



# Indian summer monsoon features in the NCEP analysis and forecast system

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The diagnosis of the summer monsoon features over India are investigated using global analysis and forecast system (GFS) of the National Center for Environmental Prediction (NCEP). In addition, the performance of the NCEP GFS model in capturing the observed rainfall variability of the summer monsoon features over India through diagnostic parameters. We delineate the variability between two normal monsoon seasons with basic meteorological fields and significant parameters of kinetic energy, heat and moisture budgets. The 1200 UTC operational analyses and forecasts (day1 through day5) data for summer monsoon seasons of June, July, August and September (JJAS) of 2010 and 2011 are considered. Although both are normal monsoon seasons with seasonal rainfall (JJAS) departure of about  $-3.1\%$  and  $2.1\%$  respectively, during 2010 and 2011, some differences are observed in the spatial distribution of rainfall. The diagnostic fields reasonably reproduced the variations in analyses and forecast fields of up to 5 days. The model forecasts of day1 delineated that the Indian summer monsoon features are well captured, whereas in day3 and day5, forecast depicts some differences. Overall the NCEP analysis and forecast fields not only produces mean monsoonal flow, but also captures seasonal variability realistically. This is evident from the large-scale balances represented by the analyses and model forecasts.

**Keywords.** Summer monsoon; seasonal variability; NCEP analysis and forecast; kinetic energy; heat and moisture.

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## 1. Introduction

Each year Indian summer monsoon is beautifully illustrated as regional scale anomalies in general circulation of the atmosphere. Predicting monsoon rainfall is a challenging task due to the complex interaction between convective systems and large-scale monsoonal flow. Yield in agriculture sector is very much dependent on health of the monsoon; in a good monsoon year crop production increases while a bad monsoon season brings deficit rainfall resulting in reduction in crop produce (Webster

and Yang 1992). It is therefore very important to have a seasonal outlook of the monsoon season with the comprehensive understanding. It is also important to understand the interannual variability of the seasonal monsoon rainfall. State of the monsoon climate can be characterized using climatological gradients of winds, temperature and moisture. Horizontal and vertical gradients of these parameters can cause thermodynamic and hydrodynamic instabilities. Energy is derived from the mean circulation for initiation of disturbance. Both the internal dynamics and large-scale boundary

parameters (e.g., sea surface temperature, soil moisture and snow, etc.) change in seasonal rainfall (Shukla 1987). Therefore, it is important to analyze diagnostic aspects of boundary conditions to understand variability of summer monsoons.

Numerous studies have been carried out on the diagnostic aspects of the atmosphere, albeit, a few are associated to the summer monsoon (Chu *et al.* 1981; Kung and Tanaka 1983; Sardeshmukh and Held 1984; Raju *et al.* 2005; Raju and Bhatla 2014) through the analysis of kinetic energy, heat and moisture budgets. Few studies focused on the contrasting features of extreme years and illustrated the variability using various meteorological fields at synoptic scale (Krishnamurti *et al.* 1989, 1990; Ramesh *et al.* 1996; Raju *et al.* 2002, 2010). Nevertheless, there is limited modeling and observational study, which highlights the differences between the normal years. In this study, we address the diagnosis of seasonal variability and the model's ability to capture this feature. We demonstrate the manifestation of rainfall variations in terms of basic meteorological fields and energetics in the analysis and model forecast during summer monsoon over India. Further, the performance of the NCEP model in simulating the observed seasonal variability is elucidated through the analysis of kinetic energy, heat and moisture budget terms.

## 2. Methods and materials

The large-scale budgets are derived from the equations of motion and other conservation laws. In general, the time mean atmospheric circulation is a combination of a stable mean component, which varies slowly, and another rapidly varying eddy component. The circulations over the tropics are determined by the mean flow and extra-tropical flow patterns are driven by eddy flow. Since the circulations during summer monsoon over Indian subcontinent is primarily driven by mean component; therefore in this study, the time mean is separated into mean and eddy, respectively, and interpreted the mean part only. The budgets are estimated from the daily analysis of 12 UTC and forecast fields up to 5 days. The large scale budget equations are stated in the flux form with pressure as the vertical coordinate and given in Raju *et al.* (2002). The contributions from the respective eddy terms are insignificant. Therefore, in this study, the discussion pertains to the significant terms in

the budget equations of kinetic energy, heat and moisture, which are responsible for the advancement of the circulation over south Asian region during summer monsoon.

The National Center for Environmental Prediction (NCEP) has been producing medium range weather forecasts and available to the public for more than two decades. The data has been widely using around the globe for various downscaling application over specific regions. The comprehensive details of the model and its data assimilation techniques are documented in the various studies (Kanamitsu 1989; Parrish and Derber 1992; Parrish *et al.* 1997; Wang and Lei 2014). The 1200 UTC NCEP analyses and forecasts (day1 through day5) fields available at 1 degree horizontal grid for JJAS of 2010 and 2011 are used. We endeavoured to investigate this variability in the meteorological parameters and diagnostic fields. The basic meteorological fields of geopotential height, temperature, zonal wind, meridional wind and relative humidity are analyzed over the region covering from 15°S to 45°N and 30° to 120°E at 12 pressure levels from 1000 to 100 hPa.

A comparison of the vertical velocity obtained from the spectral statistical interpolation procedure in the NCEP with the vertical velocity derived using the kinematic technique (O'Brien 1970) renders that the Hadley cell is closer to the monsoon climatology. Therefore, we employ the kinematic technique using uninitialized wind with a limitation that the vertical velocity disappears at top and bottom of the atmosphere (i.e.,  $\omega = 0$  at  $P = 1000$  and 100 hPa). The consistency of the vertical motion thus computed represents Hadley circulation in a more realistic way over the tropics. The vertical velocity field computed using the kinematic technique is considered to estimate the significant terms of kinetic energy, heat and moisture budget. The centered difference scheme is used to estimate the various space derivatives and budget terms are computed at each grid points and

Table 1. Important features of the Indian summer monsoon of 2010 and 2011.

Monsoon	2010	2011
Onset	31 May	29 May
Withdrawal	27 September	23 September
Breaks	Nil	Nil
Rainfall (JJAS)	846 cm	881 cm
Depression	0	2

integrated vertically to analyse the net tropospheric distributions.

### 3. Brief description of seasonal feature of 2010 and 2011

The summer monsoon season (JJAS) of 2010 and 2011 were normal rainfall with slight variation in all India summer season rainfall departure of about  $-3.1\%$  and  $2.1\%$ , respectively. A brief description of various elements associated with the Indian summer monsoon season of 2010 and 2011 are illustrated in table 1. The normal dates of onset and withdrawal over India are 1st June and 13th September, respectively.

In order to evince the observed variability between the two years (2010 and 2011), the seasonal rainfall distribution over India is delineated in figure 1. The gridded observed rainfall derived from IMD revealed some similarities in 2010 and 2011 summer monsoon. The maximum zone of rainfall is noticed over the west coast of India and east Indian states during 2010 and 2011. The rainfall pattern is in agreement with the rainfall climatology of the summer season with the maximum over west coast and the Bay of Bengal. The rainfall pattern in 2010 denotes the maximum intensity of rainfall occurred over the North Telangana, Chhattisgarh, East Maharashtra and southern part of Madhya Pradesh. Also heavy rainfall observed over Uttarakhand and adjacent part of Uttar Pradesh. The rainfall distribution of 2011 summer monsoon season depicts the

maximum rainfall observed over central part of India (Madhya Pradesh and Gujarat). In all subsequent illustrations, the left and right column panels correspond to the monsoon seasons of 2010 and 2011, respectively. The left column four figures correspond to (a) analysis, (b) day1, (c) day3 and (d) day5 forecasts of JJAS 2010. Similarly, the right column four figures correspond to (e) analysis, (f) day1, (g) day3 and (h) day5 forecasts of JJAS 2011.

### 4. Results and discussion

Primarily, we intended to demonstrate the seasonal variation of the summer monsoon over India is diagnosed based on rainfall. Since rainfall is considered to be the end-product of any atmospheric phenomena, the diagnostic fields ought to capture the essential features in the rainfall. Further, when we simulate atmospheric systems of various scales, it is anticipated that the simulation retains the mean features of the systems. The numerical model performance is assessed based on realistic simulations of the mean and transient eddy components of the atmospheric phenomena. The synthesis of the objectives is to comprehend the seasonal variability and the performance of the model.

The information of the systematic errors of the operational model is crucial to interpret various forecast products (Mohanty and Ramesh 1995; Rao *et al.* 2003). The principal error characteristics are succinctly stated based on some meteorological

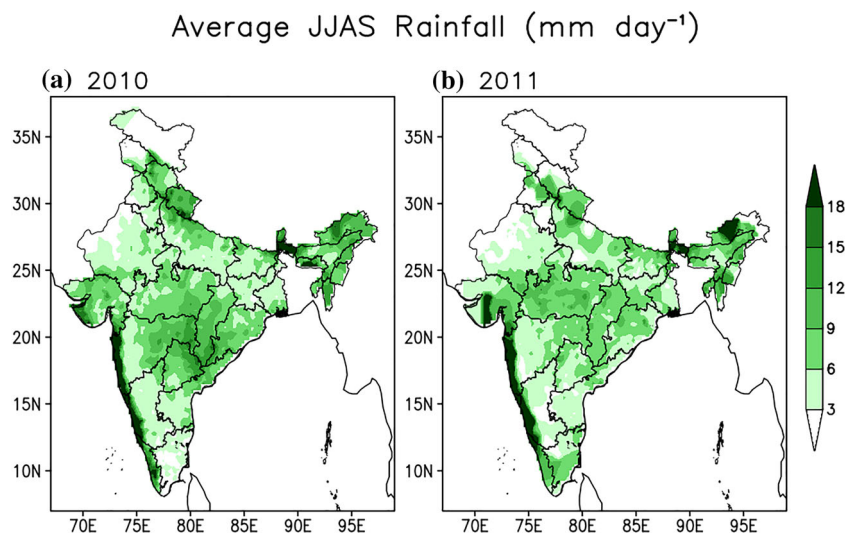


Figure 1. Spatial distribution of JJAS rainfall during (a) 2010 and (b) 2011.

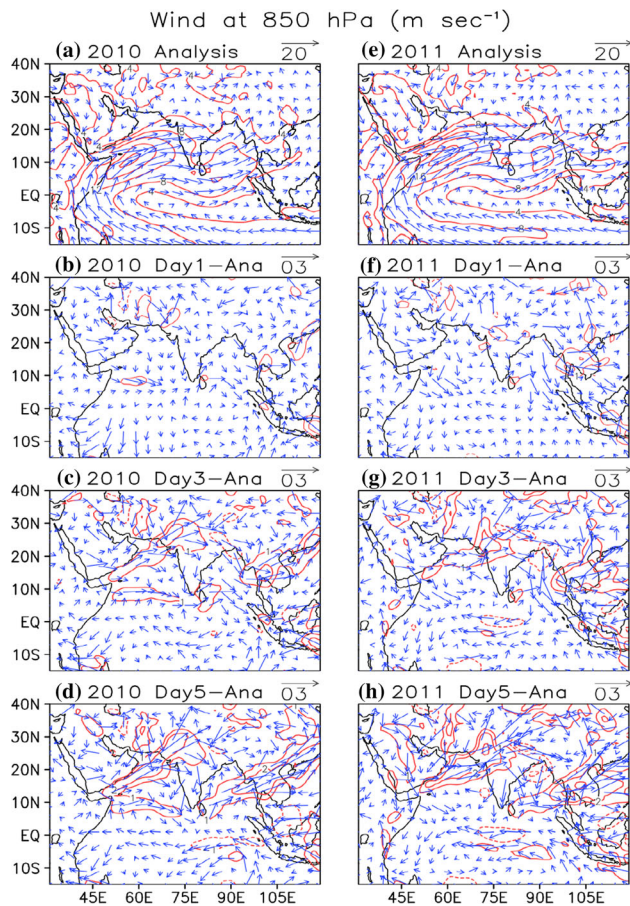


Figure 2. Geographical distribution of wind at 850 hPa (units:  $\text{m sec}^{-1}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

variables. Figure 2 represents the lower level circulation (850 hPa) for 2010 (left panel) and 2011 (right panel) summer monsoon season of analysis and forecast fields. The circulation patterns at 850 hPa reveal that low level (LLJ) feature are well represented in NCEP analysis in both 2010 and 2011 monsoon seasons. The difference in day1, day3 and day5 with respect to analysis field shows less bias; however, the bias increases with increase of forecast period.

The upper level circulation at 200 hPa (figure 3) illustrate that strong Tropical Easterly Jet (TEJ) noticed on 2010 and 2011, nonetheless the intensity of TEJ decreases in the forecast fields. It is also observed that bias in the wind field include weakening of Tibetan anti-cyclone, and increase of easterly wind in the forecast in the south equatorial region. It is noticed that the distribution of easterlies over south of equatorial region is more prominent in 2011 monsoon season as compared

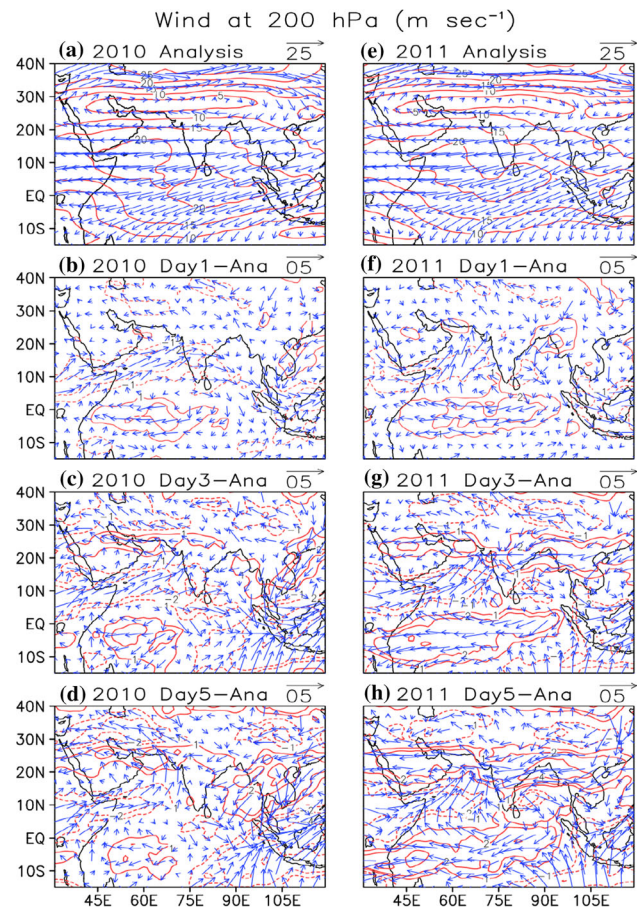


Figure 3. Geographical distribution of wind at 200 hPa (units:  $\text{m sec}^{-1}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

with 2010. Further, the temperature and specific humidity ( $\text{g kg}^{-1}$ ) at 925 hPa are presented in figures 4 and 5. The low level temperature (figure 4) during summer season of 2010 and 2011 reveals that the analysis captures the observed monsoon features that heat low over north west India, Tibetan high. In the forecast of day1, day3 and day5 show the warm bias in the low levels at 925 hPa with maximum over northwest India, whereas cold bias is observed over Gujarat and Western Ghat in day3 and day5 forecast. The higher cold bias also notices over west Arabian Sea and south equatorial Indian Ocean in the 2010 monsoon season as compared to 2011. The warm bias also observed at 500 hPa (figures not presented) in the forecast fields and this bias increases with the increase of forecast length. The specific humidity ( $\text{g kg}^{-1}$ ) at low level (925 hPa) depicts less bias in the day1 forecast against the analysis over the Indian region. Whereas day3 and day5

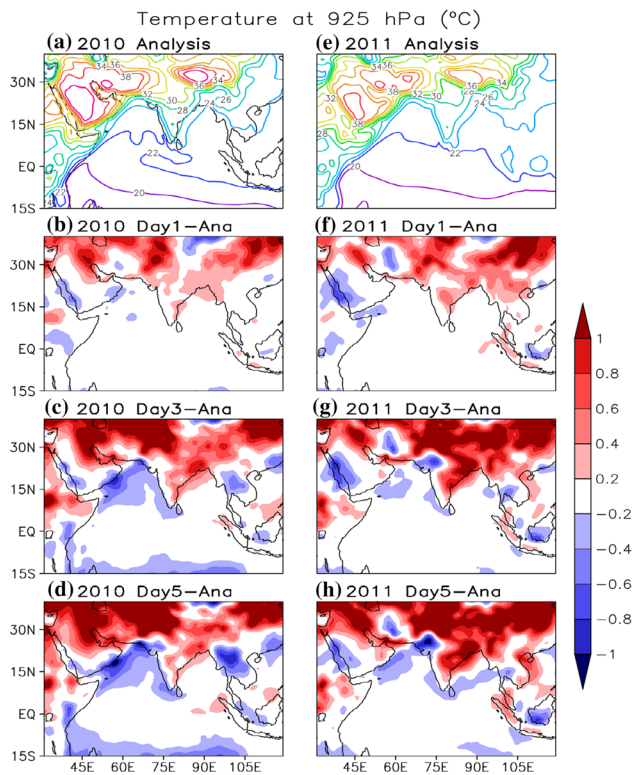


Figure 4. Geographical distribution of temperature 925 hPa (units: °C) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

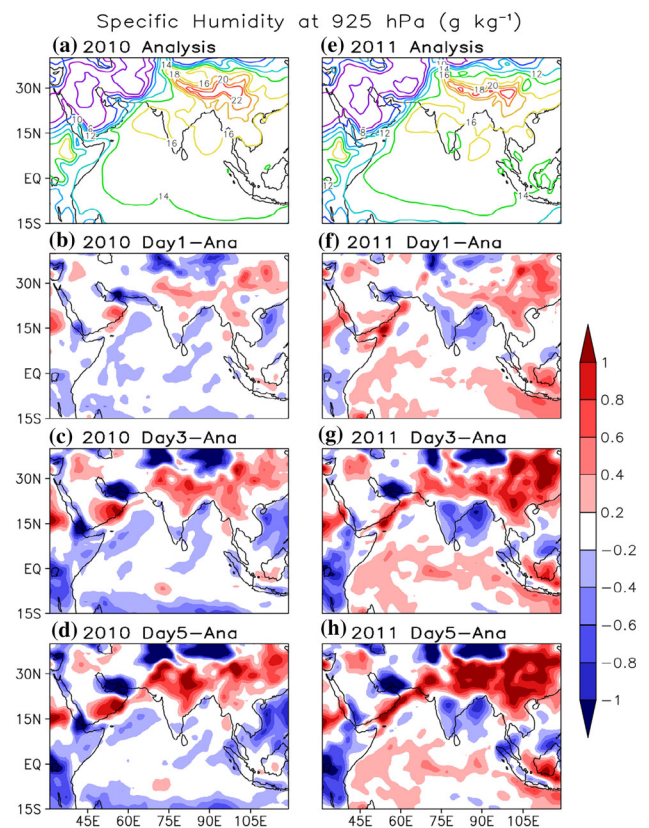


Figure 5. Geographical distribution of specific humidity (units:  $\text{g kg}^{-1}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

shows higher humidity over monsoon trough region in both seasons (figure 5). The excess evaporation over monsoon trough region in day3 and day5 forecast leads to the higher temperature (figure 4). The higher negative specific humidity ( $\text{g kg}^{-1}$ ) anomaly noticed in southern peninsular India during 2011 as compared to 2010 monsoon season in day3 and day5 forecast. The seasonal variability of the diagnostic fields, the significant terms in the kinetic energy, heat and moisture budget over the Indian summer monsoon domain and their association with rainfall are presented below.

#### 4.1 Kinetic energy budget

The intensity of the global circulation is determined by the balance between production and dissipation of kinetic energy. Further, the development and deterioration of the synoptic and subsynoptic scale atmospheric instabilities are strongly influenced by the rate of kinetic energy generation and dissipation. Thus, akin to some of the important processes in the fundamental energy cycle of the atmosphere, the generation and

dissipation of the kinetic energy are significant for better understanding of the large-scale atmospheric dynamics.

The large scale balance of kinetic energy over the Indian summer monsoon domain is controlled by three important terms, the horizontal flux divergence, adiabatic generation and frictional dissipation of kinetic energy. The horizontal flux divergence of kinetic energy for JJAS 2010 and JJAS 2011 is depicted in figure 6. The analysis of 2010 JJAS shows strong divergence flux over the eastern Arabian Sea, Bay of Bengal and the coast off east Africa. However, the Indian Ocean, North Arabian Sea and Persian regions delineate flux convergence. The flux divergence/convergence zones are associated with the TEJ entrance/exit. Earlier studies reveal that the maximum flux divergence over Bay of Bengal is stronger during normal and deficient monsoon years and the Arabian Sea maximum is stronger during surplus monsoon years (Mohanty *et al.* 2005). During the normal monsoon season, the sea surface temperature of the eastern Indian Ocean is warmer against

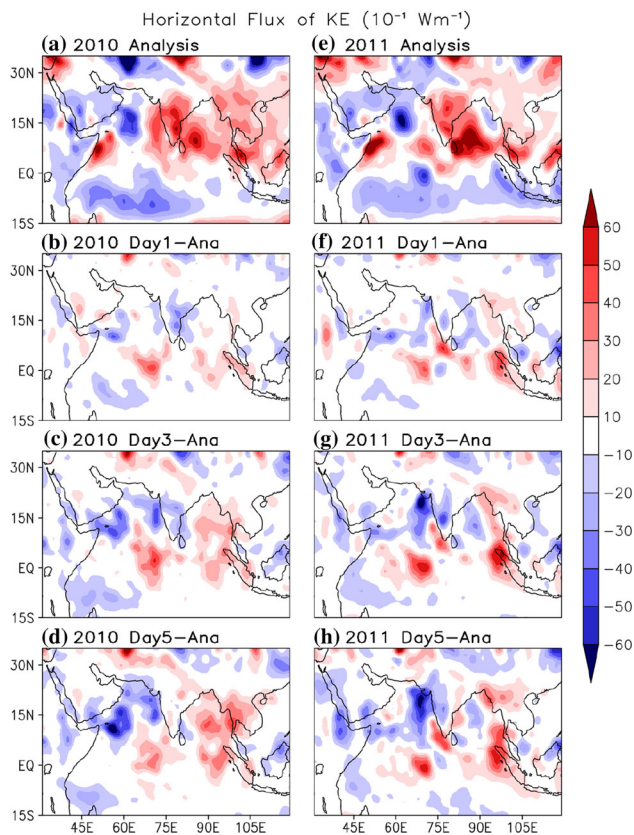


Figure 6. Geographical distribution of vertically integrated horizontal flux divergence of kinetic energy (units:  $10^{-1} \text{ Wm}^{-2}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

its western counterpart (Webster *et al.* 1999). Hence the maximum rainfall zone is located off Indonesia and adjoining Bay of Bengal. However, during excess monsoon season, this maximum shifts to the western Indian Ocean due to the anomalous warming (Raju *et al.* 2002). The flux divergence distribution of kinetic energy for 2011 (figure 6e) is in agreement with that of 2010. However, there are some differences noticed over east African divergence maxima, which is extended up to the southwest Arabian Sea during 2011. The stronger divergence flux over the Bay of Bengal is observed in 2011 as compared to 2010. The flux convergence is stronger over the north Arabian Sea and central and eastern Indian Ocean during 2011. The model forecasts for day1, day3 and day5 reveal the following features. The model reproduced most of the analyzed features, such as the Bay of Bengal, Arabian Sea and east African maximum divergence, the flux convergence zone over north Arabian Sea and west Indian Ocean. In general, the

flux divergence of kinetic energy is underestimated over Indian region in day1 (figure 6b and f) and day3 (figure 6c and g) forecasts. This is attributed to the systematic bias of the model, namely underestimation of southeasterly trade winds, in turn, underestimation of cross-equatorial flow. Nonetheless, the model retains most of the analyzed features by day5 over the Indian region and surrounding Bay of Bengal (figure 6d and h). The flux convergence maximum noticed over the south equatorial region in the analyses (figure 6a and e) is slowly growing in the model, with an increase in the forecast period. This may be due to the maximum convergence in the forecast fields as compared to analysis which may attribute to the stronger easterly flow at upper level. The flux convergence over north Arabian Sea is overestimating with an increase in the forecast period in 2010, whereas in 2011 it regains its analyses features in the forecast period. It completely got vanished by day5. Apparently, the cross-equatorial circulation systematically underestimated in the model forecasts destroys this essential feature. Despite that, the divergence flux over the Bay of Bengal is higher during 2010 as compared to 2011. This is also corroborated by the model forecasts in all ranges.

The adiabatic generation of kinetic energy for JJAS 2010 and 2011 is illustrated in figure 7. Positive values correspond to the production of kinetic energy from the available potential energy (APE) and negative values denote the transformation of kinetic energy back to APE. The adiabatic generation shows strong zones of kinetic energy production over the central Bay of Bengal, India, eastern Arabian Sea and off east Africa. These zones are identical to the horizontal flux divergence of kinetic energy. The zones of maximum adiabatic generation of kinetic energy over the Bay of Bengal and East Africa are very crucial for the advancement and strengthening of the summer monsoon circulation, as the former corresponds to the entrance of TEJ and the latter to the entrance of the LLJ. The strong LLJ and TEJ most likely beget the excess rainfall during the summer monsoon. The zonal and meridional parts of adiabatic generation of the kinetic energy (figures not shown here) contribute for production over the Arabian Sea and Bay of Bengal, respectively, and contributing to the generation of kinetic energy which is a unique feature confined to the monsoon over India. Except for small pockets over the western Indian Ocean and

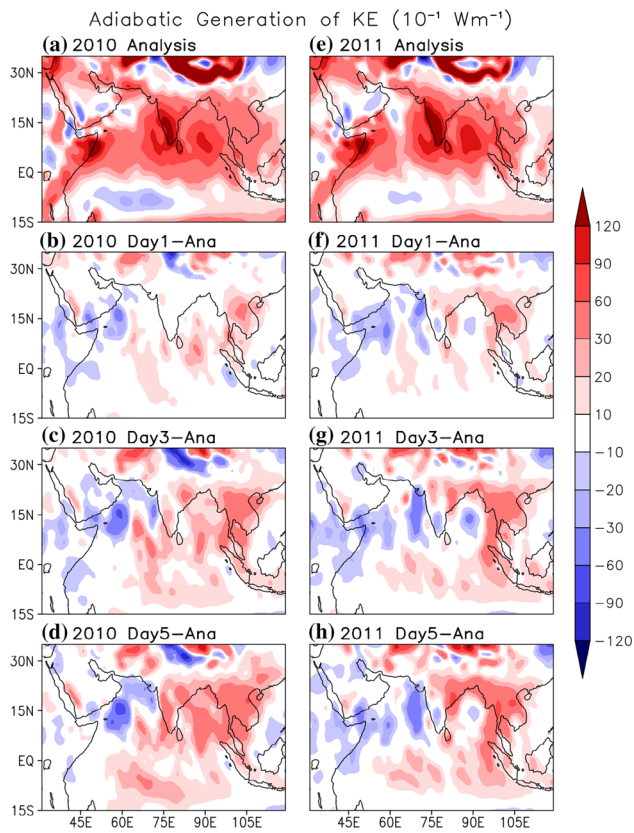


Figure 7. Geographical distribution of vertically integrated adiabatic generation of kinetic energy (units:  $10^{-1} \text{ W m}^{-2}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

Arabia, the entire monsoon domain indicates predominant generation of kinetic energy. The geographical distribution of kinetic energy production delineated by the analyses during 2010 and 2011 are similar except for a slight difference over the Indian subcontinent. The production maximum was very intense during 2011 compared to that of 2010. The model forecasts capture these features in all ranges of forecasts. In the case of 2010, the model produces realistic features in day1 forecast, albeit slightly overestimate the generation of kinetic energy over peninsular India in day3 and day5 forecast. Whereas in 2011, the adiabatic generation of kinetic energy over off East African Coast and Indian peninsular region is underestimated in day1 to day5 forecasts due to the systematic biases elucidated earlier. The model captured the seasonal variability in terms of adiabatic generation reasonably well. Further, the model captures the maximum generation during 2010 over the Bay of Bengal, compared to 2011 realistically. The large-scale balance of kinetic

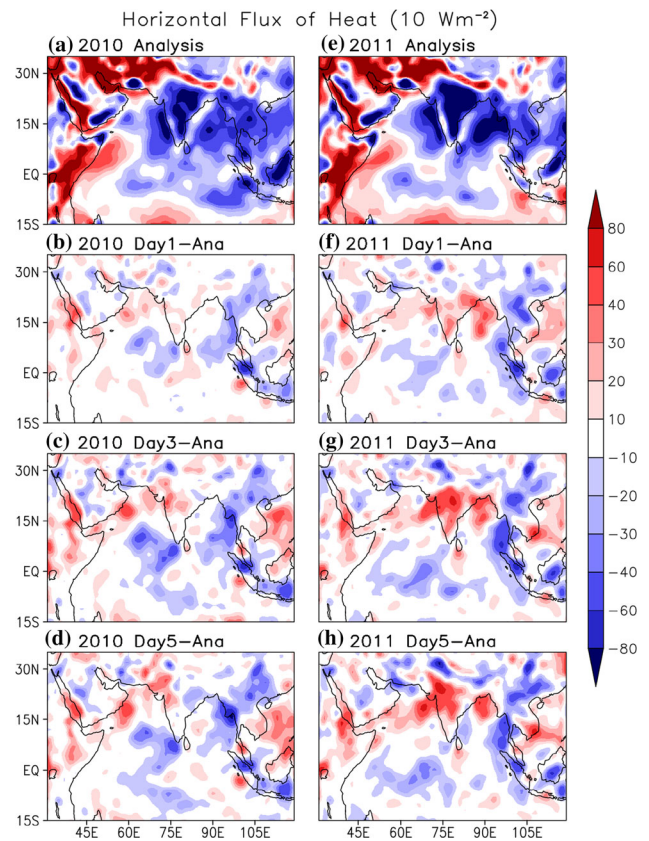


Figure 8. Geographical distribution of vertically integrated horizontal flux of heat (units:  $10 \text{ W m}^{-2}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

energy indicates that the summer monsoon domain is characterized as the source. Kinetic energy is generated over the Indian summer monsoon region and horizontally transported out of the domain. This feature is evident in the forecasts also. Further, the seasonal variability in the kinetic energy balance terms is in agreement with the observed variability in terms of rainfall.

As noticed from the large scale balances of kinetic energy, the model captured the seasonal mean summer monsoon features in the analyzed and model forecasts reasonably well during 2010 and 2011. Evidently, these two are normal monsoon years with more intensity over the Bay of Bengal delineated by various terms in the budgets. The model forecasts captured this essential signature, despite underestimating various parameters in the large-scale balances. Further, this is in close agreement with the ground truth in terms of observed seasonal rainfall. The model essentially captured the observed variability in the analysis and forecasts.

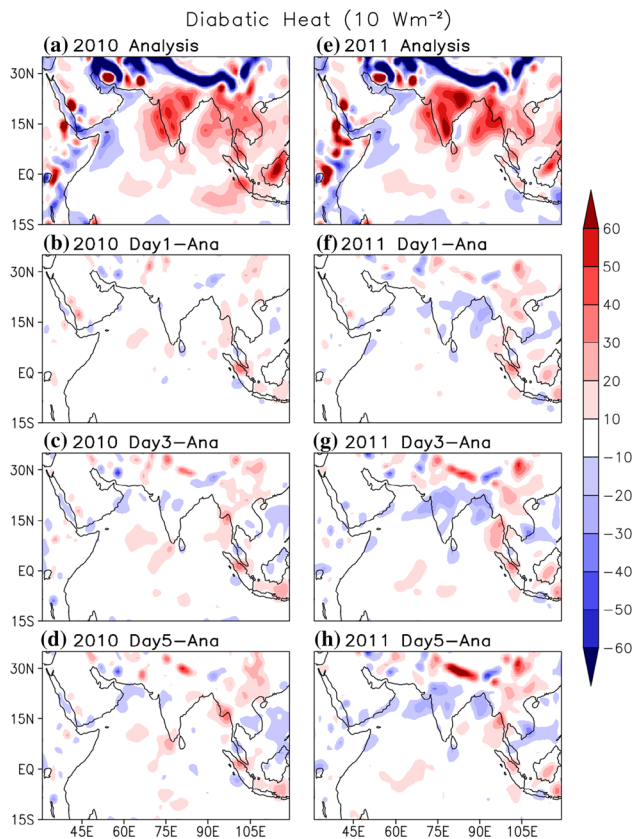


Figure 9. Geographical distribution of vertically integrated diabatic heat (units:  $10 \text{ W m}^{-2}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis and for JJAS 2011, (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

#### 4.2 Heat and moisture budget

The horizontal heat flux of vertically integrated from 1000 to 100 hPa is illustrated in figure 8. The convergence flux of heat is dominated over the entire monsoon region with maxima over the Bay of Bengal, Indian landmass and the Arabian Sea. The divergence maxima are noticed along the east African coast during 2010 and 2011 monsoon season. The forecasts evince an increasing tendency in the Arabian Sea (maximum).

The analysis of diabatic heating distribution reveals that the whole monsoon regions is observed as heat source during the monsoon period with maximum during 2011 as compared with 2010. In the forecast of day1 to day5, the heat sources are well predicting with a minimum bias, albeit a slight clod bias in day3 and day5 forecast during 2011 (figure 9g and h).

The horizontal moisture flux vertically integrated from 1000 to 100 hPa is elucidated in figure 10. The analysis of 2010 and 2011 denotes

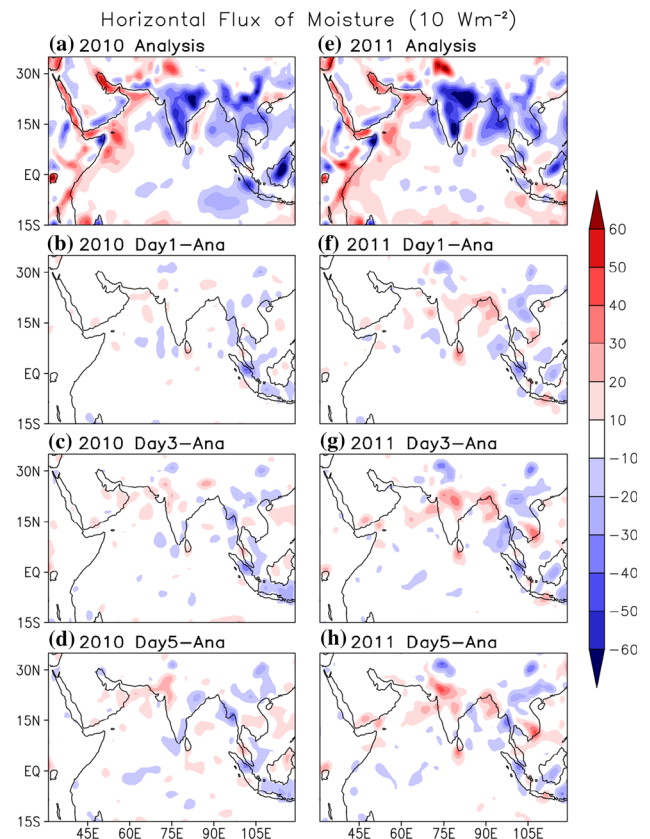


Figure 10. Geographical distribution of vertically integrated horizontal flux of moisture (units:  $10 \text{ W m}^{-2}$ ) for JJAS 2010 (a) analysis, (b) day1-analysis, (c) day3-analysis, (d) day5-analysis, and for JJAS 2011 (e) analysis, (f) day1-analysis, (g) day3-analysis, and (h) day5-analysis.

the flux convergence of moisture exist over the monsoon region with a maximum zone over the Bay of Bengal and the Arabian Sea. The coast of east Africa and north Arabian Sea receive maximum divergence flux of moisture. The forecasts from day1 to day5 depicts that the model mimic these features fairly well. Albeit, the entire Indian region depicted slight negative bias in the forecast against the analysis, i.e., the flux convergence decreases with increase of forecast period. Overall, the monsoon season of 2010, the model forecast shows less bias with slight decrease of flux convergence over northwest Indian region in day3 and day5 forecast (figure 10c and d). Whereas in 2011, monsoon season denotes the decrease of moisture flux convergence over the central Indian region and head Bay of Bengal. This moisture flux convergence provides the required net moisture over the monsoon region to sustain the maximum condensation that usually occurs over south Asia. Due to the variations of net moisture flux in the forecasts, the rainfall



predictions show corresponding variations. It appears that the moisture convergence plays a dominant role in controlling the diabatic heating patterns, which in turn maintain the south Asian monsoon circulation.

## 5. Conclusions

The analyses and model forecasts considered for the two monsoon seasons enunciate these aspects elegantly.

There is less bias in low level circulation in day1 with respect to analysis field, albeit, this bias increases with increase of forecast period. The forecast of day1, day3 and day5 show the warm bias in the low levels at 925 hPa with maximum over northwest India and monsoon trough region, whereas cold bias is observed over Gujarat and Western Ghat in day3 and day5 forecast. These warm bias in day3 and day5 are due to the higher specific humidity ( $\text{g kg}^{-1}$ ) over the monsoon trough region.

The balance requirements of the large-scale budgets are satisfied by both analysis and forecasts in various ranges. This is manifested in multitude of budget terms of kinetic energy, heat, and moisture during 2010 and 2011. The mean monsoon circulation is captured by the NCEP analyzes and forecast system fairly well. Nevertheless, it is underestimated in the day1 and day3 forecasts. However, by day5, the model retains most of the analyzed features. The interesting aspect of the study is the seasonal variability noticed in terms of rainfall. This variability is captured by analysis and model forecasts realistically in terms of diagnostic fields. It is demonstrated that the model effectuates the observed variability in the analyzed and forecast atmosphere over the summer monsoon domain reasonably well.

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## Author statement

P V S Raju: Conceptualization of the study, data processing and computations, manuscript preparation with support of co-authors. Akhilesh Mishra: Interpretation of the results and preparing first draft of the manuscript. A B T Sundari: Data processing and preparation of the figures.

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