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Inter-hemispheric and inter-zonal moisture transports and monsoon regimes

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ABSTRACT: The principal objectives here are to quantify the strengths of global monsoon circulations in terms of cross-equatorial moisture transport and to verify its behaviour during two extreme years of precipitation over the Amazon Basin. The National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data sets for the period 1950–2012 are used in this study and the results are compared with calculations from ERA-Interim data. During the South Asian summer monsoon (JJA), the transport is 82.1×10^7 kg s^{-1} between 30° and 90°E from the Southern Hemisphere (SH) to the Northern Hemisphere (NH) and reverses to 41.4×10^7 kg s^{-1} from NH to SH in northern winter (DJF). Over South America between 30° and 90°W, the values are 31.4×10^7 kg s^{-1} in DJF from NH to SH and 21.5×10^7 kg s^{-1} in JJA from SH to NH. Although there is no wind reversal from summer to winter seasons over the South American monsoon region, the moisture transport across the equator reverses. The transports during a weak and a strong monsoon in the Amazon Basin are distinctly different suggesting that the cross-equatorial moisture transport can be used as a Monsoon Intensity Index (MII). For the South American monsoon, the DJF index is 28.5×10^7 kg s^{-1} in the dry year 2004–2005 and 45.1×10^7 kg s^{-1} in the wet year 2011–2012 as against the climatological value of 31.4×10^7 kg s^{-1}. There is an indication of an inverse relation between the MIIs over the Amazon Basin and the Australian sectors. The annual mean moisture transport across the equator is from SH to NH and is equivalent to three Amazon River discharges.

KEY WORDS South American and Indian monsoons; moisture transport; rainfall seasonality

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1. Introduction

There are many descriptions and definitions of monsoon circulations or regimes from the early studies of Walker (1924) and Ramage (1971) to the more recent works of Asnani (1993) and Krishnamurti *et al.* (2013). A monsoon system is like a sea breeze-land breeze reversal from summer to winter occupying thousands of km. Moist winds from the oceans to the continents transport copious amounts of water and impart intense rainfall to the continents. In monsoon regions, the seasonality of rainfall is a conspicuous and dominant characteristic.

Monsoon regions are found in tropical and subtropical regions of the globe. The lower tropospheric wind reversal is viewed as an important characteristic of the monsoon regimes (Chang, 2004; Krishnamurti *et al.*, 2013). A juxtaposition of a continent in one hemisphere and an ocean in the other hemisphere, in the tropics and near tropics, is ideal for a monsoon regime as in the case of South Asian monsoon. The South Asian summer monsoon is very well studied (Ramage, 1971; Keshavamurty and Awade, 1974; Asnani and Misra, 1975; Parthasarathy and Mooley, 1978; Zhou and Lau, 1998; Krishnamurthy and Goswami, 2000; Goswami, 2004) due to its affect on the economy of the Indian subcontinent and adjoining regions. Besides South Asia, four more monsoon regions are recognized in the literature: West Africa (Thorncroft and Lamb, 2004), Australia (Hendon, 2004), western North America (Ropelewiski *et al.*, 2004) and tropical and subtropical South America (Jones and Carvalho, 2002; Grimm *et al.*, 2004; Vera *et al.*, 2006; da Silva and Carvalho, 2007; Raia and Cavalcanti, 2008). That is, the seasonal rainfall in the South American continent east of the Andes is also viewed as monsoon. In this case, it is reasonable to think that the North Atlantic Ocean to the north and the South American Continent to the south provide the necessary land-sea contrast. In the same manner, the Indonesian sea to the north and the Australian continent to the south also provide conditions for a monsoon regime. Similar large-scale sea-land contrasts drive the West African and North American monsoon systems.

In austral summer (October through March), the rainfall over central Brazil, except Nordeste, is around 1400 mm and it is about 400 mm or less in austral winter (April through September) (Figueroa and Nobre, 1990), which is a large seasonal variation. This suggests that there is a significant seasonal change in the wind regime over South

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Table 1. Comparison between the Indian and the South American Summer Monsoons.

Characteristic	Indian Summer Monsoon	South American Summer Monsoon	
Surface winds	Wind reversal from NE in NH Winter to SW in NH summer.	No significant wind reversal.	D
	Northeastward low-level Somali jet directed towards Indian Peninsula 15 m s^{-1}.	Southward low-level jet from the Amazon Basin east of the Andes 8 m s^{-1}.	S
	Cross-equatorial flow in the Arabian Sea east of Kenya highlands 10 m s^{-1}.	Cross-equatorial flow from 75° to 30°W.	S D
	Southeast trades turn clockwise near the equator.	No such turning near the equator.	
Rainfall	Average 4-month rainfall over India ~800 mm.	Average 4-month rainfall over Amazonia >1200 mm.	D
Pressure centres	Mascarene High near 30°S and 60°E drives the winds.	North and South Atlantic subtropical highs drive the trades.	D
Monsoon trough	Near the foothills of the Himalayas.	Seasonal South Atlantic Convergence Zone (SACZ).	S
Upper tropospheric pressure centres	Monsoon High over Tibet, a thermal high maintained by release of latent heat and highland radiation absorption.	Bolivian High maintained by latent heat release by vigorous convection.	S D
Upper tropospheric winds	Easterly jet stream over the monsoon trough south of Tibetan High.	No such jet stream north of the Bolivian high.	D
Land-sea contrast	Indian Ocean to the south of the Indian subcontinent.	Tropical North Atlantic to the north of South America.	S
Onset	May 20 in southern India advancing to north India by 25 June.	October 10 in NW Amazon advancing quickly to Southeast Brazil by November 01.	S
Retreat or withdrawal	October 15 in NW India.	March 25 in southeast Brazil and April 30 in northern Amazon Basin.	S
Moisture source	Indian Ocean, especially the western portion including the Arabian Sea.	Northern and Southern Tropical Atlantic Oceans, mainly the area between the two subtropical highs.	D
Sea surface temperature	Due to evaporation, there is cooling in the Arabian Sea from 30 to 28 °C in June.	**Waters of the tropical Atlantic (45°–15°W; 10°N–20°S) are warmer from January to May (above 27 °C).**	
Areal rivers	From east of Kenya and Somalia into Indian Peninsula oriented SW–NE.	Parallel to the equator from 0° to 55°W and from southern Amazon into northern Argentina and southern Brazil.	S
Cross-equatorial moisture transport	**95.3 × 10^7 kg s^{-1} in JJA from south to north (4.5 Amazon River discharges).**	**31.4 × 10^7 kg s^{-1} in DJF from north to south (1.5 Amazon River discharges).**	D
Spatial variation of rainfall	Seasonal rainfall varies from ~8000 mm in northeastern India to only about 350 mm east of the Western Ghats.	More evenly distributed over the Amazon Basin and the central and southeastern Brazil and scanty rain over Northeast Brazil.	D
Breaks in monsoon	Five or six periods of break monsoon with little rain extending over 1–2 weeks each.	Breaks are observed over central and southeastern Brazil, not many details available.	S
Evapotranspiration	Not known.	Contributes 32% for the rainfall over the Amazon Basin.	
Topographic effects	Himalayas have southeast to northwest orientation and block the southwesterly monsoon winds.	The Andes have a north to south orientation and block the predominantly easterly trades.	S
Teleconnections with other monsoon regimes	Not known.	**Inverse relation with Australian sector indicated.**	

S and D indicate similarity and disparity, respectively. Findings of the present work are shown in bold. NE, northeast; SW, southwest; NW, northwest.

American tropics and subtropics, responsible for the seasonal variability of rainfall. The winds are essentially easterly throughout the year over South American tropics east of the Andes and there is no seasonal reversal of winds. However, when the annual mean wind is subtracted, the lower tropospheric flow shows seasonal reversal required for the seasonality of rainfall (Zhou and Lau, 1998). Other common ingredients associated with monsoons are a surface high-pressure centre over the ocean that drives the winds and a low-pressure region over the continent, called monsoon low or trough, into which the winds are drawn.

The literature thus far published brought out many aspects of the monsoon regimes and their inter-annual and intra-seasonal variabilities of rainfall in the regions

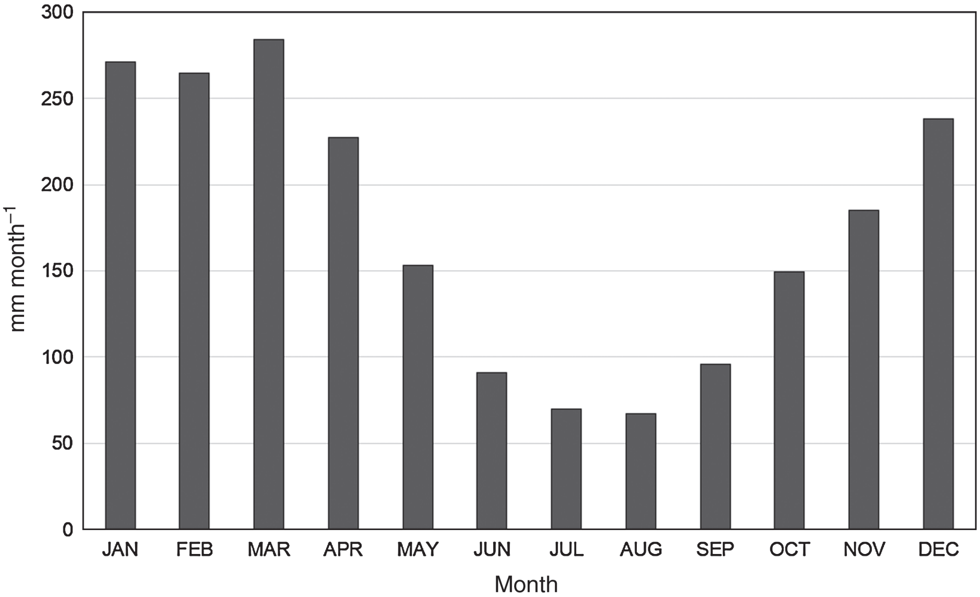

Figure 1. Fifty-year climatology of monthly precipitation over a rectangular area around the Amazon Basin (15°–0°S; 75°–45°). Data from GPCC version 2011, 1°×1° grid resolution.

affected by these regimes. One important aspect, the moisture transport, has not received much attention. Saha (1970) made an effort to understand the water vapour transport by the South Asian summer monsoon winds over the Indian Ocean and the adjoining seas. Recently, Arraut and Satyamurty (2009), Carvalho *et al.* (2010) and Satyamurty *et al.* (2013a, 2013b) showed that the moisture transport into the tropics of the South American continent is essentially performed by the trade winds. Satyamurty *et al.* (2013a, 2013b) identified the source regions for the moisture of the Amazon Basin. However, several aspects of the flow of moisture like the inter-hemispheric and inter-zonal transports that influence the precipitation over the continents did not receive sufficient attention.

The objectives of the present contribution are to quantify the seasonal and annual inter-hemispheric and inter-zonal transports of moisture in the tropical and subtropical regions associated with monsoon regimes of the globe and to verify the monsoon behaviour in contrasting years of rainfall over South America (wet-Amazon and dry-Amazon years). The South Asian monsoon system is considered prototypical with which the South American monsoon system is compared. Special emphasis is given to the South American monsoon region.

2. A brief comparison of South American and Indian monsoons

From the existing literature (Ramage, 1971; Keshavamurty and Awade, 1974; Asnani and Misra, 1975; Parthasarathy and Mooley, 1978; Zhou and Lau, 1998; Krishnamurthy and Goswami, 2000; Jones and Carvalho, 2002; Goswami, 2004; Grimm *et al.*, 2004; Vera *et al.*, 2006; da Silva and Carvalho, 2007; Raia and Cavalcanti, 2008), similarities and differences are drawn between the summer monsoon systems of South America and India (Table 1). The most striking differences are in the precipitation and surface wind characteristics. India receives an average of 800 mm in the 4-month rainy season from June to September and the Amazon Basin receives more than 1400 mm in the 6-month period from November through April (Figure 1). In the case of South American monsoon, the months preceding the monsoon season (October) and succeeding the monsoon season (May) produce more than 150 mm each in the Amazon Basin. Distinct from the South Asian monsoon, two subtropical highs, one each in the North and South Atlantic Oceans, jointly drive the humid trades into the Amazon Basin. Over South American tropics, the winds are predominantly easterly throughout the year. The South Asian monsoon region occupies a wide stretch from 30° to 120°E while the South American monsoon affects the region between 90° and 30°W. There is an easterly jet in the upper troposphere south of the Tibetan High over North India during the South Asian monsoon season and no such jet is observed north of the Bolivian High in the South American monsoon case.

However, there are many similarities between the two regimes like the presence of a low-level monsoon trough and an upper level monsoon high. The South Atlantic Convergence Zone (SACZ, Kodama, 1992; Figueroa *et al.*, 1995) extending from the Amazon Basin southeastward into the South Atlantic during southern summer is the counterpart of the Indian monsoon trough near the foothills of the Himalayas. In a wider sense, the SACZ may be considered equivalent to the Meiyu-Baiu front near the Pacific coast of Asia. The upper tropospheric Bolivian High is similar to the Tibetan High. The northerly low-level jet east of the Andes from the Amazon Basin into southern Brazil and northern Argentina is somewhat similar to the Somali jet.

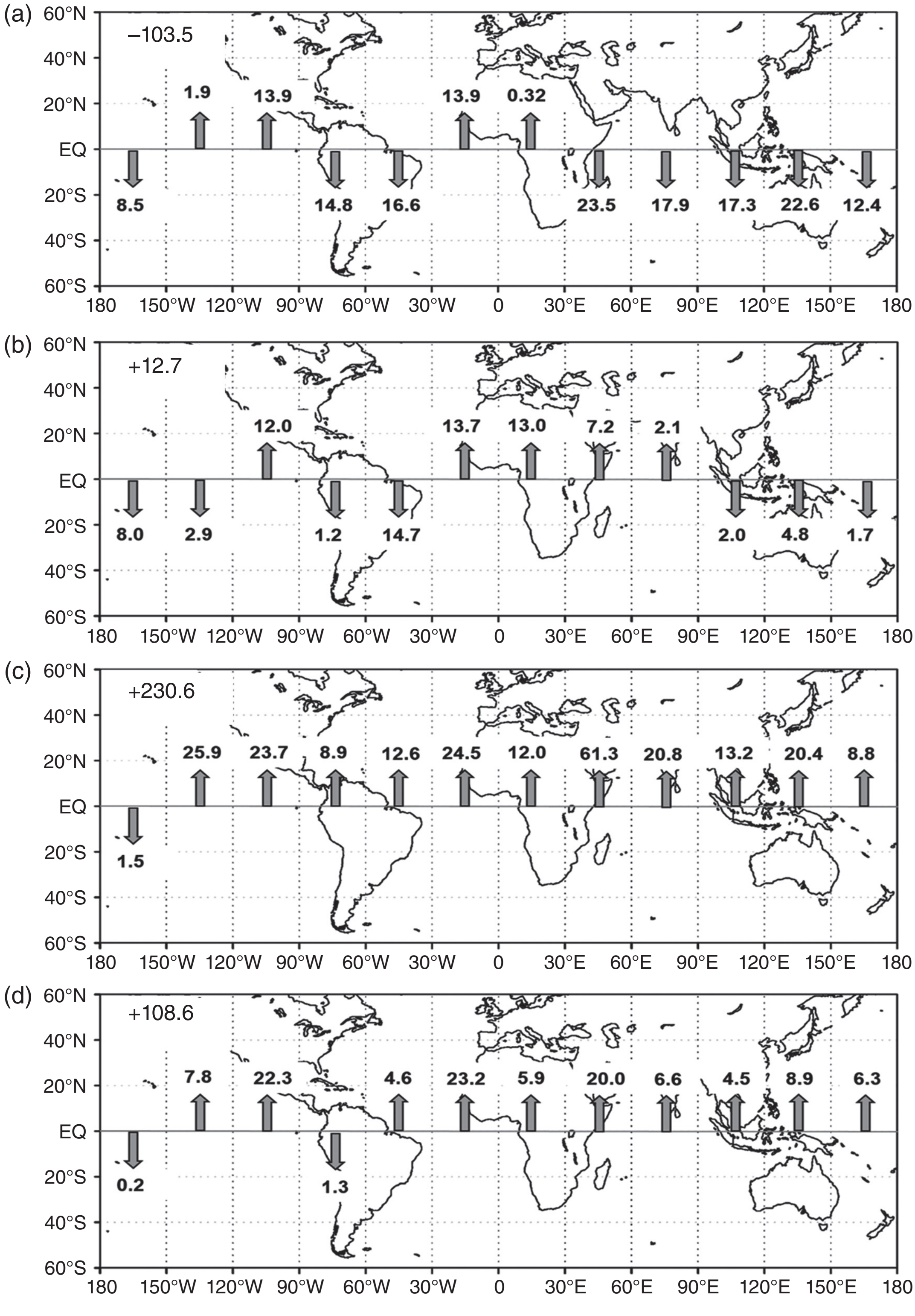

Figure 2. Sixty-two year (1950–2012) climatology of seasonal moisture transport at intervals of 30° longitude across the equator. (a) DJF, (b) MAM, (c) JJA and (d) SON. The arrows indicate the direction. The number in the upper left corner is the sum that crosses the equator from one hemisphere to the other. Units: $\times 10^7$ kg s^{-1}. Negative sign indicates transport from Northern Hemisphere to Southern Hemisphere.

3. Data and analysis

The latitude circles are divided into 12 stretches of 30° longitude each, 0°–30°E, 30°–60°E, 60°–90°E, etc. The vertically and zonally integrated moisture fluxes, i. e. moisture transports over the longitudinal stretches of 30°, are calculated over the equator and over the 30°N, 20°N and 20°S latitude circles on daily basis using Equation (1).

$$WT_m(i) = -\int_{\lambda i-15}^{\lambda i+15} \int_{1000}^{300} \left(q\, v \frac{\mathrm{d}p}{g} \right) R \cos \varphi \, \mathrm{d}\lambda \qquad (1)$$

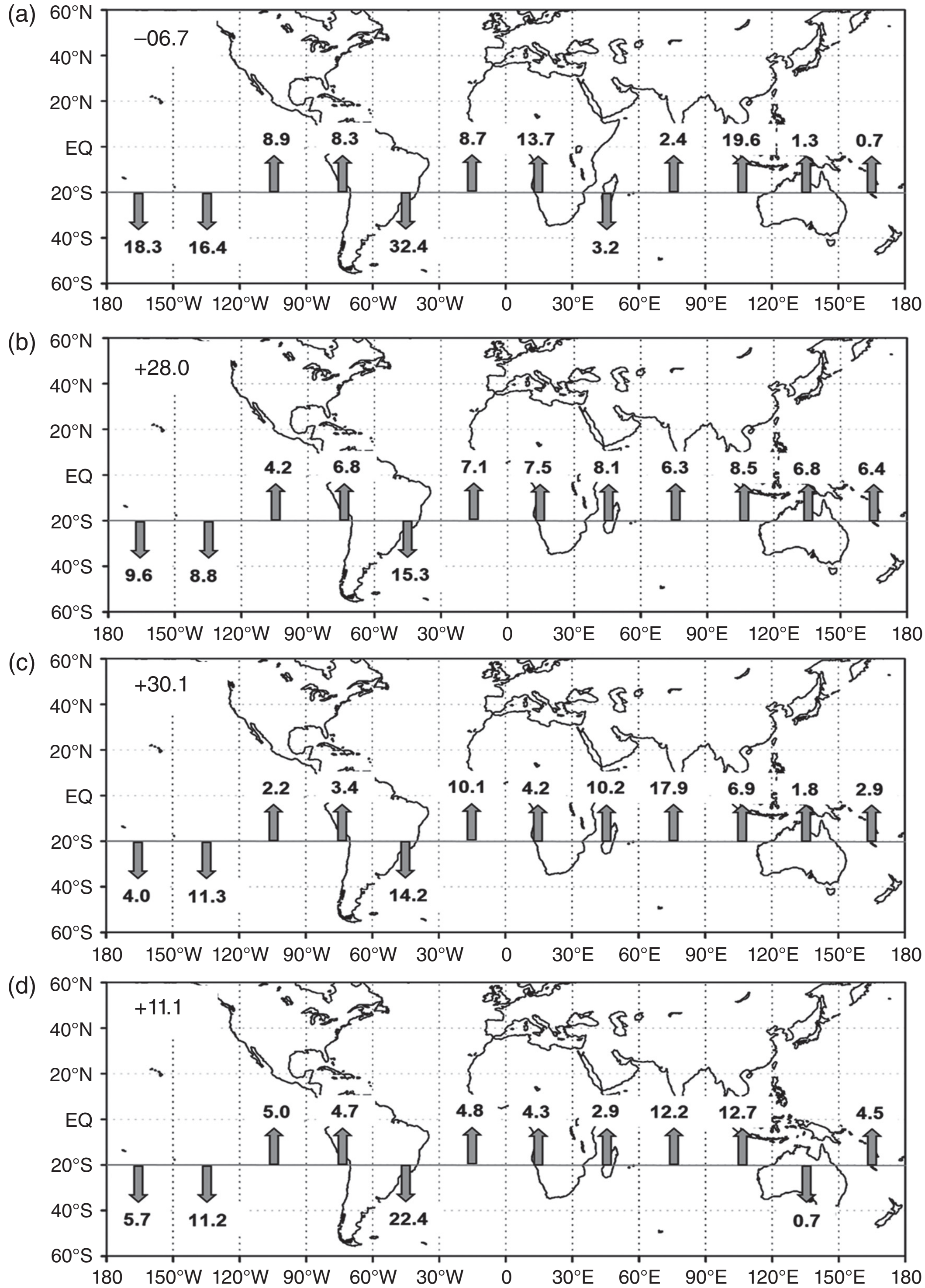

Figure 3. Same as in Figure 2 except for across the 20°S latitude circle.

where $i = 1, 2, 3, \ldots, 12$. $WT_m(i)$ is the meridional water vapour or moisture transport across the latitude circle over the ith stretch of 30° longitude. q, v, p and T are the specific humidity, meridional component of wind, pressure and temperature, respectively. R, φ, λ are the radius of the earth, latitude and longitude and g is the acceleration of gravity. The outer integral is over the 30° longitude stretch considered, and the inner integral is over $p = 1000$ hPa (or surface) to $p = 300$ hPa in the vertical. Eight levels (1000, 925, 850, 700, 600, 500, 400, 300 hPa) over the oceans and between five and eight levels over the continents, depending on the geographical elevation, are used in the integration. Moisture transport by winds above 300 hPa level is very small (less than 5% of the total) due to small values of q, and is not considered.

The daily transports are averaged to obtain seasonal values. Averages of the transports over the 62-year period 1950–2012 are presented in this study as climatology.

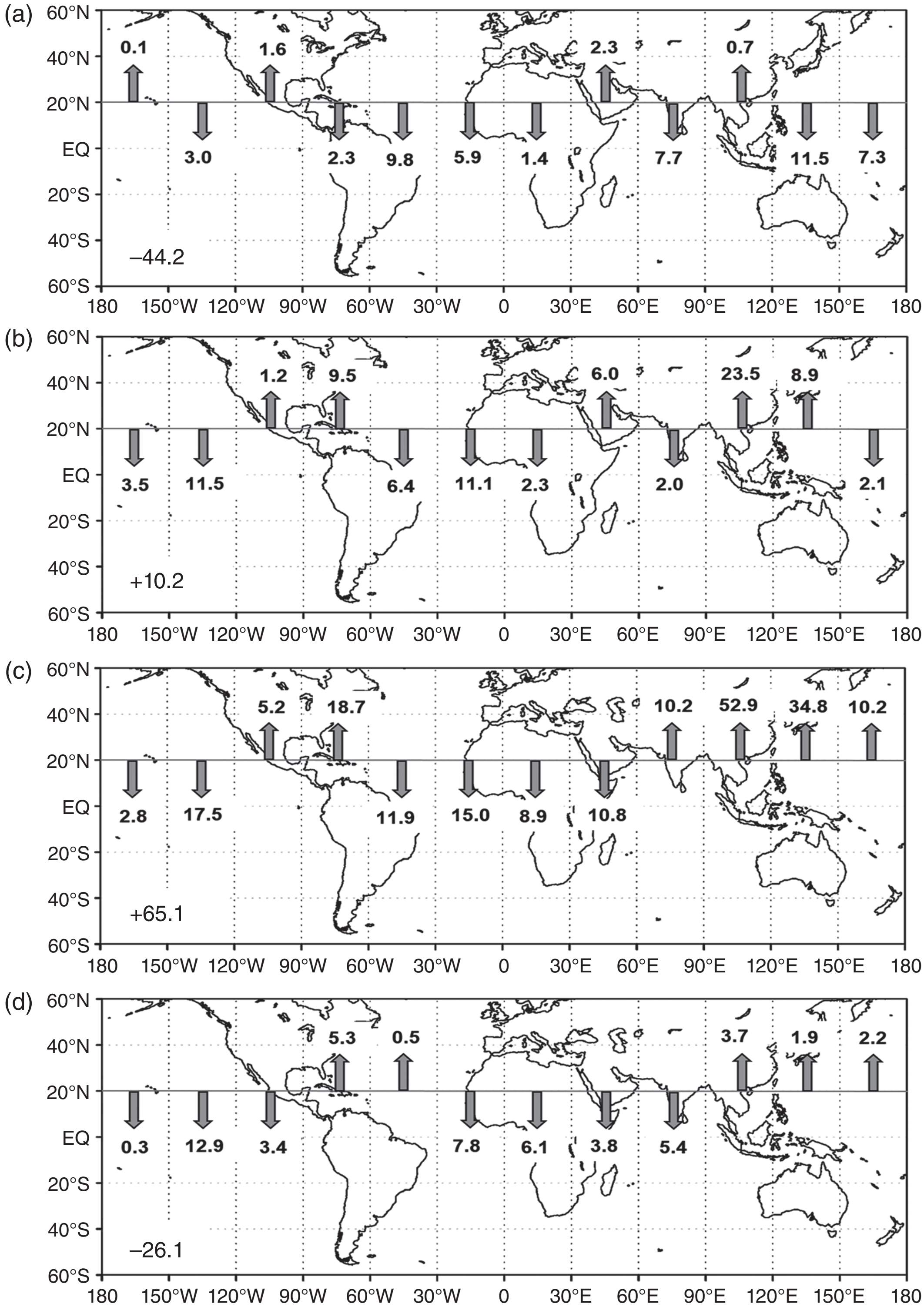

Figure 4. Same as in Figure 2 except for across the 20°N latitude circle. The sum around the latitude circle is shown in bottom left corner.

The transports over two contrasting years 2011–2012, a very wet year (Satyamurty *et al.*, 2013a, 2013b), and 2004–2005 a dry year (Marengo *et al.*, 2008) for the Amazon Basin, are also presented in order to quantify the importance of the moisture transport in the South American monsoon. The wind, temperature and humidity data are obtained from the NCEP/NCAR (National Centers for Environmental Prediction / National Center for Atmospheric Research) Reanalysis 1 (Kalnay *et al.*, 1996). The data, especially the humidity, may have some deficiencies over the tropical South America due to fewer upper air soundings from the region, but the data set comes from consistent analyses for a long period of 62 years. That is, the analyses are performed using one single methodology for all the 62 years. The meridional moisture transports from the ERA-Interim (ERAI) data

Table 2. Sixty-two year climatology of inter-zonal and inter-hemispheric (meridional) moisture transport at 20°S, 0°, 20°N and 30°N integrated around the globe.

	DJF	MAM	JJA	SON	Annual mean
20°S	−06.7	+28.0	+30.1	+11.1	+15.6
	8.8	7.2	9.7	7.5	
Equator	−103.4	+12.7	+230.6	+108.6	+62.5
	20.7	22.1	12.5	12.0	
20°N	−44.2	+10.2	+65.1	−26.1	+01.2
	11.5	7.1	7.3	6.7	
30°N	+72.1	+79.9	+62.1	+33.5	+61.9
	6.3	5.8	7.1	5.2	

DJF, December, January and February (Austral summer); MAM, March, April and May (Austral autumn) season; JJA, June, July and August (Austral winter) season; SON, September, October and November (Austral spring) season. Top and bottom lines of rows are, respectively, means and standard deviations. Units: $\times 10^7$ kg s^{-1}. + and − signs indicate south to north and north to south transports, respectively.

Table 3. Meridional moisture transport at 20°S, 0°, 20°N and 30°N integrated from 90°W to 30°W.

	DJF	MAM	JJA	SON	Annual mean
20°S	−24.1	−08.5	−10.8	−17.7	−15.3
	6.6	6.7	5.2	5.2	
Equator	−31.4	−15.9	+21.5	+03.3	−05.6
	8.6	8.5	6.4	5.3	
20°N	−12.1	+03.1	+06.8	+05.8	+00.9
	8.2	6.3	5.9	5.2	
30°N	+23.1	+22.7	+21.1	+14.1	+20.2
	8.6	8.5	6.4	5.3	

DJF, December, January and February (Austral summer); MAM, March, April and May (Austral autumn) season; JJA, June, July and August (Austral winter) season; SON, September, October and November (Austral spring) season. Top and bottom lines of rows are, respectively, means and standard deviations. Units: $\times$ 10^7 kg s^{-1}. + and − signs indicate south to north and north to south transports, respectively (South American monsoon sector).

Table 4. Meridional moisture transport at 20°S, Equator, 20°N and 30°N integrated from 30° to 120°E.

	DJF	MAM	JJA	SON	Annual mean
20°S	+18.8	+23.9	+35.0	+27.8	+26.4
	9.7	8.3	5.3	5.5	
Equator	−58.7	+07.3	+95.3	+31.1	+18.8
	7.6	8.0	6.6	6.5	
20°N	−04.7	+27.5	+52.3	−05.5	+17.4
	5.2	6.8	8.8	7.8	
30°N	+07.9	+11.9	+07.8	+04.6	+08.1
	2.8	6.0	8.5	5.5	

DJF, December, January and February (Austral summer); MAM, March, April and May (Austral autumn) season; JJA, June, July and August (Austral winter) season; SON, September, October and November (Austral spring) season. Top and bottom lines of rows are, respectively, mean and standard deviations. Units: $\times$ 10^7 kg s^{-1}. + and − signs indicate south to north and north to south transports, respectively (Asian monsoon sector).

set are used for comparison. The ERAI reanalysis is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF - Dee *et al.*, 2011). There are no significant trends in the rainfall over the Amazon Basin as a whole in the past 70 years (Satyamurty *et al.*, 2009) and, therefore, a long period climatology over the Amazon Basin obtained from 62 years of data is considered robust.

4. Inter-hemispheric and inter-zonal atmospheric moisture transports

Figure 2 shows the seasonal climatology of the inter-hemispheric (across the equator) moisture transports in the atmosphere. In northern winter (DJF), the cross-equatorial transport (Figure 2(a)) is mostly from Northern Hemisphere (NH) to Southern Hemisphere (SH), especially over the Indian Ocean coinciding with the Indian winter monsoon, over Indonesia-Australia sector coinciding with the Australian monsoon, and over the Amazon Basin coinciding with the South American summer monsoon. In northern spring (MAM), the transports (Figure 2(b)) weaken but continue to be from the NH to the SH over the Australian and South American sectors. Over the Indian Ocean, the transports reverse their direction into the NH. In northern summer (JJA, Figure 2(c)), the transports are from the SH to the NH, except in the Central Pacific Sector. The transport is very intense in the East African sector with a value of over 600 million kg s^{-1}. This transport makes the Somali jet very humid and after crossing the equator it turns to northeast providing copious amounts of water to the Indian Subcontinent. The transports from the SH to the NH over South America in southern winter (JJA) are in the reverse direction, i. e. opposite to those in the DJF season. Although the surface winds in this sector (figure not shown) are predominantly easterly in both the seasons, the reversal of direction is readily observed in the meridional moisture transport. In the transition season September through November (SON), the transports (Figure 2(d)) weaken but are mostly from the SH to the NH. There is a tendency for the monsoon circulation to continue in the following autumn season, both over the Indian Ocean (Figure 2(c) and (d)) and over the Amazon Basin (Figure 2(a) and (b)).

Three sectors behave in a different fashion. Over western Africa between 30°W and 30°E and over eastern Pacific between 120° and 90° W, the transports are from the SH to the NH in all seasons. These transports occur north of the oceanic desert regions like eastern tropical South Atlantic and eastern tropical South Pacific. Over the mid-Pacific sector between 180° and 150°W, the transport is always from the NH to the SH with an abrupt change in the intensity from SON to DJF feeding the South Pacific Convergence Zone.

The zonally averaged global transport is from the SH to the NH in all seasons except in southern summer (DJF) that coincides with the peak rainy seasons in Brazil (South American tropics) and Australia. It is important to note that there is net annual transport from the SH to the NH of the order of 62 $\times$ 10^7 kg s^{-1} in the atmosphere. This transport amounts to nearly three Amazon River discharges,

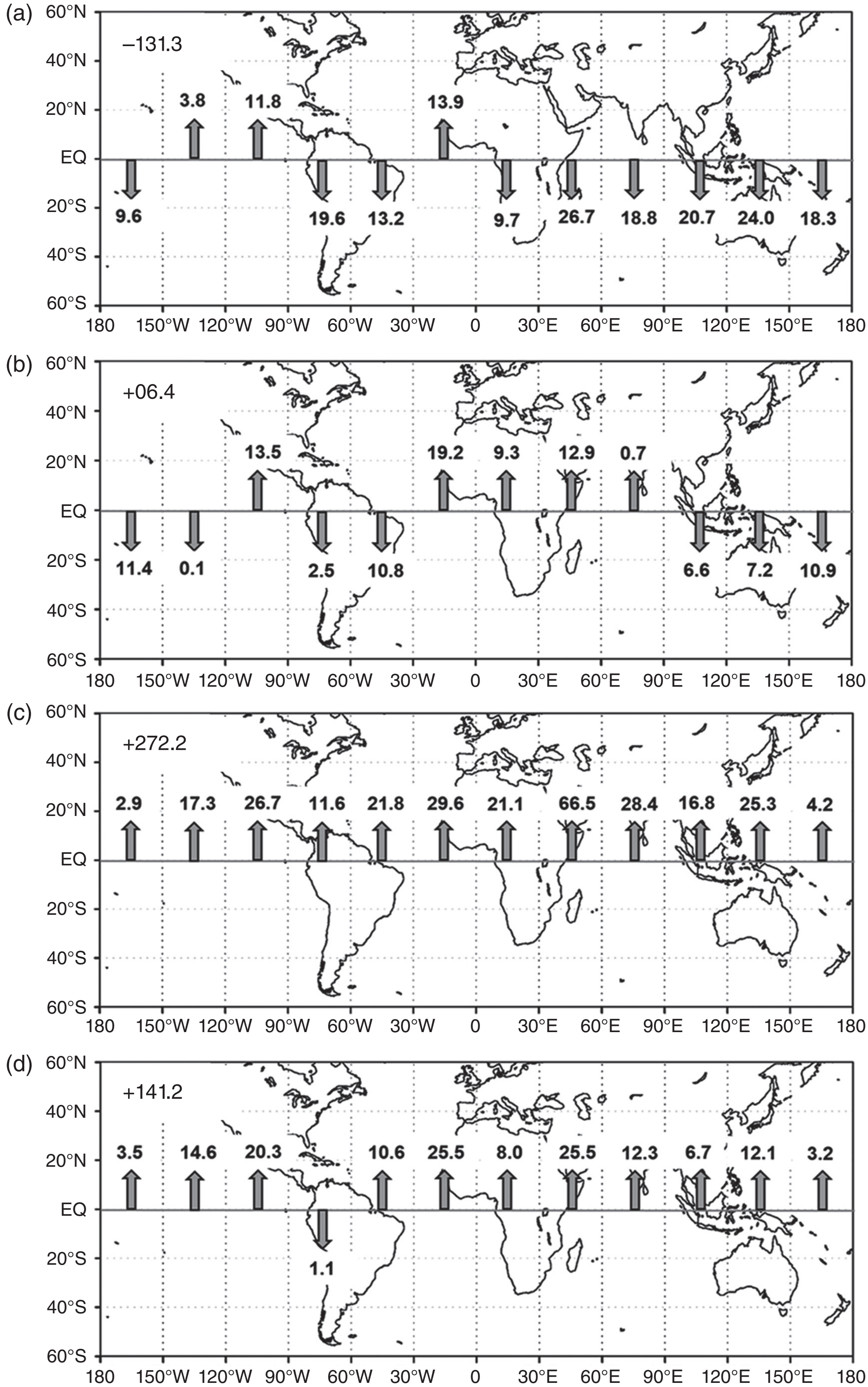

Figure 5. Seasonal inter-hemispheric moisture transports with ERA-Interim data set for the period 1980–2010. (a) DJF, (b) MAM, (c) JJA, (d) SON. Numbers in the top left corner of the panels are the total transports across the equator in the season. Units: $\times 10^7$ kg s^{-1}.

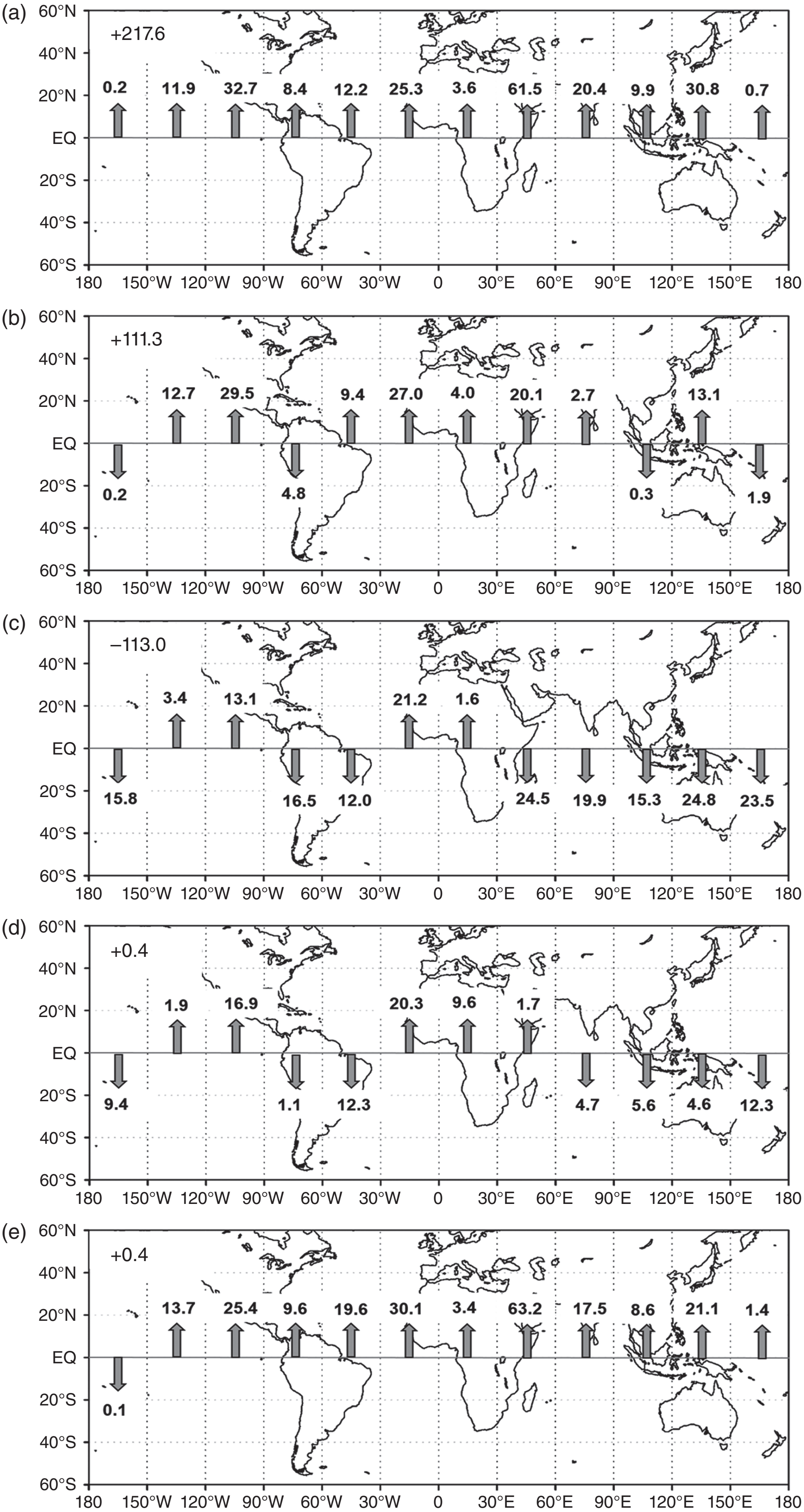

Figure 6. Seasonal moisture transport across the equator at intervals of 30° longitude for the year 2004–2005. (a) JJA_2004, (b) SON_2004, (c) DJF_2005, (d) MAM_2005 and (e) JJA_2005. The sum (around the globe) that crosses the equator from one hemisphere to the other is given in the top left corner. Negative sign indicates transport from Northern Hemisphere to Southern Hemisphere. Units: $\times 10^7$ kg s^{-1}.

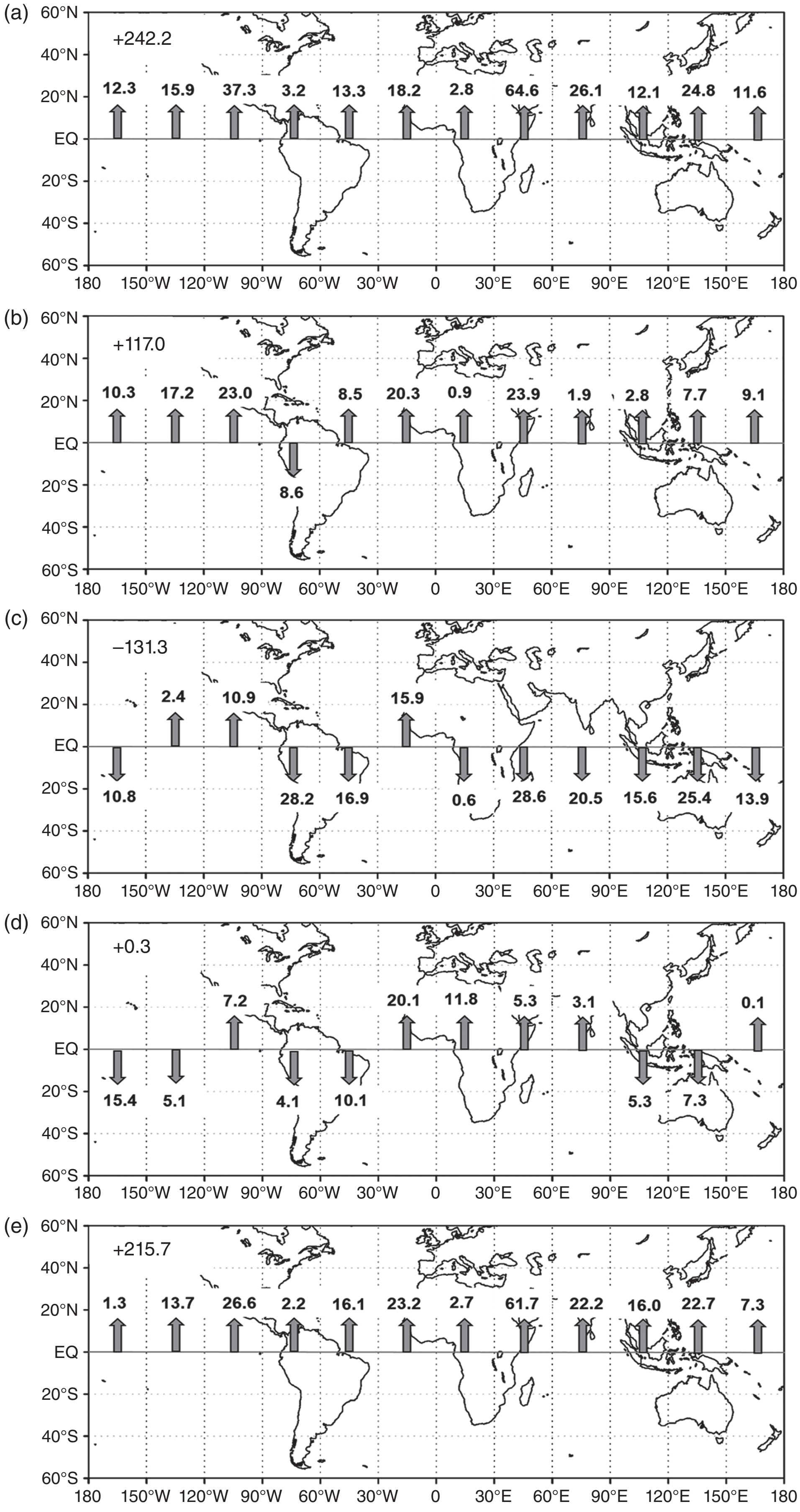

Figure 7. Same as in Figure 6 except for the wet year 2011–2012.

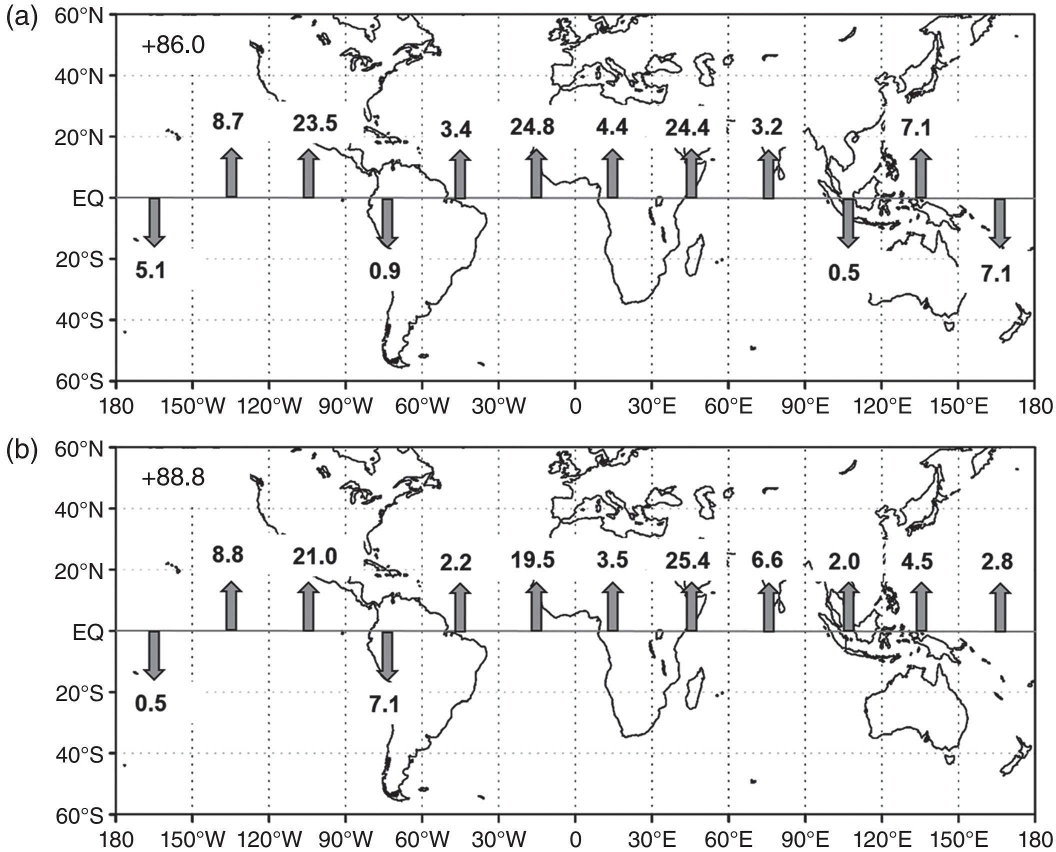

Figure 8. Annual moisture transport at intervals of 30° longitude across the equator in (a) 2004–2005 and (b) 2011–2012. The number in the top left corner is the sum around the globe or the sum that crosses the equator from one hemisphere to the other. Units: $\times 10^7$ kg s^{-1}.

which is about 200 million kg s^{-1}. Being long-term climatology, this implies that evaporation exceeds precipitation in the SH and precipitation exceeds evaporation in the NH. It is known that, on the average, there is more rainfall than evapotranspiration over the continents and more evapotranspiration than rainfall over the oceans (Satyamurty *et al.*, 2013a, 2013b) and the excess water over the continents is transported by the rivers back to the oceans. Because of larger ocean area in the SH, there is more evaporation than precipitation while in the NH, due to less ocean area, more rainfall than evapotranspiration is observed. The excess moisture in the SH atmosphere is transported to the NH. This is accomplished by the near surface northward meridional winds across the equator. It is interesting to note that while the total transport from the NH to the SH in DJF is 103.5×10^7 kg s^{-1}, the transport from the SH to the NH in JJA is 230.6×10^7 kg s^{-1}. Once again, these differences are a manifestation of the inter-hemispheric geographical difference.

If we consider the reversal of cross-equatorial moisture transport from summer to winter as an indicator of the monsoon regimes, we can recognize two sectors, namely, from 90° to 30°W and from 30° to 180° E. The first sector is the South American monsoon sector, the second being the joint Indian, South Asian and Australian monsoon sectors. Over West Africa, the inter-hemispheric moisture transport is from south to north throughout the year, i. e. there is no seasonal reversal.

Table 5. Mean of Monsoon Intensity Index (MII) for five wettest monsoon seasons (DJF) and five driest monsoon seasons in the Amazon Basin over South American and Australian monsoon sectors.

Amazon basin situation	Five-year mean MII South American sector (90°–60°W)	Five-year mean MII Australian sector (120°–150°E)
Wet-Amazon year	−21.9	−16.5
Dry-Amazon year	−11.7	−25.2

Units: 10^7 kg s^{-1} per 30° longitude. Negative sign indicates transport of moisture from NH to SH. Wettest years: 1953, 1976, 1989, 2009 and 2012. Driest years in the Amazon Basin: 1958, 1963, 1997, 2005 and 2010.

Across the equator between 30° and 90°E in JJA (Figure 2(c)), the transport of 82.1×10^7 kg s^{-1} feeds the monsoon rainfall over the Indian subcontinent. The transport of 43.5×10^7 kg s^{-1} from the NH to the SH in DJF (Figure 2(a)) between 120°E and 150°W feeds the rains in the SH over Australia, New Zealand and further south. Over the South American sector, there is a transport of 31.4 $\times 10^7$ kg s^{-1} from the NH to the SH in DJF, the mid-rainy season in Brazil and the transport is reversed in JJA (Figure 2(c)).

The transports across the 20°S latitude circle presented in Figure 3 are very weak compared with those across

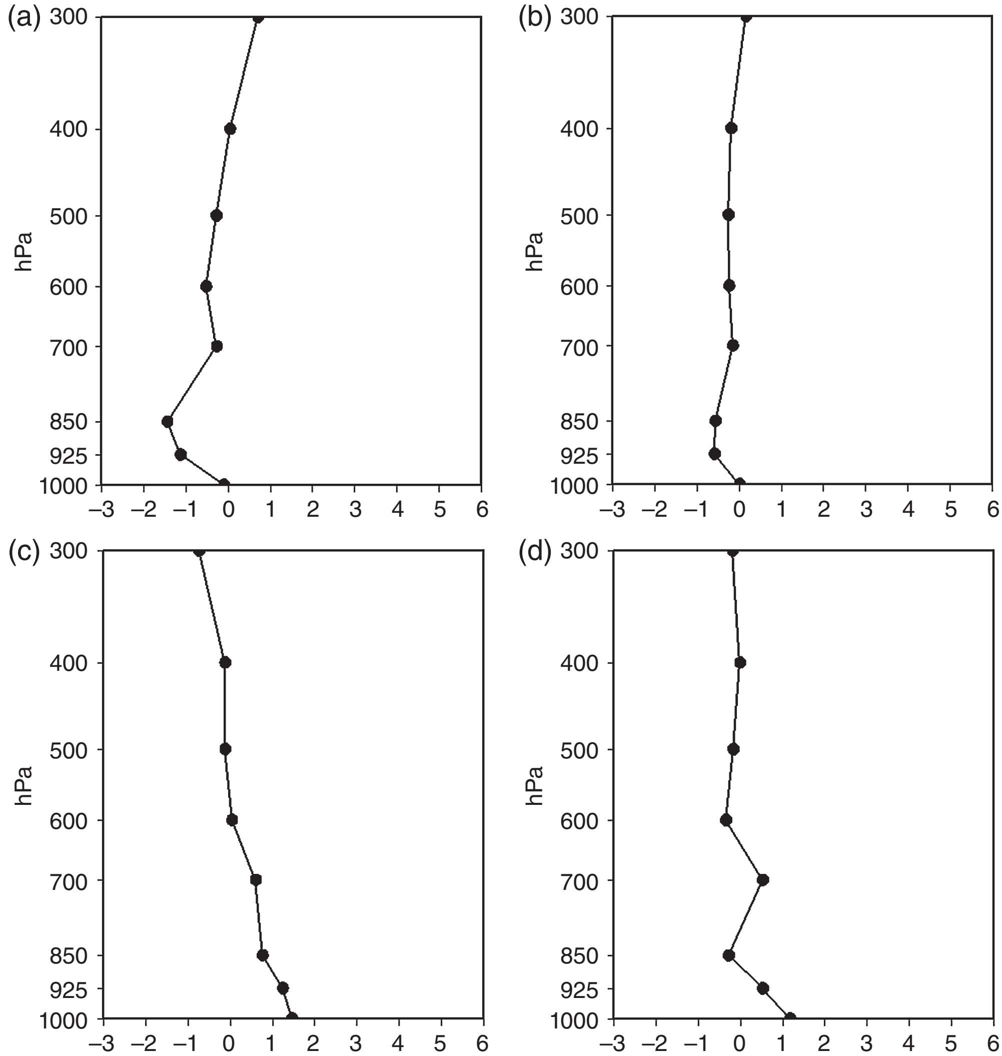

Figure 9. Sixty-two year climatology of vertical distribution of meridional wind across the equator in the sector 90°–30°W (South American monsoon sector). (a) DJF, (b) MAM, (c) JJA, (d) SON. Units: m s^{-1}.

the equator. In all seasons, the transport is from north to south in the mid South Pacific (180°–120°W) and is from south to north in eastern South Pacific (120°– 60°W), characteristic of a permanent lower tropospheric anticyclonic circulation. In the eastern Brazil sector (60°– 30°W), the transport is from north to south, away from the semiarid Northeast. West of Africa in the South Atlantic and in the Indian Ocean the transports are from south to north. One pattern emerges from these transports: the transports are away from the deserts, semiarid regions and subtropical highs of the SH such as the Northeast of Brazil and the Namibian desert. That is, the atmospheric moisture transports are divergent over the desert and semiarid regions of the tropics and subtropics. The annual mean zonal mean transport across 20°S is from south to north and is of the order of 15×10^7 kg s^{-1}. Noting that the northward transport at the equator is 62×10^7 kg s^{-1}, the atmosphere in the region between 20°S and the equator loses 47×10^7 kg s^{-1} on the annual average. This amount is replenished by excess evaporation over the southern tropical oceans.

Figure 4 shows the transports across the 20°N latitude circle. They are weaker than those across the equator but are stronger than across the 20°S, especially in the two extreme seasons. The transport to north of 20°N is very intense over Indochina sector (90°–150°E) in northern summer and provides water for China and the Baiu frontal region. The north to south transport in all seasons in the eastern North Pacific is away from the desert regions of California and the adjoining ocean. The southward transport in all seasons between 30°W and 30°E is away from the Saharan desert. Over the Indian subcontinent, the seasonal reversal of the transport is observed at 20°N also. The zonal mean annual mean transport across 20°N is almost nil compared with the transports across the equator and 20°S. That is, in the region between the equator and 20°N, there is convergence of moisture on annual basis. This convergence plays two important roles: maintenance of the inter-tropical convergence zone (ITCZ) in the NH and reduction of demand for evaporation from the oceans, thus maintaining the surface waters in tropical oceans of the NH warmer (ex. Gulfstream).

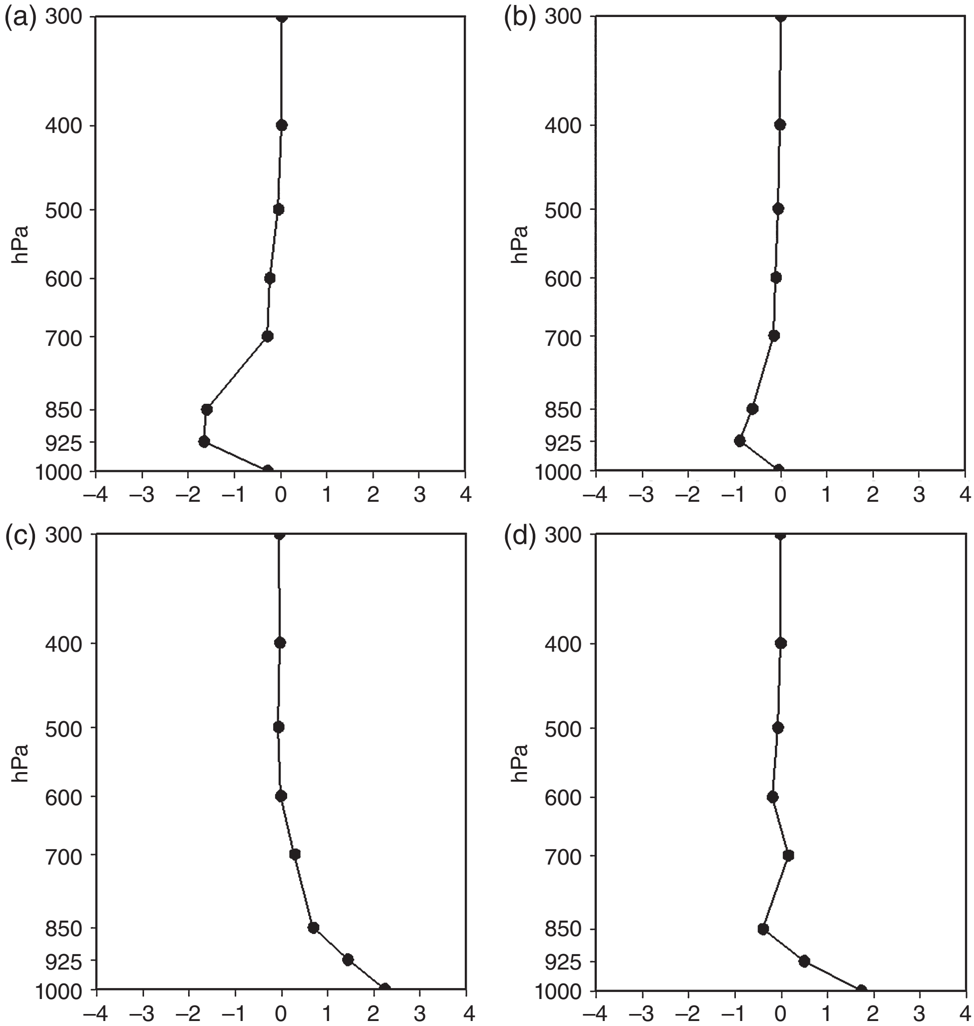

Figure 10. Same as in Figure 9 except for meridional moisture flux. Unit: $\times 10^2$ kg m^{-1} s^{-1}.

The transport across the 30°N latitude circle (figure not shown) is to the north and is, on annual basis, as strong as across the equator. That is, there is divergence of moisture transport in the belt between 20° and 30°N. This is expected because the subtropics of the NH have the infamous desert regions like Sahara.

The circumpolar meridional transports presented in Figures 2–4 are summarized in Tables 2–4. The tables provide the standard deviations of the seasonal mean transports for assessment of their inter-annual variability. In general, the transports in Table 2 present standard deviations smaller than 10×10^7 kg s^{-1}, except especially at the equator. The variability observed in MAM is high compared to the climatological seasonal mean cross-equatorial transport, and its effects on rainfall and climate variability in the tropics makes an interesting study. These MAM cross-equatorial moisture transport characteristics are also observed in the South American and South Asian monsoon sector calculations given in Tables 3 and 4. One important observation is that the annual mean transport across 20°N is negligible in the circumpolar mean and in the American sector, but is large in the Asian monsoon sector. That is, the Asian monsoon penetrates deeper into the continent north of India. In JJA, transport to the north of 20°N is very large. In comparison, the transport to the south of the Amazon basin in the South American sector (Table 3) in DJF also is similarly large.

A Monsoon Intensity Index (MII) can readily be quantified in terms of the meridional moisture transport across the equator over a 30° or 60° longitude stretch into the region considered and in the 3-month rainy season of the region. As an example, the cross-equatorial transport between 90° and 30°W in DJF can be considered as MII of the South American monsoon. This can be used as a useful measure of the strength of the monsoon in the sector and season considered. The climatological values of MII are approximately 314, 821 and 399 million kg s^{-1} per 60° longitude, for the South American, South Asian and Australia and West Pacific monsoons, respectively. Thus, the strongest monsoon regime is in the South Asian sector and the weakest monsoon regime is the South American sector. However, the rainfall over South American tropics (~2000 mm year^{-1}) is heavier than over the other two regions (<1200 mm year^{-1}) (Parthasarathy and Mooley, 1978; Figueroa and Nobre, 1990; Asnani, 1993). This is because the rainy season is longer there and the moisture

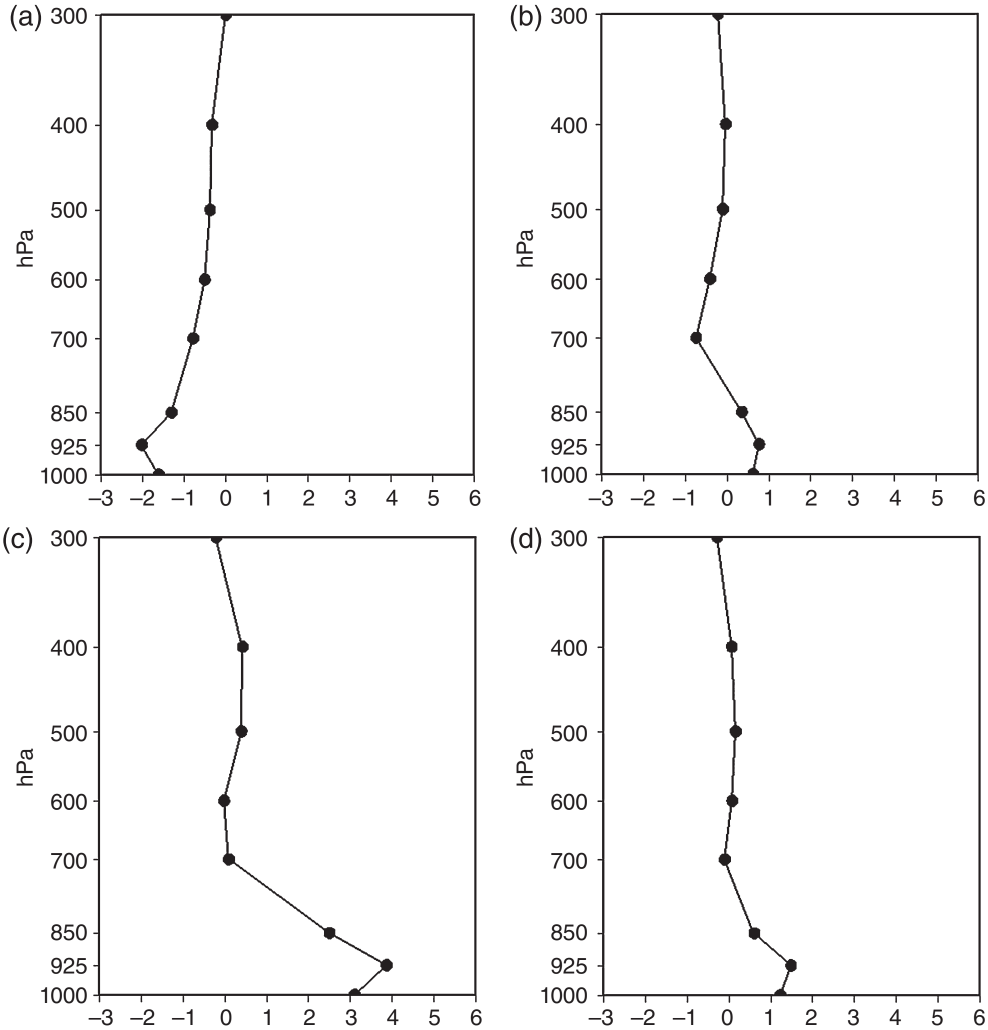

Figure 11. Sixty-two year climatology of vertical distribution of meridional wind across the equator in the sector 30°–120°E (South Asian monsoon sector). (a) DJF, (b) MAM, (c) JJA, (d) SON. Units: m s^{-1}.

transport from the tropical South Atlantic by the easterly trade winds into the Amazon Basin is large (Satyamurty *et al.*, 2013a, 2013b). The moisture transport between 25°S and 5°N across 45°W longitude (figure not shown) is of the order of 45×10^7 kg s^{-1}. Near the western border of the Amazon Basin, the lower tropospheric easterly trade winds are blocked by the steep Andes and the moisture transport there is all meridional. Thus, the convergence of moisture transport is very high over the Amazon Basin (Satyamurty *et al.*, 2013a, 2013b) and explains the precipitation.

In order to gain confidence in the results discussed, calculations of moisture transports across the equator are made with the ERAI data set for the 30-year period 1980–2010 and (Figure 5) for comparison purpose. There is a good qualitative agreement between Figures 2 and 5. The ERAI data set (Figure 5) in general presents larger intensities of transports than the NCEP/NCAR data set (Figure 2). The total annual mean inter-hemispheric transports are 248.4 and 288.5 units, respectively, from NCEP/NCAR and ERAI data sets. That is, the transports in the ERAI analyses are about 16% higher than the NCEP/NCAR analyses. However, all other characteristics such as reversal of direction from DJF to JJA in all monsoon regimes remain unchanged.

5. Inter-annual variability of inter-hemispheric moisture transport

The inter-annual variabilities of the seasonal mean moisture transports are given in Tables 2–4 by the standard deviations. The standard deviations of the inter-hemispheric transports are, in general, larger than the meridional transports at other latitude circles presented. Here, we examine the meridional transports of moisture over the equator during the four seasons of the two contrasting years, 2004–2005 reported to be a dry year (Marengo *et al.*, 2008) and 2011–2012 reported to be a wet year (Satyamurty *et al.*, 2013a, 2013b) in the Amazon Basin. Figures 6 and 7 present the seasonal meridional transports of moisture across the equator for the two contrasting years. The cross-equatorial transport (or MII) during the mid-rainy season (DJF) for the

South American tropics slightly reduced to 28.5×10^7 kg s^{-1} in the dry year (Figure 6(c)) and increased to 45.1×10^7 kg s^{-1} during the wet year (Figure 7(c)) from the climatological value of 31.4×10^7 kg s^{-1} (Figure 2(a)).

Rainfall over most parts of Australia is the lowest of all the continents, except Antarctica, and is highly seasonal. Monsoon season in Australia extends from December to April during which about 90% of the annual rainfall is received (Hendon, 2004). Figures 6(c) and 7(c) show that over the Australian sector, the MII in DJF of 2004–2005 (a dry-Amazon year) increased substantially to 63.6×10^7 kg s^{-1} in DJF of 2011–2012 (a wet-Amazon year). The annual average of the moisture transports across the equator during contrasting years of 2004–2005 and 2011–2012 are shown in Figure 8. Although the differences between the two contrasting years are small on the whole, it is clear that over the South American monsoon sector (90°–30°W) the transport is from south to north in the dry year and from north to south in the wet year. Over the Australian sector, the transport is near zero in the dry-Amazon year and is substantially large from south to north in the wet-Amazon year. These results indicate that the South American and Australian MIIs may have an inverse relation.

In order to verify the inverse relation, five wettest years (1953, 1976, 1989, 2009, 2012) and five driest years (1958, 1963, 1997, 2005, 2010) in the Amazon basin since 1950s are considered and the mean cross-equatorial transports into the South American and Australian sectors for the Austral summer season (DJF) are presented in Table 5. It is observed that all the transports are from the NH to the SH. However, while the transport over South American sector reduced nearly to 50% from the wet-Amazon to dry-Amazon years, the transports over the Australian sector increased more than 50%. Further confirmation and explanation of the indicated inverse relation will await a future investigation.

Figures 9 and 10 present the climatological vertical profiles of the meridional component of wind (v) and moisture flux across the equator [$F\_EW = \int_{90W}^{30W} \rho v q \, R \, d\lambda$, where $\rho = \frac{p}{RT_v}$ is density, R is the gas constant of dry air and $T_v = (1 + 0.608q)$ is virtual temperature], respectively, averaged over the South American sector (90°–30°W) for the four seasons. The fluxes above 700 hPa level are very small compared to those in the layer below, indicating that most of the meridional moisture transport occurs in the near surface layer. There is a similarity between the v and F_EW profiles near the surface. The differences between the summer and winter seasons are evident. The maximum meridional wind level comes down from 850 hPa in DJF (Figure 9(a)) to the surface in JJA (Figure 9(c)). The maximum northerly wind in this season is of the order of 1.5 m s^{-1} at 850 hPa level. The maximum southerly wind in JJA is weaker, of the order of 1 m s^{-1}. The moisture flux is from the NH to the SH in DJF (Figure 10(a)) and reverses in JJA (Figure 10(c)), following the v profile. In the transition season MAM, the v and moisture flux profiles bear similarity with the DJF profiles, and in SON the profiles bear similarity with the preceding JJA profiles, albeit with reduced intensities.

Similar calculations for the Asian monsoon sector (30°–120°E) are shown in Figures 11 and 12. The magnitudes of the meridional winds across the equator in the lower troposphere, in their respective monsoon seasons, are higher in the Asian sector (~4.0 m s^{-1}) than in the South American sector (Figures 11(c) and 9(a)). Thus, the moisture fluxes are also stronger in the Asian monsoon than in the South American monsoon (Figures 10(a) and 12(c)). The maximum flux in the case of Asian monsoon of the order of 5×10^2 kg m^{-1} s^{-1} occurs right near the surface whereas it occurs between 850 and 950 hPa in the case of South American monsoon. This difference is perhaps due to the sea surface over the Indian Ocean and the land surface over the Amazon Basin.

It is interesting to know which part of the monsoon sector contributes for the moisture transport. In other words, where exactly the monsoon aerial river crosses the equator? Figures 13 and 14 show the longitude-height sections of the moisture fluxes for the South American and Asian monsoon sectors, respectively. These figures support the water vapour transport results shown in Figure 2. That is, the lower tropospheric water vapour transport across the equator over the South American sector is from the NH to the SH in austral summer (Figure 13(a)) and reverses direction in austral winter (Figure 13(b)). This reversal is characteristic of monsoon regimes. The northerly flux of moisture occupies a deeper layer just east of the Andes and a shallower layer in the eastern part of the Amazon Basin during monsoon season (Figure 13(a)). The southerly moisture flux in the South Asian monsoon sector (Figure 14(b)) also is vigorous over the western portion in JJA. The reversal of the direction of the flux in DJF (Figure 14(a)) is evident. The fluxes occupy a somewhat deeper layer over the South Asian monsoon sector.

6. Discussion and conclusion

While Krishnamurti *et al.* (2013) and many others before defined a monsoon regime in terms of seasonal reversal of near surface winds, Asnani (1993) defined it in terms of the seasonal meridional migration of the ITCZ. The latter view, although captures all the monsoon systems of the globe, includes regions with very little annual and seasonal rainfall such as the Northeast of Brazil also. Moreover, it is very difficult to identify a clear cut ITCZ over interior continental areas such as the Amazon Basin. Over such regions, the ITCZ is blurred by widespread convective activity. In this study, the monsoon regimes in the tropics and subtropics of the globe are identified by examining the climatological cross-equatorial and cross-zonal moisture transports in the atmosphere. The global net annual cross-equatorial moisture transport is from the SH to the NH. This transport is equivalent to three Amazon River discharges. Monsoon strength in a given longitudinal sector is quantified by the intensity of cross-equatorial moisture transport over a stretch of 30° or

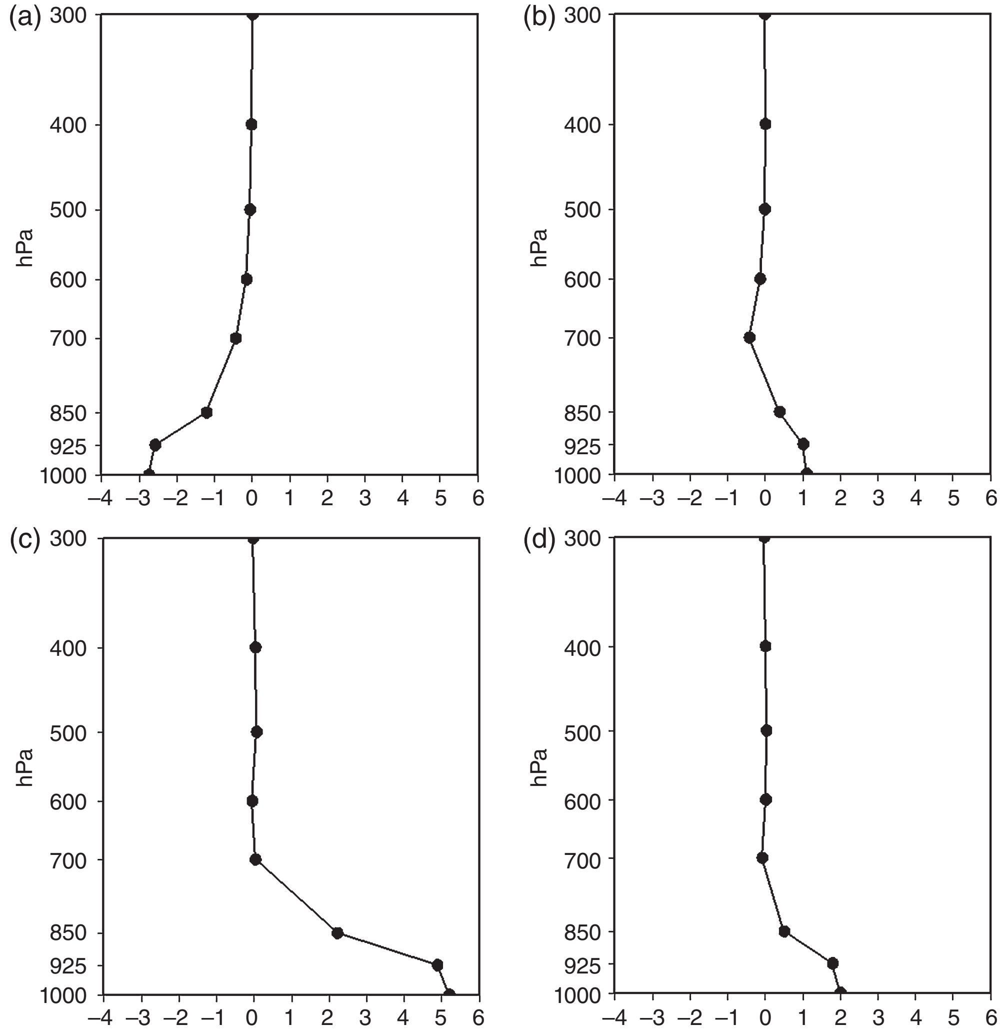

Figure 12. Same as in Figure 11 except for meridional moisture flux. Unit: $\times 10^2$ kg m^{-1} s^{-1}.

60° longitude and is designated MII. The Asian monsoon is three times stronger than the South American monsoon, although the seasonal rainfall over the Amazon Basin is heavier than over India. This is explained by the duration of the monsoon season over the Basin which stretches from October through May. Another reason is the copious amount of moisture transport into the basin by the easterly trades. Over the South American sector, most of the cross-equatorial moisture transport in DJF occurs in the layer below 700 hPa between 70° and 45°W. It is concentrated around 65°W east of the Andes and 850 hPa level.

The MII over the Amazon Basin in the DJF season was weakened by only about 10% in the dry year 2004–2005 and was strengthened by 40% in the wet year 2011–2012 with respect to its climatological value. The year 2005 was reported to be dry year in the Amazon basin (Marengo *et al.*, 2008). But, in terms of the moisture convergence in the whole basin that year was not an extreme year (Satyamurty *et al.*, 2013a, 2013b). The rainfall in 2005 was not distributed uniformly over the basin and there was less rainfall in the southwestern portion of the basin. This study also shows that the northerly moisture flux into the basin in 2005 was not significantly less than the climatological value. Nevertheless, the MII is a useful measure of the intensity of monsoon rainfall.

The convection over the Amazon Basin, often moist and deep, is supported by many sources of moisture. The transport from the Tropical Atlantic accomplished by the trade winds, the evaporation from the inundated areas and the transpiration by the tropical forest are the three main sources that keep the atmosphere near saturation. And, the daytime solar heating provides the necessary energy to destabilize the atmospheric column as well as maintain the evapotranspiration process. The result is heavy rain showers throughout the year, more so in the rainy season from October through April. The precipitation is, however, modulated by the synoptic and mesoscale atmospheric disturbances such as the frontal incursions from the south (Amorim Neto *et al.*, 2015) and the propagation of instability lines from the east (Cohen *et al.*, 1995). In anomalously, more (less) humid years, the moisture transport into the basin and its convergence over the basin are significantly larger (smaller).

There is an indication that the monsoons over the Australian and South American sectors are inversely related, which shows that the droughts and floods in the Amazon

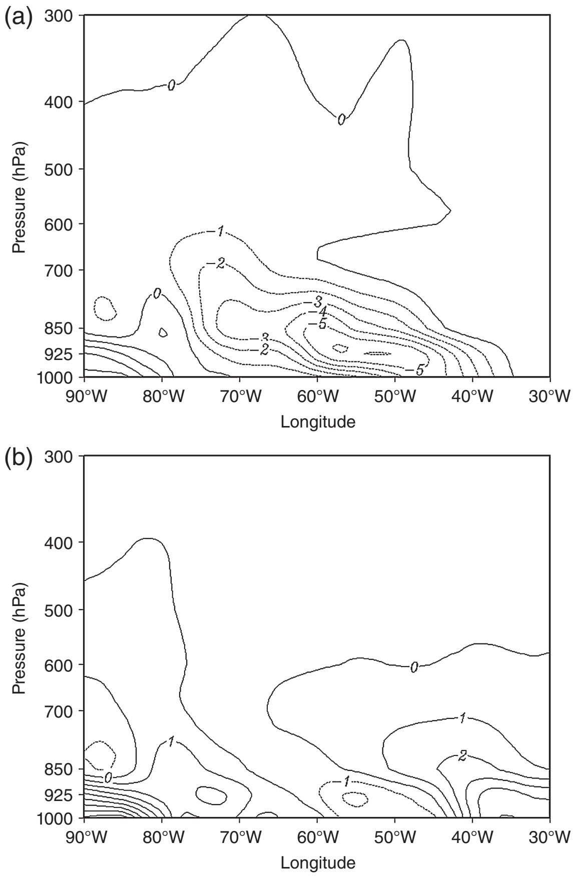

Figure 13. Height-longitude section of climatological moisture flux (qv) across the equator in the sector 90°–30°W. (a) DJF and (b) JJA. Unit: kg m^{-2} s^{-1}.

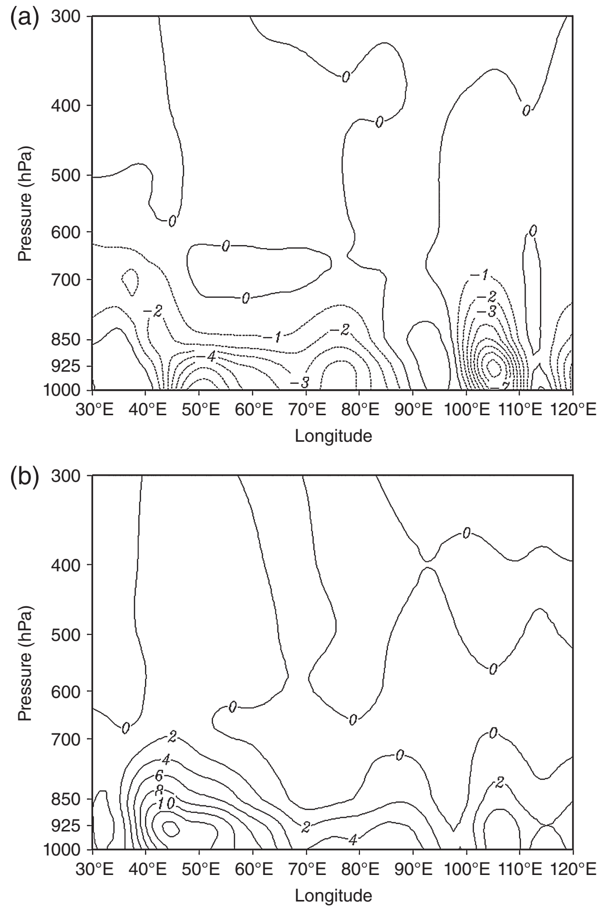

Figure 14. Same as in Figure 13 except for the longitudinal strip 30°–120°E.

Basin are a manifestation of a planetary scale oscillation, although just examining only ten extreme precipitation years is not sufficient to draw definite conclusions. A more detailed study, taking into account all the contrasting wet and dry years in the Amazon Basin since 1950s, is being contemplated for a future work. On the annual basis, the moisture transport across 20°N is very small (2.9 × 10^{7} kg s^{-1}) compared with the values across the equator and across 20°S. This means that the moisture in the part of the globe north of 20°N nearly recycles on annual basis. Transport of moisture means transport of latent heat. In the South Asian sector across the equator, the transport of heat from the SH to the NH is about 2 × 10^{15} J s^{-1} during the summer monsoon season JJA and over the South American sector, it is about 0.7 × 10^{15} J s^{-1} in DJF.

In JJA, 30 × 10^{7} kg s^{-1} flow from south of 20°S into the tropics while 231 units cross the equator northward to contribute to the rainfall mainly in the Asian monsoon region. That is, there is net divergence of moisture between 20°S and the equator during the NH summer, which is replenished by evaporation from the southern seas. In this season 65 × 10^{7} kg s^{-1} cross 20°N contributing to rainfall in China and adjoining countries.

The results obtained are considered robust because the climatology is based on 62 years of reanalysis data which are the best set available for the purpose of this study. A comparison of the calculations of inter-hemispheric transports obtained from NCEP/NCAR and ERAI data sets showed good qualitative agreement and therefore the results and conclusions presented in this study seem qualitatively sound.

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