Aerial Rivers and Lakes: Looking at Large-Scale Moisture Transport and 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 is an analogy between the main pathways of moisture flow in the atmosphere and surface rivers. Opposite to surface rivers, aerial rivers gain (lose) water through evaporation (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, because of diffluence, 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 is transported northeastward, but weaker flow over southern Amazonia heads southward toward 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 the flow from Amazonia and subtropical rainfall are not strong. However, some months within the set of dry seasons observed showed a strong increase (decrease) occurring together with an 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 owing to the exchange 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. This work specifically considers the large-scale moisture flow over Amazonia, which veers southward to flow toward 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 forests than over the adjacent ocean.

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- 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 extratropical latitudes, where the flow shows turbulence in the large scale. At any given time a small number of these structures, generally around four or five, can account for more than 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); however, little is mentioned in 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 across South America east of the Andes (Arraut and Satyamurty 2009). This last pathway was called an aerial river in Arraut and Satyamurty. 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 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 proposed here 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.

SEASONAL AERIAL RIVERS

When studies aiming to relate moisture transport and rainfall are carried out on 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, on 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 flow shows the mean convergence. It can be inferred to often be 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 and Wallace (1998) showed this flow to intensify preceding cool-air incursions, in response to the deepening of the northwestern 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 a large southward extension, finding their flow into the subtropics to be 10 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 25°S, 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 toward them to occur in the majority of cases. Salio et al. (2007) showed that subtropical mesoscale convective complexes (MCCs) are 3½ times more common on days when a Chaco jet is present than on 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. Arraut (2007) 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) found 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 into 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 a year-round systematic moisture source to the atmosphere because it would dry out.

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

$$P - E = R_t + S, \qquad (1)$$

where P is precipitation, E is evaporation, R_t is the total runoff [surface plus underground $(R_s + R_u)$], and 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 runoff. If the soil is moistening, then precipitation is exceeding evaporation by more than the value of runoff.

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 Interim Reanalysis (ERA-Interim) (Dee et al. 2011). ERA-Interim is a gridpoint dataset with a 1.5° horizontal resolution and 37 vertical pressure levels, between 1000 and 1 hPa, provided at 6-h intervals. As noticed by Dee and Uppala (2008), ERA-Interim performs much better than its predecessors, such as the 40-yr ECMWF Re-Analysis (ERA-40) (Uppala et al. 2005) and the Japanese 25-year Reanalysis (JRA-25) (Onogi et al. 2007), particularly when it comes to humidity analysis. Known problems with ERA-40, such as the excessive tropical precipitation (Uppala et al. 2005) and the method used for humidity analysis (Andersson et al. 2005), 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 dataset (Huffman et al. 2009) is also used. It is composed of monthly fields with 1° horizontal resolution. The studied period is from January 1989 to December 2008, common to both datasets.

Moisture transport, in meters per second, was calculated at 6-h intervals and integrated from surface pressure to 1 hPa to give QV (kg m^{-1} s^{-1}):

$$QV = \int_{P_s}^{1hPa} q\mathbf{v}\frac{dP}{g}, \qquad (2)$$

where $\mathbf{v}$ is the wind vector (m s^{-1}), q the specific humidity (kg kg^{-1}), P is pressure (N m^{-2}), and g 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 6-h values. The amount of water vapor transported across a longitudinal or latitudinal segment is simply the line integral of the vertically integrated moisture transport
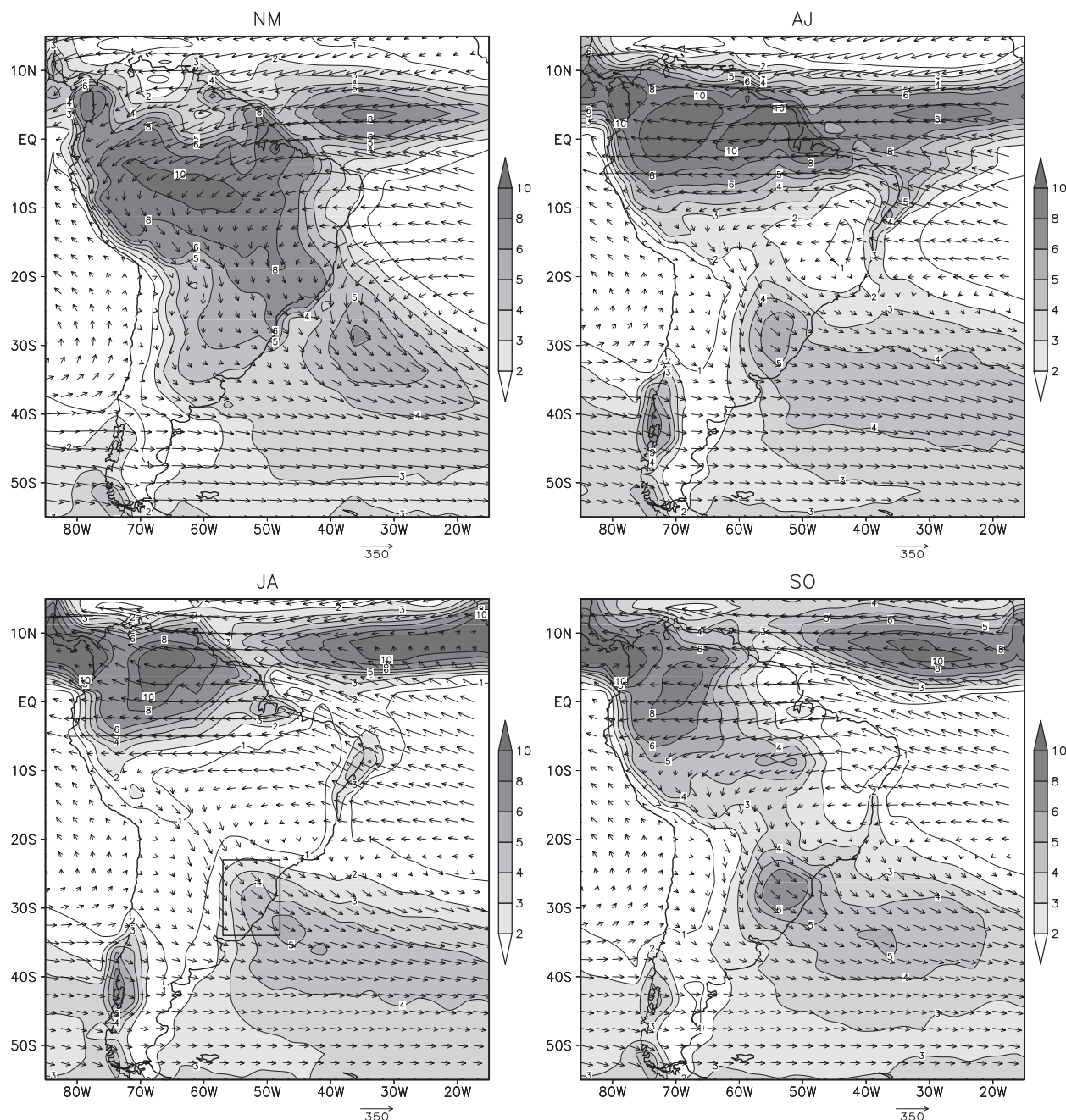
FIG. 1. Mean seasonal precipitation (shaded, mm day^{-1}) and vertically integrated moisture transport (vectors) are shown for NM (Nov–Mar), AJ (Apr–Jun), JA (Jul–Aug), and SO (Sep–Oct).

component perpendicular to that segment. For convenience, the values obtained in kilograms per second are converted to gigaton per day multiplying by 864×10^{-10}.

For some comparisons, temperature and humidity from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) 40-Year Reanalysis (Kalnay et al. 1996), full-resolution ERA-40 (Uppala et al. 2005), and level-3

data from the Atmospheric Infrared Sounder (AIRS) (Le Marshall et al. 2006) on board the *Aqua* satellite were used. The resolutions of these monthly datasets are 2°, 1.125°, and 1°, 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
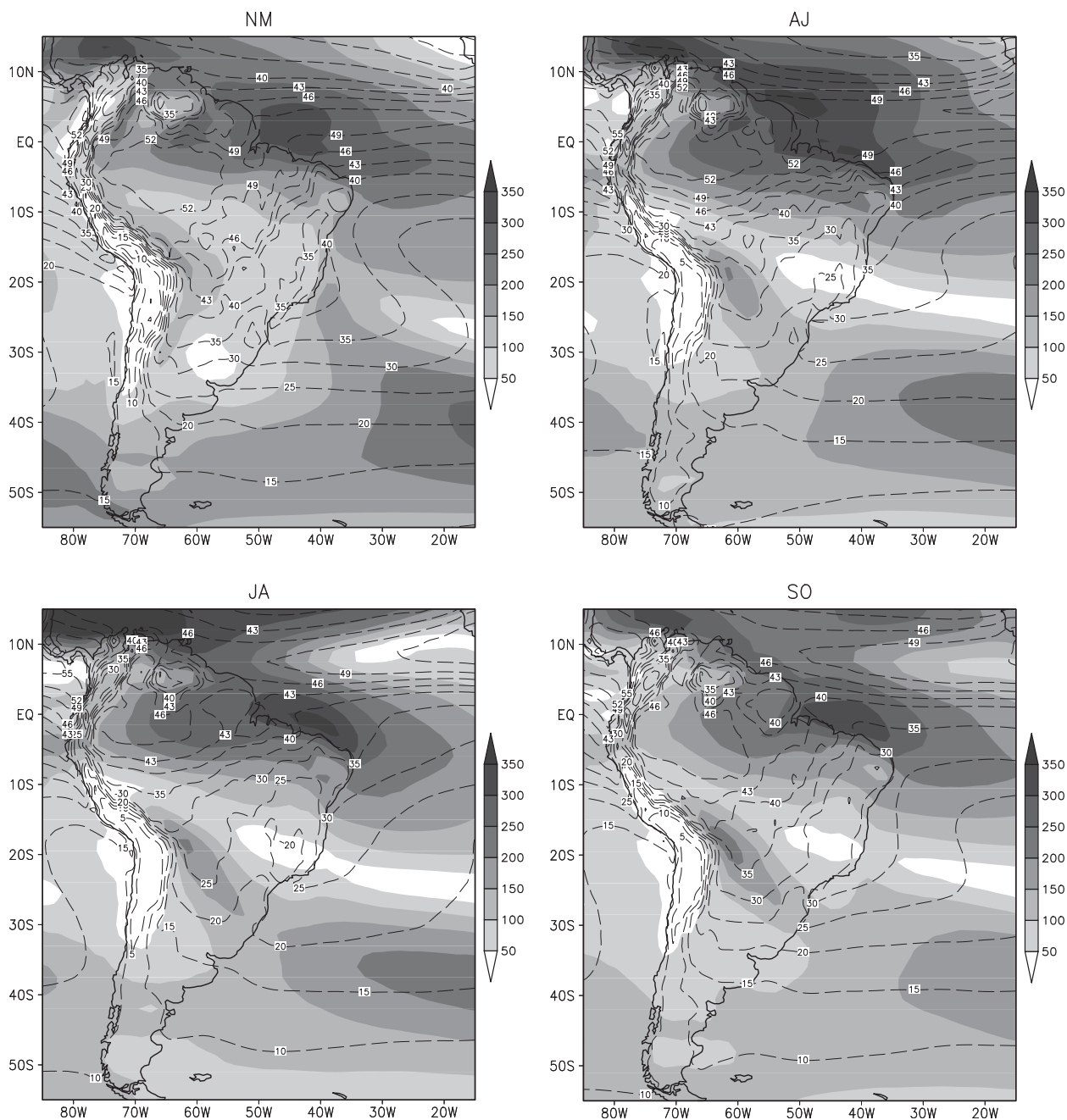
FIG. 2. Magnitude of mean seasonal vertically integrated moisture transport (shaded, kg m^{-1} s^{-1}) and precipitable water (contours, kg m^{-2}) are shown for NM (Nov–Mar), AJ (Apr–Jun), JA (Jul–Aug), and SO (Sep–Oct).

transport across 12°S, zonally averaged from 75° to 55°W. 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 Student's *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 analyzed 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 and
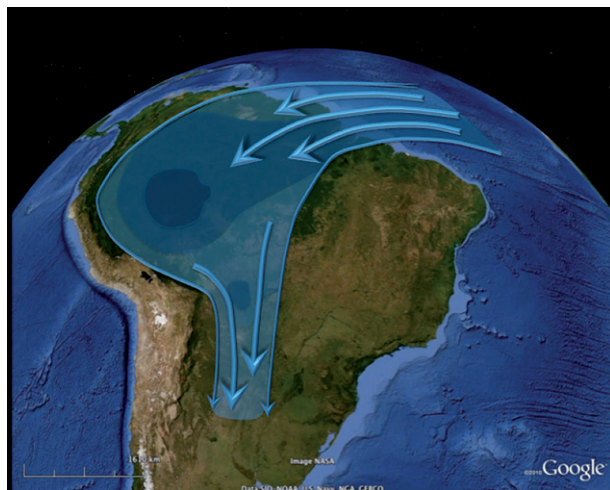
FIG. 3. Schematic representation of the aerial rivers and lake system over South America in the wet season.

300 hPa were built. These anomalies were used to highlight 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 Fig. 1. November–March (NDJFM) was termed "wet." The South Atlantic convergence zone (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–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–June (AMJ) and September–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 that 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 interhemispheric flow is strong, and most of the moisture entering western Amazonia comes from the northern tropical ocean. During the other seasons both hemispheres provide important contributions.

Year-round, part of this moisture veers over western Amazonia and is transported southward, toward high rainfall areas in the subtropics. The amount of moisture leaving Amazonia toward 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 lakes

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, as does the moisture that flows east of the Andes, toward the subtropics.

Figure 2 shows the magnitude of the vertically integrated moisture transport in shades of gray. Precipitable water is shown in contours. It can be seen that the moisture transport decreases inland, downstream of the trade wind confluence. This decrease is, at least in part, due to diffluence. The pattern is very similar to that of a liquid flowing into a wider channel. It can also be seen in Fig. 1 that there is generally broadening of the moisture pathway when advecting from the ocean into Amazonia. Precipitable water increases inland from 50° to 65°W and the equator to 10°S, so the decrease in transport must be due to diminishing wind speed in low levels. These are the reasons for 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 is transported toward Central America. In the wet season most of the outflow is toward 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 (10°–0°S, 70°–50°W) and the adjacent Atlantic (equator–10°N, 50°–30°W) is shown in Fig. 4 for the seasons defined here. Data from four different sources are used: *Aqua* AIRS (2003–09), ERA-40 (1980–2001), ERA-Interim (1989–2008), and NCEP (1980–2001). From September to June the atmosphere over Amazonia is more moist up to 700 hPa. From November to March it is more moist over the whole column, up to 300 hPa. In July to August there is a discrepancy between the datasets: NCEP and ERA-Interim showing more moisture over the forest between 900 and 650 hPa, *Aqua* AIRS showing the opposite, and almost no difference to be seen in ERA-40.
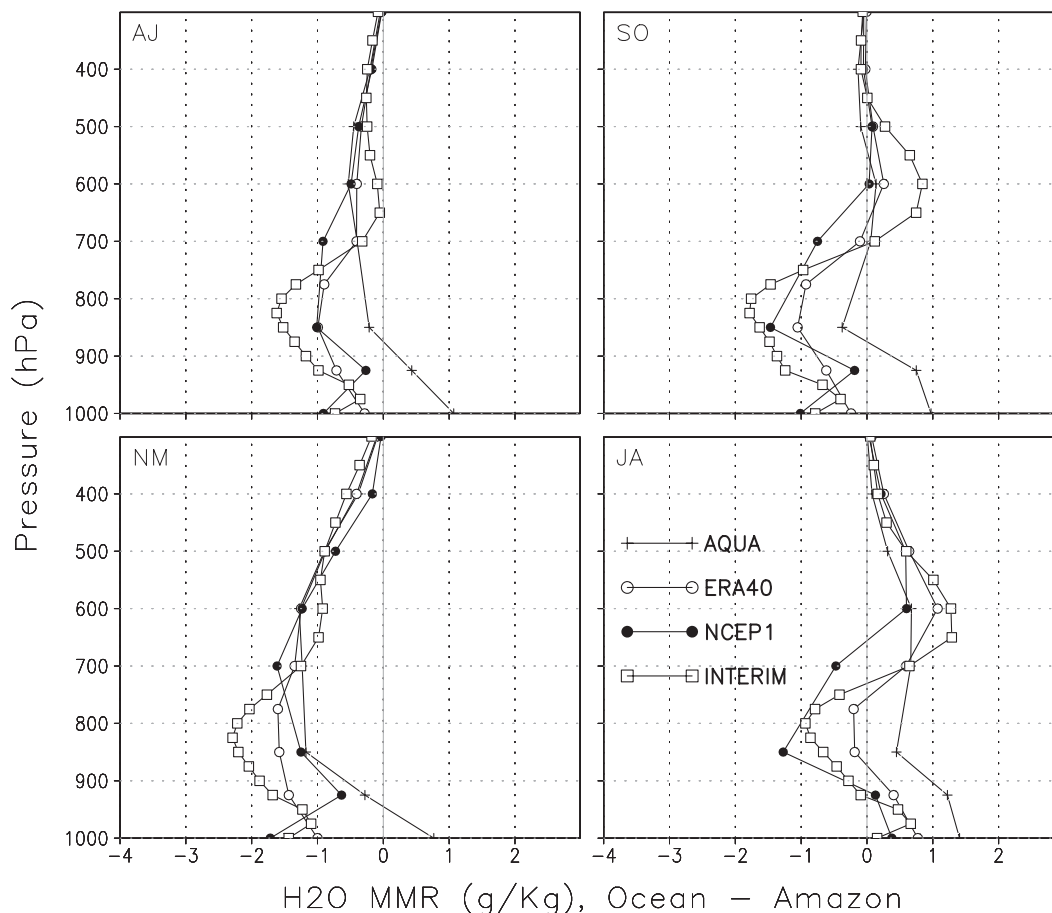
FIG. 4. Mean seasonal differences between the vertical profile of water vapor over the Atlantic (equator–10°N, 50°–30°W) and Amazonia (10°S–equator, 70°–50°W) are shown for AJ, SO, NM, and JA. Data from NCEP (solid circles) and ERA-40 (open circles) are averaged between 1980 and 2001, while ERA-Interim (squares) is averaged between 1989 and 2008, and satellite data from AIRS (crosses) are averaged between 2003 and 2009.

Figure 5 is like Fig. 4 but for temperature. Year-round the lower layer of the atmosphere, from just above 1000 to 800 hPa in AMJ and to 750 hPa in the remaining seasons, is warmer over Amazonia. Only in AMJ is there a discrepancy because *Aqua* AIRS shows no difference in this layer.

The higher temperature in the low levels over Amazonia raises 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.

1) DIVERGENCE OF MOISTURE TRANSPORT

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

$$P - E = -\nabla \cdot QV, \qquad (3)$$

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 reliability of the field is considered to be low. Having said this, a simple validation can be carried out by comparison with rainfall. Convergence is expected where rainfall is high—particularly for local maxima, which are important to supply water to river basins. The cool seasons, AMJ and JA, bear the comparison better over the continent. NDJFM and SO show excessive dryness in
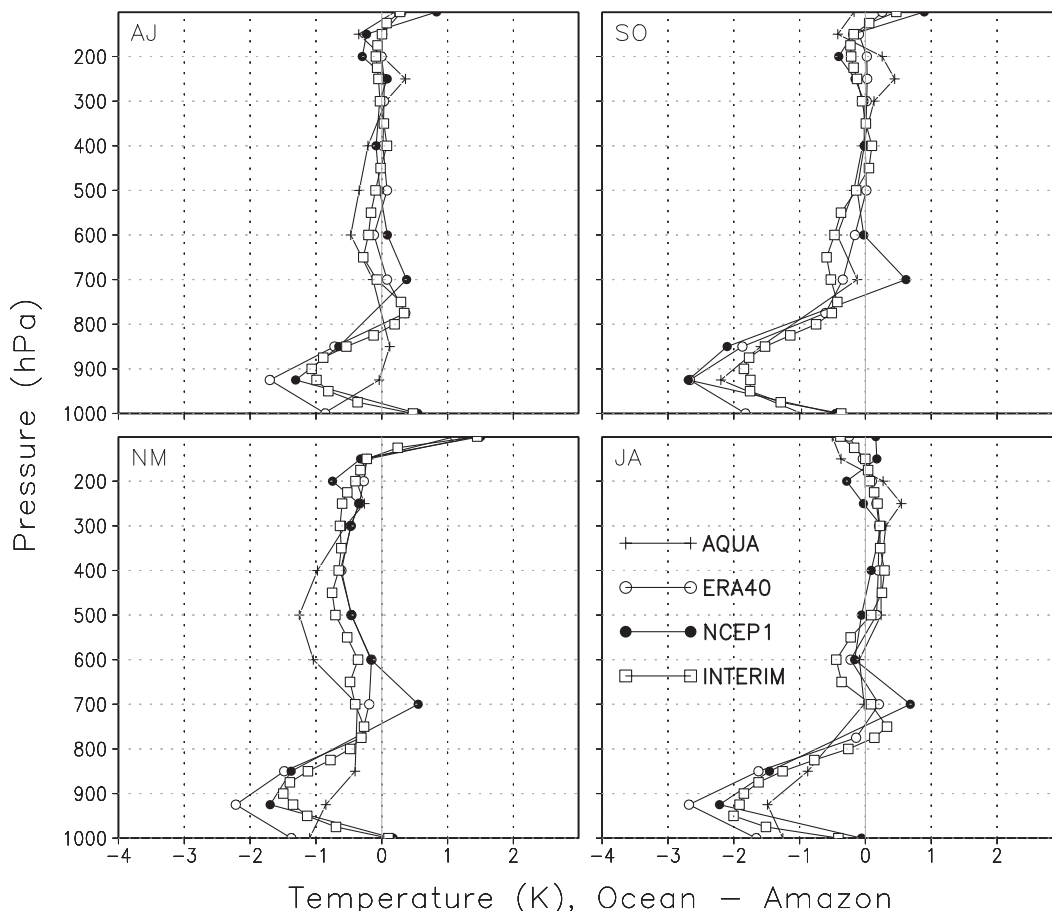
Fig. 5. As in Fig. 4 but for air temperature.

southwestern Amazonia and excessive convergence of moisture east of the Andes from 20°S to beyond 35°S. In AMJ 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, coinciding, in both cases, with 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} in AMJ and between 4 and 5 mm day^{-1} in JA. 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 10° to 25°S 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 10°S tropical flow acquires a northerly component. According to these data, southern Amazonia acts as a source of moisture to the subtropics.

Moisture is also contributed by evaporation from the soil along the aerial river. In this way, subtropical precipitation is fed by the rain falling farther north earlier in the year.

2) Moisture balance of the dry-season aerial river

How much moisture does the aerial river feed into 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 with limits 23°–10°S, 70°–50°W (shown in Fig. 6JA) superimposed on the season's long-term mean moisture flow. It can be seen that all flow coming from Amazonia enters through the northern and western boundaries, shown in Fig. 1. Through the eastern boundary, moisture is transported from the adjacent Atlantic, and the aerial river leaves the box through the southern (mainly) and also the
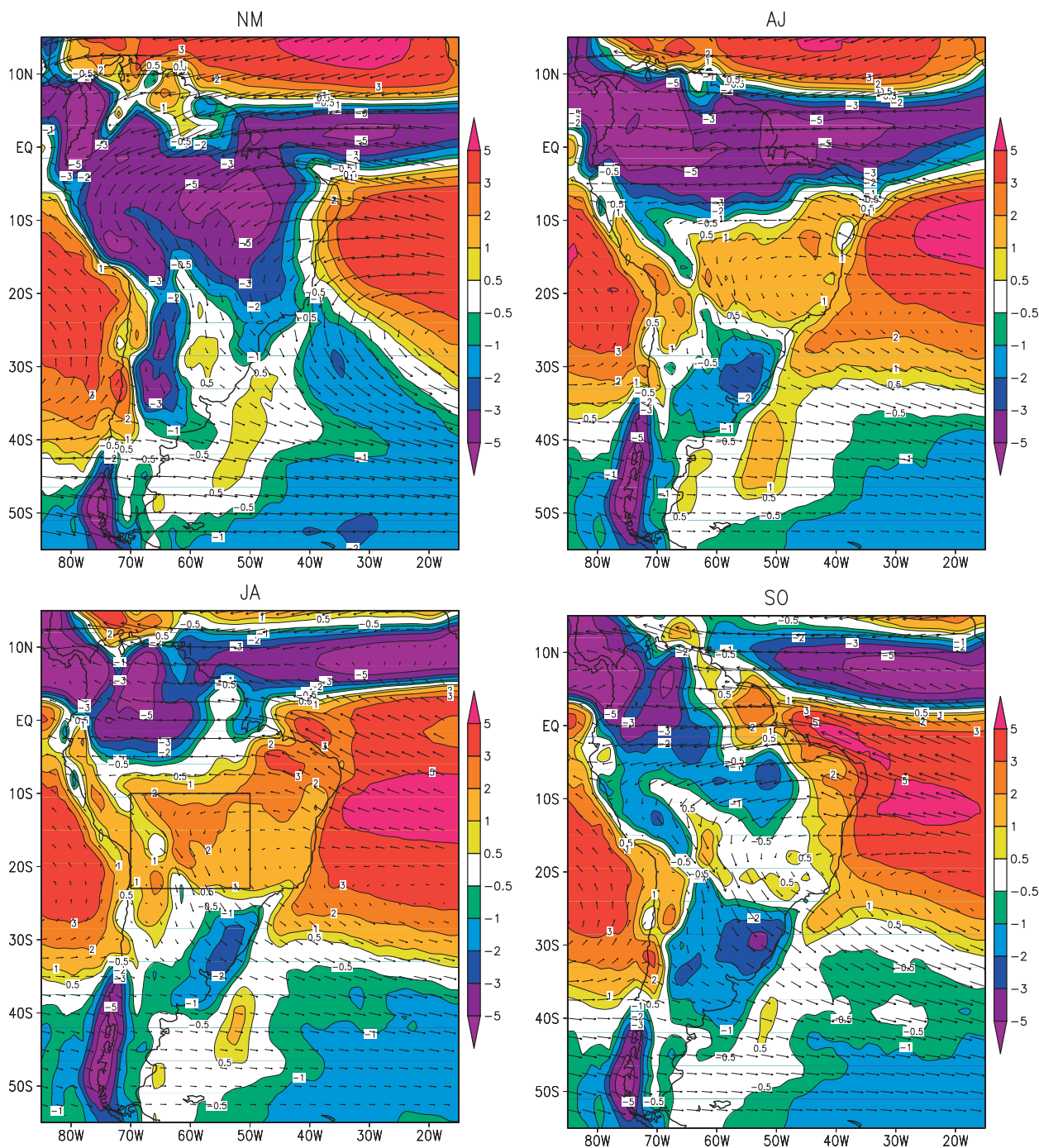
FIG. 6. Mean seasonal vertically integrated moisture transport (arrows) and its divergence (colors, mm day^{-1}) are shown for NM, AJ, JA, and SO.

eastern boundaries. The flow across the eastern boundary was plotted versus 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 characteristic 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
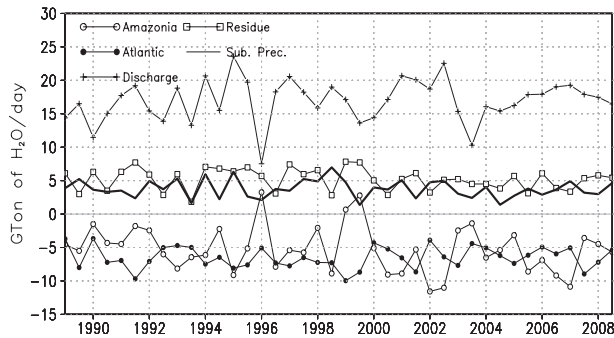
FIG. 7. Water balance (Gt day^{-1}) for the area depicted in Fig. 6 (23°–10°S, 70°–50°W) for the dry months between 1989 and 2008. Inflow is divided into two contributions: Amazonia (open circle) and Atlantic Ocean (filled circle). Discharge (+) is the outflow from this region into the subtropics, and the residue (squares) is the difference between inflows and outflows. The line without symbols is the precipitation averaged over 34°–23°S, 57°–48°W.

as residual. Also, the discharge represents the total amount of moisture delivered to the continental rainfall region.

Discharge of the aerial river is plotted in Fig. 7. It mostly varies between 10 and 23 Gt 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 Amazonia discharge shows a larger spread and thus a greater effect on 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 more *moist* air, and not more air, is transported to the subtropics.

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 12°S from 75° to 55°W. It was correlated to rainfall at each point, and the results are displayed in Fig. 8. A Student's 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, up to 0.5, are found within regions of intense rainfall. These areas are larger in NDJFM 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 plain line (no markers) in Fig. 7 shows rainfall over the region 34°–23°S, 57°–48°W, which is depicted in the JA panel of Fig. 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 weak. 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 Fig. 9. 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 strengthened South Atlantic high. This situation constitutes an intensification of climatology, so there is, in fact, more moisture traveling from the deep tropics to the subtropics and the rainfall region. The "weak" composite shows the opposite situation, with anomalous flow heading northwestward from the area with decreased rainfall to the tropics and veering northeastward toward 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 their 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 in the west tropical Atlantic (0.5°C), adjacent to the southeastern and southern regions of Brazil and to Uruguay (1.0°C), and over the eastern tropical Pacific (1.0°C), shown in Fig. 10. This last one seems to be associated with a mature positive phase of the El Niño–Southern Oscillation phenomenon.

The spatial structures 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-3 trend in the subtropics and midlatitudes of the Southern Hemisphere (30°S, 60°S), with an apparent blocking in the South Atlantic (60°S, 45°W). In contrast, 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, a strong wave-3 trend (30°–60°S)
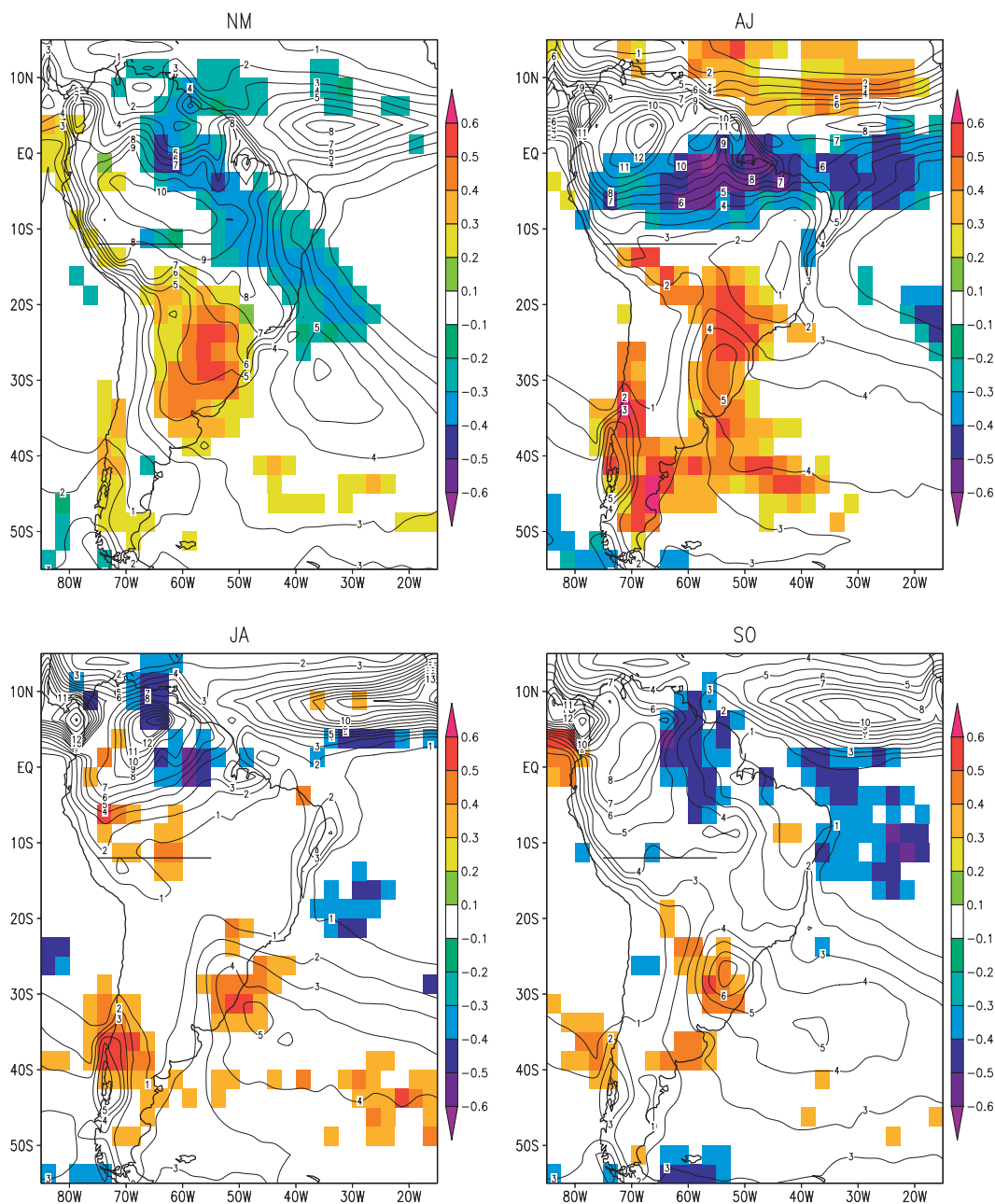
FIG. 8. Colors show correlations between the meridional moisture transport across 12°S between 75° and 55°W (indicated by the grayscale horizontal line) and rainfall at each grid point. Values below the 95% significance level are masked out. Contours show the long-term mean seasonal rainfall, for reference (kg m^{-2}).

appears—related to a strong blocking structure at low latitudes (60°S, 120°W), which are all part of the Antarctic Oscillation pattern.

4. Discussion 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 an aerial river and aerial lake are proposed and used as a framework for considering large-scale moisture transport. They consist of a symmetry/analogy between the main pathways of moisture flow in the atmosphere and surface rivers and lakes. Aerial rivers and lakes lose (gain) water through precipitation (evaporation), while the opposite takes place in their surface counterparts.
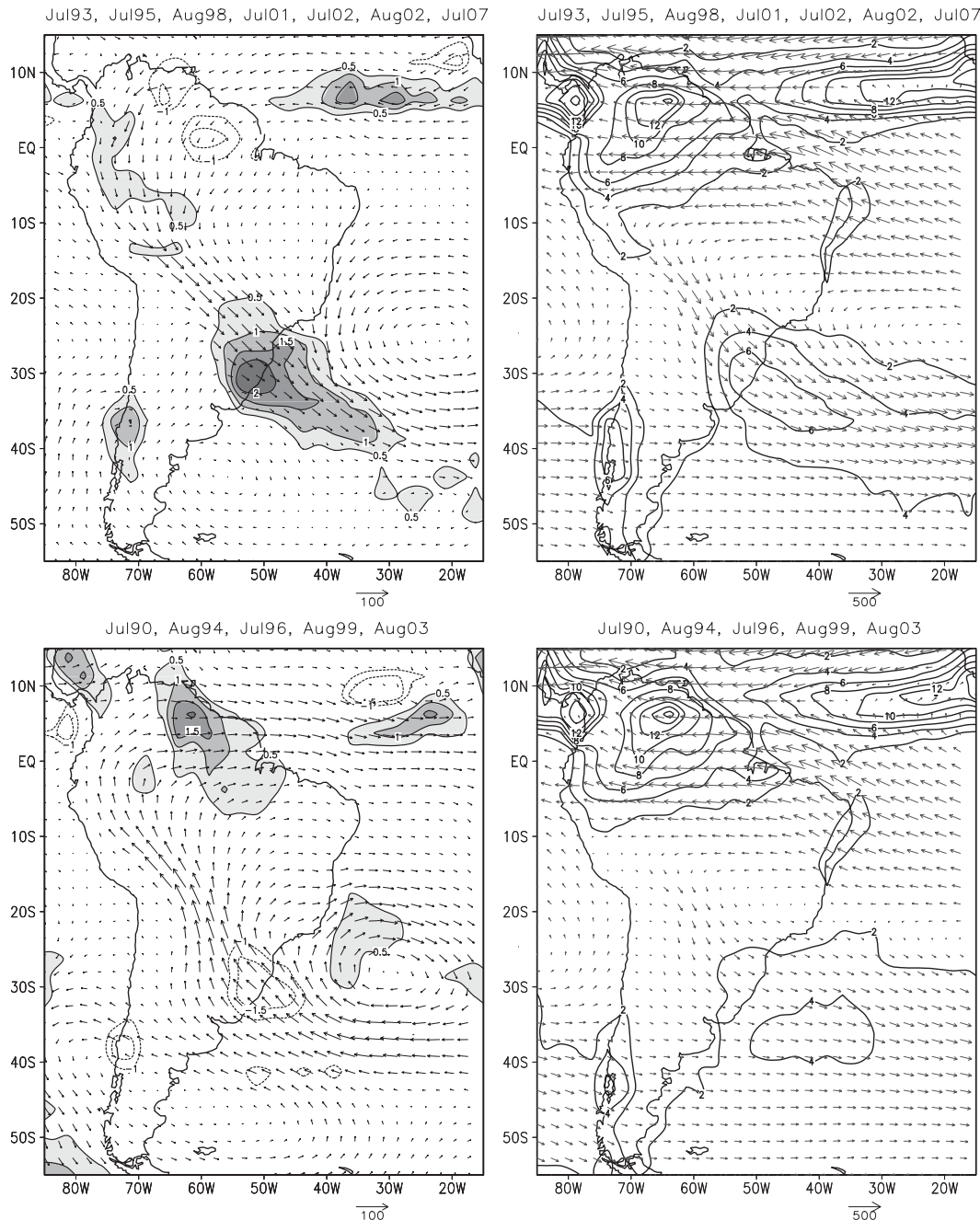
FIG. 9. (left) Anomaly and (right) full field composites for months when enhanced (diminished) rainfall was accompanied by an intensification (weakening) of the climatological moisture transport (vectors) pattern are shown in the top (bottom) panels.

The magnitude of the vertically integrated moisture transport is the discharge at each point, and precipitable water is like the mass of a liquid column (which is directly proportional to its height) multiplied by an equivalent speed, it gives the discharge.

Trade wind flow into Amazonia forms an aerial river, as does the moisture flow east of the Andes, which heads toward the subtropics. Both are present year-round. Aerial lakes are the sections of a moisture pathway in which the flow slows down and broadens, because of diffluence, and becomes "deeper," with high amounts of precipitable water. This is the case over Amazonia downstream of the trade wind confluence. In the wet season (NDJFM) flow from the aerial lake is transported
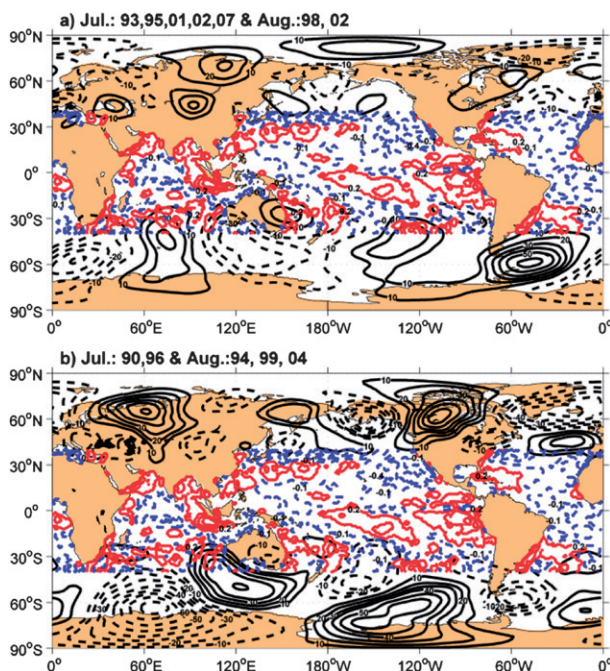
FIG. 10. Black contours show composites of monthly-mean meridional anomalies of geopotential at 300 hPa for the (a) strong and (b) weak periods. Solid (dotted) lines are positive (negative) values starting with 10 gpm (-10 gpm) with interval 10 gmp. Also, differences of the monthly mean of the SST between the strong and weak periods are shown in both graphics. Positive (negative) values are in red (blue). SST anomalies values start with $0.1C°$ ($-0.1C°$) with interval $0.1C°$.

mainly toward the subtropics, while in the dry season (JA) it is mostly toward Central America.

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

The role of the land surface as a source or a sink of moisture to the atmosphere is an issue that has generated 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 continental 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 farther north earlier in the year. Calculations of large-scale moisture transport divergence are not considered highly reliable, and these results on surface water sources must be compared with other datasets. For the moment they can only be considered a good hypothesis. The forest has an elaborate root system that 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 behavior 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 Gt 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 greatest effect on 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 that 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 is subject to very different dynamical influences, it would be interesting to investigate how these coherent anomaly patterns of such large scale arise.

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