Granger Causal Analysis between the NAO and SSTs in the North Atlantic basin

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ABSTRACT

This paper uses Granger causality test techniques to investigate the causal order of the air-sea interactions between the anomalous NAO index and the NCAR/NCEP SST anomalies over the northern hemisphere. Compared to the simple lead/lagged correlation, the Granger causality analysis is generally more reliable since it ensures that any apparent oceanic influence upon the atmosphere is uniquely provided by the ocean and is not related to preceding anomalies in the atmosphere itself (and vice versa when looking at the atmospheric influence upon the ocean). Using this technique, it is found that on seasonal timescales, preceding SST anomalies around the Gulf Stream region show significant Granger causality with the wintertime NAO. In contrast, the preceding NAO anomalies' influence on the wintertime SST field is rather restricted. Additional findings show that regions of the SST field can cause up to 20% of the variance in the winter NAO. Importantly the regions that show significant causality with the wintertime NAO are limited to the Gulf Stream extension. In contrast to simple correlation analysis, our analysis does not show significant causality related to SST anomalies in either the Greenland or subtropical regions. These results suggest that the Gulf Stream SSTs have an important influence in initiating disturbances of the atmospheric circulation over the wintertime North Atlantic. The dynamics related to this influence still need to be investigated further.

1. Introduction

The North Atlantic Oscillation (NAO), usually defined in terms of the difference in sea level pressure between Iceland and the Azores, is the prominent source of atmospheric variability over the North Atlantic region, especially in winter (Hurrell, 1995; Kushnir, 1999). In addition, it is well correlated with large-scale changes in sea surface temperatures (SSTs) across the basin (Bjerknes, 1964). However, the role that the air-sea interactions play in the dynamics of the NAO has not been fully understood. Although it is generally believed that the atmosphere forcing dominates in such interactions over the North Atlantic basin, generating the sea surface temperature (SST) anomalies through turbulent heat fluxes or anomalous wind stress (Frankignoul, 1985; Cayan, 1992), it is also suggested that the ocean participates in the dynamics through the influence of SST anomalies. Particularly, since the well mixed ocean upper layer has a large heat capacity, an oceanic thermal signal can persist for several months, allowing for a persistent thermal forcing of the overlying atmosphere (Frankignoul, 1985; Kushnir, et al., 2002).

Recently, evidence of the possible oceanic forcing of the NAO has been suggested by climate modeling studies (e.g., Rodwell et al., 1999) and studies using observational data (e.g., Czaja and Frankignoul, 1999, 2002, hereafter referenced as CF99 and CF02, respectively). In the latter studies, which used the maximum covariance analysis (MCA) technique, the authors found a significant correlation between the winter time NAO (the first MCA mode of 500-hPa anomalies in their analysis) and the leading mode of anomalous SST from the previous summer. The link between ocean and atmosphere at such long leads seems to be a result of the long persistence of the North Atlantic SST anomalies and thus serves as an evidence of the oceanic forcing of the NAO (Kushnir, et al., 2002).

However, generally the simple correlation analysis is not a satisfying method to assign causal order between highly coupled systems such as the atmosphere and the ocean. For example, although the wintertime NAO may be correlated with anomalous SSTs from earlier seasons, this correlation may be due to the persistence, or even influence, of preceding atmospheric anomalies, which also influenced the underlying SSTs during the previous seasons. Thus the analysis described above can not exclude the possibility that the apparent oceanic forcing signal is not uniquely provided by the ocean, but may also have existed within the atmosphere. Therefore, it is the purpose of this paper to introduce a new statistical technique, known as Granger Causality analysis, to address this question.

2. Methodology

For the purpose of causal order analysis, the two-way interactions between the anomalous NAO and each grid-point SST anomaly can be described using a vector autoregression (VAR) model as in equations (1) and (2),

$$NAO_t = \alpha_1 + \sum_{i=1}^{L} \beta_{1i} NAO_{t-i} + \sum_{i=1}^{L} \gamma_{1i} SST_{t-i} + e_{1t} \qquad (1)$$

$$SST_t = \alpha_2 + \sum_{i=1}^{L} \beta_{2i} NAO_{t-i} + \sum_{i=1}^{L} \gamma_{2i} SST_{t-i} + e_{2t} \qquad (2)$$

where α's, β's, and γ's are regression coefficients, e's are error terms, and L is the lag length, which can be determined using a likelihood ratio test developed by Sims (1980). The lagged terms in the equations are included because it is expected that the current (winter, for example) status of the seasonal NAO and SST anomalies depends on not only their concurrent interactions, but also their past status, i.e. from the previous fall, summer, and so on. Note that although the concurrent terms NAO_t and SST_t are absent on the right hand side, their effects still exist through the other regression coefficients (Enders, 1995).

The Granger causality test (Granger, 1969) is devised to analyze the causal order in such VAR models. To determine if the SST field has causal effects on the NAO, for example, the first step in the Granger causality test is to jointly restrict the coefficients of γ's in (1) to zero thus excluding the SST terms from (1) (Kaufmann and Stern, 1997), which then can be written as:

$$NAO_t = \alpha_1^{'} + \sum_{i=1}^{S} \beta_{1i}^{'} NAO_{t-i} + e_{1t}^{'} \qquad (3)$$

where the superscripts indicate that they are the restricted estimates of the coefficients. If the restricted model (3) explains about the same variance as the unrestricted model (Eq.1), it suggests that any precursor information contained in the SST field is also found within the preceding NAO anomalies as well, indicating that the wintertime NAO anomaly cannot be uniquely attributed to the preceding SSTs. Therefore, the second step is to evaluate quantitatively whether there is a significant difference between the unrestricted estimate from (1) and the restricted estimate from (3). A test statistic can be constructed as follows (Kaufmann and Stern, 1997):

$$\omega = \frac{(RSS_r - RSS_u)/s}{RSS_u/(T-k)}, \qquad (4)$$

where RSS means the sum of squared residuals with subscript 'r' and 'u' indicating the 'restricted' and 'unrestricted' versions, T is the number of observations, k is the number of regressors in the unrestricted equation (1), and s is the number of coefficients restricted to zero in (3). By definition, ω follows a standard $F(s, T\text{-}k)$ distribution. Note the null hypothesis here is that the SST field does not 'Granger cause' (hereafter 'cause' for simplicity) the NAO. Therefore, if the value of ω exceeds the critical value, it means the difference between the restricted and the unrestricted models are significant at the relevant level of significance, $p(F)$, in which case we should reject the null, or say that those SST grid-points cause variability in the NAO. Otherwise we have to accept the null that the SST field has no causal influence on the NAO. In the same way, we can also test if the NAO causes anomalies in the SST field.

It is important to emphasize that the difference in variance explained between the restricted and the unrestricted models, measured by the term $(RSS_r - RSS_u)$ in (4), is related to information uniquely contained in the lagged SST field since the atmospheric information is always included in both models. It is the explicit isolation of this unique information that is one of the desirable features of the Granger causality analysis compared to the simple correlation techniques.

At seasonal timescale, the models given by (1) and (2) need some adjustment before they can be applied to our practical problem. This is because equations (1) and (2) basically represent interactions that are symmetric over seasons, i.e., in these equations it is assumed the SST field interacts with the NAO in the same way during other seasons as it does in winter. However, this is generally not the case. Also, we are often more interested in the air-sea interactions during the winter when the NAO is most pronounced. Therefore, we modify model (1) and (2) as follows to explicitly fit our problem:

$$NAO_{Winter} = \alpha_{10} + \sum_{i=Fall}^{Spring} \beta_{1i} NAO_i + \sum_{i=Fall}^{Spring} \gamma_{1i} SST_i + e_{1t} \qquad (5)$$

$$SST_{Winter} = \alpha_{20} + \sum_{i=Fall}^{Spring} \beta_{2i} NAO_i + \sum_{i=Fall}^{Spring} \gamma_{2i} SST_i + e_2 \qquad (6)$$

The maximum lag length in (5) and (6) is set to 3, i.e. the previous spring. It should be noted that by rewriting the model in the form as (5) and (6), we actually break the time series into smaller subsets, one for each season (spring, summer, fall, and winter), each with their own coefficient. However, the Granger causality analysis of (5) and (6) still has clear physical meaning in that we are testing if there is unique information contained in the SST (NAO) field from previous seasons which is useful to predict the winter NAO (SST). It is recognized that "causality" within this context is a statistical quantity, not a physical one, that depends upon the appropriateness of the statistical models themselves; for instance, if variability in both the wintertime NAO and the preceding SSTs are actually the result of changes in sunspot activity, this model will erroneously attribute the causality to the SST field. At the same time, however, this causality test is more rigorous that simple lag correlation statistics in that it removes 'false positives' in which apparent lag relations are in fact the result of auto-correlation within the predicted field itself (see below).

3. Data sets

The NAO index time series used in this study is as defined in Hurrell (1995) and Jones et al. (1997). In addition, we use the NCEP/NCAR reanalysis monthly mean SST data set, which has global coverage with a spatial coverage of 192 (longitude) × 92 (latitude) grid points at Triangular-62 resolution (approximately 2 degrees in latitude and longitude). A description and evaluation of the reanalysis SST dataset can be found in Hurrell and Trenberth (1999). Both the NAO index and the SST data set have temporal coverage from 1/1948 to 12/2000 with monthly frequency. Monthly anomalies are created by subtracting the monthly climatology from the monthly data. In addition, a linear trend is removed from the anomalous NAO time series and SST time series at each grid point. The time series are then converted to seasonal data by averaging the 3 monthly values in the corresponding season. The seasons here are defined as: March, April, and May (MAM) for spring; June, July and August (JJA) for summer; September, October and November (SON) for fall; December, January and February (DJF) for winter. Therefore, the seasonal data sets have time coverage from 1948 spring to 1999 winter.

4. Analysis Results

We first regress the winter NAO index (Figure 1(a)) onto the concurrent (winter) SST field. The correlation map (Figure 1(b)) shows a well-known tripole pattern over the North Atlantic basin. In particular, over the southeast of Greenland ($50^oN - 65^oN$, $15^oW - 55^oW$) and in the subtropics ($10^oN - 25^oN$, $20^oW - 60^oW$) the SST is negatively correlated with the NAO, while between these two negative centers is a positively correlated area located over the extension of the Gulf Stream ($25^oN - 45^oN$, $30^oW - 60^oW$). This tripole pattern is consistent with many other studies mentioned above. For example, the leading MCA mode of SST in CF02, called the North Atlantic Horseshoe (NAH) pattern, has a similar structure but is shifted to the north east.

We apply the Granger causality test introduced above, based upon equations (5) and (6), to investigate the causal relations between the two fields. For SST anomalies at each grid point, we test both whether the NAO causes variability in the SSTs, and whether the SSTs cause variability in the NAO. The results are shown in Figure 2, where the shaded values represent $r_u^2 - r_r^2$, i.e. the difference between the r^2 statistic for the unrestricted and the restricted equations; this difference gives an estimate of the amount of variance in the wintertime NAO (SST) anomaly that can be explained uniquely by the preceding SST (NAO) fields. The white contour lines indicate the areas that passed the 95% significance test using the ω statistic introduced above. In panel (a) which tests if the NAO causes variability in the SSTs, we see that only over small and sparse areas does the previous NAO statistically significantly influence the wintertime SST field. In comparison, in panel (b) which tests whether SSTs cause variability in the NAO, we can see much more concentrated and consistent influences centered over the Gulf Stream area, where SSTs from previous seasons can explain up to 20% of the variance of the winter NAO. This region corresponds to the positive center on the correlation map (Figure 1) with a northeastern shift. In both panels, however, there are no important causal relations over Greenland or the subtropical regions. To verify these results, we run the Granger causality tests two more times and change the lag length at every grid point to 2 (the previous summer) and 4 (the previous winter). It is found that the NAO shows more influence on the SST field when the lag lengths increase to 4 (not shown), which may be the result of persistent subsurface temperature anomalies that re-appear the following winter (Rodwell and Folland, 2002). However, in testing if the SST causes the NAO, all results indicate a similar pattern as in Figure 2(b), i.e., SSTs around the Gulf Stream extension continue to have significant causal influence on the winter NAO.

The results of Figure 2 suggest that the status of the NAO during previous seasons is not useful in explaining winter time SSTs over most parts of the North Atlantic basin. In contrast, SSTs around the Gulf Stream from the previous summer and spring may contain information related to the NAO during the following winter, which is not found in the previous state of the atmosphere itself. The first result seems reasonable when we consider the temporal characteristics of the NAO. The persistence time-scale of the NAO is typically of the order of 20-30 days and the surface turbulent heat fluxes are dominated by short time scale weather changes (Frankignoul, 1985). Hence, even if the NAO strongly forces SST fluctuations, its influence would mainly produce weekly or monthly anomalies. For seasonal anomalies, the high frequency signals are filtered out, and the causal influence may be restricted. On the other hand, due to the large heat capacity of the ocean, an SST signal can persist for months to seasons. Therefore, it is possible for a persistent SST signal to initiate and force a seasonal-type anomaly in the atmosphere. The second result agrees with the study of CF02. In particular, the influencing center around the Gulf Stream region shown in Figure 2(b) is in agreement with the corresponding part of the NAH pattern in the previous study. Using the Granger causality technique, however, the apparent tripole pattern disappears. This discrepancy may be partially due to the fact that we test the whole SST field in our analysis instead of decomposing it into several leading modes. Further, it also suggests that the anomalous SSTs around the Gulf Stream may be more important in initiating disturbances of the atmospheric circulation over wintertime North Atlantic, while the tripole pattern may be the overall result of positive feedbacks [CF02] between these two fields (see below).

To evaluate the Granger causality results with those from simple correlation analysis, we calculate the correlation coefficients between the winter time NAO and SSTs from the previous fall and summer (Figure 3). In both panels the NAO time series is significantly correlated with the earlier SSTs around the Gulf Stream (the averaged value of the correlation coefficients *r* in this region is about 0.5). These results are in agreement with the result of Figure 2(b). However, it should be noted that such agreement does not always exist. As an example, the winter NAO is significantly correlated with grid-point SSTs during the following spring, i.e., when the NAO leads the SSTs by a season (not shown). However, the Granger causality test between the wintertime NAO and the following springtime SSTs (not shown) indicates that much of this lead correlation is actually related to the state of the wintertime SST field itself and therefore cannot be uniquely attributed to the preceding NAO field. As such, the Granger causality test is generally stricter and more reliable than simple lag correlations.

To further verify these results, we define three SST indices by spatially averaging SSTs over the previously-identified Greenland (GL) and Subtropical (ST) regions, which show significant concurrent correlations (Figure 1), along with the Gulf Stream region (GS) which shows significant causal relations (Figure 2). The area-averaged SST anomalies for the proceeding June-November are shown in Figure 4, along with the correlation coefficients for the wintertime NAO (separate values for each season are given in Table 1). It can be seen that all the concurrent SST indices are well correlated with the NAO in winter, with signs of the correlations in agreement with the negative-positive-negative tripole pattern. Among these indices, however, only the Gulf Stream SST region has significant correlations with the following winter NAO. In addition, Granger causality analysis also indicates only the GS SST 'causes' variability in the NAO (not shown). These results are in agreement with modeling work done by Wu and Gordon (2002), which indicated that the Gulf Stream variability in autumn could influence the wintertime atmosphere over the NAO region. Here we are seeing a very similar relationship within the observed and analyzed fields, indicating that such a mechanism may be operating within the actual ocean/atmosphere system as well. In addition, our results indicate that this process operates on interannual time-scales as well as the decadal/interdecadal time-scales described by Wu and Gordon (2002).

5. Conclusion

In the analysis above, we use Granger causality test techniques to investigate the causal order of the interactions between the NAO and SSTs. We found that although the concurrent correlation map of the winter time NAO and SSTs shows a well-known tripole pattern over the North Atlantic basin, the influences of the preceding seasons' NAO anomalies on the wintertime SST field are very limited. Instead, we find that the preceding state of the ocean shows a significant causal relation with the wintertime atmospheric circulation patterns. The main source for this influence appears to be centered over the Gulf Stream area. Although these results are in agreement with the simple correlation maps of the winter NAO and preceding SSTs from earlier seasons, we believe the results of Granger causality are more rigorous tests for causality within the coupled system. To further evaluate these results, we defined three SST indices by area-averaging the SSTs near the centers of the typical tripole pattern, including the Greenland (GL), the Gulf Stream (GS), and Subtropics (ST), respectively. We found that only the GS SST show significant lead correlation with the winter NAO. In addition, the GS index is also the only index that 'Granger causes' anomalies in the winter NAO. These results suggest that the anomalous Gulf Stream SSTs are most important in initiating disturbances of the atmospheric circulation over wintertime North Atlantic. In addition, these results suggest that the full tripole pattern (for instance, as identified in CF02) may instead represent the overall effect of positive feedbacks between the ocean and the atmosphere in this region. The ocean/atmosphere dynamics related to these different processes still need to be investigated, however using the Granger causality test in this context, it appears we have been able to better delineate possible sources of forcing within this coupled system.

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FIGURE CAPTIONS

FIG 1. (a) The wintertime (DJF) NAO, normalized such that the variance is unity; (b) concurrent correlation map of NAO and SSTs during wintertime. Thick white lines represent values with significance greater than 95% percentile.

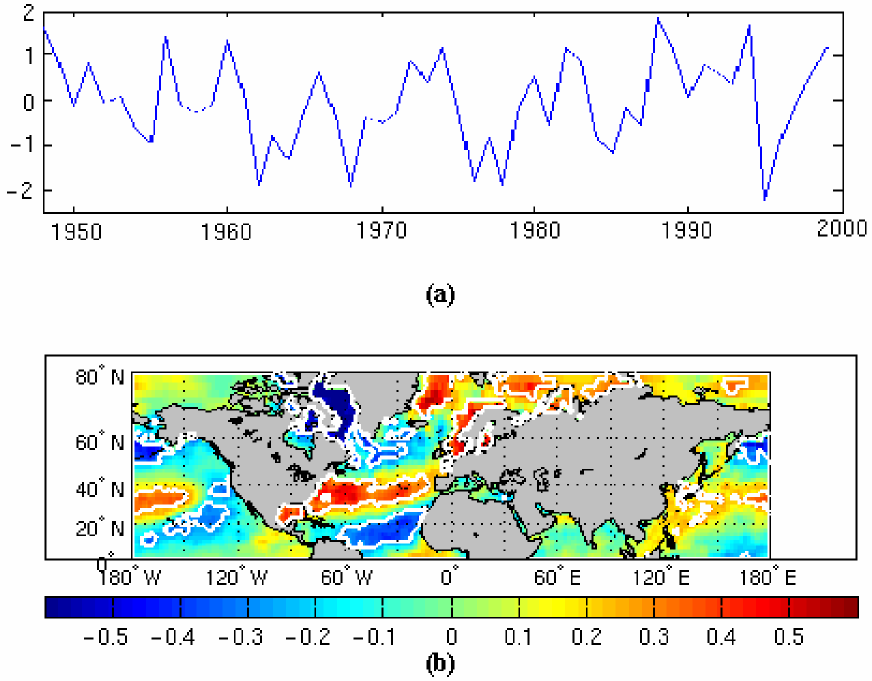
FIG 2. Granger causality analyses using seasonal data, for the winter (DJF): (a) SST grid-point variability 'caused' by NAO; (b) NAO variability 'caused' by each SST grid-point. The color bar shows the value of $(r_u^2 - r_r^2)$ and the white contour shows the 95% significant level tested using the ω statistic. The meaning for these statistics is explained in the text.

FIG 3. Correlation of the winter time NAO and previous SSTs: (a) SSTs from SON (b) SSTs from both JJA and SON. In both figures, thick white lines represent values with significance greater than 95% percentile.

FIG 4. Correlation of the winter NAO (DJF) and the SST indices averaged through June to November: (a) Greenland; (b) Gulf Stream; (c) Sub-Tropics. See text for averaging domains. All of the indices are normalized such that they have unit variance.

TABLES

TABLE 1. Correlation coefficients between the wintertime NAO and SST indices of different seasons. Significant (95% level) values are in bold font.



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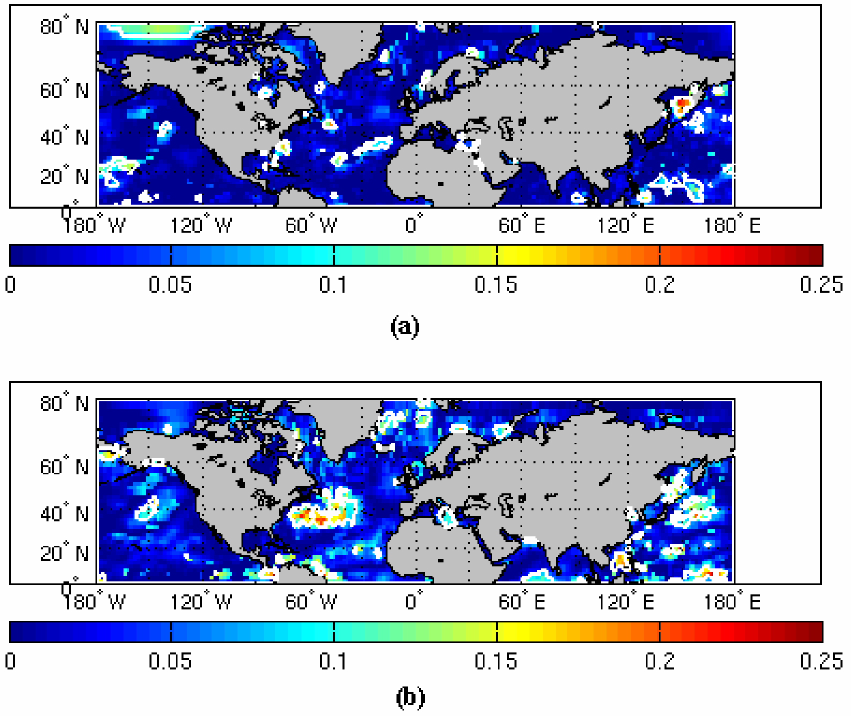

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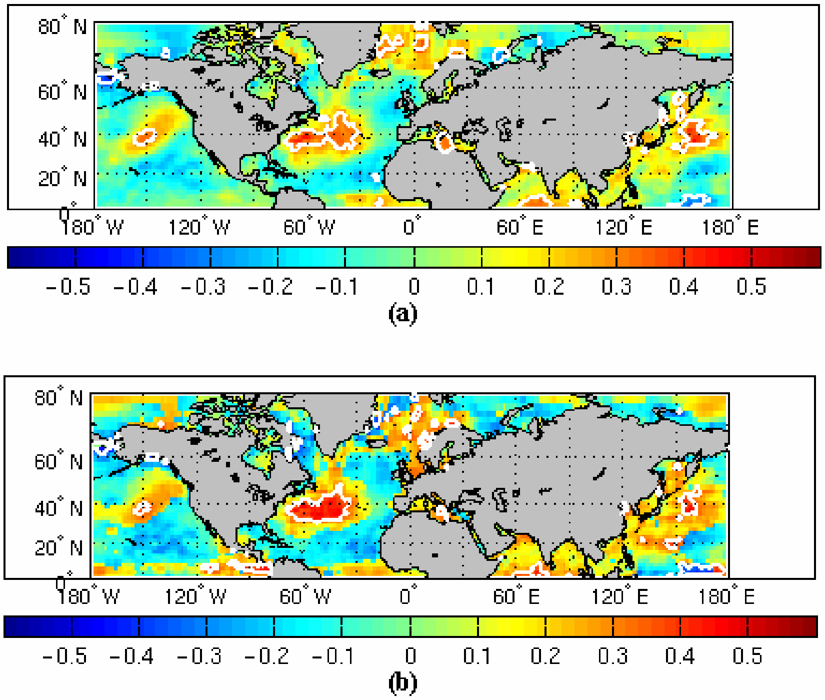

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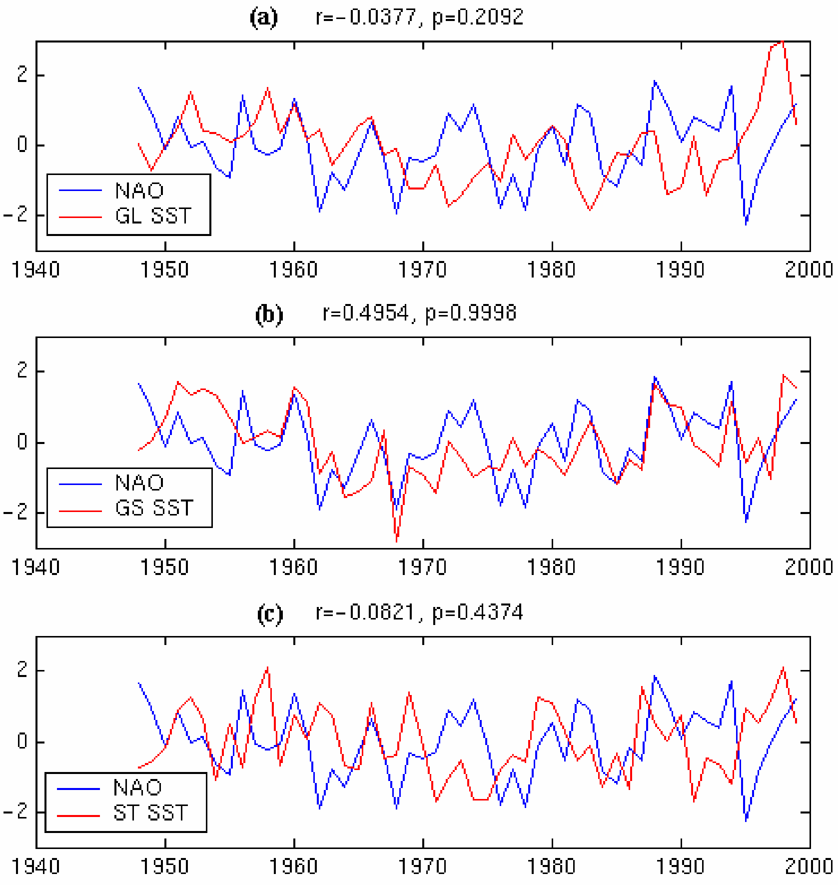

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TABLE 1. Correlation coefficients between the wintertime NAO and SST indices of different seasons. Significant (95% level) values are in bold font.

	Spring	**Summer**	**Fall**	**Winter**
GL SST	-0.1136	-0.1038	0.0362	**-0.3246**
GS SST	0.2584	**0.4895**	**0.4778**	**0.4284**
ST SST	0.1357	-0.0334	-0.1289	**-0.3848**