3. Recent (mainly 200 years) and current climate change
3.4. Baltic Sea

3.4.3 Sea level and wind waves

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1. Introduction

The sea-surface height is nowadays a very important indicator of climate variability and long-term changes. The understanding of the processes which drive future climatic trends of the sea-surface height on global to regional scales presumes the understanding of the multi-year to decadal (long-term) variability in the observational period. This requires an accurate assessment of past and recent global and regional changes of the sea surface height, including changes in mean and extreme sea-levels and wind generated waves. Here, we address possible evidence for sea-surface height changes in the observational period (mainly the last two decades) and the main known causes. We introduce the datasets which are nowadays available for the study of sea-level and wind waves and review the major published research findings which can be derived from it for the Baltic Sea region. (…)

Definition of Key Terms

Mean sea-level is here defined as an average height of the sea surface, neglecting short-term effects of tides and surges, but including extreme sea-level variations. In addition, on a shorter timescale, as impacts of storm phenomena, changes in direction and strength of wind generated waves at the sea surface and storm surges may play a major role in the context of future climate changes. Thus, variations in the height of the sea surface (thereafter defined more generalized as *sea level*) can be regarded as interactions of tides, surges and changes in the mean sea-level and, in addition, *wind waves*, ranging widely over space and time.

Both, surges and wind waves, cause sea surface height variations over short timescales due to changes in winds and atmospheric pressure differences on the sea surface. However, both effects should not be confounded, since they display different spectra, and cover different space and time scales. For the purpose of climate change assessment, the most relevant timescales are of inter-annual to decadal nature.

The changes in mean Baltic Sea level can be seen as the sum of global, regional and local effects. There exist several definitions of key terms for the understanding of these effects in the literature. Thus, a clear definition of these key terms is of high relevance.

Hereafter, the *global mean sea level* (GMSL) is defined as relative or absolute sea level (long-term average of ocean-surface height) at a given time, averaged over the global ocean. Changes in *local sea level* (LSL) are defined as changes in sea level at a specific locality. We use the term *eustatic sea level* for describing changes in the global mean sea-level due mainly to the contribution of mass exchanges between land ice and oceans. A smaller contribution is caused by water reservoirs for economic purposes. In addition, the effect of mass redistributions on gravity and ocean floor heights as a result of water mass exchange between land ice and oceans is named as *symphonic*.

Absolute sea-level (ASL) is defined here as the height of the sea (ocean) surface at a given location relative to a geocentric reference such as the reference ellipsoid and is measured by satellite altimetry. It is also referred to as *sea-surface height* (SSH) in the literature. On the other hand, *relative sea level* (RSL) is defined as the height of the ocean surface relative to the sea floor (relative to land) at a given location and is measured using tide gauges (or sea-level reconstructions using information from the geological record). RSL is the most important value for impact studies.

Here, the general term *sea level* is used to describe the height of the ocean surface involving both –relative and absolute sea level. Changes in the *mean sea-level* are defined as a long-term average height of the sea surface, neglecting short-term effects (as of tides and surges). According to Woodworth et al 2011, mean sea-level is defined as the average of sea-level time-series into annual mean values.

2. Sources of data

2.1 Sea-level observations

Tide gauges

The most direct measurement of sea level rise of the last century is from tide gauges. Globally, the coverage of sea-level data from tide gauges is limited temporally and geographically. There exist much more tide gauge data from the Northern Hemisphere and for the second half of the twentieth century (**Fig.1** left panel, Woodworth et al 2011). The long tradition for high quality oceanographic observations of the Baltic Sea is reflected in the dense network of tide gauge stations along the Baltic coastline. Many of the available sea-level time-series can be obtained through the web page of the Permanent Service for Mean Sea level (PSMSL), which collects monthly and annual mean sea level measurements from around the world. These data are freely available online (Woodworth and Player 2003, www.psmsl.org). In the archives, stations with a full history of reference levels (benchmark datum history) have had their data adjusted to a fixed, revised local reference (RLR). Although the RLR data are screened for over time relative to a reference benchmarks on the nearby land, corrections for the movement of the benchmarks themselves are not applied. However, the PSMSL RLR records are the most common source of data for global and regional studies of historic sea level rise.

In addition to the PSMSL data, historical sea-level time-series are available from different sources e.g. for Stockholm/Sweden (1774-2000; Ekman 2003) Kronstadt/ Russia (1816-1999; Bogdanov et al. 2000), Travemünde/Germany (since 1826; Jenssen and Töppe 1986) but also from diverse national institutions. As stated by the PSMSL; the exclusion of these datasets from the PSMSL database can stem from different reasons: "either because the data is not available in the monthly or annual mean format used by the PSMSL or because is not true Mean Sea Level". However, the presence of a number of published papers (e.g. Andersson 2002, Omstedt et al 2004, Chen and Omstedt 2005, Jervejeva et al 2006), besides the original literature, which used some of these long historical time-series for analyses should, stand for a verification of the data quality (Hünicke et al. 2008).

The Stockholm time series belongs to the world's oldest sea-level records (Ekman 2003; see also Woodworth 1999 for comparison with other world´s oldest sea-level records). The Baltic Sea is one of the most investigated sea-level sites of the world with a remarkable number of long and high quality sea-level records and more than 45 stations with at least 60 years of data continued until recent times. From this data set, 34 of the stations are included in the PSMSL RLR archive. However, significant differences seem to exist in the datasets, depending on the data source (Dimke and Fröhle 2009).

Today, existent historical sea-level documents are still distributed over various archives of national authorities of the Baltic Sea countries. For example, for the German Southern Baltic Coast Richter et al. (2007) found six different archives of different national state authorities. These records are often incomplete, and lack important additional information and a systematically cataloguing. There is still a huge amount of historical sea-level documents which is not available to sea-level researchers due to missing homogeneous digital time-series.

To produce homogeneous data sets out of these historical documents (written on paper) requires much effort, considerinng not only the various sources of uncertainties e.g. due to different measurement techniques and - sampling frequencies (e.g. Ekman 2010, Richter et al 2007) but also the changes on the reference points or geodynamic and anthropogenic (technological) changes in the region (e.g. Bogdanov et al. 2000).

Nowadays, the tide gauge operation, the processing, distribution and archiving of the data lies under the responsibility of one main national agency per country, for instance the meteorological and hydrological Institutes (MHI) as the SMHI in Sweden, the EMHI in Estonia, the FMHI in Finland or the Wasser- und Schifffahrtsamt (WSA) in Germany. No basin wide freely accessible network exists which would combine all available long sea-level records from tide gauges. However, long Baltic sea-level records from different sources (and not only PSMSL) have been used in a wide range of research papers on global (e.g. Douglas 1992, Nakada and Inoue 2005, Jevrejeva et al. 2006, 2008, Merrifield and Merrifield 2009, Woodworth et al. 2009, Houston and Dean 2011, Church and White 2011) and regional sea level studies (**Table 1). Figure 1** (right panel) shows long Baltic Sea sea-level records with at least 60 years of data, continued until recent times, from PSMSL together with other long Baltic sea-level datasets used in published literature.

For some applications, e.g. the study of extremes and storm surges, higher frequency data (than monthly average data) is needed. Some high frequency data is available from the PSMSL and the University of Hawaii Sea level Center (UHSLC, http://ilikai.soest.hawaii.edu/). However, most of it is in national archives and historical data are generally only available through the national agencies that are responsible for collecting the data. Real-time observations are available through the Baltic Operational Oceanographic System (BOOS, www.boos.org).

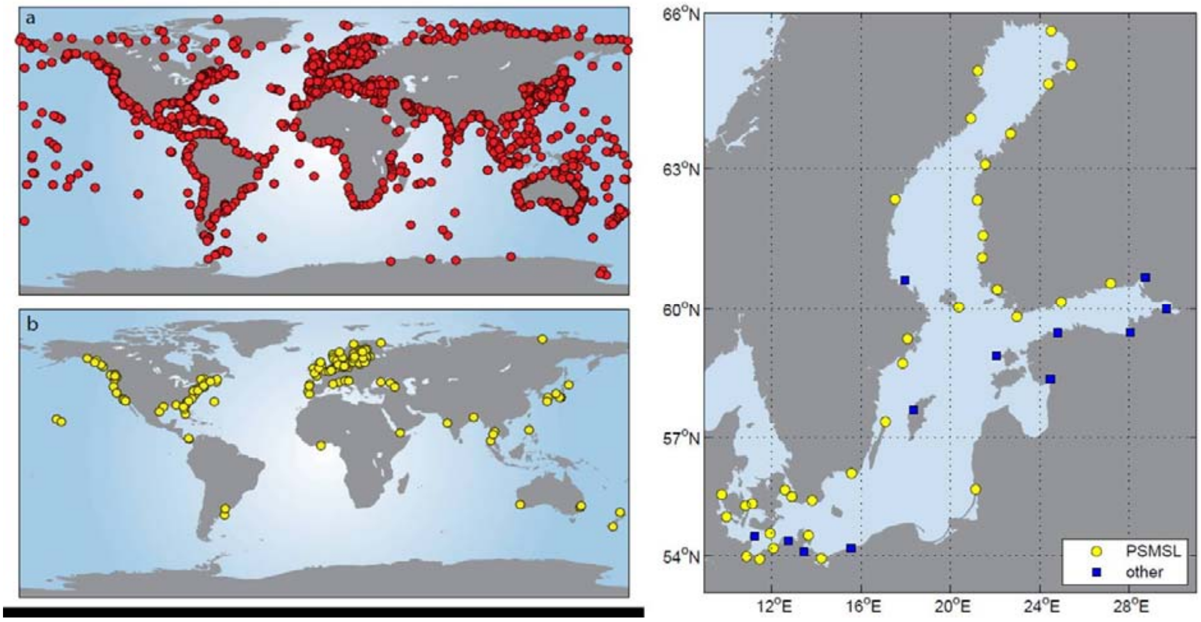

Fig.1: Globally distributed sea-level stations represented in the dataset of the Permanent Service for Mean Sea Level (PSMSL) (left panel a) and stations with long records containing more than 60 years of data (left panel b) (from Woodworth et al. 2011). Right panel: long Baltic Sea sea-level records 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**).

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

Tide-gauge-derived SSH records are based on local observations of relative sea-level, presenting the position of sea level with respect to land. Thus, these data include not only changes in absolute sea level but also the vertical crustal movements, which can be of different origin and can take various forms. In the Baltic Sea Region, the most evident phenomenon is the long-term and more or less constant changes of the earth crust caused by Glacial Isostatic Adjustment (GIA, rebound from the last Ice Age) (e.g. Milne et al, 2001). On timescales up to 200 years, the trend caused by GIA can be assumed to be approximately linear (e.g. Hünicke and Zorita 2006). However, other effects which can lead to a contamination of tide gauge-derived SSH records by vertical movement can be short-term, e.g. due to earthquakes (e.g., see Talbot and Slunga 1989) or varying in time over periods of years and decades e.g. due to sinking of piers because of unstable foundations or sinkage of land through groundwater pumping etc. These uncertainties have to be taken into account by the analysis of tide gauge data.

Satellite altimetry

The use of satellite radar altimeters to measure global sea-surface height (SSH) began in 1978 with a measurement accuracy of tens of metres. More recent high quality satellite altimeter missions such as TOPEX/Poseidon, launched 1992 and Jason-1 (launched 2001), satellites which were specifically designed to measure SSH, are able to provide a space-time point accuracy of a few centimetres. Thus, since 1992, satellite altimetry is an independent source of sea surface height measurements of the open ocean, allowing for more accurate estimates of globally averaged and regional sea-level change (Cazenave et al 2008). The development of satellite radar altimetry techniques, complemented in 2002 by satellite temporal gravity, made precise quasi-global and near-continuous measurements of SSH available for the study of sea-level variability and change (Woodworth et al 2011) and has been used extensively to map recent years' global sea level changes, verifying the suggestion (derived by the analysis of tide gauge records) that sea-level change is not spatially uniform (e.g. Cazenave and Lovell 2010). (…)

Satellite altimeter holdings are usually available as 'along track' datasets (with a time-series of heights at a number of latitude grid points for each satellite pass) or as 'gridded' datasets (mapped and gridded on a 1°*1° resolution). The spatial coverage of these monthly datasets is limited on both Earth tide poles due to technical caveats (65°S to 65°N). (Reference) Combined satellite datasets are freely available from different sources[1], with or without inverse barometer correction, seasonal (annual +semi-annual) signal removed or GIA correction. While the application of these corrections is often necessary for the study of mean global sea-level, it has to be treated with great care for regional purposes. For instance, the comparison of tide gauge data with data derived from satellite altimetry in the Baltic Sea Region requires either a correction of tide gauge data for the GIA effect or the use of satellite data uncorrected for the GIA. Therefore the application of these corrections strongly depends on the research question. At present (2011), there are only some studies for the Baltic Sea Region available in the literature which analyses satellite datasets, together with tide gauge readings (e.g. Liebsch et al. 2002, Novotny et al 2005, Madsen et al. 2007, Hünicke and Zorita 2011 (…)

There are two other factors to be aware of when using satellite altimetry products. First, the raw altimetric measurements are corrected for various effects before they can be used, and some of these corrections are not valid in the near-coastal zone, typically 50 km from any coast or island (Madsen et al. 2007). The most important of these corrections is the wet tropospheric correction (Obligis et al. 2011). Second, the gridded altimetry products are interpolated in space and time, and across missing data. Thus, interpolating should only be done with great care in the coastal zone, where the variability in space and time is much larger than in the open ocean. Some products include many of these interpolated data, while other products mask out areas permanently which may have periods with valid measurements, for instance in case of seasonal ice cover. Along-track data with customizable processing are available from the RADS database (Naeije et al. 2008, rads.tudelft.nl), but further studies may facilitate the use of coastal altimetry in the Baltic Sea and interlock the satellite altimetry and tide gauge measurements.

Another important feature of the satellite era is the application of Global Positioning Systems (GPS) to measure continuously the rates of vertical land movements (stated thereafter also as station velocities). Before the satellite era, sea level changes could only be assessed relative to a point on land (for example Ekman (1996) uses a zero point in Amsterdam). Permanent GPS observations ongoing since the 1990s have now accumulated for a sufficiently long time series to allow the determination of the isostatic uplift with accuracy from 0.4 mm/yr (Vestøl 2006) and 0.5 mm/yr (Lidberg et al. 2007) to 1.4-2.2 mm/yr (Richter et al. 2011) (add information from Lidberg 2010). Such GPS measurements are collected in the BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and Tectonics) and EUREF (EUREF, 2011/online/) networks as well as by the Satellite Positioning Service of the German State Survey (SAPOS), giving a good coverage in Germany, Denmark, Sweden and Finland, while the coverage in other countries around the Baltic is limited (Lidberg et al. 2007; Knudsen and Vognsen 2010; Richter et al. 2011). The BIFROST network started in 1993 and is composed of the permanent GPS network SWEPOS (SWEPOS^{TM}, SWEPOS,

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[1] e.g. www.aviso.oceanobs.com, sealevel.colorado.edu, www.cmar.csiro.au/sealevel,

2011/online/) in Sweden and FinnRef (FinnRef®, FGI, 2011/online/) in Finland. There exist also a GPS station network in Norway (SATREF®, SATREF, 2009/online/). A combined study of GPS stations relevant for the GIA process in Fennoscandia was presented by Lidberg et al. (2010) within the BIFROST project.

2.2 Wind waves –instrumental measurements and visible observations

Instrumental measurements

Long-term instrumentally measured wave data are available only at three sites and give quite a fragmented picture of the wave patterns (**Fig. 2**). The longest instrumental measurements have been performed using upward-looking echo-sounders at Almagrundet (1977–2003) (Broman et al. 2006). A directional wave-rider is active at Darss Sill since 1991 (Soomere et al. 2011) and in the northern Baltic Proper in ice-free time since 1996 (Kahma et al. 2003; Tuomi et al. 2011). Among those only the data from Almagrundet and Darss Sill allow to draw conclusions about changes of the wave climate. Numerous relatively short-term wave measurement sites around Finland in the 1980s and 1990s are briefly described in (Soomere 2008).

Visual observations

The outcome of historical wave observations from ships and results of semi-empirical hindcasts has been formulated in several generations of wave atlases for the Baltic Sea (Rzheplinsky 1965; Lopatukhin et al. 2006a) and its sub-basins (Rzheplinsky and Brekhovskikh 1967). The differences in some properties of the wave climate from these sources reflect the development of generic understanding about the open sea wave fields and their hindcast rather than changes to the Baltic Sea waves.

Visual observations from the eastern Baltic Sea coast, currently available for 6 sites from Lithuania up to the eastern Gulf of Finland (**Fig. 2**), cover a much longer time interval (since 1954 partially up to present). Differently from ship-based wave observations that are consistent with the instrumental records (Gulev and Hasse, 1998; Gulev et al. 2003) and have been extensively used for estimates of wave climate changes (Gulev and Hasse 1999; Gulev et al. 2003), visual wave observations from coastal sites have been less frequently used for wave climate studies.

On one hand, such data pose intrinsic quality and interpretation problems, have a poor temporal resolution, contain a large fraction of subjectivity and a substantial level of noise (Zaitseva-Pärnaste et al. 2009) and only conditionally characterise the open sea wave fields (Soomere 2005). On the other hand, they have exceptional temporal coverage: regular observations, started in the mid-1950s at many locations on the eastern coast of the Baltic Sea, have been carried out using a unified procedure until today (Zaitseva-Pärnaste et al. 2011). As they characterise the north-eastern (downwind) parts of the Baltic Sea, they form an extremely valuable data set for the identification of changes in the local wave climate.

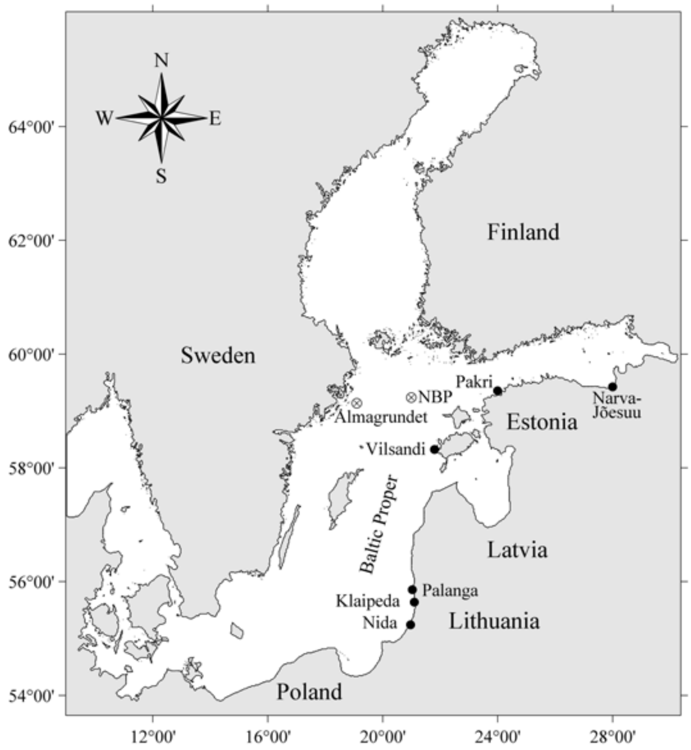

Fig.2: Location of long-term (> 15 years) instrumental wave measurements (⊗) and visual observations (dots) in the Baltic Sea. (NB! Darss Sill site in SW Baltic Sea will be added.)

Wave observations are usually performed 2–3 times a day in a >4 m deep area located about 200–400 m from the waterline using perspectometers and/or buoys or bottom-fixed structures to better characterise the wave properties. Data from Lithuanian sites (Palanga, Klaipeda, Nida) (Kelpšaite et al. 2008; 2011; Zaitseva-Pärnaste et al. 2011) characterise wave fields in the SE Baltic Sea. The Vilsandi data set (Soomere and Zaitseva 2007) reflects wave fields in the northern Baltic Proper (nBP). The observation conditions were particularly good at Pakri: the observer was located on the top of a 20 m high cliff and the water depth of the area over which the waves were observed was 8–11 m. Pakri data (Zaitseva-Pärnaste et al. 2009) mirror waves at the entrance to the Gulf of Finland and the Narva-Jõesuu data (Räämet and Soomere 2010a; Räämet et al. 2010; Soomere et al. 2011) characterizes wave properties in the eastern part of the Gulf of Finland.

All the listed sites only conditionally represent the open sea wave conditions. The sheltering effect of the shoreline and the relatively small water depth may at times significantly alter the local wave properties. The potential distortions obviously affect the results of single observations but apparently do not significantly alter the qualitative features of the overall wave statistics and evidently do not impact on the nature of long-term variations and trends in wave properties. The visually observed wave height matches the numerically simulated significant wave height well (Räämet and Soomere 2010a), whereas the estimated wave period is a few tenths of a second shorter than the peak period (Gulev and Hasse, 1998, 1999). In order to remove the bias caused by a systematically larger number of observations per day during relatively calm spring and summer seasons on the Estonian coasts, the analysis of the wave data is based on the set of daily mean wave heights.

2.3 Dynamical Modelling Data

2.3.1 Sea level

Still need to be written (including a review of the following literature: Carlsson 1997, 1998a, b; Janssen 2002; Suursaar et al. 2002, 2006; Meier et al. 2004; Novotny et al. 2006 (to be continued).

3.3.2 Wind Waves -Regional and basic-wide simulations

The observational data sets are complemented by long-term numerical hindcasts, both regional and basin-wide, of wave fields. Several attempts to numerically reconstruct the Baltic Sea wave climate have been undertaken for many areas of the Baltic Sea (Soomere and Räämet 2011). Many of these cover either relatively short periods (a few years) (Jönsson et al. 2003; Tuomi et al. 2011), concentrate on limited regions (e.g. Mietus and von Storch 1997; Paplińska 1999, Blomgren et al. 2001, Soomere 2005) or focus at single sites (Kelpšaite et al. 2009; Suursaar and Kulllas, 2009a, 2009b; Suursaar, 2010). This is not unexpected because long-term reconstructions of the Baltic Sea wave fields are still a complicated task and usually contain high uncertainties (Cieślikiewicz and Paplińska-Swerpel 2008; Kriezi and Broman 2008). An overview of the relevant literature until 2007 and a description of the basic features of the wave climate are presented in Soomere (2008).

The largest source of uncertainties in wave simulations is the wind information. Although its quality has been increased within the last decade and in many applications its spatial resolution has been increased to about 10 km, simulations of long-term changes to wave fields are still hampered by substantial temporal inhomogeneity in the wind fields (Tuomi et al. 2011), considerable differences in the quality of available wind information in different regions of the Baltic Sea (Räämet et al. 2009; Soomere and Räämet 2011Oceanologia), and by a probably generic inability of even the most advanced atmospheric models to properly reproduce the air flow in several sub-basins of the Baltic Sea (Keevallik and Soomere 2010).

Long-term numerical reconstructions of changes to the entire Baltic Sea wave climate have been performed for 1958–2002 based on the output of NCAR/NCEP wind reconstructions (Augustin 2005, Weisse and Günther, 2007; Weisse and von Storch, 2010) and for 1970–2002 based on adjusted geostrophic winds (Räämet and Soomere, 2010a, Soomere and Räämet 2011).

3. Mean Baltic Sea-level change

3.1 Main factors affecting Baltic Sea-level change

The overall mean sea level change on the coasts of the Baltic Sea is a competition between postglacial rebound and eustatic and regional sea-level change. In addition, meteorological factors affect the local patterns of sea level in the semi-enclosed sea. The Baltic Sea level can deviate remarkably from the North Sea level outside the Danish Straits (Madsen 2011). (…)

3.1.1 Global mean sea level change

3.1.2 Regional distribution of sea level change

This two sections will be written after cross-chapter approval with Section 4.3.4 ‘Changes in the Baltic Sea level’ within ‘4.3 Projections of future climate change’ (Lead Author: Ole Bossing)

3.1.3 Regional versus Local sea-level changes

Land Movement

The Baltic Sea is a region strongly influenced by glacial isostatic adjustment (GIA) as a consequence of the unloading of ice masses after the Last Glacial with a maximum uplift of the Earth crust in the Bothnian Bay with roughly 10 mm/year (resulting in a negative trend in sea-level) and a subsidence in parts of the Southern Baltic Coast of about 1 mm/year (resulting in a slight positive trend) (e.g. Hammarklint 2009). Although the overall pattern of land movement is dominated by the GIA, it may be modified by local natural or human-caused land uplift or subsidence (see Section 2.1), as is the case for Tallinn (Suursaar 2011).

Nowadays, different methods exist to study land movement effects. Traditionally, land uplift rates in the Baltic have been determined from sea level measurements (e.g. Vermeer et al 1988), based on local (e.g. tide gauge) observations of long-term relative sea-level trends, presenting the position of sea-level with respect to land and therefore include both: the signal related to vertical crustal movements and to (absolute) sea-level changes. The first consistent map of the postglacial uplift of Fennoscandia (relative to land) was constructed by Ekman (1996), mainly on the basis of sea-level records, but also considering lake level records and repeated high precision levelling. Rosentau et al (2007) used the map of Ekman (1996) and augmented it with data from gauge measurements from the Southern Baltic Sea. Subsequently, Harff et al (2010) introduced a map of absolute vertical crustal movement (based on Ekman 1996 and Rosentau et al 2007) by re-calculating the values under the assumption of 1mm/year of eustatic sea-level rise for the 20th century. Here, the value of eustatic sea-level rise was estimated from observed gauge measurements in the Baltic Sea Region after Hupfer et al (2003). This method was applied before by Ekman (1998) who presented vertical velocities based on apparent land uplift of the crust relative to sea level observed at tide-gauges during the 100 years period 1892-1991 (from Ekman 1996) by applying an eustatic sea-level rise of 1.2 mm/year, deriving the rise of the geoid (relative to the ellipsoid) on computations of Ekman and Mäkinen (1996).

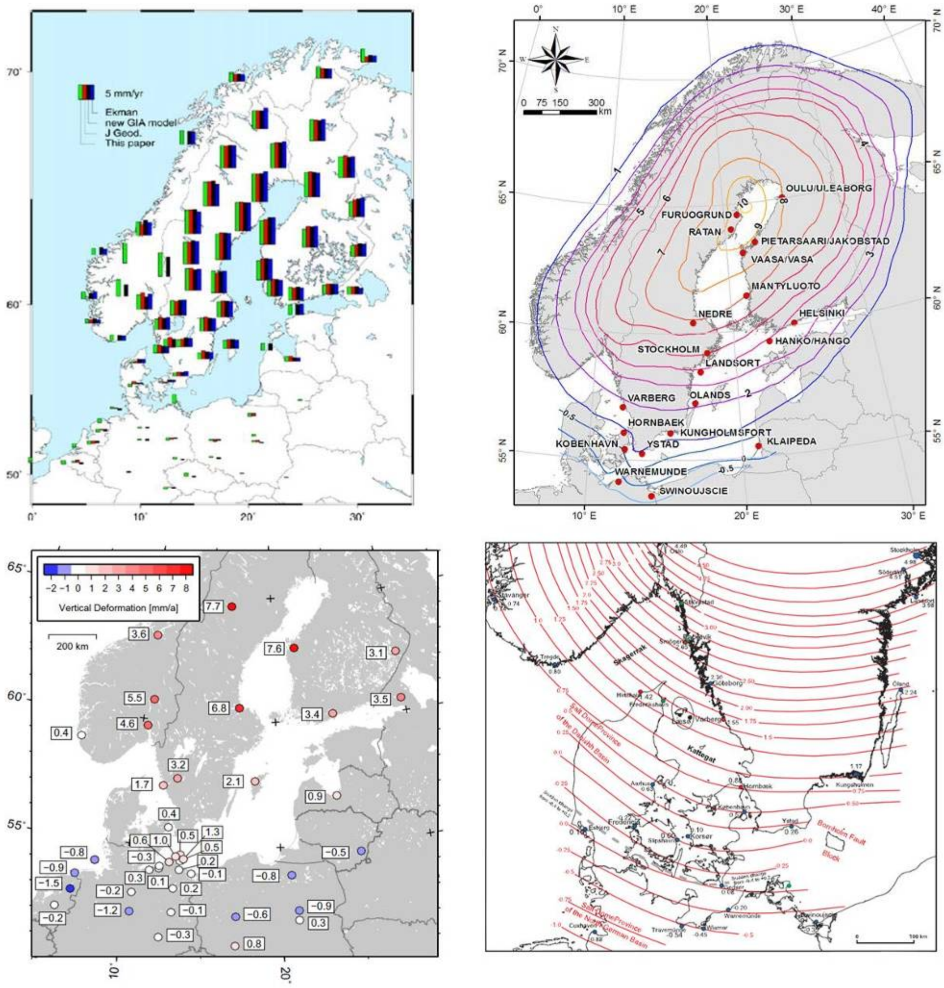

Fig. 3: Estimation of vertical velocities (for tide gauge correction) derived by different methods (from Harff et al. 2010, Richter et al. 2011, Lidberg et al 2010, Hanssen et al. 2011) (Figure capture need to be complemented)

A common method to correct trends of tide gauge measurements for the GIA effect, and often used in global sea-level studies is the application of ice load models (e.g. Peltier 1998), but this method is not able to consider other land motions (e.g. sinking piers or short-term motions due to earthquakes). Milne et al (2001) considered the GIA correction for the Baltic tide gauge records as critical because of the large GIA amplitude (~10 mm/yr) relative to the global trend (~1 to 3mm/yr) (Peltier and Tushingham 1991). Missing: review of Groh et al. 2010, Hansen et al. 2011!

However, recently, new geodetic techniques such as the application of GPS allow for measures of more precise absolute rates of vertical land movements and lead to considerable progress by comparison with results derived from tide gauges, GIA (ice load) models or corrections from geological data.

Within the BIFROST network, vertical land movements (thereafter also called station velocities) based of observations at permanent GPS stations in Sweden and Finland (1993-2000) were presented by Johansson et al. (2002) and Scherneck et al. (2002) and used by Milne et al 2001, 2004 e.g. for the estimation of regional sea-level rise, together with Fennoscandian tide gauge records. An update of station velocities was presented by Lidberg et al (2007) for the period 1996 to mid 2004, including some additional sides of Norway, Denmark and northern Europe, showing much smaller uncertainties in station velocity compared to Johansson et al (2002). The reason for that can be found in development and hardware changes at the GPS sites in the early phase of the BIFROST effort, which leaded in transitional shifts in the position time series (Lidberg et al 2010). Summarising, Lidberg et al (2010) provides an overview of published station velocity results (**Fig.3**).

The analysis of GPS data could demonstrate that ongoing 3D crustal deformation in Fennoscandia is dominated by GIA. The high advantage of GPS measurements is that they measure rates of vertical land movement, no matter if those movements are due to GIA or to other geological processes, but the disadvantage lies in the relatively short time span (since 1990s). For the purpose of the study of sea-level changes, the determination of vertical crustal deformation rates is most interesting for the calculation of absolute sea-level trends. Some studies have been performed which used permanent GPS observations to determine crustal deformation rates, and applied these and repeated levelling data to reduce the relative sea-level changes observed by tide gauges yielding an estimate for the absolute sea level change.

The values provided in these 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).

Missing: review of Hammarklint 2009

Meteorological influence

In addition to the long-term sea level rise and land uplift, sea level in the semi-enclosed Baltic Sea is controlled by meteorological factors. Especially, wind forcing plays a key role, affecting the Baltic Sea in two ways – persistent winds from southwest or northeast transport water in or out of the Baltic Sea, thereby raising or lowering the Baltic Sea level as a whole. Temporary winds redistribute the water within the Baltic Sea, producing high or low sea levels at the ends of the Baltic depending on the wind direction (Ekman 2007).

The Baltic Sea level variations correlate with the NAO index, which represents the large-scale circulation over the Northwest Atlantic (e.g. Andersson 2002). The correlation is especially strong in winter (e.g. Suursaar and Sooäär 2007), and in northern and eastern parts of the Baltic Sea (Johansson et al. 2004, Suursaar et al. 2006). In the central and eastern parts of the Baltic Sea, winter sea level variations at decadal time scale are well explained by the sea-level pressure variations, while in the southern part, area-averaged precipitation seem statistically better explain the decadal variations (Hünicke et al. 2008, Hünicke and Zorita 2007, Hünicke and Zorita 2008). This result agrees with the low correlation between the winter NAO index and winter sea level in the southern Baltic (Jevrejeva 2006). Missing: review of Feneglio-Marc 2001, Lehmann et al. 2010 (…)

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

The trends in coastal Baltic Sea level display a strong influence of the isostatic dynamics following the last deglaciation 10000 years ago. Thus generally speaking, sea-level is falling in the northern Baltic, where the continental crust is rising and sea-level is rising in the Southern Baltic, where the continental crust is sinking. Superposed to this long-term trends that affect relative sea-level, many climate factors, like changes in water density, changes in the total volume of the Baltic Sea and currents can modulate the absolute sea-level in the whole or parts of the Baltic Sea. Thus sea-level may display considerable variability in a large range of time scales, ranging from minutes through the annual cycle, and to decadal time scales.

3.2.1 Mean Baltic Sea level trends

Some studies have been performed that used permanent GPS observations to determine crustal deformation rates, and applied these and repeated levelling data to reduce the relative sea-level changes observed by tide gauges yielding an estimate for the absolute sea-level change. For instance, Milne et al (2001) estimated a regional sea-level rise of 2.1 +/- 0.3mm/year. Other studies found values in the range of 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). (add Hammarklint 2009) 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). However, it has to born in mind that regional long-term trends of sea-level can deviate substantially from the global mean and in the last 5 decades may be regionally negative (IPCC).

Figure 4 maps secular (100 years) sea-level changes based on long tide-gauge measurements of the entire Baltic region compiled by Richter (2011) based on data from PSMSL and data compiled on the basis of historical documents. The pattern of relative sea-level trends shows a clear north-south gradient, reflecting the crustal deformations due to the GIA effect. 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 varying around 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. According to Richter et al. (2011), this systematic effect is revealed by the large-scale pattern of relative sea-level trends throughout the entire Baltic Sea region.

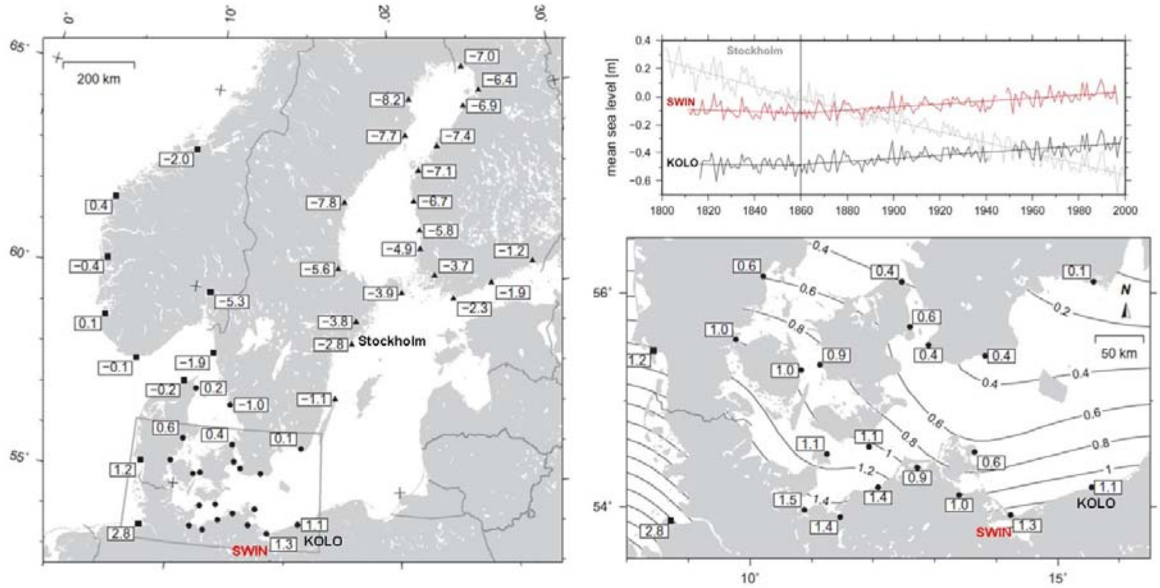

Fig.4: Maps of secular (100 years) relative sea-level changes, based on tide gauge measurements of the entire Baltic Sea Region (left panel) and, in more detail, the Southern Baltic Coast (right panel below) together with the changes in linear trend of the (arbitrarily shifted) annual relative sea-levels 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).

The spatial pattern of long-term trends of sea-level should, in general, also reflect the spatially varying fingerprints of sea-level changes due to recent mass changes of the polar ice-sheets and accordingly, the change in the gravity field of the geoid (Tamisiea et al. 2003, Milne et al. 2009) As demonstrated by Mitrovica et al. 2001, the pattern caused by the melting of the Greenland ice-sheet is negligible for the Baltic Sea Region, as its zero-line intersects the region and the remaining variations are below the accuracy of the derived relative sea-level rates, varying between 0.1 and 0.3mm/year. On the other hand, the pattern caused by the melting of the Antarctic ice-sheet does affect the Baltic region, but can be expected to be nearly constant over the region.

Richter et al (2011) analysed the variation of the annual mean relative sea levels at long tide gauge records, such as the Polish tide gauges Swinoujscie and Kolobrzeg (Fig.4 right panel). Here, 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 behaviour climatic effects related to the Little Ice Age, according to what was stated before by Ekman (2009 and references therein), who found a trend increase of 1.01mm/a for the Stockholm time-series (for comparison, also included in Fig. 4). However, it has to born in mind that due to temporal 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.

The long-term trends of relative Baltic Sea level in the period with direct observations have been analysed by Barbossa (2008), who not only estimated the trends in the median sea-level but also trends in the quantile of the distributions of monthly mean sea-level in different gauge 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 could contribute. In the Estonian case, due to the form of coastlines the fingerprint of forcing by the atmospheric circulation at interannual time scales is clearly detectable, and so it is reasonable to think that the atmospheric circulation, in particular of the North Atlantic Oscillation (NAO) may also be involved in the long-term trends of the upper sea-level quantiles in wintertime. However, the NAO exhibits a positive trend only in the last decades of the instrumental record, and not over the whole 20th century. Also, the NAO trend in the very last two decades has been negative (Pinto and Raible 2011).

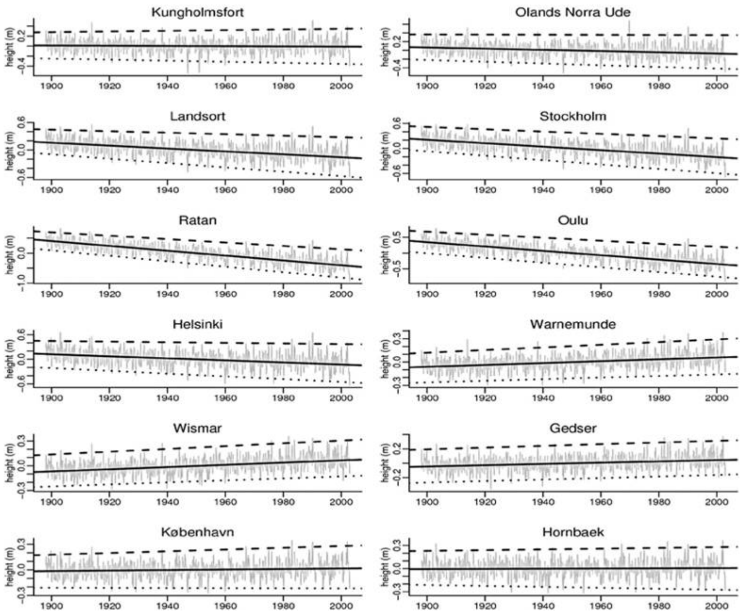

Fig.5: Time series of 3 quantiles (median, and the 1% and 99% quantiles) of the distribution of de-seasonalized monthly sea-level in several stations of the Baltic Sea in the period 1890-2010 (from Barbossa 2008).

Baltic sea-level has undergone decadal variations around the quasi-linear long-term trend dominated by isostatic movements. An illustration of these, wintertime mean decadal variations in the last 200 years in 5 stations in the Baltic Sea was 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

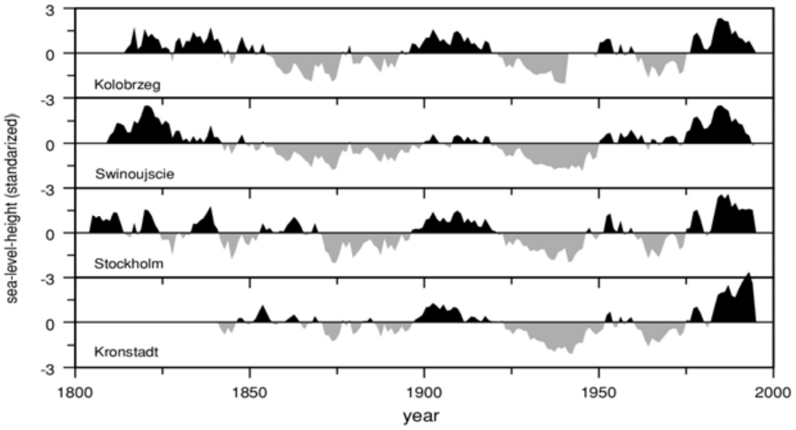

Fig.6: Long records of monthly mean sea-level in the Baltic Sea, after the long-term linear trend has been removed, and the series smoothed by a 11-year running mean to highlight the decadal variations. (from Hünicke et al. 2008)

3.2.2 Changes in seasonal variability

The slow changes in Baltic sea-level have been also found to depend on the season. Baltic sea-level displays an annual cycle with generally higher values during the winter months and lower values in the spring time. The long-term trends in the seasonal sea-level have been studied by Hünicke and Zorita (2008) who found that the difference between winter maximum and spring minimum has slightly widened during the 20th century. This increase has not been steady and is superposed to large decadal variations. The physical mechanisms for this increase should still be analysed in a more detailed way, but the most obvious mechanisms, like wind forcing and thermostatic effect are not able to explain either the patterns or the magnitude of the widening of these annual cycle.

However, the decadal variations in the differences between the seasonal sea-level can be due to slow variations in the wind forcing, especially at regional scales and in locations were the coast line is favourable to the action of the wind. For instance, in the Gulf of Riga and Väinameri area, results obtained with the help of a 2-dimensional hydrodynamical model indicate that relatively modest increase in wind speed (2 m/s) could be responsible for a mean sea level increase of up to 2-5 cm, in addition to an analogous change in the Baltic Sea mean sea level (Suursaar and Kullas, 2006). Consequently, a total wind-induced average sea level rise of 7–10 cm could occur at locations like Pärnu and Matsalu, Estonia). There, changes of a similar magnitude probably occurred already between 1950 and 1990. Still missing: Review of Barbossa and Fernandez 2008

3.2.3 Is Baltic Sea level accelerating?

A relevant question in the context of anthropogenic climate change is whether or not global sea-level rise is accelerating its pace. Future projections of the magnitude of sea-level rise are still very uncertain due to the difficulty of estimating the effects of warming on the dynamics of polar ice sheets. Also, the spread in the projections of future thermosteric effect simulated by the suite of climate models is wide, between 20 and 60 cm in the global mean. Presently, global sea-level is rising at a pace of about 3 mm/year (IPCC), but if this trend remains unchanged trough the 21st century, the sea-level rise by 2100 would attain a figure of 30 cm. The projections obtained by global climate models, therefore, imply an acceleration from the present rate of global sea-level rise. This is not necessarily the case for regional sea-level rise, especially for the Baltic Sea with complex coastlines and a series of different processes modulating the response to global greenhouse warming. Nevertheless, the question of whether the rate of sea-level rise in the Baltic Sea is increasing is relevant also for adaptation to climate changing and other planning purposes.

There are different possible approaches to the definition of 'acceleration'. One is the determination of a linear sea-level rate in sliding windows of fixed length, for instance 30 or 50 years. If the linear rates in the last windows in the record are 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 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, a different definition of 'acceleration' would claim that there exists acceleration. These two different definitions may be illustrated by the results achieved by Richter et al 2011.

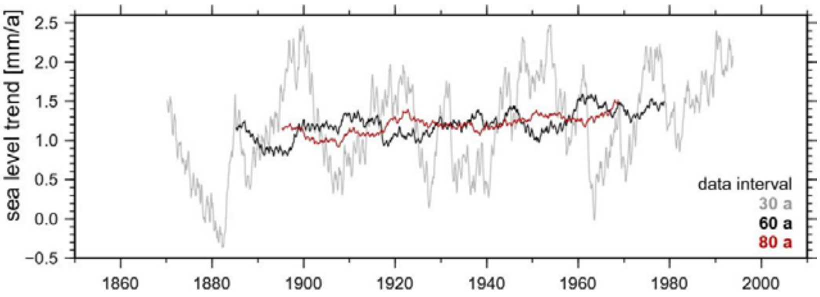

Fig.7 Linear trends calculated in sliding windows of fixed length for the annual sea-level record in Warnemünde (Germany). The three series show the results for different window lengths (from Richter et al. 2011).

Fig.7 shows the linear trends calculated in sliding windows of fixed length for the annual mean sea-level in a station in the Southern Baltic, Warnemünde (Germany). The 30-year trends indicate that the present rate is not unprecedented in the record. However, the 60-year sliding trends display a visible upward trend. Depending on which definition of acceleration adopted, the same record may be considered, or not, to show acceleration.

4. Extreme Sea levels

This section still needs to be structured more efficiently (including evaluation of Figures).

4.1 Main factors affecting extreme sea levels in the Baltic Sea

Because of the elongated shape, semi-enclosed configuration and the presence of shallow bays exposed to the direction of possible strong winds, considerable short-term sea level variations or storm surges can occur in some specific parts of the Baltic Sea. Such extreme sea level variations in the Baltic Sea are mainly due to wind (wind set-up); smaller contributors may be the inversed barometer effect, wave set-up and propagation or amplification of remotely generated long waves. Winds affect the sea level in two principal ways (e.g. Samuelsson and Stigebrandt 1996, Ekman 2007). Firstly, storm may build up a short-term sea level slope within the Baltic Sea, resulting in strongest deviations at the „ends" of the Baltic (in the Belt Sea and in the gulfs of Finland, Bothnia and Riga). Secondly, when a strong persistent wind from south-west or north-east is blowing over the Baltic Sea and its entrance, water is transported into or out of the Baltic, thereby raising or lowering the Baltic Sea level as whole. Although the amplitude of such events alone normally amount to less than 50 cm, they can provide preconditions for much larger local-scale storm surges, when combined with short-term storm-winds during cyclones.

All over the sea, both extreme high and low sea-level events tend to occur in meteorologically more variable winter months. However, owing to the large meridional extent of the sea, the required forcing conditions, as well as storm surge risks, may strongly vary in different parts of the Baltic Sea.

(1) In the eastern part of the Gulf of Finland, where the highest Baltic surges can occur, such events have been analysed by Klevannyy et al. (2001), Nekrasov et al. (2007), and Averkiev & Klevannyy (2010). As most of the cyclones above Scandinavia and the Baltic Sea are travelling from SW or W to the east, the storm surges are usually generated in the eastern or north-eastern sections of the sea, and particularly in the bays off the nodal (central) part of the sea, like the Neva Bay of St. Petersburg (up to 424 (421?) cm). At the same time, negative surges or sea level lowerings occur along the opposite, Swedish, Danish or German coasts. Also, those high and low sea level areas evolve in time, as the cyclones travel through a particular area.

(2) Narrow bays in the Belt sea and in the south-western Baltic is the region of the second highest storm surges (up to 340 cm in Travemünde, 300-320 cm in Flensburg and Kiel), but also of the

deepest negative surges (values and references on German and Danish (Baltic) still need to be added). The maxima in many tide gauges of the area were all established by one spectacular north-easterly storm in November 1872, which caused the sea level to reach a height of about 300-340 cm at Travemünde and its surroundings, and negative surge of about 1 m occurred in the Gulf of Finland (Ekman 2009). According to Ekman, A. Colding, who analysed the event in 1881 in Denmark, already concluded then that a storm raises the sea level at coast proportionally to the square of the wind velocity; the effect is also proportional to the length of the open sea over the wind is blowing and inversely proportional to the depth of the sea.

(3) The third major storm surge prone area is the Gulf of Riga, and particularly the Pärnu Bay (up to 275 cm); the fourth is the northern part of the Bothnian Bay (Kemi, 201 cm).

Lying close to the nodal line of the sea, the Lithuanian and Latvian coasts to the Baltic Proper, as well as Gotland, Åland and the leewardly located Swedish coasts, will not experience high sea level events over 190 cm even during extreme storms. According to Dailidiene et al. (2006), the maximum in Lithuania (in Klaipeda) occurred 186 cm (on October 1967) and the minimum of -91 cm in 1984. In Latvia, Ventspils displayed its maximum of 148 cm; inside the Gulf of Riga. In Riga-Daugavgriva the maximum of 229 cm occurred in 2nd November 1969. At the Polish coast, the highest sea level of 217 cm was recorded in 1874 in Kolobrzeg (Kowalewska-Kalkowska and Wisniewski 2009).

As a general rule, in the eastern section of the sea near the coasts of Lithuania, Latvia, Estonia, Russia and Finland, strong east winds tend to lower the sea level, and west winds to raise it (Suursaar et al. 2002, 2006a). This applies to both short-time variations, as well as for low-frequency variations through the corresponding changes in the Baltic seawater volume. The lowest recorded sea level in the Gulf of Riga (-130 cm at Riga, -125 at Pärnu) occurred on December 1959 after a month with strong (20 m/s) east winds during an anticyclonic blocking pattern (Suursaar et al. 2002).

For extreme surges in the coastal waters of Estonia and St. Petersburg (and for negative surges in the Swedish and Danish coasts), the centre of a powerful cyclone should bypass Estonia to the north over the Scandinavian Peninsula and Bothnian Sea to make the local wind direction to turn from SW to NW (Suursaar et al. 2006b; Averkiev and Klevannyy 2010). As the strongest winds occur a few hundred kilometres to the right from the cyclone track, reduced friction above the sea surface and the elongated shape of the Baltic Sea together with the Pärnu Bay (in case of Pärnu tide gauge) or Gulf of Finland (for Narva-Jõesuu and St. Petersburg) provides a span for surge wave to increase towards the east with also diminishing water depth and gulf width converges. Most notably, since the founding of St.Petersburg as the capital of Russia in 1703 there have been about 300 floodings events due to the sea level rise above the critical value of 160 cm (Bogdanov et al., 2000). The worst event occurred on 19 November 1824 (+424 cm), killing 569 people, the second highest was in 1924 (+380 cm). In 1970 the decision was taking to build a 25km dam with huge closable gates to protect the city, which was finished only recently in 2011.

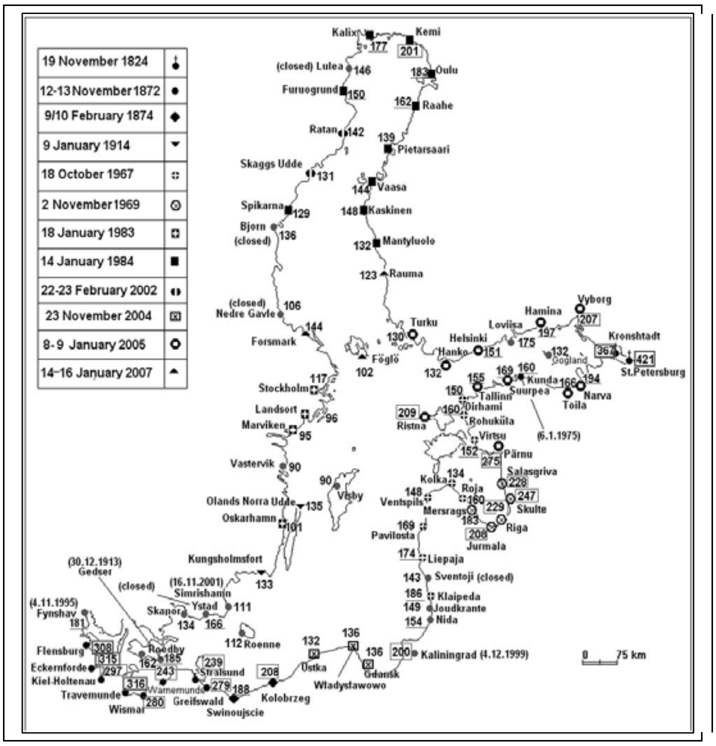

Fig.8: Historical water level maxima (cm) in the Baltic Sea. Data are given in the national water levelling systems, (from Averkiev and Klevannyy 2010)

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).

Over the period 1923-2010, the Pärnu sea level record identifies 30 individual events higher than the critical value of 150 cm, 24 of which occurred between the months of October–March and 6 between the months of April–September. Since 1923, the two highest sea level events off the Estonian coast were 253 cm on 19th October 1967 and 275 cm on 9th January 2005. The later was produced by the cyclone Gudrun, which attained of a hurricane-like power according to the mean wind speed measurements (up to 34 m/s) in Denmark. New sea-level records were established not only at most of the Estonian tide gauges, but also in Helsinki (151 cm), Hamina (197 cm), Hanko (132 cm) and Turku (130 cm). However, previous maxima were not surpassed both in Bothnian Bay (201 cm in Kemi from 1982) and in St.Petersburg, where the sea level height reached a relative modest height of 230 cm. Gudrun’s eye passed 300 km north of Estonia, heading from SW to NE and creating strong SW winds (and later W–NW winds once it passed) reaching an average of 28 m/s over one hour period. Another factor contributing to Gudrun’s storm surge was the relatively high background sea level in the Baltic (70 cm) at that time (Suursaar et al. 2006b). The higher background sea level was the result of strong cyclonic activity during the preceding month, which had the effect of pushing additional water through the Danish Straits into the Baltic Sea.

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

When looking at temporal variations in Baltic high sea level events, Johansson et al. (2001) corrected the Finnish series (13 stations, mostly covering period from1923 to 1999) with annual mean values and found a significant 2-4 mm/yr rise in maxima. At the same time, the rise in minima was only around 1 mm/yr. Along the Lithuanian coast, the average rise in maxima were around 2-3 mm/yr (Dailidiene et al. 2006). Corrected by the local uplift rates (taken from map by Vallner et al. 1988), Suursaar and Sooäär (2007) found a remarkable 3.5-11 mm/yr rise in Estonian maximum sea levels. Even if omitting the last prominent event of 2005, the rise in maximum sea levels was significantly higher than the rise of mean sea level rise (1-2.6 mm/yr) and the rise in minima (0.8-3.1 mm/yr). (…)

Using hydrodynamic modelling experiments, Suursaar et al. (2006a) and Suursaar and Kullas (2006) explained the hydrodynamic mechanism responsible for these differences. As Estonian and Finnish tide gauges are both regionally and locally windward, they are more sensitive to wind climate changes. Analysis of local wind data from Estonian coastal stations have shown that, although the mean wind speed has probably mostly decreased over the period of last 50 years, the westerly wind component, as well as maximum wind events have increased (Suursaar and Kullas, 2009a,b; Suursaar 2010). This is in good agreement with findings on changes of cyclones trajectories above the Baltic Sea (Sepp et al. 2005, Jaagus et al. 2008). Modelling experiments showed that in case of a decadal trend in wind conditions the sea level change rates of a semi-enclosed basin may deviate from the global estimates.

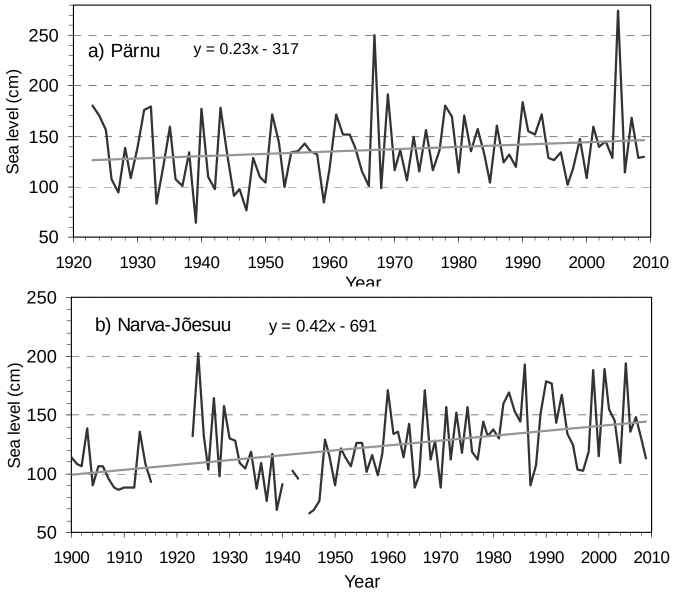

Fig.9: Decadal variations in annual maximum sea levels at Pärnu (a) and Narva-Jõesuu (b) together with linear trendlines (from: Suursaar and Kullas 2009b; Suursaar 2010).

A positive trend in wind speed and storminess should result in a steeper than average sea level trend on the windward side (and especially in maximum values), and one that is less steep on the leeward side (Suursaar and Sooäär 2007). However, as the meridional extension of the Baltic Sea is about 1200 km, the climatological tendencies and trends in storm surge heights may be rather different. While cyclones count (storminess) has probably increased over the northern section of the Baltic Sea, it has decreased above central Europe and southern Baltic. (…)

It is important to give an idea of the possible extreme sea levels we can ever expect in the future. There are basically two possibilities for such estimation, either through dynamical or statistical modelling. Normally, every storm surge prone area (city, port) has established its own critical sea level values, usually based on return statistics of long measuring periods. There is a common miscoception that, as soon as we discover the “right” theoretical distribution function, we can extrapolate the return period outside the length of the empirical series. However, some caveats have to be considered. Evidently, an estimation of the frequency of extreme events for long return periods can be valid for certain established climatologically equilibrium and climate changes will lead to future changes in the return periods of extreme events. However, since extreme events are rare the empirical estimations of the frequency of extreme events cannot be up date fast enough due to the ongoing climatologically changes. There are many examples worldwide of „storms of the century“ or surges „once in thousand years“ that actually occur quite frequently. Also, in some locations, the return statistics may be a suitable description at all. For example, the plots of empirical return periods against the corresponding theoretical distributions showed a more or less a satisfactory fit in case of three Estonian tide gauges, but failed in case of Pärnu maxima (Suursaar and Sooäär, 2007). Only very unusual probability distributions could probably describe or predict the two extreme sea level events of 253 cm or 275 cm (**Fig.10**), because the existing bulk of the data does not carry sufficient statistical information about the possible extreme sea level values. Due to the specific configuration of the Gulf of Riga and Pärnu Bay, the sea level is proportional to the wind speed in the power of 2.4 (Suursaar et al. 2002, 2006a), and at the upper range of wind speeds, a slight incremental increase in wind speed yields an exponentially higher incremental increase in storm surge level. Probability of an outstanding Pärnu storm surge therefore appears as a product of probabilities of these three events: a suitable wind speed and direction, and a high boundary sea level. Alternatively, using hydrodynamic modelling, Suursaar et al. (2006b) found that considering the 30 m/s sustained wind speed, the direction of SW, and the Baltic mean sea level of 70 cm, the maximum sea level may easily reach 310 cm at Pärnu.

Averkiev & Klevannyy (2010) simulated the extreme sea levels for the entire Gulf of Finland depending on cyclone parameters and trajectories. They predicted as much as 590 cm at St.Petersburg, 478 at Ust Luga, 238 cm at Kotka, 186 cm at Helsinki, 159 cm at Tallinn and 335 cm at Pärnu – however, the wind speed he used was about 40 m/s.

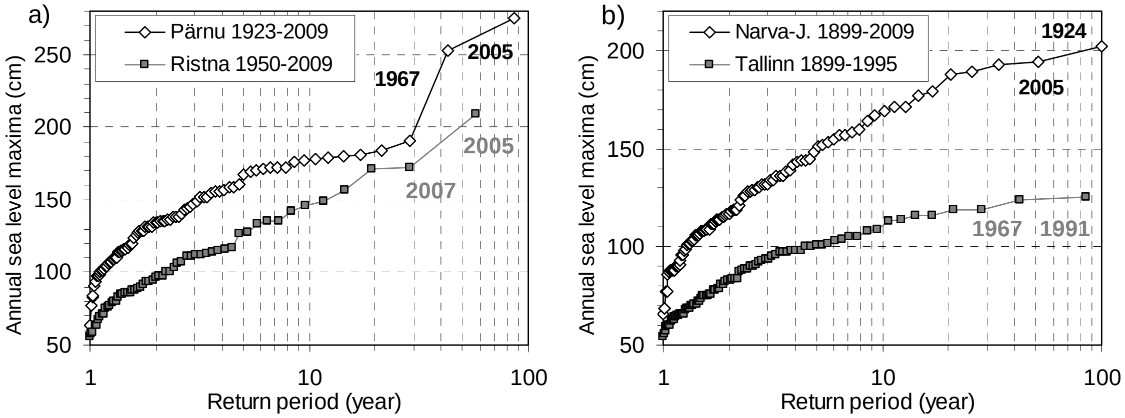

Fig. 10 Empirical return periods based on annual maximum sea level data from Estonia: at (a) Pärnu and Ristna, and (b) Narva-Jõesuu and Tallinn.

5. Wind waves

Both the status of the wave climate and its changes are the key elements of oceanography and coastal science. This is not only because surface waves are a major driver of processes occurring in the surface layer, nearshore, and coastal area, but also because the wave climate is one of the most sensitive indicators of changes in the wind regime in semi-enclosed sea areas. The potential for an increase in wave heights, for example, in the North Sea (18%) is substantially greater than that of the wind speed (7% for the 99%-iles; Grabemann and Weisse 2008).

The Baltic Sea is a challenging area for wave scientists. Its extremely complex geometry and the associated high variability of wind fields give rise to extensive spatio-temporal variability in the wave fields and thus require a high spatial resolution of numerical wave simulations. The spatial resolution of numerically reconstructed global wave data sets such as the KNMI/ERA-40 Wave Atlas (1.5°×1.5°) (Sterl and Caires 2005) is insufficient for the Baltic Sea. The presence of ice often substantially affects the wave patterns and complicates both visual observations and instrumental measurements. As floating devices are normally removed well before the ice season (Kahma et al. 2003, Tuomi et al. 2011), the measured wave statistics (especially in the northern Baltic Sea) has extensive gaps for the windiest period that frequently occurs just before the ice cover forms. Consequently, several commonly used characteristics are meaningless for seasonally ice-covered seas (Tuomi et al. 2011). This calls for new techniques for unambiguous estimation of the wave statistics. On top of that, relatively shallow areas, widely spread in this basin, and convergent wind patterns may lead to unexpectedly high waves, formed in the process of wave refraction and/or optional wave energy concentration in some areas (Soomere 2003, 2005; Soomere et al. 2008a); also, specific wave generation conditions under so-called slanting fetch frequently occur in some sub-basins (Pettersson et al. 2010).

5.1 Long-term wave properties

The sources of wave information (see Section 2) are used to depict the long-term wave properties (including average and extreme heights, occurrence distributions and height-period combinations) and their spatial variations in the Baltic Sea. In essence, the Baltic Sea wave climate is highly intermittent, mostly very mild and largely follows the seasonal variation in the wind speed. 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.

The sea, however, occasionally hosts furious wave storms in certain seasons that drive the significant wave height well over 8 m in the northern Baltic Proper (Soomere et al. 2008a, Tuomi et al. 2011), over 6 m in the Darss Sill area (Soomere et al. 2011b) and in the Bothnian Sea (Kahma, FMI?), and over 5 m in the Gulf of Finland (Tuomi et al. 2011). 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.

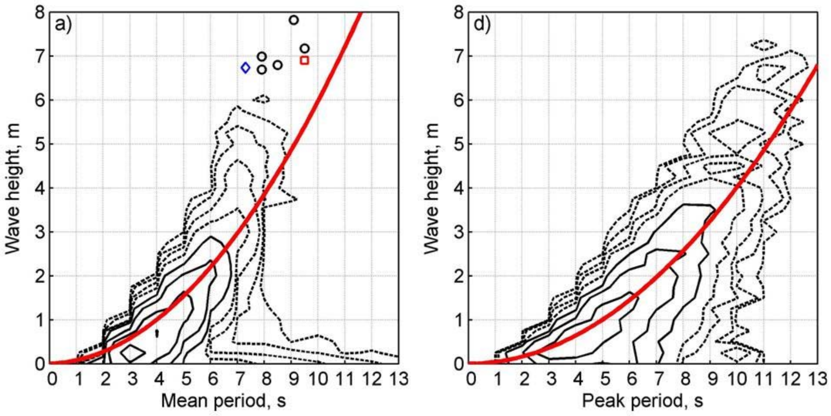

Fig.11: Scatter diagram of the frequency of occurrence of wave fields with different heights and periods: a) Almagrundet 1977–2003 (adapted from Broman et al. 2006); d) northern Baltic Proper 1996–2002 (based on data from Kahma et al. 2003). The red line denotes wave fields with a Pierson-Moskowitz spectrum.

Several observation sites reveal short-time (on weekly scales) features in the wave activity; e.g. a relatively calm period at the end of December and the beginning of January in the northern Baltic Sea (Soomere et al. 2011BER). These features are, most probably, site-specific and persist for a few decades (Soomere et al. 2011OceanSci). The presence of a strong seasonal course in the wave heights in the entire Baltic Sea region is a well-known feature that stems from the similar course in the wind speed, which obviously mirrors the analogous cycle in cyclone generation over the North Atlantic. This variation is evident in all long-term observation and measurement sites as well as in numerical simulations using different models. The monthly mean wave height varies by a factor of 2 in coastal areas and up to three times in the offshore regions, mostly (but not perfectly) following, the seasonal course of the wind speed (Räämet et al. 2010). The calmest months are from April to July and the windiest ones October–January.

The most frequent periods are 3–5 s in the offshore and 2–4 s in the coastal areas (Soomere 2008). The majority of the combinations of wave heights and periods roughly corresponds to the wave fields with a Pierson-Moskowitz spectrum in the northern Baltic Proper and along the eastern coast (Soomere 2008; Räämet et al. 2011), signifying a large proportion of fully saturated seas in this region; however, the properties of the roughest seas match better a JONSWAP spectrum. In the Darss Sill area, however, wave fields with a JONSWAP spectrum (i.e. fetch-limited waves) play a relatively large role (Soomere et al. 2011). The combinations of wave heights and periods in the most extreme storm once in a few decades are well defined (Soomere 2008, Räämet et al. 2010): the wave heights are as described above and the mean wave periods are 8–9 s in the offshore and 6–8 s in the nearshore. The proportion of swells is very limited.

5.2 Spatio-temporal patterns of variations

The pool of existing wave studies in 2006–2011 reflects a number of mismatches between long-term changes to wave properties at selected sites. For example, wave activity was found to rapidly increase at both (eastern and western) coasts of the northern Baltic Sea in the 1990s and decrease radically after about 1997 (Broman et al. 2006; Soomere and Zaitseva 2007). Simultaneuosly, the annual mean wave height had a deep minimum at the Lithuanian coast according to visual observations (Zaitseva-Pärnaste et al. 2011). These variations were almost invisible in numerical simulations of the entire Baltic Sea wave fields (Soomere and Räämet 2011) and also in local wave climate reconstructions using a fetch-based model and local wind data (Suursaar and Kullas 2009a). Moreover, the temporal course of wave heights in the northern Baltic Sea does not follow a gradual increase in the annual mean wind speed in the northern Baltic Proper (Island of Utö, Soomere and Räämet 2011).

Recent numerical reconstructions of changes to the entire Baltic Sea wave fields (Soomere and Räämet 2011) have brought increasing evidence that these mismatches actually are an intrinsic part of the rich spatio-temporal pattern of changes to the Baltic Sea wave fields which is simply not resolved by the existing wave observation network. Several features of this pattern become evident in through the spatial structure of interannual to (multi-)decadal changes in wave heights and propagation directions. The spatial scales of such patterns in the open sea vary from >500 km for interannual variations down to about 100 km for long-term trends.

5.2.1 Reflections of changes to wind properties

Will be written after cross-chapter check with 3.2. (Lead Author: Anna Rutgersson)

5.2.2 Interannual variations and (multi-)decadal changes

The most extensive interannual and decadal variations in wave properties exist, not surprisingly, in the visually observed wave data (**Fig. 12**). Interestingly, the appearance and spatial coherence of such variations has undergone major changes. Variations in the annual mean wave height at all visual observation sites are the most similar except for the first three years (1954–1956). In other words, the short-term (1–3) year interannual variability in the wave intensity seems to have the same pattern (with a typical spatial scale of > 500 km) over a large region from the southern Baltic Proper up to the eastern Gulf of Finland from the mid-1950s until the mid-1980s. This coherence is lost in the mid-1980s (Soomere et al. 2011): since then, years with relatively high wave intensity at Vilsandi correspond to relatively calm years in Narva Bay and vice versa.

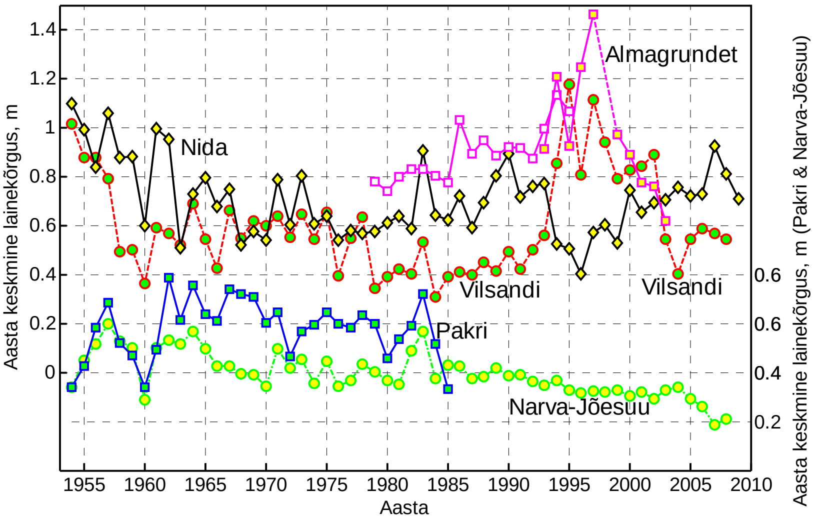

Fig.12: Annual mean observed (Nida, Vilsandi, Pakri, Narva-Jõesuu) and instrumentally measured (Almagrundet) wave height. Notice that for some years the high wave activity at Vilsandi is mirrored by relatively low wave heights at Almagrundet apparently because of changes in the prevailing storm direction for single years. The use of climatologically corrected data sets (ie. replacing the missing or doubtful entries by the climatological values for the particular measurement day) does not change the overall pattern of decadal variations but considerably suppresses their magnitude (Soomere et al. 2011). (The final version will be in English; the vertical axis is the annual mean wave height).

The data from all three sources reveal substantial variations in the annual mean wave height that are uncorrelated for different regions of the Baltic Sea. The variations are most drastic in the observed data sets and in the Almagrundet data (**Fig. 3**). There is an overall gradual decrease in the wave height from about 1960 until the end of the 1970s. The wave height substantially increases in the northern Baltic Proper from the mid-1980s until the mid-1990s. This trend follows the analogous trends for the southern Baltic Sea and for the North Atlantic (Gulev and Hasse 1999; Weisse and

Günther 2007) but was replaced by a drastic decrease since 1997. The wave height at the SE Baltic Sea coast showed, contrariwise, a rapid decrease until about 1996 and a rapid increase since then.

Such extensive variations raise the question about the significance of different factors (such as instrument failure, observers' error or noise) in the data. The data from Almagrundet for 1997–2003 was even assessed as doubtful by Broman et al. (2006) because the annual mean wind speed in the northern Baltic Proper continued to increase. The simultaneous changes at Almagrundet and Vilsandi, with a similar relative range on both the eastern and the western coasts, still signify large-scale decadal variations in wave properties, the magnitude of which may be overestimated because of the coastal effects. In particular, the decrease in wave activity since the mid-1990s is similar to a certain decrease in the intensity and duration of severe wave heights in the North Sea since about 1990–1995 (Weisse and Günther 2007) where the wave activity in 2004–2005 was equal to the global minimum that occurred at the beginning of the 1980s. The increase in wave activity at Almagrundet and Vilsandi, however, matches well an almost twofold increase in the number of low pressure observations below 980 hPa at Härnosand for the 1990s (Bärring and von Storch 2004).

Similar variations were much weaker or almost missing in all numerical reconstructions, both based on realistic wind information and spectral models and on one-point winds from coastal stations and simplified fetch-based models (Suursaar and Kullas 2009a, 2009b; Suursaar 2010). Similarly to Augustin (2005), several fetch-based models revealed different tendencies in the average and extreme wave heights.

The relatively small size of the Baltic Sea, frequent large-scale homogeneity in the wind fields and the short saturation time and memory of wave fields make it possible to use simplified wave hindcast schemes (Soomere 2005), high-quality wind data from a few points (Blomgren et al. 2001) and/or properly calibrated simple fetch-based wave models (Suursaar and Kullas 2009a, 2009b, Suursaar 2010) to reproduce local wave statistics with an acceptable accuracy. The use of such models for the identification of changes to wave statistics is limited as they basically reproduce the changes in the local wind field only. For certain locations along the Estonian coast, these models have demonstrated that the overall wave intensity changes quasi-periodically and reveals no statistically significant trend but the extreme waves (in terms of 99%-tile significant wave height) has decreased at the northern coast of Estonia (Suursaar 2010).

The overall course in the wave activity in different parts of the Baltic Sea reveals no clear long-term trend (Soomere and Zaitseva 2007, Soomere 2008, Soomere et al. 2011OceanSci) except for Narva-Jõesuu, where wave intensity is gradually decreasing (Soomere et al. 2011). Instead, a quasi-periodic variation with a typical scale of about 25 years can be identified for all the data sets. Although quite large variations in the average wave periods (from about 2.3 s in the mid-1970s up to 2.65 s around 1990) were found in the wave periods in simulations with a fetch-based model (Suursaar and Kullas 2009), there is apparently no substantial changes to the most frequent wave periods as well as to the distribution of the frequency of occurrence of different periods in most of the Baltic Sea (Soomere et al 2011OceanSci). Also, there is no published evidence about changes to numerically simulated wave propagation directions. Such changes, however, were attached to the patterns of changes in erosion and accumulation sections of the Lithuanian coast (Kelpšaite et al. 2011). Substantial changes to visually observed wave directions occurred at Narva-Jõesuu during the last half century: the most frequent wave approach direction turned by more than 90 degrees, from NW to SW (Räämet et al. 2010).

5.2.3 Spatial patterns of variations

The spatial pattern of hindcast long-term average wave heights in the Baltic Sea for 1970–2007 based on adjusted geostrophic winds (**Fig. 13 left**) contains several local maxima in the Baltic Proper: in an area to south of Gotland and east of Öland, and in the NE Baltic Proper (Räämet and Soomere 2010). A similar hindcast using high-resolution HIRLAM winds for 2000–2008 (Tuomi et al. 2011) shows a qualitatively similar pattern but somewhat different distribution of the maxima. **Figure 13 (right)** suggests that the trends in wave heights in adjacent areas of the open sea may be drastically different and, thus, the locations of the maxima of wave heights may change in time.

According to the geostrophic wind information, the decrease in wave intensity has been the greatest between Öland and Gotland, and to the south of these islands down to the Polish coast. The spatial pattern of changes is largely uncorrelated with the areas of high and low wave intensity. The already large wave heights in the Arkona basin increase, while the wave activity in the neighbouring area of large waves decreases at almost the same rate (by about 15% in 40 years). The increase in wave heights in the Arkona basin is consistent with the reported gradual increase in the modelled wind speed over this sea area (Pryor and Barthelmie 2003; Pryor et al. 2005); notice, however, that the local maximum in the Arkona Basin is not represented in some other hindcasts (M. Meier, personal communication). As the hindcast matches the measured long-term wave height well for the Darss Sill (Soomere et al. 2011OceaSci), the local maximum may also stem from the overestimation of geostrophic wind speeds in this part of the basin (cf. Pryor and Barthelmie 2003). A considerable increase in wave activity is indicated by the model from the coast of Latvia to the sea area between the Åland archipelago and Sweden.

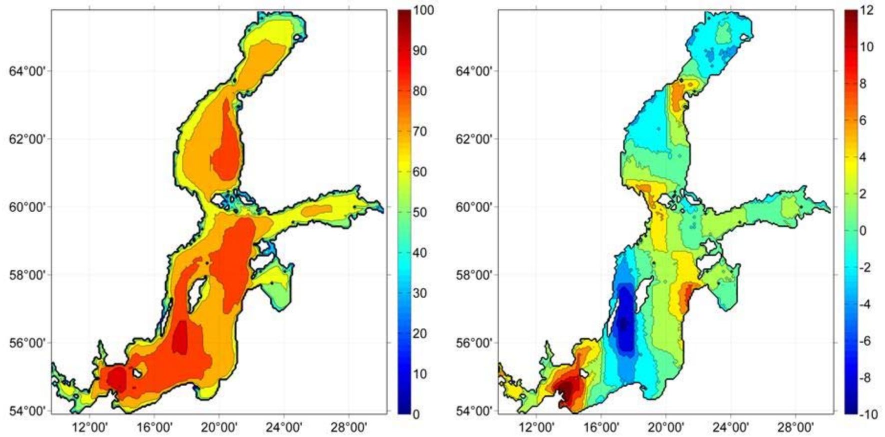

Fig.13: (left) Numerically simulated average significant wave height (colour bar, cm; isolines plotted after each 10 cm) in the Baltic Sea in 1970–2007 (from Räämet and Soomere 2010); (right) Long-term changes in the annual average significant wave height (cm, based on the linear trend, isolines plotted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

A very similar pattern is found for extreme waves (the threshold for the 1% highest waves, or equivalently, for the 99%-quantile of significant wave height for each year, is calculated over the entire set of hourly hindcast wave heights for each year in Soomere & Räämet (2011)). The spatial pattern of changes to the extreme wave heights largely follows the one for the average wave heights. There are, however, areas in which the changes to the average and extreme wave heights are opposite, as hypothesized in (Soomere and Healy 2008) based on data from Estonian coastal waters.

The discussed changes not necessarily become evident in sub-basins of the Baltic Sea. There has been effectively no change in the annual average significant wave height at the Darss Sill (Soomere et al. 2011). The threshold for the 1% highest waves (that has considerably decreased in 1991-2010), the extreme wave heights show a sawtooth-like behaviour, with a gradual increase for 1958–1990 from about 4 m to about 5 m, a drastic decrease in 1991–1992 and an increase since then again (Soomere et al. 2011). In contrast to the gradual increase in the mean wind speed over most of the Baltic Proper (Pryor & Barthelmie 2003, Broman et al. 2006), there is a very slow decrease (about 0.01 m/s/year) in the annual mean wind speed at Kalbådagrund (Soomere et al. 2010). Therefore, drastic long-term variations in the wave properties are unlikely in this gulf. The numerical simulations indicate very minor changes in the annual mean wave height in the entire gulf (Soomere et al. 2010). Suursaar and Kullas (2009b) noted a decreasing trend in 99% quantile near the north Estonian coast and a weak, opposite, gradually increasing trend in the average wave height. Simulations using the WAM model show that, unlike the average wave height, there has been a substantial decrease (by about 10%) in the maximum wave heights near the southern coast of the gulf and an almost equal increase to the north of the axis of the gulf (Soomere and Räämet 2011). This feature is apparently related to the major changes in the wind direction over the Estonian mainland: the frequency of SW winds has increased considerably over the last 40 years (Kull 2005).

6. Summary and Conclusion

Need to be complemented and revised. (…)

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. (…)

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