The DOI for this manuscript is doi: 10.1175/2011JCLI4189.1

Aerial Rivers and Lakes: looking at large scale moisture transport, its relation to Amazonia and to Subtropical Rainfall in South America

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ABSTRACT

This is an observational study of the large scale moisture transport over South America, with some analyses on its relation to subtropical rainfall. The concept of Aerial Rivers is proposed as a framework, it's an analogy between the main pathways of moisture flow in the atmosphere and surface rivers. Opposite to surface rivers, Aerial Rivers gain water through evaporation and lose it through precipitation. The magnitude of the vertically integrated moisture transport is discharge and precipitable water is like the mass of the liquid column, multiplied by an equivalent speed it gives discharge. Trade wind flow into Amazonia and the north/northwesterly flow to the subtropics, east of the Andes, are Aerial Rivers. Aerial Lakes are the sections of a moisture pathway where the flow slows down and broadens, due to difluence, and becomes deeper, with higher precipitable water. This is the case over Amazonia, downstream of the trade wind confluence. In the dry season, moisture from the Aerial Lake goes northeastwards, but weaker flow over southern Amazonia heads towards the subtropics. Southern Amazonia appears as a source of moisture to this flow. Aerial River discharge to the subtropics is comparable to that of the Amazon River. The variations of the amount of moisture coming from Amazonia have an important effect over the variability of discharge. Correlations between flow from Amazonia and subtropical rainfall are not strong. However, some months within the set of dry seasons showed strong increase (decrease) occurring together with important increase (decrease) in subtropical rainfall.

1. Introduction

In this paper the large scale moisture transport over South America is studied throughout the year, using a novel approach. Some exploratory analyses are presented regarding the relation between this transport and subtropical rainfall. Emphasis is given to the dry season, when the potential effects of deforestation over the exchanges of moisture between the surface and the atmosphere would be more intensely felt.

The South American subtropics are quite humid in comparison to the usually drier subtropical belts of the planet, which are generally under the subsidence branch of the Hadley cell. Although there is clearly a wet season, there are areas with high rainfall throughout the year. These areas are fed by large scale moisture transport. In this work is considered specifically the large scale moisture flow that goes over Amazonia and veers southwards to flow towards the subtropics, and the rainfall areas that it feeds. The South Atlantic Convergence Zone (SACZ) region receives most of its moisture from the northerly branch of the South Atlantic Subtropical High and is not dealt with here.

The following questions are considered:

- Is Amazonia a source of moisture for the atmosphere? When and where? There has been much speculation on this issue because of measurements (such as in Nobre et al. (1991)) showing a moister atmosphere over the forest than over the adjacent ocean.
- How much moisture is delivered by the large scale flow to the high rainfall regions in the subtropics?
- What is the importance of moisture coming from Amazonia to this flow?

- What is the role of exchanges with the surface along the way?
- How is the variation of the amount of moisture leaving Amazonia related to the variation of subtropical rainfall?

a. Aerial Rivers

The term atmospheric river was proposed in Newell et al. (1992), Newell and Zhu (1994) and Zhu and Newell (1998) in reference to filamentary structures in the vertically integrated moisture flow field, which are responsible for very intense transport. These are typical of the extra-tropical latitudes where the flow shows turbulence in the large scale. At any given time a small number of these structures, generally around 4 or 5, can account for over 90% of the poleward moisture transport in the midlatitudes. The moisture flow east of the Andes was identified as a filamentary structure and therefore an atmospheric river in Newell et al. (1992), but is little mentioned in the subsequent literature on the subject, probably because it holds little dynamical resemblance to the more poleward lying rivers.

Preferential pathways of moisture flow can also be identified in the tropics, although they could not be described as filamentary. Oftentimes moisture will flow over large distances from the deep tropics to the subtropics and beyond. Observations show that long term mean high rainfall in the southern subtropics during southern summer occurs where the trade winds flow poleward after undergoing sharp turns: the South Pacific Convergence Zone (SPCZ), the SACZ (Kodama 1992)) and South America east of the Andes (Arraut and Satyamurty (2009)). This last pathway was called an aerial river in Arraut and Satyamurty (2009). The section of this flow lying adjacent to the Andes will, on some occasions, develop a core of particularly high speed called the South American Low Level Jet.

Intense moisture fluxes are often called moisture conveyor belts in the literature. However, this analogy draws attention away from the fact that exchanges between the surface and the atmosphere take place all along the way. In some cases these may be quite intense, as with moisture coming from the tropical Atlantic and going over Amazonia on its way to the South American subtropics. **The term aerial river is here proposed for all preferential pathways of moisture flow, filamentary or broad**, because a near complete symmetry/analogy can be established with the surface rivers. Aerial rivers lose water through precipitation and gain it through evaporation, while with surface rivers just the opposite takes place. The magnitude of the vertically integrated moisture transport is the discharge at each point, and precipitable water is like the mass of the liquid column, which is directly proportional to its height, multiplied by an equivalent speed it gives discharge. Use of the aerial river image also allows for the slower broader and moister sections of a moisture pathway, such as over Amazonia, to be suitably described as Aerial Lakes, as will be done later in this paper.

1) Seasonal Aerial Rivers

When studies aiming to relate moisture transport and rainfall are carried out in the weather time scale, the path of moisture feeding the rainfall can be directly identified. However, in this work we intend to identify the preferential pathways, or aerial rivers, in the longer climatic time scales.

Locations of strong rainfall over the continent must be characterized by large scale convergence of moisture transport in the atmosphere. In this way mean rainfall can be used to identify the main regions of mean convergence. If the long term mean moisture transport exhibits a predominant pathway leading to an important rainfall region, that's the flow showing the mean convergence. It can be inferred to be often the pathway of moisture during individual rainfall events. This way of linking the weather and the climate time scales was used in Arraut and Satyamurty (2009). In the present work it is used to identify predominant pathways of moisture flow to the subtropics throughout the year, or seasonal aerial rivers.

b. East of the Andes moisture transport and subtropical weather and climate

Weather and climate in the South American subtropics, particularly during summer and adjacent months, result in large part from the interplay between the inflow of moisture from the tropics and the incursion of synoptic disturbances originated in the midlatitudes. Garreaud 1998 showed this flow to intensify preceding cool air incursions, in response to the deepening of the North Western Argentinean Low (NAL), moistening the subtropical plains. Consequently, intense rainfall occurs ahead of the incursion. Salio et al. (2002) undertook a systematic study of summertime Chaco Jet events, a special case of South American Low Level Jet with large southward extension, finding their flow into the subtropics to be ten times stronger than climatology, fostering intense rainfall, which accounts for an important part of the seasonal total. A baroclinic wave train extending from the Pacific into the continent was found in the extratropics. Seluchi et al. (2003) and Saulo et al. (2004) showed that, south of $25S$, intense moisture flow to the east of the Andes is mostly synoptically driven and due to the intensification of the NAL. Siqueira and Machado (2004) studied convective systems associated with frontal incursions, finding enhancement of moisture transport from Amazonia towards them to occur in the majority of cases. Salio et al. (2007) show that subtropical Meso-Scale Convective Complexes (MCCs) are $3\frac{1}{2}$ times more common in days when a Chaco Jet is present than in other days. The northeastward advancement of a baroclinic zone causes their displacement. Mendes et al. (2007) studied cyclogenesis over the southern region of South America and observed a moist-entropy reservoir northwest of the cyclone formation, due to an intensification of the northerly flow along the eastern flanks of the Andes. In Arraut (2007) is presented a systematic study of summertime fronts, showing intense moisture transport from the tropics to take place prior to and during the frontal events, geostrophically accelerated by an intense NAL. Saulo et al. (2007) find the intense convergence of low level winds associated with deep convection to introduce ageostrophic components in the northerly moisture flow into the subtropics.

c. Is Amazonia a source of moisture for the atmosphere?

The possible role of Amazonia as a source of moisture for the atmosphere and the variability in time and space of this source is presently under debate, largely motivated by observations of moister air over the forest than over the adjacent Atlantic during southern summer (see for instance Nobre et al. (1991)). Insight on this issue can be gained by considering the water balance for the whole basin. In this case precipitation is the only external source, while water is lost to evaporation and to river discharge into the ocean. The basin cannot be an all year round systematic moisture source to the atmosphere, or it would dry out.

The moisture balance equation for the surface (Peixoto and Oort (1992)) is considered.

$$P - E = R_t + S \tag{1}$$

where P is precipitation, E is evaporation, R_t Is the total runoff (surface + underground, $R_s + R_u$), S is the variation in soil and surface water storage.

For the whole basin $R_t > 0$ always. If $P - E < 0$ then $S < -R_t < 0$. If $S > 0$, then $P - E > R_t$. In other words, net evaporation occurs at the expense of soil moisture, which must be decreasing by a value larger than runnoff. If the soil is moistening, then precipitation is exceeding evaporation by more than the value of runnoff.

The hydrological response to rainfall in such a large basin as Amazonia is a complicated matter. However, during the wet season, there is overall moistening of the soil, leading one to expect that the basin is acting as a sink of moisture, even though atmospheric humidity is at its highest, as will be seen. Nothing can be inferred from soil drying alone. Particularly in the dry season, when intense rainfall is restricted to a smaller area over Amazonia, there can be important spatial variability in the source sink behavior. It is worth investigating if the forest acts as a source of moisture to the subtropics in its driest season.

2. Data and Calculations

Most of the data used in this study consist of temperature, specific humidity, wind fields and surface pressure taken from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA Interim reanalysis Dee et al. (2011). ERA Interim is a gridpoint dataset with a 1.5^o horizontal resolution and 37 vertical pressure levels, between $1000\,hPa$ and $1\,hPa$, provided at 6hr intervals. As noticed by (Dee and Uppala 2008), ERA Interim performs much better than its predecessors, such as ERA40 Uppala et al. (2005) or JRA-25 Onogi et al. (2007), particularly when it comes to humidity analysis. Known problems with ERA40 such as the excessive tropical precipitation Uppala et al. (2005) and the method used for humdity analysis Andersson (2004) were corrected in ERA Interim, significantly reducing the bias in both total column water vapor and tropical precipitation Dee and Uppala (2008). The Global Precipitation Climatology Project (GPCP) version 2.1 combined precipitation data set (J. et al. 2009) is also used. It is composed of monthly fields with 1^o horizontal resolution. The studied period is from January 1989 to December 2008, common to both data sets.

Moisture transport, in $m\,s^{-1}$, was calculated at 6hr intervals and integrated from surface pressure to $100\,hPa$ to give QV $(kg\,m^{-1}\,s^{-1})$. Divergence of QV was calculated by finite differencing.

$$QV = \int_{P_s}^{1\,hPa} q\overrightarrow{v}\frac{dP}{g}, \tag{2}$$

where $\overrightarrow{v}$, is the wind vector $(m\,s^{-1})$, q is the specific humidity $(kg\,kg^{-1})$, P is pressure $(N\,m^{-2})$ and g is the acceleration due to gravity $(m\,s^{-2})$. Divergence of QV was calculated using finite differences.

The monthly and longer term means of moisture transport and divergence were obtained by averaging the six hourly values. The amount of water vapor transported across a longitudinal or latitudinal segment is simply the line integral of the vertically integrated moisture transport's component perpendicular to that segment. For convenience, the values obtained in $kg\,s^{-1}$ are converted to to $Gt\,day^{-1}$ by multiplying by $864X10^{-13}$.

For some comparisons, temperature and humidity from NCEP/NCAR 40-year Reanalysis

(Kalnay et al. 1996), full resolution ECMWF ERA40 Reanalysis (Uppala et al. 2005) and from Level-3 data of the Atmospheric Infrared Sounder (AIRS) (Le Marshall et al. 2006) on board of AQUA satellite were used. The resolutions of these monthly datasets are 2^o, 1.125^o and 1^o respectively.

An exploratory analysis was undertaken on the relation between moisture outflow from Amazonia and rainfall in subtropical South America, for each season. This outflow was represented by the meridional moisture transport across 12S, zonally averaged from 75W to 55W. Deseasonalized time series were prepared for each season by taking each monthly mean within the season, for every year of the studied period, and subtracting the corresponding long term monthly mean. The same was done for rainfall, and the two time series were correlated at each grid point. A Students t test was used to evaluate the statistical significance of these correlations.

For the dry season, the large scale situation for months with strong (weak) moisture transport from Amazonia, Aerial River discharge and subtropical rainfall was analysed through compositing analysis. In search of global oceanic and atmospheric characteristics related to these situations, the sea surface temperature (SST) difference between them was calculated, as well and composites of the meridional geopotential height anomalies at $850\,hPa$ and $300\,hPa$ were built. These anomalies were used to highlight the atmospheric waves in high latitudes.

3. Results

a. *Climatological Features of Precipitation and Moisture Transport*

1) Annual March of Precipitation

Long term monthly mean fields were used to identify qualitative spatial patterns in subtropical rainfall. These were then used to divide the year into seasons. Long term mean rainfall and moisture transport are shown for these seasons in Figure 1. November to March (NM) was termed "wet". The SACZ pattern is configured and rainfall is high over all of southern hemisphere Amazonia, with a diagonal band extending from its west into the subtropics and Atlantic. It is also when the subtropical plains east of the Andes receive the most rainfall. July to August (JA) was termed "dry". In the subtropics fairly high rainfall is only present over southern Brazil, where the end of a diagonal band of precipitation, with its maximum over the southwestern Atlantic, touches the continent. There were two transition seasons, April to June (AJ) and September to October (SO), quite similar in their subtropical patterns: both have high rainfall restricted to southern Brazil, with a local maximum contained in the diagonal band, which extends into the ocean.

2) Moisture Transport

Amazonia lies fully in the path of the moisture laden trade winds, and throughout the year it receives most or part of the flow coming from the trade wind confluence. During the wet season inter-hemispheric flow is strong and most of the moisture entering western Amazonia comes from the northern tropical ocean. During the other seasons both hemispheres give important contributions.

All year round part of this moisture veers over western Amazonia and is transported southwards, towards high rainfall areas in the subtropics. The amount of moisture leaving Amazonia towards the South varies greatly within the year. East of the Andes there is confluence with flow coming zonally over the continent from the Atlantic.

b. Aerial rivers and lake

Applying the aerial river concept to the situation over South America it can be said that the trade winds flowing into Amazonia form an aerial river. So does the moisture flow east of the Andes, towards the subtropics.

Figure 2 shows the magnitude of the vertically integrated moisture transport in shades of grey. Precipitable water is shown in contours. It can be seen that moisture transport decreases inland, downstream of the trade wind confluence. This decrease is, at least in part, due to difluence. The pattern is very similar to that of a liquid flowing into a wider chanel. It can also be seen in Figure 1 that there is generally a broadening of the moisture pathway when coming from the ocean into Amazonia. Precipitable water increases inland from $50W$ to $65W$ and the Equator to $10S$, so the decrease in transport must be due to diminishing wind speed in the low levels. These are the reasons for here referring to the atmosphere over Amazonia as an aerial lake of moisture. The aerial lake over Amazonia is deeper in the west, but flow speed diminishes in such a way that discharge is lower. In the dry season most of the moisture leaving the aerial lake system goes towards Central America. In the wet season most of the outflow is towards the South American subtropics.

Figure 3 shows a schematic representation of the aerial rivers and lake system over South America during the wet season.

A comparison between moisture profiles over Amazonia ($70W-50W$,$10S-0S$) and the adjacent Atlantic ($50W-30W$ $EQ-10N$) is shown in Figure 4, for the seasons here defined. Data from four different sources are used: Aqua Airs (1980-2001), the reanalysis ECMWF ERA40 (1980-2001), ERA Interim (1989-2008) and NCEP(1980-2001). From September to June the atmosphere over Amazonia is moister up to $700\,hPa$. From November to March it is moister over the whole column up to $300\,hPa$. In July to August there is a discrepancy between the data sets, with NCEP and Interim showing more moisture over the forest between $900\,hPa$ and $650\,hPa$, Aqua Airs showing the opposite and almost no difference to be seen in ERA40.

Figure 5 is like Figure 4 but for temperature. All year round the lower layer of the atmosphere, from just above $1000\,hPa$ to $800\,hPa$ in AJ and $750\,hPa$ in the remaining seasons, is warmer over Amazonia. Only in AJ there is some discrepancy, because Aqua Airs shows no difference in this layer.

The higher temperatures in the low levels over Amazonia raise the saturation vapor pressure, allowing for higher specific humidity, since evapotranspiration is abundant. This temperature difference can be at least partially explained by higher convective heating over the forest.

(i) Divergence of Moisture Transport

Panels in Figure 6 show the climatological seasonal divergence of the vertically integrated moisture flow. The mass conservation equation for water in the atmosphere is recalled:

$$P - E = -\nabla \cdot\ QV, \tag{3}$$

where P is precipitation, E is evaporation and $\nabla \cdot QV$ is the divergence of the vertically integrated moisture transport. The local time variation of precipitable water is dismissed as small in monthly and seasonal means over high rainfall areas. Positive values of divergence indicate net evaporation whereas negative values indicate net precipitation. The divergence field is obtained through finite differencing at the price of increased error. Furthermore the divergence is the sum of two partial derivatives and in the large scale being dealt with here, these show large cancellation, increasing the relative magnitude of the error. For these reasons the field is considered of low reliability. Having said this, a simple validation can be carried out by comparison with rainfall. Convergence is expected where rainfall is high, particularly on the local maxima, important to supply river basins. The cool seasons, AJ and JA, bear the comparison better over the continent. NM and SO show excessive dryness in southwestern Amazonia and, excessive convergence of moisture east of the Andes from 20S to over 35S. In AJ moisture converges on a roughly zonal band straddling the Equator and also over Southern Brazil. In JA it converges on the extreme north of the continent and Southern Brazil, coniciding, in both cases, with the high rainfall. The maximum intensity of convergence in the tropics exceeds $5\,mm\,day^{-1}$, while rainfall exceeds $12\,mm\,day^{-1}$. In the subtropics the highest values lie between 2 and $3\,mm\,day^{-1}$ and rainfall is between 5 and $6\,mm\,day^{-1}$ and 4 and $5\,mm\,day^{-1}$ respectively. Convergence is lower than precipitation, as it should be, because $E > 0$ always.

In JA, the dry season, there is divergence over most of the latitudinal strip from 10S to 25S, east of the Andes, with values between 1 and $3\,mm\,day^{-1}$, indicating that the surface is acting as a source of moisture to the atmosphere. This includes southern Amazonia and the area under the aerial river path. Around 10S tropical flow acquires a northerly component. According to this data, southern Amazonia is acting as a source of moisture to the subtropics, and so is the soil along the aerial river. In this way, subtropical precipitation is fed by the rain falling further north, earlier in the year.

(ii) Moisture Balance of the Dry Season Aerial River

How much moisture does the aerial river feed to the subtropical rainfall region? How much does it receive from net soil evaporation along its course? What is the moisture contribution coming from Amazonia and what is its importance relative to the total flow?

In this section these questions are addressed, for the dry season, by calculating the moisture balance of the aerial river, using an adequately defined box, which is shown in Figure 1, superimposed on the season's long term mean moisture flow. Its limits are $70W - 50W$ and $23S - 10S$. It can be seen that all flow coming from Amazonia enters through the northern and western boundaries. Through the eastern boundary comes moisture from the adjacent Atlantic, and the aerial river leaves the box through the southern (mainly) and also the eastern boundaries. The flow across the eastern boundary was plotted against latitude for each of the months in the 20 dry seasons, a total of 40 months (not shown). The aim was to determine if the incoming and outgoing flow could be easily separated. In all months but one, it showed only one sign change. That is to say, for all months but one, there is a latitude separating the incoming transport and the outflowing aerial river, making it simple to distinguish between them. The box is built so as to exclude completely the region of long term mean moisture convergence. In this way the contribution of net soil evaporation to the aerial river can be calculated as a residue. Also the discharge represents the total amount of moisture delivered to the continental rainfall region.

Discharge of the aerial river is plotted in Figure 7. It mostly varies between 10 and $23\, Gton\, day^{-1}$. This is comparable to the discharge of the Amazon River. The amount of moisture from Amazonia and from the Atlantic are similar in their mean values. However, the first one shows a larger spread and thus shows a larger effect over the discharge variability. Net evaporation from the surface follows closely the other two terms in quantitative importance. It is relevant to note that it increases the moisture flow by raising specific humidity, so that moister air, and not more air, is delivered to the subtropics.

1) Moisture Transport and Rainfall

It is now asked, how does the amount of moisture leaving Amazonia correlate to subtropical rainfall in each season?

The moisture leaving Amazonia was represented by the meridional component of moisture transport across $12S$, from $75W$ to $55W$. It was correlated to rainfall at each point, and results are displayed in Figure 8. A Students t test was applied and only values above the 95% significance level are displayed. These correlations are only of interest where there is abundant rainfall. For reference, long term seasonal mean rainfall is shown in contours.

In all seasons, areas with moderate correlations, of up to 0.5, are found within regions of intense rainfall. These areas are larger in NM and JA. Our main interest however is in the dry season. When rainfall is infrequent, the forest's elaborate root system plays an essential role in retaining and accessing soil moisture. For this reason, dry season evapotranspiration is most likely to be affected in a scenario of deforestation.

The thick line in figure 7 shows rainfall over the region 57W to 48W and 34S to 23S, which is depicted in the JA panel of Figure 1. This was compared to moisture from Amazonia and also to the aerial river discharge. The aim was to look for months when all three were strong and when all three were week. These are situations when the amount of moisture coming from Amazonia has an important effect on discharge. That this may cause the corresponding alteration in rainfall is an important possibility. To gain qualitative understanding of these situations, composites were built for the full fields and for their anomalies. These are shown in Figure 10. The "strong" situations show anomalous transport all the way from the northern Atlantic to the area of increased rainfall in the subtropics. It also shows a strenghthened South Atlantic High. This situation constitutes an intensification of climatology, so their is in fact more moisture travelling from the deep tropics to the subtropics and the rainfall region. The "weak"composite shows the opposite situation, with anomalous flow heading northwestwards from the area with decreased rainfall to the tropics and veering northeastwards towards the tropical ocean. This pattern represents a weakening of climatology, so there is in fact less flow from the deep tropics into the subtropics. There is also a weakening of the South Atlantic High.

The tropical and subtropical parts of the large scale moisture flow over South America are generally under quite different dynamical influences. For this reason it is interesting to observe organized anomaly patterns with such large latitudinal extension, and it will be important to investigate there cause in the future.

The spatial distribution of the monthly mean SST difference between periods of intense and weak moisture fluxes present three areas of positive SST located on the west tropical Atlantic ($.5^oC$), adjacent to the Southeastern and Southern regions of Brazil and to Uruguay (1.0^oC), and over the eastern tropical Pacific (1.0^oC). This last one seems to be associated with a mature positive phase of the El Nio /Southern Oscillation phenomenon.

The spatial structure of the mean meridinonal anomalies of geopotential height at 300 hPa for the two periods show contrasting characteristics in low latitudes, both north and south. The strong situation appears related to a positive North Atlantic Oscillation (NAO) pattern, and a weak wave three trend in the subtropics and midlatitudes of the Southern Hemisphere (30S 60S), with an apparent blocking in the south Atlantic (45W 60S). On the other hand, the weak situations are characterized by a strong positive phase of the Pacific North Atlantic pattern and a strong negative phase of the NAO. In the Southern Hemisphere appears a strong wave 3 trend (30S -60S) related to strong blocking structure at low latitudes (120W 60S), which are all part of the Antarctic Oscillation Pattern.

4. Discussions and Conclusions

This was an observational study of the large scale moisture transport over South America, with some initial analyses on its relation to subtropical rainfall.

The concepts of Aerial River and Aerial Lake are proposed and used as a framework for considering large scale moisture transport. They consist of a symetry/analogy between the main pathways of moisture flow in the atmosphere and the surface rivers and lakes. Aerial Rivers and Lakes lose water through precipitation and gain it through evaporation, while the opposite takes place with their surface counterparts. The magnitude of the vertically integrated moisture transport is the discharge at each point, and precipitable water is like the mass of the liquid column, which is directly proportional to its height, multiplied by an equivalent speed it gives discharge.

Trade wind flow into Amazonia forms an aerial river. So does the moisture flow east of the Andes, which goes towards the subtropics. Both are present all year round. Aerial Lakes are the sections of a moisture pathway where the flow slows down and broadens, due to difluence, and becomes "deeper", with higher precipitable water. This is the case over Amazonia, downstream of the trade wind confluence. In the wet season (NM) flow from the Aerial Lake goes mainly towards the subtropics, while in the dry season (JA) it goes mostly to Central America.

Moisture flow from Amazonia towards the subtropics shows moderate correlations with subtropical rainfall throughout the year, but these correlations are somewhat larger for the wet (NM) and the cool transition (AJ) seasons.

The role of the land surface as a source or a sink of moisture to the atmosphere is an issue that has been generating great debate, especially concerning Amazonia. According to calculations of long term mean moisture transport divergence, southern Amazonia is a source of moisture for the atmosphere and for the continent's subtropics during the dry season. The same was found for the surface under the Aerial River east of the Andes. Subtropical rainfall is partly fed by rain further north, from earlier in the year. Calculations of large scale moisture transport divergence are not considered of high reliability and these results on surface water sources must be compared other data sets. For the moment they can only be considered a good hypothesis. The forest has an elaborate root system, which stores and makes use of water deep in the soil. This is particularly useful when rainfall is less frequent, as in southern Amazonia during the dry season. For this reason it is possible that the moisture source behaviour would not persist in a deforestation scenario.

Discharge of the Aerial River east of the Andes to the subtropics during the 20 dry seasons varied between 10 and $23\,Gton\,day^{-1}$, comparable to the Amazon river discharge. The two most important contributions were flow from Amazonia, and zonal flow coming from the Atlantic, but they were followed closely by local net soil evaporation. Showing the largest spread, flow from Amazonia had the largest effect over discharge variability.

Months were selected within the dry seasons when flow from Amazonia, discharge and subtropical rainfall were all particularly strong (weak). They were found to present moisture transport patterns which were an intensification (weakening) of climatology, with increased (decreased) transport all the way from the tropical Atlantic to the subtropics. Given that tropical and subtropical flow are subject to very different dynamical influences, it would be interesting to investigate how these coherent anomaly patterns of such large scale arise.

Acknowledgments.

The first author thanks Dr. J. L. Arraut for helpfull discussions. This research was partially financed by the national funding agency CNPq. The full resolution ERA40 data used was obtained through an agreement between the European Centre for Medium Range Weather Forecasts (ECMWF) and the Brazilian Centre for Weather Forecasts and Climate

Studies (CPTEC). Standard resolution ERA-Interim dataset was obtained free of charge from ECMWF servers. GPCP and AIRS data were obtained from NASA servers.

REFERENCES

Andersson, e. a., E., 2004: Assimilation and modeling of the atmospheric hydrological cycle in the ecmwf forecasting system. *Bull. Am. Meteorol. Soc.*, **86**, 387402.

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`.

Arraut, J. M. and P. Satyamurty, 2009: Precipitation and water vapor transport in the southern hemisphere with emphasis on the South American region. *J. Appl. Meteor. Climatol.*, **114**, G01 003.

Dee, D. and S. Uppala, 2008: Variational bias correction in era-interim. ECMWF Technical Memo n. 575, pp. 26.

Dee, D. P. et al., 2011: The era-interim reanalysis: configuration and performance of the data assimilation system. *Quart. J. R. Meteorol. Soc.*, **137**, 553–597.

J., H. G., R. F. Adler, D. T. Bolvin, and G. Gu, 2009: Improving the global precipitation record: GPCP Version 2.1. *Geophys. Res. Let.*, **36 (L17808)**.

Kalnay, E., et al., 1996: The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Met. Soc.*, **77**, 437–472.

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.

Le Marshall, J., et al., 2006: Improving global analysis and forecasting with AIRS. *Bulletin of the American Meteorological Society*, **87 (7)**, 891–894, doi:10.1175/BAMS-87-7-891, URL http://journals.ametsoc.org/doi/abs/10.1175/BAMS-87-7-891, http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-87-7-891.

Mendes, D., E. P. Souza, I. F. Trigo, and P. M. A. Miranda, 2007: *On precursors of South American cyclogenesis*.

Newell, R. E., N. E. Newell, Y. Zhu, and C. Scott, 1992: Tropospheric rivers? - a pilot study. *Geophys. Res. Let.*, **19**, 2401–2404.

Newell, R. E. and Y. Zhu, 1994: Tropospheric rivers: A one year record and a possible application to ice core data. *Geophys. Res. Let.*, **21**, 113–116.

Nobre, C. A., P. Sellers, and J. Shukla, 1991: Amazonian deforestation and regional climate change. *J. Climate*, **4 (10)**, 957–988.

Onogi, K. et al., 2007: The jra-25 reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.

Peixoto, J. and A. Oort, 1992: *Physics of climate*. Springer-Verlag, New York.

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.

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., 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.

Uppala, S. et al., 2005: The era-40 re-analysis. *Quart. J. R. Meteorol. Soc.*, **131**, 29613012.

Zhu, Y. and R. E. Newell, 1998: A proposed algorithm for moisture fluxes from atmospheric rivers. *Mon. Wea. Rev.*, **126**, 725–735.

List of Figures

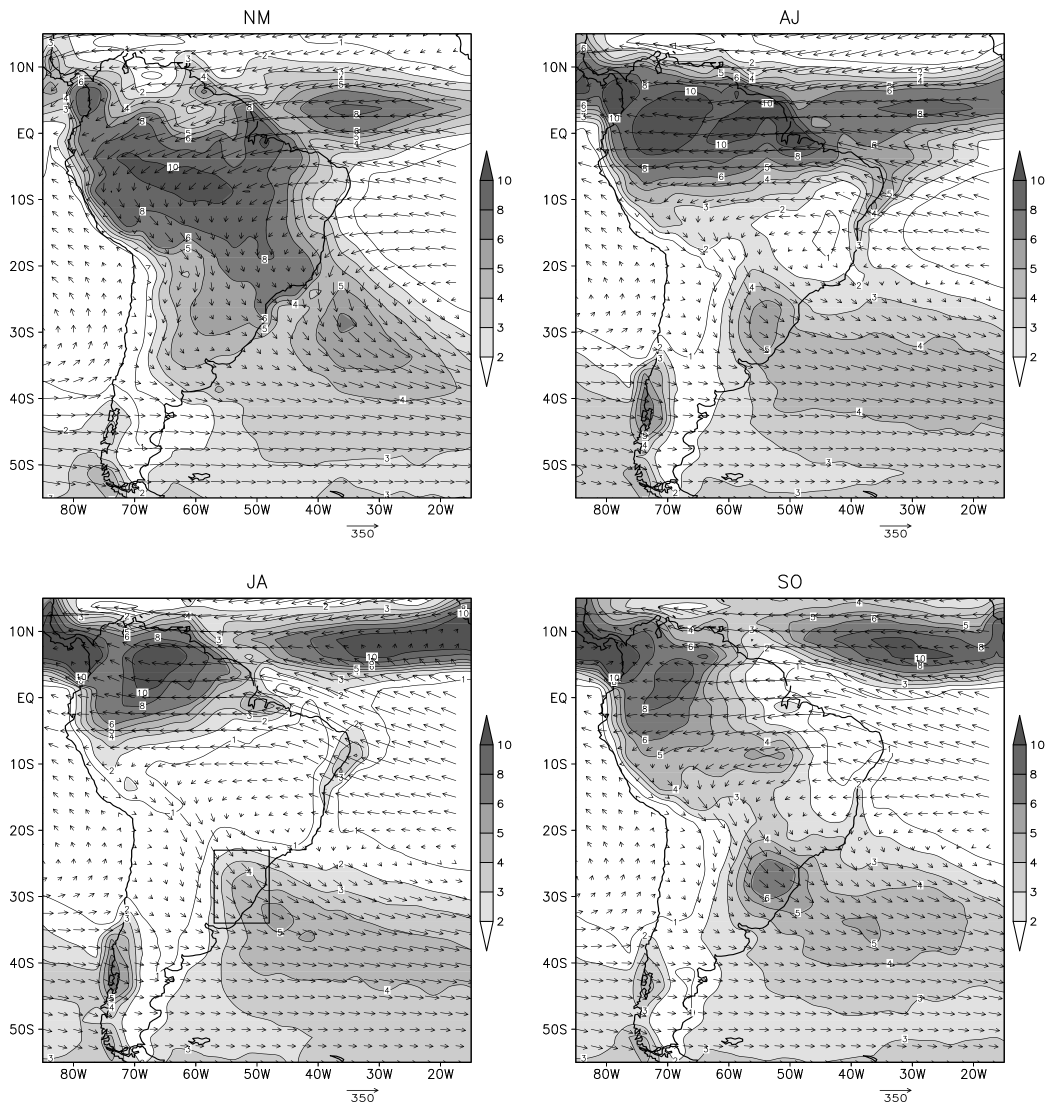

FIG. 1. Mean seasonal precipitation (shaded, $mm\,day^{-1}$) and vertically integrated moisture transport (arrows) are shown for Nov-Mar (NM), Apr-Jun(AJ), Jul-Aug (JA), Sep-Oct(SO).

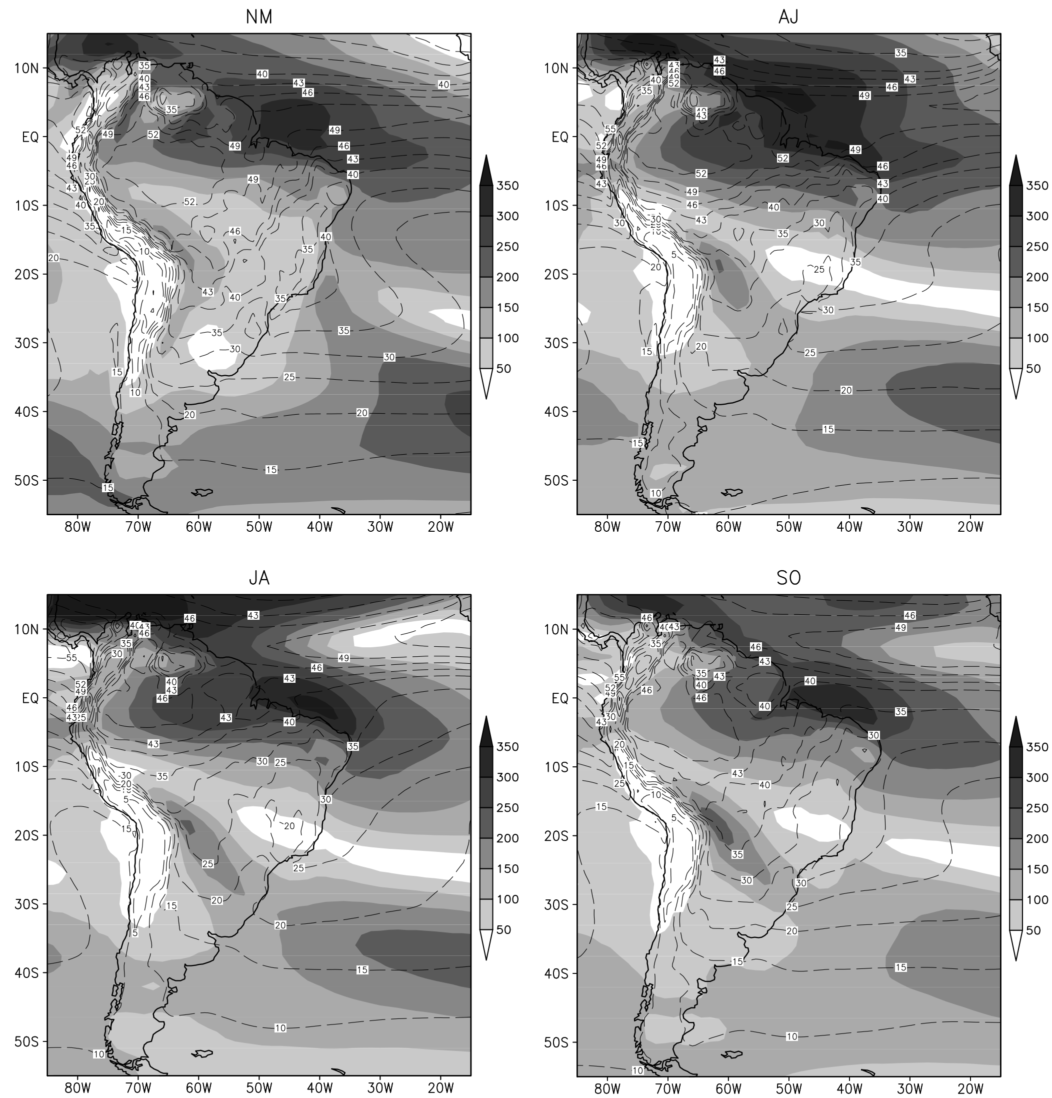

FIG. 2. Magnitude of mean seasonal vertically integrated moisture transport (shaded, $kg\, m^{-1}\, s^{-1}$) and precipitable water (contours, $kg\, m^{-2}$) are shown for Nov-Mar (NM), Apr-Jun(AJ), Jul-Aug (JA), Sep-Oct(SO).

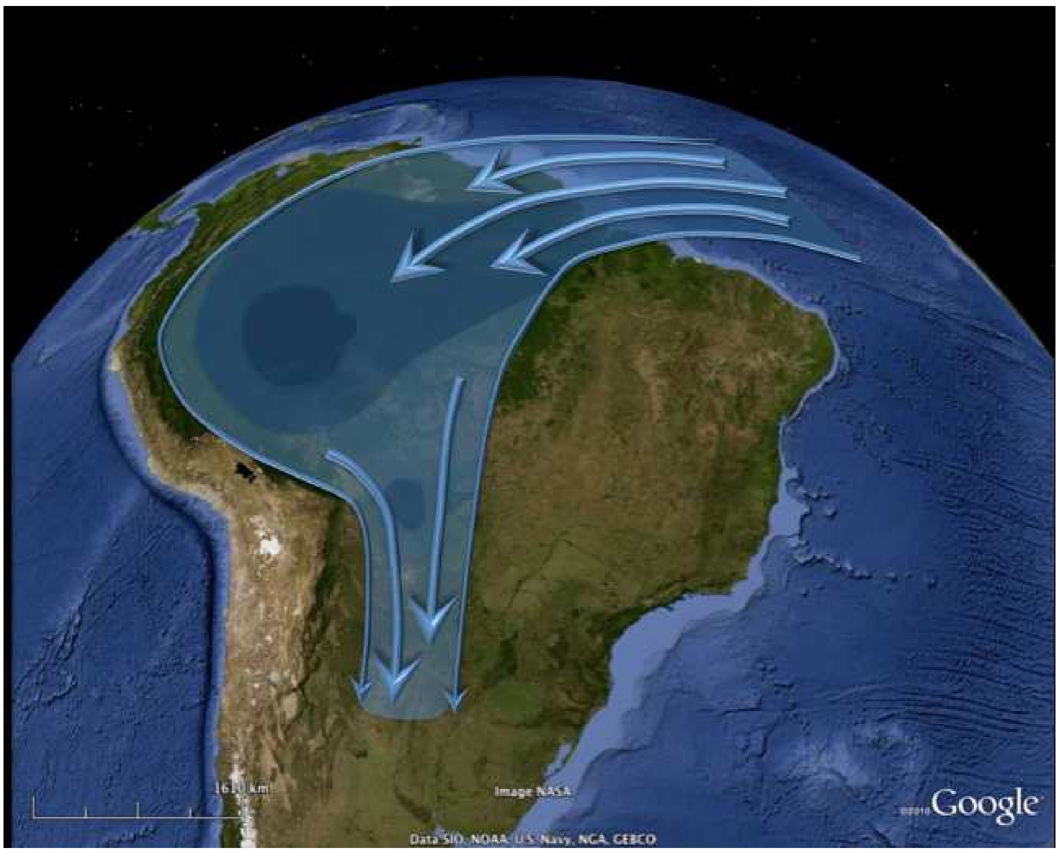

Fig. 3. Schematic representation of the aerial rivers and lake system over South America in the wet season.

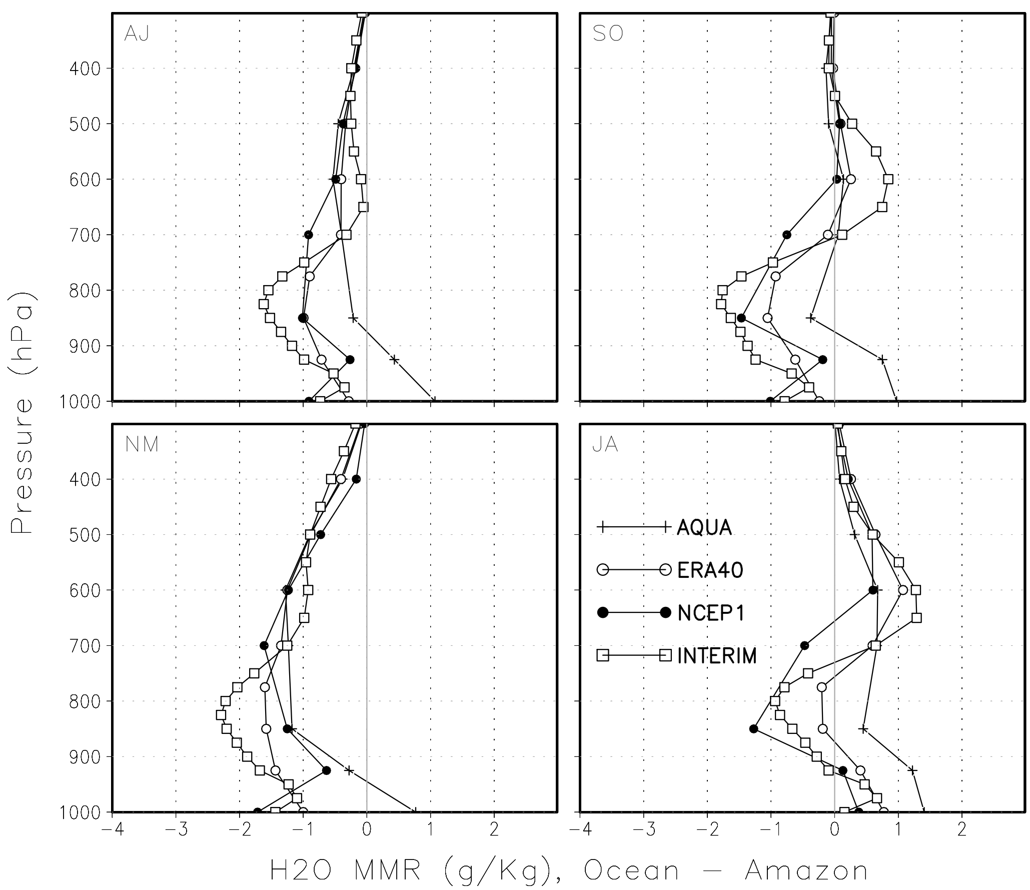

FIG. 4. Mean seasonal differences between the vertical profile of water vapor over the Atlantic (50W-30W EQ-10N) and Amazonia (70W-50W 10S-EQ) are shown for Nov-Mar (NM), Apr-Jun(AJ), Jul-Aug (JA), Sep-Oct(SO). Data from NCEP (dark circles) and ERA-40 (open circles) are averaged between 80-01, while ERA-Interim (squares) is averaged between 89-08 and satellite data from AIRS (crosses) is averaged between 03-09.

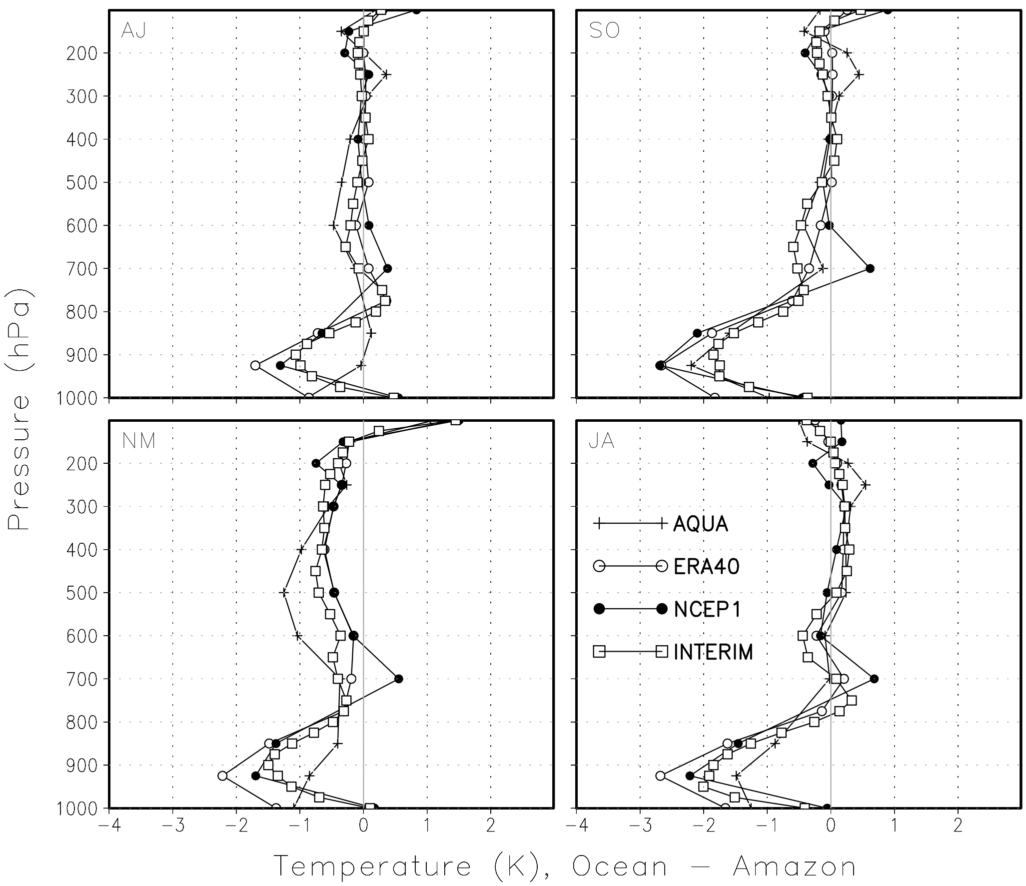

FIG. 5. Mean seasonal differences between the vertical profile of air temperature over the Atlantic (50W-30W EQ-10N) and Amazonia (70W-50W 10S-EQ) are shown for Nov-Mar (NM), Apr-Jun(AJ), Jul-Aug (JA), Sep-Oct(SO). Data from NCEP (dark circles) and ERA-40 (open circles) are averaged between 80-01, while ERA-Interim (squares) is averaged between 89-08 and satellite data from AIRS (crosses) is averaged between 03-09.

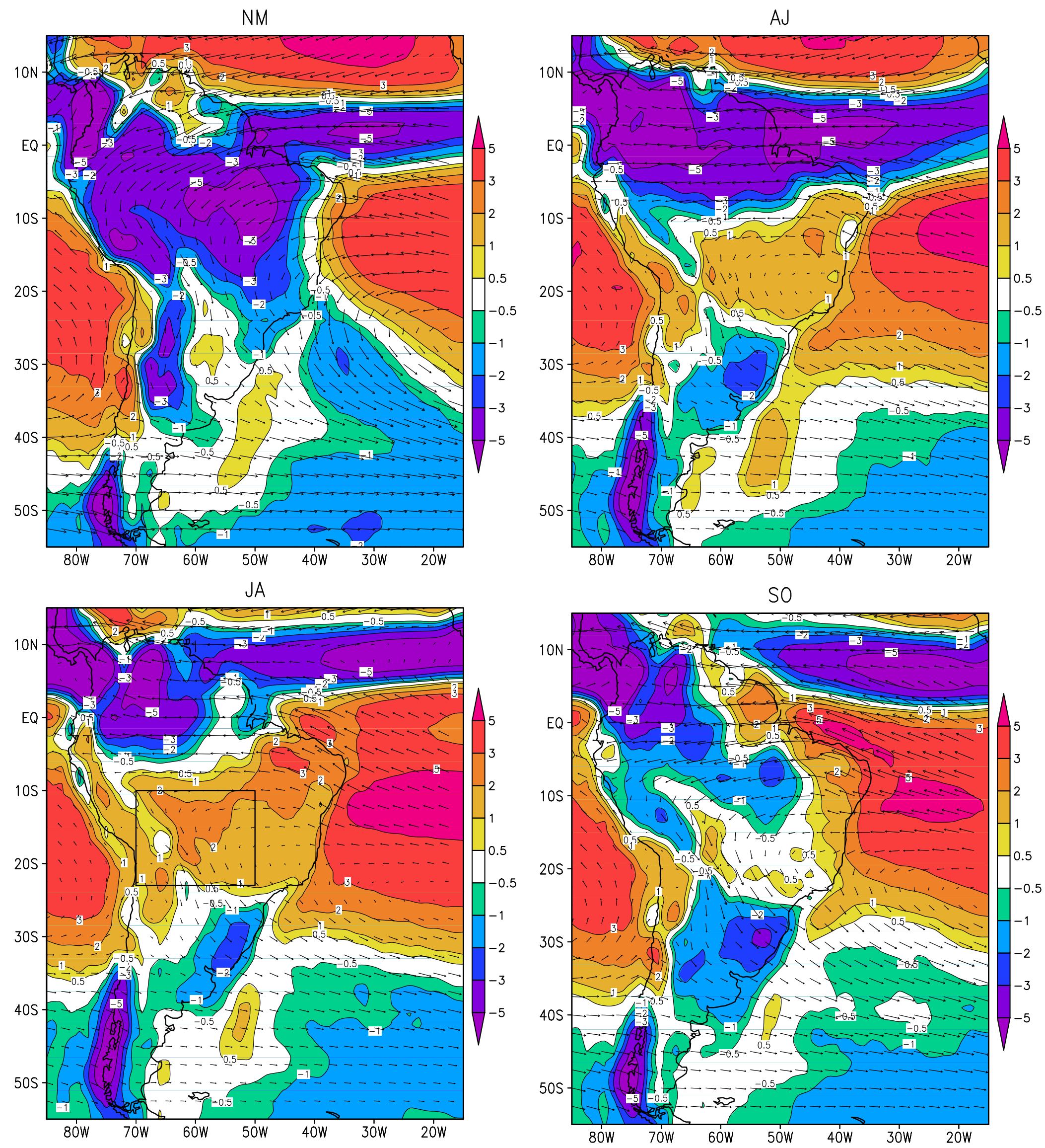

FIG. 6. Mean seasonal vertically integrated moisture transport (arrows) and its divergence (colors, $mm\,day^{-1}$) are shown for Nov-Mar (NM), Apr-Jun(AJ), Jul-Aug (JA), Sep-Oct(SO).

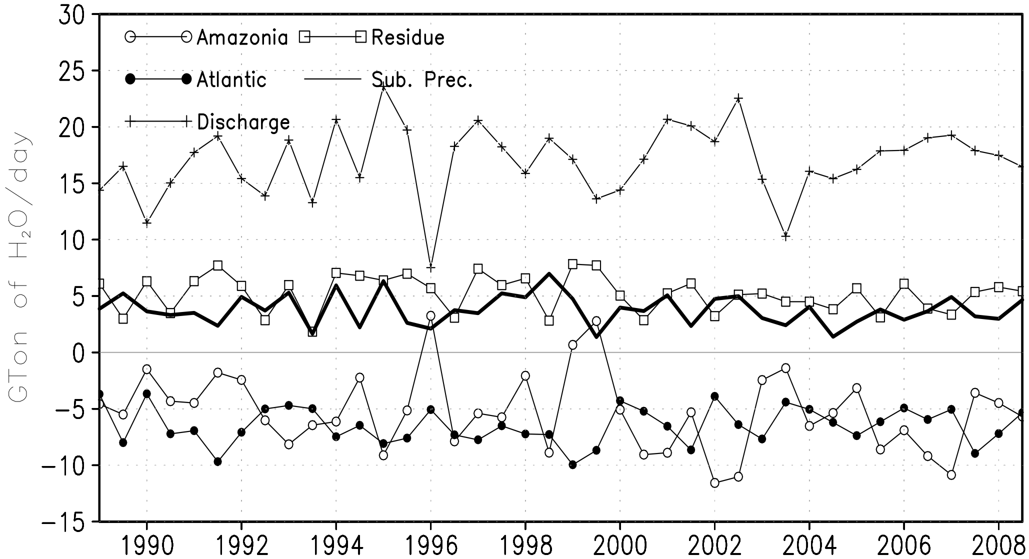

FIG. 7. Water balance ($GTon\,day^{-1}$) for the area depicted in Figure 6 (70-50W 23-10S) for the dry months between 1989 and 2008. Inflow is divided into two contributions: Amazonia (open circle) and Atlantic ocean (filled circle). Discharge (+) is the outflow from this region into the subtropics, and the residue (squares) is difference between in and out flows. The thick line is the precipitation averaged over 57-48W and 34-23S.

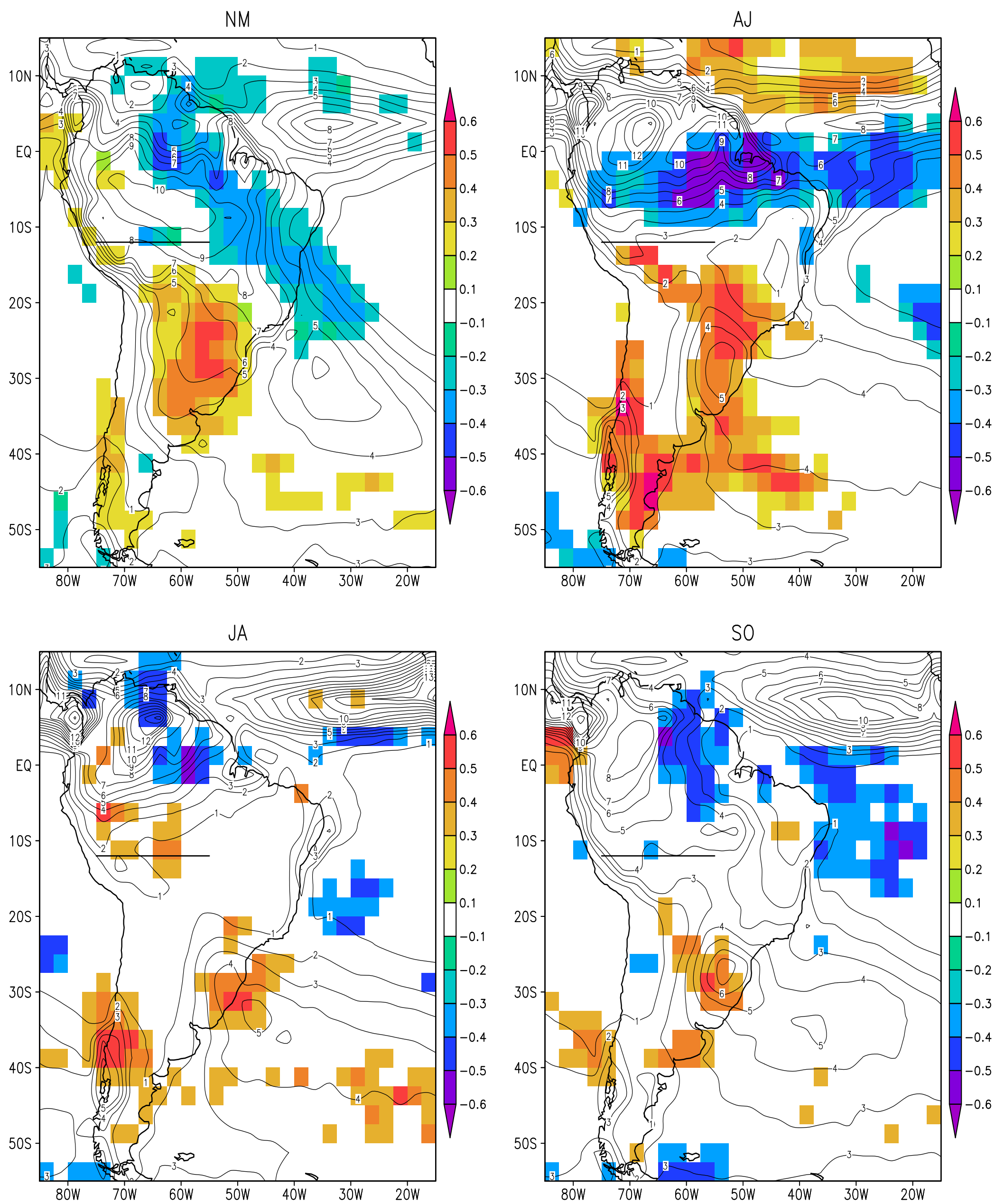

FIG. 8. The colors show correlations between the meridional moisture transport across 12S, from 75W to 55W (indicated by thick black line) and rainfall at each grid point. Values below the 95% significance level are masked out. Grey contours show the long term mean seasonal rainfall, for reference ($kg\,m^{-2}$).

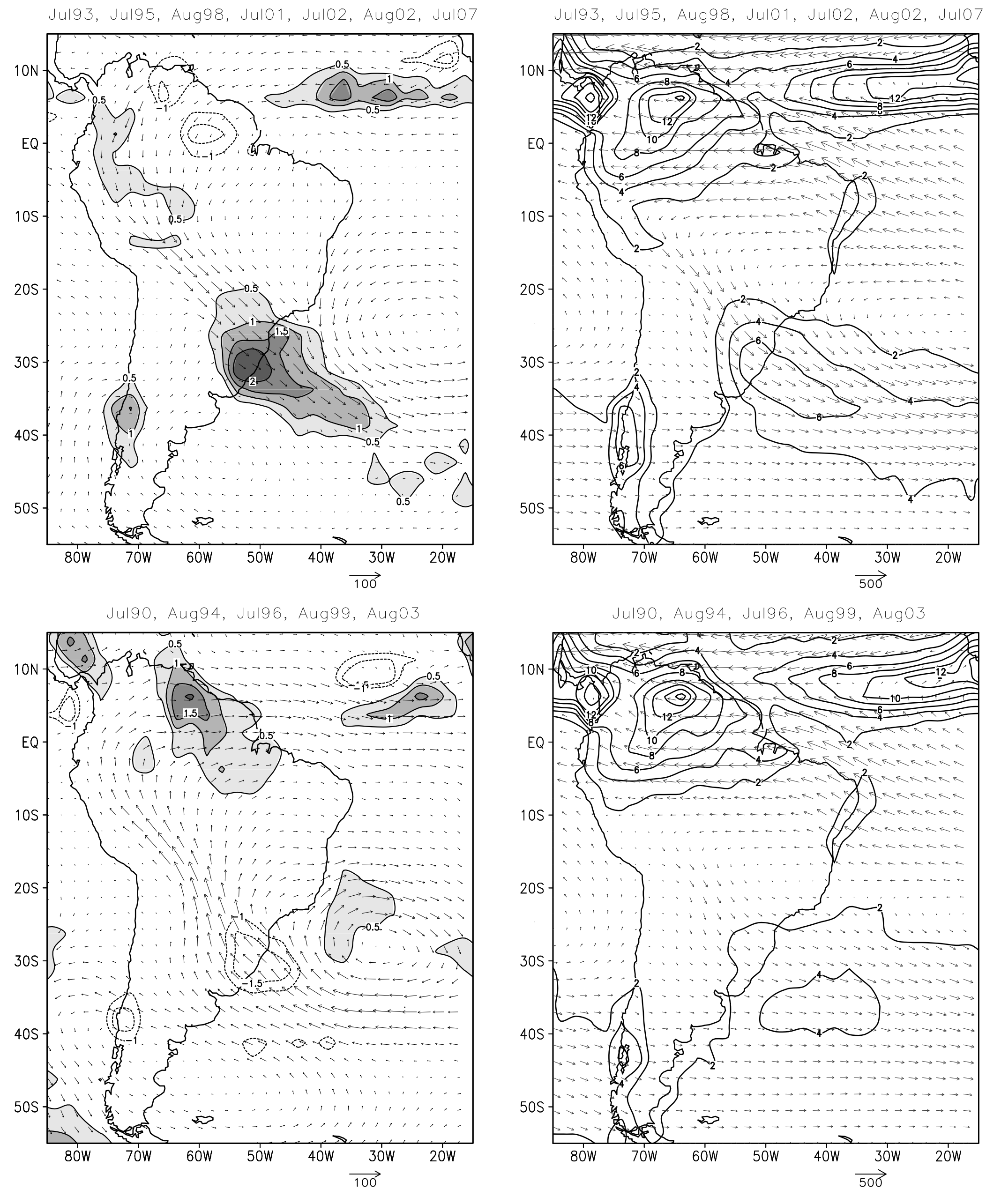

Fig. 9. Anomaly (left) and full field composites (right) for months when enhanced (diminished) rainfall was accompanied by an intensification (weakening) of the climatological moisture transport (arrows) pattern are shown in the top (bottom) panels.

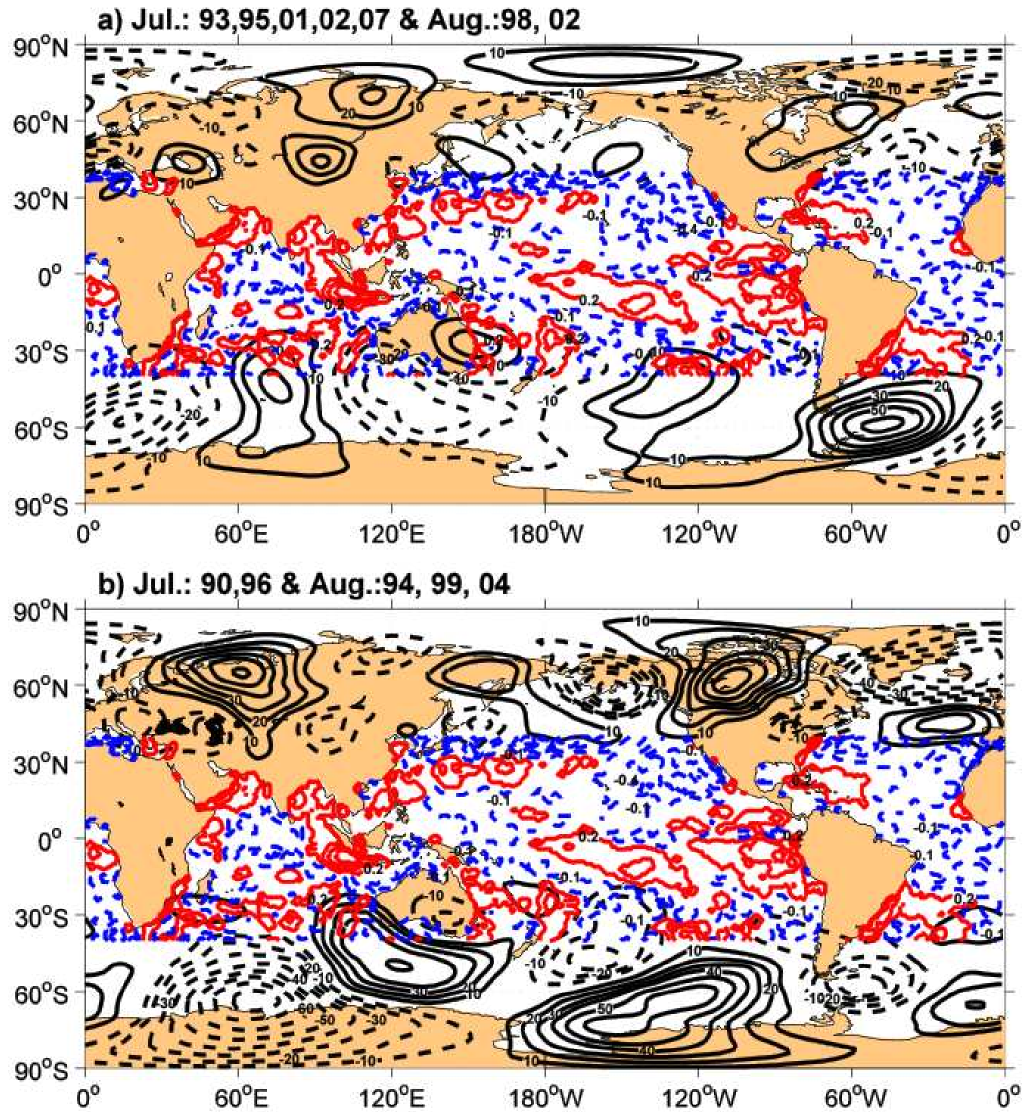

FIG. 10. Black contours show composites of monthly mean meridional anomalies for the a) strong b) weak periods. Full (dotted) lines are positive (negative) values. Also, differences of the monthly mean of the SST between the strong and weak periods are shown in both graphics. Positive (negative) values are in red (blue).