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Temporal variability of the Baltic Sea level based on satellite observations

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The main objective of this paper is to determine what are the most important time scales of variability of the sea level in the open Baltic Sea. The study is based on the 7-day resolution multimission global gridded sea level anomalies (SLA) for years 1992–2012 distributed by AVISO. For comparison satellite-derived SLA from the North Sea and North Atlantic, coastal data from the Stockholm tide gauge, the NCEP meteorological data, and river runoff data from the Balt-HYPE model have been also analyzed. We have applied time series analysis algorithms (Bendat and Piersol, 2011). Supporting earlier research, our results show that the variability of the sea level in the open Baltic Sea is highly coherent with the sea level in the North Sea. We have found out that the annual peak is not well pronounced in the open Baltic Sea SLA spectrum, but the semiannual peak is the most prevailing. In contrast, the annual peak is significant in the North Sea SLA power spectrum. The coherence between the open Baltic Sea and the Stockholm SLA is high and the SLA variability in these two locations is in phase. The results of the cross-spectral analysis between the SLA in the Baltic Sea and meteorological parameters (wind stress magnitude, zonal and meridional wind stress components, and barometric pressure at sea level) show that coherence is highest with the zonal wind stress component. Coherence between the river runoff and the SLA in Stockholm is not significant.

1. Introduction

One of the most direct pieces of evidence of climate change is the observed rise of globally averaged sea level (IPCC, 2007; Meehl et al., 2007; Rahmstorf, 2007; Horton et al., 2008; Church et al., 2010). Because of possible negative consequences for safety and regional economy, the impacts of sea level rise are of particular concern in coastal regions. These regional trends can differ significantly from global trends. One region where sea level has been closely monitored for many years is the landlocked, non-tidal Baltic Sea, located in densely populated northern Europe. Understanding sea level trends and variations in this region is crucial, because of their impacts on coastal infrastructure, and also because of their links with the mechanisms of exchange of water between the Baltic and the North Seas (Samuelsson and Stigebrandt, 1996; Gustafsson and Andersson, 2001; Ekman, 2009). This exchange has a key influence on water balance, deep-water renewal rates, and other oceanographic processes in the Baltic Sea. In particular, the major events of oceanic water inflow affect the eutrophication status of the Baltic Sea (e.g., Omsted et al., 2004; HELCOM, 2009; Leppäranta and Myrberg, 2009).

Previous research on Baltic Sea levels has been mostly based on coastal tide gauge time series data (e.g. Ekman and Makinen, 1996; Hünicke and Zorita, 2006, 2008; Hünicke et al., 2008; Ekman, 2009; Donner et al., 2012). This research has greatly increased our understanding of the spatial and temporal variability of the Baltic Sea levels. For example, it has been shown that trends in local sea levels recorded by coastal stations vary with the geographic positions of these stations (e.g., Ekman, 2009). It has been also documented that the variability of the Baltic Sea level is significantly correlated with large-scale wind and air pressure fields, which are strongly influenced by the North Atlantic Oscillation (NAO) index (e.g., Andersson, 2002; Jevrejeva et al., 2005; Ekman, 2009; Stramska and Chudziak, 2013). Other meteorological quantities such as air temperature and precipitation also considerably influence the level of the Baltic Sea (Hünicke and Zorita, 2006).

Interpretation of the tide gauge data in terms of the basin scale trends and patterns of variability of the Baltic Sea level can be difficult. Nonuniform spatial distribution of tide gauges, tectonic land uplift and regional postglacial rebound rates, as well as topographic effects can have substantial impacts on the interpretation of data recorded by coastal stations (e.g., Peltier, 1998, 2004;

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Soudarin et al., 1999; Tamisiea et al., 2010). In contrast, these issues should not confound analysis of the open sea levels obtained from satellite altimetry. In the last 20 years satellite altimetry methods (TOPEX/Poseidon, ERS-1 and -2, GFO, Envisat, Jason-1 and 2) for routine monitoring of sea levels have been increasingly popular and are now used as a standard of reference (e.g., Cotton et al., 2004; Bouffard et al., 2008, 2011; Vignudelli et al., 2011). Satellite measurements of sea levels allow us to take a unique look at sea levels globally and regionally (e.g., Leuliette et al., 2004; Church and White, 2006; Nerem et al., 2010; Vignudelli et al., 2011).

The main objective of this paper is to determine what are the most important time scales of variability in the Baltic Sea level observed from satellites. Previous studies investigating the Baltic Sea level variability were mostly based on long-term (50 years and more) monthly coastal data records (e.g., Ekman and Stigebrandt, 1990; Ekman, 2009; Plag and Tsimplis, 1999; Hünicke and Zorita, 2008). In comparison to these previous studies, our analysis is based on open sea satellite-derived data that are not affected by coasts and have better temporal resolution (weekly data), though time series data available for our analysis are considerably shorter (about 20 years). Therefore our research is focused on the most recent variability of Baltic Sea level. Our research should be of interest to regional physical oceanographers and to modelers who are interested in using altimetry data for improving their models. A target audience includes also researchers and coastal managers interested in better understanding conditions favoring the occurrence of storm surges and coastal erosion.

2. Data sets and methods

This study is based on Sea Level Anomalies (SLA) extracted from the delayed time (DT) multimission global gridded data product available at AVISO (www.aviso.oceanobs.com). The SLA data are continuously updated by AVISO and referenced to the 7-year (1993–1999) mean sea surface height. For this study we have used all the available DT SLA data, covering the time period from October 4, 1992 to July 18, 2012 (almost 20 years). The SLA data have been interpolated by AVISO on 1/3° spatial resolution Mercator grid with 7-day temporal resolution, using computing methods based on objective analysis. The error in the SLA data estimated by AVISO is about 1–2 cm. Thus, these research quality data allow monitoring of ocean sea level variability due to seasonal and climatic variations. Detailed information about standard data processing methods can be found at www.aviso.oceanobs.com. For our study we have extracted data for the open Baltic Sea, in a region that is not likely to be affected by sea ice (55.44°N, 18.33°E). For comparison we have also used satellite altimetry data from the North Sea (56.93°N 5.0°E) and the North Atlantic (55.06°N, 20.0°W) (see Fig. 1). Another data set used in our study includes the coastal tide gauge records from Stockholm. Research quality daily data of relative sea levels recorded at this station have been provided by the University of Hawaii (Sea Level Center, uhslc.soest.hawaii.edu). Note that the local tide gauges measure sea level relative to the local land surface, this is why the measurement is referred to as the "relative sea level" (RSL). Land surfaces are dynamic, and in particular the glacial isostatic adjustment (GIA, see Peltier, 1998, 2004) is known to affect the relative sea level recorded in Stockholm. However these vertical movements of land should not significantly affect the periodic variability of the SLA on scales as short as ~2 years and less, which are considered in this paper. For our analysis, we have converted tide gauge data to sea level anomalies by subtracting the 7-year mean (1993–1999) from the original time series.

To evaluate the role of atmospheric forcing we have used the meteorological data from the NOAA-CIRES Climate Diagnostic Center NCEP/NCAR (National Centers for Environmental Prediction and National Center for Atmospheric Research) Reanalysis 2. The Reanalysis Project employs a state-of-the-art analysis/forecast system to assimilate global meteorological data from various available sources from 1948 to the present. In particular we have used the daily zonal and meridional wind stress components and barometric pressure at sea level. The NCEP data from 1992 to 2012 were extracted for locations in the open Baltic Sea (56.19°N, 20.63°E) and in the North Sea (56.19°N, 5.63°E). In addition, in our analysis we have also used river runoff data for the Baltic Sea basin. These data were taken from the HYPE model for years 1988–2008 (model Balt-HYPE, data at balt-hypeweb.smhi.se, Donnelly et al., 2011). The hydrological Balt-HYPE model has been driven by data from the NCEP reanalysis and verified with in situ data (Donnelly et al., 2011). After 2008 HYPE model data were not available.

To define the most important temporal scales of variability of the SLA, we performed a time series analysis using algorithms described by Bendat and Piersol (2011). First, we subtracted off a linear trend, which was fitted to each time series record by a least-square method. A series transformed this way had a mean value of virtually zero. Next, the power spectra of the data series were

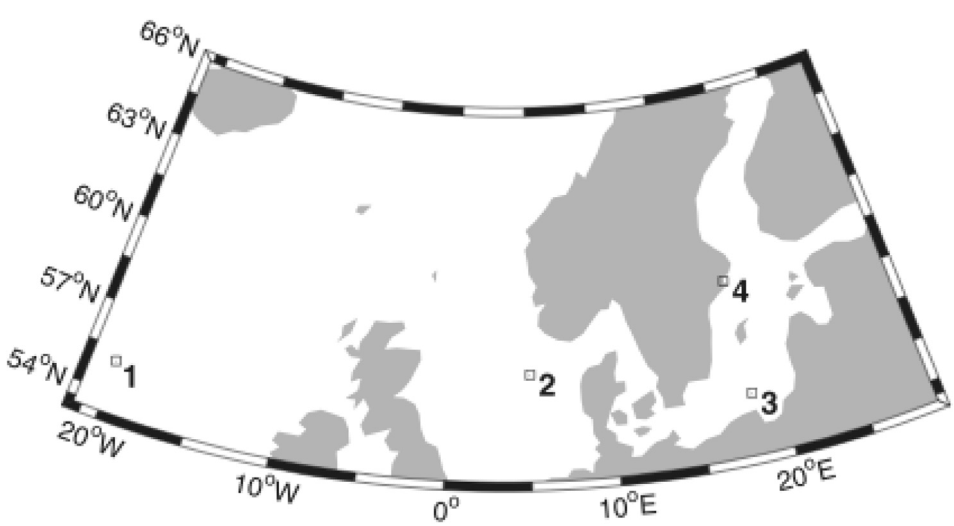

Fig. 1. Map showing the geographical positions corresponding to the data series used in this paper: 1 – North Atlantic, 2 – North Sea, 3 – open Baltic Sea, 4 – Stockholm.

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obtained using a Fourier transform of the autocovariance function. To describe joint properties of the time series considered, we applied a Fourier transform to the crosscovariance functions and estimated squared coherence and phase functions. The Parzen weighting function was applied to the covariance functions. According to the Nyquist theorem our analysis is limited to periods longer than 14 days, or more conservatively longer than 28 days (Bloomfield, 2000). Thus, the relatively rapid variations of sea level in response to wind events on time scale of few days are not included in our analysis. Despite of these limitations our analysis covers a range of scales that are of interest in the Baltic Sea.

In all cases considered here, each time series record consists of a total number of $N = 1024$ data points. The auto- and cross-covariance functions were calculated with the maximum time lag $M = 150$. This corresponds to the frequency resolution bandwidth of 0.00095 cycle/day. The M value of 150 is a little beyond the value usually recommended ($M = 0.1N$), but this higher value of M increased the spectral resolution. Tests with gradually increasing the time lag from 100 to 150 indicated that the calculated spectra changed smoothly, and there were no spurious effects. Therefore all Figures included in the Results section are based on calculations with $M = 150$. The standard error is ~34% of the power spectral estimates. The coherence above 0.283 is statistically significant at 95% confidence level (Bloomfield, 2000).

3. Results and discussion

In Fig. 2 we have plotted full (~20-years long) time series of the 7-day resolution sea level anomalies (SLA) used in this study. Time series shown in Fig. 2 include the SLA in the North Atlantic, North Sea, and open Baltic Sea (Baltic Proper). In addition sea level anomalies based on Stockholm observations are plotted in Fig. 2. It is clear that there are many scales of variability present in the data. Visual inspection of the time series leads to the conclusion that many patterns of variability are similar in the Baltic and North Seas SLA time series. It is also obvious that the time series from the coastal station in Stockholm are characterized by the greatest amplitude of variability (standard deviation = 18.8 cm), while the data from the North Atlantic have the smallest amplitude (standard deviation = 6.5 cm). The standard deviations for the SLA time series in the open Baltic Sea and North Sea are 14.2 and 9.3 cm, respectively. These standard deviations were estimated after removing a small multiyear trend (for example 0.33 cm/year in the open Baltic Sea, Stramska and Chudziak, 2013).

The power spectra estimated for the SLA in the open North Sea and North Atlantic are displayed in Fig. 3a. Fig. 3b compares the power spectra obtained for the SLA time series in the open Baltic Sea and at the coastal station in Stockholm. The spectra are plotted as a function of frequency, but for convenience we have marked on

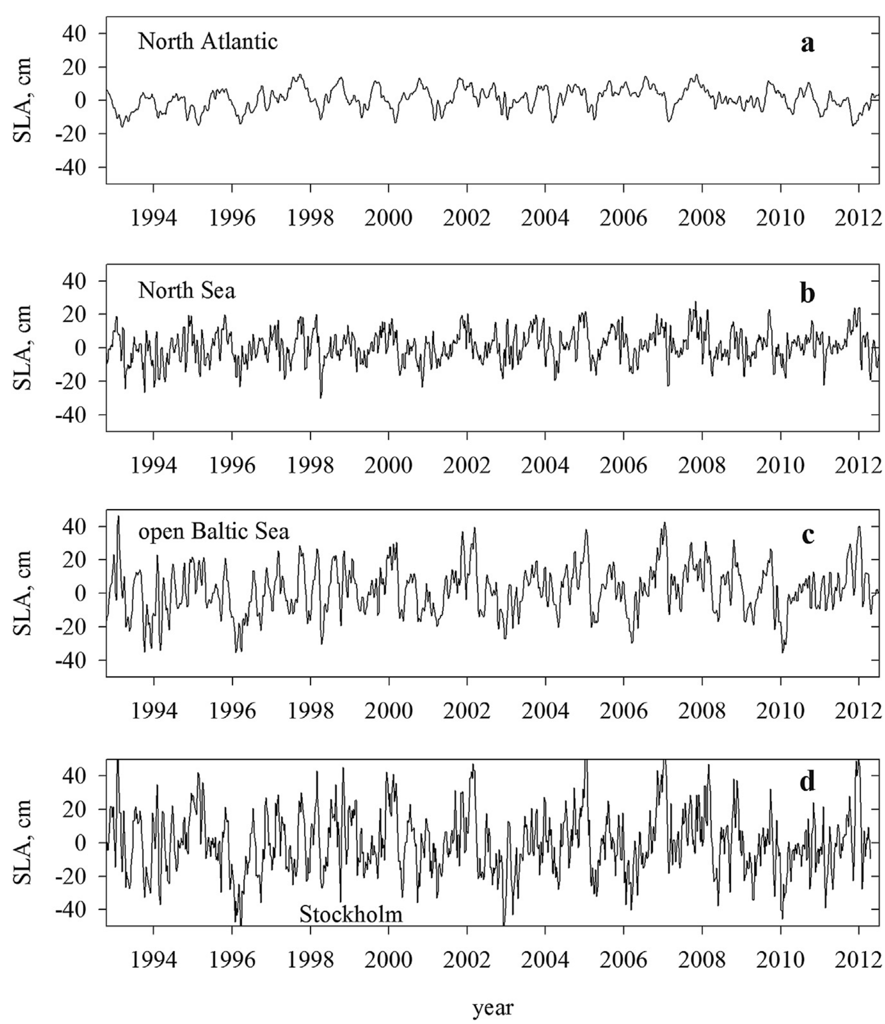

Fig. 2. Time series of sea level anomalies (SLA) used in this study. See Fig. 1 for the geographical position corresponding to each of the time series.

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the bottom axis (black dots) the periods of 2 years, 1 year, 6 month, and 3 month. The most dominant peak in the SLA power spectra in the North Atlantic and North Sea is the annual peak. In contrast the annual peak is not well pronounced in the open Baltic Sea and Stockholm power spectra. This can be also noticed in Fig. 4, where we compared the normalized power spectral density for the SLA in the open Baltic Sea and Stockholm with the normalized power spectral density of the wind stress magnitude in the Baltic Sea. The power spectra displayed in Fig. 4 are normalized to the total variance of each data set, respectively. The power spectrum of wind stress magnitude exhibits a striking annual maximum. The power spectra of the SLA in the open Baltic and Stockholm have statistically significant peaks (95% level) for the time periods of ~2 years, 6 months and 3 months. The annual peak is not significant. The 6-month peak is also present in the North Sea data, but not in the North Atlantic data (Fig. 3). The fact that the annual peak is not well pronounced in the Baltic Sea time series (coastal and open sea data) might seem somewhat surprising. This peak has been described before in the literature (see Hünicke and Zorita, 2008; Ekman, 2009; and the references therein). Note however, that these previous results were based on monthly data and long data records (50 years and more). Longer data records might be more efficient in separating the annual cycle, in particular if this cycle is well defined and strong in some years.

Importantly, as has been noted by Ekman (2009), the annual cycle in the Baltic Sea level is somewhat asymmetrical and can be decomposed by the spectral analysis into two or more harmonics. This asymmetry of the annual sea level cycle in the Baltic Sea is also seen in our data sets (Fig. 5). The 19-year averaged SLA shown in Fig. 5 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 quite asymmetric. The time period when the SLA series in the open Baltic Sea are below annual mean value is shorter than the time period when the average SLA series are above the annual mean value. In addition, the annual amplitude in the averaged SLA time series seems to be much more pronounced in the Baltic Sea data than in the North Atlantic data. We suggest that the monthly averaged Baltic Sea level data might lead to some deformation of the temporal progression of the annual cycle, making it seem to be more symmetrical than it really is. The 7-day data can likely better resolve the time evolution of this cycle than the monthly data. In this case, the 7-day time series data (better resolving the asymmetry of the annual cycle) can lead to a more pronounced semiannual peak in a power spectrum in comparison to the power spectrum based on monthly data. Therefore, the annual peak in the power spectrum based on the 7-day data would be weaker than in the power spectrum based on the monthly data.

Figs. 6–8 summarize the results of the cross-spectral analysis between selected pairs of the SLA time series. In these figures solid and dashed lines indicate the squared coherence and phase functions, respectively. The coherence above 0.283 is statistically significant at 95% level (Bloomfield, 2000; Bendat and Piersol, 2011). Note that for an ideal linear system the coherence would be one. Our data sets are generally characterized by coherence less than one. This can result from not quite a linear response of the system. In addition a coherence less than unity can be due to the fact that

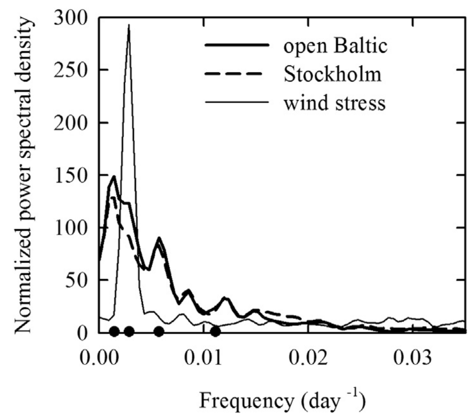

Fig. 4. Comparison of the normalized power spectral density for SLA in the open Baltic Sea and at coastal station in Stockholm with the normalized power spectral density of wind stress magnitude. Power spectra are normalized to the total variance. The frequencies corresponding to periods of 2 years, 1 year, 6 month, and 3 month are marked by black dots on the *X* axis.

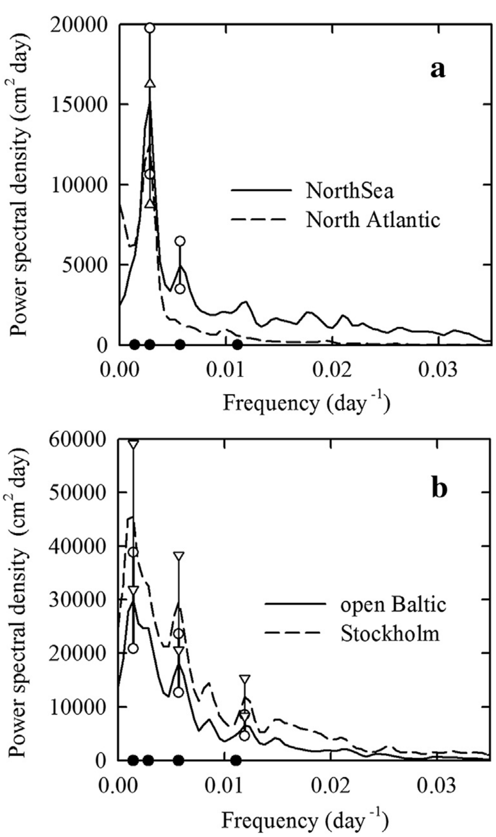

Fig. 3. Power spectral density of SLA calculated from time series shown in Fig. 2. a) North Atlantic and North Sea. b) Open Baltic Sea and Stockholm. Vertical bars indicate standard errors of the most significant peaks. The frequencies corresponding to periods of 2 years, 1 year, 6 month, and 3 month are marked by black dots on the *X* axis.

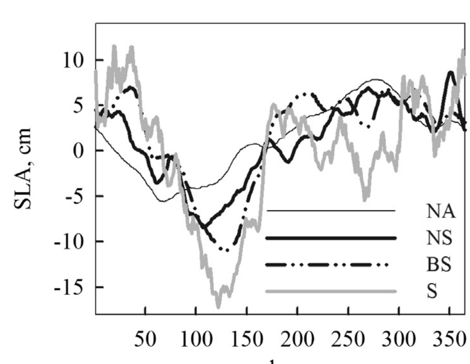

Fig. 5. Annual cycle in the 19-year averaged SLA in the North Atlantic (NA), North Sea (NS), open Baltic Sea (BS) and Stockholm (S).

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other inputs (not included in the analysis) contribute to the observed output (SLA variability). Nevertheless, the coherence values displayed in Figs. 6–8 indicate that the data series are significantly correlated with each other in some frequencies. In particular, in Fig. 6 we can see that the coherence between SLA in the North and Baltic Seas is above 0.3 for frequencies lower than 0.007 and higher than 0.022 cycle/day (periods longer than about 140 days and shorter than about 45 days). A similar pattern is observed in Fig. 7 for the coherence spectrum between the SLA in the North Sea and in Stockholm, but the coherence values are lower. The highest coherence among the SLA data sets considered is, as one would expect, between the SLA in the open Baltic Sea and in Stockholm (Fig. 8). In this case the coherence is around 0.7 for frequency lower than 0.007 cycle/day (periods >140 days) and varies between 0.5 and 0.8 for periods between 50 and 150 days. We have also estimated the coherence between the SLA in the open Baltic Sea and in the North Atlantic, but these SLA time series are not significantly correlated (results not shown).

The dashed lines in Figs. 6–8 indicate the phase shift between various time series. The SLA in the open Baltic Sea and in Stockholm are in phase with the SLA in the North Sea at lower frequencies. At higher frequencies the Baltic Sea SLA are delayed in comparison to the SLA in the North Sea (Figs. 6 and 7). The observed oscillations of phase are meaningless when there is not significant coherence between the data series. The SLA in the open Baltic Sea and in Stockholm (Fig. 8) are in phase and the phase spectra vary smoothly, which is indicative of a good correlation. The small slope in the phase spectrum can indicate that there is a time delay of few days between the data series. This time delay is consistent with the observations that SLA variability on the time scales considered is mainly caused by persistent winds redistributing water between the Atlantic Ocean (the North Sea) and the Baltic Sea (e.g., Ekman, 2009). If we assume the current speed of ~1 m/s we can estimate that it will take about 3.5 days to transport the water mass over a distance of 300 km. Thus the time delay of few days is not unrealistic when considering a relationship between SSH in distant locations of the Baltic Sea. Because our system is not quite linear, the estimated phase function is not exactly a simple straight line.

Summarizing these results, it is evident from our analysis that the SLA variability in the Baltic Sea is coherent with the SLA variability in the North Sea. This observation is in agreement with previous analyses of the Baltic Sea level data (e.g. Ekman, 2009). Note that prior publications stressed that annual patterns in the Baltic Sea level variability recorded by the tide gauges depend on the geographical location of the tide gauge (e.g., Hünicke and Zorita, 2008). One of the reasons for this is that sea level

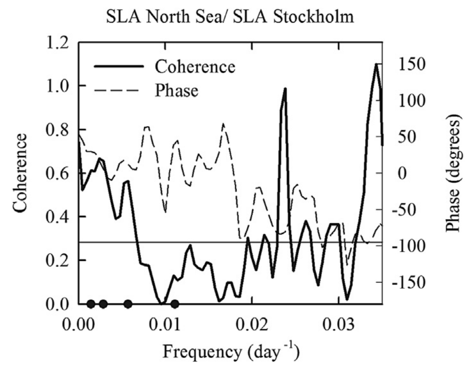

Fig. 7. Squared coherence (solid line) and phase functions (dashed line) between the SLA in the North Sea and at the coastal station in Stockholm. Horizontal line indicates that the coherence >0.283 is significant at 95% confidence level. The frequencies corresponding to periods of 2 years, 1 year, 6 month, and 3 month are marked by black dots on the *X* axis.

variability observed at a coastal station is significantly influenced by the geometry of the coast and the direction of the wind. This is also most likely the reason why the coherence between the SLA in the open Baltic Sea and in Stockholm is significantly less than one, while the coherence between the satellite-derived SLA in different parts of the Baltic Proper (results not shown) is approximately equal one in the frequency range discussed here.

We have attempted to check what are the links between atmospheric forcing and the SLA in the Baltic Sea. The results of the cross-spectral analysis between the meteorological parameters (wind stress magnitude, zonal and meridional wind stress components, and barometric pressure at sea level) and the SLA in the open Baltic Sea can be summarized as follows. Among the meteorological quantities considered, the coherence is highest between the zonal wind stress component and the SLA. The results are shown in Fig. 9. (We obtained similar results if the zonal wind stress component from the North Sea instead from the Baltic Sea was used in this analysis). The coherence between the wind stress magnitude and the SLA as well as the coherence between the meridional wind stress component and the SLA (not shown) is generally lower than the coherence shown in Fig. 8, and significantly different from zero only for frequencies between 0.0033 and 0.0048 cycle/day (periods 210–350 days). The coherence between barometric pressure and the SLA (not shown) is not significant at lower frequencies, but increases at higher frequencies, exceeding a value of 0.4 at frequency 0.023 cycle/day (period of ~45 days). This is in agreement with the conclusion reached before by Ekman (2009) that the

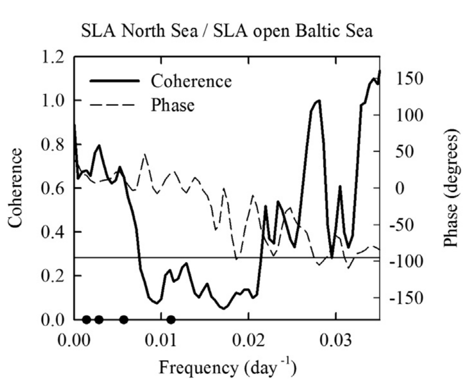

Fig. 6. Squared coherence (solid dark line) and phase functions (dashed line) between the SLA in the North Sea and in the open Baltic Sea. Horizontal line indicates that the coherence >0.283 is significant at 95% confidence level. The frequencies corresponding to periods of 2 years, 1 year, 6 month, and 3 month are marked by black dots on the *X* axis.

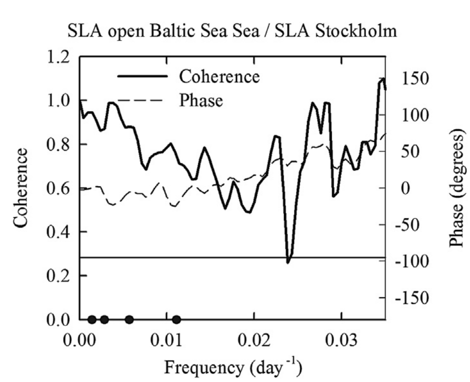

Fig. 8. Squared coherence (solid line) and phase functions (dashed line) between the SLA in the open Baltic Sea and at the coastal station in Stockholm. Horizontal line indicates that the coherence >0.283 is significant at 95% confidence level. The frequencies corresponding to periods of 2 years, 1 year, 6 month, and 3 month are marked by black dots on the *X* axis.

response of the Baltic Sea level to barometric pressure is more evident at shorter times scales.

Finally, we have considered the influence of the water runoff on the SLA. Water runoff into the Baltic Sea was approximated by a total discharge from the 75 largest rivers in the region, and estimated by the Balt-Hype model (Donnelly et al., 2011). River data were not available after 2008. Therefore, our analysis is based on the 20-years time series starting in 1988, and is limited to river discharge and the SLA in Stockholm. (The time period when both the river runoff data and the satellite-derived SLA were available was too short for this analysis, since the satellite data were available from October 1992). The coherence between river discharge and Stockholm SLA is not significant; it is above the 0.283 value only for periods of about 210–260 days (results not shown).

The interpretation of our results is generally in agreement with Ekman (2009). Ekman distinguished the two most important time scales in the variability of the Baltic Sea level. These are: 1) short-term variations (time scale of days) in response to barometric pressure and short-term wind events; this variability affects more the sea level near the coasts than at the open sea and is significantly influenced by the geometry of the coastline and wind direction; and 2) long-term variability (time scale of months) in response to persistent winds redistributing water in the North Atlantic, North Sea, and Baltic Sea; this variability affects the level of the entire Baltic Sea. Our analysis was mostly limited to long-term variability. The time scale on the order of days cannot be resolved by our 7-day resolution time series data. We plan to extend this analysis to shorter time scales after we reprocess the satellite altimetry data in the Baltic Sea using the novel methods of coastal altimetry (Bouffard et al., 2008, 2011; Vignudelli et al., 2011). This reprocessing will also allow for a better spatial resolution and will allow us to quantify the geographical/regional differences in the SLA variability. Such data will also allow us to make a better interpretation of the coastal effects through more rigorous comparisons of the satellite-derived altimetry data with coastal stations. Finally, in the nearest future, we plan to complete comparisons of satellite-derived SLA with our numerical model of the Baltic Sea.

4. Summary

There have been only few attempts to use satellite altimetry data in the Baltic Sea in the past. These include analyses of sea level data (e.g., Poutanen and Stipa, 2001; Madsen et al., 2007) and validation of the operational wave models (Sølvsteen and Hansen, 2006). Our results based on time series analysis of almost 20-years of data of satellite altimetry in the open Baltic Sea support some of the earlier findings based on coastal data (e.g., Ekman, 2009). We have confirmed that the variability of the sea level in the Baltic Sea is coherent with the sea level in the North Sea. However, we found that, unlike in the North Sea, the annual peak is not well pronounced in the open Baltic Sea SLA spectrum. The semiannual peak is the most prevailing in the open Baltic Sea SLA spectrum. This is in contrast to earlier publications, which reported that the annual peak in the Baltic Sea level variability as highly significant. We suggest that one of the reasons for this discrepancy is that we have used data series with a higher temporal resolution (7 days in comparison to monthly data used in previous research). The annual cycle of the open Baltic Sea level is asymmetrical, as suggested by Ekman (2009). This asymmetrical cycle is probably decomposed by the spectral analysis into 2 or more components of variability in our 7-day resolution SLA time series. We have documented that the SLA variability is in phase in the open Baltic Sea site considered and at the coastal station in Stockholm. The coherence between the SLA in these two locations is high, but significantly less than unity. One of the most likely reasons for this is the fact that the sea level in Stockholm is influenced by the coastal topography, while the open sea data are not. The results of the cross-spectral analysis between meteorological parameters (wind stress magnitude, zonal and meridional wind stress components, and barometric pressure at sea level) and the SLA in the open Baltic Sea show that the coherence is highest between the zonal wind stress component and the SLA. In addition our results indicate that the coherence between the river runoff and the SLA in Stockholm is not significant. Our analysis is limited to variability on a long-term scale (>month), because the time scale on the order of days cannot be resolved by our 7-day resolution time series data. In the near future, we plan to extend the results presented in this paper to shorter time scales after the satellite altimetry data in the Baltic Sea are reprocessed using the novel methods of coastal altimetry (Bouffard et al., 2008, 2011; Vignudelli et al., 2011).

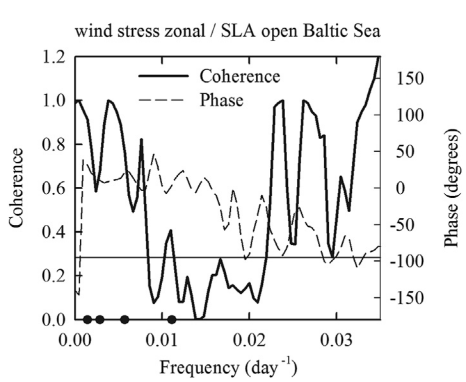

Fig. 9. Squared coherence (solid line) and phase functions (dashed line) between zonal component of wind stress and SLA in the open Baltic Sea. Horizontal line indicates that the coherence >0.283 is significant at 95% confidence level. The frequencies corresponding to periods of 2 years, 1 year, 6 month, and 3 month are marked by black dots on the *X* axis.

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