Seasonal variability in the Baltic Sea level*

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Abstract

Sea level is subject to spatial and temporal variability on different scales. In this paper we investigate seasonal variability in the open Baltic Sea level using daily satellite altimetry data for the period 1 January 1993–31 December 2010. Our results indicate that there is a well-pronounced seasonal cycle in the 18-year average sea level and in its standard deviation. The average annual SLA amplitude in the open Baltic Sea is about 18 cm. The seasonal cycle of the SLA in the Baltic Sea is asymmetric in shape. In the autumn and winter (about 240–260 days per year),

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the 18-year average daily SLA are higher than the 18-year annual average SLA. In the spring and summer (about 100–120 days per year), the 18-year average daily SLA are lower than the 18-year annual average SLA. A similar asymmetry of the seasonal cycle is not observed in the North Sea and North Atlantic SLA data. The annual pattern of the sea level variability in the Baltic Sea is evident if one considers multi-year average time series, but the cycle can be obscured in some years.

1. Introduction

Sea level has received a lot of attention in recent years, as it provides some of the most direct evidence for global change (e.g. IPCC 2007, Meehl et al. 2007, Rahmstorf 2007, Horton et al. 2008, Church et al. (eds.) 2010). Sea level is subject to both spatial and temporal variability. Eustatic changes are driven by changes in the water mass of the global ocean, for example, as a result of the melting of continental ice (e.g. Church et al. (eds.) 2010). Steric changes are forced by the variability in the water volume (i.e. thermosteric and halosteric effects), independent of the change of the water mass (e.g. Steele & Ermold 2007). Temporal fluctuations of sea level cover scales with periods ranging from days to centuries. For example, variability on time scales shorter than climatic includes periodic changes related to tides and the Chandler wobble (e.g. Gross 2000). In addition, seasonal and synoptic variability is driven by meteorological forcing (atmospheric pressure, winds, evaporation and precipitation), water balance (river runoff, redistribution of water between ocean basins) and changes in sea surface topography (changes in water density and currents). It is important to document and understand this variability, in particular in coastal regions where higher sea levels can increase the likelihood of intense storm surges (Tebaldi et al. 2012).

Sea level has been carefully observed for many years in the landlocked, non-tidal Baltic Sea (e.g. Ekman 2009). It is well known that sea level variations in this region are important not only because of their impact on coasts and coastal infrastructure (e.g. Łabuz & Kowalewska-Kalkowska 2011), but also because they are closely linked to the exchange of water between the Baltic and the North Sea (Samuelsson & Stigebrandt 1996, Gustafsson & Andersson 2001, Ekman 2009). This exchange has crucial consequences for the Baltic Sea water balance, deep-water renewal rates and associated oceanographic processes, for example, the eutrophication status of the Baltic Sea (e.g. Omstedt et al. 2004, HELCOM 2009, Leppäranta & Myrberg 2009).

Most previous research on sea levels in the Baltic Sea has been based on coastal tide gauge records (e.g. Ekman & Makinen 1996, Hunicke & Zorita 2006, 2008, Hunicke et al. 2008, Ekman 2009, Donner et al. 2012). These records are significantly influenced by isostatic rebound from the last deglaciation. The vertical movement of the land is estimated to be about 10 mm year^{-1} in the northern Baltic Sea (rising) and about -1 mm year^{-1} (sinking) in the southern Baltic Sea (Ekman 2009). Sea level time series measured by coastal gauges include these strong linear trends due to isostasy in addition to other trends. Careful analysis of tide gauge data has shown that the variability of sea level in the Baltic Sea is significantly influenced by large-scale wind and air pressure fields, and is correlated with the North Atlantic Oscillation (NAO) index (e.g. Andersson 2002, Jevrejeva et al. 2005, Ekman 2009). Variability of precipitation has also been shown to affect Baltic Sea levels (Hunicke & Zorita 2006). In addition, it has been recognized that the annual cycle is characterized by the maximum sea level in winter months and the minimum level in spring and summer. There are reports that the amplitude of this cycle increased in the 20th century (e.g. Ekman & Stigebrandt 1990, Plag & Tsimplis 1999, Hunicke & Zorita 2008, Ekman 2009).

In the last 20 years new methods for the routine observation of sea levels based on satellite altimetry have been increasingly used as a standard of reference and have provided invaluable time series of sea level data (e.g. Cotton et al. 2004, Bouffard et al. 2008, 2011, Vignudelli et al. 2011). Altimetry permits one to avoid many of the problems associated with the use of tide gauge data, such as the influence of postglacial rebound and topographic effects on the interpretation of the monitored sea levels (e.g. Peltier 1998, 2004, Soudarin et al. 1999, Tamisiea et al. 2010). Satellite altimetric measurements provide consistent global and regional time series of sea level, sea level anomalies and geostrophic currents (e.g. Leuliette et al. 2004, Church & White 2006, Nerem et al. 2010, Vignudelli et al. 2011).

In a previous paper we discussed multiyear Baltic Sea level trends (Stramska & Chudziak 2013). The main objective of the present paper is to investigate seasonal variability in the open Baltic Sea level. Our research is based on satellite altimetry data and is focused on the most recent times, as the analysed data cover 18 years, from 1 January 1993 to 31 December 2010. Improved knowledge of SLA variability is vital, for example, for the better prediction of coastal erosion, as well as for an improved understanding of regional physical oceanography in the Baltic Sea, in particular conditions regulating water inflow events.

2. Data sets and methods

The main data series used in this study are the Sea Level Anomalies (SLA) extracted from the delayed time (DT) multi-mission global gridded data product available at AVISO (www.aviso.oceanobs.com). The daily data are available with a 1/3° spatial resolution on a Mercator grid and cover the period from 1 January 1993 to 31 December 2010 (18 years). These research-quality data allow the ocean sea level variability to be investigated on seasonal and multiyear scales. The SLA data are referenced to the 7-year mean sea surface height (January 1993 to December 1999). The details of standard processing applied to satellite altimetry data are available at www.aviso.oceanobs.com. For our study we have extracted data for the open sea region in the Baltic Proper. In this region the SLA time series are not contaminated by the presence of sea ice. Note that the SLA data are currently not available in near-coastal zones of the Baltic Sea owing to the radiometer land mask (but it will be possible to reprocess the data in the future and to extend the data coverage; see e.g. Madsen et al. 2007). We have analysed the data from 5 locations extending over the area of the Baltic Proper to evaluate the spatial variability. Our analysis has led us to the conclusion that from the statistical point of view the results are similar in all five locations (spatial variability does not influence the main conclusions drawn from our analysis). Therefore we describe in greater detail the results for only one open Baltic Sea location (indicated in Figure 1 as station 3). For comparison we have also analysed time series data from one location in the North Sea and one in the North Atlantic (stations 1 and 2 in Figure 1).

In addition, we have used daily data from the Stockholm coastal tide gauge station (station 4 in Figure 1). Research-quality daily data of relative sea level recorded at this station have been provided by the

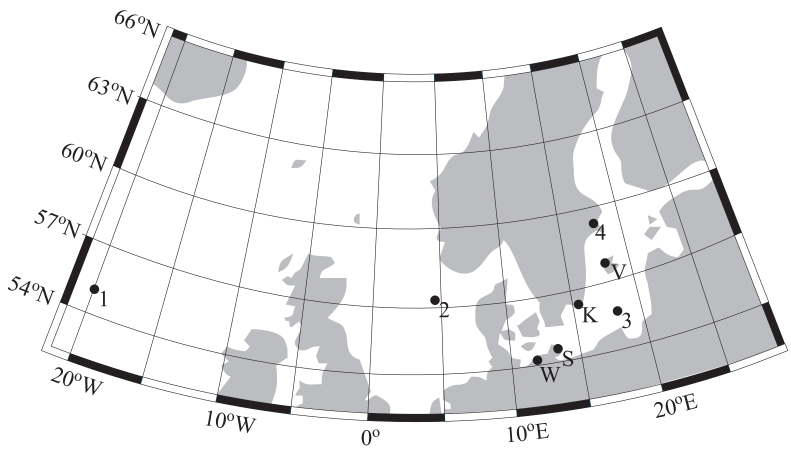

Figure 1. Map showing the geographical positions corresponding to the various time series data used in this study. (1 – North Atlantic, 2 – North Sea, 3 – open Baltic Sea, 4 – Stockholm, W – Warnemünde, S – Sassnitz, K – Kungsholmsfort, V – Visby)

University of Hawaii Sea Level Center (uhslc.soest.hawaii.edu). We have also used monthly averaged tide gauge records for Warnemünde, Sassnitz, Kungsholmsfort and Visby provided by the Permanent Service for Mean Sea Level (PSMSL, see http://www.psmsl.org and Woodworth & Player 2003). These data have been obtained from the PSMSL repository, and the basic quality-control procedures defined by the PSMSL have already been applied. Note that the local tide gauges measure sea level at a single location relative to the local land surface, which is why the measurement is referred to as relative sea level (RSL). RSL records are influenced by the fact that land surfaces are dynamic, with some locations rising or sinking in response to glacial isostatic adjustment (GIA, see Peltier 1998, 2004), tectonic uplift, and self-attraction and loading (SAL, e.g. Tamisiea et al. 2010). For our analysis, we have converted tide gauge data to SLA by subtracting the 7-year mean RSL (1993–1999), as was done with the satellite data.

River data for the Baltic Sea basin were taken from the HYPE model of the water runoff (model Balt-HYPE, data at balt-hypeweb.smhi.se) set up at the Swedish Meteorological and Hydrological Institute (SMHI). The model has been validated against daily river runoff values recorded within the framework of BALTEX (The Baltic Sea Experiment) and GRDC (the Global Runoff Data Centre) using a number of representative gauged basins upstream and at the river outlets (Donnelly et al. 2011). For our analysis we have used the reconstruction of historic water discharges in a daily time-step from 1993 to 2008. After 2008 such data ceased to be available.

Statistical estimates of standard deviation and skewness have been calculated according to (Stanisz 2006).

3. Results

In Figure 2 we have plotted the full 18-year long time series of the daily sea level anomalies (SLA) used in this study. These time series include the SLA in the open Baltic Sea, North Sea and North Atlantic, as well as coastal data from Stockholm. Visual inspection of these series leads to the conclusion that of all the SLA time series shown in Figure 2, the Baltic Sea data have the greatest amplitude of variability, while the data from the North Atlantic have the smallest amplitude. In addition, the coastal SLA data from Stockholm have a significantly larger standard deviation than the open Baltic Sea data (see Table 1). It is important to remember that there is some discrepancy in the spatial scales represented by the satellite and coastal data. All the satellite data used in this study are spatially averaged and gridded on a $1/3^{\circ}$ spatial resolution Mercator grid, while the coastal data are based on measurements made at a specified point in space. Thus,

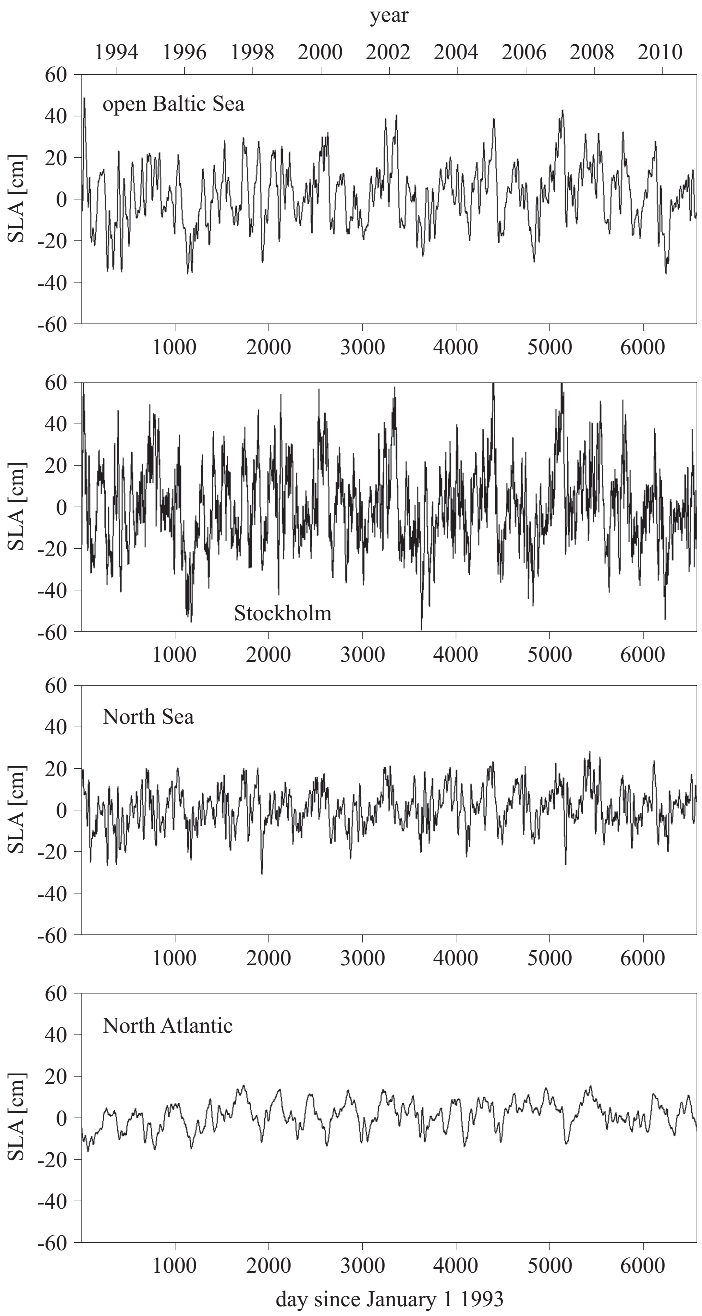

Figure 2. Time series of the 18-year daily sea level anomalies (SLA) used in this study. Data for the open Baltic Sea, North Sea and North Atlantic are based on the merged-mission satellite altimetry SLA data product. Coastal time series converted to anomalies are presented for Stockholm. Geographical locations for all the time series analysed in this paper are shown in Figure 1

Table 1. SLA seasonal cycle summary (based on the 18-year averaged detrended daily SLA time series)

Station	Position	Minimum SLA (day of the year)	Maximum SLA (day of the year)	Amplitude	Days when SLA is below average
open Baltic Sea	55.44N 18.33E	−11.17 (128)	6.99 (35)	18.17	52–172
Stockholm	59.32N 18.08E	−17.23 (122)	11.50 (19)	28.73	68–168
North Sea	56.93N 5.0E	−8.41 (107)	8.67 (351)	17.07	38–180
North Atlantic	55.06N 20.0W	−5.64 (69)	7.86 (276)	13.49	12–185

the observed large variability of SLA in Stockholm can be partly explained by the fact that these data were not spatially averaged.

There is much similarity between the patterns of variability in the SLA data from the Baltic and North Seas. This observation is in agreement with earlier reports that there is significant coherence between the coastal sea level data in the Baltic and North Seas (e.g. Ekman 2009, Stramska 2013). In Figure 3 the data have been redisplayed as time series plotted separately for every year (i.e. 1993–2010). Thus, each grey line in Figure 3 indicates daily data for a different year, and the thick black line represents the 18-year averaged daily time series. Figure 3 stresses the differences between the data sets analysed. The departure of the daily data from the 18-year average is the smallest in the North Atlantic, somewhat larger in the North Sea, larger still in the open Baltic Sea, while the data from the Stockholm coastal station exhibit the largest daily standard deviations of all the data sets shown in Figure 3 (see also Table 2). The 18-year average SLA displays a regular (symmetric) annual cycle in the North Atlantic, but when we look at the Baltic Sea SLA data, we note that the annual cycle is much less regular (more asymmetric). The period when the 18-year average daily SLA series in the open Baltic Sea are below the average value of 0 cm is shorter ($\sim$ 100–120 days) than the period when the 18-year average SLA series are above the average ($\sim$ 240–260 days, see Table 1). The annual cycle seems to be even more asymmetric at the coastal station in Stockholm than in the open Baltic Sea. In addition, the annual amplitude in the 18-year average daily SLA time series seems to be much more pronounced in the Baltic Sea data than in the North Sea data. The average amplitude of this cycle is more than 28 cm in Stockholm, about 18 cm in the open Baltic Sea, and about 17 cm the North Sea. The

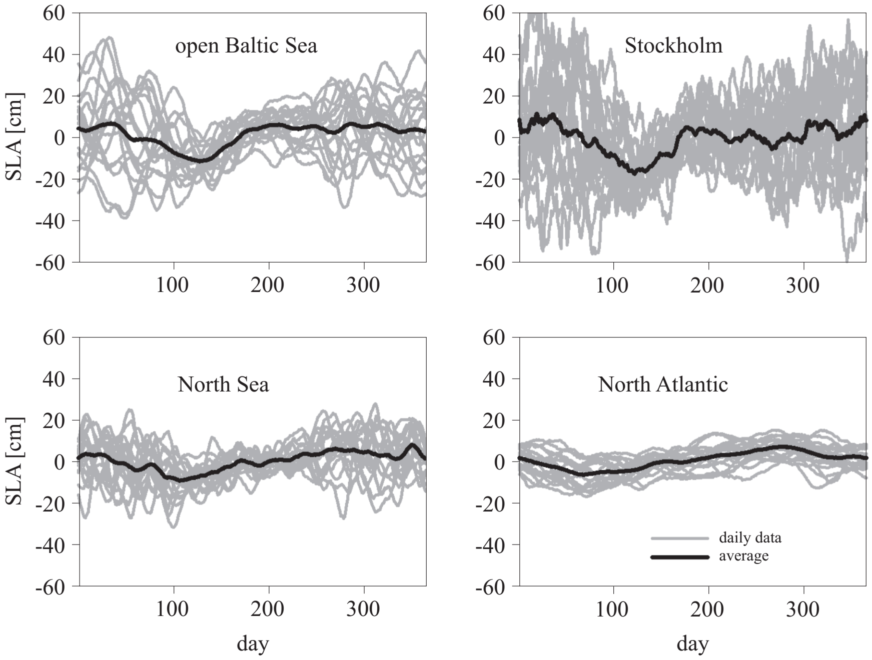

Figure 3. Annual records of the daily SLA in 1993–2010 (grey lines) and the 18-year averaged daily time series (black lines)

Table 2. Statistical information for the detrended 18-year daily SLA time series

Station	Standard deviation (STDEV) [cm]	Minimum STDEV (day of the year)	Maximum STDEV (day of the year)	Time when STDEV is below average	Skewness
Baltic Sea	14.24	4.71 (189)	22.87 (31)	108–261	0.08
Stockholm	19.47	8.04 (178)	33.56 (24)	95–259	0.29
North Sea	9.20	3.12 (206)	13.37 (313)	105–252	−0.04
North Atlantic	6.30	3.52 (154)	6.97 (49)	not well defined	−0.13

smallest amplitude of the average seasonal cycle ($\sim$13.5 cm) is observed in the North Atlantic. What is more, in Figure 3 we observe that the interannual variability of the SLA is more pronounced in the winter and autumn (larger data spread) than in the spring and summer. This is also

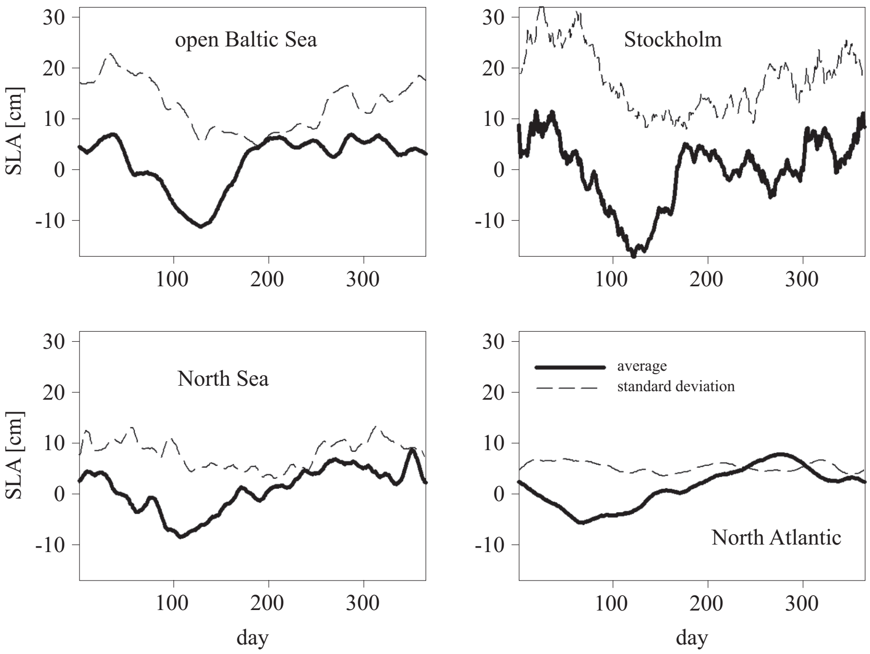

Figure 4. Comparison of annual patterns in the 18-year averaged daily SLA (solid line) and daily standard deviations (dashed lines)

illustrated in Figure 4, where we have plotted time series of the 18-year average daily SLA and time series of the daily standard deviations estimated from the 18-year time series. The data shown in Figure 4 indicate that there is a prominent annual cycle of the daily SLA standard deviation (STD) in the Baltic Sea and North Sea data, with significantly larger STD values in winter and in autumn and smaller ones in spring and summer. STD values are generally highest in the Baltic Sea and lowest in the North Atlantic. The annual cycle of variability of STD in the North Atlantic is not well pronounced. Note also that the annual patterns in the 18-year average daily SLA time series and time series of the 18-year daily standard deviations are shifted in time with respect to each other. The minimum in the 18-year average daily time series is observed earlier than the broad minimum in the STD (see Figure 4). On average the annual minimum in the SLA time series is observed earliest in the year in the North Atlantic ($\sim$ day 69), later in the North Sea (day 107) and finally in the Baltic Sea ($\sim$ day 125). This regional shift in the timing of the annual minimum is not evident in the time series of the STD, which are characterized by a rather broad and poorly defined annual minimum.

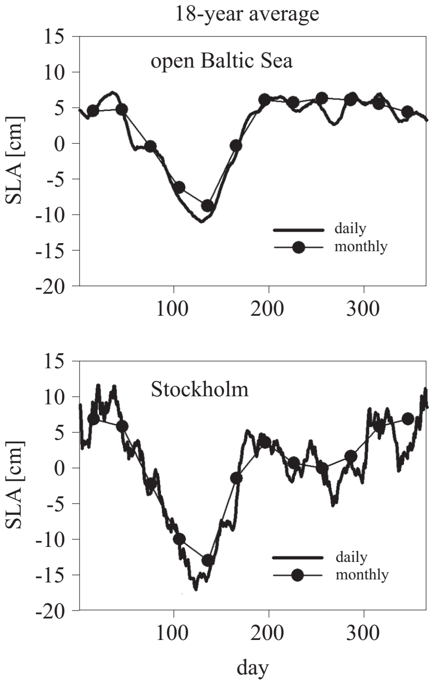

Figure 5. Comparison of the seasonal cycle of SLA based on the 18-year averaged daily and monthly time series for the open Baltic Sea and Stockholm respectively

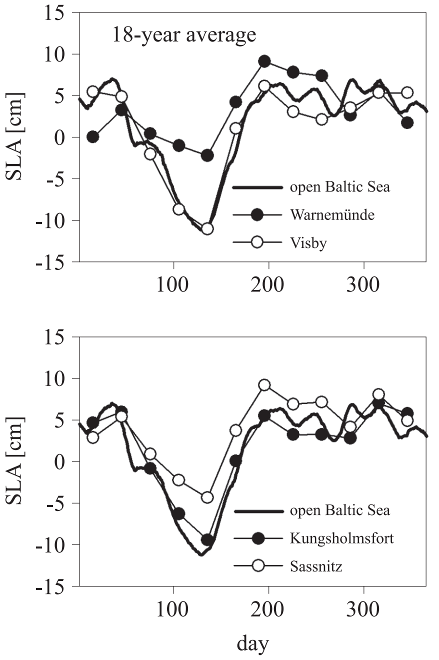

Figure 6. Comparison of the seasonal cycle of SLA in the open Baltic Sea (18-year averaged daily SLA data) and at coastal stations in Warnemünde, Visby, Kungsholmsfort, and Sassnitz (18-year averaged monthly data)

Earlier research on the seasonal cycle of the Baltic Sea level was usually based on monthly coastal data (e.g. Ekman 2009). The results stressed that the amplitudes of the annual cycle observed at different coastal stations could vary significantly. In addition, it was reported that there was a significant increase in the amplitude of the annual cycle in recent years (e.g. Hunicke & Zorita 2008). However, a recent spectral analysis based on the 20 years of the 7-day resolution SLA data for the open Baltic Sea revealed that the seasonal variability is associated with a well-pronounced semi-annual peak and that the annual peak is not significant in the SLA power spectra (Stramska 2013). This raises the question whether this discrepancy is due to the fact that monthly data significantly deform the shape of seasonal cycle in comparison to higher resolution data. To look more closely into this issue we have overlain in Figure 5 the daily and monthly SLA data in the open Baltic Sea and in Stockholm. It seems that the main features of the seasonal cycle (including its asymmetry) are reflected rather well in the monthly data. Additionally, coastal data from Warnemünde, Visby, Kungsholmsfort and Sassnitz superimposed on the open Baltic Sea daily SLA data are shown in Figure 6. These data support the earlier findings that there can be a significant difference in the amplitude of the observed seasonal cycle between different coastal stations. To examine

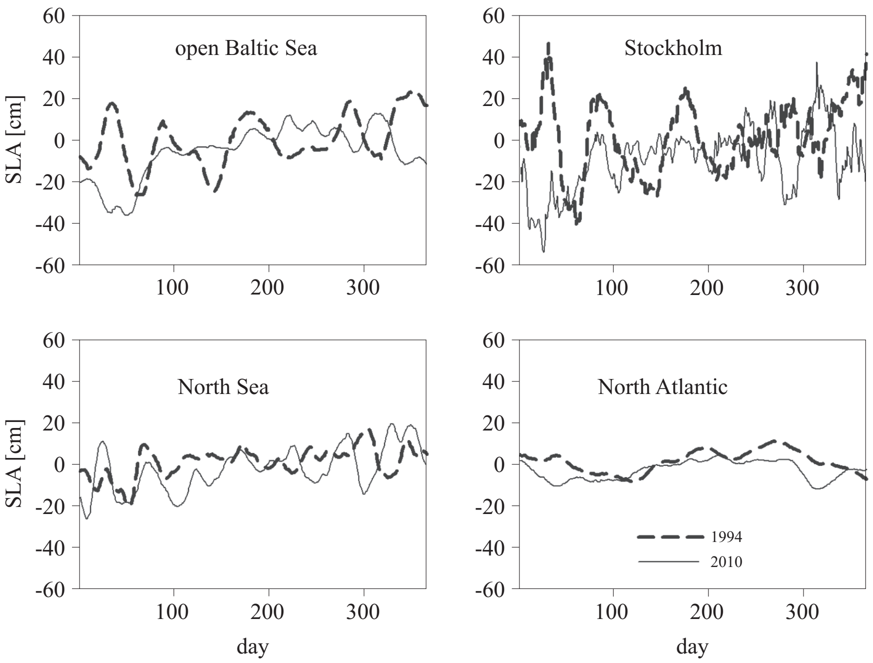

Figure 7. Daily time series of the SLA in years 1994 and 2010. This Figure shows that in some years the annual cycle is not evident in the time series data

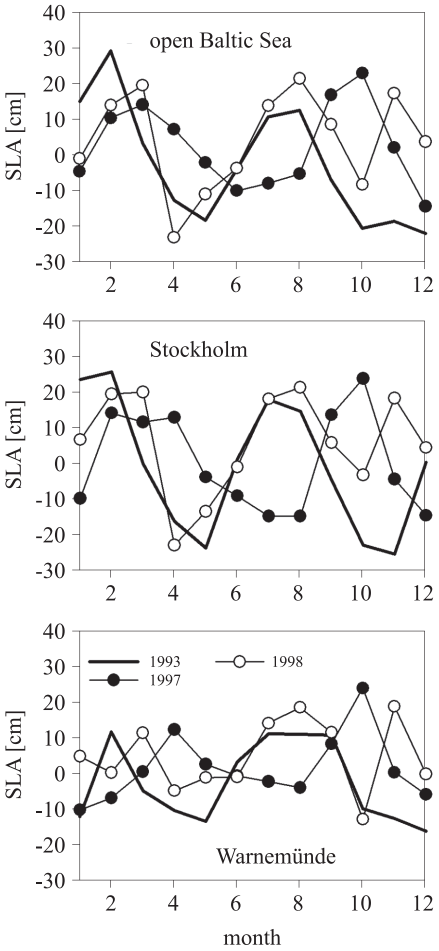

Figure 8. Example monthly averaged SLA data showing that the annual variability in some years is dominated by the semi-annual cycle

the seasonal SLA variability in greater detail, we have plotted examples of daily and monthly SLA time series for selected years in Figures 7 and 8 respectively. These examples clearly show that the annual cycle is often not well pronounced in the Baltic Sea annual time series, and that a shorter-term variability can dominate the annual cycle.

We have compared the SLA time series displayed in Figure 2 to the normal (Gaussian) distributions. This is shown in Figure 9, where the histograms are based on detrended experimental data and the solid line indicates the Gaussian probability density function calculated assuming the values of the mean and standard deviation estimated from the detrended time series data (shown as histograms). The histograms for different geographical locations are different. In particular, the distribution is narrowest for the North Atlantic data and widest for the Stockholm coastal time series. In all cases the experimental data depart from the normal

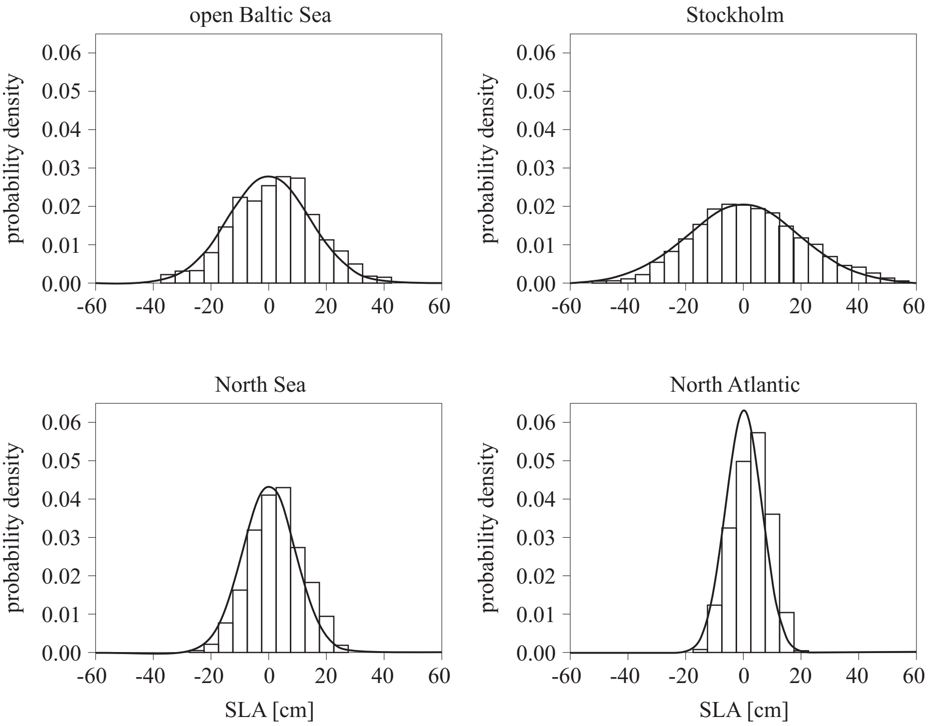

Figure 9. Histograms for detrended SLA time series and corresponding normal probability density distributions obtained using mean and standard deviation estimates from experimental data shown as histograms

distribution, but this departure is minimal. The skewness is negative for the North Sea and North Atlantic data and positive for the open sea and coastal Baltic Sea data sets. To evaluate the seasonal variability of the SLA frequency distribution we have also estimated the skewness for the 18-year data series grouped into monthly data sets (Figure 10). The results shown in Figure 10 indicate that there is a seasonal pattern in the skewness, with the maximum skewness in April in the open Baltic Sea and Stockholm data.

The interannual variability in the two contrasting phases of the seasonal cycle of the SLA can be linked to some regional processes. In winter the SLA variability has the largest means and standard deviations. The interannual variability of the winter SLA data in the Baltic and North Seas is closely related to the large-scale climate variability. This conclusion is based on a significant correlation between the Hurrell NAO index and the winter averaged SLA in the Baltic and North Seas (e.g. Ekman 2009; see also Stramska & Chudziak (2013) for the satellite altimetry data). A similar correlation is statistically not significant in the North Atlantic. In spring

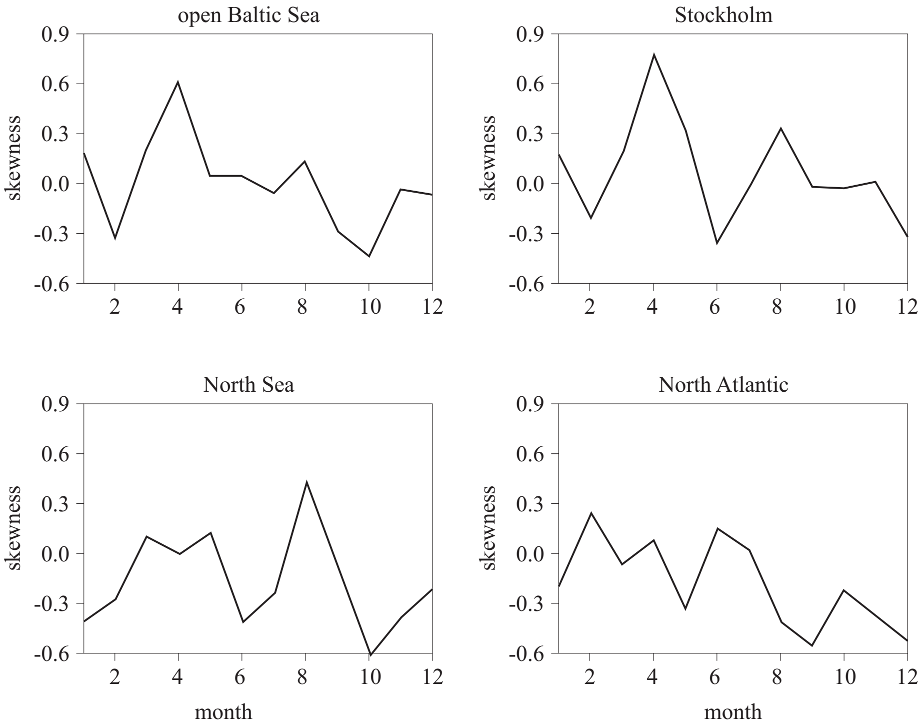

Figure 10. Seasonal changes of the skewness based on the 18-year daily SLA data grouped into consecutive months

(May) the SLA data in the Baltic Sea are characterized by the lowest means and standard deviations. Our analysis indicates that the spring SLA data in the Baltic and North Seas do not show a statistically significant correlation with the NAO index. Other authors (e.g. Ekman 2009) have reached similar conclusions, based on coastal data. Another possibly important reason for the interannual variability of the SLA in the Baltic Sea in spring is river runoff. Let us recall that the hydrography of the semi-enclosed Baltic Sea is significantly influenced by rivers: this is seen, for example, in the annual water salinity patterns (Leppäranta & Myrberg 2009) and in the satellite ocean colour data for the open Baltic (Stramska & Świrgoń 2013). The river runoff into the Baltic Sea basin has its maximum average and standard deviation values in April–May (Figure 11), i.e. at the time of the year when the sea level variability is at its lowest and when wind forcing is relatively low. Therefore, it would seem that in spring the situation should be the most favourable for detecting the influence of water runoff on the interannual SLA variability in the Baltic Sea. However, the results of our analysis (an example for the month of May is shown in Figure 12) indicate that the influence of rivers on interannual SLA variability is not significant

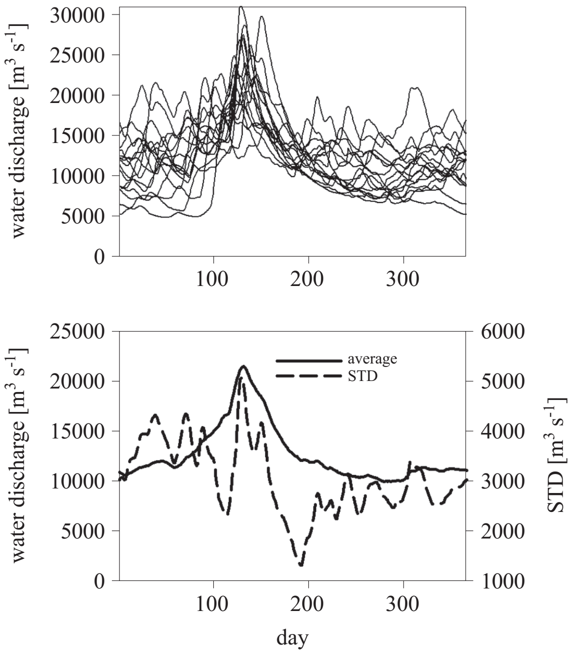

Figure 11. (Upper panel) Daily time series from 1993–2008 of the water discharged into the Baltic Sea by the 75 largest rivers (based on the Balt-HYPE model, data from balt-hypeweb.smhi.se). (Lower panel) Comparison of annual patterns in the 15-year averaged river runoff (solid line) and its daily standard deviations (dashed lines)

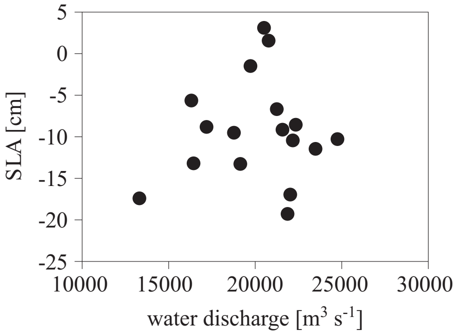

Figure 12. Example scatterplot showing the lack of correlation between the monthly averaged SLA and river runoff in the month of May, based on data from 1993–2008

at any time of the annual cycle. Most likely other influences (in particular wind and air pressure variability) have stronger effects on the SLA, so it is not possible to document the impact of river runoff using the simple correlational analysis approach applied in this study.

4. Summary

There have been a few attempts to use satellite altimetry data in the Baltic Sea in the past. These include the analysis of sea levels (e.g. Poutanen & Stipa 2001, Madsen et al. 2007) and validation of operational wave models (Sølvsteen & Hansen 2006). In this paper we have applied the 18-year SLA time series to investigate the seasonal cycle of sea level variability in the Baltic Sea. Our results indicate that there is a well-pronounced seasonal cycle in the 18-year averaged sea level and in its standard deviation. The average annual SLA amplitude in the Baltic Sea is ~ 18 cm. The shape of the seasonal cycle of the SLA in the Baltic Sea is asymmetric. In autumn and winter (about 240–260 days per year), the 18-year average daily SLA are higher than the 18-year annual average SLA. In spring and summer (about 120 days per year), the 18-year average daily SLA are lower than the 18-year annual average SLA. A similar asymmetry was not observed in the North Sea and North Atlantic SLA data. It is important to stress that the annual pattern of sea level variability in the Baltic Sea is observed only if one considers multi-year average time series. In the single annual SLA time series, one can often observe minimum SLA values in winter, when the average data records show the highest sea levels. The annual cycle of the SLA standard deviation is characterized by the largest values in winter. We have also found that the probability density distribution of SLA in the Baltic Sea is characterized by a small, but statistically significant departure from the normal distribution and that the skewness of the distribution changes seasonally.

The annual sea level cycle has been described in the past based on global (e.g. Pattullo et al. 1955, Tsimplis & Woodworth 1994, Vinogradov et al. 2010) and regional data sets (e.g., Plag & Tsimplis 1999, Hunicke & Zorita 2008, Dangendorf et al. 2012). In general, amplitudes of the annual sea level cycle in the open ocean are less than 15 cm and are typically larger in the Northern Hemisphere than in the Southern Hemisphere. On the European side of the North Atlantic Ocean annual amplitudes generally increase from south to north. Recent detailed comparisons of the annual sea level cycle based on tide gauges and altimetry data records (Vinogradov et al. 2010) lead to the conclusion that the amplitudes of the annual cycle recorded by tide gauges are usually amplified in comparison to the altimetry-detected seasonal cycle. In addition, the annual cycle is generally enhanced in shallow water regions in comparison to deep waters, with differences in phases of about 1–2 months. We have noted that the SLA annual cycle in the open Baltic Sea is consistent in different locations in the open Baltic Proper (based on satellite altimetry data). In contrast, the shape of the annual cycle observed at the Baltic Sea coastal stations depends on their geographical location. These differences between the coastal and open sea SLA annual cycle can be attributed, for example, to gradients in atmospheric fluxes at land/sea boundaries, impacts of seasonal patterns in coastal circulation and interactions with topography, river influences etc.

The discrepancies between the SLA annual cycle observed in the open sea and at coastal stations have to be taken into account if one wants to develop an improved understanding of the oceanographic process affecting the entire Baltic Sea. For example, tide gauge data may be of limited use for assimilation into the numerical models of the Baltic Sea. This is in contrast to satellite altimetry data, which provide consistent and stable data sets, reflecting the annual cycle in the open sea regions. A similar observation was made when we analysed the sea level trend in the Baltic Sea (Stramska & Chudziak 2013). We concluded that if one is interested in changes of the absolute sea level in the Baltic Sea in comparison to the open ocean trends, one ought to use a consistent multi-year sea level trend in the Baltic Sea derived from satellite altimetry. This trend differs significantly from trends derived from tide gauge data.

In the future, it will be extremely important to carry out a reanalysis of the satellite altimetry data in the Baltic Sea, using novel approaches of coastal altimetry (e.g. Bouffard et al. 2008, 2011, Vignudelli et al. 2011). The reanalysed data would be characterized by improved spatial and temporal resolution in comparison to the traditional altimetry data used in this study. In particular, the coverage in coastal regions would be significantly improved, as coastal altimetry methods allow the data to be recovered from as near to the coast as about 2–5 km. It would be interesting to analyse the spatial variability of the SLA data in coastal regions of the Baltic Sea. Such an analysis would undoubtedly lead to an improved understanding of tide gauge data records and how they can be used to infer information pertinent to the basin scale processes in the Baltic Sea. Oceanographic research in the Baltic Sea would greatly benefit from consistent, high-resolution altimetry data combined with the tide gauge data sets.

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