NOTES AND CORRESPONDENCE

Observed Atlantic SST Anomaly Impact on the NAO: An Update

CLAUDE FRANKIGNOUL

LOCEAN/IPSL, Université Pierre et Marie Curie, Paris, France

ELODIE KESTENARE

LEGOS/OMP/UMR5566, Toulouse, France

(Manuscript received and in final form 16 March 2005)

ABSTRACT

The Pan-Atlantic sea surface temperature (SST) anomaly pattern that was found in a previous study to have a significant impact on the North Atlantic Oscillation (NAO) in early winter seemed to reflect the nearly uncorrelated influence of a horseshoe SST anomaly in the North Atlantic and an SST anomaly in the eastern equatorial Atlantic. A lagged rotated maximum covariance analysis of a slightly longer dataset shows that the horseshoe SST anomaly influence is robust, but it deemphasizes the center of action southeast of Newfoundland, Canada. On the other hand, it suggests that the link between equatorial SST and the NAO was artificial and due both to ENSO teleconnections and the orthogonality constraint in the maximum covariance analysis.

1. Introduction

By investigating the covariability between SST and tropospheric anomalies when SST leads by more than the atmospheric persistence, Czaja and Frankignoul (1999) showed that North Atlantic SST anomalies had some predictive skill of atmospheric anomalies during certain seasons. In particular, a so-called horseshoe SST anomaly in summer and fall was associated with the North Atlantic Oscillation (NAO) in early winter. Drévillon et al. (2001), Czaja and Frankignoul (2002, hereafter CF), and others have confirmed and refined this finding. In a maximum covariance analysis (MCA) of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), CF suggested that the early winter NAO was also influenced, but to a lesser extent and in a nearly uncorrelated way, by an SST anomaly that was centered in the eastern equatorial Atlantic and resembled the zonal equatorial (or Atlantic Niño) SST mode. Sensitivity studies with atmospheric general circulation models show somewhat conflicting results because they either point to the Tropics/subtropics (Sutton et al. 2001), the midlatitude storm track (Peng et al. 2003), or the equatorial region (Drévillon et al. 2003) as the dominant center of Atlantic SST influence on the extratropical atmosphere. It is, thus, of interest to clarify the relative importance of the SST centers of action in the observations.

In CF, the horseshoe and equatorial SST anomaly influence distinctly appeared in separate MCAs with only extratropical or tropical SST anomalies, but the MCA was unable to separate them when SST was considered between 20°S and 70°N, resulting in a Pan-Atlantic SST anomaly pattern. Because it could be a result of the spatial orthogonality of the maximum covariance patterns, we use a rotated MCA that removes the orthogonality constraint and has been found to better separate different physical modes (Cheng and Dunkerton 1995). To better single out the influence of the Atlantic, we also remove the ENSO teleconnections prior to the analysis.

2. Data and method

Monthly geopotential height anomalies at 500 mb (hereafter Z500) and SST anomalies in the ice-free ar-

Corresponding author address: Claude Frankignoul, LOCEAN/IPSL, Université Pierre et Marie Curie, case 100, 4 place Jussieu, 75252 Paris Cedex 05, France.
E-mail: cf@lodyc.jussieu.fr

eas of the Atlantic, north of 20°S, were taken from the 1958–2002 NCEP–NCAR reanalysis, extending CF's analysis by 5 yr. To reduce the influence of trends and low-frequency changes, a third-order polynomial was removed by least squares fit. Some of the ENSO influence was also removed. ENSO was defined by the first two principal components of the monthly SST anomalies in the tropical Pacific between 12.5°N and 12.5°S. Seasonally varying regression coefficients were determined by least squares fit for each variable and grid point, using successive sets of 3 months to get smoothly varying estimates. To take into account the phase asymmetry of the ENSO signal, the regression was done separately for positive and negative values of the principal components. This seems well adapted because the ENSO teleconnection pattern changes between El Niño and La Niña conditions, but depends linearly on the tropical heating in the former case, and is independent of it in the latter one (Straus and Shukla 2002). The amount of removed variance only exceeds 20% for SST north of South America and is less than 20% for Z500, except in the Tropics, where it reaches up to 45% off of equatorial South America.

The MCA isolates pairs of spatial patterns and their associated time series by performing a singular value decomposition of the covariance matrix between two fields. Each field is expanded into orthogonal patterns that optimize their covariance, with the time series being orthogonal to one another between the two fields. As discussed in Cheng and Dunkerton (1995), pairs of patterns that are more geographically localized and easier to interpret physically can be obtained by applying a varimax orthogonal rotation to a subset of singular vectors, thereby creating spatial patterns that are no longer orthogonal within each field, but tend to have a larger amplitude in the regions where the covariance between the two fields is large. Here, the varimax rotation is performed using the first eight pairs of MCA modes that generally represented between 95% and 98% of the square covariance (SC). The results were largely insensitive to an increase in the number of pairs, but were sometimes slightly different with less than seven pairs. To establish whether the MCA modes are meaningful, statistical significance was estimated using a moving-blocks bootstrap approach (von Storch and Zwiers 1999) as in CF: each MCA was repeated 100 times, linking the original SST anomalies with randomly scrambled atmospheric ones based on blocks of two successive years to reduce the influence of serial correlation. Because rotation redistributes the SC between a subset of pairs, statistical significance was estimated prior to rotation. The quoted significance levels indicate the percentage of randomized SC and correlation for the corresponding mode that exceed the value being tested. It is an estimate of the risk of rejecting the null hypothesis (Z500 and SST are independent) when it is in fact true, following the standard statistical convention. A smaller significance level indicates the presence of stronger evidence against the null hypothesis than a larger one.

Here we only consider Z500 in November–December–January (NDJ) and we focus on the negative lags when SST leads. We show homogeneous maps for SST and heterogeneous maps for Z500 (the projection of both fields onto the SST time series), referred to as maximum covariance patterns, which preserve linear relations between the variables (see CF).

3. Pan-Atlantic air–sea interactions

Figure 1 (left) shows the maximum covariance patterns of the first MCA mode in the 20°S–70°N domain for the negative lags that are better than 10% significant in SC (as in CF, the second mode is not significant). A Pan-Atlantic SST anomaly in summer and fall that combines the horseshoe and the zonal equatorial SST modes is correlated with the early winter NAO. The patterns are similar to those in CF, but adding 5 yr to the NCEP–NCAR data has reduced the magnitude of the SC by 30%–40%, depending on the season. To a lesser extent, the correlation is also smaller, and, at several lags, the estimated significance level is larger. The Atlantic SST influence on the NAO may, thus, vary with the time period considered. A lagged MCA of subsets of the data suggests that the strongest oceanic influence occurred in the 1980s and 1990s.

The varimax rotation has practically no influence on the maximum covariance patterns at lag ≥ 0 (not shown), but it alters the SST anomaly pattern when SST leads by more than 1 month (lag 1, in part, reflects the atmospheric forcing of the SST), while affecting little the atmospheric pattern. Between lag 2 (similar to lag 3, but less significant) and 5, rotation singles out the horseshoe SST anomaly, also reducing its amplitude southeast of Newfoundland and enhancing it off Western Europe at lag3, and off Africa at lag4 and 5 (Fig. 1, right). The zonal equatorial SST mode has been eliminated, and it does not appear in the second rotated mode. At lag6 [SST in May–June–July (MJJ)] when the equatorial SST signal is strongest, however, rotation only reduces the amplitude of the equatorial SST. Because significance is limited and no corresponding covariability is found when reducing the SST domain to

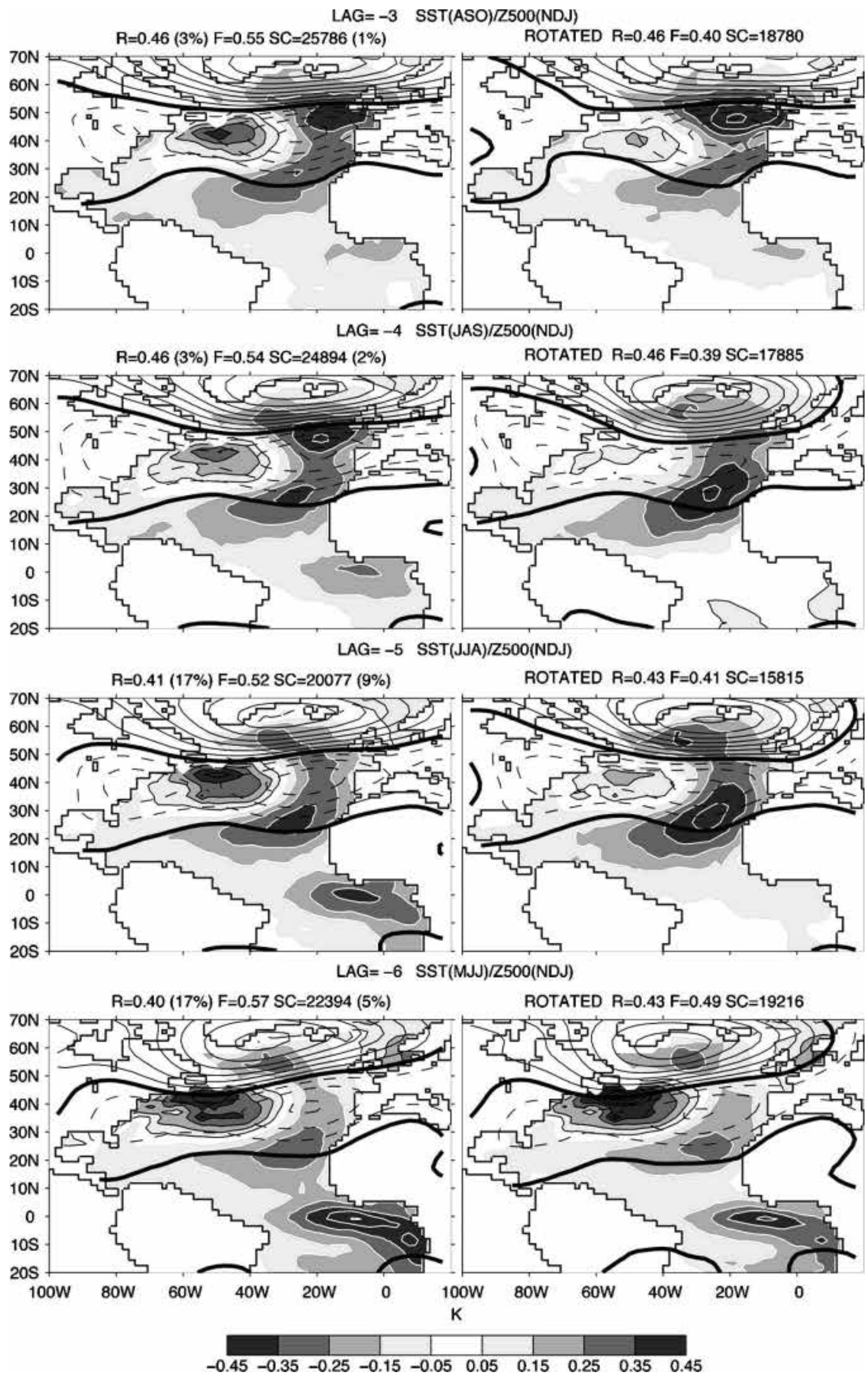

FIG. 1. Maximum covariance pattern for NDJ Z500 (contour interval 5 m with negative values dashed) and SST (grayscale in K with white contours for positive values and black contours for negative values) anomalies for the first mode at lags −3 to −6 (SST leads) (left) without and (right) with rotation. The correlation *R* between the MCA time series, the SC fraction *F,* and the SC are given for each lag, as well as the estimated significance level (in parentheses).

20°S–20°N, the lag-6 Pan-Atlantic pattern is probably artificial and a result of the limited sample.

The regression that is used to remove the ENSO influence indicates that the strongest SST signals associated with El Niño are 1) a strong warming off of western Africa between January–February–March (JFM) and April–May–June (AMJ), and 2) a cooling off of the coast of South Africa and in the Gulf of Guinea be-

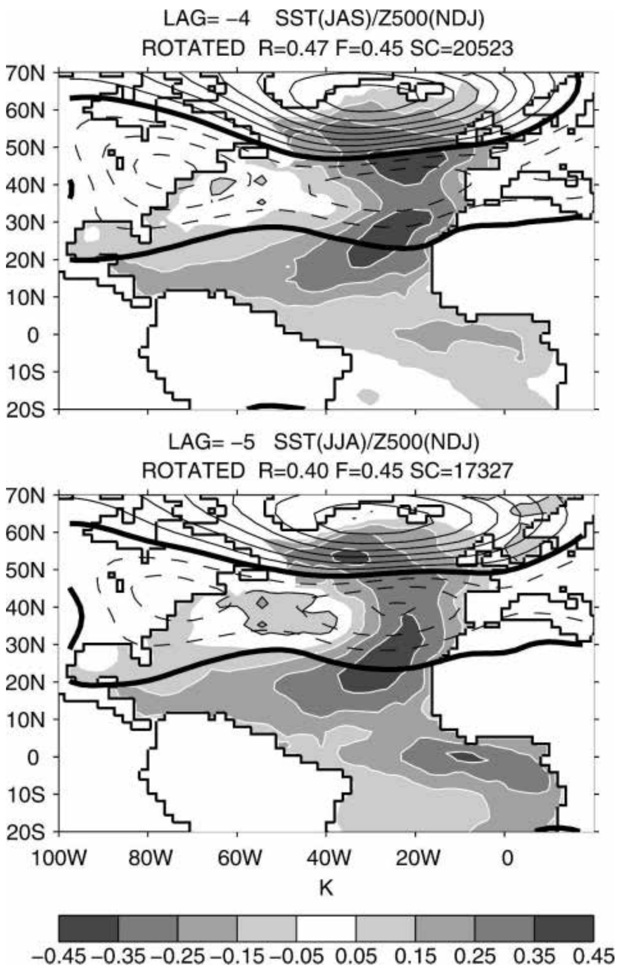

FIG. 2. As in Fig. 1 (right) for lags −4 and −5 when ENSO is not removed.

tween February–March–April (FMA) and MJJ. The signals are opposite during La Niña, except that 2 is delayed by 2 months. Yet, ENSO removal had little impact in the standard MCA analysis. However, it significantly affected the rotated patterns: when ENSO is not removed, rotation only slightly decreases, but does not eliminate, the equatorial part of the SST anomaly (Fig. 2). The ENSO teleconnections should, thus, be removed to single out the intrinsic Atlantic air–sea interactions.

4. Equatorial SST forcing

When the SST domain is limited to 20°S–20°N, the first MCA mode shows that the zonal equatorial SST mode leads a NAO-like signal at lag 1 and 2. The patterns (Fig. 3, left) are very similar to those in CF, but the SC and the correlation are smaller, and the significance level is larger, because of both ENSO removal and inclusion of the 1998–2002 data. Contrarily to the Pan-Atlantic case, the second MCA mode in the tropical case is also significant, and it shows an SST anomaly dipole.

To investigate whether the SST monopole (mode 1)–dipole (mode 2) pair is robust, or results from the spatial orthogonality, a rotated MCA was performed. As shown in Fig. 3 (right), rotation separates at both lags the equatorial part of the SST signal from its north tropical part. This may be expected, but, interestingly, the first rotated MCA mode corresponds to the horseshoe SST–NAO mode discussed above, even though SST is only considered south of 20°N, and the correlation is higher than in the standard MCA. The equatorial SST signal is found in the second rotated mode, but it is associated with a Z500 anomaly that is rather similar to the eastern Atlantic pattern. Because statistical significance is limited and the correlation is low, the second rotated mode seems of little interest, even if it were reflecting a true relationship. In any case, the apparent influence of the equatorial SST on the NAO has again disappeared.

Note that performing a rotated MCA is not equivalent to performing regional MCAs, because the latter can still be affected by the spatial orthogonality constraint. The results might, perhaps, depend on the rotation technique, but rotation provides an easy way to assess the robustness of MCA patterns.

5. Conclusions

Removing the orthogonality constraint in the MCA and using a slightly longer dataset than in CF confirms the influence of the North Atlantic horseshoe SST anomaly on the NAO in early winter. It suggests that the main SST center of action is in the eastern subtropical Atlantic at a few months lead and deemphasizes that southeast of Newfoundland. Because a third-order polynomial had been removed from the anomaly time series, the signal is not the result of trends and interdecadal variations as in van den Dool et al. (2004), but, rather, of the interannual variability (see also Fig. 6 in CF). As discussed, for example, in Cassou et al. (2004), the horseshoe SST anomaly is a summer mode that is driven by the atmosphere and persists until late fall, when the atmospheric conditions become favorable to its forcing the NAO via an interaction with the synoptic eddies.

It is comforting that the horseshoe SST anomaly influence is found to be robust at a time when atmospheric models are beginning to reproduce its impact (see also Rodwell et al. 2004). On the other hand, the influence of the zonal equatorial Atlantic (or Atlantic

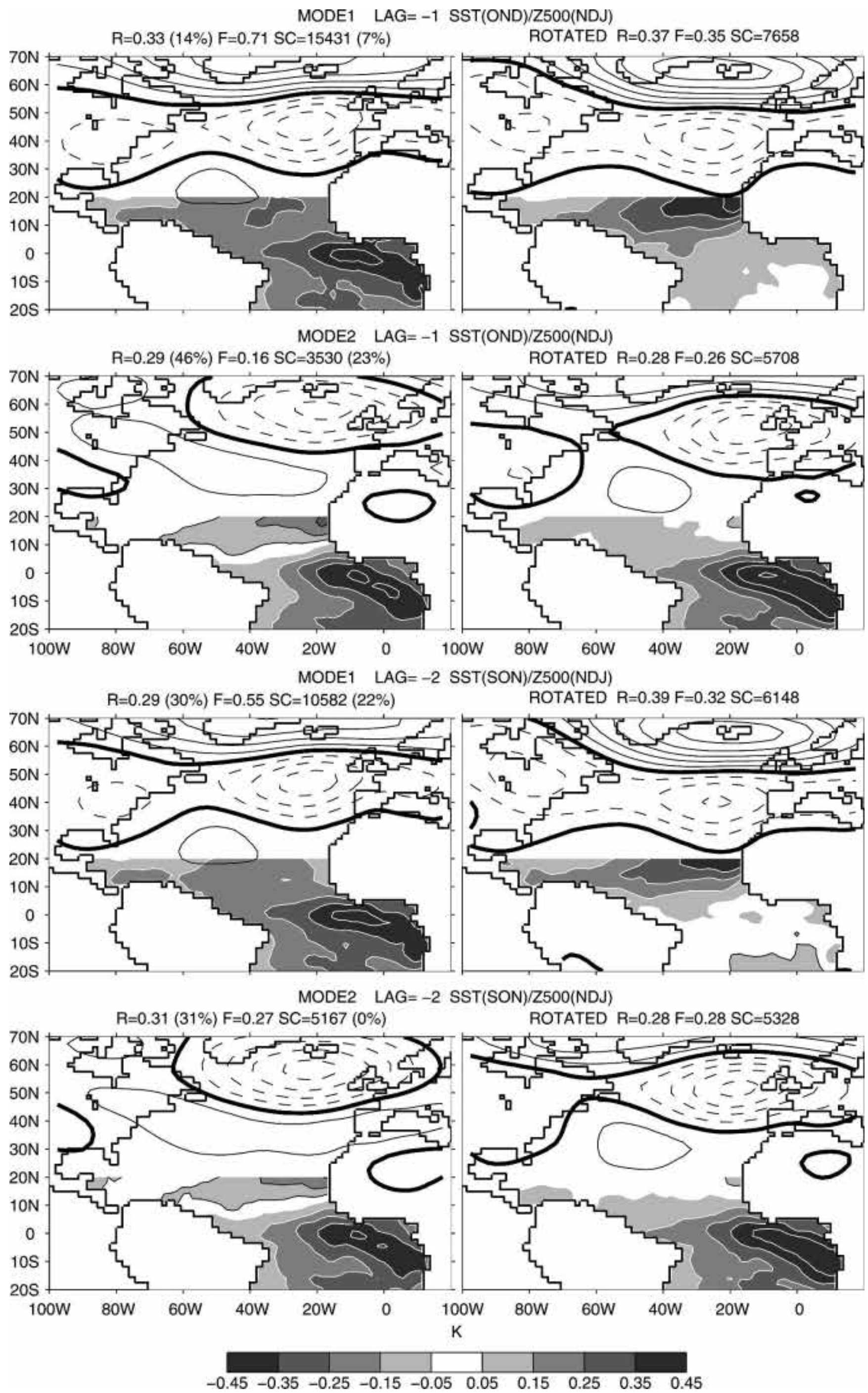

FIG. 3. Maximum covariance pattern for Z500 anomalies in NDJ and tropical SST anomalies at lags (top two panels) −1 and (bottom two panels) −2 for modes 1 and 2 (left) without and (right) with rotation. See Fig. 1 for notations.

Niño) SST mode on the NAO that was detected in CF is artificial and, in part, linked to ENSO teleconnections. There is also no evidence that the fall equatorial SST triggers the midlatitudes via Rossby wave propagation, as in the simulations of Drévillon et al. (2003).

Acknowledgments. Thanks to Nathalie Sennéchael for her help. The NCAR–NCEP reanalysis data were provided through the NOAA Climate Center (information online at http://www.cdc.noaa.gov/). Support to CF from the Institut Universitaire de France and NSF

Grant 826778005410 at the Woods Hole Oceanographic Institution is acknowledged.

REFERENCES

Cassou, C., C. Deser, L. Terray, J. W. Hurrell, and M. Drévillon, 2004: Summer sea surface temperature conditions in the North Atlantic and their impact upon the atmospheric circulation in early winter. *J. Climate,* **17,** 3349–3363.

Cheng, X., and T. J. Dunkerton, 1995: Orthogonal rotation of spatial patterns derived from singular value decomposition analysis. *J. Climate,* **8,** 2631–2643.

Czaja, A., and C. Frankignoul, 1999: Influence of the North Atlantic SST on the atmospheric circulation. *Geophys. Res. Lett.,* **26,** 2969–2972.

——, and ——, 2002: Observed impact of Atlantic SST anomalies on the North Atlantic oscillation. *J. Climate,* **15,** 606–623.

Drévillon, M., L. Terray, P. Rogel, and C. Cassou, 2001: Midlatitude Atlantic SST influence on European winter climate variability in the NCEP–NCAR reanalysis. *Climate Dyn.,* **18,** 331–344.

——, C. Cassou, and L. Terray, 2003: Model study of the wintertime atmospheric response to fall tropical Atlantic SST anomalies. *Quart. J. Roy. Meteor. Soc.,* **129,** 2591–2611.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Peng, S., W. A. Robinson, and S. Li, 2003: Mechanisms for the NAO responses to the North Atlantic SST tripole. *J. Climate,* **16,** 1987–2004.

Rodwell, M. J., M. Drévillon, C. Frankignoul, J. W. Hurrell, H. Pohlmann, M. Stendel, and R. T. Sutton, 2004: North Atlantic forcing of climate and its uncertainty from a multi-model experiment. *Quart. J. Roy. Meteor. Soc.,* **130,** 2013–2032.

Straus, D. M., and J. Shukla, 2002: Does ENSO force the PNA? *J. Climate,* **15,** 2340–2358.

Sutton, R. T., W. A. Norton, and S. P. Jewson, 2001: The North Atlantic Oscillation—What role for the ocean? *Atmos. Sci. Lett.,* **1,** 89–100.

van den Dool, H., A. Johansson, M. Chelliah, A. Shabbar, and S. Saha, 2004: Seasonal-to-decadal predictability and prediction of North American climate—The Atlantic influence. *CLIVAR Exchanges,* Vol. 9, No. 3, 23–25.

von Storch, H., and F. W. Zwiers, 1999: *Statistical Analysis in Climate Research*. Cambridge University Press, 342 pp.