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Precipitation and Water Vapor Transport in the Southern Hemisphere with Emphasis on the South American Region

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Abstract

December to March climatologies of precipitation and vertically integrated water vapor transport were analyzed and compared in order to find the main paths by which moisture is fed to high rainfall regions in the southern hemisphere in this season. The southern tropics (20°S to 0°) exhibit high rainfall and receive ample moisture from the northern trades, except in the eastern Pacific and the Atlantic Oceans. This inter-hemispheric flow is particularly important for Amazonian rainfall, establishing the North Atlantic as the main source of moisture for the forest during its main rainy season. In the subtropics the rainfall distribution is very heterogeneous. The meridional average of precipitation between 35°S to 25°S is well modulated by the meridional water vapor transport through the 25°S latitude circle, being greater where this transport is from the north and smaller where it is from the south. In South America, to the east of the Andes, the moisture that fuels precipitation between 20°S and 30°S comes both from the South and from the North Tropical Atlantic Oceans whereas between 30°S and 40°S it comes mostly from the North Atlantic after passing over the Amazonian rainforest. The meridional transport (across 25°S) curve exhibits a double peak over South America and the adjacent Atlantic, which is closely reproduced in the mean rainfall curve.

This corresponds to two local maxima in the two dimensional field of meridional transport: the moisture corridor from Amazonia into the continental subtropics and the moisture flow coming from the southern tropical Atlantic into the subtropical portion of the South Atlantic Convergence Zone. These two narrow pathways of intense moisture flow could be suitably called “aerial rivers”. Their longitudinal positions are well defined. The yearly deviations from climatology for moisture flow and rainfall correlate well (0.75) for the continental peak but not for the oceanic peak (0.23). The structure of two maxima is produced by the effect of transients in the time scale of days.

1. Introduction

Extensive regions of high precipitation receive moisture from the large scale atmospheric flow in the lower troposphere. Some previous studies have identified important pathways through which moisture is brought to fuel precipitation in specific areas. D'abreton and Tyson (1995) undertook a detailed study of the field of water vapor transport and its convergence in the inter-seasonal and interannual time scales, to investigate the sources of moisture for the rainy season in Southern Africa. They found that humidity comes both from the Atlantic and from the Indian Oceans in the early summer and mostly from the Indian Ocean later in the season. Kodama (1992, 1993), who investigated the common features of subtropical precipitation areas, identified the meridional moisture transport by the equator-to-pole branches of the subtropical highs as essential for the formation and maintenance of the Subtropical Convergence Zones (STCZs). To this end the author calculated temporal correlations between the intensity of these flows and the precipitation in the STCZs.

The main goal of this paper is to explore a simple method to study the transport of water vapor to rainfall regions. It is based on the fact that climatological precipitation is closely related to vertically integrated climatological water vapor convergence (Satyamurty et al. 1998). With this in mind one can say that the climatological field of vertically integrated water vapor transport shows the main pathways through which water vapor flows into areas of high rainfall. In some cases the main source regions for moisture feeding specific rainfall areas may be inferred. This approach is taken from Arraut (2007) which showed that the North Atlantic trade winds are the main providers of moisture for its humid subtropics, after travelling over the Amazon forest, in the December, January, February and March season.

South America exhibits important peculiarities in its rainfall and moisture transport regimes when compared to the two other continental land masses of the hemisphere: during summer its subtropics receive ample moisture coming from the tropics and abundant rainfall. These peculiarities are linked to the presence of the Andes, which is a meridional mountain chain extending from the deep tropics to the midlatitudes on the west of the continent. The topography of South America can be seen in Figure 1. Using five days of satellite derived winds Virji (1981) observed intense flow from the tropical Atlantic into the continent executing an anti-cyclonic turn over Amazonia and heading southwards. He postulated the existence of a low level jet east of the Andes. This was later confirmed both through direct observations and reanalysis studies (Vera et al. 2006, references therein). When the exit region of this jet is located south of 25°S it is termed Chaco Jet because if flows over the Gran Chaco region.

Nogués-Paegle and Mo (1997) were the first to observe that the enhancement of precipitation over the South American subtropical plains was linked to enhancement of moisture flow from the tropics towards the region during summer. Furthermore, those authors detected a tendency for wet conditions in this region to be accompanied by dry conditions over the South Atlantic Convergence Zone (SACZ) and vice-versa. This seesaw pattern in the intra-seasonal time scale is associated with an alternation in the large scale moisture flow regime from intense transport east of the Andes to intense flow in the western branch of the Atlantic Subtropical High.

Li and Le Treut (1999) studied moisture transport over the South American continent using 17 years of European Centre for Medium Range Weather Forecasts (ECMWF) Reanalysis data. They found enhanced northerly transport across 27.5°S to be associated with enhanced (diminished) precipitation in a diagonal region to its south (north). This they stated to be a confirmation of the above mentioned seesaw pattern and attributed to the north-south displacements of the SACZ.

Transient disturbances are a major cause for the intensification of moisture transport east of the Andes and precipitation over the South American subtropics during summer, according to many previous studies. Garreaud and Wallace (1998) show this to occur before cool air incursions as a geostrophic response to a strengthening of the Northwestern Argentinean Low (NAL). The subtropical plains are thus supplied with moisture that fuels precipitation when two days later the atmosphere is destabilized by the advancement of the colder air in low levels. Siqueira and Machado (2004) studied the variability of convective systems associated with the incursion of frontal systems. During summer these systems accounted for over 45% of the total daily convective variability. In that work, the frontal incursions were classified according to their interaction with tropical convection. The enhancement of moisture transport from Amazonia towards the disturbances was observed in all categories.

The geostrophic response to the intensification of the NAL was shown to be the mechanism behind the formation of the Chaco Jet in a case study (Saulo et al. 2004) and is also very important during the incursion of summertime fronts, providing moisture for intense rainfall (Arraut 2007). Salio et al. (2002) characterize the large scale synoptic situation typical of Chaco Jet events. Salio et al. (2007) show that these events provide a suitable environment for the formation of Mesoscale Convective Complexes in subtropical South America. In each of the above mentioned cases the authors report the presence of a transient trough straddling the Andes at high levels with a maximum of wind speed downstream. According to Garreaud and Wallace (1998) and Seluchi et al. (2003), the strong westerlies above the Andes at high levels produce adiabatic heating east of the mountains at low levels due to the Foehn effect, thus contributing to the intensification of the NAL and of northerly moisture transport into the subtropics.

As mentioned in the previous paragraph, the Chaco Jet is situated below the **entrance** region of an upper level jet. Uccellini and Johnson (1979) had shown that ageostrophic circulations on the **exit** region of an upper level jet would favor low-level jet formation. Saulo et al. (2007) considered the interactions between the upper and low-level (Chaco) jets in South America as well as the synergism between the Chaco Jet and organized convection in its exit region. They found that the events begin with the geostrophic intensification of northerly moisture carrying flow due to the deepening of the NAL. This fosters organized convection that enhances low level convergence and thereby strengthens the Chaco Jet. Upward motion in the convective region contributes to high level divergence which weakens the westerlies upstream and strengthens them downstream, enhancing the upper jet.

2. Data and Calculations

All climatological fields presented in this paper were calculated for December to March seasons, from 1981/82 to 2001/02.

Rainfall data were obtained from the GPCP version 2 Combined Precipitation Data Set (Huffman et al. 2001), which provides monthly means on a $1^\circ \times 1^\circ$ spatial grid. All other data used are part of the European Centre for Medium Range Weather Forecasts ERA40 reanalysis, provided at six hour intervals at a $2.5^\circ \times 2.5^\circ$ spatial grid.

Water vapor transport was vertically integrated from the surface to 650 hPa, assuming that the water vapor content above this level is negligible for our purposes, and is given by:

$$Q\vec{V} = \int_{P_s}^{650\,hPa} q\vec{V}\frac{dP}{g}, \tag{1}$$

where

$$Q\vec{V} = (Qu, Qv), \tag{2}$$

where q is the specific humidity, g is the acceleration of gravity, P is pressure and P_S is pressure at the surface. P_S is not provided in ERA40 and was calculated using 1000 hPa geopotential and temperature ($\phi_{1000},\ T_{1000}$), geopotential at the surface (ϕ_S, given by topography) and 2 meter temperature (T_{2m}), using the ideal gas law and a linear variation of temperature with geopotential, which leads to the expression:

$$Ps = 1000\,hPa\left(\frac{T_{2m}}{T_{1000}}\right)^{-\frac{1}{\Gamma R}}, \tag{3}$$

where Γ is given by

$$\Gamma = \frac{T_{2m} - T_0}{\phi_s - \phi_0}, \tag{4}$$

where R is the ideal gas constant for dry air.

Climatological moisture transport is obtained by calculating $Q\vec{V}$ at six hour intervals for the whole period studied and taking the long term average. December to March moisture transport climatology is shown in figure 2 and will be discussed in section 3.

3. Climatological Precipitation

Figure 2 shows the austral summer rainfall climatology. Except for the Atlantic and east Pacific oceans, the latitudinal band between the Equator and 20°S, receives large amounts of rainfall. The subtropical band, between 20°S and 40°S, is notoriously drier with very unevenly distributed precipitation. The Subtropical Convergence Zones (STCZs; subtropical portions of the SPCZ and the SACZ) receive considerable precipitation, as does subtropical South America east of the Andes. There are also very dry stretches and others that appear moderately humid. To better illustrate this pattern, seven subdivisions are made in longitudinal sectors according to rainfall amounts, with results presented in Figure 2. The South American subtropics east of the Andes and the oceanic portion of the SACZ have similar rainfall amounts and are thus joined in a single sector despite having different rainfall regimes, as stated earlier (Nogués-Paegle and Mo 1997). The spatial pattern they exhibit suggests a separation along the dotted line at 50$^{\circ}W$ in Figure 2.

The zonal average of rainfall over each of the seven sectors is shown in Figure 3. In the midlatitudes rainfall is around 3 mm/day and shows a homogeneous distribution. From 40°S to slightly south of 20°S they separate into three distinct groups. The driest of these are the eastern sectors of the three oceans and part of the contiguous land masses. The Pacific Ocean/South America (PSA) sector extends over a narrow strip of the continent's western coast and is clearly delimited by the Andes Cordillera, to the east of which there is high rainfall. There are two sectors with moderate rainfall: the westernmost stretches of the Pacific and Indian oceans, together with the eastern coasts of Australia (AuP) and Africa (AfI) respectively. The most humid sectors are the two STCZs and South America east of the Andes (SPCZ and SA+SACZ). Rainfall increases rapidly from the midlatitudes towards the subtropics, where it approaches 5mm/day. The decrease in rainfall towards the tropics exhibited by the SA+SACZ sector is not a feature of the convergence zone but shows that the simple meridional boundary used here is not fully adequate for its diagonal orientation. In lower latitudes the SACZ sector includes a part of the east Atlantic tropical desert.

4. Climatological Water Vapor Transport

a. Tropics

Figure 4 shows streamlines of the climatological vertically integrated water vapor flux in the global atmosphere for the austral summer. In this season, humidity flow in the Northern Hemisphere tropics has a distinct north to south component which reflects the same feature in the Northern Hemisphere trade winds (not shown). Over the Atlantic and east central Pacific, confluence of the northern and southern trades occurs slightly north of the Equator where Inter-Tropical Convergence Zones (ITCZs) appear in Figure 2. Elsewhere, moisture flow from the northern tropics distinctly crosses the equator into the Southern Hemisphere, contributing moisture to the high rainfall areas in the southern tropics. In Amazonia this inter-hemispheric inflow is the main source of moisture. Eastern tropical Africa also receives flow coming mostly from the Northern Hemisphere, although some of it goes over the Southern Indian Ocean before reaching the continent. In order to better understand the interdependence between the southern tropical rains and humidity flow coming from the Northern Hemisphere, meridionally averaged precipitation, from 0 to 18°S, alongside the cross-equatorial moisture transport is shown in Figure 5. Climatological rainfall is comparable to humidity convergence and not directly to moisture transport and, therefore, the relative scale is arbitrary. However the shapes of the humidity transport curve and the rainfall curve are similar in that they have peaks and troughs in similar places over most of longitudes, except for the stretch between 60°E and 120°E approximately. Furthermore, the West Central Pacific and Amazonia, which exhibit the highest rainfall in the Tropics, receive the strongest inter-hemispheric moisture flow. This suggests an important interdependence between tropical rain and cross-equatorial flow in the Southern Hemisphere, in the long-term means. Over South America this inter-dependence is particularly strong, given that the coincidence in shape between both curves is remarkable.

b. Subtropics

Going back to figure 4, it can be seen that the moisture flow from the Northern Hemisphere generally does not go beyond the southern tropical latitudes. The only exception occurs over South America, where the North Atlantic trades turn anti-cyclonically over Amazonia and head southwards to almost 40°S. The eastward flow from the South Atlantic high also turns southwards quite sharply when approaching the continent. The Andes chain is an important contributor to this pattern. Due to its blocking effect over the low-level zonal flow the moisture brought by the Atlantic trade winds into the continent is retained, preventing outflow into the Pacific, and leaves it no other path but to go southwards. One can see that the mountain chain marks a discontinuity in the meridional flow, which is from the north on its eastern side and from the south on its western side.

In the Southern Hemisphere, the three gyres associated with the three subtropical highs are the most prominent features of the humidity flow. In the Atlantic and in the east Pacific the northern branches of these gyres are mostly formed by trade winds, which turn anti-cyclonically close to the east coast of South America and over the central Pacific, bringing flow meridionally into the subtropical SACZ and SPCZ. Together with subtropical South America to the east of the Andes, these constitute the high rainfall group, which leads us to state that high rainfall in the subtropics is fueled by moisture collected by the trade winds and occurs where these winds are sharply deflected into flowing southwards.

Figure 6 shows meridionally averaged rainfall between 25°S and 35°S and moisture flow across 25°S. In this latitudinal stretch the three groups of longitudinal sectors are well separated from each other in rainfall (see Figure 3). This figure allows for a better assessment of the relationship between climatological meridional flow and precipitation in the subtropics. As stated earlier when describing Figure 5, only the shapes of the curves are compared here. The subtropical gyres are reflected in the alternation of sign of the meridional transport. The similarity between the shapes of the curves is more striking here than in the Tropics and shows that precipitation in this subtropical band is well modulated by the meridional moisture transport, being greater where flow is from the north and smaller where it is from the south. Only in coastal Africa (around 30°E) precipitation attains a local maximum while meridional transport becomes negative due to a local feature of the circulation over Madagascar (not shown).

Over South America and the adjacent Atlantic (65°W to 20°W) the meridional transport from the north is particularly intense and has a double peak, one inland and one over the coastal ocean, which are also present in the precipitation.

Previously Li and Le Treut (1999), using an earlier version of ECMWF reanalysis, studied the vertical cross section of moisture transport along 27.5°S, over the South American continent. In analyzing the climatological field ($\bar{qv}$) those authors considered its decomposition into the mean and transient flow contributions:

$$\bar{qv} = \bar{q}\bar{v} + \bar{q'v'}, \tag{5}$$

where q' and v' are the anomalies with respect to the climatologies $\bar{q}$ and $\bar{v}$. They found two maxima of northerly transport over the continent centred around 850 hPa, in their $\bar{q}\bar{v}$ field. In the same longitude interval our vertically integrated $\bar{QV}$ field shows only the westernmost peak in Figure 6. A visual estimate of what their $\bar{QV}$ field would be, based on their Figure 2 (not reproduced here), indicates that the pattern of two maxima over the continent would be somewhat weakened by adding the transient flow contribution and further weakened by the vertical integration, but it is difficult to know whether it would still be present. In any case, discrepancies do not seem large and may be attributed to the use of different data sets.

Those authors also consider rainfall anomalies during strong events of northerly moisture transport over the continent and obtain increased rainfall centered over La Plata River. Seluchi and Marengo (2000) show a double maximum in meridional mass transport over the continent and ocean, at longitudes similar to those shown in Figure 6.

In this work a very close spatial association between climatological rainfall and moisture transport is evidenced, both over the continent and the adjacent ocean. The western peak in meridional moisture flow corresponds to the moisture corridor from the Amazon into the continental subtropics while the eastern peak corresponds to flow from the southern trades into the SACZ region. As will be discussed later, this spatial association cannot be inferred from studies of temporal associations, such as Li and Le Treut (1999), and vice-versa.

Although, as stated earlier, the blocking of the zonal flow by the Andes plays an important role in promoting this meridional transport, it cannot account for the double peak structure. Furthermore the SPCZ region, where there is no physical barrier, also exhibits considerable meridional flow. Regarding the continental peak, previous work has been pointing to an important role played by transients by means of the intensification of the NAL (Nogués-Paegle and Mo 1997; Salio et al. 2002; Seluchi et al. 2003; Salio et al. 2007; Saulo et al. 2007).

It should be noted that the close associations between precipitation and meridional moisture transport shown in this section do not signify that this component is responsible for most of the moisture supply. It means that during the studied season precipitation in the tropical and subtropical southern hemisphere is fueled by moisture from more northerly latitudes.

5. South America

Figure 1 shows the same field as Figure 4 except that it is focused over South America and the Atlantic region. Vectors instead of stream lines allow for an assessment of the magnitude of this transport. The inflow of moisture through the northern coast of the continent is very intense, and has a maximum downstream of the trade wind confluence. Most of the moisture entering at this spot and to the north of it flows over Amazonia. A noticeably weaker transport leaves this region southwards after an anti-cyclonic turn, having maximum intensity close to the Andes and exhibiting difluence over the subtropics. To the south of the trade wind confluence moisture entering the continent does not go beyond the northeast region of Brazil before turning sharply anti-cyclonically and heading south. There is confluence of these two southward currents around 25°S and 55°W, where rainfall is above 5 mm day^{-1} (see Figure 2). South of 30°S rainfall over the continent is mostly fed by the flow coming from Amazonia, while the oceanic portion of the SACZ receives moisture flow coming directly from the South Atlantic, without passing over the continent.

The Tropical North Atlantic is the main source of moisture for rainfall in tropical and in most of subtropical South America in the December to March season. This is the rainiest season for both regions. Before reaching the continental subtropics, flow coming from the North Atlantic traverses Amazonia and no doubt receives moisture from the forest. However this moisture comes ultimately from the North Atlantic for the most part.

a. Interannual Variability

Both in the tropics and in the subtropics climatological precipitation and northerly moisture transport show a strong association in the spatial distribution of their intensities. An interesting question is if these associations are also present in the annual means. It is important to note that this is not to be expected a priori. The availability of moisture is a necessary but not a sufficient condition for the occurrence of rainfall and consequently increases in moisture transport need not be accompanied by increases in rainfall and vice-versa. Importantly, these two quantities alone do not provide information about the role of local evapotranspiration for rainfall. The presence of a large temporal correlation between meridional moisture transport and rainfall for any given region can be considered an important climatological trait. Having said this, the interannual variabilities of moisture transport and rainfall in two key regions, the SACZ and the continental subtropics, are examined.

The meridional vapor transport and average rainfall for each of the 21 individual seasons were considered, similar to what was shown in figure 6. For these 21 seasons (not shown), the longitudinal positions of the double peaks and of the local minimum between them show very little interannual variability. The longitudinal limits of the SA and SACZ regions can therefore be well defined in this time-scale, for the period studied. For each of the 21 seasons the meridional mean rainfall considered in the last section (35S to 25S) was averaged between these longitudinal limits, resulting in area averages over the rectangles shown in figure 1. The meridional moisture transport was averaged over the northern border of each rectangle. Curves of the area averaged rainfall and zonally averaged transport against time are shown in Figures 7 (SA) and 8 (SACZ).

The SACZ region shows a low correlation between meridional moisture transport and rainfall: 0.23. The SA region on the other hand shows a 0.75 correlation. As mentioned earlier, transient synoptic baroclinic disturbances are a very important cause of rainfall in the South American subtropics. They act as a common cause for the enhancement of northerly moisture transport (by intensifying the NAL) and the destabilization of the atmospheric column where they pass. For this reason they produce intense precipitation. However, these are phenomena of a synoptic time-scale. The interannual correlation between meridional moisture transport and rainfall shown here poses the question of whether interannual variations in rainfall and meridional moisture transport in subtropical South America can be attributed to the interannual variability of these frontal incursions. This issue will not be dealt with here, but transients of the time scale of days will be considered in a general manner.

b. Daily Variability

In Figure 9 climatologies of the zonal and meridional components of water vapor transport are shown, together with the standard deviations of daily means with respect to these climatologies.

Firstly, it can be observed that the two local maxima identified in the meridional transport (and clearly represented here) are also present in the standard deviation field. In fact, the mean meridional transport and its standard deviation exhibit remarkably similar spatial patterns south of 15°S. This is not so for the zonal component. Instead, away from the Andes, the standard deviation of this component is similar in its pattern to the meridional one, suggesting a common source of variability.

In the subtropics the standard deviation of the meridional component is similar to, and often larger than its mean. Assuming a normal distribution this signifies not only a large variability in the intensity of this transport but also that on a day to day basis it may often change sign and flow from south to north. These phenomena are called cool air incursions (Garreaud and Wallace 1998). In the tropics the zonal component is predominant. Its standard deviation is much smaller than its mean, signifying that, although the intensity may fluctuate, strong eastwards flow is almost always present. In summary, the figure confirms that, while moisture inflow to the South American continent in the tropics is a permanent feature of the circulation, its transport to the subtropics is intermittent.

The similarity between the spatial patterns of mean and standard deviation of the meridional component suggests that the effect of transients may produce, as its climatological signature, the double maxima in the mean field. Comparing Figures 9 and 2, it can be noted that rainfall in the subtropics also exhibits a spatial distribution very similar to the meridional moisture transport and its standard deviation. From this it can be inferred that transients and meridional moisture transport hold strong enough causal relations with rainfall to produce these similarities.

Figure 10 shows climatologies of geopotential and wind, both at 850 hPa. The fields are representative of the lower troposphere. It can be seen that geostrophy plays an important role in producing the two maxima of meridional transport. East of the Andes is the climatological signature of the Chaco Low and the NAL. It is surrounded by an elongated trough. These structures are geostrophically related with the wind field all the way to 15$^\circ S$. Evoking the known relationship between the intensification of the NAL and frontal incursions, this can be seen as evidence of the climatological importance of these systems. Over the ocean, close to the southeastern coast of Brazil, the other meridional wind maximum is geostrophically related to the western branch of the South Atlantic High. Transient troughs travelling over the southern Atlantic in these latitudes promote geostrophic acceleration of the meridional moisture transport as they approach the subtropical high. These are not necessarily associated to the SACZ, since they need not be stationary. Although some of these are baroclinic systems causing intense rainfall, the southern subtropical Atlantic is the exit region for dissipating disturbances leaving the South American continent. In other words, many of the transient troughs that visit the SACZ region may promote meridional moisture transport but not significant precipitation. Whether or not this might account for the absence of a large temporal correlation between moisture transport and rainfall in the interannual time-scale is speculative. A comparative study of the moisture transport and rainfall in the SA and SACZ regions in shorter time-scales, intra-seasonal and daily, would be interesting.

6. Summary and conclusions

In this paper the December to March climatological pattern of precipitation in the Southern Hemisphere was analyzed, in the tropics and the subtropics, and compared to the climatological field of vertically integrated water vapor transport in order to detect important pathways of moisture to high rainfall regions and in some cases, infer the source regions of moisture. This simple approach relies on the fact that climatological precipitation is closely linked to climatological vertically integrated water vapor convergence. Special attention was given to the South American region.

The tropical latitudes exhibit high rainfall around the globe, except in the eastern Pacific and Atlantic Oceans while in the subtropics precipitation has a much lower zonal mean and is more heterogeneously distributed. A subdivision of this latitudinal band into sectors was proposed, according to the amount of rainfall they received. Seven sectors were found, which split into three groups, receiving rainfall amounts around 3 mm day^{-1}, quite lower than this and quite larger than this.

Except in the longitudes of the Atlantic and Pacific ITCZs, water vapor from the Northern Hemisphere crosses the Equator into the Southern Hemisphere, fueling precipitation in the southern tropics. For tropical Africa and particularly Amazonia, this inter-hemispheric inflow is the main source of moisture. Since evaporation takes place mainly in the tropical oceans, it can be inferred that the Northern Tropical Atlantic is the main source of moisture for Amazonian rainfall.

In the subtropics precipitation is well modulated by meridional moisture transport, being higher where it is from the north and lower where it is from the south. The highest precipitation regions are those where the trade winds, laden with moisture collected in the tropical oceans, head towards the subtropics after executing sharp anti-cyclonic turns. For the STCZs this flow comes from the southern trades. For South America east of the Andes moisture comes both from the northern and southern trades for precipitation between 20°S and 30°S and predominantly from the northern trades, after flowing over vast extensions of Amazonian rain forest, between 30°S and 40°S. Although the forest may recycle this moisture several times, its source is ultimately the ocean. This establishes the North Atlantic as the main source of water vapor for the southern South American subtropics and an important source for its northern portion.

Meridional moisture flow in the subtropics is particularly intense over South America and the adjacent Atlantic where it exhibits two local maxima, one close to the Andes, to the east, and another off the coast of southeastern Brazil. The first corresponds to moisture flow from Amazonia into the continental subtropics while the other corresponds to moisture flow from the tropical Atlantic into the subtropical portion of the SACZ. These two narrow pathways of intense moisture flow can be suitably called "aerial rivers".

The longitudinal positions of these maxima and of the local minimum between them is well defined in that it shows very little variability between individual seasons. For these two regions the interannual variability of precipitation and moisture transport was explored. In the SACZ region the temporal correlation between precipitation and meridional moisture transport was rather small, 0.23, while in the SA region it was quite large: 0.75. Further investigation is needed to account for this large difference in behavior.

The climatologies of the zonal and meridional components of moisture flow were compared to the standard deviation of their daily means, revealing that the mean meridional transport and its standard deviation have remarkably similar spatial patterns in the subtropics, suggesting that the two maxima be a climatological signature of the effect of transients. Rainfall climatology also exhibits a spatial pattern very similar to that of meridional moisture flow and its standard deviation. This is further evidence of the role of transients as important contributors to climatological rainfall. In these fields no important difference was observed between the SACZ and the SA regions that might account for the very distinct interannual behaviors.

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References

Arraut, J. M., 2007: Fronts and frontogenesis during summer: geometrical and dynamical aspects and the influence over rainfall on the South American subtropics (in Portuguese). Ph.D. thesis, Centro de Previsão de Tempo e Estudos Climáticos - INPE, Rodovia Presidente Dutra Km40 Cachoeira Paulista, São Paulo, Brasil, URL `http://urlib.net/sid.inpe.br/mtc-m17@80/2007/12.19.10.53`.

D'abreton, P. C. and P. Tyson, 1995: Divergent and non-divergent water vapour transport over southern Africa during wet and dry conditions. *J. Climate,* **55**, 47–59.

Garreaud, R. D. and J. M. Wallace, 1998: Summertime incursions of midlatitude air into subtropical and tropical South America. *Mon. Wea. Rev.,* **126**, 2713–2733.

Huffman, G. J., R. Adler, M. Morrissey, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, 2001: Global precipitation at one-degree daily resolution from multi-satellite observations. *J. Hydrometeor.*, **2**, 36–50.

Kodama, Y.-M., 1992: Large-scale common features of subtropical precipitation zones (the Baiu frontal zone, the SPCZ and the SACZ) Part I: Characteristics of subtropical frontal zones. *J. Met. Soc. Japan*, **70 (4)**, 813–835.

Kodama, Y.-M., 1993: Large-scale common features of subtropical precipitation zones (the Baiu frontal zone, the SPCZ and the SACZ) Part II: Conditions of the circulation for generating STCZs. *J. Met. Soc. Japan*, **71 (5)**, 581–610.

Li, Z. X. and H. Le Treut, 1999: Transient behavior of the meridional moisture transport across South America and its relation to atmospheric circulation patterns. *J. Geophys. Res.*, **26 (10)**, 1409–1412.

Nogués-Paegle, J. and K. Mo, 1997: Alternating wet and dry conditions over South America during summer. *Mon. Wea. Rev.*, **125**, 279–291.

Salio, P., M. Nicolini, and C. Saulo, 2002: Chaco Low-Level Jet events characterization during the austral summer season. *J. Geophys. Res.*, **107 D (24)**, 32 1 – 17.

Salio, P., M. Nicolini, and E. Zipser, 2007: Mesoscale convective systems over southeastern South America and their relationship with the South American Low-Level Jet. *Mon. Wea. Rev.*, **135**, 1290–1310.

Satyamurty, P., C.A. Nobre, and P.L. Silva Dias, 1998: *Tropics: South America*, Vol. 49, 119–140. American Meteorological Society, Boston, MA.

Saulo, C., J. Ruiz, and Y. G. Skabar, 2007: Synergism between the Low-Level Jet and organized convection in its exit region. *Mon. Wea. Rev.*, **135**, 1310–1326.

Saulo, C., M. E. Seluchi, and M. Nicolini, 2004: A case study of a Chaco Low-Level Jet event. *Mon. Wea. Rev.*, **132**, 2669–2683.

Seluchi, M. E. and J. Marengo, 2000: Tropical-midlatitude exchange of air masses during summer and winter in South America: climatic aspects and examples of intense events. *Int. J. Climatol.*, **20**, 1167–1190.

Seluchi, M. E., C. Saulo, M. Nicolini, and P. Satyamurty, 2003: The Northwestern Argentinean Low: A study of two typical events. *Mon. Wea. Rev.*, **132**, 2361–2378.

Siqueira, J. R. and L. A. T. Machado, 2004: Influence of frontal systems on the day-to-day convection variability over South America. *JC*, **17**, 1754–1766.

Uccellini, L. W. and D. R. Johnson, 1979: The coupling of upper and lower tropospheric jet streaks and implications for the development of severe convective systems. *MWR*, **107**, 662–703.

Vera, C., et al., 2006: Toward a unified view of the american monsoon systems. *J. Climate*, **19**, 4977–5000.

Virji, H., 1981: A preliminary study of summertime tropospheric circulation patterns over South America estimated from cloud winds. *Mon. Wea. Rev.*, **109**, 599–610.

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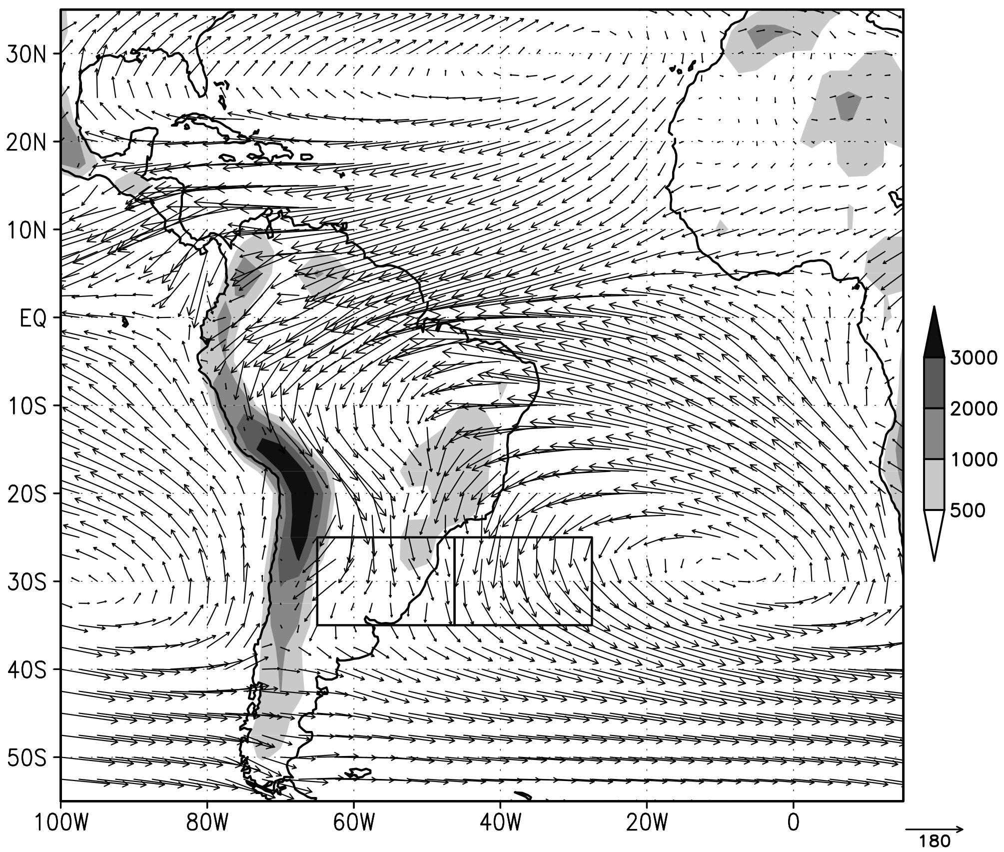

FIG. 1. Vectors: Dec to Mar moisture transport climatology (1981 to 2002) [$kg\ m^{-1}\ s^{-1}$]. Shaded: terrain elevation [m]. Rectangles show areas over which rainfall is averaged in section 5.

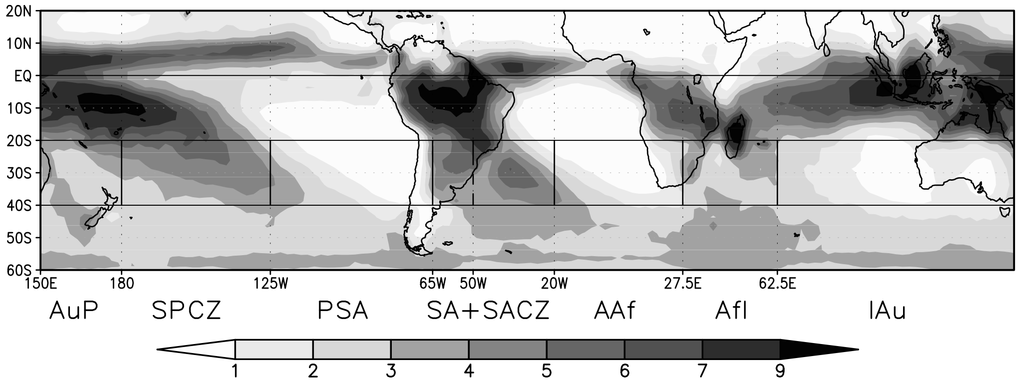

FIG. 2. Dec to Mar rainfall climatology (1981 to 2002) [$mm\ day^{-1}$] from GPCP data. Abbreviations for the seven sectors are given below the map and are described in the text.

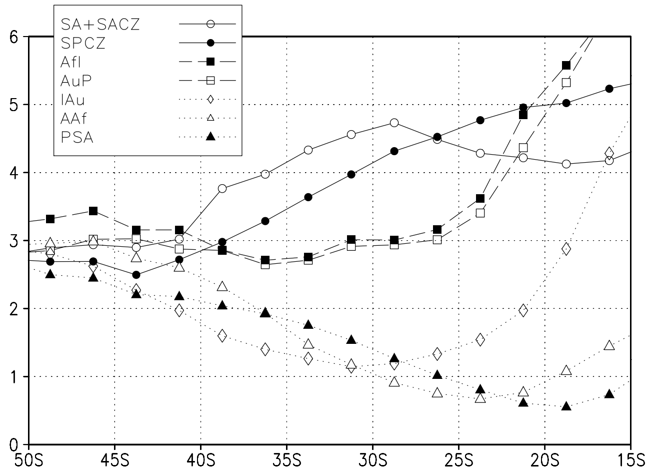

FIG. 3. Zonal mean Dec to Mar climatology (1981 to 2002) of precipitation for the sectors indicated in Figure 2.

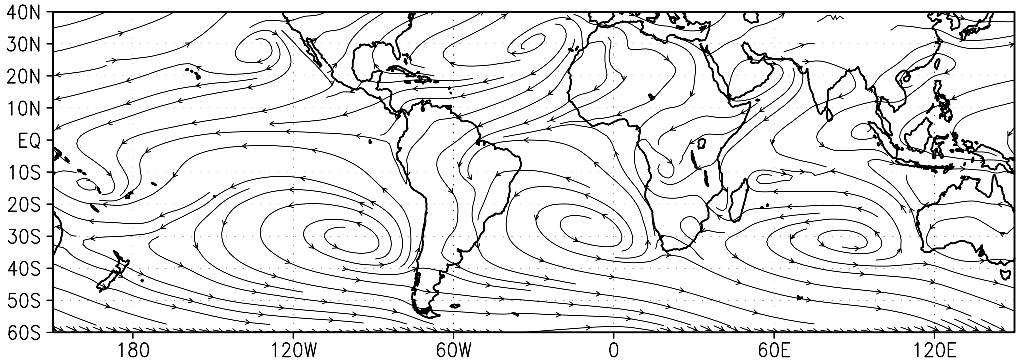

FIG. 4. Stream lines of the DEC to MAR climatology of humidity transport (1981 to 2002).

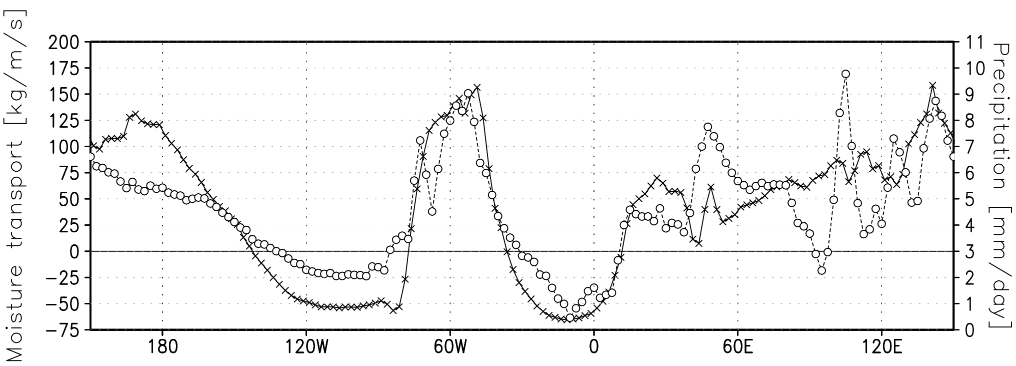

FIG. 5. Open circles: Meridional water vapor transport across the equator [$kg\ m^{-1}\ s{-1}$]. Crosses: meridional average of rainfall from 0 to 18°S [$mm\ day^{-1}$].

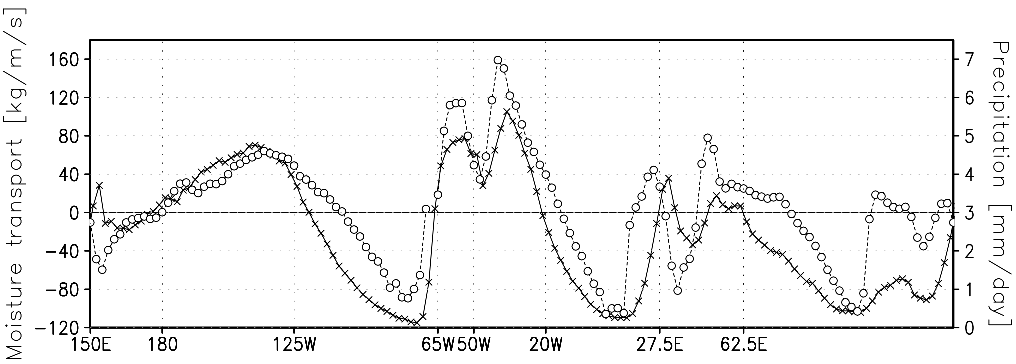

FIG. 6. Open circles: Meridional water vapor transport across the 25°S [$kg\ m^{-1}\ s^{-1}$]. Crosses: meridional average of rainfall from 25 to 35°S [$mm\ day^{-1}$].

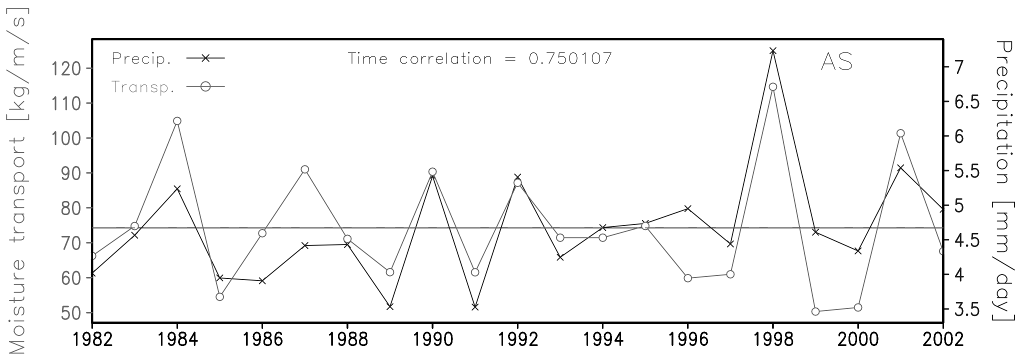

FIG. 7. Open circles: Meridional water vapor transport across the 25°S, averaged from 65°W to 47.5°W [$kg\ m^{-1}\ s^{-1}$]. Crosses: Area averaged rainfall, from 25 to 35°S and 65°W to 47.5°W [$mm\ day^{-1}$].

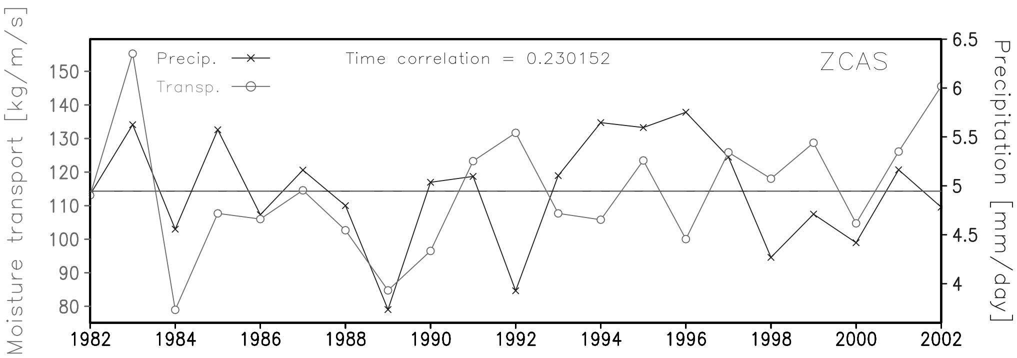

FIG. 8. Open circles: Meridional water vapor transport across the 25°S, averaged from 47.5°W to 27.5°W [$kg\ m^{-1}\ s^{-1}$]. Crosses: Area averaged rainfall, from 25 to 35°S and 45°W to 27.5°W [$mm\ day^{-1}$].

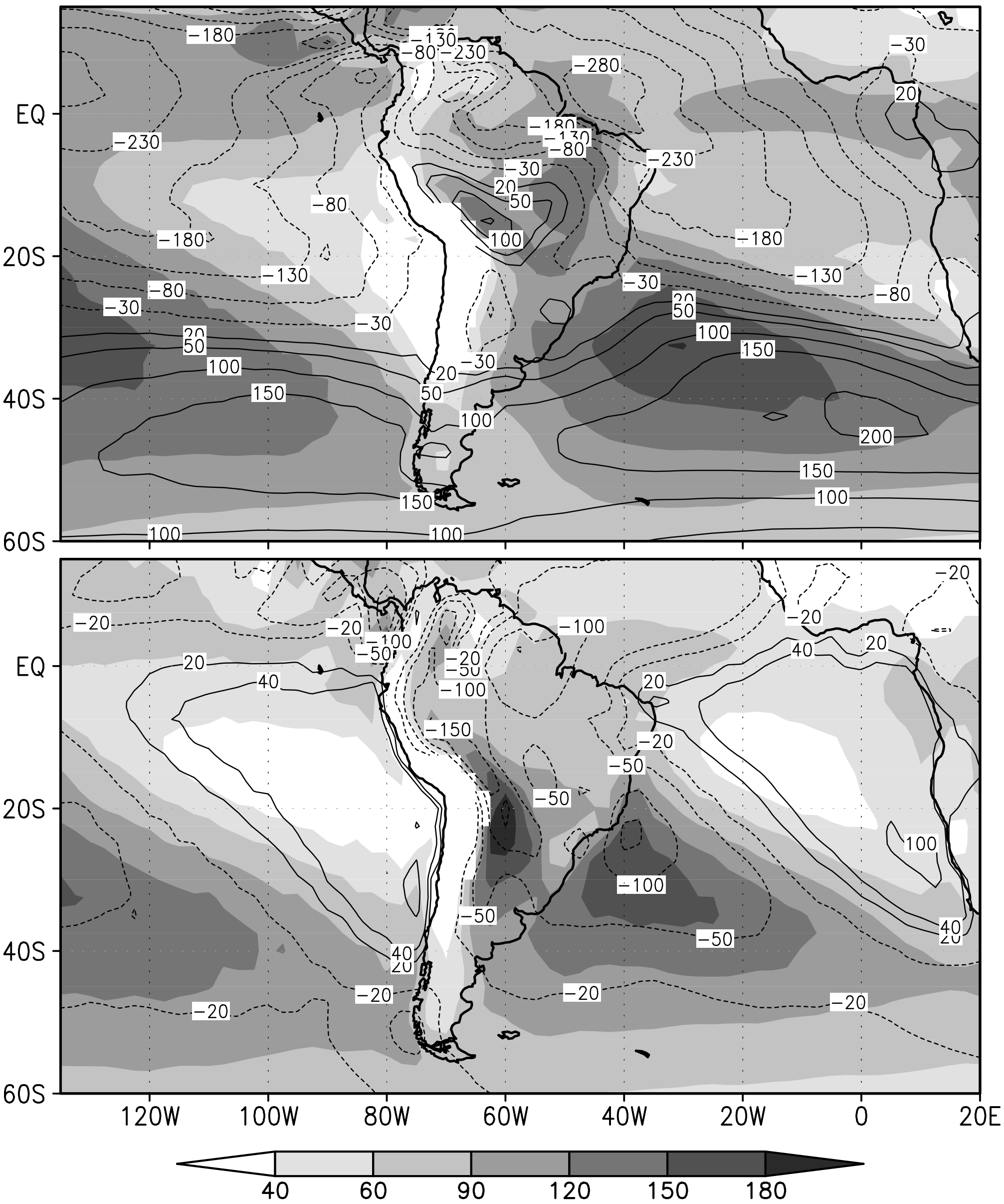

FIG. 9. Contours show the zonal and meridional components of the DEC to MAR moisture transport climatology (1981 to 2002). Respective standard deviations of daily means are shaded. [$kg\ m^{-1}\ s^{-1}$]

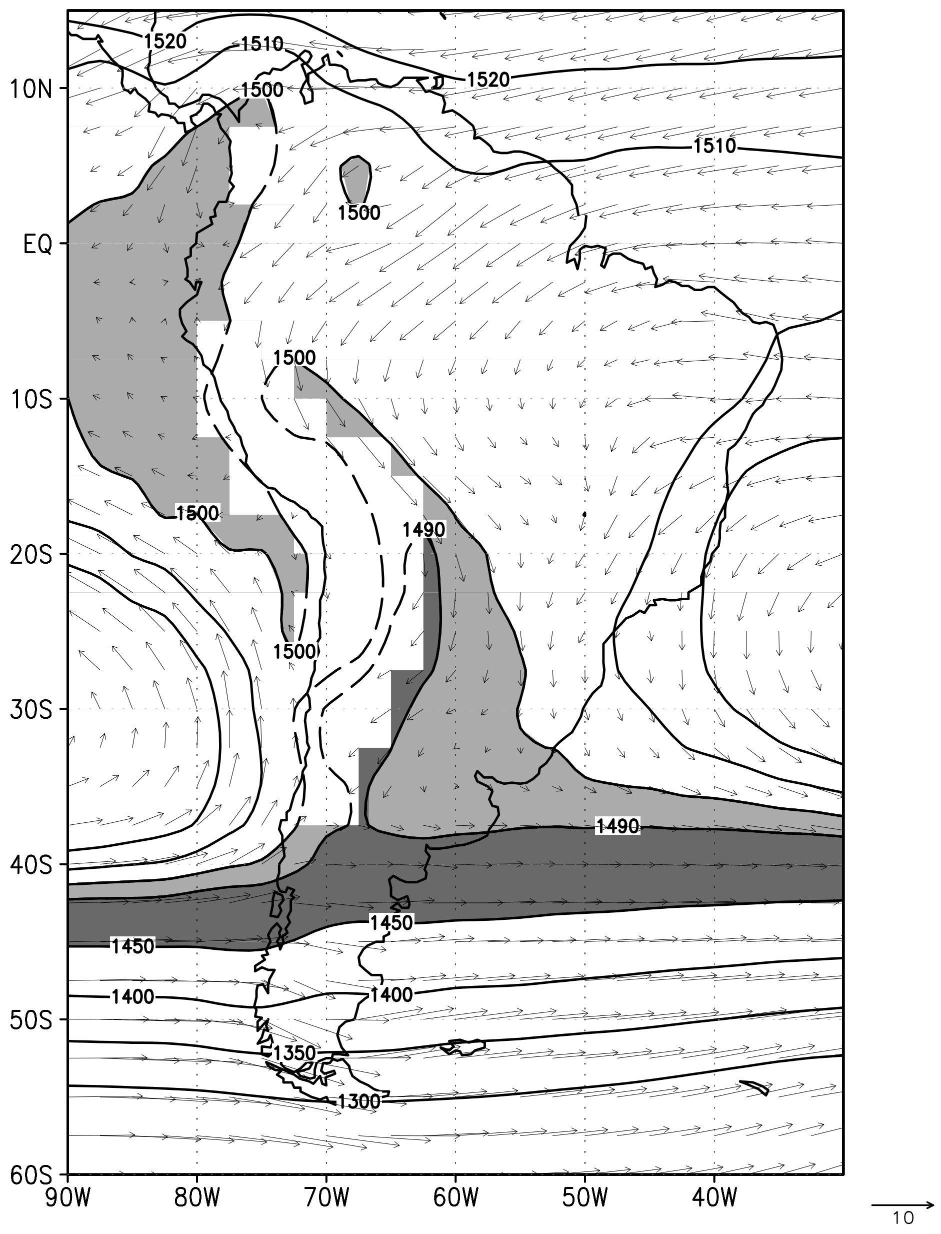

FIG. 10. Dec to Mar Climatology (1981 to 2002) of geopotential height [m] and 850 hPa wind [$m\ s^{-1}$]. Topography is masked out. For clarity interpolated geopotential contours below topography are shown in dotted lines.