doi:10.5697/oc.55-2.319
OCEANOLOGIA, 55 (2), 2013.
pp. 319–337.

Recent multiyear trends in the Baltic Sea level*

KEYWORDS
Baltic Sea
Regional oceanography
Marginal and semi-enclosed seas
Sea level: variations and mean

Małgorzata Stramska[1,⋆]
Natalia Chudziak[2]

[1] Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, 81–712 Sopot, Poland;

e-mail: mstramska@iopan.gda.pl

⋆corresponding author

[2] Department of Earth Sciences,
Szczecin University,
Mickiewicza 16, 70–383 Szczecin, Poland

Received 13 February 2013, revised 3 April 2013, accepted 5 April 2013.

Abstract

Sea level rise is one of the most direct consequences of climate change. It has been documented that sea level rise is globally subject to considerable spatial heterogeneity. There is an increased awareness of the need to create regional data records and projections of sea level trends, because specific regional processes can cause regional trends to diverge significantly from global averages. In this paper available multimission satellite altimetry data were used to estimate the multiyear trend in the Baltic Sea level. The estimated trend is about 0.33 cm yr^{-1}, similar to the globally averaged sea level trend, but significantly larger than the regional

* This work was supported through the SatBałtyk project funded by the European Union through the European Regional Development Fund, (contract No. POIG.01.01.02-22-011/09 entitled 'The Satellite Monitoring of the Baltic Sea Environment').

trends estimated in the North Sea and North Atlantic. The decadal scale variability in the sea level trend in the Baltic Sea does not indicate a significant acceleration of the trend in recent years. Our analysis confirms that the interannual variability of sea level in the Baltic in winter is significantly correlated with the North Atlantic Oscillation index.

1. Introduction

Sea level rise is one of the most direct consequences of climate change and is associated with substantial socio-economic risks (IPCC 2007, Church et al. 2010). The projections of the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) for the last decade of the twenty-first century compared to the last decade of the twentieth century predict a sea level rise of 18–59 cm if the changes in the ice sheets are not taken into account (IPCC 2007, Meehl et al. 2007). If the ice sheet changes observed from 1993 to 2003 are scaled with the global temperature, the projected sea level rise could be as high as 79 cm or more (76 cm in Meehl et al. 2007). Satellite and in situ observations indicate that since the start of projections in 1990, the sea level has been rising at a rate which is near the upper limit of the IPCC AR3 and AR4 projections or even faster (Rahmstorf 2007, Horton et al. 2008). Thus, the uncertainty regarding the estimates of the global sea level rise and future trends is still quite large, and this motivates interest to continue efforts to observe and analyse sea level trends. In addition it has been documented that sea level change is subject to considerable regional spatial heterogeneity.

The impacts of sea level rise are of particular concern in coastal regions, which are often densely populated and economically important. There is an increased awareness of the need to create regional data records and projections of sea level trends. Specific regional processes can cause regional trends to diverge significantly from global averages. In an intercontinental water body such as the Baltic Sea, regional sea level variability is particularly important for coastal management and socio-economic reasons. In addition, sea level variations in the Baltic Sea, forced by the wind patterns over the North Sea and the Baltic Sea entrance, are closely interrelated with the exchange of water through the Danish Straits (Samuelsson & Stigebrandt 1996, Gustafsson & Andersson 2001, Ekman 2009). Since sea levels control the processes responsible for the inflow of oceanic water and for deep-water renewal in the Baltic Sea, they are of crucial importance for many marine processes, including eutrophication and climate-related ecosystem trends and relationships. Owing to the diversity of processes driving sea level variability, the accurate estimation of long-term sea level trends in the Baltic Sea is a challenging problem (e.g. Ekman 2009).

Most of the published work on sea level variability in the Baltic Sea has been based on tide gauge data. However, tide gauges are located on coastlines, and these observations always include coastal effects such as land movements, or wave and wind surges. Another option is to use satellite altimetry data. Altimetry missions in the last 20 years (TOPEX/Poseidon, ERS-1 and -2, GFO, Envisat, Jason-1 and 2) have provided invaluable sea level data sets and other products (such as waves and winds) (Cotton et al. 2004). With satellite altimetry many of the problems associated with the use of tide gauges (related to tectonic uplift, regional postglacial rebound, storm surges etc.) can be avoided. Because of this, altimetric measurements of sea level trends are now commonly used as the standard of reference (Leuliette et al. 2004, Church & White 2006).

The main objective of this paper is to analyse the available data from satellite altimeters (1992–2012) and to characterize multiyear trends in the Baltic Sea level. So far, there have been only a few attempts to use satellite altimetry data in the Baltic Sea (e.g. Poutanen & Stipa 2001, Madsen et al. 2007, Sølvsteen & Hansen 2006). The main advantage of our analysis is that we use longer time series, which allow the local sea level trends to be estimated with greater confidence. Our analysis will lead to an improved understanding of the link between the regional sea level trend in the Baltic Sea and the global trend, and may be helpful in studies projecting the effects of global change on a regional scale. This study is a contribution to the SatBałtyk project (Satellite Monitoring of the Baltic Sea Environment, www.iopan.gda.pl/projects/SatBaltyk).

2. Data sets and methods

Sea surface height measurements from satellite radar altimeter missions (e.g. TOPEX/Poseidon, Jason-1, Jason-2) provide estimates of global and regional sea level. They have been available since late 1992 and give a global and regional view of sea level rise due to volumetric change in the oceans (e.g. thermal expansion, ice sheet melt). We have used these data to investigate regional sea level trends in the Baltic. Sea Level Anomaly (SLA) data were extracted from the delayed time (DT) multimission global product available at AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data, www.aviso.oceanobs.com). We have used the basic product, which is provided with a 7-day temporal resolution and a $1/3^\circ$ spatial resolution on a Mercator grid. These are research quality data, which permit the study of ocean variability due to seasonal and climatic variations. The Sea Level Anomaly (SLA) data are referenced to the 7-year mean (1993–1999) of the sea surface height. Full

Figure 1. Map showing the geographical positions corresponding to the time series data used in this study (based on Google Maps)

details of the standard processing methods applied to satellite altimetry data are available at www.aviso.oceanobs.com. For our study we have extracted data for the open Baltic Sea. We have selected 3 locations (A, B and C in Figure 1) to explore the spatial variability of the data. The geographical positions of these sites correspond approximately to the long-term monitoring stations BY15, BY10, and BCSIII in the Swedish National Marine Data Archive (http://produkter.smhi.se/pshark/datamap_nationell.php?language=e#). The selected study sites lie within the Baltic Proper to avoid contamination of the sea level time series by sea ice in winter. For comparison, we have also extracted time series data for one location in the North Sea and one in the North Atlantic (the geographical coordinates corresponding to each time series record are listed in Table 1). To estimate sea level trends we have used the full available satellite data record (4 October 1992 to 7 July 2012). For comparisons with coastal data (see below), we have converted the satellite altimetry data to the monthly averages, because coastal data are available with this temporal resolution.

For comparison with satellite data we have used data from six coastal stations from the Baltic Sea (listed in Figure 1 and Table 2). We have used monthly averaged tide gauge records 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. The data used in our study cover the time period from 1 January 1993 to 31 December 2011. After 2011 data were not available. Note that the local tide gauges measure sea level at a single location relative to the local land surface, a measurement referred to as relative sea level (RSL). Because land surfaces are dynamic, with some locations rising or

Table 1. Trends in sea levels with their standard errors derived from merged 7-day resolution satellite altimetry SLA data (4 October 1992–7 July 2012, $p < 0.05$, confidence level 95%) and the standard deviations of the monthly averaged SLA estimates

Station	Position	Trend (standard error) [cm yr^{-1}]	Standard deviation for monthly averaged data, [cm]
Baltic Sea, site A	57.29°N	0.33	13.00
(near BY15)	20.00°E	(0.08)	
Baltic Sea, site B	56.56°N	0.33	13.08
(near BY10)	19.67°E	(0.08)	
Baltic Sea, site C	55.44°N	0.33	12.85
(near BCSIII)	18.33°E	(0.08)	
North Sea, site D	56.93°N	0.23	7.62
	5.00°E	(0.05)	
North Atlantic, site E	55.06°N	0.14	6.36
	20.00°W	(0.04)	
Global average		0.31	
(Nerem et al. 2010)			

sinking, relative sea level changes recorded at coastal stations can differ from the global trends of sea level and vary across the Baltic Sea coast. All the tide gauge records presented in our paper have been converted to RSL anomalies by subtracting the 7-year mean (1993–1999), as was done with the satellite data.

For a proper interpretation of the relative sea level trends at a specific coastal location, the effects due to global oceanic volume changes, and issues such as glacial isostatic adjustment (GIA, Peltier 1998, 2004), tectonic uplift, and self-attraction and loading (SAL, e.g. Tamisiea et al. 2010) must be considered. For example, in some locations in the Baltic Sea (e.g. Bothnian Sea), GIA contributes much more to the observed local sea level change (8 mm yr^{-1} or more) than the global rise in sea level, and as a result the RSL is decreasing. In Table 2 we show, for comparison with observed RSL trends, the data from the glacial isostatic adjustment (GIA) model (the VM4 earth model, Peltier 1998, 2004) obtained from PSML (www.psmsl.org/train_and_info/geo_signals/gia/peltier/). For assessing local land movements one can also use GPS measurements. Therefore, we have downloaded the available estimates on the land vertical movement in the Baltic Sea from the GPS database provided by SONEL (Système d'Observation du Niveau des Eaux Littorales, www.sonel.org).

Table 2. Trends in relative sea surface levels and standard deviations of the monthly averaged tide gauge data used in this study. The station identification includes its ID, the coastline and station codes from the PSMSL. GIA-VM4 indicates the average glacial isostatic adjustment obtained from the VM4 earth model (see http://www.psmsl.org/trainandinfo/geo-signals/gia/peltier/). In addition, land vertical movement from SONEL GPS database (www.sonel.org/) is shown for some stations

Station	Position	Trend (Standard error)	Standard deviation for monthly averaged data, [cm]	GIA, long-term rate of vertical motion of the solid earth, [cm yr^{-1}]	Land vertical movement from GPS network [cm yr^{-1}] (length of data record)
Stockholm (sta ID 78; coastline 50; sta code 141)	59.32°N 18.08°E	−0.02 cm yr^{-1} (trend statistically not significant)	16.40	0.421	
Koserow (sta ID 1448; coastline 120; sta code 1)	54.06°N 14.00°E	0.25 cm yr^{-1} (trend statistically not significant)	11.24	0.017	
Warnemünde (sta ID 11; coastline 120; sta code 12)	54.17°N 12.10°E	0.45 cm yr^{-1} ($p < 0.05$, standard error = 0.11)	9.75	−0.006	0.118 (7.8 years)
Visby (sta ID 2105; coastline 50; sta code 96)	57.64°N 18.28°E	0.08 cm yr^{-1} (trend statistically not significant)	15.03	0.158	0.299 (11.8 years)
Kungsholmsfort (sta ID 70; coastline 50; sta code 81)	56.11°N 15.59°E	0.35 cm yr^{-1} (trend statistically not significant)	13.60	0.060	
Sassnitz (sta ID 397; coastline 120; sta code 4)	54.51°N 13.64°E	0.56 cm yr^{-1} ($p < 0.05$, standard error = 0.14)	11.72	0.014	0.142 (7.9 years)

The Hurrell principal component (PC) based index of the North Atlantic Oscillation (NAO) (Hurrell et al. 2003, Hurrell & Deser 2009) averaged for the months of December, January and February was obtained from http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-pc-based.

3. Results

Satellite altimetry time series data covering almost 20 years with a 7-day resolution from the open sea locations shown in Figure 1 have been used to estimate local sea level trends. For each time series record we have estimated its trend and the standard error of the trend (Table 1). From the results shown in Table 1 we conclude that there is a consistent, statistically significant ($p < 0.05$) trend of about 0.33 cm yr^{-1} in sea level in the Baltic Sea Proper. The differences between the examined locations in the Baltic Sea are not statistically significant. For comparison, according to Nerem et al. (2010), the rate of globally averaged sea level rise is currently estimated at 0.31 cm yr^{-1} (or 0.34 cm yr^{-1} if the correction for global isostatic adjustment is taken into account). A similar estimate of the global trend has been published by the Commonwealth Scientific and Industrial Research Organization (CSIRO, 0.32 mm yr^{-1}, see www.cmar.csiro.au/sealevel/sl_hist_last_15.html) and by AVISO (0.32 mm yr^{-1}, see www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/). Thus, the sea level trend in the Baltic Sea is similar to the globally averaged trend derived from satellite altimetry data. Note that in the past, the trend in the Baltic Sea level was estimated at about 1 mm yr^{-1}, based on long-term (~ 50 years and more) coastal data records (e.g. Ekman 2009). Table 1 shows that the trend in the Baltic Sea level is somewhat higher than the regional trends in the North Sea and North Atlantic estimated from the same AVISO data set. In addition, Table 1 compares standard deviations of monthly averaged SLA data and shows that the Baltic Sea monthly averaged SLA are characterized by significantly larger (almost two times) standard deviations than the North Sea and North Atlantic time series.

In order to compare satellite data with coastal data we had to convert the satellite data to monthly averages, so as to match the temporal resolution of the coastal data. Time series of the monthly averaged sea level anomalies estimated from satellite data in the period 1 January 1993–31 December 2011 in the Baltic Proper are plotted in Figure 2. For comparison, Figure 3 presents time series of the monthly RSL anomalies from certain tide gauge stations in the Baltic Sea encompassing the same time period. Comparison of the time series from Figures 2 and 3 shows that the shorter-term (annual

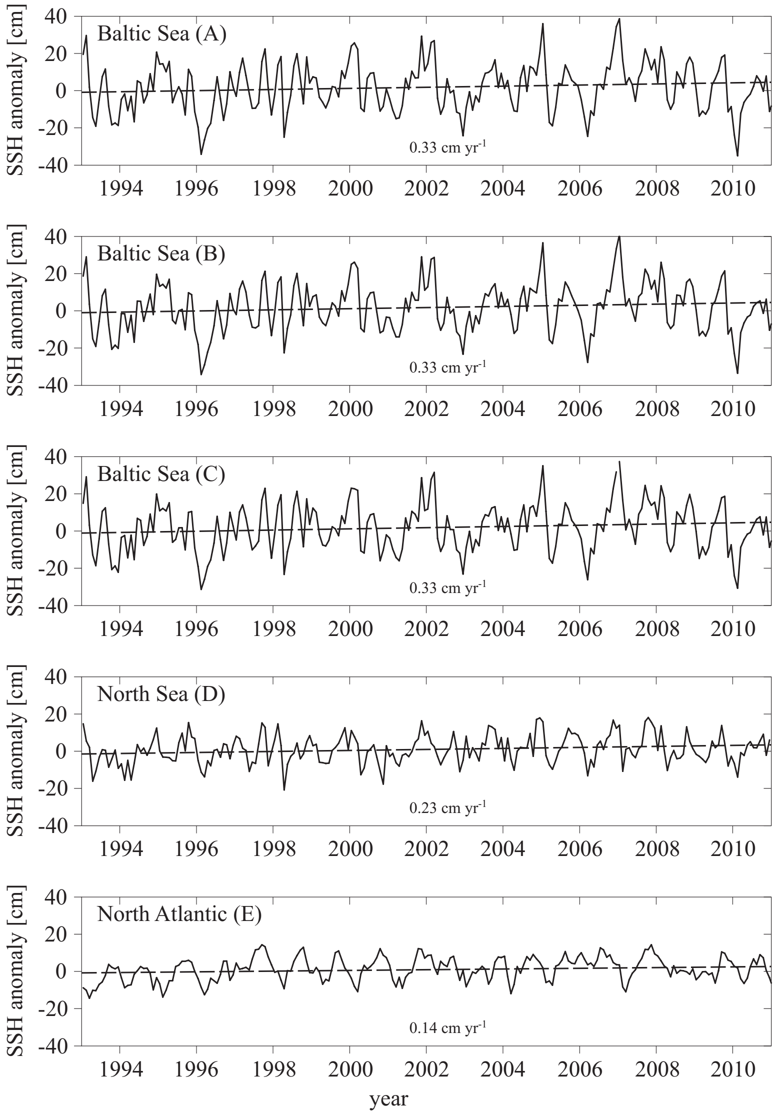

Figure 2. Time series of the monthly averaged sea level anomalies estimated from the merged mission satellite altimetry data in the Baltic Proper (stations A, B and C in Figure 1) in 1993–2011. For comparison, similar time series in the North Sea (station D) and the North Atlantic (station E) are also shown. Geographical positions, trends and standard deviations for each time series record are listed in Table 1

and shorter) temporal patterns of variability are similar in all these Baltic Sea data sets. However, the multiyear trends estimated using coastal data (Figure 3 and Table 2; note that some trends are not statistically significant)

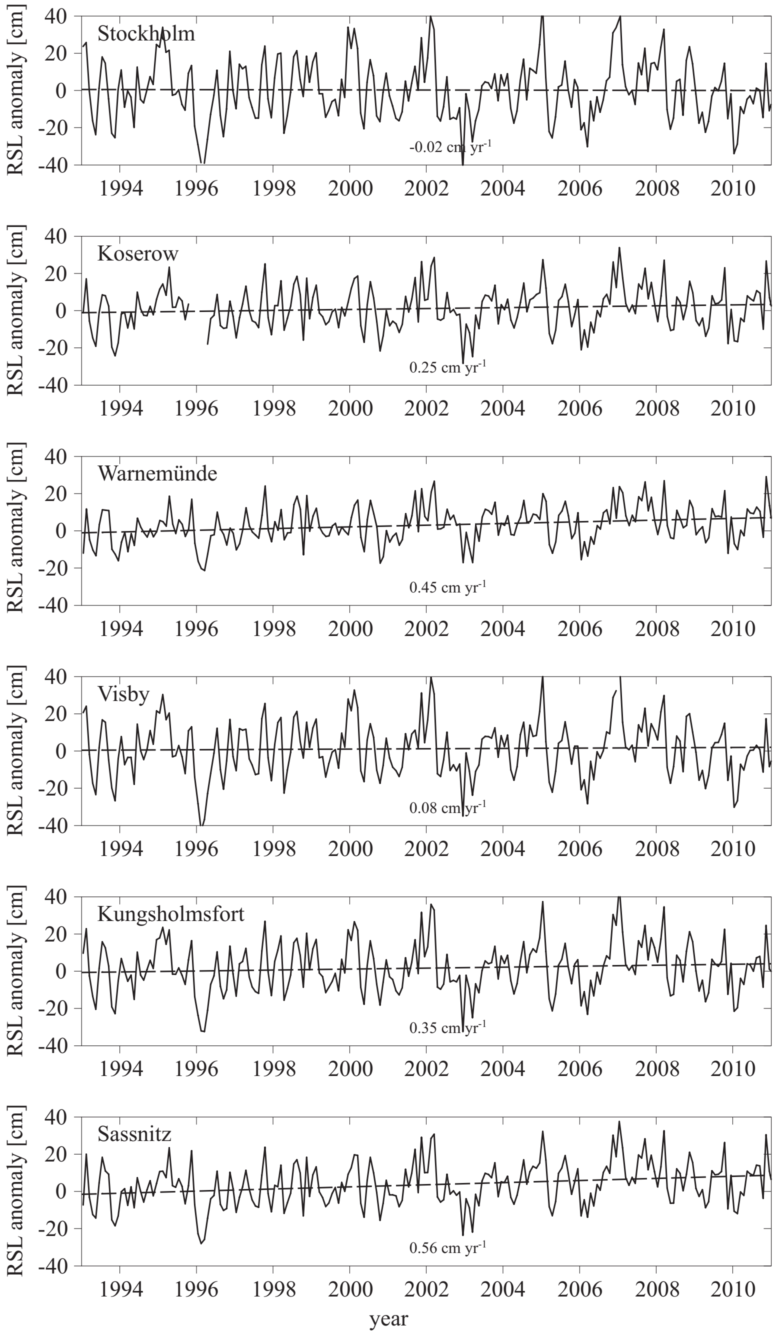

Figure 3. Example time series of the monthly averaged relative sea level (RSL) anomalies derived for selected coastal stations in the Baltic Sea for the period 1993–2011

differ significantly from the satellite estimates (shown in Figure 2 and Table 1). In addition, coastal trends vary between the coastal stations. There are several reasons for this. First of all, tide gauge measurements are more difficult to compare than satellite altimetry data, because tide gauges are referred to local reference systems not yet connected to a common global datum. This is not a problem if we are only investigating trends in sea level anomalies. However, further difficulties arise from the fact that the measurements at any given tide gauge station include both the effect due to global sea level rise and effects related to local vertical land movements (such as subsidence or glacial rebound). In addition, local coastal sea levels are influenced by the variability of coastal currents and weather patterns, which can lead to significant storm surges in the Baltic Sea. These effects depend on the local coastal topography. Because the absolute elevations of both land and water level change, the trends in the land-water interface can also vary spatially and temporally. All these effects make coastal data extremely difficult to interpret in terms of climate-induced sea level trends. This is why, depending on the rates of vertical land movement and local topographic effects, the observed local sea level trends can differ significantly from the average rate of global sea level rise. This is also why such local trends vary considerably from one location to the next on the Baltic Sea coast. The significant regional variability of coastal sea level trends displayed in Figure 3 and Table 2 shows that it is extremely difficult to state exactly what portion of the observed trend should be attributed to the global trend. Even if we take into the account the estimates of the vertical movement of the land (listed in Table 2), we are still faced with coastal sea level trends, which depend on the geographical position of the station in question. The estimated sea level rise is, however, consistent in the open sea altimetry data, which do not depend significantly on the geographical position of the measurement (on the spatial scale considered). Hence, the main advantage of using satellite SLA data in the Baltic Sea is that, unlike coastal measurements, altimetric data are not affected by vertical land motion and other coastal processes.

Nevertheless, a lot of our interest in sea level trends is related to the possible consequences of sea level rise in coastal regions. It is clearly important to be able to relate changes in the sea level in the open sea to coastal conditions. Such relationships are local. A better understanding of these relationships will require more detailed studies and comparisons of various data sets (satellite and in situ) in the future. At present, altimeter-based sea surface height data for the Baltic Sea are of limited use for such detailed research. The reason for this is that good quality satellite altimetry data are currently available only for the open sea area. Near the coasts the altimetry data are degraded owing to the land contamination of the radar and microwave radiometer signals or are not available because of the landmask applied to the data (but see Madsen et al. 2007). Recently, new techniques for reprocessing data specific to coastal altimetry have become available, such as waveform retracking and corrections using ancillary water vapour estimates (e.g. Larnicol et al. 1995, Vignudelli 1997, Ayoub et al. 1998, Nardelli et al. 1999, Vignudelli et al. 2000, 2003, 2005, 2011, Bouffard et al. 2008a, 2008b, 2011). We plan to explore these techniques in the near future. These new approaches will most likely lead to an improved spatial resolution and the reconstruction of local sea levels close to the coasts.

Another important problem when studying long-term sea level changes is the question of whether there is any systematic temporal variability. Our time series data indicate that interannual sea level variability in the open Baltic Sea in winter is significantly influenced by large-scale climate oscillations. This is shown in Figure 4, which demonstrates that there is a significant correlation between the winter-averaged (December–February) Baltic Sea SLA and the winter-averaged (December–February) North Atlantic Oscillation (NAO) index. A similar correlation (but with a lower correlation coefficient) is also evident in the North Sea data set, but not in the North Atlantic data (Figure 4). The NAO index is determined from the sea level pressure difference between the Azores and Iceland, which controls the strength of the westerly winds over the North Atlantic, as well as many other aspects of the North Atlantic climate. In the Baltic Sea, the variability in sea level can be explained mainly by the modulation of the intensity of the westerly winds associated with the NAO. Stronger westerlies cause a more significant sea level rise in the coastal regions of the North Sea. Due to the inflow of water from the North Sea as a hydrodynamic response to wind forcing, stronger westerlies also correspond to an increased sea level rise in the entire Baltic Sea (e.g. Ekman 2009). The correlation between NAO and sea level is statistically significant for some coastal stations in the Baltic Sea: for example, it is evident in the Stockholm tide gauge record shown in Figure 4. However, in general, the influence of NAO on RSL in the Baltic Sea varies depending on the geographical position of the station. The statistical link between the NAO and RSL is regionally very heterogeneous. This has been described before in studies based on coastal data records (e.g. Andersson 2002, Jevrejeva et al. 2005, Ekman 2009). For instance, it has been shown based on long-term data records that the correlation in winter between the NAO index and sea level in the Gulf of Bothnia might reach 0.8, but it is only around 0.3 at Warnemünde in the southern Baltic. In the 19-year time series used in our study, the correlation for

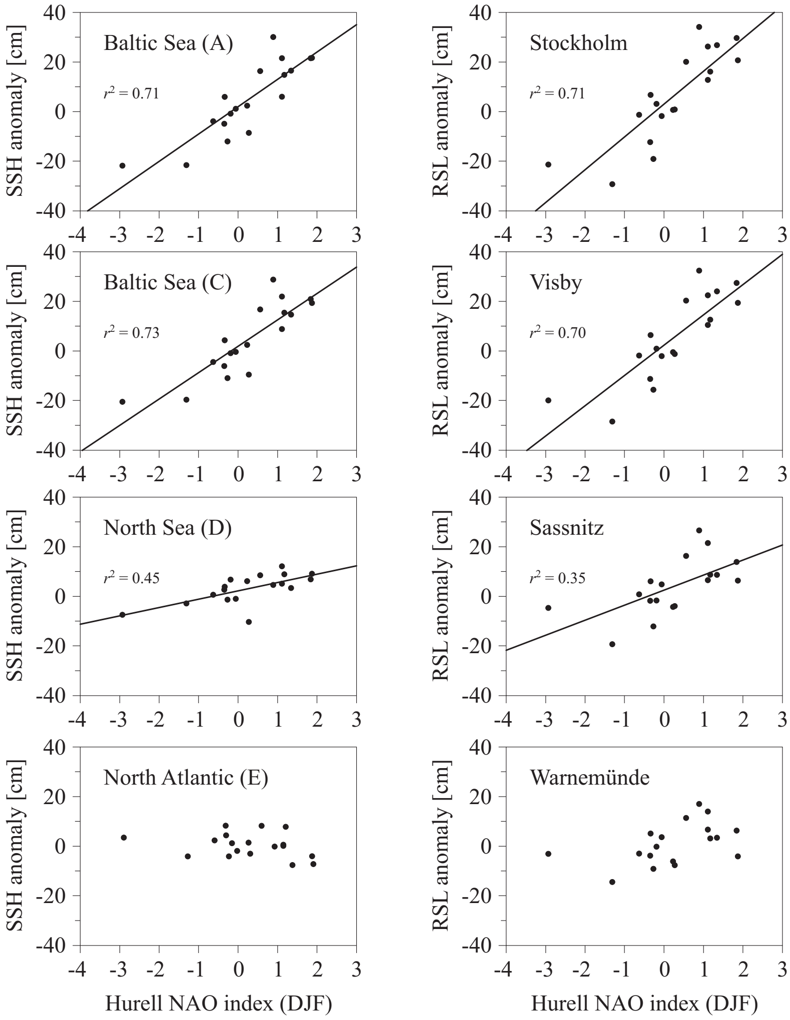

Figure 4. Winter-averaged (DJF) sea level anomalies as a function of Hurrell winter (DJF) North Atlantic Oscillation (NAO) index (Hurrell et al. 2003, Hurrell & Deser 2009). This is a principal component (PC) based NAO index obtained as the time series of the leading Empirical Orthogonal Function (EOF) of sea level pressure (SLP) anomalies over the Atlantic sector, 20°–80°N, 90°W–40°E (see http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-pc-based). Squared correlation coefficients are shown when the correlations were statistically significant ($p < 0.05$)

Warnemünde is not significant statistically. It has also been shown that the sea level variations along the Baltic coast cannot be explained solely by NAO variability. Meteorological factors such as temperature and precipitation can also influence Baltic Sea levels (Hünicke & Zorita 2006, 2008, Hünicke et al. 2008).

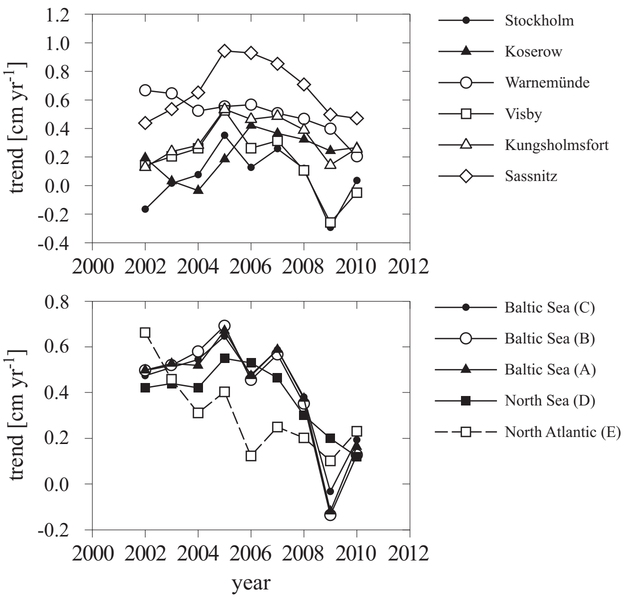

Figure 5. Temporal variability of the decadal sea level trends in the coastal data (upper panel) and satellite data (lower panel)

We will now examine the temporal variability of the multiyear trend in sea level. For this purpose, we estimated linear trends using a moving window of 11 years in width. The estimated temporal variability of the sea level trend in the Baltic Sea based on satellite altimetry and coastal data is presented in Figure 5. These results show that local sea level trends are not uniform in time. The figure visualizes the accelerating or decelerating sea level trends. The temporal changes in the trend could be due to the variability of the global trend as well as to long-term variations in some local conditions, for example, meteorological forcing by air pressure, wind patterns and heating. A detailed interpretation of such effects is beyond the scope of the present paper and will be the subject of future research. Note that trends in some coastal data (Figure 5a), albeit less pronounced, display a similar qualitative behaviour as the trend change in Baltic Sea altimetric data (Figure 5b). A similar pattern in the temporal variability of the trend seems to be present in the North Sea data, but the pattern is different in the North Atlantic data set. However, it needs to be stressed that the detection of these decadal changes in the sea level trend is a very challenging undertaking, owing to the substantial variability in sea levels in the Baltic

Sea and the relatively short data records. These results should therefore be treated with caution.

4. Discussion and summary

The Baltic is a semi-enclosed sea located in northern Europe and drains into the North Sea. The significant influx of freshwater from rivers to the Baltic gives rise to a permanent two-layer salinity structure in this sea with a persistent halocline and estuarine-like water exchange with the North Sea (e.g. Omstedt et al. 2004). The mean sea surface topography difference between the northern Baltic and the North Sea of about 35–40 cm is due to river runoff and resulting salinity gradient (Ekman & Mäkinen 1996). The variability of the sea level forced by weather patterns is linked to the intensity of water exchange between the Baltic Sea and the North Sea. Importantly, some conditions can lead to major inflows of oceanic water into the Baltic Sea, which are critically important for the ecological state of this sea, because they renew the bottom waters (Leppäranta & Myrberg 2009). In recent years the general public, politicians and scientists have become concerned that the 'environmental health' of the Baltic Sea has worsened. Reports have been published describing the increase of 'dead bottom areas', major regime shifts, more frequent harmful algal blooms and increasing anthropogenic eutrophication (see HELCOM 2009). It is therefore important to improve our understanding of the dynamic connections of this marine system with the external ocean, and to obtain a better understanding of the possible cause-effect relationships between sea level variability, its impact on water exchange with the ocean, and their influence on other important environmental processes.

Traditionally, datasets from tide gauge records have been used to characterize the patterns in sea level variability in the Baltic. Such data display a substantial spatial heterogeneity of sea level trends, reflecting the diverse local and regional processes impacting on tide gauge records. By considering satellite data in addition to coastal data, we can gain a better understanding of the influence of global sea level trends on the Baltic Sea. Many recent studies have focused on similar issues in various geographical regions, exploring the potential of altimetric data products in marginal seas and coastal provinces. Special data processing approaches have been tested. Such data have been used in the Mediterranean Sea (e.g. Larnicol et al. 1995, Vignudelli 1997, Ayoub et al. 1998, Nardelli et al. 1999, Vignudelli et al. 2000, 2003, 2005, 2011, Bouffard et al. 2008a, 2008b, 2011), the Barents and White Seas (e.g. Lebedev & Tikhonova 2002, Lebedev et al. 2003), the Black Sea (e.g. Ginzburg et al. 2003, Eremeev et al. 2004) and the Caspian Sea (e.g. Lebedev & Kostianoy 2005). However, the benefits of altimetric data have yet to be fully explored in the Baltic Sea. The spatial and temporal resolutions of the data used in this paper are too low to study extremes occurring as a result of storm surges in the Baltic, but even these coarse resolution data provide new and interesting observations. It would be exciting to apply new data processing approaches to satellite altimetry data in the Baltic Sea and to fully exploit the satellite altimetry data in this region. We plan to start this work in the near future.

A greater understanding of sea level trends, as well as the relationship between global and local sea levels, will provide critical information about the impact of the Earth's climate on the status of the Baltic Sea. Changes in sea level are directly linked to a number of atmospheric and oceanic processes. Changes in global temperatures, coverage of glaciers and ice sheets, as well as regional hydrological cycles, weather patterns and storm frequency/intensity are examples of the effects of a changing climate. All these processes are directly related to sea level trends. Therefore, sea level observations can provide an important key to enhancing our understanding of the impact of climate change in our region. By combining projections of global sea level rise (for example IPCC 2007) with local rates of relative sea level change based on observations in the Baltic Sea, coastal managers and administrators will be better able to plan for the impact of sea level rise in long-term scenarios.

Acknowledgements

We are grateful to AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data, www.aviso.oceanobs.com), the PSMSL, (the Permanent Service for Mean Sea Level www.psmsl.org) and SONEL (Système d'Observation du Niveau des Eaux Littorales, www.sonel.org) and the NCAR (The National Center for Atmospheric Research http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-pc-based) for making available the data sets used in this study.

References

Andersson H. C., 2002, *Influence of long-term regional and large-scale atmospheric circulation on the Baltic sea level*, Tellus A, 54 (1), 76–88, http://dx.doi.org/10.1034/j.1600-0870.2002.00288.x.

Ayoub N., Le Traon P. Y., De Mey P., 1998, *A description of the Mediterranean surface variable circulation from combined ERS-1 and TOPEX/Poseidon altimeter data*, J. Mar. Syst., 18 (1), 3–40, http://dx.doi.org/10.1016/S0924-7963(98)80004-3.

Bouffard J., Roblou L., Birol F., Pascual A., Fenoglio-Marc L., Cancet M., Morrow R., Ménard Y., 2011, *Introduction and assessment of improved* *coastal altimetry strategies: case study over the North Western Mediterranean Sea*, [in:] *Coastal altimetry*, S. Vignudelli, A. G. Kostianoy, P. Cipollini & J. Benveniste (eds.), Springer Publ., 1st edn., 297–330 , http://dx.doi.org/10.1007/978-3-642-12796-0_12.

Bouffard J., Vignudelli S., Cipollini P., Ménard Y., 2008a, *Exploiting the potential of an improved multimission altimetric dataset over the coastal ocean*, Geophys. Res. Lett., 35, L10601, http://dx.doi.org/10.1029/2008GL033488.

Bouffard J., Vignudelli S., Hermann M., Lyard F., Marsaleix P., Ménard Y., Cipollini P., 2008b, *Comparison of ocean dynamics with a regional circulation model and improved altimetry in the Northwestern Mediterranean*, Terr. Atmos. Ocean. Sci., 19 (1–2), 117–133, http://dx.doi.org/10.3319/TAO.2008.19.1-2.117(SA).

Church J. A., White N. J., 2006, *A 20th century acceleration in global sea level rise*, Geophys. Res. Lett., 33, L01602, http://dx.doi.org/10.1029/2005GL024826.

Church J. A., Woodworth P. L., Aarup T., Wilson W. S. (eds.), 2010, *Understanding sea-level rise and variability*, Wiley-Blackwell, Chichester, Oxford, Hoboken, 456 pp.

Cotton D., Allan T., Menard Y., le Traon P. Y., Cavaleri L., Doombos E., Challenor P., 2004, *Global altimeter measurements by leading Europeans, requirements for future satellite altimetry*, Tech. Rep. European Project EVR1-CT2001-20009, Brussels, 47 pp.

Ekman M., 2009, *The changing level of the Baltic Sea during 300 years: a clue to understanding the Earth*, Summer Inst. Hist. Geophys., Åland Islands, 168 pp.

Ekman M., Mäkinen J., 1996, *Mean sea surface topography in the Baltic Sea and its transition area to the North Sea: a geodetic solution and comparisons with oceanographic models*, J. Geophys. Res.-Oceans, 101 (C5), 11993–11999, http://dx.doi.org/10.1029/96JC00318.

Eremeev V. N., Korotaev G. K., Radaikina L. N., 2004, *Monitoring of the Black Sea dynamics based on satellite technologies*, Phys. Oceanogr., 14 (2), 114–126, http://dx.doi.org/10.1023/B:POCE.0000037874.11966.dc.

Ginzburg A. I., Kostianoy A. G., Sheremet N. A., 2003, *Mesoscale variability of the Black Sea as revealed from TOPEX/POSEIDON and ERS-2 altimeter data*, Issled. Zemli iz Kosmosa, 3, 34–46, (in Russian).

Gustafsson B. G., Andersson H. C., 2001, *Modeling the exchange of the Baltic Sea from the meridional atmospheric pressure difference across the North Sea*, JGR, 106 (69), 19731–19744, http://dx.doi.org/10.1029/2000JC000593.

HELCOM, 2009, *Eutrophication in the Baltic Sea – an integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region*, Balt. Sea Environ. Proc., No. 115B, 148 pp.

Horton R., Herweijer C., Rosenzweig C., Liu J., Gornitz V., Ruane A. C., 2008, *Sea level rise projections for current generation CGCMs based on the semi-empirical method*, Geophys. Res. Lett., 35 (2), http://dx.doi.org/10.1029/2007GL032486.

Hurrell J. W., Deser C., 2009, *North Atlantic climate variability: the role of the North Atlantic Oscillation*, J. Mar. Syst., 78 (1), 28–41, http://dx.doi.org/10.1016/j.jmarsys.2008.11.026.

Hurrell J. W., Kushnir Y., Ottersen G., Visbeck M. (eds.), 2003, *The North Atlantic oscillation: climate significance and environmental impact*, 2003, Geophys. Monogr. Ser., 134, 279 pp., http://dx.doi.org/10.1029/GM134.

Hünicke B., Luterbacher J., Pauling A., Zorita E., 2008, *Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years*, Tellus A, 60 (2), 384–393, http://dx.doi.org/10.1111/j.1600-0870.2007.00298.x.

Hünicke B., Zorita E., 2006, *Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century*, Tellus A, 58 (1), 141–153, http://dx.doi.org/0.1111/j.1600-0870.2006.00157.x.

Hünicke B., Zorita E., 2008, *Trends in the amplitude of Baltic Sea level annual cycle*, Tellus A, 60 (1), 154–164, http://dx.doi.org/10.1111/j.1600-0870.2007.00277.x.

IPCC, 2007, *Climate change 2007: the physical science basis. Contribution of working group 1 to the fourth assessment report of the Intergovernmental Panel on Climate Change*, [in:] *Intergovernmental Panel on Climate Change* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, Tignor & H. L. Miller (eds.), Cambridge Univ. Press, Cambridge, New York, 996 pp.

Jevrejeva S., Moore J. C., Woodworth P. L., Grinsted A., 2005, *Influence of large-scale atmospheric circulation on European sea level: results based on the wavelet transform method*, Tellus A, 57 (2), 183–193, http://dx.doi.org/10.1111/j.1600-0870.2005.00090.x.

Larnicol G., Le Traon P. Y., Ayoub N., De Mey P., 1995, *Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of TOPEX/POSEIDON altimetry*, J. Geophys. Res.-Oceans, 100 (C12), 25163–25177, http://dx.doi.org/10.1029/95JC01961.

Lebedev S. A., Kostianoy A. G., 2005, *Satellite altimetry of the Caspian Sea*, Sea Publ., Moscow, 366 pp., (in Russian).

Lebedev S. A., Tikhonova O. V., 2002, *Application of satellite altimetry for investigation of sea level variation of the southeastern Barents Sea*, [in:] Proc. 4th Int. Sci. Tech. Conf. 'Modern methods and technology of oceanological research', Moscow, Russia, 15–17 November 2002, Vol. 2, 58–64, (in Russian).

Lebedev S. A., Zilberstein O. I., Popov S. K., Tikhonova O. V., 2003, *Analysis of temporal sea level variation in the Barents and the White Seas from altimetry, tide gauges and hydrodynamic simulation*, [in:] *International workshop on satellite altimetry*, C. Hwang, C.K. Shum, J. C. Li (eds.), IAG Symposia, Vol. 126, Springer Verlag, Berlin, Heidelberg, 243–250.

Leppäranta M., Myrberg K., 2009, *Physical oceanography of the Baltic Sea*, Springer-Praxis Book Ser. Geophys. Sci., Springer, Chichester, 378 pp., http://dx.doi.org/10.1007/978-3-540-79703-6.

Leuliette E., Nerem S. R., Mitchum T., 2004, *Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change*, Mar. Geod., 27 (1–2), 79–94, http://dx.doi.org/10.1080/01490410490465193.

Madsen K. S., Høyer J. L., Tscherning C. C., 2007, *Near-coastal satellite altimetry: sea surface height variability in the North Sea-Baltic Sea area*, Geophys. Res. Lett., 34, L14601, http://dx.doi.org/10.1029/2007GL029965.

Meehl G. A., Stocker T. F., Collins W. D., Friedlingstein P., Gaye A. T., Gregory J. M., Kitoh A., Knutti R., Murphy J. M., Noda A., Raper S. C. B., Watterson I. G., Weaver A. J., Zhao Z.-C., 2007, *Global climate projections*, [in:] *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, Tignor & H. L. Miller (eds.), Cambridge Univ. Press, Cambridge, New York, 996 pp.

Nardelli B., Santoleri R., Marullo S., Iudicone D., Zoffoli S., 1999, *Altimetric sea level anomalies and three-dimensional structure of the sea in the Channel of Sicily*, J. Geophys. Res.-Oceans, 104 (C9), 20585–20603, http://dx.doi.org/10.1029/1999JC900103.

Nerem R. S., Chambers D. P., Choe C., Mitchum G. T., 2010, *Estimating mean sea level change from the TOPEX and Jason altimeter missions*, Mar. Geod., 33 (1), 435–446, http://dx.doi.org/10.1080/01490419.2010.491031.

Omstedt A., Elken J., Lehmann A., Piechura J., 2004, *Knowledge of the Baltic Sea physics gained during the BALTEX and related programmes*, Progr. Oceanogr., 63 (1–2), 1–28, http://dx.doi.org/10.1016/j.pocean.2004.09.001.

Peltier W. R., 1998, *Postglacial variations in the level of the Sea: implications for climate dynamics and solid-earth geophysics*, Rev. Geophys., 36 (4), 603–689, http://dx.doi.org/10.1029/98RG02638.

Peltier W. R., 2004, *Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G(VM2) model and GRACE*, Ann. Rev. Earth. Planet Sci., 32, 111–149, http://dx.doi.org/10.1146/annurev.earth.32.082503.144359.

Poutanen M., Stipa T., 2001, *Temporal and spatial variation of the sea surface topography of the Baltic Sea*, [in:] *Gravity, geoid and geodynamics 2000*, M. G. Sideris (ed.), IAG International Symposia Vol. 123, Springer-Verlag, Berlin, Heidelberg, New York, 398 pp.

Rahmstorf S., 2007, *A semi-empirical approach to projecting future sea level rise*, Science, 315 (5810), 368–370, http://dx.doi.org/10.1126/science.1135456.

Samuelsson M., Stigebrandt A., 1996, *Main characteristics of the long-term sea level variability in the Baltic Sea*, Tellus A, 48 (5), 672–683, http://dx.doi.org/10.1034/j.1600-0870.1996.t01-4-00006.x.

Sølvsteen C., Hansen C., 2006, *Validation of the operational wave models WAVEWATCH-III and Mike21-OSW against satellite altimetry and coastal buoys*, Royal Danish Administr. Navig. Hydrogr., Copenhagen, 53 pp.

Tamisiea M. E., Hill E. M., Ponte R. M., Davis J. L., Velicogna I., Vinogradova N. T., 2010, *Impact of self-attraction and loading on the annual cycle in* *sea level*, J. Geophys. Res.-Oceans, 115, C07004, http://dx.doi.org/10.1029/2009JC005687.

Vignudelli S., 1997, *Analysis of ERS-1 altimeter collinear passes in the Mediterranean Sea during 1992–1993*, Int. J. Remote Sens., 18 (3), 573–601, http://dx.doi.org/10.1080/014311697218953.

Vignudelli S., Cipollini P., Astraldi M., Gasparini G. P., Manzella G. M. R., 2000, *Integrated use of altimeter and in situ data for understanding the water exchanges between the Tyrrhenian and Ligurian Seas*, J. Geophys. Res., 105 (C8), 19649–19663, http://dx.doi.org/10.1029/2000JC900083.

Vignudelli S., Cipollini P., Reseghetti F., Fusco G., Gasparini G. P., Manzella G. M. R., 2003, *Comparison between XBT data and TOPEX/Poseidon satellite altimetry in the Ligurian-Tyrrhenian area*, Ann. Geophys., 21 (1), 123–135, http://dx.doi.org/10.5194/angeo-21-123-2003.

Vignudelli S., Cipollini P., Roblou L., Lyard F., Gasparini G. P., Manzella G. M. R., Astraldi M., 2005, *Improved satellite altimetry in coastal systems: case study of the Corsica Channel (Mediterranean Sea)*, Geophys. Res. Lett., 32, L07608, http://dx.doi.org/10.1029/2005GL022602.

Vignudelli S., Kostianoy A. G., Cipollini P., Benveniste J. (eds.), *Coastal altimetry*, Springer-Verlag, Berlin, Heidelberg, 578 pp., http://dx.doi.org/10.1007/978-3-642-12796-0.

Woodworth P. L., Player R., 2003, *The permanent service for mean sea level: an update to the 21st century*, J. Coast. Res., 19 (2), 287–295.