Atmospheric Circulation Anomalies during Episodes of Enhanced and Reduced Convective Cloudiness over Uruguay

ALVARO DÍAZ

Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Universidad de la República, Montevideo, Uruguay

PATRICIO ACEITUNO

Department of Geophysics, Universidad de Chile, Santiago, Chile

(Manuscript received 24 September 2002, in final form 6 March 2003)

ABSTRACT

Regional and large-scale circulation anomalies associated with periods of enhanced and reduced convective cloudiness over Uruguay are studied for austral spring and summer, when rainfall associated with deep convection is more frequent in this region. The analysis was performed at a submonthly timescale, considering that the essential nature of the mechanisms producing rainfall is not well captured by anomalies calculated on a monthly or seasonal basis in regions where precipitation is highly episodic.

Periods of enhanced and reduced convective cloudiness over Uruguay are characterized by a marked dipolar structure in the outgoing longwave radiation anomaly field along eastern South America from 10° to 40°S, with the centers of the dipole located over the South Atlantic convergence zone (SACZ) and over a broad region including Uruguay, southern Brazil, and northeastern Argentina. This dipole, which corresponds to one of the key factors of climate dynamics in South America during spring and summer, seems to be part of a much larger wavelike quasi-barotropic structure that includes alternating centers of negative and positive geopotential height and temperature anomalies in the southern portion of the continent, and farther upstream in the southern Pacific. At the regional scale, periods of enhanced convection and rainfall over Uruguay are associated with the following features: a warm-core anticyclonic circulation anomaly in the middle and upper troposphere, centered on 34°S, 45°W, approximately; an intensified Chaco low in northwestern Argentina that favors a reinforced northwesterly flow of warm and moist air from the Amazon basin; and an anomalously strong subtropical jet along eastern South America. Periods with reduced convective cloudiness over Uruguay are characterized by circulation anomalies that are broadly opposite to those described before, although some significant asymmetries in their intensity are documented. No major differences were detected in the circulation anomaly patterns between spring and summer, although some changes in the wavelike structure associated to the dipole were found.

Considering the extent of circulation anomalies described here for the austral summer semester, it seems plausible that they also characterize rainfall anomalies over a broader region in southeastern South America.

1. Introduction

The southeastern portion of South America (SESA) lies in the subtropical band of the continent and includes the territory of Uruguay and the surrounding areas of southern Brazil, southern Paraguay, and northeastern Argentina. The combination of a benign climate and a fertile soil makes of this relatively flat low-level region one of the richest of the world for agriculture and pasture. Nevertheless, climate vagaries, particularly those characterized by prolonged dry spells or widespread floods, cause strong socioeconomic impacts, particularly on the functioning of many water-dependent economic activities and on the planning and managing of water resources for hydroelectric generation.

Climate in SESA is shaped by a combination of tropical and extratropical phenomena. Relatively cold conditions (mean temperature in the 8°–12°C range) prevail during winter in connection with extratropical cold fronts and associated transient incursions of midlatitude air into subtropical and tropical South America. Although this extratropical influence persists throughout the year (Garreaud and Wallace 1998), the relatively warm and humid conditions and the development of convective cloudiness and rainfall during spring and summer (mean temperature in the 20°–25°C range) are linked to moisture flux convergence associated with northerly low-level advection from the Amazon basin

Corresponding author address: Ing. Alvaro F. Díaz, Facultad de Ingeniería, Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Julio Herrera y Reissig 565, Montevideo 11300, Uruguay.
E-mail: adiaz@fing.edu.uy

(Berbery and Collini 2000). Furthermore, the high frequency of cyclogenesis over SESA, particularly during winter and spring, is a local factor contributing to the development of cloudiness and rainfall (Gan and Rao 1991). The combined effect of these factors explains a rather even distribution of precipitation throughout the year, with an annual mean that varies from around 900 mm over the southern sector to near 1700 mm in the interior of southern Brazil (Díaz et al. 1998).

Rainfall variability in SESA has been documented for a wide range of timescales from long-term trends to submonthly changes. Long records exhibit a marked positive trend during the second half of the twentieth century (Krepper et al. 1989; Castañeda and Barros 1994; Minetti and Vargas 1997). This remarkable feature has also been revealed in streamflow series (Mechoso and Pérez-Iribarren 1992; Genta et al. 1998).

Many studies document the relationship between ENSO and the interannual rainfall variability in SESA, in the sense that above- (below) normal rainfall tends to occur during the warm (cold) ENSO phase (Kousky et al. 1984; Ropelewski and Halpert 1987, 1989, 1996; Aceituno 1988; Kiladis and Diaz 1989; Kousky and Ropelewski 1989; Pisciottano et al. 1994; Díaz et al. 1998; Grimm et al. 1998; Montecinos et al. 2000; Grimm et al. 2000). The ENSO signal is highly significant during the austral spring and early summer, and to a lesser extent during winter (Montecinos et al. 2000).

Interannual rainfall variability over SESA has also been related to sea surface temperature (SST) anomalies in the adjacent Atlantic Ocean. Specifically, Díaz et al. (1998) and Doyle and Barros (2002) linked the occurrence of relatively wet (dry) conditions in Uruguay and southern Brazil with above- (below) average SST in the southwestern portion of the subtropical Atlantic. According to Barros et al. (2000) and Díaz (2000) this relationship is particularly strong during the early part of the austral summer (December and especially in January).

At the intraseasonal and submonthly scales, rainfall variability in SESA during the austral summer has been linked to a multiscale dipole in convective cloudiness with centers in the South Atlantic convergence zone (SACZ) and SESA. This dipolar structure was first presented by Casarin and Kousky (1986), who detected a significant negative correlation between 15-day outgoing longwave radiation (OLR) anomalies over southern Brazil and over the SACZ. Alternating wet and dry conditions over South America during austral summer were documented by Nogués-Paegle and Mo (1997), indicating a seesaw pattern in rainfall between the SACZ region and the subtropical plains on the southeastern portion of the continent. Furthermore, by regressing high-pass-filtered OLR over the region 20°–30°S, 40°–30°W (on the SACZ axis), against OLR and other parameters on a global grid, Liebmann et al. (1999) identified patterns of circulation anomalies during December–January–February (DJF) associated with submonthly variability in the strength of the SACZ. They found a marked dipole in convective cloudiness anomaly along eastern South America, associated with upper-tropospheric cyclonic (anticyclonic) circulation anomalies when convection is above- (below) normal over the SACZ.

TABLE 1. Percentage of days with precipitation above 1 mm in OND and JF at five stations in Uruguay during the period 1979–93.

Station	Lat (S)	Lon (W)	OND	JF
Bella Unión	30°12′	57°35′	23.1	22.3
Tacuarembó	31°44′	55°59′	19.3	23.6
Young	32°42′	57°38′	21.5	23.1
Treinta y Tres	33°13′	54°23′	22.5	24.2
Montevideo	34°51′	56°12′	22.1	20.7

Several studies have shown that some regional circulation anomalies in South America develop as part of a large-scale wavelike structure in the Southern Hemisphere. Specifically, Nogués-Paegle and Mo (1997) describe a well-defined wave pattern in the 200-hPa height field in association with enhanced precipitation in the subtropical plains. On the other hand, Liebmann et al. (1999) document a wave train in the 200-hPa streamfunction extending into the SACZ region from the south Pacific, when the SACZ is intensified in DJF. Regarding this issue Robertson and Mechoso (2000) concluded that the interannual circulation variability in southern South America during January–February–March (JFM) is dominated by an equivalent barotropic gyre centered in the region between the SACZ and SESA, which exhibits a cyclonic rotation when the SACZ is anomalously strong. They interpret this structure as a locally forced stationary Rossby wave. Li and Le Treut (1999) found a tropical–extratropical wavelike structure in the 300-hPa height anomaly field during episodes of intense southward moisture transport to the east of the central Andes during DJF. Also relevant to large-scale forcing of regional climate anomalies in South America are the results discussed by Berbery et al. (1992), Kiladis and Weickmann (1992), Grimm and Silva Dias (1995), Cazes and Pisciottano (2000), and Mo and Nogués-Paegle (2001).

Building upon these studies that have focused mostly on the austral summer, we analyze the regional and large-scale circulation anomalies associated with wet and dry submonthly periods in Uruguay during austral spring [October–November–December (OND)] and summer JFM. As in most regions in the world, rainfall in Uruguay is highly episodic. Thus, different from the study of circulation anomalies associated with anomalies in other variables (i.e., temperature, humidity, or pressure), annual, seasonal and monthly precipitation information comes from a relatively small number of rainy days during the considered period. Information in Table 1 highlights this situation indicating percentages of rainy days around 20%–25% during October–Feb-

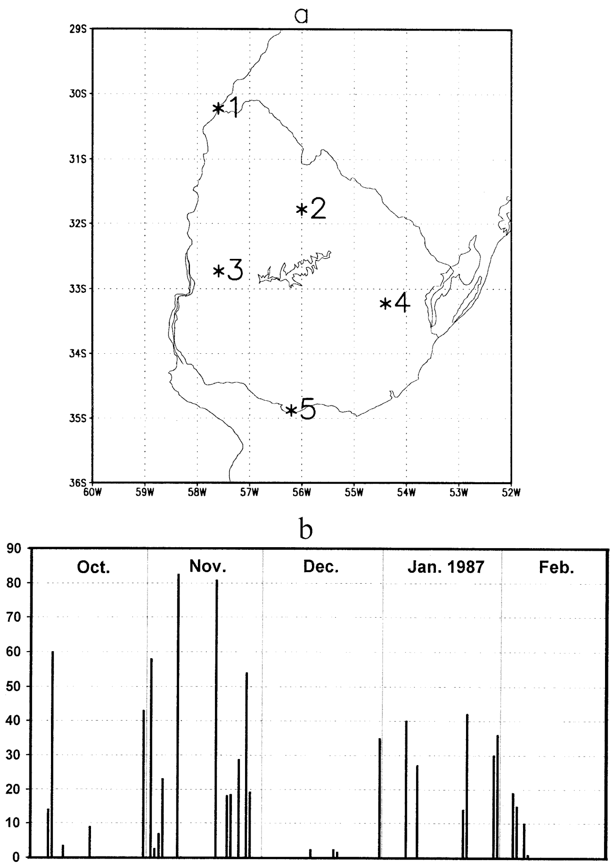

FIG. 1. (a) Location of selected rainfall stations in Uruguay: 1, Bella Unión; 2, Tacuarembó; 3, Young; 4, Treinta y Tres; 5, Montevideo. (b) Evolution of daily rainfall (in mm) at Tacuarembó from Oct 1986 to Feb 1987.

ruary. The evolution of daily rainfall at Tacuarembó from October 1986 to February 1987 shown in Fig. 1b is an example of the clustering of rainy days within this region. Considering this fact, we postulate that the essential nature of the mechanisms producing rainfall is better captured by anomalies calculated for submonthly wet periods. Accordingly, the main objective of this study is to contribute to a better identification and understanding of circulation anomalies associated to wet and dry episodes in Uruguay and the surrounding region in SESA throughout the austral summer semester (October–March), and the differences between spring and summer.

Datasets and methodology are presented in section 2. Anomaly circulation patterns during periods of enhanced and reduced convection over Uruguay are examined in section 3. Results are discussed in section 4 and conclusions are summarized in section 5.

2. Data and methodology

Daily data of OLR obtained by the National Oceanic and Atmospheric Administration's (NOAA's) polar-orbiting satellites were used to identify periods with enhanced and reduced convective cloudiness over SESA during the austral summer semester (October–March). This dataset, available at the Climate Prediction Center (CPC), is obtained from averages of day and night passes of the satellites and is organized on a global grid with a 2.5° × 2.5° latitude–longitude resolution. The subset considered in this study includes a total of 2734 days during the period 1979–93. A complete description of the global OLR dataset is presented in Liebmann and Smith (1996).

The relationship between OLR and rainfall in Uruguay during the austral summer semester was examined at the seasonal timescale by correlating the average precipitation at 13 stations evenly distributed over the country, with OLR averaged over a 7.5° × 7.5° latitude–longitude box covering Uruguay (Fig. 2), during the period 1979–93. A negative correlation was obtained both for OND (−0.48) and JFM (−0.85), reaching the 90% and 99% significance levels, respectively.

The 11-day periods of anomalously high and low OLR over the region indicated in Fig. 2 were selected according to the following procedure. The length of the periods was subjectively chosen to identify relatively long wet and dry spells at the submonthly scale, intending to leave aside the short wet episodes associated with transient synoptic-scale disturbances. Accordingly, periods having at least 5 days with OLR below 220 W m^{-2} or above 270 W m^{-2} were identified as candidates for wet and dry episodes, respectively. These thresholds approximately define the lowest and highest quintiles of the OLR distribution in this region. The final selection was made trying to avoid overlapping, which actually occurred in less than 10% of the cases. Based on this general criterion, a total of 47 episodes of enhanced convective cloudiness was selected during the period 1979–93, with 31 of them in OND and 16 in JFM. Regarding periods with reduced convective cloudiness, a total of 63 were chosen, with 22 in OND and 41 in JFM.

In order to assess the pertinence of using OLR to identify wet and dry episodes in Uruguay, available daily rainfall data from five stations (Fig. 1a) were analyzed for the period October–February, 1979–93. It was concluded that during selected periods with low (high) OLR, wet (dry) conditions are prevalent. Based on these results, we will use indistinctly ''wet conditions'' and ''enhanced convective cloudiness'' to indicate anomalously low OLR values, and ''dry conditions'' and ''reduced convective cloudiness'' to designate above-average OLR values.

Anomaly patterns of atmospheric circulation composited over 11-day wet and dry periods in Uruguay were studied using data of geopotential height, temperature, and zonal and meridional components of the wind at 200, 500, and 850 hPa, extracted from the global daily reanalyses prepared by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the

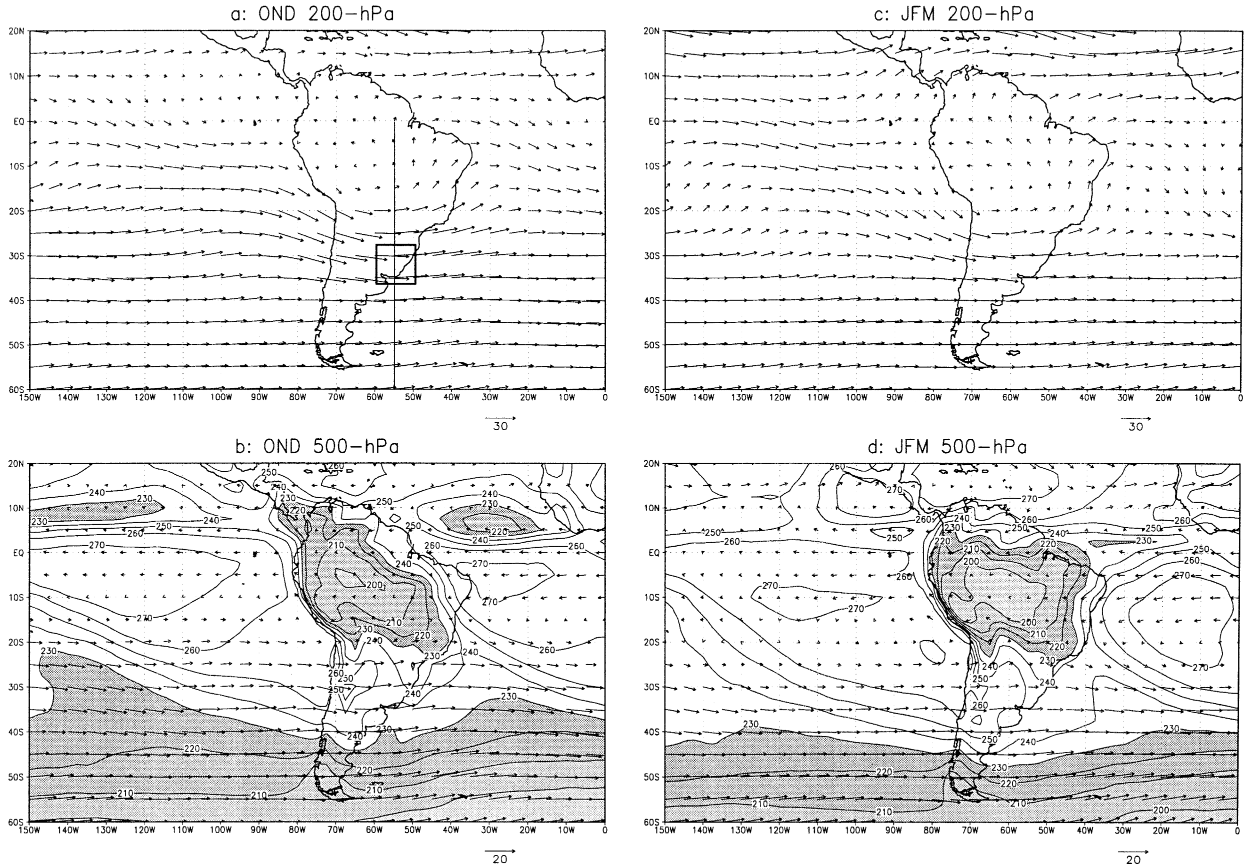

FIG. 2. OLR and average wind fields at 500 and 200 hPa during OND and JFM, 1979–93: (a) 200 hPa, OND; b) 500 hPa and OLR, OND; (c) 200 hPa, JFM; d) 500 hPa and OLR, JFM. Shaded regions indicate OLR under 230 W m^{-2}. Box centered over Uruguay, indicates the region used to identify 11-day periods of enhanced and reduced convection: Solid line in (a) indicates the position of the zonal wind meridional cross section described in section 3c. Wind speed units are m s^{-1}.

period 1979–93. Data are organized on a global grid with a 2.5° × 2.5° latitude–longitude resolution. For each 11-day period, the anomaly at individual grid points was calculated as the difference between the average of the specific variable over that period and the 1979–93 monthly mean. For periods evenly shared by two months, climatology of both was considered as the reference to compute the anomaly.

Additionally, a meridional cross section of the zonal component of the wind along 55°W, from the equator to 60°S (see Fig. 2), was analyzed using wind data at eight levels between 1000 and 100 hPa obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (details in Kalnay et al. 1996). The use of the NCEP reanalysis for this aspect of the study is explained by the fact that the availability of ECMWF data was limited to three levels. Considering the seasonal changes in the average circulation from spring to summer (Fig. 2), this study was performed separately for OND and JFM.

3. Results

a. Climatology

Mean patterns of OLR, 200-, and 500-hPa wind fields for austral spring (OND) and summer (JFM) are presented in Fig. 2. Basic features of the regional circulation are similar in both seasons, but some differences are apparent. In particular, the region with deep convection over the continent is considerably larger during summer, as revealed by the area with OLR below 200 W m^{-2}. On the other hand, the upper-tropospheric anticyclonic circulation over the central Andes is better organized during summer, but the intensity of the upper-air westerlies in subtropical South America is stronger during spring. Finally, no major changes in the position of the SACZ are noticed between spring and summer, although its intensity is a bit higher during the latter season.

b. OLR anomaly patterns

Composites of OLR anomalies characterizing 11-day episodes of low and high OLR values over Uruguay during OND and JFM are presented in Fig. 3. Anomaly patterns over eastern South America are very similar to those obtained by stratifying OLR over Uruguay at the seasonal (OND and JFM) and monthly scales (not shown), featuring a well-defined dipole, with one center over Uruguay and the other over the SACZ. No major differences are apparent between spring and summer. However, during episodes of enhanced and reduced convection over Uruguay, opposite anomalies prevail over the highland region in the central Andes during spring (Figs. 3a,b), but departures of the same sign are observed in both regions during the austral summer (Figs. 3d,e). The spatial pattern of the first EOF of OLR presented in Fig. 4 for spring and summer exhibits a well-defined dipolar structure. These patterns and those presented in Fig. 3, together with the ones emerging from several previous studies, provide convincing evidence of the intrinsic nature of the dipolar behavior of convective cloudiness along eastern South America.

c. Regional circulation anomalies

Composites of circulation anomalies during 11-day wet and dry periods in Uruguay during OND and JFM are presented in Figs. 5 and 6, including patterns of geopotential height and wind at 200 and 500 hPa, and temperature and wind at 850 hPa. We call attention to the fact that the use of geopotential height anomalies introduces a bias toward the high-latitude anomalies.

Episodes of enhanced convection over Uruguay during spring is characterized by a well-defined nucleus of positive quasi-barotropic geopotential height anomaly centered over the subtropical Atlantic near 30°S eastward from SESA (Figs. 5a–5c). This feature goes along with an anticyclonic circulation anomaly over a large portion of subtropical South America at 200 and 500 hPa. Negative height anomalies centered around 40°S on the west side of the continent explain a cyclonic vortex in the anomaly wind field around this region. Farther upstream, positive height anomalies develop over the southeastern Pacific (centered on 58°S, 115°W). This feature, and the associated anticyclonic circulation anomaly in the entire tropospheric column, is coherent with a significant weakening of the midlatitude westerlies in the southern Pacific (40°–60°S). The positive height anomalies in the southeast (SE) Pacific occur in the region with maximum blocking activity in the Southern Hemisphere (60°S, 120°W), as documented by Sinclair (1996) and Renwick and Revell (1999). Over the continent the positive height anomalies in the region between SESA and the SACZ contrast with the negative anomalies in the southern portion of the continent, favoring an anomalously strong subtropical jet stream. The relatively warm conditions over Uruguay and southern Brazil (Fig. 5c) are favored by the intensified northwesterly flow feeding the area of enhanced convection in SESA with warm and moist air from the Amazon basin, and contributing to the development of a relatively strong low-level jet along the eastern flank of the central Andes. Furthermore, this feature is consistent with a strengthened Chaco low in northwest (NW) Argentina, as revealed by the presence of negative 850-hPa height anomaly over this region during periods of enhanced convection over Uruguay (not shown). The cold-core quasi-barotropic cyclonic circulation anomaly over the southern tip of the continent during these episodes is consistent with the negative temperature anomalies at 850 hPa revealed in Fig. 5c for the same region. Anomaly patterns of geopotential height are characterized by a quasi-barotropic wavelike structure with regions of positive anomalies stretching from midlatitudes in the South Pacific toward subtropical South America.

Patterns of circulation anomalies during 11-day episodes of enhanced convection over Uruguay in summer (Figs. 6a–6c) exhibit approximately the same features described for spring (Figs. 5a–c). Specifically, the well-defined dipolar structure in the OLR anomaly pattern, with above-average convective cloudiness over SESA and a weakened SACZ (Fig. 3d), associates with a large warm-core anticyclonic circulation anomaly (Figs. 6a–6c) centered between both regions (around 34°S, 45°W) and covering most of the SE portion of the continent. The wavelike quasi-barotropic structure at midlatitudes is very similar to that described for spring, although during summer the center of the negative height anomalies near the southern tip of the continent is located eastward from its position in spring. Furthermore, during this season the positive height anomalies suggesting ridging and blocking in the SE Pacific are centered at a northward position (50°S). As in spring, the enhanced subtropical–extratropical baroclinicity over the continent implied by the temperature and height anomaly fields presented in Figs. 6a–6c is coherent with a strengthened subtropical jet, and an overall intensification of the westerlies from 30° to 35°S over the continent. Close to surface, positive 850-hPa height anomalies over NW Argentina and over the region between the SACZ and SESA (not shown) are consistent with a weakened SACZ. Similar to spring, the associated anticyclonic circulation anomaly centered over the subtropical east coast of the continent favors an intensified advection of warm and humid air toward SESA from the Amazon basin.

The regional circulation anomalies characterizing dry periods in Uruguay during spring and summer are broadly opposite to those described for episodes of enhanced convection. In spring (Figs. 5d–5f), a relatively weak and small cold-core cyclonic circulation anomaly over the SACZ replaces the dominating anticyclonic circulation anomaly observed during episodes of enhanced convection. On the other hand, the southern portion of the continent is under the influence of a large quasi-barotropic warm-core anticyclonic circulation anomaly that exerts a blocking effect on the westerly flow. This feature, combined with the negative height anomalies in the SE Pacific, is coherent with enhanced

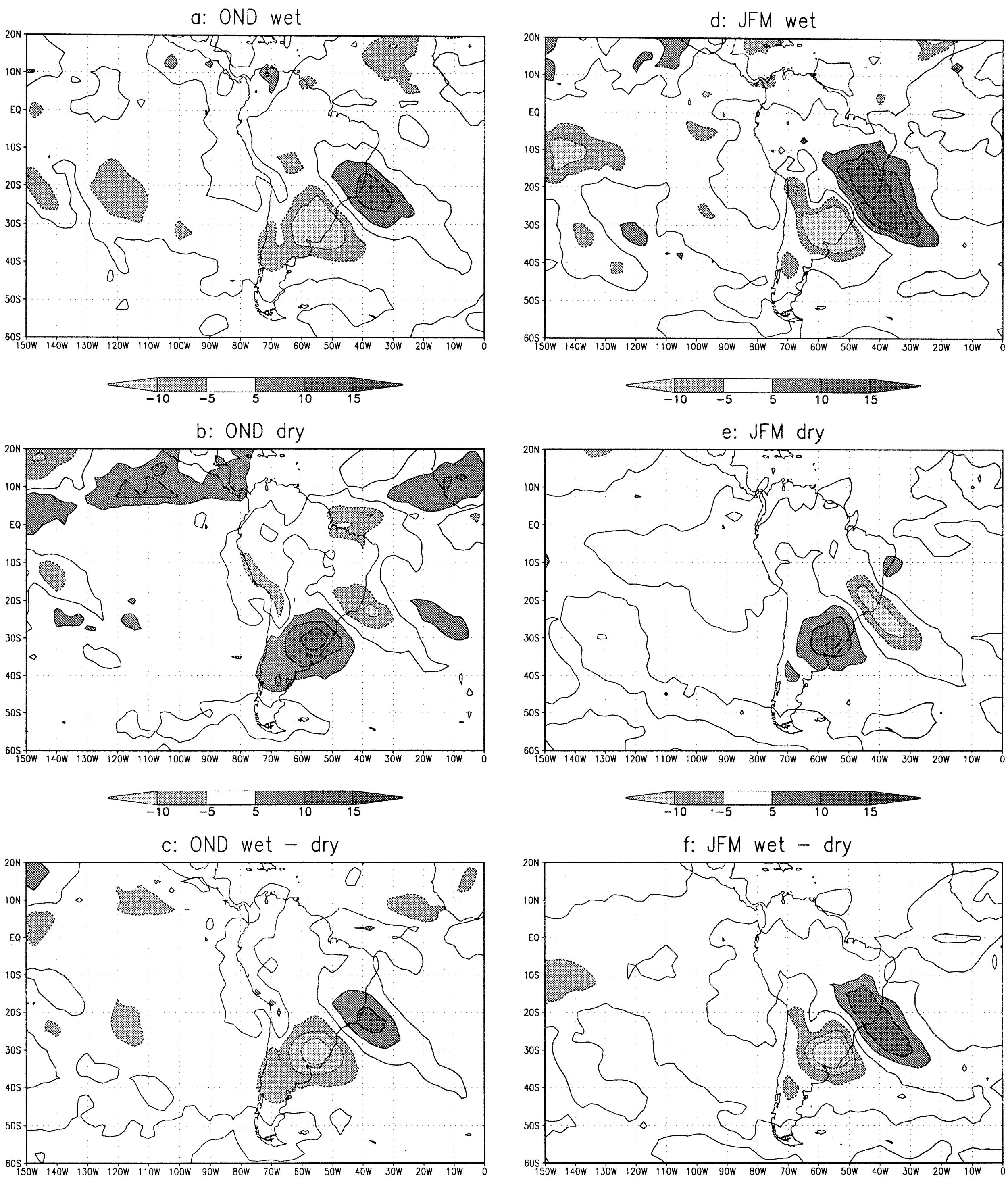

FIG. 3. OLR anomaly patterns during 11-day episodes of (a), (d) intense and (b), (e) weak convective cloudiness over Uruguay (location in Fig. 2), and (c), (f) their difference during (a), (b), (c) OND and (d), (e), (f) JFM.

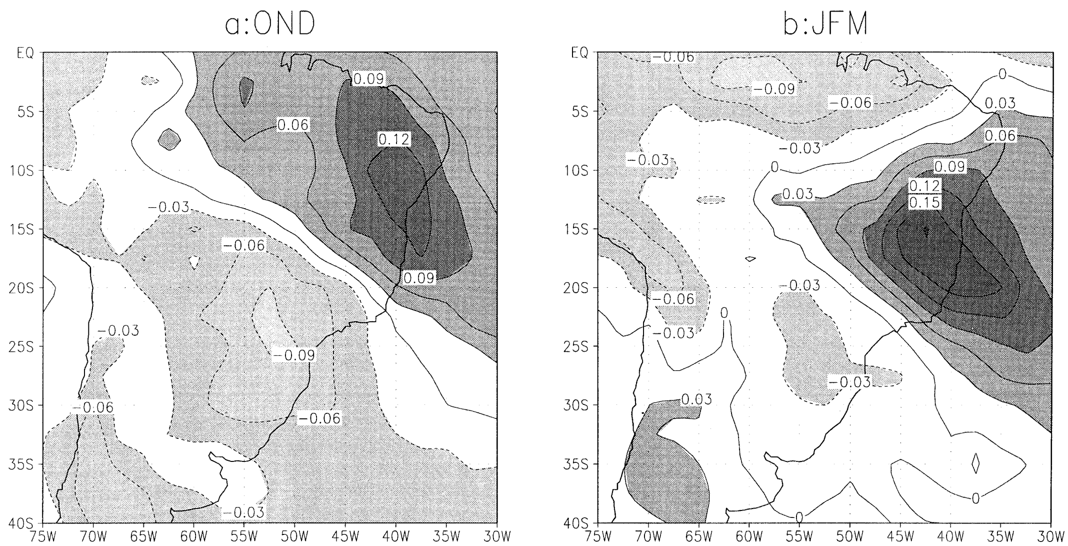

Fig. 4. Spatial patterns of the first unrotated EOF of seasonal OLR during (a) OND and (b) JFM for 1979–93. Percentage of explained variance is 32% in both cases.

westerlies over the southern tip of the continent and surrounding oceans.

Circulation anomalies during summer dry conditions in Uruguay are presented in Figs. 6d–6f. Relatively stronger negative geopotential height and cyclonic circulation anomalies prevail over the region between the SACZ and SESA, as compared with the same feature during dry periods in spring (Figs. 5d–5f). Furthermore, the positive height anomalies over the southern portion of the continent are considerably weaker in summer (Figs. 6d–6f) than in spring. The circulation anomaly patterns also include quasi-barotropic positive and negative height anomalies centered at around 60°S, 95°W, and 50°S, 150°W, respectively. Near the surface, the negative temperature anomalies prevailing over SESA are consistent with advection of relatively cold and dry air masses from the south as indicated by the wind anomaly field in the entire tropospheric column (Figs. 6d–6f).

In spite of the fact that circulation anomaly patterns during periods of enhanced convective cloudiness over Uruguay are broadly opposite to those when convection is weak, the use of the compositing technique allows for the detection of significant asymmetries between them. Specifically, the anticyclonic height anomalies centered over the subtropical Atlantic near 30°S and over the southeastern Pacific (58°S, 115°W) during wet episodes in OND and JFM (Figs. 5a,b and 6a,b) are considerably stronger than the cyclonic height anomalies over the same regions during dry events (Figs. 5d,e and 6d,e). However, caution should be exerted when interpreting these asymmetries, considering that rainy days in Uruguay account only for 20%–25% of the time (see Table 1). Thus, the relatively low frequency of wet days could bias the climatological mean toward that typical of dry conditions, giving rise to associated weaker anomalies during dry episodes.

Figures 5 and 6 also reveal some significant changes in the structure of the wavelike anomaly pattern. Specifically, positive (negative) height anomalies over SESA and the adjacent Atlantic domain during wet (dry) periods are stronger for the austral summer as compared to those in spring. However, over the southern portion of the continent, where opposite anomalies occur, it is in spring when they are stronger.

d. Subtropical jet stream over SESA

Circulation anomaly patterns in Figs. 5 and 6 suggest significant changes in the strength of the subtropical jet over eastern South America during wet and dry episodes in Uruguay. To further document these changes, composites of a meridional cross section of the zonal wind component at 55°W (see Fig. 2) were calculated for 11-day wet and dry episodes during spring and summer, using NCEP reanalysis (Fig. 7). The subtropical jet over SESA is stronger in spring, when wind speed exceeding 30 m s^{-1} is observed between 28° and 38°S (Fig. 7c). In summer, westerlies are weaker over this latitudinal band (Fig. 7f). Anomalously wet conditions in SESA have been related to a reinforced subtropical jet, particularly during El Niño episodes (Kousky et al. 1984).

During episodes of enhanced convection and rainfall over Uruguay the subtropical jet is anomalously strong over eastern South America, exceeding 35 m s^{-1} in spring and 30 m s^{-1} in summer (Figs. 7a,d), but it remains roughly at its climatological position. During dry periods, westerlies at the mean latitude of the subtropical jet are relatively weaker, and no jetlike structure is observed (Figs. 7b,e). These features seem to be a local

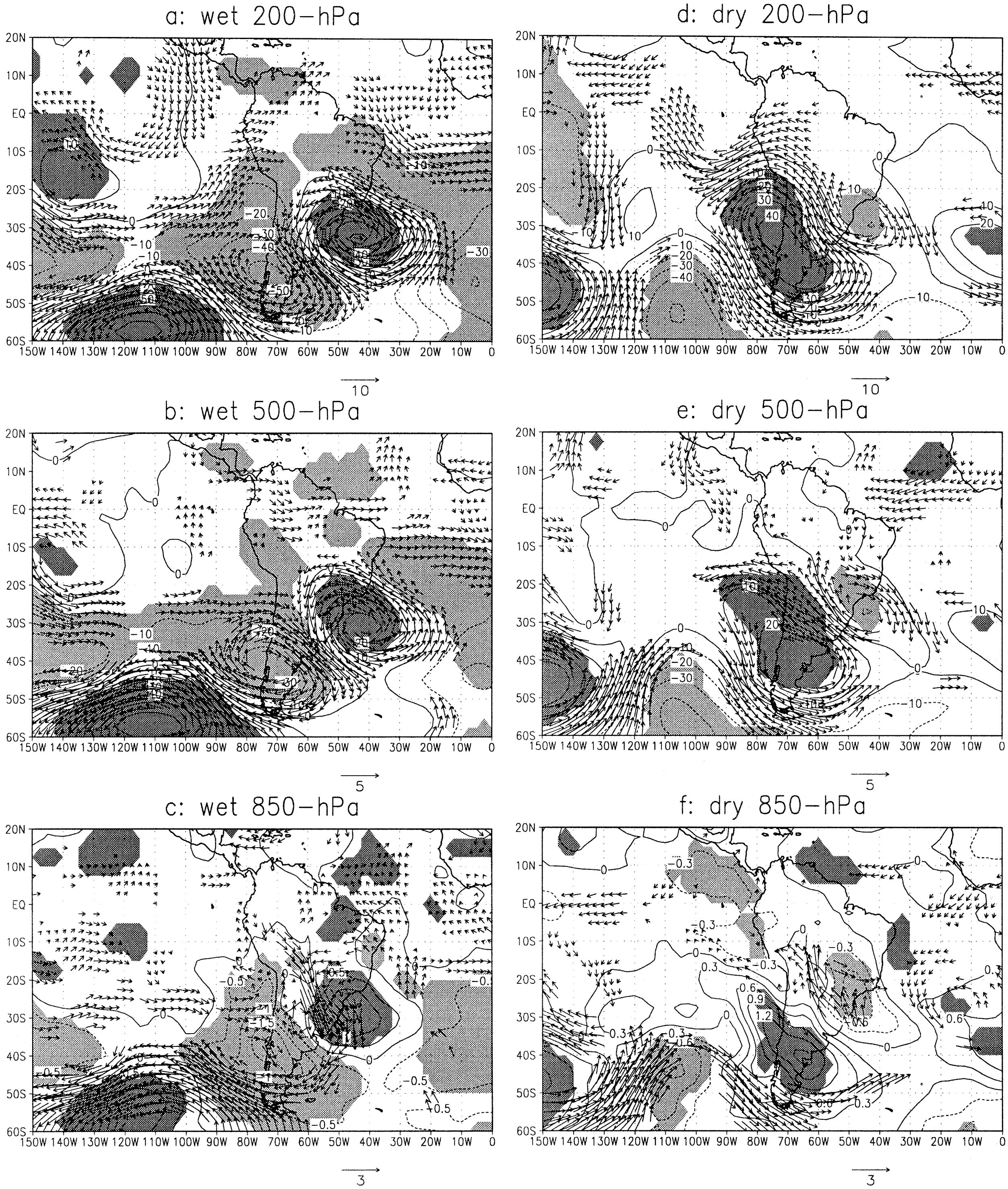

FIG. 5. Circulation anomalies for composites of 11-day episodes of (a), (b), (c) enhanced and (d), (e), (f) reduced convective cloudiness over Uruguay during OND. (a), (d), and (b), (e) Show geopotential height and wind anomalies at 200 and 500 hPa, respectively; (c), (f) show temperature and wind anomalies at 850 hPa. Shading denotes statistical significance at the 95% level for height and temperature anomaly fields according to a Monte Carlo test. Wind anomalies are shown at grid points where statistical significance at the 95% level is reached by either the zonal or the meridional component. Units are m, m s^{-1}, and °C. A scale for wind speed is included in each panel.

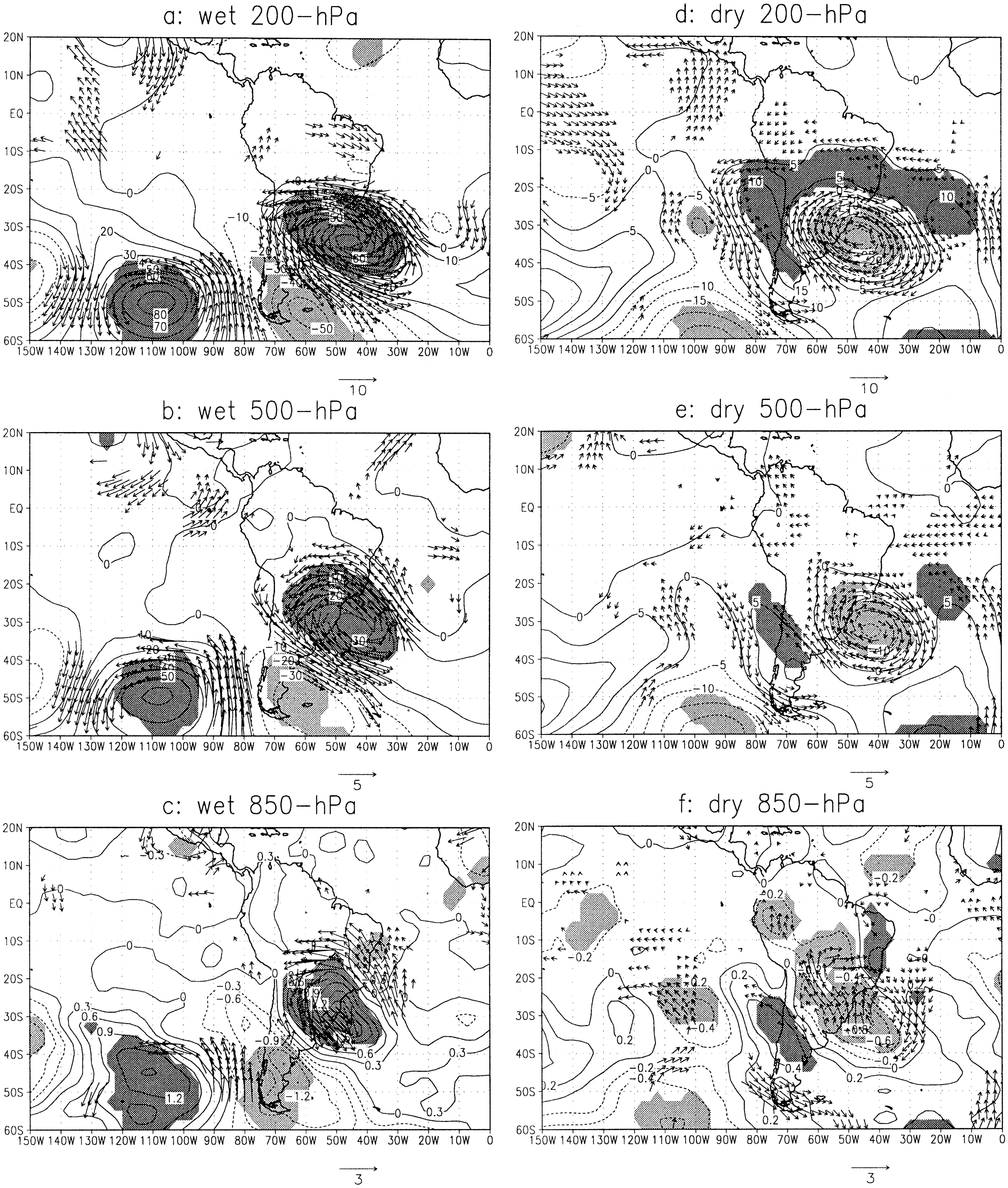

FIG. 6. Same as in Fig. 5, except for JFM.

manifestation of the upper-tropospheric wavelike height anomalies shown in Figs. 5a,d and 6a,d, featuring an increased (reduced) baroclinicity in the region of the subtropical jet along eastern South America during episodes of enhanced (reduced) convection over Uruguay.

4. Discussion

Circulation anomalies linked to episodes of enhanced and reduced convective cloudiness over Uruguay during austral spring and summer are discussed and compared

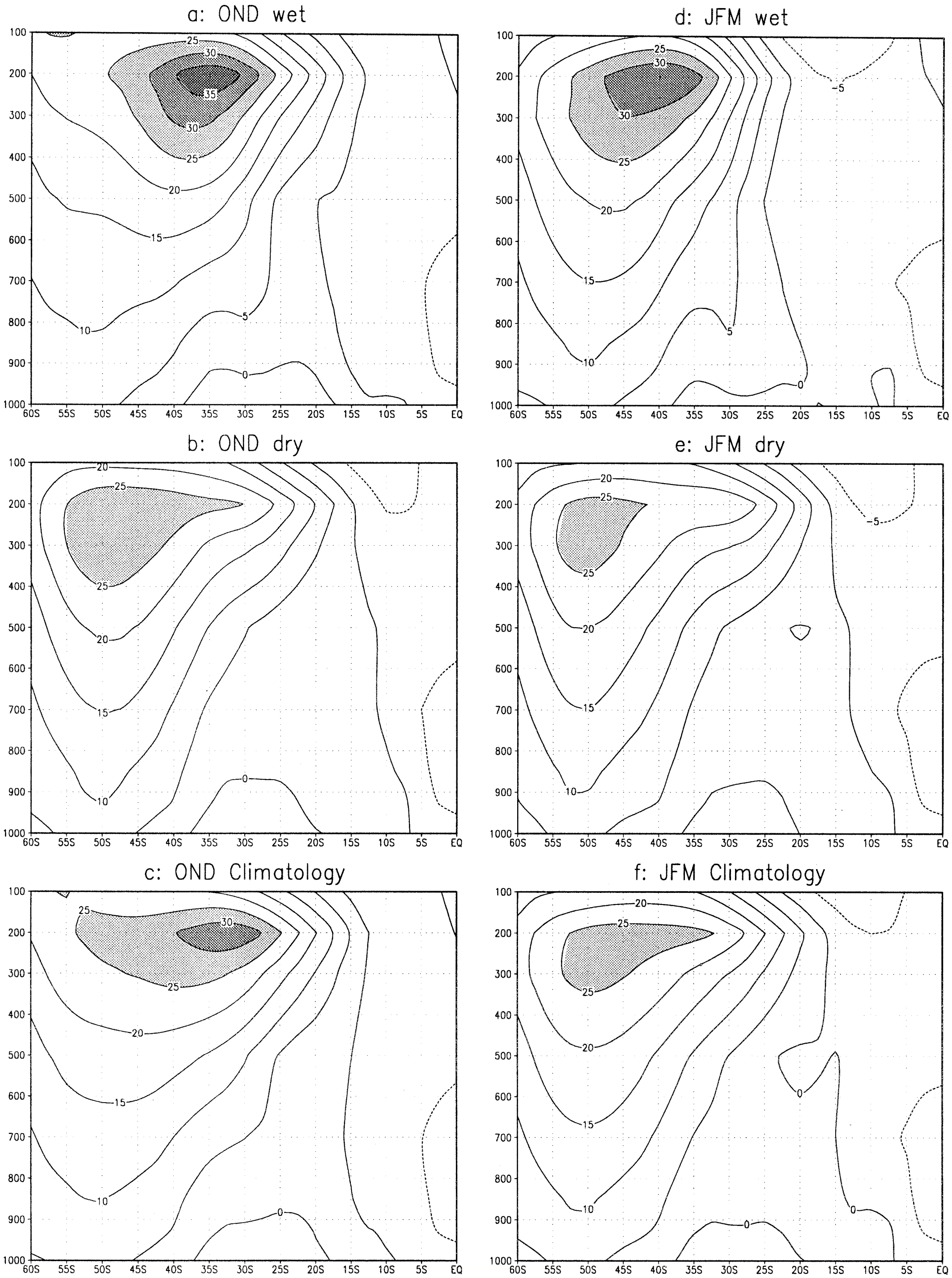

FIG. 7. Meridional cross section of the zonal wind component (m s^{-1}) at 55°W (Fig. 2), for (a), (b), (c) OND and (d), (e), (f) JFM during 1979–93, corresponding to composites of 11-day episodes of (a), (d) enhanced and (b), (e) reduced convective cloudiness over Uruguay; (c), (f) climatology.

with results from previous studies. Considering the pervasive nature of the dipole associated with these circulation anomalies, it is not surprising that results presented in this paper exhibit a considerable degree of coherence with those associated with other aspects of climate dynamics in South America.

In our approach we focused on the specific characteristics of circulation anomaly patterns during wet and dry 11-day episodes in Uruguay, and we were able to assess their asymmetries and the specific differences between spring and summer.

The pioneering study by Casarin and Kousky (1986) documented the main characteristics of the OLR dipole in eastern South America and described circulation anomalies for dry periods in southern Brazil. For the common period 1979–85 our dry events in Uruguay mostly coincide with their dry episodes in southern Brazil. Thus, their OLR anomaly pattern corresponding to these conditions is very similar to ours corresponding to weak convection over Uruguay (Figs. 3b,e). Furthermore, the cyclonic circulation anomaly at middle- and upper-tropospheric levels over SESA and the adjacent Atlantic Ocean during dry episodes in Uruguay (Fig. 5d and particularly Fig. 6d) is also a typical feature described by these authors for dry conditions in southern Brazil (see their Fig. 5b).

The patterns of circulation anomalies described in section 3 for submonthly periods of enhanced and reduced convective cloudiness over Uruguay during austral spring and summer are in agreement with those described by Nogués-Paegle and Mo (1997), from the analysis of the fifth rotated EOF of intraseasonal filtered OLR pentad anomalies in the region 40°S–40°N, 180°–20°E, during austral summers.

A marked dipole in convective cloudiness anomaly along eastern South America was also documented by Liebmann et al. (1999), although in their case the southern center of the dipole is located in a position slightly northward from that indicated in our study. This is explained by the fact that their dipole emerges from correlating OLR with itself over a region within the SACZ. Additionally, the upper-tropospheric cyclonic (anticyclonic) circulation anomalies documented in their study when convection is above- (below) normal over the SACZ (their Fig. 4c) are comparable to those described in the present study for episodes of reduced (enhanced) convective cloudiness over Uruguay (Figs. 5a,d and 6a,d). The contrast between above-normal surface temperature in the southern portion of the continent and negative temperature anomalies at lower latitudes along the Atlantic coast indicated in their Fig. 9c, when convection is enhanced over the SACZ, is also similar to the temperature anomaly pattern we have found at 850 hPa when convective cloudiness is weak over Uruguay (Figs. 5f and 6f).

Several studies have shown that regional circulation anomalies similar to those we have documented for periods of enhanced and reduced convection over Uruguay are part of a large-scale wavelike structure in the Southern Hemisphere of the same type as presented in Fig. 8 (Nogués-Paegle and Mo 1997; Liebmann et al. 1999; Li and Le Treut 1999). Specifically, the tropical–extratropical wavelike structure documented by Li and Le Treut (1999) for the 300-hPa height anomaly field during episodes of intense southward moisture transport into subtropical South America during DJF is very similar to those we have described for the 500- and 200-hPa height anomaly fields during wet episodes in Uruguay (Figs. 5a,b; 6a,b; and 8a). Related to this matter, Robertson and Mechoso (2000) documented an equivalent barotropic gyre centered in the region between the SACZ and SESA, when studying the interannual and interdecadal variability of the SACZ. This prevalent structure, which they interpreted as a locally forced stationary Rossby wave, is basically the same as those in Figs. 5 and 6, for episodes of enhanced and reduced convection in Uruguay during spring and summer.

Some features in the regional circulation during wet and dry episodes in Uruguay can be identified in particular key modes of circulation over South America described in earlier diagnostic studies. Specifically, Kousky and Kayano (1994) identified principal modes of circulation for the South American sector (20°N–50°S, 10°–100°W), applying combined EOF analysis to pentad values of anomalous OLR and 250-hPa wind (zonal and meridional components). Data were filtered to study modes on both the interannual and intraseasonal timescales, considering the entire year. The dipole in convective cloudiness and the associated upper-troposphere circulation anomalies over eastern South America discussed in our study appear in their third combined unrotated EOF component of the low-pass-filtered time series (used to determine the principal modes of interannual variability). Besides, that mode suggests an association between above-normal convective cloudiness over SESA and the development of upper-troposphere anticyclonic anomalies over this region and the adjacent Atlantic Ocean, which is confirmed by our study. On the other hand, Lenters and Cook (1999) identified five leading modes of variability, accounting for the 77% of the total variance, applying EOF analysis on 5-day running mean 200-hPa geopotential height over tropical and subtropical South America and adjacent Pacific and Atlantic Oceans during DJF from 1985 to 1993. The spatial pattern of their third EOF component (their Fig. 4c), characterized by an anticyclonic circulation anomaly around 30°S on the eastern coast of South America, is very similar to the 200- and 500-hPa anomaly patterns described here for wet and dry episodes in Uruguay (Figs. 5, 6). They associate this circulation mode with changes in the strength and position of the SACZ.

Results from case studies not focusing on the specific topic of this paper also reveal some of the key features that we describe in connection with OLR anomalies over Uruguay. Specifically, Kalnay et al. (1986) studied the global circulation anomalies associated with a strong stationary wave on eastern South America during January 1979, characterized by a cyclonic circulation anomaly at 200 hPa over SESA and the adjacent Atlantic, and anomalously strong (weak) convection over the SACZ (SESA). These persistent features, related by these authors to a strong South Pacific convergence zone (SPCZ), include all of the regional circulation anomalies we have described for dry conditions in Uruguay (Figs.

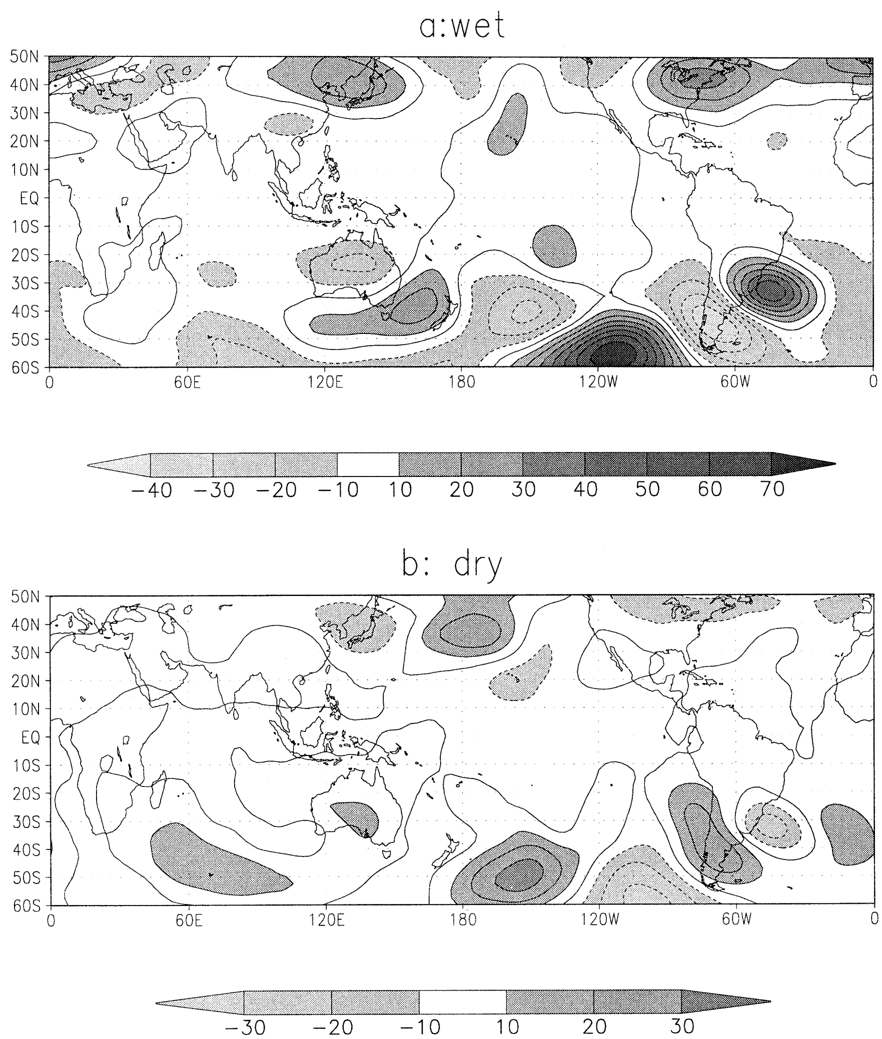

FIG. 8. The 200-hPa geopotential height anomalies for 11-day composites of (a) enhanced and (b) reduced convective cloudiness over Uruguay during Oct–Mar 1979–93. Units are m.

5 and 6). In a case study discussed by Salio et al. (2000), the frequency of the low-level jet (LLJ) eastward from the central Andes is analyzed for two contrasting wet and dry months in SESA. During the dry January 1985 the SACZ was anomalously strong, while in January 1988 it was relatively weak and positive rainfall anomalies prevailed in the subtropical portion of the continent including SESA. They found an increased frequency of LLJs occurring during the latter month, which is consistent with the typical conditions described in this study for wet episodes in Uruguay, that is, enhanced lower tropospheric northwesterly flow along the eastern side of the Andes (Fig. 6c). Regarding this matter, results summarized in Fig. 5c and 6c are also consistent with those obtained in earlier studies (see, e.g., Nogués-Paegle and Mo 1997; Doyle and Barros 2002), showing that the LLJ and the associated northwesterly flow of warm and humid air toward the plains in subtropical South America are closely linked to regional circulation anomalies occurring during wet episodes in SESA.

The possible influence of the intraseasonal Madden–Julian oscillation (MJO) on the functioning of the dipole in convective cloudiness over eastern South America was not addressed in our study. However, the connection between the Australian region and SESA suggested by Fig. 8 may be relevant for the suspected link between MJO and rainfall anomalies associated with the dipolar structure of convective cloudiness along eastern South America, mentioned in several studies (Casarin and Kousky 1986; Kousky and Cavalcanti 1988; Berbery and Nogués-Paegle 1993; Grimm and Silva Dias 1995; Nogués-Paegle and Mo 1997).

SST anomalies in the southwestern Atlantic may also play a key role in modulating the dipole in convective cloudiness along eastern South America. Regarding this issue, Doyle and Barros (2002) document a dipolar structure in rainfall, similar to the OLR anomaly patterns presented in Figs. 3 and 4. Specifically, they detected the occurrence of abundant rainfall in SESA, contrasting with relatively dry conditions over the continental extension of the SACZ when positive SST anomalies prevail in the southwestern Atlantic during January. They documented opposite rainfall anomalies associated with negative SST anomalies.

The seesaw in convective cloudiness and rainfall described in this and previous studies suggests the existence of a similar structure in hydrological regimes along eastern South America. This contrasting hydrological response is partially documented by Robertson and Mechoso (1998) at the interdecadal timescale. A careful selection of basins within the domains of the SACZ and SESA should give a clearer signal of the dipole in river flow discharges at the interannual and intraseasonal timescales.

5. Conclusions

Submonthly (11 day) dry and wet periods in Uruguay during austral spring and summer are characterized by a dipole in the anomaly field of convective cloudiness along eastern tropical and subtropical South America (10°–40°S), which seems to be part of an intrinsic mode of atmospheric variability in South America during this time of the year. Thus, when convective cloudiness is anomalously strong over Uruguay, the same signal is observed over a broader region in the southeastern portion of the continent, including southern Brazil and the plains of northeastern Argentina, while the SACZ is weaker than average. Opposite anomalies prevail during dry periods in Uruguay, featuring reduced convection over SESA and a strong SACZ.

Main regional circulation anomalies associated with episodes of enhanced and reduced convective cloudiness over Uruguay during spring and summer are indicated in Fig. 9 and described below.

a. Enhanced convection over Uruguay

- Weakened convection over the SACZ.
- Warm-core anticyclonic circulation anomaly in the middle and upper troposphere, centered over the Atlantic at around 34°S, 45°W, and extending over eastern subtropical South America, although involving a broader area in summer.
- The previous feature is part of a much larger wavelike quasi-barotropic structure that includes alternating negative and positive height and temperature anomalies with centers in the southern portion of the continent (negative) and farther upstream, at around 55°S, 110°W (positive), and 40°S, 150°W (negative).
- Enhanced baroclinicity along the eastern coast of South America favoring a stronger-than-average subtropical jet stream.

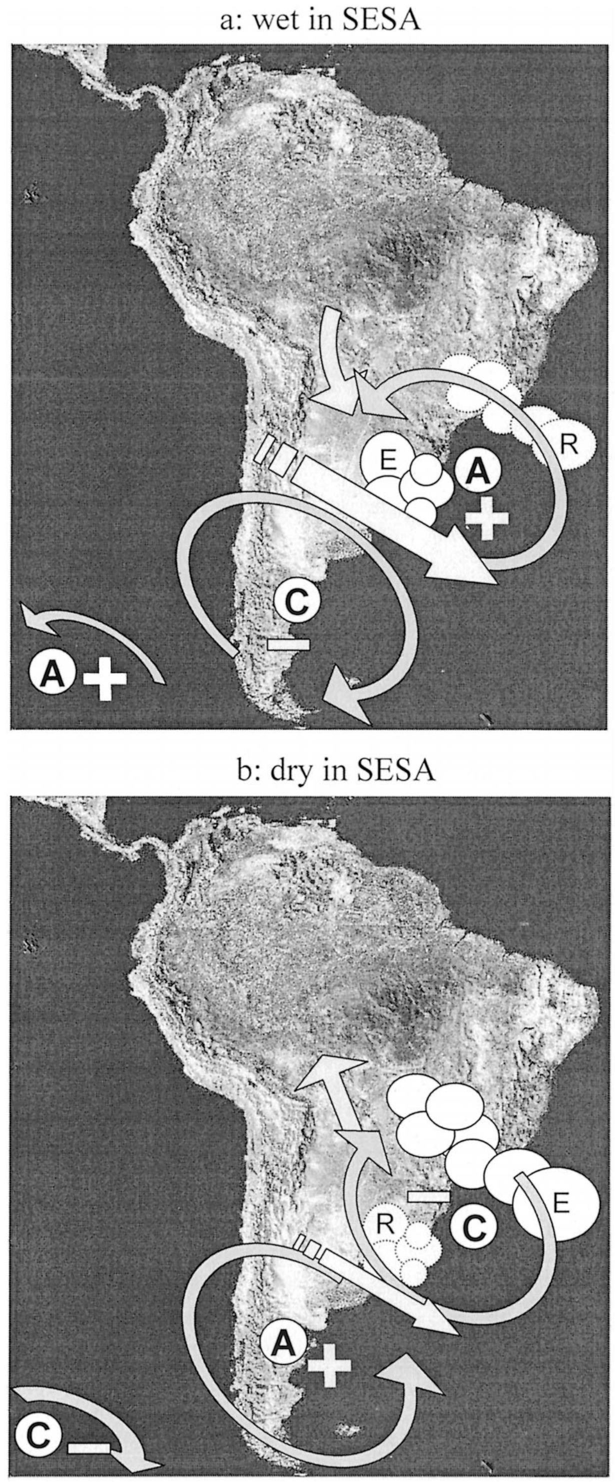

FIG. 9. Regional circulation anomalies characterizing periods of (a) enhanced and (b) reduced convective cloudiness over Uruguay during austral spring and summer. Letters A and C represent anticyclonic and cyclonic circulation anomalies, respectively. Plus and minus signs stand for positive and negative temperature anomalies. Enhanced and reduced convective cloudiness are indicated by letters E and R, respectively. The relative strength of the subtropical jet stream is represented by arrows of different sizes. The arrow eastward from the central Andes indicates the direction of the low-level wind anomaly.

- An intensified Chaco low in northwestern Argentina leading to a reinforced northwesterly flow of warm and humid air toward SESA. This condition favors the occurrence of episodes of low-level jet along the eastern flank of the central Andes.

b. *Reduced convection over Uruguay*

Anomaly patterns during episodes of reduced convection over Uruguay are broadly opposite to those described above, particularly with reference to the large-scale wavelike anomaly pattern in the atmospheric circulation. Specific features are as follows.

- Enhanced convection over the SACZ.
- Cold-core cyclonic circulation anomaly in the middle and upper troposphere, centered over the Atlantic at around 30°S, 45°W. In comparison with spring, this anomaly is stronger during summer, reaching a larger area over SESA and the adjacent Atlantic.
- Quasi-barotropic warm-core anticyclonic circulation anomalies centered in southern South America. This feature is considerably larger in spring than in summer, stretching from the subtropical Pacific to the extratropical Atlantic.
- Reduced baroclinicity along the eastern coast of South America between 30° and 50°S, explaining a weakened subtropical jet stream.
- A weaker-than-normal Chaco low in northwestern Argentina that favors a weakened advection of warm air to SESA from the Tropics.

Given the extent of circulation anomalies described here in relation with wet and dry conditions in Uruguay, it seems plausible that they also characterize the occurrence of rainfall anomalies over a broader region in southeastern South America.

Changes in the intensity, frequency, and duration of episodes in each phase of the dipole may to a large extent modulate the intraseasonal and interannual climate anomalies on eastern South America (10°–40°S). Those changes could be forced by larger-scale factors, including, for example, regional and/or global SST anomalies. Further study is needed to substantiate this issue.

Acknowledgments. This paper is part of a M.Sc. thesis developed by A. D. at the Instituto de Mecánica de los Fluidos e Ingeniería Ambiental, Universidad de la República, Uruguay (IMFIA-UR). We wish to acknowledge Aldo Montecinos, Rafael Terra, and three anonymous reviewers for their constructive comments on the original manuscript. Rainfall data for stations in Uruguay were kindly provided by Dirección Nacional de Meteorología (Uruguay). The Grid Analysis and Display System (GrADS) was used for producing most of the figures. This work was partially supported by IAI (Cooperative Agreement ATM-9209181, Subaward UCAR S97-74046, UCAR/UR) and the Dept. of Geophysics of Universidad de Chile. The authors also acknowledge the support of Comisión Sectorial de Investigación Cientifica and IMFIA-UR.

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.

Barros, V., M. González, B. Liebmann, and I. Camilloni, 2000: Influence of the South Atlantic convergence zone and South Atlantic sea surface temperature on interannual summer rainfall variability in southeastern South America. *Theor. Appl. Climatol.,* **67,** 123–133.

Berbery, E. H., and J. Nogués-Paegle, 1993: Intraseasonal interactions between the Tropics and extratropics in the Southern Hemisphere. *J. Atmos. Sci.,* **50,** 1950–1965.

——, and E. Collini, 2000: Springtime precipitation and water vapor flux convergence over southeastern South America. *Mon. Wea. Rev.,* **128,** 1328–1346.

——, J. Nogués-Paegle, and J. D. Horel, 1992: Wavelike Southern Hemisphere extratropical teleconnections. *J. Atmos. Sci.,* **49,** 155–177.

Casarin, D. P., and V. E. Kousky, 1986: Anomalies de precipitacao no sul do Brasil e variacoes na circulacoes atmosférica. *Rev. Bras. Meteor.,* **1,** 83–90.

Castañeda, M. E., and V. R. Barros, 1994: Long-term trends in rainfall along southern South America eastward from the Andes (in Spanish). *Meteorologica,* **19,** 23–32.

Cazes, G., and G. Pisciottano, 2000: Climate variability in southeastern South America related to ENSO: A numerical study. Preprints, *Sixth Int. Conf. on Southern Hemisphere Meteorology and Oceanography,* Santiago, Chile, Amer. Meteor. Soc., 186–187.

Díaz, A. F., 2000: Simultaneous relationships between SST anomalies in the southwestern Atlantic Ocean and precipitation in a basin in Uruguay. Preprints, *Sixth Int. Conf. on Southern Hemisphere Meteorology and Oceanography,* Santiago, Chile, Amer. Meteor. Soc., 370–371.

——, C. D. Studzinski, and C. R. Mechoso, 1998: Relationships between precipitation anomalies in Uruguay and southern Brazil and sea surface temperature in the Pacific and Atlantic Oceans. *J. Climate,* **11,** 251–271.

Doyle, M. E., and V. R. Barros, 2002: Midsummer low-level circulation and precipitation in subtropical South America and related sea surface temperature anomalies in the South Atlantic. *J. Climate,* **15,** 3394–3410.

Gan, M. A., and V. Rao, 1991: Surface cyclogenesis over South America. *Mon. Wea. Rev.,* **119,** 1923–1302.

Garreaud, R. D., and J. M. Wallace, 1998: Summertime incursions of midlatitude air into subtropical South America. *Mon. Wea. Rev.,* **126,** 2713–2733.

Genta, J. L., G. Perez-Iribarren, and C. R. Mechoso, 1998: A recent increasing trend in the streamflow of rivers in southeastern South America. *J. Climate,* **11,** 2558–2862.

Grimm, A. M., and P. L. Silva Dias, 1995: Analysis of tropical–extratropical interactions with influence functions of a barotropic model. *J. Atmos. Sci.,* **52,** 3538–3555.

——, S. E. Ferraz, and J. Gomes, 1998: Precipitation anomalies in southern Brazil associated with El Niño and La Niña events. *J. Climate,* **11,** 2863–2880.

——, V. R. Barros, and M. E. Doyle, 2000: Climate variability in southern South America associated with El Niño and La Niña events. *J. Climate,* **13,** 35–58.

Kalnay, E., K. C. Mo, and J. Paegle, 1986: Large amplitude, short-scale stationary Rossby waves in the Southern Hemisphere: Observations and mechanistic experiments to determine their origin. *J. Atmos. Sci.,* **43,** 252–275.

——, and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.
Kiladis, G. N., and H. F. Diaz, 1989: Global climate anomalies associated with extremes in the Southern Oscillation. *J. Climate,* **2,** 1069–1090.
——, and K. M. Weickmann, 1992: Circulation anomalies associated with tropical convection during northern winter. *Mon. Wea. Rev.,* **120,** 1900–1923.
Kousky, V. E., and I. F. A. Cavalcanti, 1988: Precipitation and atmospheric circulation anomaly patterns in the South American sector. *Rev. Bras. Meteor.,* **3,** 199–206.
——, and C. F. Ropelewski, 1989: Extremes in the Southern Oscillation and their relationship to precipitation anomalies with emphasis in the South American region. *Rev. Bras. Meteor.,* **4,** 351–363.
——, and M. T. Kayano, 1994: Principal modes of outgoing longwave radiation and 250-mb circulation for the South American sector. *J. Climate,* **7,** 1131–1143.
——, M. T. Kagano, and I. F. Cavalcanti, 1984: A review of the Southern Oscillation: Oceanic–atmospheric circulation changes and related rainfall anomalies. *Tellus,* **36A,** 490–504.
Krepper, C. M., B. Scian, and J. Pierini, 1989: Time and space variability of rainfall in central-east Argentina. *J. Climate,* **2,** 39–47.
Lenters, J. D., and K. H. Cook, 1999: Summertime precipitation variability over South America: Role of the large-scale circulation. *Mon. Wea. Rev.,* **127,** 409–431.
Li, Z. X., and H. Le Treut, 1999: Transient behavior of the meridional moisture transport across South America and its relation to the atmospheric circulation patterns. *Geophys. Res. Lett.,* **26,** 1409–1412.
Liebmann, B., and C. A. Smith, 1996: Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteor. Soc.,* **77,** 1275–1277.
——, G. Kiladis, J. Marengo, T. Ambrizzi, and J. D. Glick, 1999: Submonthly convective variability over South America and the South Atlantic convergence zone. *J. Climate,* **12,** 1877–1891.
Mechoso, C. R., and G. Pérez-Iribarren, 1992: Streamflow in southeastern South America and the Southern Oscillation. *J. Climate,* **5,** 1535–1539.
Minetti, J. L., and W. M. Vargas, 1997: Trends and jumps in the annual precipitation in South America south of the 15°S. *Atmósfera,* **11,** 205–221.
Mo, K. C., and J. Nogués-Paegle, 2001: The Pacific–South American modes and their downstream effects. *Int. J. Climatol.,* **21,** 1211–1229.
Montecinos, A., A. Díaz, and P. Aceituno, 2000: Seasonal diagnostic and predictability of rainfall in subtropical South America based on tropical Pacific SST. *J. Climate,* **13,** 746–758.
Nogués-Paegle, J., and K. C. Mo, 1997: Alternating wet and dry conditions over South America during summer. *Mon. Wea. Rev.,* **125,** 279–291.
Pisciottano, G., A. Díaz, G. Cazes, and C. R. Mechoso, 1994: El Niño–Southern Oscillation impact on rainfall in Uruguay. *J. Climate,* **7,** 1286–1302.
Renwick, J. A., and M. J. Revell, 1999: Blocking over the South Pacific and Rossby wave propagation. *Mon. Wea. Rev.,* **127,** 2233–2247.
Robertson, A. W., and C. R. Mechoso, 1998: Interannual and decadal cycles in river flows of southeastern South America. *J. Climate,* **11,** 2570–2581.
——, and ——, 2000: Interannual and interdecadal variability of the South Atlantic convergence zone. *Mon. Wea. Rev.,* **128,** 2947–2957.
Ropelewski, C., and M. Halpert, 1987: Global and regional scale precipitation patterns associated with El Niño/Southern Oscillation. *Mon. Wea. Rev.,* **115,** 1606–1626.
——, and ——, 1989: Precipitation patterns associated with the high index phase of the Southern Oscillation. *J. Climate,* **2,** 268–284.
——, and ——, 1996: Quantifying Southern Oscillation–precipitation relationships. *J. Climate,* **9,** 1043–1059.
Salio, P., M. Nicolini, and C. Saulo, 2000: Low level circulation characteristics during two extreme precipitation regimes over South America. Preprints, *Sixth Conf. on Southern Hemisphere Meteorology and Oceanography,* Santiago, Chile, Amer. Meteor. Soc., 334–335.
Sinclair, M. R., 1996: A climatology of anticyclones and blocking for the Southern Hemisphere. *Mon. Wea. Rev.,* **124,** 245–263.