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On temporal wind variations forcing salt water inflows into the Baltic Sea

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ABSTRACT

Salt water inflows into the Baltic Sea are important processes for maintaining the general stratification and the ventilation of the bottom water in deep basins of the central Baltic. These events occur randomly during the winter season at intervals from one to several years. This pattern changed in the mid-seventies when only weak or no major inflows were observed. During that period a steady loss of salt together with a steady increase in hydrogen sulphide concentrations was observed in the central Baltic deep water.

It is generally assumed that strong westerly winds force a salt water inflow. Long time series of daily wind records at the meteorological station Arkona and sea level observations at Landsort between 1951 and 1990 have been analyzed in order to find characteristic sequences being associated with inflow events. A necessary condition for a salt water inflow is for the wind to blow from west for several tens of days. The weighted mean of the yearly cycle of the wind components for years without and with salt water inflows revealed that this condition happens usually in November and December. However, in years with inflows, a long-lasting easterly wind occurs in October and early November just before the strengthening of westerly winds. A similar sequence is observed in the yearly cycle of the mean sea level of the Baltic Sea, i.e., in years with inflows a lowering of the mean sea level precedes the increase of the sea level in November to December. Hence, major salt water inflows are very likely forced by a sequence of easterly winds in late autumn lasting for 20–30 days followed by strong to very strong westerly winds of similar duration.

1. Introduction

The Baltic Sea is a semi-enclosed sea located in humid latitudes. The excess of fresh water in its drainage area causes it to have a stable stratification consisting of an upper layer of brackish water with a salinity of about 7–8 PSU and a salty bottom layer of about 10–14 PSU in the Baltic proper. This stratification prevents in most parts of the Baltic Sea the ventilation of the bottom layer by local vertical convection during the winter season. Hence, the only mechanism to ventilate the bottom layer is advection of saline and oxygenated North Sea water through the Danish Straits into the bottom layer of the different basins of the Baltic Sea.

On average, the fresh water surplus of the Baltic is balanced by a net outflow of $1.4 \cdot 10^4$ m^3/s of water through the Belt Sea (Jacobsen, 1980). This outflow of brackish water is associated with a steady export of salt. The salt balance of the Baltic Sea is maintained by advection of salty North Sea water by both intermittent barotropic currents and baroclinic bottom currents. Averaged over several months there appears an outflow of low saline water in the surface layer and inflow of high saline water in the bottom layer (Knudsen, 1900).

The barotropic current is driven by sea level

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differences between the Kattegat and the Arkona Basin and the baroclinic current is driven by the stationary part of the baroclinic pressure gradient due to the salinity difference between the Kattegat water and the brackish surface water in the Arkona Basin (Knudsen, 1899; Wyrtki, 1953, 1954a; Lass et al., 1987).

The sill depths of the Danish Straits are rather shallow, 18m at the Darss Sill and 7 m at the Drogden Sill, respectively. This reduces considerably the baroclinic pressure gradient at the sill depths. Hence, the steady component of the bottom current in the Belt Sea is much less than that in straits with deeper sill depths, e.g., the Strait of Gibraltar. The dominating part of the water exchange between the North Sea and the Baltic is therefore excited by wind driven sea level differences between Kattegat and Arkona Basin causing barotropic water transport fluctuations in the Belt Sea with time scales between 1 to 10 days which are of the order of $2 \cdot 10^5$ m^3/s (Hela, 1944). Due to the associated advection of water masses the position of the salinity interface oscillates between the Kattegat and the Darss Sill. Simultaneously, the water transport through the Belt Sea adjusts the Baltic sea level to that of the Kattegat after about 10 days (Wyrtki, 1954b; Lass et al., 1987). This terminates the driving force of the transport. Hence, also the distance is limited over which the salinity interface is advected in the Belt Sea. Therefore, a very special time sequence of sea level elevation in the Kattegat is required to advect the salinity interface by barotropic currents the 300 km distance via the Great Belt from the Kattegat to the Darss Sill resulting in a major salt water inflow into the Baltic.

Major salt water inflows contribute the largest part in maintaining the stratification and ventilation of deep water in the Baltic Sea. Based on their definition of major salt water inflows into the Baltic (MBI's) Matthäus and Franck (1992) identified 90 of these events between 1897 and 1976 in the salinity measurements from the Danish light vessel "Gedser Rev" (Fig. 1). Statistical analysis of these events revealed that they are very intermittent occurring only during the winter season at intervals from one to several years. A mean MBI has according to Matthäus and Franck (1992) a duration of about 30 days during which the sea level of the Baltic increases by about 60 cm. It consists of two phases. In the first phase, lasting 20 days in the Darss Sill area, 140 km^3 water with salinity below 17 PSU are flowing into the Baltic rising its mean sea level by 38 cm. The 2nd phase, the main inflow period, is 10 days long at the Darss Sill. During this period 80 km^3 water with salinity exceeding 17 PSU is entering the Arkona Basin rising the mean sea level of the Baltic additional by 22 cm. In the main phase of the MBI, $1\text{–}5 \cdot 10^9$ t salt are transported into the bottom layer of the Arkona Basin.

The lack of effective major salt water inflows

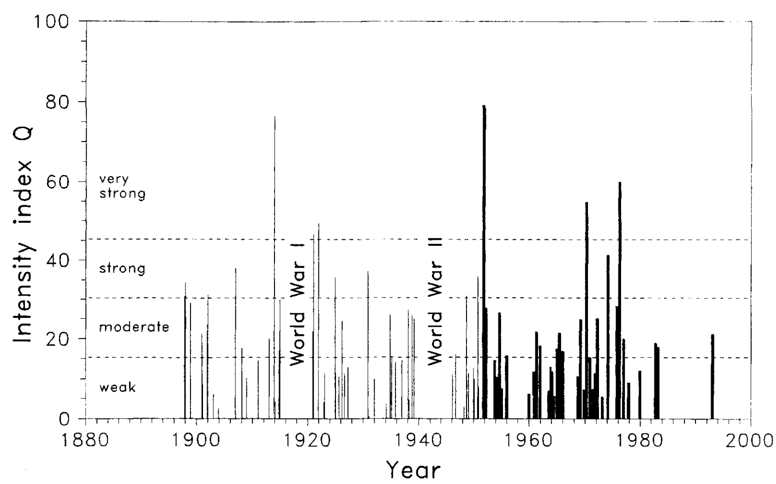

Fig. 1. Sequence and intensity of major Baltic inflows (MBIs) during the present century. The 36 events included in this study are indicated by heavy columns. The intensity index Q is defined according to Matthäus und Franck (1992).

between 1976 and the end of 1992 and the corresponding dramatic changes of salinity and oxygen in the deep water of the eastern Gotland Basin, described by Matthäus (1990) and Franck and Matthäus (1992), have emphasized the problem of understanding the forcing mechanism of a major salt water inflow. Wyrtki (1954a) has shown that strong west winds are necessary to force a salt water inflow over the Darss Sill. Dickson (1971, 1973) and Börngen (1983) as well as Börngen et al. (1990) pointed out that both fluctuations with a period of three years in sea level pressure over the North East Atlantic and in the salinity of the Kattegat deep water correlate with inflow events.

However, dynamical reasons mentioned above and the observation that sea level fluctuations on the corresponding time scale in the Kattegat are governed by the zonal component of the wind over the North Sea (Lass and Schwabe, 1990) indicate that a very special time sequence of winds with time scales on the order of one month may cause major salt water inflows. Moreover, the existence of the extended phase of reduced number of inflow events between 1976 and 1992, depicted in Fig. 1, suggests that some properties of the driving wind field must have changed compared to the time before 1976. Hence, properties of long time series of both wind measured at the meteorological station at Arkona and sea level records at Landsort have been analyzed in order to reveal possible climatic changes in the wind field. The results are described in the following sections.

2. The data

According to Lass and Schwabe (1990) wind measurement in the Belt Sea are highly correlated with sea level variations in the Kattegat as well as with sea level variations in the southern Baltic Sea. Since sea level inclinations are determined by the integral action of the wind stress over basin wide scales this indicates that wind measurements in the Belt Sea are rather representative for large areas over the North Sea and the Baltic Sea. This may be due to large scales of atmospheric pressure systems which have spatial scales on the order of 1000 km. Moreover, the good correlation between mean values of the geostrophic zonal component calculated from sea level pressure between southern Norway and the southern coast of the Baltic Sea, and daily means of the zonal wind component measured at Arkona as described by Matthäus and Schinke (1994), are supporting the idea that local wind in the Belt Sea may be representative for large areas of the North Sea and the Baltic Sea. Comparisons of wind measurements at Arkona with wind measured on open sea platforms in the Belt Sea, e.g., at the Danish light vessel "Mön Süd" by Müller (1982) and a mast at the Darss Sill by Nehring et al. (1995), indicate reduced wind speeds during south-westerly and enhanced wind speeds during north easterly winds at Arkona. But daily mean values of the east component at both positions agree fairly well.

The wind data of Arkona have been published for the time between 1950 and 1990 in the "Täglicher Wetterbericht des Meteorologischen Dienstes der DDR", Potsdam. A total of 36 major salt water inflows occurred during this time (cf. Fig. 1) forming the investigation period studied in this paper. The wind measurements were performed every 6 h on the weather station Arkona located at the northern tip of Rügen island. The instruments are attached at a mast 25 m above the ground and about 55 m above the sea level. Daily mean values of the wind vector have been calculated. The time series of daily wind vectors between 1950 and 1990 are the basic data for this study. The wind vector is considered to be a velocity vector. Hence, a positive east component of the wind means wind from west and a positive north component wind from south, respectively.

The spatial mean value of the Baltic sea level variations is fairly well represented by the sea level variations at Landsort tide gauge station (Lisitzin, 1974; Jacobsen, 1980). The daily means of the sea level at Landsort were calculated from hourly measurements. Landsort sea level record is subject to significant isostatic/eustatic sea level variations of about 30 cm during the present century. In order to remove this long-term variations the sea level record has been high pass filtered by subtracting the 5-year running mean from the original record. Signals with a time scale of about one month are not affected by the characteristic of the used filter.

3. Results

The time series of both the east and north components of the daily wind vectors are shown

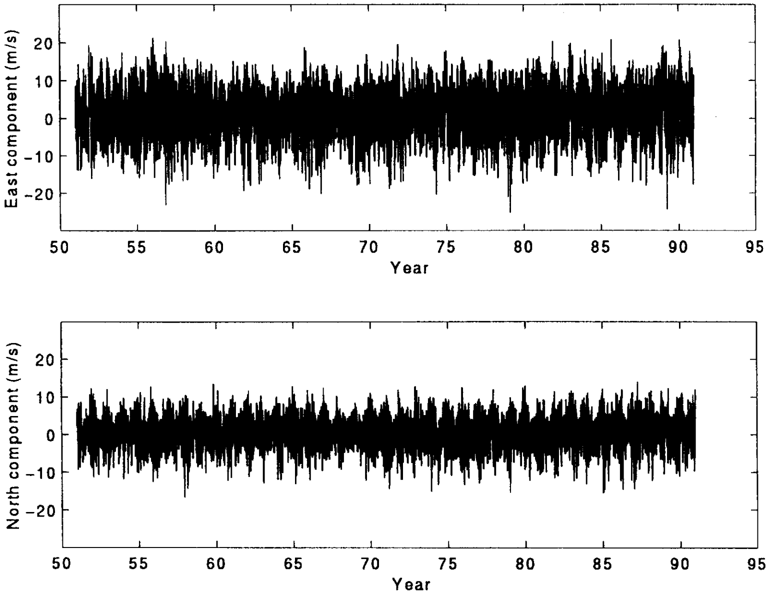

Fig. 2. Daily means of east (upper panel) and north component (lower panel) of wind at Arkona.

in Fig. 2. The mean values of the wind components taken over the whole time series are rather weak. But, the standard deviations (STD) are about 4 × larger (Table 1) than their corresponding mean values.

The mean yearly cycle of the east and north components has been estimated by calculating the mean and standard deviation (STD) for a given Julian day of the year from the ensemble of 40 years between 1951 and 1990. The results are shown in Fig. 3. The mean values of components are near zero during spring and summer and are about 2–3 m/s during autumn and winter. The east component has a phase of larger values in July. The standard deviations of both components reveal a well pronounced yearly cycle with high values in the winter season and low values in the summer season. This corresponds well with the observation of Matthäus and Franck (1992) that

Table 1. *Wind statistics at Arkona*

East component		North component	
Mean	STD	Mean	STD
1.5 m/s	5.9 m/s	0.8 m/s	3.7 m/s

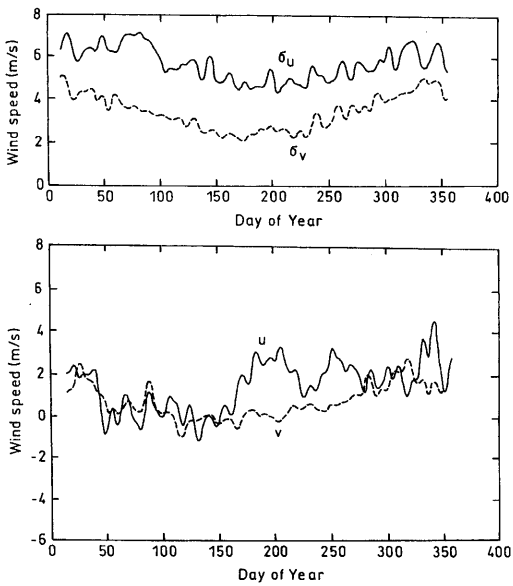

Fig. 3. Mean yearly cycle of standard deviations of east (sigma *u*) and north component (sigma *v*) (upper panel) and mean values of east (*u*) and north component (*v*) of the wind at Arkona (lower panel) between 1951 and 1990.

major salt water inflows occur only during the winter season. The time series of the wind (see Fig. 2) suggests that most of the wind variability is at a time scale of days. This is emphasized by the histogram of the zero crossings of both the time series of the north and the east components shown in Fig. 4. Zero crossing of the wind components after less than 5 days are rather typical whereas that of more than 10 days are rare events according to Fig. 4.

The lack of major salt water inflows between 1976 and the end of 1992 is according to our working hypothesis due to certain changes in the wind field on a time scale between 10 days and one to two months. This suggests to look for changes in statistical properties of the wind record at Arkona during two phases of different probability of inflow events. Firstly, a phase of a normal sequence of major salt water inflows occured during 1951 to 1976, and secondly a phase of reduced salt water inflows was observed during 1976 and 1992. But, there is no indication of a obvious change of the statistical properties in the time series of the wind components shown in Fig. 2 between both phases. Also, the power spectra of both phases (not shown here) have no significant differences as well.

A normalized two dimensional frequency distribution has been estimated in which the occurrence was counted how often a wind component lies between the values u and u + du without changing its sign in the time interval between the times t and $t + dt$. This two dimensional frequency distribution is shown for each component and the two phases in Fig. 5 and Fig. 6, respectively. The distribution has two different characteristic patterns. The pattern for wind durations less than 5 days is rather symmetrical with respect to the small positive value of the most likely value of both components, i.e., values larger and smaller than this value are equally likely. There are no significant differences beween both phases with respect to short durations of the wind components. The pattern for wind durations larger than 10 days has a remarkable asymmetry compared to wind of a few days duration. The most likely value of both, the east and north component of the winds has shifted to negative values. Moreover, the probability of both winds with long lasting negativ east and negativ north components are somewhat

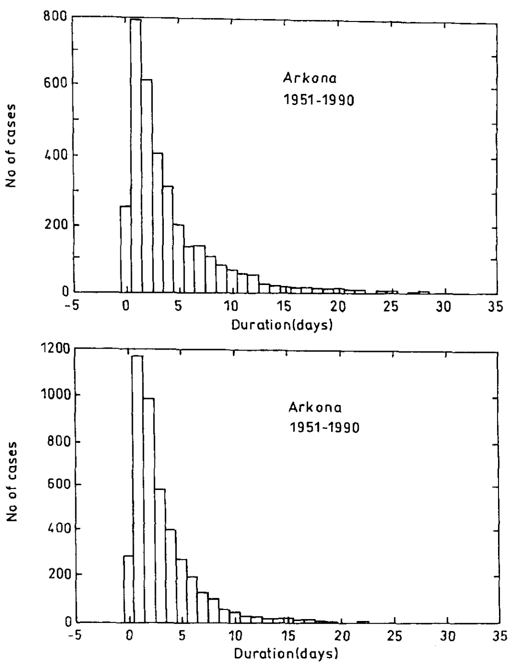

Fig. 4. Frequency distribution of the duration between two zero crossings of east (upper panel) and north (lower panel) component of wind at Arkona.

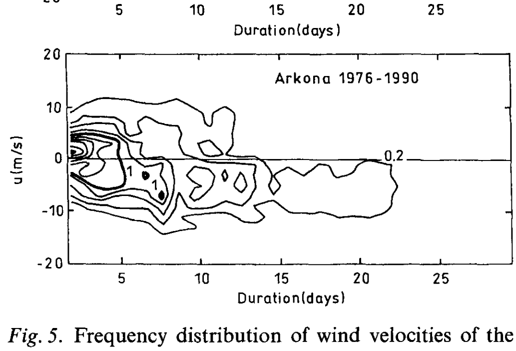

Fig. 5. Frequency distribution of wind velocities of the east component (u) at Arkona for a given duration between two zero crossings during a period of normal inflow activity (upper panel) and a period of reduced inflow events (lower panel).

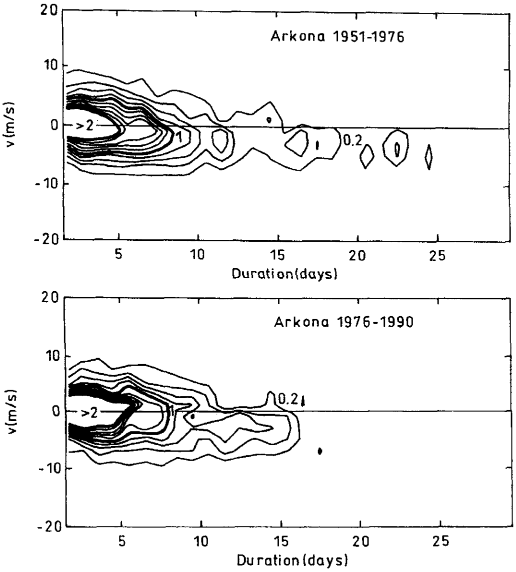

Fig. 6. Frequency distribution of wind velocities of the north component (v) at Arkona for a given duration between two zero crossings during a period of normal inflow activity (upper panel) and a period of reduced inflow events (lower panel).

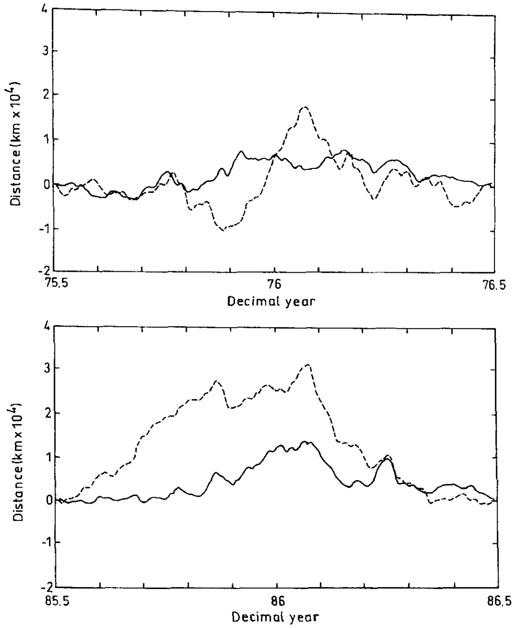

Fig. 7. Yearly pseudo wind track anomaly of east (dashed line) and north (full line) component of wind at Arkona in a year with MBIs (upper panel) and a year without MBIs (lower panel).

larger during the normal phase compared to the phase of reduced major salt water inflows.

In order to demonstrate the physical meaning of this result we have integrated the deviation of the wind component from its yearly mean with respect to time. The resulting pseudo particle track is depicted for a selected year with a major salt water inflow (1975–1976) and for a selected year without a major inflow (1985–1986) in Fig. 7, respectively. In the case of an inflow event an air particle moves in October westward and subsequently during November to January over vast distances eastward. This is a typical sequence of the pseudo path of an air particle during an inflow event. In the winter season of 1986 the air particle moved more or less steadily eastward from June 1985 to January 1986 and it moved steadily in westerly direction from January to end of May 1986. Hence, there seems to be a typical sequence of the east component of the wind in case of inflow events consisting of negative values of one month duration followed by positive values of about two months duration.

In order to demonstrate this with more statistical significance, two different yearly means of the wind components beginning from 1 July and ending at 30 June of the next year have been calculated. One yearly mean was calculated from the ensemble of all years without a major salt water inflow according to the criteria given by Matthäus and Franck (1992). A second weighted mean was calculated from the ensemble of all years with a major salt water inflow. The weight was proportional to the intensity index given by Matthäus and Franck (1992) and normalized by the sum of the intensities in the whole wind record. This scheme has been applied as well for both the wind components (Fig. 8) as for the sea level at Landsort (Fig. 9). The used scheme of ensemble averaging smears out the expected signal since the inflow events do not occur at the same time of the year. But, the inflow events are not of the same length, and they have no unique starting point. Hence, using the beginning of an inflow event for the ensemble averaging would smear out the signal as well.

The maximum of the east component of the wind occurs during early December without any significant difference between years with and with-

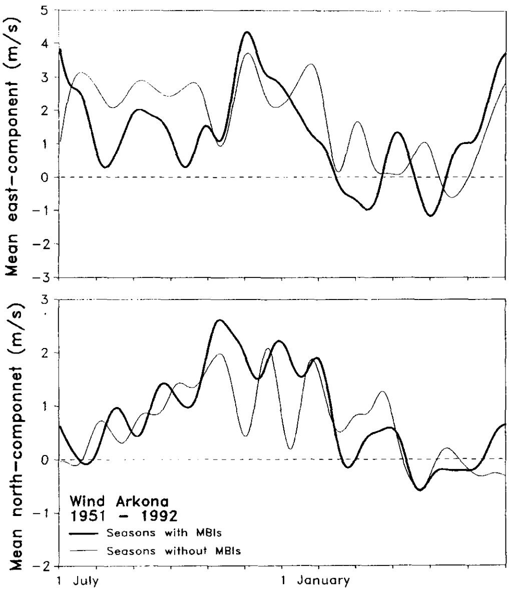

Fig. 8. Ensemble mean values of daily east (upper panel) and north component (lower panel) of wind at Arkona for seasons with and without MBIs. The values are low pass filtered with a cut-off period of 30 days.

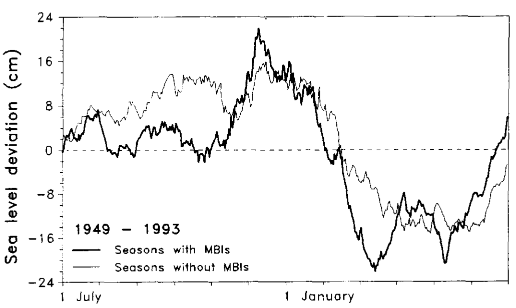

Fig. 9. Ensemble mean values of daily deviations from the 5-year running mean value of sea level at Landsort for seasons with and without MBIs.

out a major inflow event. Simultaneously, at this time of the year the north component is bigger in the ensemble with inflow events compared to the ensemble without inflow events. However, the most remarkable difference in the zonal component occurs in August to October, before the onset of maximum east component of the wind. During this time of the year, but in particular in October the wind has a significantly smaller east component (likelyhood more than 90% according to the t-test) in years with major salt water inflows compared to years without inflow events. This coincides with the two canonical sequences of mean Baltic sea level shown in Fig. 9. In case of an inflow event the mean Baltic sea level remains low until the phase of maximum east component of the wind starts in November. Subsequently, the sea level rises to a maximum value in early December. In contrast, during years without inflow events, the mean sea level starts to increase slowly already from July until it reaches its maximum value in early December. This increase is interrupted by a small gap in November which is due to the weakened east component of the wind at this time (Fig. 8). The sea level remains high until it descends from early February to early June. The mean sea level of the Baltic in October is different between both ensemble means with a likelyhood of more than 99% acccording to the *t*-test.

4. Discussion

Exceptionally few major salt water inflows into the Baltic Sea occurred between 1976 and the end of 1992. During this phase a significant loss of salt in the deep layer of the Gotland Basin with a simulaneously depletion of oxygen and increase of hydrogen sulphide was observed. It is argued that this lack of major salt water inflows was due to changes in the wind field over the North Sea and the Baltic Sea compared to the time interval before.

An analysis of daily wind vectors between 1951 and 1992 revealed no significant changes of the wind between both phases on time scales less than 5 days and more than one year. The probability of both negative north and negative east components of the wind with a duration of more than 10 days was slightly larger during the period of regular inflow events than during the period of reduced inflow from 1976 to 1992. A characteristic sequence of the zonal component of the wind during an inflow event consists of a one month phase of a negative east component subsequently followed by a 2-months phase of large positive values.

Indeed, the canonical yearly cycle of the wind components and the mean water level of the Baltic Sea in seasons with salt water inflows depict a weak zonal component during August to October associated with a low mean sea level. This is followed by an increase of the east component of the wind during November to its maximum at early December together with a rise of the mean sea level of the Baltic. In contrast, the canonical yearly cycle during seasons without inflow events lacks both the phase of weak east component of the wind in October and the corresponding lowering of the mean sea level. For the remaining part of the year the time sequence of the wind and the mean sea level have no significant differences. The physical meaning of the observations can be understood in the frame of the model of barotropic water exchange between a semi-enclosed sea and an ocean (Stigebrandt, 1983; Lass, 1988).

According to this model simulation, the barotropic current in the Belt Sea behaves like a band pass filter with maximum current velocity at a period of about 10 days to forcing by sea level variations in the Kattegat. If the zonal wind component increases slowly during more than 3 months beginning in July, as observed in years without inflow events, it causes only a sea level increase in the Kattegat which is smaller than the sea level increase in the Baltic caused by the fresh water surplus (about 8 cm/month). The net flow in the Danish Straits is directed to the Kattegat. Hence, only inflow of salt water as a dense bottom current is possible.

In years of salt water inflows, a sustained low value of the east component of the wind in October causes the Baltic sea level to drop. The following long lasting wind with large values of the east component force a sudden and sustained high sea level in the Kattegat, driving a strong barotropic inflow in the Belt Sea which exceeds the fresh water outflow by far. The inflow stops until the mean sea level of the Baltic is adjusted by the associated mass flow to the sea level of the Kattegat. If the increase of water volume of the Baltic Sea is larger than the volume of the channel consisting of the Great Belt, the Fehmarn Belt and the Mecklenburg Bight to the Darss Sill, the salty Kattegat water can be advected over the Darss Sill, into the Arkona Basin. Subsequently, the salt water flows into the Arkona Basin and ventilates the bottom layers there and in the connected deep basins.

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