Polar vortex controls coupling of North Atlantic Ocean and atmosphere

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[1] The structure of the North Atlantic leading atmospheric winter variability mode strongly depends on the state of the polar stratospheric vortex. If the polar vortex is strong, one teleconnection pattern emerges in the upper troposphere, while two mostly independent ones appear when the vortex is weak. The anomaly patterns associated with the different polarities of these modes show strong differences in the wind fields and in the correlation of atmospheric variability with the sea surface temperature of the North Atlantic. Only when the polar vortex is strong, does a basin-wide tripole correlation pattern exist between tropospheric variability and sea surface temperature. Under weak vortex conditions one of the variability modes correlates with the subtropical, the other with the subpolar gyre. These results suggest that a NAO index based on near surface pressure that fails to account for the state of the polar vortex is a suboptimal representation of the tropospheric circulation variability.
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1. Introduction

[2] The North Atlantic Oscillation (NAO) [*Hurrell*, 1995; *Hurrell et al.*, 2003] dominates atmospheric circulation and climate over the North Atlantic (NA) and adjacent regions to a large degree. NAO is an inherent barotropic variability mode, mainly of the troposphere, and with a life cycle of approximately two weeks. It is driven by the interaction of baroclinic synoptic and planetary waves [*Feldstein*, 2003]. Several studies [e.g., *Baldwin and Dunkerton*, 2001; *Perlwitz and Graf*, 1995, 2001] showed that the polarity of the NAO index in winter depends on the state of the stratospheric polar vortex. Wind anomalies associated with the strength of the polar vortex extend to the upper troposphere [*Christiansen*, 2003]. Upper tropospheric wind shear influences the preferred area of growth of baroclinic eddies and, therefore, of storm tracks. Hence, changes in polar vortex regimes over time will lead to changes in the variability structure of the NAO [*Castanheira and Graf*, 2003; *Perlwitz et al.*, 2000].

[3] Another way of looking at atmospheric variability is the concept of the Arctic Oscillation (AO, based on surface pressure) or the Northern Annular Mode (NAM, including higher atmospheric layers) introduced by *Thompson and Wallace* [1998]. These are based on EOF analysis and stress zonally symmetric variability. *Castanheira and Graf* [2003] concluded that the structure of the AO results from regime shifts of the stratospheric polar vortex and does not by itself represent a physical mode [*Castanheira et al.*, 2002].

[4] Since AO/NAM indices are highly correlated with NAO, statistical analyses in many cases show similar results for NAO or AO/NAM indices. In particular, large anomalies of the strength of the northern polar vortex descending to the lower stratosphere are followed by anomalous circulation and weather regimes in the troposphere, which resemble the features of the NAM [*Baldwin and Dunkerton*, 1999, 2001; *Thompson et al.*, 2002].

[5] Atmospheric circulation can influence the ocean by changing surface fluxes of heat, momentum and fresh water on an inter-annual to decadal time scale [*Cayan*, 1992; *Kushnir*, 1994]. The index of the NAO is related to the field of sea surface temperatures (SST) of the NA [*Bjerknes*, 1964] and the correlation between the NAO index and SST typically exhibits a tripole pattern reaching from the (sub) tropics to (sub) polar latitudes [*Kushnir*, 1994; *Deser and Blackmon*, 1993]. These observational results are supported by studies with coupled ocean-atmosphere models, which have suggested that decadal cycles in the subtropical gyre of the NA can be generated [*Groetzner et al.*, 1998] by changes in atmospheric circulation. Even the thermohaline circulation, one of the main drivers of the Gulf Stream, can be influenced by such changes [*Timmermann et al.*, 1998; *Delworth and Dixon*, 2000]. In observations [*Walter and Graf*, 2002], as well as in coupled Ocean Atmosphere models [*Raible et al.*, 2001], multi-decadal regimes were identified when NA SST was either correlated to global tropical geopotential heights or to NAO-type structures. The reasons for these changes in the correlation patterns are unclear.

[6] Since (multi-) decadal regime shifts of the strength of the winter polar stratospheric vortex have been observed [*Christiansen*, 2003; *Perlwitz and Graf*, 1995] and have also been detected in a 600-year control run of an ocean-atmosphere coupled model without any external forcing [*Feser et al.*, 2000], it is of interest to study how changes in the structure of the NA leading atmospheric variability mode, which are influenced by the stratospheric polar vortex, lead to changed correlation between the index of tropospheric variability and NA SST.

2. Data and Methods

[7] We used reanalysis data of geopotential height and SST from the National Centres for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) for the winter months December to March from 1958 to 1998. The annual cycle and trends have been removed. The reanalysis data provide fairly accurate information in

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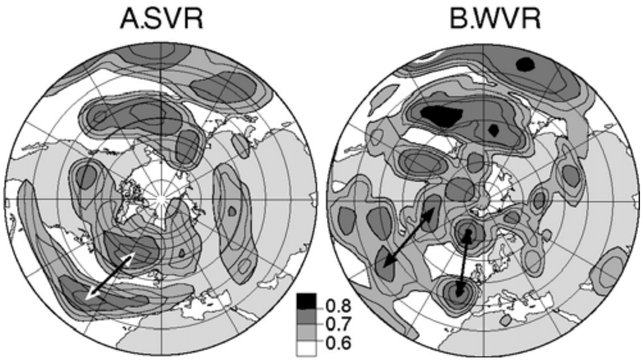

Figure 1. Teleconnectivity for monthly mean 300 hPa geopotential height for (left) strong polar vortex regime (SVR) and (right) weak polar vortex regime (WVR). Only values above 0.6 are shown. Isoline interval is 0.05. The arrows indicate the location of the teleconnections.

the northern extra-tropics, and also in the upper troposphere [*Kistler et al.*, 2001]. We adopted thresholds of >20 m/s at 65°N and 50 hPa for the strong (SVR) and <10 m/s for the weak (WVR) polar vortex regime [*Castanheira and Graf*, 2003] and defined 71 months as SVR and 32 months as WVR. Results in this study are mainly based on monthly anomalies, which reflect a time scale of stratospheric variability of several weeks [*Baldwin and Dunkerton*, 2001] rather than the tropospheric NAO time scale of two weeks [*Feldstein*, 2003].

[8] We performed a teleconnectivity analysis (TA) [*Wallace and Gutzler*, 1981] for the upper troposphere (300 hPa) geopotential height fields separately for strong (SVR) and weak (WVR) stratospheric polar vortex regimes. TA is a search algorithm where the maximum negative correlation between a given data point and all other points in a field is identified. Doing this for all data points of a field, a "pattern of teleconnectivity" emerges. Centres of maximum teleconnectivity are potential teleconnections. The teleconnection over the Pacific resembles the Pacific North America (PNA) pattern. Since its structure does not change between the polar vortex regimes we will not discuss this here.

[9] In the SVR, there are two zonally elongated areas of strong teleconnectivity over much of the North Atlantic (Figure 1, left). Their centres are located southeast of Greenland and in the subtropical central North Atlantic, respectively (NA-SVR pattern in the following). In the WVR there are two meridionally oriented dipole patterns (Figure 1, right). All teleconnections describe clearly separated dipole patterns over the NA when the correlation fields are computed (not shown here). The western NA-WVR pattern comprises centres of action over northeastern Canada and over the western part of the subtropical North Atlantic. The eastern NA-WVR pattern is found with centres of action northwest of Iceland/east of Greenland and just west of the Iberian Peninsula. Eastern and western NA teleconnection patterns were also identified by *Wallace and Gutzler* [1981] and were separated by *Barnston and Livezey* [1987] using rotated EOF analysis of geopotential height fields. In neither study was separation used for strong and weak vortex. Index time series were constructed for the eastern (65°–70°N, 27.5°–35°W and 37.5°–40°N, 15°–22.5°W) and western (62.5°–65°N, 77.5°–82.5°W and 35°–37.5°N, 55°–62.5°W) NA-WVR patterns, and for NA-SVR (55°–60°N, 30°–45°W and 30°–35°N, 35°–45°W) using the difference of normalized geopotential height anomalies at the southern and northern centres of action of the respective teleconnection pattern. The eastern NA-WVR index is highly correlated (0.91) with the classical NAO index, but the western NA-WVR and NA-SVR indexes are much less well correlated (0.62 and 0.74, respectively). Eastern and western NA-WVR indices are only marginally correlated (0.18) and, thus, both can be seen as describing linearly independent processes [see also *Barnston and Livezey*, 1987].

3. Results and Discussion

[10] Composite anomalies of the wind fields at the 850-hPa level are shown in Figure 2 for both polarities of the three indices. Only those months were included when the index exceeds +(−) 0.5 standard deviations from the long term mean, leaving 11(10) months for each WVR and 26(24) for the SVR. Very clear differences appear between the SVR and WVR composites. In WVR differences in

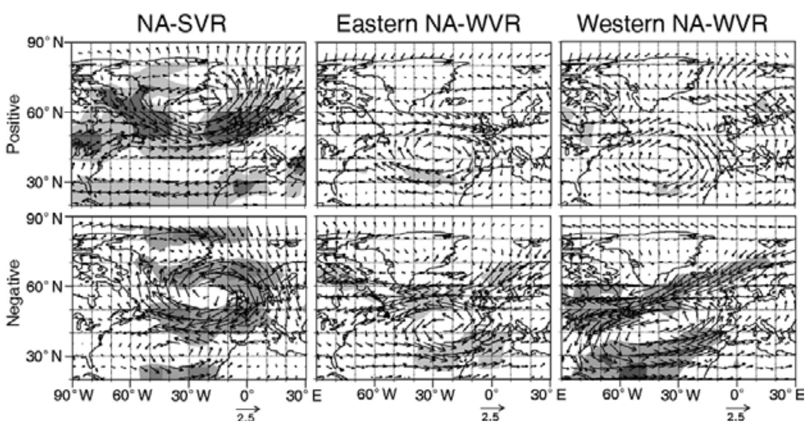

Figure 2. Composite anomalies for the wind anomaly (from the 1958–1998 mean) at 850 hPa for the positive (top) and negative (bottom) phase of NA-SVR (left), eastern NA-WVR (middle) and western NA-WVR teleconnection indices exceeding 0.5 standard deviations. Shadings indicate anomalies above the 95% (light) and 99% (dark) significance level according to a *t*-test. Arrows at the bottom of Figure 2 indicate wind anomalies of 2.5 m/s.

winds around the Azores high with anti-cyclonic (cyclonic) flow anomalies evolve for the positive (negative) polarity of the index. The centre of the flow anomaly is further to the west for the western NA-WVR composite. Stronger (weaker) westerlies occur between 50° and 60°N. These anomalous winds reach Western Europe only for the eastern NA-WVR. The wind anomalies are rather large and can reach well above 5 m/s. Flow around the Icelandic low is not much affected by the NA-WVR. For the western NA-WVR negative polarity composites the strong cyclonic flow anomaly stretches over the whole NA.

[11] The composites for the two polarities of the NA-SVR index have a completely different structure. While for the positive polarity westerlies are enhanced over the NA between 40° and 60°N, these anomalies result from stronger cyclonic flow around the Icelandic low with its centre just southwest of Iceland. Anomalously strong northwesterly winds blow from the Davis Strait into the central Atlantic and continue as south-westerlies over northwest Europe. In the negative phase of the NA-SVR both centres of action of the NAO seem to play a minor role. Wind anomalies in the subtropical Atlantic suggest a weaker than normal and southward displaced Azores High. The prominent wind anomaly is strong anti-cyclonic flow over the eastern NA with a centre at 20°W, 55°N. This indicates a blocking high situation, which cannot be captured with a standard NAO analysis without separating between the stratospheric regimes. It also implies storm tracks, which extend far to the north over the central Atlantic and from there towards North Europe, while from a standard NAO analysis one would expect a storm track towards southwest Europe and the Mediterranean [*Walter and Graf*, 2004]. These differences of the variability patterns are significant enough to suggest an impact of stratospheric regimes on ocean-atmosphere coupling.

[12] The monthly to seasonal correlations between NA SST and the atmosphere are strongest when the atmosphere leads by about one month [*Deser and Timlin*, 1997]. In Figure 3 the correlation patterns between the three new upper-tropospheric NAO indices and the NA SST are shown for periods with the respective regimes (WVR and SVR) for the years 1958–98. In addition a "classic" NAO (Figure 3a) was used with geopotential height differences of the 1000 hPa level between (62.5°–67.5°N, 17.5°–22.5°W) and (32.5°–37.5°N, 22.5°–27.5°W). Here no differentiation was made between the stratospheric regimes. The tripole correlation pattern known from previous studies [*Bjerknes*, 1964; *Kushnir*, 1994; *Deser and Blackmon*, 1993] is obvious for all indices. However, strong differences are evident as well. The weakest absolute correlation (well below 0.4) is found between the NA SST field and a "classic" NAO. The area with a positive correlation between 20° and 40°N is mainly confined to the western North Atlantic for the western NA-WVR and NA-SVR patterns, whereas, for the eastern NA-WVR pattern, the maximum correlation is in the central to eastern North Atlantic. The negative correlation in the mid-latitude to sub-polar North Atlantic between 40° and 60°N, associated with large anomalies in near-surface wind over the Labrador Sea and the midlatitude North Atlantic (Figure 2), is more clearly defined by the NA-SVR pattern than for the two NA-WVR patterns. Fluctuations of the NA-SVR pattern index are therefore related to strong anomalous advection of either cold air from the Labrador Sea region or warmer maritime air from the (south-) east. The negative correlation in the tropical North Atlantic is much stronger for the western NA-WVR pattern (maximum about −0.6) and the NA-SVR pattern (maximum about −0.4) than for the eastern NA-WVR pattern. The correlation in the latter case does not even exceed the 95% significance level.

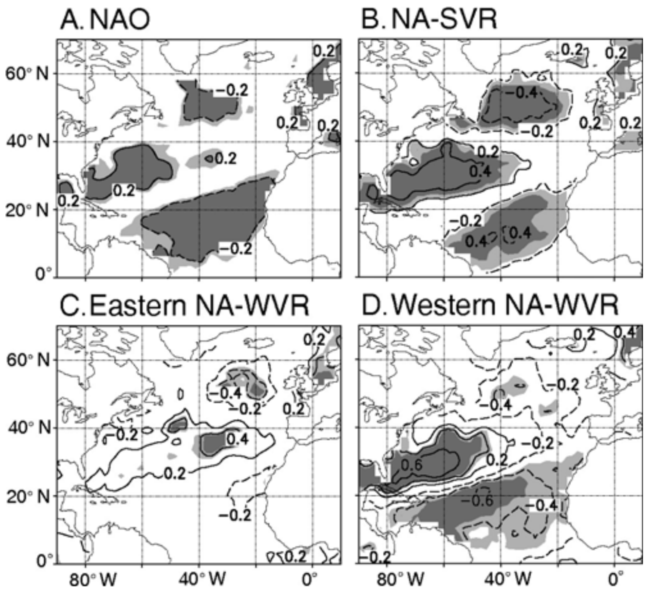

Figure 3. Lagged correlation between (a) "classic" NAO, (b) NA-SVR, (c) eastern NA-WVR and (d) western NA-WVR indices and North Atlantic sea surface temperature. Teleconnection indices lead the SST by one month. Isoline interval is 0.2 and zero contours are omitted. Shadings indicate statistical significance above the 95% (light) and 99% (dark) level.

4. Conclusions

[13] Our conclusions from the above analysis are (i) that the state of the polar stratospheric vortex has an important effect on the horizontal structure of the main NA tropospheric variability mode, and (ii) that the structural change affects the coupling between atmosphere and ocean. If the polar vortex is strong, one single teleconnection emerges over the central NA. This teleconnection is associated with large wind anomalies over the northern part of the NA. Circulation varies from strong cyclonic in the positive phase (deep Icelandic low) to anticyclonic in the negative phase (blocking high over the northeast Atlantic). If the polar vortex is weak, two teleconnection patterns exist which are only weakly coupled. Both WVR teleconnections are associated mainly with the wind field of the subtropical high. If the index is positive, the anticyclonic circulation is stronger, if it is negative, it is weaker. Only during periods of strong stratospheric vortex does the tropospheric variability mode reveal a clear tripole correlation pattern with NA SST, while the eastern NA-WVR index mainly correlates to the sub polar gyre and the western NA-WVR index to the sub tropic gyre. The ensembles used to calculate the above correlations are rather small due to the short time series of available data

and are to be taken with caution. However, supporting results were found in a coupled ocean atmosphere model [*Raible et al.*, 2001] and using 100 years of surface observations [*Walter and Graf*, 2002].

[14] Our results show that it is important to consider the role of the polar vortex in winter in process studies of atmospheric variability and also of ocean atmosphere coupling. An interesting question will be if the western NA-WVR teleconnection provides the atmospheric link between tropical Pacific and Atlantic SST variability. Coupled ocean-atmosphere models should be examined to ascertain whether they reproduce the observational relationships shown here.

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