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ORIGINAL PAPER

Influence of macroscale and regional circulation patterns on low- and high-frequency sea level variability in the Baltic Sea

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Abstract

The atmospheric impact on sea level variability in the Baltic Sea on different time scales was investigated. The Northern Hemisphere teleconnection patterns, namely, the North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and Scandinavia (SCAND) patterns, were employed, and a strong but non-stationary relationship was found. The SCAND appeared to be most relevant to the mean monthly Baltic Sea level variations throughout the year. A negative correlation indicates that a cyclonic centre over Scandinavia in the negative phase of SCAND enhances western circulation, which then triggers water inflow through the Danish straits. The AO annular mode reveals a positive and slightly stronger relationship with the Baltic Sea level than the NAO. The rapid increases in the Baltic Sea level recognized in this study, namely, those exceeding 24 cm within a 5-day period, mainly occur in the cold season. These increases are associated with the development of specific synoptic conditions in the Euro-Atlantic region, characterized by a shift from high to low pressure over Europe and a rapid increase in the pressure gradient during the week preceding the sea level rise. Rapid increases are associated with cyclones coming from the North Atlantic, which move 1500–2000 km during the week preceding the strong rise of the Baltic waters. The cyclone tracks may be shifted north or south, while the final position is over the Norwegian Sea.

1 Introduction

The Baltic is an inland sea of the Atlantic Ocean, enclosed by lands from the north, east and south, while in the west, it is connected to the main oceanic area by the narrow Danish straits and the North Sea. The Baltic Sea basin itself has a relatively small size, with an area of 393,000 km^2 and with an average depth of 54 m (maximum depth reaching 459 m) (Leppäranta and Myrberg 2009). The transition area to the Atlantic Ocean is shallower, as the two sills in the entrance area, i.e. the Drogden Sill in the Sound and the Darss Sill in the Belt Sea, have depths of 8 and 18 m, respectively. Therefore, the water exchange between the semi-enclosed Baltic Sea and open waters of the North Sea is limited by the shallow and narrow connections through the Belt Sea and the Sound. The transition of waters is essentially barotropic and is mainly driven by the sea level differences between the southern Kattegat and the Baltic proper (e.g. Jacobsen 1980; Stigebrandt 1980; Andersson 2002; Stanev et al. 2018).

The water exchange through the Danish straits is considered the main factor governing the variability in the volume of Baltic waters and of the sea level. The inflow from the Atlantic Ocean is predominantly governed by meteorological factors, namely, large-scale wind and air pressure fields (e.g. Andersson 2002; Jevrejeva et al. 2005; Dailidienė et al. 2006; Hünicke and Zorita 2006; Suursaar and Sooäär 2007; Stramska et al. 2013; Omstedt et al. 2014; Hünicke et al. 2015). According to Andersson (2002), sea level oscillations in the Baltic Sea are influenced by the large-scale zonal wind component over the North Atlantic. A significant co-variability between the Baltic Sea mean sea level in winter and the North Atlantic Oscillation (NAO) index was found, and this was explained by the association between the NAO and the strength of zonal winds. Persistent westerly wind conditions under the positive NAO phase, particularly if preceded by an earlier eastern circulation, can trigger the western currents and inflows of oceanic waters to the Baltic Sea (Andersson 2002; Lehmann et al. 2017).

It has been emphasized in several studies that the large volume transport of highly saline and oxygenated water from

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the Atlantic Ocean into the Baltic Sea is essential for water restoration (e.g. Lehmann and Post 2015). The renewal of stagnant water in the deep Baltic layers is strongly linked to the episodic processes called major Baltic inflows (MBIs), which mean rapid and intense transport of highly saline and oxygenated oceanic water through the Danish straits. According to Schinke and Matthäus (1998), MBIs are preconditioned by atmospheric forcing, which is characterized by two phases: high pressure, associated with easterly winds, encompassing the Baltic region at first, followed by strong and persistent westerly zonal winds, caused by a high gradient pressure field over North Atlantic and Europe. MBIs are rare phenomena, occurring sporadically (from 5 to 7 events per decade). Since the mid-1970s, the frequency and intensity of MBIs have decreased to only one per decade. Lower MBI frequency may be associated with the increase in western flow during the last several decades with the concurrent reduction in the occurrence of easterly winds, which decrease the mean sea level of the Baltic Sea before the inflow events (Schimanke et al., 2014; Lehmann and Post 2015; Lehmann et al. 2017). However, since 2014, MBIs were recognized each year in 2014, 2015 and 2016 (Nausch et al. 2014, 2015; Gräwe et al. 2015; Mohrholz et al. 2015; Naumann et al. 2017; after Stramska and Aniskiewicz 2019).

Despite the decreasing frequency of MBIs after the mid-1970s, decreases in the frequency of rapid and large changes in the volume of Baltic Sea waters have not been observed. Lehmann and Post (2015) analysed the events of intense inflows to the Baltic Sea caused by atmospheric forcing. They introduced the concept of large volume changes (LVCs) which represent sea level increases by at least 29 cm (corresponding to 100 km^3 of Baltic water volume change). Analysis of the atmospheric circulation patterns associated with LVCs in the Baltic Sea allowed separating the sequence of synoptic conditions favourable to the most effective inflows. According to Lehmann and Post (2015), these conditions occur if eastern airflow with anticyclonic vorticity over the western Baltic prevails for approximately 1 month before the main inflow period and the mean sea level of the Baltic Sea is reduced. This is immediately followed by the period of strong to very strong westerly winds, which trigger the inflow and forces LVCs (Lehmann and Post 2015). Furthermore, the occurrence of LVCs has been related to pathways of deep cyclones associated with strong pressure gradients and varying wind conditions over the Baltic Sea area (Lehmann et al. 2017). Apart from the strong westerly winds necessary to force large inflows, the changing wind directions during the approach and passage of deep cyclones appear to be essential for LVC occurrence. Lehman et al. (2017) obtained four main routes of deep cyclones associated with LVCs, which agreed with the climatology, i.e. the storm tracks compiled by Van Bebber (1891).

The aim of this study was, at first, to recognize the impact of macroscale pressure conditions in the Euro-Atlantic region on low-frequency decadal sea level variability in the Baltic Sea. Although many studies have been conducted on the influence of NAO, less studies provided information concerning other than NAO Northern Hemisphere teleconnection patterns. In this study, the Scandinavia pattern (SCAND) apart from NAO was employed and running correlations between each pattern and seasonally averaged sea level were recognized. Despite the many studies on the atmospheric forcing of the Baltic Sea water exchange and sea level variability, there are still questions concerning the reasons for the changes of the Baltic Sea waters which are extreme in volume and rapid in time. Thus, the main aim of the study was to recognize the atmospheric forcing of high-frequency variability in Baltic Sea level. The rapid increases were considered and, firstly, their seasonal and decadal frequency was analysed. Furthermore, the different pathways of the short-term development of the sea level pressure field before rapid increases in sea level were recognized. This assessment allowed us to define different tracks of cyclones, which contribute to triggering rapid increases in sea level, as measured at the tide gauge station in Landsort.

2 Data and methods

2.1 Sea level data

Sea level data from the Swedish tide gauge station in Landsort (Fig. 1) for the period 1948–2017 were used in the study. Landsort sea level data are known to describe the mean sea level changes of the entire Baltic Sea very well, and they have been used in several studies (e.g. Franck and Matthäus, 1992; Lehmann, 2002; Lehmann and Post 2015; Lehmann et al. 2017; Mohrholz 2018). Hourly sea level data from Landsort are available in the Swedish Meteorological and Hydrological Institute (SMHI) archives at http://opendata-download-ocobs.smhi.se/explore/. The source hourly data were first recalculated to the daily means, which became the basis for the initial analysis and further recalculations. Daily changes in sea level (ΔSL), which made the basis for the analysis of the sea level variability, were computed according to Eq. (1):

$$\Delta SL = SL_n - SL_{n-1} \qquad (1)$$

where SL_n represents the sea level on a particular day and SL_{n-1} represents the sea level on the previous day. The 5-day sums of ΔSL were computed, and extreme positive values were selected and applied to the analysis of atmospheric forcing of the rapid sea level increases.

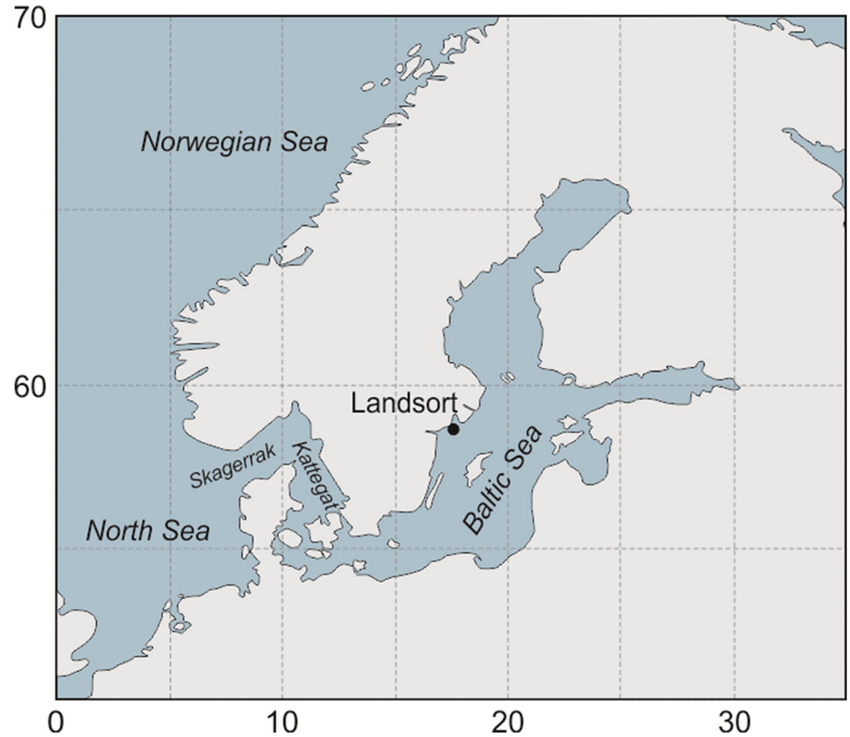

Fig. 1 The Baltic Sea region with the location of the Landsort tide gauge

2.2 Atmospheric data

Monthly indices of Northern Hemisphere teleconnection patterns derived from the Climate Prediction Center (CPC) (available from 1950 to now at https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml) were applied in the first stage of the atmospheric analysis. Rotated principal component analysis (RPCA) was used to identify the Northern Hemisphere teleconnection patterns (Barnston and Livezey 1987). Unlike station-based indices, the PCA-based techniques consider the seasonal changes in teleconnection patterns, including slight changes in the locations of the centres of action (NCAR 2015, 2017; Bednorz et al. 2019). Three teleconnection patterns dominant and relevant for the Baltic Sea region were taken into consideration, namely, the NAO, the Arctic Oscillation (AO) and the Scandinavia pattern (SCAND). The NAO is a predominant macroscale circulation type over the Euro-Atlantic region, and its positive phase, which is associated with a high-pressure gradient over the Northern Atlantic, has already been discussed in the context of the atmospheric preconditions of sea level variability in the Baltic Sea (Schinke and Matthäus 1998; Andersson 2002; Meier and Kauker 2003; Lehmann et al. 2017). However, the influence of the other two patterns (AO and SCAND) has not yet been recognized. The SCAND pattern, which consists of a primary circulation centre over Scandinavia, with weak centres of opposite signs over western Europe and eastern Russia/western Mongolia, is particularly relevant for the Baltic Sea region, especially in summer, when the NAO weakens. The positive phase of SCAND is associated with positive pressure anomalies (sometimes reflecting major blocking anticyclones) over Scandinavia and western Russia, which trigger the eastern circulation. The negative phase is associated with negative height anomalies in these regions, which denotes the location of cyclones triggering a western flow over the Baltic Sea. The seasonal variability in the correlation between the NAO, AO and SCAND indices and monthly sea level at the Landsort station has been calculated, as well as the multiannual variability in the correlation computed in the 20-year window, for each of four seasons (DJF, MAM, JJA, SON).

Following Andersson (2002), who claimed that regional atmospheric circulation patterns more accurately describe the variability in the Baltic Sea level than large-scale patterns, the relationships between the 5-day means of sea level and the sea level pressure (SLP) fields were established using Pearson's correlation coefficient. The statistical significance of the correlation was tested using Student's t distribution for the probability level $p = 0.000001$ and at the large degree of freedom values $r > |-0.1|$ were statistically significant.

In the last stage of the atmospheric analysis, the rapid increases in sea level in Landsort were taken into consideration. The events of the 5-day increases by at least 24 cm were selected. The value of 24 cm is close to the 99th percentile of all computed 5-day changes in sea level and is comparable to the threshold adopted by Lehman and Post (2015) and Lehmann et al. (2017), who analysed the LVCs defined by sea level differences of at least 29 cm. This value corresponds to a change in the Baltic Sea volume of approximately 100 km^3. Cases selected according to the accepted threshold of 24 cm/5-day were analysed in terms of pressure conditions in the days preceding the rapid sea level change. The cases were clustered using the minimum variance method (Ward 1963; Wilks 2011), to which standardized SLP values for the 6 days preceding the rapid change were employed. Clustering methods, including Ward's method, are often used in climatology, for example, in differentiating weather types (Kalkstein et al. 1987). As a result, three clusters were separated, revealing the three ways of SLP field development and different tracks of cyclones that triggered rapid sea level increases.

3 Results

3.1 Influence of macroscale circulation patterns on sea level long-term decadal variability

Sea level variability is related to pressure patterns, i.e. cyclones and anticyclones occurring in the mid-latitudes of the Euro-Atlantic region, and this is associated with the Northern Hemisphere macroscale circulation patterns. Significant relationships were found between the monthly average sea level and macroscale circulation indices. The SCAND exhibits the strongest influence on sea level variability in the Baltic Sea throughout the year, and in most months, the correlation coefficient exceeds |− 0.6|; this value decreases to below |− 0.5| in only July and December (Fig. 2). The negative phase of SCAND means negative pressure anomalies, i.e. cyclonic activity over Scandinavia, which interacts with sea level increases in the Baltic basin. In the positive phase of the SCAND, a blocking system spreads over northern Europe and restrains eastward movement of the North Atlantic low-pressure systems. Besides, the Scandinavian anticyclones enhance eastern circulation over the Baltic region, which leads to a decrease in sea level.

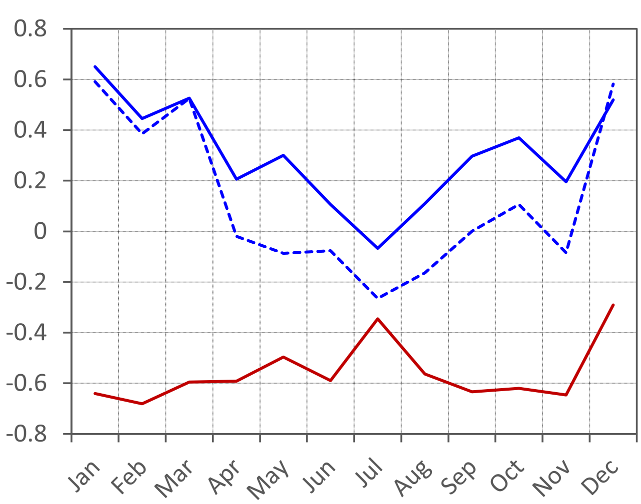

Fig. 2 Monthly variability in the correlation coefficients between the monthly average sea level and macroscale circulation indices AO (dashed blue line), NAO (solid blue line) and SCAND (red line)

The NAO, which is considered the most prominent and recurrent pattern over the middle and high latitudes, reveals the weakest influence on the sea level in the Baltic Sea among the three considered patterns. This pattern can be observed at any time of the year; however, its influence on the weather over the Atlantic and its neighbouring continents is most pronounced in the cold season. This phenomenon is mainly because of the seasonal variation in the oscillation strength and partly because of the seasonal changes in the spatial patterns of the NAO dipole centre locations. Both centres are located over the Northern Atlantic; however, the summer NAO has a smaller spatial scale than its winter counterpart, and both centres are shifted north, which means that the summer southern dipole is located over northwestern Europe rather than over the Azores-Spain region. Only the winter NAO distinctly influences the sea level in Landsort; the correlation coefficient from December to March ranges between 0.4 and 0.6. In the late spring, summer and autumn, the NAO weakens, and its influence on cyclonic activity and the weather in Europe diminishes; the correlation coefficient between the monthly mean sea level and the NAO index from April to August is negative and lower than |− 0.3|; it remains close to 0 until November (Fig. 2).

The AO pattern is similar to the NAO pattern, and their indices are strongly correlated. The AO is an annular mode and encompasses the middle and high latitudes of the entire Northern Hemisphere. While the PCA-based indices of NAO and SCAND are identified at the 500 hPa geopotential level, the loading pattern of the AO is defined as the leading mode of the empirical orthogonal function of the monthly mean 1000 hPa geopotential heights. The AO index correlates slightly better with the Baltic Sea level than the NAO index; however, the correlation is significant in only winter months (Fig. 2).

The relationships computed on the seasonal time scale show a strong influence of the SCAND pattern on the sea level in every season and significant influences of the AO and NAO

Table 1 Seasonal variability in the correlation coefficients between the daily sea level at the tide gauge station in Landsort and macroscale circulation indices. Values statistically significant at $p = 0.01$ are in bold

	AO	NAO	SCAND
DJF	**0.718**	**0.665**	**−0.704**
MAM	**0.472**	0.118	**−0.599**
JJA	0.015	−0.273	**−0.551**
SON	**0.353**	0.079	**−0.702**

patterns in winter (Table 1). The AO pattern reveals a moderate impact in spring and autumn.

The phases and intensity of macroscale circulation patterns were variable during the analysed period, and as a consequence, their influence on the Landsort sea level was non-stationary. The running correlation for the winter season (DJF in Fig. 3) computed in the 20-year window (+ 9/− 10 years for a given year) shows an increased influence of all analysed macroscale circulation patterns on the sea level in Landsort since the late 1970s. At that time, a shift to the NAO/AO positive phase was observed in winter, and SCAND shifted to the negative phase. These evolutions of the winter pressure field over the Euro-Atlantic region induced increasing cyclonic activity over the North Atlantic and Scandinavia, which favoured the increased sea level in the Baltic Sea. Specific relationships were identified for the spring, when the correlation coefficient for the NAO appeared to be extremely non-stationary and changed from − 0.6 in the beginning to 0.7 in the middle of the studied period. The summer PCA-based NAO is characterized by a different position of its southern centre, which shifted north-eastward and therefore encompassed western and part of central Europe. Thus, a positive phase of the NAO induces a decrease in the sea level in the Baltic Sea. The increasing correlation with the SCAND index during the summer since the 1990s can be related to a slight shift of the SCAND to a negative phase period and, consequently, to the increasing cyclonic activity over Scandinavia. The constantly high correlation between the SCAND index and sea level in Landsort was observed in autumn (Fig. 3).

3.2 SLP field evolution and tracks of cyclonic centres associated with short-term rapid sea level increases

Sea level data from the Landsort tide gauge station were correlated with the SLP field in different setups, and the highest correlation coefficients were obtained between the mean 5-day sea level and the prior 3-day SLP field (Fig. 4). The highest correlation, exceeding |− 0.55|, appeared over Scandinavia and Bothnian Bay, indicating a strong influence of low-/high-pressure systems extending over northern Europe and the north-eastern Atlantic Ocean on increases/decreases in the Baltic Sea level. At the same time, an area of positive correlation extended in the south with a centre located over the Iberian Peninsula (correlation coefficient exceeding 0.4). A southwest-northeast dipole of opposite correlation centres indicates that a higher-than-normal pressure gradient over the majority of Europe is strongly associated with extreme states of sea level in the Baltic Sea. The correlation field with the highest negative values over Scandinavia confirms the strong relationship between the sea level in the Baltic Sea and the SCAND pattern depicted in the previous chapter.

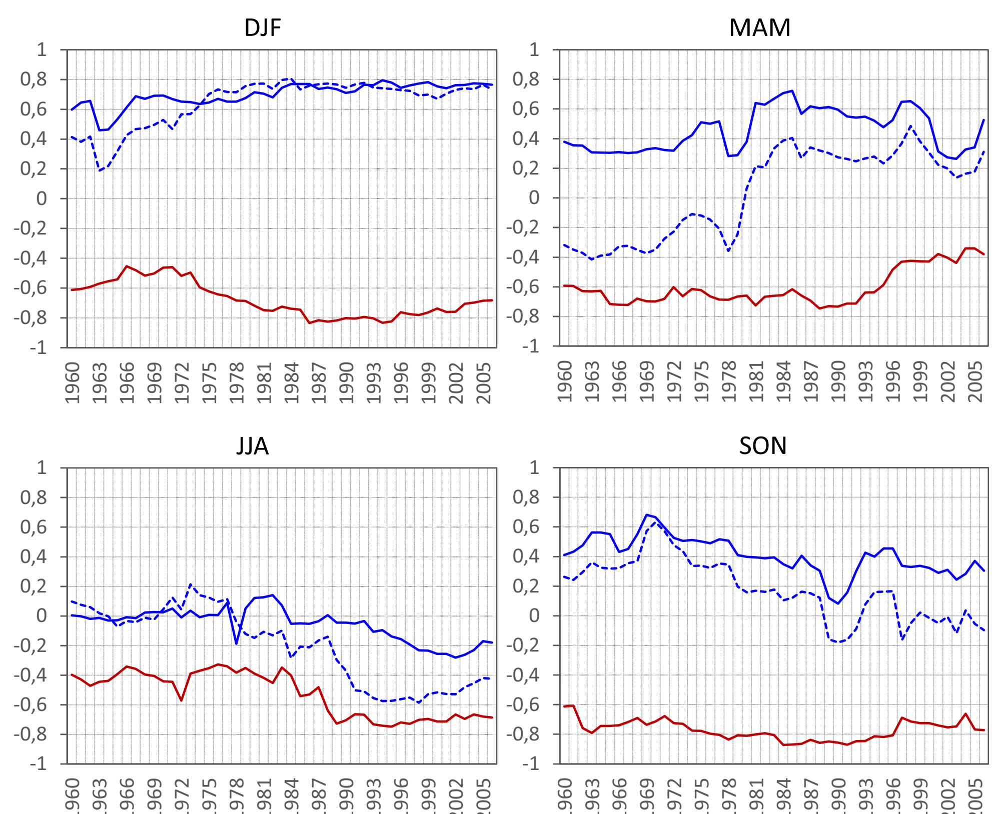

Fig. 3 Running correlation (20-year window, + 9/− 10 years for a given year) between the mean sea level in Landsort and macroscale circulation indices: AO (dashed blue line), NAO (solid blue line) and SCAND (red line) for winter (DJF), spring (MAM), summer (JJA) and autumn (SON)

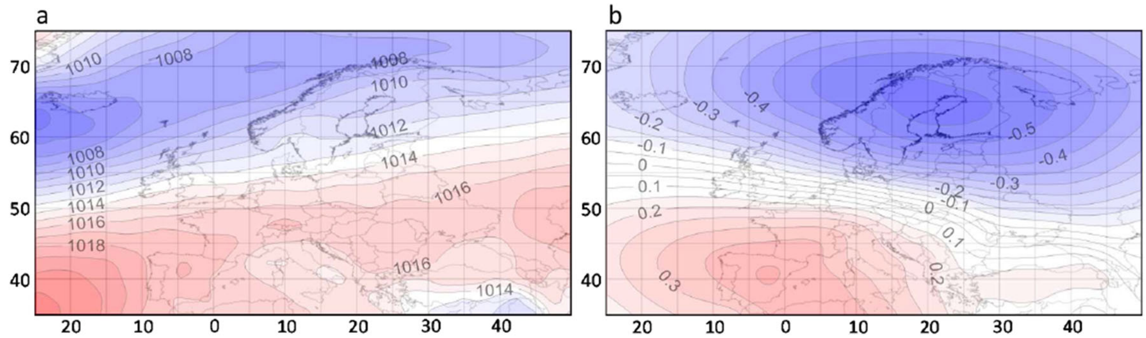

Fig. 4 Mean SLP [hPa] in the period from1948–2017 (**a**) and the correlation field between SLP and the lagged 3-day mean 5-day sea level at the tide gauge station in Landsort (**b**)

The largest dynamic changes in the Baltic Sea level are observed from November to February. The mean daily increases (blue line in Fig. 5) and decreases (red line in Fig. 2) averaged for the 60-year period exceeded 2 cm/day in winter, while in summer, they were the lowest and close to 1 cm/day. The increasing sea level variability in late autumn and winter is associated with the growing cyclonic activity and the higher gradients of the air pressure field in the cold season than in summer.

In the next step, 142 cases with exceptionally fast increases in sea level at the Landsort station, according to threshold described in Chapter 2, were selected. These cases appeared mainly in autumn and winter, precisely from September to March when 88% of all cases were identified (Fig. 6a). In late spring, from the end of April to the beginning of June, a rapid increase in sea level did not appear at all during the 70-year study period.

The annual number of cases with a rapid rise in sea level slightly increased from 1948 to 2017; however, the trend was very weak and not statistically significant (Fig. 6b). The highest annual number of cases, amounting to 5, was identified in 1998 and 2008. Several years did not experience rapid increases in sea level at all. Each year with the recognized MBI events, such as 1998, 2014, 2015 and 2016 (Stramska and Aniskiewicz, 2018), experienced at least one event with a rapid sea level increase.

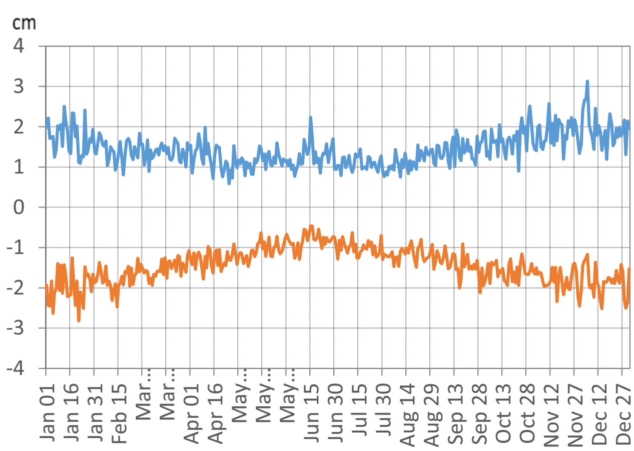

Fig. 5 Seasonal course of the daily increases (blue) and decreases (red) in sea surface elevation at the Landsort station averaged for the period 1948–2017

Composite and anomaly SLP maps were constructed for all 142 cases with rapid increases in sea level. A deep low extends over the north-eastern Atlantic Ocean and Scandinavia, reaching < 994 hPa in the centre. The highest negative anomalies (exceeding |− 14 hPa|) were found over the northern part of the North Sea (Fig. 7). At the same time, positive SLP anomalies covered part of Europe south to 55°N latitude, reaching 7 hPa west to France. A much higher than average (compare Figs. 5a and 7a) pressure gradient indicates a strong western airflow over western Europe and the Baltic Sea region, which induces an inflow of oceanic waters to the Baltic Sea through the Danish Straits.

After excluding subsequent 5-day periods with rapid increases in sea level in the Baltic Sea, the total number of 135 cases was divided into three groups, taking into consideration the mean daily SLP fields in the seven successive days before the rapid change. Thus, three different ways of SLP development leading to rapid sea level rise were distinguished. Composite SLP maps for the days preceding the rapid increase in sea level were constructed for each cluster (Fig. A in the supplementary material). The indication of the cyclonic centres on each map allowed us to follow the tracks of cyclones that induced the inflow of oceanic waters to the Baltic Sea and caused a distinguished increase in the water volume in the basin. In Fig. 8, only the beginning (column a) and the end (column b) of the 7-day period before an extreme increase in sea level were depicted, together with locations of cyclonic centres during the following days. In each of the four groups, cyclones originated from the North Atlantic, i.e. from the western sector; however, they differed in intensity and location of their tracks, which could be shifted north or south. A common feature of all the distinguished situations is a strong pressure gradient over the Baltic Sea region, particularly over the western side of the basin, which significantly intensified western winds.

The first distinguished type of SLP development that triggered a rapid sea level increase in the Baltic Sea consisted of

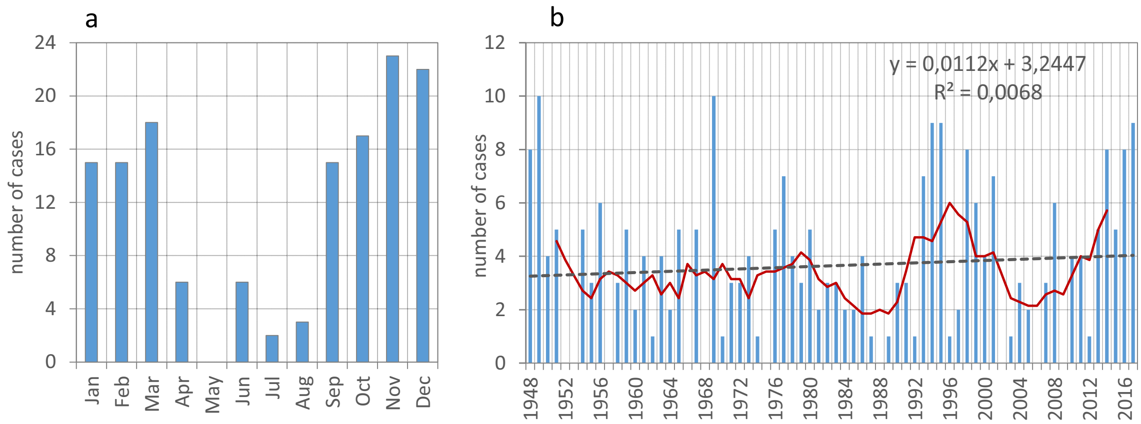

Fig. 6 Monthly (**a**) and annual (with a trend line and equation) (**b**) number of cases with a 5-day increase in the sea surface elevation at the Landsort station by at least 24 cm in the period from 1948 to 2017

the largest number of cases (63 out of 135). At the beginning of the week preceding the rapid increase, the Baltic Sea region was under a vast anticyclonic system that spread over Europe, except its northernmost part, and the anticyclonic centre was located over Poland, western Ukraine and Belarus (Fig. 8a, Type 1). Over the main Baltic basin, the SLP amounted to 1020 hPa, and the pressure gradient was very weak. The evolution of the pressure field was quick, and after 7 days, the extensive low with a centre located north of the Danish Straits covered northern Europe (Fig. 8b, Type 1). The source region of the cyclone was located over Iceland, and the long cyclone track ran across the North Atlantic and ended over the north-eastern part of the Norwegian Sea. At the same time, the centre of the high-pressure system moved westwards. A south-north dipole of the SLP established a strong pressure gradient over the Danish Straits and the Baltic Sea. This pattern triggers western winds, which are the main force inducing the inflow of oceanic water through the Danish Straits.

The second distinguished cluster consisted of 42 cases and represented a relatively stable pattern of SLP during the week preceding a rapid increase in sea level in the Baltic Sea. The development of the SLP field mainly consisted of the shifts of the cyclonic centre north- and eastward and the deepening of both high- and low-pressure centres. The cyclone track ran across the North Atlantic similar to the first type; however, in the final stage, the low-pressure centre was much deeper than its counterpart in Type 1. The SLP reached less than 990 hPa in the cyclonic centre, which was located over the north-eastern part of the Norwegian Sea in the final stage of SLP field development. The high-pressure area in the south enhanced during the 7-day period, and in the last day, SLP exceeded 1024 hPa over the Azorean region. Deepening of the pressure centres led to the strengthening of the pressure gradient, which established good conditions for Baltic inflow.

The last type, consisting of 40 cases, represented the most spectacular change in the SLP pattern. During the 7-day period, an evolution occurred from a weak-gradient and high-pressure field over Europe to a low-pressure system with a strong SLP gradient over Scandinavia and the Baltic Sea. Cyclone track 3 differed from the first two and was shifted considerably southwards. The cyclone originated from the North Atlantic mid-latitudes (approximately 60°N), and after the north-eastward displacement, its centre reached the final position over the southern part of the North Sea. In the beginning, the anticyclone, with a centre (< 1023 hPa) located over eastern Europe, brought southern and south-eastern

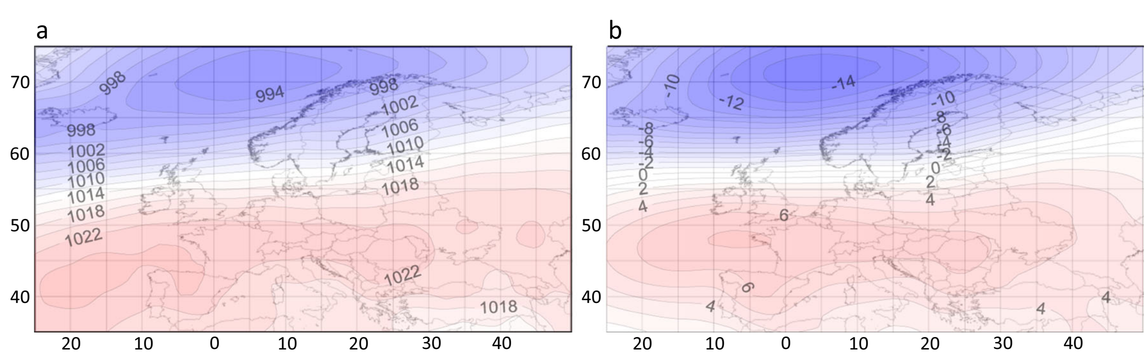

Fig. 7 SLP [hPa] composite (**a**) and anomaly [hPa] (**b**) maps for the events of rapid (by at least 24 cm) 5-day increases in sea level in the Baltic Sea

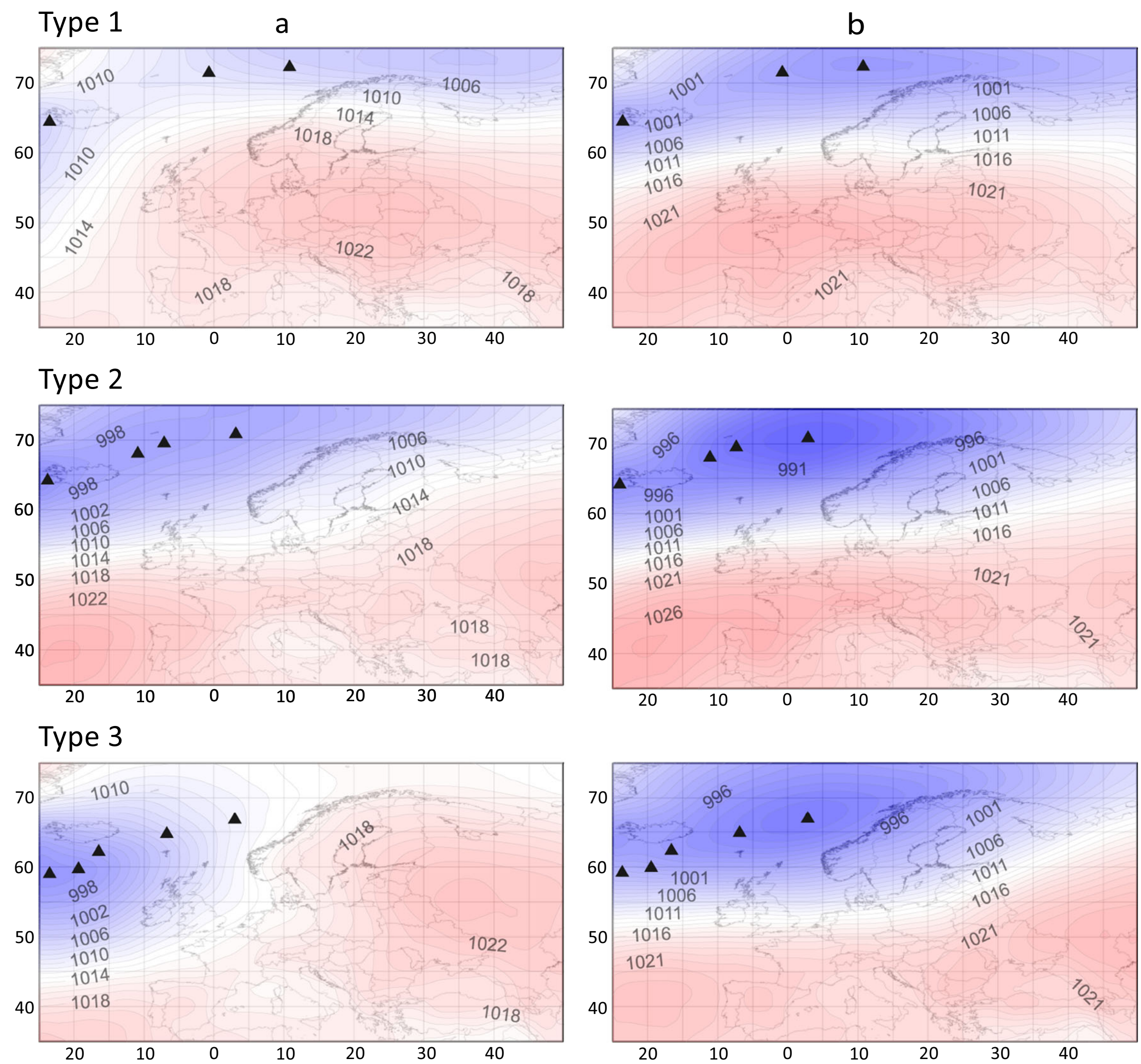

Fig. 8 SLP (hPa) field a week prior to rapid changes (**a**) and on the first day of the rapid increase in sea level (**b**). Positions of the cyclonic centres during the week preceding a rapid change in sea level marked with triangles

circulation and fostered a decrease in sea level. In the following days, the high-pressure system retreated to the southeast, still maintaining its strength.

4 Discussion

It was proved in the first stage of the study that the long-term decadal variability of sea level in the Baltic Sea is strongly related to the macroscale circulation patterns, namely, SCAND and NAO, identified by the CPC in the Euro-Atlantic region. In previous studies, significant co-variability between the Baltic Sea winter mean sea level and the winter NAO index was documented (Andersson 2002; Lehmann et al. 2017). The correlation, however, appeared to be non-stationary, and it achieved the highest level (0.8) since the end of the 1970s, which was reaffirmed in this study. Besides, a smaller correlation between the NAO and Baltic Sea level was found in the summer season (Dailidienė et al. 2006; Hünicke and Zorita 2006; Suursaar and Sooäär 2007; Hünicke et al. 2015). Similar decadal variability of correlation with NAO was found by Hünicke and Zorita (2006), who also detected the geographical pattern of the relationship, which is in general stronger in the north of the Baltic Sea basin, and it is weaker, but geographically more homogeneous, in summer. Jevrejeva et al. (2005) revealed a similar geographical pattern of the NAO influence on winter sea level variability, which is much weaker in the southern Baltic Sea (also Hunicke et al. 2008). Andersson (2002) explains the NAO impact on variations in the Baltic sea level by the association between the NAO and the strength of the zonal geostrophic wind stress over the North Atlantic and the North Sea, while the non-stationarity of the correlation was explained by the eastward shift of the NAO dipoles since the last two decades of the twentieth century (Lehmann et al. 2017). The AO annular mode, which is strongly related to the NAO, revealed a similar but stronger relationship with the Baltic Sea level than its Euro-Atlantic counterpart.

However, among the macroscale circulation patterns recognized in the Euro-Atlantic region, the SCAND appeared to be most relevant to the Baltic Sea level variations throughout the year. The primary circulation centre of SCAND (anticyclone in the positive phase) was located over Scandinavia, and its sign and strength strongly modified the wind conditions over the Baltic region and the North Sea. The blocking system over northern Europe in the positive SCAND phase restrained the activity of the North Atlantic lows, while the negative phase enhanced the cyclonic activity. The importance of the Scandinavian centre of action was also identified on the map of the correlations between the mean 5-day sea level at the tide gauge in Landsort and the daily SLP. Unlike the NAO, which summer dipoles are shifted north-eastward in regard to the winter location, the northern centre of the SCAND was constantly located north of the Baltic Sea, varying in only the strength of the pattern, which—as well as the entire NH pressure field—weakened in summer. The non-stationarity of the relationship between the winter SCAND index and Baltic Sea level can be explained by the shift in the winter index towards a negative phase at the end of the twentieth century and beginning of the twenty-first century. A significant relationship between the SCAND pattern and sea level at Stockholm tide gauge was found by Karabil et al. (2018); however, they concentrated on a new invented atmospheric variability mode called Baltic Sea and North Sea Oscillation (BANOS), which resembles NAO, with eastwards-shifted centres. The BANOS index revealed a strong connection to the off-shore sea level variability in the period 1993–2013, explaining locally up to 90% of the interannual sea level variance in winter and up to 79% in summer. Both SCAND and BANOS have their northern centres located in the vicinity of the Baltic Sea, which explains their strong impact on the low-frequency variability of the Baltic Sea level. The increases in sea level at the tide gauge in Landsort reflect volume changes in Baltic waters and are mainly caused by inflow through the Danish straits (Stigebrandt 1980; Carlson, 1997), and these processes are preconditioned by specific atmospheric factors. In previous studies, particular attention was paid to the occurrence of MBIs and their atmospheric impact (e.g. Schinke and Matthäus 1998; Lass and Matthäus 1996; Matthäus and Schinke 1994). Lehmann and Post (2015) and Lehmann et al. (2017) provided a description of atmospheric circulation patterns and cyclone tracks associated with LVCs. The defined volume changes are rather long processes, and the duration of the LVC was estimated to be approximately 40 days (Lehmann et al. 2002, 2017; Lehmann and Post 2015). The correlations disclosed in this study, including the field of correlation between the mean 5-day sea level at the tide gauge in Landsort and the daily SLP, proved that the atmospheric impact on the Baltic Sea level is detectable at different time scales from seasonal to daily.

The rapid increases in the Baltic Sea level, as elaborated in this study, are relatively rare and mainly occur in the cold season. These extreme events are associated with the specific development of synoptic conditions in the Euro-Atlantic region, characterized by a shift from high to low pressure over Europe and a rapid increase in the pressure gradient in the week preceding an increase in sea level. Schinke and Matthäus (1998) analysed the atmospheric forcing of MBIs and recognized two phases of the evolution of the pressure field. They contended that westerly zonal winds, which provide the direct force pushing waters into the Baltic Sea, are preceded by the phase of high pressure associated with easterly winds over the Baltic Sea region. The rapid 5-day increases in Baltic Sea level recognized in this study are associated with cyclones coming from the North Atlantic. These cyclones move 1500–2000 km during the week preceding the strong rise of the Baltic waters, and their tracks may be shifted north or south, while the final position in the week preceding rapid sea level changes is over the Norwegian Sea. Lehman et al. (2017) found an increasing linear trend of the number of deep cyclones mainly over the North Atlantic, north of approximately 52°N in the period from 1950 to 2010, which concurs with the shift in the NAO to the positive phase. They recognized four main routes of deep cyclones during the ongoing LVC periods, which approach from the west and move east or northeast towards the Baltic Sea or Scandinavia.

5 Conclusions

Among macroscale circulation patterns, the SCAND, which northern centre is located in the vicinity of the Baltic Sea, appeared to be most relevant to the low-frequency variability of the Baltic Sea level. The influence of SCAND on mean sea level is strong throughout the year, while the influence of NAO is much less pronounced in summer than in the other seasons. The correlations are non-stationary and they become in general stronger since 1980s.

The short-term rapid increases in the Baltic Sea level are associated with the specific development of synoptic conditions in the Euro-Atlantic region, characterized by a shift from high to low pressure over Europe. This is associated with the deep cyclones which move from the North Atlantic to the northeast. Three typical tracks of cyclones, preceding rapid increase in sea level, were distinguished, each of them causing an increase in pressure gradient over northern Europe and intensifying western winds over the Baltic Sea.

As proven in this study, the relationships between atmospheric conditions and changes in the Baltic Sea level can be recognized on different temporal scales, and both high- and low-frequency variability in sea level are preconditioned by the dynamic evolution of the pressure field over the Euro-Atlantic region. The obtained results contribute to the general knowledge of sea-atmosphere coupling, which is particularly explicit in an example of a small sea basin, such as the Baltic Sea.

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Availability of data and material Manuscript has associated data in data repository.
Code availability None.

Authors' contributions Ewa Bednorz designed and directed the project, wrote most of the article, proceeded most of the computation and draw most of the figures; Arkadiusz M. Tomczyk participated in writing and editing the manuscript as well as in computation and drawing figures.

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Compliance with ethical standards

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