# Long term water level and surface temperature changes in the lagoons of the southern and eastern Baltic

OCEANOLOGIA, 53 (1-TI), 2011.
pp. 293–308.

**KEYWORDS**
Baltic Sea lagoons
Water level
Sea surface temperature
Variability
Climate changes

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Received 6 October 2010, revised 17 February 2011, accepted 17 February 2011.

## Abstract

The paper studies variations in the water level and surface temperature of coastal lagoons along the southern and south-eastern shores of the Baltic Sea: the Curonian Lagoon, Vistula Lagoon, and Darss-Zingst Bodden Chain. Linear regressions for annual mean water level variations showed a positive trend in water level, but at different rates. The highest rate during the period between 1961–2008 was recorded for the Curonian and Vistula lagoons ($\sim 4$ mm year$^{-1}$), the lowest for the Darss-Zingst Bodden Chain (approximately $\sim 1$ mm year$^{-1}$). The warming trend of the mean surface water temperature in the lagoons was 0.03°C year$^{-1}$ in the period 1961–2008. Moreover, the variability in annual water temperature and sea level as well as their extreme values have increased most dramatically since the 1980s.

## 1. Introduction

The global sea surface temperature is more than 1°C higher now than 140 years ago, and the sea surface temperature (SST) in European seas is increasing more rapidly than in the global oceans (Coppini et al. 2007). For instance, in the period 1982–2006, the SST in the North Sea, the Baltic Sea and the Mediterranean Sea rose respectively five, six and three times faster than the global average SST (0.01°C year$^{-1}$). In the Baltic Sea, despite some regional differences, there has been a positive trend in the yearly mean SST with an average increase of 0.8°C in 15 years (1998–2004) (Siegel et al. 2006).

There are many estimates (due to varying methods and periods of calculation) of the global average rate of water level rise in the 20th century derived from tide-gauge records: for example, $1.7 \pm 0.5$ mm year$^{-1}$ (Bates et al. 2008 (eds.)), $1.61 \pm 0.19$ mm year$^{-1}$ (Wöppelmann et al. 2009) and $1.59 \pm 0.09$ mm year$^{-1}$ (Collilieux & Wöppelmann 2011). The estimated eustatic sea level rise in the North Sea was 1.3 mm year$^{-1}$ during the last century (Christiansen et al. 2001). The same average rate of mean water level rise ($1.5 \pm 0.5$ mm year$^{-1}$) was estimated for the Finnish coast of the Baltic Sea (Johansson et al. 2004). The rise in sea level was recorded at many tide gauges along Baltic Sea coasts at the end of the 20th century (Kalas 1993, Stigge 1993, Fenger et al. 2001, Ekman 2003, Kahma et al. 2003, Dailidienė et al. 2006, Suursaar et al. 2006). The average sea level rise for the period 1965–2001 for the German North Sea coast was 1.88–1.95 mm year$^{-1}$, and for the German Baltic Sea coast it was 1.14 mm year$^{-1}$ (Jensen & Mudersbach 2004).

The regional analysis of long-term variations in water level is directly connected to the problems concerning the erosion of coasts, inundation of land, security of hydro-engineering equipment, development of port infrastructure and seaside towns, safety of waterfront installations and the local population, recreation, and ecosystem stability. The Baltic coastal zone is being subjected to intense human pressure; it therefore plays a key role as an interface for trade, development of municipal activities, industry, shipping, energy generation, agriculture, fishery and tourism (Schernewski

& Schiewer 2002). Climate changes should be considered when formulating strategies of sustainable development in Baltic Sea coastal areas.

Historically, the ecosystems of the Baltic lagoons studied here are rather young ($\approx$4 000 years old); they are sensitive to eutrophication and are subject to intense anthropogenic pressure. Lagoons provide essential buffering and filtering functions. Being both links and mediators between terrestrial ecosystems and the open sea (Schiewer 2002), coastal lagoons could be very vulnerable to the direct impacts of climate change. The aim of this research was to study and compare trends in sea level and water temperature changes from the beginning of the last climatic period (1960s) to the present for three lagoons located along the southern and south-eastern shores of the Baltic Sea: the Darss-Zingst Bodden Chain (Germany), the Vistula Lagoon (Poland–Russia), and the Curonian Lagoon (Lithuania–Russia) (Figure 1). The working hypothesis behind the study was that

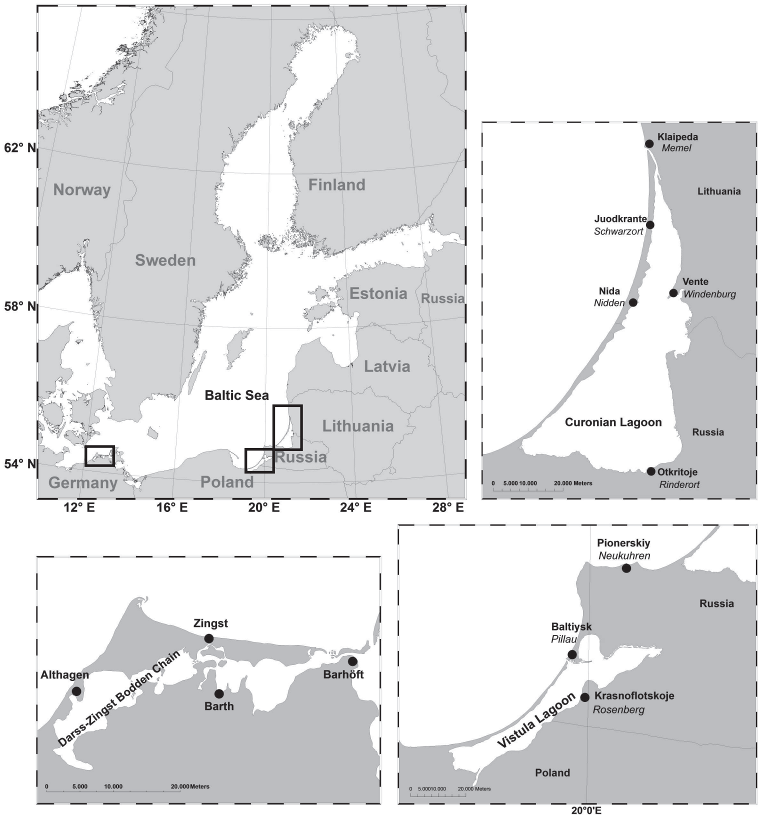

**Figure 1.** The Darss-Zingst Bodden Chain and the Vistula and Curonian Lagoons on the southern and south-eastern Baltic coast. The locations of the hydrographic water level measuring stations on each lagoon are shown

these lagoons should demonstrate a similar response to climate changes, although this could differ as a result of the influence of adjacent sea areas.

## 2. Study sites

The lagoons discussed in this study are shallow transitory basins each with only one connection to the Baltic Sea. The basic morphometric and hydrological characteristics of the lagoons are presented in Table 1. The Curonian Lagoon (CL) is the biggest Baltic lagoon (Figure 1). It is separated from the open sea by the relatively narrow sandy and wooded Curonian Spit (0.5–3 km wide) and connected to the sea solely through the Klaipėda Strait at the northern end of the lagoon. The lagoon is a terrestrial runoff-dominated system, and its hydrology is strictly related to the discharge from the catchment area. However, the lagoon water being hypereutrophic, its quality is controlled mostly by physical factors such as the wind regime, temperature, water level variations and transparency (Gasiūnaite et al. 2008).

**Table 1.** Selected morphological and hydrological parameters of the Baltic coastal lagoons. (Data collected from Sea map No. 1624 printed 1997, BSH Rostock; Žaromskis 1996, Gailiušis et al. 2001, Schiewer 2002, Chubarenko et al. 2005, Schumann et al. 2006, Chubarenko & Margonski 2008, Dailidienė & Davulienė 2008)

| Parameter, dimension | Darss-Zingst Bodden Chain | Vistula Lagoon | Curonian Lagoon |
|---|---|---|---|
| surface area [km$^2$] | 197 | 838 | 1584 |
| volume [km$^3$] | 0.4 | 2.3 | 6.3 |
| catchment area [km$^2$] | 1594 | 23871 | 100458 |
| mean depth [m] (excluding shipping channels) | 2.0 | 2.7 | 3.8 |
| maximum depth [m] (excluding shipping channels) | 3.9 | 5.2 | 5.8 |
| maximum length [km] | 66 (ferry route) | 91 | 93 |
| width [km] | 0.14–8.5 | 2–11 | 0.8–46 |
| length, coast line [km] | 143 | 270 | 325 |
| discharge from rivers [km$^3$ year$^{-1}$] | 0.29 | 3.68 | 22.18 |
| mean salinity [PSU] | 5.6 | 3.2 | $\sim 1.0$ |
| salinity range [PSU] | $< 0.5$–14.7 | $< 0.5$–6.5 | $< 0.5$–7.5 |
| inflow of seawater [km$^3$ year$^{-1}$] | 2.76 | 17.0 | 5.5 |

The Vistula Lagoon (VL), the second largest lagoon in the Baltic (Chubarenko & Margonski 2008), lies parallel to the Baltic shore and is 91 km long (Figure 1). It is separated from the Baltic Sea by a relatively narrow sandy, completely wooded barrier, which is cut by the lagoon inlet, the Baltiysk Strait, into two segments – the Vistula Spit to the south, and the Baltiysk Spit to the north. The inlet, which is significantly shorter than the Klaipėda Strait, ensures intensive ventilation of the lagoon by seawater. The present trophic state has been assessed as polytrophic/eutrophic.

The Darss-Zingst Bodden Chain (DZBC) is one of the shallow areas of inner coastal waters, known locally as 'Bodden', on the southern coast of the Baltic Sea (Schlungbaum & Baudler 2000). It is subdivided into several basins connected by narrow streams. The lagoon stretches along the shore and has a long, shallow connection to the Baltic Sea at its easternmost end. The total cross-section of this inlet is 4.5 times less than that of the Vistula Lagoon (Chubarenko et al. 2005). Water exchange between the lagoon and the Baltic Sea is governed by wind-induced differences in water level between the lagoon and the coastal waters.

## 3. Material and methods

This study is based on analysis of long-term changes of water level and water surface temperature, derived from historical monitoring data of the coastal stations. The water level, air and water temperature measurements for this study were obtained from four stations in the Curonian Lagoon (Figure 1): in the Klaipėda Strait (lagoon inlet), on the western shore (Vente station) and on the eastern shore (Nida and Juodkrante) which belongs to Lithuania. The Otkrytoye station (southern part of the CL) belongs to Russia, but its data has not been used for the studies because some periods were unreliable. Two stations in the Vistula Lagoon are located in the Baltiysk Strait (lagoon inlet) and at Krasnoflotskoye on the eastern shore of the central part of the lagoon. Data for the Darss-Zingst Bodden Chain was taken from the stations at Althagen, Zingst and Barth (all on the lagoon itself) also from Barhöft (the lagoon inlet). The sea conditions (water level and SST) were represented by data from Port Pionerskiy, which is located at the open Baltic sea coast between the Vistula and Curonian Lagoons, and by SST measurements on the sea shore at Zingst, and Klaipėda. As historical data has been used, both the current and the historical names of the locations are given in the plot legends and tables: Klaipėda/Memel, Baltiysk/Pillau, Krasnoflotskoye/Rosenberg, Nida/Nidden, Pionerskiy/Neukuhren.

We analysed the variations in the annual mean water level without specifically revealing their eustatic and isostatic components, for the periods of 1840–2008 for Baltiysk/Pillau, 1898–2008 for Klaipėda/Memel, 1937–2008 for Zingst, and 1961–2008 for all the other points. It is remarkable that all the lagoons lie on the periphery of the Fennoscandian land uplift, and that all had the same rate of land subsidence: 0 mm $\text{year}^{-1}$ (Ekman 2003, 2009) and $-1$ mm $\text{year}^{-1}$ (Vestøl 2006). This information is taken into account in the Discussion and Conclusions.

The rate of water level [mm $\text{year}^{-1}$] and SST [°C $\text{year}^{-1}$] changes at the various stations were evaluated using linear regression, which expresses unidirectional tendencies (trends) of water level and temperature changes over time. To eliminate irregular fluctuations in the illustrations of long-term trends, yearly mean values were smoothed by using the 11-year moving average (band width). The information on the quality of the regression was assessed by the $R^2$ determination coefficient, which gives the square of the correlation coefficient, and by Student's t-test.

As the atmospheric conditions in the Baltic region were driven by the inflow of air masses from the west, the annual mean water level changes in the CL, VL and DZBC were compared with values of the North Atlantic Oscillation index (NAO index). The NAO index is associated with changes in the oceanic and atmospheric heat flux towards Europe and changes in the atmospheric moisture and oceanic freshwater fluxes (Hurrell 1995); it is therefore an important indicator of climate changes. We used the winter (December to March) NAO index based on the difference in normalized sea level pressure between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland) when analysing the relation between the sea level and NAO index variability.

## 4. Results

Positive trends in water level variations were found for the three lagoons (Figure 2), but the trend rate differs. Water levels in the CL and VL rose significantly by 18 cm in the period between 1961 and 2008 (Table 2), while in the DZBC the water level increase was three times less (by 6 cm). The maximum rate during 1961–2008 was $\sim 4$ mm $\text{year}^{-1}$, recorded in the CL and the VL, and the minimum (approximately 1 mm $\text{year}^{-1}$) was in the DZBC (Table 2). The rate of water level rise in the lagoons also varied over time (Figure 2 and Table 2). The most informative data comes from the Baltiysk/Pillau station, where water levels have been measured since 1840. In the period from 1840 to 2008 there were several cycles of water level rise and fall, each lasting for up to four decades. For the period from 1961 to 2008 we perceive similar tendencies in water level fluctuations for our three

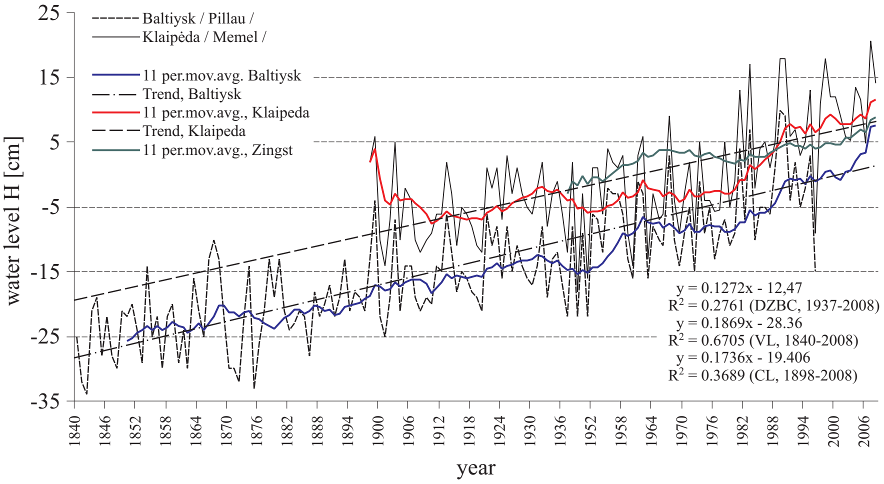

**Figure 2.** Long term variations in annual mean water level on southern and south-eastern Baltic coasts: Baltiysk/Pillau (1840–2008, VL), Klaipėda/Memel (1898 –2008, CL) and Zingst Bodden (DZBC, 1937–2008)

**Table 2.** Characteristics of measured water level trends for three Baltic lagoons and for the open Baltic coastal station at Pionerskiy

| Measurement point (lagoon) | Years | Water level increase due to trend [cm period$^{-1}$] | Linear water level trend [mm year$^{-1}$] | |
|---|---|---|---|---|
| | | | [mm year$^{-1}$] | R$^2$ |
| Zingst Bodden (DZBC) | 1937–2008 | 9 | 1.3 | 0.28 |
| Baltiysk/Pillau (VL) | 1937–2008 | 23 | 3.4 | 0.47 |
| Klaipėda/Memel (CL) | 1937–2008 | 23 | 3.3 | 0.43 |
| Zingst Bodden (DZBC) | 1961–2008 | 6 | 1.2 | 0.19 |
| Baltiysk/Pillau (VL) | 1961–2008 | 18 | 3.9 | 0.45 |
| Klaipėda/Memel (CL) | 1961–2008 | 18 | 3.8 | 0.4 |
| Krasnoflotskoye/ Rosenberg (VL) | 1961–2008 | 18 | 3.8 | 0.46 |
| Nida/Nidden (CL) | 1961–2008 | 18 | 3.9 | 0.35 |
| Zingst Bodden (DZBC) | 1991–2008 | 9 | 5.5 | 0.41 |
| Baltiysk/Pillau (VL) | 1991–2008 | 16 | 9.9 | 0.51 |
| Klaipėda/Memel (CL) | 1991–2008 | 8 | 5 | 0.17 |
| Krasnoflotskoye/ Rosenberg (VL) | 1991–2008 | 9 | 5.7 | 0.28 |
| Pionerskiy/Neukuhren (Baltic Sea) | 1991–2008 | 10 | 6 | 0.17 |

lagoons, as expressed by the 11-year moving average. These are repeated cycles of rise and stabilization (Figure 2): 1950–1960 (stable rise), 1961–1979 (stabilization), 1980–1991 (stable rise), 1992–2002 (stabilization).

From a comparison of the long-term monthly mean water level changes during separate thirty-year periods (1961–1990 and 1979–2008) at the Klaipėda stations in CL (Figure 3a) and at Zingst in DZBC (Figure 3b), it was inferred that the recent sea level rise was greater in all the seasons. The sea-level increase took place throughout the year, although this process was more intensive in the period from January to March. In addition, the variability of the monthly mean sea-level in the cold periods is more significant than in the warm periods. A non-uniform 'shift' (towards greater values) of the mean annual seasonal variation curve for 1979–2008 by 3–12 cm for CL and 3–7 cm for DZBC in comparison with the similar curve for 1961–1990 corresponds to climate changes, which manifest themselves differently at different seasons.

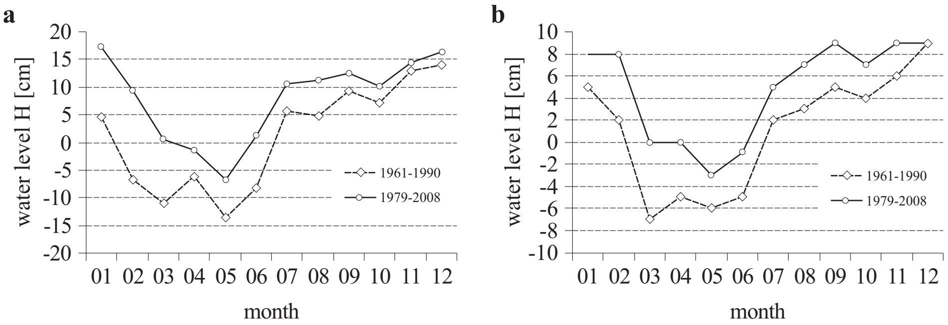

**Figure 3.** Seasonal variations in monthly mean water level for 30-year periods (1961–1990 and 1979–2008) at the stations in Klaipėda/Memel, CL (a) and Zingst, DZBC (b)

The seasonal dependence of trend characteristics is much more pronounced for CL than for DZBC (Figure 4a): the rate of water level increase is greatest in January–March (up to 0.8 mm year$^{-1}$) and June (nearly 0.5 mm year$^{-1}$), but less in late autumn. For DZBC the trend is nearly 2 mm year$^{-1}$ for the whole year except February–March (3–4 mm year$^{-1}$) and December (no increase at all). The maximum determination coefficient (Figure 4b) for these linear regressions in May–June for CL and June–September for DZBC indicates that the level rise in these months is almost linear.

Regression analysis results show that the water temperature in the lagoons is rising at a faster rate than on Baltic Sea shores. According to the assessment, the warming trend of the mean surface water temperature in the Curonian lagoon and in the Lithuanian coastal waters of the Baltic Sea rate

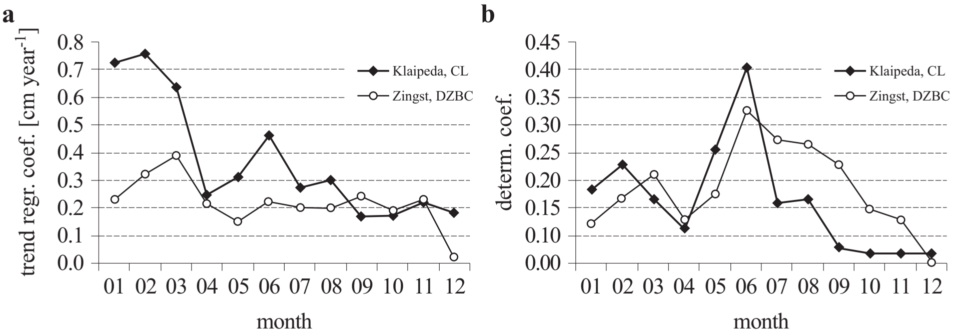

**Figure 4.** Values of (a) linear trends [mm year$^{-1}$] and (b) determination coefficients ($R^2$) for calendar month water levels in the CL (Klaipėda station) and DZBC (Zingst Bodden station) in the period of 1961–2008

was about 1.4°C in the period of 1961–2008 (Table 3). The warming trend of the mean surface water temperature in the Curonian Lagoon was 0.03°C year$^{-1}$ in 1961–2008, and ca 0.05°C year$^{-1}$ in 1977–2002 (CL and VL), and 0.06°C year$^{-1}$ in the DZBL (1977–1992). A more detailed comparison between lagoons was impossible, because of the lack of data and the unequal periods.

**Table 3.** Linear trends for water temperature (SST) on southern and south-eastern Baltic coasts

| Measurement point (lagoon) | Years | Increase due to trend in water temperature (SST) [°C period$^{-1}$] | Water temperature (SST) – linear trend [°C year$^{-1}$] | $R^2$ |
|---|---|---|---|---|
| Zingst Ostsee (Baltic Sea) | 1961–2008 | 1.9 | 0.04 | 0.37 |
| Nida/Nidden (CL) | 1961–2008 | 1.4 | 0.03 | 0.33 |
| Nida/Nidden (Baltic Sea) | 1961–2008 | 1.4 | 0.03 | 0.33 |
| Zingst Ostsee (Baltic Sea) | 1977–2002 | 2.3 | 0.09 | 0.55 |
| Zingst Bodden (DZBC) | 1977–1993 | 1.0 | 0.06 | 0.25 |
| Nida/Nidden (CL) | 1977–2002 | 1.3 | 0.05 | 0.30 |
| Nida/Nidden (Baltic Sea) | 1977–2002 | 0.8 | 0.03 | 0.14 |
| Klaipėda/Memel (Baltic Sea) | 1977–2002 | 1.0 | 0.04 | 0.29 |
| Baltiysk/Pillau (VL) | 1977–2002 | 0.8 | 0.03 | 0.14 |
| Krasnoflotskoye/ Rosenberg (VL) | 1977–2002 | 1.3 | 0.05 | 0.29 |
| Pionerskiy/Neukuhren (Baltic Sea) | 1977–2002 | 1.3 | 0.05 | 0.25 |

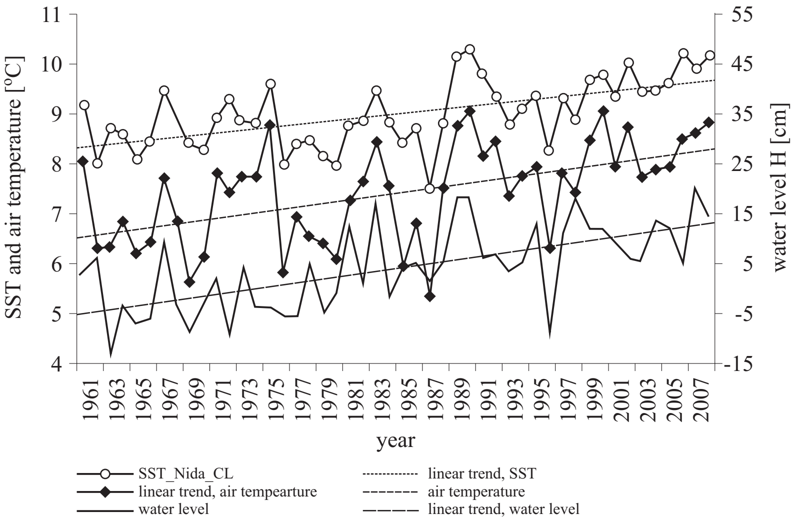

**Figure 5.** Annual mean water level, surface temperature (SST) and air temperature as well as their linear trends in the Curonian Lagoon in the period of 1961–2008 (updated data, Dailidienė et al. 2006)

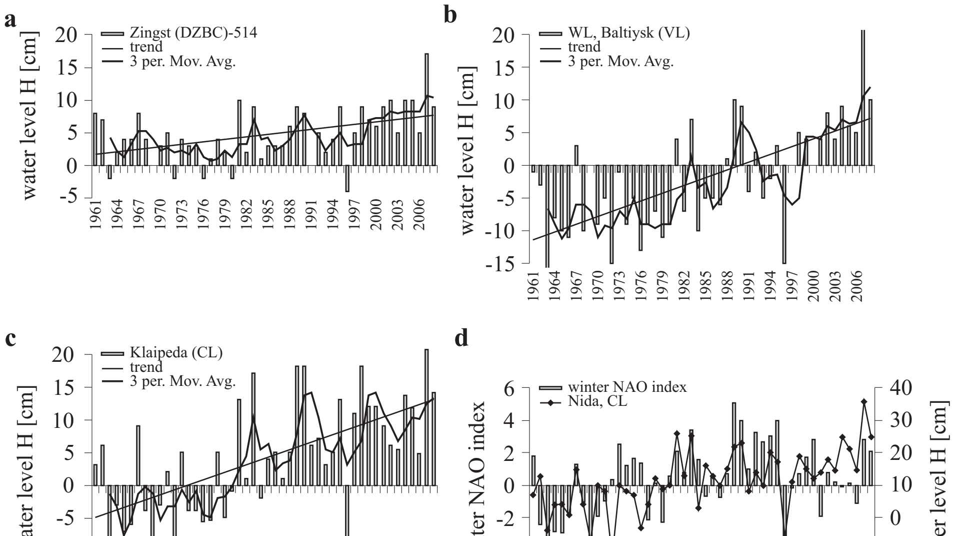

**Figure 6.** Water level variations at DZBC (a), VL (b), CL (c), and comparison (d) of water level variations at Nida (CL) with variations in the winter NAO index from 1961 to 2008

The rise in water temperature and water level in the lagoons is due to changes in the air temperature (Figure 5) and atmospheric circulation. In addition, the variability in the annual mean water temperature and water level as well as their extreme values have increased very dramatically since the late 20th century, when the winter NAO index was mostly in the positive phase for several years (1988–1995) (Figure 6).

It was found that the winter NAO index varied in the same way as the mean annual water level variation (Figure 6) in the lagoons under study in 1961–2008. The correlation analysis showed a positive correlation between the winter NAO index and the annual water level variations in the lagoons. Correlation coefficients between the NAO index and water level variations at Klaipėda/Memel, Baltiysk/Pillau and Zingst were 0.58, 0.62 and 0.43 respectively, with a statistical significance of 99.9%. This suggests that the changes in air mass dynamics in the North Atlantic are partly reflected in the interannual fluctuations of the water level on the coasts and in the lagoons of the south-eastern Baltic Sea.

## 5. Discussion and conclusions

The present-day water level variations on Baltic Sea coasts are determined by three main factors: the post-glacial uplifting of the Fennoscandian land mass, the global rise in eustatic water level, and the atmospheric circulation. Highly influential in this respect is the mesoscale atmospheric variation of circulation, which determines the air masses flowing into the North Atlantic region, as well as the formation and development of cyclones and anticyclones. The predominance of westerly inflows air masses leads to higher water levels in the eastern Baltic.

When comparing the long-term tendencies in water level rise in the Baltic lagoons, we see that the rate of this rise increases as we move from the southern to the south-eastern shores: it is approximately 4 mm year$^{-1}$ in the CL and VL, but only 1 mm year$^{-1}$ in the DZBC. However, the structure of seasonal water level variations remains the same, independently of the average climate scale period, and the mean monthly level increased by 3 –10 cm in nearly all months. On the basis of an analysis of seasonal variations of monthly averaged water level, we see that the trend in annual mean water levels is influenced by high water level in the January–March months.

Some of the most important factors affecting the long-term mean water level change in the coastal lagoons on the southern and south-eastern Baltic are land uplift, the rise in the global eustatic mean sea level, the prevailing wind with respect to the shore, and changes in freshwater gain. The eustatic change of sea level has a global influence, whereas tectonic movements can change the response on a regional scale. According to recent investigations, a land subsidence of $-1$ mm year$^{-1}$ (Vestøl 2006) for southern and south-eastern Baltic shores should be taken into consideration when calculating the absolute water level rise in these lagoons. If we take these trends into account when calculating water level rises for longer periods (1937–2008, Table 2), land subsidence practically cancels out any climatically induced water level changes in the DZBC, but not in the CL or VL, where the trend is strongly pronounced.

In addition, the mean annual water level in the coastal lagoons of the Baltic Sea is determined by the direction of the prevailing wind with respect to the location of the sea coast and lagoon. Analyses of the relations between the wind direction distribution and the water level in the Baltic Sea at Klaipėda (CL) show that the water level in the south-eastern part of the Baltic Sea along the Lithuanian coast increases when westerly winds are dominant and decreases when easterly winds prevail (Dailidienė et al. 2006). Indeed, an area of low pressure established itself over northern Europe during the research period, and the resulting cyclonic circulation was dominated by strong westerly winds. Since the 1960s these westerly airflows have intensified (Bukantis et al. 2001, BACC 2008), as a result of which climate change can cause rapid water level rise in the south-eastern lagoons (CL and VL). On the southern Baltic coast the dominant south-west winds may also have less influence on water level rise, as a result of which the magnitude of the water level rise in the DZBC was half that in the CL and VL. Since the 1960s, westerly airflows have intensified during winter, and this has caused an increased frequency of maritime air-masses entering the Baltic area, which have caused higher winter air temperatures and enhanced precipitation (Bukantis et al. 2001, BACC 2008). This process could have led to the more intensive water level rise in January–March observed in the recent period of 1979–2008. On the other hand, the precipitation data for 1978–2008 show less rainfall in the central and northern areas of the Baltic, but more in the southern part (Lehmann et al. 2010). The annual runoff from the River Nemunas into the Baltic has decreased in recent years. According to Dailidienė & Davulienė (2008) the mean Nemunas runoff of $503 \pm 40$ m$^3$ s$^{-1}$ in 1984–2005 was less than this river's long-term runoff of 664 m$^3$ s$^{-1}$ for the period 1811–1995. The catchment area of the Nemunas makes up 5.6% of the entire catchment area of the Baltic Sea and 96% of the catchment area of the Curonian Lagoon. From this we can conclude that if rainfall had increased in the south-eastern Baltic region, the rises in water level risings would have been greater.

Generally, based on the results of this study, regression analysis showed that the rate of increase in the annual average water temperature in coastal Baltic waters appears to be lower than in the lagoons. During the research period (1961–2008) the water temperature and water level trends in the southern and south-eastern coastal lagoons of the Baltic Sea were positive, but maximal anomalies in the coastal lagoons were observed only in the last two decades, and it seems that the processes due to climate change occurred in many regions worldwide (IPCC 2007). A similar annual variation in warming trend was observed in the sea surface temperature of the Baltic Sea (BACC 2008, Lehmann et al. 2010).

Sea level and temperature rise is evident in all three coastal Baltic lagoons, but in the context of their different hydrographic regimes, these tendencies manifest themselves in a variety of ways in time and magnitude. In conclusion, future changes in climate system components may have a stronger effect on Baltic Sea coastal areas, such as lagoons, boddens and haffs. The rise in water temperature determines the level of eutrophication, and water level rise intensifies coastal erosion. Processes resulting from climate change, such as the changes in annual water level and water temperature, are not expected to be geographically uniform in the Baltic Sea; therefore, data on their distribution are needed for an assessment of their impact on coastal regions.

## Acknowledgements

The authors thank Rostock University for financing the working seminars at the Zingst Biological Station, where this paper was initially prepared, grant No. 08-05-92421 (ECOSUPPORT Project) of the Russian Fund for Basic Researches for supporting data collection and processing for the VL, and the CLIMSEAS Project for supporting the work with reference literature. Data for the CL were provided by the Department of Marine Research of the Environmental Protection Agency of the Republic of Lithuania. Data for the VL, overviewed in the Climate Atlas... (2007), were collected by the Russian National Hydrometeorological Service. Data for DZBC were taken from the Zingst Maritime Observatory of Leipzig University, the National Board for Environment and Nature in Stralsund, the Zingst Biological Station of Rostock University, and the Federal Office for Sea Traffic and Hydrography (BSH) in Rostock.

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