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On the changing nature of the regional connection between the North Atlantic Oscillation and sea surface temperature

Katrin Walter and Hans-F. Graf
Max-Planck-Institut für Meteorologie, Hamburg, Germany

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[1] Evidence is presented that the correlation between the North Atlantic Oscillation (NAO), in terms of the NAO index, and the North Atlantic sea surface temperature (SST) is not stationary. This is inferred from both reanalysis data from the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the Kaplan sea surface temperature data set. Two phases of winterly North Atlantic atmosphere-ocean covariability are identified by means of linear regression and correlation analysis. During the recent decades since the late 1960s/early 1970s and during the first 3 decades of the twentieth century, the North Atlantic SST is strongly correlated to the regional atmospheric circulation in the North Atlantic sector, i.e., the North Atlantic Oscillation. During these periods the NAO index, defined as the difference of normalized sea level pressures on the Azores and Iceland, is characterized by pronounced decadal variability and by mainly positive values. In contrast, the NAO index is only weakly correlated to the North Atlantic SST from the 1930s to the early 1960s, when the NAO index is characterized by weak decadal variability. Remote influences, in particular from the tropical Pacific region, become important, especially for the SST in the western tropical North Atlantic. *INDEX TERMS:* 3319 Meteorology and Atmospheric Dynamics: General circulation; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); *KEYWORDS:* North Atlantic Oscillation, sea surface temperature, nonstationarity, decadal variability, atmospheric circulation modes, tropical North Atlantic

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1. Introduction

[2] The winterly circulation and surface temperature over the North Atlantic and western Europe is strongly influenced by the North Atlantic Oscillation (NAO). It is the dominant mode of variability in the North Atlantic region and is characterized by a meridional oscillation in atmospheric mass between centers of action near Iceland and over the subtropical Atlantic, leading to a concurrent variation in the strength of the Iceland low and the Azores high [*Walker and Bliss*, 1932; *Glowienka-Hense*, 1990; *Hurrell*, 1995; *Hurrell and van Loon*, 1997]. The NAO shows variability on all timescales. *Thompson and Wallace* [1998] suggested that the NAO may be part of a zonally symmetric variability mode, the Arctic Oscillation, with a primary center of action over the Arctic and opposing centers over the midlatitude Atlantic and Pacific. *Deser* [2000], however, presented evidence that for seasonal mean data, the connection to the Pacific basin is negligible compared to the connection between the Atlantic and the polar region. In this paper, we focus on the North Atlantic region only, hence we refer to the NAO.

[3] The mechanisms influencing the NAO have not been fully understood up to now. Many studies suggest that atmosphere-ocean interaction is a determining factor for both the atmospheric and the oceanic circulation in the North Atlantic region. It has long been recognized that fluctuations in sea surface temperature (SST) and NAO are related [*Bjerknes*, 1964]. The atmospheric circulation can influence the ocean by changing surface fluxes of heat, momentum, and fresh water. *Cayan* [1992] analyzed composites of winter months characterized by positive and negative NAO. He concluded that the NAO is responsible for generating systematic large-amplitude anomalies of wind speed, latent and sensible heat fluxes, and hence of sea surface temperature over much of the extratropical North Atlantic. *Deser and Blackmon* [1993] and *Kushnir* [1994] found that the interannual to quasidecadal SST variation in the North Atlantic is strongly correlated to the atmospheric circulation over that area. This conclusion is supported by experiments with an ocean general circulation model (OGCM) showing that realistic large-scale SST anomalies can be produced with prescribed observed atmospheric forcing [*Luksch*, 1996]. *Grötzner et al.* [1998] suggested from a coupled GCM experiment that the wind-driven circulation in the North Atlantic may be characterized by decadal cycles in the subtropical gyre, which incorporates the tropical and midlatitude North Atlantic Ocean. The atmospheric circulation may even have the potential to influence the thermohaline circulation [*Timmermann et al.*, 1998; *Delworth and Dixon*, 2000].

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[4] However, uncertainty and ambiguity exists regarding the influence of the midlatitude ocean on the atmospheric circulation. Numerous experiments with more or less simplified atmospheric models and prescribed SST anomalies suggest that there might be some influence of the midlatitude ocean on the atmospheric circulation [e.g., *Kushnir and Held*, 1996; *Peng et al.,* 1997; *Peng and Whitaker*, 1999; *Walter et al.*, 2001], although the strength of the atmospheric response most likely depends on the atmospheric circulation itself, i.e., on the activity of synoptic eddies, and on the ability of the models to capture those fluctuations. *Rodwell et al.* [1999], *Latif et al.* [2000], and *Mehta et al.* [2000] were able to reconstruct especially the multiyear fluctuations of the NAO index in ensemble model experiments with prescribed observed SST anomalies, suggesting that the NAO would be predictable if the SST anomalies could be predicted. However, as stated by *Mehta et al.* [2000], those results are strongly influenced by the ensemble size. *Bretherton and Battisti* [2000] argue that one must be careful in using these AGCM runs with prescribed SST for interpreting the variability of the coupled system: The ensemble averaged surface energy fluxes in the prescribed-SST runs appear to damp the low-frequency SST anomalies, whereas in nature they act to drive them. *Barsugli and Battisti* [1998] presented evidence that coupling between atmosphere and ocean in midlatitudes acts to enhance the variance in both media and to decrease the energy flux between them.

[5] The SST in the North Atlantic is not only influenced by the atmospheric NAO phenomenon. Numerous studies with observational or reanalysis data [e.g., *Hastenrath et al.*, 1987; *Curtis and Hastenrath*, 1995; *Nobre and Shukla*, 1996; *Enfield and Mayer*, 1997; *Hastenrath*, 2000] and several modeling studies [*Hameed et al.*, 1993; *Saravanan and Chang*, 2000] suggested that the El Niño/Southern Oscillation phenomenon (ENSO) considerably influences the SST in the tropical North Atlantic. Warm SST events in the tropical Pacific are accompanied by positive SST anomalies in the (western) tropical North Atlantic. *Hastenrath* [2000] and *Nobre and Shukla* [1996] presented evidence that the link between the tropical Pacific and the North Atlantic region might be accomplished, possibly through barotropic Rossby wave propagation [*Hoskins and Karoly*, 1981], by a wave train-like teleconnection pattern extending from the equatorial Pacific across North America to the North Atlantic. *Curtis and Hastenrath* [1995] showed that, in January, the subtropical high over the North Atlantic and, thus, the meridional pressure gradient is weakened during Pacific warm phases, which implies weakened northeast tradewinds, and, as primary consequences, reduced latent heat fluxes in the tropical North Atlantic and anomalous Ekman downwelling (i.e., reduced upwelling) equatorward of 20°N. In the subsequent months this results in warm SST anomalies in the tropical North Atlantic.

[6] In most studies the correlation between oceanic and atmospheric variables in the North Atlantic region is regarded as stationary, i.e., not changing much with time. However, the atmospheric circulation in the North Atlantic region in terms of the variability of the NAO index has not been uniform since the beginning of the observations in the nineteenth century, and before, as can be inferred from proxy data [*Appenzeller et al.*, 1998]. *Raible et al.* [2001] presented evidence that the correlation between NAO and North Atlantic SST may not be independent of the structure of NAO variability. They found that, in a 600-year experiment with the coupled GCM ECHAM4/HOPE, the strength of the correlation between the NAO and the North Atlantic SST is sensitive to the decadal variability of the NAO. They detected two different regimes of North Atlantic atmosphere–ocean interaction connected with the strength of the decadal variability of NAO: During periods in which the NAO shows high variability on the decadal timescale, the North Atlantic SST is strongly correlated to the NAO, whereas this correlation is weaker during periods characterized by weak decadal variability of the NAO. The latter mode is characterized by a strong PNA pattern linking the tropical Pacific region and the North Atlantic region.

[7] In this paper we examine whether the ocean-atmosphere connection in the North Atlantic region remained unchanged in the presence of the changes in the frequency domain of the NAO during the twentieth century. Nonstationarity would be associated with changes in the relative importance of remote influences from outside the North Atlantic sector on the SST. We use reanalysis data and other data sets reconstructed on the basis of observations. The data sources are introduced, and index time series are defined in section 2. In section 3 we discuss concurrent variations of an observed NAO index and reanalyzed geopotential height and SST data from the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data set. Temporal changes in the relative importance of remote and regional influences on SST are further examined in section 4. For this purpose we make use of an optimally smoothed observational SST data set [*Kaplan et al.*, 1997, 1998] comprising also the first half of the twentieth century, which is not captured by the reanalysis.

2. Data and Analysis

[8] Concurrent variations of SST and tropospheric geopotential heights and their relations to the North Atlantic Oscillation are examined in this paper by means of linear correlation and regression analysis, the first indicating the strength, and the second giving the pattern of a connection.

2.1. Data

[9] Two data sets are used in this study. One is the reanalysis data set from the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR [*Kalnay et al.*, 1996; *Kistler et al.*, 2001]), covering the years 1948 to present. The variables discussed in this paper are the SST (Gaussian 192 × 94 grid, approximately 1.875° × 1.9°) and the 1000- and 500-hPa geopotential heights (2.5° × 2.5° grid).

[10] The NCEP/NCAR reanalysis data set is known to be affected by two major changes in the observing system [*Kistler et al.*, 2001]: The first was from 1948 to 1957, when the upper-air operational network was established. The second change took place in 1979 due to the introduction of satellite data. The changes in the observational data basis lead to the generation of jumps and spurious trends. *Kistler et al.* [2001] therefore recommended not to estimate trends

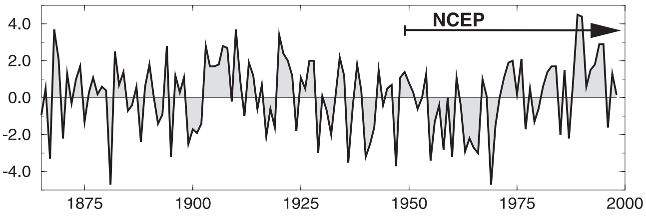

Figure 1. NAO index as the difference between the normalized sea level pressure at Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland, averaged over the JFM season (data from J. Hurrell's website http://www.cgd.ucar.edu/~jhurrell/nao.html). The arrow denotes the period for which NCEP reanalysis data is available.

with the reanalysis. *Pawson and Fiorino* [1999] showed that, in the tropics, reanalyzed stratospheric NCEP/NCAR temperatures near the tropopause underwent a large discontinuous increase near 1979, when satellite-based observations became available. *Kistler et al.* [2001] found that the reliability of especially the upper-level reanalyses in the Southern Hemisphere suffers from the lack of upper-air observations before the satellite era, and in particular before 1958, whereas, in the Northern Hemisphere extratropics, the reanalysis provides fairly accurate initial conditions for forecasts, even before 1958.

[11] In this study we focus on the large-scale interannual and decadal variability near or at the surface and in the midtroposphere. Every analysis is performed with raw as well as with detrended data in order to reduce possible influences from trends. When using 500-hPa geopotential height data, we only discuss the Northern Hemispheric extratropics. The results derived from analyses with sea surface temperature and 1000-hPa geopotential height data are revealed to be reliable in the regions of interest (in the Northern Hemisphere) because the features discussed in section 3 can be fairly well reproduced with a different sea surface temperature data set (the Kaplan SST data set; see next paragraph) and mean sea level pressure data sets (e.g., updates of the data set by *Jones* [1987] and of the NCAR mean sea level pressure data set described by *Trenberth and Paolino* [1980]).

[12] Another data set used in this study is the SST data set by *Kaplan et al.* [1997, 1998]. It is based on observations, and covers also the first half of the twentieth century, which is not captured by the NCEP reanalysis. Optimal smoothing on empirical orthogonal function (EOF) basis is applied to monthly anomalies from the UK Met Office historical sea surface temperature data set (version MOHSST5) of the Global Ocean Surface Temperature Atlas (GOSTA). The data record ranges from 1856 to 1991 with a spatial resolution of 5° × 5°. However, the observational data basis in the North Atlantic region is especially sparse until about 1900. Thus, we only use data from 1900 to 1991.

[13] The tropical North Atlantic region is known to be strongly influenced by both the NAO and the ENSO phenomenon. Therefore, an index for the tropical North Atlantic (TNA) SST is defined as the area average of SST over 10°N–20°N, 20°W–60°W in the NCEP/NCAR data set and over 12.5°N–22.5°N, 20°W–60°W in the Kaplan data set. The SST anomaly averaged over the NINO3.4 region (5°N–5°S, 120°W–170°W) is used as an index for the ENSO phenomenon.

2.2. NAO Index

[14] Following *Hurrell* [1995] the polarity and strength of the North Atlantic Oscillation is described in terms of the NAO index, defined as the difference between the normalized sea level pressure anomalies at two stations near the subtropical high and the Icelandic low, respectively. The NAO index used throughout this paper (Figure 1; data from J. Hurrell's website http://www.cgd.ucar.edu/~jhurrell/nao.html) is computed from JFM mean sea level pressure anomalies (relative to the 1865–1984 mean) at Ponta Delgada, Azores, and Stykkisholmur/Reykjavik, Iceland. The pressure anomalies are normalized by division of each JFM mean pressure by the long-term standard deviation (1865–1984).

[15] JFM means are discussed throughout this paper because the centers of action of the North Atlantic Oscillation are most pronounced during that season. However, the main features discussed in this paper are the same for DJF means.

[16] The variability of the NAO index has not been uniform since the beginning of the observations in the nineteenth century (Figure 1). We applied a Morlet wavelet analysis [*Torrence and Compo*, 1998] to the JFM mean NAO index. The local wavelet power spectrum is presented in Figure 2. As already mentioned by *Appenzeller et al.* [1998], the NAO index time series is revealed to be nearly white. The significance of the local wavelet power spectrum was therefore tested using a white noise background spectrum. Figure 2 shows several peaks of wavelet power for periods between 7–8 and 20 years. Especially, fluctuations with periods around 16 years are pronounced from 1895 to 1920/1925. This peak is significant above the 90% level. From 1965/1970 on, there are two other peaks for periods around 16 and 8 years, respectively. The first is not significant above the 90% level, but may possibly have

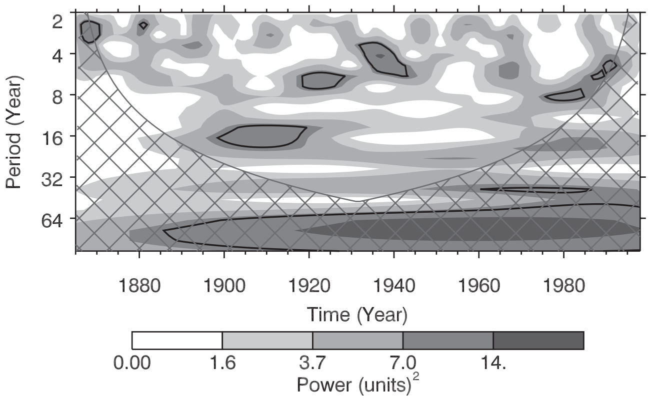

Figure 2. Local wavelet power spectrum of the JFM mean NAO index. The analysis is based on a Morlet wavelet with a characteristic frequency of 6. The contour levels are chosen so that 70, 50, 25, and 5% of the wavelet power is above each level, respectively. The cross-hatched region corresponds to the cone of influence where zero padding has reduced the variance. The black contour is the 90%-significance level, using a white noise background spectrum. See work by *Torrence and Compo* [1998]. (Software was provided by http://www.ResearchSystems.com.)

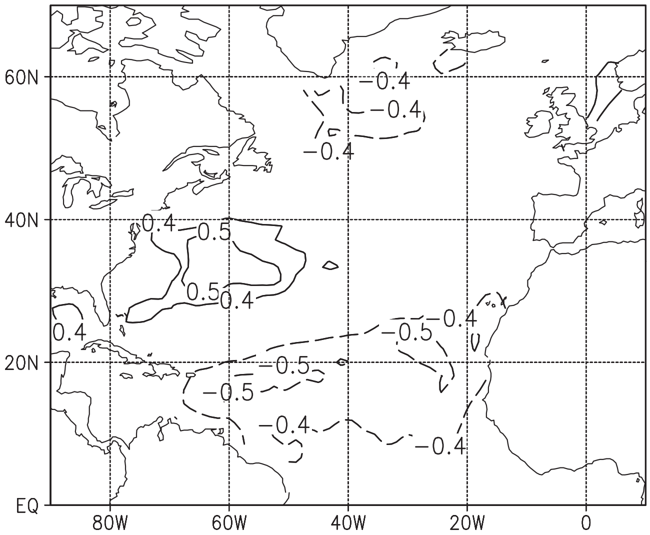

Figure 3. Correlation coefficient between NAO index and reanalyzed SST at each grid point in the North Atlantic region calculated from JFM seasonal means for 1949–1998. Only values exceeding ±0.4 are shown.

been artificially reduced by zero padding, as low-frequency variability at the end of the time series can already be seen in Figure 1. From 1940 to the mid-1960s, there is only little variance for periods between 7–8 and 20 years. This is also true for the second half of the nineteenth century. In summary, during the first 3 decades of the twentieth century and since the mid-1960s/early 1970s, the NAO index showed pronounced decadal variability. Figure 1 shows that the NAO index was also characterized by mainly positive values during these years. In contrast, the decadal variability was reduced during the second half of the nineteenth century and from the 1940s to the 1960s. These years are therefore characterized by (relatively) more interannual variability, as there are peaks in the wavelet power spectrum for periods shorter than 6–4 years.

[17] Figure 1 shows that the 1930s–1960s were additionally characterized by a negative trend of the NAO index, whereas the recent 3 decades were characterized by a strong positive trend, which is unprecedented in the last few centuries [*Appenzeller et al.*, 1998]. These trends correspond to the peak in the wavelet power spectrum for periods around 64 years (Figure 2), which shall not be further commented on.

2.3. Analysis

[18] In section 3 two subperiods with lengths of 20 and 30 years are discussed separately in order to take into account the changes in the variability structure of the NAO mentioned in section 2.2. One subperiod ranges from 1949 to 1968, characterized by weak decadal and, thus, (relatively) more interannual variability of the NAO index. The second subperiod ranges from 1969 to 1998, characterized by pronounced decadal variability of the NAO index. Linear trends are subtracted prior to the calculation of correlation or regression coefficients. However, correlation maps from raw data are very similar to the ones discussed in this paper, even concerning the magnitudes of the coefficients. Thus the changes in correlation do not seem to be dependent on linear trends.

[19] We apply null hypothesis testing as a simple way of mapping correlations which clearly stand out of noise [*Fisher*, 1958]. However, as discussed by *Nicholls* [2001], this method has to be applied very cautiously. One reason is that the significance levels are chosen arbitrarily and that the threshold values corresponding to them depend on the sample size. Thus, even physically reasonable correlations can be ignored as nonsignificant if the sample size is small. However, *Nicholls* [2001] also admits that plotting confidence levels, for example, would result in very complex maps. Therefore, as also proposed by *Nicholls* [2001], our figures showing regression coefficients display also the values in regions where the null hypothesis (correlation not

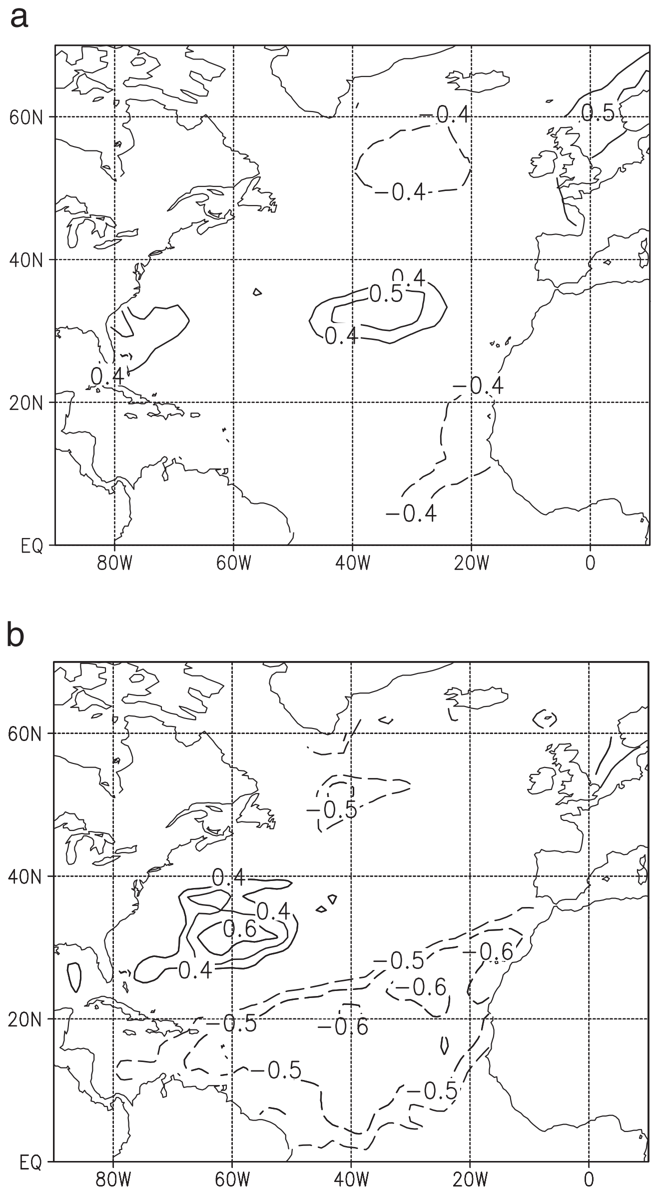

Figure 4. Correlation coefficient between NAO index and reanalyzed SST at each grid point in the North Atlantic region calculated from JFM seasonal means (a) for 1949–1968 and (b) for 1969–1998. The linear trends are subtracted before calculating the correlation coefficients. Only values exceeding ±0.4 are shown.

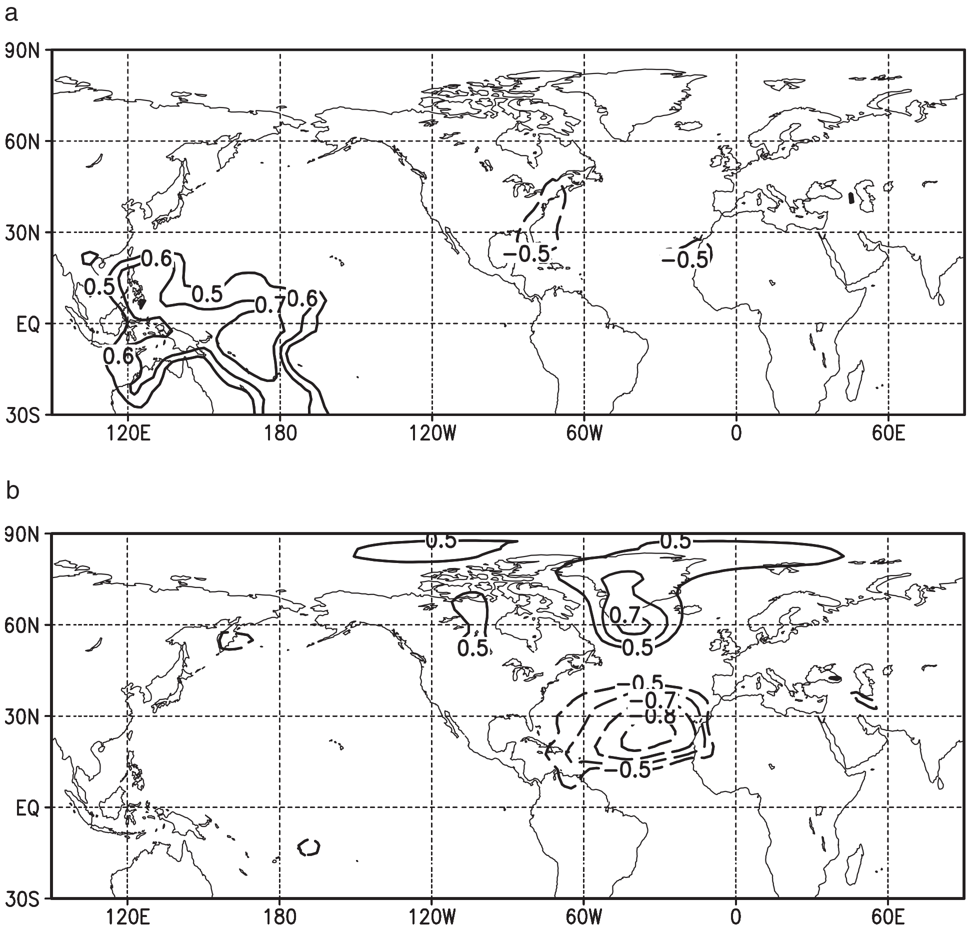

Figure 5. Correlation coefficient between the TNA SST index and the 1000-hPa geopotential height at each grid point calculated from JFM seasonal means of NCEP reanalysis data (a) for 1949–1968 and (b) for 1969–1998. Only values greater than 0.5 or lower than −0.5 are shown. The linear trends are subtracted.

different from zero) was not rejected. The regions in which it was rejected are shaded. Under the assumption that each season is independent of the rest, a correlation coefficient larger than ±0.56 or ±0.46 corresponds to significance above the 99% level for the 20- or 30-year period, respectively. However, in figures which only display the correlation coefficient, only values above ±0.4 or ±0.5 are shown, respectively. This is only because we want to keep the figures as simple as possible and discuss only the large-scale features in the regions of interest. These are still eminent when the small correlation values are not shown.

[20] In section 4 the percentage of variance of the TNA index of tropical North Atlantic SST explained by the either the NAO index or the NINO3.4 index is discussed. Every explained variance (squared correlation coefficient) is computed from a 25-year window sliding through the data. The linear trends are subtracted from the time series for every 25-year window before calculating the explained variance. However, the features described in section 4 remain unchanged if trends are included.

3. Patterns of Ocean-Atmosphere Covariability

[21] As mentioned in the introduction, the atmospheric circulation can interact with the ocean by surface heat and momentum fluxes. The strength of the (concurrent) correlation between the JFM means of NAO index (Azores–Iceland) and reanalyzed North Atlantic SST is presented in Figure 3. The map of correlation coefficients for the period 1949–1998 shows the well known tripole structure with maximum correlation coefficients of more than ±0.5. Between 50°N and 70°N, that is, southeast of Greenland, and in the (sub)tropics between 10°N and 30°N the SST is anticorrelated with the NAO index. Between these two centers of negative correlation an area emerges with positive correlation between SST and the NAO index. Its center is located in the western North Atlantic between 25°N and 40°N, that is, in the subtropical gyre region. There is no significant correlation with South Atlantic SST. The tripole SST pattern is consistent with the anomalous surface heat and momentum fluxes associated with the NAO [*Cayan*, 1992]. Similar patterns are derived and described in numerous previous studies, [e.g., *Bjerknes*, 1964; *Deser and Blackmon*, 1993; *Kushnir*, 1994]. The tripole pattern also resembles the leading empirical orthogonal function (EOF) mode of North Atlantic SST variability explaining 29.6% of the total variance (not shown). This indicates that a large fraction of the North Atlantic SST variability is related to the North Atlantic Oscillation.

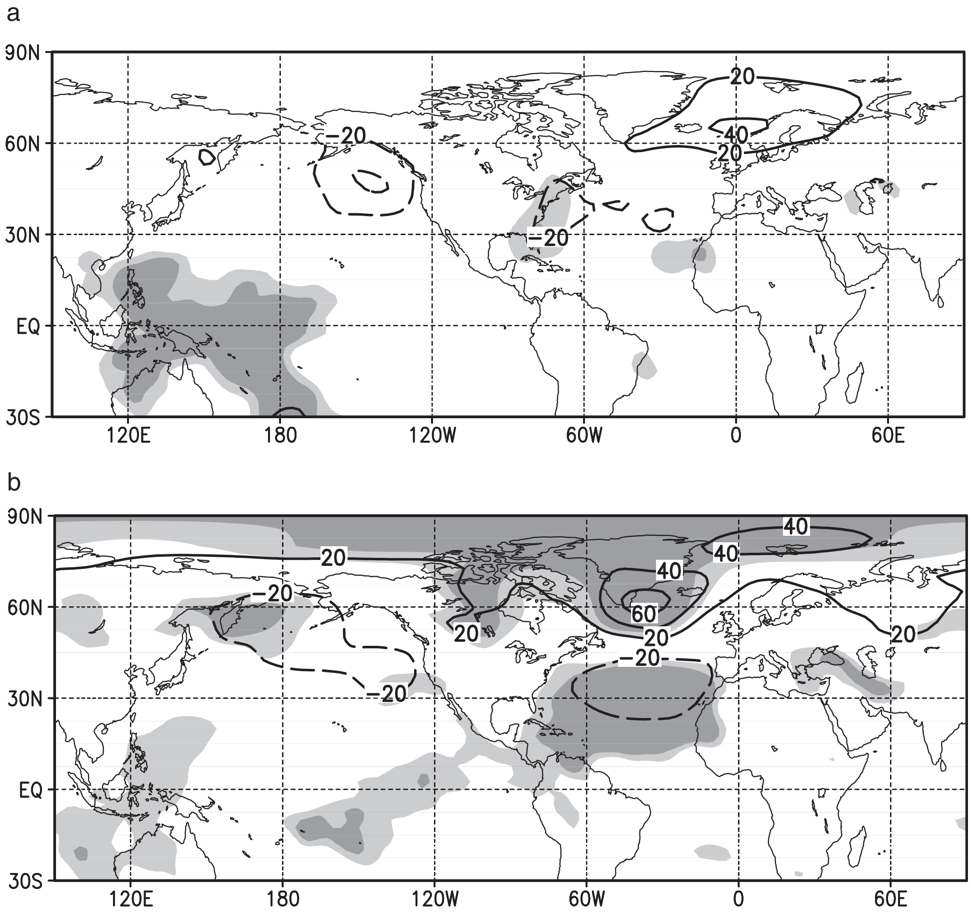

Figure 6. Linear regression coefficient (gpm/K) between the TNA SST index and the 1000-hPa level geopotential height field calculated from JFM seasonal means of NCEP reanalysis data (a) for 1949–1968 and (b) for 1969–1998. Shading indicates that the correlation is significant above the 95% (light) and the 99% (dark) level. The linear trends are subtracted.

[22] The change in the variability structure of the NAO in the late 1960s/early 1970s (see section 2.2) coincided with changes in the above mentioned correlations: Separate correlation maps between the NAO index and North Atlantic SST for the two subperiods 1949–1968 and 1969–1998 show that the correlation between the NAO index and the North Atlantic tripole SST pattern is not stationary. During the first subperiod (1949–1968, Figure 4a), the North Atlantic SST is rather weakly correlated to the NAO index. The correlations are not significant above the 99% level except for the positive midlatitude center, which moved to the central North Atlantic. In contrast, during the second subperiod, 1969–1999 (Figure 4b), the correlation pattern clearly shows the well known tripole structure. The correlation is stronger in the subtropical as well as in the positive midlatitude center in comparison to the entire period correlations. The maximum correlation in each center exceeds −0.6 and 0.6, respectively. Especially, the subtropical center (of anticorrelation) is broader and stronger than for the entire NCEP/NCAR period. In this region a strong Azores high is related to a strong negative SST anomaly: A strong Azores high corresponds to enhanced northeast trades resulting in both cooling of the sea surface due to anomalous fluxes and in enhanced upwelling of cold deep water off the North African coast due to strengthened Ekman transports. This is reflected by the fact that the subtropical center of strong anticorrelation extends up far to the northeast, i.e., to the upwelling region off the North African west coast.

[23] In summary, the North Atlantic SST is significantly correlated to the NAO index only since the last decades, when the NAO index is characterized by pronounced decadal variability and by mainly positive values. In the subperiod 1969–1998, especially, the subtropical center of anticorrelation is broader and stronger than for the entire NCEP/NCAR period. Thus, this region is regarded in the following in order to further document the altered ocean-atmosphere connections. An index for the tropical North Atlantic (TNA) SST is defined as the area average of SST over the grid points in the box 10°N–20°N, 20°W–60°W.

[24] Separate correlation maps between the TNA index of tropical North Atlantic SST and the 1000-hPa geopotential height at each grid point for the two subperiods 1949–1968 (Figure 5a) and 1969–1998 (Figure 5b) support the previous conclusion that the correlation between the NAO index and the North Atlantic SST is not stationary. During the first subperiod (1949–1968), the TNA SST-index is

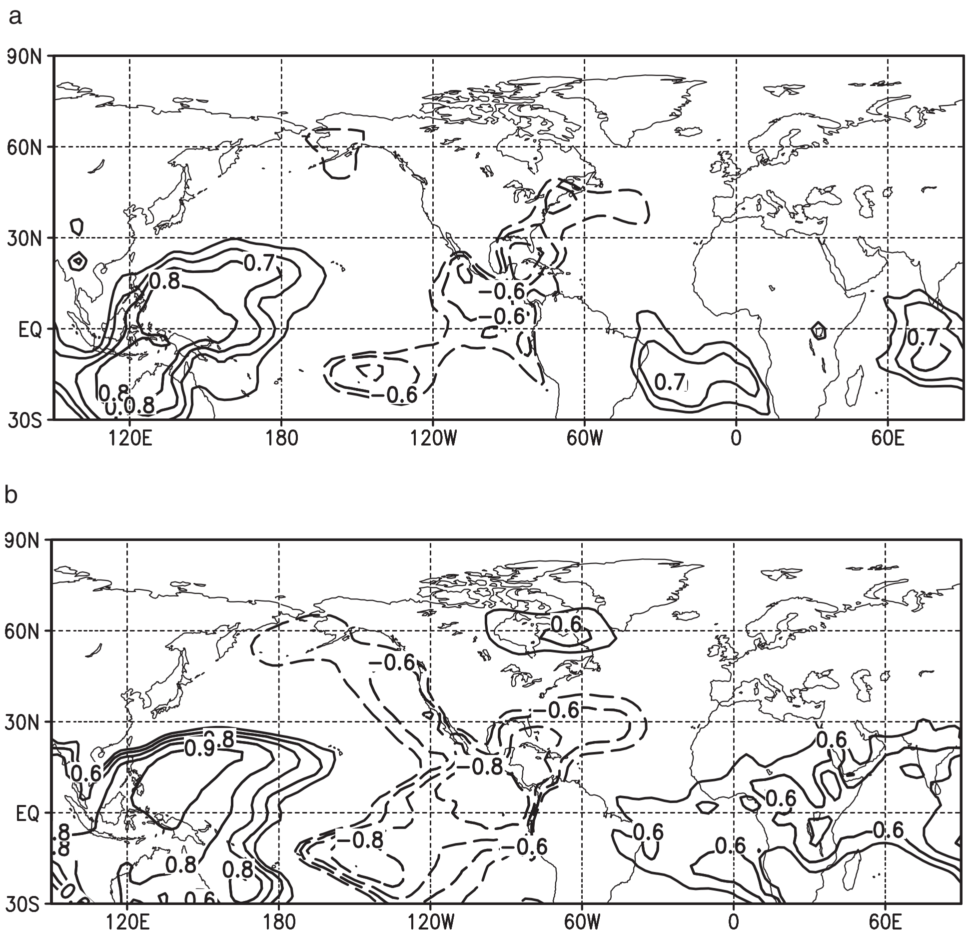

Figure 7. As in Figure 5 but for correlation between the SST averaged over the NINO3.4 region and the 1000-hPa geopotential height at each grid point.

only weakly correlated with the regional atmospheric circulation in the North Atlantic sector, whereas there is strong correlation with the geopotential height in that region during 1969–1998. The latter period is characterized by a dipole structure over the North Atlantic with maximum correlation of more than −0.8 and 0.7, respectively. In the following we refer to the latter period as the "regional period" and to the period 1949–1968 as the "global period" because, then, connections with regions outside the North Atlantic region become important.

[25] We repeated the above mentioned analysis with different mean sea level pressure (SLP) data sets (updates of the data set by *Jones* [1987] and of the NCAR data set described by *Trenberth and Paolino* [1980]). Both data sets cover the Northern Hemisphere north of 15°N. In that region the regression and correlation patterns of sea level pressure with SST indices derived from NCEP reanalysis and from the Kaplan SST data set (not shown) are very similar to the corresponding patterns calculated from NCEP reanalysis data alone. That is, the results from the NCEP reanalysis do not seem to be strongly contaminated by the inconsistencies in that data set (section 2.1).

3.1. Regional Period

[26] A map of linear regression coefficients between the TNA SST index and the 1000-hPa geopotential height (Figure 6b) shows a dipole pattern with a positive pressure anomaly southeast of Greenland and a negative one with center at 30°N and 35°N over the subtropical Atlantic. The dipole structure resembles the meridional seesaw pattern associated with the North Atlantic Oscillation [e.g., *Barnston and Livezey*, 1987]. The correlation in both centers of the dipole pattern is significant above the 99% level.

[27] The correlation between TNA SST index and 1000-hPa geopotential height over the subtropical North Atlantic increases slightly (from about −0.83 to about −0.88) if the TNA SST index of the MAM season is taken and the atmosphere leads the SST by 1–2 months (not shown), whereas the pattern remains almost unchanged. This indicates an influence of the atmospheric circulation on the SST. On the basis of weekly mean data, *Deser and Timlin* [1997] found that the large-scale covariation between wintertime atmospheric circulation and SST over the North Atlantic or the North Pacific is closest if the atmosphere leads the SST by 2–3 weeks. They assume that the 2- to 3-week timescale reflects the high-frequency stochastic forcing of the oceanic mixed layer by the atmosphere. For monthly mean data, the maximum correlation between atmospheric circulation and extratropical SST is achieved if the atmosphere leads the ocean by 1 month [*Wallace and Jiang*, 1987]. However, corresponding to our results from seasonal mean data, they found that the maximum correlations in the North Atlantic

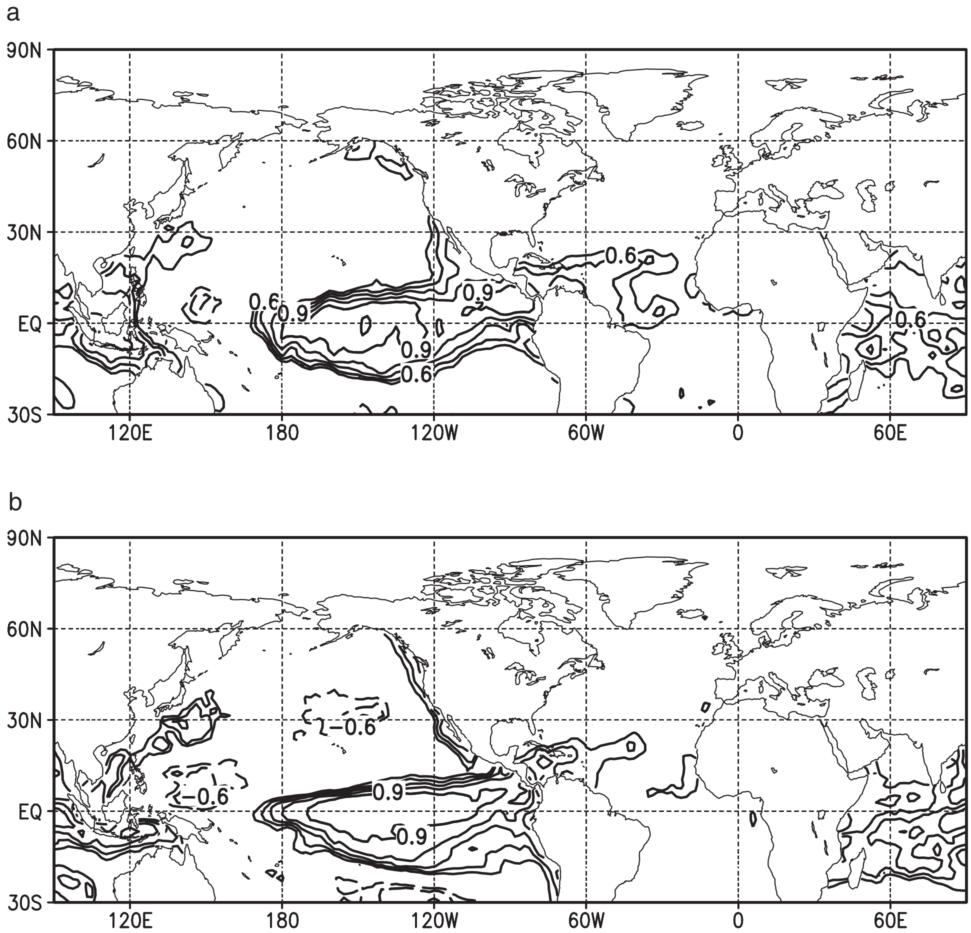

Figure 8. As in Figure 5 but for correlation between the SST averaged over the NINO3.4 region and the SST at each grid point.

region are only slightly stronger than for contemporaneous fields. This is likely to be due to the averaging process.

3.2. Global Period

[28] During times when the connection between North Atlantic SST and NAO is weak, other, remote, influences become important for the tropical North Atlantic SST: From 1949 to 1968 the TNA SST index is strongly correlated with the 1000-hPa geopotential height over a wide region covering the tropical West Pacific (Figures 5a and 6a). The maximum correlation coefficient exceeds 0.7 and is therefore highly significant.

[29] The atmospheric variability in the western tropical Pacific region is strongly influenced by the anomalous Walker Circulation, which is involved in the ENSO phenomenon [*Bjerknes*, 1969]: The anomalous Walker Circulation is associated with an east-west surface pressure seesaw across the tropical Pacific consisting of one pressure anomaly over the tropical West Pacific/Indonesia and one of opposite sign over the central/eastern tropical Pacific [*Walker*, 1924; *Walker and Bliss*, 1932; *Bjerknes*, 1969]. The connection of this pressure seesaw with the tropical Pacific SST is demonstrated with a correlation map between the NINO3.4 SST index and the 1000-hPa geopotential height (Figure 7). The center of action in the tropical West Pacific corresponds to the area strongly correlated with the TNA SST index (Figure 5a). Note that from 1969 to 1998 (Figure 7b) the pressure dipole over the tropical Pacific associated with the NINO3.4 SST emerges more clearly than during the period 1949–1968 (Figure 7a). That is, although the Southern Oscillation is more pronounced in the period 1969–1998, there is less influence on North Atlantic SST than from 1949 to 1968 (Figure 8).

[30] It is the SST in the western part of the tropical North Atlantic that is especially strongly correlated to the NINO3.4 SST in 1949–1968 (Figure 8a), whereas there is weaker correlation with North Atlantic SST in 1969–1998 (Figure 8b). Warm SST events in the tropical Pacific are accompanied by a weakened subtropical high in the western North Atlantic sector/Caribbean region (Figure 7; see also Figure 6a) and therefore by reduced northeast trade winds over the western tropical North Atlantic (not shown), leading to positive SST anomalies in that region at least in 1949–1968 (Figure 8a). As mentioned in the introduction, this feature is described in numerous studies using observational and reanalysis data [e.g., *Hastenrath et al.*, 1987; *Curtis and Hastenrath*, 1995; *Nobre and Shukla*, 1996; *Enfield and Mayer*, 1997; *Hastenrath*, 2000] and is confirmed by several modeling studies [*Hameed et al.*, 1993; *Saravanan and Chang*, 2000]. However, most of these studies point out that the effects of the ENSO phenomenon on the tropical North Atlantic SST appear to be maximum

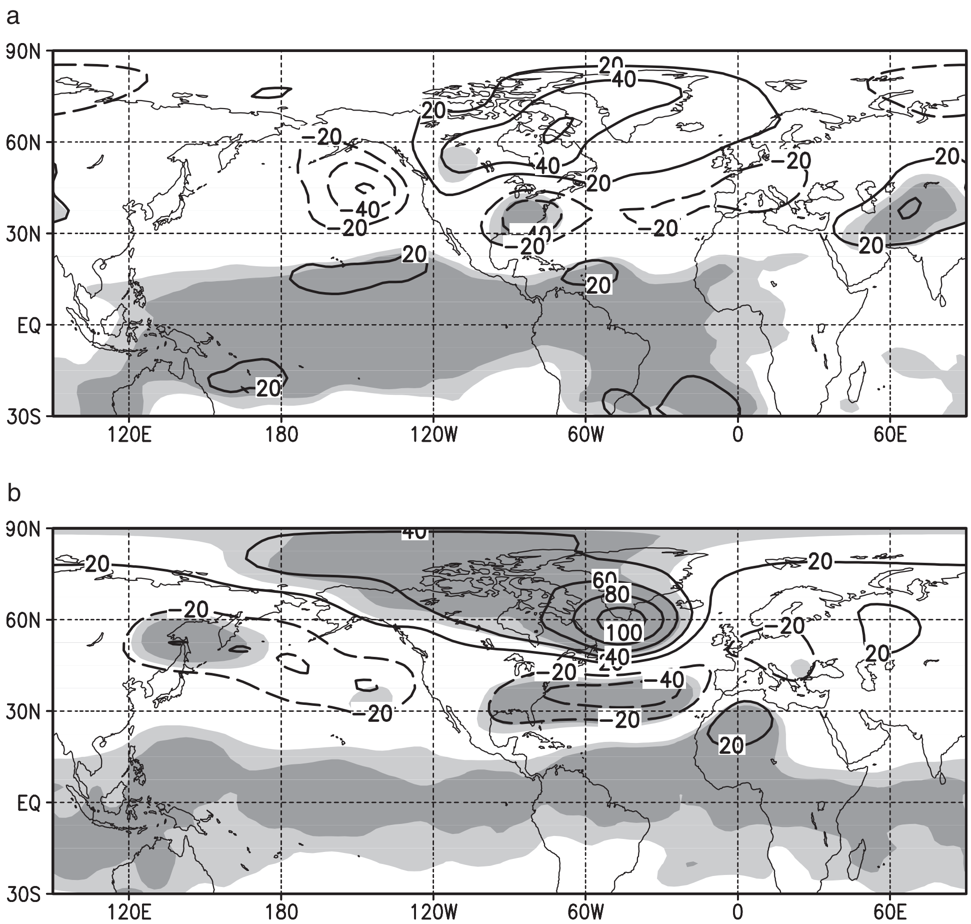

Figure 9. Linear regression coefficient (gpm/K) between the TNA SST index and the 500-hPa geopotential height field calculated from JFM seasonal means of NCEP reanalysis data, (a) for 1949–1968 and (b) for 1969–1998. Shading indicates that the correlation is significant above the 95% (light) and the 99% (dark) level. The linear trends are subtracted. The tropics are shown but are not discussed because of the lack of upper-air observational data in that region before 1958.

during the boreal spring season, i.e., several months after the mature phase of ENSO. Corresponding to that, we also find that the correlation between the NINO3.4 index and the SST increases to more than 0.7 in the western tropical Atlantic if the SST of the MAM season is regarded, that is, if the NINO3.4 index leads the SST by 2–3 months (not shown). The correlation patterns, however, are not very different and therefore are not discussed in the following.

[31] A remaining question is how the information is transferred from the tropical Pacific to the subtropical Atlantic. *Nobre and Shukla* [1996] and *Hastenrath* [2000] present evidence that a wave train-like teleconnection pattern, which extends from the tropical Pacific across North America to the North Atlantic, might be involved in connecting the two regions. A map of regression coefficients between the TNA SST index and the geopotential height of the 500-hPa level (Figure 9a) shows an extratropical wave train extending across North America with three major centers of action: a negative one over the southeastern United States, a positive one over Canada, and a negative one over the Northern Pacific. This wave train-like pattern is reminiscent of the blend of the Pacific/North American (PNA) and the Tropical/Northern Hemisphere (TNH) teleconnection patterns described by *Barnston and Livezey* [1987]. However, in Figure 9a, only the centers of action over Canada and over the southeastern United States are significantly correlated with the TNA SST index above the 99% level, and only the latter has a significant imprint on the 1000-hPa geopotential height (Figure 6a). Still, the strength of the correlations and regression coefficients increases if the geopotential height leads the SST by about 1 month, i.e., TNA index of the JFM season versus geopotential height of the DJF season (Figure 10). This is evident even over the midlatitude North Pacific. The latter center of action has also a stronger imprint on the corresponding correlation maps of the 1000-hPa geopotential height, where the correlation with the TNA index is about −0.6.

[32] A map of linear regression coefficients between the TNA SST index and the 500-hPa geopotential height for the period 1969–1998 (Figure 9b) does not show a clearly emerging correlation to a wave train-like pattern across North America. Instead, the regression pattern is again dominated by regional structures over the North Atlantic. Three meridionally arranged centers of action emerge: one over southern Greenland, one over the subtropical North

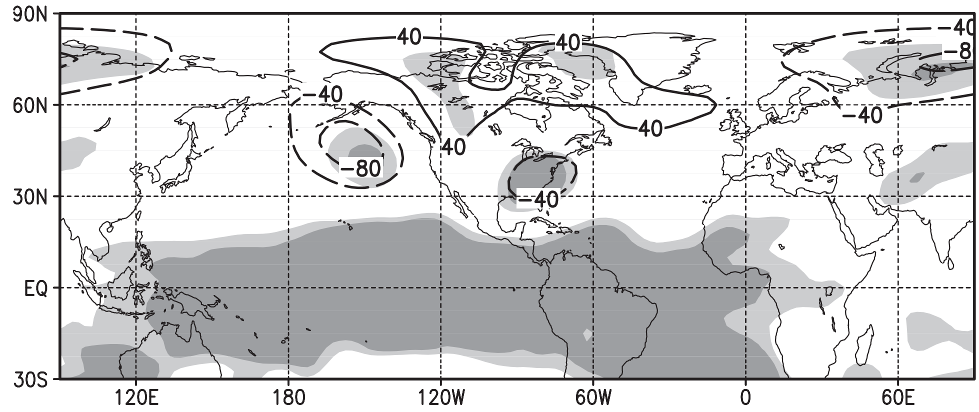

Figure 10. Linear regression coefficient (gpm/K) between the TNA SST index of JFM season and the 500 hPa level geopotential height field of the DJF season calculated from NCEP reanalysis data for 1949–1968. Shading indicates that the correlation is significant above the 95% (light) and the 99% (dark) level. The linear trends are subtracted.

Atlantic, and a third one located over the tropical North Atlantic and northern Africa. Especially, the northernmost anomaly is much stronger than any anomaly in the map for the period 1949–1968 (Figure 9a). Hence, during the period 1969–1998, the regional atmospheric circulation pattern in the North Atlantic sector obviously surpasses a possible imprint of the tropical Pacific variability on the North Atlantic geopotential height (e.g., Figure 7b). However, an influence from the tropical Pacific is also present during that period. This is revealed by lagged correlations between TNA SST in spring and the 1000-hPa geopotential height in winter with maxima of more than 0.6 over the western tropical Pacific (not shown). However, this influence still appears to be weaker than the one from the regional circulation in late winter (JFM and following months with maximum correlations of more than −0.8 over the subtropical North Atlantic, not shown).

[33] In summary, it is determined from NCEP/NCAR reanalysis data that the wintertime correlation between the North Atlantic SST and the regional atmospheric circulation is not stationary: Since the recent decades (1969–1998), the North Atlantic SST is strongly related to the regional circulation in the North Atlantic sector, that is, to the NAO, which is characterized by pronounced decadal variability during this period. In contrast, the period 1949–1968 is characterized by a connection of, especially, the western tropical North Atlantic SST with the atmospheric circulation over the tropical Pacific.

4. Temporal Behavior During the Twentieth Century

[34] In the previous section, two periods of time with fixed boundaries were discussed separately. These periods

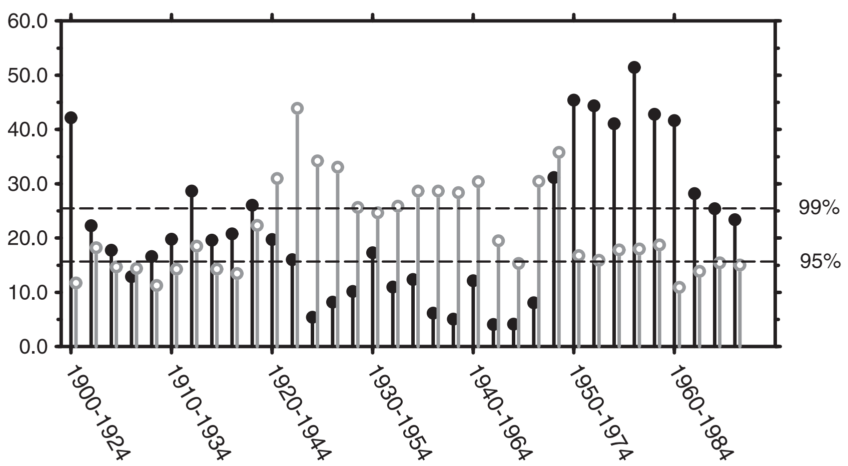

Figure 11. Percentage of variance of the JFM mean TNA SST index explained by the NAO index (black dots/vertical lines) and by the SST averaged over the NINO3.4 region (shaded circles/vertical lines). Each value is computed for a 25-year period. Only the results for periods beginning in even years are shown. The 25-year linear trends have been subtracted from the time series before calculating each correlation. The 99- and 95%-significance levels are also shown (dashed lines). The underlying SST data set has been derived by *Kaplan et al.* [1997, 1998].

were found to be characterized by different patterns of North Atlantic ocean-atmosphere covariability. In the following, we examine whether these two states inferred from NCEP/NCAR reanalyses can also be identified (in another data set) if the boundaries of the intervals are moved back or forth in time and if similar periods of covariability already appeared before the beginning of the NCEP/NCAR period. The SST data source used throughout this section is the Kaplan data set [*Kaplan et al.*, 1997, 1998].

[35] Both the first EOF of North Atlantic SST and the correlation pattern between the NAO index and North Atlantic SST are characterized by a tripole structure (not shown) similar to the corresponding patterns deduced from NCEP/NCAR reanalysis (Figure 3). From 1969 to 1991 the SST in each of the three centers is strongly correlated with the NAO index (±0.6, not shown). This is reflected by the percentage of variance of the TNA SST index explained by the NAO index. The values for periods starting in even years are shown in Figure 11 (black vertical lines). The NAO index and TNA SST index are significantly correlated above the 99% level for periods comprising the late 1960s/1970s and the subsequent years during that interval. Only a rather small fraction (<20%) of the TNA SST index variance can be explained by the variability of the NINO3.4 SST index (shaded vertical lines in Figure 11).

[36] In contrast, from the 1930s to the 1960s the NAO index is characterized by weak decadal variability and is, on the average, slightly negative (Figure 1). The correlation between NAO index and TNA SST index is rather weak; that is, most of the time the explained variance is below 15%, whereas a large fraction of the TNA SST variance can be explained by NINO3.4 SST variability (significant above the 99% level).

[37] Corresponding to the end of the twentieth century, the NAO index is also predominantly positive and characterized by pronounced decadal variability during the first 3 decades of the twentieth century (Figures 1 and 2). The fraction of variance explained by fluctuations of the NAO index is most of the time significant above the 95% level, although it is not as large as during the end of the twentieth century. For the period 1900–1924, the explained variance is about 40%. The fraction of TNA SST variance explained by the NINO3.4 SST fluctuations is most of the time below the 95%-significance level, in contrast to the subsequent decades.

[38] In summary, two periods are identified during which NAO index and tropical North Atlantic (TNA) SST are strongly correlated and influences from the tropical Pacific are weak ("regional periods"): One is from the 1960s/1970s to the end of the data record [1991], and there are indications for another one from the beginning of the twentieth century until the 1920s/1930s. During the latter period, however, the correlation with the NAO index is not as strong as at the end of the century. During these two periods, the NAO index shows pronounced decadal variability and is primarily positive. In the (global) period, i.e., from the 1930s to the 1960s, when the NAO index is characterized by weak decadal variability, the regional correlation between the NAO index and TNA SST is also weak. Correlations with the tropical Pacific SST (in terms of the NINO3.4 SST index) become more important for the tropical North Atlantic SST. Hence the results from the observational data set support the hypothesis gained from NCEP/NCAR reanalysis, proposing periods when the North Atlantic sector is dominated by regional correlations between atmospheric and oceanic variables (regional periods) and others, when remote connections with the tropical Pacific region are preferred (global periods). From Figure 11 one cannot infer when exactly, i.e., in which year, the transitions between the periods take place. However, the two transitions must have happened sometime during the 1920s and 1960s, respectively, possibly over several years.

5. Summary and Conclusions

[39] The North Atlantic Oscillation is associated with a basin-wide tripole sea surface temperature (SST) anomaly pattern in the North Atlantic. By means of linear correlation and regression analysis, applied to both NCEP/NCAR reanalysis and an optimally smoothed SST data set [*Kaplan et al.*, 1997, 1998], it is inferred that these correlations are not stationary. Two phases are identified, characterized by either a close or weak relationship between the NAO and, especially, the SST in the tropical North Atlantic (regional or global periods). A close relationship (regional period) is observed during the recent decades (since the 1960s/1970s) and, in outlines, during the first 3 decades of the twentieth century. The NAO index then shows enhanced variability on the decadal timescale and is predominantly positive. In contrast, the regional circulation over the North Atlantic is of minor importance for the North Atlantic SST from the 1930s to the early/mid 1960s. Effects from outside the North Atlantic region, particularly from the tropical Pacific, dominate (global period). During this period, the SST in the tropical North Atlantic (TNA) is strongly correlated with both the SST in the central/eastern and the (low level) geopotential height in the western tropical Pacific. This indicates a connection with the El Niño/Southern Oscillation (ENSO) phenomenon. The tropical North Atlantic SST is then correlated with a wave train-like pattern, which extends from the tropical Pacific over the extratropical Northern Pacific and North America to the western part of the tropical North Atlantic region. In years of warm (cold) SST in the tropical Pacific, the latter goes along with a weakening (strengthening) of the North Atlantic subtropical high and, thus, of the northeast tradewinds over the tropical North Atlantic (not shown). The wave train-like pattern is reminiscent of a blend of the Pacific/North American (PNA) and the Tropical/Northern Hemisphere (TNH) pattern presented by *Barnston and Livezey* [1987], who argue that the blend of the mutually independent patterns is an artifact of averaging. Both patterns can be associated with variability in the tropical Pacific region, i.e., also with ENSO (*Mo and Livezey* [1986]). Although a link via a wave train-like teleconnection pattern across North America has also been proposed by *Nobre and Shukla* [1996] and *Hastenrath* [2000], additional studies are required on possible mechanisms of transferring information from the tropical Pacific to the North Atlantic.

[40] The time period covered by the data sets used for this study is too short to prove that the identified periods are atmospheric regimes. However, findings from *Raible et al.* [2001], who examined a 600-year experiment with the coupled GCM ECHAM4/HOPE, agree with our results. They identified two regimes of North Atlantic atmos-

phere-ocean interaction connected with the decadal variability of the NAO: Periods of enhanced decadal variability of the NAO index were characterized by strong correlation of the North Atlantic SST and the NAO index, whereas periods of low decadal variability of the NAO index were characterized by a dominant PNA pattern linking the tropical Pacific and the North Atlantic region. Our results together with the findings of *Raible et al.* [2001] indicate that the atmosphere-ocean covariability in the North Atlantic sector may not be regarded as stationary.

[41] The periods we found to be characterized by different SST-atmosphere covariation match exactly with the periods of interdecadal North Atlantic SST variability defined by *Kushnir* [1994]. He remarked that the middle- and high-latitude North Atlantic SST is characterized by cold anomalies before 1920 and during the 1970s and 1980s and by warm anomalies from about 1930 to 1960. This interdecadal fluctuation is associated with a basin-scale pattern, which is largely of one polarity, and has maxima near Iceland, in the Labrador Sea, and northeast of Bermuda. *Kushnir* [1994] found that the atmosphere mostly damps the local interdecadal SST anomalies, except in the northern part of the North Atlantic, where the atmospheric circulation acts to maintain the SST anomalies. He argues that the interdecadal SST variability therefore may be governed by large-scale ocean dynamics. However, as discussed in the introduction, the role of oceanic forcing for the midlatitude atmospheric circulation is not yet clear.

[42] It is also conceivable that a change in the structure of the tropospheric circulation patterns may have lead to a change in ocean-atmosphere interaction. *Corti et al.* [1999] found that the years 1949–1970 were dominated by different modes of winterly 500-hPa geopotential height variability than were the years 1971–1994. H.-F. Graf and J. M. Castenheira (Structural changes of climate variability, submitted to *Journal of Geophysical Research*, 2001) showed that these two sets of variability modes can be related to regimes of either strong or weak stratospheric polar vortex. Moreover, observations show that the number of years with strong polar vortex has increased since the 1970s. A physical explanation for the changes in the atmospheric variability structures is presented by *Perlwitz and Graf* [2001], who showed that the reflection-transmission properties of vertically propagating tropospheric waves are considerably different in weak and strong polar vortex regimes. However, further studies are necessary to determine how the altered reflection/transmission properties of the vertically propagating waves exactly influence the structure of the NAO. If tropospheric circulation patterns change in the North Atlantic sector, it is feasible that the oceanic feedback to the atmosphere might be influenced. This may result in a stabilization (destabilization) and a strengthening (weakening) of the regional atmosphere-ocean interaction in the North Atlantic sector so that influences from the tropical Pacific become less (more) important.

[43] It is further conceivable that, if the atmospheric circulation shows pronounced decadal variability, the correlation between NAO index and North Atlantic SST is more intense due to the longer timescales of the ocean. The ocean is then able to develop larger SST anomalies reaching into deeper layers. The temperature anomalies may therefore be long-living, i.e., persist for several winters. Decadal cycles as described by *Grötzner et al.* [1998] may evolve, resulting in a decadal forcing of the atmosphere.

[44] From our results alone we cannot determine the physical mechanisms leading to a transition between the two phases of North Atlantic atmosphere-ocean covariability or what the role of the greenhouse effect is. It is necessary to examine whether the observed changes in the atmospheric circulation patterns and/or the different timescales of the NAO variability can change the oceanic response in a way that can account for the different phases of covariation. Both topics can be treated, for example, with experiments applying ocean models forced by the different observed circulation patterns with different temporal variability spectra.

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H.-F. Graf and K. Walter, Max-Planck-Institut für Meteorologie, Bundesstraße 55, D-20146 Hamburg, Germany. (graf@dkrz.de; katrin.walter@dkrz.de)