On the Functioning of the Southern Oscillation in the South American Sector. Part II: Upper-Air Circulation

PATRICIO ACEITUNO*

Departamento de Geologia y Geofisica, Universidad de Chile, Santiago, Chile

(Manuscript received 7 March 1988, in final form 29 September 1988)

ABSTRACT

The functioning of the Southern Oscillation (SO) in the South American sector is analyzed with particular emphasis on the upper-air circulation anomalies. Throughout the year, but especially during austral summer, the negative SO-phase (defined as anomalously low/high pressure at Tahiti/Darwin) is typically associated with a relatively warm tropical troposphere, while negative temperature anomalies prevail during the positive SO-phase. Outside the tropics, upper-air circulation anomalies are most pronounced during the winter. Thus, in boreal winter the negative SO phase is associated with reduced 500 and 200 mb heights at 20–30°N, but positive height departures southward of 20°N. The implied steepening of the meridional thickness gradient is consistent with anomalously intense upper-air westerlies over the Gulf of Mexico and Caribbean region. In austral winter during the negative SO phase, relatively cold tropospheric conditions prevail over the southern portion of South America. Case studies for extremes of the SO during January-February reveal broadly opposite anomaly patterns during the positive SO phase compared to those during the negative SO phase.

1. Introduction

The sustained interest in the Southern Oscillation (SO) is reflected in a long series of articles published since the end of the last century [for a review of SO research see Hastenrath (1985), pp. 253–258]. In the South American sector, the most pronounced and best documented SO-related climatic anomalies occur in association with El Niño events during the negative SO phase (characterized by anomalously low/high pressure in Tahiti/Darwin). The most conspicuous features during these episodes are the anomalously warm surface waters in the tropical eastern Pacific, and the torrential rains in the coastal areas of northern Peru (Rasmusson and Carpenter 1982). Further details about SO-related anomalies in the surface climate are described in Aceituno (1988).

Regarding the upper-air circulation, research over more than a decade has produced ample evidence that the tropical troposphere is relatively warm during the negative SO phase, when positive SST departures are apparent in the tropical eastern Pacific (Newell and Weare 1976; Newell 1980; Angell 1981; Horel and Wallace 1981, Hastenrath and Wu 1982; Angell and Korshover 1984; Parker 1985; Rogers 1988). The vertically expanded tropical troposphere during the negative SO phase seems instrumental for enhanced upper-air westerlies at higher latitudes (Chiu and Lo 1979; Hastenrath and Wu 1982; Arkin 1982). Studies of global climate variability have furthermore documented the existence of teleconnection patterns closely linked to the SO (Horel and Wallace 1981; Wallace and Gutzler 1981; Karoly 1986). The present investigation, drawing on the aforementioned studies and based on a more comprehensive observational dataset, attempts to improve the understanding of the annual cycle characteristic of the SO in the South American sector, particularly with respect to variations in tropospheric thickness patterns, and associated departures in zonal circulation.

2. Data

Geopotential height and zonal wind at 850, 500, and 200 mb were analyzed to represent the lower, middle and upper troposphere, respectively. Monthly values of these radiosonde data published in *Monthly Climatic Data for the World* (U.S. Weather Bureau, ESSA, NOAA 1951–84) were obtained on magnetic tape from the National Center for Atmospheric Research. Station locations are indicated in Fig. 1.

Records of surface land stations and ship observations are described in Aceituno (1988). Monthly records of air temperature at the surface were compiled for stations in South and Central America and the Caribbean, mainly for the period 1951–83 (Aceituno

---

[*] This work was performed while the author was a graduate student at the Department of Meteorology, University of Wisconsin, Madison.

Corresponding author address: Dr. Patricio Aceituno, Dept. of Geology and Geophysics, Universidad de Chile, Casilla 2777, Santiago, Chile.

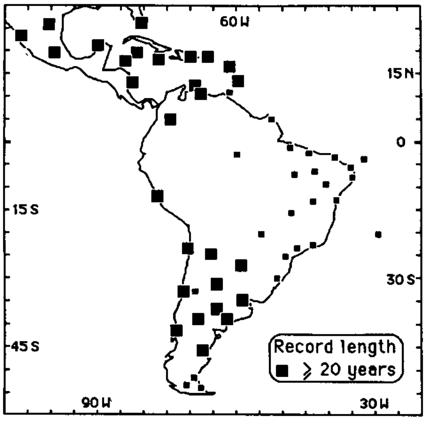

FIG. 1. Orientation map for radiosonde stations. Large squares represent stations with available geopotential records for 20 or more yr.

1988, Fig. 1b), but as far back as 1941 when possible. Values beyond physically reasonable limits were discarded after comparison with neighboring stations. Ship observations of sea surface temperature (SST) in the tropical Atlantic and eastern Pacific Oceans, obtained from the National Climatic Center at Asheville, North Carolina (Hastenrath and Lamb 1977) and compiled into 5° square values for individual months, were analyzed here for the period 1948–83.

The difference of monthly atmospheric pressure at Tahiti (18°S, 150°W) minus Darwin (12°S, 131°E), as tabulated by Parker (1983), was used as an index of the SO (SOI) during 1935–83. This easily defined index is closely related to other SO indices (Wright 1984).

3. Background circulation

Figure 2 shows the flow patterns at 200, 500, and 850 mb, during the extremes of the annual cycle in January–February and July–August. This, along with the description of the annual cycle of surface climate in Aceituno (1988), serves as a background for the discussion of circulation anomalies in sections 4 and 5.

The 200 mb flow in austral winter (Fig. 2d) is relatively weak over tropical South America and the Caribbean, while in the subtropical portion of the continent the westerlies reach their annual maximum, with speeds exceeding 30 m s^{-1}. During austral summer (Fig. 2a), a well-defined anticyclonic circulation develops over tropical South America in response to diabatic heating of the atmospheric column in regions of intense convection (Gutman and Schwerdtfeger 1965; Virji 1981; Kousky and Kagano 1981; Aceituno 1988, Fig. 4a therein). Strong westerlies prevail over southern South America, as well as the Gulf of Mexico and Caribbean region, where speeds reach their annual cycle maximum at this time of the year.

The circulation at 500 mb (Fig. 2b, e) is relatively weak over tropical South America, particularly during austral summer (Fig. 2b). In the southern portion of the continent, westerlies prevail all year round, being most intense during austral winter (Fig. 2e). Also apparent in Fig. 2 is the Southern Hemispheric subtropical westerly jet, with its northernmost position in austral winter (Fig. 2d, e) and a location farthest poleward in austral summer (Fig. 2a, b). Over the Gulf of Mexico and Caribbean region, winds alternate between westerly in boreal winter (Fig. 2b) and easterly during the boreal summer (Fig. 2e). These seasonal changes in the wind regime are consistent with the seasonal shifts of major circulation features such as the near-equatorial trough and the subtropical highs.

The 850 mb flow patterns are presented in Fig. 2c, f. Over the Caribbean the circulation is similar to that at the surface (Aceituno 1988, Fig. 4a, d). Over the continent, the meridionally extended barrier of the Andes effectively separates the Atlantic–Amazon domain from the Pacific. Over the southern portion of the continent strong westerlies prevail throughout the year, in accordance with the steep meridional pressure gradient.

4. Correlation analysis

Relationships between the SO and the interannual variability of height and zonal wind fields at 200, 500 and 850 mb are explored through the analysis of patterns of correlation with the pressure difference between Tahiti and Darwin. Bimonthly correlation patterns based on 37 radiosonde stations with records of at least 15 yr illustrate the annual functioning of the SO. Correlation coefficients were tested for significance at the 5% level, assuming independence between observations taken 1 yr apart.

Figure 3 shows bimonthly maps with patterns of correlation between the SOI and the 200 mb height, which essentially represents the mean temperature of the tropospheric column. The prevailingly negative correlations in Fig. 3 are consistent with various earlier studies indicating an anomalously warm troposphere during the negative SO phase (Newell and Weare 1976; Newell 1980; Angell 1981; Horel and Wallace 1981; Hastenrath and Wu 1982; Angell and Korshover 1984; Parker 1985; Rogers 1988). Figure 3 also shows marked seasonal changes in the SO-related height anomalies, with largest negative correlations (around −0.8) over the tropics at the height and latter part of the austral summer semester (January–April; Fig. 3a, b). This is also the time of the year with the closest relationship between the SO and SST, particularly in the tropical eastern Pacific and the Caribbean. In fact, the negative SO phase is associated with positive SST departures in these regions (Aceituno 1988, Fig. 8), which may contribute to the concomitant anomalously warm tropospheric conditions.

To substantiate the relation between upper-air topographies and surface temperature, an SST index was

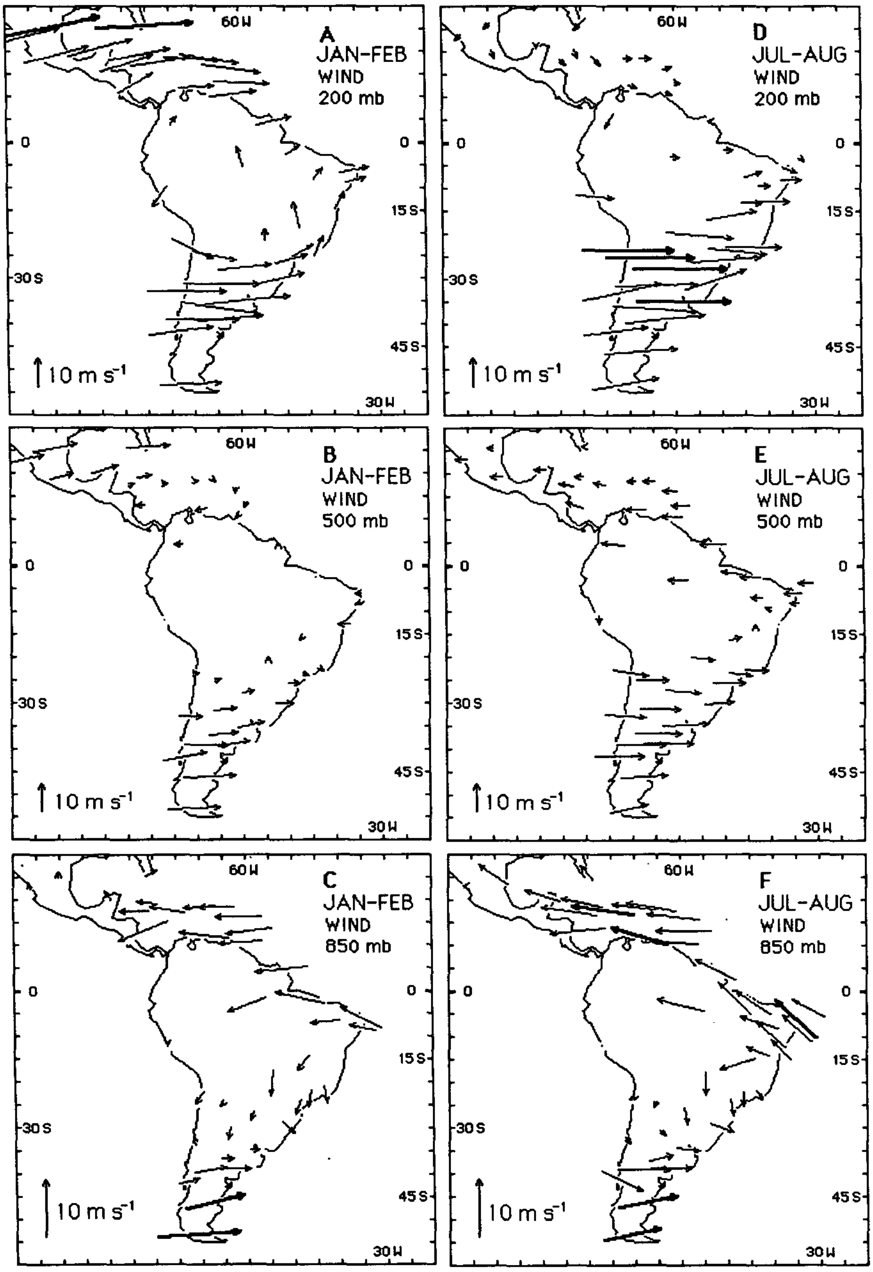

FIG. 2. Upper-air wind fields from radiosondes. January–February: (a) 200 mb; (b) 500 mb; (c) 850 mb. July–August: (d) 200 mb; (e) 500 mb; and (f) 850 mb. A scale for wind speed is included in each panel. Arrows in boldface indicate wind speed exceeding 30 m s^{-1} (panels a, d) and 10 m s^{-1} (panels c, f).

compiled for the Caribbean area indicated in Fig. 3a, and correlated with the January–February and March–April 200 mb height at ten stations contained in the belt 10°–20°N. The resulting correlations, between +0.5 and +0.8, are significant at the 5% level.

Regarding the correlations of 200 mb height with the SOI (Fig. 3), significant negative values over the Caribbean contrasting with the small positive values over Mexico and Florida during the latter part of the austral summer (Fig. 3b) suggest an enhanced meridional height gradient at 200 mb over the Northern Hemisphere subtropics during the negative SO phase. Composite analyses of El Niño situations (Rogers, 1988) support this conjecture.

Figure 4 shows bimonthly maps of correlation between the SOI and the 500 mb height calculated from

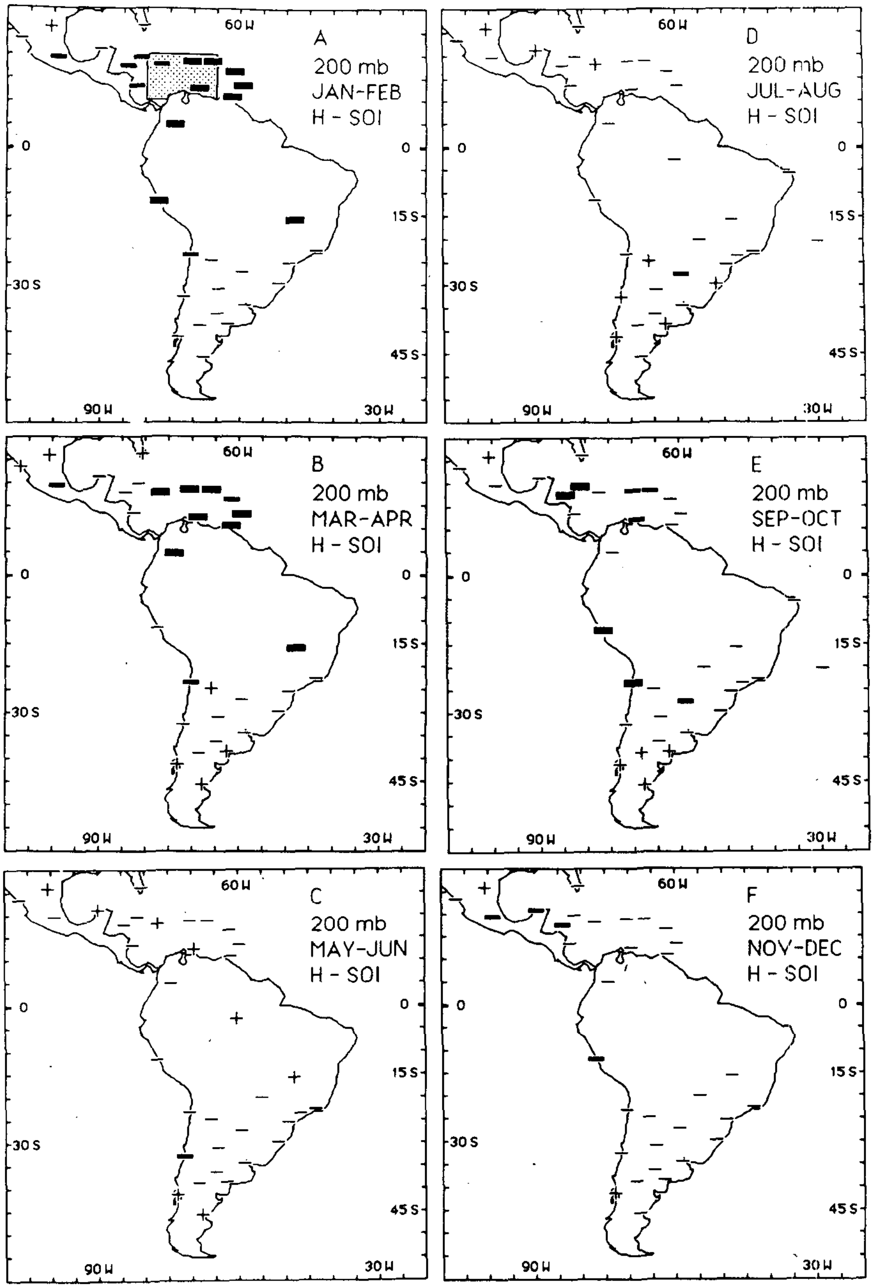

FIG. 3. Patterns of correlation between a Southern Oscillation index (Parker 1983) and the 200 mb height obtained from radiosondes: (a) January–February, (b) March–April, (c) May–June, (d) July–August, (e) September–October, and (f) November–December. Plus and minus signs indicate the sign of the correlation, and boldface type denotes values that reach the 5% significance level. Largest signs denote absolute values beyond 0.50. Dot raster in panel (a) indicates the area for which a SST index was compiled for correlation with 200 mb height from Caribbean upper-air stations.

radiosondes. Similar to the 200 mb height correlation maps (Fig. 3), the correlation patterns in Fig. 4 suggest positive height departures over the tropics during the negative SO phase and an enhanced meridional height gradient over the subtropics of both the Northern and Southern hemispheres. The SO-related height anomalies over the tropics are most pronounced during the austral summer semester, when significant negative correlations prevail over tropical South America and the Caribbean (Fig. 4a, b) with largest negative values

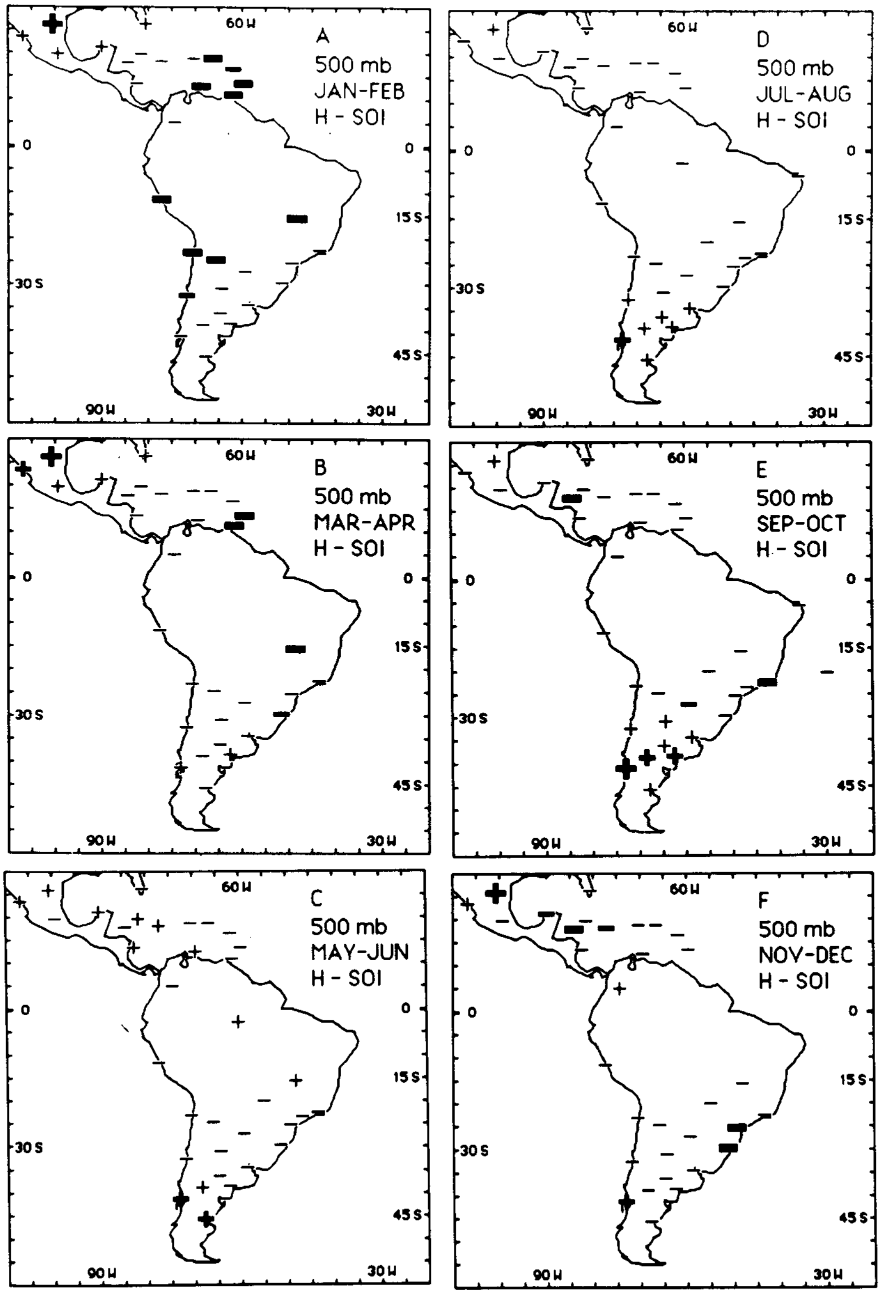

FIG. 4. Patterns of correlation between a Southern Oscillation index (Parker 1983) and the 500 mb height at radiosonde stations: (a) January–February, (b) March–April, (c) May–June, (d) July–August, (e) September–October, and (f) November–December. Symbols as in Fig. 3.

around −0.75. The negative correlations over tropical South America and the Caribbean contrasting with the significant positive correlations over Mexico and Florida during the boreal winter (Fig. 4f, a, b), and over the southern portion of South America during the austral winter (Fig. 4c, d, e) suggest enhanced meridional height gradient in the subtropics of both hemispheres during the negative SO phase in the respective winter semester. The association between surface air temperature and 500 mb height over southern South America during the austral winter is borne out by the similarity of their patterns of correlation with the SOI (Fig. 4 herein, and Aceituno 1988, Fig. 8c, d, e therein), indicating a tendency for relatively cold conditions during the negative SO phase in the austral winter. During the austral summer semester (Fig. 4a, b, f), negative correlations prevail over South America, suggesting weak SO-related anomalies in the meridional height gradient for this time of the year.

Figure 5 shows bimonthly maps of correlation between SOI and 850 mb height. Patterns are broadly similar to those of the surface pressure correlation maps (Aceituno 1988, Fig. 5), reflecting the close relationship between 850 mb height and surface pressure. Most relevant are the significant positive correlations over the Caribbean at the height and during the latter part of the austral summer (Fig. 5a, b) with largest values around +0.50. The corresponding height departures during the positive SO phase are consistent with the tendency for anomalously high surface pressure over the Caribbean and the northern portion of the tropical Atlantic inferred from the pressure correlation patterns (Aceituno 1988, Fig. 5a, b). The significant positive height correlations over the southern portion of South

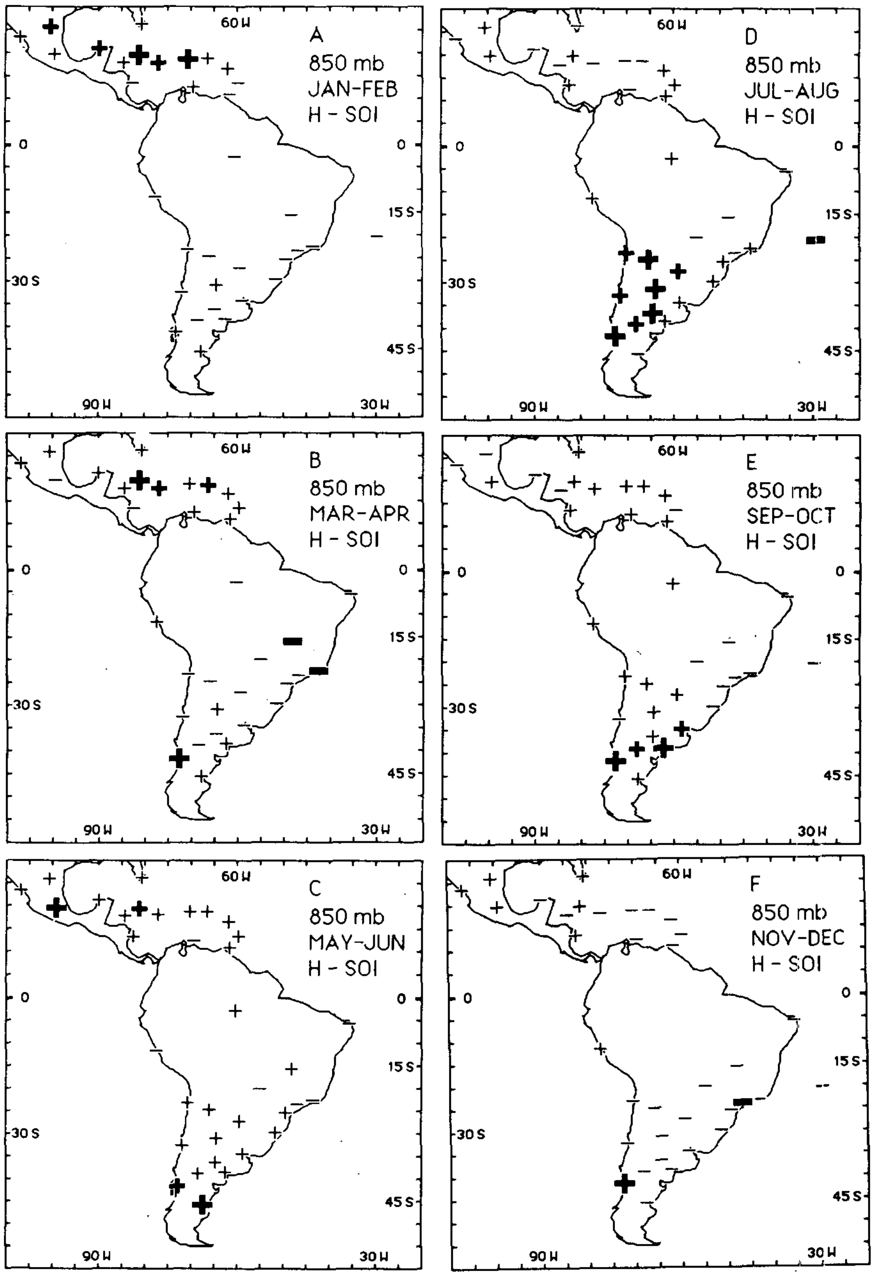

FIG. 5. Patterns of correlation between a Southern Oscillation index (Parker 1983) and the 850 mb height at radiosonde stations: (a) January–February, (b) March–April, (c) May–June, (d) July–August, (e) September–October, and (f) November–December. Symbols as in Fig. 3.

America during the austral winter (Fig. 5c, d, e) confirm the tendency for anomalously high pressure during the positive SO phase, inferred from the surface pressure correlation maps (Aceituno 1988, Fig. 5c, d, e).

In summary, the correlation analysis for constant pressure topographies in the tropics reveals a tendency for a relatively cold/warm troposphere during the positive/negative SO phase, most markedly during the austral summer. By contrast, in the subtropics, the positive/negative SO phase is characterized during the winter by anomalously warm/cold conditions. This implies reduced/enhanced meridional thickness gradients in the positive/negative SO phase during the respective winter, when the thermal contrasts between the lower and high latitudes are largest.

Figure 6 shows bimonthly patterns of correlation between the 200 mb zonal wind component and the SOI. Correlations are weak, although during the austral summer (Fig. 6a, b) a coherent group of significant negative values is apparent, northward of approximately 15°N with largest negative values around −0.75. This suggests for the negative SO phase a southward displaced and anomalously intense subtropical jet over North America. The enhanced zonal circulation is consistent with the increased meridional height gradient inferred from the correlation patterns in Fig. 3a, b, f as well as with previous studies reporting enhanced subtropical westerlies during warm episodes in the tropical Pacific (Chiu and Lo 1979; Hastenrath and Wu 1982; Arkin 1982). In the Southern Hemisphere, the relationship between the SO and the zonal circulation is weak, and there is no indication of enhanced westerlies during the negative SO phase.

The SO-related anomalies in the atmospheric circulation at 500 mb are discussed in relation to Fig. 7, showing bimonthly maps of correlation between the SOI and the 500 mb zonal wind component. Values are small, with the exception of the significant negative zonal wind correlations (largest values around −0.8) over Mexico and the Caribbean in January–February and March–April (Fig. 7a, b), indicating enhanced westerlies during the negative SO phase. These wind anomalies are consistent with the increased meridional height gradient inferred from the correlation maps in Fig. 4a, b. In the Southern Hemisphere correlations are weak; although the negative correlations (largest values around −0.50) prevailing in the subtropical portion of the continent during the austral winter (Fig. 7c, d, e) indicate a weak tendency for enhanced westerlies during the negative SO phase, in agreement with the enhanced meridional height gradient inferred from Fig. 4c, d, e.

The analysis of bimonthly maps of correlation between the SOI and the 850 mb zonal wind component (not shown here) indicates a weak relationship over South America. In the Caribbean, negative correlations prevail at the height and during the latter part of the austral summer (January–April) suggesting enhanced trade winds during the positive SO phase. This feature is also conspicuous in the surface wind correlation patterns (Aceituno 1988, Figs. 6a, 7a).

In synthesis, the upper-air circulation departures are related to the SO mainly during the austral summer semester, when the SO-related surface temperature, pressure, and wind anomalies are most conspicuous (Aceituno 1988). The results discussed here for the South American sector, namely the tendency for positive height departures in the tropics and anomalously intense westerlies in the subtropics during the negative SO phase, are consistent with the conclusions from earlier studies dealing with global SO-related circulation anomalies.

The 500 mb height departures over Mexico and Florida during the boreal winter (Fig. 4a, b) are also interesting in relation to the SO-related 500 and 700 mb height anomaly patterns of standing waves proposed for the Northern Hemisphere (Wallace and Gutzler 1981; Horel and Wallace 1981). During the negative SO phase these are characterized by positive height anomalies over western Canada and negative departures over the North Pacific and the southeastern United States. The weak tendency for negative 500 and 200 mb height departures over the southern portion of South America during the negative SO phase in the austral winter (Figs. 3, and 4c, d, e) is consistent with Karoly's (1986) findings of negative 200 mb departures over that area in a composite of three El Niño events. According to Karoly's study these height anomalies are part of a weak equivalent-barotropic pattern of standing waves extending from Australia over the South Pacific Ocean to South America.

The rather weak SO-related anomalies documented in this study for the meridional height gradient at 200 and 500 mb and zonal winds over the southern portion of South America, a feature also revealed in Karoly (1986), contrast with the otherwise strong relationship found at other longitudes. Specifically, the negative SO phase is associated with an anomalously intense 500 mb zonally averaged geostrophic wind over the subtropics (van Loon and Rogers 1981) and strong 200 mb westerlies over the subtropical South Pacific Ocean (Arkin 1982). Karoly's (1986) analysis further suggests that the SO-related anomalies in the 200 mb meridional height gradients over the subtropics in the Southern Hemisphere are largest over oceanic areas.

5. Case studies

The correlation patterns discussed in section 4 have been interpreted mainly in terms of circulation anomalies during the negative SO-phase. The discussion focuses now on the circulation departures during particular episodes in the positive and negative SO phases at the height of the austral summer (January–February), when largest SO-related circulation anomalies are apparent. Upper-air wind departures for 200, 500 and

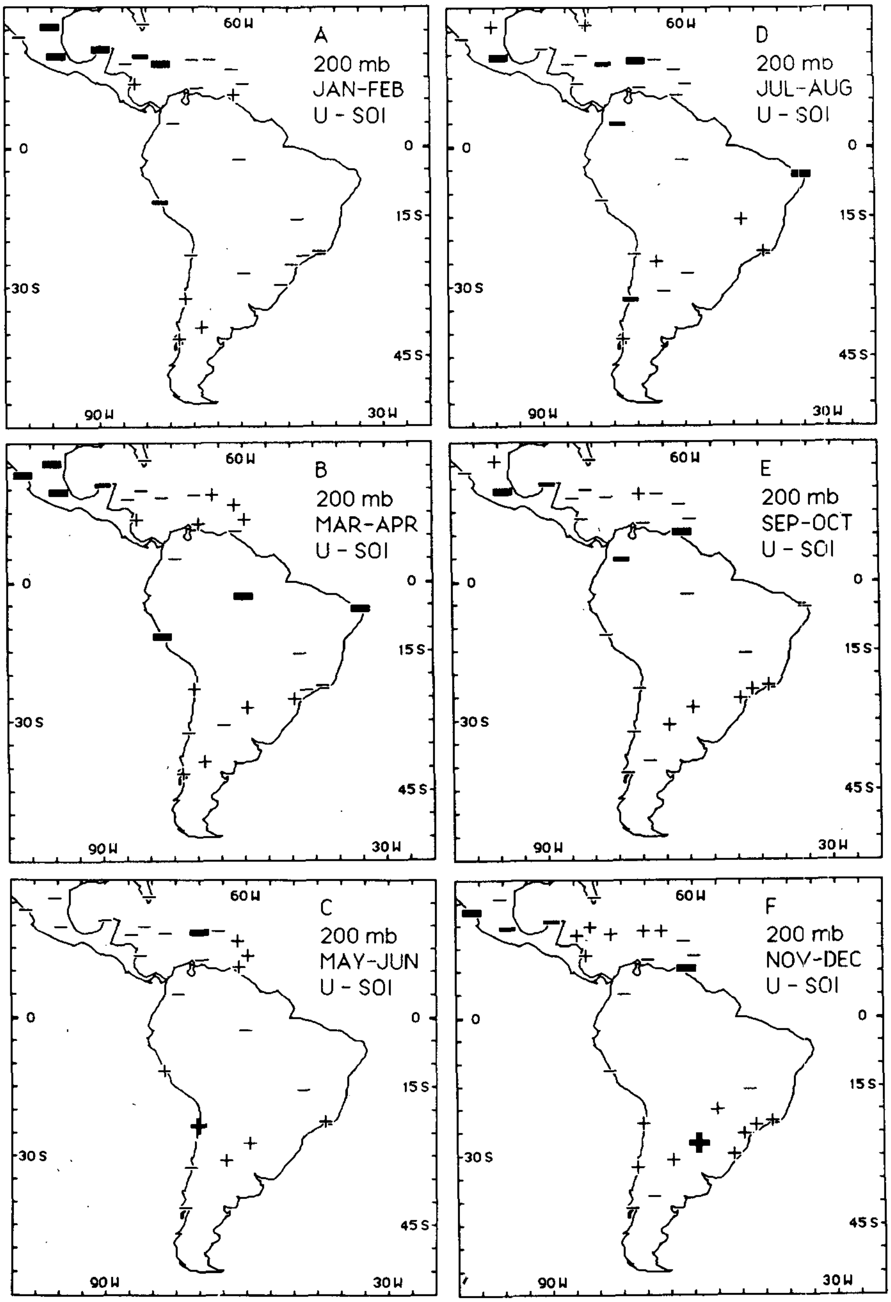

FIG. 6. Patterns of correlation between a Southern Oscillation index (Parker 1983) and the 200 mb zonal (u) wind component at radiosonde stations: (a) January–February, (b) March–April, (c) May–June, (d) July–August, (e) September–October, and (f) November–December. Symbols as in Fig. 3.

850 mb and standardized anomalies for 200, 500 and 850 mb heights, SST, and air temperature at land stations were calculated during the period 1970–83. Largest positive SOI values for January–February during this period were observed in 1971 and 1976, while the extreme negative ones were apparent in 1973 and 1983 during El Niño episodes.

Figure 8 shows anomaly circulation patterns for January–February 1971, at the peak of the period with positive SO phase preceding the onset of the 1972 El Niño episode. The height anomalies (Fig. 8a, c, e) are predominantly negative, most conspicuously at the 200 and 500 mb levels, indicating a cold tropical troposphere in accordance with the correlation analysis (Figs. 4a, 5a). The concomitant vertical expansion of the atmospheric column over the Northern Hemisphere subtropics, to be inferred from the positive height departures there (Fig. 8a, c), entails a weakened meridi-

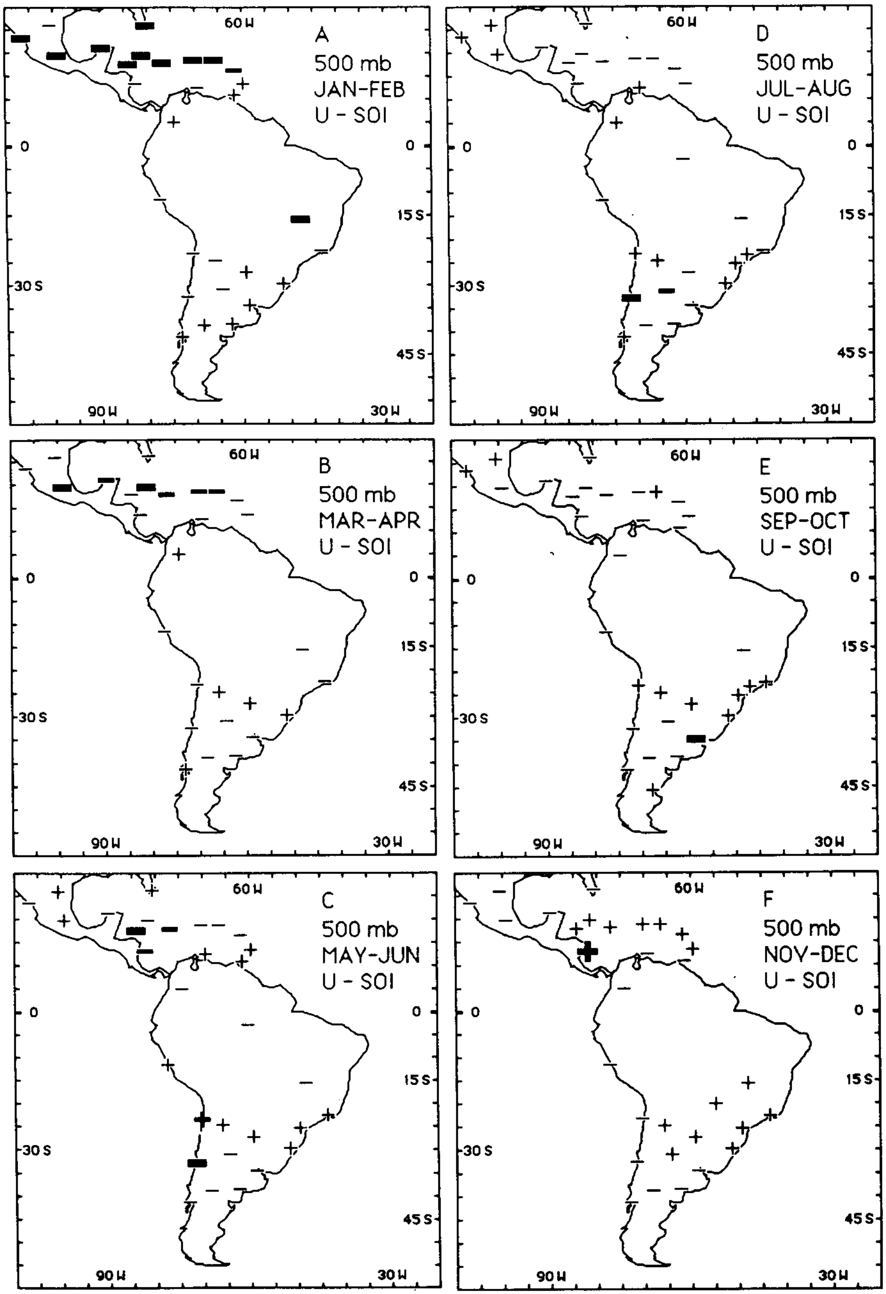

FIG. 7. Patterns of correlation between a Southern Oscillation index (Parker 1983) and the 500 mb zonal (u) wind component at radiosonde stations: (a) January–February, (b) March–April, (c) May–June, (d) July–August, (e) September–October, and (f) November–December. Symbols as in Fig. 3.

onal height gradient. The thickness anomaly pattern implied by Fig. 8a, c is consistent with the negative surface temperature departures in the eastern Pacific and portions of the western North Atlantic and the South American continent (Fig. 8g) characteristic of the positive SO phase. At variance with the surface correlation analysis (Aceituno 1988, Fig. 8a) are the anomalously warm conditions in the tropical South Atlantic and eastern Brazil (Fig. 8g), which may be peculiar to this episode.

The pattern of wind departures (Fig. 8b, d, f) should be appreciated with reference to the climatic mean flow patterns (Fig. 2). Overall, the departure patterns are most coherent for the Northern Hemisphere, where SO-related circulation anomalies are most pronounced at this time of the year (Ref. Figs. 3 to 7). Thus, marked

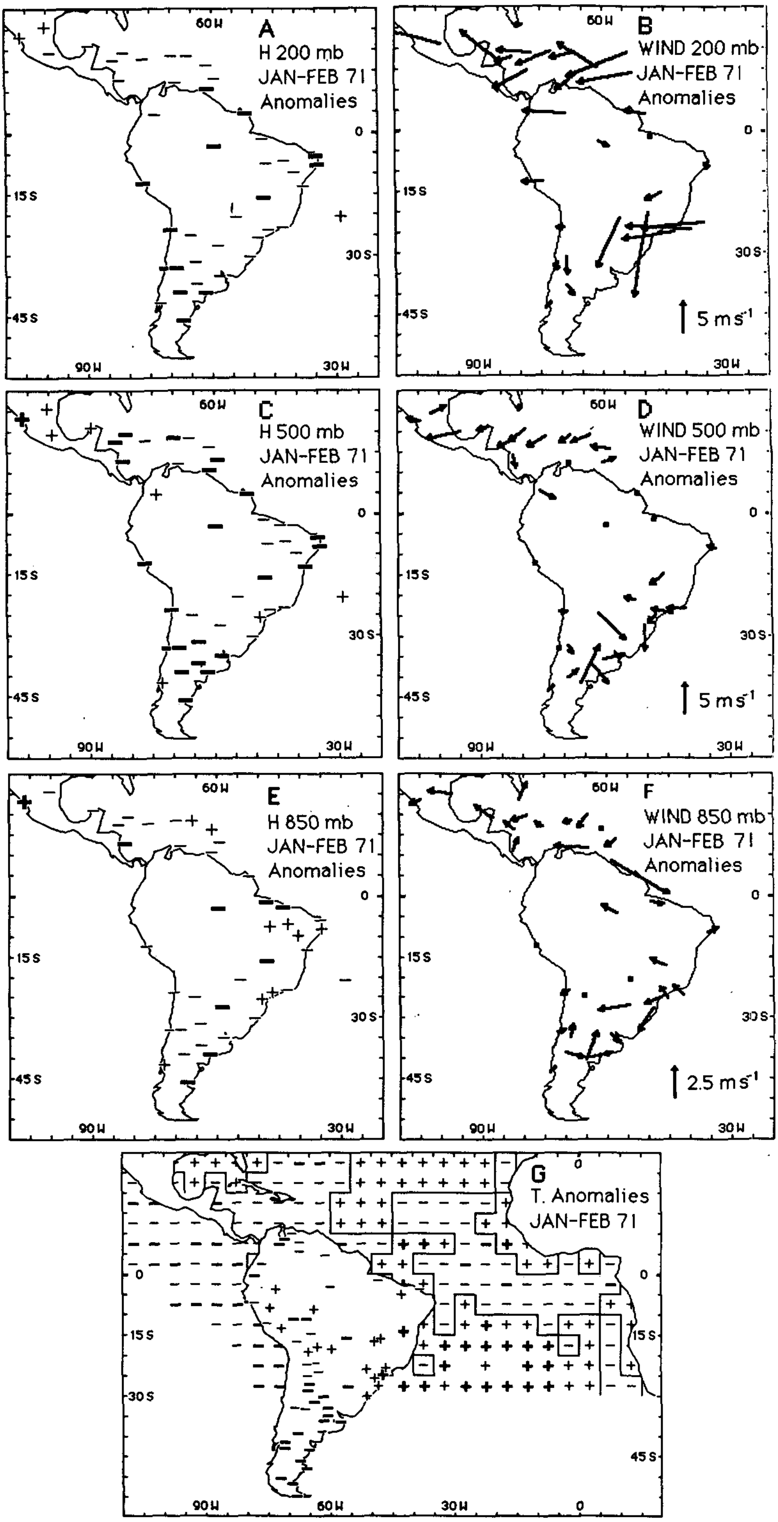

FIG. 8. Anomaly patterns during the positive SO phase in January–February 1971: (a) 200 mb height, (b) 200 mb wind, (c) 500 mb height, (d) 500 mb wind, (e) 850 mb height, (f) 850 mb wind, and (g) SST and air temperature at land stations. Upper-air wind departures (panels b, d, and f) are calculated with respect to 1970–83. Anomalies of upper-air height (panels a, c, and e), SST, and air temperature (part f) are standardized with respect to 1970–83. Positive and negative signs (panels a, c, e, and g) indicate the sign of standardized anomalies, with boldface denoting values beyond one standard deviation from the mean. Wind departures corresponding to speed anomalies exceeding 0.5 m s^{-1} are indicated by arrows (see scale in panels b, d, f).

easterly departures are apparent at 200 and 500 mb in the northern portion of the map area, in good agreement with the aforementioned weakened meridional height gradient (Fig. 8a, c), as well as with the wind correlation patterns (Fig. 6a, 7a).

Figure 9 shows anomaly circulation patterns for January–February 1976, when the SOI, although strongly positive, was quickly changing toward the negative SO phase from the peak positive value reached earlier in 1975. Major features depicted in Fig. 9 are similar to the analogous January–February 1971 situation depicted in Fig. 8. Thus, negative 200 and 500 mb height anomalies prevail over the tropics, reflecting a relatively cold tropical troposphere. By contrast, over the Northern Hemisphere subtropics, 200 and 500 mb height departures are weakly negative or even positive, which would likewise entail a relatively weak meridional height gradient over the greater Caribbean region. The predominantly positive height departures at 850 mb, particularly over the Caribbean, reflect the anomalously high surface pressure characteristic of the positive SO phase. The relatively cold tropical troposphere is consistent with the negative surface temperature departures in most of the tropics (Fig. 9g).

The easterly wind departures at 200 and 500 mb (Fig. 9b, d) over the subtropics in the Northern Hemisphere are again consistent with the aforementioned weakened meridional height gradient and with the wind departures suggested by the correlation analysis for the positive SO phase (Figs. 6a, 7a). The 850 mb wind anomaly patterns (Fig. 9f) show strengthened northeast trades in the Caribbean domain, in good agreement with the departures indicated by the correlation analysis.

Atmospheric and oceanic anomalies in January–February 1973, during the mature phase of the 1972–73 El Niño, are documented in Fig. 10. In major respects, departure characteristics contrast with the cases of positive SO phase depicted in Figs. 8 and 9. Thus, positive height anomalies prevail at 200 and 500 mb most markedly over the tropics (Fig. 10a, c), indicating a relatively warm tropical troposphere and enhanced meridional height gradients in the subtropics of both hemispheres. The increased tropospheric mean temperature is consistent with the anomalously warm waters in the eastern Pacific and in a large portion of the tropical Atlantic, and with the positive air temperature departures at stations in tropical South America (Fig. 10g). The positive 850 mb height anomalies over Northeast Brazil (Fig. 10e) reflect the characteristic positive departures in surface pressure during the negative SO phase (Aceituno 1988, Fig. 5a therein), while the negative departures over subtropical South America (Fig. 10a) seem to be a particular feature of this episode. Consistent with the aforementioned steepened meridional height gradients, the 200 and 500 mb westerly wind component appears strengthened over the subtropics of both hemispheres (Fig. 10b, d).

Circulation anomalies at the peak of the strong 1982–83 El Niño are documented in Fig. 11. Major pattern characteristics are similar to those of the January–February 1973 El Niño shown in Fig. 10, and opposite to the cases of positive SO phase (January–February 1971 and January–February 1976) depicted in Figs. 8 and 9. As is characteristic of the negative SO phase, 200 and 500 mb height departures are positive in the tropics, consistent with the anomalously warm surface waters in the eastern tropical Pacific and in much of the tropical Atlantic and the positive temperature departures in tropical South America (Fig. 11g). By contrast, the 200 and 500 mb height departures are negative in the northern portion of the map area (Fig. 11a, c). All these features are consistent with the correlation analysis (Fig. 3 and 4) and imply enhanced meridional height gradients over the greater Caribbean area.

Westerly wind departures at 200 and 500 mb prevail over the northern portion of the map area (Fig. 11b, d), consistent with the aforementioned steepened meridional height gradient, as well as with the correlation analysis (ref. Figs. 6a, 7a). The 850 mb map (Fig. 11f) shows weakened northeast trades, consistent with wind departures inferred from the correlation analysis.

During the positive SO phase in January–February 1971 and 1976 the departures in 200 and 500 mb height, in tropical Atlantic and eastern Pacific SST, and the temperature at land stations (Figs. 8 and 9, parts a, c, f), collectively indicate an anomalously cold tropical troposphere. Contrasting with the negative height departures over the tropics, weak positive height departures were apparent in the Northern Hemisphere subtropics (Figs. 8 and 9, parts a, c). In agreement with the implied weakened meridional height gradient are the anomalously weak westerlies at 200 and 500 mb over the greater Caribbean area (Figs. 8b, d; 9d).

During the January–February 1973 and 1983 cases of negative SO phase (Figs. 10 and 11) circulation departures are broadly opposite to the positive SO cases. Prominent in the 1973 and 1983 episodes are the anomalously warm conditions in the tropics, illustrated by the positive 200 and 500 mb height departures (Figs. 10a, c and 11a, c), the anomalously warm waters in the tropical eastern Pacific and Atlantic, and the positive temperature anomalies at stations in tropical South America (Figs. 10g, 11g). The markedly positive height departures over the tropics, contrasting with the only weakly positive or even negative height anomalies over the subtropics (Figs. 10, 11; parts a, c), entail an enhanced meridional height gradient, and consistent with this, westerlies are enhanced in the subtropics of both hemispheres (Figs. 10, 11; parts b, d).

In synthesis, the case studies of extreme positive and negative SO phase at the height of the austral summer confirm the major SO-related circulation departures deduced from the correlation analysis in section 4, and demonstrate that circulation departures during the positive SO phase are broadly opposite to those during the negative SO phase.

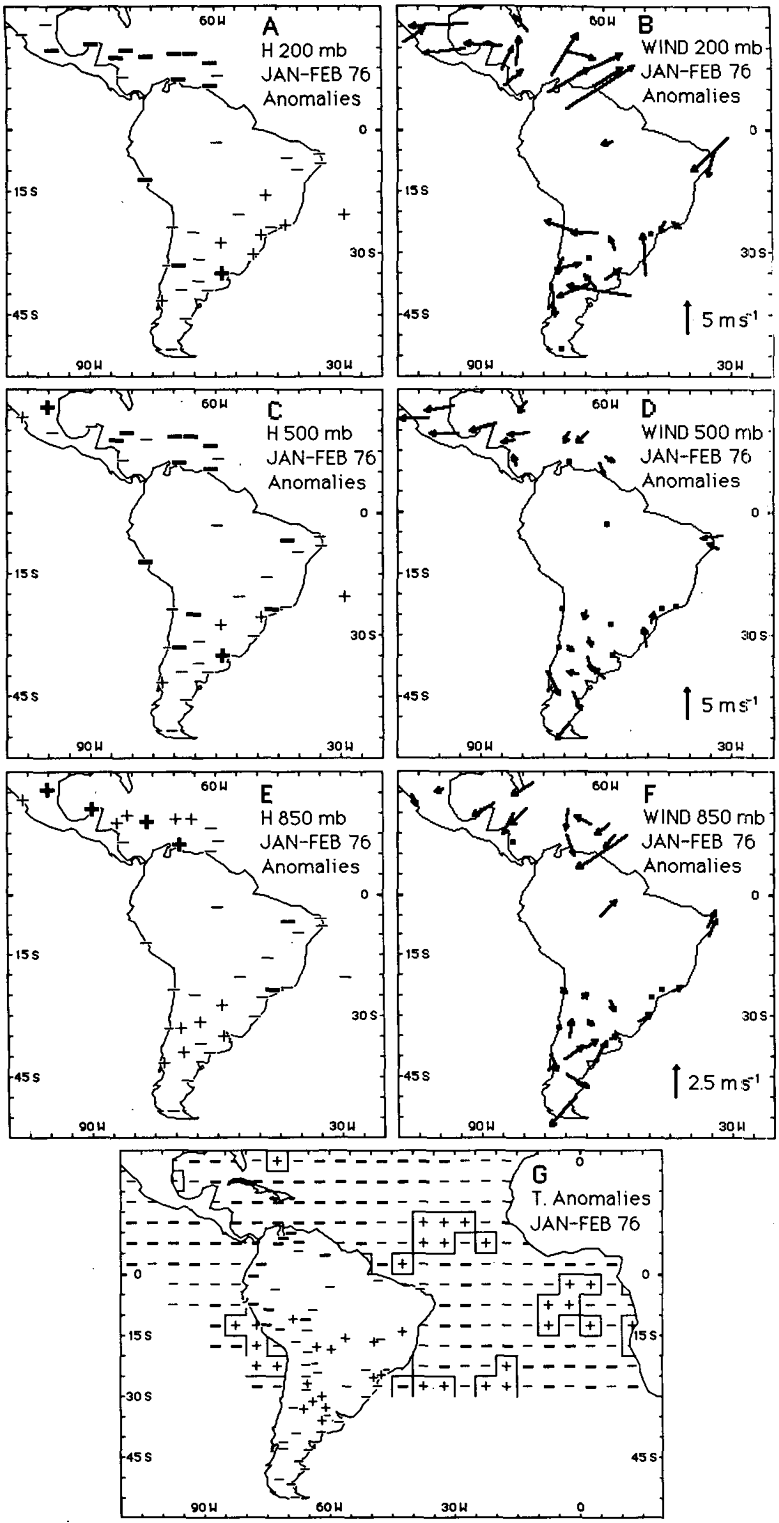

FIG. 9. As in Fig. 8 but for January–February 1976.

6. Conclusions

Anomalous upper-air circulation patterns in the South American sector have been analyzed with the focus on the Southern Oscillation. As for the surface climate (Aceituno 1988), SO-related upper-air circulation anomalies are most conspicuous during the austral summer semester, although an anomalously warm/

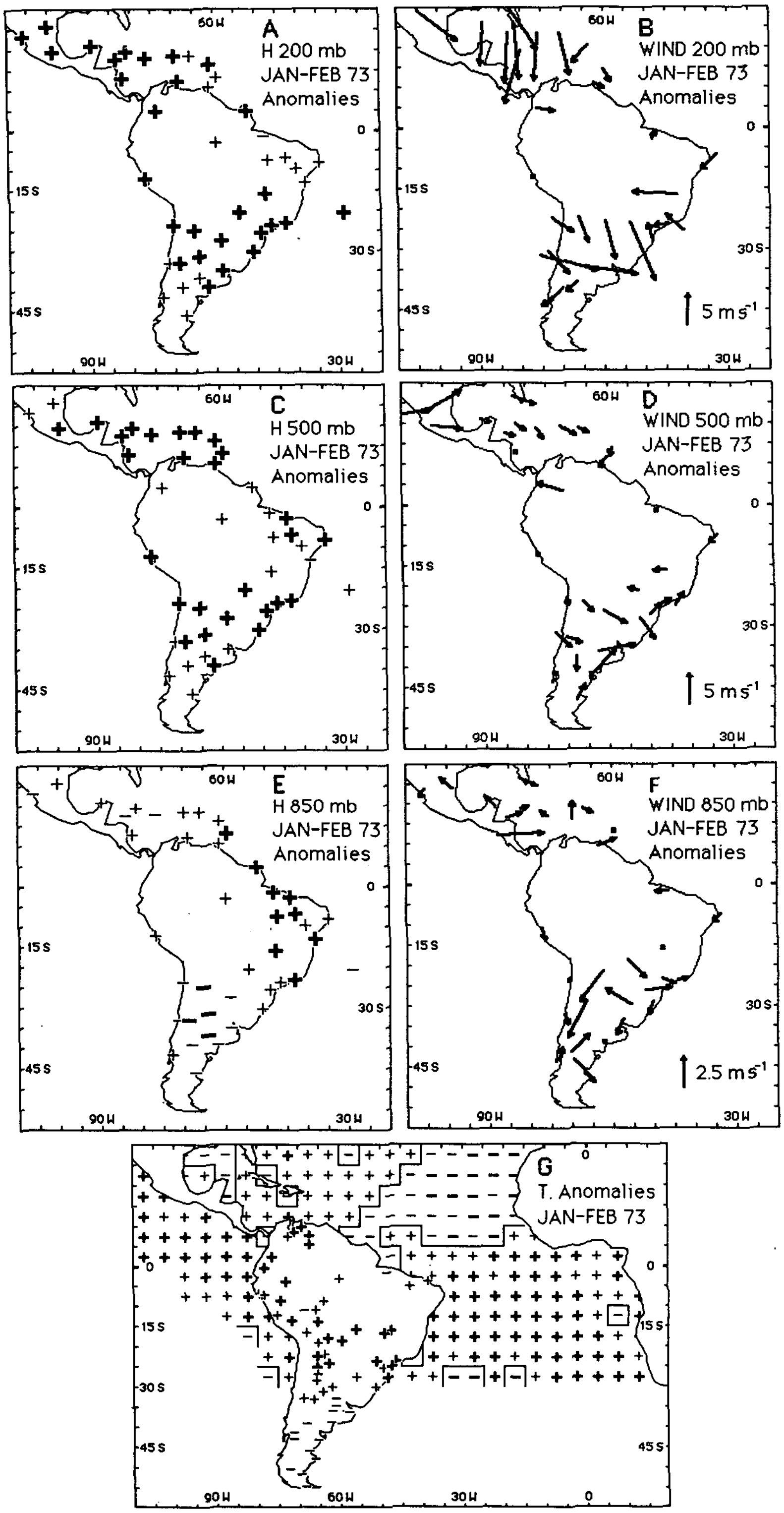

FIG. 10. As in Fig. 8 but during the negative SO phase in January–February 1973.

cold tropical troposphere during the negative/positive SO phase is a persistent feature throughout the year.

During the austral winter semester (April–October) in the negative SO phase, the perennially positive SST departures in the eastern Pacific and anomalously warm conditions at land stations are associated with a

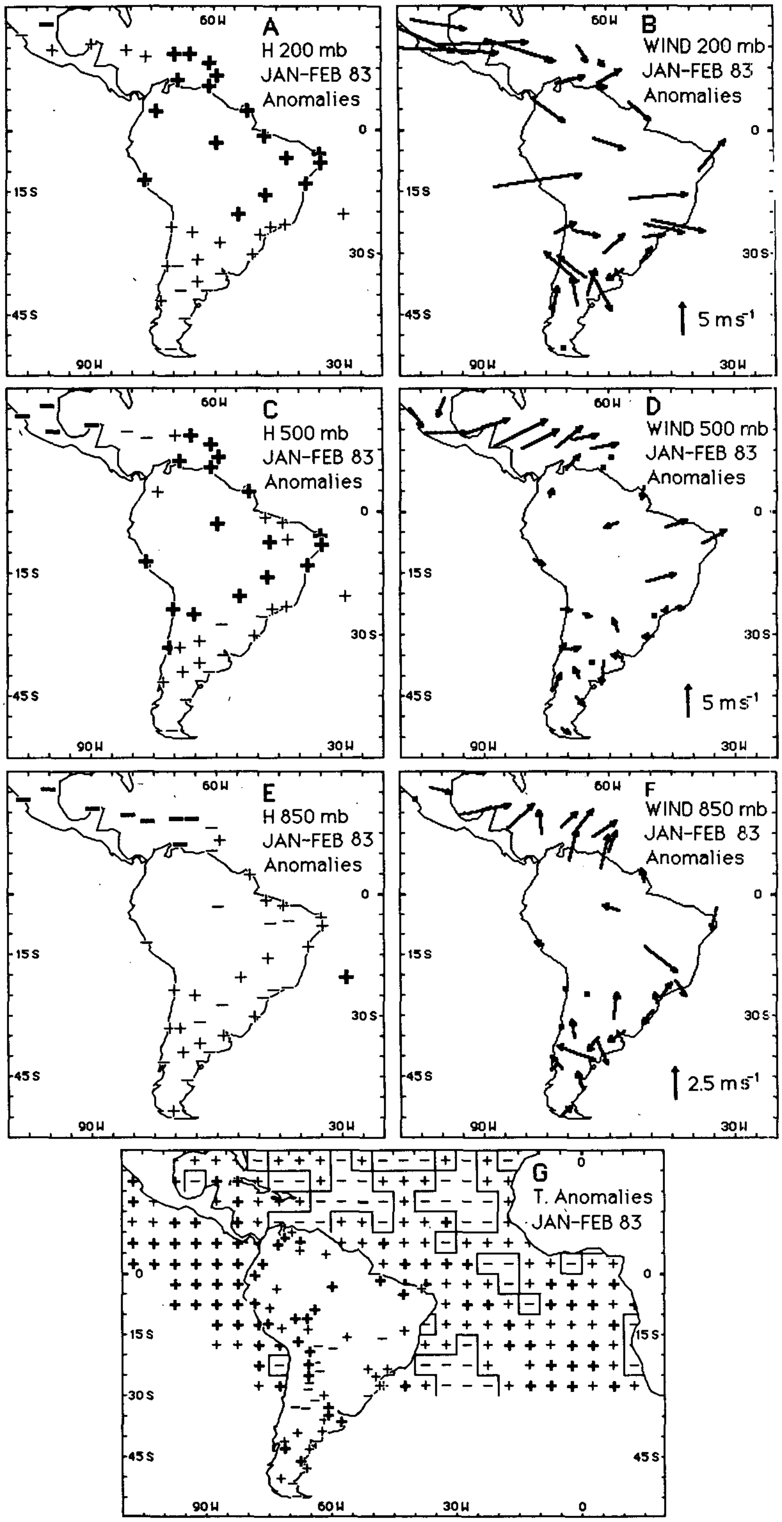

FIG. 11. As in Fig. 8 but during the negative SO phase in January–February 1983.

weak tendency for positive height departures at 500 and 200 mb over the tropical Americas. Contrasting with this thickness anomaly pattern, relatively cold surface conditions and negative 500 and 200 mb height departures develop in southern South America. Consistent with the implied steepening of meridional height gradients are intensified upper-air westerlies over the Southern Hemisphere subtropics. These thickness and upper-air flow anomaly patterns are accompanied by negative departures in surface pressure (Aceituno 1988) and 850 mb height, reflecting the weakened Pacific subtropical high characteristic of the negative SO phase.

In the austral summer semester (November–April) during the negative SO phase, positive 200 and 500 mb height departures over tropical South America and the Caribbean are larger than in winter. Meridional height gradients and strengthened upper-air westerlies are particularly pronounced over the greater Caribbean area. Concurrently, negative height departures at 850 mb are apparent over the Gulf of Mexico and Caribbean region, consistent with the negative surface pressure anomalies characteristic of the negative SO phase (Aceituno 1988). Circulation anomalies during the positive SO phase are broadly inverse to these characteristics of the negative phase.

In the tropics, but particularly over the Caribbean domain, during the austral summer the SOI correlates negatively with SST (Aceituno 1988) and with 200 and 500 mb height, but positively with surface pressure (Aceituno 1988) and 850 mb height. Outside the tropics, relatively warm/cold tropospheric conditions prevail during the positive/negative SO phase. These anomalies, showing an equivalent barotropic structure, seem to be part of hemispheric teleconnection patterns of standing waves that propagate from the tropics poleward. It is hoped that the present study of upper-air circulation anomalies, together with its companion paper dealing with the surface climate (Aceituno 1988), may contribute to understanding the functioning of the Southern Oscillation in the South American sector.

Acknowledgments. The author wishes to thank Professor Stefan Hastenrath for his assistance and guidance and Drs. Julia Nogues-Paegle and Richard Rosen for their helpful comments on the original manuscript. This investigation is part of a Ph.D. dissertation sponsored by the World Meteorological Organization and the University of Chile, and it has also been funded by NSF Grants ATM84-13575 and ATM-8722410 and NOAA Grant NA86AA-D-AC064.

REFERENCES

Aceituno, P., 1988: On the functioning of the Southern Oscillation in the South American sector. Part I: Surface climate. *Mon. Wea. Rev.*, **116**, 505–524.

Angell, J. K., 1981: Comparison of variations in atmospheric quantities with sea-surface temperature variations in the equatorial Eastern Pacific. *Mon. Wea. Rev.*, **109**, 230–243.

——, and J. Korshover, 1984: Some long-term relations between equatorial sea-surface temperature, the four centers of action and 700 mb flow. *J: Climate Appl. Meteor.*, **23**, 1326–1332.

Arkin, P. A., 1982: The relationship between interannual variability in the 200 mb tropical wind field and the Southern Oscillation. *Mon. Wea. Rev.*, **110**, 1393–1404.

Chiu, W.-C., and A. Lo, 1979: A preliminary study of the possible statistical relationship between the tropical Pacific sea surface temperature and the atmospheric circulation. *Mon. Wea. Rev.*, **107**, 18–25.

Gutman, G., and W. S. Schwerdtfeger, 1965: The role of latent and sensible heat for the development of a high pressure system over the subtropical Andes, in the summer. *Meteor Rundsch.*, **18**, 1–7.

Hastenrath, S., 1985: *Climate and Circulation of the Tropics.* Reidel, 455 pp.

——, and P. J. Lamb, 1977: *Climatic Atlas of the Tropical Atlantic and Eastern Pacific Oceans.* University of Wisconsin Press, 113 pp.

——, and M.-C. Wu, 1982: Oscillations of upper-air circulation and anomalies in the surface climate of the tropics. *Archiv Meteor. Geophys. Bioklim.*, Ser. B, **31**, 1–37.

Horel, J. D., and J. M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813–829.

Karoly, D. J., 1986: Southern hemisphere circulation features associated with the El Niño-Southern Oscillation events. (411–413) Extended Abstracts, *Second Int. Conf. on Southern Hemisphere Meteorology.* Amer. Meteor. Soc., 482 pp.

Kousky, V. E., and M. T. Kagano, 1981: A climatological study of the tropospheric circulation over the Amazon region. *Acta Amazonica,* **11**, 743–758.

Newell, R. E., 1980: Climate and the ocean. *Amer. Scientist,* **67**, 405–416.

——, and B. C. Weare, 1976: Factors governing tropospheric mean temperature. *Science,* **194**, 1413–1414.

Parker, D. E., 1983: Documentation of a Southern Oscillation index. *Meteor. Mag.*, **112**, 184–188.

——, 1985: The influence of the Southern Oscillation and volcanic eruptions on temperature in the tropical atmosphere. *J. Climatol.*, **5**, 273–282.

Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, **110**, 354–384.

Rogers, J. C., 1988: Precipitation variability over the Caribbean and tropical Americas associated with the Southern Oscillation. *J. Climate,* **1**, 172–182.

Van Loon, H., and J. C. Rogers, 1981: The Southern Oscillation. Part II: Associations with changes in the middle troposphere in the northern winter. *Mon. Wea. Rev.*, **109**, 1163–1168.

Virji, H., 1981: A preliminary study on summertime tropospheric circulation patterns over South America estimated from cloud winds. *Mon. Wea. Rev.*, **109**, 599–610.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the northern hemisphere winter. *Mon. Wea. Rev.*, **109**, 784–811.

Wright, P. B., 1984: Relationships between the indices of the Southern Oscillation. *Mon. Wea. Rev.*, **112**, 1913–1919.