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"The Andes & Associated Circulations over Central & Eastern South America"

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The Andes and Associated Circulations over Central and Eastern South America

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Abstract

The Andes Cordillera is the major mountain chain in the Southern Hemisphere. The geometry of the cordillera and its location play an important role not only in determining the stationary atmospheric patterns, but also in controlling the structure of the transient weather systems over the continent. Here we review some effects of the Andes Cordillera on the atmospheric circulations over South America, from large to smaller scales systems.

1 Introduction

The understanding of regional climate and weather of a particular place requires the knowledge of the physiographic features, the prevailing winds and the interactions between these entities. The Andes Cordillera, with its elevations generally over 2000 m, and widths of about 400 km (Figure 1), represents a huge barrier to the prevailing winds from the west in subtropical latitudes, and to the trade winds in the tropical latitudes. It is a narrow Cordillera that extends from about 40°S all the way to Central America. Over Bolivia, between the latitudes 15° and 21°S, the Cordillera becomes wider and with heights over 4000 m, forming the Bolivian Altiplano. A secondary maximum in elevation in South America is located over Brazil, south of 15°S, which forms the Brazilian Highlands.

The direct control of topography on weather regimes in South America can be imediately seen by the distribution of precipitation. On the eastern slopes of the Andes Cordillera in Peru and Ecuador and on the western slopes in Colombia are regions of precipitation maxima (Figueroa e Nobre, 1990). Low level easterly-northeasterly flow over Amazonia carry moisture towards the eastern slopes of Peru, the barrier effect of the Andes mechanically lifts the air causing heavy precipitation. Similarly, in western Colombia, a turn to the west of the easterly trades north of the equator brings moisture from Pacific Ocean inland. The annual total precipitation in those locations exceed 3000m.

In this article, a review of the main features of circulation in South America which are affected by the presence of the Andes will be given. The subject will be covered in a downscaling fashion, from the large scale semi-permanent circulations of the Bolivian High and the South Atlantic Convergence Zone (SACZ), to the transient systems down to the smaller scales features: frontogenesis, Low Level Jet and zonda winds.

3 Large Scale Circulations

3.1 Bolivian High

In South America, a large portion of landmass is located on the tropical latitudes, this feature combined with the elevated heat source such as the Bolivian Plateau, the Brazilian highlands and the moisture transported from the Amazon Basin, are the ingredients necessary to produce a well-established monsoonal circulation over South America during austral summer. Latent heat released from this continental convective activity produces an upper-level anticyclonic circulation. High geopotential values are generally centered over the Bolivian Altiplano at upper levels during summer. This feature is known as the Bolivian High.

The Bolivian High is part of the monsoonal system of South America. The continent has been considered monsoonless because there was no observed wind reversal at lower levels. Zhou and Lau (1997) showed using NASA-GEOS-1 assimilated data that a direction reversal of perturbation wind occurs in the lower levels between January and July. They recognized that the South American monsoon is a component that is missing in many climate studies.

3.1.1 Characteristics

Along the tropical region, three anticyclonic circulations can be found in the upper troposphere: the Bolivian High over Bolivia, another to the north of Australia and the third one over Africa. These anticyclones share common features, such as: the position to the west/southwest of maximum precipitation regions and location within 10°N- 20°S; a pronounced trough to the east, except in Africa, where it is weak during summer; and a cross-equatorial flow that feeds the subtropical jet in Northern Hemisphere.

The trough downstream the anticyclone generally becomes very pronounced during summer and an intense cyclonic vortex is formed (Figure 2.a) This strong cyclonic vortex affects the weather of Northeast Brazil. At the lower troposphere, one convergence band is positioned to the southeast of the Bolivian High, the South Atlantic Convergence Zone - SACZ; and to the northeast, another convergence band, the Intertropical Convergence Zone - ITCZ. These 4 systems are the main predominant features of the South American summer circulation.

Figure 2.b shows the 200hPa wind speed and streamlines on 8 January, 1996, 12UTC, taken from National Center for Environmental Prediction (NCEP) analyses. The Bolivian high is indicated by the letters AB. Another anticyclone is found to the southeast of AB, this circulation is related to the SACZ at lower levels. The days that followed, the anticyclones merged and an intensification of the upper level circulation was observed over this region.

3.1.2 Origin

The existence of the Bolivian High was known since 60's and 70's (Gutman and Schwerdtfeger, 1965; Schwerdtfeger, 1976). However, only after a study using winds retrieved from satellite (Virji, 1981), this high pressure center over the Bolivian Altiplano was confirmed.

According to Silva Dias et al. (1983), the Bolivian High is as consequence of the latent heat released in the areas of deep convection over the Amazon, which generate Rossby and mixed-Rossby-gravity waves. Rao and Ergogan (1989) computed heat sources around the Bolivian Plateau using observations for January 1979, and found that latent heating was the main source, which could be stronger than that over Tibetan Plateau. Sensible heat flux played an important role in initiating the convection. However, recent modelling studies suggest that sensible heat over the Andean highlands has no effect in causing the anticyclone (Tanajura, 1996; Lenters and Cook, 1997).

3.1.3 Effects of the Andes

In the studies carried out by Kleeman (1989), Gandu and Geisler (1992), Figueroa et al. (1995) and Lenters and Cook (1997), they suggested that the effects of the Andes over the Bolivian High is small. However, Kleeman (1989) and Figueroa et at. (1995) suggested that the barrier effect of the Andes can influence the formation of the surface Chaco Low, positioned to the north of Argentina.

In the simulations of South America summer circulation, Tanajura (1996) shows the importance of the Andes in transporting moisture from the Amazon to the south of the continent.

3.2 South Atlantic Convergence Zone - SACZ

The South Atlantic Convergence Zone can be detected in the infra-red satellite images as a quasi-stationary cloud band that extends in the NW-SE direction from the Amazon region towards the South Atlantic Ocean. It is normally observed from November through March. Figures 3.a,b,c,d are satellite images showing a SACZ that formed in the period of 1-19 January, 1996.

3.2.1 Characteristics

The SACZ is one of the Subtropical Convergence Zones (STCZ) studied by Kodama (1992, 1993). These bands show many common features, such as: they are quasi-stationary systems; associated with strong convective activity to the west and a subtropical high pressure to the east; exhibit strong equivalent potential temperature and moisture gradients; have baroclinic structure and convectively unstable regions; and are related to the Subtropical Jet.

In Paegle and Mo (1997) study, based on two reanalysis datasets, NCEP and DAO/NASA, the convection related to the SACZ is shown to go through a seesaw pattern, of increased and decreased convective activity of about 8 days. During wet conditions, reduced precipitaion was observed to the south of SACZ, while in dry conditions, positive precipitation anomalies were observed over Northeast Argentina and South of Brazil. This result is in agreement with Kousky and Casarin's work (1986). Increased activity pattern occurred more often during ENSO years. This interannual variability of SACZ was also studied by Quadro (1994), who found that SACZ was either absent or out of its climatological position during ENSO years. These results suggest that a possible mechanism for dissipation of SACZ may be related to subsidence over Amazonia, which occur generally during ENSO events.

3.2.2 Origin

Kodama (1993) studied the large scale conditions during periods of active and inactive STCZ, and noticed that the formation of these zones were associated with the presence of the Subtropical Jets in latitudes between 30°-35°S and a poleward flow in the lower troposphere to the west of subtropical high.

Figueroa et al. (1995) used a numerical model in eta (η) vertical coordinates with Andes topography and a thermal forcing in the Amazon. A SACZ was generated in response to this forcing. This study suggested that this convergence zone was formed independent of the presence of the Andes, however, an intensification of the zone in its climatological position was caused by the inclusion of the Andes.

Using a general circulation model, Lenters and Cook (1995) showed that the presence of the continent was found to be important for the formation of the SACZ. According to their work, the maximum precipitation over the Amazon region was associated with a thermal low at lower levels in this region. Despite the low resolution, R30, of the spectral GCM used by Lenters and Cook (1997), they also found that the Andes had influenced the position of the SACZ.

3.2.3 Effects of the Andes

Figueroa (1997) performed GCM simulations at T63L28, with and without the Andes, and tried to explain the role of the Andes over SACZ. The main results of his work are:

- The formation of the SACZ shows no dependence on the Andes, on the South Pacific Convergence Zone, on the Intertropical Convergence Zone or African convection. However, in the absence of tropical convection over South America, this zone is also absent.

- The transients from mid-latitudes over South America has influence on SACZ, but are not the only condition for maintenance of the zone, tropical convection must also be present.

- The Andes are responsible for positioning the maximum of precipitation observed during summer at about 50°-60°W and 7°-15°S (Figure 4.a). This position is a consequence of the barrier effect of the Andes. The lower troposphere easterlies/northeasterlies blow over the tropical region, when they meet the concave eastern slopes of the Andes, between 5°S and 20°S, these winds are deviated toward the central region of South America creating a zone of convergence and maximum of precipitation.

- In the absence of the Andes, the centre of maximum precipitation is formed at about 0°-5°S and 60° -50°W, equatorward of the climatological position (Figure 4.b). Consequently,the Andes influence indirectly in the position and intensification of the SACZ, through "anchoring" the rainfall maxima over the central tropical South America. In the Absence of the Andes, the SACZ is displaced to the southeast of its climatological position.

4 Transient systems

The convective activity in the SACZ is strongly modulated by the cyclones that travel across Argentina and reach Southeast Brazil. Sinclair (1995) built a climatology of cyclogenesis for the Southern Hemisphere based on geostrophic vorticity taken from ECMWF analyses for the period 1980-1986. Genesis in South America occurred frequently to the southeastern part of the continent, with two maxima: one at about 35°S, over Uruguay, and another over the Argentina coast, at about 45°S. Sinclair suggests that this maximum is associated with frequent lee cyclogenesis due to the Andes. Surface heating has little importance as the region is located near cold waters.

Gan e Rao (1994) applied a lag correlation analysis to geopotential heights. They obtained a wavelike pattern moving eastward which exhibited orographic effects such as the anticyclonic turning of the trajectory of the low level disturbance, the distortion of the correlation isolines and the elongation of the maximum correlation center after crossing the Andes. The trajectory of the disturbance was tracked and showed that it penetrates into the continent from the west at about 45°S, where the Andes heights are lower, after this point, the trajectory changes abruptally to northeast up to about 30°S and then moves eastward and southeastward towards the ocean. The importance of the Andes was shown in a GCM simulation (Seluchi et al.,1998) where the heights of the Cordillera was increased by 1000 m all along and resulted in better description of the transient cyclones and anticyclones.

5 Smaller scales effects

5.1 Lee side Frontogenesis

Lupo and Bosart (1997) examined the characteristics of cold air surges in South America and identified potential vorticity gradient oriented meridionally east of the Andes during anticyclonic events. They suggested that the Andes funneled the low-level cold air equatorward, by negative potential vorticity advection which caused the surface anticyclone to be elongated.

Knight and Bosart (1997) used NCAR/PSU mesoscale model to examine this equatorward expansion of the anticyclone. They showed that on the equatorward side of the anticyclone, the air ascends the mountains, cools adiabatically, decelerates and turns ageostrophically equatorward, toward lower pressure, favouring frontogenesis to the east of the Andes.

Ten-year reanalysis data from ECMWF and NCEP, reveal that the region between the latitudes 30°S and 40°S, to the east of the Andes, is climatologically favourable to frontogenesis (Mattos, personal communication), corroborating previous works.

An example of frontogenesis that occurred to the east of the Andes was predicted by the 40km-grid Eta model at CPTEC (Black, 1994; Climanálise, 1996) is shown in Figure 5. Low level cold air turn anticyclonically as it flows past the southern end of the Andes. This equatorward cold air outbreak helps to create a frontal zone between 20°Sand 40°S. The frontogenesis process can be followed by the sequence of 12-hour interval.

5.2 Low Level Jet

Low level jets can be described as a shallow layer of high wind speed generally observed during the night. Alternative hypotheses offered for LLJ's are:

1. .mountain barriers deflecting poleward (Wexler, 1961).
2. mass adjustment processes associated with leeside cyclogenesis (not boundary force dynamics mechanism), as studied in Ucellini and Johnson, 1979.
3. inertial oscillation with a supergeostrophic wind at night, as a response to a time dependent variation in the effective eddy viscosity in the boundary layer (Blackadar, 1957).
4. Diurnal oscillation in a thermal wind component over sloping terrain like the ones generated by land surface heterogeneities or other diurnally forced baroclinic zones (Holton, 1967, Fast and Mc Corcle, 1989). Particular attention shoul be given to this mechanism considering the presence of the Andes.

Bonner (1968) listed 3 criteria for identifying LLJ occurrences which differ by their intensities : 1. wind speed over 12 ms^{-1} between surface and 1500 m; 2. a northerly wind component (for Southern Hemisphere); and 3. a wind shear larger than 6 ms^{-1} within the layer of maximum wind speed and 3000 m.

In South America, a maximum meridional northerly wind has been observed to the east of the Andes in the central region of the continent (Virji, 1981). This northerly jet plays an important role in transporting moisture from the Amazon region southwards. Night-time observations (21:00 LST) taken at two stations north of Argentina, Salta and Resistencia, show that this moisture transport is maximum in the layer between 300-600 m and is present throughout the year (Berri and Inzunza, 1993).

The low time and spatial resolution of vertical sounding observations impedes a better description of the low-level jet. Wang and Paegle (1996) showed that uncertainty in the calculations of moisture flux is larger over South America than over North America, since the latter is an observation rich region. Those calculations were based on analysis models which have different treatment of boundary layer. They suggest that a better representation of the LLJ could reduce more critically the discrepancies. They observed southerly wind overnight reversal to northerly jet which accounted for large moisture flux. The diurnal fluctuations of moisture flux accompanied the diurnal oscillation of the low-level wind.

Nogués-Paegle and Mo (1997) noticed that the Low Level Jet located to the east of the Andes, over Argentina, at about 25-30S, was stronger during periods of weaker SACZ. When convection reintensified in the SACZ, the LLJ was replaced by southerlies. Composite for the weak SACZ phase from the 10-summer re-analyses showed the strong diurnal cycle of the vertically integrated moisture flux which was caused by the Low Level Jet.

The term Low Level Jet has been used loosely over this region without checking for Bonners' criteria. Based on the model outputs, Bonner criteria of LLJ can be slightly modified to match available operational fields as follows: 1. wind speed > 12 m/s between the surface and 850 hPa; 2. northerly winds; and wind shear between 850 hPa and 700 hPa and/or between 900 and 700 hPa must be at least 6m/s.

The Regional Eta model forecasts for the period from September 1997 until February 1998 showed that can be satisfied over South America and classified into three major types (Figure

6.a,b): *A*, between 30° and 35°S; *B*, between 10° and 15°S; and *C*, which extends from 10° to 35°S. The type *A* is fed by Atlantic Ocean air mass during transient anticyclone northeastward progression. Type *B* was the most frequent one, occurring more than 90% of the period. Type *C* shows clearly its role in transporting moisture from the Amazon region to feed a convergence zone located over southeastern South America. This type occurred about 50% of the period. Figures 7.a,b,c show the mean wind and shear at 950, 900 and 850 hPa taken from LLJ cases of December 1997. The maximum of wind and shear are located at about 20°S, with maximum speed at about 900 hPa. All these jets are observed to follow approximtely the eastern border of the Andes. This suggests the importance of the sloping terrain in generating these jets. The inertial oscillations may also be playing part as the 900 hPa winds averaged for the LLJ cases show an anti-clockwise turn, with increased speed at night time (Saulo et al. to be submitted)

Although modeling results have shown the existence of the LLJ from about 10°S over Bolivia to 25°-30°S, until recently there was hardly any observational evidence confirming the existence and structure of the LLJ except in Northern Argentina. Recently the presence of the LLJ episodes have been shown for Bolivia as Figure 8 clearly depicts for January and February 1998 based on soundings from Michael Douglas, 1998..

5.3 Foehn effect - Zonda

To the lee of the Andes, between the latitudes of 30°-35°S, in northwest Argentina, a foehn type of wind is observed to occur. This wind is locally known as zonda wind, it is a sudden uncomfortably warm and dry wind that blows from the Andes. This phenomenon generally preceeds a cold front passage across Argentina. Observations from two radiosondes taken on each side of the Andes, showed that the event occurred mainly within the layer between 500 and 850 hPa, and revealed a strong inversion at the bottom of that layer (Norte, 1988).

Using an objective analysis method Seluchi and Norte (1993) developed a tool for forecasting zonda events. The analyses were based on several stations in the vicinity of both sides of the mountains. The technique provided reasonable forecasts of the event. The inclusion of a sounding located more to the north, Mendonça, at about 32°S, produced better results than a sounding to the south, Puerto Mountt at about 41°S.

The scarcity of data in this region is notorious and a reliable description of the meteorological phenomena is not possible. Numerical atmospheric model with complete physics can provide a more approximate description of the structure of the atmosphere during a zonda wind occurrence. Figure 9. shows vertical cross sections of 24-hour forecast of: vertical velocity, zonal wind and potential temperature, taken along the latitude of 30°S. These forecasts were produced by the 40 km resolution Eta model and verify on 5 June 1998, 12UTC. The main features of this phenomenon are the strong descent of air to the lee side of the Andes, of one order of magnitude higher than the surroundings; strong winds from the upper level jet reaching mid-troposphere, and a deceleration of the jet above mountain; isentropes dive from about 600 hPa down to about 800 hPa. The strong deceleration of the upper level jet is a result of the downward momentum transport caused by the drag exerted by the Andes on the atmosphere. This deceleration can also be detected from global analyses (Figure 10).

6 Final considerations

This short review of the Andes mountain role on circulations – from semi-stationary, large-scale circulations to mesoscale features – attempts to illustrate the fundamental importance of this north-south barrier to weather and climate in South America. However, there is a suite of key questions on the role of the Andes still in search of answers. The detailed role of the barrier on the equatorial deflection of the mid-latitude storm track east of the Andes and on its high intra-seasonal variability is poorly known. Addtionally, the maximum of precipitation east of the Andes over the low lands of western Amazonia (Annual Precipitation > 3m)is thought to be related to the Andes, but a mechanism is still lacking. On the mesoscale, the scarcity of observations has prevented fully understanding the dynamics of the LLJ and its importance as a duct of moisture from Amazonia to southeastern South America.

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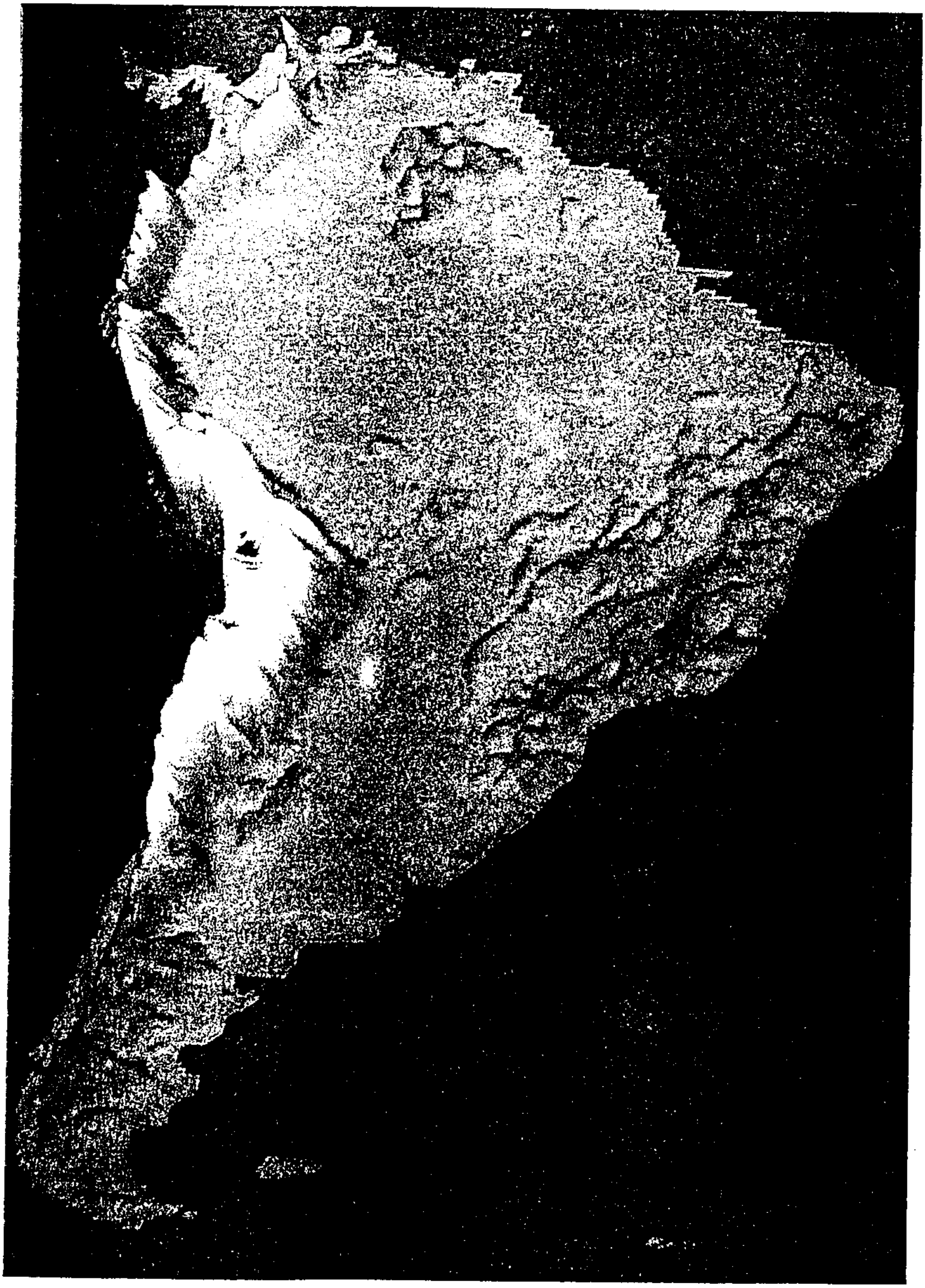


Fig.1

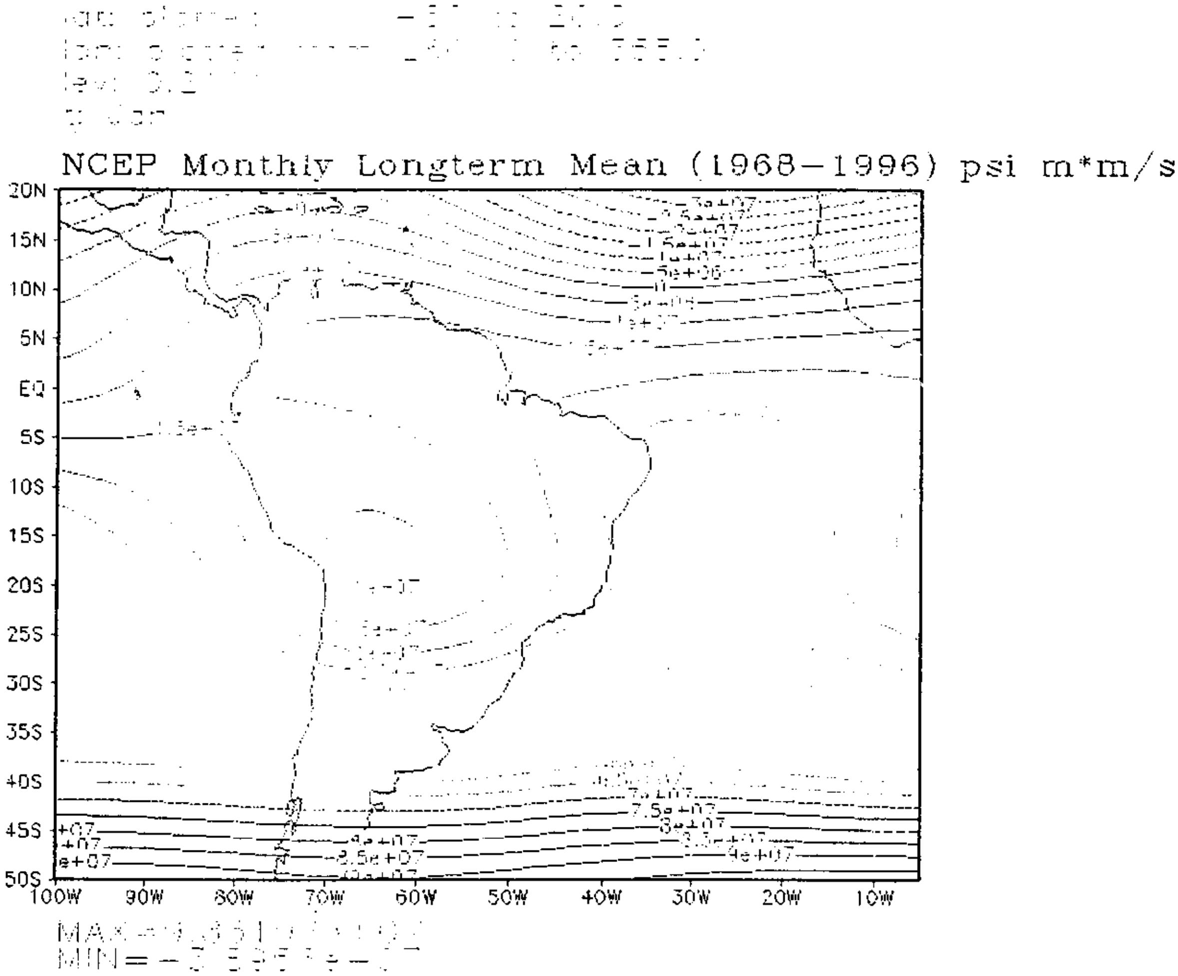


Figure 2.a NCEP monthly longterm streamfunction mean (1968-1996), ψ ($m^2 s^{-1}$), at 0.2 σ-level, over South America provided by the *NOAA-CIRES/Climate Diagnostics Center*.

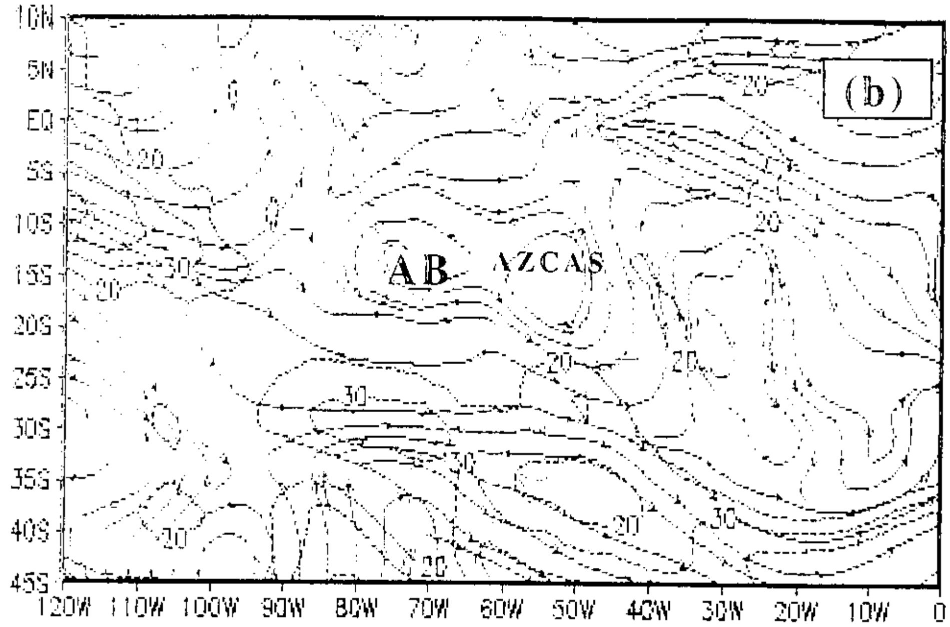
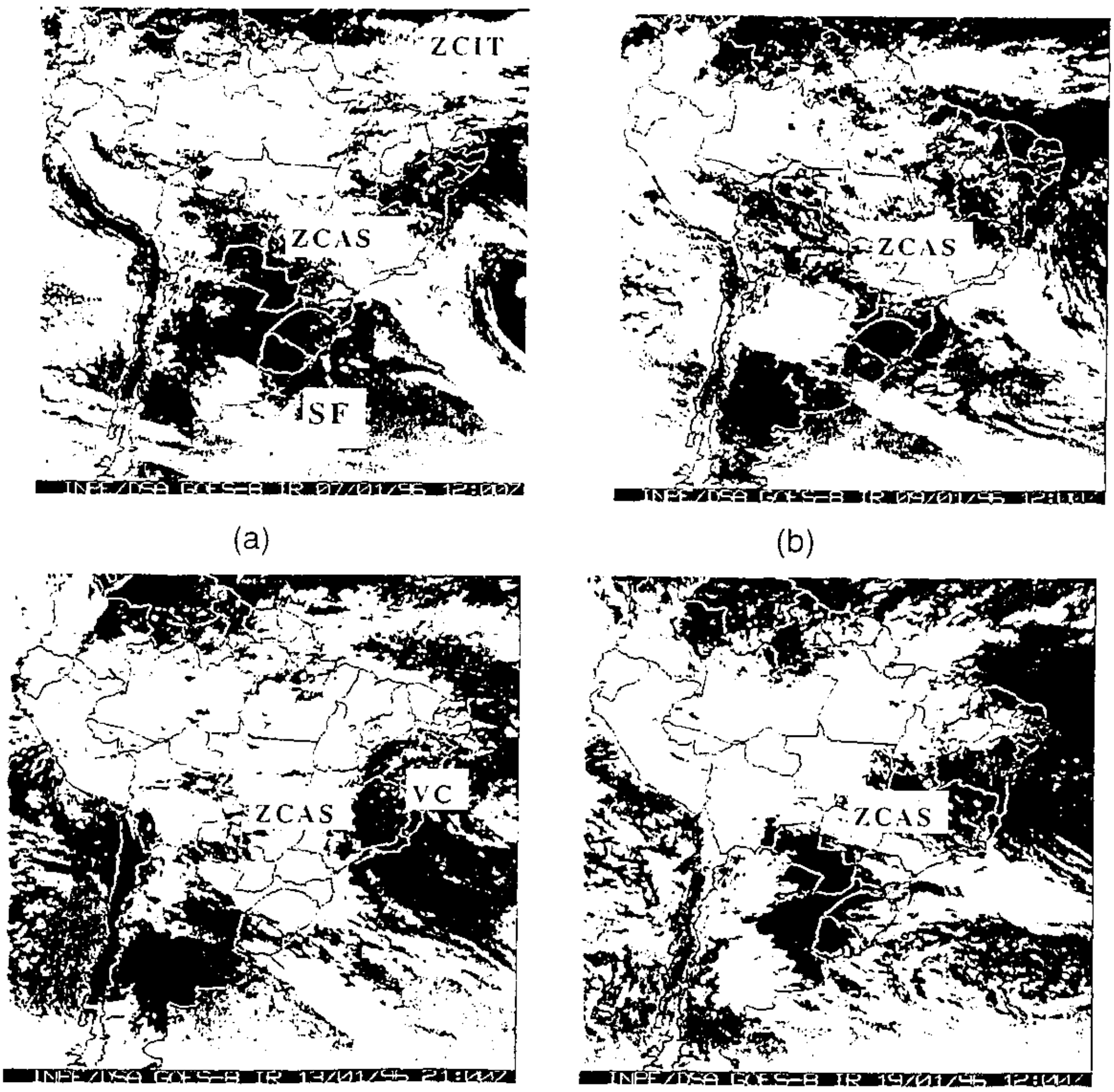


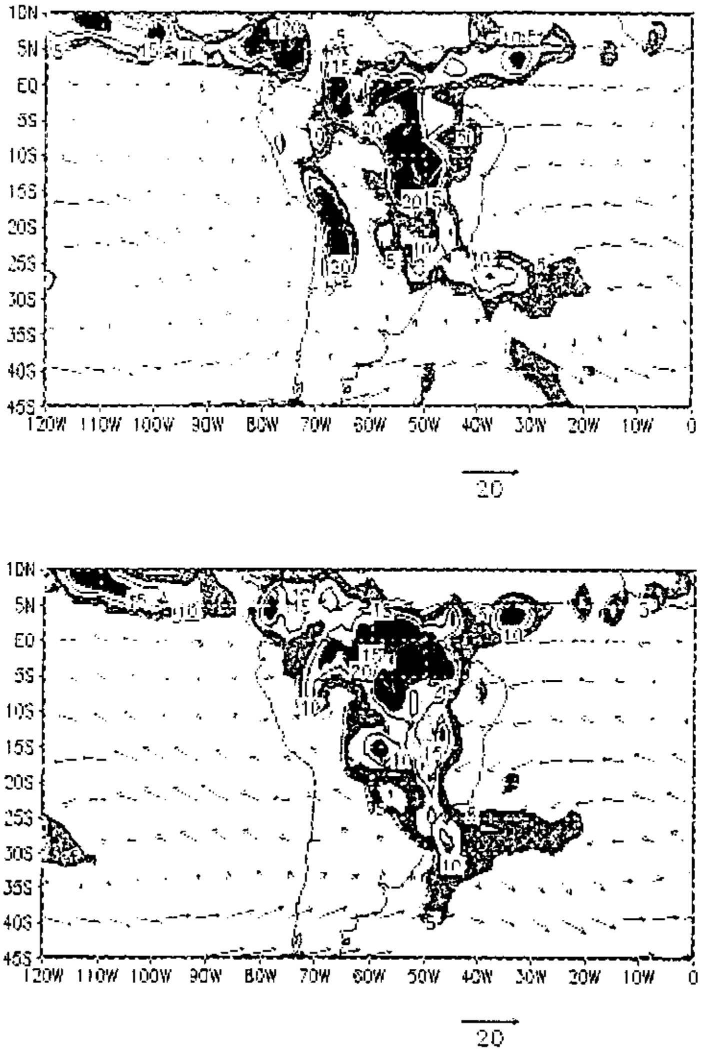
Fig.2



(a) (b)

(c) (d)

Fig.3


10N 5N EQ 5S 10S 15S 20S 25S 30S 35S 40S 45S
120W 110W 100W 90W 80W 70W 60W 50W 40W 30W 20W 10W 0
20

(a)

(b)

Fig. 4

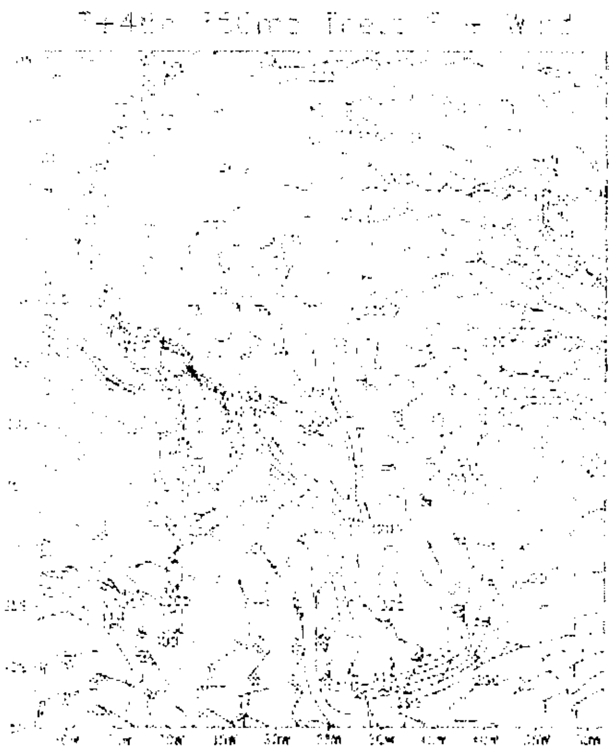


FIG.5

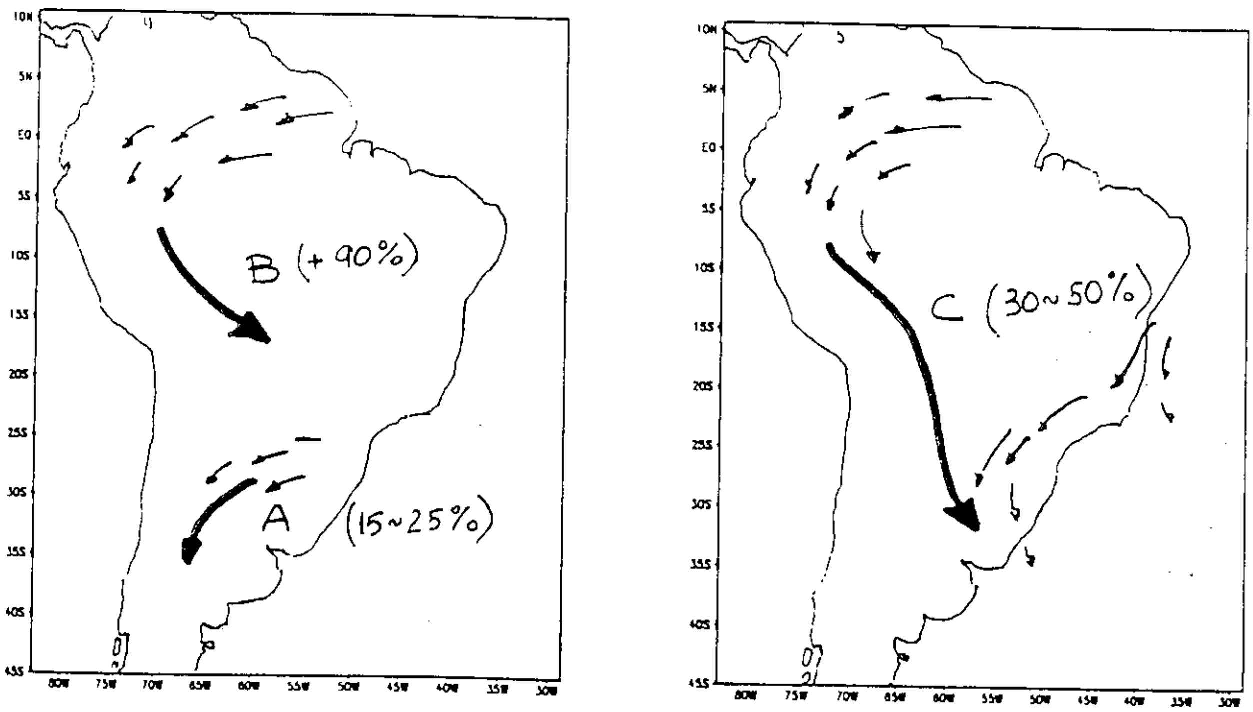

B (+90%)
A
(15~25%)
C (30~50%)
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
45S
80W
75W
70W
65W
60W
55W
50W
45W
40W
35W
30W

Fig. 6

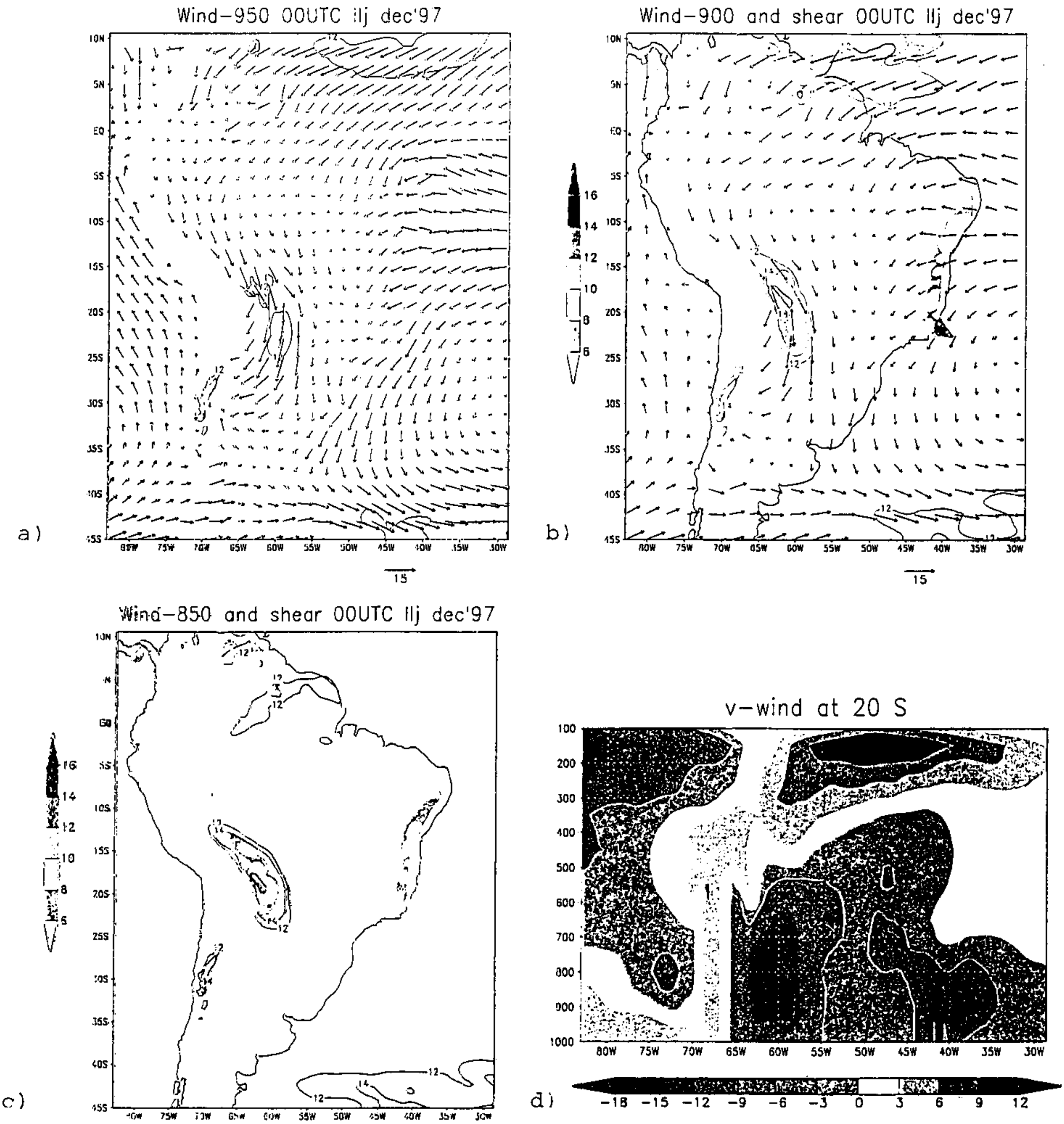
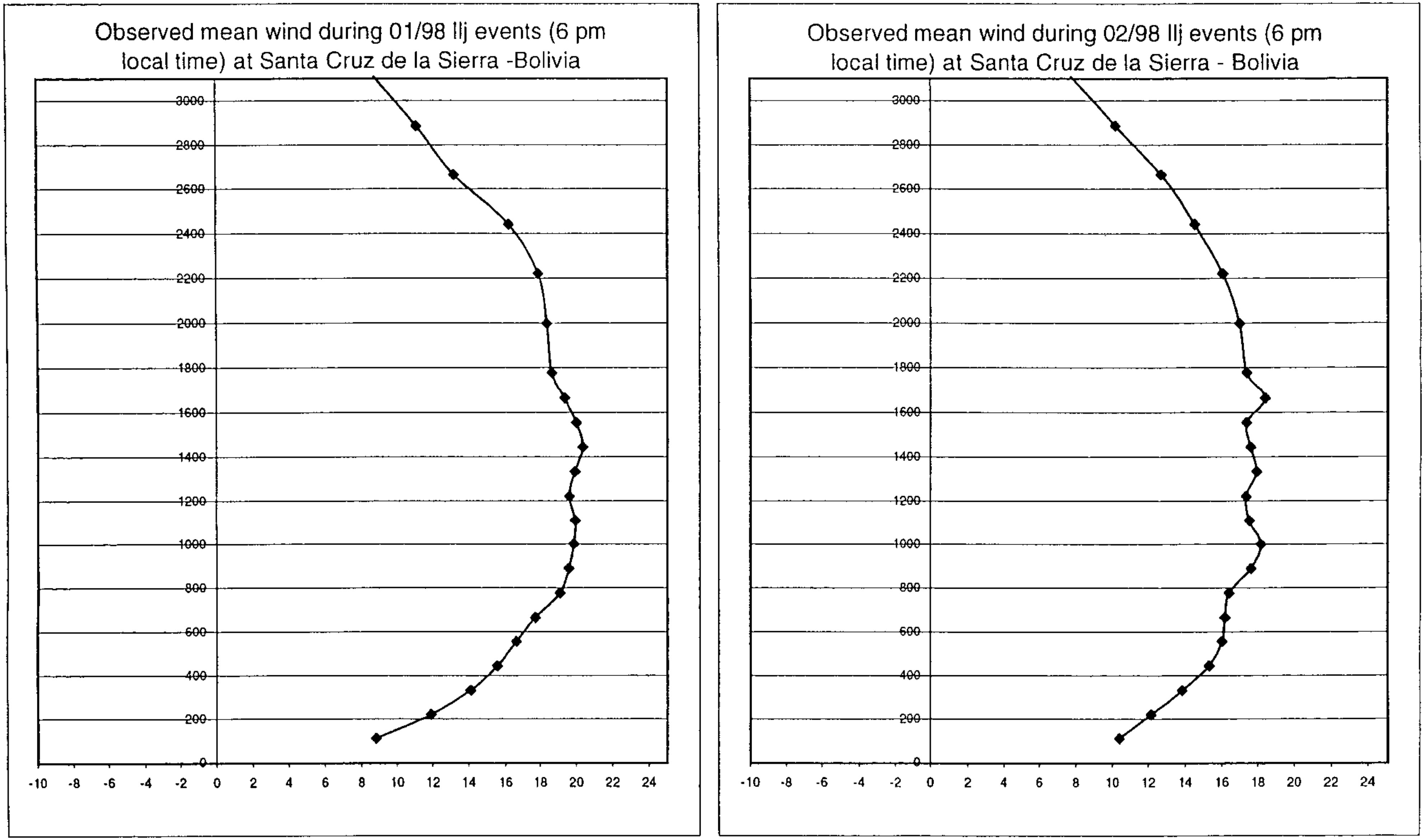

Wind−950 00UTC llj dec'97
Wind−900 and shear 00UTC llj dec'97
Wind−850 and shear 00UTC llj dec'97
v−wind at 20 S
a)
b)
c)
d)
10N
5N
EQ
5S
10S
15S
20S
25S
30S
35S
40S
45S
80W 75W 70W 65W 60W 55W 50W 45W 40W 35W 30W
15
16
14
12
10
8
6
100
200
300
400
500
600
700
800
900
1000
−18 −15 −12 −9 −6 −3 0 3 6 9 12

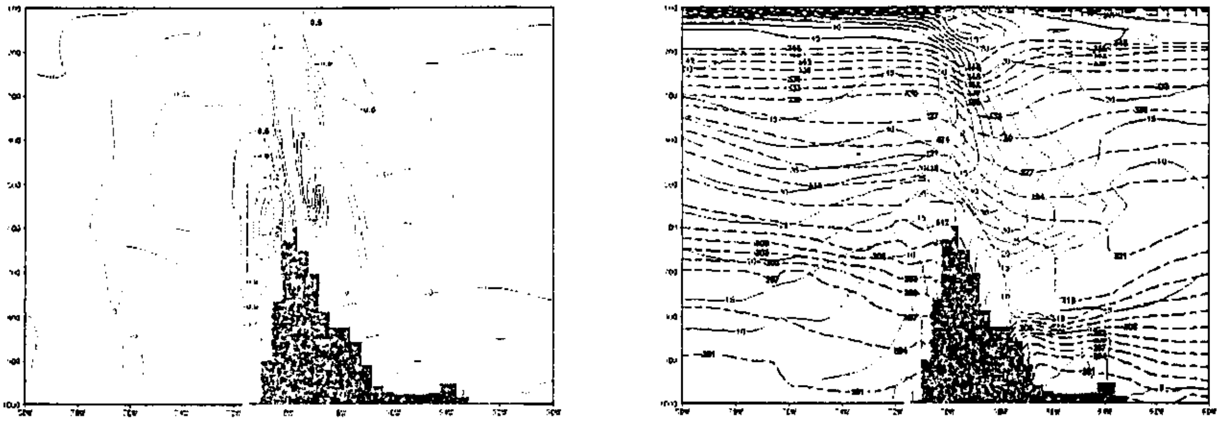
Fig. 7


Observed mean wind during 01/98 llj events (6 pm local time) at Santa Cruz de la Sierra -Bolivia
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24
Observed mean wind during 02/98 llj events (6 pm local time) at Santa Cruz de la Sierra - Bolivia
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 22 24

(A)

(B)

Fig. 8



(a) (b)

FIG. 9

FIG. 10