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Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil

Summer Circulation Patterns Related to the Upper Tropospheric Vortices over the Tropical South Atlantic

M. T. Kayano, N. J. Ferreira, and **M. C. V. Ramírez**

With 9 Figures

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Summary

Daily 200-hPa relative vorticity data have been used to study the dominant patterns related to the cyclonic vortices over the South Atlantic Ocean in the vicinities of northeast Brazil, during the 1980–1989 period. Reference modes were obtained through empirical orthogonal function (EOF) analysis of the 200-hPa filtered vorticity anomalies over northeast Brazil, considering all the southern hemisphere (SH) summers within the study period. The amplitude time series of the first reference mode, separately for each SH summer, was correlated with the corresponding filtered vorticity anomalies in a larger area extending from 20 °N to 40 °S and between 120 °W and 20 °W. The correlation patterns feature a wave-like structure along eastern South America, with three main centers: the first one, over the South Atlantic off the northeast Brazil coast, is associated with the cyclonic vortices; the second one, over eastern Brazil, represents the corresponding anomalously amplified ridges; and the third one, over southern Brazil/Uruguay, is related to the equatorward incursions of midlatitude upper level troughs. This wave-like pattern is consistent with the vortex formation mechanism suggested in previous works. Another wave-like pattern southwest-northeast oriented is evident over the tropical southeastern Pacific, for some years. The interannual variability of these patterns is discussed in this paper.

1. Introduction

The prominent climatological circulation feature over South America is an intense quasi-stationary upper level anticyclone, which spreads over most of the continent north to 30 °S, during the SH summer. Numerical studies have shown that this feature stems from the strong tropical heat source in the Amazon (e.g., Silva Dias et al., 1983; DeMaria, 1985; Kleeman, 1989). This anticyclone, generally known as the Bolivian high (BH) (Virji, 1981), evidences the Rossby wave dispersion as a response to this tropical heat source (Silva Dias et al., 1983).

Frequently the downstream trough associated with the BH encompasses a closed cyclonic vortex over northeast Brazil or neighbouring oceanic areas. This system is quite similar to the northern hemisphere (NH) subtropical upper tropospheric vortices observed in the north Pacific and north Atlantic oceans during the NH summer (e.g., Palmer, 1951; Simpson, 1952; Riehl, 1954). These systems are cold cored, are confined to the middle and upper troposphere and are extremely persistent.

The formation nature and maintenance of these NH systems have been extensively studied (e.g., Ramage, 1962; Carlson, 1967; Frank, 1970; Kelley and Mock, 1982; Chen and Chou, 1993). The South Atlantic vortices have been observed for quite a long time (Aragão, 1976; Virji, 1981; Kousky and Gan, 1981; Rao and Bonatti, 1987). Virji (1981) noted upper level closed cyclonic vortices forming just off the east coast of Brazil, near the axis of the mid-ocean trough, during the SH summer. Aragão (1976) and Kousky and Gan

(1981) have shown that these systems play an important role in the northeast Brazil rainfall distribution.

Based on polar orbiting satellite images for the 1975–1979 period, Kousky and Gan (1981) were the first to provide a climatological statistics for the South Atlantic vortices. Recently, Ramírez et al. (1997) presented a new climatological statistics for these vortices based on the wind, temperature and satellite images for the 1980–1989 period. Both analyses show that the South Atlantic vortices are cold cored, are more frequent during the SH summer and are closely related to the BH.

Concerning the mechanism of vortex formation, Kousky and Gan (1981) proposed that the warm advection in the low troposphere, in the equatorside of an active cold front, has an important role in amplifying the upper level downstream ridge, what ensues a strengthening of the downstream trough. Ramírez et al. (1997) found indications that the SH summer vortices develop primarily according to this mechanism. In addition, they noticed that the subtropical troughs in the north Pacific and north Atlantic oceans may also play an important role in amplifying the BH ridge in its southeast sector, thus contributing indirectly to the vortex development.

A question not directly addressed in previous studies of the South Atlantic vortices concerns the role played by the low frequency variability related to the El Nino/Southern Oscillation (ENSO) cycles on these vortices. Ramírez et al. (1997) found significant interannual variations in the yearly total number of vortices, that may likely be related to the low frequency variability of the tropical atmosphere. On the other hand, the relationship between the ENSO cycles and the occurrence of rainfall anomalies over northeast Brazil has been documented in a number of papers (e.g., Kousky et al., 1984; Kayano et al., 1988; Ropelewski and Halpert, 1987; Ropelewski and Halpert, 1989).

The present study focuses on the analyses of the upper tropospheric vorticity patterns related to the South Atlantic vortices over South America/South Atlantic sector. Emphasis is given on the interannual variations of these patterns during the SH summer.

2. Data and Methodology

The data consist of daily analyzed 200-hPa zonal and meridional wind components at 12:00 Z obtained from the European Centre for Medium Range Weather Forecasts (ECMWF), for the 1980–1989 period. These data have a spatial resolution of 2.5 degrees in latitude and longitude. The domain of study extends from 20 °N and 40 °S and between 120 °W and 20 °W. The relative vorticity was computed for this area.

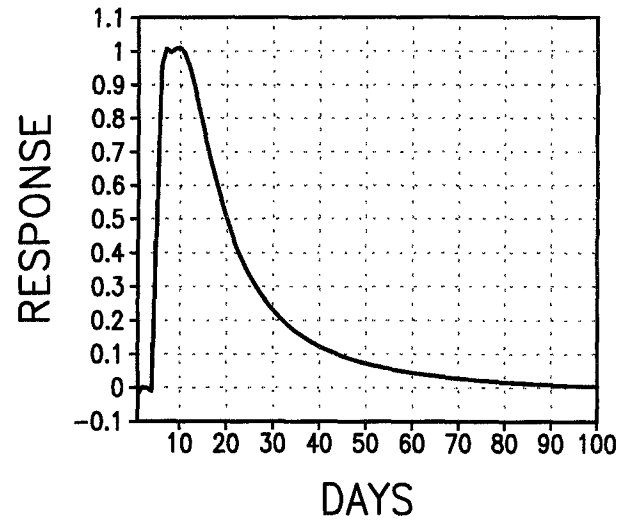

Fig. 1. Response of a Lanczos band-pass filter with 31 weights and cutoff frequencies at 0.05 day^{-1} and 0.2 day^{-1}

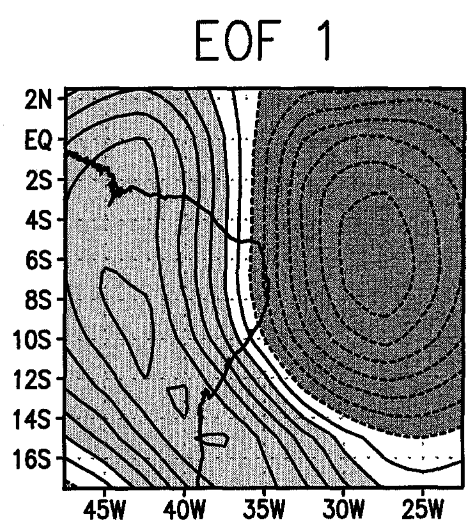

Fig. 2. The first reference mode patterns for 200-hPa vorticity during the SH summer. The loadings are contoured with interval of 0.1. Negative (positive) loadings are contoured with dashed (solid) lines. Dark (light) shades indicate loadings less (greater) than −0.1 (0.1)

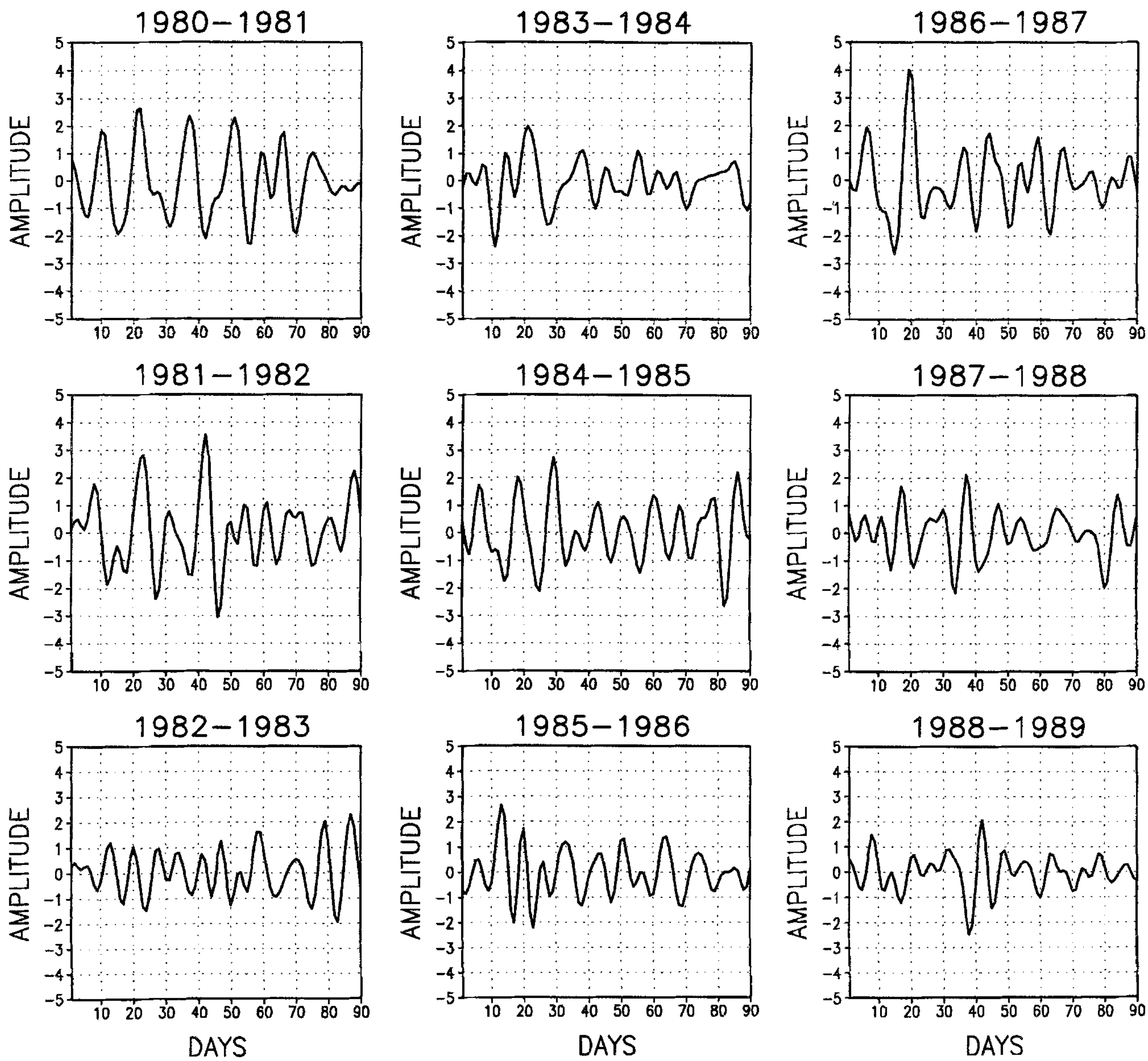

Fig. 3. The amplitude time series for the first reference mode shown in Fig. 2

Since the 10-year vorticity dataset gives a rather noisy daily climatology, 3-month seasonal means for the period of study were used to compute the daily anomalies. Temporal band-pass filtering on vorticity anomalies was performed by applying a Lanczos filter (Duchon, 1979) with 31 weights and specifying a frequency response of 0.5 at the periods of 5 and 20 days (Fig. 1).

EOF calculations were performed using the SH summer filtered vorticity anomalies over northeast Brazil (an area between 47.5 °W and 22.5 °W and 2.5 °N and 17.5 °S), where vortices have frequently been observed (e.g., Kousky and Gan, 1981; Ramírez et al., 1997). This analysis provides the reference modes and the corresponding principal component time series (amplitude time series of the modes). The filtered vorticity anomaly time series in each gridpoint in the entire domain of study were then correlated with the reference amplitude time series. Correlations were computed separately for each summer in order to make the analyses of the interannual variability of the correlation patterns possible. The EOF calculations were performed using the correlation matrix.

3. Results

3.1 Reference EOF Modes

The first two modes explain respectively, 18.0% and 13.5% of the total variance for the SH summer filtered 200-hPa vorticity data. The first mode has its largest loadings over the South Atlantic just off the northeast Brazil coast and over eastern Brazil (Fig. 2). For positive amplitudes (Fig. 3), this mode features negative loadings over the South Atlantic near the northeast Brazil coast and positive loadings over eastern Brazil. These patterns are similar to those observed during the initial stages of an upper level cyclonic vortex over the South Atlantic sector. The amplitude time series for this mode exhibits significant interannual variability.

Information both on the intensity of the vortex in the South Atlantic off the northeast Brazil coast and on its frequency of occurrence can be obtained by inspections of the amplitude time series for the first mode (Fig. 3). Quite intense vortices occur at nearly regular intervals of 10–14 days during the following periods: 1980–1981 SH summer, February 1983, December 1984 and December 1986. Otherwise, weaker vortices seem to occur more frequently (one vortex every 6–8 days), as indicated by the amplitude time series during: mid January 1982–February 1982, December 1982–January 1983, January 1985–February 1985, January 1986–February 1986, January 1987–February 1987 and during most of the 1987–1988 and 1988–1989 SH summers. The amplitude time series can also provide information on the persistence of vortices off the northeast Brazil coast. For example, the positive amplitudes lasting more than 12 days near the end of February 1988 indicate a persistent vortex.

The second mode shows its largest loadings centered over northeast Brazil (Fig. 4). For positive amplitudes (Fig. 5), the negative loadings over this region correspond to an upper level cyclonic vortex. Since only a few vortices form over northeast Brazil and the observed vortices over this area are already in their mature stages (Ramírez et al., 1997), it seems reasonable to infer that this mode describes the upper level vorticity patterns associated with a mature vortex. Like the first mode, the second mode amplitude time series provides information on the intensity of the vortex over northeast Brazil and on its frequency of occurrence.

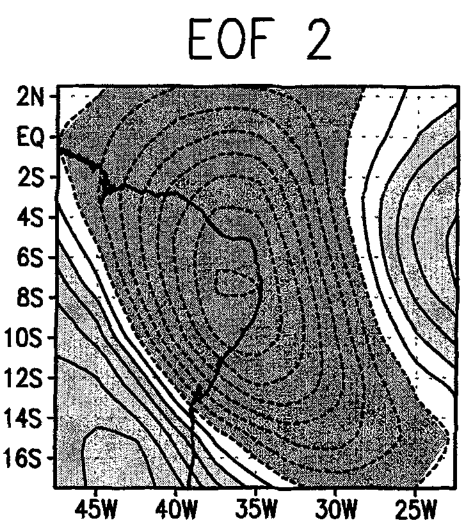

Fig. 4. Same as Fig. 2, except for the second reference mode. Display is the same as in Fig. 2

3.2 Correlated Patterns for the First EOF

For conciseness, only the correlation patterns for the entire study area corresponding to the first mode are discussed. In order that the correlation be significantly different from zero at the 95% level, the absolute correlation coefficient must exceed approximately $2/(N)^{1/2}$, where N is the number of degrees of freedom (Panofsky and Brier, 1968). The time series for the SH summer has 90 days, so that the threshold for correlations to be significant is 0.21. Thus, in the analysis of the correlation patterns, only the absolute correlations exceeding this value were considered.

The SH summer patterns exhibit significant interannual variability (Fig. 6). A common feature for all summers is a wave-like pattern oriented in the southwest-northeast direction along eastern South America and adjacent areas,

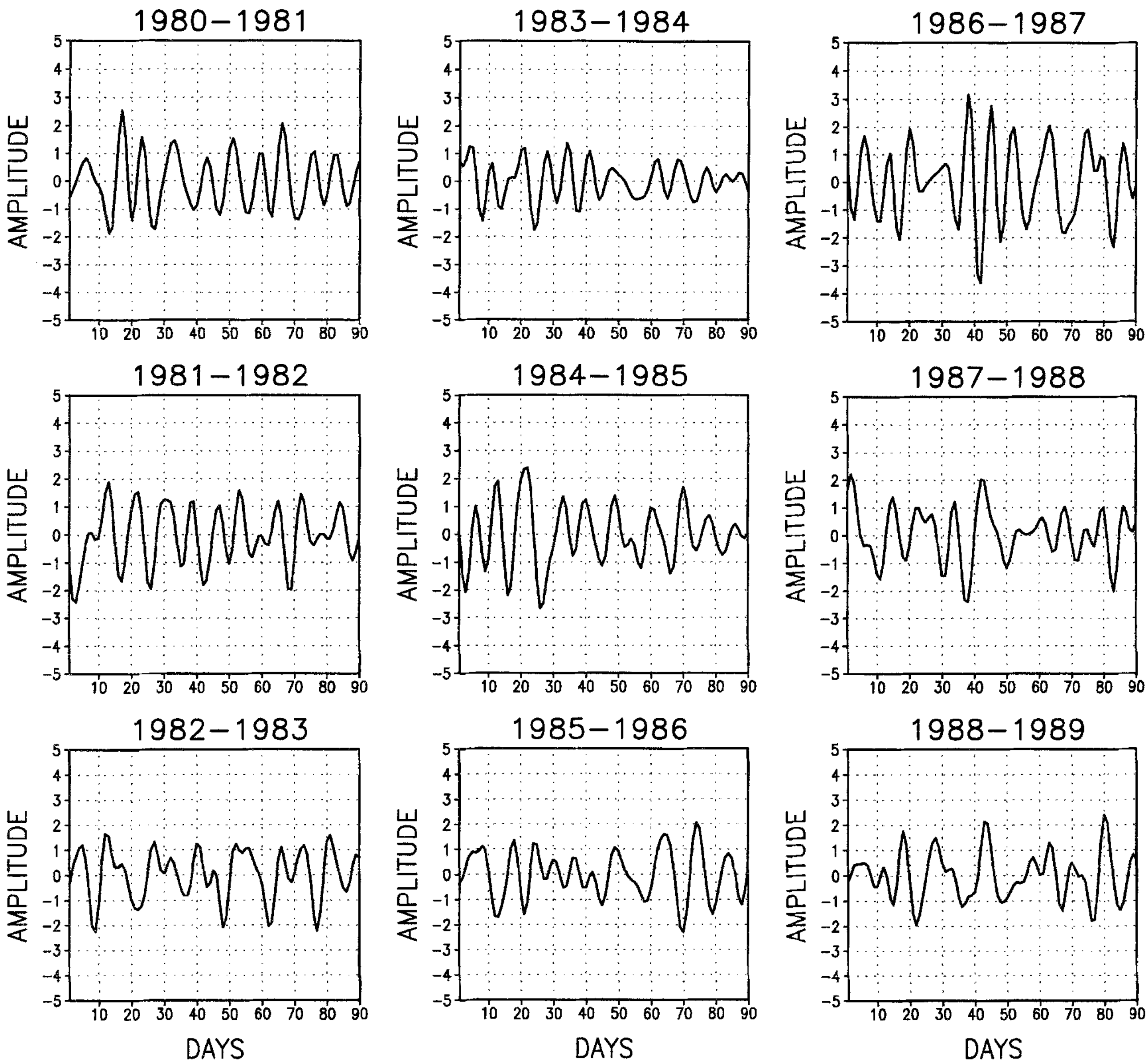

Fig. 5. The amplitude time series for the second reference mode shown in Fig. 4

with the largest negative correlations in the South Atlantic close to northeast Brazil. These negative correlations imply the presence of an upper tropospheric cyclonic vortex. To the southwest of this system, positive correlations in an area elongated in the southeast-northwest direction are related to an upper level strengthened ridge. Previous works (Kousky and Gan, 1981; Ramírez et al., 1997) have shown that this ridge is not only associated with the BH but its amplification contributes to the development of the vortex over the South Atlantic off the northeast Brazil coast. Negative correlations are found over southern Brazil/Uruguay and contiguous oceanic areas, for most summers. These negative correlations reflect the equatorward incursion of a midlatitude upper level trough.

The centers of extreme correlations associated with the wave-like pattern over eastern South America show significant interannual variations

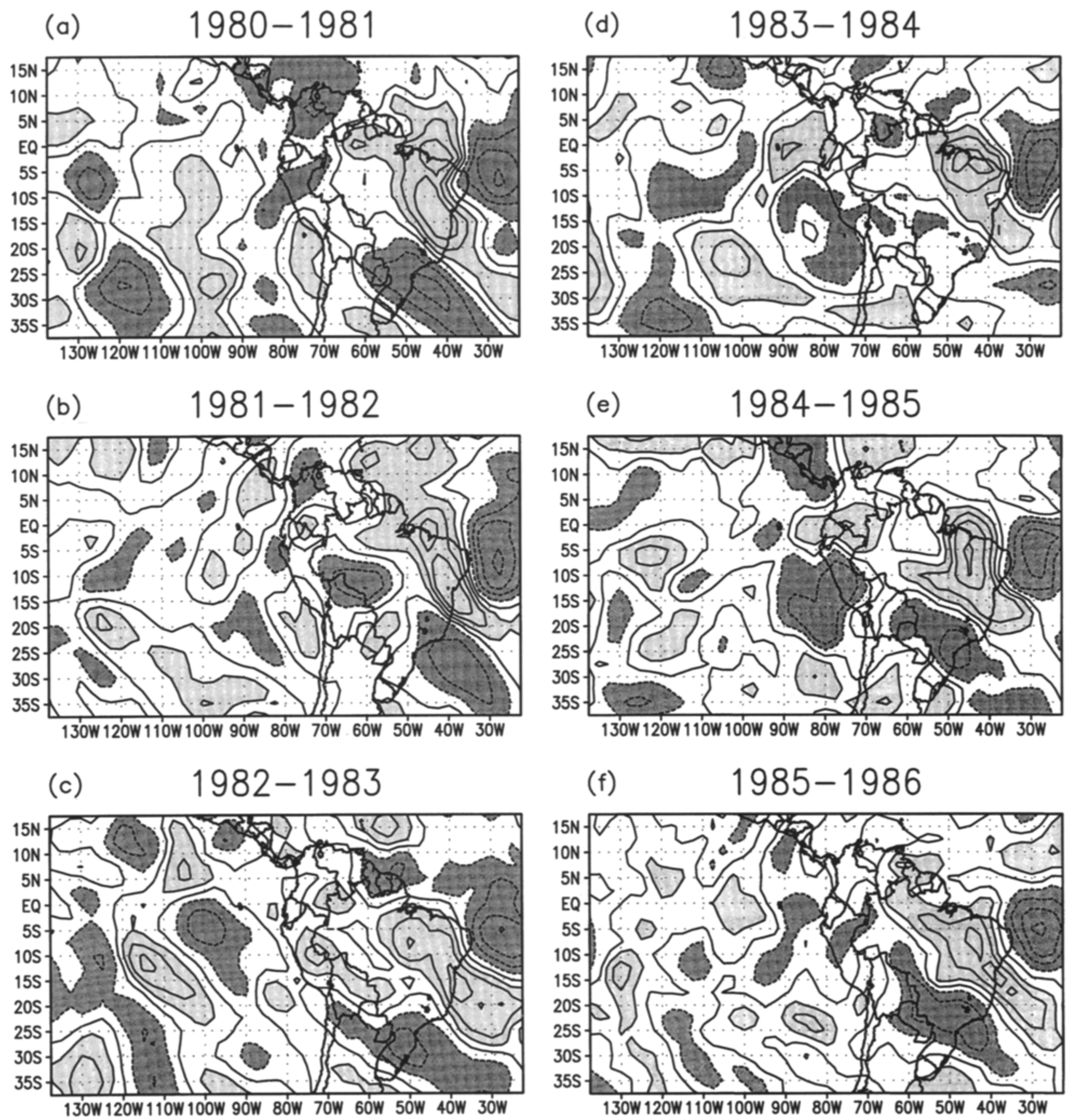

Fig. 6. Correlation patterns for the first reference mode. Contour interval is 0.2. Negative (positive) loadings are contoured with dashed (solid) lines. Dark (light) shades indicate loadings less (greater) than −0.2 (0.2)

regarding their locations and intensities. The extreme absolute values of the correlations vary from 0.6 for the 1988–1989 SH summer to 0.8 for the others summers. The maximum correlations associated with the upper level ridge over South America are centered over the coastal areas for some summers (1980–1981, 1981–1982, 1982–1983), and further inland for others (1983–1984, 1984–1985, 1986–1987). The largest negative correlations associated with the midlatitude trough also exhibit variability in their positions, with their extreme locations being off

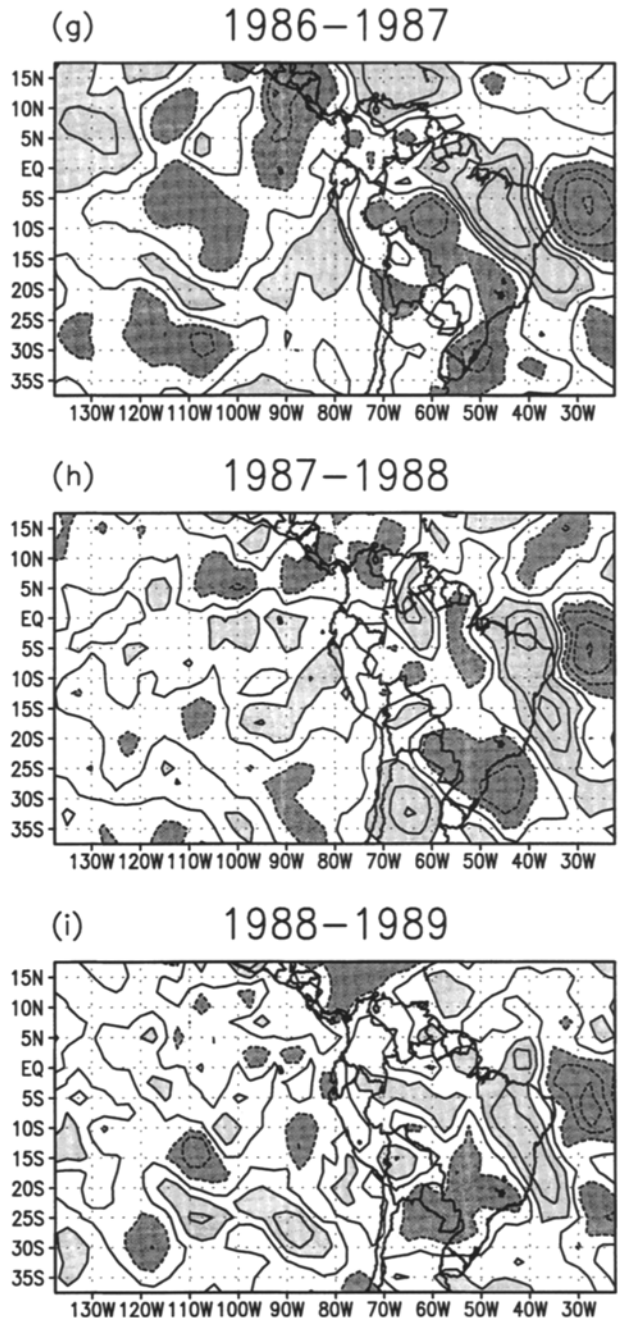

Fig. 6. (Continued)

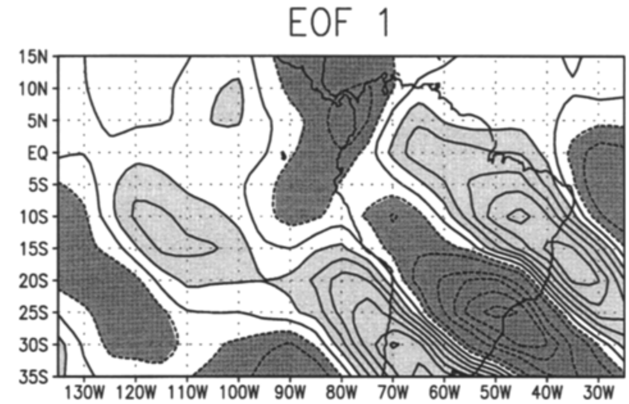

Fig. 7. First mode patterns for 200-hPa vorticity for the entire study area and for all SH summers. Display is the same as in Fig. 2

the coast during 1981–1982 summer and inland during 1988–1989 summer.

The largest correlations are found over the northeast Brazil coast, eastern Brazil and southern Brazil/Uruguay. However, during some summers there is another southwest-northeast oriented wave-like pattern in the tropical southeastern Pacific, with centers elongated in the southeast-northwest direction. Negative correlations are found in the subtropical South Pacific Ocean between 120 °W and 110 °W, flanked to northeast by positive correlations. Further northeast negative correlations are also observed close to the equator. This pattern is more prominent during the 1980–1981, 1982–1983 and 1983–1984 SH summers and barely detectable for the other summers.

Another important feature found in the correlation patterns is the occurrence of extreme correlations in the area of the climatological position of the BH. Negative correlations are there observed during the summers of 1984–1985 and 1986–1987. Inspections of daily wind data indicate that the negative correlations reflect a northward and westward displacements of the BH during the 1984–1985 SH summer and the 1986–1987 SH summer, respectively. As it would be expected, positive correlations are found over north Peru and Ecuador during the 1984–1985 summer, and just off the Peruvian and Chilean costal areas, during the 1986–1987 summer.

3.3 EOF Vorticity in the Domain of Study

EOF calculations were performed using the filtered vorticity anomalies in the entire domain

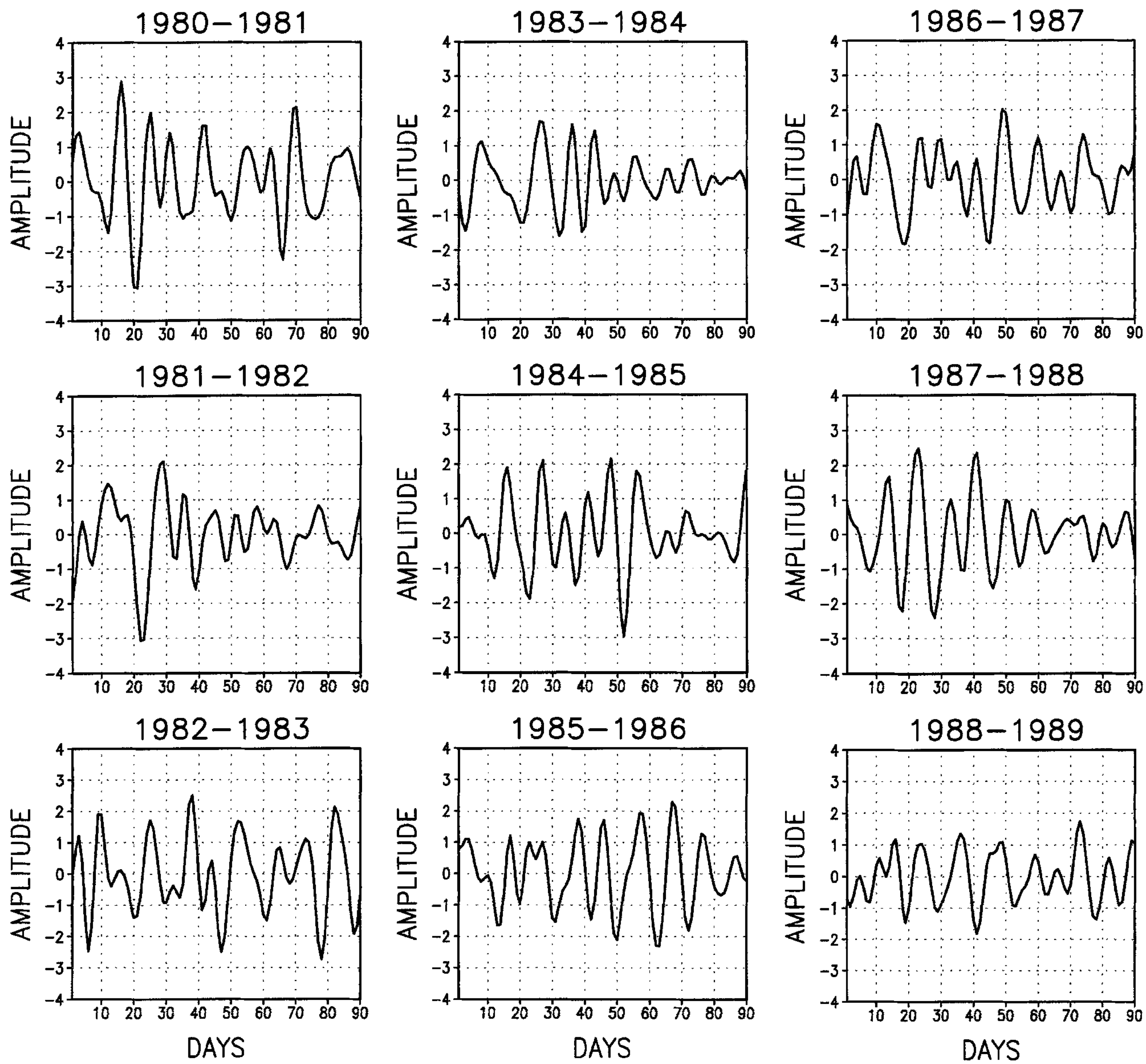

Fig. 8. Amplitude time series of the first mode shown in Fig. 7

of study for the SH summers. In this analysis, the filtered anomalous time series were taken at every other gridpoint, thus reducing the horizontal resolution to 5 degrees in latitude and longitude. This analysis provides a general view of the dominant 200-hPa vorticity patterns during the SH summer.

The first mode for the 200-hPa vorticity anomalies has its largest loadings over eastern South America (Fig. 7) and it explains 6% of the total variance of the filtered vorticity data during the SH summers. This mode shows a wave-like pattern over eastern South America. It also features a hardly noticeable wave-like pattern over tropical southeastern Pacific. These patterns are similar to those found to be related to an upper level vortex off the northeast Brazil coast observed for individual summers. Indeed, for positive amplitudes (Fig. 8), the wave-like patterns over eastern South America represent

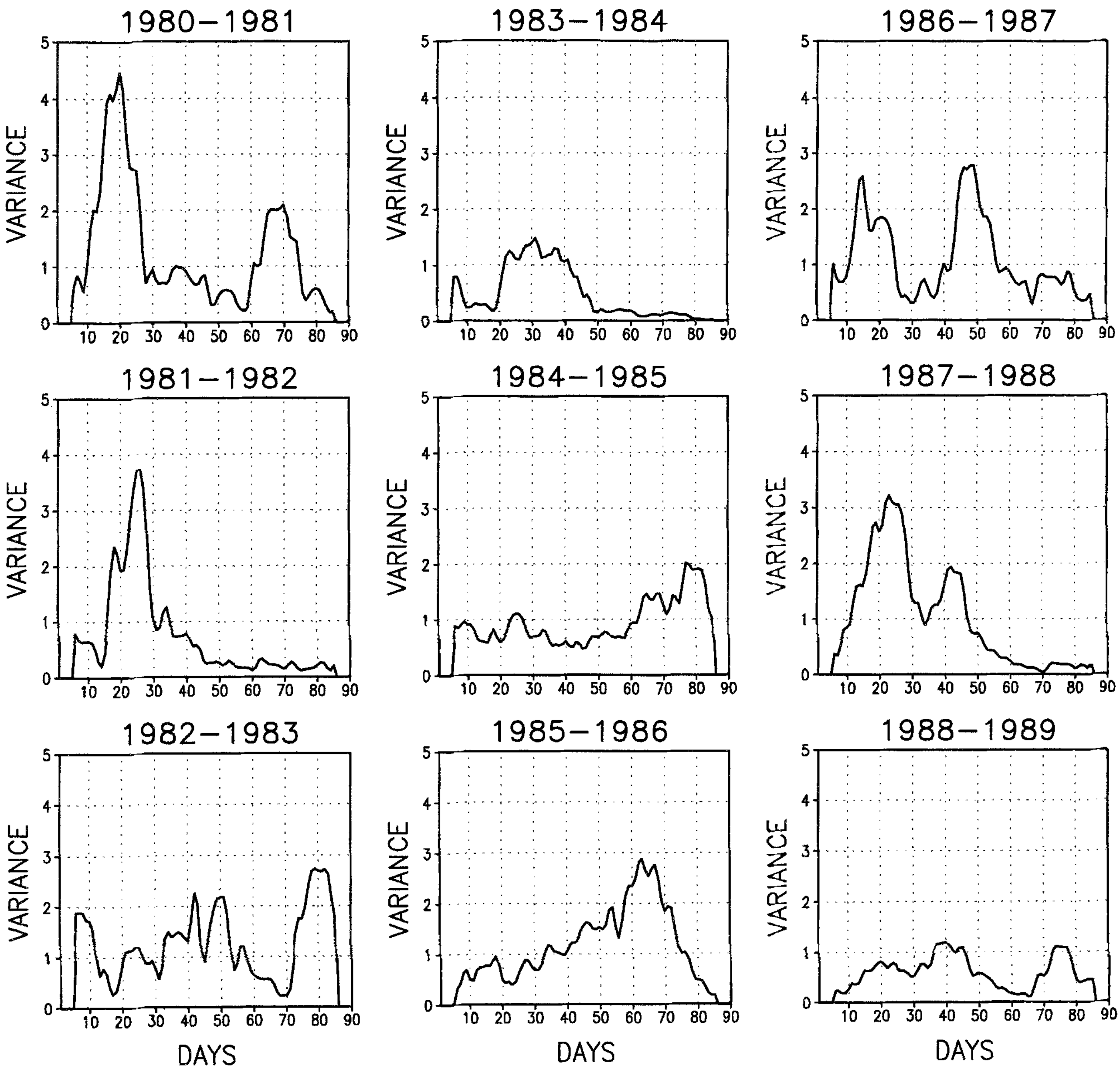

Fig. 9. The variance of time series shown in Fig. 8, computed for overlapping 11-day periods

an upper tropospheric vortex over South Atlantic off the northeast Brazil coast, an intensified upper level ridge over eastern Brazil and a further southwest pronounced upper level trough associated with a southern midlatitude cold front.

Analyses for individual summers have shown that the secondary wave-like pattern in the tropical southeastern Pacific does not occur in every summer. Since it shows up in the EOF analysis for all summers and for the entire study area, one can deduce that this pattern is part of the upper level vorticity patterns related to the vortex over South Atlantic off the northeast Brazil coast.

The first mode patterns show strong interannual variability (Fig. 8), which can clearly be seen by computing the variance of the amplitude for this mode, using overlapping 11-day periods for each summer (Fig. 9). The variances are relatively smaller for the summer of 1983–1984 and 1988–1989 than for other summers, and considerably large for December 1980 and December 1981.

4. Conclusion

The dominant 200-hPa vorticity patterns related to cyclonic vortices over the South Atlantic in the vicinities of northeast Brazil were determined using daily data for the 1980–1989 period. Reference modes were obtained through EOF analysis of the 200-hPa filtered vorticity anomalies for the SH summers over an area encompassing the northeast Brazil. The first two modes describe evolving regional vorticity patterns related to the initial (first mode) and mature (second mode) stages of a vortex over the South Atlantic sector.

The amplitude time series of the first reference mode was correlated with the filtered vorticity anomalies in the domain of study, which extends from 20 °N to 40 °S and between 120 °W and 20 °W. A common feature for all summers is a wave-like pattern along eastern South America. This pattern is southwest-northeast oriented, thus implying a northward transport of momentum. This pattern consists of three main centers: the first one over the South Atlantic off the northeast Brazil coast, with negative correlations associated with the cyclonic vortex; the second one over eastern Brazil, with the positive correlations related to the anomalously amplified ridge; and the third one over southern Brazil/Uruguay, with the negative correlations associated with the equatorward incursion of the midlatitude upper level trough. This three centers essentially describe the regional atmospheric circulation features taking part in the vortex formation mechanism put forth by Kousky and Gan (1981). The analyses in the present paper revealed that this pattern exhibits significant interannual variability.

For the summers of 1980–1981, 1982–1983 and 1983–1984, another southwest-northeast oriented wave-like pattern is evident in the tropical southeastern Pacific, with negative correlations in the subtropical area between 120 °W and 110 °W, flanked to northeast by positive correlations. Further northeast negative correlations are found close to the equator. Such a pattern is more pronounced during the 1982–1983 summer, a period with strong El Niño. This suggests that this secondary wave-like pattern may be connected with the El Niño related variations in the tropical atmosphere. Since this wave-like pattern appears in an EOF analysis for all summers and for the entire study area, it is likely that this pattern may have a secondary role in the vortex formation over South Atlantic off the northeast Brazil coast.

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Authors' addresses: Mary T. Kayano, Nelson J. Ferreira and María C. V. Ramírez, Instituto Nacional de Pesquisas Espaciais, C. P. 515, 12201–970 São José dos Campos, SP, Brazil.