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Upper tropospheric cyclonic vortices in the tropical South Atlantic

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ABSTRACT

An analysis of subtropical 200 mb cyclones is made for the South Atlantic. The cyclones are observed to occur primarily during the summer months and generally form near the axes of the mid-oceanic troughs. The relationship between cyclone formation and the presence of 200 mb anticyclones over the continental areas is discussed. Proposed mechanisms for cyclone formation are considered. The cyclones are characterized by a cold core and a direct thermal circulation—the cold air sinking and warm air on the periphery rising. The cloud pattern associated with the cyclones is found to depend on the direct thermal circulation, the vortex location and its direction of movement. The effects of South Atlantic 200 mb cyclonic vortices on Brazilian weather are discussed.

1. Introduction

Several recent studies have investigated rainfall systems affecting Northeast Brazil during the rainy season (November–May). Ramos (1976), in his study of the 1972 rainy season, noted that most of the seasonal rainfall occurs in association with a relatively small number of precipitating systems, which generally move east to west. Kousky (1979) demonstrated the relation between Southern Hemisphere frontal systems and rainfall, pressure and cloudiness over the Northeast. Aragão (1976) studied the upper air circulation pattern associated with precipitation events in the Northeast, and noted the frequent presence of a cold cyclonic circulation at high levels. Recently, Virji (1981) also noted the existence of upper tropospheric closed cyclonic vortices which quite often form during the Southern Hemisphere summer just off the east coast of Brazil and, in general, track westward over Brazil at a speed of about 4–6° longitude per day. Virji found that as these vortices propagate westward the convective activity over Amazonas gradually becomes suppressed and the 200 mb Bolivian anticyclone weakens. No reference was made to the effects these vortices have on convective activity over the Northeast. This paper focuses on upper tropospheric cyclonic vortices which form in the vicinity of tropical Brazil with emphasis on their climatology, formation and effects on Brazilian weather, especially that for the Northeast.

Northern Hemisphere subtropical upper tropospheric cyclonic vortices have received considerable attention (e.g., Palmer, 1951; Simpson, 1952; Riehl, 1954, 1977; Ramage, 1962). The subtropical cyclone (Ramage, 1962) is generally confined to the middle and upper troposphere where, due to its direct thermal circulation and lack of dissipative mechanisms, it is extremely persistent. Frank (1970) discussed the vertical extent of and weather associated with closed upper level cold lows in the subtropical North Atlantic. He found that the amount of cloudiness and precipitation is proportional to their vertical extent, which in only about 10% of the cases reaches the surface. The centers of the vortices are generally characterized by minimum cloudiness and sinking motion.

The importance of extratropical troughs, which extend deep into the tropics, in causing rainfall over

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Venezuela during the Northern Hemisphere summer, has been discussed by Riehl (1977). He found that some troughs remain nearly stationary, while others experience a westward displacement of up to 8° longitude per day. The active weather is found in the direction to which the vortex is propagating. The development of a low latitude trough just north of South America has been documented by Gray and Clapp (1978), using geoestationary satellite data. They showed that the trough developed ahead of an amplifying mid-latitude system along the east coast of North America. Considerable cloudiness developed to the east of the trough axis extending in an anticyclonic band from the Amazon Basin to northwestern Africa.

In Section 3, we present some climatological data concerning the regions in which Southern Hemisphere low latitude upper tropospheric cyclones form, and an example of a 200 mb cyclone over the tropical South Atlantic. In Section 4, we discuss proposed processes for vortex formation, their maintenance and effects on Brazilian weather. Also, in Section 4, we compare our results with those of similar studies for Northern Hemisphere subtropical 200 mb cyclones.

2. Data

Polar orbiting satellite data (infrared and visible) form the basis for our climatological analysis. These data, in the form of microfilm copies of mosaics made using images for an entire day, are available from the National Climatic Center, Asheville, North Carolina. In general, the infrared (IR) data accentuate high cirrus clouds which may be too thin to appear in visible imagery. For this reason, the IR mosaics offer the best means for analyzing the upper tropospheric flow pattern.

Satellite images only, for the period 1975–1979, were used to determine areas in which low latitude upper tropospheric cyclones form, and to obtain their seasonal distribution. The area of the Southern Hemisphere included in our analysis is 0–40° S and 10–170° W. Although our principal region of interest is the subtropical South Atlantic, the South Pacific has been included in our analysis in order to provide more information concerning vortex formation, spatial distribution and seasonal occurrence. Since we are basing our climatological analysis on satellite images, only those vortices which have a well defined cloud pattern are included.

In addition to the polar orbiting satellite data, grid point values of the zonal and meridional wind components, taken from the National Meteorological Center (NMC) analyses, are used to draw conventional streamline analyses and to compute vorticity. The NMC analyses are based on: (1) conventional radiosonde and rawinsonde data, (2) satellite derived winds and temperature profiles, (3) aircraft reports and (4) a numerical forecast based on previous analyses. The use of winds extracted from animated geoestationary satellite imagery greatly helps to improve analyses over the Pacific and Atlantic Oceans, as well as over the Amazon Basin. Although certain errors arise due to the use of satellite derived winds, as well as due to the scarcity of conventional data, the NMC analyses should be adequate to qualitatively determine the flow pattern. Further analysis is necessary in order to determine to what degree these data may be used quantitatively.

3. Results

3.1. *Climatological aspects*

The seasonal distribution, showing the total number of closed 200 mb cyclonic vortices per month plus the number of vortex days (two vortices present on the same day represent two vortex days) for each month, is given in Table 1. It is apparent that the vortices form mainly during the summer with January being the month of peak activity. No vortices were observed during May–September, the Southern Hemisphere winter season. Closed upper tropospheric cyclonic vortices in the tropical South Atlantic are generally found between 25–45°W and 10–25°S (Fig. 1a). This region corresponds to the mean axis of the 200 mb mid-Atlantic trough during summer (see e.g., Newell et al., 1972, p. 122). For the South Pacific (Fig. 1b), the cyclonic vortices are observed over a much broader longitudinal range (110–160°W) within the latitude range of 15–30°S. Again, as in the case for the Atlantic, this corresponds to the region of the mid-oceanic trough (Newell et al., 1972, p. 122), which is much broader in the Pacific than in the Atlantic.

By comparing the summer and winter mean 200 mb circulation patterns presented by Newell et al.

Table 1. *Total number of 200 mb subtropical cyclones having well defined cloud patterns, and total number of vortex days (number in parentheses) during 1975–1979 in the South Atlantic and South Pacific. Months with only four (three) years of data are indicated by one (two) asterisk(s)*

	Jan	Feb*	Mar**	Apr*	May*	Jun*	Jul*	Aug*	Sep**	Oct**	Nov**	Dec**	Total
10–50° W	6	4	2	0	0	0	0	0	0	0	0	3	15
	(24)	(21)	(17)									(6)	(68)
50–90° W	0	0	0	0	0	0	0	0	0	0	0	0	0
90–130° W	4	0	1	1	0	0	0	0	0	0	0	2	8
	(16)		(3)	(2)								(5)	(26)
130°–170° W	6	1	4	3	0	0	0	0	0	1	1	3	19
	(20)	(4)	(8)	(7)						(2)	(2)	(6)	(49)
Total	16	5	7	4	0	0	0	0	0	1	1	8	42
	(60)	(25)	(28)	(9)						(2)	(2)	(17)	(143)

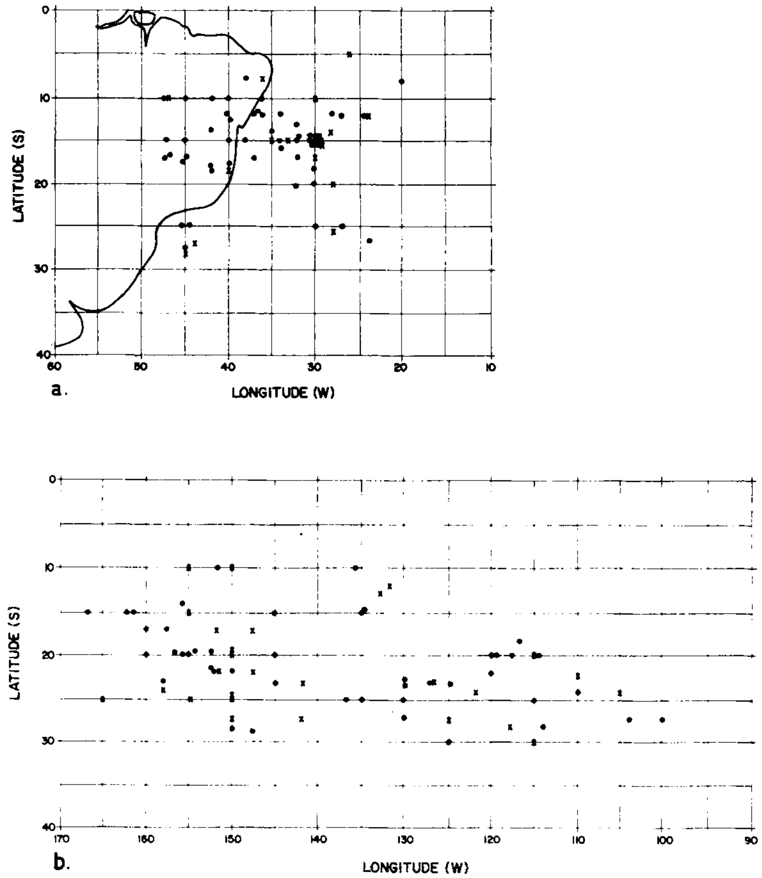
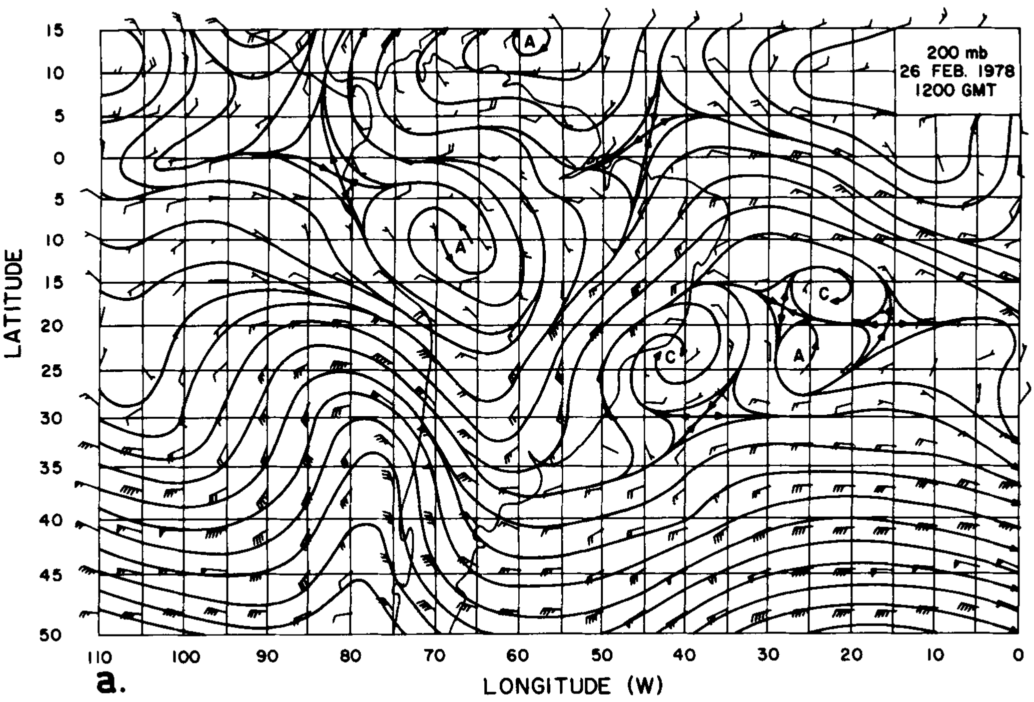


Fig. 1. The positions of subtropical 200 mb closed cyclonic vortices observed in mosaics of polor orbiting satellite data (1975–1979) for the (a) South America–South Atlantic zone and (b) South Pacific region. The position that each vortex had on the first day on which an identifiable circulation existed is indicated by an X. Subsequent positions are indicated by dots.


200 mb
26 FEB. 1978
1200 GMT
LATITUDE
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LONGITUDE (W)
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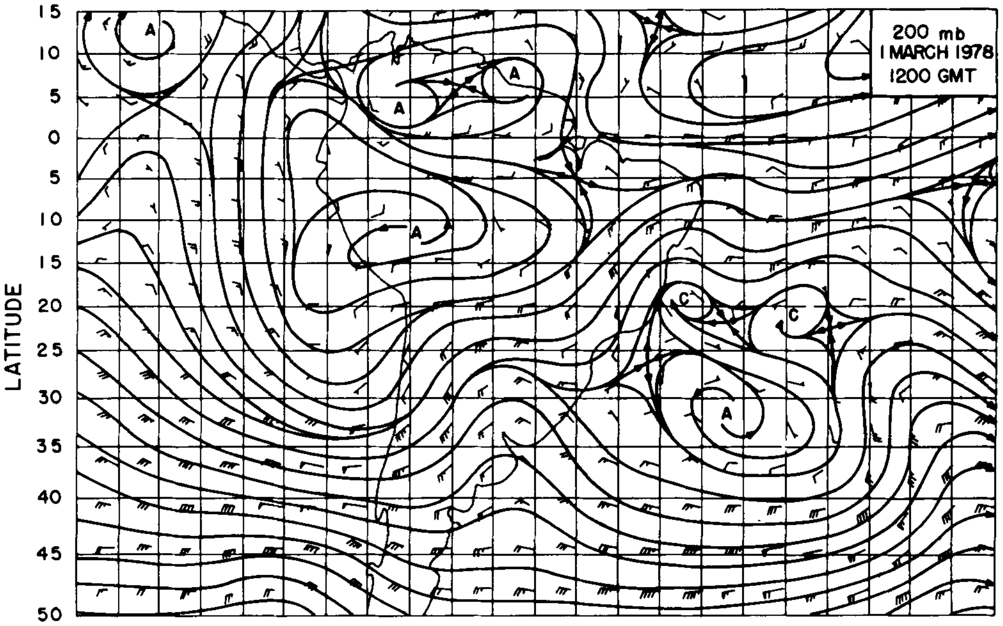
a.


200 mb
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A
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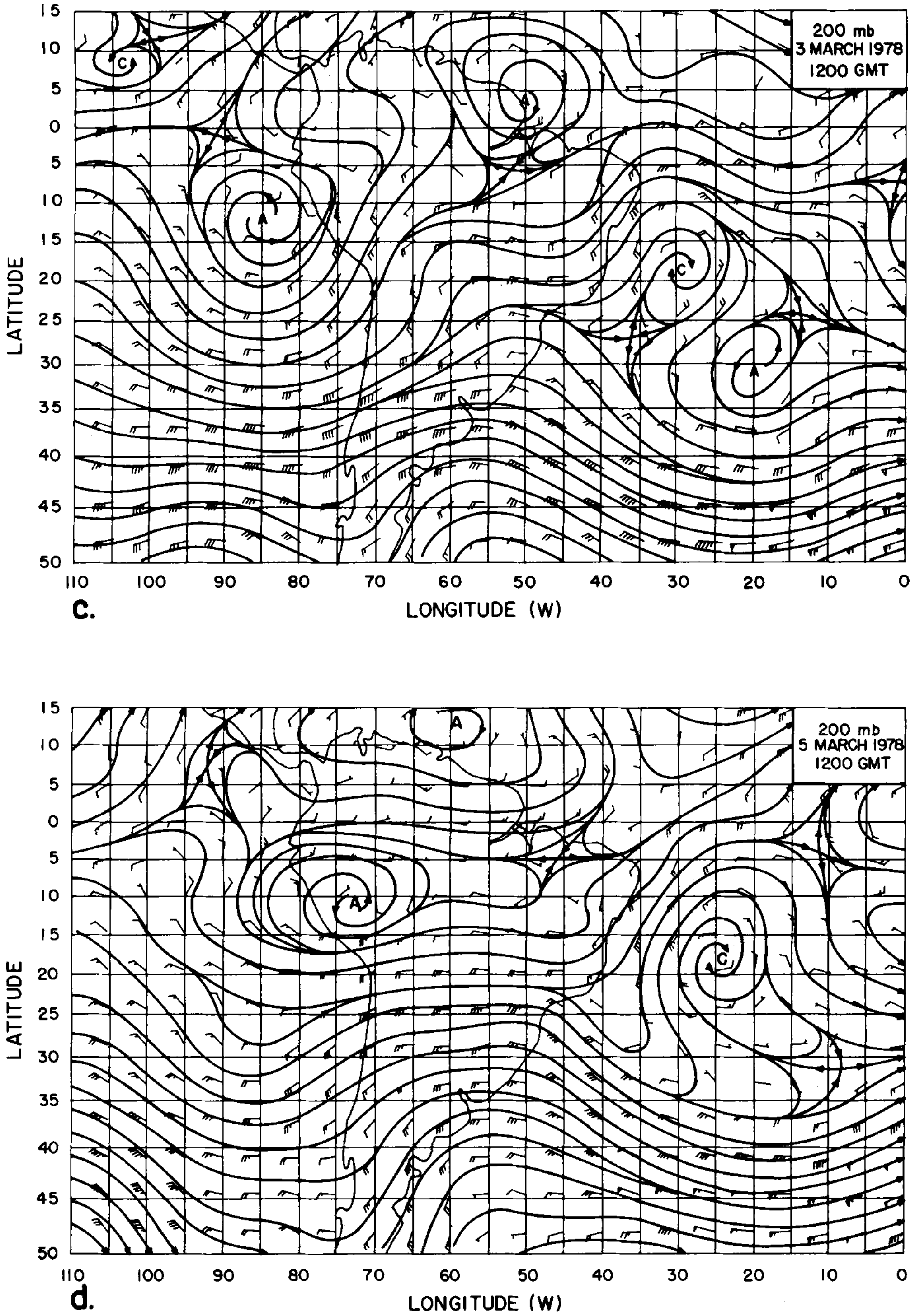
Fig. 2.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200 mb
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Fig. 2.

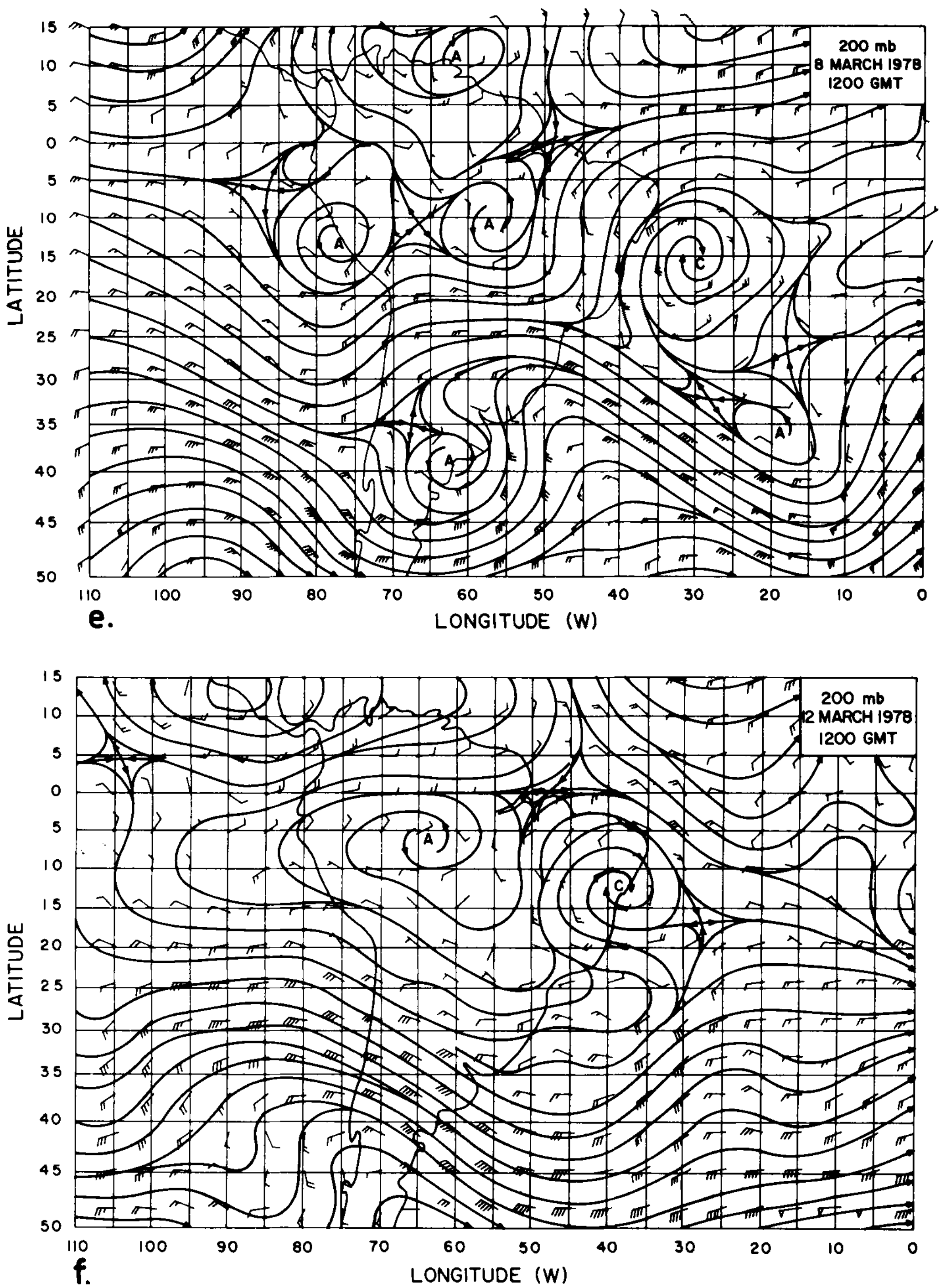

Fig. 2. Streamline analyses (200 mb) for (a) 26 February 1978, (b) 1 March 1978, (c) 3 March 1978, (d) 5 March 1978, (e) 8 March 1978 and (f) 12 March 1978, all at 1200 GMT.

(1972, pp. 122–123), one notes that the summer regime has considerable meridional flow at low latitudes, while the winter flow pattern is more nearly zonal. The meridional character of the summer 200 mb flow pattern is undoubtedly a result of strong heating over the three major continental regions of the Southern Hemisphere (South America, Africa and Australasia) which leads to the development of strong 200 mb anticyclones over these continents (for the region of South America, see e.g., Gutman and Schwerdtfeger, 1965; Schwerdtfeger, 1975) and downstream troughs over the neighboring oceanic areas. A comparison between the mean 200 mb flow patterns of Newell et al. (1972) with the results in Table 1 indicates a positive correlation between cyclone occurrence and the meridional character of the flow pattern. This implies a direct relationship between the intensity of the 200 mb continental anticyclones and the formation of 200 mb cyclonic vortices in the mid-oceanic troughs.

3.2. *Case study (25 February–20 March 1978)*

Using the NMC grid point data, 200 mb streamline analyses were constructed for the period 25 February–20 March 1978. During this period, a closed cyclonic vortex formed near the southeast coast of Brazil, initially moved eastward, then intensified and meandered westward before dissipating over the State of Bahia. The first evidence of a closed cyclonic circulation occurred on 26 February (Fig. 2a) in advance of a strongly intensifying ridge over northern Argentina. The circulation of the vortex remained relatively weak through 1 March (Fig. 2b), but then intensified markedly during 2–3 March as a mid-latitude trough and frontal system advanced northeastward over southern Brazil (Fig. 2c). The vortex continued moving eastward until 5 March (Fig. 2d), after which it meandered westward (Fig. 2e) eventually crossing the Brazilian coast near Salvador, Bahia on 12 March (Fig. 2f). The cold core nature of the vortex is evident in the vertical cross section shown in Fig. 3. Coldest temperatures are found at mid-levels of the troposphere, while temperatures near the surface are relatively unaffected by the presence of the vortex. After crossing the coast, the vortex continued inland where it became quasi-stationary and began to dissipate.

A longitude–time section of the vertical component of 200 mb absolute vorticity at 15° S, for the period 1–16 March, is shown in Fig. 4. The eastward movement of the vortex up to 5 March and the general westward movement thereafter are readily apparent in the analysis. The path that the vortex took is shown in Fig. 5. A well defined cyclonic circulation was present from 26 February to 16 March, a total of 19 days. After 16 March, the circulation became elongated and the center became very difficult to locate.

Other cases, similar to the one illustrated above, have been analyzed. In nearly every case it was possible to detect an amplification of an upstream upper level ridge just prior to the formation of the closed cyclonic vortex. In most cases the intensifying ridge was related to an active upstream frontal system, which had penetrated to fairly low latitudes.

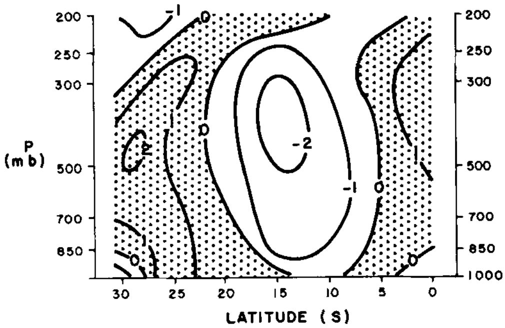

Fig. 3. North–south vertical cross section of temperature departures for 12 March 1978 at 40° W longitude. A longitudinal mean temperature for each level was first computed. Then the departure was determined by taking the NMC grid point temperature and subtracting out the mean. Units are °C.

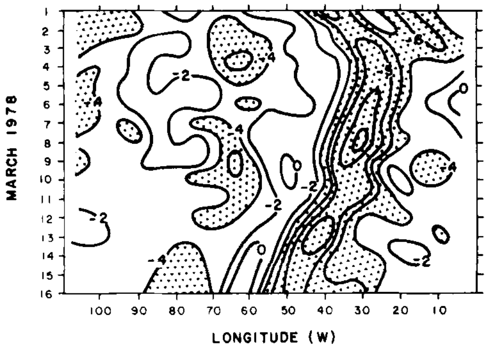

Fig. 4. Longitude–time section of the vertical component of absolute vorticity ($\zeta + f$), for 15° S at 200 mb, for the period 1–16 March 1978. Shaded areas correspond to regions of cyclonic relative vorticity. units 10^{-5} s^{-1}.

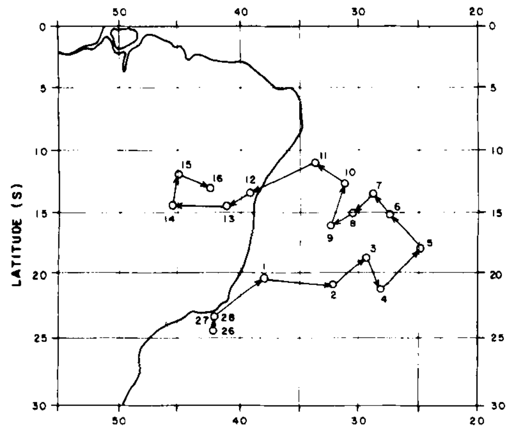

Fig. 5. Path of the 200 mb cyclone 26 February–16 March 1978.

4. Discussion

In many cases, such as the example shown in the preceding section and the case illustrated by Gray and Clapp (1978), cyclonic vortices form or intensify downstream from strongly amplifying mid-latitude frontal systems, which have penetrated fairly deep into the subtropics. In general, strong warm advection, especially at low and mid-levels, precedes an active cold front. This warm advection serves to amplify the upper level ridge downstream, which in turn aids the amplification of the next downstream trough. This proposed mechanism of vortex formation is schematically illustrated in Fig. 6. Fig. 6a shows the unperturbed 200 mb summer circulation pattern over South America and the South Atlantic. Fig. 6b shows a superimposed active mid-latitude upper level trough over South America, its attendant surface cold front in southern Brazil and a strong upper level ridge extending from southeastern Brazil out over the Atlantic. Also evident is a sharpening of the trough in the western Atlantic. In the final part of the sequence (Fig. 6c), the cold front moves to southeastern Brazil and an upper tropospheric closed cyclone forms in the western Atlantic.

The cloudiness associated with closed 200 mb low latitude cyclones varies considerably depending on their intensity and vertical extent (Frank, 1970). The middle and high cloud pattern frequently observed in situations similar to Fig. 6c is illustrated in Fig. 7. Note that the cloudiness associated with the subtropical cyclone together with the cloudiness of the extratropical low pressure and frontal system has an s-shaped configuration. The center of the upper level subtropical cyclone, as noted by Frank (1970), is generally a clear region characterized by subsidence.

We have noted on many occasions cumulonimbus activity near the centers of strong 200 mb cyclones. This is generally the case of cyclonic vortices passing over warm oceanic waters or over continental areas. This convective activity shows a marked diurnal variation especially in cases of vortices passing over land areas (Fig. 8). Presumably, heating from below together with cold middle

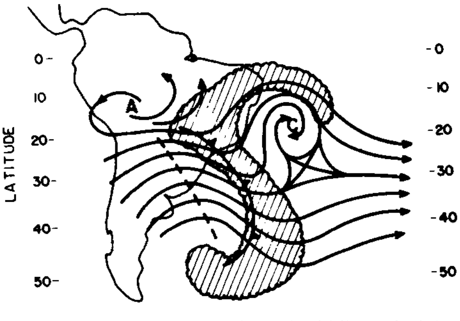

Fig. 7. Schematic illustration of middle and high clouds for the situation in Fig. 6c.

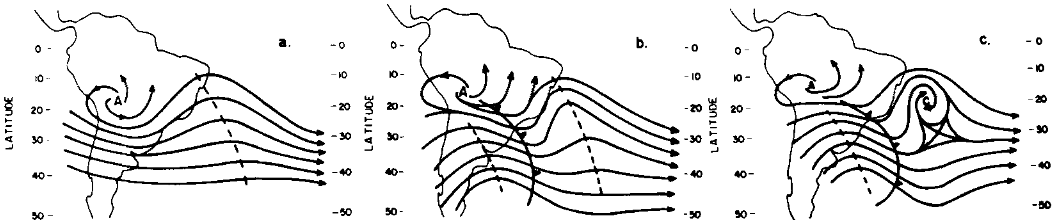

Fig. 6. Schematic sequence for the formation of a 200 mb subtropical cyclone in the South Atlantic.

and upper levels of the vortex produces a situation sufficiently unstable to overcome the effects of general subsidence. It is possible that heating (sensible heating near the surface with the heat being advected upwards by convective activity in the vortex) eventually leads to dissipation of the system.

In general, the 200 mb subtropical cyclone is extremely persistent (e.g., Ramage, 1962; Palmer, 1951). Cyclones located over oceanic areas nor-

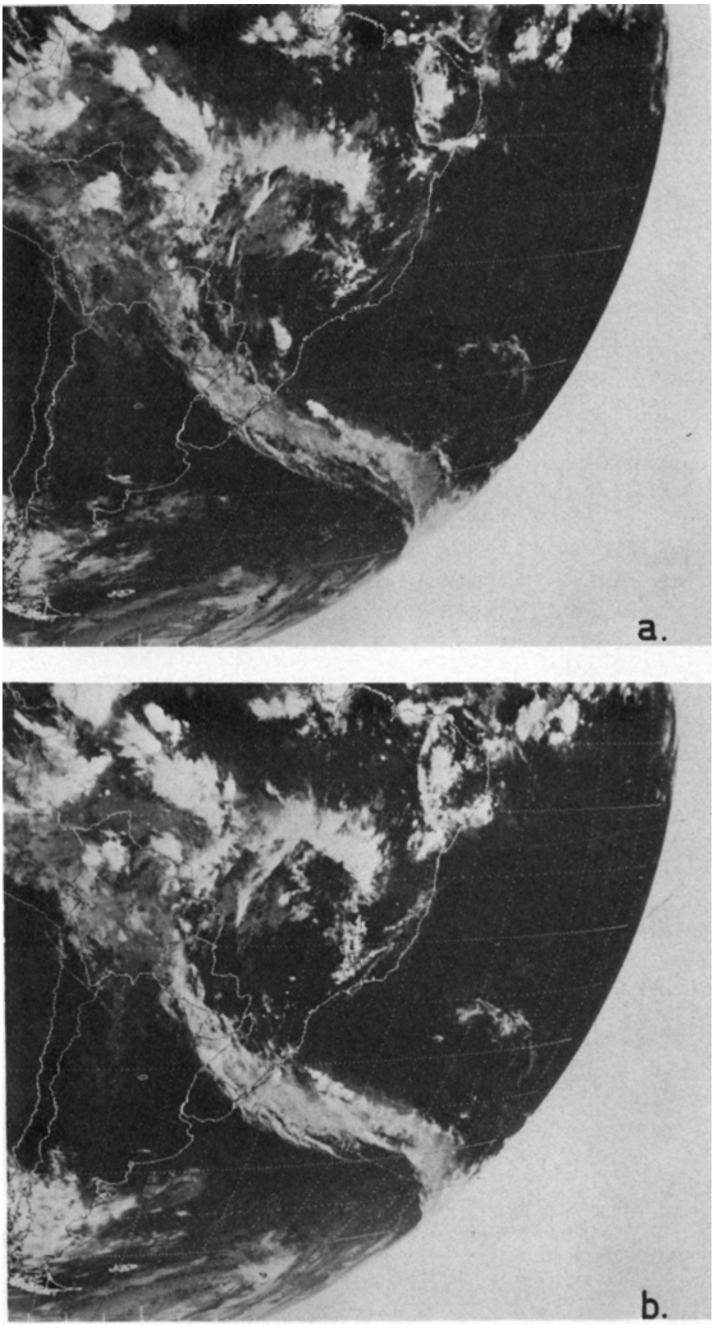

Fig. 8.

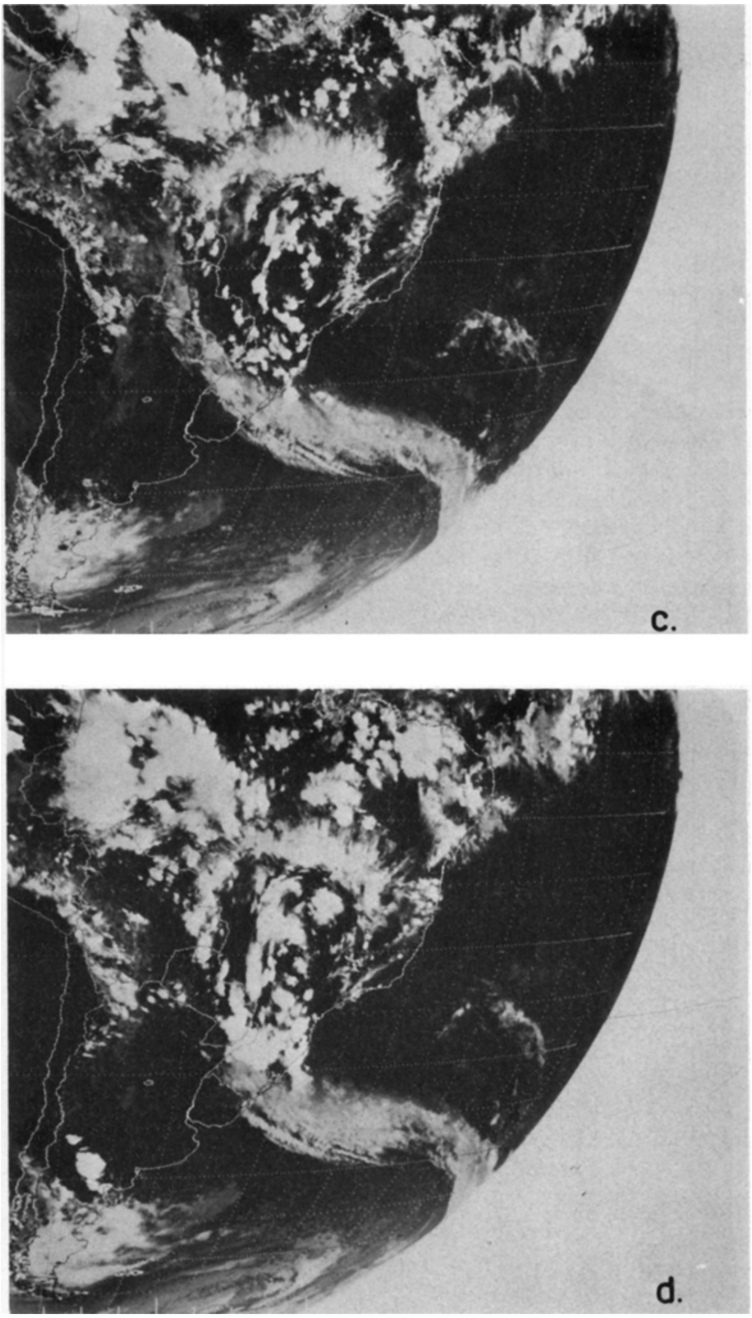

Fig. 8. SMS-2 IR images for 3 March 1980 at (a) 1200 GMT, (b) 1500 GMT, (c) 1800 GMT and (d) 2100 GMT.

mally do not dissipate, but become absorbed into the mid-latitude westerlies by strong troughs which pass by at higher latitudes (Ramage, 1962). The cyclonic vortices are maintained by a direct thermal circulation, cold air sinking in the center and relatively warm air rising on the periphery

(Frank, 1970). Using a static stability characteristic of mid-levels within the vortex and a sinking motion of 30–60 mb per day,[1] we calculate adiabatic warming of 1–3 °C per day. This warming is probably compensated by radiative cooling, which for the GATE area has been shown to be of the order of 1–3 °C per day (Smith et al., 1977). Latent heat release in the convective towers on the fringe of the vortex helps to maintain the temperature gradient and therefore, the strength of the vortex. Fig. 9 shows, in a schematic form, the vertical circulation associated with the 200 mb vortex system.

If the vortex were symmetric and stationary, then the cloud pattern might look similar to Fig. 10a. Here we have neglected the β effect which would cause certain asymmetries in the cloud pattern. If the vortex were to move westward, the sinking motion to the west of the center would be enhanced. This can be demonstrated by applying the vorticity equation:

$$\frac{\partial \zeta}{\partial t} + \mathbf{V}\cdot\nabla(\zeta + f) = -(\zeta + f)\nabla\cdot\mathbf{V}$$

where the symbols have their usual meaning. The effect of displacement, assuming the intensity, or strength, of the vortex to be constant, is measured by $\partial\zeta/\partial t$. Since $-(\zeta + f) > 0$ for cyclonic disturbances in the Southern Hemisphere, we may qualitatively express the effects of displacement as

$$\frac{\partial \zeta}{\partial t}\alpha\nabla\cdot\mathbf{V}$$

Therefore, to the west of a westward moving cyclone $\partial\zeta/\partial t < 0$, which implies an enhancement of the 200 mb convergence to the west of the vortex center. This results in an increase in the circulation, as well as a westward displacement of the western cell shown in Fig. 9. Thus, the greatest convective activity is found in the direction of movement, as indicated schematically in Fig. 10b, and in the SMS images in Fig. 8 for a northward moving cyclone. This feature was also observed by Riehl (1977) in his study of low latitude 200 mb troughs, which effect Venezuelan rainfall.

Since the 200 mb cyclones that affect Brazil most frequently enter the continent near Salvador, Bahia (13° S 38° W), they can have a pronounced effect on the weather over the entire Northeast region of Brazil. In general, except near the center of the vortex, the weather over the southern and central parts of the Northeast improves as the vortex moves onshore. The northern portion of the region, however, experiences enhanced convective activity with heavy rains and, in some cases, flooding. Fig. 11 indicates the effect that an approaching 200 mb vortex has on the Northeast. Fig. 11a shows an elongated cyclonic vortex located near 17° S and 30° W. At this time, the vortex was moving northward and intensifying. Seven days later, the vortex passed over Salvador, Bahia (Fig. 11b). Note the arc of clearing well inland over Brazil and the convective activity near the center of the vortex and over the northern Northeast. Once over Brazil, the vortex travelled southwestward to a position over south-central Brazil (Fig. 8) where it gradually dissipated.

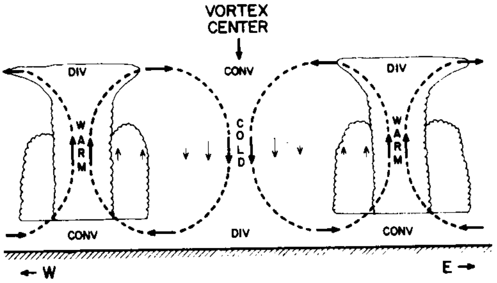

Fig. 9. Schematic vertical cross section through the cyclonic vortex system.

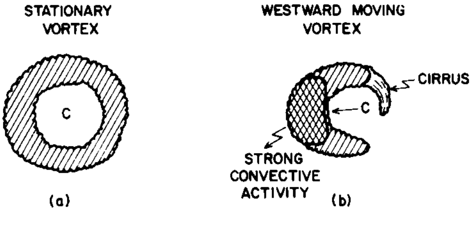

Fig. 10. Idealized cloud distribution associated with (a) a stationary symmetric 200 mb cyclone and (b) a westward moving cyclone.

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[1] The vertical motion was estimated by assuming steady state conditions and using (a) the 200 mb wind and vorticity patterns to calculate vorticity changes following the flow, thereby estimating the 200 mb divergence and (b) the continuity equation, where it was assumed that there is no net divergence in the column, zero vertical motion at 200 mb and that the level of non-divergence is near 500 mb.

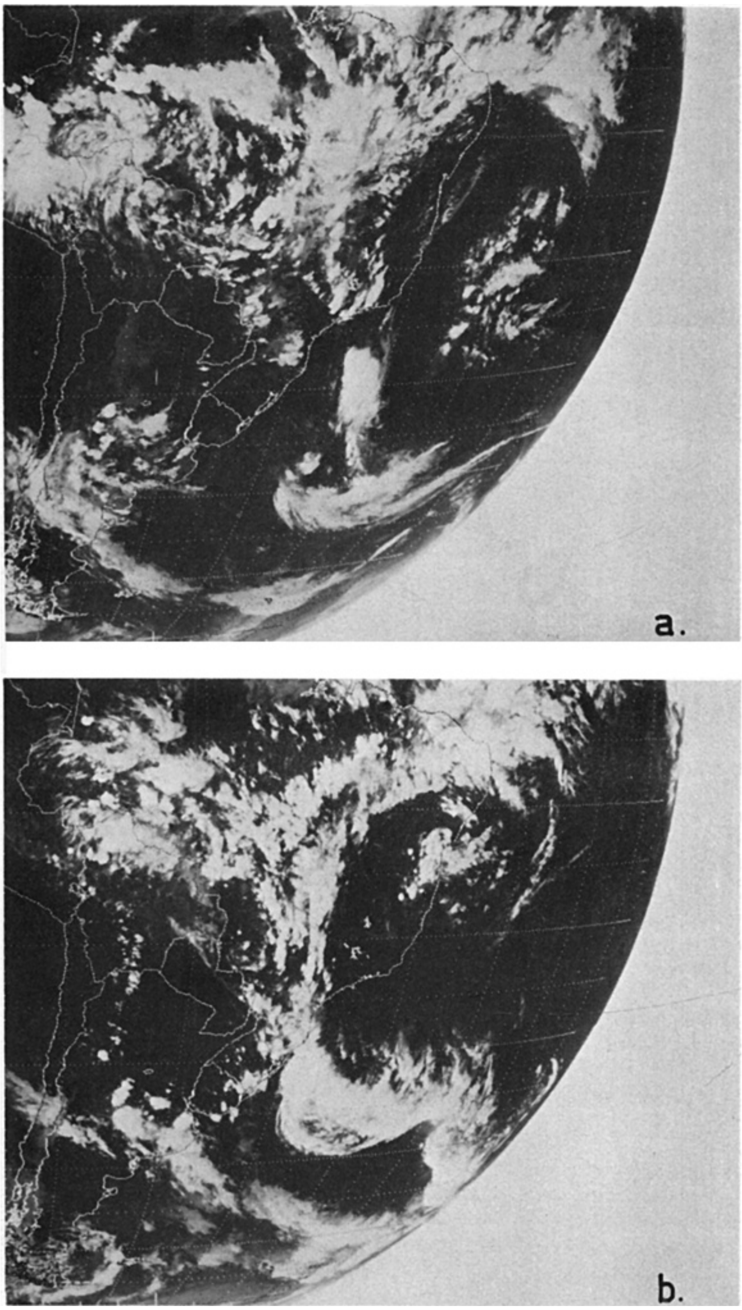

Fig. 11. SMS-2 IR images at 1800 GMT for (a) 22 February 1980, and (b) 29 February 1980.

5. Summary and conclusions

Closed 200 mb cyclonic vortices form in the vicinity of the mid-oceanic troughs in the South Pacific and South Atlantic, primarily during the summer months. There seems to be a direct relationship between the occurrence of these vortices and the presence of 200 mb anticyclones over continental areas. A mechanism for vortex formation is proposed, which is based on the amplification of an upstream ridge. It is speculated that cold frontal systems, penetrating to low latitudes, are closely linked to the ridge amplification and, therefore, indirectly are responsible for the vortex formation.

The cloudiness associated with the vortices is generally enhanced in the direction in which the vortices are moving. Some cumulonimbus activity may be present near their centers, especially over continental areas where this activity shows a marked diurnal variation. Sensible heating at the earth's surface possibly leads to dissipation of the vortices that track over continental areas.

As 200 mb cyclones in the tropical South Atlantic advance westward toward the Brazilian coast, the southern and central portions of the Northeast experience improving weather due to the influence of sinking motion. At the same time, convective activity over the northern Northeast is greatly enhanced.

6. Acknowledgements

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ЦИКЛОНИЧЕСКИЕ ВИХРИ В ВЕРХНЕЙ ТРОПОСФЕРЕ ТРОПИЧЕСКОЙ ЮЖНОЙ АТЛАНТИКИ

Проделан анализ субтропических циклонов на уровне 200 мбар для южных районов Атлантики и Тихого океана. Согласно наблюдениям циклоны существуют главным образом в летние месяцы и, как правило, формируются вблизи осей средних океанических ложбин. Обсуждается соотношение между образованием циклона и присутствием антициклона на уровне 200 мбар над континентом. Рассматриваются процессы формирования циклона. Циклоны характеризуются холодным ядром и прямой теплои циркуляцией—холодный воздух опускается, а теплый воздух на периферии поднимается. Найдено, что облачность, связанная с циклоном, зависит от прямой термической циркуляции, положения вихря и его направления движения. Обсуждается влияние циклонических вихрей южной Атлантики на уровне 200 мбар на погоду в Бразилии.