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On the statistical relationship between the geostrophic wind and sea level variations in the Baltic Sea

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The relationship between the Baltic Sea levels and the geostrophic wind was analysed using observations covering the entire Baltic Sea from the early 20th century to the present. A well-defined location in the southern Baltic Sea was found where the zonal geostrophic wind correlated best ($r = 0.5–0.8$) with the detrended monthly mean sea levels everywhere along the Baltic Sea except in the southwestern part. The sea levels also correlated with the wind of the previous month ($r = 0.4–0.6$). This partly delayed correlation is due to the mechanism by which the atmosphere affects sea levels: a combination of water transport in the Danish Straits, and direct effects of wind and air pressure inside the Baltic Sea basin. An estimate was calculated for the detrended variation in the water volume of the Baltic Sea. The simple regression model based on the zonal geostrophic wind explained 75% of the detrended variation in the water volume. The variation correlated well ($r = 0.995$) with monthly mean sea levels at Föglö in the Åland Islands.

Introduction

The Baltic Sea is a semi-enclosed intra-continental sea, connected to the North Atlantic through the shallow and narrow Danish Straits (Fig. 1), which considerably limit water transport between the Baltic Sea and the North Sea. Due to this semi-enclosed nature, the Baltic Sea exhibits its own characteristic sea level variability, strongly controlled by local meteorological conditions. It also experiences effects originating from outside, such as the global mean sea level rise due to the melting of continental ice sheets. Understanding the mechanisms of this variability allows us to develop better estimates of flood risks, as well as to predict future changes in the local sea level variability. A simple model that is able to estimate the Baltic Sea water volume without using any sea level measurements is of great value both for land uplift studies and for studies estimating the relation between the global sea level and the sea level in the Baltic Sea (e.g. Johansson *et al*. 2003).

Wind and air pressure are the most important factors controlling the Baltic Sea level. Early documented remarks on the connection between wind and sea levels in the Baltic Sea originate from the late 17th century (Ekman 2010). More systematic studies on the Baltic sea level variability were published by e.g. Witting (1918), Hela (1944) and Lisitzin (1974). They also studied in detail the relationship of wind and air pressure variations with sea levels.

More recently, several studies have focused on the relationship between sea levels and the

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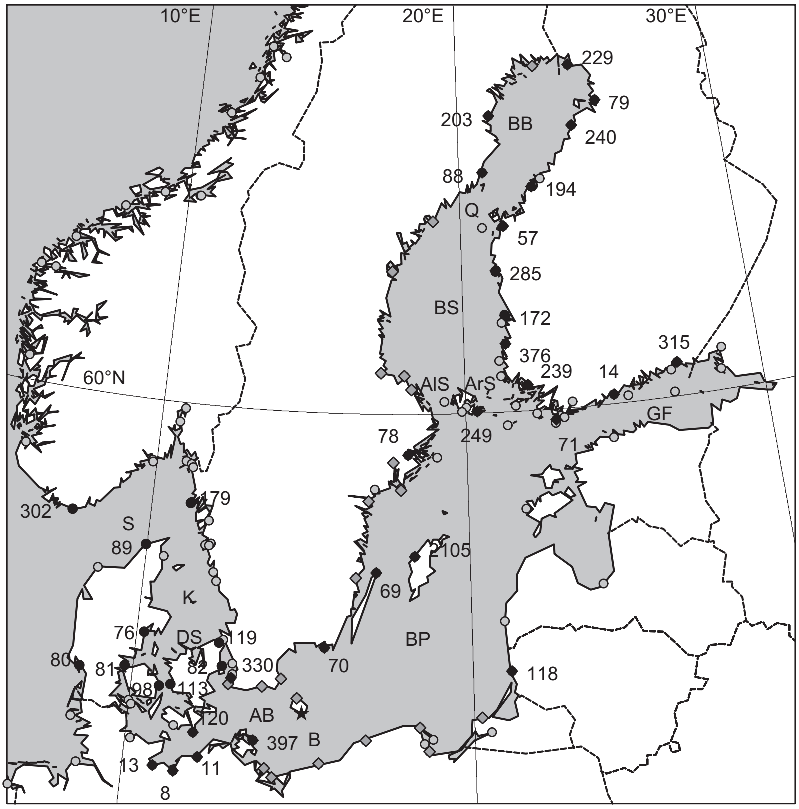

Fig. 1. The PSMSL tide gauge stations: those with data covering the period 1933–2012 are given with their ID numbers in the Baltic Sea (black diamonds) and the straits between the North Sea and the Baltic Sea (black circles). Other Baltic Sea stations with more than 240 months of data in 1933–2012 (gray diamonds), and other PSMSL stations (light gray circles) are also shown, as well as the Bornholm wind/pressure grid point 55°N, 15°E (black asterisk, B). The denoted sub-basins of the Baltic Sea are: Bothnian Bay (BB), the Quark (Q), Bothnian Sea (BS), Åland Sea (AlS), Archipelago Sea (ArS), Gulf of Finland (GF), the Baltic Proper (BP), and Arkona Basin (AB). The straits between the North Sea and the Baltic Sea are Skagerrak (S), Kattegat (K) and the Danish Straits (DS).

North Atlantic Oscillation (NAO) index (e.g. Heyen *et al*. 1996, Kahma 1999, Johansson *et al*. 2001, Andersson 2002, Johansson *et al*. 2003, Jevrejeva *et al*. 2005, Dailidiene *et al*. 2006, Hünicke and Zorita 2006, Suursaar *et al*. 2006, Suursaar and Sooäär 2007). The NAO index describes the large-scale atmospheric conditions over the North Atlantic. It represents the north–south air pressure gradient, and is thus connected with westerly flow over the North Atlantic and northern Europe (e.g. Jones *et al*. 1997, Hurrell and Deser 2009). Johansson *et al*. (2003) showed that 40% of the year-to-year sea level variability on the Finnish coast, i.e. the northeastern coast of the Baltic Sea, correlates with the NAO index.

The NAO index, however, represents the atmospheric conditions over the entire North Atlantic. More local atmospheric indices usually better describe the sea level variability in the Baltic Sea. Lehmann *et al*. (2002) showed that a Baltic Sea Index (BSI), based on air pressure difference between Poland and Norway, accounts for about 50% of the Baltic sea level variability. Andersson (2002) defined a Baltic Atmospheric Circulation (BAC) index as a combination of pressure differences close to the Baltic Sea entrance, explaining more than 80% of winter sea level variance, and also correlating well in the other seasons. Johansson *et al*. (2014) found that the zonal geostrophic wind, calculated from the air pressure field over the southern Baltic Sea, explains 84%–89% of the year-to-year sea level variability on the Finnish coast. Johansson (2014) further showed that the monthly mean zonal geostrophic wind explains about 80% of the month-to-month sea level variability. This correlation has a time lag: the monthly mean sea levels correlate with the zonal geostrophic wind of the previous month as well as the same month.

In this work, we extend the analysis of Johansson (2014) over the entire Baltic Sea. The goal is to find out how the relationship between the geostrophic wind and sea levels, which is strong on the Finnish coast, behaves in other areas of the Baltic Sea. The correlation between the NAO index and sea levels has been shown to be weaker in the southwestern Baltic Sea than on the Finnish coast (e.g. Johansson *et al*. 2003, Hünicke and Zorita 2006), so the question of differences among different areas is of relevance.

The principles of the physical mechanisms by which air pressure and wind stress affect sea levels have been known for a long time (e.g. Witting 1918, Hela 1944). In practice, however, the relationship is complicated because of the different spatial and temporal scales involved in the various processes (Johansson 2014). To avoid the complications of the physical approach — which essentially would necessitate the use of a dynamical model — this study is based on statistical analyses. We are working on a further approach utilizing a dynamical model, but that will be the subject of another paper.

Furthermore, the physical factors affecting the Baltic Sea are correlated among themselves. For instance, westerly winds and low air pressure may separately lead to higher sea levels, but as westerly winds and low air pressure often occur together in connection with cyclonic activity, which of the two physical mechanisms is involved, and to what extent? A statistical method does not answer this, but these relationships are useful as they may simplify calculations. Our main purpose is to find a single regressor — either wind or air pressure — that adequately describes all these atmospheric effects.

Theory

The Baltic Sea consists of several sub-basins with different orientations and bottom topographies; it has an average depth of 54 m and maximum depth of 460 m. The average salinity of the Baltic Sea is 7‰, with an internal salinity gradient from 25‰ in the Danish Straits to 4‰ in the Bothnian Bay, and zero in river mouths. This gradient results in a permanent sea level gradient of 35–40 cm between the North Sea and the inner Bothnian Bay, and a somewhat smaller gradient in the eastern part of the Gulf of Finland (Witting 1918, Ekman and Mäkinen 1996). The Baltic Sea is ice-covered in winter, the length of the ice season being 5–7 months, and the annual maximum extent of the ice cover varying from 12.5% to 100% (e.g. Leppäranta and Myrberg 2009). The Danish Straits, and beyond them the seas of Kattegat and Skagerrak, connect the Baltic Sea to the North Sea.

An overview of the different factors affecting sea levels in the Baltic Sea on various time scales was given in Johansson (2014). The present paper deals with monthly mean sea levels, and thus the shorter-term variability is not described in detail here. The main factors affecting the local month-to-month sea level behaviour are wind and air pressure variations. Changing weather patterns affect sea levels over periods of hours and days, but this effect is also highly relevant on longer time scales, as monthly and even annual mean wind and pressure conditions vary significantly. Wind stress forces sea level gradients between different parts of the Baltic Sea. Southwesterly winds, for instance, raise water high in the northeastern parts of the sea. Air pressure differences affect sea levels by the inverse barometer effect: theoretically, a pressure change of 1 hPa corresponds to a sea level change of 1 cm. In practice, as the Danish Straits limit large changes in the water volume of the Baltic Sea, a theoretical inverse barometric response to short-term pressure changes does not occur, but rather the pressure gradient over the Baltic Sea determines the internal redistribution of water (e.g. Hela 1948, Lisitzin 1974).

Water transport between the Baltic Sea and the North Sea is predominantly driven by the sea level difference between the two seas. In inducing such a sea level gradient, atmospheric factors play an important role. Westerly winds, for instance, raise water from the North Sea towards the straits, and at the same time drive water away from the southwestern corner of the Baltic Sea next to the straits. Such a configuration results in a sea level gradient that favours the inflow of water. Air pressure variations alter the North Sea level outside the straits, and pressure gradients over the Baltic Sea redistribute water, the resulting gradient driving water through the straits. The freshwater budget — river runoff, precipitation and evaporation — also contributes to the water volume of the Baltic Sea. (e.g. Lisitzin 1974).

The total range of variability of the Baltic Sea water volume is 500 km^3, corresponding to a sea level range of 130 cm. The main contributor to this is the water transport in the Danish Straits, with instantaneous flows of as much as 25 km^3 per day (sea level change 6 cm per day). The mean annual river runoff to the Baltic Sea amounts to 440 km^3 (110 cm), while a maximal monthly runoff to 87 km^3 (22 cm). The mean annual precipitation and evaporation amount to 215 km^3 (55 cm) and 175 km^3 (45 cm), respectively (e.g. Leppäranta and Myrberg 2009). These contributions are thus minor compared with the capacity of the Danish Straits for an outflow of up to 750 km^3 (180 cm) of water per month.

Due to the limited transport capacity of the Danish Straits, the observed changes of several tens of centimetres in the Baltic Sea average level take more than a week to occur, even in ideal conditions. This delayed response is also evident in the monthly mean sea levels (Johansson 2014), and it must be taken into account in the analysis of the relationship between atmospheric factors and sea levels.

The Danish Straits also convey into the Baltic Sea the global large-scale sea level rise. This sea level rise results from changes in ocean density and circulation, and the melting of land-based ice sheets, glaciers and ice caps. The global average rate for this sea level rise was 1.7 ± 0.2 mm yr^{-1} in 1901–2010, and since 1971, 2.0 ± 0.3 mm yr^{-1} according to the Fifth Assesment report of the Intergovernmental Panel on Climate Change IPCC (Rhein *et al*. 2013). During recent decades, satellite altimeter measurements of the world oceans showed higher rates, such as 3.2 ± 0.4 mm yr^{-1} in 1993–2010 (Rhein *et al*. 2013).

However, this rising sea level trend is not evident everywhere on the coastline of the Baltic Sea, as in many parts the sea level is actually declining in relation to the bedrock. This is due to the postglacial land uplift of the Fennoscandian area around the Baltic Sea: the recovery of the Earth's crust from the deformation caused by the last ice age. The crustal uplift rates vary from a rise of 10 mm yr^{-1} around the Quark area between the Bothnian Sea and the Bothnian Bay to a slow sinking in the southwestern Baltic Sea (e.g. Lisitzin 1964, Vermeer *et al*. 1988, Ekman 1996, Vestøl 2006, Lidberg *et al*. 2007, Johansson *et al*. 2003, Richter *et al*. 2011, Johansson *et al*. 2014).

Data

Sea levels

The sea level has been measured in the Baltic Sea since the 18th century, including some of the world's longest historical sea level time series (Ekman 1988, Bogdanov *et al*. 2000). In this study, we utilize the long-term time series of monthly-mean sea levels stored in the Permanent Service for Mean Sea Level (PSMSL) database (*see* Holgate *et al*. 2013 and http://www.psmsl.org/data/obtaining/).

For our analyses we chose the stations with "revised local reference" (RLR, cf. http://www.psmsl.org/data/obtaining/) data suitable for time series analyses covering the years 1933–2012 with a maximum of 155 months of data missing. This included 26 stations on the coasts of the Baltic Sea, and ten stations on the coasts of the Danish Straits, Kattegat and Skagerrak or immediately outside the entrance from the North Sea to Skagerrak (Fig. 1 and Table 1). We denote the latter group of stations as those "in the straits". The Baltic Sea station set includes Sassnitz, where two years are missing at the beginning, and Klaipeda, where one year is missing at the end of the 80-year period under study.

In addition to the stations mentioned above, a larger set of Baltic Sea stations was used for some of the analyses. This data set contained all stations with more than 240 months of RLR data available during the period 1933–2012 — altogether 48 stations with varying time spans (Fig. 1 and Table 2). The available sea-level stations were not evenly distributed around the

Baltic Sea; the northeastern part was generally well represented while there were less data from the southeastern part.

The PSMSL data underwent a quality check to detect erroneous data, datum discontinuities, etc. The RLR time series were reduced to a common datum (reference level) for each station to ensure their suitability for time series analyses, with no inhomogeneities due to changes or uncertainties in the reference level. Most of the stations used had no apparent quality issues. We excluded all data that were flagged suspicious by the PSMSL quality check.

In our recent studies of the sea level variability on the Finnish coast (such as Johansson *et al*. 2003, 2014, Johansson 2014), we used a slightly different set of the sea level data. This data set, known as the sea level data archive of the Finnish Meteorological Institute, was based on the same observations as the PSMSL data set for those 13 Finnish tide gauges which are still operating, but there were differences on how the

Table 1. The tide gauge data used in this study, from the PSMSL database (Holgate *et al.* 2013 and http://www.psmsl.org/data/obtaining/), with data in 1933–2012. "Baltic Sea" includes the stations on the coasts of the Baltic Sea basin (black diamonds in Fig. 1), and "Straits" the stations on the coasts of the Danish Straits, Kattegat, Skagerrak and North Sea outside the entrance to Skagerrak (black circles in Fig. 1).

	Station ID	Name	Years of data	Months missing in 1933–2012
Baltic Sea	229	Kemi	1920–2012	33
	79	Oulu	1889–2012	54
	240	Raahe	1922–2012	75
	203	Furuögrund	1916–2012	5
	194	Pietarsaari	1914–2012	15
	88	Ratan	1892–2012	3
	315	Hamina	1928–2012	14
	57	Vaasa	1883–2012	75
	285	Kaskinen	1926–2012	22
	14	Helsinki	1879–2012	1
	172	Mäntyluoto	1910–2012	19
	376	Rauma	1933–2012	6
	239	Turku	1922–2012	21
	71	Hanko	1887–2012	133
	249	Föglö	1923–2012	49
	78	Stockholm	1889–2012	0
	118	Klaipėda	1898–2011	127
	2105	Visby	1916–2012	0
	69	Ölands N. Udde	1887–2012	0
	70	Kungsholmsfort	1887–2012	1
	330	Klagshamn	1929–2012	13
	397	Sassnitz	1935–2012	155
	120	Gedser	1892–2012	10
	11	Warnemünde 2	1855–2012	2
	8	Wismar 2	1848–2012	2
	13	Travemünde	1856–2012	96
Straits	98	Slipshavn	1896–2012	37
	113	Korsør	1897–2012	25
	81	Fredericia	1889–2012	11
	82	København	1889–2012	25
	76	Aarhus	1888–2012	37
	119	Hornbæk	1891–2012	22
	89	Hirtshals	1892–2012	52
	179	Smögen	1911–2012	0
	302	Tregde	1927–2012	25
	80	Esbjerg	1889–2012	19

missing data were interpolated. Such small differences have no significant effect on the results, which we confirmed by repeating some of the analyses of this paper with the sea level data of Johansson (2014).

Air pressure and geostrophic wind

Daily sea level pressure (slp) data for the years 1899–2012 were obtained from the DS010.0 data set (*see* http://rda.ucar.edu/datasets/ds010.0/, Trenberth and Paolino 1980). The slp data, assembled from the grids of various meteorological chart digitization projects and operational analyses, were available on a 5° latitude/longitude grid over an area extending from 15°N to 85°N.

The zonal (U_g) and meridional (V_g) geostrophic wind components were calculated from the daily mean slp (P) gradients:

$$U_\mathrm{g} = -\frac{1}{f\rho}\frac{\partial P}{\partial y}, V_\mathrm{g} = \frac{1}{f\rho}\frac{\partial P}{\partial x}, \tag{1}$$

where f stands for the latitude-dependent Coriolis parameter and ρ for the air density, which is a function of pressure and temperature (for the latter a constant value of 283 K was used). The geostrophic winds were first calculated at the intermediate points of the grid and then interpolated onto the 5° latitude/longitude grid, which essentially results in each grid point value representing a gradient over a 10° spatial span. Monthly means were calculated from the daily wind and pressure values.

The geostrophic wind is the ideal air flow for which the Coriolis force balances the pressure gradient force. The real surface wind generally has smaller speed, and it is directed left from the geostrophic wind in the northern hemisphere, due to frictional force (Holton 1972). The sea levels are naturally affected by the real surface wind. However, as this study is based on statistical analyses, we considered the geostrophic wind as a kind of "atmospheric index", similar to pressure gradients like the NAO index, representing both the wind conditions and the pressure field.

The use of the geostrophic wind, calculated from air pressure, rather than the surface wind, is further justified by the better availability of long and homogeneous observation time series.

Table 2. Additional Baltic Sea tide gauges from the PSMSL database (Holgate *et al.* 2013 and http://www.psmsl.org/data/obtaining/), with more than 240 months of data in 1933–2012, but not covering the entire 80-year period (gray diamonds in Fig. 1).

Station ID	Name	Years of data	Months missing in 1933–2012
2101	Kalix	1974–2012	502
2102	Skagsudde	1982–2012	695
122	Draghällan	1898–1967	540
1211	Spikarna	1968–2012	430
90	Björn	1892–1976	432
2103	Forsmark	1975–2012	511
99	Nedre Gävle	1896–1986	313
31	Nedre Södertälje	1869–1970	504
68	Landsort	1887–2005	84
2104	Marviken	1964–2012	382
289	Kaliningrad	1926–1986	411
64	Gdańsk	1951–1999	372
2106	Oskarshamn	1960–2012	334
645	Wladyslawowo	1951–1999	372
644	Ustka	1951–1999	372
643	Kolobrzeg	1951–1999	372
1812	Tejn	1992–2012	719
2107	Simrishamn	1982–2012	593
72	Ystad	1887–1981	372
2	Swinoujscie	1811–1999	229
2108	Skanör	1992–2012	710
1448	Koserow	1977–2012	593

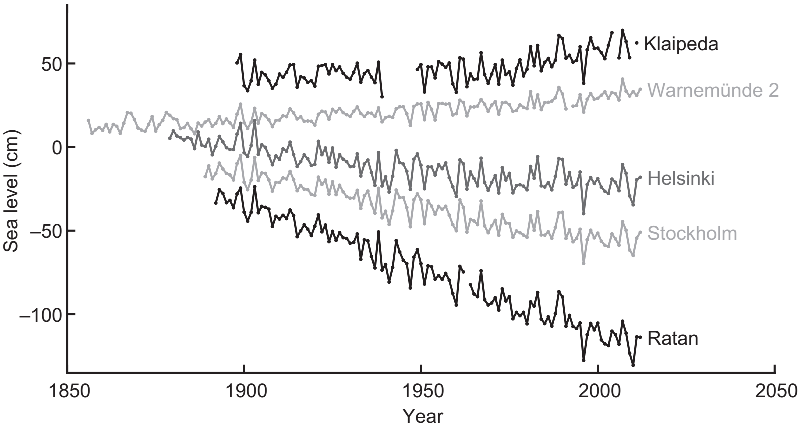

Fig. 2. Observed annual mean sea levels at some Baltic Sea stations: Ratan in the Bothnian Bay, Helsinki in the Gulf of Finland, Stockholm on the west coast of the Baltic Proper, Klaipeda on the southeastern Baltic Proper, and Warnemünde on the southwestern Baltic Sea. The time series are vertically shifted for clarity.

Pressure measurements dating back to the late 19th century are more reliable than surface wind observations, as pressure is less affected by factors like relocations of equipment or environmental changes around the observation site (BACC Author Team 2008).

Methods

Detrending the time series

The sea levels on the Baltic Sea coasts exhibit long-term trends, depending on location, and ranging from about 8 mm yr^{-1} decline to 1.5 mm yr^{-1} rise (Fig. 2). These trends are a combination of the location-dependent postglacial land uplift, the global or large-scale mean sea level rise, and other factors such as changes in regional meteorological conditions. From the beginning of our time series up to 1960, the apparent trend is very linear, but then changes (Johansson *et al*. 2001). Up to the 1990s, the change is due to the changes in the water balance and relate to the atmospheric forcing we are studying (Johansson *et al*. 2003). Therefore, this change will not adversely affect our analysis. From 1990 on, the global sea level rise has accelerated, and this additional change will result in a slight rising trend in the last 15 years of our detrended time series (e.g. Johansson 2014). While any study extending to the future would require this curvature to be removed, it is so marginal in our data that we did not removed it.

The main focus of this study was on the long-term trends, but rather on the atmosphere-induced month-to-month variability, and finding a simple parametrization for it. Thus, as a first step in the data analysis, we detrended the sea level time series by removing the long-term linear trend in 1933–2012. Accordingly, we also detrended the wind and air pressure time series. The trends in the atmospheric factors, however, also have some relevance from a sea level viewpoint. We discuss this briefly below.

Baltic Sea water volume and average sea level

From the detrended sea levels at the 48 stations around the coastline we calculated an estimate for the variation in the monthly mean water volume in 1933–2012. The monthly mean sea levels were first linearly interpolated or extrapolated from the available station data to gridpoints with 10´ latitude and 20´ longitude resolution over the entire Baltic Sea. The interpolations seemed reasonable and not drastically affected by the varying availability of sea level stations (Fig. 3). Occasionally, individual stations showed values that suspiciously deviated from those at the other stations (*see* Fig. 3a), but those cases were few in number, and their effect on the time series of the water volume was minor.

We used the topography (landmask) data of Seifert *et al*. (2001) to determine the sea surface area a_j of each grid cell, and calculated the

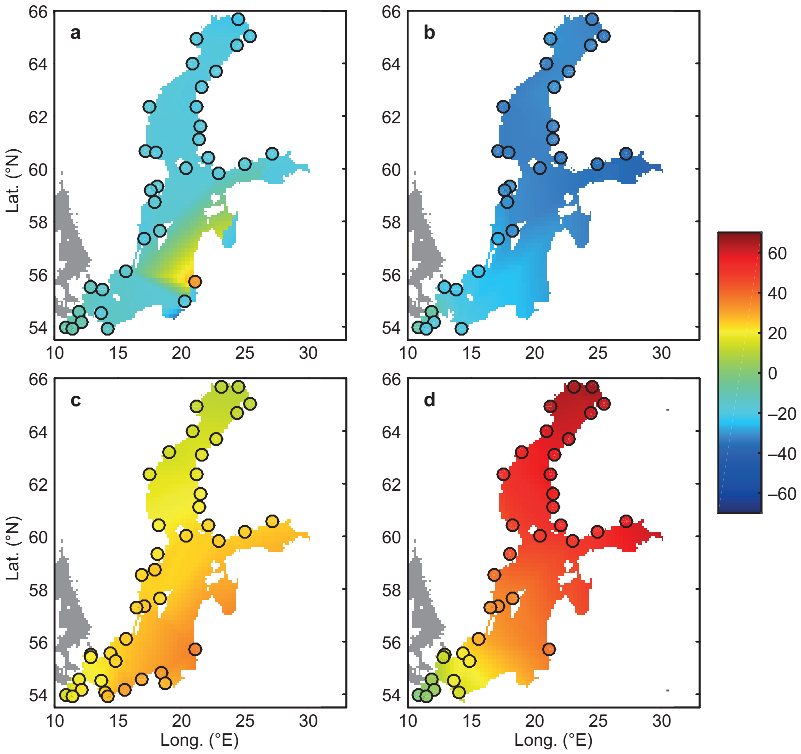

Fig. 3. Interpolated Baltic Sea levels (cm) for some representative months with varying availability of observed tide gauge data (circles). (**a**) May 1937, 34 stations, (**b**) February 1942, 29 stations, (**c**) October 1997, 42 stations, and (**d**) December 2011, 36 stations.

detrended water volume estimate V_d from the interpolated sea levels h_j over all the grid points j. To relate this water volume variation to the sea level variation, we also calculated the corresponding average level of the Baltic Sea H_d:

$$V_d = \Sigma_j a_j h_j,\ H_d = (\Sigma_j a_j h_j)/(\Sigma_j a_j), \qquad (2)$$

The number of available sea level stations changed with time, ranging from 28 to 42 for individual months in 1933–2012. The geographical distribution of available stations also changed, and it was usually biased, with more stations in the northeastern part of the Baltic Sea, and very few data from the southeastern part.

The fact that there is no long term trend in H_d, as calculated from the detrended sea level observations, does not imply that the water volume would not have a long-term trend. It naturally does, as any trend in local sea levels anywhere on the Baltic Sea coast also implies a trend in the water volume. This includes trends due to large-scale sea level rise, land uplift, changes in atmospheric conditions, and other factors affecting sea levels.

The geoid is the physical reference level for sea level variations. The Baltic Sea water volume below the geoid is reduced as the bottom of the basin rises with land uplift, and therefore, strictly speaking, the relation between the mean sea level over the Baltic Sea and the Baltic Sea water volume changes with time. In the Bothnian Bay and the Bothnian Sea, the land uplift during the studied period was of the same order as the monthly sea level variations we were interested in. Fortunately, both the land uplift and the small change in the geoid may be taken as linear in the time scale of the study. By using detrended sea level time series we removed these linear trends and ended up with a nearly one-to-one relation between the detrended mean sea level H_d and the detrended water volume V_d, the remaining error being the variation in the surface area of the low-lying coast.

Relationship between atmospheric factors and the Baltic Sea level

The relationships of wind and air pressure to the sea level were first studied by calculating the Pearson correlations (r). Winds and pressures at different grid points over the Baltic Sea and surroundings (45–75°N, 20°W–40°E, with 5° resolution) were compared with the sea levels at each of the stations with data from the period 1933–2012 (Table 1). Three atmospheric variables were used: the zonal and the meridional geostrophic wind components, and the mean sea level pressure. In addition to the observed sea level data, we also performed the analysis for the Baltic Sea average level, H_d. The stations in the Baltic Sea and those in the straits were compared to see whether some properties of the relationship specific to the Baltic Sea are evident. The wind/pressure grid points that showed the strongest correlation were extracted and used in further analyses.

Johansson (2014) showed that the monthly mean sea levels on the Finnish coast correlate with the zonal wind and the air pressure of the same month, as well as those of the previous month. To find out whether this also applies to other coasts of the Baltic Sea, we calculated correlations with different time lags: the atmospheric variations preceding the sea level variations, and vice versa.

Some studies show that the correlation between sea levels and the atmospheric phenomena is stronger in winter (Andersson 2002, Hünicke and Zorita 2006, Suursaar and Sooäär 2007). We thus calculated the correlation and regression coefficients related to the zonal wind separately for different calendar months for a few representative stations.

Finally, to study whether the correlation changed in time, we calculated it for overlapping 30-year periods for some stations that had sea level data for a longer period between 1899 and 2012.

As is further reasoned below, it turns out that the zonal geostrophic wind alone is sufficient to represent the effect of the atmospheric factors on sea levels. However, zonal geostrophic winds of both the current and previous months have to be taken into account, as the correlations show a delay. To quantify this relationship, a two-variable linear regression was fitted to the detrended monthly mean sea levels h_d at each station i with respect to the detrended zonal geostrophic wind U_{gd} at the chosen grid point in the same (m) and the previous ($m - 1$) month, to yield the regression coefficients p_0 and p_1, respectively. Using these regression coefficients, estimates w_d for the detrended atmosphere-related sea level variations were calculated as:

$$\begin{aligned} w_d(i, m) &= p_0(i)U_{gd}(m) + p_1(i)U_{gd}(m - 1) \\ &= w_{d0}(i, m) + w_{d1}(i, m) \end{aligned} \quad (3)$$

for each station i. Below, we refer to the two detrended atmosphere-related sea level components w_{d0} and w_{d1} as “instant” and “delayed”, respectively.

Contributions of different components to the observed variability

The detrended monthly mean sea level h_d at a site i is thus a sum of three components: the instant and delayed atmosphere-related variations w_{d0} and w_{d1}, and other residual variations ε_d:

$$h_d(i, m) = w_{d0}(i, m) + w_{d1}(i, m) + \varepsilon_d(i, m) \quad (4)$$

The residual variations ε_d were calculated for each sea level station by subtracting the atmosphere-related variations w_d from the detrended monthly mean sea levels h_d.

Analogously, the Baltic Sea average level H_d can be expressed as:

$$H_d(m) = W_{d0}(m) + W_{d1}(m) + E_d(m) \quad (5)$$

where W_{d0} and W_{d1} denote the instant and delayed atmosphere-related variations, and E_d the residual variations of the average sea level. W_{d0} and W_{d1} were obtained by regression analysis of H_d in the same way as for the monthly mean sea level observations above (Eq. 3), and E_d was obtained by subtracting these atmosphere-related variations from H_d.

Sea level variation at any station is a sum of the variation in the Baltic Sea average level and intra-basin variation, and this also applies to each component of Eq. 4 separately: they consist of the variation in the average level and intra-basin variation.

Thus, there are altogether six components of detrended sea level variation at each station:

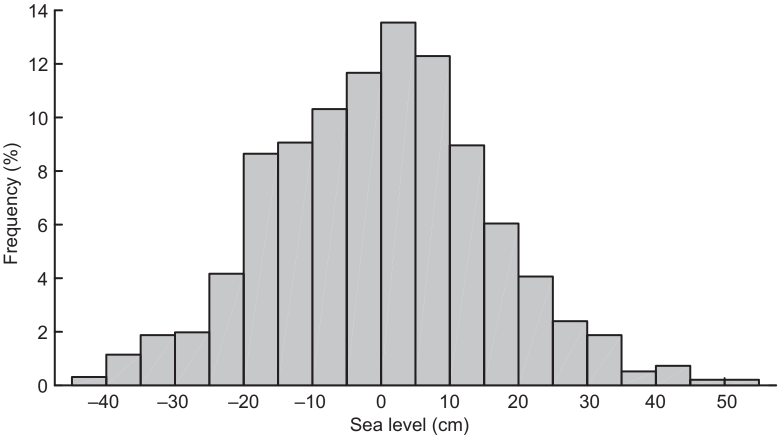

Fig. 4. Frequency distribution of the detrended monthly mean Baltic Sea average level H_d in 1933–2012.

$$h_\mathrm{d}(i,m) = W_\mathrm{d0}(m) + W_\mathrm{d1}(m) + E_\mathrm{d}(m) + w_\mathrm{l0}(i,m) + w_\mathrm{l1}(i,m) + \varepsilon_\mathrm{l}(i,m) \quad (6)$$

where the intra-basin instant and delayed atmosphere-related variations, and residual variations are denoted by w_l0, w_l1, and ε_l, respectively. These were calculated by subtracting the variation in the Baltic Sea average level from the variations at each station:

$$\begin{aligned} w_\mathrm{l0}(i,m) &= w_\mathrm{d0}(i,m) - W_\mathrm{d0}(m),\\ w_\mathrm{l1}(i,m) &= w_\mathrm{d1}(i,m) - W_\mathrm{d1}(m),\\ \varepsilon_\mathrm{l}(i,m) &= \varepsilon_\mathrm{d}(i,m) - E_\mathrm{d}(m). \end{aligned} \quad (7)$$

We calculated the standard deviations (s) of each of the components in Eqs. 4 and 6 in 1933–2012 in order to study their roles in sea level variability in different parts of the Baltic Sea.

Results

The Baltic Sea average level

The Baltic Sea average level H_d ranged from –43 to +51 cm in 1933–2012 (Fig. 4). The observed monthly mean sea levels at all Baltic Sea stations showed a high correlation with H_d (r = 0.59–0.995). The correlation was the highest around the Åland Sea and the Archipelago Sea, and the lowest in the Arkona Basin in the southwestern Baltic Sea.

In the literature, variations in the average level or the water volume of the Baltic Sea have been estimated with the sea level data e.g. from Stockholm (e.g. Ekman 1998), from Föglö/Degerby (Hela 1944, Lisitzin 1962), and from Landsort (Lehmann *et al*. 2002). Correlation with H_d at all those stations was very high ($r >$ 0.99), and thus the sea levels at them represent well the variation in the water volume. Föglö (station ID 249), located in the Åland Islands, showed the highest correlation (r = 0.995).

Correlation of sea levels with atmospheric variables

Of the three atmospheric variables studied, the zonal geostrophic wind showed the strongest correlation with sea levels (Table 3). For 20 Baltic Sea stations out of 26, the wind grid point with maximum correlation was 55°N, 15°E — a point located over the island of Bornholm in the southern Baltic Sea. Johansson *et al*. (2014) obtained a similar result for the Finnish sea levels. Although the geostrophic wind calculated for this point actually represents the pressure gradient over a south–north span of 10°, as described above, and thus has not much to do with the exact location, for simplicity we denote this grid point as "Bornholm" from now on.

For two more stations, the maximum correlation was obtained at a grid point near Bornholm. Only four stations — at which correlations were weak (r < 0.4) — showed the largest correlation with wind at another grid point at 45°N, 35°E. In those cases, however, the spatial distribution of the correlation did not show a well-defined maximum (Fig. 5) and therefore the point where the correlation for those stations reached its maximum has no physical significance.

The correlations between sea level and the meridional geostrophic wind were much weaker ($|r| < 0.5$), and the wind grid point of maximum correlation varied (Table 3). The correlations were negative, southerly winds correlating with a low sea level.

The grid point with the strongest correlation between pressure and sea level also varied (Table 3). The correlation showed a spatial distribution among sea level stations similar to that of the zonal wind: correlation was highest in the northeastern Baltic Sea. Negative correlation coefficients denote high pressure correlating with a low sea level, as is physically appropriate.

The stations in the straits showed a behaviour similar to those around the Baltic Sea. The cor-

Table 3. Correlation coefficients r between the monthly mean zonal (U_g) and meridional (V_g) geostrophic winds, sea level pressure (P), and the sea levels at chosen stations as well as the Baltic Sea average level H_d. Strong correlations ($r > 0.5$) are set in boldface. “Location” gives the coordinates of the atmospheric grid point with maximum correlation.

Station ID	r, U_g	Location (°N, °E)	r, V_g	Location (°N, °E)	r, P	Location (°N, °E)
229	**0.79**	55, 15	–0.43	75, –15	**–0.76**	70, 15
79	**0.80**	55, 15	–0.41	75, –15	**–0.77**	70, 15
240	**0.81**	55, 15	–0.41	70, –15	**–0.77**	70, 15
203	**0.80**	55, 15	–0.41	70, –15	**–0.75**	70, 15
194	**0.82**	55, 15	–0.41	70, –15	**–0.76**	70, 15
88	**0.82**	55, 15	–0.41	70, –15	**–0.75**	70, 15
315	**0.84**	55, 20	–0.44	45, 25	**–0.77**	65, 25
57	**0.82**	55, 15	–0.40	70, –15	**–0.75**	70, 15
285	**0.83**	55, 15	–0.41	70, –15	**–0.74**	65, 20
14	**0.83**	55, 15	–0.44	45, 25	**–0.76**	65, 25
172	**0.83**	55, 15	–0.39	45, 25	**–0.75**	65, 20
376	**0.83**	55, 15	–0.40	45, 25	**–0.75**	65, 20
239	**0.83**	55, 15	–0.43	45, 25	**–0.75**	65, 20
71	**0.83**	55, 15	–0.42	45, 25	**–0.75**	65, 25
249	**0.81**	55, 15	–0.42	45, 25	**–0.74**	65, 20
78	**0.78**	55, 15	–0.42	45, 25	**–0.71**	65, 20
118	**0.70**	55, 15	–0.44	45, 25	**–0.67**	65, 25
2105	**0.75**	55, 15	–0.46	45, 25	**–0.69**	65, 25
69	**0.72**	55, 15	–0.44	45, 25	**–0.66**	65, 25
70	**0.65**	55, 15	–0.44	45, 25	**–0.61**	65, 25
330	**0.54**	55, 15	–0.39	45, 25	**–0.52**	60, 25
397	**0.53**	50, 20	–0.43	45, 25	**–0.54**	60, 25
120	0.27	45, 35	–0.30	45, 25	–0.31	55, 35
11	0.37	45, 35	–0.45	50, 15	–0.46	55, 35
8	0.32	45, 35	–0.47	55, 10	–0.43	55, 40
13	0.24	45, 35	–0.37	55, 10	–0.29	50, 35
H_d	**0.78**	55, 15	–0.43	45, 25	**–0.71**	65, 25
98	**0.60**	50, 20	–0.40	45, 25	**–0.60**	60, 25
113	**0.53**	50, 20	–0.35	45, 25	**–0.52**	60, 25
81	**0.53**	50, 20	–0.24	45, 25	–0.48	60, 20
82	**0.71**	55, 15	–0.46	45, 25	**–0.68**	65, 25
76	**0.68**	55, 15	–0.32	70, –20	**–0.66**	65, 20
119	**0.78**	55, 15	–0.48	45, 25	**–0.75**	65, 25
89	**0.85**	55, 10	–0.37	45, 25	**–0.78**	65, 20
179	**0.79**	55, 10	–0.39	70, –20	**–0.74**	65, 15
302	**0.73**	50, 10	–0.41	70, –20	**–0.70**	60, 05
80	**0.88**	55, 05	**–0.50**	70, –15	**–0.84**	65, 10

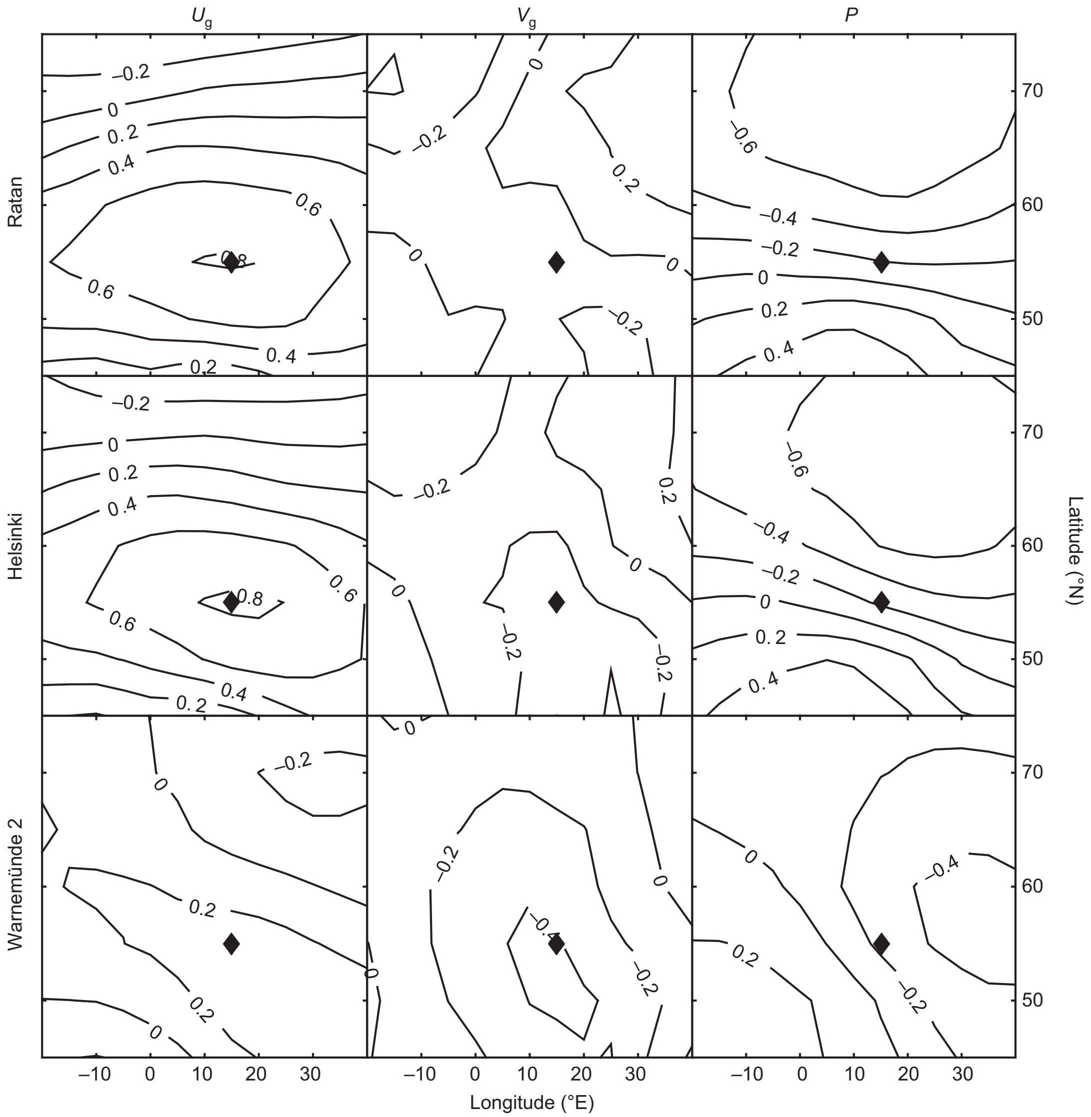

Fig. 5. The correlation coefficients *r* between the sea levels at Ratan, Helsinki and Warnemünde, and zonal (U_g) and meridional (V_g) geostrophic wind as well as air pressure (*P*) at different locations above the Baltic Sea and its surroundings. The black diamonds show the Bornholm grid point (55°N, 15°E).

relations between sea levels and the zonal wind or air pressure were high, while the meridional wind showed a weaker correlation. Also, the grid points with the maximum correlation were not far from those for the Baltic Sea stations. The highest correlation with the zonal geostrophic wind was at Esbjerg, the station located outside the straits on the west coast of Denmark. In this case, the wind grid point with the maximum correlation was also more westerly than for the other stations, located west of Esbjerg over the North Sea. The Baltic Sea average level, H_d, behaved in a way similar to the majority of the sea level stations in the Baltic Sea.

Each of the three atmospheric variables represents a slightly different aspect of the atmospheric variation. However, zonal wind and pressure are strongly correlated (r = –0.89). Thus, we considered it sufficient to choose only one of them as a regressor when aiming to describe their effect on sea levels. We chose the zonal wind because of the slightly higher correlation. Since the correlation between sea level and meridional wind was weak, and since further analyses (not detailed here) revealed that it would not add much to the results, it was not used as an additional regressor.

We chose to use the zonal wind at the Bornholm point, as it showed the maximum correlation with most of the sea level stations. The correlation coefficients between the zonal geostrophic wind at the Bornholm point and the monthly mean sea levels varied from 0.05 to 0.84 in the Baltic Sea (Table 4). The zonal wind of the previous month also showed a high correlation ($r > 0.5$) with sea levels in the Baltic Sea. We call these two correlations "instant" and "delayed", respectively, in accordance with the terminology used above with Eq. 3. No other time lag — wind variations preceding sea level variations, or vice versa, — showed a correlation. While the instant correlation between sea levels and the zonal wind was strong in the northeastern Baltic Sea, and weaker in the southwest, the delayed correlation was more consistent ($0.4 < r < 0.6$) over the entire area.

For the sea level stations in the straits, the respective instant correlation coefficients varied from 0.46 to 0.85. The delayed correlation was weaker than that found for the Baltic Sea (r = 0.16–0.48), and generally decreasing from the Danish Straits to Kattegat, Skagerrak and the North Sea.

Regression coefficients and the changes in time

The regression coefficients p_0 and p_1 (Eq. 3) behaved consistently with respect to station location in the Baltic Sea (Fig. 6). The instant coefficients p_0 increased from southwest to northeast. The westerly winds thus raise the sea level in the northeastern part of the basin, while there is not much effect in the southwestern part. The delayed coefficients p_1 were more uniform over the entire area, westerly winds raising sea levels.

The delayed effect is clearly restricted to the Baltic Sea, as the regression coefficients p_1 decreased in the Danish Straits, being around zero in Kattegat and Skagerrak. The instant regression coefficients p_0 varied more in the Straits, and Esbjerg on the North Sea showed a higher coefficient than any of the Baltic Sea stations.

The instant correlation and regression coefficients in the Baltic Sea showed no difference between different calendar months (Fig. 7). The correlation was high year round in the northeast, and weak in the southwest. The delayed correlation, on the other hand, was slightly stronger in winter and weaker in summer. The correlation existed throughout the century (Table 5), although with a clear tendency towards stronger correlation in the latest decades.

Table 4. Correlation coefficients between monthly mean zonal geostrophic wind over Bornholm (55°N, 15°E) and the sea levels at chosen stations in the Baltic Sea and the straits, using wind of the same (r_0) and previous (r_1) month as the sea levels. Strong correlations ($r > 0.5$) are set in boldface.

Station ID	r_0	r_1
229	**0.79**	**0.54**
79	**0.80**	**0.57**
240	**0.81**	**0.56**
203	**0.80**	**0.57**
194	**0.82**	**0.56**
88	**0.82**	**0.57**
315	**0.84**	**0.53**
57	**0.82**	**0.54**
285	**0.82**	**0.56**
14	**0.83**	**0.54**
172	**0.83**	**0.56**
376	**0.82**	**0.55**
239	**0.82**	**0.54**
71	**0.82**	**0.55**
249	**0.81**	**0.55**
78	**0.77**	**0.58**
118	**0.70**	**0.54**
2105	**0.75**	**0.56**
69	**0.72**	**0.57**
70	**0.65**	**0.59**
330	**0.54**	**0.58**
397	**0.51**	**0.58**
120	0.21	**0.59**
11	0.31	0.49
8	0.16	0.45
13	0.05	**0.50**
H_d	**0.78**	**0.57**
98	**0.57**	0.38
113	**0.52**	0.48
81	0.46	0.38
82	**0.71**	0.39
76	**0.68**	0.22
119	**0.78**	0.24
89	**0.84**	0.16
179	**0.78**	0.23
302	**0.63**	0.19
80	**0.85**	0.21

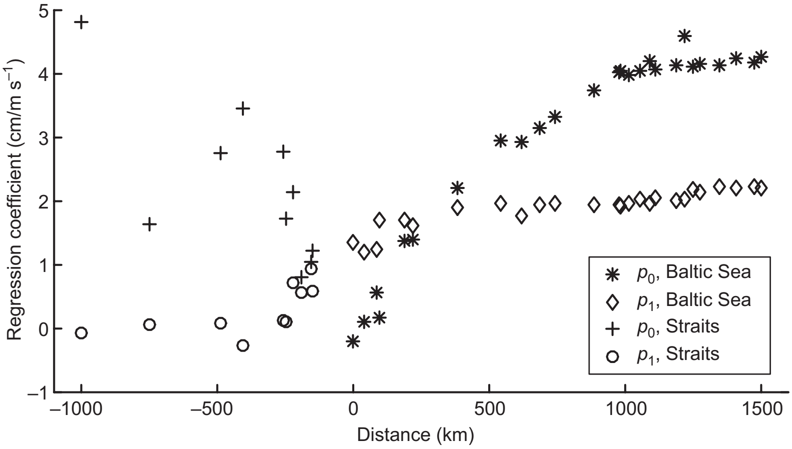

Fig. 6. Regression coefficients for the two-variable linear regression of sea levels as a function of zonal geostrophic wind above Bornholm; p_0 for the instant and p_1 for the delayed component, see text. The data are plotted as a function of the distance from the southwesternmost Baltic Sea station, Travemünde (station ID 13). The Baltic Sea stations are shown with positive distance, the stations in the straits with negative distance. For Tregde and Esbjerg, approximated values of –750 and –1000 km were used, respectively, as the distance from Travemünde to these stations along the waterways and round the Jutland peninsula is considerably longer than the shortest distance between the stations.

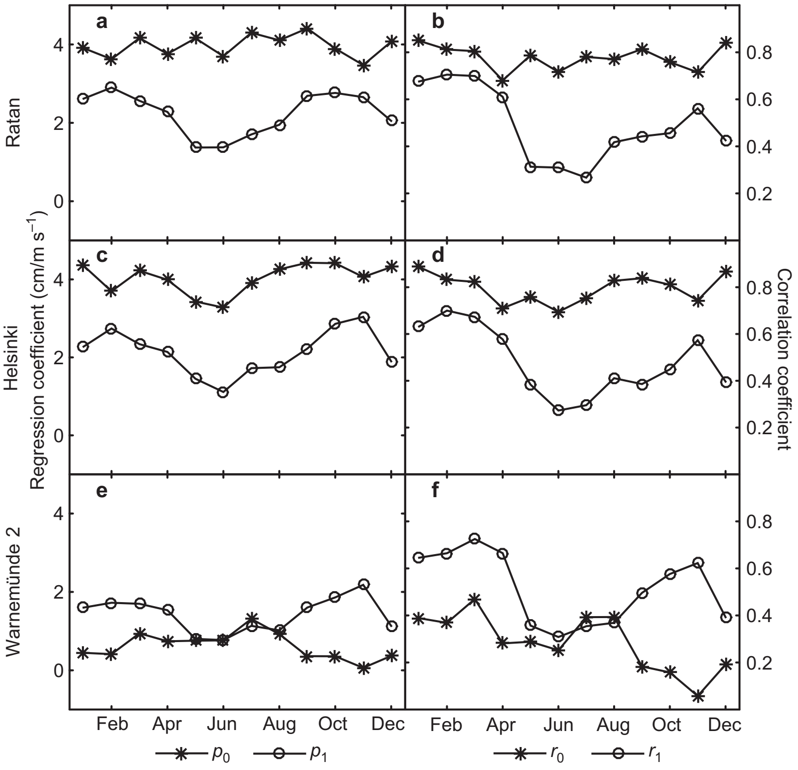

Fig. 7. Seasonal behaviour of the instant (subscript 0) and delayed (subscript 1) (**a**, **c**, **e**) regression (p), and (**b**, **d**, **f**) correlation (r) coefficients between the sea levels at Ratan, Helsinki and Warnemünde, and the zonal geostrophic wind.

Variability of sea level components

The observed variability of the detrended monthly mean sea levels increased in the Baltic Sea from southwest to northeast, being the smallest (s = 8 cm) in the Arkona Basin and the

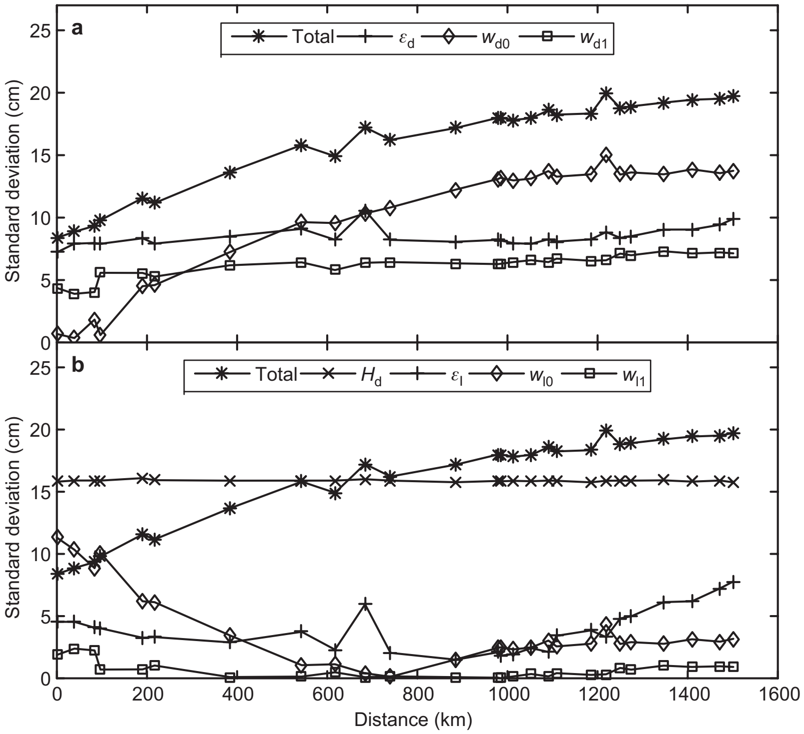

Fig. 8. Standard deviation of the detrended monthly mean sea levels at some Baltic Sea tide gauges in 1933–2012. The data are plotted as a function of the distance from the southwesternmost station, Travemünde (station ID 13). "Total" denotes the total observed variance. In **a**, the components correspond to Eq. 4; thus w_{d0} and w_{d1} denote the instant and delayed atmosphere-related variations, and ε_d the other (residual) variations. In **b**, the components correspond to Eq. 6; thus H_d denotes the monthly mean Baltic Sea average level (consisting of the components W_{d0}, W_{d1} and E_d), and w_{l0} and w_{l1} denote the instant and delayed atmosphere-related intra-basin variations, and ε_l the other (residual) intra-basin variations.

greatest (s = 20 cm) in the Gulf of Finland and the Bothnian Bay (Fig. 8a). This was mainly due to the instant atmosphere-related variability w_{d0} behaving this way, s increasing from 0 to 15 cm. The delayed variability w_{d1} was more uniform over the entire Baltic Sea, s ranging from 4 to

Table 5. The instant and delayed correlation coefficients between the detrended zonal geostrophic wind and monthly mean sea levels at selected stations in overlapping 30-year periods. Correlation coefficients for periods with more than 3 months of missing data are set in italics.

	Years	88 Ratan	14 Helsinki	78 Stockholm	118 Klaipėda	11 Warnemünde
Instant (r_0)	1903–1932	0.76	0.77	0.71	0.64	0.24
	1923–1952	0.76	0.80	0.73	*0.61*	0.25
	1943–1972	0.77	0.81	0.75	*0.72*	0.31
	1963–1992	0.85	0.87	0.82	0.76	0.42
	1983–2012	0.84	0.85	0.80	*0.73*	0.32
Delayed (r_1)	1903–1932	0.55	0.47	0.51	0.43	0.38
	1923–1952	0.50	0.46	0.49	*0.40*	0.41
	1943–1972	0.52	0.49	0.51	*0.53*	0.44
	1963–1992	0.60	0.57	0.60	0.58	0.54
	1983–2012	0.62	0.60	0.64	*0.59*	0.52

7 cm. The residual variations were also uniform over the entire area, s ranging from 7 to 11 cm.

The Baltic Sea average level (s = 16 cm) dominated the detrended sea level variations in most parts of the Baltic Sea (Fig. 8b). The majority of the delayed atmosphere-related variations as well as the residual variations were part of the average level variation, as the intra-basin components of those (w_{11} with s = 0–2 cm and ε_1 with s = 1–8 cm) were much smaller than the respective variations in Fig. 8a. In the Baltic Proper and the northeastern Baltic Sea, also most of the instant atmosphere-related variability was part of the average level variability, only s = 0–4 cm being intra-basin. In the southwestern Baltic Sea, on the contrary, subtracting the average level from the sea level variations resulted in an opposite instant atmosphere-related component with s = 6–11 cm.

The Baltic Sea average level (with s = 16 cm in 1933–2012) also consists of three components (Eq. 5). Of those, the greatest was the instant atmosphere-related variability W_{d0} with s = 11 cm. For the delayed atmosphere-related variability W_{d1}, s = 6 cm, and the residual variability E_d, s = 8 cm.

Discussion and conclusions

On the mechanisms of the atmospheric effect on sea levels

There is no obvious physical explanation for why there is a well-defined location at Bornholm where the zonal wind has the best correlation with the monthly average sea level of the Baltic. Most studies have assumed that the zonal wind in the North Sea or Kattegat should be relevant (eg. Gustafsson and Andersson 2001). While speculations could be presented about the physical mechanism, we believe that the question will be better answered by dynamical modelling. But as already said, this will be the subject of another paper.

On the other hand, the delay in the correlation between the sea levels and zonal geostrophic wind is readily understood by the well-known mechanisms of the inflow and outflow of water in the Danish Straits (e.g. Hela 1944, Lisitzin 1974, Samuelsson and Stigebrandt 1996, Gustafsson and Andersson 2001). We determined how the westerly wind is related to a high sea level. But actually, the variable related to zonal wind is water transport in the Danish Straits, that is, the change in sea level. The relationship is thus cumulative, as a westerly zonal wind corresponds to a sea level rise, rather than to a high sea level. The limited transport capacity of the straits also delays the changes in the water volume, as it takes longer than a week for the Baltic Sea level to change considerably. When prevailing westerly winds have accumulated water into the Baltic Sea, it remains there for a while, and also shows up in the next month's mean sea level.

This delayed and cumulative response differs from the behaviour of the internal sea level variations in the Baltic Sea: the response of the sea level gradient to wind forcing takes less than two days, and it is thus practically instantaneous on a monthly time scale. In such a case, westerly winds in practice correspond to high sea levels, and the relationship is immediate. The combination of these two mechanisms results in the partially delayed response. This might also partly explain the linear relationship between wind speed and sea level, as theoretically a sea level change on the coastline should be proportional to the square of the wind speed. We found, however, that the relationship between the monthly mean sea levels and the zonal wind component is best described as linear.

There is also another explanation for the deviation from a quadratic relationship. For simplicity, we illustrated above the mechanism of the relationship between the zonal wind and the sea levels by describing the physical effect of westerly winds on sea levels. However, as the analysis in this paper was statistical, and the air pressure and the wind as well as other atmospheric phenomena are all correlated, different physical effects are included to some extent: the inverse barometric effect of the pressure as well as the effect of the seasonal ice cover, among other factors.

A high concentration ice cover alters the effect of atmospheric factors on sea levels by, for instance, attenuating the piling-up effect of wind (Lisitzin 1957, Omstedt and Nyberg 1991). Thus, the relationship between atmospheric factors and sea levels is most likely modified by the extent of the ice cover, which in turn depends on the severity of the ice winter. Data on the annual maximum extent of the Baltic Sea ice cover date back to the early 18th century (Seinä and Palosuo 1993). However, analysing the effect of ice on the correlation between atmospheric factors and sea levels is not straightforward, as the effect is intertwined with the wind and pressure conditions. The severity of the ice winter correlates with the zonal wind and air pressure: mild ice winters generally have more westerly winds and lower air pressure than severe ice winters. Thus, the effect of ice cover is already included in the correlation between wind and sea level, and cannot be easily separated, at least when only monthly mean data are used.

The role of different components of sea level variability

The variation in the Baltic Sea average level accounted for most of the observed sea level variability at most of the stations studied (Fig. 8b). The intra-basin variations on top of this average level had two main components. In the northeastern Baltic Sea, residual variations not related to the zonal wind added some centimeters to the total variability. In the southwestern Baltic Sea, however, the local variations were dominated by an atmosphere-related component which was in an opposite phase with the (atmosphere-related) average level variations, thus counteracting them. This is physically relevant: a westerly wind adds water to the Baltic Sea, but at the same time drives water from southwest to northeast inside the basin.

It is seen, however, that the intra-basin delayed atmosphere-related variations — component w_{11} — are very small (Fig. 8b). This supports the conclusion above that the delayed response is caused by the effect of the narrow and shallow Danish Straits on the atmosphere-induced water transport between the North Sea and the Baltic Sea, not by any internal sea level variations in the basin.

The sea level stations in the straits and outside, while showing a generally strong instant correlation with the zonal wind, also showed a delayed correlation that decreased with increasing distance from the Baltic Sea basin. Atmospheric phenomena have a local effect in the straits and the North Sea as well as in the Baltic Sea: a westerly wind raises water against the west-facing coastline. The effects related to water transport in the Danish Straits, however, naturally do not affect the stations outside the straits.

The atmospheric phenomena, represented by the zonal geostrophic wind, accounted for about 75% of the month-to-month variations in the Baltic Sea average level and thus also of the water volume. However, about 25% of those variations were not accounted for. These might include variations controlled by other phenomena. These residual variations also include all those atmosphere-related variations in the inflow and outflow of water through the Danish Straits that cannot be described by our simple linear regression.

Atmosphere-related long-term trends in sea levels

This study was based on detrended time series of sea levels and the zonal geostrophic wind. However, as the month-to-month variations in sea levels are related to month-to-month variations in the zonal wind, it is natural to assume that a long-term trend in the zonal geostrophic wind would also generate a long-term trend in sea levels.

The zonal geostrophic wind at the Bornholm point had an increasing trend of 0.015 m s^{-1} yr^{-1} in 1933–2012. Multiplied by the sum of the regression coefficients p_0 and p_1, this corresponds to a sea level increase of 0.2–1.0 mm yr^{-1}. A trend of such magnitude should be taken into account when the long-term sea level changes are analysed. Although smaller, it is still comparable to the rates of the global mean sea level rise of 2–3 mm yr^{-1}. It is also of the same order as the uncertainty estimates of the land uplift rates in recent studies (e.g. Vestøl 2006, Lidberg *et al*. 2007, Johansson *et al*. 2014). For instance, when the local rates of sea level rise are studied to analyse the “fingerprint” effect of the melting of continental ice sheets (Mitrovica *et al*. 2001, Tamisiea *et al*. 2003), this location-dependent atmospheric contribution on the trend should definitely be taken into account.

We did not include the analysis of long-term sea level trends in the Baltic Sea in this paper, as it is a subject that deserves a detailed study on its own.

Atmospheric effects on short-term sea level variability

Wind and air pressure are also important drivers of sea level variations on shorter time scales than a month, ranging from day-to-day variability induced by varying weather patterns, up to extreme storm surges. Most such effects were left outside the analyses of this study, which was based on monthly mean sea levels.

Studying the correlation between wind and sea levels using only the observed monthly means has an obvious limitation. We only found the instant correlation with no time lag, and the delayed correlation with a time lag of one month. The relationship is more continuous, however, consisting of effects with time lags ranging from zero to two months. Thus, analyses with a higher time resolution might reveal more of the nature of the correlation, e.g. exactly how it decays with time. This would eventually allow more precise estimates of the atmosphere-related sea level variations on a more detailed time scale. These issues are left for future studies.

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