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Sea level variability at the Lithuanian coast of the Baltic Sea

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The aim of the paper is to analyse the sea level variability at the Lithuanian coast during the last 100 years using all data available in Lithuania. The analysis, based on sea level data of the Klaipėda Strait for 1898–2002, clearly shows that the long-term sea level increased by about 13.9 cm. Furthermore, it is remarkable that the increase is not found to be linear during the study period. Only a negligible increase is found at every Lithuanian tide gauge until World War II. Starting from the middle of the last century the increase in sea level is more pronounced having a rate of about 3 mm per year since the 1970s. This rise leads to manifold practical problems concerning activities in the coastal areas. The water rise will intensify the intrusion of salty water into the Curonian Lagoon slowly changing the ecosystems in its northern part. The reasons behind this rise are related to enhanced and more frequent advection of warm and moist maritime air masses during the cold season (October–March). This is coupled with intensified air flow from the west with increasing air temperatures followed by rise in water temperatures and thermal expansion of sea water, the global rise of the sea level also playing an important role. The annual mean sea level fluctuation is found to be linked with the winter North Atlantic Oscillation (NAO) index. When the NAO index is positive during winter, the dominating and enhanced westerly flow across the North Atlantic advects relatively warm maritime air over northern Europe. These strong westerly winds cause more frequent flooding events in the southeastern part of the Baltic Sea at the Lithuanian coast.

Introduction

The study of the mean sea level and its variation has important practical and theoretical aspects. The sea level may be analysed as one of the indicators of fluctuations in the regional atmospheric circulation. The mean sea level is an important basis for geodesic levelling.

Information about changes in sea level has been necessary for harbor reconstructions, building settlements, towns and enterprises next to water bodies as well as for navigation security. Therefore systematic sea level observations have been performed at the Lithuanian coast of the Baltic Sea and in the Curonian Lagoon (also known as Kuršių marios, Kursky Zaliv, Kurisches Haff, Courland Lagoon) as is the case all over Europe since the beginning of the 19th century. The sea level observations started in Klaipėda Strait in 1810, but systematic observations have been performed since 1898. Analysis of sea level changes in the study area was made by various authors (Lazarenko 1961, Dubra 1978, Jarmalavičius *et al*. 1996).

Investigation of sea level variations has a long tradition in all countries of the Baltic Sea. The findings of various authors (Lisitzin 1957, 1966, Lazarenko 1961, Kalas 1993, Stigge 1993, Fenger *et al*. 2001, Johansson *et al*. 2001, 2004, Baerens 2003, Ekman 2003) help us to understand the reasons for similarities as well as differences of the sea level fluctuations in various coastal regions of the Baltic Sea.

Eustatic change of sea level has a global influence while tectonic movements are important mostly on a regional scale. The changes in sea level along the coast of the Baltic Sea result mainly from the uplift of the Scandinavian land plate with simultaneous lowering of the southern Baltic coast (Lisitzin 1957, 1966a, Ekman 2003, Johansson *et al*. 2004). In the Baltic Sea area the long-term sea level trends also depend on the geographical location of the measurement site as a result of the land uplift of Fennoscandia. The mean sea level of the global ocean is increasing, but this effect is partially balanced by the land uplift which increases towards the north (Andersson *et al*. 1992). Consequently, the calculated rate of sea level rise was estimated to be about 1.7 mm year^{-1} in the southeastern Baltic Sea, while it reverses to –9.4 mm year^{-1} in the northwestern Gulf of Bothnia (Raudsepp *et al*. 1999). One of the most significant parts of the above-mentioned studies was the elimination of meteorological effects on sea level. The effect of meteorological factors on mean sea level was studied e.g. by Lisitzin (1966b).

Ekman (2003) used the historical sea level time series from Stockholm to demonstrate the key role played by winter climate, especially that of wind forcing. It was pointed out that there exists a relationship between the Stockholm sea level and the North Atlantic Oscillation (NAO) winter values. Johansson *et al*. (2001, 2004) studied the Baltic Sea water balance and correlation with the NAO index and confirmed that the sea level variability along the Finnish coast correlated with the NAO index whereas Kahma *et al*. (2003) found that the correlation between long-term mean sea level and the NAO index was stronger during winter.

The long-term climate change has cyclic fluctuations. At present we are experiencing the warming period (IPCC 1992). It is known that to a large extent this warming process is influenced by astronomic and climatic factors, although anthropogenic factors are getting more and more important. According to the data of various authors, sea level in the World Ocean rises with a speed of 1.0 mm to 1.9 mm year^{-1} (Basalykas 1985, IPCC 1992, Kalas 1993, Subrata 1993, Jarmalavičius *et al*. 1996, Raudsepp *et al*. 1999, Johansson *et al*. 2001, Vestergoard 2002).

The World Meteorological Organization (WMO) established an Intergovernmental Panel of Climate Change in 1988, where scientists from various countries around the world pay great attention to the studies of sea level change as one of the main indicators of climate change. IPCC (2001) stated that the global mean sea level rose linearly during the 20th century by about 1–2 mm year^{-1} (Johansson *et al*. 2004). IPCC (2001) presents scenarios of the global mean sea level change in the 21st century, based on the Special Report on Emission Scenarios (SRES). According to these scenarios calculated by Nakičenovič *et al*. (2000), the global mean sea level will rise 9–88 cm during 1990–2100 (Johansson *et al*. 2004). The rise in the global mean sea level results from the rise in the air temperature determining the thermal expansion of the seawater and melting of glaciers.

It was found that a global mean sea level rise of 50 cm from 1990 to 2080 would lead to a sea level rise of 33–46 cm in Danish waters (Fenger *et al*. 2001). It can be expected that by the year 2100 many regions currently experiencing relative sea level fall will instead have a rising relative sea level (Fenger *et al*. 2001). An example of the ongoing rise of the sea level could be the northern part of the Baltic Sea, the Gulf of Finland: the declining trend of mean sea level will probably not continue in the future, because the accelerating rise in the global mean sea level will balance the land uplift (Johansson *et al*. 2004). Land movements, both isostatic and tectonic, will continue through the 21th century at rates which are unaffected by climate change.

Change in sea level is not expected to be geographically uniform in the Baltic Sea, so information about its distribution is needed for the assessment of the impact on coastal regions. Therefore the aim of this paper is to analyse the long-term tendency in sea level changes, to study the variability of annual mean sea level in our region as well as to assess the importance of some meteorological and oceanographic parameters, in particular wind distributions, air and sea water temperature. In our analysis here the long-term time series of sea level data from seven Lithuanian tide gauges are used (Fig. 1).

The daily variations of sea level are determined by short-term changes of atmospheric forcing. The regime of a monthly mean sea level change during a year depends on seasonal changes in hydrological and meteorological conditions. The regime of long-term sea level is affected by the entirety of climatic, geological, eustatic and astronomic factors. In order to assess the influence of these factors on the sea level in the Lithuanian marine waters, the annual variability of the annual sea level and its correlation with NAO index were examined. The variability of monthly mean sea level was analysed along with extreme values of sea level and long-term seasonal change of the sea level.

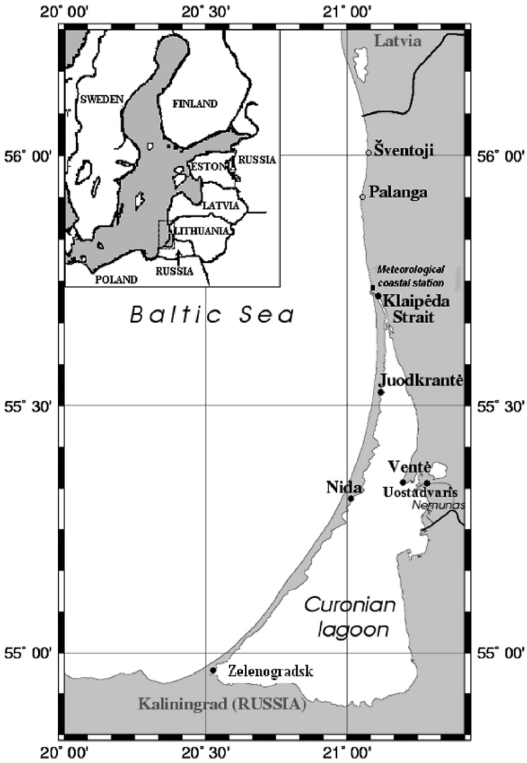

Fig. 1. Locations of the Lithuanian tide gauges: operative (bold circle) and closed (transparent circle) gauges (Table 1).

Study site, material and methods

In this paper the general peculiarities of long-term fluctuations of sea level in the southeastern part of the Baltic Sea at the Lithuanian coast including the Curonian Lagoon are analysed. The data of sea level available are from seven tide gauges: two of them are located on the Baltic Sea shore near Palanga and Šventoji, one tide gauge is in the Klaipėda Strait, three tide gauges are on the Curonian Lagoon shore near Juodkrantė, Ventė and Nida and one at the mouth of the Nemunas River near Uostadvaris (Fig. 1).

Lithuania has an about 92-kilometer long coastline of the Baltic Sea. It is a complex area including terrestrial and marine features: sandy beaches, dunes, fens, inshore waters and an underwater slope, a few moraine cliffs. The coast of the sea is open, exposed to the prevailing winds and waves.

The area of the Curonian Lagoon is about 1584 km^2. The Lagoon is a semi-enclosed almost fresh water body, which is separated from the sea by a narrow sandy spit (minimum width is about 400 m). In some extreme cases during stormy weather, the Curonian Spit is flooded and the water flows over it into the Lagoon near Zelenogradsk (Russian territory). This event was last observed in 1983 (Dubra *et al*. 1998). Only the narrow Klaipėda Strait in the northern part of the Lagoon connects it with the Baltic Sea Proper and the water exchange between the Curonian Lagoon and the Baltic Sea takes place here. According to Gailiušis *et al*. (2001), in 18% of all cases marine water penetrates the Curonian Lagoon. Therefore river discharge has a strong influence on water level in the Lagoon. The Nemunas River flowing into the Baltic Sea through the Curonian Lagoon is the third largest river runoff to the Baltic Sea. Its annual discharge is on average 22 km^3.

About 26% of the Curonian Lagoon area belongs to the Lithuanian Republic, the other part to the Russian Federation. The length of the

Table 1. The Lithuanian tide gauges, periods of available data, long-term mean, maximum and minimum sea levels. Standard deviation and 95% confidence interval of long-term mean sea level.

Station	Observation periods with available data	Mean sea level (cm)	S.D.	95% confidence interval	Max. (cm)	Min. (cm)
Šventoji	1926–1931, 1945–1958	0	6.1	2.7	143	–79
Palanga	1922–1925	–1	6.4	7.3	85	–58
Klaipėda Strait	1898–1940, 1949–2002	–1	7.9	1.6	185	–91
Juodkrantė	1901–1915, 1925–1938, 1955–2002	6	7.3	1.6	149	–70
Nida	1925–1938, 1948–2002	8	7.6	1.8	154	–70
Ventė	1925–1942, 1955–2002	10*	7.9	1.9	164	–72
Uostadvaris	1901–1915, 1925–1932, 1961–1965, 1973–1985, 1997–2002	21	8.2	2.3	146	–49

*The revised value of long-term mean sea level. The correction for sea level of Ventė station is calculated from levelling according to heights of benchmarks (Dailidienė *et al.* 2004).

coastline of the Lagoon in the Lithuanian territory is about 150 km (Žaromskis 1996). Small inlets, bays and capes engrave this coastline, which has a complex shape with sandy dunes.

The analysis was based on historic sea level data from the southeastern part of the Baltic Sea, and from the northern and central parts of the Curonian Lagoon that belong to Lithuania. Data from seven tide gauges were run by the Center of Marine Research, Klaipėda for the whole working period up to the year 2002 (Fig. 1 and Table 1). The sea level data available at the Palanga and Sventoji stations have only historic importance due to the episodic observation sessions (Table 1). Nowadays there is no working sea level measurement station at the Lithuanian coast of the Baltic Sea.

The earliest sea level data are from the Klaipėda Strait, starting from 1898 (at that time Klaipėda was under German government and was called Memel). Here the equipment for the sea level measurement was installed in 1811, however data are present only starting with 1898. Since 1880 the sea level has been measured at Uostadvaris (at that time known as Kuwertshof) and Ventė (Vindenburg). Here the Seibt-Fuss limnographs were used from 1905 to 1944 and from 1906 to 1926, respectively. The monthly mean sea level data are found in the archives until the year 1939 for every Lithuanian tide gauge.

During World War II, the sea level at the Lithuanian coast was measured episodically and no data are present (Table 1). It should be admitted that during this period data time series were interrupted in the whole region of the eastern and southeastern part of the Baltic Sea due to the global extent of the conflict. Therefore the data could not be restored applying the extrapolation or other methods.

The tide gauges at Klaipėda, Nida and Uostadvaris have been instrumented with Rordans type sea level chart recordings since 1954, 1955 and 1960, respectively. Hourly sea level data with an accuracy of 1 cm are available at these stations.

Until World War II the tide gauge levelling system applied in Lithuania was changing several times from the German Normal Zero to Lithuanian National system. In 1961 the Baltic height system (BS) was established in Lithuania and other Baltic states (Lazarenko 1961, Dubra 1978). This system is based on the tide gauge Kronstadt (–500 cm), Russia.

The longest time series of the tide gauge in the Klaipėda Strait covers the period of over 100 years, from 1898 to 2002 with the interruption from 1940 to 1948 (Table 1). Historically more attention is paid to this station as the only Lithuanian harbor is located in the Klaipėda Strait. Therefore the levelling of higher precision compared to the Curonian Lagoon has been carried out here. The tide gauge in the Klaipėda Strait has been instrumented with data recording units (SUTRON) for real-time operation and telecommunication (with an accuracy of 1 mm) since 2004. Upgrading of the station is done according to the BOOS-PAPA project. The hourly real-time sea level data from this station are available at the homepage of the international BOOS organization (www.boos.org).

Linear regression was applied to study trends, and correlation analysis — to study relations between different time series. A statistical significance was evaluated using Student's *t*-test. Trend analysis was applied to sea level, surface water temperature and air temperature long-term changeability studies. Trend analysis is one of the most appropriate methods when working with the parameters exhibiting irregular fluctuations. In order to eliminate these fluctuations, the 15-year moving (floating) averages were calculated as well.

The time series of annual mean sea level starting with 1961 were used for comparison of all Lithuanian tide gauges. The annual mean sea level data were also compared with the wind and air temperature from the Klaipėda marine station operated by the Lithuanian Hydrometeorological Service. This station is located near the Baltic Sea coast and represents the meteorological conditions in this area (Fig. 1).

The study of monthly mean sea level variability comprises the cold (October–March) and the warm (April–September) periods of the year. These periods were analysed separately because the perennial air temperature changes are larger during the cold period of the year than during the warm period (Bukantis *et al.* 2001). A linear regression and 15-year moving averages were calculated from the monthly mean sea level data.

We used winter (December through March) mean North Atlantic Oscillation index (NAO) based on the difference of normalized sea level pressure between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland when analysing the relation between the sea level variability and the NAO index. The NAO index is associated with changes in oceanic and atmospheric heat flux towards Europe and changes in the atmospheric moisture and oceanic freshwater fluxes, and is therefore an important indicator of climate change (Buch *et al.* 2001).

Results

Long-term variability

Long-term mean sea level was calculated from annual mean sea level data for all Lithuanian tide gauges joining all available data in the period of 1898–2002 (Table 1). The mean sea level difference between the tide gauges depends on the geographical location. Therefore, the highest long-term mean sea level was obtained for the tide gauge Uostadvaris located in the mouth of the Nemunas River, and it decreased towards the sea. According to the data, the sea level slope of about 22 cm was established between tide gauges Uostadvaris and Klaipėda Strait (Table 1). This slope and its long-term change are important when analysing the long-term seawater flooding along the southeastern coast of the Baltic Sea. The rise in sea level could reduce the sea level slope and stimulate salty water intrusions into the northern part of the Curonian Lagoon.

The time series of the annual mean sea level data of the tide gauge Klaipėda Strait were used for the trend analysis in the period of 1898–2002. It was found that the rate of long-term sea level rise was changing during different periods of the 20th century (Fig. 2). A slight and statistically not significant rising tendency was observed until World War II. However, a more pronounced rise was observed during the last half of the 20th century. Linear regression analysis showed that the sea level rose by about 16 cm in the Klaipėda Strait and about 12 cm in the Curonian Lagoon

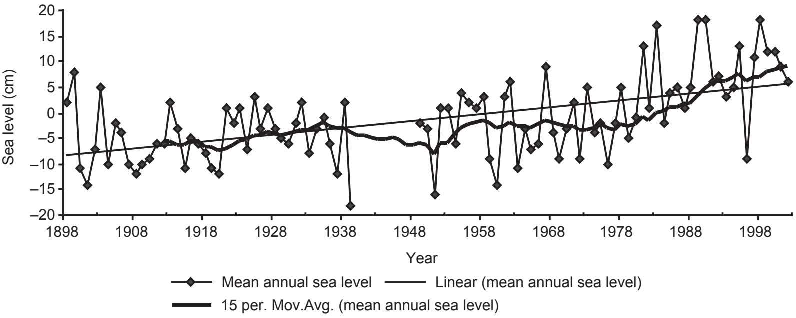

Fig. 2. Annual mean sea level with linear trend and the 15-year moving averages (Mov.Avg.) in the Klaipėda Strait in 1898–2002.

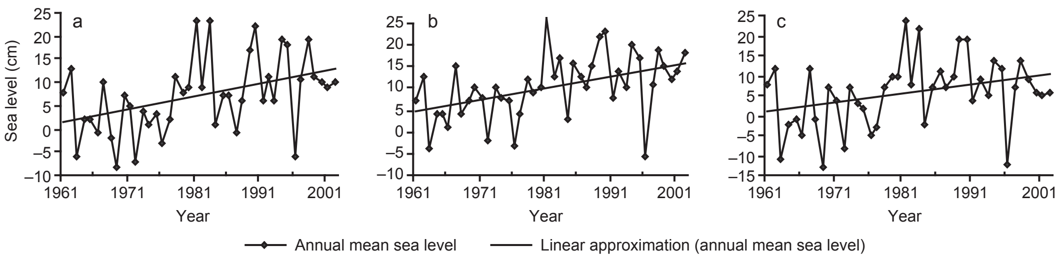

Fig. 3. Annual mean sea level with linear trend of the Curonian Lagoon tide gauges: (**a**) Juodkrante, (**b**) Nida and (**c**) Vente in 1961–2002.

in the period 1961–2002 (Figs. 2 and 3, Table 2). The time series of the analysed period were divided into two equal periods and statistical significance was evaluated using Student's *t*-test. A statistical test for the means of the sea level prior to 1981 and after 1981 gave significance equal to or higher than 0.05 at every station.

In toto the sea level rose in the Klaipėda Strait region by about 13.9 cm during 1898–2002 (Table 2). Land movements were not eliminated from this obtained value. This is because researchers recommend different estimations of land sinking in the Lithuanian region. It varies from 0 to –2 mm year^{-1} (Jarmalavičius *et al.* 1996, Baerens 2003, Mäkinen 2003). However, the rate of sea level rise (1.3 ± 0.2 mm year^{-1}) in the Lithuanian region during the 20th century, is similar to the global mean sea level rise rate, which is 1 mm year^{-1} (Basalykas 1985, Raudsepp *et al.* 1999). This value is also similar to the average mean sea level rise rate (1.5 ± 0.5 mm year^{-1}) at the Finnish coast of the Baltic Sea (Johansson *et al.* 2004) and corresponds to eustatic sea level rise (1.3 mm year^{-1}) in the North Sea during the last century proposed by Christiansen *et al.* (2001).

The variability of sea level on the annual time scale is studied using the time series of annual medians and the annual standard deviations of the tide gauge in the Klaipėda Strait (Fig. 4). The trends show that the annual median and the annual standard deviations increase in the analysed period of 1898–2002. The results of the comparison show that the time series of annual median and mean annual sea level as well as their 15-year moving averages are similar (Fig. 4).

Table 2. Trends in the annual mean sea level for the Lithuanian tide gauges.

Station	Years	Increase (cm period^{-1})	R^2	t	$p <$
Klaipėda Strait	1898–2002	13.9	0.28	5.16	0.001
Klaipėda Strait	1961–2002	15.9	0.32	4.37	0.001
Juodkrantė	1961–2002	11.8	0.19	2.12	0.05
Nida	1961–2002	11.6	0.28	3.14	0.01
Ventė	1961–2002	9.9	0.11	2.33	0.05

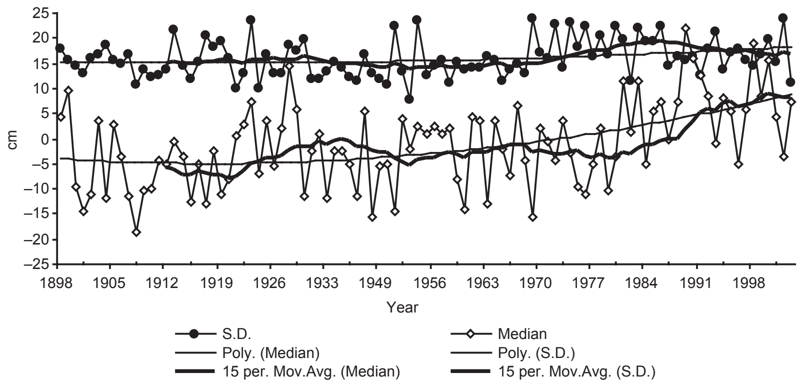

Fig. 4. Annual standard deviations (upper line group) and annual medians of sea level (lower line group) along with polynomial (Poly.) trends and 15-year moving averages (Mov.Avg.) for the tide gauge Klaipėda Strait in 1898–2002.

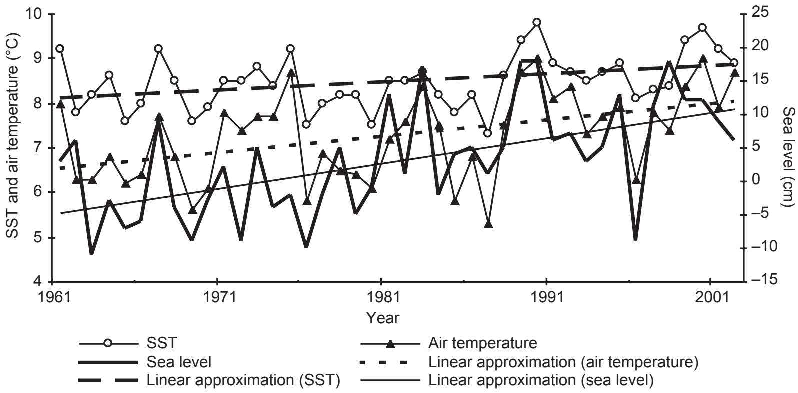

Fig. 5. Annual mean sea level, sea-surface temperature (SST) and air temperature along with linear trends in 1961–2002.

It is known, that the rise in the mean sea level in the Baltic Sea is a result of the local rise in the sea surface temperature and of the increase in the water volume of the Baltic Sea due to the thermal expansion of the World Ocean. So, in this study, based on the analysis of local measurement data, the estimated rise in water level only explains the local Baltic response to global warming.

If we compare long-term variations of annual mean sea level and its trends with the annual mean water surface temperature and with air temperature at the Klaipėda station (Fig. 5), we can see that the variations and tendencies resemble each other. During the last decades of the 20th century an enhanced rise of all of the above mentioned parameters is observed. According to the data of the Klaipėda stations, the long-term mean air temperature and the long-term mean water temperature calculated for the climatic period of 1961–1990 are 7.0 °C and 8.4 °C, respectively. However, higher annual mean air temperature and water surface temperature have been observed since 1988, except for the year 1996 (Fig. 5).

The correlation between the annual mean sea level and the annual mean water surface temperature was analysed for every Lithuanian tide gauge in the period of 1961–2002. Correlation coefficient of 0.6 ($p < 0.01$) was found for the tide gauge Klaipėda Strait. Correlation got weaker from the Klaipėda Strait towards the central part of the Curonian Lagoon. Weak correlation, of about 0.4 ($p < 0.01$) was found in the tide gauges Juodkrantė and Nida. However, no correlation between the annual mean sea level and the annual mean surface water temperature was found at the stations Ventė and Uostadvaris which are most influenced by the Nemunas River (Fig. 1).

The correlation with the NAO index

The variability of the sea level in the Baltic Sea correlates with the North Atlantic Oscillation (NAO) index (Johansson *et al*. 2001, 2004, Ekman 2003, Kahma *et al*. 2003). A higher

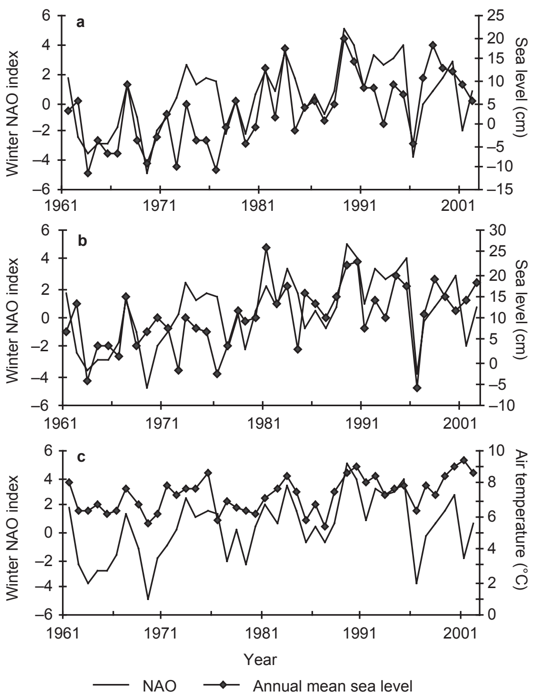

Fig. 6. Annual variation of the winter NAO index along with the annual mean sea level of tide gauges (**a**) Klaipėda Strait and (**b**) Nida located in the central part of the Curonian Lagoon in 1961–2002. The comparison of fluctuations between the winter NAO index and annual mean air temperature of (**c**) Klaipėda meteorological station in 1961–2002.

NAO index means that the air pressure is higher than average over the southern part of the North Atlantic or lower than average over the northern part. When the NAO index is positive during winter, enhanced westerly winds across the North Atlantic advect relatively warm maritime air over a large part of Europe. Generally, according to Johansson *et al*. (2001), winds having a large zonal component, associated with a high NAO index (anomaly), tend to keep the Baltic Sea level high.

Table 3. Correlation between the winter NAO index and the annual mean sea level for the Lithuanian tide gauges.

Station	Years	*R*	*t*	*p* <
Klaipėda Strait	1898–2002	0.44	4.05	0.001
Klaipėda Strait	1961–2002	0.67	2.94	0.01
Juodkrantė	1961–2002	0.64	2.79	0.01
Nida	1961–2002	0.58	2.74	0.01
Ventė	1961–2002	0.66	2.87	0.01
Uostadvaris	1995–2002	0.71	1.13	0.3

The correlation between the winter NAO index and the annual mean sea level of the Curonian Lagoon was studied (Table 3). The NAO index for the mean winter period (December through March) constructed from surface air pressure difference between 2 stations — Lisbon, Portugal, and Stykkisholmur, Iceland — was used (Hurrell *et al.* 1995). It was found that the long-term variations of the winter NAO index well resembled the long-term annual mean sea level of tide gauges Klaipėda Strait and Curonian Lagoon during 1961–2002 (Figs. 6 and 7a). The correlation coefficient ranged from 0.58 to 0.66 ($p < 0.01$) except for the tide gauge Uostadvaris, which is located in the mouth of the Nemunas River (Table 3). The correlation for the Klaipėda Strait in the period of 1989–2002 was weaker as compared with that in the earlier period of 1961–2002. The correlation coefficients were 0.44 and 0.67 ($p < 0.001$ and $p < 0.01$, respectively). The annual mean air temperature measured at the Klaipėda station on the coast of the Baltic Sea well resembled the winter NAO index fluctuations in the period of 1961–2002 (Fig. 6c). The correlation was 0.63 ($p < 0.001$) (Fig. 7b). This suggests that the sea level fluctuations in the southeastern part of the Baltic Sea and the Curonian Lagoon are caused by variations in air mass dynamics in the North Atlantic areas. The long-term variations in sea level are likely to be connected with the global long-term climatic variations.

The variability of monthly mean sea level

The variability of the monthly mean sea level and the 15-year moving averages for the warm and cold periods of the year were analysed (Fig. 8). When analysing the long-term change in monthly mean sea level in different periods, it becomes evident that the increase in sea level is more pronounced in the cold period of the year. The rise in sea level in recent decades was related to more frequent advection of warm and wet air masses during the cold period, stronger movement of air from the west, rising air temperature (Bukantis *et al.* 2001, Ekman 2003, Hurrell *et al.*

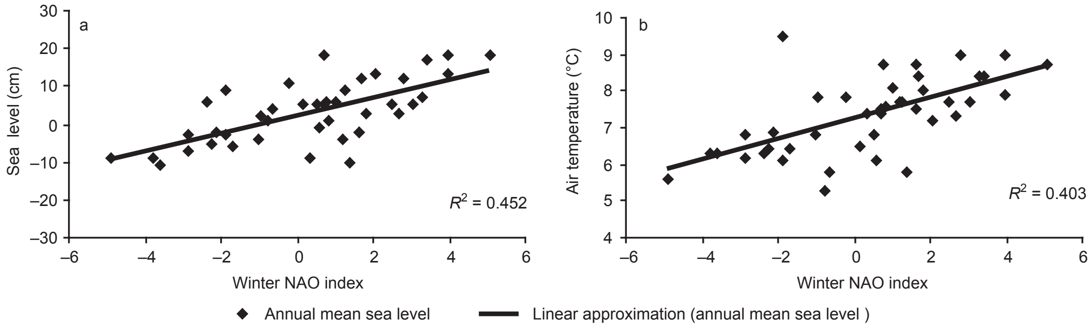

Fig. 7. Correlation (**a**) between the winter NAO index and the annual mean sea level, and (**b**) between the winter NAO index and the annual mean air temperature in Klaipėda in 1961–2002.

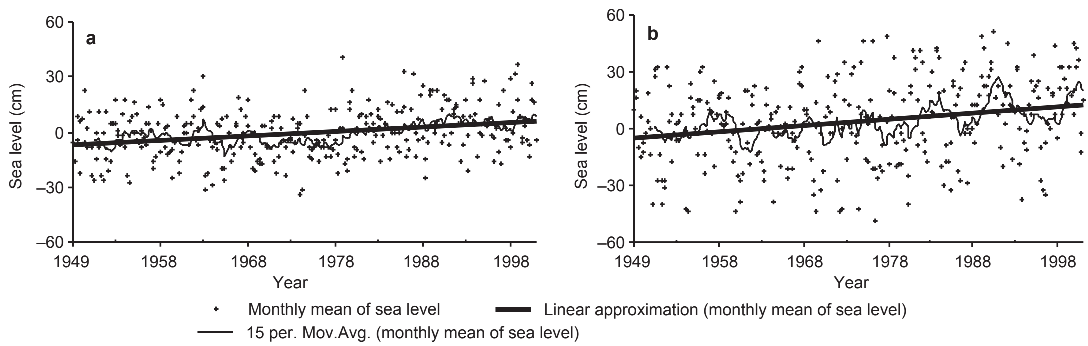

Fig. 8. Trend of monthly mean change of sea level for tide gauge Klaipėda Strait in 1949–2002 (**a**) during the warm period of the year from April to September and (**b**) during the cold period of a year from October to March.

2003). During warm winters the run-off of water originated from precipitations in river basins proceeds faster as compared with cold winters, causing winter flooding and higher sea level in the Lagoon. The amplitude of variability of the monthly mean sea level in the cold period is larger than in the warm period (Fig. 8).

Extreme values of sea level

If we compare the dominating wind directions in the period of 1990–2002 in Klaipėda with the winds during 1961–1990 (Fig. 9), we notice that the probability of southeasterly wind has decreased. At present, a single dominating wind direction cannot be clearly distinguished, but generally westerly wind blows most often on the Lithuanian coast of the Baltic Sea. Strong westerly wind forms the extreme conditions for sea level to rise on the coast in the area studied. The rising and lowering of sea level are directly

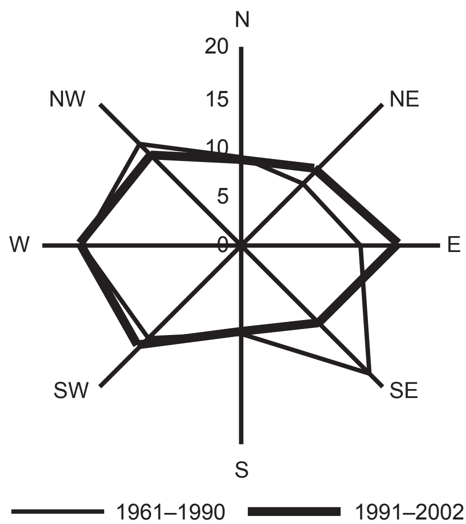

Fig. 9. Wind roses in Klaipėda, 1961–1990 and 1991–2002.

dependent on the wind direction in respect to the shore (Fig. 10). Higher sea level in the south-

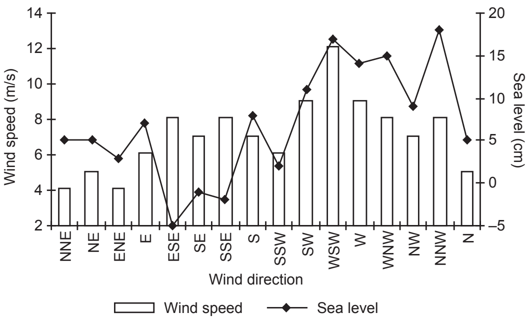

Fig. 10. Change of sea level according to the dominant directions of wind, 2001.

eastern part of the Baltic Sea is observed for westerly wind and lower sea level when easterly wind directions dominate.

Extreme values of sea level for the tide gauge Klaipėda Strait indicate increase in amplitude of sea level fluctuation during the analysed period of 1898–2002 (Fig. 11). Extreme values of sea level (sea level higher than 100 cm) have been more frequent than before along with the increased frequency of the stormy weather conditions since the middle of the 20th century. The annual extreme values (maximum/minimum) change (rise/fall) by about 10 cm during the period of 1961–2002 (Figs. 12 and 13). According to the long-term observations, the highest and the lowest sea levels are formed in the northern part of the Lagoon and especially in the Klaipėda Strait (Table 1). The extreme values of sea levels in the Strait are 186 cm (1967) and –91 cm (1984). The amplitude of the long-term variations in the Strait is 276 cm. The amplitude variations gradually decrease from the northern part of the Curonian Lagoon towards the southern (e.g. near Juodkrante — 230 cm, near Nida — 220 cm).

The long-term seasonal change of sea level

The long-term seasonal change of sea level in Klaipėda Strait reflects the general rise and changes in seasonal alternation of sea level in the southeastern part of the Baltic Sea during the analysed period of 1961–2002 (Fig. 14). This period was divided into two data series covering equal periods and the long-term monthly mean sea level were compared. It was found that the higher sea level was characteristic for the 1961–1981 period as compared with the 1982–2002 period. At the end of the 20th century the sea level was higher every month except November and December. Here it should be admitted that the highest sea levels during the year were observed at the end of summer and the beginning of autumn in 1961–1981. However, during the period 1982–2002 a remarkable shift took place and at present the highest sea levels throughout the year are found in wintertime.

The seasonal variations of long-term mean sea level in the central part of the Curonian Lagoon are mainly determined by fresh water inflow from the Nemunas River. Statistically the largest sea water level is expected during spring flooding in April. However, during the last decades the sea level in January–March was higher than during spring flooding (Fig. 14). It is important to note that in the long-term change of the Nemunas River discharge the decrease tendency is observed (Gailiušis *et al*. 2001). Therefore the discussed increase in sea level in the Curonian Lagoon is most likely to be related with the climate change determining warmer winters and the sea level increase in the Baltic Sea.

Conclusions

The regional analysis of fluctuations in the long-term sea level is necessary for research of climate change and the related global sea level rise as well as due to land movement. Changes in the sea level may be considered as one of the indicators of fluctuations in the regional atmospheric circulation as well.

The accuracy of the pre-war measured sea level data is a common problem. However, all the analysed tide gauges in the Lithuanian marine waters show the increasing trend in the sea level, and the results are in accordance with those published in other papers.

The results reveal clear sea level variability in the Lithuanian part of the Baltic Sea. The increase of sea level is associated with changes in atmospheric circulation. A distinct tendency of the sea level rise is observed during the last half

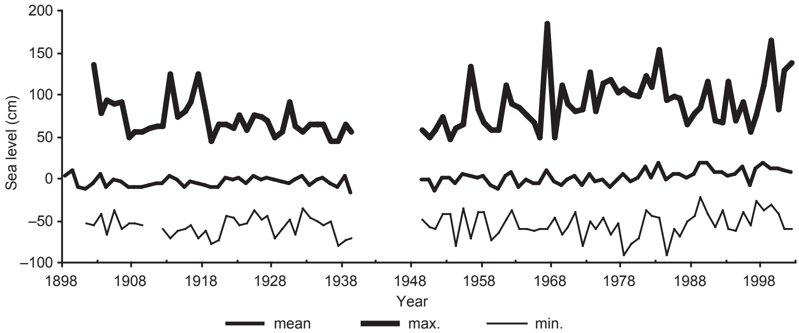

Fig. 11. Change in annual mean, maximum and minimum sea level in the Klaipėda Strait in 1898–2002.

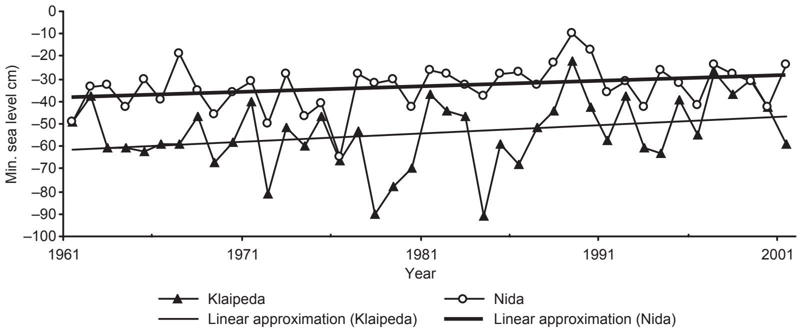

Fig. 12. Annual minimum sea level with a trend in Nida on the Curonian Lagoon side and the Klaipėda Strait in 1961–2002.

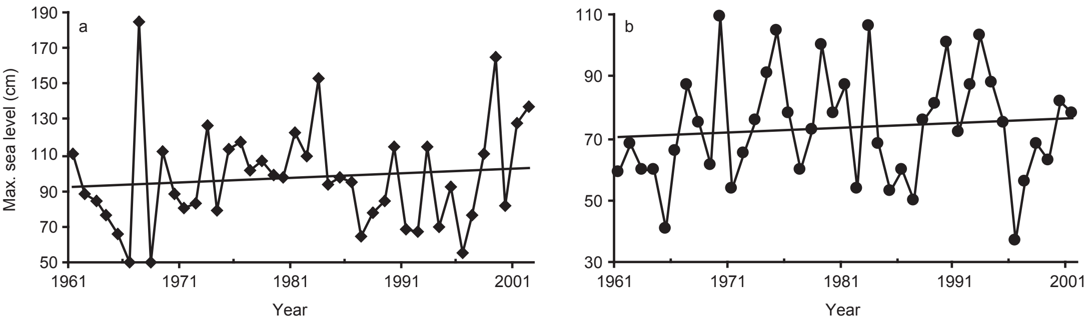

Fig. 13. Annual maximum sea level with a trend in (**a**) the Klaipėda Strait and (**b**) Nida on the Curonian Lagoon side in 1961–2002.

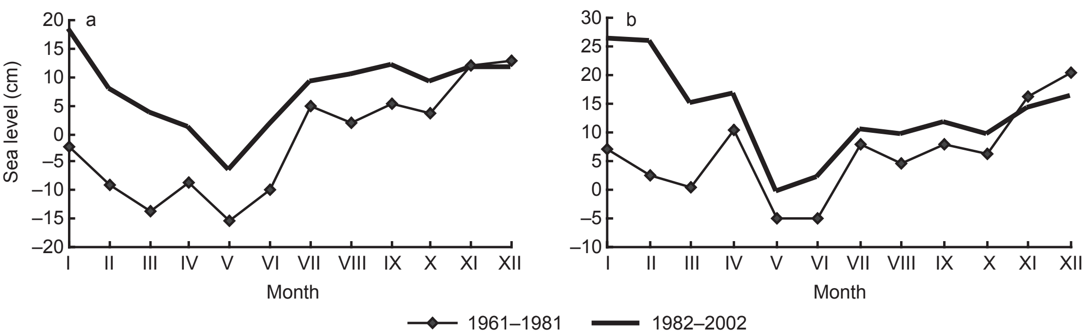

Fig. 14. Long-term seasonal change of sea level in (**a**) the Klaipėda Strait and (**b**) Nida located in the central part of the Curonian Lagoon in two 21-year periods, 1961–1981 and 1982–2002.

of the 20th century. Since the middle of the 20th century the extreme (especially maximums) sea level values have also become more frequent. Additionally, the variability of annual mean sea level as well as its extreme values increased most dramatically since the beginning of the 1970s (Figs. 2 and 12). This is in accordance with the results concerning the annual cycle of sea level of Ekman (2003) using the Stockholm historical data, and by Johansson using the data from 13 tide gauges at the coast of Finland (Johansson *et al*. 2001).

The rate of sea level rise is uneven during different periods. A stronger rising tendency in the long-term sea level change at the Baltic Sea and of the Curonian Lagoon coast became evident at the end of the 20th century. Sea level has risen by about 3 mm per year in all Lithuanian tide gauge time series since the 1970s. The rate of sea level rise of 1.3 mm year^{-1} during the period 1898–2002 is close to the rate of the global eustatic mean sea level rise (Table 3).

The annual mean of sea level rise is more intensive during the cold period of the year than during the warm period. The rise in sea level in recent decades is related to more frequent advection of warm and wet Atlantic air masses during the cold period, and to intensified zonal circulation. The rising and lowering of sea level directly depend on the direction of wind in respect to the shore (Fig. 12). The highest sea levels in the south-eastern part of the Baltic Sea are observed when winds blow from the western directions, whereas the lowest levels are observed when easterly winds prevail.

Long-term (1898–2002) seasonal change of sea level in the Klaipėda Strait indicates general water rise in the Baltic Sea. The seasonal sea level fluctuation in the central part of the Curonian Lagoon is characterized by rather significant sea level rise in April as a result of ice melting and increase in river discharge. The largest spring flood is expected to take place in April, but in recent decades the highest sea level was observed in January–March indicating warm and shorter winters. Therefore, statistical mean sea levels, which are regarded as standard in Lithuania, should be corrected according to increasing trends.

The results here clearly showed an increase of the sea level taking place on all time scales in the coastal area of Lithuania. According to Žaromskis (2001), the water rise will intensify the intrusion of salty water into the Curonian lagoon and slowly changing the ecosystems in its northern part. This would foster further studies of sea level variability in the area also because of the important practical and economical consequences of the potential further rise.

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