdz \tag{3}$$

where D is the total water depth $D = \eta + H$, η the sea surface elevation, H the mean water level, $\overline{\rho}$ the depth averaged density, p is the vertical density profile over the water column, g the gravitational acceleration and z the vertical coordinate. For a given density profile, ϕ (J m^{-3}) represents the amount of work required to bring about complete vertical mixing per unit of volume and thus a measure to quantify the strength of the stratification. In Fig. 1.8a, the potential energy anomaly and standard deviation for the Arkona buoy (Fig. 1.1) is shown. For both scenarios, no significant trend is visible for the mean. Only the variability in the B1 run is slightly increased. Further, the stratification in the B1 scenario is on average stronger than under the A1B emission scenario. This seems surprising; since the stronger decrease in surface salinity for A1B (Fig. 1.7) would lead to a strengthening of the stratification. On the other hand, due to the increase in temperature, stratification is weakened. Therefore, both effects cancel each other. More interesting are the time series of annual minimum and maximum of ϕ (Fig. 1.8b). The spread between the annual maximum and minimum in the B1 run is higher than for the A1B run. The higher variability in the B1 emission scenario (Fig. 1.5) supports these findings. In addition, both model runs show lower annual minima than in the control run. This can be caused by the increase in highly energetic strong wind events. Thus, the occurrence of a less stratified Arkona basin is much more probable in the near future.

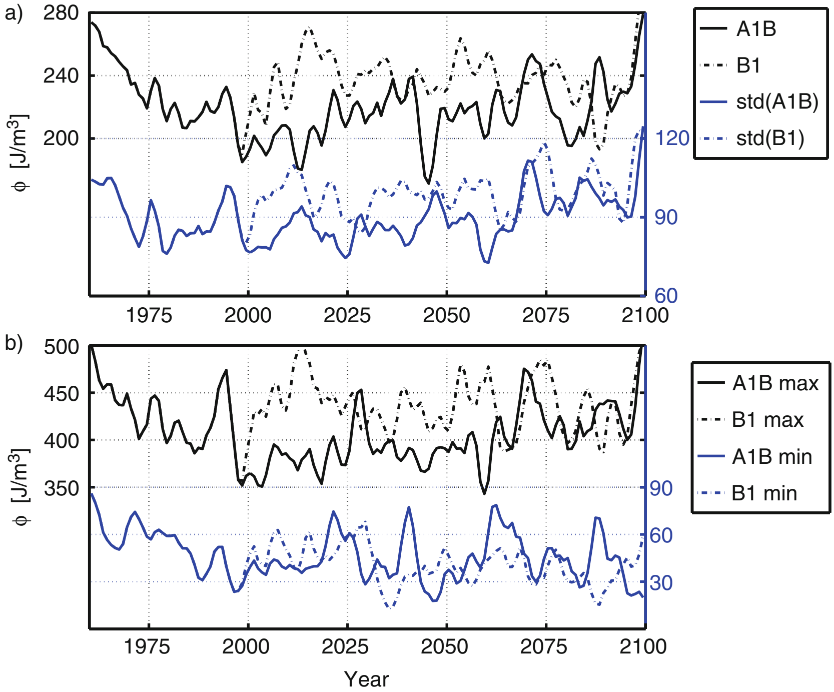

Fig. 1.8 Projected changes in potential energy anomaly in the Arkona Basin. (**a**) Annual mean and standard deviation and (**b**) annual maximum and minimum. The data are smoothed by using a 5-year running mean

1.4.6 Storm Surges

Changes in the return period and thus the occurrence of severe storm surges are of great practical interest. Depending on the return period of a 30 or 50-year surge, dykes and coastal protections will be designed. In Fig. 1.9 the projected changes for Sassnitz (Fig. 1.9a) and Wismar (Fig. 1.9b) are given. For comparison, also the return period, estimated from the observations, is shown. In this plot, the effect of sea level rise is included. For Sassnitz, there is a significant increase of surges with a return period of over 20 years. These changes hold for both scenarios. For Wismar, similar effects are visible, but not as pronounced as for Sassnitz.

To understand, if the changes in the return period are caused by the sea level rise or due to changed atmospheric conditions (Fig. 1.5), we again performed a Wilcoxon rank sum test with the tail distribution, based on the 99 percentile (Table 1.4). For the test the sea level rise was subtracted from the time series, thus all distributions have a vanishing mean. This enables us to directly compare the distribution functions. The results of this test are given in Table 1.4. The P-values indicate that due to the changed atmospheric forcing, there will be a significant change

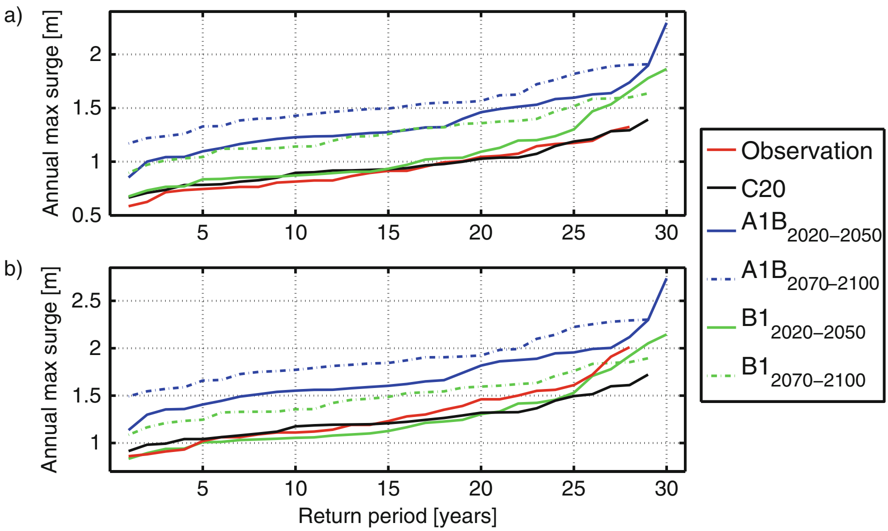

Fig. 1.9 Projected changes in return period for annual storm surge for (**a**) Sassnitz and (**b**) Wismar

Table 1.4 Statistical analysis of storm surges for the gauge stations Sassnitz and Wismar (Fig. 1.1). Given are the P-values of the Wilcoxon rank sum test for the tail distribution (sea surface elevation > 99 Percentile). The mean surface elevation is removed from all pdfs

Station	Scenario	99 Percentile (cm)	1970–2000	2020–2050	2070–2100
Sassnitz	A1B	0.56	0.37	< 0.05	< 0.05
Sassnitz	B1	0.56	0.37	< 0.05	< 0.05
Wismar	A1B	0.68	0.31	< 0.05	< 0.05
Wismar	B1	0.68	0.31	0.44	< 0.05

(at the 5% significance level) in the return period of storm surges. The only exception is Wismar in the period 2020–2050; here the changes are not significant.

To illustrate the change in sea level distribution in Fig. 1.10 the right side of the distribution is shown. To have a better visual comparison, the mean is removed. A widening of the distribution of sea level elevations is visible, to allow more extremes.

1.5 Discussion and Conclusion

In this paper, transient climate simulations, covering the period 1960–2100, were carried out using a high resolution ocean model (GETM) for the Western Baltic Sea. These simulations are based on the IPCC scenarios A1B and B1. Despite the