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CAVIAR: Climate variability of the Baltic Sea area and the response of the general circulation of the Baltic Sea to climate variability

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Abstract

The warming trend for the entire globe (1850-2005) is 0.04°C per decade. A specific warming period started around 1980 and continues at least until 2005, with a temperature increase of about 0.17°C per decade. This trend is equally well evident for many areas on the globe, especially on the northern hemisphere in observations and climate simulations. For the Baltic Sea catchment, which lies between maritime temperate and continental sub-Arctic climate zones, an even stronger warming of about 0.4°C per decade appeared since 1980. The annual mean air temperature increased by about 1°C until 2004. A similar warming trend could be observed for the sea surface temperature of the Baltic Sea. Even the annual mean water temperatures averaged spatially and vertically for the deep basins of the Baltic Sea show similar trends. We provide a detailed analysis of the climate variability and associated changes in the Baltic Sea catchment area as well as in the Baltic Sea itself for the period 1958-2009, in which the recent acceleration of the climate warming happened. Changes in the atmospheric conditions causes corresponding changes in the Baltic Sea, not only for temperature and salinity but also for currents and circulation. These changes in the physical conditions have strong impact on the marine ecosystem structure and processes.

Introduction

The warming trend for the entire globe (1850-2005) is 0.04°C per decade. A specific warming period started around 1980 and continues at least until 2005, with a temperature increase of about 0.17°C per decade. This trend is equally well evident for many areas on the globe, especially on the northern hemisphere in observations and climate simulations [Trenberth et al 2007]. For the Baltic Sea catchment (Fig. 1), which lies between maritime temperate and continental sub-Arctic climate zones, an even stronger warming of about 0.4°C per decade appeared since 1980.

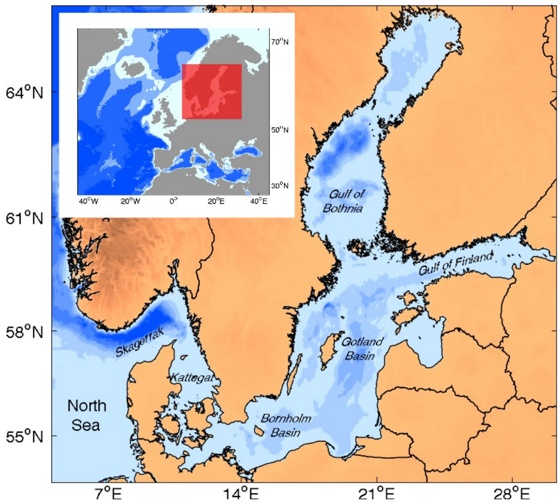

Figure 1: General map of the Baltic Sea area with additional wiser map of the north-east Atlantic/European area.

The annual mean air temperature increased by about 1°C until 2004. A similar warming trend could be observed for the sea surface temperature of the Baltic Sea. Even the annual mean water temperatures averaged spatially and vertically for the deep basins of the Baltic Sea show similar trends. A detailed assessment of climate variability of the Baltic Sea area for the period 1958-2009 [Lehmann et al 2010] revealed that the recent changes in the warming trend s ince the mid-1980s, are associated with changes in the large-scale atmospheric circulation over the North Atlantic. The analysis of winter sea level pressure (SLP) data highlighted considerable changes in the number and pathways of deep cyclones (<980 hPa) in parallel with the eastward shift of the North Atlantic Oscillation (NAO) centres of action. Additionally, a seasonal shift of strong wind events from autumn to winter and early spring exists for the Baltic area. Lehmann et al [2002] showed that different atmospheric climate regimes force different circulation regimes in the Baltic Sea. Furthermore, as climate, to a large extent, controls patterns of water circulation and biophysical aspects relevant for biological production, such as the vertical distribution of temperature and salinity, alterations in climate may severely impact the trophic structure and functioning of marine food webs [Hinrichsen et al 2007]. To understand the processes linking changes in the marine environment and climate variability, it is essential to investigate all components of the climate system. Here we focus on the link between changes/shifts in the atmospheric conditions and their impact on the general circulation of the Baltic Sea, which is derived from 3-dimensional numerical model simulations using the Kiel Baltic Sea Ice Ocean Model [Lehmann 1995; Lehmann et al 2002]. These changes in the physical conditions of the Baltic Sea have strong impacts on the marine ecosystem structure and processes.

Changes in contribution of dominant atmospheric regimes

Following the work of Hurrel & Deser [2009] the clustering algorithm was applied over the North atlantic domain (80°W-30°E, 20°N-80°N) identifying four winter climate regimes in SLP (Fig. 2). Hurrel & Deser [2009] pointed out that two of the climate regimes correspond to the positive and negative phases of the NAO, while the third and fourth regimes display strong anticyclonic ridges over Scandinavia (the 'Blocking' regime) and off western Europe (the 'Atlantic Ridge' regime). For the period 1949-2008 all four regimes occur with about the same frequency between 23% and 26%. Lehmann et al [2010] highlighted a change in the contribution of dominant regimes for consecutive 20-year periods using cluster analysis of winter (DJFM) daily SLP data.

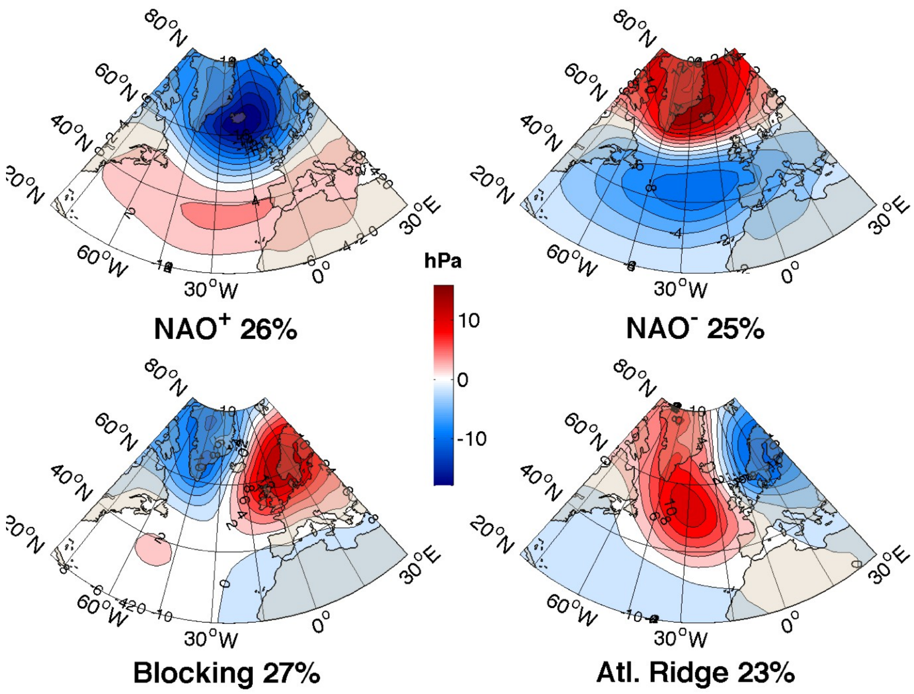

Figure 2: Winter (DJFM) climate regimes in SLP over the North Atlantic domain (80°W-30°E, 20°N-80°N) using daily data over the period 1949-2008. The percentage of each panel expresses the frequency of occurrence of a cluster out of all winter days since 1949. Contour interval is 2 hPa.

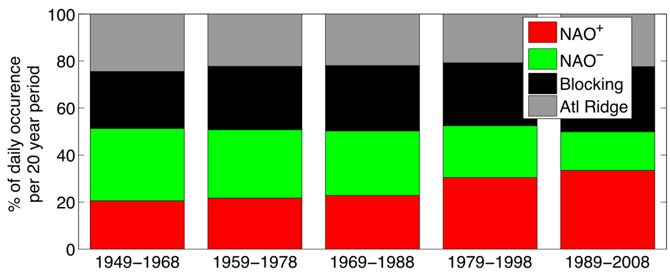

Figure 3: Contribution [%] of occurrence of dominant climate winter regimes NAO+, NAO-, Blocking and Atlantic Ridge, in different 20-year periods (P1: 1948-1968, P2: 1958-1978, P3: 1968-1988, P4: 1978-1998, P5: 1988-2008) identified by cluster analysis using daily winter (DJFM) sea level pressure anomalies from NCEP/NCAR reanalysis data (1948-2008).

The total contribution of the 'Blocking' and 'Atlantic Ridge' pattern is between 48-50% and the total contribution of the NAO pattern is between 50-52%. However, the relative contributions of the two NAO pattern are different for consecutive 20-year periods (Fig. 3). For the periods 1948-1968, 1958-1978 and 1968-1988 the NAO^- pattern is prevailing, whereas the most recent periods 1978-1998 and 1988-2008 show an increased contribution of the NAO^+ pattern. In accordance to the increased NAO^+ contribution together with the shift in strong wind events and the change in prevailing wind directions [Lehmann et al 2010], a shift in detrended monthly mean sea level anomalies can be observed for the periods 1970-1988 and 1989-2008 (Fig. 4). This seasonal change between both periods is also represented in numerical model simulations of the same period. It is important to note that the shift in monthly mean sea level anomalies occurs unidirectional over the whole Baltic Sea. This suggests a change in prevailing westerly wind situations controlling mean sea level variations. These results confirm findings of recent studies, such as Lehmann & Hinrichsen [2001] or Johansson et al [2004], that used historical sea level time series to demonstrate the key role played by winter climate, especially that of wind forcing. Lehmann et al [2002] showed that a change of the local atmospheric index (Baltic Sea Index) to positive phases results in a decrease of outflow accompanied by an increase in mean sea level due to the freshwater surplus. Consequently, a change to more frequent and more pronounced winter NAO^+ patterns would change the structure of the general circulation in the Baltic Sea.

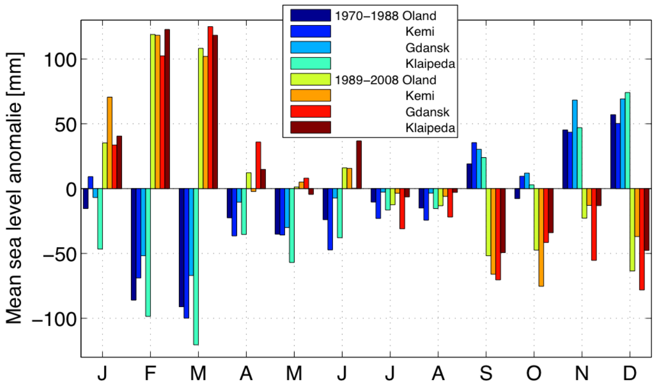

Figure 4: Detrended sea level anomalies taken from tide gauge records from the Permanent Service of Mean Sea Level data (PSMSL, maintained by the POL) for all months calculated for the periods 1970-1988 (blue-green) and 1989-2008 (yellow-red) at representative stations around the Baltic Sea.

This seasonal change between both periods is also represented in numerical model simulations of the same period. It is important to note that the shift in monthly mean sea level anomalies occurs unidirectional over the whole Baltic Sea. This suggests a change in prevailing westerly wind situations controlling mean sea level variations. These results confirm findings of recent studies, such as Lehmann & Hinrichsen [2001] or Johansson et al [2004], that used historical sea level time series to demonstrate the key role played by winter climate, especially that of wind forcing. Lehmann et al [2002] showed that a change of the local atmospheric index (Baltic Sea Index) to positive phases results in a decrease of outflow accompanied by an increase in mean sea level due to the freshwater surplus. Consequently, a change to more frequent and more pronounced winter NAO $^{+}$ patterns would change the structure of the general circulation in the Baltic Sea.

Variability within dominant regimes

Hurrel & Deser [2009] concluded from cluster analysis that there exists a large amount of within-season variance in the atmospheric circulation of the North Atlantic and that most winters are not dominated by any particular regime alone. Comparing the time history of occurrence of the four dominant atmospheric regimes with seasonal and monthly resolution confirms these findings (Fig. 5) where the two NAO regimes show larger variability than the 'Blocking' and 'Atlantic Ridge' regime.

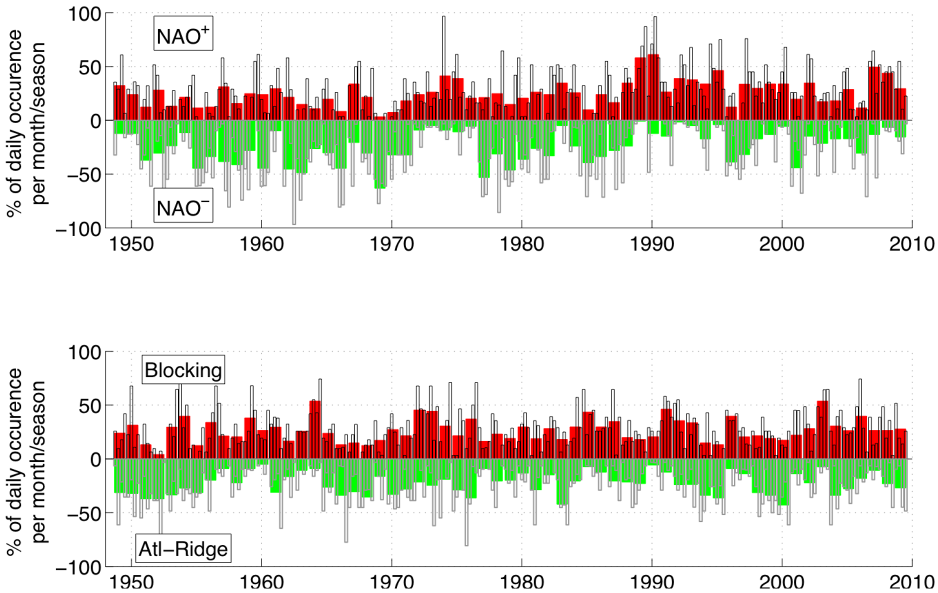

Figure 5: Time history of occurrence of the NAO, Atlantic Ridge and Blocking regimes (cf. Hurrel & Deser [2009]) over the period 1949-2009. Vertical bars give the number of daily occurrence per season (filled bars) / per month (contoured bars) during winter (DJFM) for the given regime.

This within-season variability seems to be important for the detection of characteristic circulation pattern in the Baltic Sea connected to a given dominant atmospheric regime. The temporally higher resolved time history plot gives the possibility to identify winter months with a distinct NAO + contribution, here we selected 3 individual winter months with more than 85% of daily occurrence per month. From the numerical model simulations of the period 1970-2008 it is now possible to derive the stream function and streamlines for these individual NAO+ dominated months (Fig. 6). The examples highlight different circulation patterns than the generally known broad cyclonic circulation. The connection of the circulation patterns to the prevailing wind situation becomes clear.

The first example (January 1974) shows strong south-westerly winds, resulting in a weak (about 0.2 Sv) and small cyclonic circulation pattern in the eastern central Baltic Sea, whereas along the Swedish coast and into the Gulf of Finland a broad and relative strong anticyclonic circulation pattern exist. The situation in the second example (March 1989) is slightly different, with somewhat weaker but more westerly orientated prevailing wind direction. The response of the circulation shows an intensified cyclonic gyre (about 0.4 Sv) in the central Baltic Sea, while the anticyclonic circulation is somewhat more narrowed along the southern part of the Swedish coast but extends further into the basin of the Bothnian Sea. The third example (February 1990) highlights very strong winds from the west and north-west, resulting in a strong cyclonic gyre in the central Baltic Sea (more than 0.5 Sv) and a weak and narrow anticyclonic circulation along the southern Swedish coast and into the Gulf of Finland. Concluding it is to say that there is no unique general circulation pattern that can be attributed to a NAO^+ regime. The circulation patterns heavily depend on the direction and strength of the prevailing winds. Strong westerly and north-westerly winds force a strong Ekman drift at the surface to the east or north-east, generate a strong cyclonic gyre in the central Baltic Sea, while south-westerly winds generate a broad and relatively strong counter circulation along the Swedish coast and a weak cyclonic gyre in the centre. These situations lead to changes in up- and downwelling along the coasts and in the deep basins.

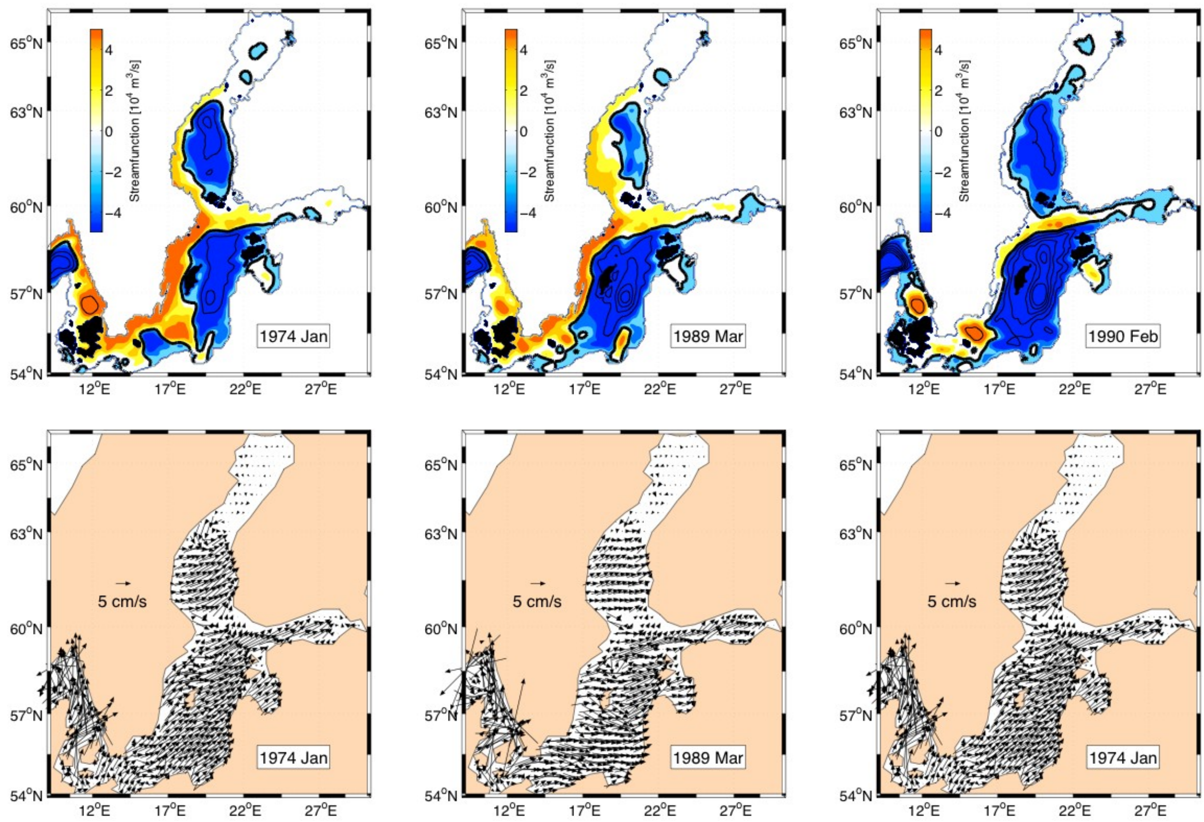

Figure 6: Stream function (top panel) and streamlines (bottom panel) representation of the average barotropic circulation for January 1974 (left), March 1989 (middle) and February 1990 (right) derived from numerical model output for dominant NAO^+ pattern Contour interval for the stream function is 0.1 Sv.

The comparison of the mean winter (DJFM) circulation pattern for the periods 1970-1988 and 1989-2008 highlights that for the later period an intensified cyclonic circulation exists in the central Baltic Sea, which is comparable to the example of February 1990, while for the first period the resulting circulation pattern is most similar to March 1989 (Fig. 6). Further analysis is needed to clearly separate the effects of different atmospheric regimes on the circulation pattern in the Baltic Sea, especially the influence/contribution of the 'Blocking' and 'Atlantic Ridge' regimes could be of importance.

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