Chapter 3.b iv Sea level and Wind waves

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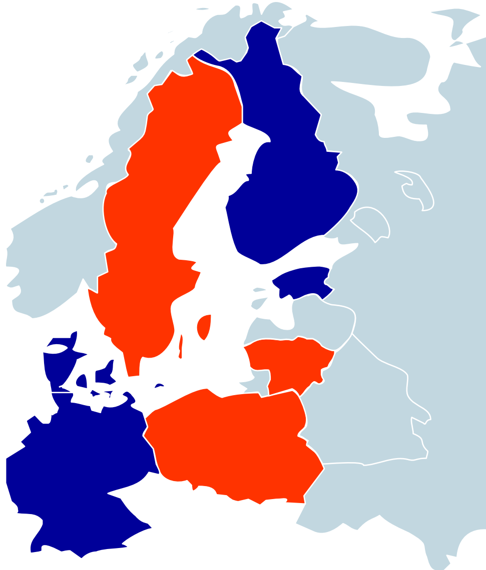

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Chapter Outline

1. **Introduction**
   Definition of Key Terms

2. **Sources of Data**
   2.1 Sea-level observations
   2.2 Wind waves –instrumental measurements and visible observations
   2.3 Dynamical Modeling Data

3. **Mean Baltic Sea-level change**
   3.1 Main factors affecting mean Baltic Sea-level change
   3.2 Baltic Sea level variability within the observational period (1800-today)

4. **Extreme Sea levels**
   4.1 Main factors affecting extreme sea levels in the Baltic Sea
   4.2 Statistics and long-term trends of extreme sea-levels

5. **Wind waves**
   5.1 Long-term wave properties
   5.2 Spatio-temporal variations

6. **Summary and Conclusion**

State of Chapter

- around 32 pages (1.5–spaced), including 15 Figures and 1 Table

- more than 160 publications assessed
  (~8 pages of references) -> (Bacc I around 50 references)

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Chapter Outline

Chapter 3.b iv Sea level and Wind waves

> 160 publications assessed

~pages	Section	Figures
	1. Introduction	
1-2	*Definition of Key Terms*	
	2. Sources of Data	
2-6	2.1 Sea-level observations	→ Fig.1 & Table 1
7-8	2.2 Wind waves –instrumental measurements and visible observations	→ Fig.2
9-10	2.3 Dynamical Modeling Data	
	3. Mean Baltic Sea-level change	BACC I: 4 Figures
10-13	3.1 Main factors affecting mean Baltic Sea-level change	→ Fig.3 - Fig.4
14-18	3.2 Baltic Sea level variability within the observational period (1800-today)	→ Fig.5 - Fig.8
	4. Extreme Sea levels	
19-21	4.1 Main factors affecting extreme sea levels in the Baltic Sea	→ Fig.9
22-23	4.2 Statistics and long-term trends of extreme sea-levels	→ Fig.10 - Fig.11
	5. Wind waves	BACC I: 3 Figures
24-27	5.1 Long-term wave properties	→ Fig.12 - Fig.13
28-32	5.2 Spatio-temporal variations	→ Fig.14 - Fig.15
	6. Summary and Conclusion	

Chapter context versus cross-items

2. Sources of Data

2.1 Sea-level observations
Tide gauges
Satellite Altimetry

2.2 Wind waves
Instrumental measurements
Visible observations

2.3 Dynamical Modelling Data
2.3.1 Sea level
2.3.2 Wind waves –regional and basin-wide simulations

→ 2.3. **Historical time frame (1000 yr) (25pp)**
Tadeusz Niedzwiedz, Silesian University, Sosnowiec, Poland

→ 3.2.1. ***Atmospheric physics*** **(15pp)**
Anna Rutgersson, Uppsala University, Sweden

→ 3.4.2. ***Sea ice*** **(15pp)**
Jari Haapala, Finnish Meteorological Institute, Helsinki,

→ 3.2.1. ***Atmospheric physics*** **(15pp)**
Anna Rutgersson, Uppsala University,

As the study of sea-level changes would not be possible without observations, one subsection will focus on the up-to-date availability of sea-level observations, including tide gauge records, and available datasets of satellite altimetry and other advanced geodetic techniques (GPS measurements). The **homogeneity** of these datasets will be briefly discussed, also in terms of **availability** due to **different data sources** (e.g. Permanent Service for Mean Sea Level, national Data Sources) and the role of absolute versus relative sea-level measurements. Also, the role of Baltic Sea level observations within the context of global mean sea-level studies will be pointed out, as the Baltic Sea is one of the world's most investigated areas in terms of long-term sea-level measurements at tide-gauges.

2. Sources of Data –sea level

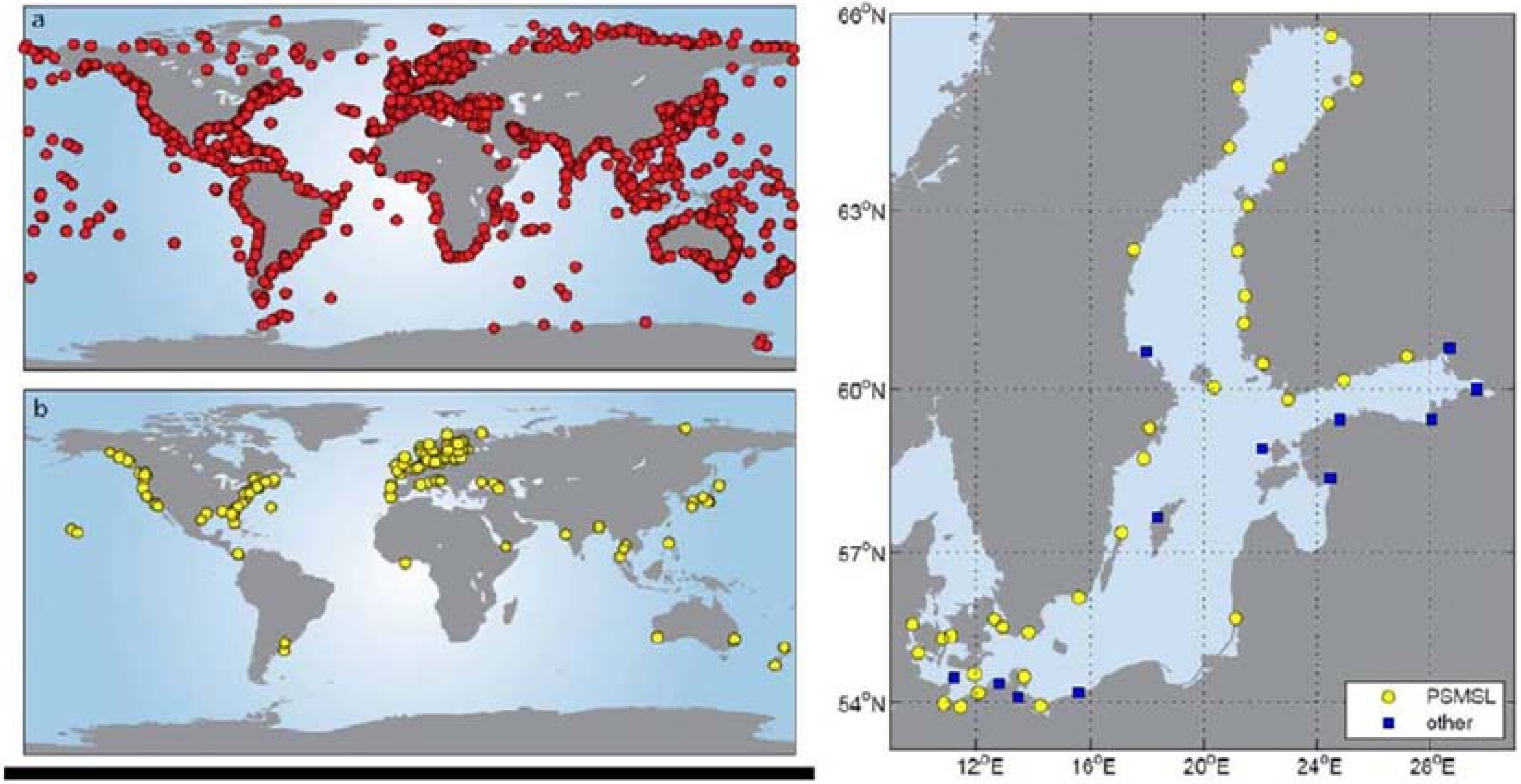


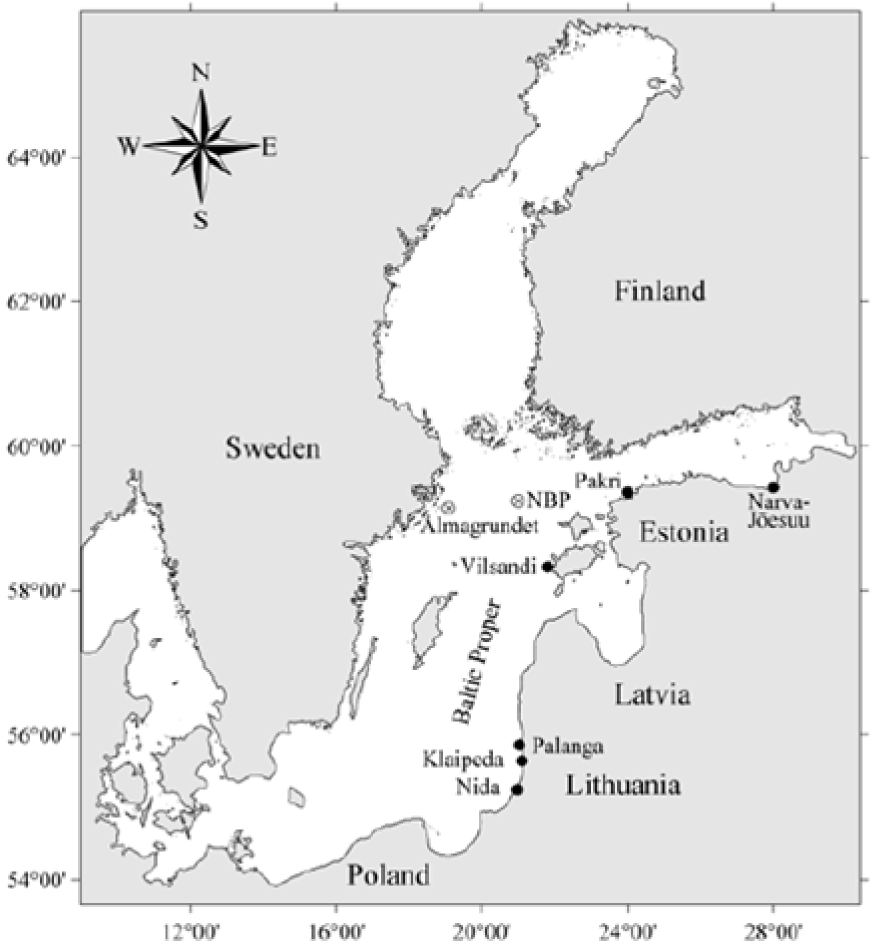
Fig.1: Globally distributed sea-level stations represented in the dataset of the Permanent Service for Mean Sea Level (PSMSL) (left panel a) and stations with long records containing more than 60 years of data (left panel b) (from Woodworth et al. 2011). Right panel: long Baltic Sea sea-level records with at least 60 years of data, respectively, continued until recent times, from PSMSL and other long Baltic sea-level datasets used in published literature (see also **Table 1**).

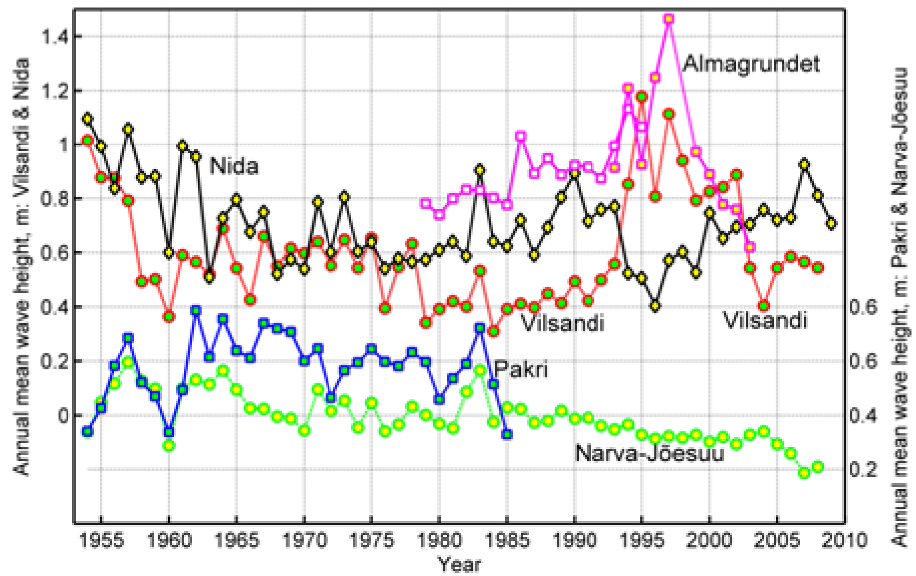
2. Sources of Data –sea level

Table 1 Sources of climatic sea-level information used in published literature (classified for the different regions of interest of the respective research papers). (need to be complemented)

Region	**References**
North Atlantic and Europe	Jevrejeva et al 2005, Barbossa et al. 2008
Baltic basin wide	Omstedt and Nyberg 1991; Heyen et al. 1996; Liebsch 1997; Carlsson 1997, 1998a, b; Janssen 2002; Baerens et al 2003; Meier et al. 2004; Novotny et al, 2006; Barbossa 2008; Hünicke and Zorita 2006, 2007, 2008; Hünicke et al. 2008; Ekman 2009 and references therein; Hünicke 2010
Southern Baltic Coast	Richter et al. 2007, 2011
Lithuania	Dailidiene et al. 2004, 2005, 2006 ; Jarmalavicius et al 2007
Russia	Bogdanov et al. 2000 ; Averkiev 2010
Estonia	Suursaar et al. 2002, 2006, Suursaar and Kullas 2006, 2009; Suursaar and Sooäär 2007; Suursaar 2010, Suursaar et al. 2010
Poland	Pruszak and Zawadzka 2005, 2008; Richter et al 2007, 2010
Germany	Liebsch 1997; Dietrich and Liebsch 2000; Liebsch et al. 2002; Jensen and Mudersbach 2004; Richter et al. 2007, 2010; Lampe et al. 2010
Denmark	Madsen et al. 2007; Knudsen et al. 2012 (?)
Sweden	Gustafsson and Andersson 2001; Kauker and Meier 2003; Omstedt et al 2004; Chen and Omstedt 2005; Hagen and Feistel 2005; Madsen et al. 2007; Hammarklint 2009; Ekman 2009 and references therein
Finland	Johansson et al. 2001, 2003, 2004;
Gulf of Bothnia	Lisitzin 1957

2. Sources of Data –wind waves





New aspects since BACC I:

-> two long-term (≥20 years) time series of instrumental wave data analysed & available

->six very long (>50 years) time series of visually observed wave data available

Fig.2: Location of long-term (> 15 years) instrumental wave measurements (⊗) and visual observations (dots) in the Baltic Sea. (NB! Darss Sill site in SW Baltic Sea will be added.)

3. Mean Baltic Sea-level change

3.1 Main factors affecting mean Baltic Sea-level change

3.1.1 global mean sea-level change

3.1.2 regional distribution of sea-level change

3.1.3 regional versus local sea-level changes

Land Movements

Meteorological Influence

3.2 Baltic Sea level variability within the observational period (1800-today)

3.2.1 Mean Baltic Sea level trends

3.2.2 Is Baltic Sea level accelerating?

→ 4.3.3. ***Sea level*** **(10pp)**

→ 3.2.1. ***Atmospheric physics*** **(15pp)**
Anna Rutgersson, Uppsala University, Sweden

→ 5.3.2. **Urban complexes (25pp)**
Sonia Deppisch, HafenCity University, Hamburg, Germany

→ 5.3.3. **Coastal erosion and coastline changes (25pp)**
NN

→ 6.2. **Global warming (25pp)**
Jonas Bhend, ETH Zürich, Switzerland; currently CSIRO, Melbourne, Australia

Following, the available knowledge of Baltic Sea level variability within the observational period (around 1800-today) will be presented with **focus on mean observed sea-level trends**. Relative sea-level trends will be mapped for the whole Baltic Sea area and the outcome of relative versus absolute sea-level changes of the different available studies will be discussed. **As the relative values are the important ones for regional impact studies, absolute values allow for a comparison with global mean sea-level values.** The question of **accelerating Baltic sea-level rise** will also be discussed. Finally, a closer look at uncertainties and caveats due to several reasons (e.g. different national height and measurement systems, different used data sources), and also due to different applied statistical methods to analyse the datasets will be presented. This is also necessary to understand the uncertainties of a global mean sea-level value in relation to a regional value.

Sea level and NAO –BACC II

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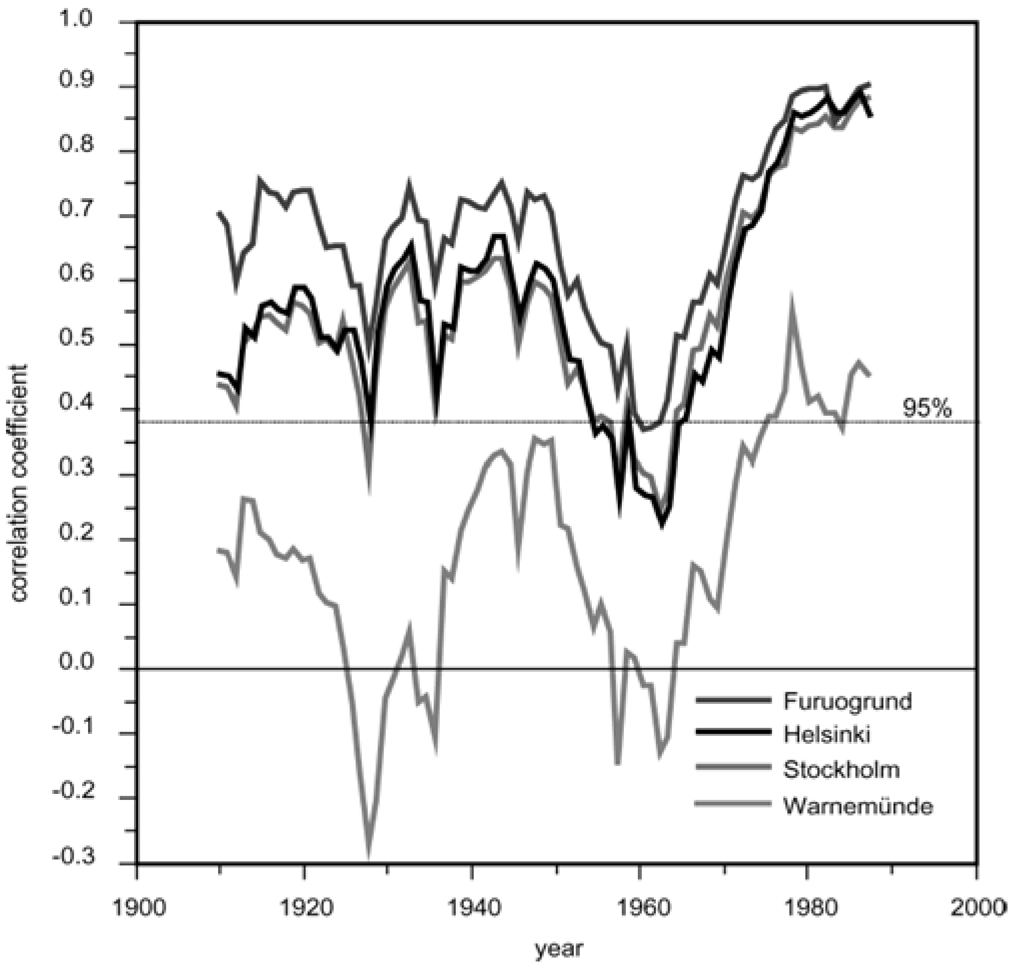
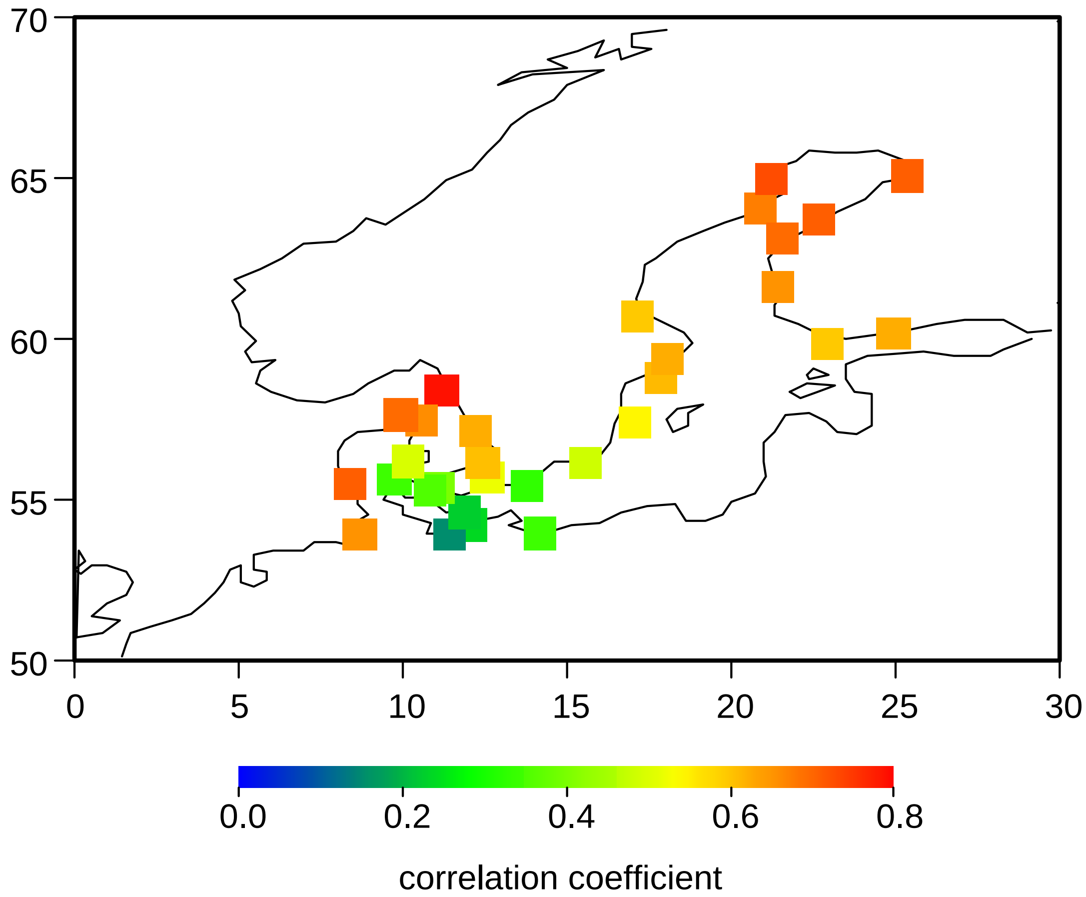


Fig. 3. Moving correlation (21-year window) between winter (DJF) mean Baltic Sea level and the winter NAO index for four selected



Correlation between the winter mean (DJF) of the NAO index and the winter mean (linearly detrended) Baltic Sea level, 1900 to 1998.

Sea level and NAO –BACC II versus BACC I

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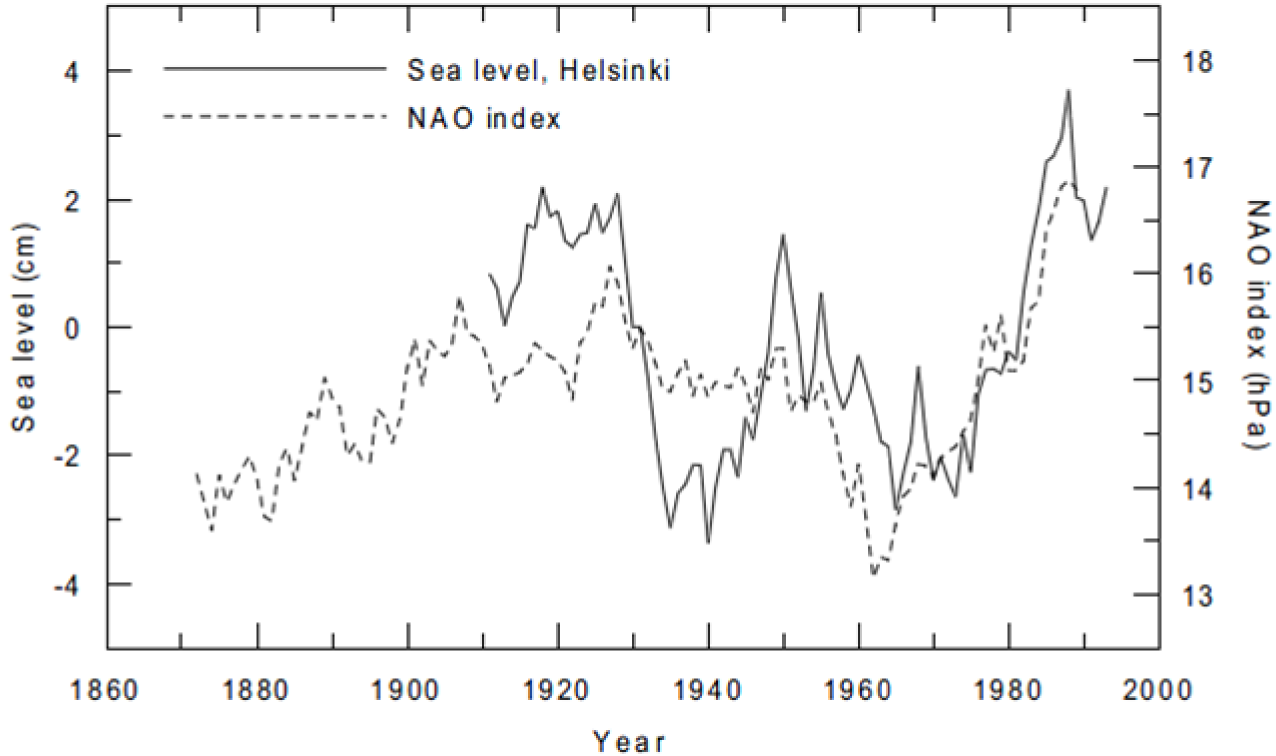


Fig. 2.57. De-trended annual mean sea level at Helsinki and the annual mean NAO index, 15-year running averages (from Johansson et al. 2001)

3. Mean Baltic Sea-level Change

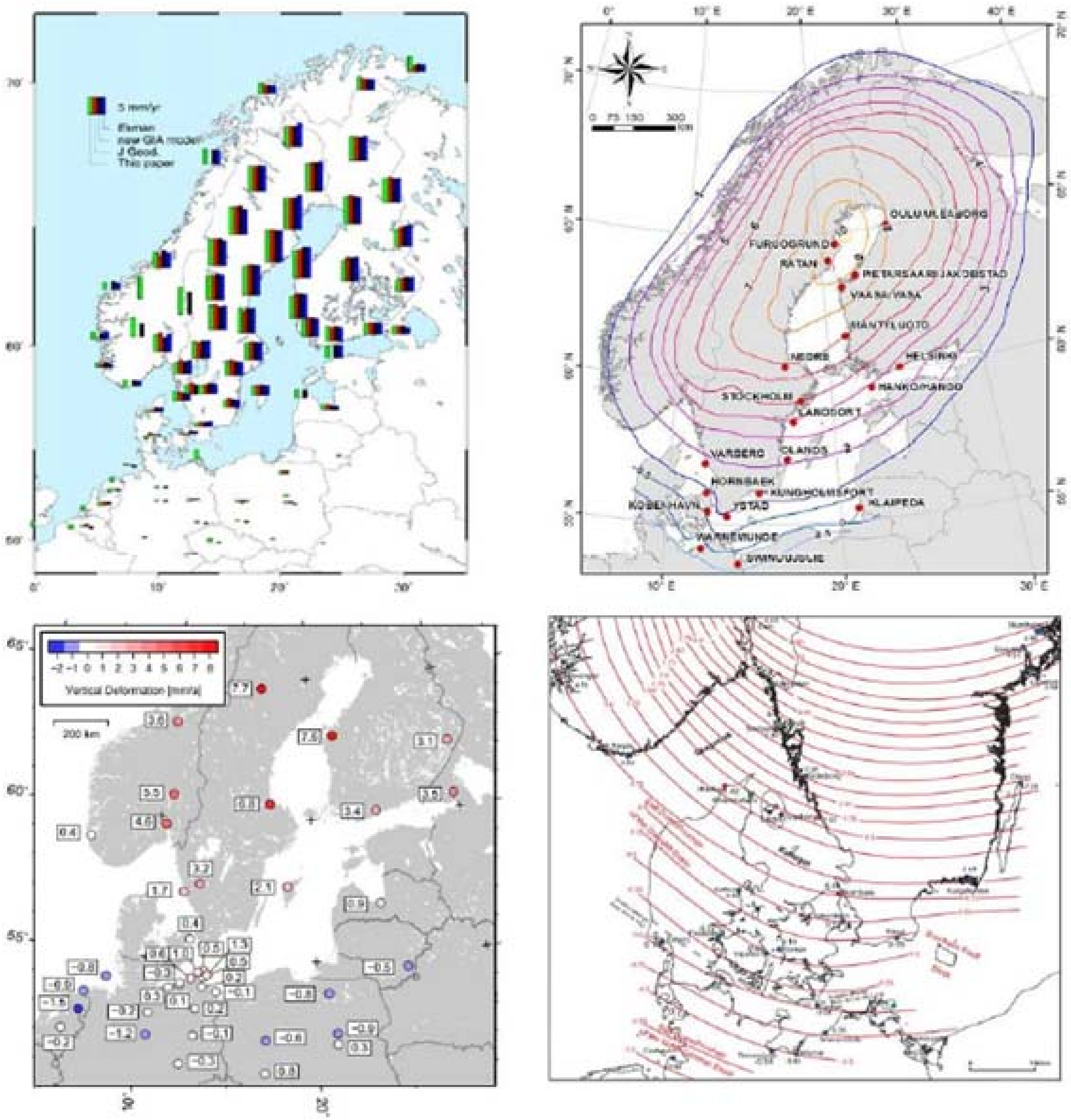


Fig. 3: Estimation of vertical velocities (for tide gauge correction) derived by different methods (from Harff et al. 2010, Richter et al. 2011, Lidberg et al 2010, Hanssen et al. 2011) (Figure capture need to be complemented)

Land Movement

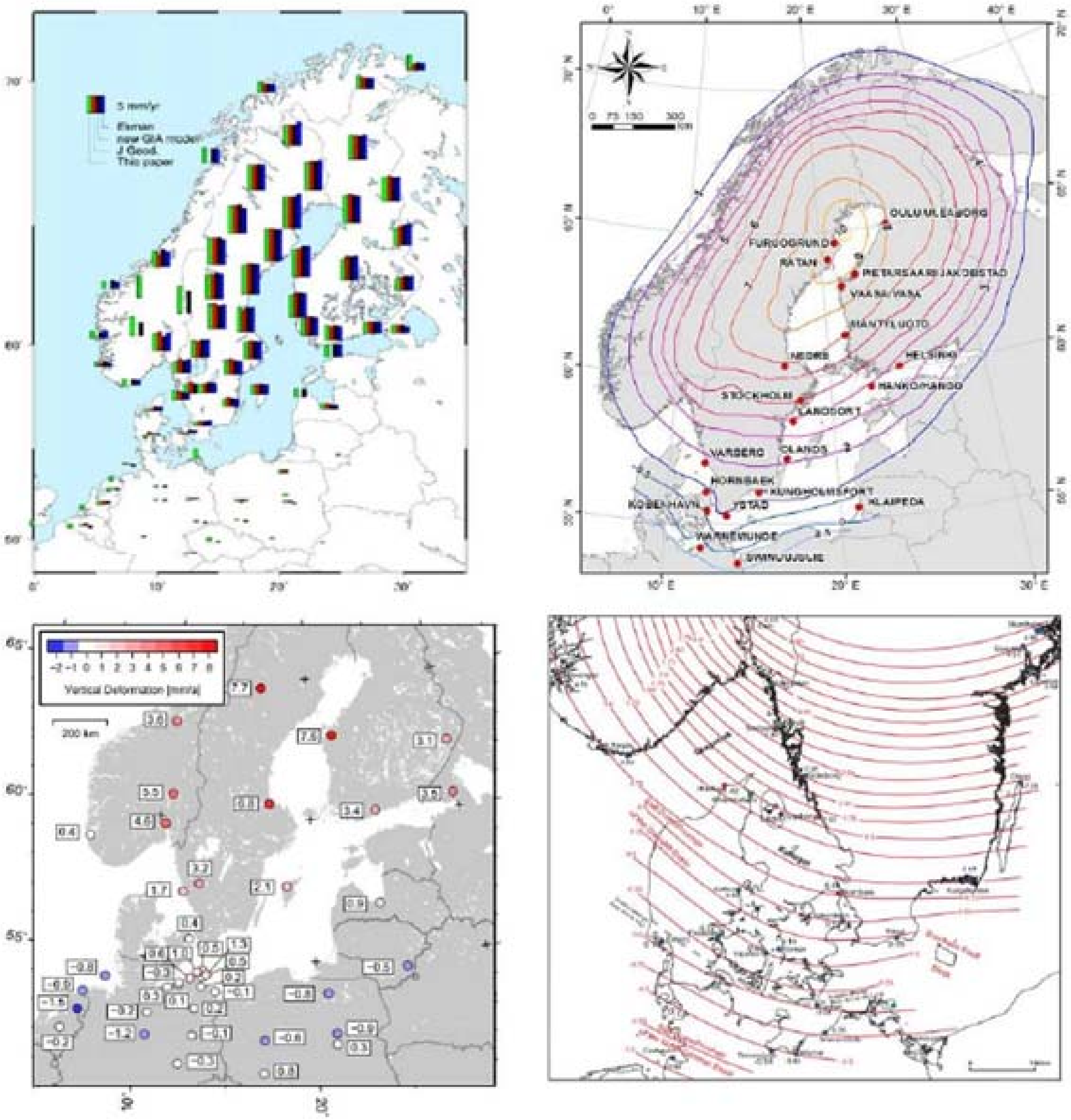
A non-climatic driver of change

-> discussion of different methods to derive land-movement values (absolute and relative to land)

(ice load models, GPS measures etc)

-> information necessary to calculate absolute sea-level change values(which allow for comparison with global mean sea-level change values)

3. Mean Baltic Sea-level Change



Land Movement

The values provided in assessed studies range from **1.3 mm/yr** between 1908 and 2007 for southern Baltic Sea stations (Richter et al. 2011) and between 1891 and 1990 for the Baltic Sea and Scandinavian coast (Vestøl 2006) to **1.8 mm/yr** between 1900 and 2000 for Danish stations (Knudsen and Vognsen, 2010). When the uncertainty of the above studies is taken into account, they are all within the error bars of the global average of 1.7 ± 0.5 mm/yr presented in the IPCC AR4 (Bindoff et al. 2007).

Fig. 3: Estimation of vertical velocities (for tide gauge correction) derived by different methods (from Harff et al. 2010, Richter et al. 2011, Lidberg et al 2010, Hanssen et al. 2011) (Figure capture need to be complemented)

3. Mean Baltic Sea-level trends (tide-gauges)

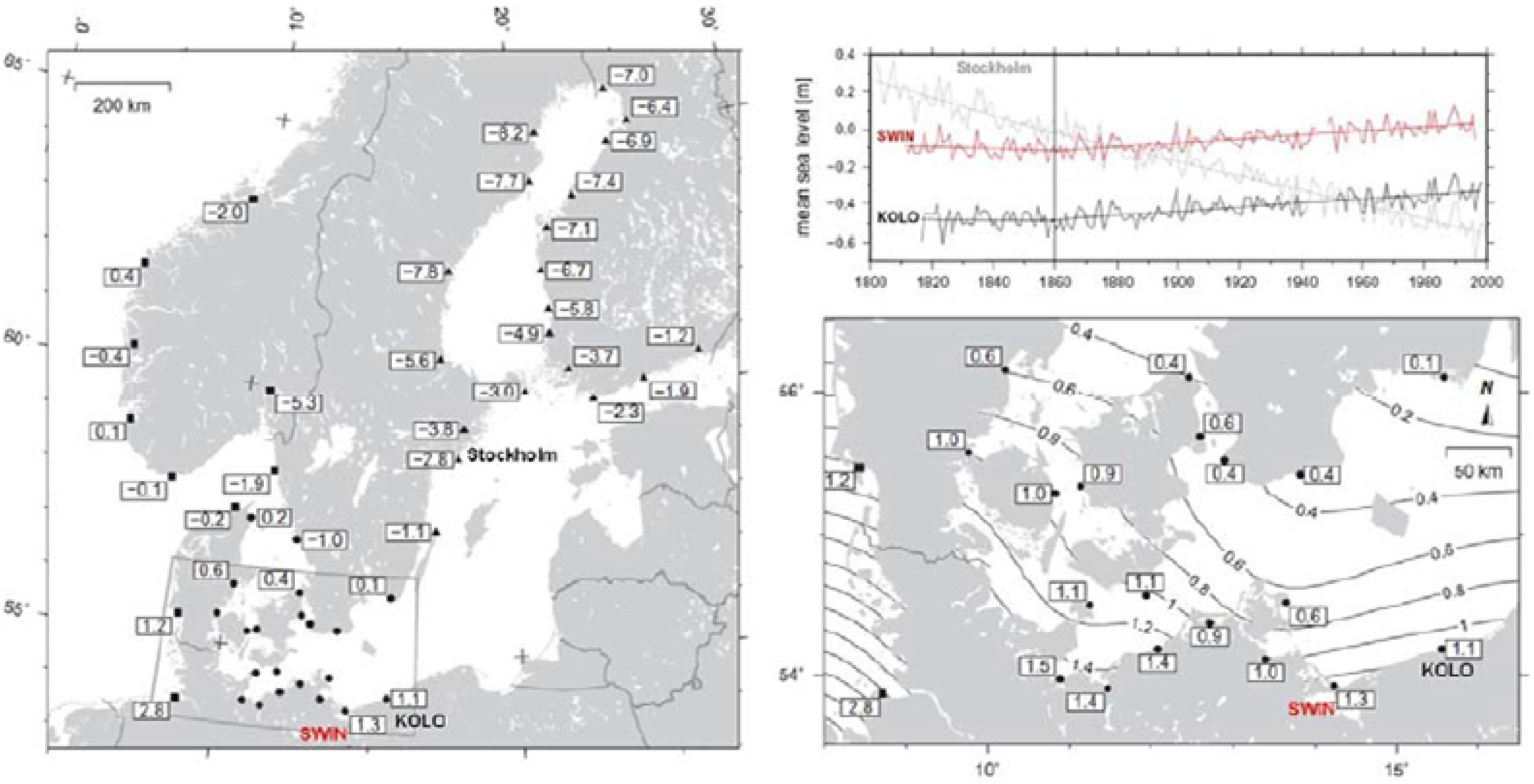
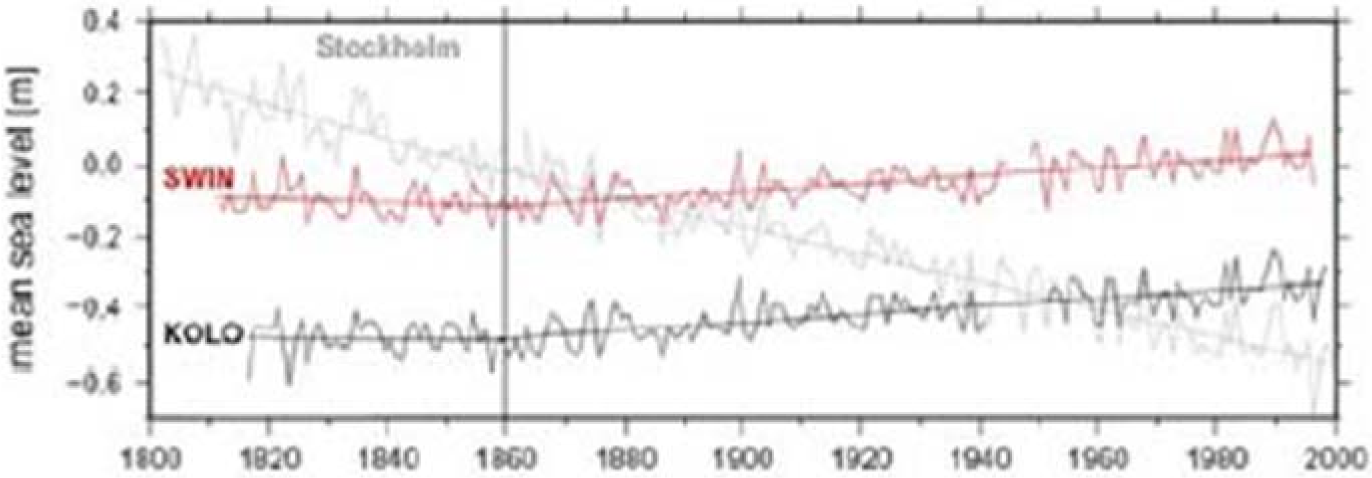


Fig.4: Maps of secular (100 years) relative sea-level changes, based on tide gauge measurements of the entire Baltic Sea Region (left panel) and, in more detail, the Southern Baltic Coast (right panel below) together with the changes in linear trend of the (arbitrarily shifted) annual relative sea-levels at Stockholm, Swinoujscie (SWIN) and Kolobrzeg (KOL) between the period before and since 1860. The symbols represent the affilation to different reference stations (dots: Warnemünde, triangles: Stockholm, squares Smögen) (from Richter et al. 2011).

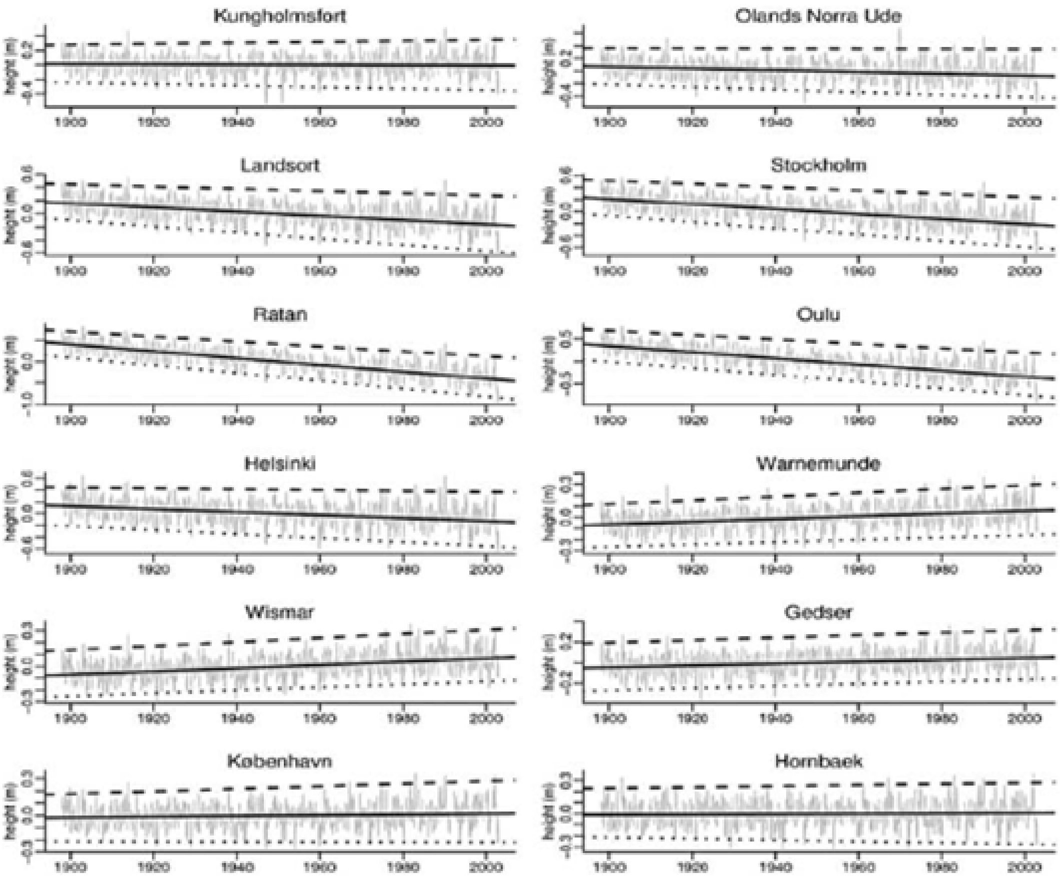
In the **northern part**, stations are characterised by **large negative relative sea-level trends with a maximum of 8.2 mm/year in the Gulf of Bothnia**, which coincides with the area of predicted maximum GIA-induced crustal uplift (e.g. Peltier 2004). Interestingly, tide gauge measurements along the **Southern Baltic coast yield positive rates hovering at 1mm/year**, which implies a rising sea level relative to the Earth's crust. However, the **pattern over the Southern region is not uniform** (**Fig.3** right panel), **displaying a clear gradient in north-easterly direction**.

Mean Baltic Sea-level trends (tide-gauges)



Swinoujscie and Kolobrzeg: both time-series **show consistent behaviour with a slightly negative trend throughout the first decades until 1860, followed by an increasing trend of around 1mm/year.** The authors suggest, as possible explanation for this trend, the climatic effects related to the **Little Ice Age**, according to what was **stated before by Ekman** (2009 and references therein), who found a **trend of 1.01mm/a for the Stockholm** time-series. However, it has to be borne in mind that due to decadal variations in the relative sea-level trend, a **comparable determination of secular relative sea-level changes at different stations requires the application of identical observation periods (Richter et al. 2011) and analyses techniques.**

Long-term trends of relative Baltic Sea level



estimated the trends in the **median sea-level but also trends in the quantile of the distributions of monthly mean sea-level** in different gauges along the Baltic Sea coast.

The trends clearly exhibit the **effect of isostasy**, but **interestingly the trends in the median sea-level do not always coincide with the trends in the extreme high and low quantiles.** Whereas the low quantiles of the distributions show basically the same trend as the median, the upper quantiles tend to display a more positive trend, **indicating that the higher values of relative sea-levels are increasing more rapidly, or decreasing more slowly in the regions with isostatic uplift.** This happens more markedly in the Northern Baltic Sea and has been also **confirmed by more locally-focused studies on Estonian sea-level** (Suursaar and Kullas 2006). The reasons for this different behaviour are not clear, and many factors like the atmospheric circulation

Fig.5: Time series of 3 quantiles (median, and the 1% and 99% quantiles) of the distribution of de-seasonalized monthly sea-level in several stations of the Baltic Sea in the period 1890-2010 (from Barbossa 2008).

Mean sea level trends –BACC II versus BACC I

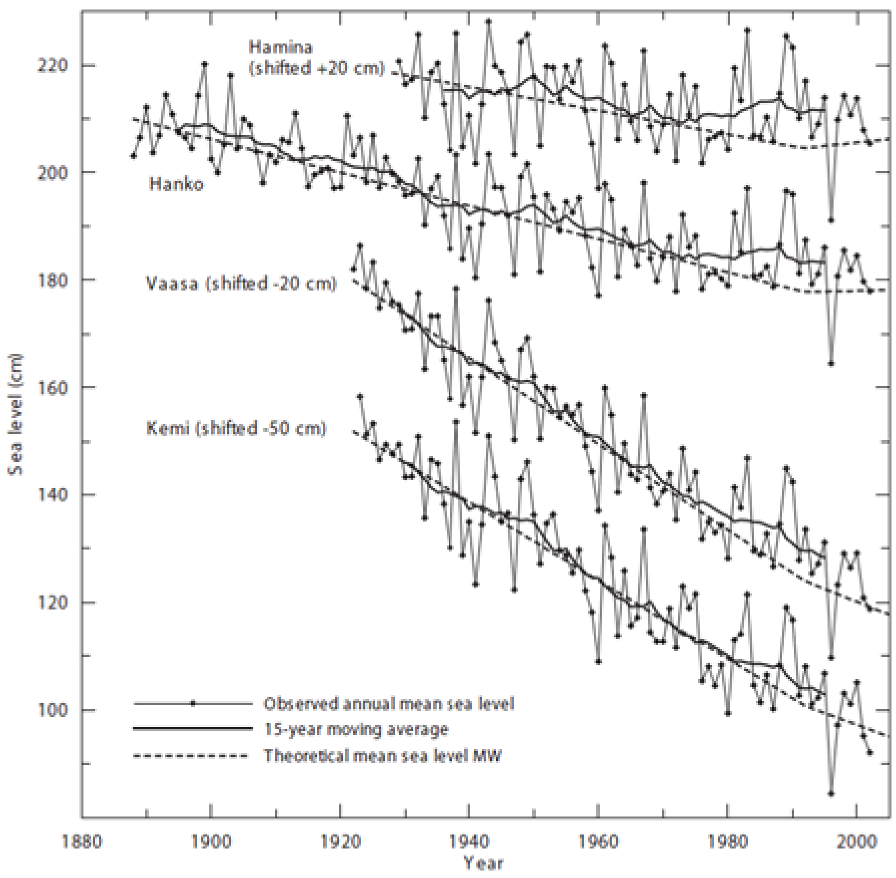


Fig. 2.56. Observed annual mean sea level and the 15-year moving averages at selected Finnish tide gauges (from Johansson et al. 2004). Hamina and Hanko are located at the eastern and western, respectively, Gulf of Finland, Vaasa and Kemi at the southern and northern Gulf of Bothnia, respectively

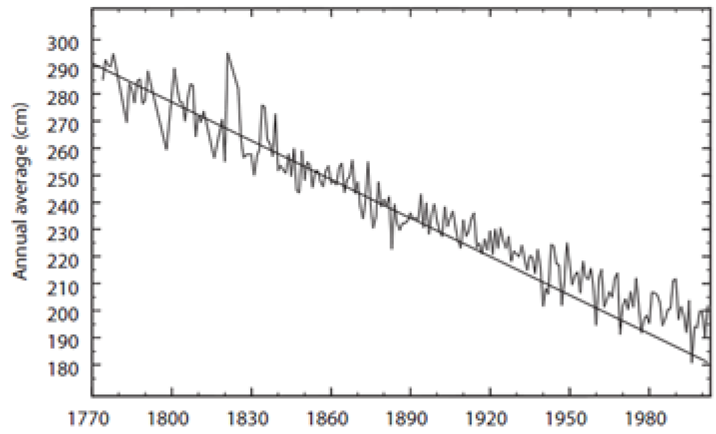


Fig. 2.54. The sea level in Stockholm 1774–2002. The linear trend is computed for 1774–1884 and extrapolated to 2002. Reproduced from Ekman (1999), recomputed and extended

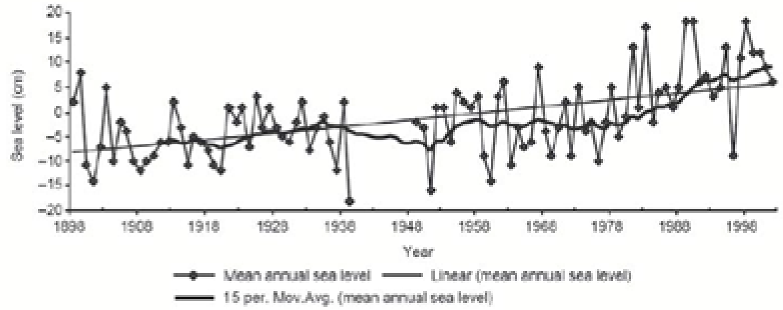


Fig. 2.55. The annual mean water level and the 15-year moving averages in Klaipeda (Dailidiene et al. 2004)

Decadal variations around the quasi-linear long-term trend

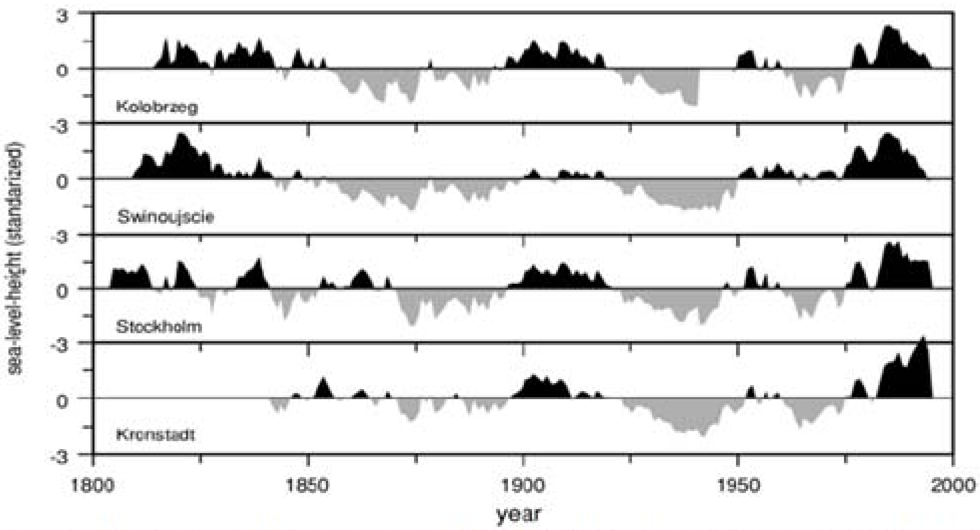


Fig.6: Long records of monthly mean sea-level in the Baltic Sea, after the long-term linear trend has been removed, and the series smoothed by a 11-year running mean to highlight the decadal variations. (from Hünicke et al. 2008)

wintertime mean decadal variations in the last 200 years in 5 stations in the Baltic Sea presented by Hünicke et al. (2008)

Ignoring the isostatic trend, in general Baltic Sea level displays **higher values around 1820, 1910 and in the recent decade**, and lower values around 1875, 1940 and 1970. However, it has to be borne in mind that the **homogeneity of the data may be compromised at the beginning of the record**. Since the **decadal variations are not completely coherent through time**, the precise mechanisms responsible for them have not been completely ascertained. These decadal variations may have been caused mainly by the atmospheric circulation, but also by precipitation and variations in the ocean currents

The question of acceleration

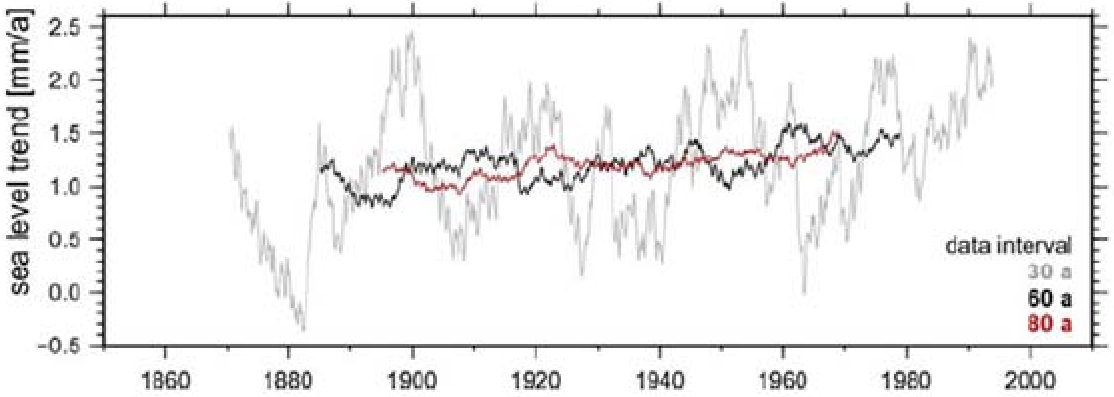


Fig.7 Linear trends calculated in sliding windows of fixed length for the annual sea-level record in Warnemünde (Germany). The three series show the results for different window lengths (from Richter et al. 2011).

-> different possible approaches to the *definition of 'acceleration‘* ->different interpretation of results

(determination of a linear sea-level rate in sliding windows of fixed length, for instance 30 or 50 years. If the linear rate in the last windows in the record is the highest, it can be claimed that the present rate of increase would be unprecedented. However, due to decadal variations in the rate of change, the linear rate in the last window may not be the highest in absolute value and yet the series of linear trends in sliding windows may itself display a long-term trend. In this case, this different definition of 'acceleration' would claim that there exists acceleration)

->only one study so far has explicatively targeted the changes in Baltic sea-level linear rates through time (Richter et al., 2011)

-> depending on which definition of acceleration adopted, the same record may be considered, or not, to show acceleration.

-> figure will be extended for other long sea-level records…

Mean Baltic Sea-level Change (Satellite data)

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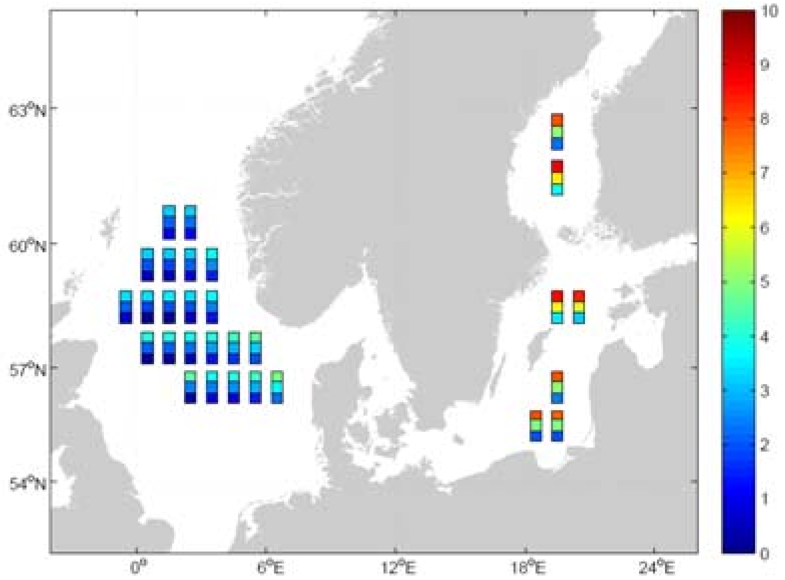
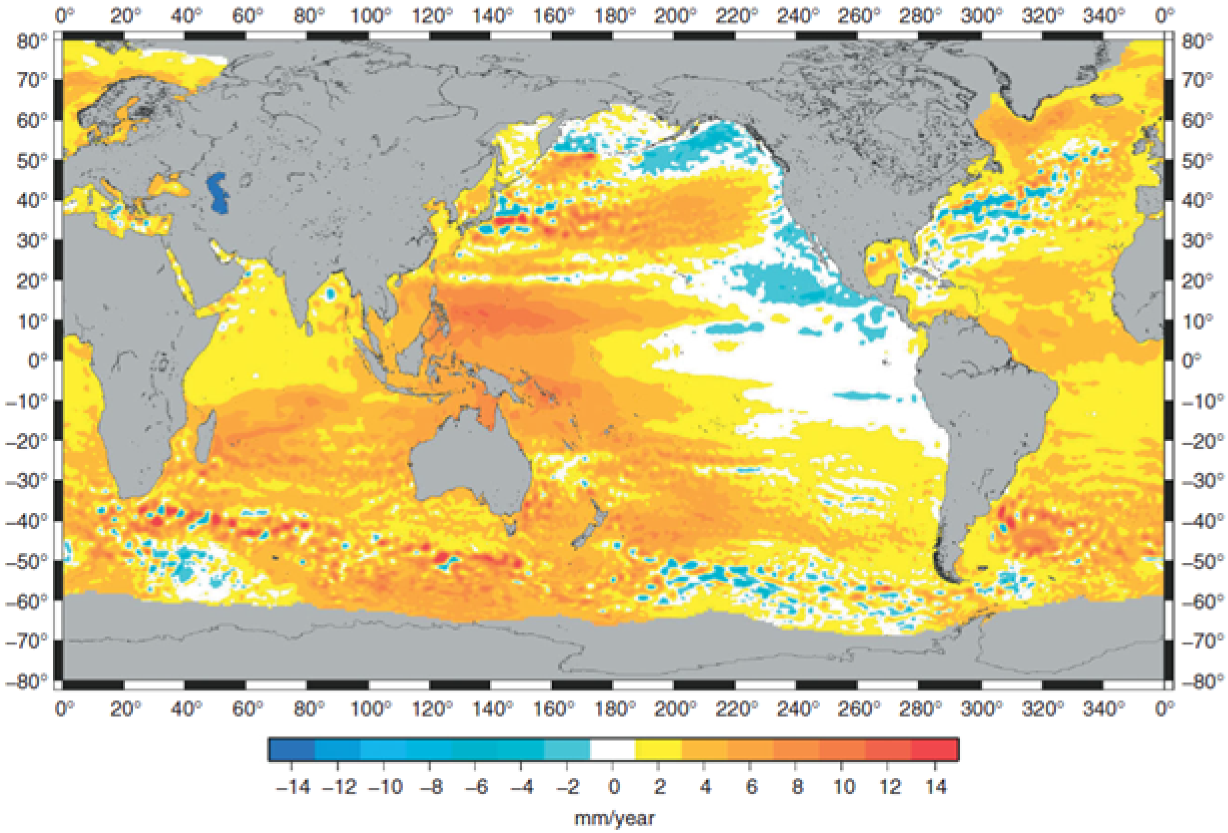


4: Linear trend in sea surface height (mm/year, center boxes) and 90% confidenc and lower boxes) as calculated from satellite altimetry.



4. Extreme Sea levels

4.1 Main factors affecting extreme sea levels in the Baltic Sea

4.2 Statistics and long-term trends of extreme sea-levels

→ 4.3.4. ***Marine physical changes (incl. sea ice, storm surges and waves)*** **(20pp)**

Physical factors for extreme sea-level events in the Baltic Sea will be briefly discussed, including the travel of meteorologically forced positive-negative surge zones along the Baltic Sea, components and typical courses of (local) storm surges and the development of minimum sea-level events (negative surges). Statistics and long-term trends of extreme sea-level will be discussed based on the available literature, focusing on return periods and return values and long-term variations in annual extremes and their connections with storm climatology. A short overview of prominent events will be given and storm surge prone areas in the Baltic Sea will be named. A map of a collection of observed historical water level maxima in the Baltic Sea will be compiled. Finally, results out of hydrodynamic modelling approaches will be compared and discussed.

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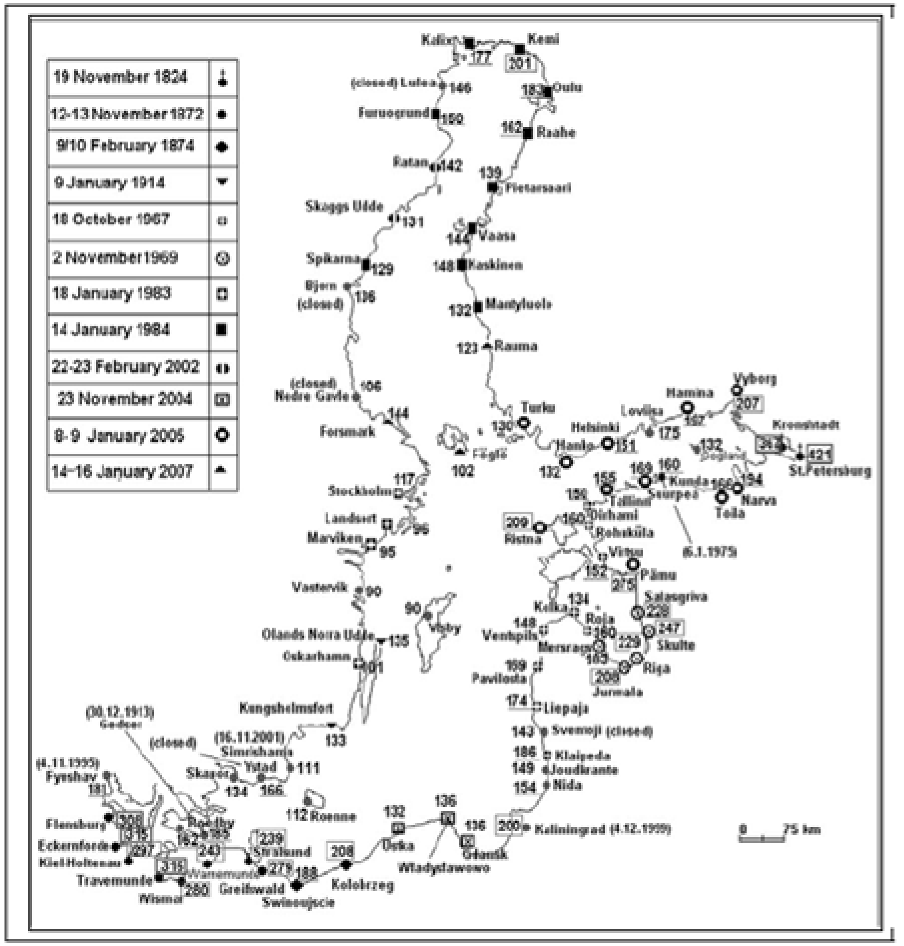

Fig.8: Historical water level maxima (cm) in the Baltic Sea. Data are given in the national water levelling systems, (from Averkiev and Klevannyy 2010)

The Figure needs to be modified by selecting less station. (Many stations in the original figure are not representative due to short duration of use of poles).

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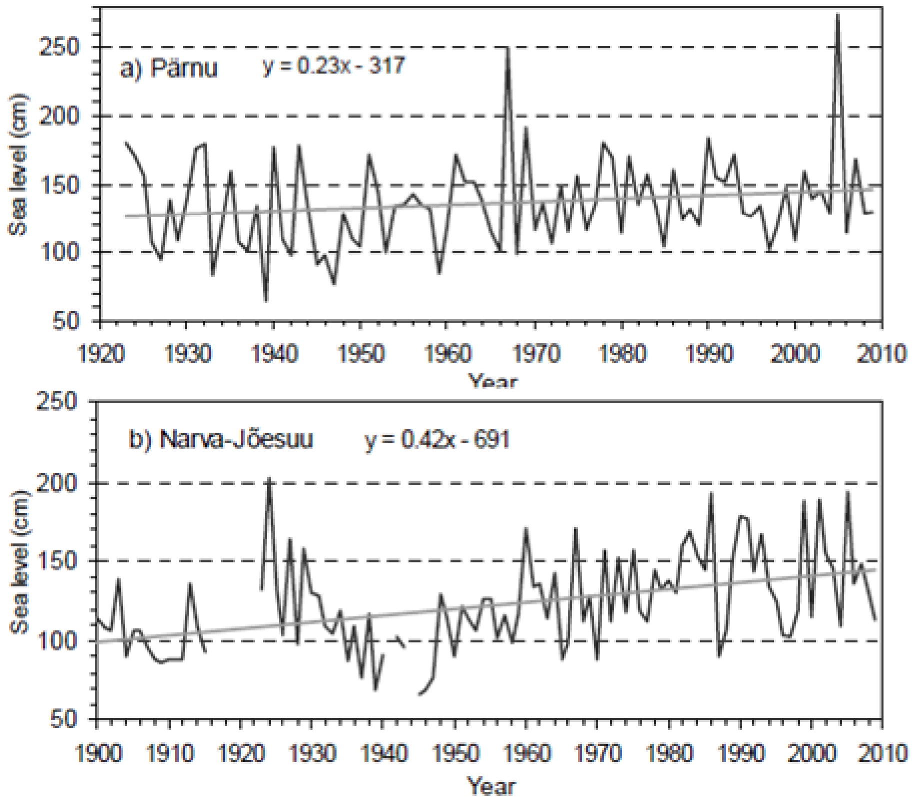

Fig.9: Decadal variations in annual maximum sea levels at Pärnu (a) and Narva-Jõesuu (b) together with linear trendlines (from: Suursaar and Kullas 2009b; Suursaar 2010).

5. Wind waves

→ 4.3.4. ***Marine physical changes (incl. sea ice, storm surges and waves)*** **(20pp)**

5.1 Long-term wave properties

5.2 Spatio-temporal variations

5.2.1 Reflections of changes to wind properties →

5.2.2 Variations at different scales

5.2.3 Spatial patterns of variations

3.2.1. ***Atmospheric physics*** **(15pp)**
Anna Rutgersson, Uppsala University, Sweden

Sources of wind wave climatologies will be discussed with focus on visual observations and instrumental measurements, regional and basic-wide simulations as well as long-term wave properties (including average and extreme heights, occurrence distributions, height-period combinations). A map will be compiled showing all up-to-date available long-term wave observations (visual and instrumental). Spatial-temporal patterns of variations will be described by focusing on inter-annual to (multi)-decadal changes and spatial patterns of variations. Consequences to safety, coastal evolution and ice cover length will be briefly issued.

→ 5.3.2. **Urban complexes (25pp)**
Sonia Deppisch, HafenCity University, Hamburg, Germany

5.3.3. **Coastal erosion and coastline changes (25pp)**
NN

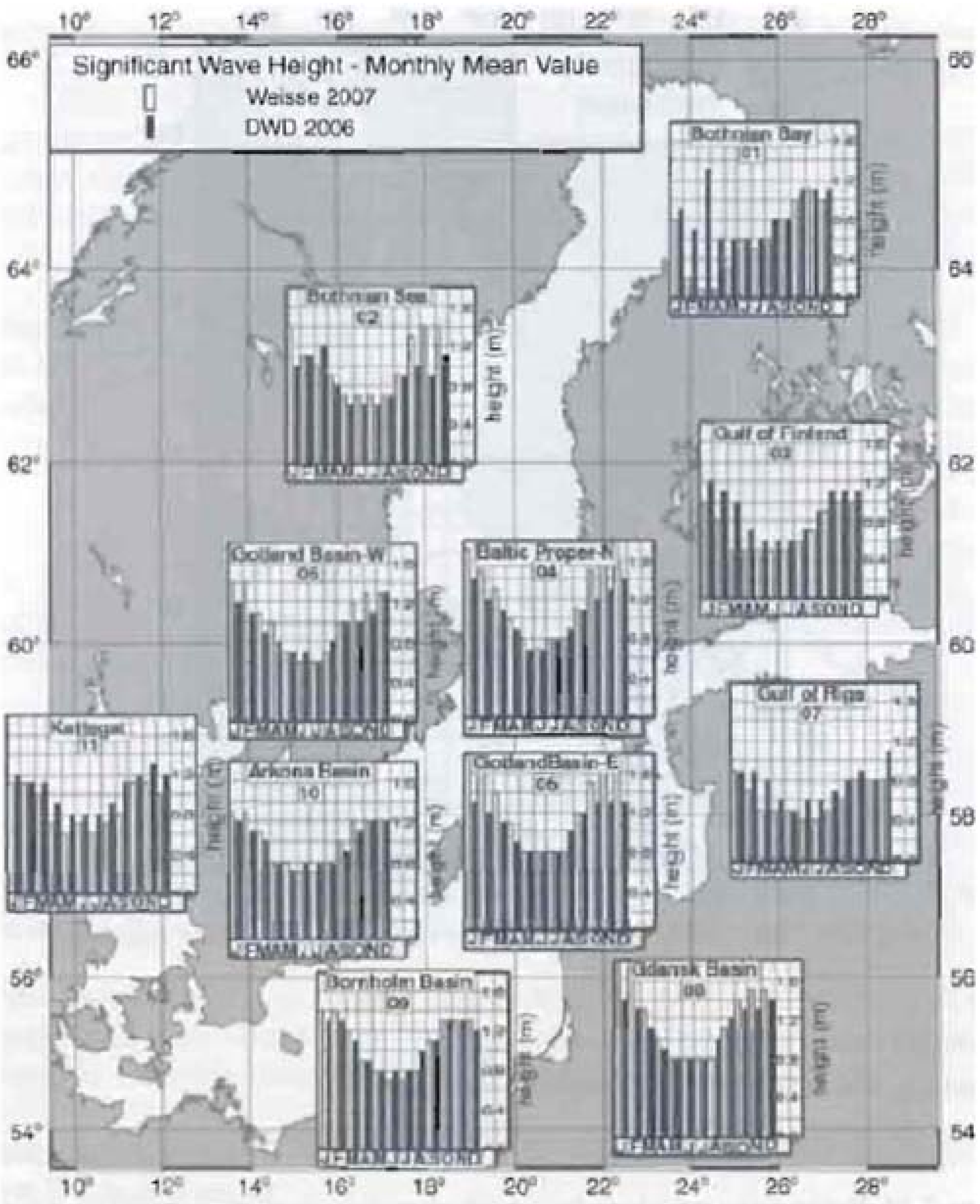

FIGURE 7.17 Monthly means of significant wave heights.

Figure XX. Monthly mean significant wave heights at selected points of the Baltic Sea based on numerical simulations and DWD observations. (Figure 7.17 from Schmager et al. 2008; perhaps amended by adding the Darss Sill and Almagrundet measured data)

In summary, the analyses of wind waves show **no significant changes in the average wave activity of the entire Baltic Sea basin**. However, there exist extensive **spatial patterns of changes**, possible leading to long-term variations in the areas with the largest wave intensity. Regional studies at **selected areas show different trend averages and extreme wave conditions caused by systematic changes in the wind direction**. Substantial a-periodic changes in the wave activity could be detected on a regional to local scale, e.g. with a peak in wave heights in the northern Baltic Proper around 1990

5. Wind waves

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The properties of waves in a particular region and storm events substantially depend on the match of the geometry of the particular sea area and the wind pattern of the storm.

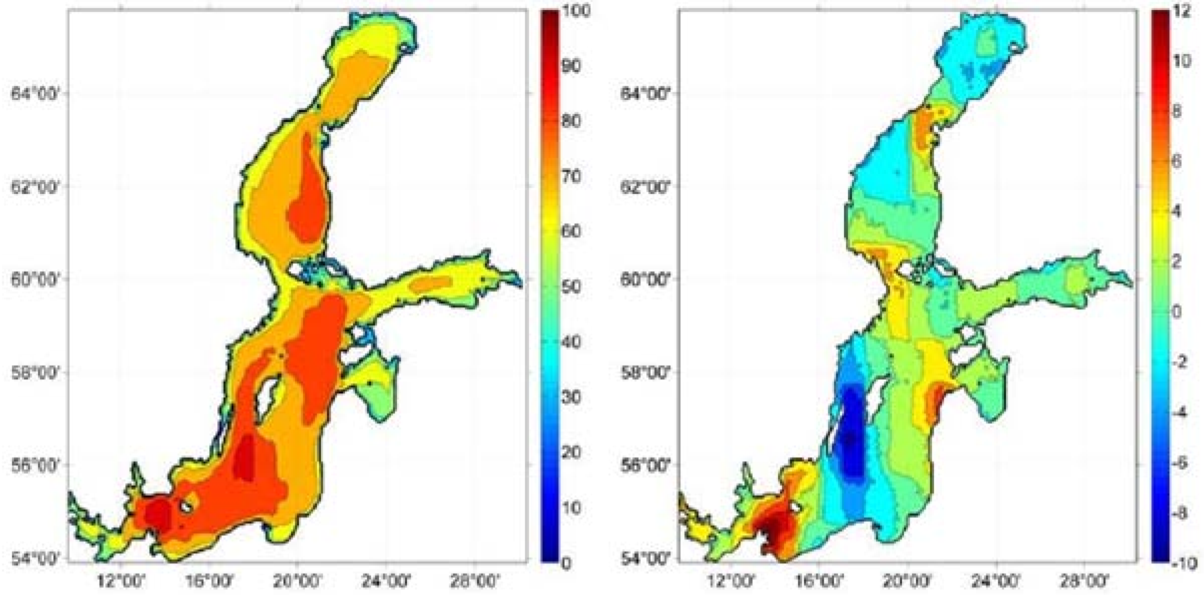

Fig.13: (left) Numerically simulated average significant wave height (colour bar, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 (from Räämet and Soomere 2010); (right) Long-term changes in the annual average significant wave height (cm, based on the linear trend, isolines plotted after each 2 cm) for 1970–2007 (Soomere and Räämet 2011).

The typical long-term significant wave heights are about 1 m in the offshore of the Baltic Proper (Broman et al. 2006; Tuomi et al. 2011), **0.6–0.8 m in the open parts of its larger sub-basins such as the Gulf of Finland** (Soomere et al. 2011 FAH) or Arkona Basin (Soomere et al. 2011b), **and well below 0.5 m in relatively large but semi-sheltered bays such as Tallinn Bay** (Soomere 2005, Kelpšaite et al. 2009). **These values are by 10–20% lower in the nearshore regions** (Suursaar and Kullas 2009a, 2009b; Suursaar 2010). **The most frequent wave heights are also about 20% lower than the long-term average wave height.**

5. Wind waves

BACC II versus BACC I

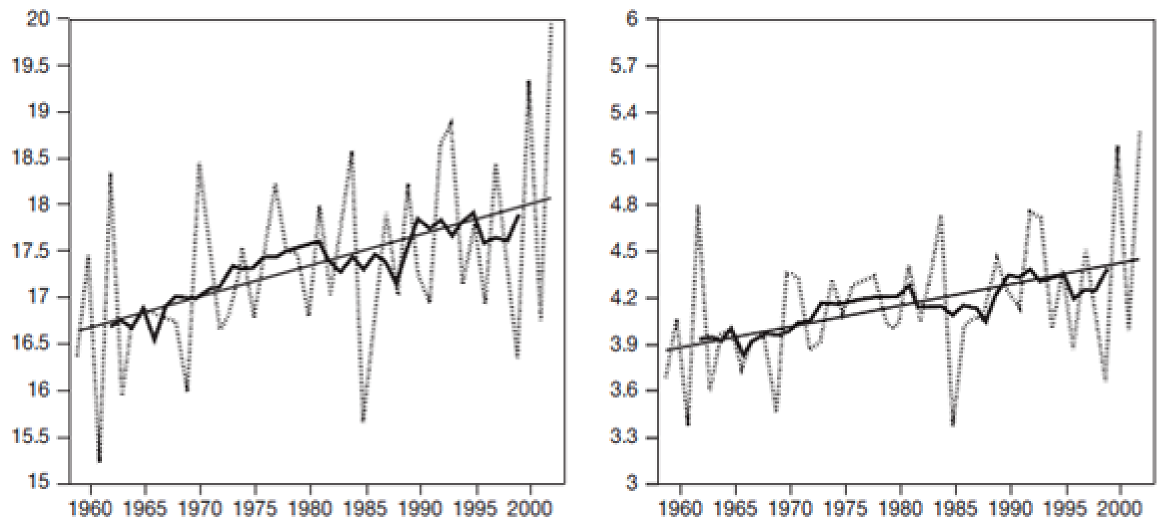

Fig. 2.64. Hindcast annual 99 percentile (*dashed*) wind speed (*left*) and significant wave height (*right*) for a representative model grid point in the Baltic proper (58° N, 20° E). The solid lines represent the 9-year running mean and the liner trend 1958–2002 (from Augustin 2005)

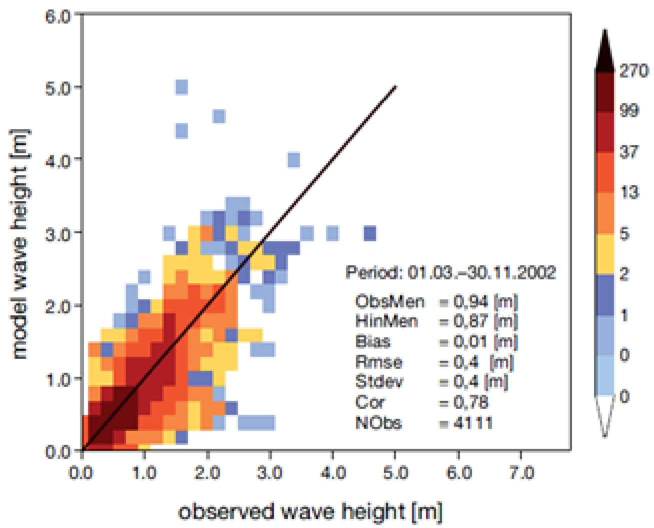

Fig. 2.63. Scatterplot showing observed (*x-axis*) and hindcast (*y-axis*) significant wave height (in meter) near Arkona for March to November 2002. Colors indicate the number of observed and model values. The total number of pairs is 4111. Some error statistics are provided in the upper left corner (from Augustin 2005)