

A study of 2014 record drought in India with CFSv2 model: role of water vapor transport

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Abstract The Indian summer monsoon season of 2014 was erratic and ended up with a seasonal rainfall deficit of 12 % and a record drought in June. In this study we analyze the moisture transport characteristics for the monsoon season of 2014 using both NCEP FNL reanalysis (FNL) and CFSv2 (CFS) model data. In FNL, in June 2014 there was a large area of divergence of moisture flux. In other months also there was lesser flux. This probably is the cause of 2014 drought. The CFS model overestimated the drought and it reproduces poorly the observed rainfall over central India (65E–95E; 5N–35N). The correlation coefficient (CC) between the IMD observed rainfall and CFS model rainfall is only 0.1 while the CC between rainfall and moisture flux convergence in CFS model is only 0.20 and with FNL data -0.78 . This clearly shows that the CFS model has serious difficulty in reproducing the moisture flux convergence and rainfall. We found that the rainfall variations are strongly related to the moisture convergence or divergence. The hypothesis of Krishnamurti et al. (J Atmos Sci 67:3423–3441, 2010) namely the intrusion of west African desert air and the associated low convective available potential energy inhibiting convection and rainfall shows some promise to explain dry spells in Indian summer monsoon. However, the rainfall or lack of it is mainly explained by convergence or divergence of moisture flux.

Keywords Indian summer monsoon · Rainfall · Moisture budget · Monsoon drought

1 Introduction

A large fraction of global population living in South Asia depends critically on summer monsoon rainfall. Several aspects of human activity such as agriculture and energy production depend on the same. For example Prasanna (2014) showed that the all India crop yield index is strongly related to all Indian summer monsoon rainfall (ISMR). Thus drought years are of serious concern for the Indian populace.

The Indian monsoon season of 2014 was erratic as there was a delay in the onset of south west monsoon in some parts of India. During June 2014 the rainfall over India was very subdued. The all India rainfall for June 2014 (92.4 mm) was the third lowest since 1901 after the years 2009 (85.7 mm) and 1905 (87.4 mm). Apart from that the rainfall during July over India was below normal. Throughout the season (1st June to end of September) the area weighted all India rainfall of 777.5 mm was 12 % less than the long period average (LPA) of 886.9 mm (MAUSAM 2015).

Breaks during the monsoon season are periods of less/no rainfall which have been the study of interest by several authors. Gadgil and Joseph (2003) made a detailed study on breaks of Indian monsoon. Previous authors Ramamurthy (1969) and De et al. (1998) have used the classical definition of break monsoon as the shift of the monsoon trough to the foothills of Himalayas. Thus break is defined in terms of surface pressure distribution and circulation rather than of rainfall, while Gadgil and Joseph (2003) used rainfall as the basis of delineating breaks. They have shown

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that the all India summer monsoon rainfall has a significant negative correlation with the number of rain-break days (CC -0.56) and positive correlation with the number of active days (CC 0.47). Thus the interannual variation of the all India summer monsoon rainfall is shown to be related to the number of break days and active spells. Krishnan and Sugi (2000) suggested that the cause of breaks involved dynamical feedbacks between monsoon convection and the extra tropical circulation anomalies. Their premise is based on a result of Ramaswamy (1962) that the monsoon breaks were influenced by the intrusion of large amplitude westerly troughs from the middle latitudes into Indo-Pakistan region in the middle and upper troposphere. Upper level circulation charts during weak monsoon periods indicate zonal asymmetric variations of the Tibetan high under the influence of the southward penetrating middle latitude troughs over west central Asia and the formation of stagnant blocking highs between 90° – 150° E over East Asia as suggested by Raman and Rao (1981).

Variations in summer monsoon rainfall over the Indian subcontinent are strongly related to variations in water vapor transport from the North Indian Ocean (NIO). The moisture transport from the NIO is related to the cross equatorial flow at low levels over the Indian Ocean (Findlater 1969) with a low level jet along the east coast of Africa called Somali Jet and with low level winds west of West coast of India.

Several studies stressed the importance of the water vapor generated South of the equator for the monsoon rainfall. Saha and Bavadekar (1973), Cadet and Reverdin (1981a, b), Cadet and Greco (1987a, b) found that the water vapor flux over the Indian Ocean South of the equator is more than that over the Arabian Sea. While other studies concluded that the Arabian Sea flux is an important source of moisture for the ISMR (Pisharoty 1965; Ghosh et al. 1978; Murakami et al. 1984; Levine and Turner 2012). Saha and Bavadekar (1977) noted that the moisture flux south of Bombay (Mumbai) has strong correlation with coastal rains and also rains over east of Western Ghats. Hastenrath and Greischar (1993) studied the heat budget of the Indian Ocean sector (30° N– 30° S, 30° E– 120° E). They found that the latent heat export is mainly supported by evaporation. They also found that in the core of the monsoon season (June–August), the latent heat flux by Boreal monsoon flow is large and maintains the abundant monsoon rainfall. Most recently Singh et al. (2014) found that there were statistically significant decreases in peak season precipitation over the core of the monsoon region and these occurred in association with significant decreases in daily precipitation variability. They found a significant increase in the dry spells and intensity of wet spells and significant decreases in the intensity of dry spells. These changes in the extreme wet and dry spell characteristics are partially

supported by low-level moisture convergence along with large-scale upper circulation.

Moisture transport by the prevailing summer monsoon winds is a basic aspect of the observed rainfall over the Indian subcontinent. The purpose of the present paper is twofold, first is to study the variations in water vapor convergence over the NIO and adjoining Indian sub continent and how are they related to the deficit rainfall in 2014 summer monsoon and the second is to study how well the ensemble forecast of 2014 predicted the monsoon with respect to moisture flux in CFS model.

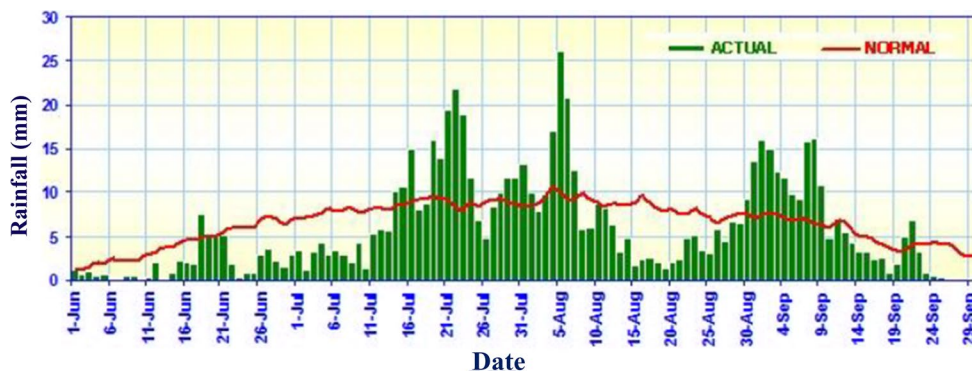
2 Data and methodology

The convergence/divergence of climate mean and 2014 anomaly are computed using NCEP FNL (2000) (operational model global tropospheric analyses, continuing from July 1999) available at daily 1° X 1° resolution to study the distribution of moisture flux. Data from 1st June to 30th September for the period 2000–2014 (rda.ucar.edu/datasets/ds083.2/) for the ISMR region 10° S– 40° N; 30° E– 120° E is used. The vertically integrated moisture convergence (integrated for 17 levels from 1000 to 300 hPa) is computed using the 6 hourly data of the variables, zonal (u) and meridional (v) wind components, air temperatures and relative humidity and surface pressure.

In this study we also used model outputs from IITM-CFSv2 T382 model integrations that were performed at the Indian Institute of Tropical Meteorology (IITM) Pune, India as a part of their Indian National Monsoon Mission Program. The CFS model is a coupled ocean–atmosphere–land model with a spatial spectral resolution of T382 for the atmosphere (equivalent to about 38 km grid spacing) with 64 sigma pressure hybrid vertical layers (Moorthi et al. 2001; Saha et al. 2014). The model has a coupled initialization scheme for the atmospheric component which is the NCEP-GFS and GFDL-MOM as the ocean component. The atmospheric component has the simplified Arakawa–Schubert scheme for convective parameterization; orographic gravity wave drag based on Kim and Arakawa (1995); sub grid scale mountain blocking of Lott and Miller (1997); Noah land surface model (Ek et al. 2003) and a two layer sea-ice model (Winton 2000).

For the analysis of the study, the model outputs were obtained from the integrations starting from 00 UTC of 5th, 10th, 15th, 20th and 25th of February initial conditions of each of the years from the 1995 to 2012 (18 years). This provided 90 data sets of the monsoon hind casts in the climate mean with the CFS model. To analyze the year 2014 we used the forecast data. We have also used IMD daily gridded rainfall ($0.5^{\circ} \times 0.5^{\circ}$) for the rainfall validation (Mitra et al. 2009). It is noted that the model initialized with February initial conditions has better skill in predicting Indian summer monsoon rainfall compared to model

Fig. 1 Daily variation of monsoon rainfall from 1 July to 30 September 2014



initialized data with May initial conditions. Thus we get five ensemble members for the above mentioned five dates and results are the average of these five ensemble members.

2.1 Calculation of moisture flux

The moisture budget equation can be written as

$$\frac{\partial w}{\partial t} = -\nabla \cdot Q + E - P \tag{1}$$

where

$$Q = \frac{1}{g} \int_{ps}^{p300} qVdp \tag{2}$$

ps is the surface pressure, g is acceleration due to gravity, and V is the horizontal vector wind. The above Eq. (1) states that the change of total precipitable water ‘ w ’ in the column is equal to the difference between evaporation (E) and the sum of precipitation (p) and the vertically integrated moisture flux divergence ($\nabla \cdot Q$). For a long period $\frac{\partial w}{\partial t}$ is negligible, then Eq. 1 can be written as

$$E = P + (\nabla \cdot Q) \tag{3}$$

For the vertical integration of moisture flux and its divergence we used data from the surface layer to 300 hPa. As NCEP FNL data system does not provide the specific humidity on pressure levels, from the available relative humidity the specific humidity ‘ q ’ is calculated by using the standard formula from one of the earlier work (Zhou and Yu 2005),

$$q = 0.622 \times \frac{e_s}{p - e_s} \times R_H \tag{4}$$

where e_s is the saturation pressure of water vapor which can be calculated from air temperature and ‘ p ’ is the atmospheric pressure. The physical quantities divergence/convergence are expressed in units of ‘mm/day’ and moisture flux ‘ $\text{kg m}^{-1} \text{s}^{-1}$ ’.

3 Results and discussion

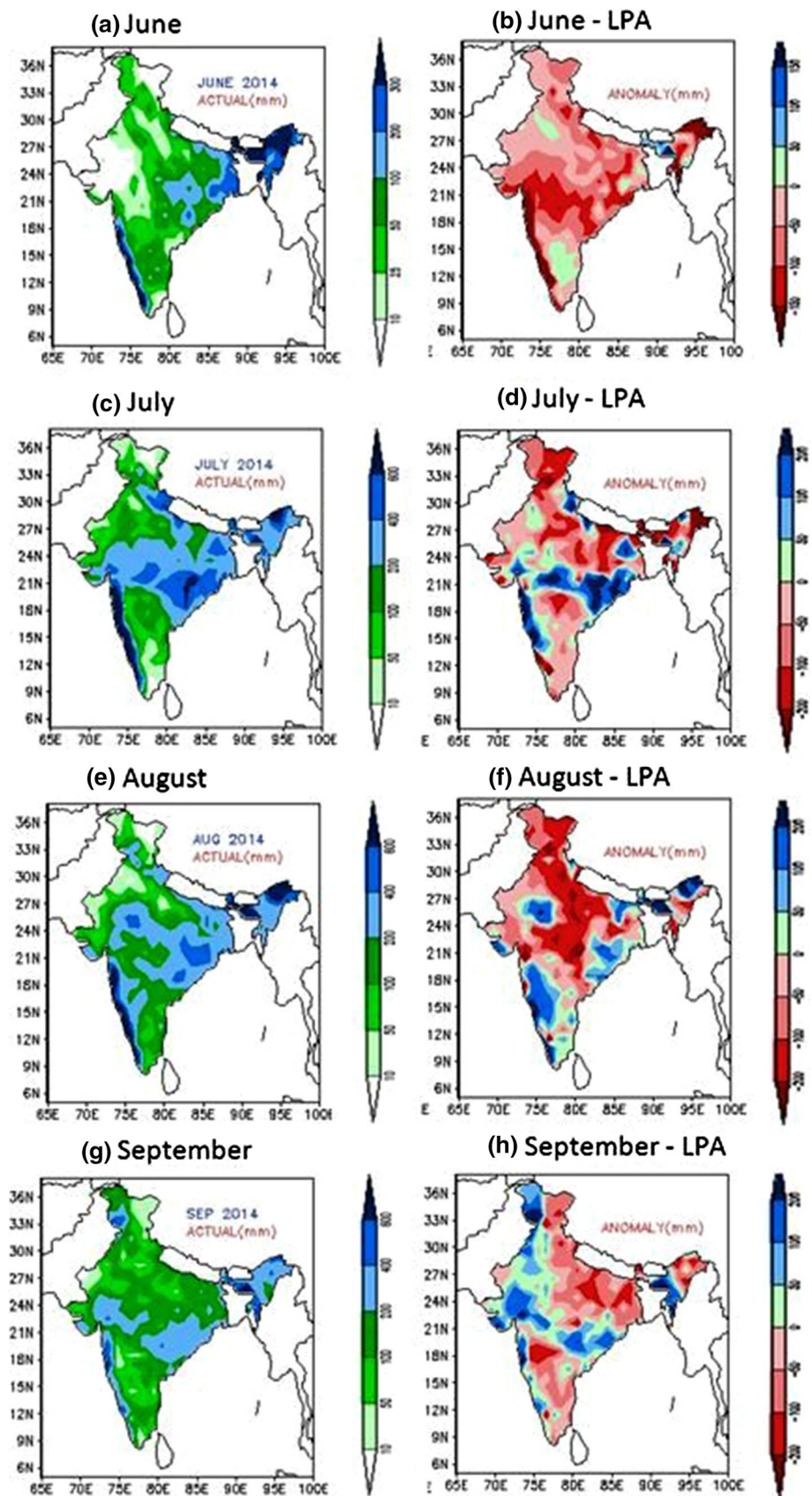
3.1 The monsoon season of 2014

The monsoon season of 2014 was unusually dry and Fig. 1 shows the daily variation of the rainfall in 2014 and the daily normal for the entire monsoon season. It can be seen from 1 June to 16 July the actual rainfall was below normal, whereas from 16 July to 10 August the rainfall was above normal. There was a break from 9 to 30 August and the rainfall revived from 30 August to 10 September and then decreased.

During the monsoon season of 2014, the rainfall was subdued over several days and month of June recorded very low rainfall as mentioned in the introduction. Figure 2a, b show the June rainfall and departure from the mean respectively. Figure 2a–h are the actual and anomalies of 2014 rainfall obtained from the IMD published reports (MAUSAM 2015). Figure 2a shows the spatial pattern of rainfall (mm) received during month of June. Parts of south peninsula and eastern region of the country in general received slightly more than 50 mm. Rainfall received by the parts of west coast was more than 200 mm. Figure 2b shows the spatial pattern of the rainfall anomaly. Except at some isolated parts rainfall anomaly was negative throughout the country. The negative rainfall anomaly over parts of central, eastern and northern region was more than 50 mm. Magnitude of negative rainfall anomaly exceeded 300 mm over parts of west coast, Assam, Meghalaya and Arunachal Pradesh. These rainfall anomalies constituted a record drought in June 2014 and the all India rainfall in this month was only 57.5 % of LPA.

Figure 2c shows the rainfall received during the month of July and Fig. 2d the departure from normal. The formation of a low pressure area in the first week of July over North Bay of Bengal and the adjoining area and its north ward movement kept rainfall activity only over the eastern parts. The rainfall activity, however all over India during the period remained subdued. The formation of a depression in the third week of July revived the monsoon activity

Fig. 2 **a** June 2014 rainfall (mm), **b** anomaly (mm) from long period average (LPA) and **c–h** are for the months of July, August and September 2014 same as mentioned in **a, b**



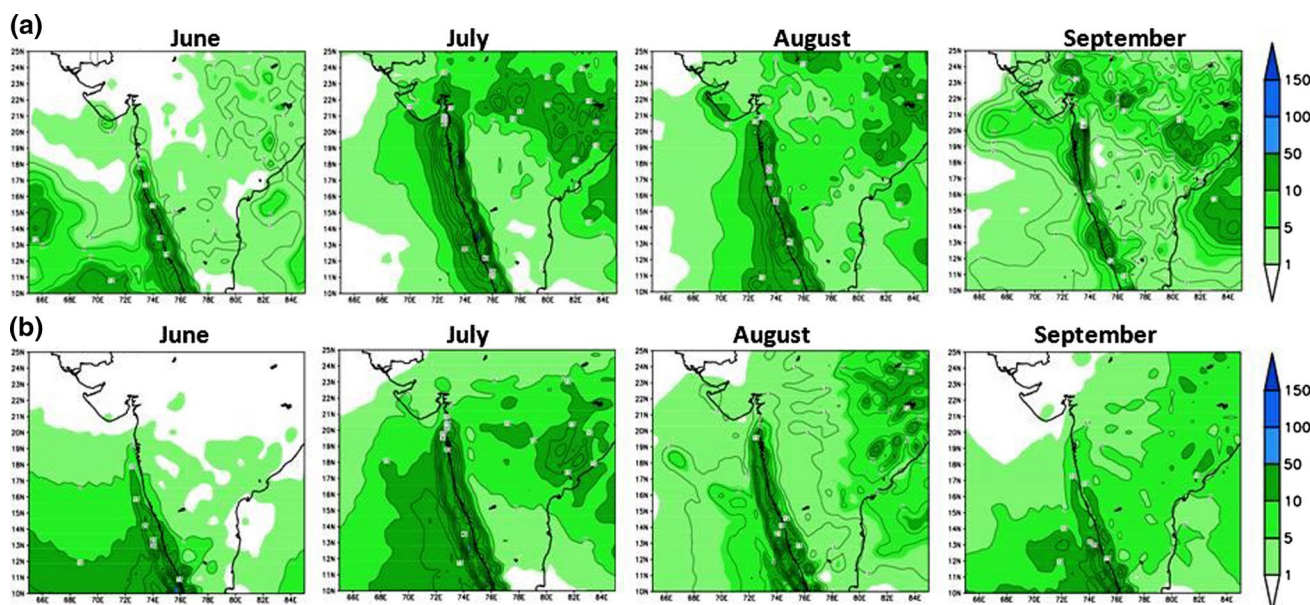


Fig. 3 **a** Observed (IMD) rainfall in mm day^{-1} from June to September 2014 (integrated over 65–85E: 10–25N). **b** CFS model rainfall in mm day^{-1} from June to September 2014 (integrated over 65–85E: 10–25N)

in the central and peninsular India. Rainfall over most of the central parts of India (core monsoon region) varied from 200 to 400 mm with some pockets of 600 mm. In Fig. 2d it can be seen that except for the west coast and small areas in central parts of India the anomaly was negative and in some areas it was of the order of 200 mm. The all India rainfall in July was 87.9 % of LPA.

Figure 2e, f show respectively the August rainfall and its departure from LPA. In August most of the east and north-east of India received normal or excess rainfall varying between 200 and 600 mm, while the majority of North West India and neighboring parts received deficient or scanty rainfall. The rainfall varied between as low as 10–50 to 50–100 mm. In this month too anomaly varied between 100 and 200 mm in central parts and it was positive in isolated pockets with values ranging between +50 and 200 mm. In this month the all India rainfall was 89.9 % of LPA.

Figure 2g, h show respectively the rainfall in September and its anomaly from LPA. The rainfall in this month over many parts of the country showed significant increases and was in excess some parts. The anomaly was negative over north east and southern peninsula. In this month the overall rainfall was 108.1 % of LPA.

From the monthly variation it can be seen that all parts of India have received deficient/scanty monthly rainfall at least once during the four months. Thus over all JJAS seasonal rainfall over India was 777.5 mm which is -12% of the normal 886.9 mm.

3.2 Rainfall and moisture flux convergence (MFC)

The actual rainfall distribution and comparison with CFS model over the area between 65E–85E; 10N–25N (comprising of the main land region and the adjoining oceanic region) and is shown in Fig. 3a, b. Figure 3a shows the distribution of the actual rainfall (IMD) and Fig. 3b CFS model rainfall over the above-mentioned area. In the month of June CFS model seems to exaggerate the drought, when compared to observation, particularly over the central parts of India. In other months the prediction of CFS is reasonable, only qualitatively. However, CFS model predicts less rainfall.

The rainfall over tropical land area is mainly due to MFC (Satyamurty et al. 2013), over the land areas evaporation explains only a small part of the rainfall. Thus we compared the IMD rainfall variation to the MFC calculated with FNL and CFS model. Figure 4a, the IMD observed rainfall and CFS predicted rainfall for the region mentioned above are compared. The correlation coefficient between these two time series is only 0.10, which shows that the model has serious difficulty in predicting the rainfall quantitatively. A careful examination of Fig. 4a shows that the observed drought in June (low rainfall) is not predicted by the model, instead the model predicts high rainfall with a maximum of 12 mm/day. While during the remaining season the model predicts very low rainfall. Thus the overall correlation leads to a low value of 0.10. Figure 4b, c are the time series plots of moisture flux convergence (MFC) of CFS/FNL and observed (IMD) rainfall respectively.

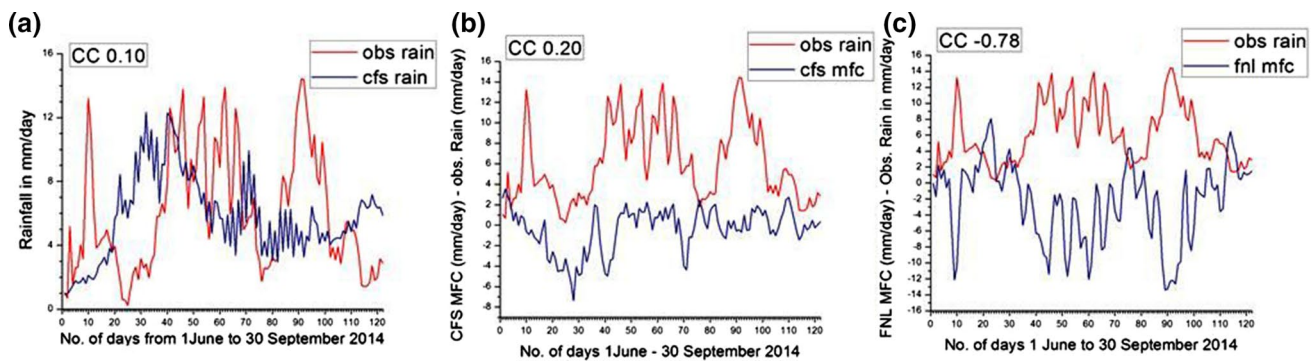


Fig. 4 Time series for 2014 monsoon period **a** monsoon period, **a** IMD observed rainfall and CFS model rainfall, **b** IMD observed rainfall and CFS moisture flux convergence and **c** IMD observed rainfall and FNL moisture flux convergence

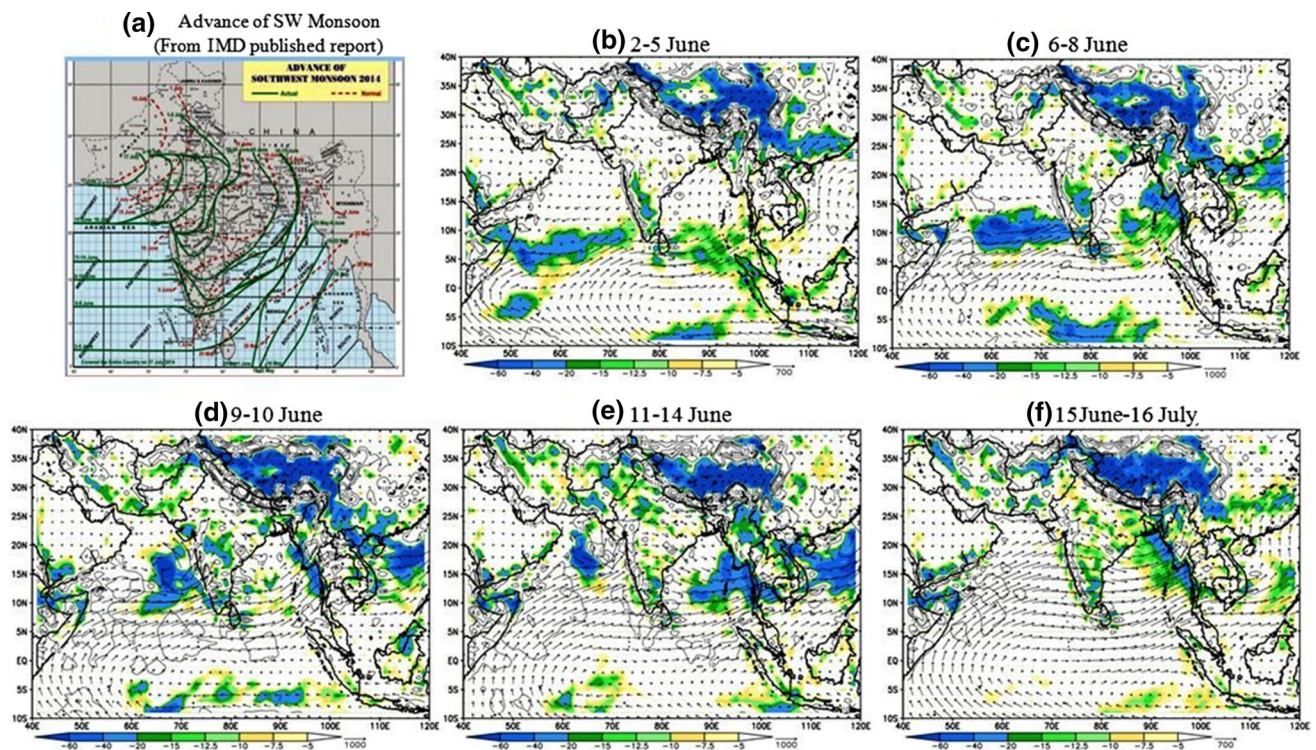


Fig. 5 **a** Advance of the south west monsoon 2014 and **b–f** moisture flux convergence according to the advance of south west monsoon as shown in **a**

From Fig. 4b, it is seen that the correlation coefficient is very low (0.2), but also of the opposite sign. Thus CFS model has serious difficulty in predicting rainfall at least over central regions of India. Figure 4c is the time variation of IMD rainfall and MFC of FNL. The correlation coefficient between these two series is -0.78 and it is significant at 99.9 % by two-sided t test and it explains more than 60 % variance of the observed rainfall. This supports the contention, that over the land area the moisture flux convergence explains a large percentage of observed rainfall and evaporation plays a minor role. However, over some places

such as subtropical oceans evaporation and divergence of moisture flux are important.

3.3 Study of moisture flux convergence for ISMR 2014

June is an onset month of Indian summer monsoon and thus it is interesting to compare the progress of monsoon (isochrones) with the moisture flux—convergence. Figure 5a shows the isochrones of advance of monsoon in 2014 compared with the normal (MAUSAM 2015). In Fig. 5a, the delay in the progress of monsoon in 2014 compared to the

normal is noted. Figure 5b–f show, the moisture flux and convergence for different periods as given in isochrones i.e. June 2–5, 6–8, 9–10, 11–14 and 15 June–16th July, 2014 with FNL Reanalysis data. In the Arabian Sea a region of high moisture flux convergence with a steady progress to the north can be noted. Less clearly a similar progress is seen in Bay of Bengal and Peninsular India. During 9–10 June (Fig. 5d), 2014 a clear onset vortex is seen (Krishnamurti et al. 1980) in the Arabian Sea. Under the influence of onset vortex the monsoon progressed further north. However, the onset vortex dissipated quickly.

Figure 6a–p shows the moisture transport and convergence and their anomalies in FNL and CFS model respectively. Figure 6a shows, the vertically integrated moisture flux and the flux divergence for the entire month of June 2014 calculated with FNL data. It is seen that the water vapor transport closely resembles the large scale monsoon circulation in the lower troposphere (Rao 1976). Over a large region near Somali coast particularly over the oceanic region there was divergence of vertically integrated moisture flux, which together with the precipitation constitutes the evaporation (Eq. 3). This evaporation makes the air above moisture laden. We also clearly see the strong moisture transport by the Somali low level-jet crossing the equator and bringing moisture from Arabian Sea towards the west coast of peninsular India. We also can see moisture convergence on the west of peninsular India. This is only qualitatively similar to the normal monsoon situation. The moisture convergence in the normal monsoon situation is responsible for the abundant precipitation near the west coast of peninsular India, because of Western Ghats, which makes the moisture-laden air to rise and precipitate. But in June 2014, an anomaly of high moisture flux (Fig. 6b) made the easterly flow on the eastward flank of a high reduced the moisture flux towards the coast. Since moisture is high in the lower levels, the vertically integrated moisture flux reflects low-level circulation. We can attribute the vertically integrated moisture flux to an anticyclonic flow on the western side of the peninsula. Thus the source for precipitation over the central parts of India is reduced. We can also see in Fig. 6a, a weak convergence of about $1\text{--}2.5\text{ mm day}^{-1}$ over central parts of India. On southern parts of China, isolated pockets of high convergence can be seen. Over East Bay of Bengal also we can see convergence of around 5 mm day^{-1} associated with the Bay of Bengal monsoon current.

Figure 6c depicts the same as 6a but with CFS data. When compared to FNL, larger areas of convergence over the main land of India with similar pattern of moisture flux are seen. Figure 6d is the anomaly of June 2014 with long term mean with CFS model output. In this also a zone of anticyclonic flux is present with small shift in the center from land area near Gujarat in Fig. 6b, to adjoining oceans.

Two zones of cyclonic flux, one in the Arabian Sea and the other in the Bay of Bengal are present in both anomaly pictures Fig. 6b, d, although somewhat dislocated in Fig. 6d.

Figure 6e, f are respectively the vertically integrated moisture flux for the month of July 2014 and its anomaly with long term mean with FNL data. The cyclonic circulation over Head Bay as mentioned earlier, induced maximum convergence of Moisture flux over peninsular and central parts of India, with a fairly strong convergence of the order of 50 mm day^{-1} . This convergence over Peninsular India and East central India seems to be responsible for the high rainfall in July as seen in Fig. 1. In the anomaly part of July 2014 with FNL data the cyclonic flux convergence is prominent at head Bay.

Figure 6g, h depict respectively the moisture flux and its convergence for July 2014 and 2014 July anomaly of the long term mean with CFS model data. In Fig. 6g, there is less convergence over north east India with CFS while there is strong convergence with FNL (Fig. 6e). Over the region of cyclonic circulation near head Bay (north of Bay of Bengal) there is convergence in FNL while in CFS there is divergence. This seems to be due to weak cyclonic flux of moisture in CFS model. In Fig. 6g, the anomaly of flux of water vapor over head Bay is quite strong in FNL where as it is weak in CFS (Fig. 6h). This seems to generate weaker convergence in this region in CFS as compared to FNL.

Figure 6i, j show the moisture convergence for the month of August 2014 and anomaly of August 2014 with long term mean with FNL data. In August 2014, there was a break in the monsoon during the period 14–21 August. The convergence of water vapor flux is substantially lower compared to July (Fig. 6g, h) in both FNL and CFS and lead to lower rainfall. A strong ridge of water vapor flux is seen over north western parts of India in FNL data where as the CFS data (Fig. 6k, l) show convergence over continental India which is higher and wide spread when compared to FNL. In Fig. 6l, a similar ridge of water vapor flux is present over north India albeit with an east-ward shift.

Figure 6m–p shows the moisture convergence for the month of September 2014 and anomaly of September 2014 with long term mean with FNL and CFS data sets. In FNL pictures, the clear cyclonic circulation of water vapor flux over head Bay continues generating convergence over peninsular India, while the rest of the country there was a divergence. The pattern with CFS, in Fig. 6o the cyclonic circulation is not well marked, also there are more convergence patches over north western region. In Fig. 6p, the anomaly of the flow of moisture flux is in opposite direction compared to FNL anomaly (Fig. 6m) from the Bay of Bengal towards the Arabian Sea and it merges with cyclonic flow.

In all the 4 months over Tibetan region there was strong convergence in FNL data while the convergence is much

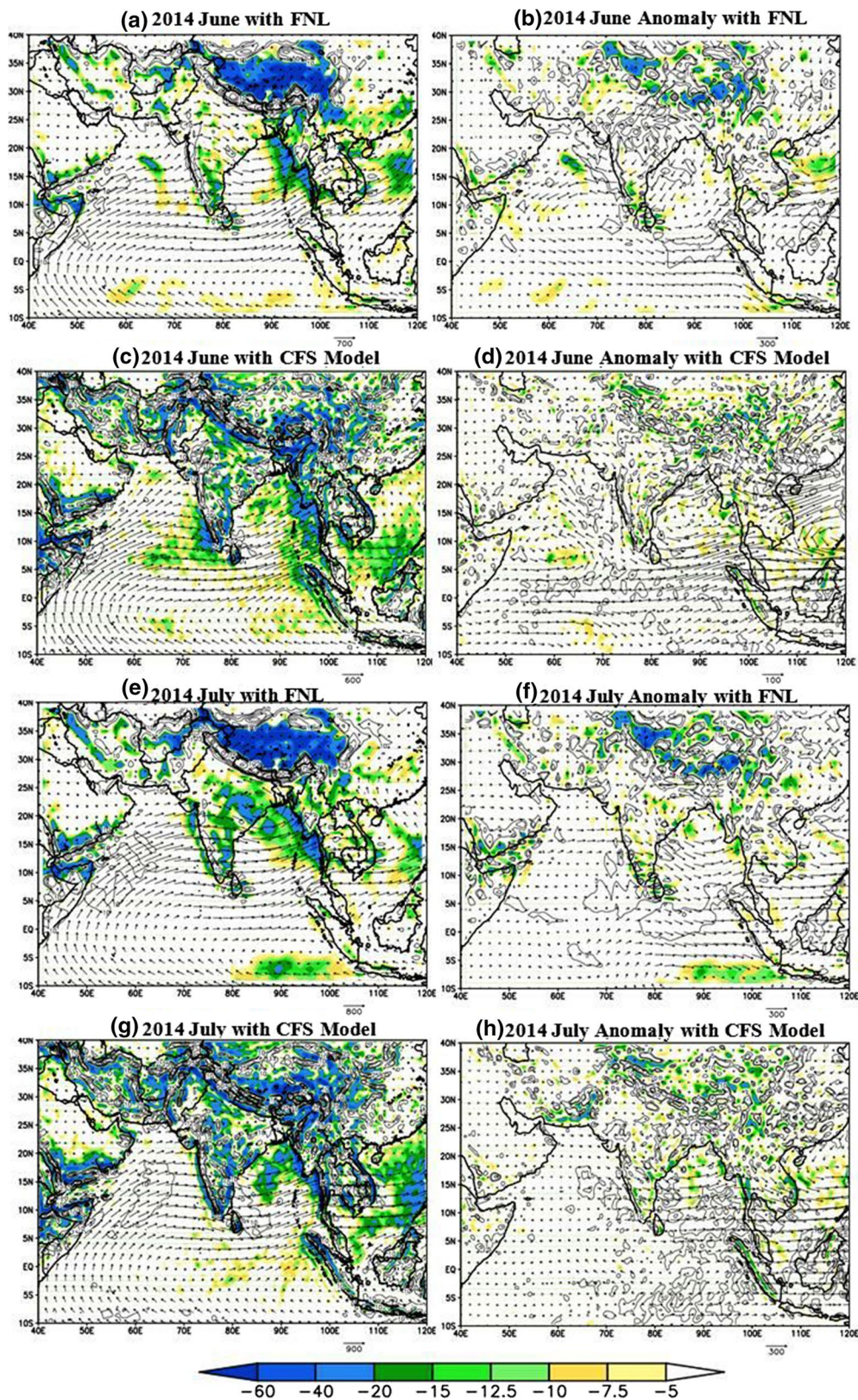


Fig. 6 a–h Vertically integrated (1000–300 hPa) moisture flux convergence (*shaded*) in mm day^{-1} and its flux (*arrow*) in $\text{kg m}^{-1} \text{s}^{-1}$ for June and July months with FNL and CFS model respectively. i–p Ver-

tically integrated (1000–300 hPa) moisture flux convergence (*shaded*) in mm day^{-1} and its flux (*arrow*) in $\text{kg m}^{-1} \text{s}^{-1}$ for August and September months with FNL and CFS model respectively

less and wide spread in CFS. Thus CFS seems to have a difficulty in reproducing the water vapor flux over the mountain regions.

3.4 Break monsoon situation in August 2014

As mentioned earlier, there was a break in the monsoon rainfall in the month of August 2014 (Fig. 1). Active/break monsoon periods arise from superposition of different time scale variations such as synoptic (around 5 days), quasi-bi-weekly (10–20 days) and the Madden Julian oscillations (30–60 days). Several studies (Rao 1976; Alexander et al. 1978; Sikka and Narasimha 1995; Choudhury and Krishnan 2011) have shown that during active phase monsoon trough zone (MT) remains on the Indo Gangetic plain and produces copious amounts of rainfall. While during the break MT migrates to the Himalayan foothills causing cessation of rainfall over most of India and intense rainfall along the foothills of Himalayas. Also less intense precipitation occurs over southern peninsula (Vellore et al. 2014).

Figure 7 shows, weekly accumulated rainfall for August 2014 and corresponding vertically integrated (1000–300 hPa) moisture flux convergence in FNL and CFS model. During the week 8–14 August 2014 there was rainfall over north-eastern and central parts of India. Weekly accumulated rainfall during this period was with a maximum of 100 mm. Over south-western parts of peninsular India there was a maximum of 200 mm. Figure 7b shows weekly rainfall for 15–21 August 2014. Virtually over most of India there was no rainfall. Only in north eastern parts near foothills of Himalayas due to the presence of monsoon trough (MT) there was about 200 mm of rainfall. Figure 7c shows, weekly rainfall for 22–28 August 2014. Again most of the Indian subcontinent was without rainfall except near foothills of Himalayas and the peninsular India.

To see how moisture transport and divergence are related to precipitation, we calculated these quantities for the above corresponding weeks. The moisture flux/divergence is shown for the period 8–14 August, 2014 (Fig. 7d) which shows that a convergence of the order of 20–40 mm day⁻¹ in the regions of rainfall are seen in Fig. 7a. Not only qualitatively (convergence) but also quantitatively the values are agreed with each other. In Fig. 7e, f, we can see the divergence in regions without rainfall and convergence in regions with rainfall. Thus the overall moisture convergence seems to agree with each other.

Figure 7g–i show the moisture flux and its convergence for the 3 weeks in August month with CFS model. While FNL is able to reproduce quite well the observed rainfall, the CFS model has difficulty in reproducing the quantitatively observed rainfall. The possible reason for this may be due to the prediction of excess convergence over the continents.

3.5 Possible causes for the 2014 drought

The manifold physical processes that cause drought over the Indian subcontinent are of different origin. These include the ENSO effect (Krishna Kumar et al. 2006), the Intra Seasonal Oscillations (ISO) (Krishnamurti and Subrahmanyam 1982; Sikka and Gadgil 1980; Wang and Rui 1990), the Indian Ocean Dipole (IOD) (Saji et al. 1999), the Himalayan ice cover (Dickson 1984; Fasullo 2004) and the Eurasian Snow cover (Barnett et al. 1989; Hahn and Shukla 1976; Bhanu Kumar 1988).

The observed conditions over the equatorial pacific in 2014 during and early part of monsoon season were close to be classified as the weak El Nino. El Nino years are weak monsoon years although all El Nino events are not entirely associated with low rainfall (Krishna Kumar et al. 2006). During normal years the upward branch of Walker circulation over low latitudes and the rising motion associated with upward branch of east–west circulations (Krishnamurti 1971) cause rainfall over Indian sub-continent. During El Nino years the shift of heat sources over the ocean surface disrupts the Walker and the east–west circulations causing sinking motions over Indian sub-continent. This leads to weaker than normal rainfall. However air-sea coupling led to the weakening of El Nino conditions from early July resulting in ENSO neutral conditions during the remaining part of monsoon season. Thus El Nino effect on monsoon rainfall of 2014 was very small.

The monsoon season 2014 was affected by strong intra-seasonal variations caused by unfavorable ISO (or Madden Julian Oscillation) resulting in a long break in monsoon spells in August 2014. However, Krishnamurti et al. (2010), noted that the relationship between the seasonal rainfall over India and seasonal IOD is not very strong and they found that the correlation between the IOD index and Indian monsoon seasonal rainfall for the last 30 years is only 0.1. Krishnamurti et al. (2010), also noted that the other factors such as Himalayan ice cover and the Eurasian Snow cover are also not robust parameters to connect with the behavior of Indian monsoon seasonal rainfall. Krishnamurti et al. (2010) proposed a new mechanism, which can cause dry spells in the Indian monsoon season. They suggested that the west Asian desert air incursion towards central India associated with the blocking high over the western Asia can inhibit the development of deep convection and can cause dry spells. To verify this hypothesis we plotted the specific humidity for 3 weeks 8–14, 15–21 and 22–28th of August 2014. Figure 8a shows the specific humidity (Fig. 8) for 8–14 August, Fig. 8b for 15–21 August and 8c for 22–28 August. In Fig. 8d, e we show the monthly mean respectively for June and July. In the week 8–14, there was good rainfall and in the remaining 2 weeks there was a break with very low rainfall. Figure 8a shows

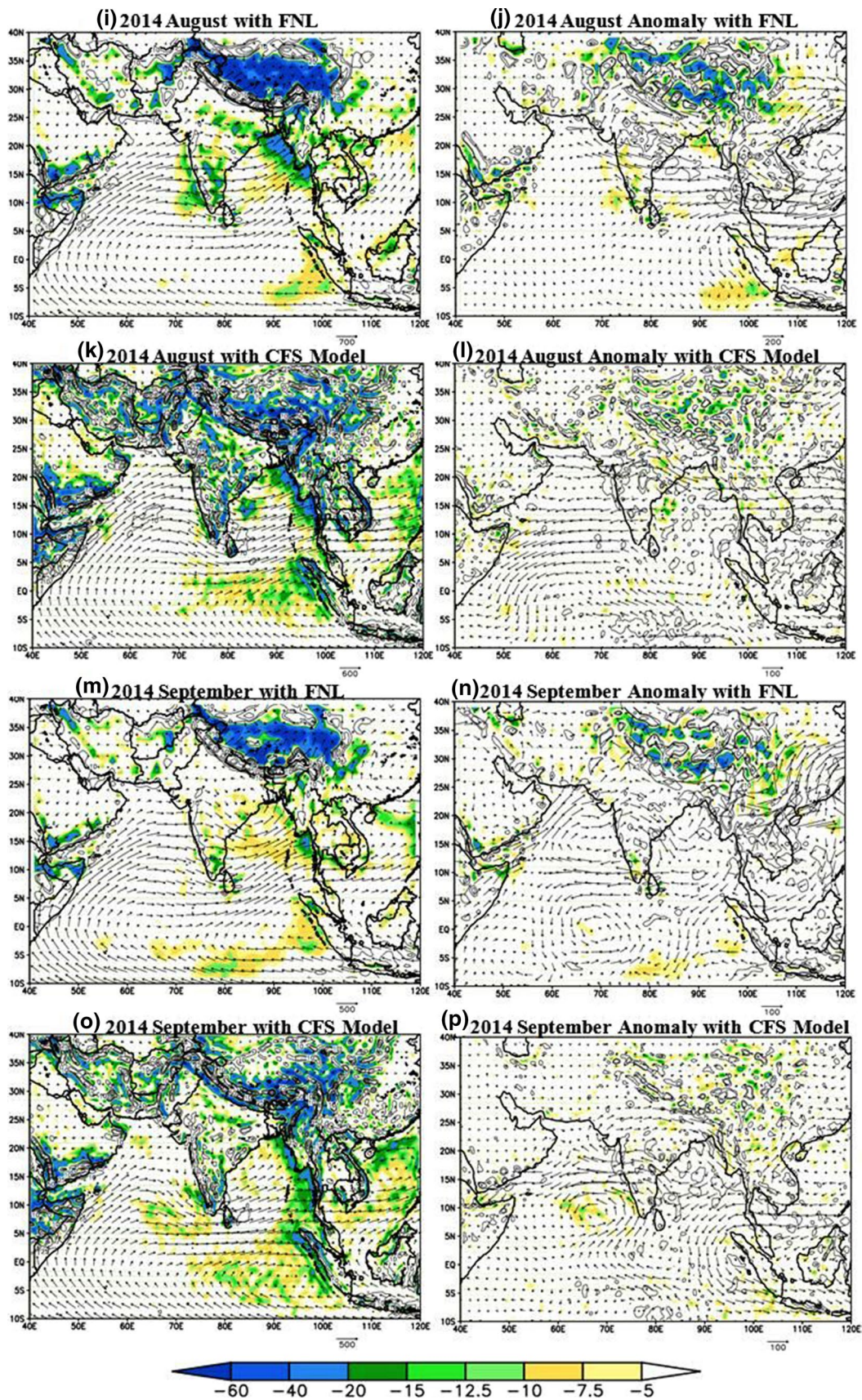


Fig. 6 continued

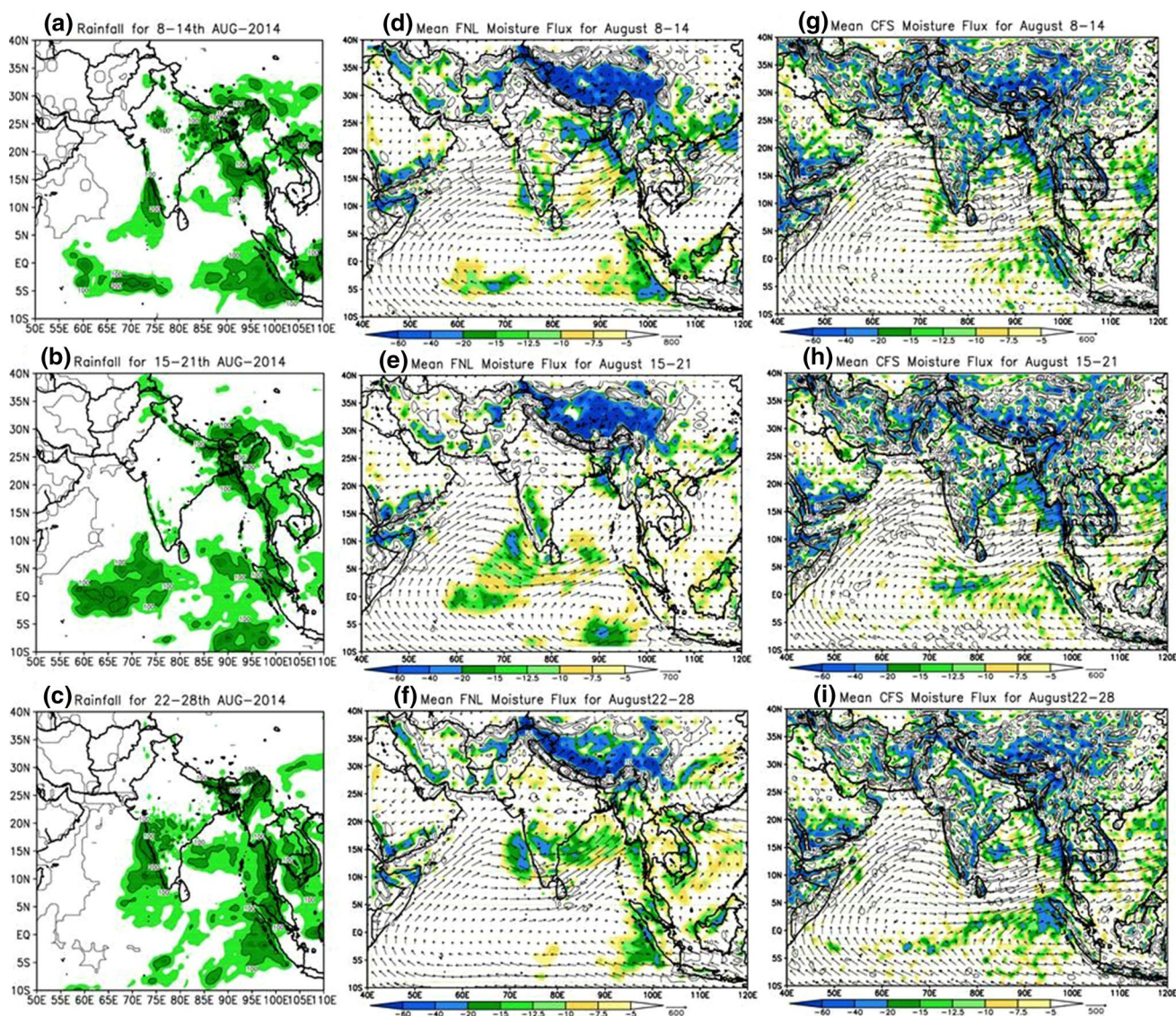


Fig. 7 a–c IMD rainfall (mm) for the week 8–14, week 15–21 week 22–28 of August 2014, **d–f** MFC (mm day^{-1}) and moisture flux ($\text{kg m}^{-1} \text{s}^{-1}$) for the same periods in FNL data, **g–i** MFC (mm day^{-1}) and moisture flux ($\text{kg m}^{-1} \text{s}^{-1}$) for the same periods in CFS data

no incursion of dry air from west, while in the remaining 2 weeks we can clearly see the relatively dry air (low humidity) incursion from west. The entire month of June 2014 was with period of low rainfall, while July was with normal rainfall. Figure 8d, e show the mean specific humidity for the entire months of June and July 2014. We can see the incursion of dry air with a tongue of 12 g kg^{-1} specific humidity in June, while during July there was no incursion. These figures seem to support the mechanism proposed by Krishnamurti et al. (2010).

Figure 9, is similar to Fig. 8 except that these values are for the CFS model. In this figure we can see that during the 3 weeks there is no incursion of dry air from the west. However, in June there was penetration of dry air with low

humidity from west into central India. This shows the CFS model has difficulty in reproducing the break monsoon condition due to the Krishnamurti's hypothesis although in June the incursion is seen. Nevertheless, the incursion of air from west in CFS model seems to be dryer than that (lower specific humidity of the order of $8\text{--}10 \text{ g kg}^{-1}$, while with FNL it is 15 g kg^{-1}) in FNL data. This seems to explain the lower rainfall in CFS model as seen earlier for the month of June compared to FNL data.

Krishnamurti et al. (2010), as mentioned earlier suggested a robust mechanism for the dry periods of Indian Monsoon Rainfall, the incursion of very dry desert air from the northwest. Figures 8 and 9 seems to confirm this hypothesis. To further test this hypothesis we plotted

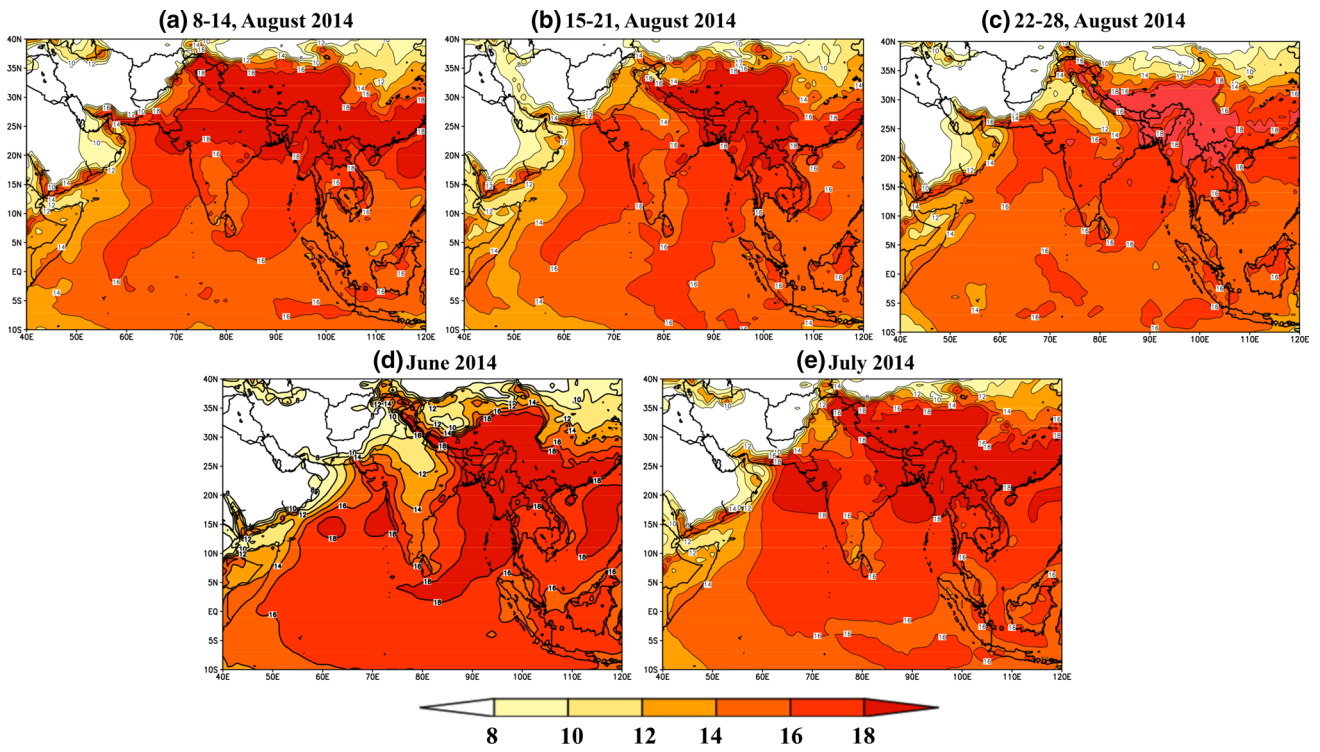


Fig. 8 925 hPa specific humidity (g kg^{-1}) with FNL data

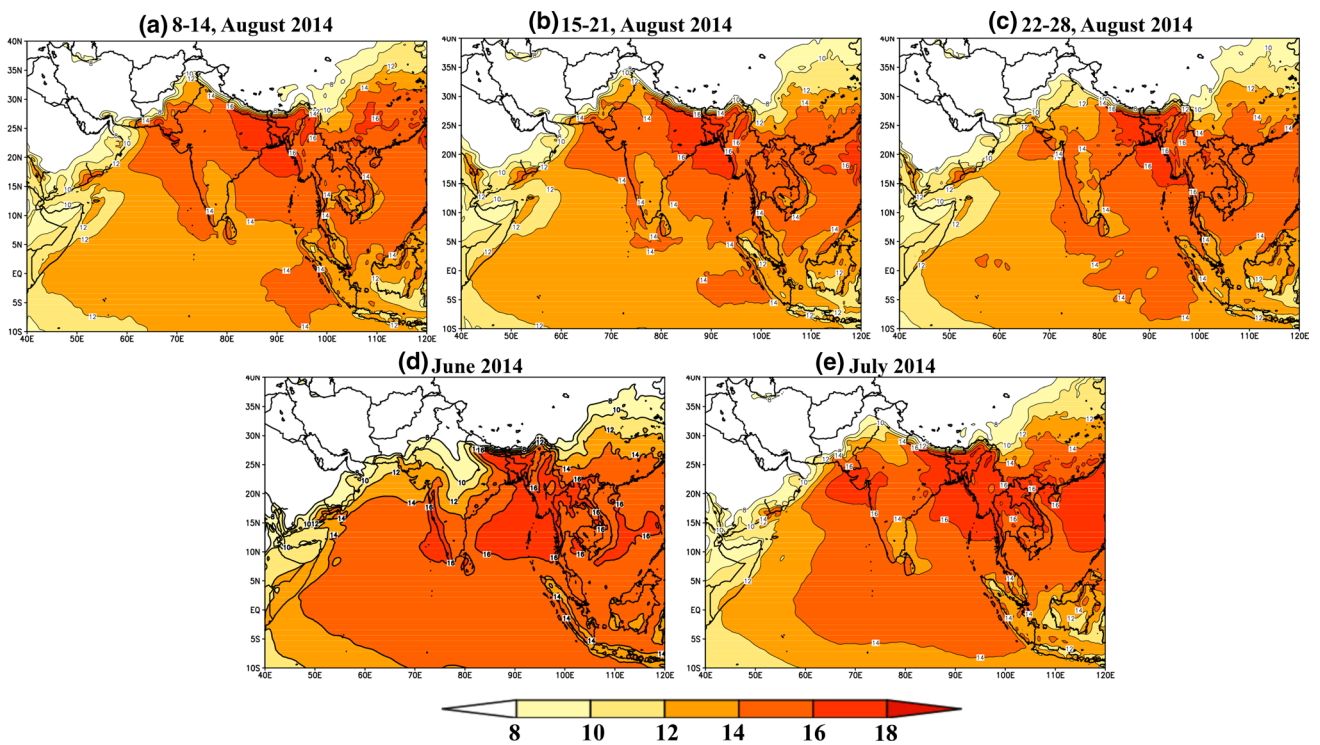


Fig. 9 925 hPa specific humidity (g kg^{-1}) with CFS model

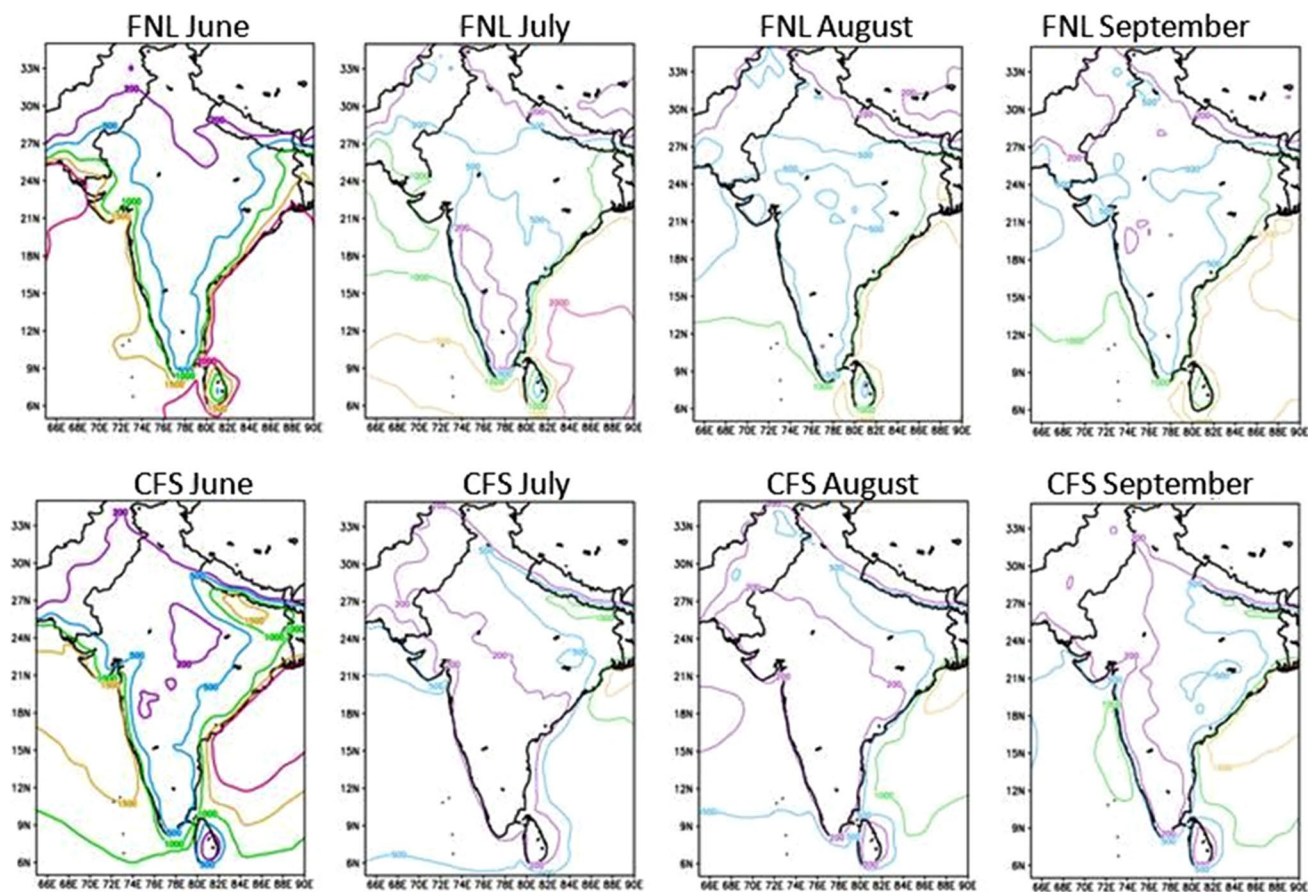


Fig. 10 Convective available potential energy (CAPE) in J kg^{-1} for 2014 monsoon months with FNL (*top panel*) and CFS (*lower panel*) model

in Fig. 10, convective available potential energy (CAPE) for four monsoon months with FNL and CFS model. It is clearly seen in June the CAPE is very low (200 J kg^{-1}) over northwestern and peninsular India, suggesting unfavorable conditions for the development of convection and the rainfall over these parts. In July, August and September as seen in FNL data the CAPE increases. In CFS model we can see lower CAPE compared to FNL in all the 4 months. This shows that the CFS model falsely predicts lower convection and rainfall compared to FNL.

However, Krishnamurti et al. (2010)'s mechanism only partially explains because it explains only the mechanism of lack of rainfall. What explains the normal or the above normal rainfall? Our results here suggest yet another processes namely the lack of moisture due to absence of convergence that causes low rainfall. It is the moisture transport and its convergence that explains the normal rainfall. Thus the moisture transport and its convergence or divergence is another basic mechanism that explains rainy or drought periods.

4 Conclusions

The summer monsoon season of India (June–September) in 2014 was unusual and ended up in a severe drought. There was a delay in the onset of monsoon in some parts of India. In June there was a record drought. Later the monsoon revived in July, but the overall seasonal monsoon rainfall of 2014 was below normal. In this paper we discussed the characteristics of water vapor transport and its divergence/convergence associated with monsoon of 2014 for both FNL and CFS model. In June 2014 the water vapor transport resembled the normal pattern but, only qualitatively. Although in July, August and September of 2014 the rainfall was higher than in June it was below normal and there was divergence of moisture flux over most of India. There was a break monsoon in August 2014 and it was associated with strong divergence of moisture flux over most of India. The magnitude of convergence agreed with the rainfall in quantity, there by showing that the moisture convergence is the principal factor for rainfall. Its absence causes drought.

The seasonal transport of moisture flux in June–September in 2014 (Fig. 6) was low.

In the month of June CFS model seems to exaggerate the drought by showing larger area with lower rainfall when compared to observations particularly over central parts of India. The CFS predicted rainfall and IMD observed rainfall for an area between 65–85E; 10–25N have a poor correlation of 0.10. This shows the model has serious difficulty in predicting quantitatively the rainfall. The rainfall over a tropical land area is mainly due to moisture flux convergence (MFC) and evaporation contributes less. The correlation coefficient between the observed rainfall and CFS–MFC for the same area mentioned earlier is only 0.20. Thus the CFS model fails to predict rainfall and is due to its inability to predict MFC correctly. The correlation coefficient between MFC of FNL and observed rainfall is -0.78 , which shows as mentioned earlier, over tropical land area MFC explains a large part of the rainfall.

We analyzed rainfall and moisture flux convergence for the break period in the month of August 2014. The CFS model is unable to predict moisture flux convergence correctly, particularly for the break period of 15–21st August. Regarding the dry air of low moisture incursion from the west, the hypothesis suggested by Krishnamurti et al. (2010) as a possible cause is confirmed. But CFS model failed to produce this dry air incursion as depicted in specific humidity figures. To further test this hypothesis we analyze CAPE for the four monsoon months with FNL and CFS data. In FNL we see low convective activity in June as shown by low values of CAPE. We see lower CAPE in CFS model, thus exaggerating the drought. CFS model seems to exaggerate the drought when compared to FNL as evidenced by several moisture variables and CAPE. The information on moisture flux associated either with weak or strong cross equatorial flow over the Arabian Sea and intrusions of dry Arabic air from west are both together may be related to the heat low particularly in June. In any case this topic needs further research.

Several scientists (Narapusetty et al. 2015 and others) have shown the dry bias of CFSv2 model. In the present paper we show it is due to false representation of low moisture convergence.

Mitigation of adverse future climate change needs accurate prediction of future climate. Thus it is necessary to know whether the drought in 2014 is in the general trend in monsoon weakening mentioned in recent literature. In a recent study Swapna et al. (2014) discussed the Indian Ocean (IO) warming and the resultant weakening of summer monsoon circulation. They found that the warming is significantly higher during the summer monsoon season than during the other seasons. This warming of tropical IO is a part of general Indo-Pacific ocean basin

wide warming (Alory et al. 2007; Alory and Meyers 2009; Du and Xie 2008; Rao et al. 2015; Tokinga et al. 2012; Hoell and Funk 2014). It is also noted that the warming of tropical IO resulted in the weakening of summer monsoon circulation and reduction of summer monsoon rainfall (Naidu et al. 2009; Swapna et al. 2014). Swapna et al. (2014) noted that in the time series of monthly mean zonal wind at 1000 hPa at Bombay (Mumbai, 72.8E, 19.1N) during the summer season, there is a weakening trend of westerly wind (their Fig. 2c) indicating a weakening of summer monsoon flow during recent decades.

The mechanism of Krishnamurti et al. (2010) partially explains only the lack of rainfall and it does not explain the normal or the above normal rainfall. But our results here suggest yet another processes namely the lack of moisture due to absence of convergence which causes low rainfall. It is the moisture transport and its convergence that explains the normal rainfall. Thus the moisture transport and its convergence or divergence is another basic mechanism that explains rainy or drought periods. Regarding the CFS model even though its performance is reasonable it has a dry bias. The model integrations are made with 3 months behind initial conditions and with this gap the model performance is satisfactory.

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References

- Alexander G, Kesavamurthy RN, De US, Chellapa R, Das SK, Pillai PV (1978) Fluctuations of monsoon activity. *Indian J Meteorol Hydrol Geophys* 29:76–87
- Alory G, Meyers G (2009) Warming of the upper equatorial Indian Ocean and changes in the heat budget (1960–2000). *J Clim* 22:93–113
- Alory G, Wijffels S, Meyers M (2007) Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms. *Geophys Res Lett* 34(2):L02606
- Barnett TP, Dümenil L, Schlese U, Roeckner E, Latif M (1989) The effect of Eurasian snow cover on regional and global climate variations. *J Atmos Sci* 46(5):661–686
- Bhanu Kumar OSRU (1988) Interaction between Eurasian winter snow cover and location of the ridge at the 500 hPa level along 75 E. *J Meteorol Soc Jpn* 66(3):509–514
- Cadet DL, Greco S (1987a) Water vapor transport over the Indian ocean during the 1979 summer monsoon. Part I: water vapor fluxes. *Mon Weather Rev* 115:653–663
- Cadet DL, Greco S (1987b) Water vapor transport over the Indian Ocean during the 1979 summer monsoon. Part II: water vapor budgets. *Mon Weather Rev* 115:2358–2366

- Cadet DL, Reverdin G (1981a) The monsoon over the Indian Ocean during summer 1975, Part. I, Mean fields. *Mon Weather Rev* 103:148–158
- Cadet DL, Reverdin G (1981b) Water vapour transport over the Indian Ocean during summer 1975. *Tellus* 33:476–487
- Choudhury A, Krishnan R (2011) Dynamical response of the south Asian monsoon trough to latent heating from stratiform and convective precipitation. *J Atmos Sci* 68:1347–1363
- De US, Lele RR, Natu JC (1998) Breaks in southwest monsoon. India Meteorological Department. Report no. 1998/3
- Dickson RR (1984) Eurasian snow cover versus Indian monsoon rainfall—an extension of the Hahn-Shukla results. *J Clim Appl Meteorol* 23:171–173
- Du Y, Xie S-P (2008) Role of atmospheric adjustments in the tropical Indian Ocean warming during the 20th century in climate models. *Geophys Res Lett* 35:L08712. doi:10.1029/2008GL036361
- Ek MB, Mitchell KE, Lin Y, Rogers E, Grunmann P, Koren V, Gayno G, Tarpley JD (2003) Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *J Geophys Res* 108(D22):8851. doi:10.1029/2002JD003296
- Fasullo J (2004) A stratified diagnosis of Indian monsoon–Eurasian snow cover relationship. *J Clim* 17:1110–1122
- Findlater J (1969) A major low-level air current near the Indian Ocean during the northern summer. *Q J R Meteorol Soc* 95:362–380
- Gadgil S, Joseph PV (2003) On breaks of the Indian monsoon. *J Earth Syst Sci* 112(4):529–558
- Ghosh SK, Pant MC, Devan BN (1978) Influence of the Arabian Sea on the Indian summer monsoon. *Tellus* 30:117–125
- Hahn DG, Shukla J (1976) An apparent relationship between Eurasian snow cover and Indian monsoon rainfall. *J Atmos Sci* 33(12):2461–2462
- Hastenrath S, Greischar L (1993) The monsoonal heat budget of the hydrosphere–atmosphere system in the Indian Ocean sector. *J Geophys Res* 98(C4):6869–6881. doi:10.1029/92JC02956
- Hoell A, Funk C (2014) Indo-Pacific sea surface temperature influences on failed consecutive rainy seasons over eastern Africa. *Clim Dyn* 43:1645–1660
- Kim Y-J, Arakawa A (1995) Improvement of orographic gravity–wave parameterization using a mesoscale gravity-wave model. *J Atmos Sci* 52:1875–1902
- Krishna Kumar K, Rajagopalan B, Hoerling M, Bates G, Cane M (2006) Unraveling the mystery of Indian monsoon failure during El-Niño. *Science* 314:115–119
- Krishnamurti TN (1971) Tropical east west circulations during northern summer. *J Atmos Sci* 28:1342–1347
- Krishnamurti TN, Subrahmanyam D (1982) The 30–50 day mode at 850 Mb during MONEX. *J Atmos Sci* 39:2088–2095
- Krishnamurti TN, Ardanuy P, Ramanathan Y, Pasch R (1980) On the onset vortex of the summer monsoon. *J Atmos Sci* 109:344–363
- Krishnamurti TN, Thomas A, Simon A, Kumar V (2010) Desert air incursions, an overlooked aspect, for the dry spells of the Indian summer monsoon. *J Atmos Sci* 67:3423–3441
- Krishnan R, Sugi M (2000) Dynamics of breaks in the Indian summer monsoon. *J Atmos Sci* 57:1354–1372
- Levine RC, Turner AG (2012) Dependence of Indian monsoon rainfall on moisture fluxes across the Arabian Sea and the impact of coupled model sea surface temperature biases. *Clim Dyn* 38:2167–2190
- Lott F, Miller MJ (1997) A new subgrid scale orographic drag parameterization: its formulation and testing. *Q J R Meteorol Soc* 123:101–127. doi:10.1002/qj.49712353704
- MAUSAM (2015) Weather in India. In: Medha K, Sunitha Devi S Kundale AP (ed) Monsoon season (June–September, 2014), vol 66, pp 657–674
- Mitra AK et al (2009) Daily Indian precipitation analysis formed from a merge of rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates. *J Meteorol Soc Jpn* 87A:265–279. doi:10.2151/jmsj.87A.265
- Moorthi S, Pan HL, Caplan P (2001) Changes to the 2001 NCEP operational MRF/AVN global analysis/forecast system. Technical procedures bulletins series no. 484, National Weather Service, Office of Meteorology, Silver Spring, MD. <http://www.nws.noaa.gov/om/tpb/484.pdf>
- Murakami T, Nakazawa T et al (1984) On the 40–50 day oscillation during the 1979 northern hemisphere summer. Part. II: heat and moisture budget. *J Meteorol Soc Jpn* 62:469–484
- Naidu CV, Durgalakshmi K, Muni Krishna K, Rao SRL, Satyanarayana GC, Lakshminarayana P, Malleswara Rao L (2009) Is summer monsoon rainfall decreasing over India in the global warming era? *J Geophys Res* 114:D24108. doi:10.1029/2008JD011288
- Narapusetty B, Murtugudde R, Wang H, Kumar A (2015) Ocean–atmosphere processes driving Indian summer monsoon biases in CFSv2 hindcasts. *Clim Dyn*. doi:10.1007/s00382-015-2910-9
- NCEP FNL (2000) National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2000, updated daily. NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. doi:10.5065/D6M043C6
- Pisharoty PR (1965) Evaporation from the Arabian Sea and the Indian southwest monsoon. In: Proceedings of the symposium on meteorological results of international Indian ocean expedition, Bombay, pp 22–26
- Prasanna V (2014) Impact of monsoon rainfall on the total food grain yield over India. *J Earth Syst Sci* 123(5):1129–1145
- Ramamurthy K (1969) Monsoon of India: some aspects of the ‘break’ in the Indian southwest monsoon during July and August. Forecasting manual 1–57 no. IV 18.3, India Meteorological Department, Poona, India
- Raman CRV, Rao YP (1981) Blocking highs over Asia and monsoon droughts over India. *Nature* 289:221–223
- Ramaswamy C (1962) Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and the subtropical westerly jet streams. *Tellus* 14(3):337–349
- Rao YP (1976) Southwest monsoon: meteorological monograph (synoptic meteorology). India Meteorological Department, Pune, N.1/1976, 367
- Rao RR, Jitendra V, Girish Kumar MS, Ravischandran M, Ramakrishna SSVS (2015) Interannual variability of the Arabian Sea warm pool: observations and governing mechanisms. *Clim Dyn* 44:2119–2136
- Saha KR, Bavadekar SN (1973) Water vapour budget and precipitation over the Arabian Sea during the northern summer. *Q J R Meteorol Soc* 99:273–278. doi:10.1002/qj.49709942006
- Saha KR, Bavadekar SN (1977) Moisture flux across the west coast of India and rainfall during the southwest monsoon. *Q J R Meteorol Soc* 103:373–374. doi:10.1002/qj.49710343613
- Saha S et al (2014) The NCEP climate forecast system version 2. *J Clim* 27:2185–2208. doi:10.1175/JCLI-D-12-00823.1
- Saji NH, Goswami BN, Vinayachandran PN, Yamagata TA (1999) A dipole mode in the tropical Indian Ocean. *Nature* 401:360–363
- Satyamurty P, Wanzeler CP, da Costa A, Manzi O, Candido LA (2013) A quick look at the 2012 record flood in the Amazon Basin. *Geophys Res Lett* 40:1396–1401. doi:10.1002/grl.50245
- Sikka DR, Gadgil S (1980) On the maximum cloud zone and the ITCZ over Indian longitude during the southwest monsoon. *Mon Weather Rev* 108:1840–1853

- Sikka DR, Narasimha R (1995) Genesis of the monsoon trough boundary layer: boundary layer experiment (MONTBLEX). *Proc Indian Acad Sci* 104:157–187
- Singh D, Tsiang M, Rajaratnam B, Diffenbaugh NS (2014) Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nat Clim Change* 4:456–461. doi:[10.1038/nclimate2208](https://doi.org/10.1038/nclimate2208)
- Swapna P, Krishnan R, Wallace JM (2014) Indian Ocean and monsoon coupled interactions in a warming environment. *Clim Dyn* 42:2439–2454
- Tokinga H, Xie S-P, Deser C, Kosaka Y, Okumura YM (2012) Slow-down of the walker circulation driven by tropical Indo-Pacific warming. *Nature* 491:439–443. doi:[10.1038/nature11576](https://doi.org/10.1038/nature11576)
- Vellore RK, Krishnan R, Pendharkar J, Choudhury AD, Sabin TP (2014) On the anomalous precipitation enhancement over the Himalayan foothills during monsoon breaks. *Clim Dyn*. doi:[10.1007/s00382-013-2024-1](https://doi.org/10.1007/s00382-013-2024-1)
- Wang B, Rui H (1990) Synoptic climatology of transient tropical intraseasonal convection anomalies: 1975–1985. *Meteorol Atmos Phys* 44:43–61
- Winton M (2000) A reformulated three-layer sea ice model. *J Atmos Ocean Technol* 17:525–531
- Zhou T-J, Yu R-C (2005) Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. *J Geophys Res* 110:D08104. doi:[10.1029/2004JD005431](https://doi.org/10.1029/2004JD005431)