The Coupled Patterns between Sea Level Pressure and Sea Surface Temperature in the Midlatitude North Atlantic

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ABSTRACT

Monthly variability of atmosphere-ocean interactions in the midlatitude North Atlantic during the winter months (November-April) is examined. Composite and singular value decomposition (SVD) analyses are applied to the observed sea level pressure (SLP) and sea surface temperature (SST) anomalies of each winter month for the period 1950-1987. The SLP anomaly composites (i.e., SLP differences between selected warm and cold SST months) are constructed based on the averaged SST anomalies over the RM region (60°-40°W and 50°-40°N). These composites shift from a positive monopole pattern in early winter to a dipole pattern in midwinter and then back to a monopole pattern in late winter.

A complementary SVD analysis reveals that the first SVD mode is dipole structured and especially dominant in midwinter. The second SVD mode is monopole featured and more dominant in early and late winter than in midwinter. By examining the spatial distributions of the SVD modes and especially their similarities to the patterns derived from other model simulations, two coupling processes are suggested. The dipole mode is suggested to be related to an atmosphere driving the ocean process and the monopole mode to an ocean forcing the atmosphere process. The month-dependency and the statistical significance of the SVD modes are subjected to two Monte Carlo tests. The results are used to further explain the shifts in the SLP anomaly composites and to indirectly estimate the predominance of the proposed coupling processes during each winter month.

1. Introduction

The predictability of low-frequency climate fluctuations associated with atmosphere-ocean interactions has become one of the major concerns in climate research. One crucial challenge is to understand to what extent the atmosphere is responding to ocean forcing as opposed to internal dynamics. Although the effect of tropical sea surface temperature (SST) anomalies on atmospheric interannual variations is relatively well known, the impact of midlatitude SST forcing is still unclear. Observational studies seem to have provided more evidence in suggesting the atmosphere driving the ocean than the ocean forcing of the atmosphere (e.g., Ratcliffe and Murray 1970; Davis 1976, 1978; Namias 1976; Palmer and Sun 1985; Wallace and Jiang 1987; Zorita et al. 1990; Deser and Blackmon 1993). General circulation model (GCM) experiments that investigate atmospheric responses to prescribed SST anomalies do not present a robust picture in the midlatitudes (e.g., Houghton et al. 1974; Palmer and Sun 1985; Pitcher et al. 1988; Lau and Nath 1990; Kushnir and Lau 1992; Ferranti et al. 1994; Latif and Barnett 1996). Dispersion observed in these GCM experiments particularly brings into question the significance of midlatitude SST forcing. However, a recent modeling study by Peng et al. (1995) suggests that disagreements among some of the GCM experiments may be related to a strong monthly variability in the midlatitude coupled system.

Using a global spectral forecast model, Peng et al. (1995) shows that the winter atmospheric response to the SST anomalies prescribed in the midlatitude North Atlantic varies significantly from month to month. With an identical warm SST anomaly pattern specified in the northwest Atlantic, an anticyclonic response is obtained in the perpetual November simulations and a cyclonic response in the perpetual January simulations. Diagnoses of heat advection in these experiments reveals that the anomalous anticyclone in November would act to maintain the warm SST anomaly if the model is coupled to an active ocean (see also Latif and Barnett 1996), whereas the cyclone in January would offset the SST anomaly. A follow-up study, using a
linear baroclinic model, demonstrates that the two responses are sustained by anomalous eddy vorticity fluxes associated with different jet stream modifications (Ting and Peng 1995).

The question remains: to what extent does this large month to month variability found in the idealized model experiments reflect nature where the atmosphere fully interacts with the ocean? A simple data analysis is performed in Peng et al. (1995) for November and January using the observed sea level pressure (SLP) and sea surface temperature (SST) records. The SLP anomaly composites for the warm SST November months and warm January months exhibit different anomaly features as well. This composite analysis is simple but indicative of a strong monthly variability in nature. Clearly, a thorough observational study is required to follow monthly variations of atmosphere–ocean interactions during the entire cold season (November–April).

The purpose of this study is to investigate how the atmosphere interacts with the ocean during each winter month in the midlatitude North Atlantic. In particular, we wish to determine how the interactions change from month to month. Initially, to evaluate the monthly variations of the SST-related SLP anomalies we perform a direct composite analysis for each month from November to April using the observed SLP and SST data. Next, we apply a singular value decomposition (SVD) analysis to find the coupled SLP and SST patterns. By inspecting the spatial distributions of the coupled patterns and especially their similarities to the patterns derived from other model simulations, two physical processes are suggested to be associated with the leading SVD modes. The SVD modes are then subjected to two Monte Carlo significance tests. The first test determines whether the SVD modes are significantly month dependent during the cold season. The second test determines whether the leading SVD modes in each month are statistically significant, and hence it indirectly estimates the predominance of the proposed coupling processes.

The data and methodology used in our analyses are described in section 2. Results from composite and SVD analyses are presented in section 3 and 4. A synopsis of the study and concluding remarks are provided in section 5.

2. Data and methodology

a. Data

The datasets we employ in our study include sea level pressure (SLP) from the National Center for Atmospheric Research (NCAR), sea surface temperature (SST) from the Comprehensive Ocean–Atmosphere Data Set (COADS), and analyzed SST data from the Geophysical Fluid Dynamics Laboratory (GFDL). The monthly SLP data archived at NCAR are on $5^\circ \times 5^\circ$ grids covering north of $15^\circ$N in the Northern Hemisphere for the period 1899–1987 (Walsh and Chapman 1990). The monthly SST data from the COADS are on global $2^\circ \times 2^\circ$ boxes for the period 1854–1992 (Slutz et al. 1985). These two datasets are also described and used in Peng and Mysak (1993) and Peng et al. (1995). A composite analysis is performed using the SLP and the original COADS SST data. We apply a SVD analysis using the same SLP data but the analyzed SST data of GFDL. The GFDL SST data are analyzed objectively from the COADS SST onto global $1^\circ \times 1^\circ$ grids for the period 1870–1988 (Pan and Oort 1990). Both our analyses are only conducted for the period 1950–1987 due to sparse coverage of the COADS SST observations over our study domain before 1950. In both analyses, the SLP and SST climatologies are calculated for each winter month at each grid point by averaging the data over the period 1950–1987. The monthly anomalies are the deviations from the monthly climatologies (i.e., monthly data minus monthly climatology).

b. Composite analysis

To examine the SST anomaly related SLP fluctuations during each month of the cold season, we adopt a composite procedure similar to that used in Palmer and Sun (1985). We first calculate the SLP and SST (COADS) anomalies for each winter month at each grid point for the period 1950–1987. A mean SST anomaly averaged over the RM region ($50^\circ$N–$40^\circ$N, $60^\circ$W–$40^\circ$W) is then used to select the warm (cold) SST months with a criteria of positive (negative) $0.6^\circ$C. The SLP anomaly composites are generated based on the selected warm and cold SST months in each winter month.

c. SVD analysis

A detailed description of the SVD method and its application can be found in Bretherton et al. (1992) and Wallace et al. (1992). Briefly, a SVD analysis begins with the construction of a cross-covariance matrix between two time- and space-dependent variables $s_i(t)$ and $z_j(t)$. The SVD of this covariance matrix identifies pairs of spatial patterns (i.e., singular vectors) that describe the squared covariance (SC) between the two variables. The first pair of patterns describes the greatest fraction of the SC. Each succeeding pair describes a maximum fraction of the SC that is unexplained by the previous pairs. The squared covariance fraction (SCF) represented by each pair of singular vectors is proportional to the square of the corresponding singular value. The expansion coefficients of a singular vector [$a_i(t)$ or $b_i(t)$] are found by projecting the vector onto its original data field. The correlation coefficient between two expansion series $r[a_i(t), b_j(t)]$ shows how strongly the coupled patterns are related. Instead of utilizing the singular vectors, one can either construct the
heterogeneous correlation maps $r[b_i(t), s_i(t)]$ and $r[a_i(t), z_i(t)]$ or the homogeneous correlation maps $r[a_i(t), s_i(t)]$ and $r[b_i(t), z_i(t)]$. The heterogeneous correlation map for the $k$th mode indicates how well the gridpoint values of one variable can be predicted from the $k$th expansion coefficients of the other variable. The homogeneous correlation map for the $k$th mode displays the spatial pattern of the covarying part between a variable and its $k$th expansion coefficients.

The study regions of our SVD analysis consist of a SLP domain of $20^\circ$–$80^\circ$N, $80^\circ$W–$0^\circ$ and a SST domain of $20^\circ$–$60^\circ$N, $80^\circ$W–$0^\circ$. A $5^\circ \times 5^\circ$ SLP grid gives a total of 221 points within the SLP domain. A coarser grid ($4^\circ \times 4^\circ$) of the GFDL analyzed SST data is employed, giving a total of 156 points within the SST domain, excluding land. The monthly SLP and SST anomalies are calculated for each winter month at each grid point for the period of 1950–1987. These anomalies are then normalized by their standard deviations in order to avoid overweighing areas with high variance (Wallace et al. 1992; Lau and Nath 1994). The coupled SLP and SST patterns identified from our SVD analysis are presented as homogeneous regression maps (generated by multiplying the homogeneous correlation maps by the temporal standard deviations of the original data field at each grid point). The homogeneous regression maps not only illustrate the anomaly polarity but also the typical amplitude represented by the SVD modes. Our discussion will focus on the first two SVD modes for each winter month since they explain most of the SC between the two fields.

One concern over using the normalized data is that it tends to render the leading modes less robust. As one will see the first SVD modes in this study are actually found to be extremely robust. In fact, we had performed the analysis using both the normalized and unnormalized data and found no significant impact on the final results. We have also examined the heterogeneous regression maps and found they are basically similar to the homogeneous maps.

3. Results of a composite analysis

The time series of the SST anomalies averaged over the RM region ($50^\circ$–$40^\circ$N, $60^\circ$–$40^\circ$W) for the winter months (November–April) of 1950–1987 is shown in Fig. 1. The SST anomalies of this region appear to fluctuate on both interannual and decadal timescales. We form the SLP composites based on this SST anomaly time series with an anomaly criteria of positive or negative $0.6^\circ$C as described in section 2. We find that the broad features in the SLP anomaly composites for the selected warm and cold SST months are quite symmetric in each winter month. For example, in November, a positive SLP anomaly center is found to occur in the warm com-
Fig. 2. The composite SLP difference fields of warm minus cold SST months for each winter month. The warm (cold) months are selected from 1950–1987 according to the SST anomaly index shown in Fig. 1 with a criteria of positive (negative) 0.6°C. The contour interval is 2 mb.
posite and a negative center is observed in the cold composite (not shown). Therefore, we present in Fig. 2 the SLP anomaly difference field of warm minus cold composite for each month of the cold season. These difference fields can be viewed as amplified pictures of the SLP anomaly patterns associated with the positive SST anomalies in the RM region.

In November, we observe that a positive monopole SLP anomaly pattern is centered around 50°N in the midlatitude North Atlantic, with the maximum anomaly over 6 mb. There is also a positive SLP anomaly center shifted northward in December, and a very weak negative center is noted to appear to the south. These anomalous features are in very good agreement with those shown in Palmer and Sun (1985) (their Fig. 11), although their difference field is averaged over the months from November to February. The January SLP anomalies, however, exhibit a dipole structure, which is noticeably different from the early winter situation. The positive center is now located farther to the north and the negative center to the south becomes stronger. A dipole-like SLP anomaly pattern is also found to appear in February and March, although the dipole axis shifts and the anomaly magnitude varies from month to month. The strongest dipole anomaly is observed in March. In April, a monopole positive SLP anomaly center is seen to return to the North Atlantic, similar to what occurred in early winter. A Student’s t-test is applied to assess the statistical significance of the SLP differences shown in Fig. 2. We find that almost all the central parts, except the southern center in January, of the monopole and the dipole SLP anomalies are significant at the 95% level (not shown). A more rigorous discussion on the statistical significance of these anomaly patterns is given in section 4.

The evolution of the SLP anomaly structures from November to April found in Fig. 2 suggests that there are two regimes in the midlatitude atmosphere–ocean coupled system during the cold season. One is characterized by a monopole SLP pattern in early and late winter (i.e., November, December, and April) and the other by a dipole pattern in midwinter (i.e., January to March). These results agree with the findings of Peng et al. (1995) in the sense that the midlatitude air–sea interactions are strongly dependent on the climatology for the given month. The monopole SLP anomaly pattern occurring in November resembles the simulated November response to a specified warm SST anomaly obtained by Peng et al. (1995) (see also Palmer and Sun 1985). This resemblance suggests that the monopole SLP anomaly observed in early and late winter involves, but not exclusively, an ocean forcing the atmosphere process. Furthermore, we notice that the dipole-structured SLP anomaly found in midwinter differs from the January responses to a fixed warm SST anomaly simulated in Peng et al. (1995) and other studies (e.g., Pitcher et al. 1988; Kushner and Lau 1992). This discrepancy implies that the dipole SLP anomaly has probably resulted from a different coupling process, such as the one to be discussed next in section 4.

The composite analysis used above is simple and direct. It provides insight into the SST and SLP relationship along with their variations during the cold season. However, the analysis is somewhat subjective in so far as the selection of the SST index region and the anomaly criteria are concerned. A more objective analysis is required to better assess the coupled relationship between SST and SLP. This motivates the SVD analysis presented in the next section. A SVD operation makes use of SST and SLP anomalies at each grid point over the entire study period.

4. Results of a SVD analysis

a. The coupled patterns

A SVD analysis is performed for each winter month using the SLP and SST data for the period 1950–1987. The temporal cross covariance matrix between the normalized SLP anomalies at 221 points and SST anomalies at 156 points is constructed and then factorized by the SVD. The homogenous regression maps for the leading SVD modes are generated according to the description given in section 2. The regression maps for the two leading SVD modes obtained in November are shown in Fig. 3. The first and second SVD modes are referred to as S1 and S2, respectively. The SCF accounted for by each SVD mode and the correlation coefficient r between the corresponding expansion coefficients are shown under each pair of regression maps. The fractions of the variances of the respective fields explained by the time series of the expansion coefficient of the same field are given in the brackets. We observe that both the S1(SLP) and S1(SST) fields exhibit a dipole structure in the North Atlantic. The northern center is somewhat stronger than the southern one implied by the S1(SLP) and S1(SST) fields. If we consider the spatial distributions of the monthly mean surface air temperature and SST isotherms (not shown), the anomalous westerlies around 50°N in the S1(SLP) field would tend to generate cold advection into that area. This may account for the negative SST anomaly in the S1(SST) field. The positive SST anomaly near the U.S. coast in the S1(SST) is also found to match the anomalous southwesterlies in the S1(SLP) field producing a warm advection into the region. The correspondence between the S1(SLP) and S1(SST) fields suggests that the dipole-structured S1 mode is likely related to a wind driven process (see also Deser and Blackmon 1993; Zorita et al. 1990). This argument is well supported by a recent ocean modeling experiment of Battisti et al. (1995). The S1 mode in November is found to account for 47% of the total SC between the normalized SLP and SST anomalies.

The S2 mode in November is characterized by a monopole pattern in the S2(SLP) and S2(SST)
fields. In particular, we note that the monopole pattern in the S2(SST) field is centered directly over the RM region. Hence, the shape and location of the anomaly pattern in the S2(SLP) field bear a strong resemblance to those appearing in the corresponding SLP composite (see Fig. 2). A similar monopole SST anomaly centered approximately 5° to the east is specified in the model experiments of Peng et al. (1995). The close agreement between the anomalies in the S2(SLP) field and the simulated November responses suggests that the S2 mode likely resulted from ocean forcing of the atmosphere process. A consistent atmospheric response to a prescribed SST anomaly is also obtained in the GCM experiment of
Palmer and Sun (1985). The S2 mode in November accounts for 23% of the SC.

Figure 4 contains homogeneous regression maps for the two leading SVD modes in December. The S1 mode again exhibits a dipole feature in both the S1 (SLP) and S1 (SST) fields. The anomaly pattern in the S1 (SST) is also found to be predictable from anomalies in the S1 (SLP) field using the previous wind-driven argument. The S1 mode in December accounts for 49% of the SC. The broad features of the S2 mode in the S2 (SLP) and S2 (SST) fields are quite similar to those obtained in November, except that the anomaly center in the S2 (SLP) field is shifted eastward. The S2 mode in December shares an even larger SCF than in November, accounting for 33% of the total SC. The characteristics of the S2 modes found in November and December suggest that ocean forcing may have exerted a considerable impact on the atmosphere in early winter. The correlation coefficient between the expansion coefficients of the S1 mode $r[a_1(t), b_1(t)]$ is 0.73, and that of the S2 mode $r[a_2(t), b_2(t)]$ is 0.81. For both the S1 and S2 modes, these are the highest coefficients found among all the

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![S1 (SLP) 35%](image1)

![S2 (SLP) 23%](image2)

![S1 (SST) 20%](image3)

![S2 (SST) 16%](image4)

**SCF=49%  r=0.73**  
**SCF=33%  r=0.81**

*Fig. 4. Same as Fig. 3 but for December.*
winter months. The SLP and SST fields appear to be most strongly correlated in December.

Regression maps for January, February, and March are presented in Figs. 5, 6, and 7, respectively. The familiar dipole pattern with an intense southern center is observed in the S1(SLP) field for each month, and the anomaly feature in the S1(SST) can also be related to the anomalous wind in the corresponding S1(SLP) field. However, the SCF of the S1 mode is found to have increased dramatically in midwinter, especially in January and March (see Figs. 5 and 7).

The S1 mode accounts for as much as 67% of the SC in January and 77% in March. In contrast, the S2 mode accounts for only 13% and 9% of the SC during these two months. We will later show that the SC associated with the S2 mode is not statistically significant in January and March. Thus, midwinter appears to be strongly dominated by atmosphere driving the ocean process. Quite likely because of that, we obtain a dipole feature in the corresponding SLP composites (see Fig. 2). The S1 and S2 modes in February account for 51% and 18% of the SC (see

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\text{SCF}=67\% \quad r=0.67 \\
\text{SCF}=13\% \quad r=0.55
\]

Fig. 5. Same as Fig. 3 but for January.
Fig. 6). It is surprising that the observed behavior during February differs more from January than March. The following statistical test shows that both the S1 and S2 modes are not significant in February.

The homogenous regression maps for the two SVD modes in April are depicted in Fig. 8. The dipole-structured S1 mode is now much weaker than in midwinter and accounts for only 39% of the SC. In contrast, the S2 mode now accounts for 22% of the SC, which is close to the value observed during November. Consequently, the monopole pattern in the S2(SLP) field is again found to resemble the SLP anomaly features in the corresponding composite field (see Fig. 2). The effect of ocean forcing appears to have returned in late winter and to be almost as strong as during early winter. Thus, we find that the coupled system in the midlatitude North Atlantic cycles between two distinct states during the cold season.

b. Statistical significance tests

In order to assess the statistical robustness of the results obtained from the above SVD analyses, we
now perform two sets of significance test using a Monte Carlo approach. We concentrate testing on the SC rather than the SCF or \( r[a_i(t), b_i(t)] \). The SC is a direct measure of the relationship between the SLP and SST anomaly fields and between the coupled SVD patterns. The SCF and \( r[a_i(t), b_i(t)] \) are indirect measures of the relationship between the coupled SVD patterns. Given two weakly related fields with a small SC, one may still find a large SCF and \( r[a_i(t), b_i(t)] \) in their leading SVD modes, even though these modes actually account for very little SC (Wallace et al. 1992). Therefore, the SCF and \( r[a_i(t), b_i(t)] \) are only meaningful when they are associated with a significant SC.

First, we employ a Monte Carlo approach to test the month dependency of the SVD modes during the cold season. The question we ask is whether using the data stratified by calendar month allows one to
identify any SVD modes that are significantly stronger than those obtained from using the unstratified data. To achieve this purpose, we use the following procedure.

1) Form a randomized dataset by selecting, at random, one calendar month from each winter (e.g., April 1951, December 1951, February 1953, ...). No given year/month is used more than once. The chronological order of SST relative to SLP is kept.
2) Perform SVD on the randomized dataset.
3) Repeat the above procedure 100 times, that is, form 100 of such randomized datasets and perform SVD on each of them.
4) Compare the results with those obtained from using the data of each month.

The results from the 100 SVD runs using the randomized datasets are shown in Fig. 9 together with the original SVD results using only the data of a given winter month. The SC shown in Fig. 9 is normalized by the number of SLP and SST data points to eliminate...
Fig. 9. Total SC and the SC accounted for by the first (S1) and second (S2) SVD modes from the SLP and SST datasets stratified by calendar month (the solid lines) and those from the 100 randomized datasets without regard for calendar month (the crosses); SC here is dimensionless and normalized by the number of SLP and SST data points (i.e., $M \times N = 221 \times 156$).
its dependence on the matrix size (Wallace et al. 1992). The total SC between the SLP and SST anomalies and the SC accounted for by the S1 and S2 modes from the original SVD run for each month are plotted by a solid line, and those from the randomized runs without regard for calendar month are marked with crosses. A SC from the stratified SLP and SST dataset is considered to be statistically significant stronger at the 95% level if it is not exceeded more than five times by the corresponding ones from the 100 randomized datasets.

By examining the results displayed in Fig. 9, we find that the total SCs given by the stratified data in December and March are significantly stronger, at the 95% level, than those given by the unstratified data. The stratified data also give a S2 mode in December and, note especially, a S1 mode in March to be stronger at the 95% significance level. The rest of the total SC and the SC accounted for by the S1 and S2 modes given by the stratified data are not seen to significantly exceed the unstratified populations. But one can still find that the S1 modes given by the stratified data tend to stay above the mean of the unstratified population in midwinter (with the exception of February); whereas the S2 modes tend to stay above the mean in early and late winter. Note that the crosses in Fig. 9 (and Fig. 10) are often overlaid and, therefore, can not be visually counted.

Since the chronological order of SST relative to SLP is kept in this test, the SCs from the stratified datasets and those from the randomized datasets should have a similar mean. If the SCs from the stratified datasets wander around the mean of the randomized populations, without exceeding the 95% significance level in any month, this would suggest that the SLP and SST relationships during the cold season are not significantly month-dependent. Clearly this is not the case for the results shown in Fig. 9. We hence conclude that this test in general supports our initial hypothesis that certain characteristics of the SVD modes are month-dependent.

Second, we employ a Monte Carlo approach to test the statistical significance of the leading SVD modes during each winter month. We again concentrate our test on the total SC between the SLP and SST anomalies and the SC associated with the first and second SVD modes. We adopt a procedure similar to the one described in Wallace et al. (1992) to perform an ensemble of SVD analyses of the scrambled SLP and SST datasets. In a scrambled SLP and SST dataset, the relationship between the two fields deteriorates to some extent, which should be reflected directly in the total SC as well as the SC of the SVD modes. For each winter month, we take the following steps.

1) Form a scrambled dataset by scrambling the SLP maps of 38 years in the time domain in order to destroy the chronological order of SST relative to SLP.

2) Perform SVD on the scrambled dataset.

3) Repeat the above procedure 100 times, that is, form 100 of such scrambled datasets and perform SVD on each of them.

4) Compare the results with those obtained from the original unscrambled data.

One concern over the procedure used in Wallace et al. (1992) is that scrambling the data would artificially increase the temporal degrees of freedom, lowering SC in the scrambled data, and making the results appear more significant than they really are. We modified their procedure by scrambling only the SLP data and fixing the order of the SST fields. Since the year to year autocorrelations of the SLP data are generally rather small, the modified procedure should greatly reduce the previous concern. Strictly speaking, however, one should still keep in mind that the scrambled datasets thus formed preserve only the spatial coherence of the observed fields, not the precise autoregressive properties in time.

The results from the 100 scrambled SVD runs for each winter month are plotted in Fig. 10, together with the corresponding results from the original SVD run based on the observations. In Fig. 10, the total SC and the SC accounted for by the S1 and S2 modes from the original SVD run are plotted again with a solid line, and those from the 100 scrambled SVD runs are marked with crosses. A SC from the observed SLP and SST dataset is considered statistically significant at the 95% level if it is not exceeded more than five times by the corresponding ones from the 100 scrambled datasets.

Figure 10 shows that the total SC between the observed SLP and SST anomalies exceeds the 95% significance level in each month of the cold season, which suggests that the two fields are significantly correlated. Both the S1 and S2 modes in November and December are found to be significant at the 95% level. This implies that, in early winter, the process of atmospheric driving of the ocean as well as that of ocean forcing of the atmosphere are effective. In January, the S1 mode is seen to be significant, while the S2 mode is insignificant. A similar situation is observed in March, suggesting that midwinter is strongly dominated by the atmosphere driving the ocean mode. However, we note that the S1 and S2 modes in February are both found not to be significant at the 95% level. The total SC in this month is observed to be the smallest among all the winter months. The characteristics of the February SVD modes were also noted to be different from those of January and March in the first test (see Fig. 9). The causes of these "unusual" phenomena in February are not clear. We are not aware of any dynamic or physical mechanisms that could account for these phenomena. Ideally speaking, if possible, longer time series of SLP and SST data would be desired in order to obtain statistically more robust results. The results
Fig. 10. Total SC and the SC accounted for by the first (S1) and second (S2) SVD modes from the observed SLP and SST dataset (the solid line) and from the 100 scrambled datasets (the crosses) for each winter month.
of the scrambled runs in April demonstrate that the S1 mode is not significant but the S2 mode is significant at the 95% level. Thus, ocean forcing of the atmosphere is suggested to be more prominent in the midlatitude coupled system in late winter.

5. Summary and conclusions

The relationship between the SLP and SST anomalies in the midlatitude North Atlantic was examined for each month of the cold season (i.e., November–April). In particular, we focused on the monthly evolution of the coupled anomaly patterns from early winter (i.e., November) to late winter (i.e., April). A composite analysis was performed using the SST anomalies in the RM region (i.e., 50°–40°N, 60°–40°W) as an index to identify the warm and cold SST months from the period 1950–1987. The SLP anomaly composite of warm minus cold SST months was constructed for each winter month. The SLP anomalies in these composites follow a clear evolutionary pattern from November to April. In early winter (i.e., November and December), we observe a positive monopole SLP anomaly pattern in the midlatitude North Atlantic associated with the positive SST anomalies in the RM region. We note that this monopole anomaly is replaced by a dipole-structured SLP anomaly in the composite field of each midwinter month (i.e., January–March). By late winter (i.e., April), a positive monopole SLP anomaly appears again in the North Atlantic, similar to that obtained in early winter. Indeed, we find that there is a strong monthly variability in the midlatitude atmosphere–ocean interactions within the cold season as suggested by the model experiments of Peng et al. (1995).

To explore a possible explanation for the shift between the monopole and the dipole anomaly patterns in the SLP composites, we applied a SVD analysis in the midlatitude North Atlantic for each winter month during the period 1950–1987. A SVD operation finds the coupled SLP and SST patterns that explain as much as possible of the squared covariance (SC) between the two fields. We observe that the first SVD mode is dipole structured and especially dominant in midwinter. The second SVD mode is monopole featured and more dominant in early and late winter than in midwinter. By examining the spatial distributions of the two leading SVD modes in the SLP and SST regression maps and especially their similarities to the patterns derived from other model simulations, two different coupling processes are suggested. The first mode is suggested to be associated mainly with a wind-driven process as supported by the ocean-modeling experiment of Battisti et al. (1995). The shape of the monopole SLP pattern (the second mode) in early winter is very similar to the simulated atmospheric response obtained in the November experiments of Peng et al. (1995). Thus, the second mode is suggested to involve, but not exclusively, an ocean forcing of the atmosphere process. One should keep in mind, however, that the above inferences concerning physics are not based on any intrinsic properties of the SVD modes. SVD analysis is only a statistical method that is indifferent to the underlying physics. A critique of the method can also be found in Newman and Sardeshmukh (1995).

We performed two Monte Carlo tests to assess the statistical robustness of our SVD results. The first test determines the month-dependency of the SVD modes during the cold season. This test in general supports our initial hypothesis that midlatitude atmosphere–ocean interactions are significantly month-dependant. The second test determines the statistical significance of the two leading SVD modes during each winter month. This test thus indirectly estimates the relative importance of the wind-driven and the ocean-forcing processes in each month. We find that the atmosphere driving the ocean mode is significant in most of the winter months, especially in midwinter. The ocean forcing the atmosphere mode is only significant in early and late winter (i.e., November, December, and April). This apparently explains why the SLP anomaly composites shift from a monopole pattern in early winter to a dipole pattern in midwinter and to a monopole again in late winter.

We have examined how the background climatological states (i.e., early, middle, and late winter) affect the predominance of the coupling processes in this study without regard for the timescales of the variations. The predominance of the coupling processes, however, can be timescale dependant as well, which requires further investigations. We speculate that low-frequency atmospheric fluctuations due to the ocean forcing in the midlatitude North Atlantic is probably more predictable in early and late winter than in midwinter. Finally, the reader may notice that the cyclonic atmospheric response to a fixed warm SST anomaly obtained in the January simulations of Peng et al. (1995) is not observed in the leading SVD modes. We mentioned earlier that the anomalous cyclone circulation developing in January would act to offset the warm SST anomaly if the model had an active ocean. Apparently, the SST and SLP anomalies associated with such a negative feedback process would be difficult to maintain in nature. The cyclonic response found in Peng et al. (1995) and in other simulations (e.g., Pitcher et al. 1988; Kushnir and Lau 1992) should be attributed largely to the idealized maintenance of the same warm SST anomaly during the entire integration.

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