Impact of cross-equatorial meridional transport on the performance of the southwest monsoon over India

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Water vapour transport over the Indian Ocean has been computed for the 30-year period (1979–2009). The monthly evolution of meridional moisture fluxes across different sections is presented. March and April clearly indicate the north to south flow of moisture across the equatorial region. During May there is intensification in the northward cross-equatorial moisture transport, which may act as a precursor of the rainy season. During the monsoon season maximum transport occurs in June with values of 1.24×10^{11} and 5.58×10^{12} tonnes/day for moisture and air flux across the equator respectively, which occurs in the lower atmospheric level between 1000 and 650 hPa. Our finding clearly shows that during the monsoon season across the equatorial cross-section major transport occurs between 42°E and 60°E. Analysis of moisture transport over two regions, i.e. (i) 6°S–6°N and 42–60°E and (ii) 1.5°S–1.5°N and 42–60°E for two good (1988, 2008) and two bad (1987, 2009) monsoon years shows that during 1987, which was a drought year, the amount of moisture crossing the equator was less by about one order of magnitude compared to 1988. While during 2008, which was a normal/good monsoon year, the amount of moisture transported was almost three times compared to 2009. This clearly indicates that the moisture transport in May can be used as a predictor of monsoon performance.

Keywords: Air flux, cross-equatorial flow, moisture transport, monsoon season.

AN important issue for operational meteorologists examining the Indian summer monsoon is the understanding of the transport of moisture. This transport contributes significantly to increased rainfall during the monsoon season over the Indian subcontinent. The significance of cross-equatorial transport of water vapour is highlighted by the presence of a large cross-equatorial flux of momentum over the western Indian Ocean during the pre-monsoon and monsoon period. It is well known that the cross-equatorial flow in the lower atmospheric levels is an important supplier of water vapour between the winter and summer hemispheres, and this has attracted much attention from meteorologists[1].

The Somali jet plays an important role during Indian monsoon season. During the monsoon, water vapour from the southern hemisphere flows into the Arabian Sea region via the Somali jet and supplies moisture to the Indian Peninsula, the Bay of Bengal, the Indo-China Peninsula, and partly to East Asia[1]. The Somali low-level jet stream flows intermittently from the vicinity of Mauritius over the northern tip of Madagascar to reach the Kenyan coast (3°S) and penetrates inland over the flat coastal strip of Kenya and lowlands of Ethiopia and Somalia and emerges out into the Arabian Sea near 9°N. Here it moves over the cold upwelling water off the Somalia coast. It then crosses the west coast of India and transports moisture to the Indian subcontinent during the southwest monsoon period. This cross-equatorial flow is an important part of the South as well as the East Asian summer monsoon systems[2,3].

Pisharoty[4], with the help of data collected by the International Indian Ocean Expedition (IIOE) during 1963–64, studied the lower tropospheric water vapour budget and concluded that evaporation from the Arabian Sea is the major contributor for rainfall over India. The net total northward flux of water vapour across an equatorial cross-section extending from 42°E to 75°E computed by Pisharoty[4] for July 1964 was 2.2×10^{10} tonnes/day. Findlater[5] computed a net northward air flux of 7.68×10^{12} tonnes/day for July from the surface to 600 hPa and over the region 35–75°E. Later Saha[6] using additional sounding data computed the fluxes across the equatorial region and found maxima in July (4.43×10^{10} tonnes/day), which was almost double that of Pisharoty[4]. Findlater[7] found that the Southern Hemispheric air of differing origin is accelerated into a well-defined stream which crosses the equator in a limited zone of longitude and becomes the southwest monsoon flow of the Arabian Sea.

Thereafter, Saha and Bavadekar[8] extended the work of Saha[6] and showed that 70% of the contribution of the Indian monsoon rainfall is from moisture flux from the Southern Hemisphere, which contradicts the results of Pisharoty[4]. The values of cross-equatorial flux obtained by Saha[6], Saha and Bavadekar[8] and Pisharoty[9] are at variance with each other. The possible reasons are twofold. (i) Pisharoty[9] used only Nairobi and Gan Island upper air data and the equatorial flux within the Somali jet was missed. Further, the data used by him on the southern boundary were inadequate for a reasonable assessment of net flux along this boundary. (ii) Saha[6] and later Saha and Bavadekar[8] re-examined the calculations using the Seychelles data for the year 1964.

Hart *et al.*[10] showed that maximum transport occurs in a low-level slab of air between 38° and 45°E and further suggested that for accurate computation of water vapour flux, good low-altitude wind and humidity observations are mandatory. The moisture flux estimated by Hart *et al.*[10] over the region 42–75°E was 3.4×10^{10} tonnes/day for June 1974. Hastenrath and Lamb[11] with the help of 60 years of ship observations and available radiosonde data for specific humidity found that the flux of moisture

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across the equator was the dominant source of moisture for the coasts of southern Asia. Cadet and Reverdin[12] computed the surface fluxes across different sections in the Indian Ocean during 1975 summer and concluded that 70% of water vapour crossing the west coast of India originates from the Southern Hemisphere. The main reason behind the different estimates could result from the lack of systematic high-resolution data over the Arabian Sea and the exclusion of moisture flux above 400 hPa.

Further investigation of water vapour transport was done as part of the first GARP (Global Atmospheric Research Program) Global Experiment (FGGE). Studies[13–17] showed that during active monsoon period there is strengthening and deepening of moisture flow over the Arabian Sea and withdrawal of summer monsoon is related with a decrease in moisture transport. Sadhuram and Rao[18] found that moisture flux from the Southern Hemisphere was the major contributor for rainfall over the Indian subcontinent. But most of the earlier studies carried out in this regard are mainly in the form of case studies or for one or two years or during specific periods.

Gimeno *et al.*[19] have shown that the Arabian Sea to be an important source of moisture for Indian monsoon rainfall. Zhu[1] observed significant association between the low-level Somali cross-equatorial flow at the inter-annual and inter-decadal timescales and the rainfall over most of the monsoon region, except in a small area in southwest India. He mainly used high-pass-filtered data for this study and because of filtering it is possible that short timescale processes are not adequately resolved. Also, the amount of moisture or momentum over the region was not assessed.

Attempts have also been made by meteorologists to correlate the Indian monsoon rainfall with different circulation features, in order to develop longrange forecast of the Indian monsoon[20]. A review of various techniques is available in the literature[21–23]. Thus, in spite of the known physical link between cross-equatorial flow and monsoon rainfall, there has been very little progress in identifying useful predictors based on it[23,24]. Moreover, Cadet and Reverdin[12] highlighted that 'much more needs to be done to estimate more accurately the transport of water vapour over the Indian Ocean, to understand its variation and their relationship with rainfall over India'. These points clearly show the need to revisit the problem of accurately computing cross-equatorial moisture and momentum flux.

Therefore, an attempt has been made in this study to compute the composite moisture transport for March–September for the period 1979–2009. New updated estimates are provided here. In addition, we have tried to find the region which can provide precursor information for the prediction of performance of monsoon rainfall in the subsequent months.

The problem of moisture transport is revisited using ERA-Interim data at fine vertical resolution available over the ocean. European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis[25] daily as well as monthly mean wind and specific humidity data at different pressure levels are used in this study. ERA-Interim data are used as they provide the necessary level of vertical resolution (in the intervals of 25 hPa from 1000 to 775 hPa and at 50 hPa interval from 750 to 300 hPa) required for this analysis. The resolution of the data is at 1.5° × 1.5°. The analysis has been carried out for the data of 30-year period, i.e. from 1979 to 2009. ERA-Interim data have been obtained from the ECMWF data server (http://www.ecmwf.int/research/era).

The high resolution (1° × 1°) gridded daily rainfall data from India Meteorological Department (IMD)[26] are used in this study. The rainfall data were prepared by IMD using observations at 1803 gauge stations spread over India[26]. IMD has considered the Shepard[27] method with directional effects for interpolation to 1° × 1° (latitude × longitude) grids.

In the present study computations of the net northward fluxes of water vapour as well as air/momentum across the equator in the western Indian Ocean using a method similar to Saha[6] have been made, but with high-resolution data

$$F_{\text{momentum}} = \frac{1}{g} \int_{P_{\text{top}}}^{P_{\text{bottom}}} v \, \mathrm{d}p, \tag{1}$$

$$F_{\text{moisture}} = \frac{1}{g} \int_{P_{\text{top}}}^{P_{\text{bottom}}} qv \, \mathrm{d}p, \tag{2}$$

where F_{momentum} and F_{moisture} are the net total northward fluxes of momentum and water vapour respectively, across the equator, p the pressure, v the meridional component of wind, q the specific humidity, g the acceleration due to gravity, and P_{bottom} and P_{top} are pressure at the bottom and top of the vertical level respectively.

Using the prescribed formula, computations have been carried out from 1000 to 300 hPa pressure level and over the region 30°S–30°N and 30–100°E. Computation of the transport of moisture shows the monthly evolution of moisture during pre-monsoon and monsoon season.

The flux of water vapour as well as air has been computed at every 1.5° × 1.5° grid interval. Equations (1) and (2) have been multiplied by a factor (1.5° × 10° km × 1000 m) to get the final units in tonnes/day. These computations offer a broad view of the spatial variation of the fluxes during pre-monsoon and monsoon season.

Long-term monthly averages of moisture and air flux are obtained using the data for the period 1979–2009. During March dominance of negative flux can be noticed over the Arabian Sea, while a small region in the southern hemisphere between 15°S and 25°S shows northward transport of moisture (Figure 1 *a*). The flow of moisture from the Southern Hemisphere towards the Northern

Hemisphere begins in April, where it flows in a narrow path along the coastal region of Mozambique. During April, northward transport can be seen to the south of the equator only (Figure 1 *b*). This situation rapidly changes in May with the beginning of a cross-equatorial transport. Maximum flux is seen near the Somali coast in May, which signals the upcoming rainy season. As the monsoon season starts there is a significant increase in the northward moisture flux near the Somali coast (Figure 1 *c*). As the monsoon starts to decay in September, which is known as withdrawal, the moisture flux also starts to decrease (Figure 1 *g*).

In case of meridional momentum transport, southward flux can be seen over the Arabian Sea during March, while positive transport is confined to a small portion (30–15°S; 30–40°E) in the Southern Hemisphere. Additionally positive transport is also evident over the northern tip of Madagascar. During April, increase in the transport is clearly seen over the Mozambique Channel region. Rapid strengthening is noticed in May, where the maximum transport is confined over the region 15°S–5°N and 35–55°E. This indirectly shows the strengthening of the southerly winds. As the monsoon season begins, rapid northward anomalies can be seen in the meridional momentum transport, where maxima is located over the region between 5°S and equator and 40°–50°E. Transport decreases slightly during August in this region, although the anomaly persists during September. Decrease in the maxima can be attributed to decrease in the strength of the southerly wind (Figures not shown).

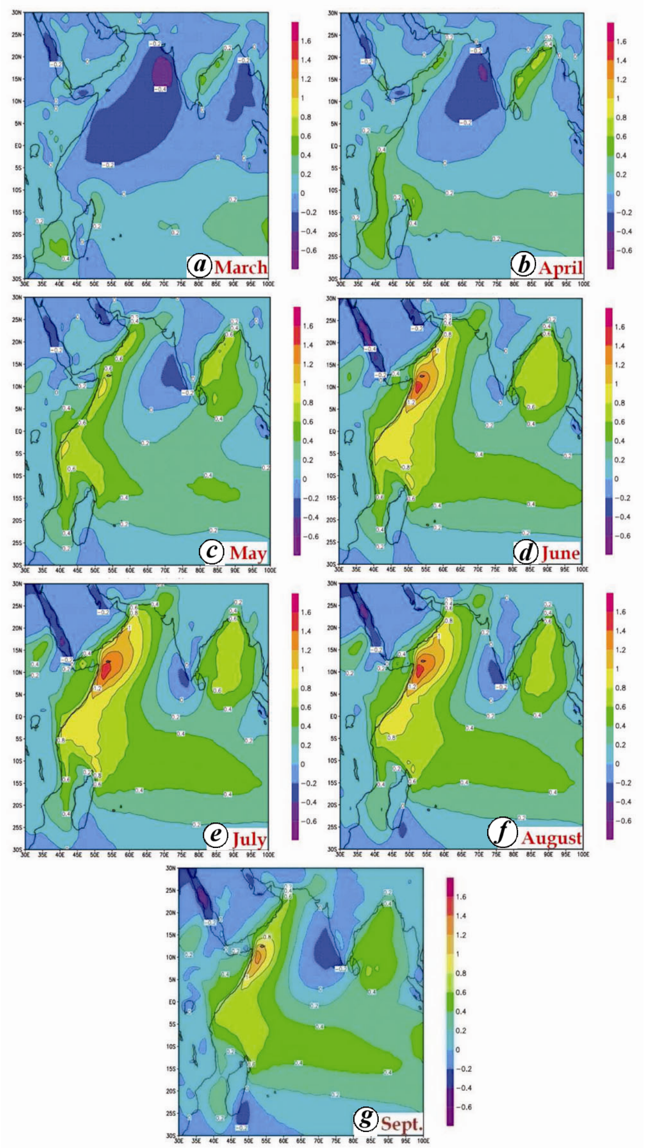

Figure 1 *a–g*. Long-term mean monthly evolution of meridional moisture transport ($\times 10^{12}$ tonnes/day) during pre-monsoon (March–May) and monsoon season (June–September).

An attempt is made to find out the longitude and level where the maximum transport is taking place in the equatorial region. For this study we adopted the method of Saha[6]; the vertical levels are divided into five different slabs, i.e. 1000–950, 950–800, 800–650, 650–550 and 550–450 hPa levels and the longitudes into four sections, i.e. 42°–50°, 50°–60°, 60°–70° and 70°–75°E. Then monthly mean values for five slabs of vertical pressure levels are computed for the above longitude intervals. The moisture flux and momentum flux across the equator are computed using eqs (1) and (2).

The monthly mean moisture transport across the equator between various longitudinal strips and different pressure-level slabs is shown in Figure 2. In March (Figure 2 *a*), most of the longitude strips show negative transport as winds are generally from the north-northeast. In April, northward cross-equatorial flow of the order of 1.61×10^{10} tonnes/day is observed in the lower level between 1000 and 800 hPa over the region between 42–50°E. Whereas rest of the region still shows southward transport at all the pressure slabs.

Rapid northward progress of moisture in the lower levels starts of May (Figure 2 *c*). Strong low-level moisture transport (9.42×10^{10} tonnes/day) can be seen in the region 42–50°E and 4.40×10^{10} tonnes/day between 50°E and 60°E. During May, maximum transport occurs in the lower troposphere between pressure levels of 950 and 800 hPa. This northward moisture transport is observed up to 550 hPa level between 50° and 60°E. As the monsoon season begins in June, a large increase in the moisture transport occurs between 1000 and 650 hPa levels (Figure 2 *d*). The moisture flux is greatest at low levels, but can be seen up to 450 hPa at all the longitudes, i.e. 42–75°E. Conditions remain essentially unchanged in July (Figure 2 *e*) and from August a significant decrease in the cross-equatorial flow can be noticed (Figure 2 *f*).

During September significant decrease is seen over the 70°–75°E region and in the upper levels of the adjoining region (Figure 2 *g*). In case of air flux/momentum transport, strong negative transport shows north to south progress of winds during March. April shows strengthening

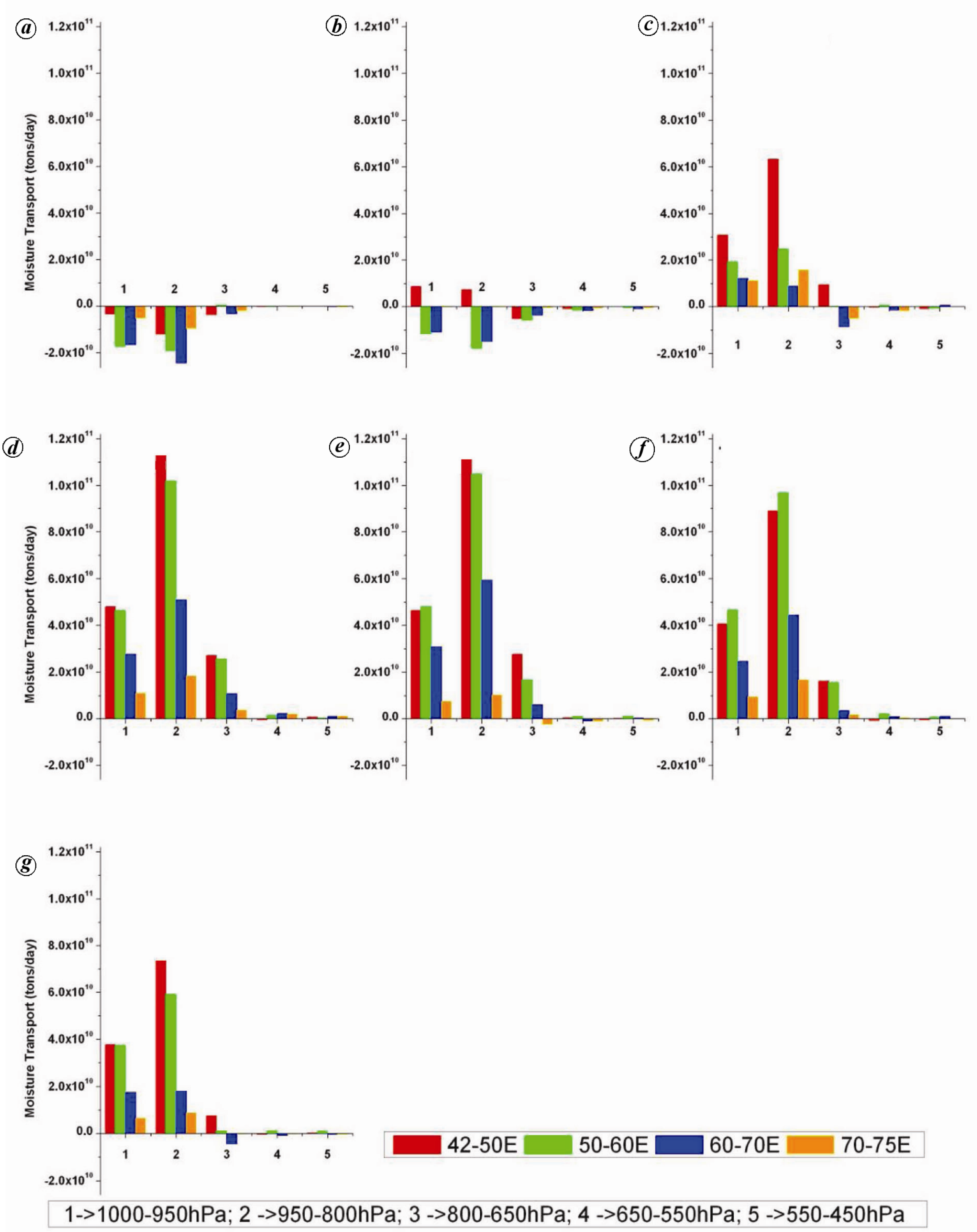

Figure 2. Meridional moisture transport (tonnes/day) for (***a***) March, (***b***) April, (***c***) May, (***d***) June, (***e***) July, (***f***) August and (***g***) September for different longitude strips and pressure-level bands. Transports computed in meridional direction; therefore, positive transport comes from the Southern Hemisphere.

of south to north transport over the region 42–50°E in the lower levels between 1000 and 800 hPa. Indication of upcoming rainy season can be guessed from May transport, which shows rapid build-up of south to northward transport of momentum in the lower levels. Beginning of rainy season can be seen with an increase in the northward transport of momentum in June. Maximum is observed in July in the pressure slab of 950–800 hPa level and over the region 42–50°E. Significant decrease can be seen in the transport as we approach towards the end of monsoon season (Figures not shown).

The net total northward flux of moisture shows southward transport in March and April (except over the region between 42–50°E in the lower levels between 1000 and 800 hPa). In May there is a rapid build-up of moisture in the Northern Hemisphere with a significant increase in the northward transport of air as well as moisture flux across the equator (Figure 3). During monsoon season maximum transport occurs in June. Moreover, it is found that the major moisture transport occurs in the lowest tropospheric levels below 650 hPa. This clearly indicates that these results are consistent with those of Fasullo[28], who stated that bulk of moisture transport occurs below 650 hPa level. Indeed we have found that during monsoon season (June–September) more than 95% of the northward moisture transport occurs below 650 hPa level.

Why does the northward transport occur in such a narrow strip? Winds originating from Mascarene high in the Southern Hemisphere pass through a narrow strip near the Mozambique Channel moving northwards to cross the equator. Major equatorial transport takes place at longitudes corresponding to the Mozambique Channel. However the dynamics of this narrow transport is yet to be properly understood.

The year 2009 was the third worst monsoon year since 1901 (ref. 3). During the 2008 southwest monsoon season (June–September), rainfall for the country as a whole was near normal. Climatology shows that beginning of the northward progress of cross-equatorial flow occurs in April over the small region in the lower level, whereas a significant increase in cross-equatorial flow up to 800 hPa is seen in May.

Meteorologists have been attempting to forecast monsoon rainfall using different techniques over the last 100 years[18]. Krishna Kumar *et al.*[23], and Kakade and Dugam[24] have emphasized the possibility of predicting monsoon performance based on cross-equatorial flow.

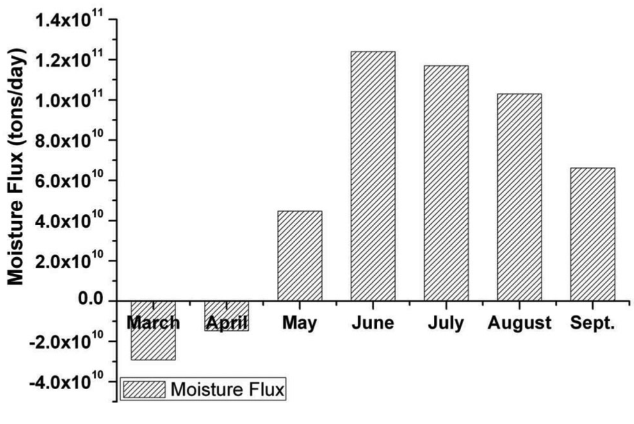

Figure 3. Net northward flux (1000–650 hPa) of moisture (tonnes/day) across the equatorial region and between 42°E and 60°E.

Climatology shows that maximum transport is in the lower pressure levels, i.e. between 1000 and 650 hPa. Therefore we have analysed the cross-equatorial meridional transport of water vapour between 1000 and 650 hPa of May for two good monsoon (1988 and 2008) and two bad monsoon (1987 and 2009) years. For this analysis we have computed the average moisture transport over the region 5°S–5°N and 40–60°E.

From Table 1 it can be seen that during 1987, which was a drought year, the amount of moisture crossing the equator is almost half compared to that in 1988. During 2008, which was a normal/good monsoon year, the amount of moisture transported is almost double that of 2009. This clearly shows that the moisture transport in May can be used as predictor of monsoon performance. Further work is needed to fully understand the role of May transport as a predictor of monsoon performance over India.

The present study is confined to the region 10.5°S–12°N and 42–70.5°E. For simplicity, the region is subdivided into cells of 1.5° × 1.5° (latitude × longitude). The moisture flux is computed from 1000–850 hPa and then the correlation of each grid box is calculated against the all-India as well as the core India rainfall (June–September). The core Indian region chosen is approximately from 18°N to 28°N and 65°E to 88°E. The core monsoon zone is similar to the area considered by Gadgil and Joseph[29].

For 30-year climatology the correlation is significant at 95% and 99% confidence level (0.36 and 0.46 respectively). Here the moisture flux for May and June is computed and correlation is calculated with the all-India rainfall. There is no significant correlation observed between May moisture flux and all-India rainfall. But June shows significant correlation over a small region covering the northern coastal tip of Somalia (figures not shown).

We now examine the correlation between moisture flux of March–June with the core India rainfall. Figure 4 shows the correlation of meridional moisture flux against core India rainfall. During March (Figure 4 *a*), a significant negative correlation is seen over the region 4.5°S–4.5°N and 43.5–52.5°E, whereas the region 9–12°N and 57–60°E shows correlation of 0.36 which is significant at 95% level of confidence. Correlation is very poor in April (Figure 4 *b*) over the study region, while May shows

Table 1. Average meridional moisture transport during May over the region 40–60°E and 5°S–5°N for above-normal (good) and below-normal (bad) monsoon years between 1000 and 650 hPa pressure level

Good monsoon	1988	1990	2008	2011
Transport (tonnes/day)	6.84×10^{10}	7.92×10^{10}	7.75×10^{10}	7.16×10^{10}
Bad monsoon	1987	1991	2009	–
Transport (tonnes/day)	3.72×10^{10}	4.96×10^{10}	5.80×10^{10}	–

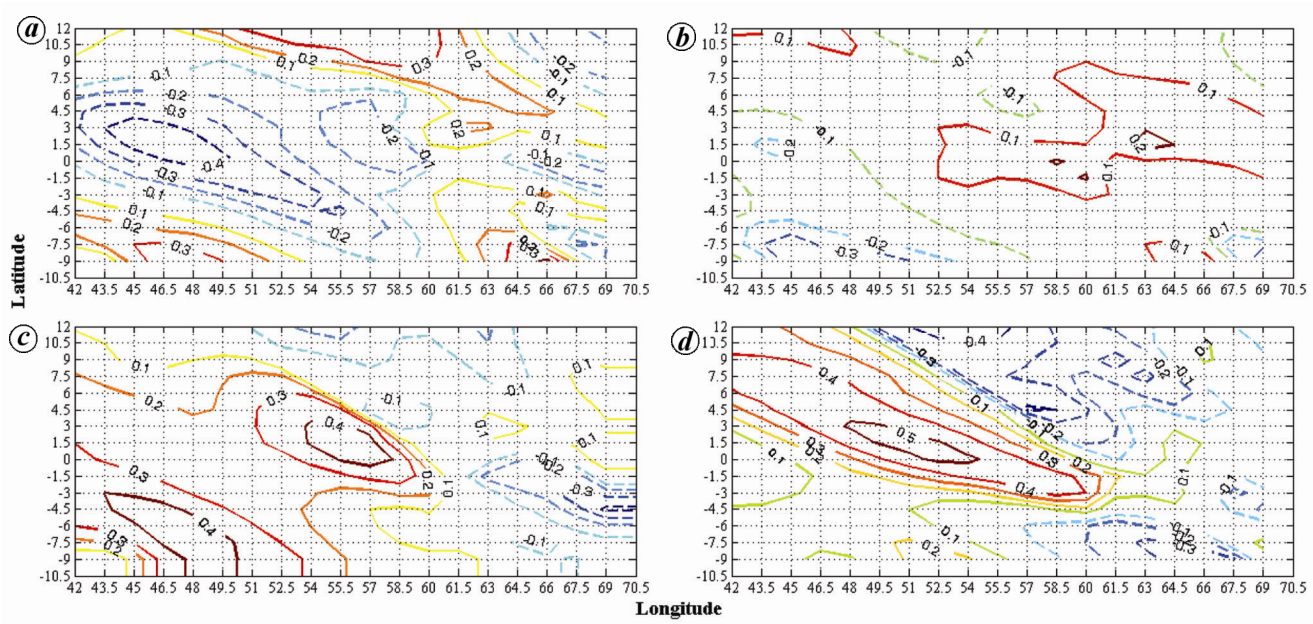

Figure 4. Plot of correlation between meridional moisture flux for (***a***) March, (***b***) April, (***c***) May and (***d***) June against the core India rainfall (June–September).

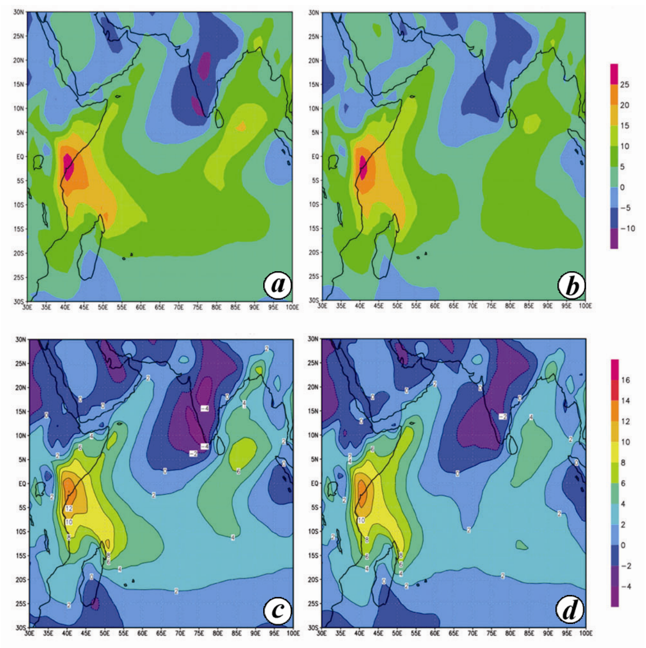

Figure 5. Thirty-year climatology for above-normal and below-normal monsoon years. ***a***, ***b***, The 1000–300 hPa May meridional moisture transport for (***a***) above-normal and (***b***) below-normal years. ***c***, ***d***, The 1000–650 hPA meridional moisture transport of May for (***c***) above-normal and (***d***) below-normal years.

positive correlation over two regions, i.e. (a) over the region 1.5–10.5°S and 42–52.5°E in a diagonal shape, and (b) over the region 1.5°S–4.5°N and 54–60°E. Both these regions show significant correlation at 95% level of confidence (Figure 4 *c*). While significant correlation (at 99% level of confidence) is observed in June over the region 1.5°S–3°N and 48–55.5°E (Figure 4 *d*).

Composite analysis for May meridional transport during the above-normal and the below-normal monsoon years has been carried out. For this purpose, 30-year climatology of meridional transport of moisture during the above-normal and below-normal monsoon years has been computed for two layers (1) between 1000 and 300 hPa and (2) between 1000 and 650 hPa pressure levels (Figure 5). Analysis clearly indicates that meridional transport is more during the above-normal years compared to the below-normal monsoon years. Also, a secondary maximum exists to the southeast of Sri Lanka during the above-normal monsoon years. Moreover, it can be observed that there is a significant increase (~ two times) in the amount of moisture crossing the equator during the above-normal monsoon years in May between 1000 and 650 hPa levels over the region bounded by 5°S–5°N and 40–60°E (Table 1). This can be seen from Figure 6 in which averaged May meridional moisture transport for the periods 1985–1991 (Figure 6 *a*) and 2007–2011 (Figure 6 *b*) have been presented. This indicates that the moisture transport during May can offer some advanced predictive skill in determining the strength of the core monsoon rainfall.

Moisture transport plays a crucial role in deciding the fate of the Indian monsoon. It has been observed that 70% of the water vapour that reaches the west coast of India is from the Southern Hemisphere and 30% comes from evaporation occurring over the Arabian Sea[12]. Diverse opinions regarding the amount of moisture crossing the equator led us to revisit the problem. Therefore,

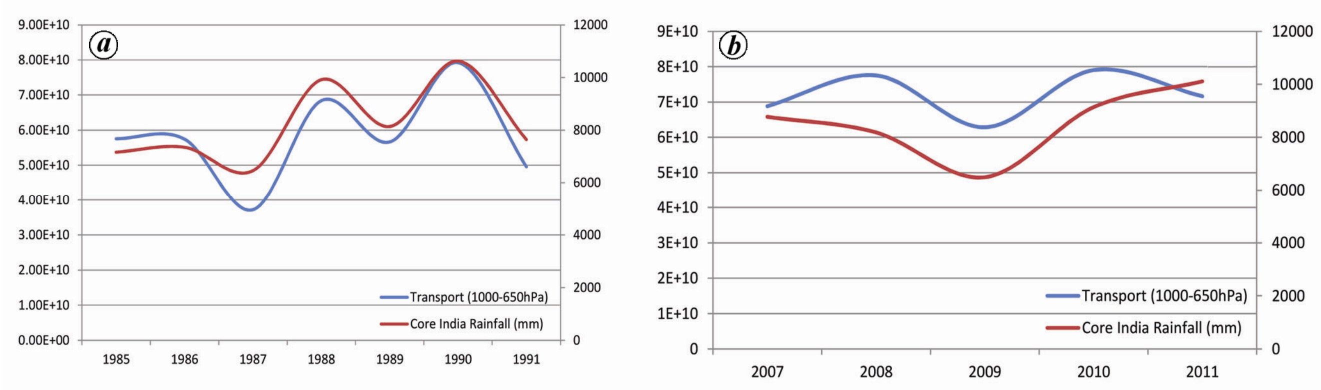

Figure 6. Meridional transport (tonnes/day) during May averaged over the region 40–60°E and 5°S–5°N between 1000 and 650 hPa pressure level for the period (***a***) 1985–1991 and (***b***) 2007–2011.

an attempt has been made to provide spatial variation of moisture during pre-monsoon and monsoon season.

Thirty-year climatology shows that during the monsoon season across equatorial cross-section, maximum moisture transport occurs in a narrow between 42° and 60°E. Maximum transport occurs in the lower troposphere between 1000 and 650 hPa during monsoon season and June shows maximum transport of moisture (1.24×10^{11} tonnes/day) across the equator. Analysis of moisture flux during the good and bad monsoon years shows that during the good monsoon (above-normal) years, the transport is almost one order more than that during bad monsoon (below-normal) years. This study also shows that the transport during May can possibly be used as a predictor of the performance of monsoon in the following months. Further work is needed to fully understand the role of May transport as a predictor of monsoon performance over India. Here we want to suggest that one can improve the prediction of monsoon performance using moisture along with SST, so that the influence of El-Niño, ENSO, IOD events can also be taken into consideration[30,31].

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A weather-based forecast model for capsule rot of small cardamom

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Small cardamom is an economically important spice crop. However, cardamom is susceptible to several diseases that significantly reduce yield. Proactive prevention of these diseases based on advance warning can enhance the efficiency of disease control and reduce environmental load of pesticides. Many of these diseases are governed by weather variables (for example, through control of fungal growth). This work presents a disease (capsule rot of cardamom) forecast model based on a set of meteorological variables. While no single weather variable provides successful simulation, an optimal combination of weather variables provides sufficient skill for advance warning of the disease.

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SMALL cardamom (*Elettaria cardamomum* L. Maton) is an economically important spice crop. The current global demand for cardamom is 40,000 tonnes annually and is expected to grow. India is a major exporter of cardamom, with a significant number of farmers dependent on it. The Cardamom Hills Reserve (CHR) in Idukki district of Kerala is a major source of this spice. The cool, humid condition prevailing in cardamom ecosystem makes the plants susceptible to several diseases. These lead to significant crop loss that adversely affects the livelihood of the farmers and the national economy in general.

Capsule rot, popularly known as *Azhukal* disease, is the most serious disease of cardamom. It was reported for the first time from plantations of Idukki district, Kerala[1]. The disease is caused by the fungal pathogen *Phytopthora meadii* MC Rae of A2 mating type[2]. It is a major problem affecting cardamom cultivation in Idukki and Waynaad districts of Kerala and Anamalai hills in Tamil Nadu[3]. The disease generally makes its appearance after the onset of the southwest monsoon. Disease symptoms develop mainly on the capsules, young leaves, panicles and tender shoots as water-soaked lesions. During favourable climatic conditions, the size of lesions enlarges and in extreme cases the whole panicle or the whole psuedostem decays completely. In such cases the rotting extends to underground rhizomes as well. The root system of such plants becomes decayed and the entire plant collapses. Crop loss can be 100% in severely disease-affected plantations.

It had been noticed in case of epidemiology of *Azhukal* disease that high disease incidence is correlated with high and persistent rainfall during the monsoon season[4]. The number of *Phytophthora* propagules increases in the soil and results in heavy disease incidence coinciding with high soil moisture levels (34.3–37.6%), low temperatures (20.4–21.3°C), high relative humidity (83–90.6%) and high rainfall (320–400 mm) during June to August[5]. Several studies have highlighted the special environmental and climatological features of the CHR, such as long-period (centennial) rainfall[6,7] and the physiological ecology of cardamom[8]. Similarly, there have been studies on the characteristics of *Phytophtora* inoculum in CHR soils[9]. Due to the dependence of disease severity (fungal growth) on weather variables, the production and sustainability of cardamom are vulnerable to changes in the regional climate[10]. However, these analyses have not yet resulted in developing a mathematical model to predict the disease.