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Article

Decadal cyclone variability in the North Atlantic

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Abstract

The unstable midlatitude ocean-atmosphere coupling motivates the definition of two decadal regimes with distinct implications for the North Atlantic cyclone variability. Phases with low (high) decadal variability of the North Atlantic Oscillation, which are connected with an annular (sectoral) spatial scale of the geopotential height teleconnection pattern, are identified as a hemispheric (regional) regime. In the hemispheric regime during a positive El Niño/Southern Oscillation (ENSO) index (warm event), the North Atlantic cyclones and the regions of enhanced precipitation shift southward while over northern Europe the cyclone activity and the rainfall are reduced. During the regional regime this impact of ENSO on the Atlantic storm track is extremely small and a clear interpretation over Europe is inhibited.

Zusammenfassung

Die instabile Atmosphäre-Ozean-Wechselwirkung in den mittleren Breiten begründet die Definition zweier dekadischer Regime mit charakteristischen Auswirkungen auf die Variabilität der nordatlantischen zyklonalen Aktivität. Phasen mit niedriger (hoher) dekadischer Variabilität der Nordatlantischen Oszillation, die mit annularen (sektoralen) räumlichen Skalen der Geopotential-Telekonnektionsmuster zusammenhängen, werden als hemisphärische (regionale) Regime identifiziert. Im hemisphärischen Regime bei einem positiven El Niño/Southern Oscillation (ENSO) Index (Warmereignis) verschieben sich die nordatlantischen Zyklonen und die Regionen erhöhten Niederschlags südwärts, während die zyklonale Aktivität und der Niederschlag über Nordeuropa reduziert sind. Im regionalen Regime ist der ENSO-Einfluss auf den nordatlantischen Stormtrack sehr schwach und eine eindeutige Interpretation über Europa nicht möglich.

1 Introduction

The state of the atmospheric circulation can be described by teleconnection indices (WALLACE and GUTZLER, 1981; BARNSTON and LIVEZEY, 1987) which refer to recurring and persistent large-scale patterns of pressure and circulation anomalies. Some of these patterns, e.g., the Pacific-North American (PNA) pattern, are related to the El Niño/Southern Oscillation (ENSO). In the North Atlantic the preferred mode of low-frequency can be considered from two different aspects: The Northern hemispheric Annular Mode (NAM) or Arctic Oscillation (AO) illustrates a coupling between the Atlantic and Pacific region describing a hemisphere mode (WALLACE and THOMPSON, 2002b) whereas the North Atlantic Oscillation (NAO) favours a regional prospect (BJERKNES, 1964).

The NAO or regional (sectoral) view on the Atlantic region suggests that the atmosphere is leading the ocean on short times, while the ocean is leading on times scales beyond one year (BJERKNES, 1964). A positive feedback between the Atlantic sea surface temperature (SST) and NAO has been identified in observations (CZAJA and FRANKIGNOUL, 2002) and in coupled atmosphere-ocean general circulation model (AOGCM) experiments (GRÖTZNER et al., 1998). The NAO is connected with an Atlantic SST tripole as described by WU and GORDON (2002). The transient-eddy fluxes in the storm track are important for the atmospheric response (PENG et al., 2002; WALTER et al., 2001).

The hemispheric (annular) paradigm is motivated by the importance of tropical variations for the North Atlantic climate (ROWNTREE, 1972; FRAEDRICH, 1994). The NAM or AO illustrates a coupling between the Atlantic and Pacific region (WALLACE and THOMPSON, 2002b). Observations (FRAEDRICH and MÜLLER, 1992) and model sensitivity experiments (MERKEL and LATIF, 2002) support an ENSO-Europe connection. The anti-correlation in the tropics and in the subtropics of the upper-tropospheric relative humidity reflects the enhanced strength (weakening) of the Hadley cell over the eastern Pacific (Atlantic) during El Niño (KLEIN et al., 1999).

During the last century the temporal behaviour of the teleconnection indices covers a wide spectral band with a distinct low-frequency contribution. The analysis of proxy data of the NAO shows phases of en-

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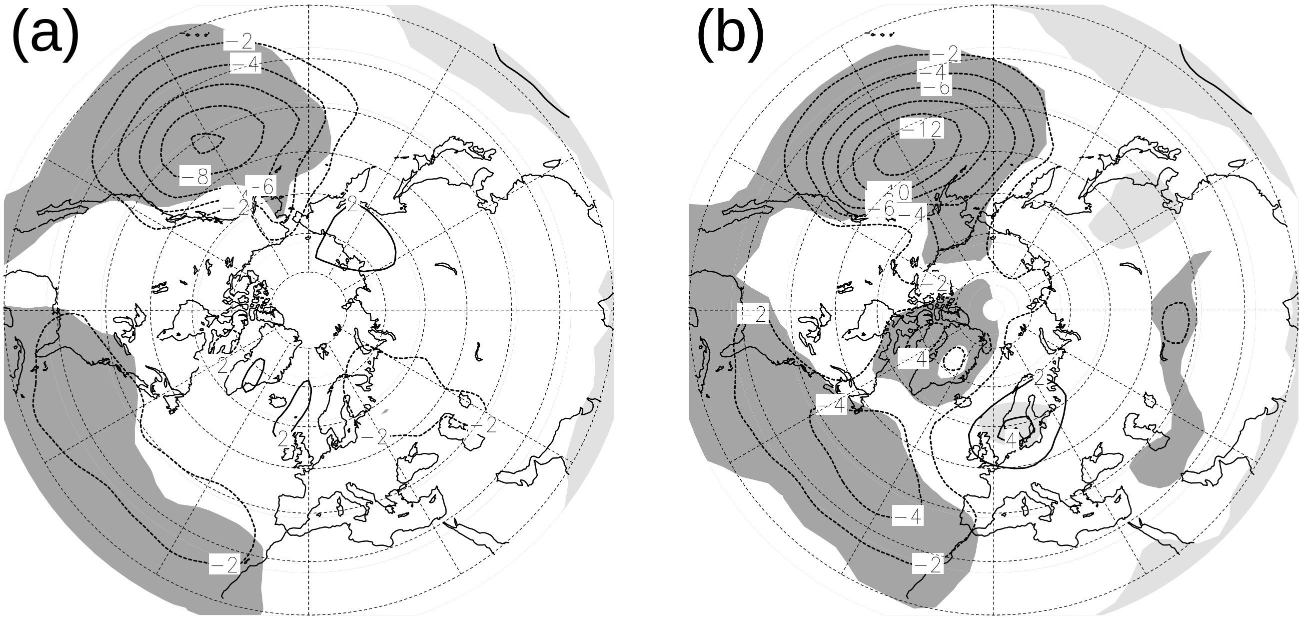

Figure 1: ENSO-Composite (El Niño minus La Niña) of sea level pressure for (a) the sectoral and (b) the hemispheric regime. Shading indicates the 90 % significance level (dark negative, light positive values).

hanced (active) and reduced (passive) decadal variability (Appenzeller et al., 1998). A synthesis of both, the temporal concept of Appenzeller et al. (1998) and the spatial aspect put forward by Bjerknes (1964) and Wallace and Thompson (2002b), has been developed by Raible et al. (2001, 2004). Appenzeller's phases are connected with characteristic spatial correlations due to the non-stationarity of the ocean-atmosphere coupling, e.g. a local NAO-SST tripole vs. a hemispheric AO-ENSO impact. These findings led to the definition of two decadal regimes: (i) a regional regime during active phases with independent sectoral patterns in Atlantic and Pacific and (ii) a hemispheric regime during passive phases with an annular pattern in connection with ENSO.

A prominent weather component with severe impacts on temperature and precipitation are the midlatitude synoptic cyclones. The variability of the midlatitude storm tracks is related to low-frequency changes of the atmospheric circulation (Lau, 1988). In the climatological mean, for a positive NAO-index the Atlantic cyclones are shifted northward and for positive ENSO anomalies the North Pacific cyclones are displaced eastward (Hoerling et al., 1997; Sickmöller et al., 2000). Entering in a series of previous studies (Raible et al., 2001, 2004) the aim of this paper is to investigate decadal variations of North Atlantic cyclones separately for each decadal regime. The phases are identified by the strength of the decadal NAO variability. The spatial scale is illustrated by a composite analysis using the ENSO-index. The analysis is based on data from a long-term AOGCM simulation and considers storm tracks, cyclone tracks and precipitation data. The paper is organised as follows: The data basis and the analysis techniques are described in Section 2. The results are presented in Section 3 followed by the conclusions in Section 4.

2 Data basis and analysis techniques

The analysis is based on a 600-yr simulation with a coupled AOGCM (Legutke and Voss, 1999, for a detailed description). The atmosphere is simulated with a GCM in triangular truncation at wavenumber T30 ($3.75^\circ \times 3.75^\circ$) and 19 hybrid sigma-pressure levels up to 10 hPa. The ocean is simulated by a primitive equations model which is based on the Boussinesq approximation and implemented on a horizontal Gaussian T42 Arakawa-E grid and 20 irregularly distributed levels. The models are coupled via the Ocean Atmosphere Sea Ice Soil coupler. A stationary climate is achieved with an annual mean flux correction scheme for present day climate conditions.

The Eulerian storm track is measured as the region of enhanced standard deviation of the band-pass filtered (2.5 to 6 days) 500 hPa geopotential height (Blackmon, 1976; Wallace et al., 1988; Lau, 1988). The filter restricts the variability to the characteristic time scale of synoptic cyclones, but a considerable amount of anomalies which are not related to cyclones, e.g., waves and high-pressure systems, is included.

The Lagrangian cyclone track is estimated as the area of enhanced cyclone occurrences. The cyclone trajectories are identified as low-pressure systems at subsequent time steps (Blender et al., 1997). To avoid spurious detections, we demand a minimum lifetime of 3 days

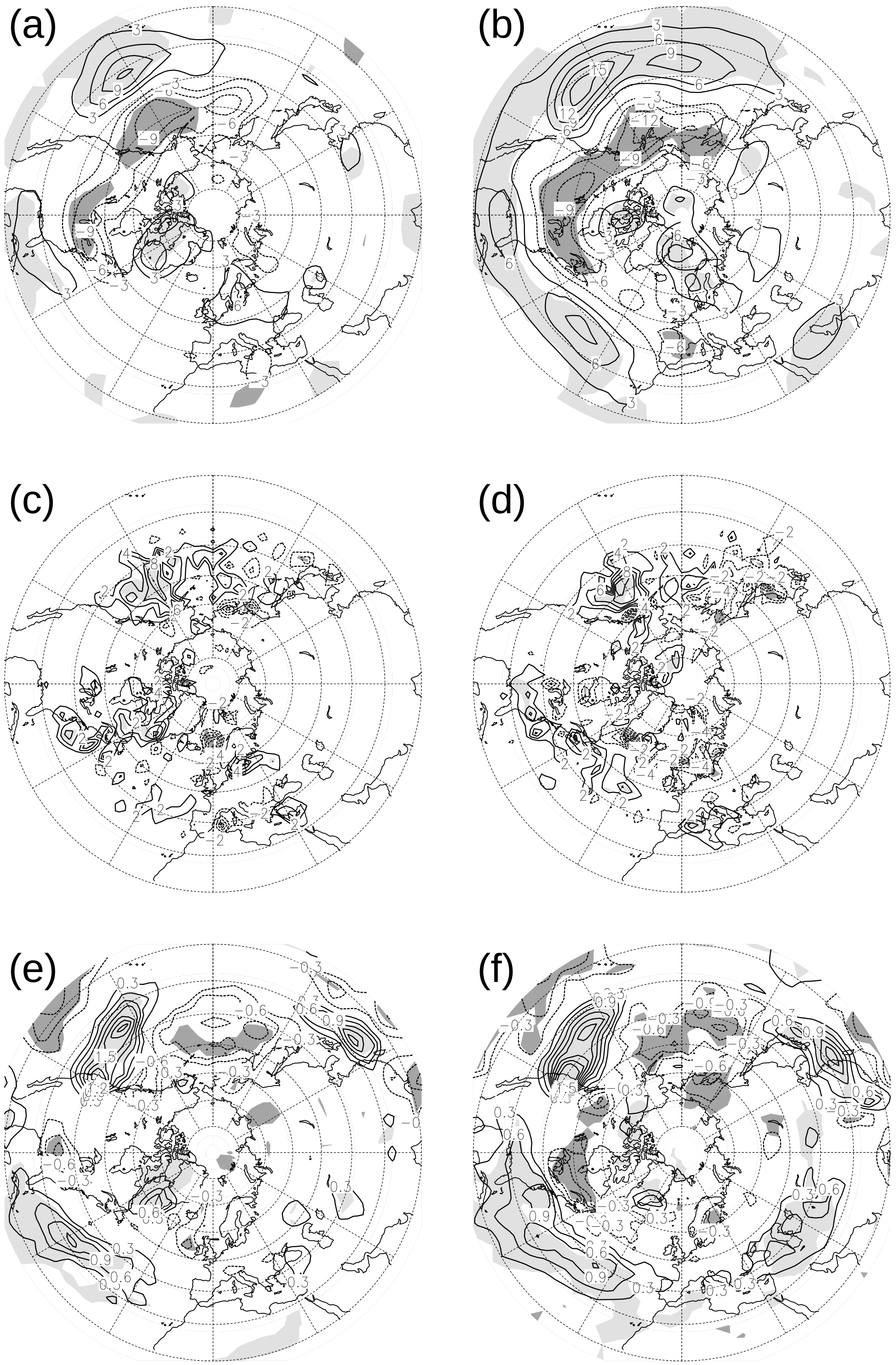

Figure 2: ENSO-Composite (warm El Niño - cold La Niña) for the sectoral (left panels) and hemispheric regime (right panels): (a,b) storm track or the 2.5–6 day bandpass-filtered standard deviation of the 500 hPa geopotential height (unit: gpm), (c,d) cyclone density (unit: number of cyclone times 100 per $(1000\ \mathrm{km})^2$), (e,f) precipitation (unit: mm per day). Note that 2b is identical to Fig. 3b in RAIBLE et al. (2004). Shading indicates the 90 % significance level (dark negative, light positive values).

and a maximum gradient of at least 30 gpm per 1000 km during the life cycle. The density of cyclones is the number of occurrences normalised by the number of observations and by the sampling area of 1000^2 km^2.

The NAO index is determined as the 500 hPa geopotential height difference between the Azores and Iceland. The geopotential height time series are standardised averages of the four most nearby model grid points in the two regions. The ENSO index is defined by the SST in the Niño 3 region (5°S–5°N, 150°W–90°W; TRENBERTH (1997)).

To distinguish between active and passive phases, the spectrum of the NAO is calculated for 30-yr windows in the 600-yr time series by the maximum entropy method. The centred variance (deviation from the long-term mean) in the 5 to 30-yr spectral band characterises active (passive) phases if the variability is above one standard deviation (below minus one standard deviation). This illustrates the non-stationarity (or high low frequency variability) of the NAO on decadal time scales which may lead to the lack of statistical averages in finite periods. Note that not all 30-yr segments can be assigned to an active or passive phase. The active and passive phases including the temporal behaviour of the 5 to 30-yr spectral band variability can be found in Fig. 3c in RAIBLE et al. (2001).

The spatial scale for each phase is displayed by a composite analysis using the ENSO index (threshold one standard deviation). The analysis is applied to the active (passive) phases in the coupled AOGCM simulation which are connected with sectoral (annular) teleconnections and named regional (hemispheric) regime. All results are derived for warm minus cold ENSO composites. Note that in both phases the composites are averaged over six cases. To analyse whether the difference is statistically significant, we applied a standard student t-test to the data using the 90% significance level. The analysis considers the winter season DJF (December to February) only.

3 Regional and hemispheric regimes

To investigate the different impacts of phases governed by regional versus hemispheric regimes on the cyclone behaviour we first show the ENSO remote influence on sea level pressure (SLP, Fig. 1a, b). Comparing the behaviour of the regional with the one of the hemispheric regime, the significant influence in the North Atlantic is restricted to approximately south of 30°N in the regional regime whereas in the hemispheric regime a clear weakening of the Azores High is evident. Note also that a significant high pressure anomaly is present over Scandinavia. This has implications for the cyclones and cyclone related variables. Therefore, the standard deviation of the band-pass filtered 500 hPa geopotential (storm track) is displayed in Fig. 2a, b, the cyclone density (cyclone track) in Fig. 2c, d, and the precipitation anomalies in Fig. 2e, f. Again the ENSO influence in phases governed by the regional regime is weak in the North Atlantic (Fig. 2a, c, e). The cyclone density shows a rather spotty picture in the North Atlantic. Only south of 30°N the precipitation shows a response (Fig. 2e) and, as an exception, an increase of cyclones and precipitation near the Labrador sea. In the hemispheric regime we find this strong southward shift of the Atlantic storm track (Fig. 2b) and a splitting at the end of the Atlantic storm track with a positive anomaly over Scandinavia. The cyclone density (Fig. 2c) resembles the behaviour of the storm track besides over Scandinavia where a significant reduction of cyclones is found explaining the significant anomalous high pressure in the SLP field (Fig. 1b).

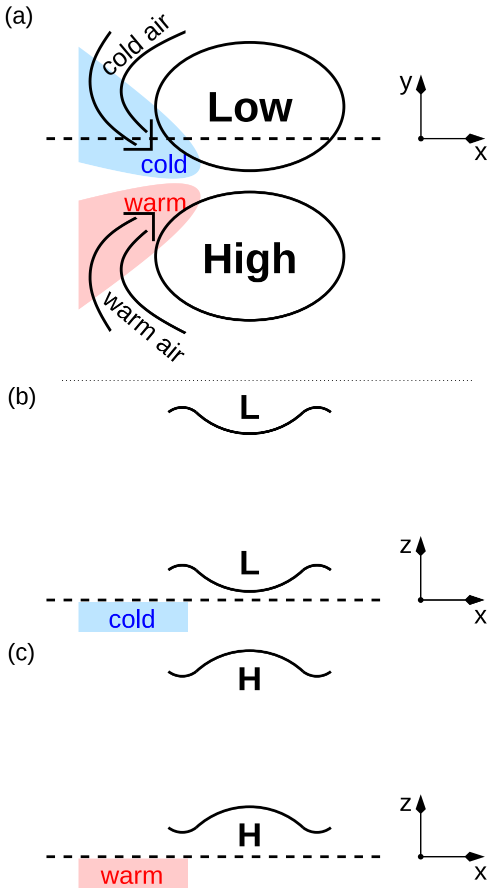

Figure 3: The regional regime and the Atlantic ocean-atmosphere mode: For a positive NAO-index the strong Iceland Low (Azores High) cools (warms) the ocean by latent and sensible heat fluxes and by anomalous Ekman transport (panel a; *xy*-section). The equivalent-barotropic atmospheric response to a cold (warm) SST anomaly (panel b; *xz*-section along the dashed line of the top panel) reinforces the Iceland Low (Azores High). Poleward oceanic advection of the warm SST anomaly (panel a) reduces the strong Iceland Low (panel c; *xz*-section alone the dashed line of the top panel) after 5 to 10 years inducing sign reversal of the NAO-index.

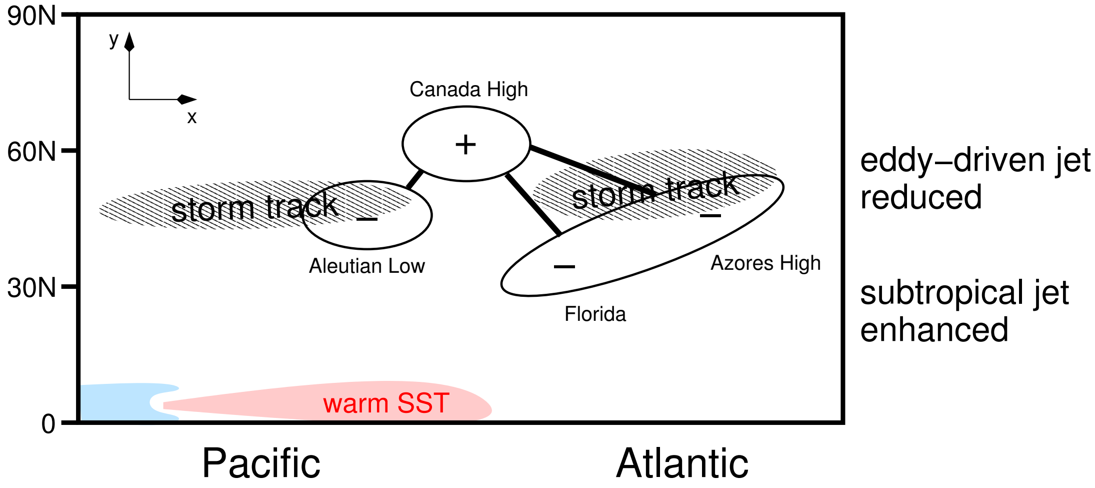

Figure 4: The hemispheric regime and the tropical ENSO mode: The warm SST anomaly in the eastern tropical Pacific leads to an intensified mean meridional mass streamfunction and an enhanced convection; the subtropical jet is stronger and displaced equatorward. The storm tracks in both basins are displaced equatorward strengthening the Canada High and the Aleutian Low and weakening the Iceland Low and the Azores High. Thus, a warm ENSO event is connected to a positive PNA- and a negative NAO-index. For a La Niña or cold ENSO event, the patterns reverse sign, (+) denotes enhanced pressure and (−) reduced pressure.

The precipitation behaves similar to the cyclone density with a weak but significant increase north of 30°N and a decrease over Scandinavia.

But there are also responses determined by ENSO which are present independent of the prevailing decadal regime: In the North Pacific the storm track composite shows a southward shift with warm ENSO events (Fig. 2a, b) as observed (TRENBERTH et al., 1998) and simulated (RAIBLE and BLENDER, 2004). Anomalous high cyclone densities (Fig. 2c, d) are found in the eastern North Pacific which are connected with above normal precipitation in these regions (Fig. 2e, f). In the tropical Atlantic a warm ENSO event is connected with a weaker than normal Hadley cell resembling findings of KLEIN et al. (1999), reduced precipitation in the tropics (outside the figure boundaries) and enhanced values in the subtropics (Fig. 2e, f). Again, these findings are independent of the decadal regime indicating that there is an ENSO response in the Atlantic also in the regional regime, but this is restricted to the subtropical Atlantic and not to the North Atlantic.

The response in the North Atlantic during the **regional regime** is controlled by a localized ocean-atmosphere mode proposed by RAIBLE et al. (2004). Conceptually, the hypothesis is a positive feedback between atmosphere and ocean leading to high decadal NAO variability (Fig. 3): During positive NAO phases, cold continental air and the southward Ekman transport cool the SST (LUKSCH, 1996, or in Fig. 3a). The well known tripole SST pattern is produced if, additionally, the Azores High forces a warm upstream (cold downstream) SST anomaly. A cold (warm) SST anomaly strengthens the Iceland Low (Azores High), shifts the Atlantic storm track (WALTER et al., 2001), and closes the positive ocean-atmosphere feedback loop (Fig. 3b). The northward advection of the anomalous warm SST favours a sign reversal of the NAO index weakening the Iceland low pressure illustrated in Fig. 3c. As the North Atlantic storm track (Fig. 2a) and the cyclone density (Fig. 2c) are not affected by ENSO, this shows that the mechanism is not connected to ENSO related variability.

For the **hemispheric regime**, which is governed by ENSO and a NAO-spectrum dominated by the interannual time scale, the following hypothesis is presented: The 500 hPa-geopotential in the Pacific is linked with the southern center of NAO (Fig. 4). A warm ENSO event is associated with a positive PNA index. In this case, the subtropical jet is anomalously strong and moves equatorward (RAIBLE et al., 2004) consistent with the Atlantic storm track (Fig. 2b) and the cyclone density (Fig. 2d). The Azores High is weaker than normal (Fig. 1b), the northern European precipitation is reduced by less cyclones while further south the cyclone occurrences and the precipitation are slightly increased (Fig. 2f). The stationary wave activity is enhanced (RAIBLE et al., 2004). The correlation between the NAO and ENSO-index is highly negative (≈ -0.6). This concept is supported by observations showing very similar results for a warm ENSO event: anomalous high (low) pressure and less (high) precipitation in northern (central) Europe (FRAEDRICH and MÜLLER, 1992). The storm track in Fig. 2b is reduced over the Iberian peninsula and increased over Northern Europe during El Niño events. Thus, the cyclone track appears to be a superior indicator for the distribution of precipitation in the midlatitudes.

In summary we find that during regional regimes with high decadal NAO variability, the connection of

North Atlantic and Atlantic cyclones with ENSO is distinctly reduced, in particular in Europe. Therefore, the analysis of the complete time interval, which includes both regimes, leads to less clear conclusions and a higher noise level.

4 Conclusions

To overcome the problem of non-stationarity in climate correlations, two regimes with different temporal and spatial variability are introduced. A regional regime is defined by high decadal variability of the NAO and a sectoral spatial scale of the geopotential height teleconnection pattern. A hemispheric regime is connected with low decadal NAO variability and an annular extension of the teleconnections.

The spatial scale of the teleconnection patterns is discussed by composites using the ENSO-index. In the hemispheric regime the AOGCM simulation shows a southward shift of the cyclones and precipitation in the Atlantic for warm ENSO events; this agrees with observations (TRENBERTH et al., 1998). The Azores High is weaker than normal. Over Europe, a warm ENSO event is connected with anomalous high (low) pressure and less (high) precipitation in northern (central) Europe (FRAEDRICH and MÜLLER, 1992, using station data). These ENSO-Europe connection with reduced precipitation in northern Europe is explained by lower cyclone frequencies. In southern Europe the cyclone frequencies and the precipitation are slightly increased. The NAO-ENSO correlation is highly negative in the hemispheric regime with 40 % explained variance, whereas the correlation vanishes completely during the regional regime. This is caused by the non-stationarity of the ocean-atmosphere coupling: a localised Atlantic mode with high decadal NAO variability during the regional regime and a tropical ENSO mode modifying the midlatitudes connected with low decadal NAO variability during hemispheric regime.

A possibility for the switch from the hemispheric to the regional regime is the ocean-troposphere-stratosphere coupling. Tropospheric eigenmodes exist in atmospheric GCM simulations, even with fixed climatological boundary conditions (BARNETT, 1987), and can be amplified by the ocean (RAIBLE et al., 2001) and the stratosphere (PERLWITZ and GRAF, 2001; WALLACE and THOMPSON, 2002a). Implications for the predictability of the European climate require further investigations.

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