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Long term couplings of winter index of North Atlantic oscillation and water level in the Baltic Sea and Kattegat

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ABSTRACT

The paper analyzes long-term time series of average winter local water level variations at 21 stations around the Baltic Sea and Kattegat. It is compared with the corresponding time series of winter index of North Atlantic Oscillation. The analysis of sea level revealed the presence of two patterns: the multi-decadal variations and an oscillation with the period of 8 years. Northern locations contained the glacial isostatic adjustment effect, which produced the isostatic sink that was observed in the southern part of the Baltic Sea. At some locations multi-decadal variations of sea level were free from those factors, which allowed determination of those variations with reasonable accuracy. The 8-year oscillation is very pronounced in the winter NAO series. It was detected at all mareographic stations, so significant part of sea level variability could be attributed to the impact of winter NAO. Further examination determined an amplitude threshold in the 8-year cycle of winter NAO for which the associated variations of sea level are temporally synchronized. This can serve as a criterion of assessment whether the Baltic Sea experiences an epoch of coupling to pressure fields from over the Atlantic or not; the analysis identified such epochs in the past.

1. Introduction

The Baltic Sea is a semi-enclosed, non-tidal basin with the area of 415,000 km^2 and the volume of 21,700 km^3 when Kattegat is included, see BACC (2008). Despite virtual isolation from the Atlantic Ocean it is highly dynamic, being strongly influenced by large-scale atmospheric circulation and hydrological processes. The restricted exchange of water due to the narrow connection with the North Sea produces a brackish environment, so the Baltic Sea is much less saline than the outer seas. The highest salinity is observed in the Danish Straits-near the North Sea connection, the lowest one is encountered in the northernmost part of Baltic Sea, in Bothnian Bay, which is situated furthermost from the North Sea.

The climate of the Baltic Sea is substantially affected by large-scale atmospheric pressure systems that control air flows over the region to a large extent: the Icelandic Low, the Azores High and the winter high/ summer low over Russia, BACC (2008). The parameter that contains information about the Icelandic Low and Azores High is known as the North Atlantic Oscillation (NAO) index. It is traditionally defined by the difference of normalized pressure between a station on the Azores and one on Iceland. Stykkisholmur (Iceland) is invariably used as the northern station, whereas either Ponta Delgada (Azores), Lisbon (Portugal) or Gibraltar are used as the southern station, (*cf.* Hurrell, 1995; Jones et al., 1997). A more recent and complex definition, related to numerical weather prediction, associates the NAO to the most significant empirical orthogonal function (EOF) of surface pressure. It is described in more detail in the NAO section.

Climate change in the North Atlantic, the North Sea and adjacent coasts was reported in a number of studies, (*e.g.* Carter and Draper, 1988; Grevemeyer et al., 2000). They find a strong association of NAO to wintertime variations of wave climate that extend up to the eastern part of the North Sea near Kattegat. Also, a non-trivial influence of the NAO on the elevation of tidal mudflats was reported in Bridgewater Bay, Bristol Channel, UK (Kirby and Kirby, 2008). It is also widely recognized that the long-term upward trend in wave climate near the end of the 20th century was coincident with the corresponding trend in NAO index. In general, dynamic links between the atmospheric patterns and wave climate variability have gained better understanding and are much better documented nowadays, (see *e.g.* Wolf and Woolf, 2006). Thus, studies on the influence of NAO on the more easterly located Baltic Sea is an appealing and timely task. First studies for the Baltic Sea region were focused on a feedback between the NAO and sea water levels. Johansson et al. (2001, 2004) found the relationship between the annual NAO index and the mean sea level near Helsinki, Finland. Andersson (2002) documented the coupling of the sea level data for Stockholm, Sweden and the winter NAO index. A significant correlation for the atmospheric

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circulation and sea level was also found for the Estonian coast, where higher westerly wind indices, including the NAO effects, were found responsible for higher sea levels, particularly during winters, Suursaar et al. (2006). Andersson (2002) and Janssen (2002) in studies on sea level variations found time-varying correlations, whose maxima occurred near the end of the examined time series: Andersson's 1825–1997 and Janssen's 1890–1993. They concluded that the growth of correlation indicates an increased potential of winter NAO index for controlling the regimes of physical processes in the Baltic Sea in winters. Różyński (2010) documented the impact of NAO in winter on shoreline evolution of a stable, sandy coastal segment in Poland. This impact was transferred through variations of wave energy supply to the shore, which also turned out to depend on NAO indices, particularly for January and to a less extent February.

The current study was inspired by the following facts. First, previous studies on sea water level variations were site-specific, but shared one common feature, *i.e.* they identified particularly strong relationships of sea water levels and winter NAO index. Second, Różyński (2010) pointed to high impact of winter wave climate on shoreline evolution, which was strong enough to remain imprinted through springs, summers and autumns for many years. Finally, the abundance of accurate long-term records of sea water levels for many locations on Baltic coast provided a logical opportunity for Baltic-wide screening of the long-term impact of winter NAO. This global goal could then be refined in order to establish a criterion indicating when the Baltic Sea basin is coupled to pressure fields generated over the Atlantic Ocean. Thus, epochs when sea water level variations in the Baltic Sea are coupled/de-coupled with the winter NAO indices could be identified.

The paper is organized in the following, standard order. First, data sets used in the analysis are presented and described. The NAO/winter NAO section contains information about the winter NAO data used in the study. Local water level data is tabulated including the locations (geographic coordinates of mareographic gauges) and time span of observations. Next, the applied time series analysis methodology is briefly recapitulated; it incorporates a succinct description of singular spectrum analysis (SSA) technique, which was applied to both the winter NAO and sea water level series. The next chapter contains the core data analysis and the search for couplings, identification of epochs of co-variability and periods of de-coupled evolution. Finally, the results are summarized by conclusions and recommendations for further research.

2. Data

The data on local sea water levels was provided by Permanent Service for Mean Sea Level (PSMSL). The data is publicly available at: http://www.psmsl.org/data/obtaining/psmsl.dat. All files have the revised level reference (Woordworth and Player, 2003). As the files contain mean monthly water levels, the average winter water level for a year n is referred to as $DJFM_n$ and can be obtained with the following equation:

$$DJFM_n = \frac{1}{121}(31\,Jan_n + 28\,Feb_n + 31\,Mar_n + 31\,Dec_{n-1}) \tag{1}$$

In this equation Jan_n, Feb_n, Mar_n and Dec_{n-1} are the mean values of local water level in months from which the mean winter sea level $DJFM_n$ is calculated. The names of mareographic stations, their geographic coordinates and time span of observations are jointly presented in Table 1, their locations on the Baltic Sea coast are also shown in Fig. 1.

The most accurate estimates of NAO index cover the measurements since January 1950. They are based on monthly mean standardized 500-mb height anomalies, obtained from the Climate Data Assimilation System for 20–90°N domain (see Barnston and Livezey, 1987). Although this procedure provides high precision value of the NAO index for each month, it could not be used for pre-1950 water level data and traditional, station-based NAO data had to be used. It originates from normalized sea level pressure measurements (SLP) at Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland for a period ranging from 1864 till 2009 – a much longer period than the data from the Climate Data Assimilation System. The winter index

Table 1
Baltic Sea water level stations used in analysis.

Area	Station	Country	Longitude (E)	Latitude (N)	Obs. period
Bothnian Bay	Oulu	Finland	25.4167	65.0333	1890–2007
	Ratan	Sweden	20.9167	64.0000	1893–2007
	Vaasa	Finland	21.5667	63.1000	1884–2007
	Helsinki	Finland	24.9667	60.1500	1880–2007
	Hanko	Finland	22.9833	59.8167	1888–1997
	Stockholm	Sweden	18.0833	59.3167	1890–2007
Baltic proper	Landsort	Sweden	17.8667	58.7500	1888–2007
	Olands Norra	Sweden	17.1000	57.3667	1888–2007
	Kungsholmsfort	Sweden	15.5833	56.1000	1888–2007
Western Baltic	Świnoujście	Poland	14.2333	53.9167	1811–1999
	Warnemünde	Germany	12.0833	54.1833	1856–2007
	Wismar	Germany	11.4667	53.9000	1849–2007
	Gedser	Denmark	11.9333	54.5667	1899–2006
Danish Straits	Copenhagen	Denmark	12.6000	55.6833	1890–2006
	Fredericia	Denmark	9.7667	55.5667	1890–2006
	Slipshavn	Denmark	10.8333	55.2833	1897–2006
	Korsor	Denmark	11.1333	55.3333	1898–2006
Kattegat	Göteborg	Sweden	11.9500	57.7167	1888–2007
	Frederikshavn	Denmark	10.5667	57.4333	1895–2006
	Hornbaek	Denmark	12.4667	56.1000	1899–2006
	Aarhus	Denmark	10.2167	56.1500	1889–2006