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On the monsoons of South America Part 2 : Interaction with extratropical disturbances and formation of tropical depressions and upper-tropospheric cyclonic vortices

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सार – इस शोध–पत्र में दक्षिणी अमरीका में दक्षिणी ग्रीष्मऋतु के दौरान ऊष्मा के निम्न परिसंचरण की अप्रगामी तंरग संरचना का पता लगाया गया है तथा यह विवेचन किया गया है कि किस प्रकार अप्रगामी तंरग दो गोलार्द्धों के पूर्व की ओर संचरित हाने वाले बहिरूष्णकटिबंधीय विक्षोभों के साथ परस्पर संबंध रखती है। ये पारस्परिक संबंध महाद्वीप के मौसम और जलवायु में पाए गए अनेक लक्षणों को स्पष्ट करते प्रतीत होते है। विशेषरूप से ये कमजोर मानसून और अवदाबों तथा ऊपरी क्षोभमंडलीय चक्रवातीय भ्रमिलताओं जैसी पश्चिम की ओर संचरित होने वाले उष्णकटिबंधीय विक्षोभों को बनाते प्रतीत होते हैं। यहाँ इन विक्षोभों के स्रोत, संरचना, विकास और गति के विषय में विचार किया गया है। इस शोध–पत्र में दक्षिणी अटलांटिक अभिसरण क्षेत्र (एस.ए.सी.जेड.) की प्रकृति और संरचना की भी जाँच की गई है और दक्षिणी गोलार्द्ध के बहिरूष्णकटिबंधीय विक्षोभों के साथ उसके पारस्परिक संबंध पर विचार किया गया है।

ABSTRACT. The paper reveals a stationary wave structure of the heat low circulation over South America during the southern summer and discusses how the stationary wave may interact with eastward-propagating extratropical disturbances of the two hemispheres. The interactions appear to explain several observed features of the continent's weather and climate. In particular, they appear to lead to formation of westward-propagating tropical disturbances, such as monsoon lows and depressions and upper-tropospheric cyclonic vortices. The origin, structure, development and movement of these disturbances are discussed. The paper also looks into the nature and structure of the South Atlantic Convergence Zone (SACZ) and discusses its interaction with the extratropical disturbances of the southern hemisphere.

Key words – Monsoon stationary wave, Monsoon lows and depressions, Upper-tropospheric vortices, S.A.C.Z.

1. Introduction

The monsoon circulation over tropical South America, the climatological aspects of which were discussed in Part 1 of this study (Saha and Saha,2002b), often interacts, either directly or indirectly, with eastward-propagating extratropical disturbances of both the southern and the northern hemispheres. Although, these disturbances keep moving, one after the other, almost throughout the year, we shall confine our attention to those that move during the southern summer. In the southern hemisphere, the cold fronts associated with these eastward-moving low-pressure disturbances extend northeastward after crossing the Andes and affect the different parts of the continent with a

frequency which gradually decreases equatorward from about nine per month in the latitude belt, 40° S - 35° S, to about three per month in the latitude belt, 20° S - 05° S (Oliveira, 1986). Several studies (Serra and Ratisbona, 1942; Kousky, 1979; Fortune and Kousky, 1983; Oliveira and Nobre, 1985; Oliveira, 1986; Marengo *et al.*, 1997; Satyamurty *et al.*,1998) have described in detail the passage of these disturbances across South America and the manner in which they affect the weather and climate of the different parts of the continent, east of the Andes. These studies show that during the passage of the cold fronts, there is a general increase in convective activity and precipitation over most parts of the continent swept over by them. The cold airmasses behind these fronts are known to usher in
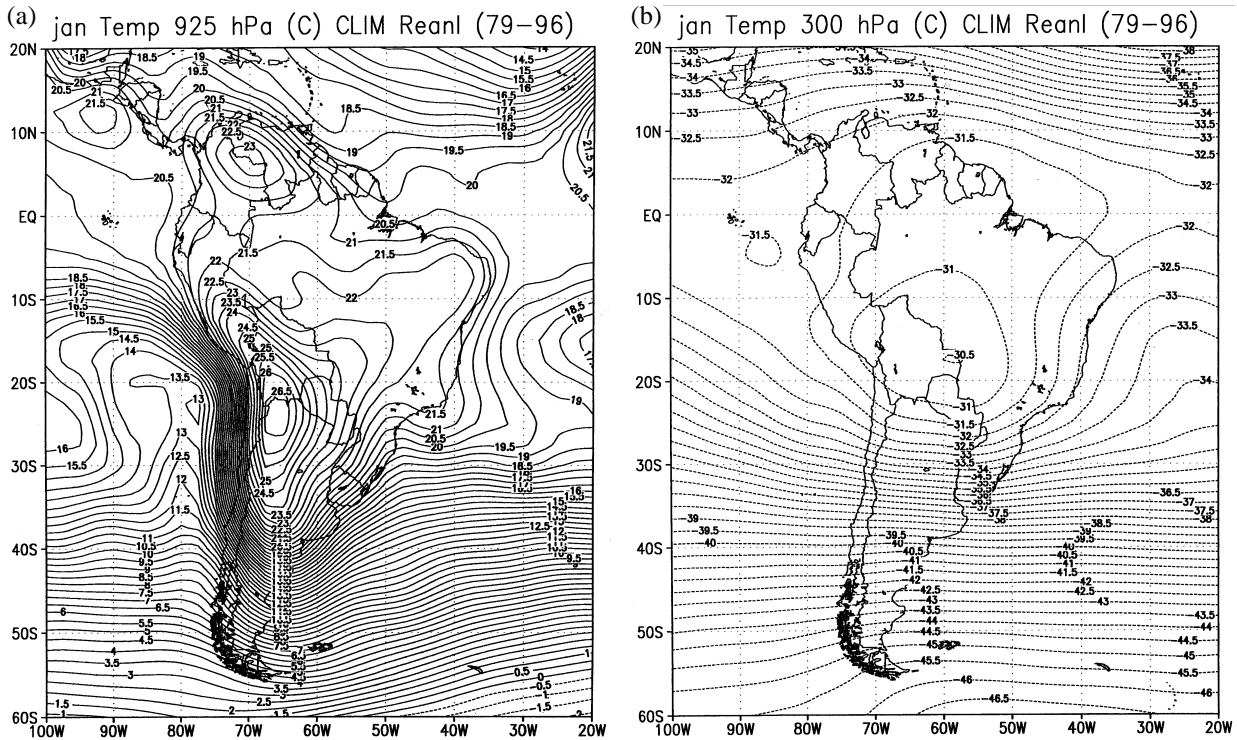
Figs. 1(a&b). (a) Mean January temperature over South America and surrounding oceans at 925 hPa and (b) Mean January temperature over South America and surrounding oceans at 300 hPa

extremely cold spells of weather to regions as far north as the equator, especially during the austral winter. The cloud bands associated with these fronts and their movement can be seen in day-to-day satellite cloud imagery. Several studies (Namias, 1972; Riehl, 1977; Hastenrath and Heller, 1977) have suggested that the extratropical disturbances of the northern hemisphere could also influence the rainfall over South America through enhanced equatorward flow of cold air in the wake of their cold fronts. A few studies (Maura and Shukla, 1982; Nobre and Shukla, 1996) have sought to relate incidence of rainfall over northeast Brazil to anomalies of sea surface temperature over areas both north and south of the equator.

However, despite remarkable progress made in our study of the influence of the extratropical disturbances on the weather and climate of South America, a detailed analysis of the manner in which the disturbances interact with the quasi-stationary monsoon circulation over the continent is yet to be made. Specifically, we need to know how these disturbances affect the circulation and weather pattern over the different parts of the continent, such as the low-level jet over the eastern foothills of the northern Andes, semi-arid conditions over the Patagonian region of Argentina, heavy rainfall producing convergence zone over southeastern Brazil and chronic drought conditions over northeast Brazil. There appears to be a suggestion from synoptic and satellite data that the interaction of extratropical disturbances with the monsoon circulation over South America may occasionally lead to formation of westward-propagating tropical disturbances, such as monsoon depressions, upper-level cyclonic vortices, etc. Kousky and Gan (1981) who studied the formation of upper-tropospheric cyclonic vortices over the South Atlantic hypothesized that these disturbances might be linked to an intensification of the upper-tropospheric high pressure ridge over southeast Brazil as a result of the latter's interaction with an extratropical disturbance of the southern hemisphere. We also need to make a detailed examination of the South Atlantic Convergence Zone (SACZ), which constitutes one of the most prominent climatological features of South America (Satyamurty *et al.*, 1998), with a view to finding out its real nature, what maintains it and how it reacts to the passage of extratropical cold fronts. In the present study, we look into some of these issues, using NCEP/NCAR Reanalysis as well as daily analyses and available satellite radiation and cloud imagery for the month of January, when summer monsoon over South America is near its peak intensity, during the years 1999 through 2002. The results are presented in the sections that follow.

The layout of Part 2 of the paper is as follows: Section 2 reviews the structure and properties of the quasi-stationary heat-low circulation over South America and surrounding oceans as well as those of an eastward-propagating extratropical wave disturbance. Section 3 discusses the interaction between the different parts of the heat-low circulation with the eastward-propagating transient wave disturbances of the southern hemisphere. Interaction with extratropical wave disturbances of the northern hemisphere is dealt with in section 4. The interactions leading to formation of tropical disturbances are discussed in section 5 with a few case studies. Section 6 discusses the problem of the SACZ and its interaction with extra tropical disturbances. The findings and conclusions are given in section 7.

2.   Structure and properties of the heat-low circulation and extratropical waves

(a)   The quasi-stationary heat-low circulation

It was mentioned in Part 1 of the study that the heat source over the South American region in January is located over the land, while heat sinks lie over the surrounding cooler oceans. This view is well supported by a study of Schaack *et al*. (1990) who computed the distributions of mass-weighted vertically-averaged heating and cooling over the different parts of the globe including South America during January. Figs. 1(a&b) which present the mean January temperature field at 850 hPa and 300 hPa respectively over South America and surrounding oceans show the structure of the heat sources and sinks over the region. It may be noted that the warmest temperatures at both the pressure surfaces during January are located over the central part of the continent covering Bolivia and adjoining areas of northern Argentina and southern Brazil, over the latitude belt, 15° S - 25° S, with ridges of warm temperatures extending in the lower troposphere [Fig. 1(a)] in   four directions across South America, one northwestwards along the eastern slopes and foothills of the northern   Andes, the second southwards along the Patagonian region of Argentina, the third northeastwards towards Northeast Brazil and the fourth southeastwards across the southeastern coast of Brazil towards the Southwestern Atlantic. Indeed, the presence of these ridges of warm temperature with troughs of cool temperature in between in alternate sectors in the zonal direction would seem to suggest the presence of two stationary waves, one along the northern and the other along the southern boundary of the heat source. The presence of these stationary waves is also suggested by the fields of pressure or isobaric heights and winds in both the lower and the upper troposphere. Based on our studies of the pressure and wind fields related to the mean temperature field, we present in Fig. 2(a)
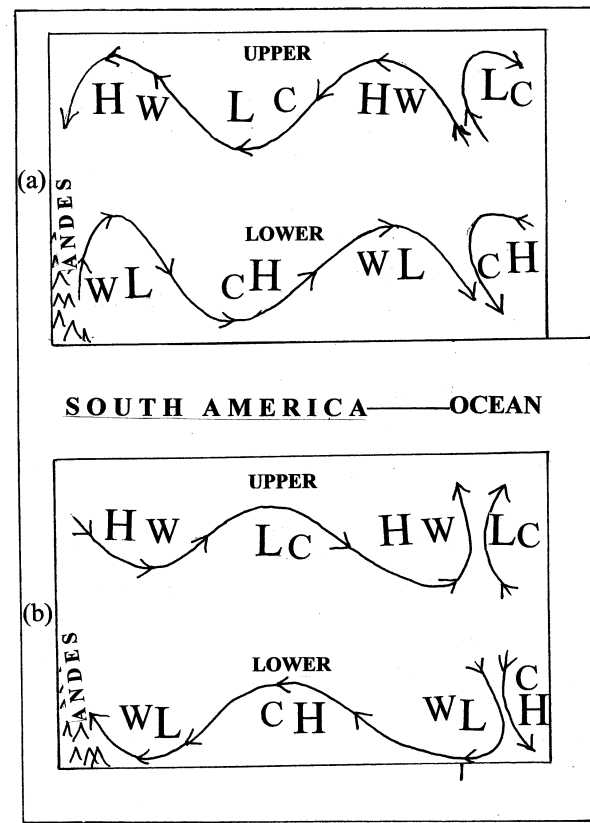
Figs. 2(a&b). Structure of the quasi-stationary wave in the temperature, isobaric height and wind fields in lower (850 hPa) and the upper (300 hPa) troposphere along (a) the northern and (b) the southern boundary of the heat source over South America. C-Cold, W-Warm, L-Low, H-High

schematic showing the streamlines and locations of troughs and ridges in the height field at 850 hPa and 300 hPa in the stationary wave along (a) the northern and (b) the southern boundary of the heat source respectively.

The above-mentioned stationary wave structure of the heat-low circulation over tropical South America would seem to   be associated with some of the well-known observed features of weather and climate over the continent, as briefly outlined below :

(i)   Low-level northwesterly jet and convection along the eastern foothills of the northern Andes

This jet which blows along the eastern foothills of the northern Andes all the way along the western boundary of Amazonas to eastern Bolivia appears to be driven by the strong horizontal temperature gradient that develops between the cold sector of the stationary wave over western

Amazonia and a warm sector of the wave along the foothills to its west, apart from the frictional effect of the mountainside (Paegle and Nogues-Peagle, 1997). The strong low-level convergence and upper-level divergence at the mountainside here leads to penetrative convection which is clearly suggested by the appearance of an elongated band of well-developed clouds in satellite cloud imagery and heavy rainfall at the source regions of the river Amazon [Fig. 15(a) of Part 1].

(ii) Semi-desert conditions over the Patagonian region of Argentina

Situated on the leeside and in the rain shadow of the southern Andes, this temperature ridge extending pole ward from the heat source centered over the Bolivian plateau [Fig. 1(a)] is part of a 'heat low' with a trough of low pressure over the Patagonian region of Argentina. Normally, this trough has warm northerly flow to the east and cold southerly flow to the west in the lower troposphere. Its existence is clearly revealed in satellite cloud imagery by appearance of an elongated thin narrow band of clouds, more or less parallel to the southern Andes. The 'heat low' maintains a hot and almost semi-desert conditions over this part of Argentina. However, as will be shown later, this trough of low pressure becomes very active when an extratropical wave disturbance after crossing the Andes arrives over the region and interacts with it. The usually-thin cloud band then flares up in intensity and cold polar air to the west rushes equator ward to invade the continent.

(iii) Zonal anomaly of rainfall over NE Brazil

The well-marked trough of low pressure over Northeast Brazil, the importance of which can hardly be over-emphasized, may well be compared with the well-known monsoon trough over India which plays a crucial role in shaping the climate of northeastern India or the monsoon trough over northern Australia which plays a similar role in the monsoon climate of Australia (Saha and Saha, 1996, 2001). It is along this trough that the deflected tradewinds of the two hemispheres meet, producing a zone of strong low-level convergence and intense rainfall. It appears to connect the monsoon circulation over South America with the Intertropical Convergence Zone (ITCZ) over the equatorial eastern Atlantic. Since most of the cloud development and rainfall occur to the west of the trough, it appears to explain the observed disparity in the distribution of rainfall between the western and the eastern parts of Northeast Brazil. For example, the mean January rainfall over the Amazon delta near Belem in the western part is about 320 mm, whereas that over the eastern part between Fort Aleza (Ceara) and Cape Roque hardly amounts to 60 mm [Fig. 15(a) of Part 1]. The presence of this trough is prominently revealed in
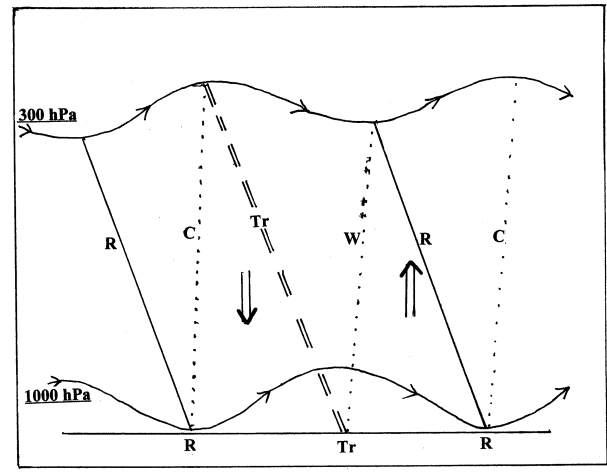

Fig. 3.   Structure of an amplifying baroclinic wave disturbance in the extratropical westerlies (after Holton, 1979). Tr denotes Trough, R- Ridge, C-Coldest, W-Warmest. Double-shaft arrows show directions of vertical motion

satellite cloud imagery by a broad and bright band of clouds extending northeastward from Central South America towards the ITCZ over the eastern Atlantic.

(iv) The South Atlantic Convergence Zone (SACZ)

The ridge of high temperature over the southeastern part of Brazil extending southeastward into the south Atlantic is associated with a well-developed trough of low pressure in the lower troposphere and a ridge of high pressure in the upper troposphere. It is a strongly baroclinic zone lying between the poleward-flowing warm Brazil ocean current in the east and the equatorward-flowing cold Malvinas current in the west. It is a strongly convergent zone with heavy rainfall (Satyamurthy *et al.*, 1998). It tilts westward with height and its associated elongated cloud band, broad and bright, oriented in a NNW-SSE direction, appears prominently in satellite cloud imagery.

In view of the observed differences in the structure and properties of the troughs and ridges of pressure and their associated circulation features along the northern and the southern boundary of the heat source, we may be justified in calling the stationary wave along the northern boundary only as the monsoon stationary wave over South America. The stationary wave along the southern boundary may be called the subtropical stationary wave. Both the stationary waves can interact with extratropical wave disturbances, as we shall see in subsequent sections.

(b) Extratropical wave disturbance

The structure and properties of an extratropical wave disturbance in the southern hemisphere is similar to those of

12Z04JAN1999 Temp 850 hPa (C) NCEP REANL

12Z04JAN1999 Wind 850 hPa (m/sec) NCEP REANL

(a)

(b)
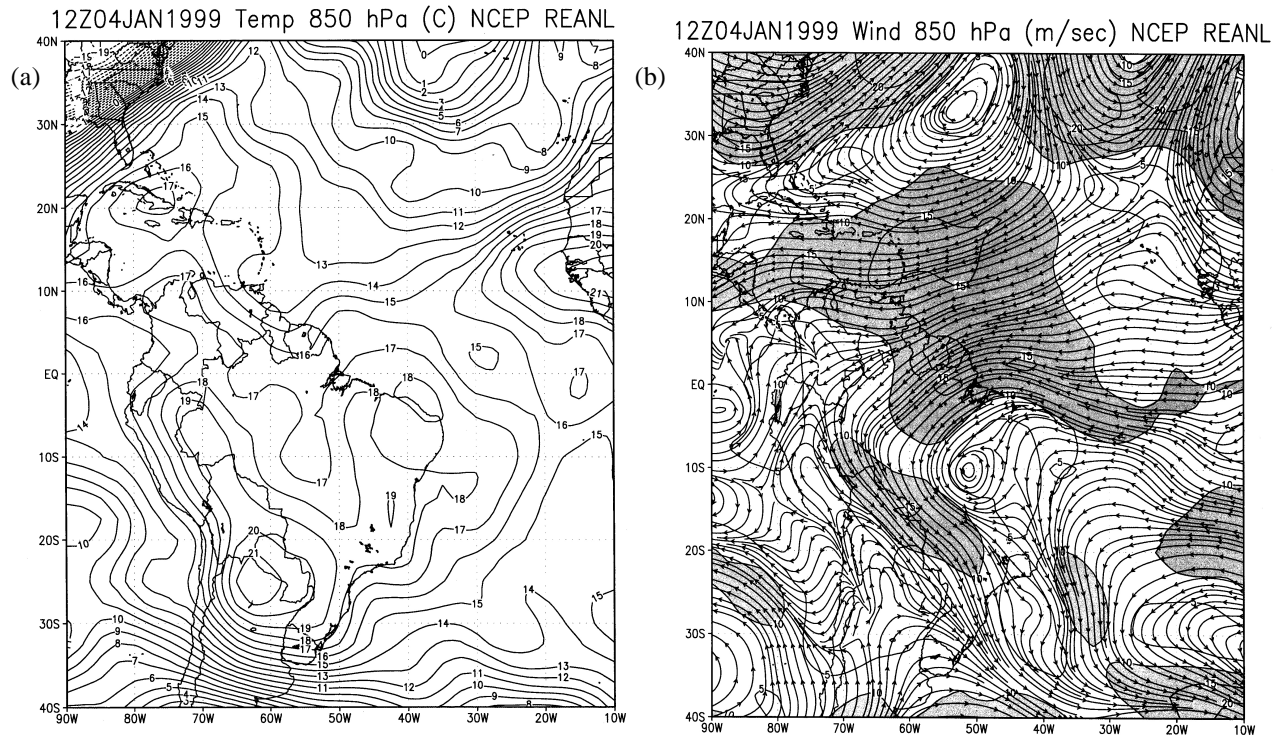
Figs. 4(a&b). 850 hPa (a) temperature and (b) wind fields at 1200 UTC on 4 January 1999 during interaction of the trough of low pressure over Argentina with an extratropical cold front

its well-known counterpart in the northern hemisphere (Palmen and Newton, 1969; Holton, 1979), except that the meridional directions of flow of warm and cold air masses are reversed. Therefore, a brief description of it only will be presented here. In the southern hemisphere, a wave disturbance in the belt of the extra tropical westerlies advects cold polar air equator ward to the west of the wave trough and warm tropical air pole ward to the east. In an amplifying wave, there is strong convergence of cold air in the lower troposphere to the west of the front and strong divergence of warm air in the upper troposphere to the east, leading to upward motion, formation of cloud and rain to the east and downward motion, clear skies and dry conditions to the west, as shown schematically in Fig. 3, after Holton (1979), which is self-explanatory. The front generally moves eastward.

In the southern hemisphere, extratropical wave disturbances usually originate in the vicinity of the polar trough over the latitude belt 50° - 60° S and move eastsoutheastward. However, over the South Pacific, the cold fronts associated with these disturbances often interact with the South Pacific Convergence Zone (SPCZ) which lies

over the tropics in an approximately WNW - ESE direction. So, the actual alignment of the cold front, as it approaches South America, is more or less, a NNW - SSE direction. However, not all eastward-propagating cold fronts interact with the stationary waves over South America in any significant way. Only those with large amplitudes and extending equatorward to at least 20° S or lower latitudes are found to interact with the monsoon circulation over South America.

3.   Interaction with extratropical wave disturbances of the southern hemisphere

As the cold front associated with an extratropical disturbance, after crossing the Andes, enters South America, it first interacts with the quasi-stationary subtropical trough of low pressure over Argentina. Now, what happens during interaction very much depends on the phase relationship between the interacting waves. If the two waves interact in the same phase, that is, if the low pressure trough associated with the cold front reaches the longitude of the low pressure trough of the stationary wave, the result may be a coupling of
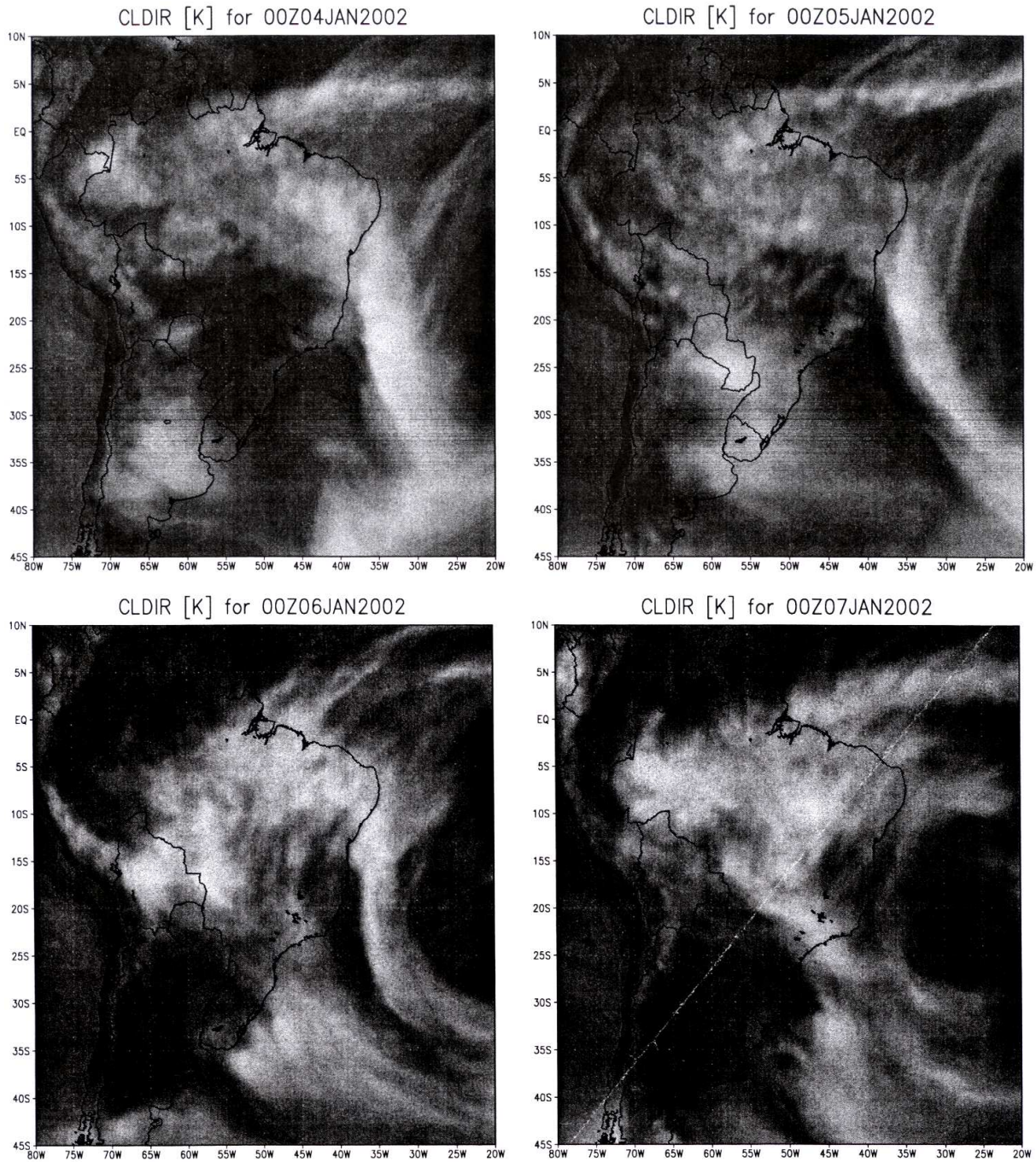
CLDIR [K] for 00Z04JAN2002

CLDIR [K] for 00Z05JAN2002

CLDIR [K] for 00Z06JAN2002

CLDIR [K] for 00Z07JAN2002

Fig. 5. Satellite infrared cloud imagery at 0000 UTC daily during the period, 4 through 7 January 2002

the two troughs leading to the formation of an extended trough and an amplification of the waves. When such is the case, the southerly winds to the west of the extended trough rushes equatorward advecting cold polar air to lower latitudes while the northerly winds to the east would rush poleward advecting warm tropical air to higher latitudes. Sometimes, when a deep cold front enters the Patagonian region, it may even extend its influence further northward

and couple up with the trough of low pressure that lies over the eastern foothills of the northern Andes. An example of such a deep penetration of the extended trough reaching almost up to the equator is presented in Fig. 4 which shows the 850 hPa (a) height and (b) wind fields at 1200 UTC on 4 January 1999. It is likely that this extended trough had a role in accelerating the strong low-level northwesterly jet along the foothills of the northern Andes, seen in Fig. 4(b). An inspection of Figs. 1(a&b) informs us that such coupling and amplification of the waves leading to large-scale exchange of cold and warm airmasses between the heat source over central South America and the heat sinks over the Atlantic ocean lying to both north and south of the equator may occur at all the low-level trough locations in South America. Successive interaction with the troughs of the subtropical stationary wave may lead to deeper penetration of cold polar air to the central and northern parts of South America as the extra tropical disturbance moves eastward. Sometimes, when the cold front penetrates deep into the tropical belt, say, north of about 20° S, the troughs of low pressure over southeast and northeast Brazil may combine and jointly interact with the cold front, giving rise to a very elongated and extended trough running almost parallel to the east coast of Brazil and then southeastward into the south Atlantic. This type of coupling may often result in an explosive growth of the extended trough and a flare-up in the intensity of the cloud bands associated with it, as evidenced by satellite cloud imagery. However, when an approaching new cold front interacts with a monsoon disturbance over central South America, the extended trough over eastern Brazil may suddenly collapse or disappear. We noted several cases of such interactions and transformations during January of the four years (1999-2002). An example is given in Fig. 5 which shows the daily satellite infrared cloud imagery of the period, 4 through 7 January 2002. On 4 January, two prominent north-south oriented cloud bands appeared, one an extraordinarily intense and bright cloud band close to the coast of eastern Brazil and adjoining southwestern Atlantic and the other an approaching, but somewhat less intense, cloud band over Argentina. Both the cloud bands were associated with eastward-propagating cold fronts after they interacted with the troughs over the respective regions. During the following three days, a remarkable change occurred in the intensity of the two cloud bands. As the cold front over Argentina continued to move northeastward while the other remained almost stationary, there was a gradual decline in the intensity of the cloud band over eastern Brazil while the intensity of the approaching cloud band increased. Then, suddenly, on 7 January, the cloud band near the east coast of Brazil totally collapsed and almost disappeared, while the approaching cloud band flared up in intensity. The reason for this dramatic change in the intensity of the two cloud bands, with the western one
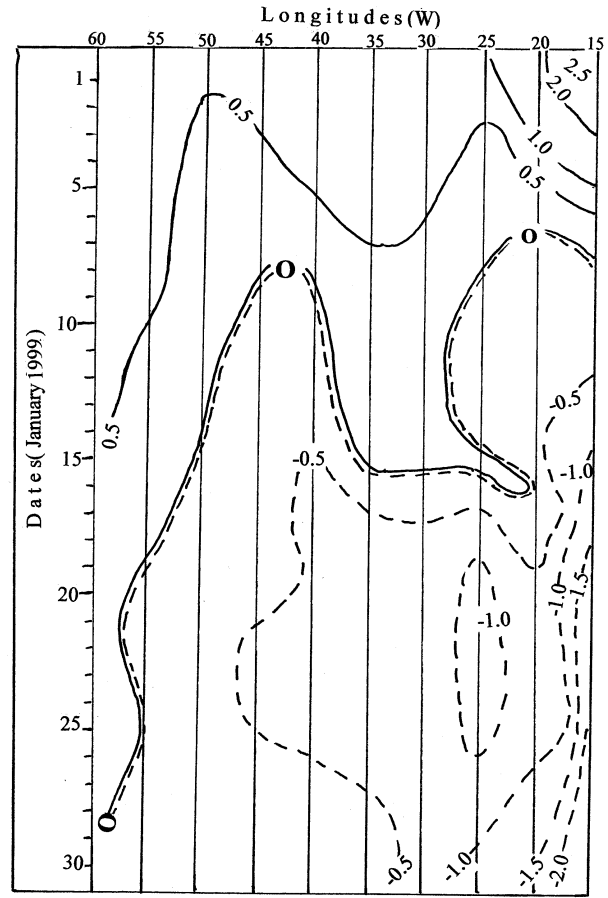

Fig. 6. Time-longitude distribution of daily SST anomaly (departure from climatological mean) along 15° N over the eastern Atlantic in January 1999

becoming more prominent and the eastern one fading, will be clear when we discuss the development of a monsoon depression over central South America in a later section.

4.   Interaction with extratropical disturbances of the northern hemisphere

Satellite as well as conventional data reveal that in January, the equatorial trough of low pressure in the north Atlantic is usually confined to the eastern part of the ocean where the tradewinds of both the hemispheres converge into a narrow latitudinal zone of warm temperatures, just north of the equator, while it almost disappears from the western part, west of about 40° W. Over the latter part, the NE trades generally cross the equator in full strength and converge into the troughs of low pressure over South America. Occasionally, however, when the trades are weak, the equatorial trough may extend westward to cover the whole equatorial belt. Namias (1972) suggested that increased
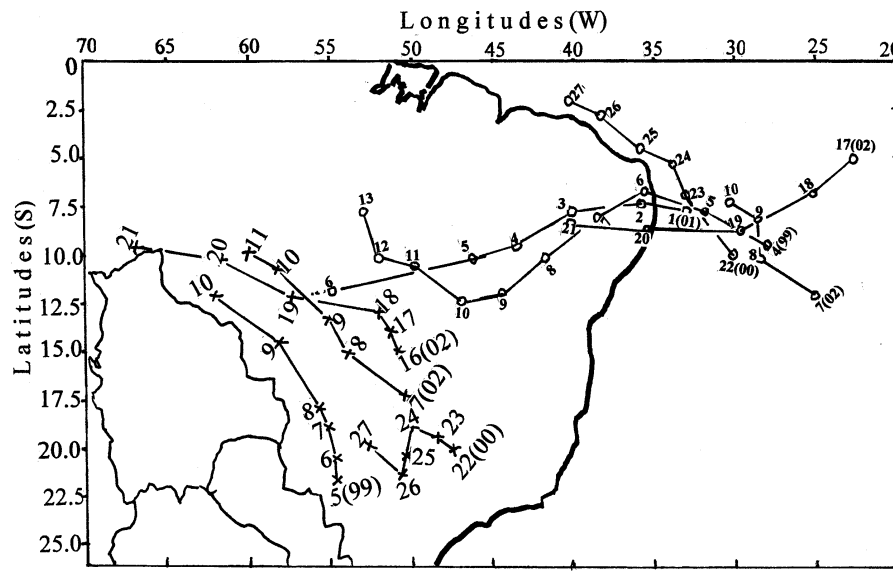
Fig. 7. Tracks of monsoon lows and depressions (crosses) and upper-tropospheric cyclonic vortices (open circles). Dates are given against each location, with the year (last two digits) given in brackets at the first location only

cyclonic activity off the coast of North America may often lead to increased rainfall over northeast Brazil which lies close to the equatorial trough, by producing a stronger Hadley circulation. Riehl (1977) who studied rainfall over Venezuela during the northern summer also proposed a similar mechanism for the effect of the extratropical disturbances of the northern hemisphere on the weather and climate of South America. Hastenrath and Heller (1977) suggested that a strengthening of the subtropical high pressure over the north Atlantic had the effect of displacing the equatorial trough southward towards the coast of Brazil and thus leading to increased rainfall over northeast Brazil. A few studies (Maura and Shukla, 1981; Nobre and Shukla, 1996) have sought to explain the variability of rainfall over northeast Brazil on the basis of sea surface temperature anomalies over the equatorial Atlantic ocean. According to these studies, development of a warm SST anomaly to the north of the equator and a cold SST anomaly to the south would have the effect of shifting the equatorial trough of low pressure northward and thereby producing increased rainfall to the north and reduced rainfall to the south. Gray and Clapp (1978) produced direct evidence of interaction between the cloud bands associated with the equatorial trough over the South American longitudes and the large-amplitude wave disturbances in the westerlies over the North Atlantic ocean.

Our investigations reveal that extratropical disturbances of the northern hemisphere exercise a profound influence on the weather and climate of South America in a variety of ways. For example, during their movement across the north

Atlantic, they modulate the intensity of the subtropical high pressure and thereby the strength of the NE trades. When a deep trough in the midlatitude westerlies moves to the eastern part of the north Atlantic, a surge of cold polar air is advected equatorward by the northerly flow behind the cold front as well as by the northeasterly flow around the high pressure cell ahead of the front. Quite often, the high pressure cell ahead of the cold front merges with the subtropical high pressure, thereby intensifying the latter and strengthening the trades. Further, it was found (Nykjaer and Van Camp, 1994; Nobre and Shukla, 1996) that upwelling along the west coast of north Africa affects the distribution of sea surface temperature (SST) over the tropical Atlantic which appeared to modulate the intensity of the subtropical high pressure and thereby the strength of the NE trades. An example of the effect of such upwelling is presented in Fig. 6 which shows in a time-longitude section the distribution of SST anomaly along latitude 15° N during January 1999. It may be seen that in the first week of the month, SST anomaly was generally warm over most of the ocean area close to the north African coast, signifying little or no significant upwelling. However, all that changed when a cold anomaly appeared at the coast by end of the week and was advected southwestward by the prevailing wind. On or around 20 January, it merged with a cold anomaly that had appeared over the mid-ocean earlier and both moved westward to extend the cold anomaly to about 60° W by end of the month. Another area where we noted significant influence of the northern hemisphere westerly troughs on South American weather and climate was when they deepened, extended to latitudes south of the equator and
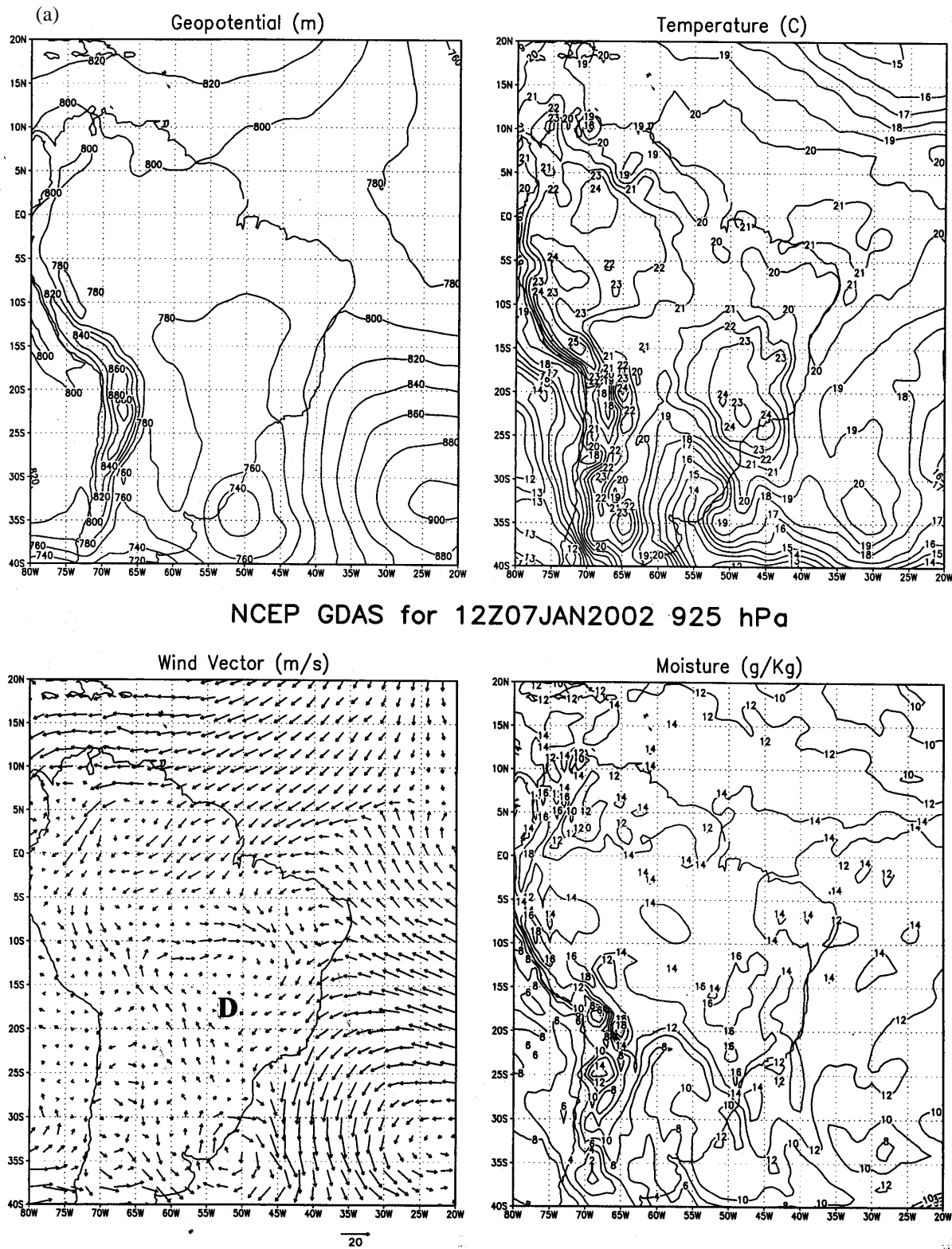
(a)

Geopotential (m)

Temperature (C)

NCEP GDAS for 12Z07JAN2002 925 hPa

Wind Vector (m/s)

Moisture (g/Kg)

Fig. 8(a). Fields of geopotential (m), temperature (° C), wind (m/s) and moisture (g/kg) at 1200 UTC on 7 January 2002 at 925 hPa. D marks the Depression center
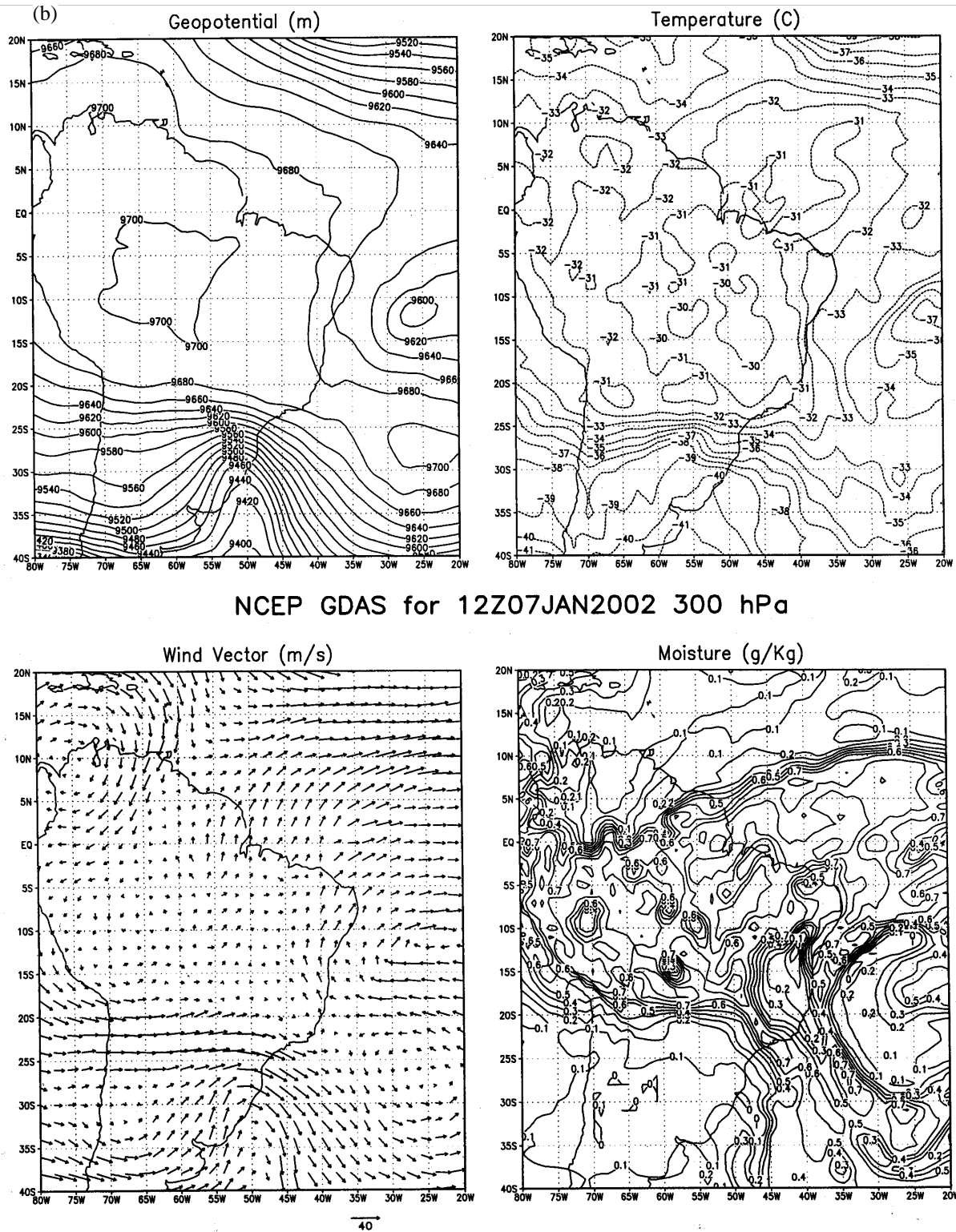
Fig. 8(b). Fields of geopotential (m), temperature (° C), wind (m/s) and moisture (g/kg) at 1200 UTC on 7 January 2002 at 300 hPa

reinforced the warm divergence from the upper-tropospheric anticyclone over Brazil and over neighbouring equatorial trough.

Our study of SST anomaly over the tropical north Atlantic during the other years revealed that there was large-scale cold anomaly during the years 2000 and 2001, but strong warm anomaly prevailed during most of January 2002.

5.   Formation of tropical disturbances

The interaction of the monsoon circulation over South America with extratropical disturbances often leads to formation of synoptic-scale tropical disturbances. This is not quite unusual, since such interactions over several other monsoon areas of the globe have been known to lead to similar effects (Saha and Saha, 2000, 2001, 2002). Two types of disturbances were noted by us over tropical South America and neighbourhood. One was formation of low-level monsoon lows and depressions over the central part of the continent, between about 15° S and 20° S, and the other upper-tropospheric cyclonic vortices over the northwestern part of the South Atlantic close to the coast of northeast Brazil. The signatures of both types were found in circulation fields as well as satellite cloud imagery. During January of the four years, 1999-2002, we could detect 5 monsoon lows/depressions (a depression is a low pressure system with a cyclonic circulation in which the maximum wind speed reaches about 10 to 15 meters per sec) and 5 upper-tropospheric cyclonic vortices. Year wise, these were as follows :

1999   Monsoon Low/depression of 5-10 January
        300 hPa cyclonic vortex of 4-13 January

2000   Monsoon Low/depression of 22-27 January
        300 hPa cyclonic vortex of 22-27 January

2001   Monsoon Low/depression of 1-5 January
        300 hPa cyclonic vortex of 1-7 January

2002   Monsoon Depression of 7-11 January
        300 hPa cyclonic vortex of 7-10 January
        Monsoon Low/depression of 16-21 January
        300 hPa cyclonic vortex of 17-21 January

The locations of initial formation and the tracks of these disturbances are shown in Fig. 7. Lack of space prevents us from describing all the details regarding the formatio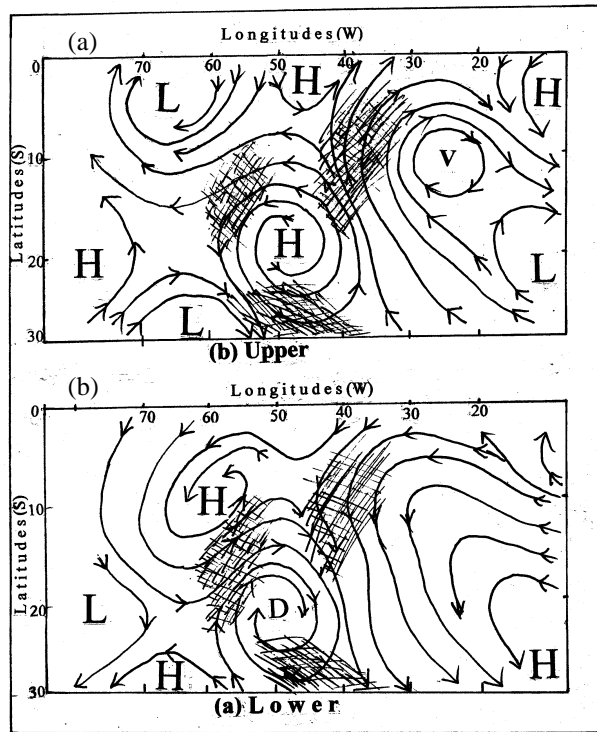n, structure, development and movement of these disturbances. However, we noted several common features amongst the disturbances of each type. So, we decided to present these details in respect of one monsoon low/depression and one upper-tropospheric cyclonic vortex, as examples only. They are as follows :

(a)   *Monsoon low/depression of 7-11 January 2002*

(*i*)   *Formation and development*

This depression first formed as a closed low with a central pressure of 1010 hPa at MSL and height of 775 gpm at 925 hPa. on 6 January over southern Brazil when the monsoon trough over the area interacted with and got coupled to a southern-hemispheric large-amplitude cold front. The coupling led to formation of an extended trough and development of the low as well as the cold front. The development of the low into a depression was indicated by a fall of about 10 gpm in the height of the 925 hPa surface and an intensification of the circulation the following day, though the surface pressure did not show any significant change. For the cold front, the 925 hPa height fell by about 15 gpm. Fields of geopotential height, temperature, wind and specific humidity associated with the coupled disturbances at 1200 UTC on 7 January may be seen in Figs. 8(a&b) which present these fields at 925 and 300 hPa respectively. The diagrams are self-explanatory and enable us to understand why the monsoon depression formed and developed near a latitude of about 20° S and further north. This is because continued warm advection from the south to the west of the depression center and cold advection from the north to the east in the lower troposphere, which were necessary for development of the depression, were only possible when the depression center was located northward of the latitude of the surface temperature maximum.

(*ii*)   *Structure*

The depression had a mean zonal wavelength of about 2500 km and amplitude of 1 to 2° C in the temperature field at about 925 hPa. Satellite infrared cloud imagery on 7 January, shown in Fig. 5, appears to provide valuable clue regarding the structure of the monsoon depression. Interestingly, the central region of the depression appears to be largely cloud-free. However, three significant cloud bands appear around it; a cloud band to the south extending southeastwards across southeast Brazil into the south Atlantic, a second to the northeast extending northwards towards the equator and a third to the northwest extending also towards the equator and almost merging with the cloud band to the northeast. These areas are marked in a schematic in Fig. 9 which shows the structure of the depression in the circulation field at two isobaric surfaces,

Fig. 10. Schematic structure of the vertical circulation in a zonal plane through the center of a monsoon depression

Figs. 9(a&b). Schematic structure of the wind, height and temperature fields in a monsoon depression over the South American region at an isobaric surface in (a) the lower and (b) the upper troposphere. Symbols are: L - Low, H - high; C - Cold, W - warm. Cloudy areas-hatched

one representing the lower troposphere and the other the upper troposphere. It also shows the warm and cold areas and highs and lows at both the surfaces. Fig. 10 shows a schematic of the vertical circulations in an approximately zonal plane through the center of the depression. It shows the warm area of the depression flanked by two cold areas in the lower troposphere and a warm high over the depression with two cold troughs on either side in the upper troposphere. There is strong upward motion to the west because of cold convergence at low levels and warm divergence aloft, while to the east the upward motion associated with the depression at the lower levels is restricted to about the mid-troposphere because of strong subsidence of cold air aloft. The cold air converging at the warm depression in the lower troposphere is the northeast trade wind in the west and the southeast trade wind in the east. There is strong downward motion at the center of the depression.

(iii) Movement

After development, the depression moved in a northwesterly direction at an average phase speed of
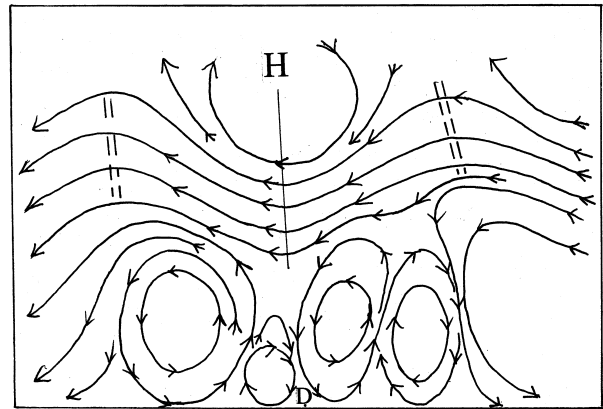
4 meters per second. This may be seen from Fig. 7 as well as the daily 925 hPa flow fields and related satellite cloud imagery for the period, 8-11 January, presented in Figs. 11 and 12 respectively. We do not know with certainty what forced the depression to move in the observed direction. However, it would appear that apart from the warm air divergence occurring in the upper troposphere to the north and northwest of the center of the depression, there was strong warm air divergence from a strongly amplifying northern-hemispheric upper-tropospheric trough which had penetrated equatorward to the latitudes of South America and was located to the northwest of the center of the depression [Fig. 8(b)]. It is likely that the depression moved in the direction of the isallobaric gradient created between the eastern and the western sides of the depression center by net convergence of cold air in the vertical air column to the east of the center and net divergence of warm air to the west. The issue should, however, be settled by actual numerical computations.

(b) Upper-tropospheric cyclonic vortex of 1-7 January 2001

Unlike a monsoon low or depression the formation of which is reported, perhaps, for the first time in our study, the formation, structure, development and movement of an upper-tropospheric cyclonic vortex over the south Atlantic close to the coast of Brazil have been studied for sometime, thanks to the work of Ramos (1975), Virji (1981) and Kousky and Gan (1981) and others. According to these studies, the vortex which develops in a trough in the climatological height / wind field at 300 / 200 hPa over the northwestern part of the south Atlantic, in general, moves westward with a well-developed band of cloud and rain and its movement is well-marked in satellite cloud imagery and distribution of rainfall. Some details regarding the
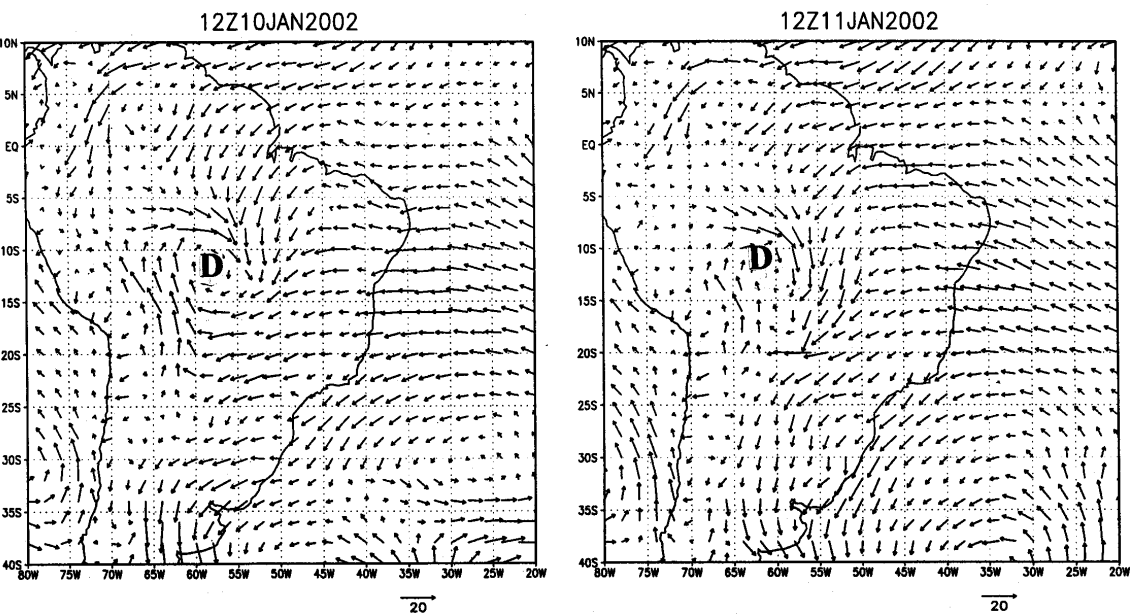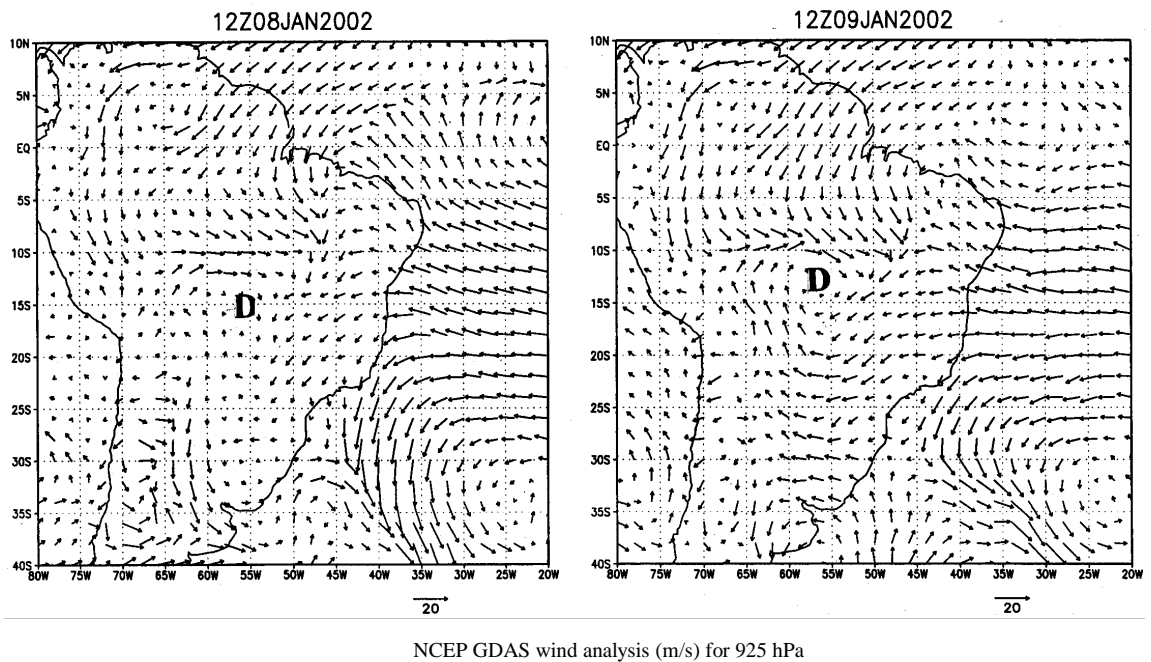
NCEP GDAS wind analysis (m/s) for 925 hPa

Fig. 11. The wind field in the monsoon depression (center marked-D) at 1200 UTC daily during the period, 8 through 11 January 2002

formation, structure, development and movement of the vortex that formed during the period, 1-7 January 2001, are as follows :

(*i*)   *Formation and development*

The vortex was located near the coast of northeast Brazil at 1200 UTC on 1 January 2001(Fig. 7). We do not

know exactly what led to the formation of this vortex. Several possibilities exist. These include: (*i*) downstream effect of an intensification of the upper-tropospheric ridge of high pressure over southeastern Brazil during its interaction with an extratropical cold front of the southern hemisphere, as visualized by some workers (*e.g.*, Kousky and Gan, 1981), (*ii*) superposition of the warm sector of an upper-tropospheric cut-off low from an extratropical cold
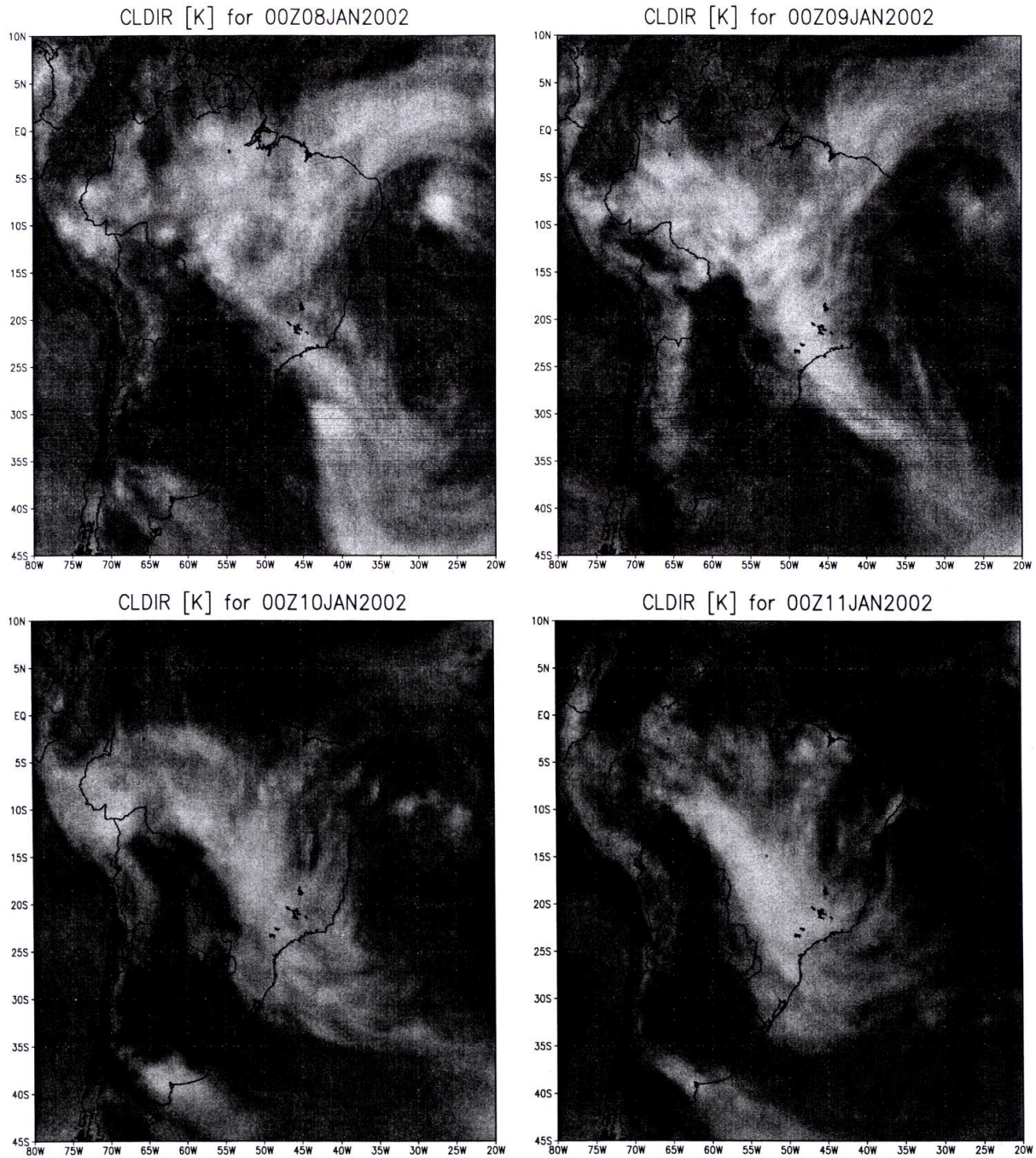
Fig. 12. Satellite infrared cloud imagery at 0000 UTC daily during the period, 8 through 11 January 2002

front of the northern hemisphere, which at 1200 UTC on 1 January was centered at 10° N, 45° W to the NNW of the center of the vortex. Strong warm air divergence from both the circulation systems could have influenced the formation of the vortex. However, a third influence may also have

been involved and that is an intensification of the MSL subtropical high pressure ridge over the southern Atlantic during the eastward passage of an extratropical disturbance, which would lead to a deepening of the upper tropospheric trough over the south Atlantic. It seems plausible that all the

MSLP (hPa)

Wind (m/s) for 925 hPa
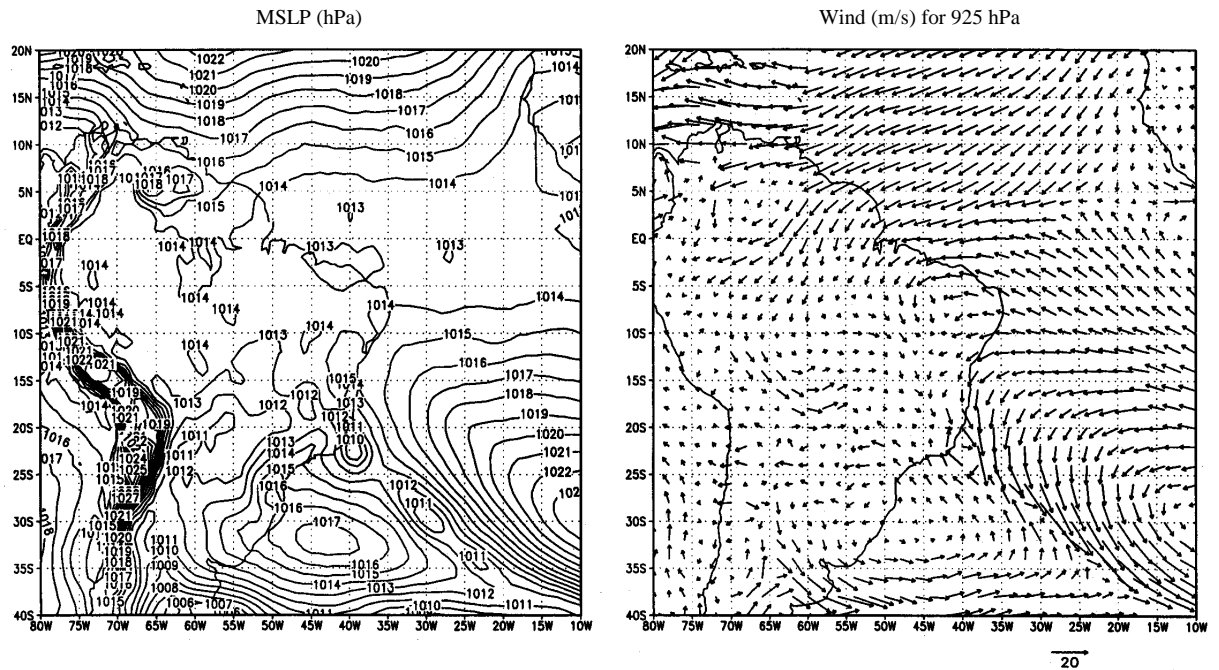
NCEP GDAS analysis for 1200 UTC 01 January 2001

Wind (m/s) for 850 hPa
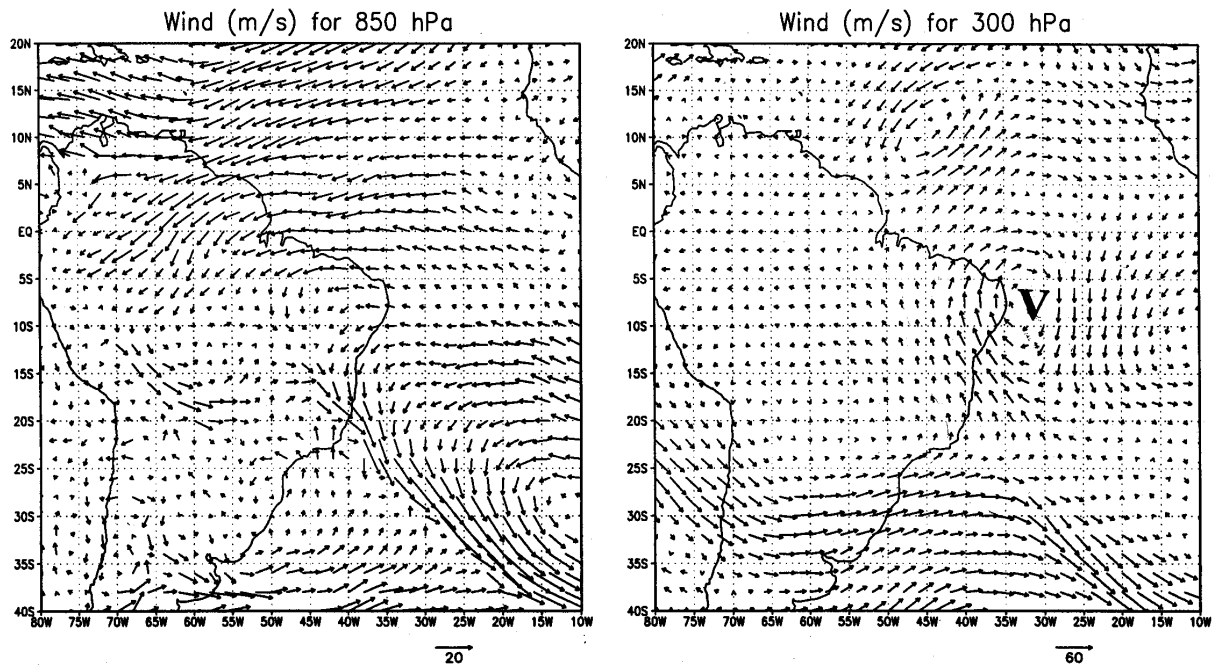
Wind (m/s) for 300 hPa

Fig. 13. NCEP GDAS analyses of MSLP (hPa) and winds at 925, 850 and 300 hPa at 1200 UTC on 01 January 2001. V marks the location of the center of the upper-tropospheric cyclonic vortex at 300 hPa

three factors mentioned above might have contributed to the formation and development of the vortex. The involvement of all the three factors is suggested by Fig. 13 which presents the MSL pressure distribution and wind fields at 925, 850 and 300 hPa at 1200 UTC on 1 January 2001.

(*ii*)   *Structure*

Kousky and Gan (1981) give a schematic of the vertical circulations in the vortex with cold air descending in the middle and warm air rising in the peripheries The observed
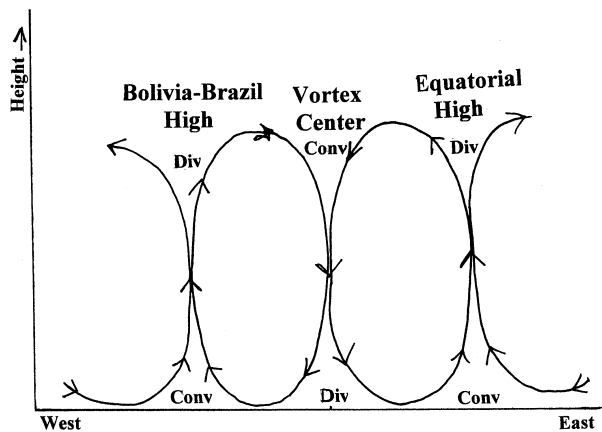
Fig. 14. Schematic model of the vertical circulation in an approximately zonal plane through the center of an upper-tropospheric cyclonic vortex located near the coast of northeast Brazil

Fig. 15. Locations of the 1014 hPa isobar (cross) at MSL and the center of the upper-tropospheric cyclonic vortex (circle) at 300 hPa along 10° S at 1200 UTC daily during the period, 1 through 7 January 2001

distributions of convection in the field of the vortex with dense towering cloud bands to the west, north and northeast and a cloud-free center would seem to support their model. However, no reason is given as to why rising motion should occur to the northeast of the center. The present study finds that the equatorial trough over the Atlantic with its warm low in the lower troposphere and warm high in the upper troposphere is as much involved in the creation and development of the vortex as any other factor mentioned earlier. Warm air divergence from the high pressure ridge over South America in the west and the equatorial trough in the east in the upper troposphere would converge at the center of the vortex which is cold, thus forcing downward motion at the center. The structure of the vertical circulations, as suggested by our study, is given by a schematic in Fig. 14.

(iii) Movement

The vortex studied by Kousky and Gan (1981) moved in a zig-zag course, first moving eastnortheastward over the ocean from a location near the coast of Brazil and then westward inland. In our study, we found that all the five vortices moved in a general westerly direction, though a few had a northwesterly track. Further, from Fig. 7, one may see that all the vortices, including the vortex of 1-7 January 2001, formed almost simultaneously with the low-level monsoon lows or depressions, moved almost in the same general direction and lasted, in some cases, almost the same life period. Evidently, there appears to be some connection between the two types of disturbances which needs to be looked into. Specifically, one may ask: what forces the vortex to move westward? We have no answer to this
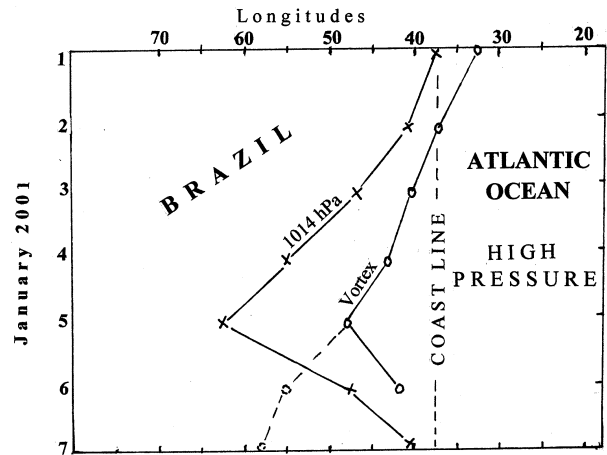
question from earlier studies. Could it be due to a MSL pressure wave which moved from east to west, as evidenced by a time-longitude diagram in Fig. 15 which shows the daily location of the 1014 hPa isobar and the location of the center of the upper-tropospheric vortex along about 10° S during the period, 1 to 7 January 2001? It is interesting to note that the isobar and the vortex center moved more or less simultaneously and in step till 5 January, after which the isobar receded and the vortex weakened and almost broke up into two parts, one part withdrawing eastward and the other continuing to move forward for a while more. Indeed, the observed close association between the movements of the MSL pressure wave and the vortex raises an important question regarding the origin and development of the vortex.

The question raised regarding a possible connection between the two types of disturbances is of fundamental interest. We do not really have a definitive answer. But our suspicion is that the connecting link is the upper-tropospheric high pressure ridge over South America, from which warm air diverges to both, *viz.*, to the monsoon low in the west and the vortex in the east.

6.   South Atlantic Convergence Zone (SACZ)

The SACZ is an extended trough of low pressure, normally oriented in a NW-SE direction, which connects the trough of the heat low over southeastern Brazil to the oceanic trough of low pressure to which the trade winds from the subtropical high pressure cells of the eastern and the western sides of the south Atlantic converge at low levels. Since the northern part of the trough is related to the
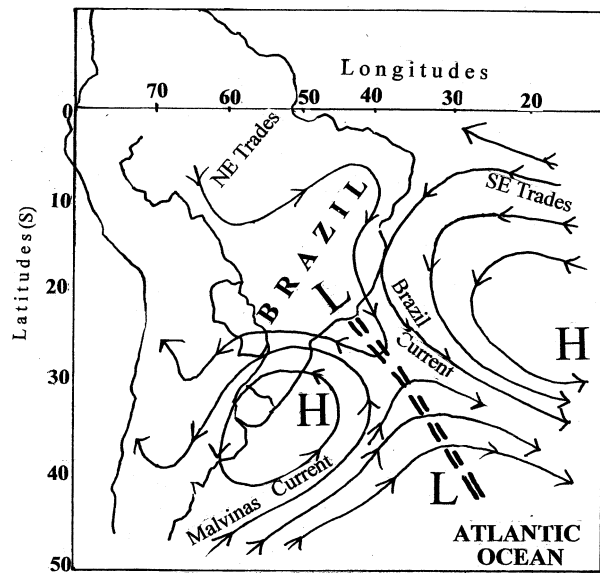
Fig. 16.   Schematic low-level flow pattern in the field of the South Atlantic Convergence Zone (SACZ) indicated by a double-dashed line. H denotes High, L- Low

Fig. 17. Meridional anomaly of mean January vertical motion (unit : 10^{-4} hPa s^{-1}) along 35° W

summer heat low over the continent, it remains active during the austral summer but almost disappears during the winter. The southern part, south of about 30° S, is a strongly baroclinic zone to which two strongly contrasting aircurrents converge. One of these aircurrents which flows from a northerly direction over the warm Brazil ocean current and also advects warm air from the heat source over the continent is warm, while the other which flows from a southerly direction over the cold Malvinas ocean current and advects extremely cold air from the polar latitudes is extremely cold. A schematic showing the mean flow patterns in the field of the SACZ is shown in Fig. 16. With strong low-level convergence of moist air and upper-level divergence, the zone is characterized by strong upward motion, heavy cloud formations and precipitation. Fig. 17, which presents the meridional anomaly of January mean vertical motion along 35° W, clearly shows strong upward motion over the SACZ between about 20° S and 35° S. Fig. 18, which presents the distribution of mean January specific humidity over South America and the surrounding oceans, testifies to large concentration of moisture along the SACZ. As we showed in Part 1 [Fig. 15(a)], there is concentration of heavy rainfall along this convergence zone.

An example of how the intensity and location of the SACZ are affected by interaction with an eastward-propagating cold front of the southern hemisphere was given in section 3 (Fig. 5) and another in section 5. In both, it was seen that the intensity flared up when the cold front merged
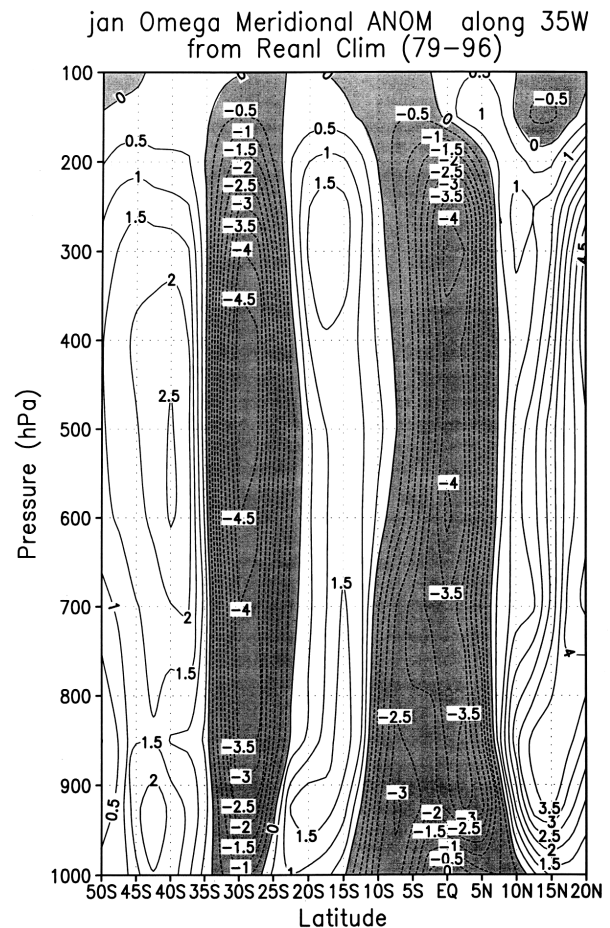
or coupled with the SACZ but dropped when it moved away. In the second example, one could see the modulation in the intensity of the SACZ as the interacting cold front moved away and another cold front approached from the west. In the latter case, the changes that occurred are well brought out by a time-longitude diagram showing the daily distribution of MSL pressure along 30° S, the approximate latitude of the subtropical high pressure ridge over the south Atlantic, during the period 1-8 January 2001, shown in Fig. 19. On 1 January when the cold front coupled up with the trough of the heat low over southeastern Brazil, the SACZ was deep and well-defined with a pressure of about 1011 hPa and located along about 30° W with high pressures on either side. However, during the following 4 days, till about 5 January, as the cold front continued its eastward movement, the SACZ moved little from its usual location along about 30° W but continually weakened till it almost disappeared from 6 January onward when it came under the influence of a new deep cold front approaching from the west. During the period, 1-5 January, the high pressure cells
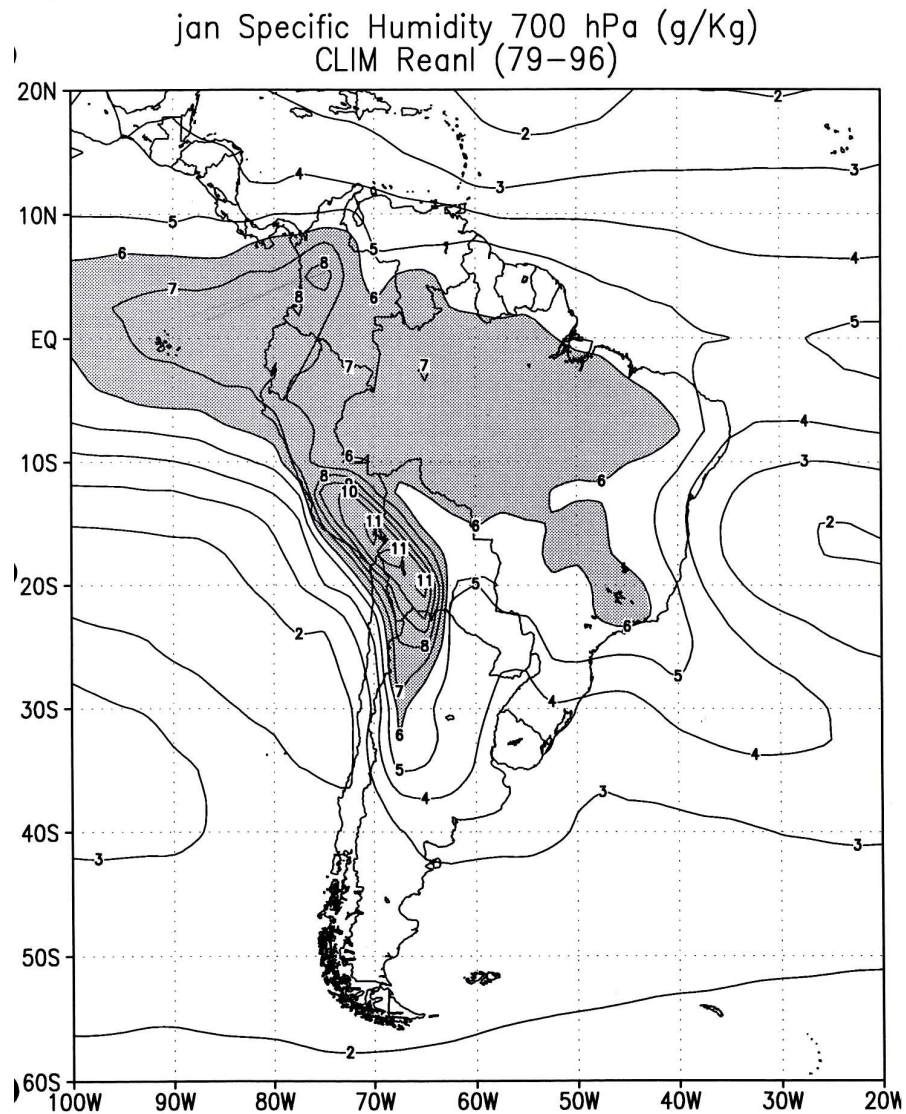
Fig. 18. Mean January specific humidity (g/kg) at 700 hPa over the South American region

on both sides of the SACZ continued to intensify. In all likelihood, it is the intensification of the high pressure cell lying to the east of the SACZ that was reflected in the westward movement of the 1014 hPa isobar and the upper-tropospheric vortex in Fig. 15. Observations show that such fluctuations in the intensity of the SACZ occur quite frequently during the southern summer.

7.   Findings and conclusion

The findings of the present study (Part 2) may be summarized as follows :

(*i*)   The summertime atmospheric circulation over South America generates two quasi-stationary waves in the lower

troposphere : a monsoon stationary wave along the northern boundary of the heat source over the continent and a subtropical stationary wave along the southern boundary.

(*ii*)   The above-mentioned stationary waves interact with the eastward-propagating extra-tropical disturbances of both the southern and the northern hemispheres, with profound effect on the weather and climate of the continent.

(*iii*) The interaction of the quasi-stationary waves with large-amplitude extra-tropical disturbances often leads to formation of westward-propagating tropical disturbances, such as monsoon lows and depressions over the continent and upper-tropospheric cyclonic vortices over the south Atlantic.
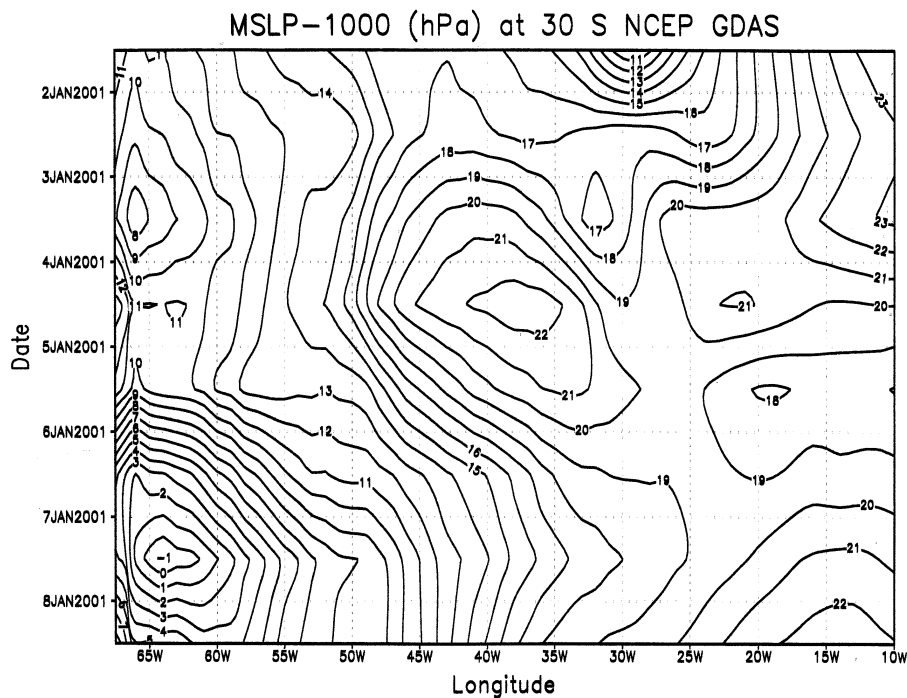
Fig. 19. Time-longitude diagram showing the distribution of MSL pressure (minus 1000 hPa) along 30° S over south Atlantic at 1200 UTC daily during the period, 1-8 January 2001

(*iv*) The observed near-simultaneity in the occurrence of monsoon lows and depressions and upper-tropospheric cyclonic vortices appear to suggest a common physical link between the two types of disturbances.

(*v*)   The South Atlantic Convergence Zone appears to be an extension of a quasi-stationary trough of the summertime heat low circulation over the South American continent into a strongly baroclinic zone of the South Atlantic where two strongly-contrasting air and ocean currents meet.

(*vi*) The interaction of the South Atlantic Convergence Zone (SACZ) with a cold front of the extratropical wave is an outstanding example of tropical-extratropical interaction. The periodic interaction leads to profound changes in the intensity and location of the convergence zone.

Several issues relating to the monsoons of South America were addressed in our study. We believe that our work may help in clarifying or throwing light on at least some of them. However, some dark or grey areas remain, which call for further study. One of these relates to the formation of monsoon lows and depressions. Why was it that as many as two well-developed depressions formed in January 2002, but only a feeble one in January 2001? Our suspicion is that in 2001, the ocean surfaces were unusually

cold and the tradewinds converging into the heat low over the continent from both sides of the equator were too strong and invasive for the heat low to remain effective. In fact, in January 2001, the heat low was relegated to a small area over the western part of the continent only. Perhaps, the same reason could be adduced for failure of a feeble low in January 2000 to develop further. Another area which requires further study is a possible physical connection between the monsoon lows/depressions over the continent and the upper-tropospheric cyclonic vortices over the South Atlantic.

Acknowledgements

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