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Pattern of long-term seasonal sea level fluctuations in the Baltic Sea near the Lithuanian coast

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Abstract The Intergovernmental Panel of Climate Change (IPCC) analyzing global climate change tendencies and their possible impacts on the natural environment and human lifestyles has determined that the ocean and sea level fluctuations are among the indicators of climate change. Annual variations of hydrometeorological conditions were found to have been predetermined not by a steady increase or decrease of one parameter but by their variations within seasons. Therefore the present paper deals with the long-term seasonal Baltic Sea level fluctuations near the Lithuanian coast. Mean monthly values of sea level measured in the port of Klaipėda were chosen for detailed analysis of sea level fluctuations in the Baltic Sea. The long-term dynamic pattern of mean sea level fluctuations near Klaipėda includes two time spans distinguished by pronounced differences of sea level rise intensity: 1898–1975 and 1976–2005. The 51-year time span for a detailed analysis of long-term seasonal sea level fluctuations (1955–2005) was chosen purposefully because it best reflects the changes of sea level rise intensity. The analysis of long-term seasonal sea level fluctuations revealed cyclic character. Yet the monthly cycle phases not always coincide. Also it was determined that the character of maximal mean monthly sea level dynamics in cold season had changed. Generalized comparative analysis of monthly sea level dynamics and climate variations showed that the sea level dynamics was a good reflection of the climate changes in cold season (October–March), whereas in warm season (April–September), sea level fluctuations were not so well reflected in climate changes.

Keywords Baltic Sea, sea level rise, seasonal water level fluctuations, climate variations.

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INTRODUCTION

A team of the Intergovernmental Panel of Climate Change (IPCC) analyzing the global climate change tendencies and their possible impacts on the natural environment and human lifestyles has determined that the ocean and sea level fluctuations are among the indicators of climate change (IPCC 1992, 1996, 2001). For this reason, the studies of the trends in sea level fluctuations are relevant not only for knowledge of climate change processes but also for development of the strategies of adaptation to the consequences of these processes. The more so as the last IPBCC report (IPCC 2007) on mitigation of the consequences of climate change contains pessimistic prognoses of increasing intensity and frequency of hydrometeorological extremes.

Fluctuations of the World Ocean level were discussed in many research works (Gornitz et al. 1982; Dziadziuszko, Jednoral 1987; Hofstede 1991; Jelgersma et al. 1993; IPCC, 1992, 1996, 2001; Raudsepp et al. 1999; Johansson et al. 2001; Fenger et al. 2002; and others). All studies emphasize accelerating rise of World Ocean level which became especially manifest at the end of the 20th c. The trends of sea water rise were also determined near the Lithuanian coasts (Jarmalavičius, Žilinskas 1996a, 1996b; Jarmalavičius et al. 2001; Dailidienė et al. 2004, 2006; Dailidienė, Tilickis 2005).

Until now, climatologists and meteorologists thought that the variations of these mean annual hydrometeorological conditions were predetermined not by a steady increase or decrease of one parameter but by their mean seasonal variations. This peculiarity of climate change also is characteristic of Lithuania (Bukantis 1994; Bukantis ir kt. 1995, 1998, 2001; Bukantis, Rimkus 2005; and others). For example, the increase of mean annual temperature in our latitudes is in the majority of cases predetermined by warming winters (Bukantis et al. 2001).

So far, Lithuanian and foreign authors have focused on the mean annual sea level fluctuations, i.e. long-term trends of the mean annual sea level dynamics. The long-term mean seasonal sea water level fluctuations have been little analyzed. But, as was pointed out above, the climate changes manifested through long-term mean seasonal variations. This means that their influence on sea level fluctuations could be traced out through analysis of long-term mean seasonal sea level fluctuation patterns. Monthly sea level fluctuations in the Lithuanian coastal zone were investigated by E. Červinskas, R. Žaromskis and I. Dailidienė (Červinskas 1959; Žaromskis 1996; Dailidienė 2007). Yet these works lack comprehensive analysis of long-term mean seasonal sea level variations.

The aim of the present paper is to evaluate the long-term mean seasonal Baltic Sea level fluctuations near the Lithuanian coast.

MATERIAL AND METHODS

Mean monthly values of sea level measured in the port of Klaipėda were chosen for analysis of sea level fluctuations in the Baltic Sea (Fig. 1). The data were obtained from the Centre of Marine Research and archives of the Lithuanian Hydrometeorological Service. Published materials also were used (Červinskas 1959).

Presented long-term pattern of mean annual sea level fluctuation near Klaipėda (Fig. 2) characterize two time spans distinguished by pronounced differences of sea level rise intensity. They are: 1898–1975 when the mean sea level rise was relatively slow (+ 0.4 mm per year) and 1976–2005 when the mean sea level rise was relatively rapid (+3.9 mm per year). Thus, the changes that took place in the 20th c. were analyzed through comparison of two 30-year time spans, which included the available oldest (1898–1927) and newest (1976–2005) measurements. The 51-year time span for a detailed analysis of long-term seasonal water level fluctuations (1955–2005) was chosen purposefully because it best reflects the changes of sea level rise intensity. It includes the period of relatively slow (1955–1975) and rapid (1976–2005) sea level rise. The analysis was based on seasonal and monthly mean, minimal and maximal water level values. To reveal the cyclic character of sea level fluctuations, the time series were smoothed with least square method.

Fig. 1. Location of the study area.

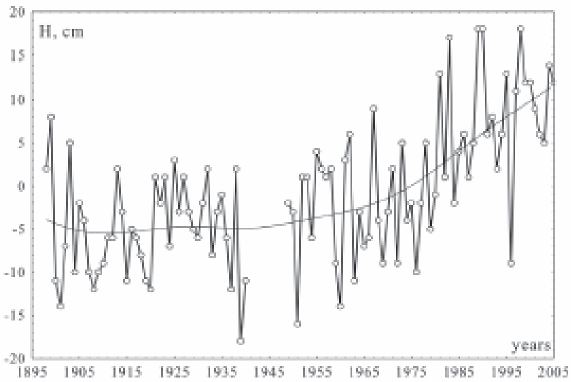

Fig.2. Long-term sea level dynamics near Klaipėda in 1989–2005.

RESULTS

Comparative analysis of long-term mean seasonal Baltic Sea level fluctuations during different seasons (two 30-year long periods including the oldest – 1898–1927 – and the newest – 1976–2005 – measuring data) showed that the sea level was higher in all seasons (Fig. 3). The most pronounced sea level rise was characteristic of winter (11.3 cm). The spring and autumn values

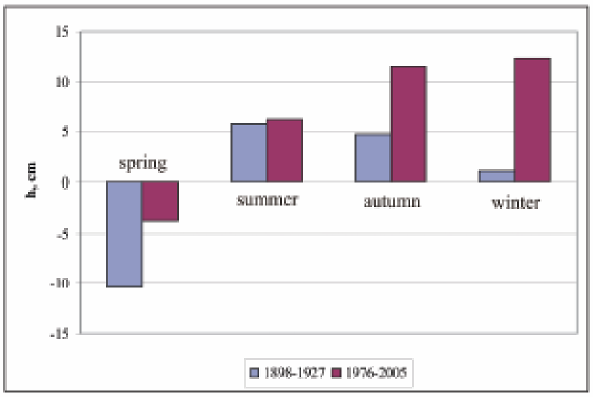

Fig. 3. Comparison of the mean seasonal sea level values in 1898–1927 and 1976–2005 in Klaipėda.

are comparable (+6.5 and +6.8 cm respectively). The smallest differences are among the mean summer level (+0.5 cm). Thus, the sea level rise in winter season accounted even for 45% of the total mean annual sea level rise, in autumn and spring for 27% and 26%, respectively, and in summer only for 2%. The determined seasonal fluctuations of mean sea level imply essential changes of the pattern of long-term fluctuation of mean annual sea level. At the beginning of the 20th c., the maximal values of sea level would occur in summer. At the end of the 20th century, the maximal values were observed in winter (Fig. 3). Spring remained the season of minimal values.

Detailed analysis of the available data showed that the annual changes of sea level fluctuation pattern also were reflected within seasons (Fig. 4). As can be seen in Fig. 4, the pattern of water level fluctuations in different time spans is relatively comparable. In different seasons and in different months (except August) the sea level was rising. The minute changes occurred in June–August and the greatest in November–April. The mean annual maximal value of sea level shifted from August to January and the minimal remained in May. It should be noted that contrary to the falling trend of sea level in August–November at the beginning of the 20th c., the end of the 20th c. was marked by the rising trend of sea level.

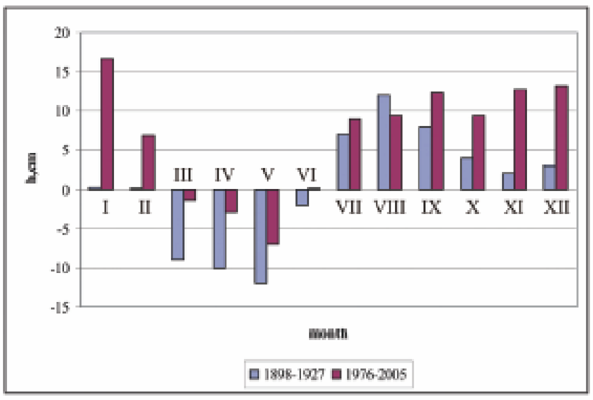

Fig. 4. Comparison of the mean monthly sea level values in 1898–1927 and 1976–2005 in Klaipėda.

The shift of maximal water level values is in good correlation with the changes of North Atlantic (NAO) index (Johannson et al. 2001; Dailidienė et al. 2006). The NAO index winter values are positive. Stronger than routine western winds blowing over the Baltic Sea condition higher sea levels in the south-eastern near-shore (Stankūnavičius, Bartkevičienė 2003). It was determined that the negative values of NAO index dominant before the 1980s were later replaced by almost exclusively positive ones (Dailidienė et al. 2006). Generalizing we can say that during the last 30 years, stronger western winds conditioned the shift of mean seasonal maximal values from summer to winter.

For the reconstruction of the dynamic of long-term mean monthly sea level fluctuation pattern in the last 51 years (1955–2005) the diagrams of mean monthly sea

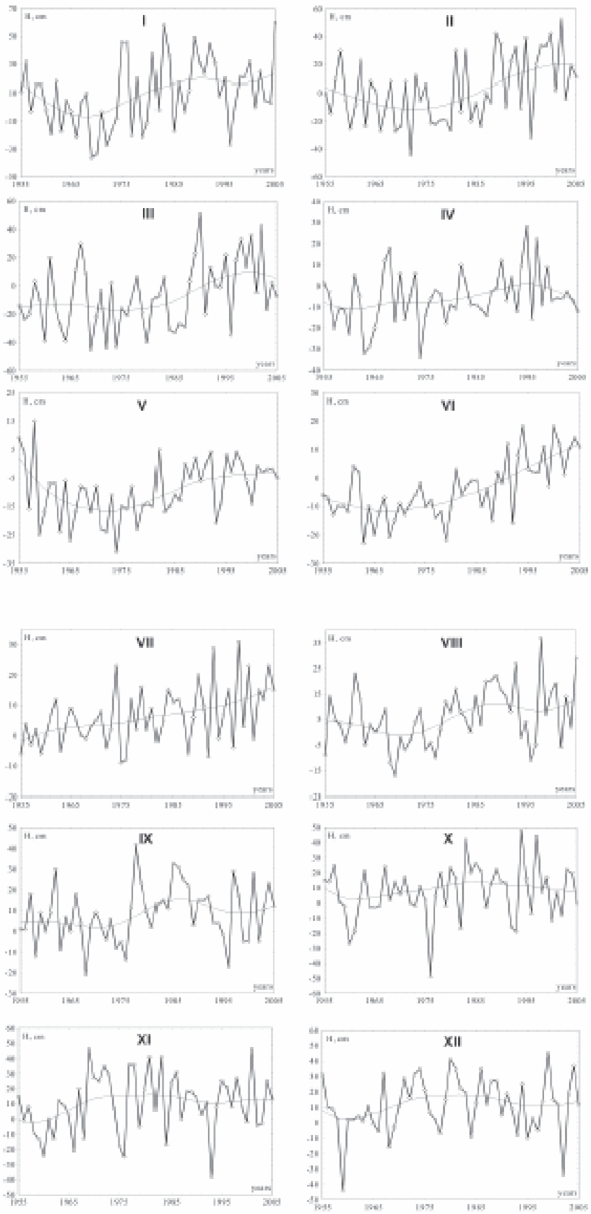

Fig. 5. Dynamics of mean monthly sea level values in Klaipėda in 1955–2005.

level values were compiled (Fig. 5). The data-generalizing curve drawn by the least squares method reveals the cyclic character of the analyzed fluctuations. As it is shown in Fig. 5, the sea level rises in all months. Yet the curve is rising unevenly reflecting some cycles. At the beginning of the year (January and February), the values of sea level are usually higher and range within a wider interval than the mean annual values. Before 1970, the sea level fluctuations followed a falling pattern that in later years was replaced by the rise which lasted until about 1991 (January) and 2000 (February). A cycle of about 30 years can be distinguished (Fig. 5). The sea level fluctuation patterns in other winter months (November and December) also reflect similar 30–35 year cycles. Yet they are marked by opposite phases.

In March, the values of sea level are lower than the mean annual ones. Though the character of sea level fluctuation pattern is partly typical of March it also reflects some individual features not characteristic of cold season.

The long-term sea level fluctuation pattern in April–August shows that these fluctuations occur within a narrower interval than in winter. In the majority of cases, they are only slightly below the long-term mean. Yet long-term individual fluctuation patterns of each of these months differ. Even the calmest (from meteorological point of view) months (May and June) are marked by long-term sea level fluctuations. They also manifest as 30–35 year cycles.

In August, the sea level fluctuation pattern changes. It is very comparable to the mean annual sea level fluctuation pattern. Moreover, a 7 year long cycle can be distinguished in the long-term water fluctuation pattern of August.

In September and October, sea levels are higher and their long-term pattern is more variable than the mean annual water fluctuation patterns. The character of fluctuations is comparable with the sea level fluctuation pattern of November–December.

The sea level fall observed in the generalized mean annual water level fluctuation pattern before 1965 was a result of coincidence of monthly fall cycles of this time span. Whereas the dramatic increase of the sea level in 1975–1990, was a result of interference of monthly sea level rise cycles. In other times spans (1966–1974 and 1991–2005), when the phases of most monthly fluctuation cycles were at variance, any pronounced fall or rise were not observed, i.e. opposite cycles hold down each other.

Notwithstanding the cyclic long-term sea level fluctuation patterns in different months, a positive linear trend was identified in all seasons of the year (Table 1).

The long-term (1955–2005) maximal and minimal monthly sea levels and amplitudes are given in Fig. 6. The minimal and maximal values given in diagrams stand not for the absolute annual minimal or maximal values but for monthly lowest and highest water fluctuation values per year. Comparison of the diagrams (Figs. 2 and 6) shows that the phase of maximal monthly sea level values rise does not coincide with the long-term fluctuation pattern of mean annual values. This is especially true of the time frame 1975–1990 when a pronounced trend of mean sea level rise has been determined. Yet in this period, the rising trend in the pattern of maximal monthly sea levels was not observed. Whereas the pattern of minimal sea levels is close to long-term mean pattern of sea level fluctuations. Moreover, during the most intensive rise of the mean long-term sea level (1975–1990), the minimal monthly sea level values were on the fall.

Table 1. Long-term monthly sea water level trends in 1955–2005 and their coefficient of determination (r^2) and significance level (p).

Month	Trend, cm/ year	r^2	p
January	0.50	0.097	0.026
February	0.60	0.145	0.006
March	0.58	0.133	0.009
April	0.23	0.071	0.058
May	0.18	0.069	0.062
June	0.45	0.423	0.000
July	0.28	0.193	0.001
August	0.27	0.124	0.011
September	0.19	0.042	0.150
October	0.18	0.023	0.290
November	0.25	0.035	0.187
December	0.18	0.023	0.288
Mean annual	0.32	0.332	0.000

Generalizing it should be pointed out that in 1955–1988 the maximal sea levels were mainly recorded at the end of the year: in November and December (even 41% of all cases). In January and February, maximal sea levels accounted only for 21%. In 1989–2005, monthly maximal values of sea level were more often recorded at the beginning of the year, i.e. in January and February (47%). In November–December these cases accounted only for 24%. The shift of maximal winter sea levels can be explained by climate changes. Climatologists (Bukantis et al. 1998) have determined that since the early 1980s the frequency of western winds at the beginning of the year has increased and the frequency of eastern winds decreased. The western winds near the Lithuanian coasts are responsible for the highest set ups.

It also should be noted that if the established cycles (of about 31–35 years) of monthly maximal values continue in the future the maximal annual water level values will again shift from January–February to November–December (after the change of cycle phase). Unfortunately due to short observation period of sea level it is impossible to say that the same cycle (30-35 years) will remain the same in the future.

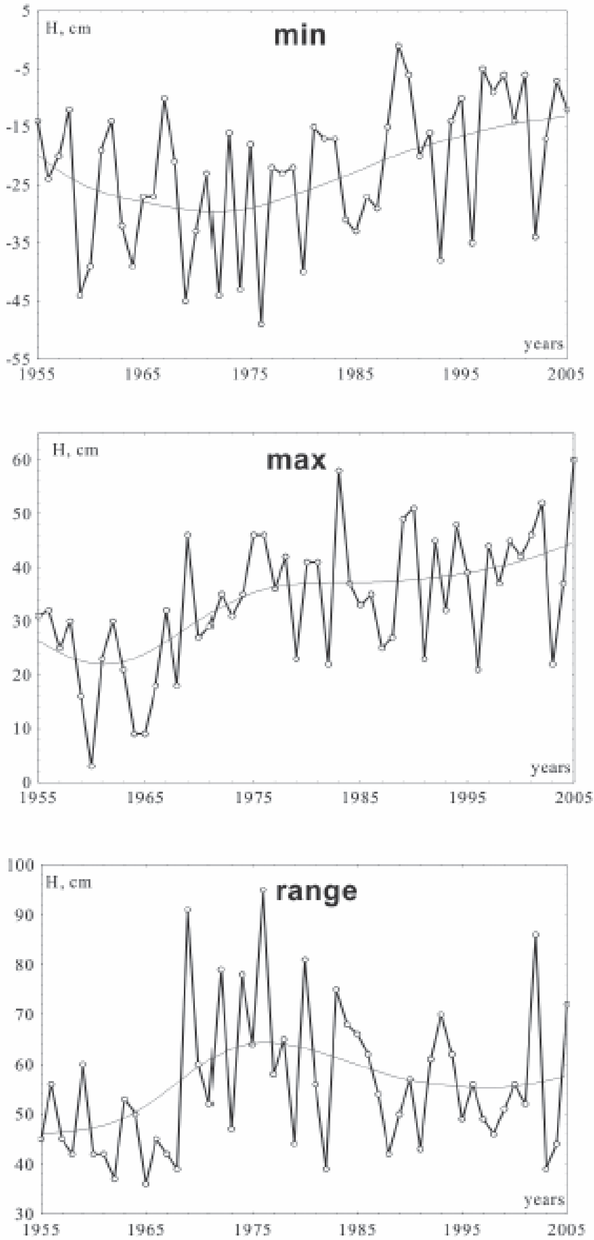

Fig. 6. Variation pattern of mean monthly minimal and maximal sea level values and the pattern of their amplitude differences in Klaipėda in 1955–2005.

DISCUSSION

If variations of sea level are driven by climate changes, the established fluctuation cycles of monthly values should also coincide with climate changes.

As in the Lithuanian coastal zone the meteorological indices are mainly related to the activity of cyclones and anticyclones it seems plausible that temporal alternation of the ratio between their activities is the main cause of cyclical fluctuations of the sea level. Analysis of the dependence between the number of days of deep cyclones (Bukantis et al. 1998) and monthly sea levels revealed that this dependence is valid also in cold seasons, i.e. October–March. Yet in April–September, the trends of monthly sea level values are little related to the activity of deep cyclones and anticyclones. Under the conditions of relatively calm weather of warm seasons, the sea level fluctuations are often predetermined by regional factors. This is proved by comparison of monthly sea levels in Klaipėda and Travemünde (Germany) (Jensen, Toppe 1986) (Fig. 7). The sea level fluctuations in both stations follow a comparable pattern (the fluctuation amplitude in the Klaipėda station is greater) only in cold seasons. In May–September, sea level fluctuations in these stations obtain individual regional features.

Based on the data analysis we may assume that sea level fluctuations are a good reflection of climate variations in cold season (October–March). Whereas in warm season (April–September), sea level fluctuations are not so well related to climate changes.

It should be noted that despite the interrelation between the sea level and climate variations it is difficult to estimate the degree to which the sea level rise is predetermined by global climate warming or variations of climate cycles. For example, the observed rise of sea level since the middle of the 1970s in Klaipėda was not determined in the mentioned Travemünde station. In the latter, the sea level dynamic patter remained the same during the whole 20th c., i.e. close to the isostatic earth crust subsidence rate in the region. Thus, the sea level rise in our coastal zone may be predetermined not only by eustatic uplift but also by interference of rising phases of monthly sea level fluctuation cycles.

CONCLUSIONS

The performed comparative analysis of long-term mean seasonal Baltic Sea level dynamics in different time spans (1898–1927 and 1976–2005) showed that the long-term sea level rose up in all seasons of the year. The greatest rise was observed in winter – 45%. In autumn and spring it accounted for 27% and 26% and in summer only for 2% of the total annual sea level rise. It was determined that the annual sea level fluctuation pattern has changed essentially. At the beginning of the 20th c., the maximal sea level values occurred in summer whereas at the end of the century they were observed in winter. Spring remained the season of minimal sea level values.

The long-term monthly sea level dynamics reveals rising trends. It was also determined that the long-term mean and maximal monthly sea level dynamics bears cyclic character. Cycles of 30–35 years were recorded. Yet the monthly cycle phases not always coincide. The Baltic Sea level rise near the Lithuanian coasts since the middle of the 1970s is partly related to the interference of the rising phases of monthly cycles. Unfortunately due to short observation period of sea level it is impossible to say that the same cycle (30–35 years) will remain the same in the future.

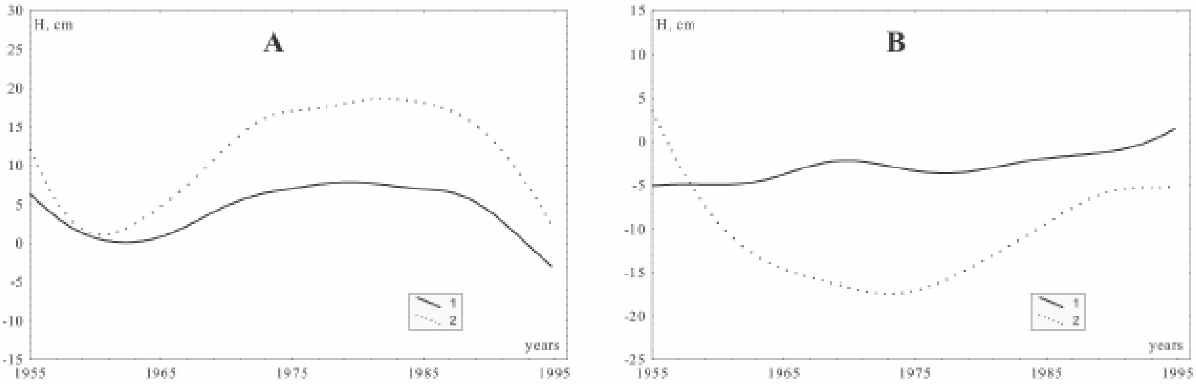

Fig. 7. Comparison of sea level dynamics in 1955–2005 levelled by the least square method in Travemünde (1) and Klaipėda (2) stations in December (A) and May (B).

It was determined that the character of maximal mean monthly sea level dynamics in cold season has changed. In 1955–1988, the maximal sea levels usually occurred at the end of the year (November–December; even 41% of the total of cases; in January–February only 21%) whereas in 1989–2005, the monthly maximal values more frequently occurred at the beginning of the year (in January–February 47% and in November–December only 24% of cases).

Generalized comparative analysis of monthly sea level dynamics and climate variations has shown that the sea level dynamics is a good reflection of the climate changes in cold season (October–March) whereas in warm season (April–September), sea level fluctuations are not so well reflected in climate changes.

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