The Relationships between Tropical Pacific and Atlantic SST and Northeast Brazil Monthly Precipitation

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(Manuscript received 15 February 1994, in final form 14 May 1997)

ABSTRACT

The monthly patterns of northeast Brazil (NEB) precipitation are analyzed in relation to sea surface temperature (SST) in the tropical Pacific and Atlantic Oceans, using singular value decomposition. It is found that the relationships between precipitation and SST in both basins vary considerably throughout the rainy season (February–May). In January, equatorial Pacific SST is weakly correlated with precipitation in small areas of southern NEB, but Atlantic SST shows no significant correlation with regional precipitation. In February, Pacific SST is not well related to precipitation, but south equatorial Atlantic SST is positively correlated with precipitation over the northern Nordeste, the latter most likely reflecting an anomalously early (or late) southward migration of the ITCZ precipitation zone. During March, equatorial Pacific SST is negatively correlated with Nordeste precipitation, but no consistent relationship between precipitation and Atlantic SST is found. Atlantic SST–precipitation correlations for April and May are the strongest found among all months or either ocean. Precipitation in the Nordeste is positively correlated with SST in the south tropical Atlantic and negatively correlated with SST in the north tropical Atlantic. These relationships are strong enough to determine the structure of the seasonal mean SST–precipitation correlations, even though the corresponding patterns for the earlier months of the season are quite different. Pacific SST–precipitation correlations for April and May are similar to those for March. Extreme wet (dry) years for the Nordeste occur when both Pacific and Atlantic SST patterns for April and May occur simultaneously. A separate analysis reinforces previous findings in showing that SST in the tropical Pacific and the northern tropical Atlantic are positively correlated and that tropical Pacific–south Atlantic correlations are negligible.

Time-lagged analyses show the potential for forecasting either seasonal mean or monthly precipitation patterns with some degree of skill. In some instances, individual monthly mean SST versus seasonal mean (February–May) precipitation relationships differ considerably from the corresponding monthly SST versus monthly precipitation relationships. It is argued that the seasonal mean relationships result from the relatively strong monthly relationships toward the end of the season, combined with the considerable persistence of SST in both oceans.

1. Introduction

The political northeast region of Brazil (hereafter referred to as NEB) is a densely populated region located approximately between 1° and 18°S and 35° and 47°W. Its climate is characterized by annual precipitation in amounts ranging between 600 and 2000 mm, realized at different times of the year for different subregions (Strang 1972; Kousky 1979; Moura and Shukla 1981; Rao et al. 1993). The eastern part of NEB has its rainy season between May and August. The southern part of the region has maximum precipitation in November–December. Finally, the semiarid northern part of NEB (hereafter referred to as Nordeste) experiences its rainy season between February and May, with very large interannual variability reaching as high as 40% of the mean.

Previous studies have identified relationships between the precipitation over the NEB and 1) ENSO events; 2) Atlantic Ocean sea surface temperature, trade winds, and sea level pressure; 3) the position of the Intertropical Convergence Zone (ITCZ) over the Atlantic Ocean; and 4) cold fronts (Namias 1972; Ratisbona 1976; Markham and McLain 1977; Hastenrath and Heller 1977; Kousky 1979; Moura and Shukla 1981; Nobre and Molion 1988; Ropelewski and Halpert 1987; Uvo 1989; Alves and Repelli 1992).

The Nordeste region exhibits not only a large variability in the total amount of precipitation from year to year (Kousky 1979) but also a high spatial and temporal variability in the precipitation within its rainy season. This monthly variability is related to the different rain-

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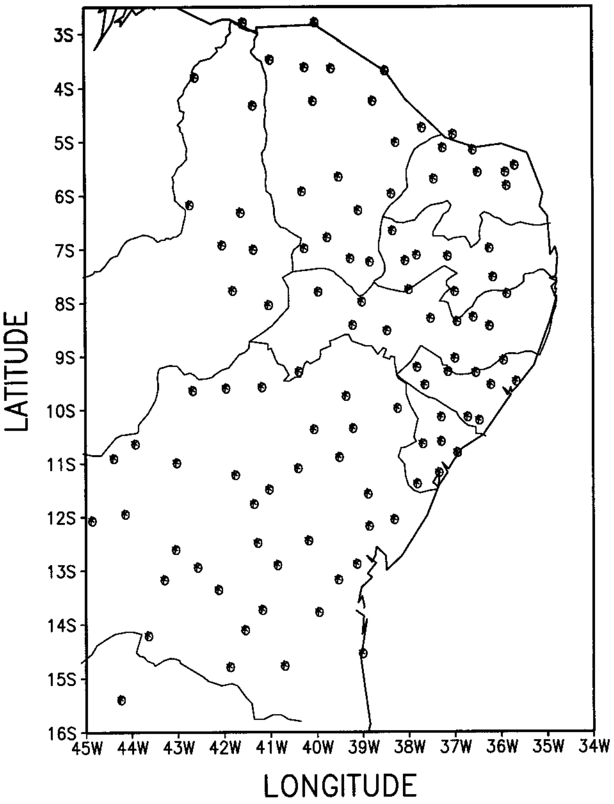


FIG. 1. Distribution of the 105 rain gauge stations over the Brazilian northeast region used to represent the precipitation field.

fall systems that cause precipitation over the region in the different months of the rainy season. During January and February, the precipitation over the Nordeste is strongly affected by cold fronts or their remnants (Kousky 1979; Oliveira 1989; Alves and Kayano 1991). Also important is the presence of high-level tropical vortices associated with the cold fronts (Kousky and Gan 1981). During February and March, the ITCZ over the tropical Atlantic Ocean reaches its southernmost position (Hastenrath and Lamb 1977), initializing what is called the ‘‘principal’’ rainy season over the Nordeste. The return of the ITCZ to its more northern position is what determines the end of the Nordeste principal rainy season (Uvo 1989; Uvo and Nobre 1989). The timing of this return is highly variable and contributes greatly to the total seasonal precipitation. The studies by Hastenrath and Heller (1977), Uvo (1989), and Uvo and Nobre (1989) show that in near-normal precipitation years, the ITCZ starts its return to the northern positions in mid-April. In a wet year, the ITCZ often remains south of the equator until early May. In dry years, the ITCZ either doesn’t reach positions south of the equator at all or retreats northward early, often during March.

To date, the diagnostic studies concerning precipitation in NEB or the Nordeste have addressed the regions as a whole (that is, regional averages) or averages over the entire rainy season. This has also been the case for the related precipitation forecasting studies (e.g., Ward and Folland 1991; Hastenrath 1990; Brito et al. 1991). While the averaged information is very useful, a more detailed space and time analysis is potentially even more useful for such applications as agriculture and water resources management. This was the motivation for the present study. Here we extend previous analyses by considering monthly averaged precipitation for an array of stations within the Nordeste and its relation to monthly SST anomalies in both the tropical Pacific and Atlantic basins.

In the following, section 2 describes the data used and section 3 the methodology. Results of the analyses are presented in section 4, followed by conclusions in section 5.

2. Data sources

For this study we have utilized monthly precipitation anomalies normalized by standard deviation for a network of 105 rain gauge stations well distributed over NEB (Fig. 1) and SST over the tropical Pacific and Atlantic for the period 1946–85.

The precipitation dataset was obtained from the Superintendência do Desenvolvimento do Nordeste and Fundação Cearense de Meteorologia e Recursos Hídricos (Brito et al. 1991); a total of 116 stations are included. A quality control analysis for this dataset was done previously at Instituto National de Pesquisas Espaciais. Following Lau and Sheu (1988), we retained only stations containing less than 10% missing data between 1946 and 1985; 105 stations remained in the dataset. Of the remaining records, a total of 3.2% of the data were missing. This relatively small percentage of missing data allowed the use of the following algorithm to approximate the missing values without seriously compromising the results. For missing data within the rainy season at a particular station, a linear temporal interpolation was made based on the precipitation of the previous and subsequent months. After this first step, 47 stations records remained with at least one missing data point, and the missing data still comprised 1.4% of the total. These remaining gaps were filled by inserting the appropriate long-term means.

The SST dataset was obtained from an analysis of the Comprehensive Ocean–Atmosphere Data Set (Pan and Oort 1990). The data were first analyzed on a 1° × 1° latitude–longitude grid, using a successive interpolation scheme and then interpolated to the Gaussian grid of the National Oceanic and Atmospheric Administration–Geophysical Fluid Dynamics Laboratory spectral model, which has a resolution of approximately 4.5° latitude × 7.5° longitude (Lau and Nath 1990). For the purpose of the present study, the latitude range from 24.75°S to 24.75°N was selected.

3. Methodology

The techniques employed for this study are based on a multivariate analysis procedure known as Singular Value Decomposition (SVD) that utilizes the cross-covariance matrix between fields of two datasets (Bretherton et al. 1992). The use of SVD allows one to isolate sets of mutually orthogonal pairs of spatial patterns that maximize the squared temporal covariance between two physical variables.

The theory of SVD is discussed and compared with other multivariate techniques in Bretherton et al. (1992) and Wallace et al. (1992). The SVD of the cross-covariance matrix $\mathbf{C}_{SZ}$ of two fields yields two matrices of singular vectors and one set of singular values. A singular vector pair describe spatial patterns for each field which have overall covariance given by the corresponding singular value.

Wallace et al. (1993) define a normalized squared covariance (NSC) that can be associated with each pair of spatial patterns. The normalized squared covariance ranges from 0, when the two fields are not related, to 1, when the variations at each grid point in the first field are perfectly correlated with the variations at all grid points in the second field. We will make use of the NSC in the present study to compare the relationship between variations in different ocean basins and rainfall variability.

From the singular vector pairs of the cross-covariance matrix, one can obtain the temporal expansion series of each field by projecting the data onto the appropriate singular vector (Bretherton et al. 1992). The so-called heterogeneous correlation maps of the left and right fields represent the correlation coefficients between the values of each grid point of the field and the expansion coefficients of the other field. In our application, the patterns shown by the heterogeneous correlation maps for the *k*th SVD expansion mode indicate how well the pattern of the precipitation (SST) anomalies relates to the *k*th expansion coefficient of SST (precipitation). The different heterogeneous maps of each field are mutually orthogonal in the space domain. The correlation coefficient between the temporal expansion series is a good indication of the strength of the relationship between the two fields.

Given only 40 yr of data, the construction and intercomparison of monthly relationships within the rainy season presents the danger of contamination from noise. Additional data would obviously help but are not available. Instead, we tested the results presented here by dividing the record into two segments and repeating all the calculations on each segment. The principal results were found to be in agreement (not shown), and we therefore believe the results described below are robust.

4. Results

SVD analyses between monthly SST and precipitation over the northeast Brazil region were done with both simultaneous and time-lagged precipitation versus SST data. The analyses were done between precipitation in NEB and SST in the tropical Pacific and Atlantic (24.75°N–24.75°S) separately. They allow us to identify not only the association between SST and Nordeste precipitation as a whole, but also the regional patterns of precipitation that relate to the Pacific and Atlantic SST during the period of the study.

It was evident from the results that only the first mode of the SVD was significant for the cases studied. In the cases where the second mode gave any significant correlation pattern, it occurred in only one of the heterogeneous maps without being related to any significant pattern of the companion heterogeneous map. Thus, results are presented only for the leading SVD mode.

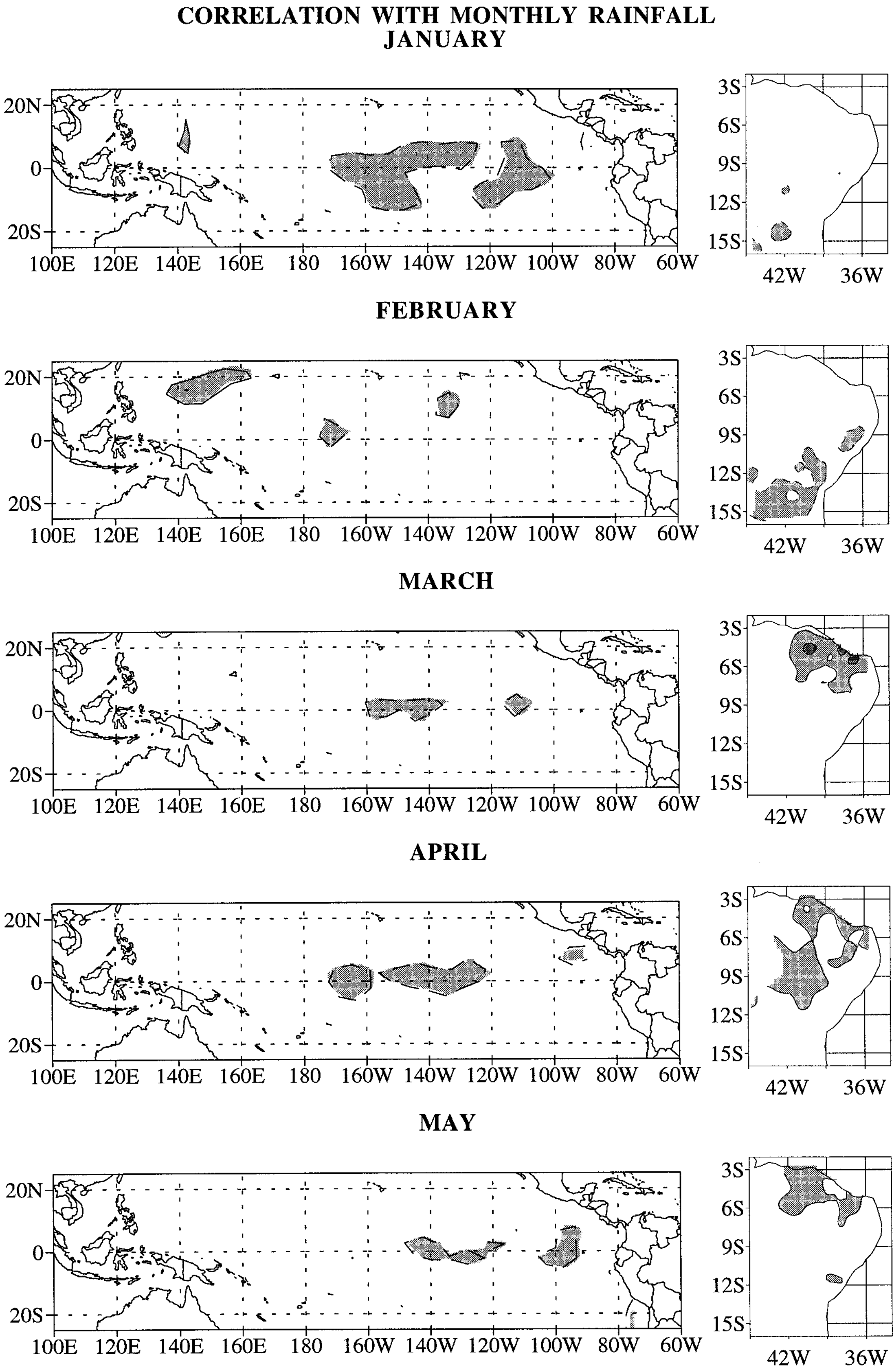
a. Simultaneous analyses

The analyses for Pacific SST and precipitation during each month of the rainy season (January–May) are presented in Fig. 2. In each of the heterogeneous maps, correlations above 0.4 and above 0.6 are shown with light and dark shading, respectively (a correlation of 0.4 is statistically significant at the 95% level). In January, SST in the central and eastern equatorial Pacific is positively correlated with precipitation over small areas in the southern part of NEB (nearly at the end of its rainy season in this month).

A somewhat larger portion of southern NEB appears in the February analyses but is not accompanied by a coherent pattern in SST, suggesting an insignificant relationship for this month. In March, the central equatorial Pacific SST shows a negative correlation with precipitation in the Nordeste region. This relationship is maintained for both April and May to varying degrees. The highest correlations in the SST field (as well as the highest NSC value—12.1%) occur in April, although the highest correlations in the precipitation field occur for March. At no time do correlations above 0.6 occur simultaneously in SST and precipitation.

A similar set of monthly analyses based on Atlantic SST is shown in Fig. 3. In this case, the relationship for January appears weak. For February, a more coherent set of patterns emerge, with SST in the southern equatorial Atlantic showing positive correlation with rainfall in the northern Nordeste. This region of NEB, including parts of the states of Ceara, Piaui, and Rio Grande do Norte, receives its seasonal rainfall in association with the annual southward migration of the ITCZ. The suggestion of the February results is that warm SST anomalies in the south Atlantic are associated with an early southward ITCZ migration and thus an early start of the rainy season.

The situation in March is quite different. For this month, no clear relationship with Atlantic SST is found (the coherent pattern of rainfall is essentially a principal component of that field alone; SVD defaults to univariate principal components of one of the fields when


CORRELATION WITH MONTHLY RAINFALL
JANUARY
FEBRUARY
MARCH
APRIL
MAY
20N
0
20S
100E
120E
140E
160E
180
160W
140W
120W
100W
80W
60W
3S
6S
9S
12S
15S
42W
36W

there is little or no covariance between the two fields). The lack of relationship in March is an unexpected result, seemingly at odds with previous studies (e.g., Hastenrath and Heller 1977; Moura and Shukla 1981). We verified this observation by performing rainfall–SST correlations using area-averaged indices (see below). The March correlations were found to be in the same sense as those for April but less than half as large. Moreover, the correlation map of the NEB rainfall index with Atlantic SST displays weak and insignificant values. Two distinguishing features of the present analysis are the inclusion of more recent data and the use of monthly anomalies of both SST and precipitation. Earlier studies involved averages of seasonal or March–May precipitation. We will return to this point below.

April presents the largest correlations of all the monthly analyses (also the largest NSC, 19.6%). It features a coherent pattern encompassing most of northern NEB and a pattern of coherent SST anomalies of one sign in the tropical North Atlantic and the opposite sign in the south Atlantic: this pattern has been identified in many previous studies, including Hastenrath and Heller (1977), Hastenrath (1978), and Moura and Shukla (1981), among others. The association, as found in earlier studies, is such that positive SST anomalies in the south Atlantic, and/or negative anomalies in the tropical North Atlantic, are associated with positive precipitation anomalies in NEB. As pointed out by Houghton and Tourre (1992) and others, the north and south components of SST are not always coincident. What appears to matter is the presence of an anomalous north–south SST gradient (Hastenrath and Greischar 1993), which is associated with anomalous positioning of the ITCZ during April. The gradient can be accomplished by an SST anomaly in either the north or south, or both, but is strongest when a dipolar anomaly is present. The analyses for May reveals much the same patterns as April, although the precipitation area is more confined to the north.

Figures 4 and 5 show the first SVD modes of February–May averaged precipitation and SST in the Pacific and Atlantic basins, respectively. For the Pacific, equatorial SST anomalies from near the dateline to the South American coast show significant negative correlation with rainfall over much of the Nordeste. For the Atlantic, even stronger correlations are evident between the basin-scale north–south gradient pattern of SST and precipitation over much of northern NEB. The NSC values for the Atlantic analysis are higher (20.6% vs 14.8%), suggesting that precipitation is somewhat more closely tied to Atlantic SST than to Pacific SST.

In summary, the present analyses have shown significant intraseasonal relationships between both Pacific and Atlantic SST and Nordeste precipitation. For the Pacific, higher correlations are found during March–May, and for the Atlantic, they are found in February and especially April–May. The Atlantic SST patterns exhibit higher normalized squared covariance than their Pacific counterparts in the months of April and May and for the rainy season as a whole.

As seen from Figs. 4–5, three regions are particularly well correlated with the NEB seasonal precipitation; we will refer to them as the equatorial Pacific, the north Atlantic, and the south Atlantic. These regions were defined by calculating the correlations between a precipitation index (normalized seasonally averaged rainfall in the 105 rain gauge stations) and seasonal mean SST over the Pacific and Atlantic. Areas in these ocean basins where the correlation coefficient was found greater than 0.3 in magnitude were defined as the regions for analysis. For each of the three regions, an SST index was calculated, defined as the spatial average of the monthly average normalized SST anomaly. Figure 6 shows a scatterplot of the Pacific SST index versus North Atlantic minus south Atlantic SST indices (averaged from February to May) for the 40 yr studied. Such a plot is motivated by the structures of the SST patterns in Figs. 4–5. Consistent with the SVD analysis, the driest years of the dataset are located in the upper right quadrant (1953, 1958, 1970, and 1983), indicating positive SST anomalies over the Pacific and positive SST differences between North and south Atlantic. In contrast, wet years are located preferentially in the lower left quadrant, indicating negative SST anomalies in the central Pacific and negative SST differences between the North and south Atlantic (1964, 1974, 1985). Situations in between these two extremes may depend on the relative strength of the Pacific and Atlantic SST patterns. This characteristic was observed to be valid either for the averaged rainy season or for individual months within the rainy season.

b. *Time-lagged analyses*

SVD analyses were also performed using the entire rainy season (February–May) precipitation over NEB and SST in each of the months January–May. Figures 6–7 display the Pacific and Atlantic results, respectively.

For both basins, the strongest correlations (and NSC values) were obtained for March–May SST, and the patterns of SST and precipitation among these 3 months were very similar. The March–May patterns for each basin analysis are furthermore very similar to the cor-

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FIG. 2. Heterogeneous correlation map for the first mode in the SVD expansion for monthly Pacific SST (left panels) and precipitation fields (right panels) for the months of January–May; solid lines denote positive and dashed lines negative values; light shading indicates values >0.4 and dark shading values >0.6.

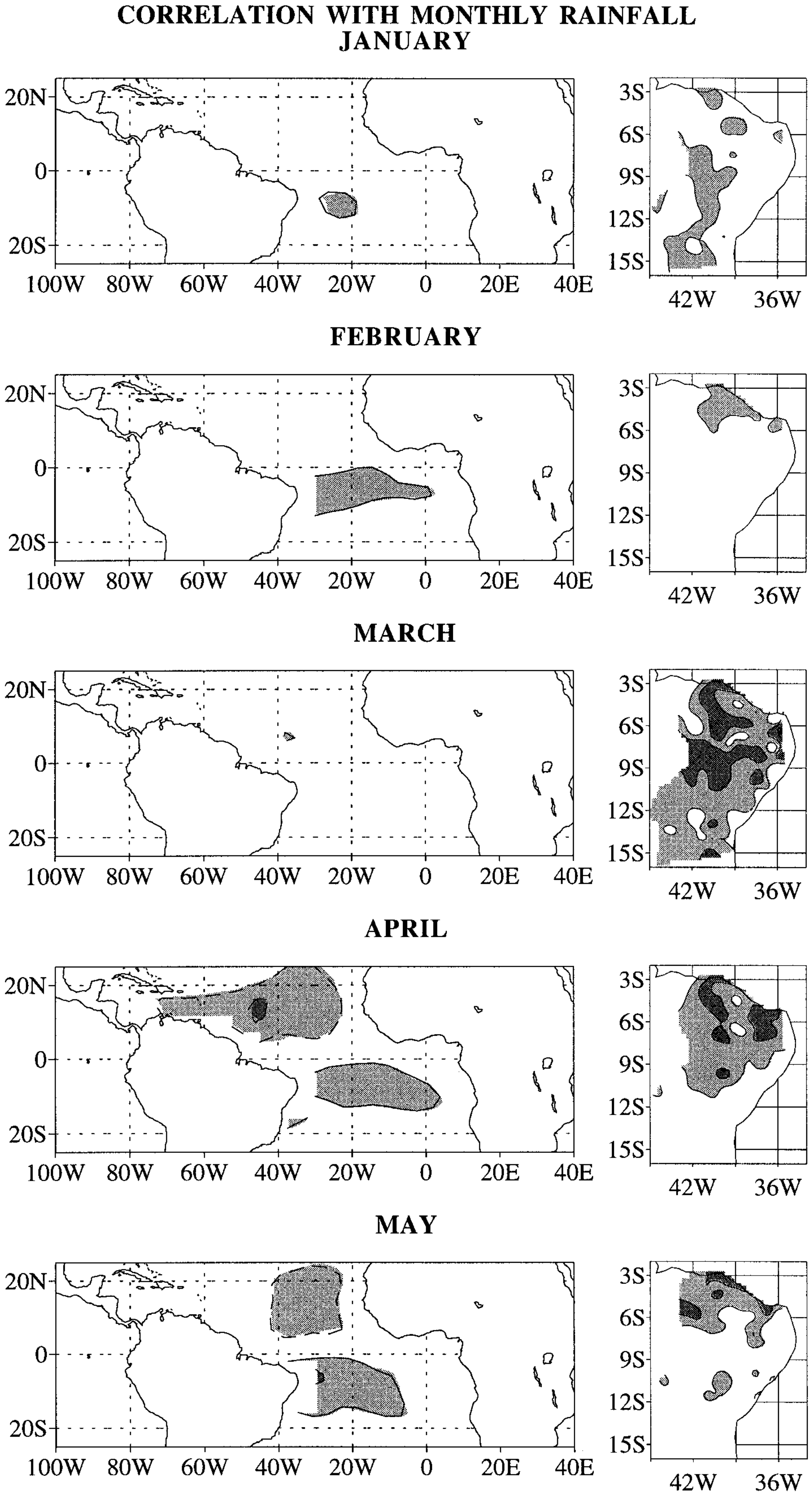

FIG. 3. As in Fig. 2 but for Atlantic SST.

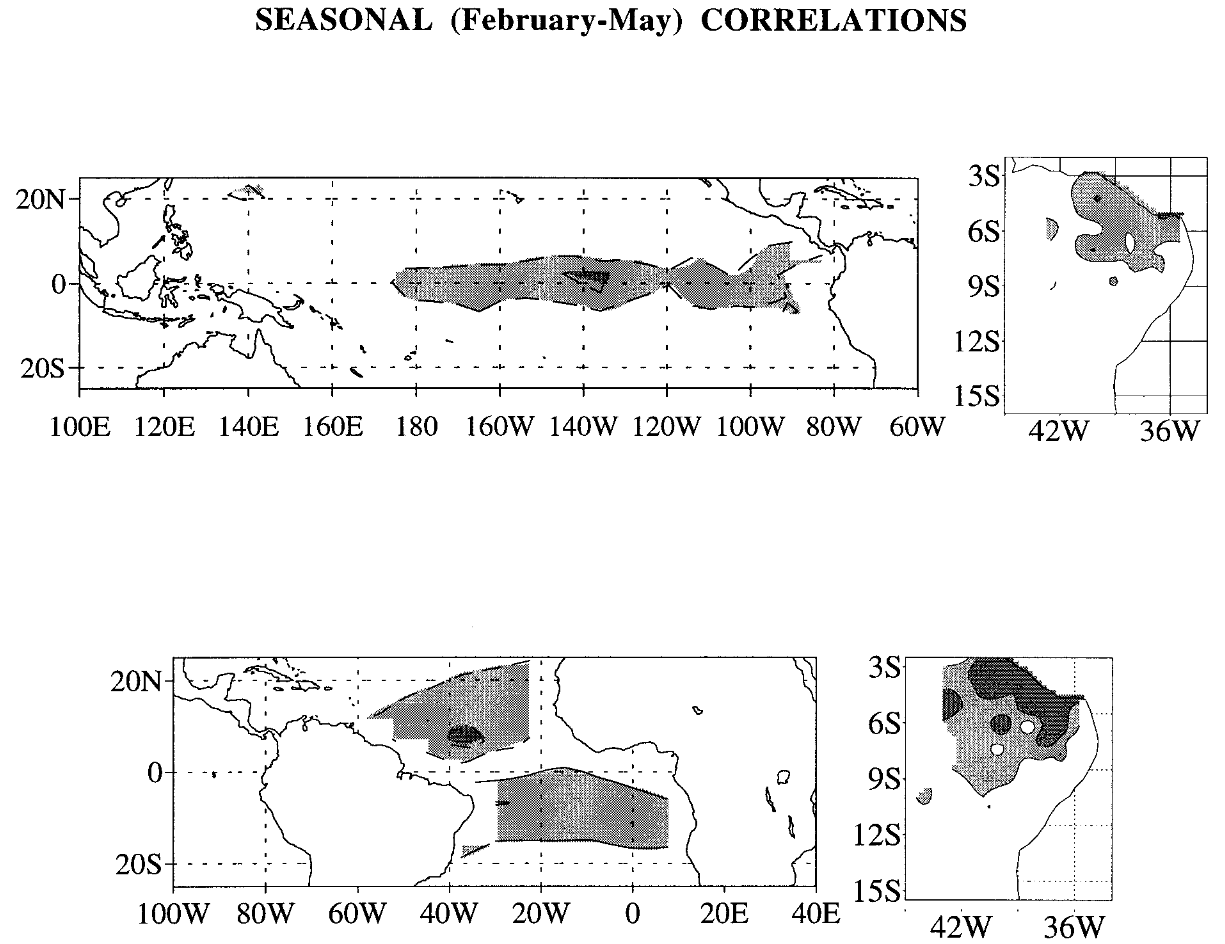
SEASONAL (February-May) CORRELATIONS

FIG. 4. Heterogeneous correlation map for the first mode in the SVD expansion for February–May averaged Pacific SST (upper left) and precipitation (upper right) fields and February–May averaged Atlantic SST (lower left) and precipitation (lower right). Contours and shading as in Fig. 2.

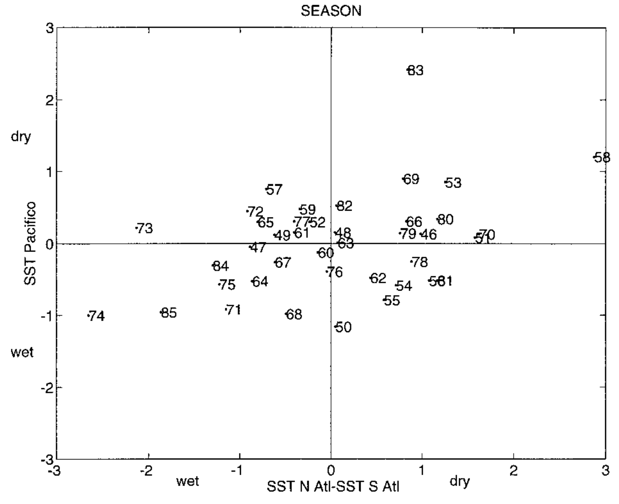

FIG. 5. Scatter diagram between Pacific SST index vs North Atlantic minus South Atlantic SST indices for the time average February–May and for the 40 yr studied. The years are identified by the last two digits of the year number.

responding patterns from the individual monthly analyses (Figs. 2–3) for the months of April and May (and even more coherent). It is especially noteworthy that the Atlantic March SST seasonal precipitation correlation pattern shows a strong association between north minus south SST and Nordeste precipitation, despite the fact that the individual monthly analysis for March showed no significant association. The patterns shown in Fig. 7 are quite consistent with previous studies (Hastenrath and Heller 1977; Moura and Shukla 1981) in which seasonal or 3-month mean precipitation anomalies were used. The present results suggest that the seasonal precipitation anomalies are primarily determined by the monthly anomalies for April and May. This is further supported by simple correlations between the seasonal precipitation index for the region and corresponding monthly indices: the April versus seasonal correlation is 0.73, the May versus seasonal correlation is 0.72, and all other correlations are less than or equal to 0.53. It is known that SST anomalies in both basins exhibit considerable persistence over timescales of 2–3

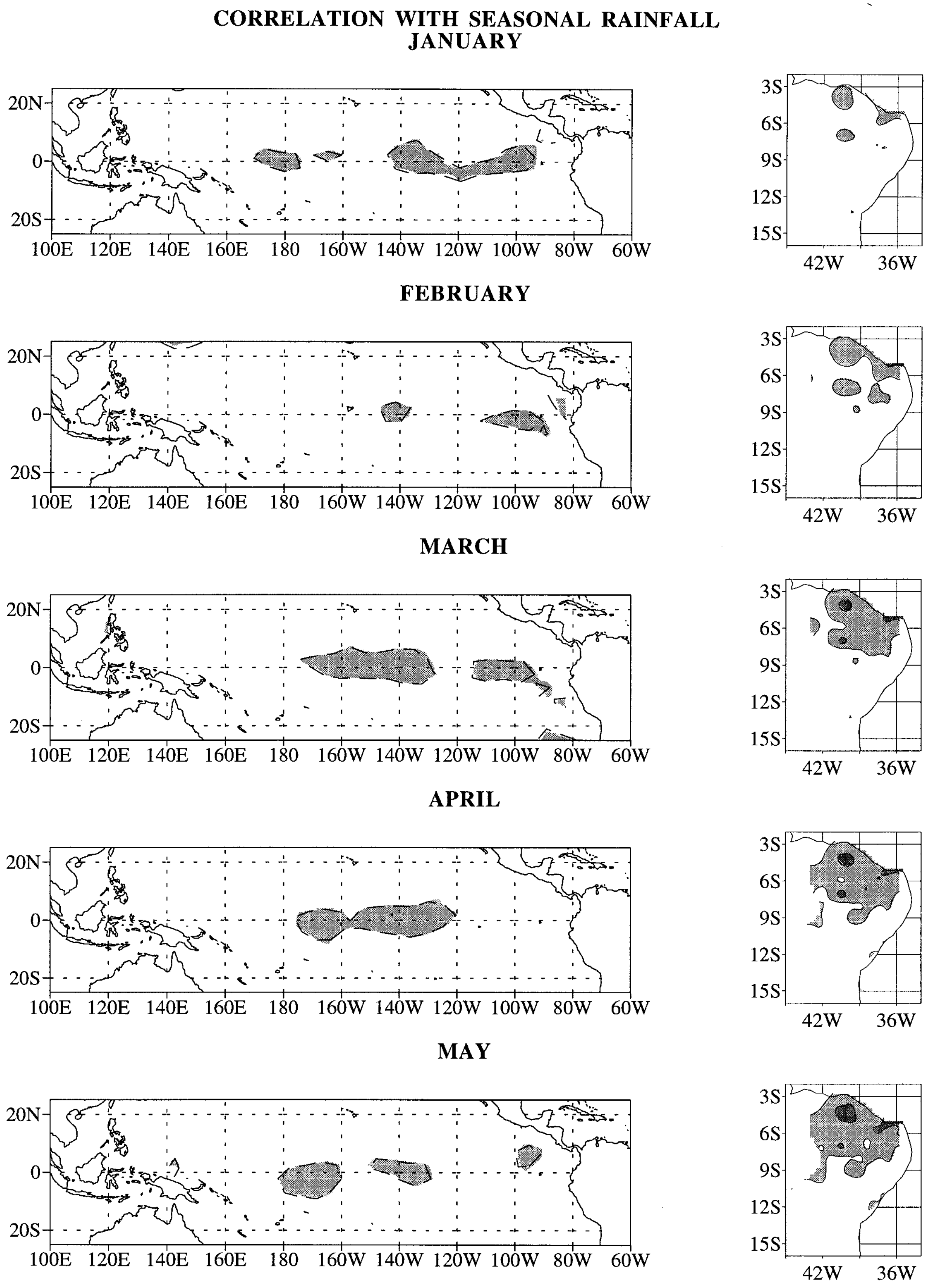

FIG. 6. As in Fig. 2 but for monthly SST and seasonal mean (February–May) precipitation.

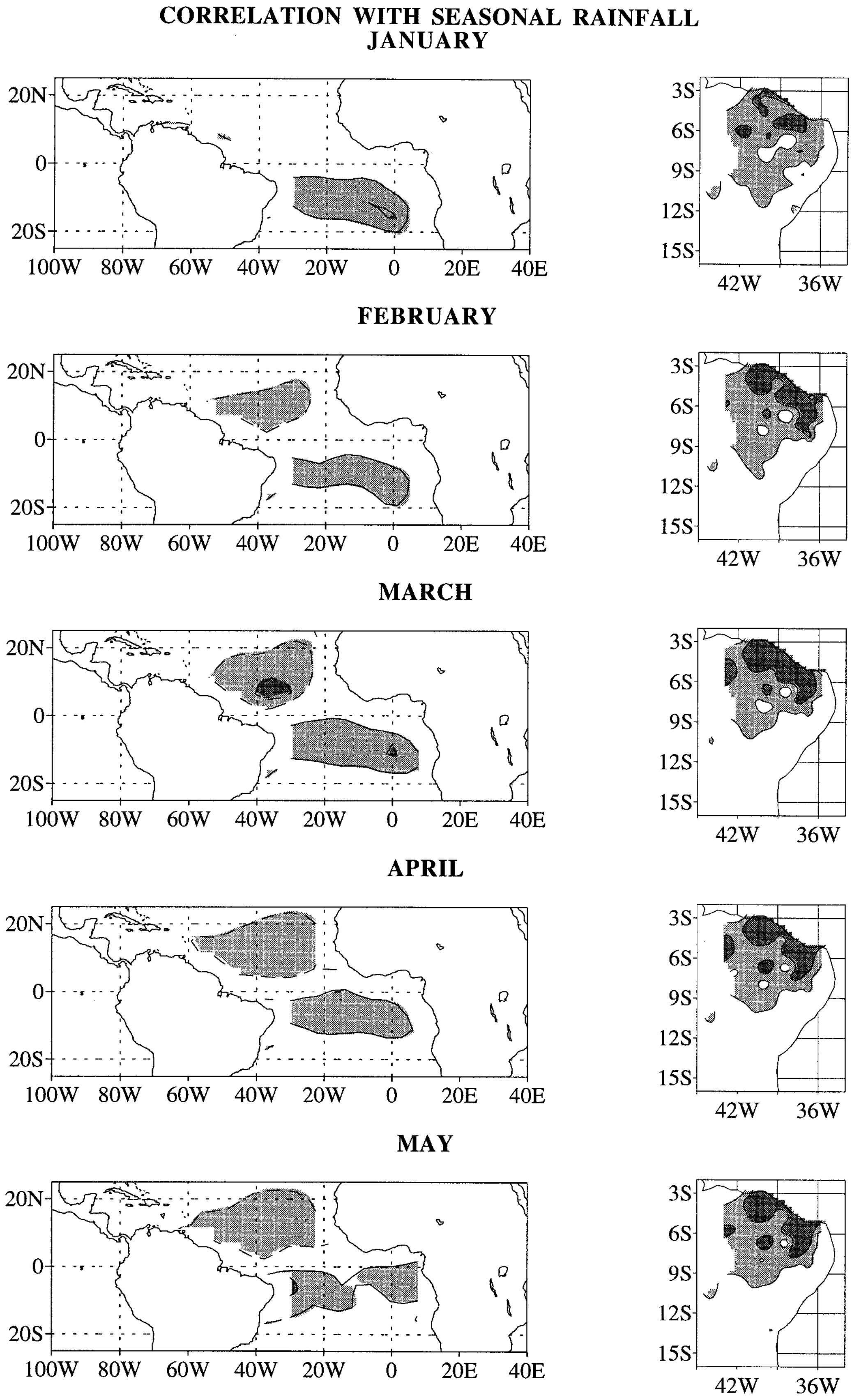

FIG. 7. As in Fig. 3 but for monthly SST and seasonal mean (February–May) precipitation.

months due to a combination of thermal inertia of the upper ocean and large-scale atmosphere–ocean interaction. This persistence property might then explain why SST patterns during January–March show good relation to seasonal precipitation even when they are not well related to concurrent monthly precipitation, the relationship deriving from the persisted SST pattern strongly affecting precipitation in April and May. The same explanation could apply to the differences between Pacific monthly and seasonal precipitation results for January and February. As in the monthly precipitation analyses, the correlations between SST and seasonal precipitation are somewhat stronger for the Atlantic, although the Pacific correlations are still significant.

The relationships depicted in Figs. 6–7 suggest the potential for seasonal rainfall predictions in regions of NEB with skill levels better than chance. This has already been demonstrated by Hastenrath and Greischar (1993) and others in the context of statistical rainfall prediction models for the Nordeste.

SVD analyses between individual months' SST anomalies from January through April and the precipitation for each subsequent month of the rainy season revealed that, in general, Atlantic SST is a better predictor of Nordeste monthly precipitation from 1–3 months in advance (not shown). An exception is that March central and eastern basin precipitation is better related to preceding Pacific SSTs (in the equatorial region) than to Atlantic anomalies. We also conducted a lagged SVD analysis between Pacific and Atlantic SST. This showed that the SST anomalies in the two oceans are well correlated, as found previously by Hastenrath et al. (1987), Ward et al. (1988), and Curtis and Hastenrath (1995), using different analysis methods. The highest correlations were found between the Pacific SST anomalies in January and the Atlantic SST anomalies in March (Fig. 8). The ENSO anomaly pattern is very well correlated (correlation coefficients greater than 0.8) with only the northern tropical Atlantic and not the southern region. During El Niño (La Niña) events, there is a tendency for positive (negative) SST anomalies to develop in the North Atlantic basin, with an associated change in the near-equatorial meridional SST gradient. As shown by Hastenrath and Heller (1977) and others, this SST gradient exhibits a particularly close relationship to precipitation over NEB. Extreme events associated with this gradient generally coincide with the appearance of the full dipole, the southern pole of which appears nearly independent of events in the tropical Pacific.

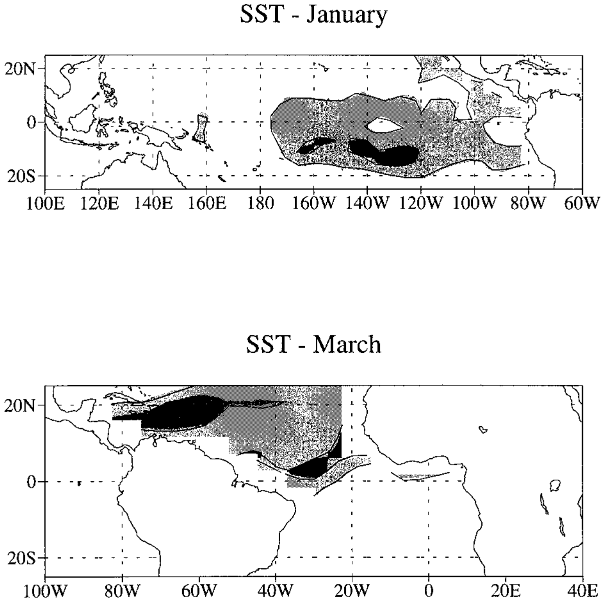

FIG. 8. Heterogeneous correlation map for the first mode in the SVD expansion for January Pacific SST (upper panel) and March Atlantic SST (lower panel). Shading and contours as in Fig. 2.

5. Summary and conclusions

We have used singular value decomposition to analyze the relationships between monthly normalized tropical sea surface temperature anomalies and monthly normalized precipitation anomalies over Northeast Brazil from January through May, considering both simultaneous and time-lagged relationships.

The results showed differing relationships between Atlantic and Pacific SST and regional precipitation during the different months of the rainy season. In January, a weak relationship between SST in the equatorial central Pacific and precipitation in areas of southern NEB was found. As the precipitation in this region at this time is controlled largely by synoptic-scale disturbances (cold fronts), an ENSO-related perturbation of synoptic activity in the region is suggested.

In February, when the rainy season in northern NEB typically starts, no significant Pacific SST–precipitation relation was found. However, SST anomalies in the south equatorial Atlantic are positively correlated with precipitation in the northern Nordeste. Presumably, positive SST anomalies in this region are associated with (and perhaps can cause) a southward displacement of the ITCZ, resulting in an early start to the rainy season.

No significant relationship between Atlantic SST and precipitation was found during March. During this month, the climatological ITCZ and tropical trough are at their southernmost position (Hastenrath and Lamb 1977) and precipitation increases markedly over the Nordeste. Evidently, SST anomalies in the Atlantic do not systematically alter this climatological progression. In view of previous studies, this result is unexpected, although there is no discrepancy; the differences result from the use of monthly versus seasonal averages. (In any case, the lack of relationship between the Atlantic SST and precipitation during March is deserving of further study.) For the Pacific, our analyses showed a relationship between equatorial central and eastern basin

SST anomalies and precipitation over portions of the Nordeste. The mechanism(s) that could account for this relationship remain to be identified.

The months of April and May were found to be the most important contributors to the interannual variations of Nordeste precipitation. The analyses showed that during these months, Nordeste precipitation is correlated positively with SST anomalies in the south tropical Atlantic and negatively with SST anomalies in the north tropical Atlantic—a pattern that has been identified in several previous studies. Repeating the analysis with February–May mean precipitation and either monthly or seasonal mean SST yielded essentially the same pattern. This directly reinforces previous results that used exclusively seasonal (or several month) mean precipitation. The important conclusion to draw from the present results is that the Atlantic SST–precipitation relationships differ markedly from February–March to April–May, but the seasonal mean precipitation–SST relationships follow the April–May patterns due to the strength of the correlations during these months. Pacific SST–precipitation relationships were found for April and May as well. These generally followed the March pattern: equatorial central and eastern Pacific SST anomalies negatively correlated with precipitation over portions of the Nordeste. The Pacific correlations were notably weaker than the Atlantic ones, suggesting the Atlantic Ocean is more directly linked to the positioning and/or strength of the ITCZ precipitation during these months.

A set of analyses between seasonal mean precipitation and monthly SST for the months of January–May confirmed previous findings that seasonal mean Nordeste precipitation can potentially be predicted from January onward with some skill. Again, better relationships exist for Atlantic SST. A strong relationship exists between Atlantic SST in March and seasonal precipitation, even though none exists for March-only precipitation. Presumably this results from the fact that SST exhibits considerable persistence over 2–3 months. In particular, anomalies in the north–south SST gradient that may exist in March can persist through April and May and result in a significant precipitation anomaly in the latter months. The same reasoning can account for the fact that correlations are found between ENSO-related Pacific SST anomalies in January and February and seasonal Nordeste precipitation, even though similar correlations are not found with monthly precipitation during these months.

An SVD analysis between Pacific and Atlantic SST showed that anomalies in the two basins exhibit significant relationships. During an ENSO event, there is a tendency for positive anomalies to develop in the northern tropical Atlantic. This is consistent with previous findings, based on somewhat smaller data records and different analysis techniques. The development of a ''dipole pattern,'' in which the largest meridional SST gradients and the largest precipitation anomalies obtain, requires anomalies of the opposite sign developing in the south tropical Atlantic; the latter seem to be of separate origin. Further studies elucidating the mechanisms of SST variability in this region, and indeed the entire tropical Atlantic, are needed.

The results obtained in this work will be used toward the development of an intraseasonal precipitation forecast for the Brazilian semiarid region. It is expected that such forecasts will become increasingly useful for agricultural planning in this region where irrigation is almost nonexistent.

Acknowledgments. This work was initiated during the First International Training Course on Theoretical and Practical Aspects of Short Term Climate Prediction of the International Research Institute for Climate Prediction at the Lamont-Doherty Earth Observatory of Columbia University, New York. We acknowledge the advice of three reviewers, which was most helpful in improving the paper. Cintia B. Uvo and Carlos A. Repelli were partially sponsored by the NOAA Office of Global Programs. Stephen E. Zebiak and Yochanan Kushnir were supported by NSF Grant ATM-92-24915 and NOAA Grant NA 16-RC0432.

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