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# Statistical analysis of upper tropospheric vortices in the vicinity of northeast Brazil during the 1980-1989 period

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RESUMEN

Los análisis diarios del Centro Europeo de Pronóstico del Tiempo a Mediano Plazo (ECMWF) para el período 1980-1989 son usados para un estudio de los vórtices ciclónicos de la troposfera alta (VCTAs) sobre el nordeste de Brasil y áreas oceánicas próximas. La ocurrencia de los VCTAs muestra una significante variabilidad interanual y estacional, encontrándose que éstos son más frecuentes en los meses de verano del Hemisferio Sur. Generalmente los VCTAs se originan sobre áreas oceánicas, con la circulación cerrada en 200-hPa, el centro más frío en 300 hPa y permanecen confinados en la alta y mediana troposfera. El tiempo medio de vida de los VCTAs varía de 4 días en junio a 11 días en febrero. Aproximadamente 57% de los VCTAs en el verano del Hemisferio Sur se originan conforme el mecanismo de formación hasta ahora conocido. El 27% de los casos de verano en el Hemisferio Sur se originan asociados a la ocurrencia de una circulación anticiclónica en la troposfera alta sobre el Atlántico sudoeste y sudeste de Brasil, a su vez asociada a frentes fríos estacionarios (Zona de Convergencia del Atlántico Sur - ZCAS). La trayectoria de los VCTAs puede ser regular o irregular. Vaguadas en latitudes medias asociadas a sistemas frontales y una bifurcación interhemisférica del flujo del oeste en la troposfera alta al noreste de América del Sur, pueden causar tales desplazamientos irregulares. Para los VCTAs con desplazamiento regular, normalmente se observa la amplificación de la dorsal del sector sudeste de la Alta de Bolivia que puede causar la circulación anticiclónica en el sudeste de Brasil y el Atlántico sudoeste.

ABSTRACT

Daily European Centre for Medium Range Weather Forecasts (ECMWF) analyses for the 1980-1989 period are used to study cyclonic vortices at the upper tropospheric levels (CVULs) in the vicinity of northeast Brazil. The occurrence of CVULs shows significant interannual and seasonal variability, with the highest frequency found during the Southern Hemisphere summer months. CVULs develop mostly over oceanic areas, with the closed circulation at 200-hPa and the cold core at 300-hPa, and remain confined to the middle and upper troposphere. The CVUL mean lifetime ranges from 4 days in June to 11 days in February. Approximately 57% of the Southern Hemisphere summer CVULs originate accordingly to the formation mechanism so far known. In 27% of the Southern Hemisphere summer cases, the vortex originates associated with the occurrence of an upper level anticyclonic circulation over southwestern Atlantic and southeastern Brazil, in turn associated with stationary cold fronts (South Atlantic Convergence Zone-SACZ). CVULs can present regular or irregular trajectories. Midlatitude trough associated with frontal systems and an inter-hemispheric bifurcation of the upper level westerlies in the northwest of South America can cause such irregular displacements. For the CVULs with regular displacement, it is common to observe an amplification of the ridge axis in the southeastern sector of the Bolivian High, which can cause the upper level anticyclone in the southwestern Atlantic and southeastern Brazil.

## 1. Introduction

Upper tropospheric vortices in the Northern Hemisphere subtropics over the Pacific and Atlantic Oceans have been observed for decades (Palmer, 1951; Simpson, 1952; Riehl, 1954). Several observational studies have focused on their synoptic characteristics, such as their vertical structure and energetics (Ramage, 1962; Carlson, 1967; Frank, 1970; Kelley and Mock, 1982; Chen and Chou, 1993). These systems are cold cored, confined to the middle and upper troposphere and are extremely persistent (Ramage, 1962). Similar systems in the South Atlantic/South American sector during the Southern Hemisphere spring and summer months have been long observed (Aragão, 1976; Virji, 1981; Kousky and Gan, 1981; Rao and Bonatti, 1987). However, opposed to the Northern Hemisphere systems, the South Atlantic cyclonic vortices at upper tropospheric levels (CVULs) have received considerable less attention.

Based on satellite data for the 1975-1979 period, Kousky and Gan (1981), were the first to provide a climatological statistics for the CVULs over the South Atlantic. They found that these vortices occur mainly during the Southern Hemisphere summer months, being characterized by a cold core and a direct thermal circulation. They suggested a close relationship between the occurrence of the vortices in the tropical South Atlantic/South American sector and the presence of an upper level anticyclonic circulation, named the Bolivian High by Virji (1981). Kousky and Gan (1981) proposed a mechanism for the CVULs formation, in which the warm advection at low tropospheric levels in the equatorside of an active cold front amplifies the downstream upper level ridge, with the subsequent strengthening of the downstream trough (Fig. 6). Recently Kayano *et al.* (1997) analyzed the upper level atmospheric circulation patterns over South America and neighboring areas, using empirical orthogonal function analysis of the vorticity anomalies for the Southern Hemisphere summer months. They observed two wave patterns associated with the CVULs formation, one along the eastern side of South America and the other over eastern Pacific.

Observational studies have suggested that CVULs affect considerably the rainfall distribution over the northeast Brazil (Aragão, 1976; Kousky and Gan, 1981). Thus, the study of such a system is of an intrinsic interest to regional climate monitoring. The purpose of this paper is to present an extended climatology of the CVULs in the South Atlantic region based on a 10-year dataset. Several features related to the CVULs formation, not addressed before, such as the movements, vertical extend, mean lifetime and associated large-scale upper tropospheric flow pattern, are now presented.

## 2. Data and methodology

The data used in this study are the 12Z daily analyzed zonal and meridional wind components and temperature at 700-, 500-, 300- and 200-hPa, obtained from the European Centre for Medium Range Weather Forecasts (ECMWF), for the 1980-1989 period. These data are in a $2.5^\circ \times 2.5^\circ$ latitude and longitude grid. The domain of this study is the tropical South Atlantic/South American sector limited by the Greenwich longitude and 120°W, and extending from 20°N to 40°S. CVULs in this study are detected through a systematic visualization of the daily wind, temperature deviations with respect to the areal means and vorticity at several upper tropospheric levels. Only the CVULs that last for at least 3 days are considered, because their impacts on the climate of the northeast Brazil are more pronounced.

The occurrence of CVULs has been confirmed through inspections of 12Z and 00Z satellite images. GOES-5 E/W infrared and water vapor channel images are available for the 1980-1983 and 1986-1989 periods, and NOAA-9 infrared images are available for the 1984-1985 period.

The monthly mean lifetime of CVULs is defined as the sum of the number of days with vortices divided by the total number of vortices in the month. Daily temperature deviations with respect to areal means are used to determine the location of the cold core of the vortex. The dynamics of the formation of the CVULs and the synoptic features that affect their movements at 200 hPa are investigated specifically for the Southern Hemisphere summer (December to February), which is the period of the highest occurrence of this type of disturbance.

## 3. Results

### 3.1. *Climatology*

The total numbers of CVULs (Table 1) exhibit significant interannual and seasonal variations, with a maximum during the Southern Hemisphere summer, January being the month with the highest value. Indeed, from a total of 176 CVULs, 46% are observed during the Southern Hemisphere summer, in agreement with Kousky and Gan (1981) findings. CVULs rarely occur during the Southern Hemisphere winter months (June to August). Concerning the annual totals, 1986 is the year with the largest value.

Table 1. Total numbers of CVULs per month and per year observed in the vicinity of northeast Brazil during the 1980-1989 period. Numbers in parentheses indicate the number of CVULs originated over the continent.

| | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 2 | 3 | 3 | 2 | 4 | 2 | 4 | 3 | 4 | 3 (1) | 30 (1) |
| Feb | 1 | 3 | 2 | 2 | 3 | 3 | 4 (1) | 2 | 2 | 4 | 26 (1) |
| Mar | 4 | 2 | 2 | 2 | 1 | 4 | 2 (2) | 1 (1) | 3 | 3 | 24 (3) |
| Apr | 1 (1) | 2 (1) | 1 | 2 (1) | 1 | 3 (1) | 3 (1) | 3 | 2 | - | 18 (5) |
| May | - | 1 (1) | - | - | 1 | - | 2 (1) | 1 | - | - | 5 (2) |
| Jun | 1 | - | - | - | 2 (1) | - | - | - | - | - | 3 (1) |
| Jul | - | - | - | - | - | - | - | - | - | - | - |
| Aug | - | - | - | - | - | | - | - | - | - | - |
| Sep | - | - | - | - | 1 (1) | 1 (1) | 1 (1) | 2 (2) | - | 2 | 7 (5) |
| Oct | 3 | - | 2 | 3 (1) | 2 | 1 | 3 (2) | 2 | 1 (1) | - | 17 (4) |
| Nov | 2 | 2 | 2 | 2 | 3 (1) | 2 (1) | 4 | 1 | 2 (1) | 2 | 22 (3) |
| Dec | 1 | 2 | 4 (2) | 2 | 3 | 2 | 2 | 3 | 3 | 2 | 24 (2) |
| Total | 15 (1) | 15 (2) | 16 (2) | 15 (2) | 21 (3) | 18 (3) | 25 (8) | 18 (3) | 17 (2) | 16 (1) | 176 (27) |

The vortices originate mainly at the upper tropospheric levels (Table 2) over the South Atlantic Ocean (Table 1). Table 2 indicates that only a few vortices initiate at 500-hPa. Vortices are in general confined to the middle and upper tropospheric levels. Out of 176 vortices, 84 are shallow, with the associated closed cyclonic circulation confined in the 200-300 hPa layer; 77 extend from 200-hPa to 500-hPa, and a few extended further down to 700-hPa. Vortices extending from 200-hPa to 500-hPa occur mainly during December and January, and shallow vortices, during February and March.

The mean lifetime of CVULs varies from 4 days in June to approximately 11 days in February (Table 2), with individual vortices having lifetime as long as 18 days. Tables 1 and 2 show that CVULs with the longest lifetimes occur during the Southern Hemisphere summer months, period in which they occur more frequently and with deeper vertical extent. The CVULs with the shortest mean lifetimes are shallow and occur in May, June and September. Thus there is a relation between the vertical extent and the duration of CVULs. Furthermore, the axes of the vortex center tilt eastward with height, and the cold core is located at 300-hPa, slightly to the east-southeast of the closed cyclonic circulation.

Table 2. Formation level, vertical extent and mean life time for CVULs observed in the vicinity of northeast Brazil during the 1980-1989 period.

| | Formation Level | | | Vertical Extent | | | Mean Life Time |
|---|---|---|---|---|---|---|---|
| Month | Upper 200-300 hPa | Middle 500 hPa | Lower 700 hPa | 200-300 hPa | 200-500 hPa | 200-700 hPa | Days |
| Jan | 30 | - | - | 11 | 16 | 3 | 10.5 |
| Feb | 25 | 1 | - | 16 | 10 | - | 10.6 |
| Mar | 19 | 4 | 1 | 14 | 6 | 4 | 7.6 |
| Apr | 14 | 4 | - | 9 | 6 | 3 | 4.8 |
| May | 5 | - | - | 4 | - | 1 | 4.6 |
| Jun | 3 | - | - | 3 | - | - | 4.0 |
| Jul | - | - | - | - | - | - | - |
| Aug | - | - | - | - | - | - | - |
| Sep | 7 | - | - | 6 | 1 | - | 4.6 |
| Oct | 14 | 2 | 1 | 12 | 5 | - | 5.6 |
| Nov | 19 | 3 | - | 7 | 13 | 2 | 6.0 |
| Dec | 17 | 6 | 1 | 2 | 20 | 2 | 9.5 |
| Total | 153 | 20 | 3 | 84 | 77 | 15 | 6.8 |

### *3.2. Upper tropospheric flow patterns related to CVUL*

Figure 1 shows schematically the different features of the 200-hPa flow related to CVULs over South America and neighboring oceanic areas during the southern summer. One of this feature, not mentioned before, is an inter-hemispheric bifurcation of the upper level westerlies (IB) at low latitudes over the eastern Pacific Ocean. IB is characterized by two anticyclonic circulations, namely the Bolivian High and an anticyclonic circulation in the Northern Hemisphere (NA in Fig. 1). Tropical incursions of midlatitude troughs in both hemispheres and the presence of an anticyclonic circulation over southern Brazil and southwestern Atlantic Ocean seem to affect the formation and displacement of the CVULs. It is worthy bearing in mind that these features do not occur simultaneously or independently from each other. Rather different combinations of them can be observed in a single day.

As an example, Figure 2a illustrates the 200-hPa circulation pattern associated with a vortex (CVUL in Fig. 1) near the northeast Brazil coast on December 20, 1980. The associated cloudiness can be observed in the infrared image given in Figure 2b. The westerly flow over the eastern Pacific splits into two parts over northern Peru (IB in Fig. 1), resulting a downstream anticyclonic couplet with centers over the central South America (BH in Fig. 1) and over the northern South America and western Caribbean Sea (NA in Fig. 1). Examining similar cases, it is found that the IB occurs between 5°N and 10°S, from 70°W to 90°W. It is also noticed that the IB may occur without the associated closed anticyclone center in the Northern Hemisphere and independently of a vortex further east.

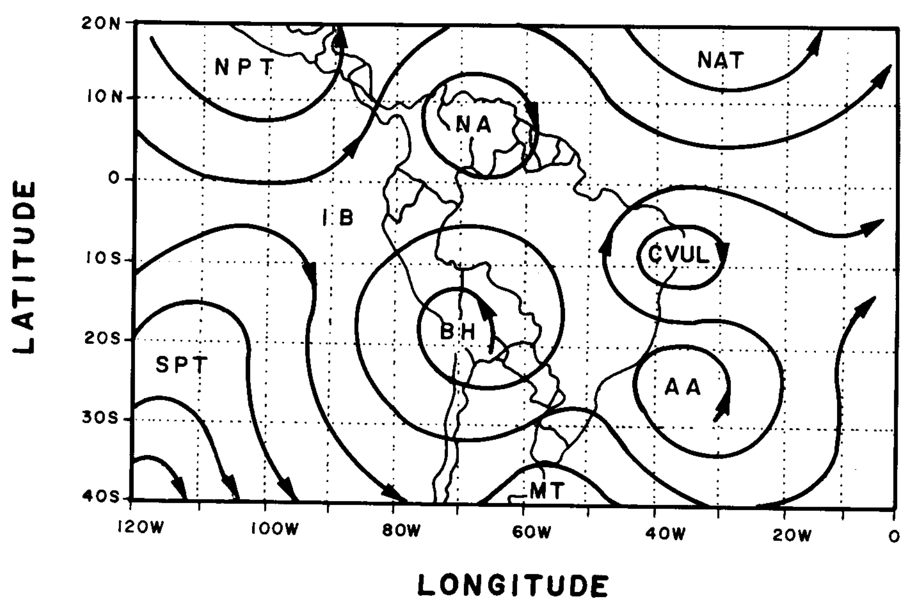
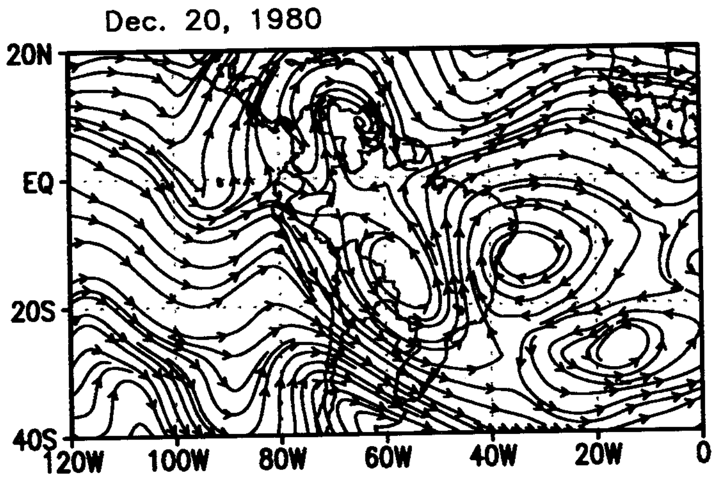



Fig. 1. Schematic 200-hPa streamlines illustrating large-scale flow patterns related to vortex in the vicinity of South America. The symbols are: IB for the bifurcation of the westerlines near the South American northwestern coast; NPT for the North Pacific subtropical trough; NAT for the North Atlantic subtropical trough; SPT for the South Pacific subtropical trough; BH for the Bolivian High; NA for anticyclonic circulation in the Northern Hemisphere; MT for the southern midlatitude trough and AA for the anticyclone in the southwestern Atlantic and CVUL for the cyclonic vortex at upper level.

An important feature shown is Figure 2a is a midlatitude trough (MT in Fig. 1) over central Argentina which could be associated with a frontal system over southern Brazil and adjacent southwestern Atlantic (Fig. 2b). It will be shown in section 3.4 that this trough may also affect the displacement of the CVULs. The subropical troughs in the North Pacific and the North Atlantic Oceans (NPT and NAT in Fig. 1) are also observed in Figure 2a. It is noticeable that when the North Pacific trough advances equatorward, it affects the circulation features south to the equator, amplifying the BH ridge in its southeastern sector, thus contributing indirectly to the CVULs formation. These troughs are frequently observed during the Southern Hemisphere spring (September to November) and fall (March to May) seasons.

2a




2b

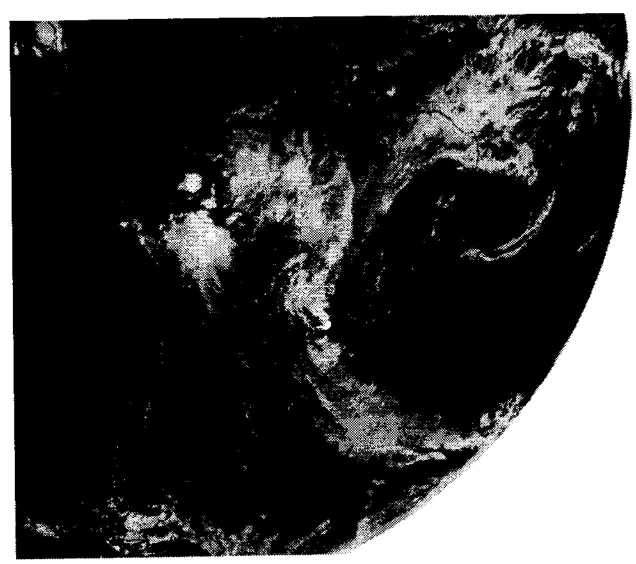


Fig. 2. (a) ECMWF 200-hPa streamlines on December 20, 1980; (b) Infrared GOES-5 satellite image on December 20 at 15:45 Z.

### *3.3. CVUL formation*

Kousky and Gan (1981) proposed that the equatorward-moving cold fronts over South America cause the amplification of the upper level ridge, and thus are indirectly responsible for CVUL formation over the South Atlantic region (Fig. 6). The analyses of 80 Southern Hemisphere CVULs showed that 57% of them develop accordingly to this mechanism, as evidence by the upper circulation patterns given in Figure 3. The 200-hPa circulation patterns on December 13, 1988 feature the Bolivian High, the downstream trough and a midlatitude trough over eastern Argentina and southern Uruguay. As this midlatitude trough moves eastward and stretches to 30°S on December 14, 1988, the Bolivian High ridge intensifies in its southeast sector. Consequently, the downstream trough sharpens, as indicated by a band of negative vorticity extending southeastward from northeast Brazil to South Atlantic. Thus, a closed upper tropospheric cyclonic circulation develops near the northeast Brazil coast on December 15, 1988.

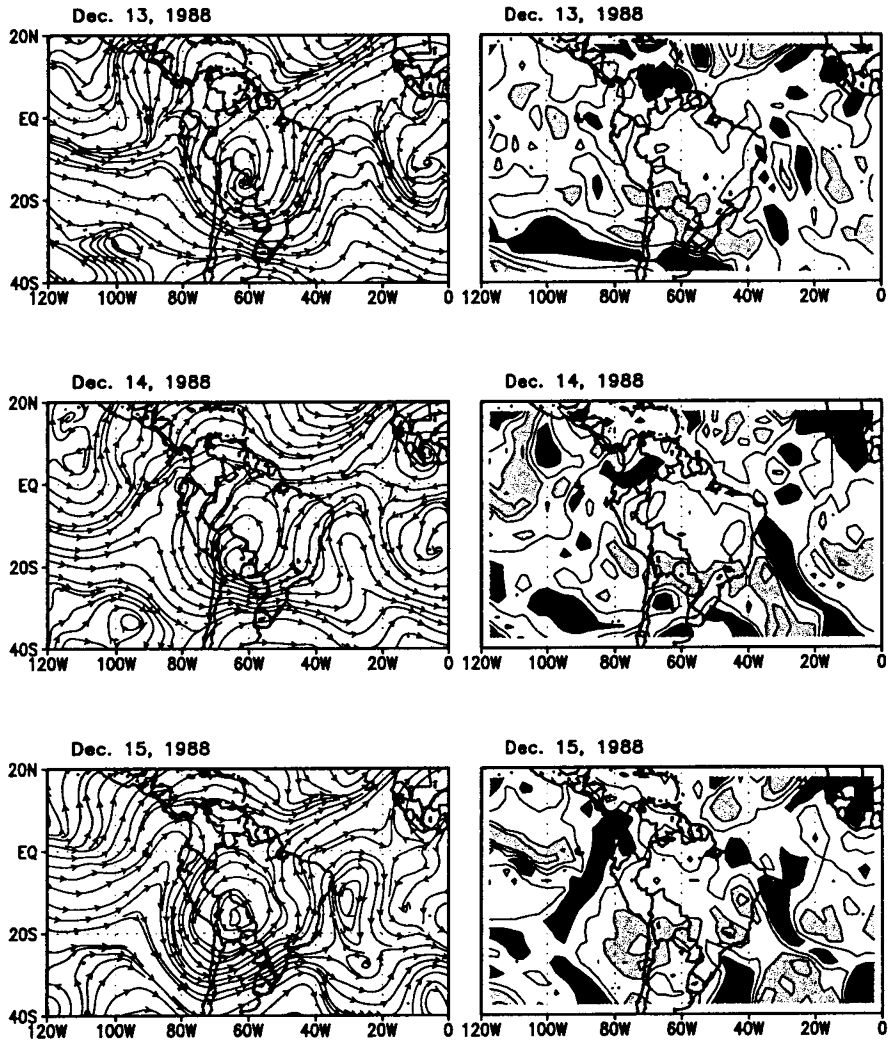



Fig. 3. ECMWF 200-hPa streamlines and vorticity for December 13, 14 and 15, 1988. For vorticity, contour interval is $3 \times 10^{-5}\ s^{-1}$. Dark (light) shades indicate values less (greater) than $-3 \times 10^{-5}\ s^{-1}$($3 \times 10^{-5}\ s^{-1}$).

In many cases, it is observed the CVUL formation associated with an upper tropospheric anticyclone (AA in Fig. 1) over the southwestern Atlantic near the southern Brazilian coast. Such cases account for 27% of the Southern Hemisphere summer vortices. The 3-day sequence of the upper tropospheric circulation fields shown in Figure 4 illustrates the vortex development on February 24, 1984. The 200-hPa circulation patterns on February 22 show the Bolivian High over northern Chile and a closed anticyclonic circulation over southern Brazil and adjacent southwestern Atlantic areas. This anticyclonic intensifies and stretches eastward by February 23, yielding to intensification of the downstream trough. As the southwestern Atlantic anticyclone extends further east by February 24, a closed cyclonic circulation develops to the north of this anticyclone, with the new center over eastern Bahia State (areas along the eastern Brazil coast between 10°S and 20°S). The positive vorticity values over the southern Brazil and adjacent southwestern Atlantic Ocean are indicative of the robustness of the anticyclone.

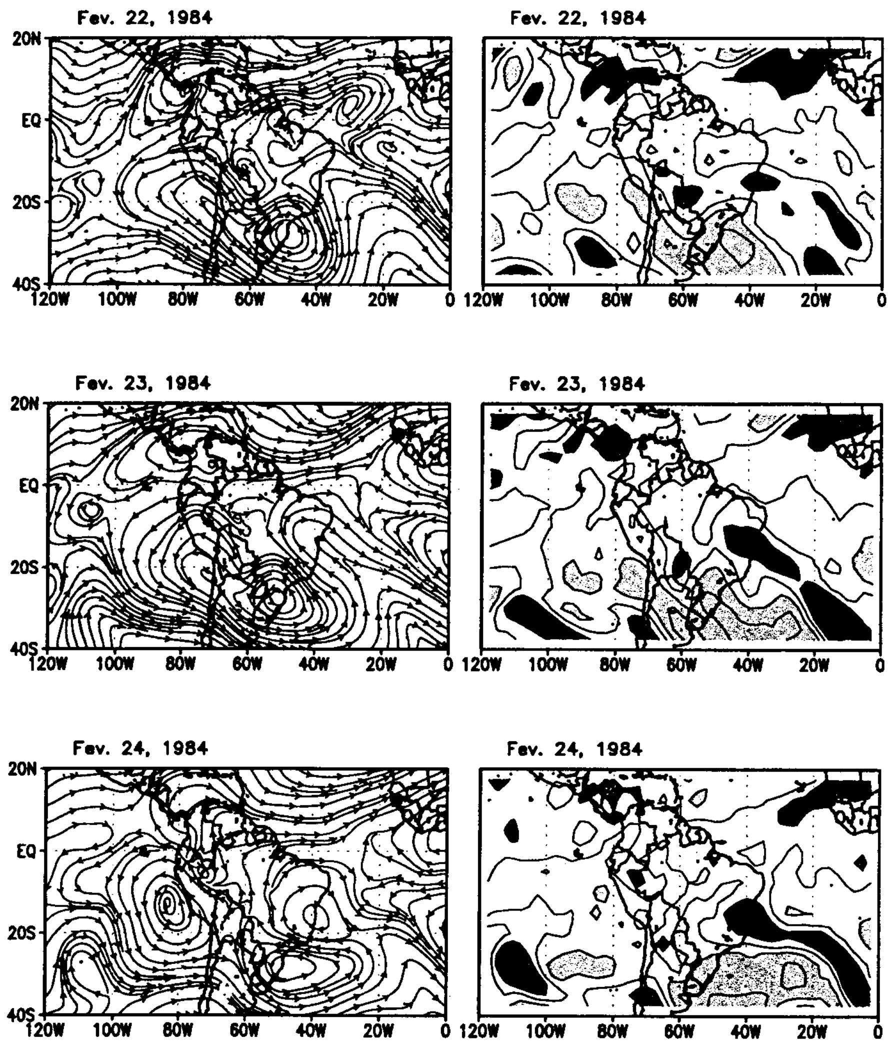



Fig. 4. Same as Figure 3, except for February 22, 23 and 24, 1984.

In addition, it is found that the subtropical upper tropospheric troughs in the vicinities of South America contribute to amplify the Bolivian High ridge, as shown for the case of December 13-15, 1985 (Fig. 5). On December 13, an intense subtropical upper tropospheric trough in the North Pacific (NPT in Fig. 1) is observed together with the Bolivian High over Bolivia and a downstream trough over northeast Brazil. By December 14, the North Pacific trough extends southeastward and aligns with the Bolivian High along the northwest-southeast direction, contributing to intensify the Bolivian High ridge in its southeastern sector and to sharpen the trough over northeast Brazil. A closed cyclonic circulation develops over northeast Brazil on December 15, 1985. There are cases (not shown) in which the subtropical trough in the North Atlantic (NAT in Fig. 1), aligned with the Bolivian High along the northeast-southwest direction, also participates indirectly to the CVUL formation.

### 3.4. *CVUL displacements*

The displacement of the CVULs are analyzed from the circulation pattern for the Southern Hemisphere summer cases. Regarding the zonal displacements, CVULs are observed to move in both directions and they may be stationary for a few days (3-4 days) during their lifetime. During periods with stationary vortices, the upper tropospheric flow features quite intense troughs in the eastern subtropical Pacific. These troughs aligning along the north-south direction are part of a well defined bifurcation of the westerlies near the South American northwestern coast.

Thirty nine vortices show westward and eastward displacements. Twenty four out of the remaining 41 vortices (with westward displacements) reach the northeast Brazil; 12 reach central Brazil and 5 reach the western South American coast.

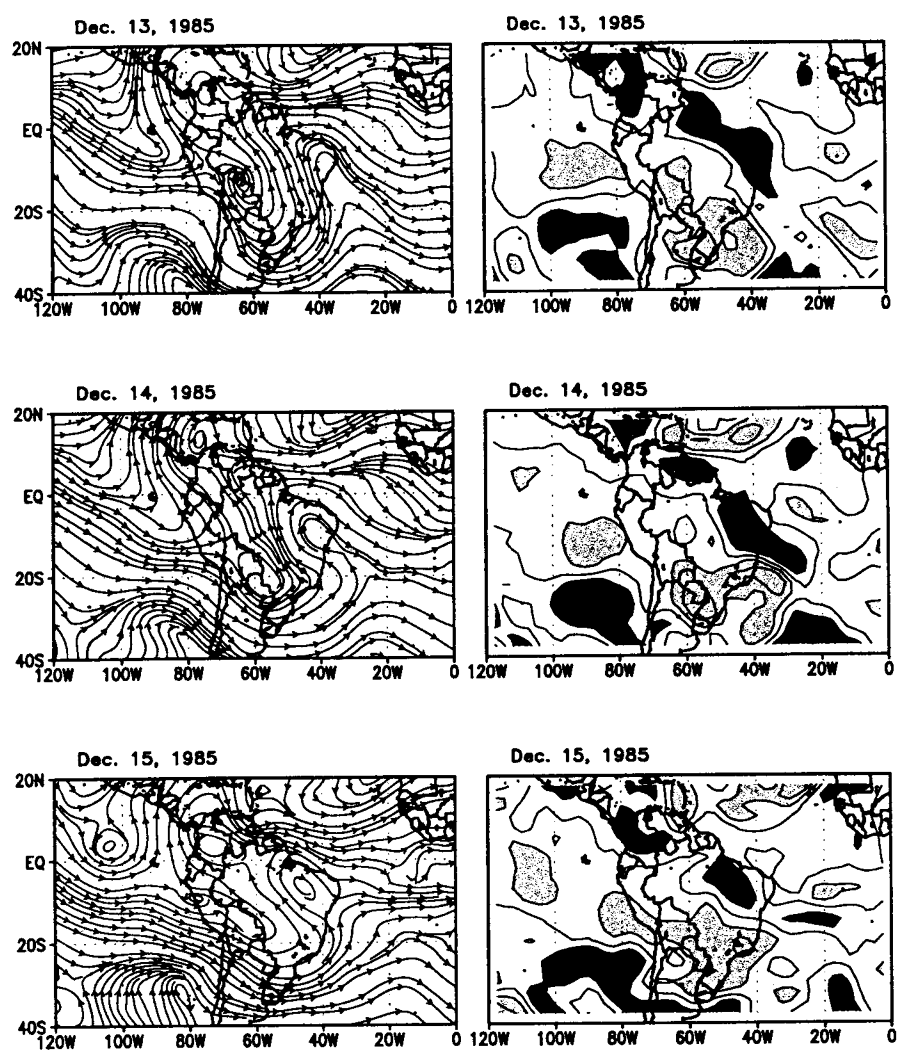



Fig. 5. Same as Figure 3, except for December 13, 14 and 15, 1985.

### *3.4.1. CVUL with eastward and westward displacements*

These vortices move over the tropical western South Atlantic and northeast Brazil. In many cases, the equatorward-moving south midlatitude upper tropospheric troughs (MT in Fig. 1) may cause the vortices to have their zonal movements reversed. The sequence in Figure 6 illustrates one of such a case. The 200-hPa circulation patterns show a vortex off the northeast Brazil coast, a zonally extended Bolivian High centered at (20°S, 60°W), and a midlatitude trough over central Argentina, on December 13, 1980. As this trough sharpens and moves eastward, the downstream ridge and trough associated with the vortex intensify, on December 15. Thus, the flow pattern exhibits a more meridional structure, particularly noticeable for the trough associated with the vortex, which acquires a northwest-southeast orientation. The southern midlatitude trough on December 16 remains intense, with the vortex oriented along the north-south direction and with its center slightly to the east relatively to its position on December 13. The midlatitude trough weakens, and anticyclonic circulation is observed over the tropical South America south of the equator and the vortex remains to the east, on December 17. As a new midlatitude upper tropospheric trough reaches the central Argentina, it contributes to orient the Bolivian High along the northwest-southeast direction causing the westward movement of the vortex on December 20.

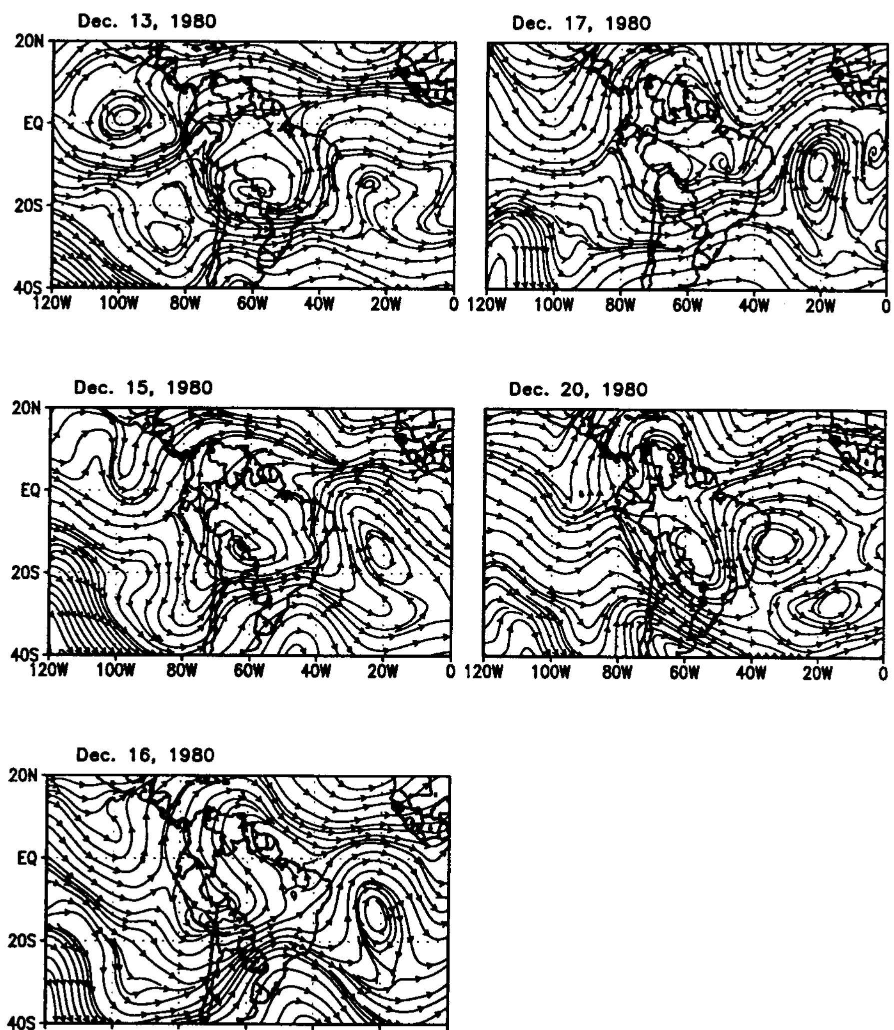



Fig. 6. ECMWF 200-hPa streamlines for December 13, 15. 16, 17 and 20, 1980.

### 3.4.2 *CVUL with only westward displacement*

These vortices are more intense and extended from 200-hPa to 500-hPa. In many cases, during their initial stages, the Bolivian High is quite intense and zonally extended. Later the Bolivian High splits into two parts, with the eastern part forming a closed anticyclone over the southwestern Atlantic (AA in Fig. 1). In general these vortices can reach areas in the northeastern and eastern Brazil. However, some of them reach the center of the continent and fewer move further west arriving to the South American western coast.

Figure 7 illustrates the 200-hPa flow patterns associated with a westward moving vortex during the period January 22-24, 1986. The upper tropospheric flow on January 22 features a vortex off the northeast Brazil coast, the Bolivian High and an anticyclone over the southwestern Atlantic. The vortex moves westward and locates to the north of the Atlantic anticyclone on January 23. It reaches the northeast Brazil on the following day.

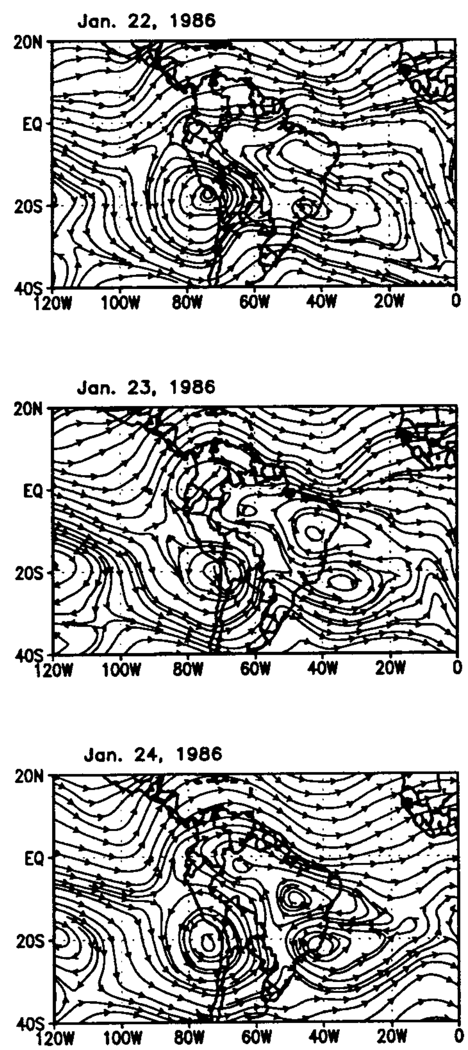



Fig. 7. Same as Figure 6, except for January 22, 23 and 24, 1986.

The sequence in Figure 8 shows a vortex reaching the center of the continent during the period January 15-21, 1986. The upper tropospheric flow on January 15 exhibits a vortex off the northeast Brazil coast and nearly symmetric Bolivian High located over Bolivia and Paraguay. The vortex remains off the northeast Brazil coast and the Bolivian High extends zonally as its ridge sharpens southeastward on January 17. As the vortex reaches the northeast Brazil, the Bolivian High spreads over southern Brazil and adjacent South Atlantic Ocean with strong winds in its southeast sector on January 19. As the vortex moves westward on January 21, so does the Bolivian High which splits into two parts, both of them featuring closed anticyclonic circulation, one centered off the Chilean coast and the other over southern Brazil.

CVULs over the continental areas were observed to strengthen due to the equatorward incursion of a midlatitude upper tropospheric trough. In these cases, the vortices may move further west reaching even the South American western coast.

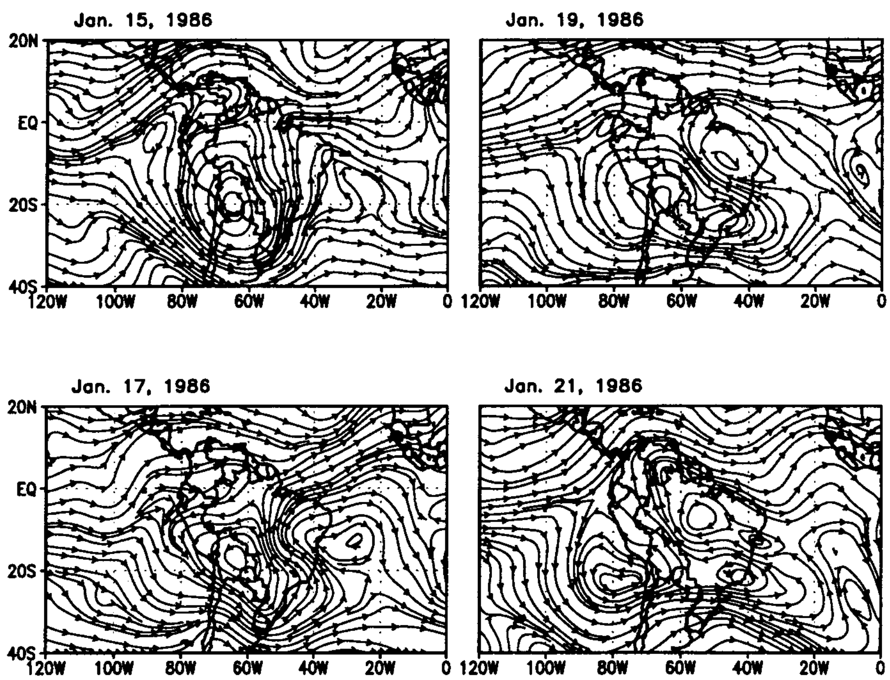



Fig. 8. Same as Figure 6, except for January 15, 17, 19 and 21, 1986.

## 4. Concluding remarks

Ten years of ECMWF daily analyzed zonal and meridional wind components and temperature data have been used to establish an extended climatology of the cyclonic vortices at upper tropospheric levels (CVULs) in the tropical South Atlantic/South American sector. This climatology considers vortices with duration of 3 days or longer which are the ones that affect more pronouncedly the climate of northeast Brazil. The occurrence of these systems shows significant interannual and seasonal variability, with the highest frequency found during the Southern Hemisphere summer months, in agreement with previous works. The austral summer upper level circulation shows the Bolivian High over western tropical South America and an associated downstream trough over northeast Brazil and surrounding areas (Virji, 1981). Such features are not observed or relatively weaker during the other seasons. Thus, the summer climatology circulation might contain a favorable condition of CVULs formation, such as the presence of a trough over northeast Brazil and adjacent areas.

The majority of the CVULs develop at the upper tropospheric levels over the tropical South Atlantic, and they remain confined to the middle and upper troposphere during their lifetime. The CVUL mean lifetime varies from 4 days in June to approximately 11 days in February. It is found that the closed circulation tilts eastward with height, a feature that was also observed for the Northern Hemisphere vortices (Erickson, 1971). The cold core associated with the vortex is observed at 300-hPa, slightly to the east-southeast of the closed cyclonic circulation.

In order to examine the synoptic features that affect the CVUL development and displacement during the rainy season in several areas over Brazil, only the Southern Hemisphere summer vortices are taken into account. Approximately 57% of these vortices evolve accordingly to the mechanism of vortex formation put forth by Kousky and Gan (1981). In 27% of the Southern Hemisphere summer CVULs, it is observed that the cold fronts remain nearly stationary over southwestern Atlantic and southeastern Brazil with an associated upper circulation anticyclone. This anticyclone in most cases is the southeastern portion of an intense and zonally extended Bolivian High whose center splits into two parts.

It is apparent from infrared satellite images that the southwestern Atlantic upper anticyclone is related to the South Atlantic Convergence Zone (SACZ), a nearly stationary band of intense cloudiness extending southeastward from south Amazon into subtropical South Atlantic, particularly evident during the Southern Hemisphere summer and spring seasons as shown by Kodama (1992). He noted an upper level divergent flow along the SACZ, which is consistent with the anticyclone observed in the present study. Apparently, the latent heat release along the SACZ intensifies the upper level anticyclonic circulation, and by circulation conservation a cyclonic center may develop to the northeast.

The amplification of the Bolivian High ridge may also result from the effect of the northern Pacific and the northern Atlantic subtropical upper tropospheric troughs, as they extend southward and align with the Bolivian High along the northwest-southeast or northeast-southwest directions. In addition, the analyses reveal that equatorward incursions of southern midlatitude troughs have an important role in modulating the east-west movements of the CVULs. On the other hand, CVULs with westward diplacements are related to a zonally extended Bolivian High, which in certain situations splits into two parts, with the eastern part forming the southwestern Atlantic upper anticyclone.

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