MAUSAM, **55**, 1 (January 2004), 41-72

551.553.21 : 551.513 : 551.582 (8)

On the monsoons of South America
Part 1 : Climatological structure and circulation

KSHUDIRAM SAHA

4008, Beechwood Road, University Park, MD 20782, U.S.A

and

SURANJANA SAHA

Environmental Modeling Center, NCEP/NWS/NOAA, U.S.A.

(*Received 13 June 2002, Modified 22 October 2003*)

सार – दक्षिणी ग्रीष्म ऋतु के दौरान महाद्वीप में ऊष्मा स्रोत तथा उसके चारों ओर के महासागरों पर उष्मा अभिगम के बीच क्रियाशील होने वाली दक्षिणी अमरीका की सुविकसित मानसून परिसंचरण की घटना को प्रमाणित करने के लिए भू–वायुमंडलीय विकिरण बजट के विश्लेषण के साथ ही परम्परागत मौसम विज्ञान संबंधी विश्लेषण का उपयोग किया गया है। इन विश्लेषणों से प्राप्त हुए प्रमाणों से यह सिद्ध होता है कि ऋतुनिष्ठ उत्क्रमण के मापदंड केवल पवन क्षेत्र में ही नहीं बल्कि तापमान, समदाब ऊँचाई, विशिष्ट आर्द्रता और वर्षा जैसे अन्य अनेक विचलनों के क्षेत्रों के भी अनुकूल होते हैं। विभिन्न ऋतुओं से परिकलित किए गए याम्योत्तरी उर्ध्वाधर परिसंचरणों से यह पता चलता है कि महाद्वीप में मानसून का आरंभ और वापसी हैडले के संचलन और मानसून परिसंचरण सेल से संबद्ध है जिसके बाद उष्मा स्रोत के मौसम संचलन होते है। इस अध्ययन से प्राप्त निष्कर्षों के आधार पर मानसून की एक संशोधित परिभाषा प्रस्तावित की गई है।

ABSTRACT. Earth-atmosphere radiation budget analyses as well as conventional meteorological analyses are used to establish a case for a well-developed monsoon circulation over South America operating between a heat source over the continent and a heat sink over the surrounding oceans during the southern summer. Evidence is produced to show that the criterion of seasonal reversal is met not only by the wind field but also by the fields of several other variables, such as temperature, isobaric height, specific humidity and rainfall. Computed meridional-vertical circulations for different seasons appear to suggest that the onset and withdrawal of monsoon over the continent are related to the movement of Hadley and Monsoon circulation cells following the seasonal movement of the heat source. A revised definition of the monsoon is proposed in accordance with the findings of the study.

Key words – South American monsoon, Heat sources and sinks, Hadley and monsoon circulations.

1. Introduction

Among the available publications on the Climates of South America (Kendrew, 1961; Taljaard, 1972; Boucher, 1975; Schwerdtfeger, 1976; Pearce and Smith, 1990; Satyamurty *et al*., 1998), few mention of the presence of a monsoon circulation over the continent, even though the monthly or seasonal variation of certain climatic elements, such as rainfall, clearly exhibit the main monsoonal characteristics of reversal between summer and winter, as found in regular monsoon lands of Asia, Africa and Australia and evident from Fig. 1 which shows the monthly variation of climatological rainfall at three selected locations in the southern hemisphere, Darwin (30 m elevation; 12.5° S, 131° E) in Australia, Lilongwe (1100 m; 14° S, 34° E) in Southern Africa and Goias (520 m; 16° S, 50° W) in South America, all in the same latitude belt, 12° S - 16° S (Pearce and Smith, 1990). Similar type of seasonal variation is also found in other climatic variables over South America. One wonders as to what could be the reason for this non-mention! One possible reason may be that the observed surface wind field over the tropics which is dominated by strong trade winds does not reveal the seasonal reversal of direction, which is laid down as the main criterion by the current definition of the monsoon (Ramage, 1971). However, following an original remark by Halley (1686) that monsoon constitutes a large-scale perturbation in the trade wind field in the tropics, a few recent studies (Van den Dool and Saha, 1993; Saha *et al*., 1994, 1998) have found evidence of monsoon circulation over several areas of the globe when they removed the annual mean from the monthly or seasonal mean of the circulation. Zhou and Lau (1997) who recently computed the perturbation wind

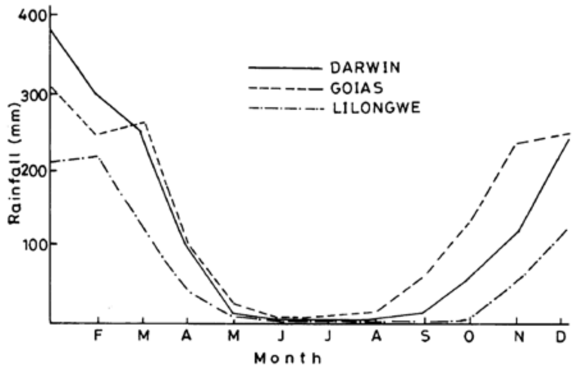


Fig. 1. Mean monthly precipitation (mm) at Darwin (12.5° S, 131° E ; Australia) , Lilongwe (14° S, 34° E; Malawi, Africa) and Goiás (16° S, 50° W; Brazil, South America)

field (by eliminating the annual mean from the monthly mean) at 850 hPa in January and July over South America found evidence of a monsoon-type circulation over South America. Their study showed not only a seasonal reversal of the wind at 850 hPa but also a mean meridional-vertical circulation with rising motion over a heat source and sinking motion over a heat sink. The present study investigates the problem of monsoons over South America by using satellite radiation data and an 18 year (1979-96) mean National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis (Kalnay *et al*., 1996) for different months of the year and a set of daily aerological and satellite data during January, 1999-2002. The paper is divided into two parts : Part 1 deals with some climatological aspects and seeks to find evidence for the presence of a monsoon in the fields of several meteorological variables, such as wind, temperature, isobaric height, moisture content and rainfall. Attempts are made to reveal the horizontal and vertical structure of the monsoon with reference to the equatorial troughs and their movement and evolution in space and time. Part 2, which is based on analysis of a set of daily surface and aerological data, will deal with the formation of monsoon depressions over South America and their interactions with mid latitude disturbances and some related problems.

2. Physical features and environmental conditions

Situated between latitudes about 12° N and 56° S, South America is a continent which extends deep into the extratropical belt of the southern hemisphere. However, the shape and dimension of the continent with its widest part in the equatorial belt but narrowing down rapidly to both north and south has created an impression (Ramage, 1971) that there can be no monsoon over this continent. It is true that longitudinally it is widest between 5° S and 10° S with an average width of about 4500 km and narrows down to both north and south. But its dimension is certainly not negligible when compared to that of Southern Africa and Australia which are well-known monsoon continents (Table 1). But for its narrow link with Panama (Central America) in the northwest, South America is totally surrounded by oceans, the Caribbean Sea to the north, the Atlantic ocean to the northeast and east and the Pacific ocean to the west and south. Thus, as a consequence of its geographical location and oceanic environment, the equatorial and tropical belts of South America are exposed to the trade winds of both the Atlantic and the Pacific oceans, while its high latitudes, south of about 40° S, come under the sway of the extratropical westerlies, or the so-called ‘roaring forties’, practically throughout the year. However, the extent to which these planetary wind systems affect the weather and climate of South America depend on the physical features of the continent and the surrounding oceans. Fig. 2 shows the topography of the continent with the high Andes mountains running almost north-south parallel to the Pacific coast and a few other less conspicuous mountain ranges and plateaux in the northern and eastern parts of the continent. It also shows major lowland areas of the Amazon basin, southern and northeastern Brazil, Paraguay, Uruguay and eastern Argentina, along with strips of lowlands of varying width lying around the coastal belts. Over the oceans, the eastern Pacific south of the equator where the strong Humboldt or Peruvian current flows northward is extremely cold due to upwelling along the Pacific coast and the cold ocean

TABLE 1

Approximate longitudinal width (km) of landmass in different latitudinal belts over the continents of South America, South Africa and Australia, south of the equator

Latitude belt	South America	South Africa	Australia
0 - 5° S	3850	3075	Ocean
5 - 10° S	4450	2775	Ocean
10 - 15° S	3850	2775	800
15 - 20° S	3225	2525	2400
20 - 25° S	2630	2100	3250
25 - 30° S	2250	1700	3800
30 - 35° S	2000	1500	3700
35 - 40° S	1500	Ocean	1000
40 - 45° S	1075	Ocean	300 (Tasmania)
45 - 50° S	850	Ocean	Ocean
50 - 55° S	725	Ocean	Ocean
55 - 60° S	Ocean	Ocean	Ocean

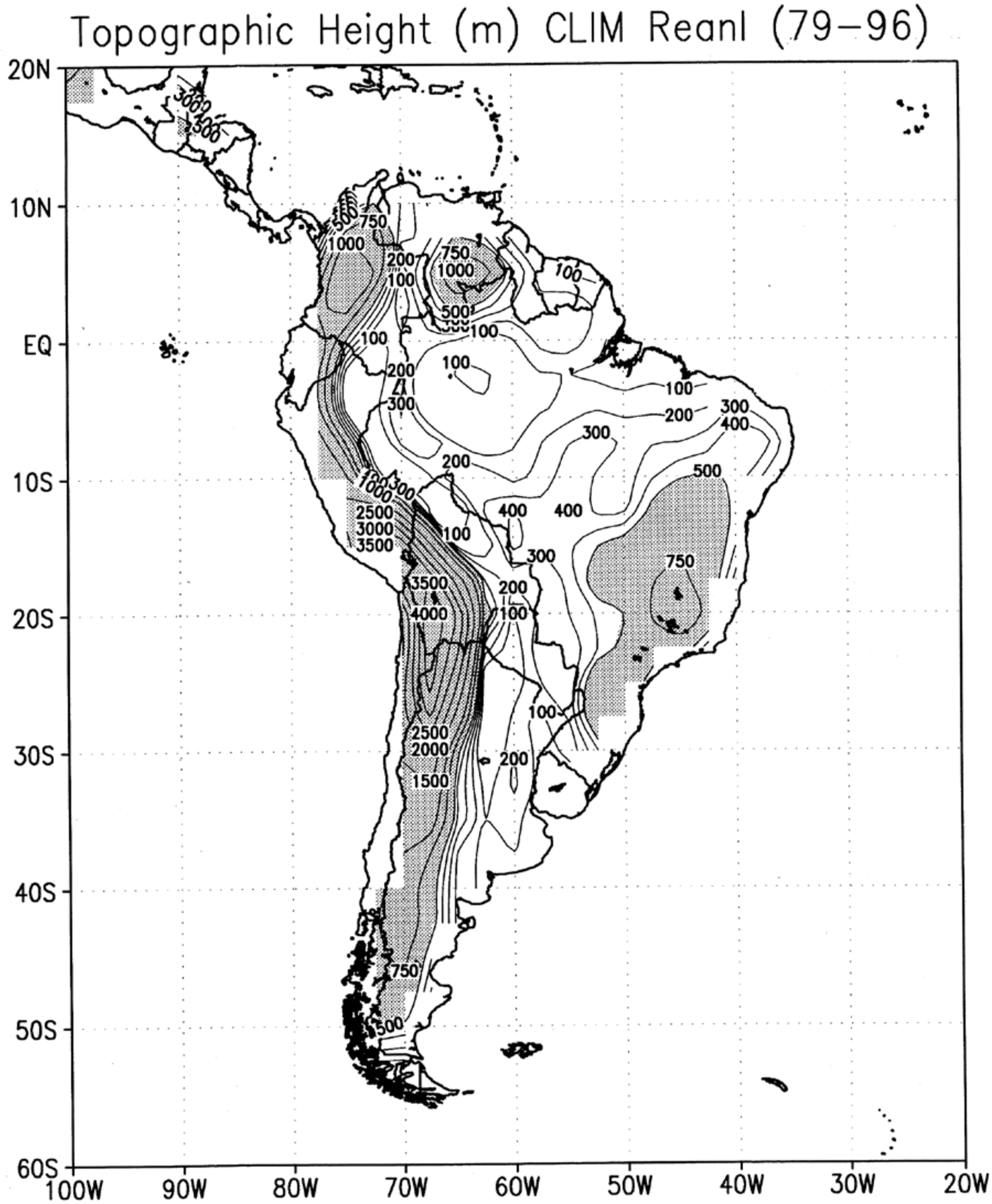


Fig. 2. Mean topographic height (m) at 2.5 degree resolution over South America

surface exerts tremendous influence upon the climates of the coastal states of Chile, Peru and Ecuador, while in the eastern Pacific north of the equator, a warm equatorial countercurrent flows eastward and influences the weather and climate of north Ecuador and Colombia. In the Atlantic south of the equator, the warm Brazil current flows pole ward close to and parallel to the east coast of Brazil and meets the cold Malvinas current flowing northeastward from the Drake passage between Cape Horn and the Antarctic peninsula. South of about 40° S,

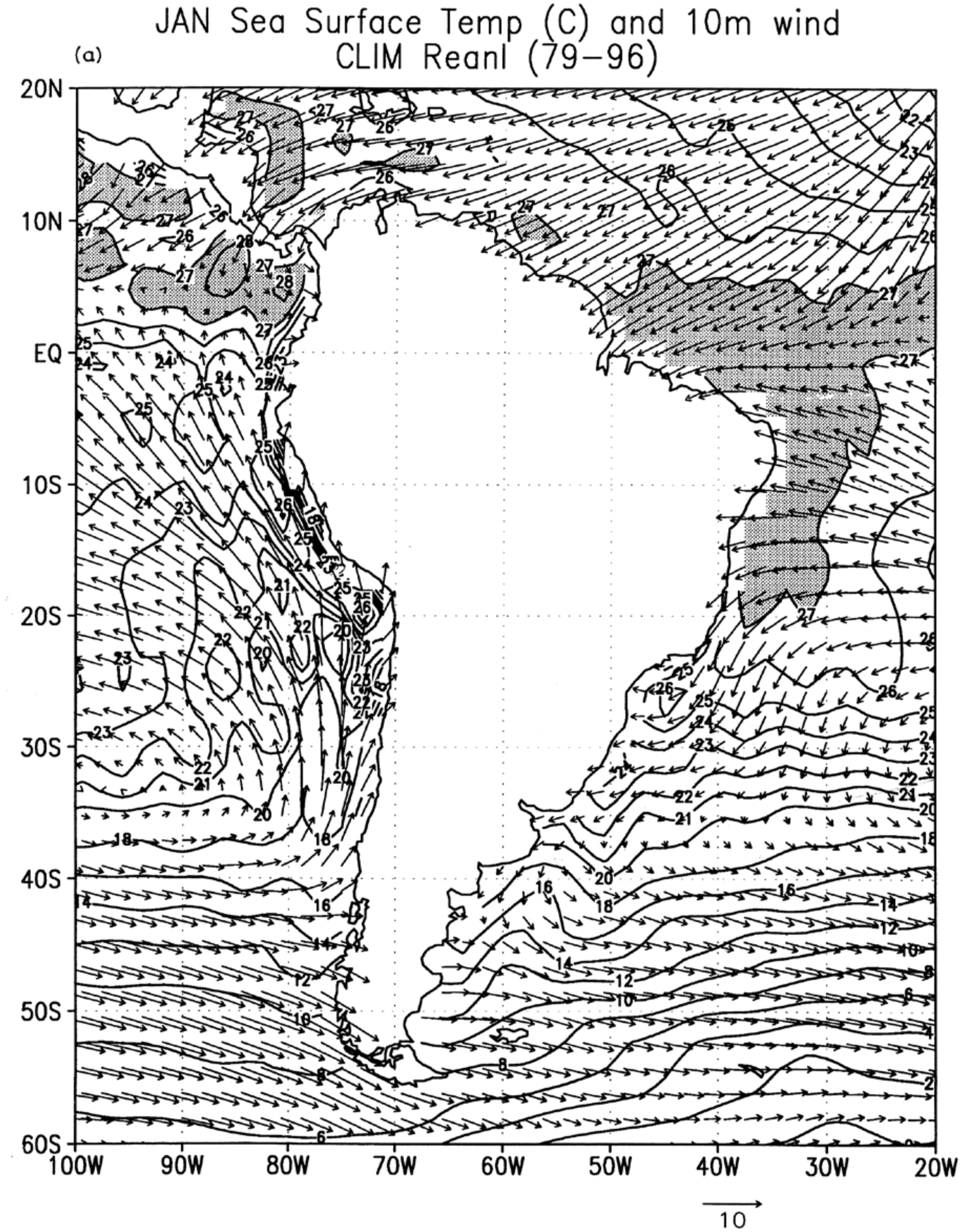


Fig. 3(a). Mean sea surface temperature (C) and 10 m-wind over oceans around South America during January

both the Pacific and the Atlantic oceans are extremely cold. Some of these oceanic features along with the sea surface temperature (SST) and prevailing wind systems at 10 metre elevation above sea level during January and July are shown in Figs. 3(a&b) respectively. However, the most outstanding physical feature of South America from

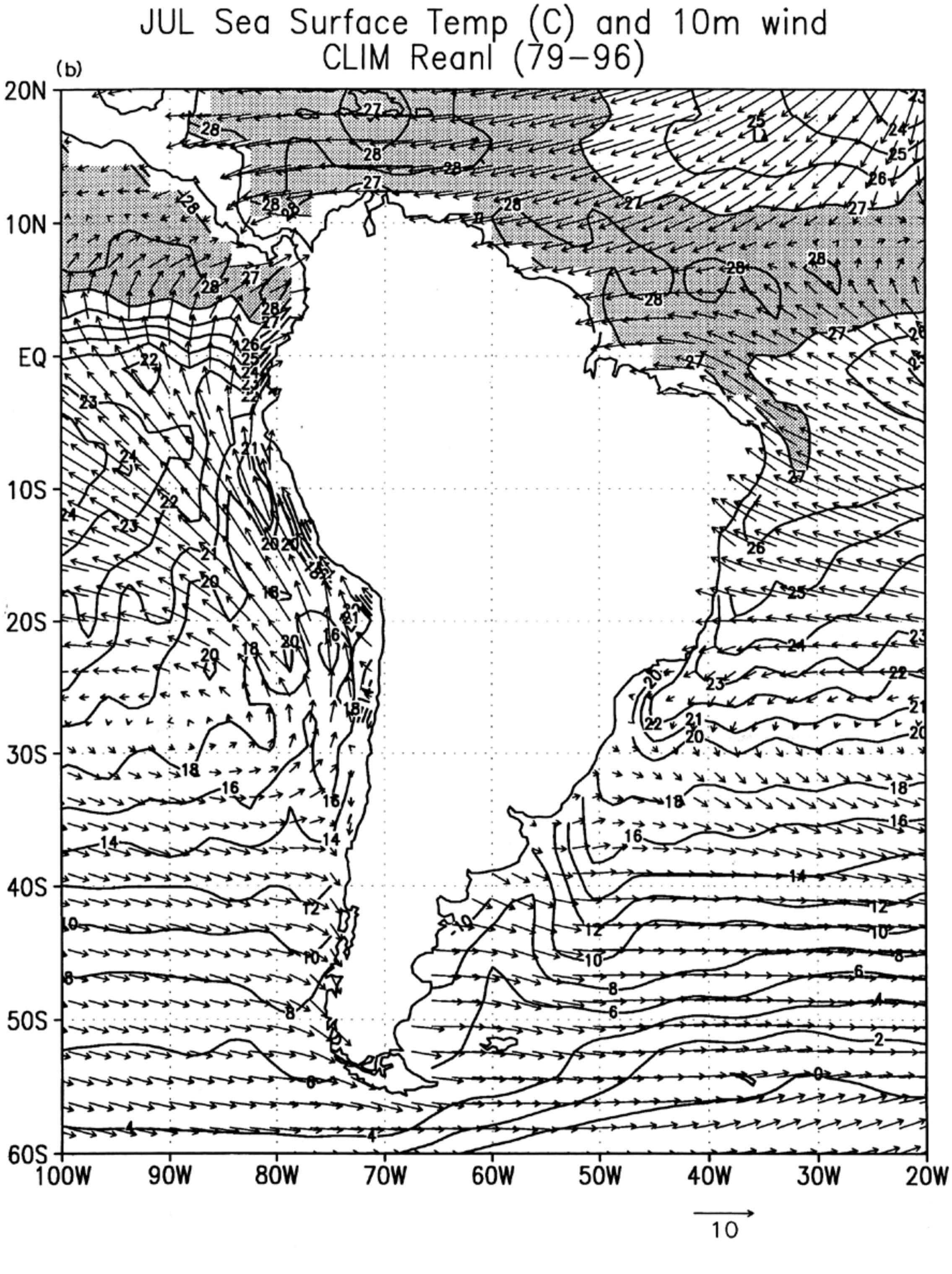
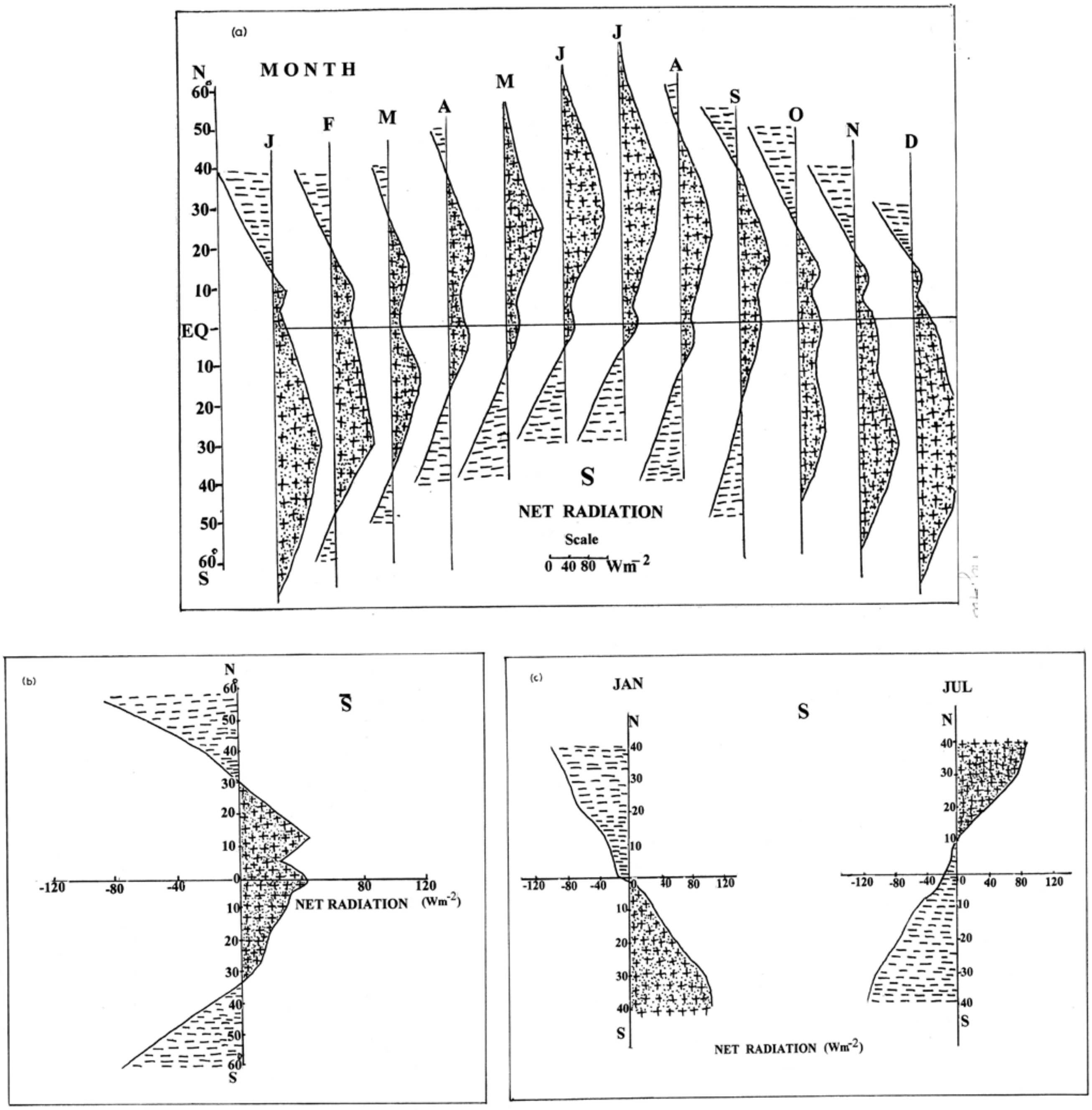


Fig. 3(b). Mean sea surface temperature (C) and 10 m-wind over oceans around South America during July

the point of view of climate appears to be the high Andes rising at places to heights well above 5000 m which serves to effectively separate the trade winds of the two great oceans and thus act as a great climatic divide. However, since the climates of countries lying on the Pacific side of the Andes are significantly different from those on the east



Figs. 4(a-c). Meridional distribution of zonally-averaged net radiation (absorbed solar radiation minus outgoing longwave radiation) over the longitudinal zone, 120.0° W - 2.5° W, during the period June 1974 through February 1978: (a) Observed monthly mean net radiations "S", (b) Annual mean net radiation $\bar{S}$ and (c) Deviation of observed monthly mean from annual mean net radiation, S', in January and July

side and an adequate treatment of both is beyond the scope of the present study, the following sections deal mainly with the meteorology and climatology of that part of South America which lies to the east of the Andes. Another very significant physical feature of South America from the point of view of the climate is the

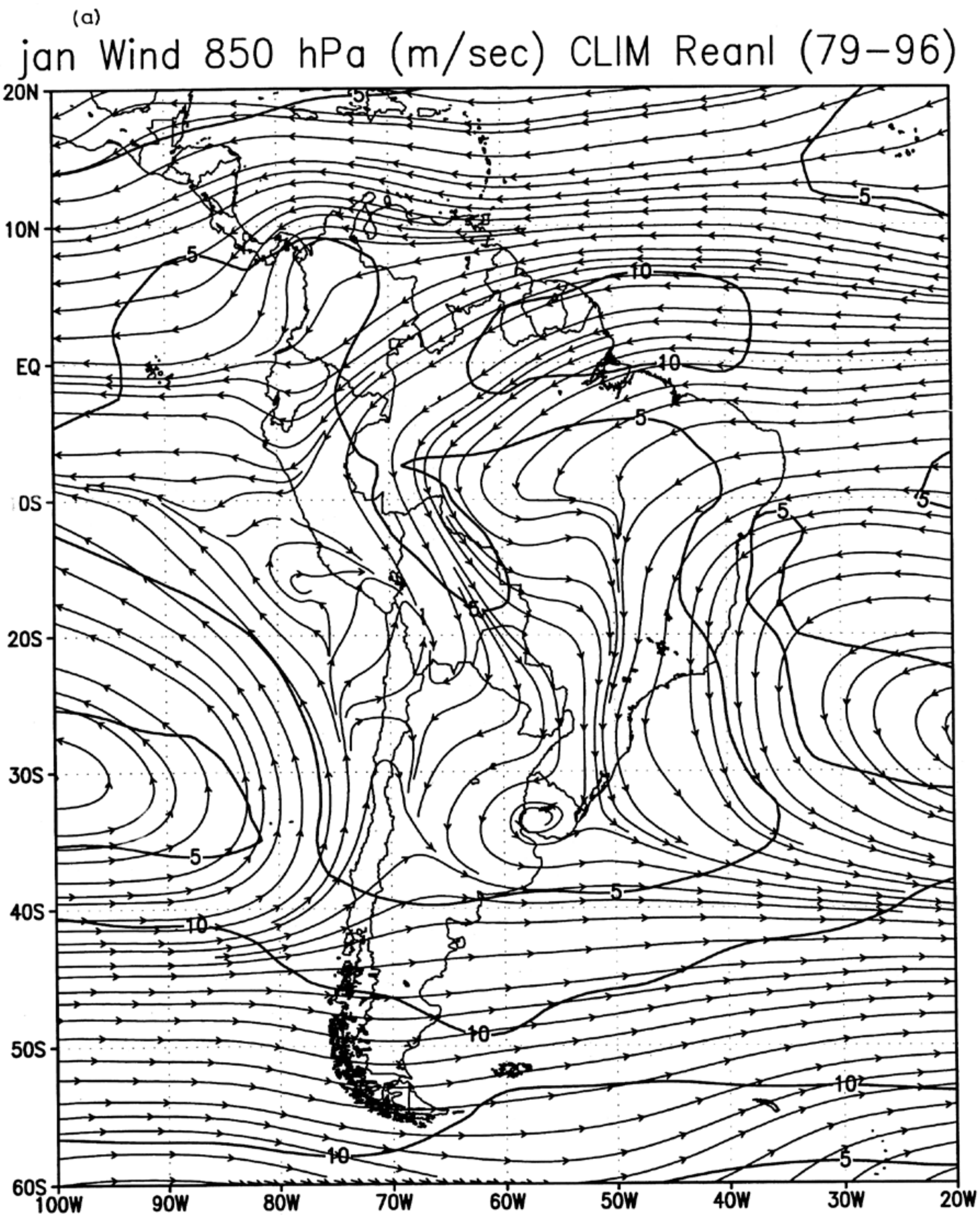


Fig. 5(a). Observed mean January wind field over South America and surrounding oceans at 850 hPa

presence of an ocean to the north of the continent. It appears to restrict the northward movement of the 'heat low' beyond the coastal belt during the northern summer, though to the northwest over Central America, the ‘heat low’ moves up to almost 35° N or even beyond.

3. Heat sources and sinks over South American region

There have been attempts in the past to study atmospheric heat sources and sinks over South America in

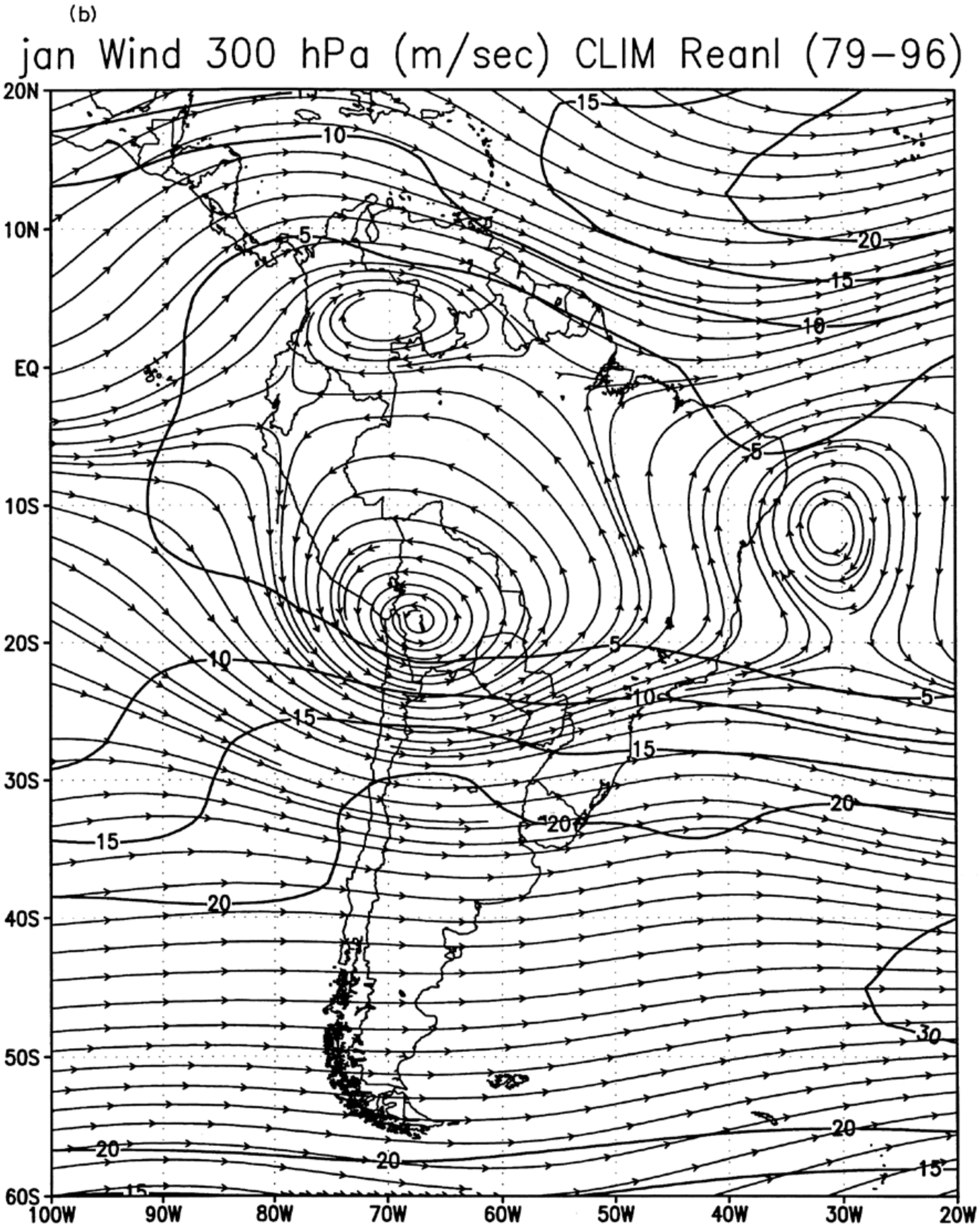


Fig. 5(b). Observed mean January wind field over South America and surrounding oceans at 300 hPa

January which is the month of the 'high sun' over the continent (Rao and Erdogan, 1988; Zhou and Lau, 1997). Rao and Erdogan (1988) identified a high-altitude heat source over the Bolivian plateau in January, which they said was associated with a monsoonal circulation over South America. Zhou and Lau (1997) who computed the total diabatic heating in January over South America found that in addition to a strong heat source over the

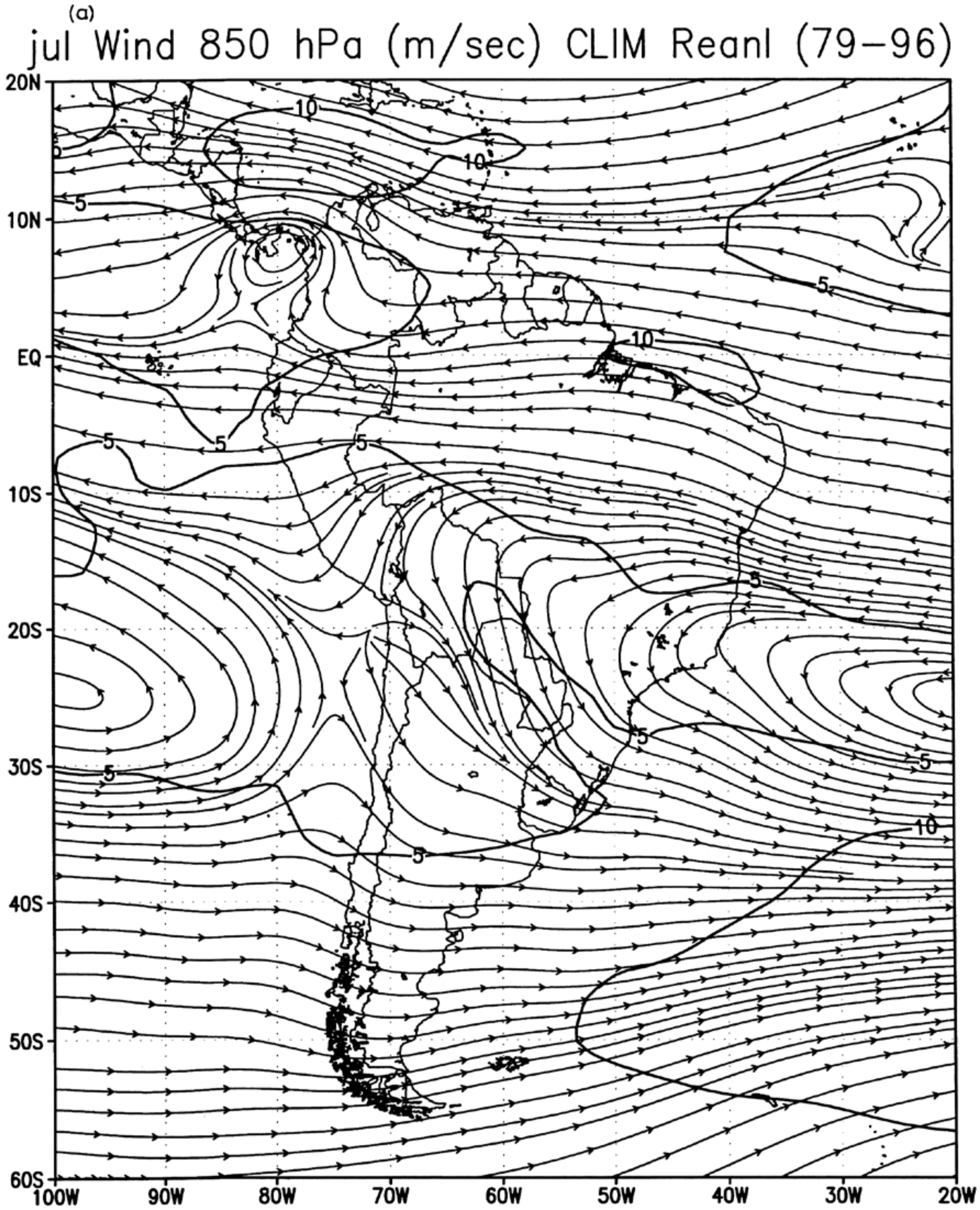


Fig. 6(a). Observed mean July wind field over South America and surrounding ocean at 850 hPa

Bolivian plateau, a strong heat source existed over southern Brazil centered at a latitude of about 20° S at 400 hPa. It is well-known that a heat source or sink in the earth-atmosphere system is determined by the distribution of net radiation (absorbed solar radiation minus outgoing long wave radiation) in the system, besides latent heat of condensation of water vapour which is a very variable quantity, and that the heat source or sink thus determined

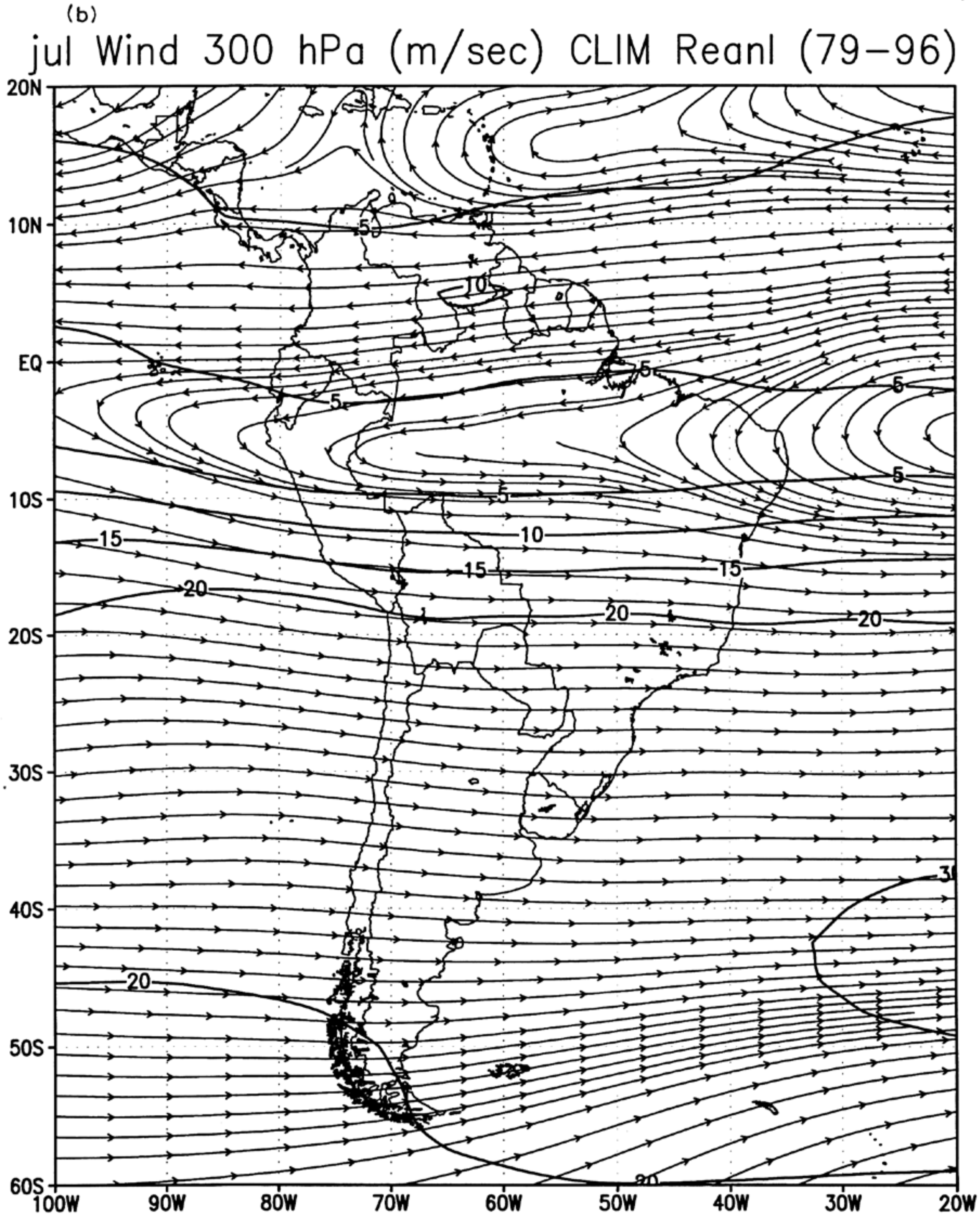


Fig. 6(b). Observed mean July wind field over South America and surrounding ocean at 300 hPa

migrates latitudinally following the seasonal movement of the sun. At any time of the year, therefore, the net radiation measured at a latitude may be broken up into two parts : (*i*) an annual mean value which remains constant with time and (*ii*) a perturbation from the annual mean value which will vary with the time of the year

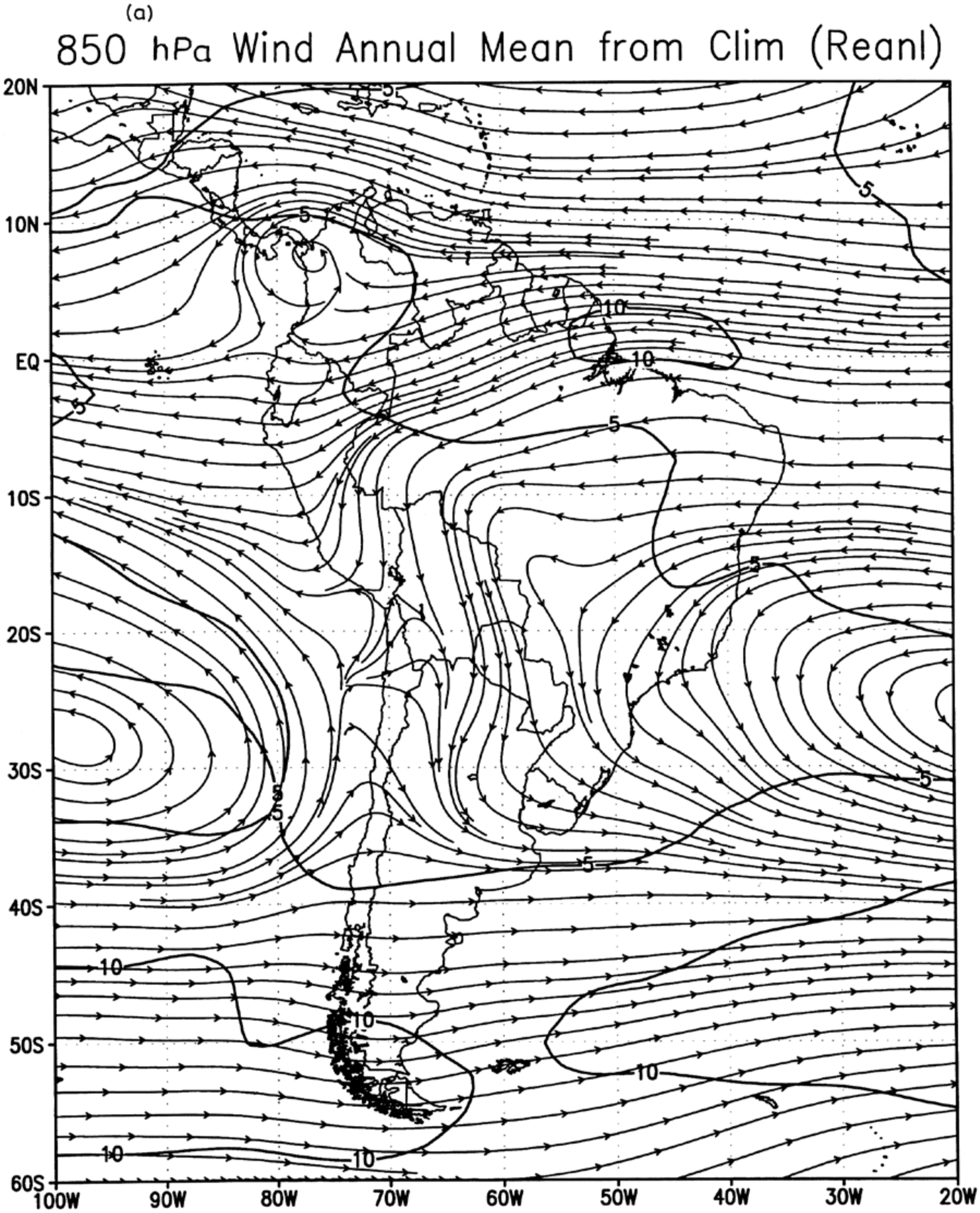


Fig. 7(a). Annual mean wind field over South America and surrounding oceans at 850 hPa

depending upon the location of the sun. Thus, if S(y,t) is the total net radiation received at latitude y at time t, it would be given by :

$$S(y,t) = \bar{S}(y) + S'(y,t)$$

where the overbar denotes the annual mean value of the net radiation and the prime the deviation from the annual mean at time t. Thus, a knowledge of the space-time distribution of S' should enable us to determine whether necessary condition for existence of a monsoon

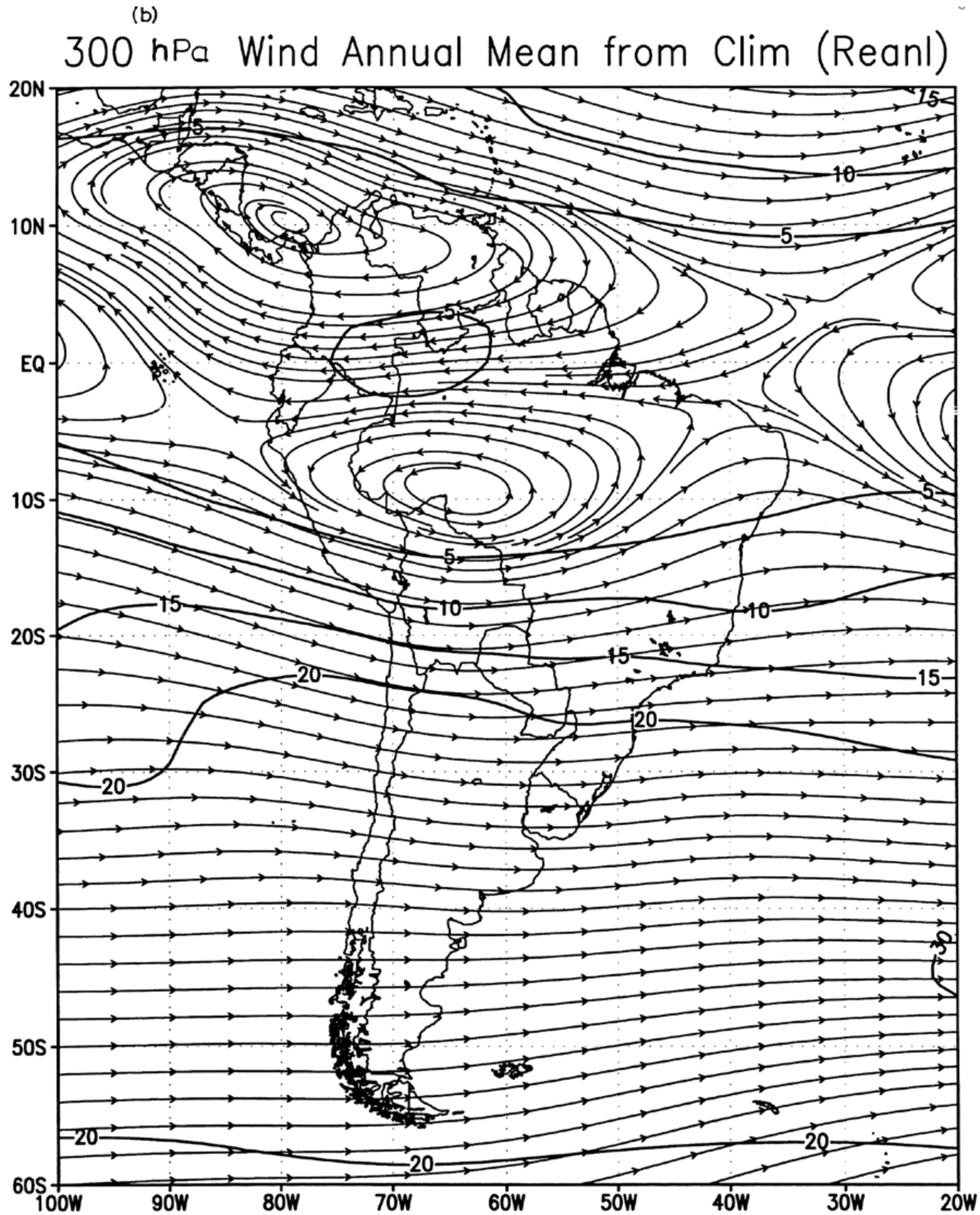


Fig. 7(b). Annual mean wind field over South America and surrounding oceans at 300 hPa

circulation exists over a region or not. In a comprehensive study of the earth's radiation budget using satellite data, Winston *et al.* (1979) presented, amongst others, meridional profiles of zonally-averaged net radiation over the globe as a whole, as well as over three longitudinal zones, one of which was the zone between 120.0° W and 2.5° W, which included South America, for different months and seasons of the year. They also presented

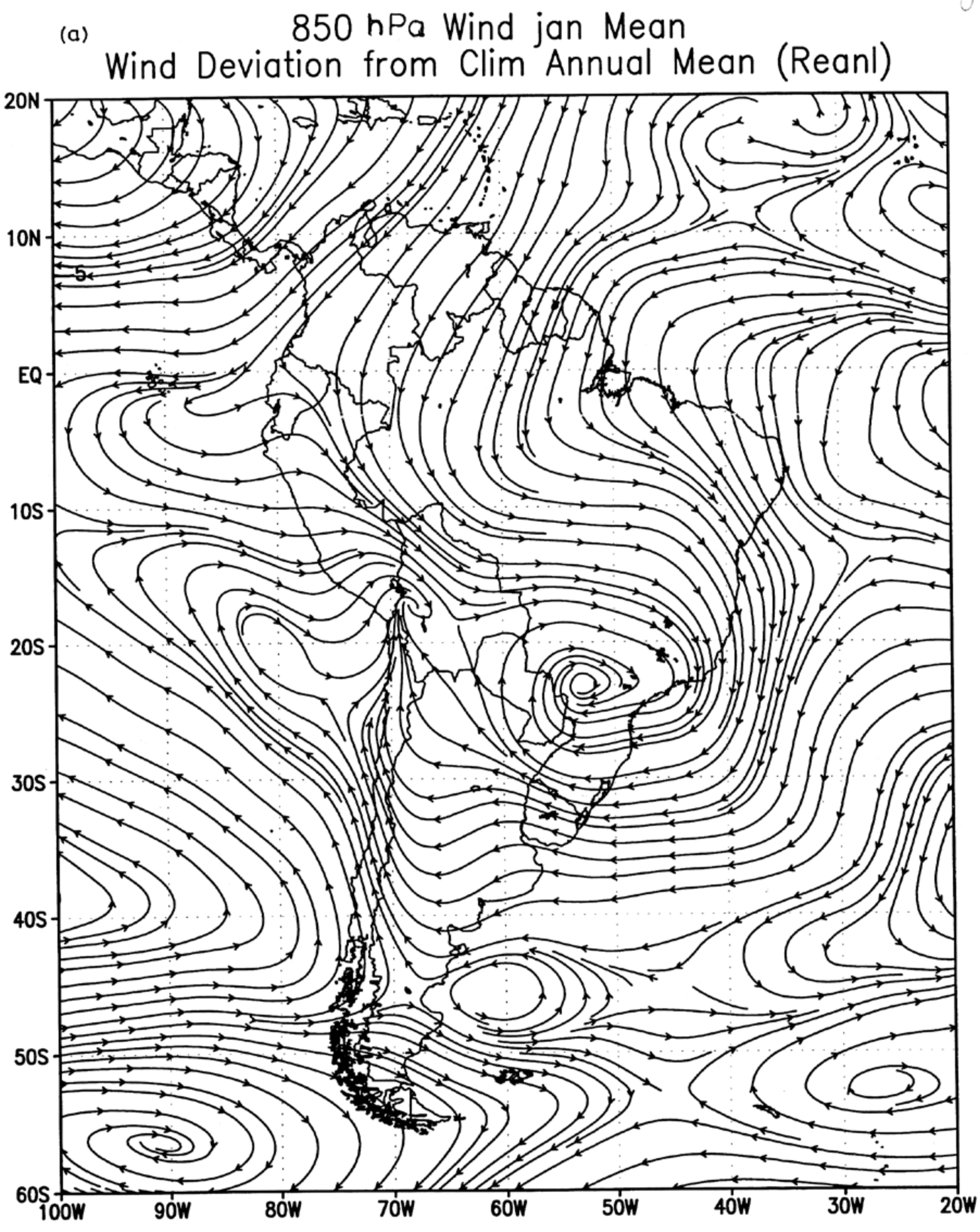


Fig. 8(a). Monsoonal (deviation of observed monthly mean from the annual mean) wind field over South America and surrounding oceans in January at 850 hPa

meridional profiles of the global average as well as the zonal averages for the three different longitudinal zones of annual mean net radiation for three successive years from June 1974 to May 1977. We used the net radiation values as given by these profiles for the longitudinal zone, 120.0° - 2.5° W, to compute the deviation values, S'. The results

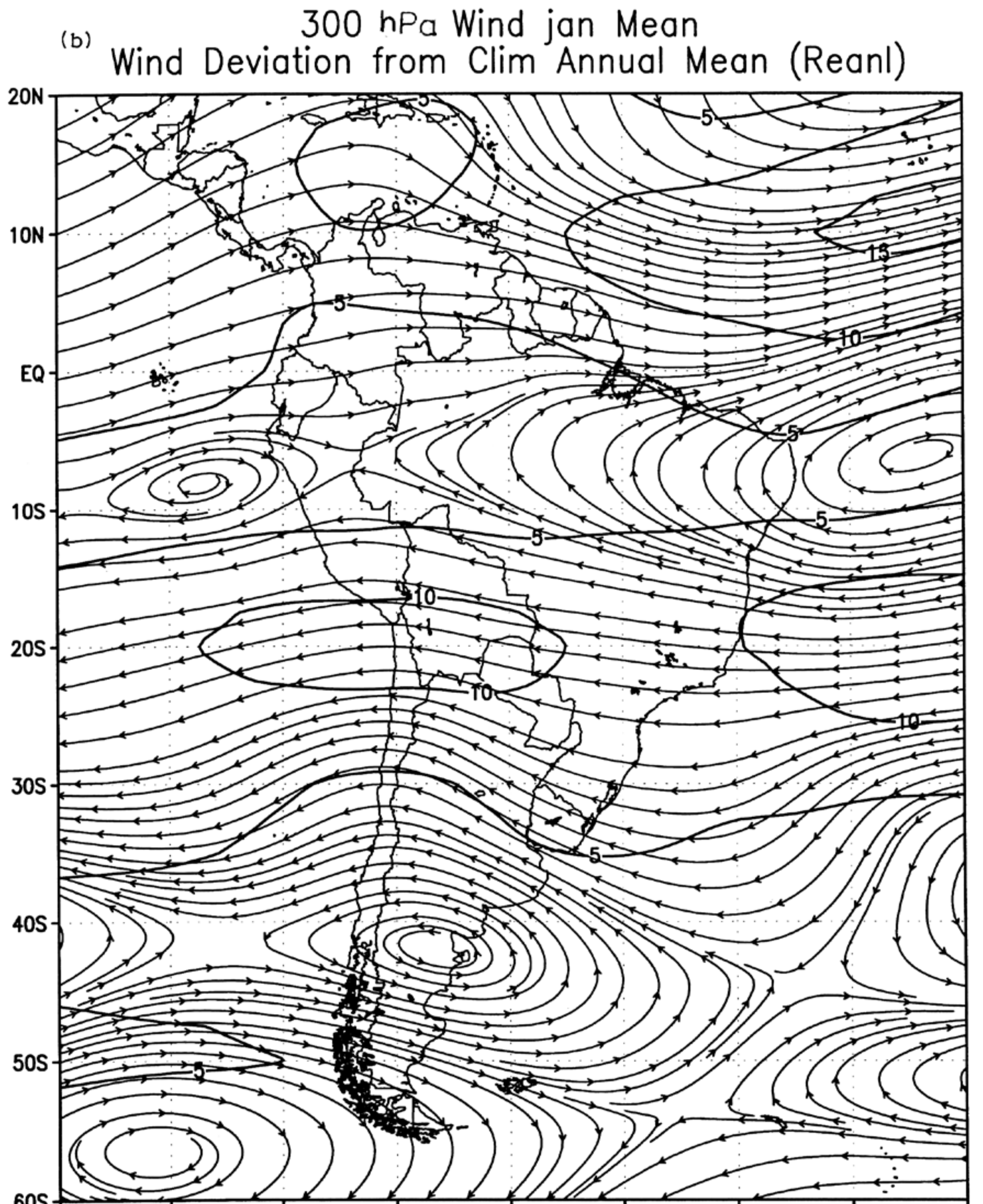


Fig. 8(b). Monsoonal (deviation of observed monthly mean from the annual mean) wind field over South America and surrounding oceans in January at 300 hPa

of our computation are presented in Figs. 4(a-c). Fig. 4(a) which presents the meridional profiles of the zonally-averaged net radiation in different months of the year shows how the observed values vary with latitude in different months of the year and oscillate seasonally with the movement of the sun. It also shows that in the course

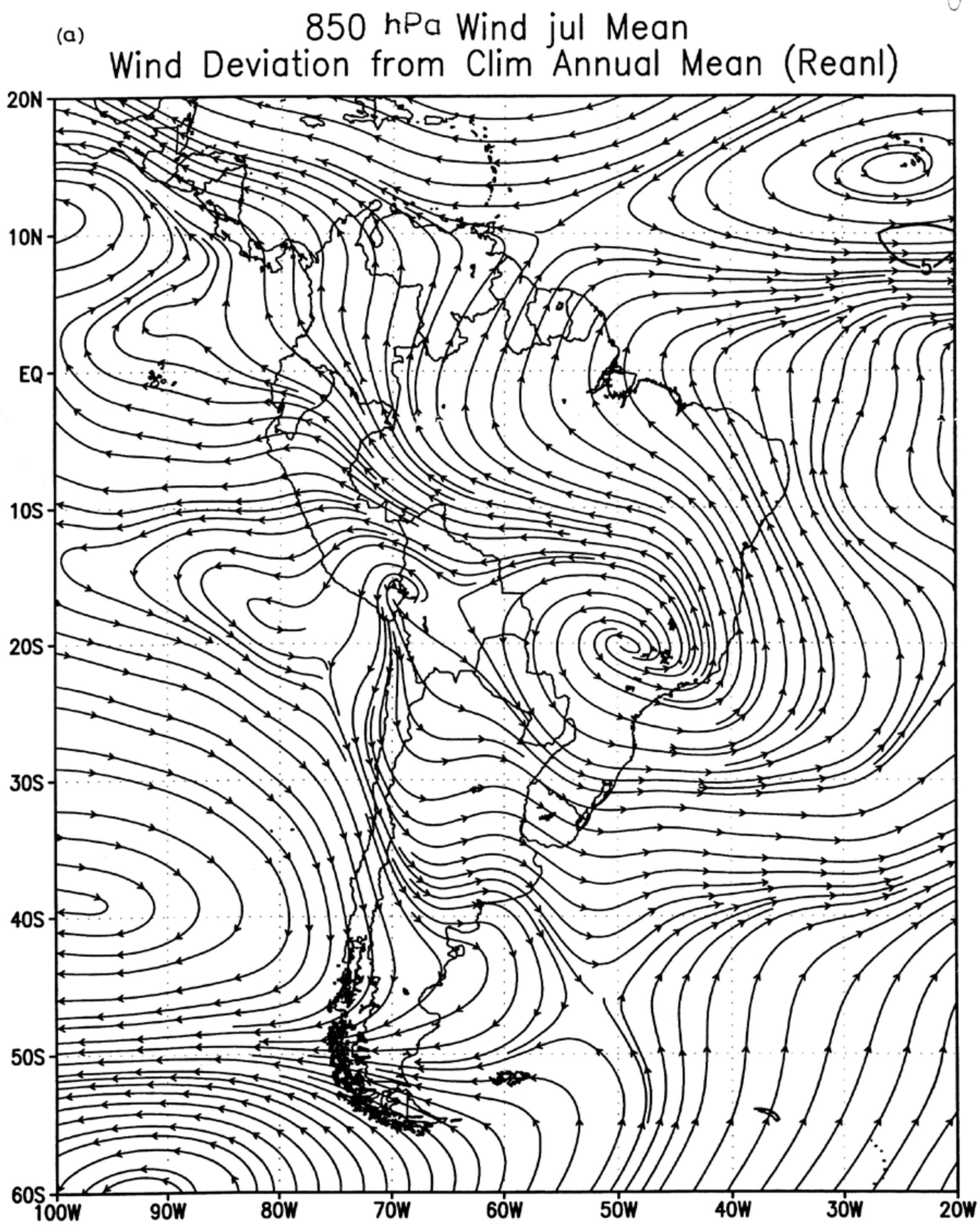


Fig. 9(a). Monsoonal (deviation of observed monthly mean from the mean annual mean) wind field over South America and surrounding oceans in July at 850 hPa

of the seasonal movement of the heat source, the equatorial region becomes warm twice, once during April-May and the second time during September-October. Further, there appears to be an appreciable dip in the intensity of the net radiation around the latitude 5° N in all the months of the year. Fig. 4(b) shows the meridional

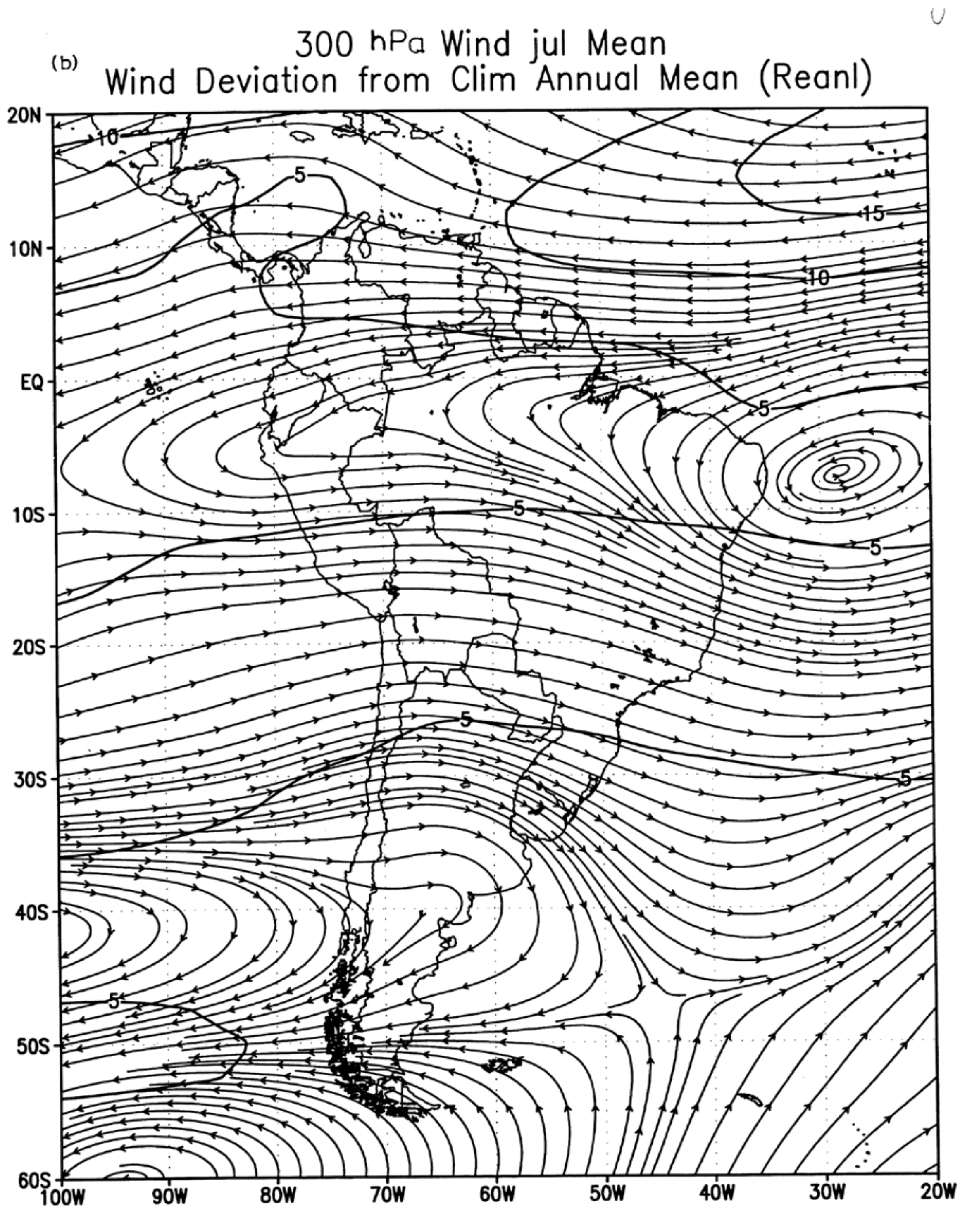


Fig. 9(b). Monsoonal (deviation of observed monthly mean from the mean annual mean) wind field over South America and surrounding oceans in July at 300 hPa

profile of the zonally-averaged annual mean net radiation over the longitudinal zone, 120.0° W - 2.5° W. In it, the whole tropical belt, 30° N - 30° S, appears as a prominent heat source except for a dip in the intensity of the net radiation near about 5° N. This dip in the value of the annual mean net radiation near 5° N appears to be real in

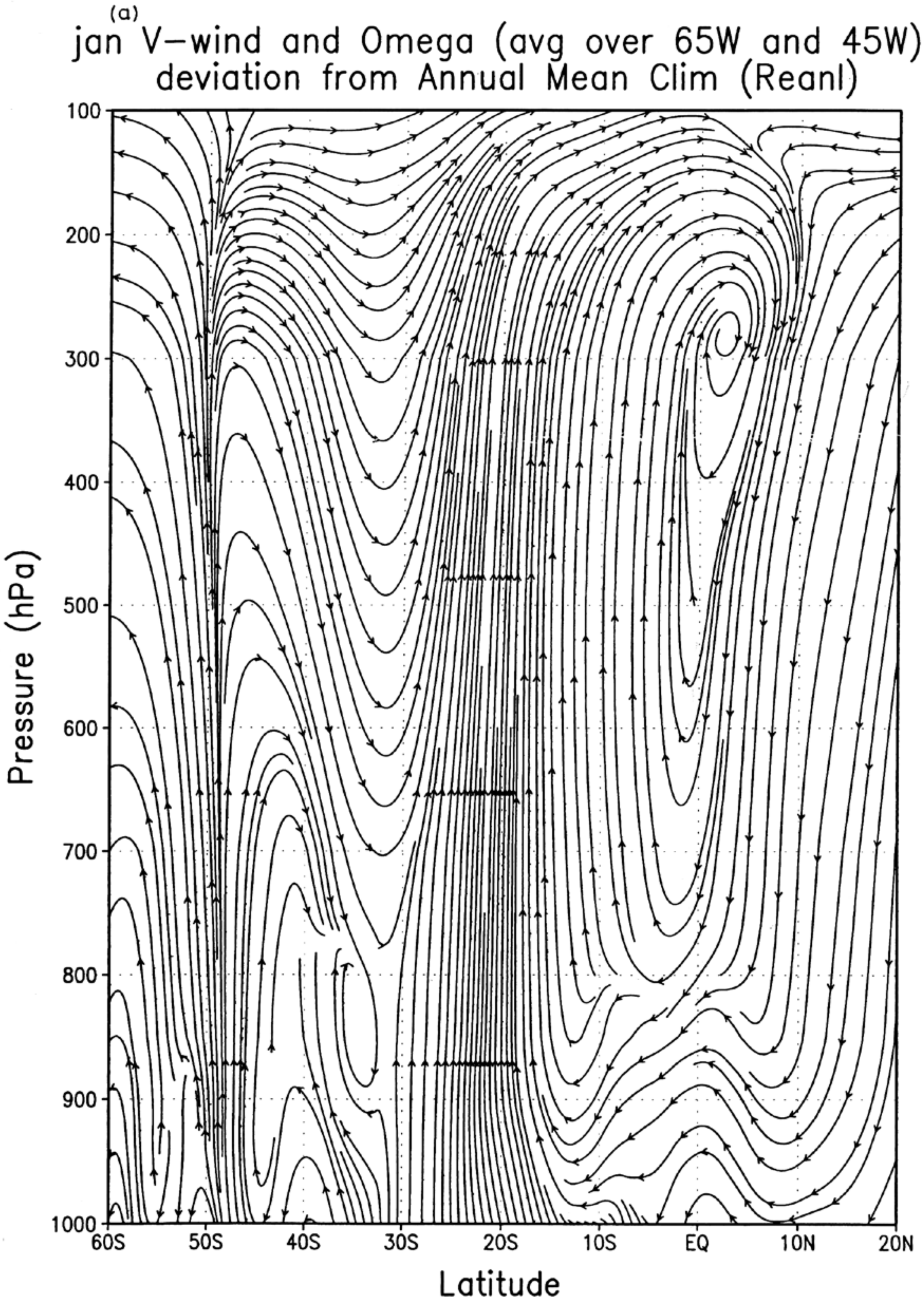


Fig. 10(a). Zonally-averaged meridional-vertical circulation over South America : January (Dec, Jan, Feb)

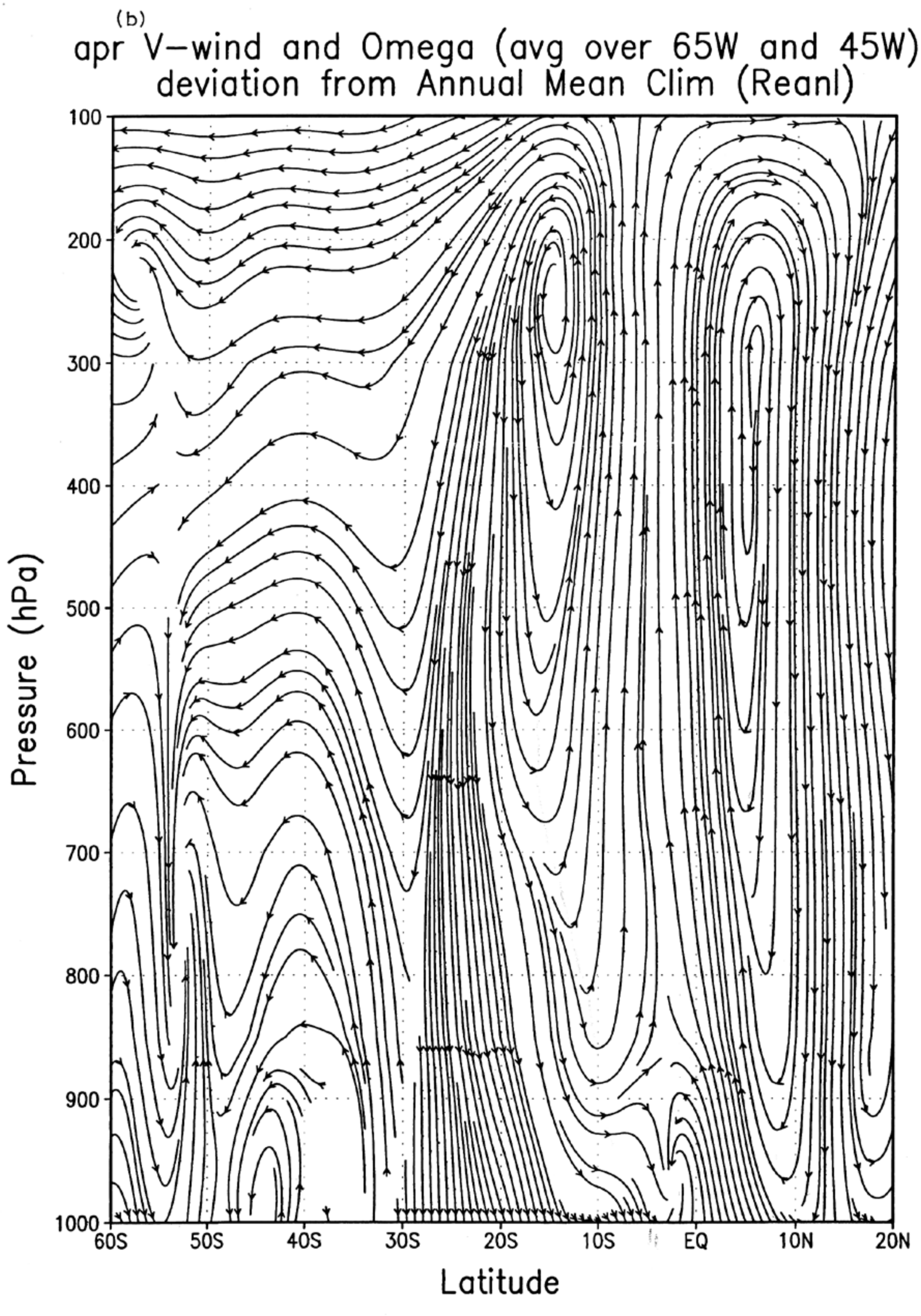


Fig. 10(b). Zonally-averaged meridional-vertical circulation over South America : April (Mar, Apr, May)

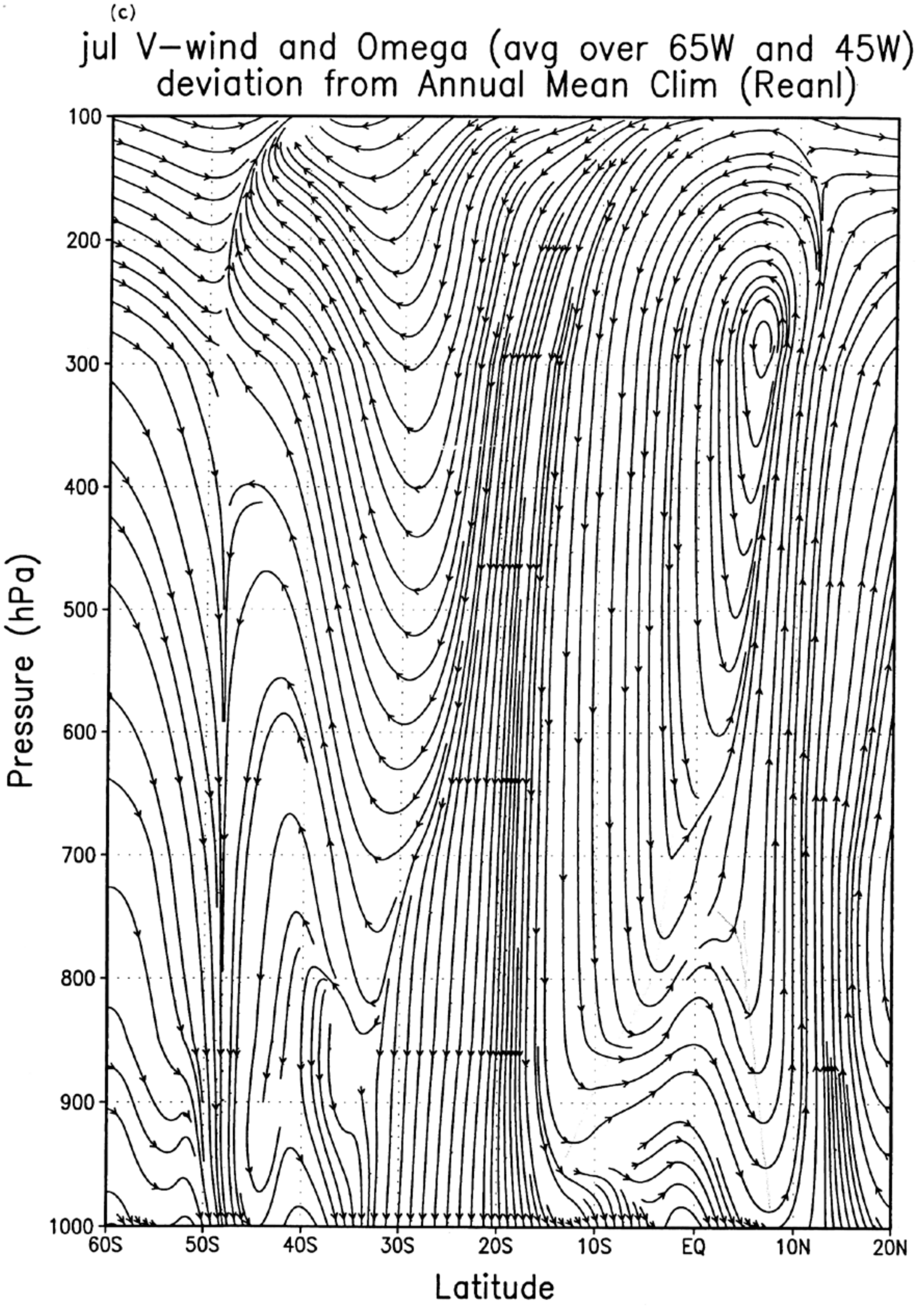


Fig. 10(c). Zonally-averaged meridional-vertical circulation over South America : July (Jun, Jul, Aug)

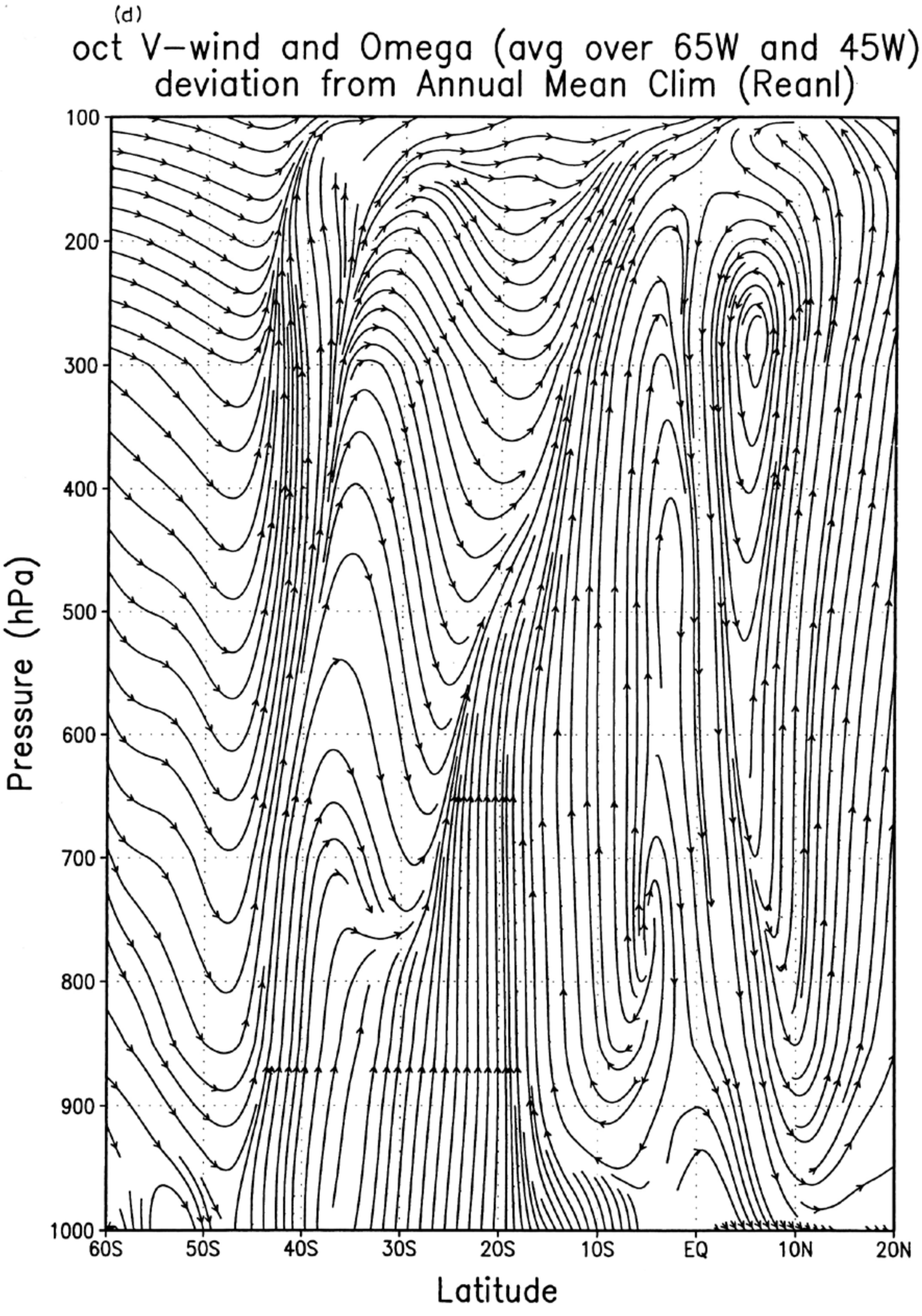


Fig. 10(d). Zonally-averaged meridional-vertical circulation over South America : October (Sep, Oct, Nov)

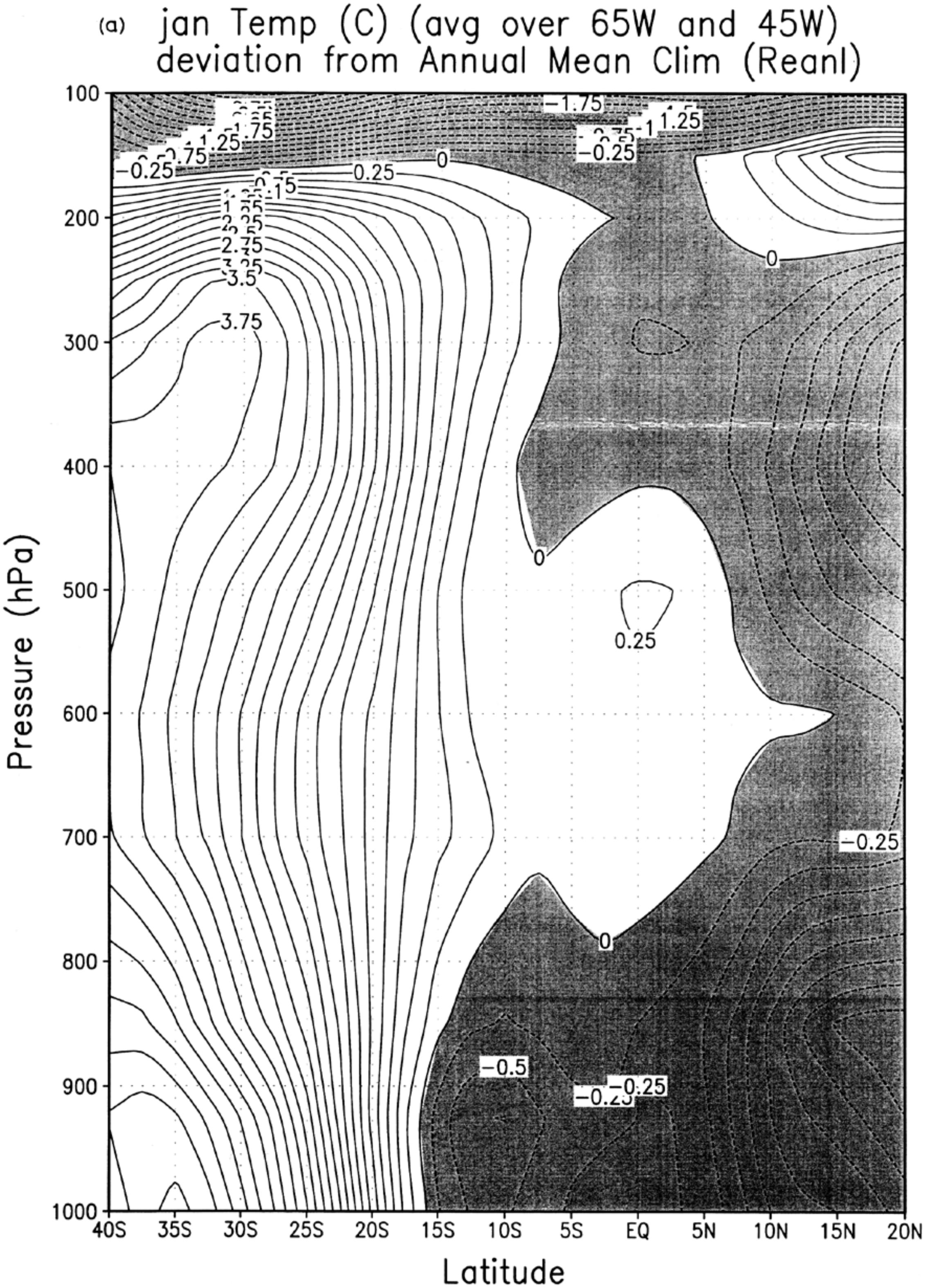


Fig. 11(a). Meridional-vertical profiles of zonally-averaged deviation temperature (C): January

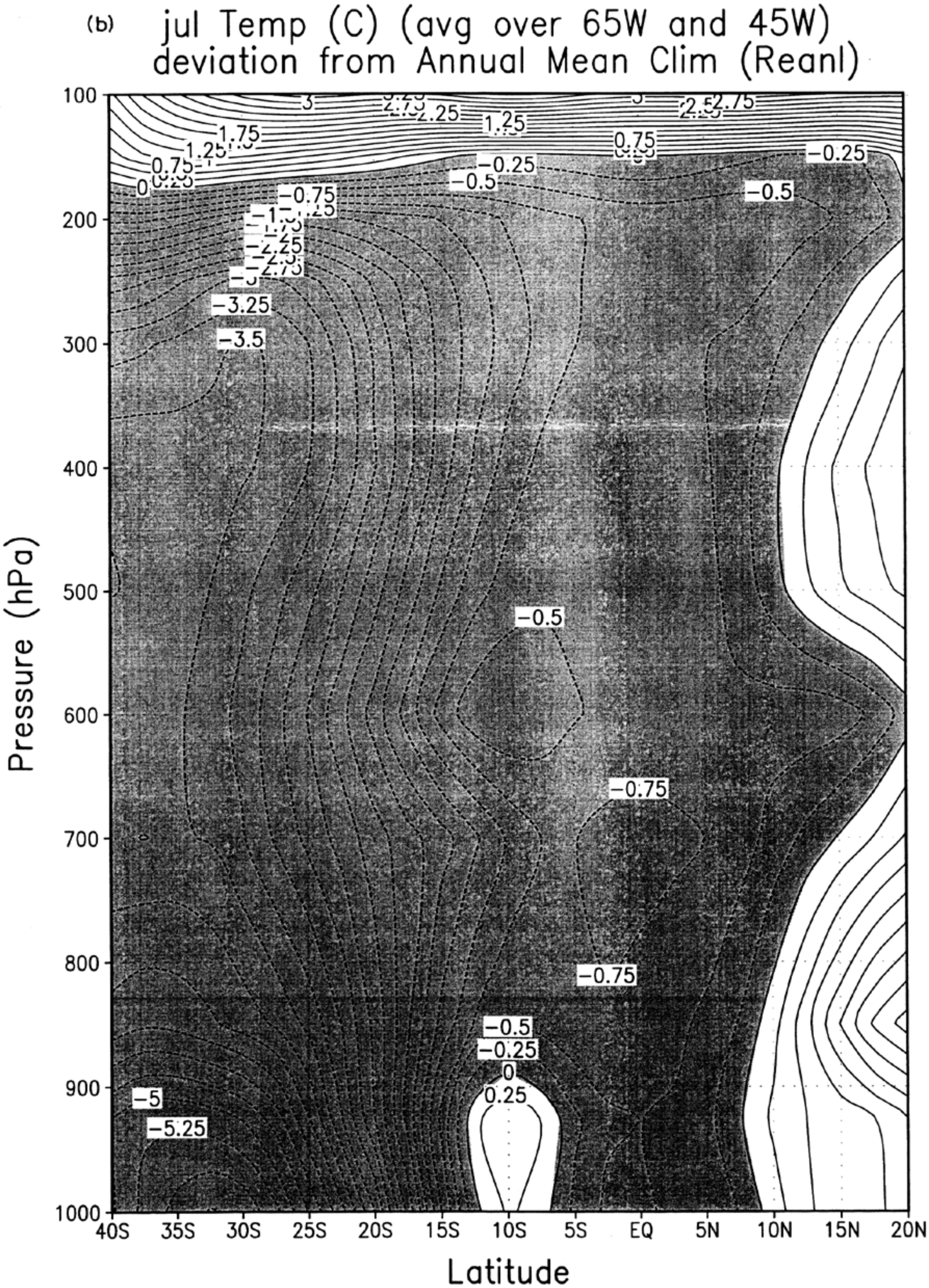


Fig. 11(b). Meridional-vertical profiles of zonally-averaged deviation temperature (C) : July that it occurred every year during the three-year period. Further, such a dip in the intensity of the zonally-averaged annual mean net radiation near 5° N was also observed over the longitudinal zone, 120° E - 122.5° W, which covered the Pacific ocean. We do not know for sure what causes this dip near 5° N. There may be divergent views regarding its origin but it appears significant that it occurs at or near a latitude where the albedo of the earth-atmosphere system is found to be high and where a prominent cloud band related to the intertropical convergence zone appears to be present over both the Atlantic and the Pacific ocean longitudinal zones almost throughout the year. Fig. 4(c) shows the deviation (monthly mean minus the annual mean) values of the net radiation for the months of January and July. In all the diagrams, the positive values which indicate a source are shown by shading with plus sign, while the negative values which indicate a sink are shown by minus sign. Fig. 4(c) brings out the seasonal reversal of the heat source and sink due to S' in both the hemispheres and suggests the possibility of the existence of a monsoon circulation over South America. Some details of this circulation as observed over South America are presented in the following section.

4. Observed, annual mean and seasonal-monsoon circulation

(*i*) *Circulation along isobaric surfaces*

The observed mean circulation over the South American region at 850 and 300 hPa for January and July are presented in Figs. 5(a&b) and Figs. 6(a&b) respectively. The annual mean circulation at 850 hPa and 300 hPa are presented in Figs. 7(a & b) respectively. A comparison of the monthly mean and the annual mean circulation patterns at the two pressure surfaces immediately brings to the fore the dominant influence of the annual mean circulation especially the tropical trade winds upon the observed monthly circulation. This dominance may be seen as much in the upper troposphere as in the lower troposphere. In Figs. 8(a&b) and Figs. 9(a&b), we present the deviation of the observed monthly mean wind from the annual mean wind at the two pressure surfaces over South America during January and July respectively. Here, in Figs. 8(a&b), one can immediately see the low-level cyclonic circulation and the upper-level anticyclonic circulation over Southern Brazil very clearly. Figs. 9(a&b) show a ridge of anticyclonic circulation at 850 hPa and a trough of cyclonic circulation at 300 hPa between the equator and about 10° S. From Figs. 8(a&b) and Figs. 9(a&b), it is evident that the monsoonal flow pattern over South America not only reverses between January and July but also between the lower and the upper troposphere.

(*ii*) *Meridional-vertical circulations : Hadley and monsoon cells*

It is well-known (Hadley, 1735) that when the heat source in the earth-atmosphere system is located at the equator, it leads to two classical idealized Hadley circulation cells, one in each hemisphere, with their common rising branch over the equatorial region and the descending branches over the subtropical belts of the two hemispheres. In such a situation, it may be anticipated that rainfall would be concentrated in the equatorial region if the rising air is sufficiently moist. Dry weather would prevail over the belts of the descending motion in both the hemispheres. Such a situation may, perhaps, occur during the transition months when the equatorial region has its warmest temperatures of the year [Fig. 4(a)]. However, the situation changes when the heat source moves away from the equator to one of the hemispheres in the course of the seasonal movement of the sun. To get an idea of the change in the vertical circulations brought about by such a movement, we computed the two-dimensional resultant streamlines by combining the vertical velocity obtained from the divergent part of the observed wind with the meridional component of the wind. However, there was a problem here. It is well-known that the vertical velocity in the atmosphere is nearly two orders of magnitude smaller than the horizontal velocity. So we had to multiply the computed vertical velocity by a factor of 100 (we tried with quite a few other factors before accepting this particular one) to yield somewhat acceptable resultant streamline patterns.. For these computations, we averaged the values of the vertical and the meridional components of the wind, after removing the annual mean, over the longitude band, 65° W - 45° W, for four months of the year, *viz*., January, April, July and October representing the four seasons over South America. The results are presented in Figs. 10(a-d) respectively. The maps appear to show the following seasonal features of the vertical circulation :

(a) *January (Summer) : Fig. 10(a)*

With the heat source lying over the broad latitudinal belt, 15° S - 30° S, covering the southern parts of Brazil and adjoining Paraguay, Bolivia and northern Argentina, the low-level air from latitudes north of the equator moves towards the heat low at levels below about 800 hPa, converges into the heat low and rises in penetrative convection from surface to almost the top of the troposphere. It then diverges in the upper troposphere towards the northern hemisphere and subsides north of the equator to almost the earth's surface, to start moving towards the heat low again. The interhemispheric vertical circulation would seem to suggest a divergent vertical circulation to remove heat from the source to the sink in a

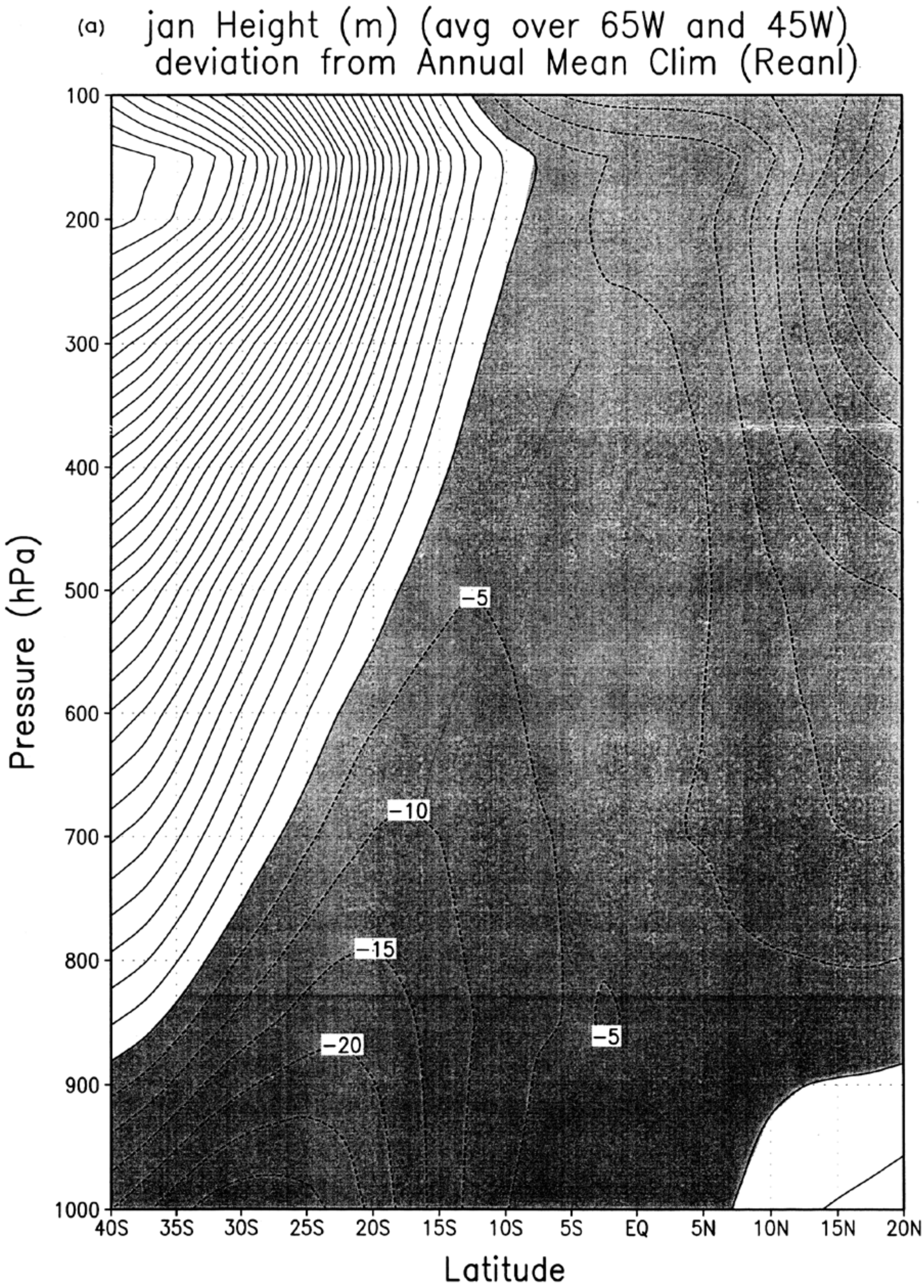


Fig. 12(a). Meridional-vertical profiles of zonally-averaged deviation isobaric height (m) : January

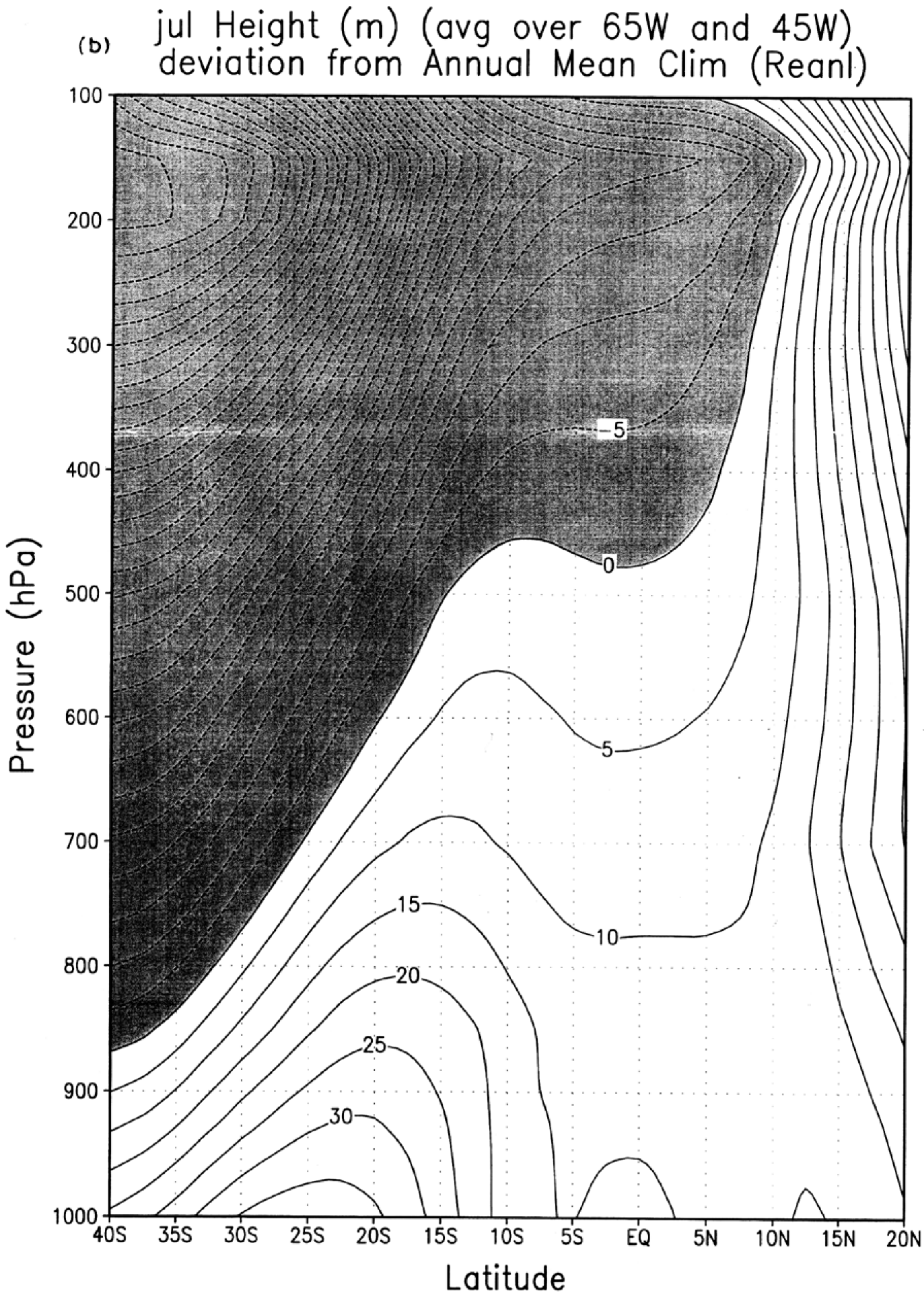


Fig. 12(b). Meridional-vertical profiles of zonally-averaged deviation isobaric height (m) : July

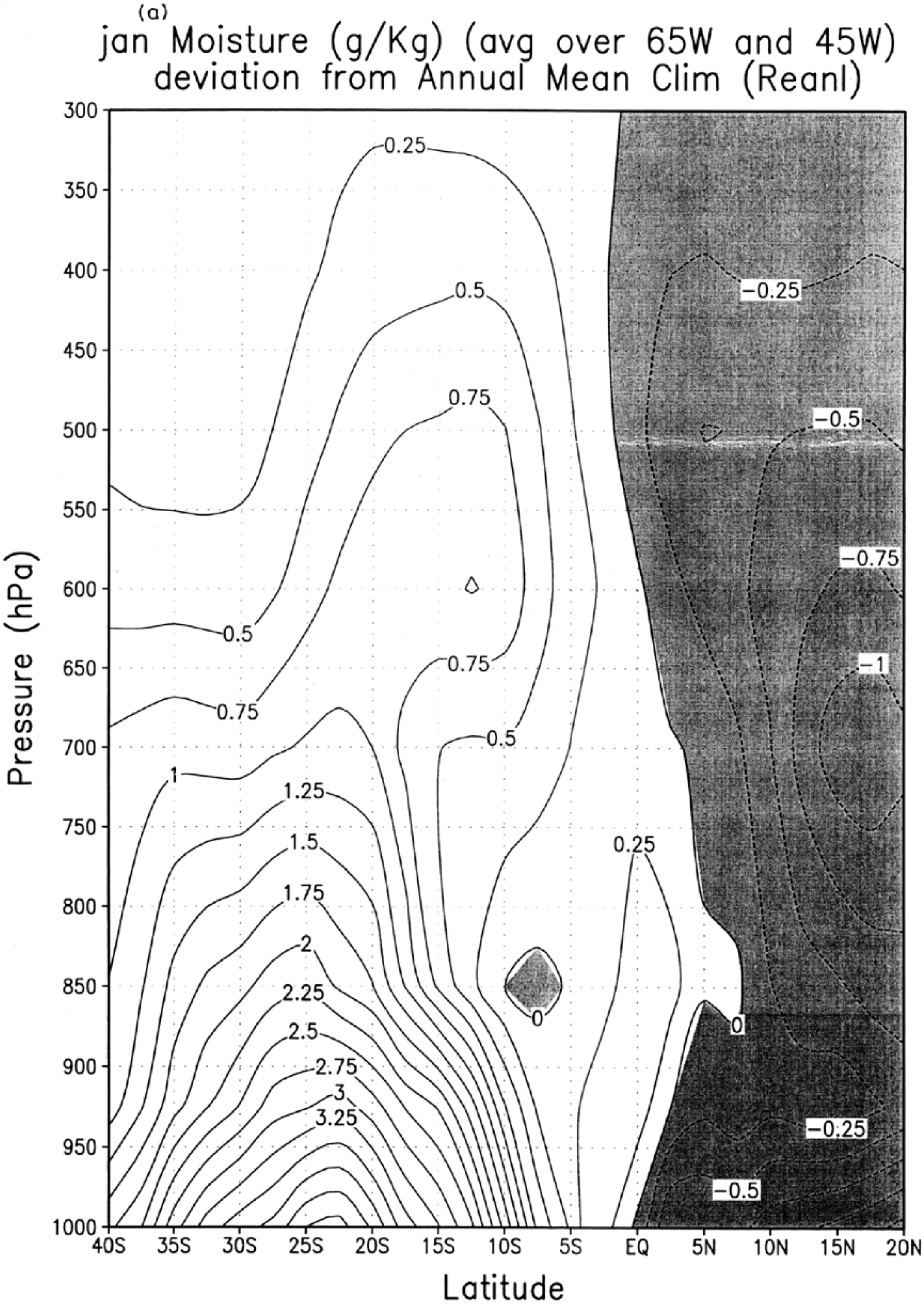


Fig. 13(a). Meridional-vertical profiles of zonally-averaged deviation specific humidity (g/kg) : January

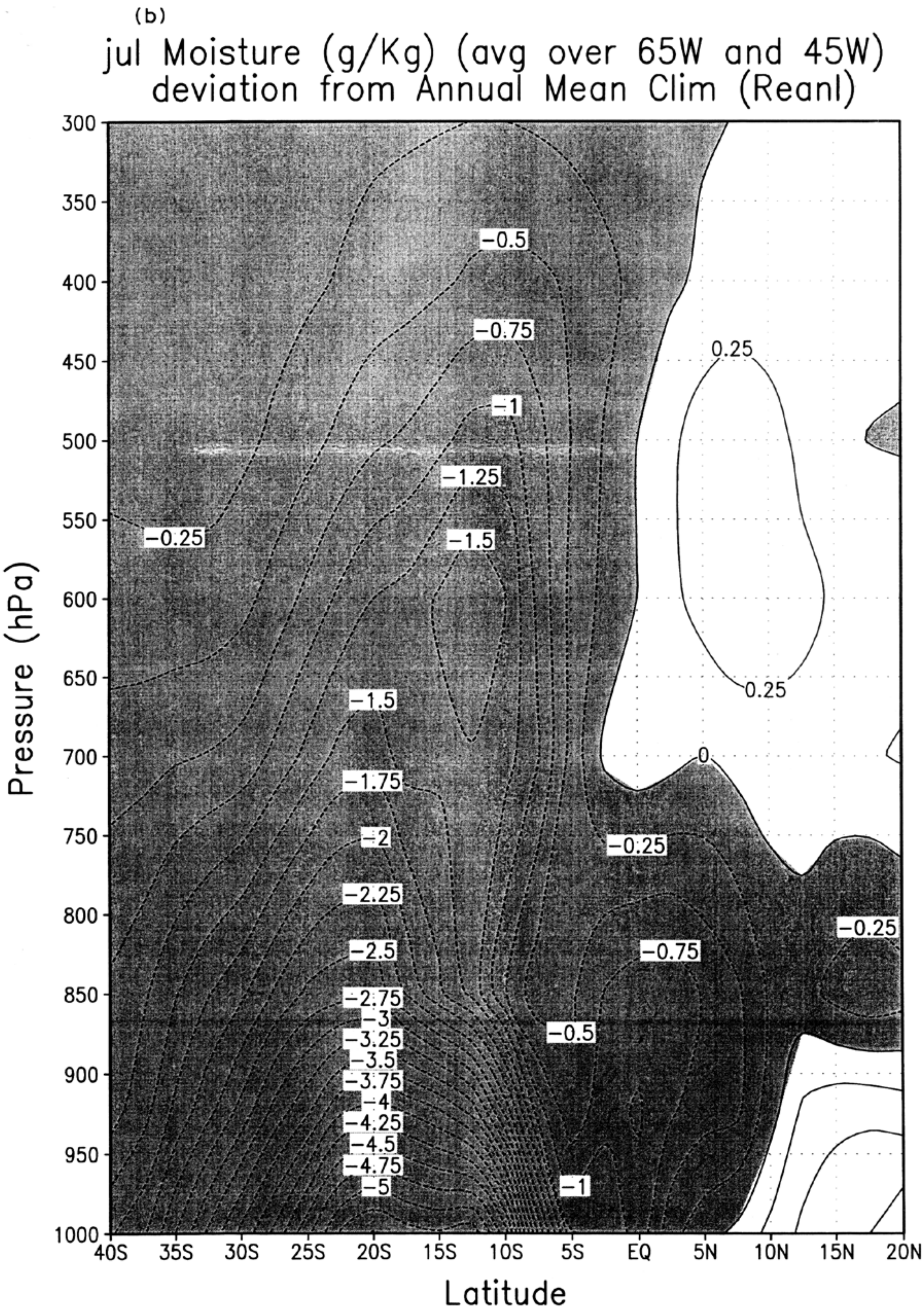


Fig. 13(b). Meridional-vertical profiles of zonally-averaged deviation specific humidity (g/kg) : July bid to restore heat balance over the region. One should, however, note that the movement of the heat source to the location in January which is the peak summer month over central South America, suggested by Fig. 10(a), must have occurred gradually from the time it was over the equator. One may ask : what happened to the Hadley circulation cells since then? A definitive answer is not possible, since we did not compute the circulation for all the months. We may, however, visualize that the Hadley cell of the southern hemisphere moved poleward along with the heat source and would still be located poleward of the heat source in January. In Fig. 10(a), there is only slight suggestion of its existence poleward of the heat source. It is evident that while the Hadley cell withdrew poleward, its place was taken over by an entirely new circulation the direction of which was reverse of that of the Hadley circulation. We call this new circulation as the summer monsoon circulation of South America. With the Hadley cell shifted poleward and cornered, the interhemispheric monsoon circulation cell now dominates the whole scene.

(b) *April (Autumn): Fig. 10(b)*

Some remarkable changes appear to have taken place in the circulation pattern since January. The heat source appears to have moved equatorward and lie over a broad latitudinal zone across the equator. Strong penetrative convection is now found over the equatorial zone between latitudes about 10° N and 10° S with strong descent of air poleward of these latitudes in both hemispheres. In other words, two Hadley-type circulation cells now dominate the scene, one in each hemisphere, with no monsoon cell in either hemisphere. This situation leads to maximum rainfall over the equatorial zone (Xie and Arkin, 1996).

(c) *July (Winter) : Fig. 10(c)*

The July pattern of vertical circulation over South America appears to be a reversal of the January pattern. The heat source and its associated strong convection has moved northward and now lies in the northern hemisphere between about 5° N and 20° N. Strong descending motion prevails over South America, south of about 5° S. The circulation pattern in the lower troposphere (below about 800 hPa) between about 5° N and 5° S appears to be rather complex and may have been generated by some surface features. However, there is little doubt that the summer monsoon is now a feature of the northern hemisphere, which followed the poleward withdrawal of the northernhemisphere Hadley circulation cell to latitudes north of 20° N.

(d) *October (Spring) : Fig. 10 (d)*

There appear to be two well-defined zones of convection, one in the northern hemisphere lying poleward of 10° N and the other in the southern hemisphere lying poleward of about 10° S. Subsidence prevails over the equatorial zone between these latitudes. This may mean that although the sun has moved into the southern hemisphere and a heat source is developing in that hemisphere, a heat source continues to linger in the northern hemisphere, creating a situation for two monsoon circulations, one in each hemisphere. Such a view appears to be supported by the October mean rainfall map (not shown) which shows two concentrated rainfall bands, one on either side of the equator with scanty rainfall over the equatorial zone.

5. Evidence of monsoon in other climatological fields

In this section, we produce climatological evidence of seasonal reversal due to monsoon over the South American region from the fields of several other meteorological variables. For these, we present zonally-averaged (averaged between 65° W and 45° W) deviation (deviation from the annual mean) values in a meridional-vertical section for the months of January and July. At the end of the section, we present the observed climatological distributions of rainfall for the months of January and July. The findings in the case of the different elements are summarized as follows :

(a) *Temperature*

Figs. 11(a&b) show the meridional-vertical profiles of the zonally-averaged deviation temperature in January and July respectively. They show that in January a temperature maximum at surface lies centered at a latitude of about 35° S, while a temperature minimum lies in the northern hemisphere north of about 20° N. In July, the fields appear to be reversed, with the warmest temperature lying in the northern hemisphere north of about 20° N and the coldest in the southern hemisphere near latitude 35° S.

(b) *Isobaric height*

The meridional-vertical profiles of the zonally-averaged isobaric height fields during January and July are presented in Figs. 12(a&b) respectively. Fig. 12(a) shows that in January a well-marked trough of low pressure associated with the ‘heat low’ over southern Brazil tilts equatorward with height reaching a pressure surface of about 500 hPa at 10° S. This equatorward vertical tilt appears to be important because it signifies slant convection and equatorward extension of the rainbelt over South America during January. In July [Fig. 12(b)], the height field appears to be reversed. The January trough of low pressure appears to have moved northward and replaced by a well-marked ridge of high pressure over central South America. The low pressure trough now lies between 5° S and 20° N.

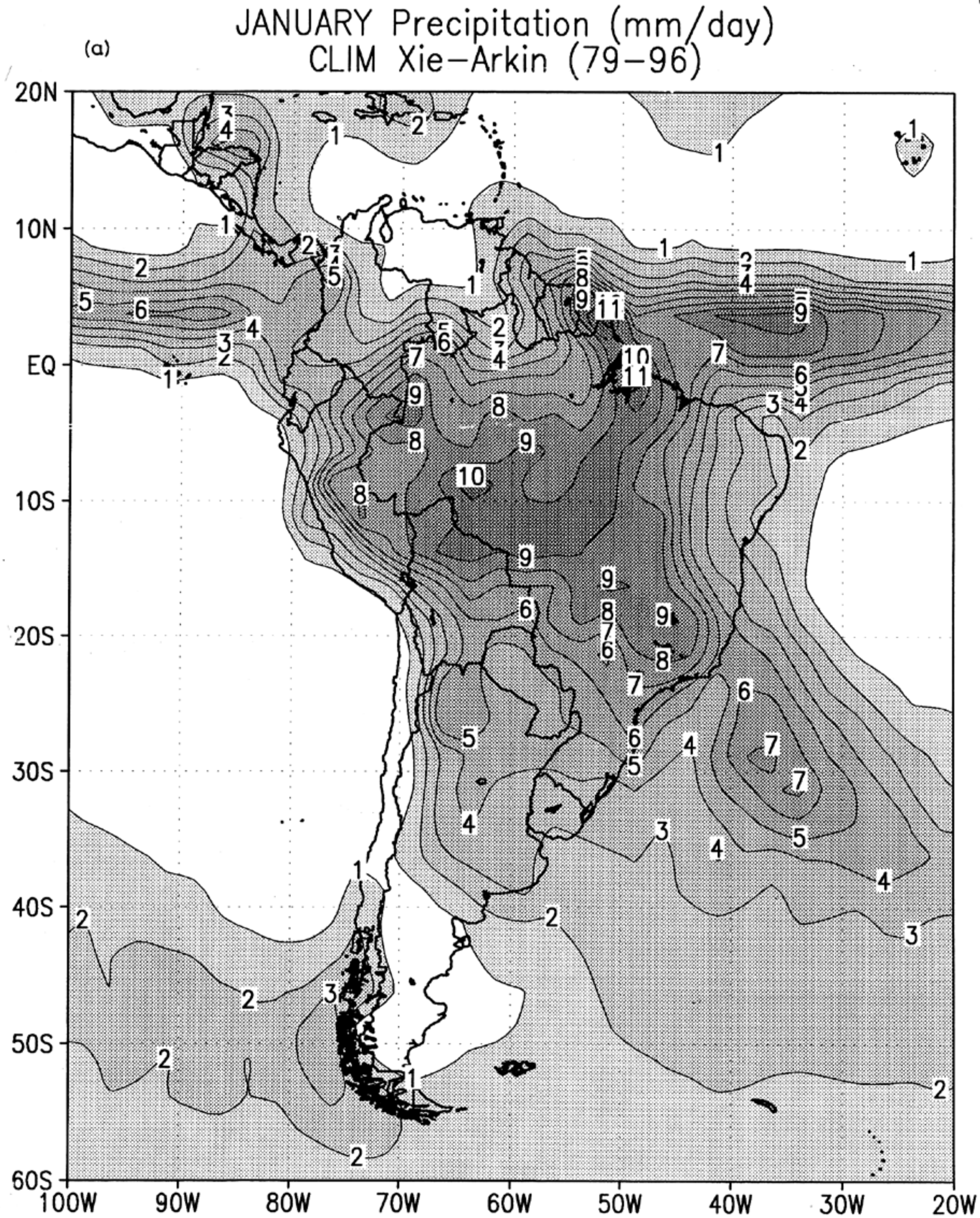


Fig. 14(a). Distribution of mean monthly rainfall (mm/day) over South America : January

(c) *Moisture (Specific humidity)*

Figs. 13(a&b) show the moisture deviation fields for the months of January and July respectively. In January [Fig. 13(a)], moist air appears to be concentrated near the center of the cyclonic circulation over central South America, while relatively dry air lies to the north of the equator. The distribution appears to be reversed in July

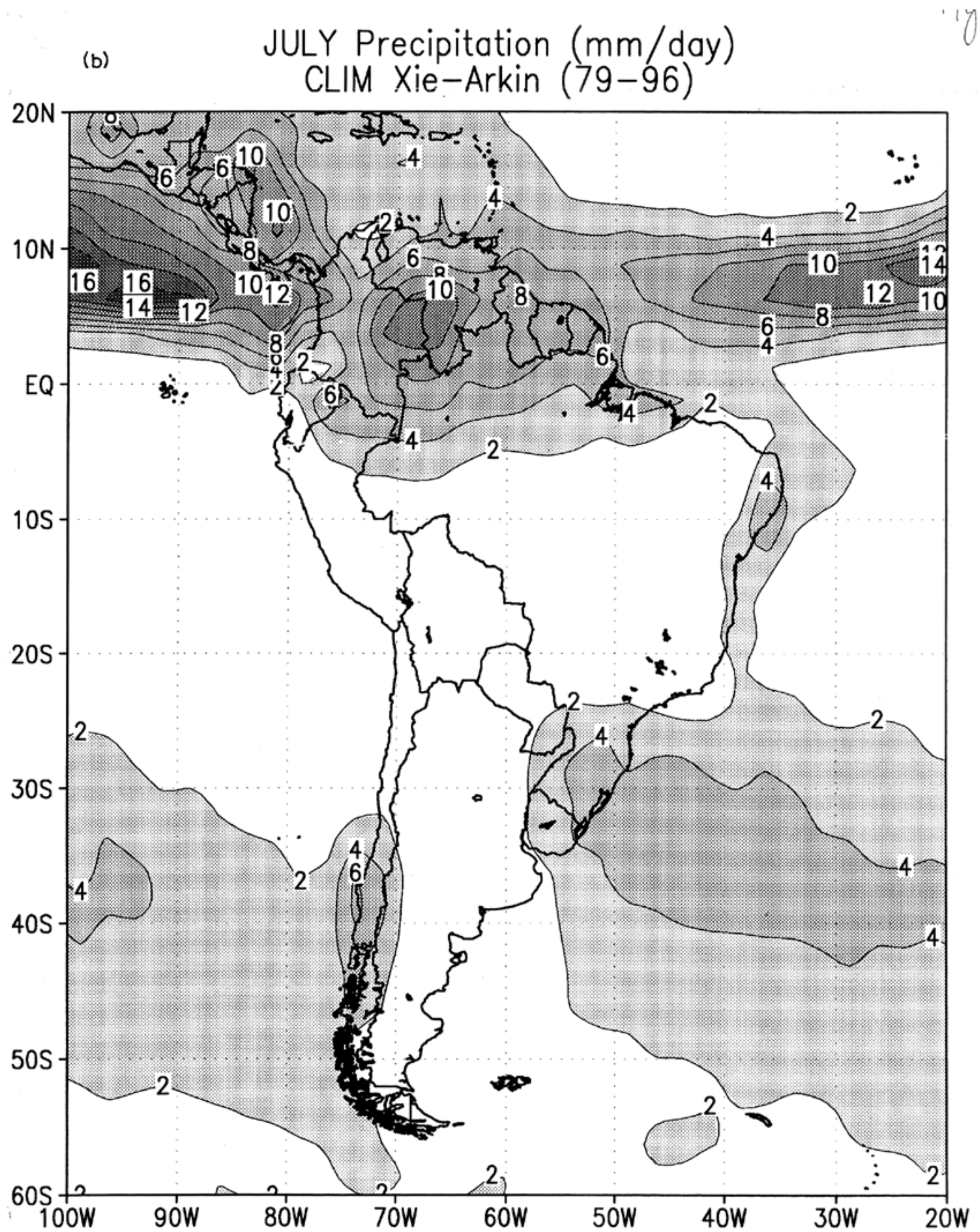


Fig. 14(b). Distribution of mean monthly rainfall (mm/day) over South America : July

[Fig. 13(b)] with relatively dry air replacing the moist air over central South America and moist air shifted to latitudes north of about 5° N.

(d) *Rainfall*

A most convincing evidence in support of a monsoon over South America comes from an examination of the seasonal distribution of rainfall over the continent (Xie and Arkin, 1996), presented in Figs. 14(a&b) for January and July respectively. In January, widespread rain falls over almost the whole of Brazil lying to the north of the 'heat low' at surface (except northeast Brazil) and extending upto the equator and beyond, with some of the heaviest falls over the Amazon river basin and the adjacent Guiyana region. In July [Fig. 14(b)], most of

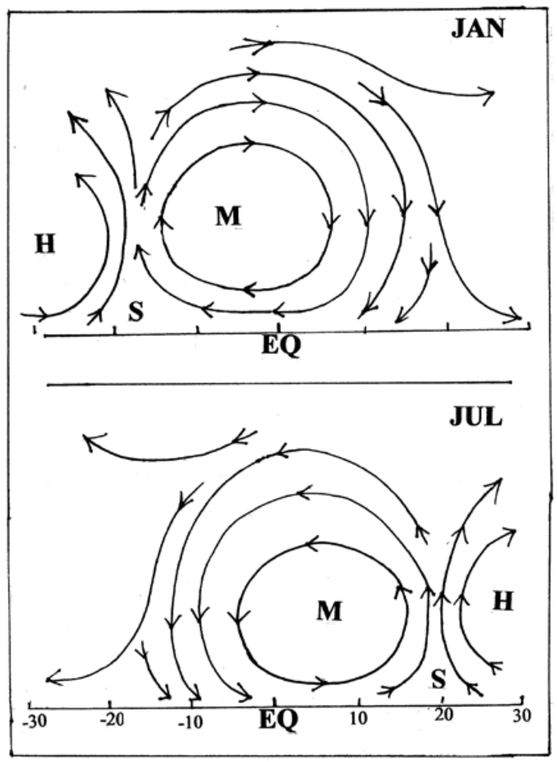


Fig. 15. Schematic showing the co-existence of Hadley and monsoon circulation cells relative to the heat source in the earth-atmosphere system in January and July. S denotes Source, M- monsoon and H- Hadley

South America (except the equatorial belt lying to the north of about 5° S and a few coastal belts in the east and south) is dry, signifying a total reversal of the rain field, which is a characteristic feature of a monsoon circulation. Incidentally, the southeastward extension of the heavy rainfall region over Brazil into southern Atlantic does not appear to be related to monsoon circulation over South America.

6. Discussion and concluding remarks

Presently, monsoon is defined by either a seasonal reversal of the prevailing surface wind or rainfall and identified over those specific regions of the globe only where these conditions are met to a large degree (Ramage, 1971). As mentioned in section 2, this definition has led to problems in identifying monsoons over some regions where they are believed to exist, however weak or strong they may be. We believe that the monsoon circulation is truly global since it is forced by the seasonal oscillation of the sun and if it is not clearly observed over any region, it may be due to extraneous factors, such as the dominance of the tradewind circulations or extremely cold ocean surfaces over the region or other orographic or physical barriers. Evidence furnished in the preceding sections leaves little doubt regarding the existence of a monsoon circulation over South America. In coming to this conclusion, we have been guided by the following definition of a monsoon circulation :

"A monsoon is a three-dimensional atmospheric circulation which is forced by the heat budget of the earth-atmosphere system when in the course of the annual oscillation of the sun the heat source moves away from the equator or its mean annual location to the summer hemisphere and consists of a horizontal rotational circulation around the heat source and sink and a vertical divergent circulation to remove heat from .source to sink with a reversal of wind direction between the lower and the upper troposphere and is characterized by seasonal reversals in the distributions of pressure, temperature, wind and rainfall and other meteorological parameters".

We believe that our definition of the monsoon circulation is consistent with what Halley (1686) observed more than three centuries ago when he said in one of the paragraphs of his paper :

"But as the cool and dense air, by reason of its greater gravity, presses on the hot and rarefied, it is demonstrable, that this latter must ascend in a continued stream, as fast as it rarefies, and that being ascended, it must disperse itself to preserve the equilibrium; that is, by a contrary current, the upper air must move from those parts where the heat is greatest : so by a kind of circulation, the north-east trade wind below will be attended with a south-westerly above, and the south-easterly with a north-west wind above. And that this is more than a bare conjecture, the almost instantaneous change of the wind to the opposite point, which is frequently found in passing the limits of the trade winds, seems to assure us; but that which above all confirms this hypothesis, is the phenomenon of the monsoons, by this means most easily solved, and without it hardly explicable".

In our view, a monsoon circulation cell co-exists with the Hadley circulation cell whenever and wherever the atmospheric heat source moves away from the equator or its annual mean position into any hemisphere. With a common rising branch at the heat source, the Hadley cell lies on the poleward side of the heat source while the monsoon cell lies on the equatorward side, as shown by a schematic in Fig. 15.

It is hoped that in the light of the results of the present study there will be renewed interest in studies of monsoon not only over South America but also over other parts of the globe.

Acknowledgements

The authors thank the reviewer for his very constructive and helpful comments. They also thank NCEP/NCAR for the Reanalysis data used in the study, John Janowiak for help with satellite cloud imagery and Dr. Huug van den Dool who offered useful comments on the first draft of the paper.

References

Boucher, K., 1975, "Global Climate", Wiley & Sons, New York, p326.

Halley, E., 1686, "An historical account of the tradewinds and monsoons observable in the seas between and near the tropics, with an attempt to assign the physical cause of the winds", Phil. Trans. Roy. Soc., London, 153-168.

Hadley, G., 1735, "Concerning the cause of the general tradewinds", Phil. Trans. R. Soc., London, **39**, 58-62.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Jenne, Roy and Joseph, Dennis, 1996, "The NCEP/NCAR 40-year Reanalysis Project", *Bull. Amer. Meteor. Soc*., **77**, 437-471.

Kendrew, W. G., 1961, "Climates of the continents", Oxford University Press, London, p608.

Pearce, E. A. and Smith, G., 1990, "The Times Books World Weather Guide", published by Times Books, Random House, Inc., New York.

Ramage, C, S., 1971, "Monsoon Meteorology", Academic Press Inc., p269.

Rao, G. V. and Erdogan, S., 1989, "The atmospheric heat source over the Bolivian Plateau for a mean January", *Boundary-Layer Meteor*., **46**, 13-33.

Saha, K., Van den Dool, H. M. and Saha, S., 1994, "On the annual cycle in surface pressure on the Tibetan Plateau compared to its surroundings", *J. Climate*, **7**, 2014-2019.

Saha, K., Van den Dool, H. M. and Saha, S., 1998, "A view of global monsoons in observed and model climatology", *Mausam*, **49**, 79-94.

Satyamurty, P., Nobre, C. A. and Silva Dias, P. L., 1998, "South America", in Meteorology of the Southern Hemisphere, edited by David J. Karoly and Dayton G. Vincent, *Amer. Meteor. Soc*., Meteor. Monograph, 27, No.49.

Schwerdtfeger, W., 1976, "Climates of Central and South America", in World Survey of Climatology, 12, (ed.-in-chief: H. E. Landsberg), Elsevier Scientific Publishing Co., Amsterdam.

Taljaard, J. J., 1972, "Synoptic Meteorology of the Southern Hemisphere", in Meteorology of the Southern Hemisphere, edited by C. W .Newton, Meteor.Monograph, 13.

Van den Dool, H. M. and Saha, S., 1993, "On the seasonal redistribution of atmospheric mass in a general circulation model", *J. Climate*, **6**, 22-30.

Winston, J. S., Gruber, A., Gray, T. I., Varnadore, M. S., Earnest, C. E., and Mannello, L. P., 1979, "Earth-atmosphere radiation budget analyses derived from NOAA satellite data June 1974-February 1978", Vol. 2, Meteorological Satellite Laboratory, U. S. Department of Commerce, Washington, D.C.

Xie, P. P. and Arkin, P. A, 1996, "Analyses of global monthly precipitation using gauge observations, satellite estimates and numerical model predictions", *J. Climate*, **9**, 840-858.

Zhou, J. and Lau, K. M., 1997, "Climatology of the South American Monsoon", Preprints of Fifth Int. Conf. on Southern Hemisphere Meteor. & Oceanography, Pretoria, South Africa, 160-161.