Nat Hazards (2007) 42:287–300
DOI 10.1007/s11069-006-9089-7

ORIGINAL PAPER

Interannual variability of onset of the summer monsoon over India and its prediction

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Received: 10 June 2005 / Accepted: 24 September 2006 / Published online: 1 March 2007

Abstract In this article, the interannual variability of certain dynamic and thermodynamic characteristics of various sectors in the Asian summer monsoon domain was examined during the onset phase over the south Indian peninsula (Kerala Coast). Daily average (0000 and 1200 UTC) reanalysis data sets of the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) for the period 1948–1999 were used. Based on 52 years onset date of the Indian summer monsoon, we categorized the pre-onset, onset, and post-onset periods (each an average of 5 days) to investigate the interannual variability of significant budget terms over the Arabian Sea, Bay of Bengal, and the Indian peninsula. A higher difference was noticed in low-level kinetic energy (850 hPa) and the vertically integrated generation of kinetic energy over the Arabian Sea from the pre-onset, onset, and post-onset periods. Also, significant changes were noticed in the net tropospheric moisture and diabatic heating over the Arabian Sea and Indian peninsula from the pre-onset to the post-onset period. It appears that attaining the magnitude of 40 $m^2 s^{-2}$ and then a sharp rise in kinetic energy at 850 hPa is an appropriate time to declare the onset of the summer monsoon over India. In addition to a sufficient level of net tropospheric moisture (40 mm), a minimum strength of low-level flow is needed to trigger convective activity over the Arabian Sea and the Bay of Bengal. An attempt was also made to develop a location-specific prediction of onset dates of the summer monsoon over India based on energetics and basic meteorological parameters using multivariate

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statistical techniques. The regression technique was developed with the data of May and June for 42 years (1948–1989) and validated with 10 years NCEP reanalysis from 1990 to 1999. It was found that the predicted onset dates from the regression model are fairly in agreement with the observed onset dates obtained from the Indian Meteorology Department.

Keywords Interannual variability · Onset · NCEP/NCAR reanalysis · Regression technique

1 Introduction

The evolution, advancement (active/break or stagnation aspects), and retreat are the most important epochs associated with the summer monsoon over India as they essentially decide the duration of the summer monsoon and quantity of rainfall over different parts of the country. The evolution process of the summer monsoon over India is characterized by the intensification of low-level flow in the equatorial western Indian Ocean during the second half of May. With an increase in the low-level wind over the Indian Ocean there is an increase in surface moisture flux and the moisture content of the air increases, reaching a level sufficient to produce deep cumulus convection and latent heat release. This provides an additional heat source and the whole circulation continues to intensify through a positive moisture feed back leading to onset of monsoon over the Indian subcontinent (Mohanty et al. 1983), which occurs towards the end of May or in early June. Once the monsoon is established in June, the strong low-level flow over India is maintained throughout July and August.

It is well-recognized that the onset of summer monsoon is accompanied by distinct changes in the large-scale circulation and rainfall distribution over Indian landmass and adjacent oceanic regions. These include the northward displacement of the upper tropospheric westerly flow to the north of the Himalayas, establishment of the upper tropical easterly jet (TEJ) stream (Koteswaram 1958) and the lower tropospheric westerly jet (Somali jet) over the Arabian Sea (Findlater 1969). The intensification of the monsoon flow is mainly dictated by the release of convective instability and tropospheric diabatic heating (Krishnamurti and Ramanadhan 1982; Mohanty et al. 1983; Pearce and Mohanty 1984; Rao and Aksakal 1994). Murakami and Ding (1982) compared the large-scale circulation and temperature fields before and after the onset of the 1979 Indian summer monsoon. They found that the maximum warming took place over the Afghanistan/western Tibetan plateau region and over the east China Sea/Japan region. They emphasized the importance of diabatic heating over the Eurasian continent as a whole in establishing the summer monsoon circulation. Although, there is no precise definition of onset of the monsoon, Indian meteorologists conventionally identify the date of onset over Kerala Coast based on a sharp increase and characteristic persistency of the rainfall (Ananthakrishnan et al. 1968). In addition to the importance of the strength of the overall monsoon in a particular year, forecasting the onset and the sub-seasonal variability (active/break periods) is of particular importance. A late or early onset of the monsoon and untimely break periods in the monsoon rainfall may have devastating effects on agriculture even if mean rainfall in the monsoon season as a whole is normal.

Forecast of the onset date of the summer monsoon over India will help in appropriate planning for agriculture and resource distribution. Several studies have been carried out to predict Indian summer rainfall based on statistical methods (Shukla and Mooley 1987; Gowarikar et al. 1989; Thapliyal and Kulshrestha 1992; Kumar et al. 1992; Timothy and Shukla 2002). However, very few studies have reported on the prediction of the onset date of the summer monsoon over India. Subbaramayya et al. (1987; 1990) developed the regression equation for the prediction of the onset date over different parts over India using wind field. Ramesh et al. (1996) determined the onset date of monsoon over the southern tip of the Indian peninsula during 1995 based on kinetic energy and net tropospheric temperature. These studies were restricted to a limited number of parameters involved in the prediction of the onset date of the Indian summer monsoon. In this study, we investigated the interannual variability of significant budget terms during the summer monsoon over India. Furthermore, an attempt was made to predict the onset date over India (Kerala coast) based on multivariate regression techniques. The data and methodology are briefly described in the next section, followed by the results and discussion of interannual variability of the summer monsoon onset and its prediction over the Kerala coast based on multiple regression analysis. Finally, a summary of the results is presented.

2 Data and methodology

The NCEP (National Centre for Environmental Prediction) reanalysis project (Kalnay et al. 1996) was based on an advanced Global Data Assimilation System (GDAS), which utilized data from diverse sources for the period 1948–1999. The daily average (00 and 12 UTC) reanalysis data sets produced at NCEP with a horizontal resolution of 2.5° on a regular latitude/longitude grid were processed for the Asian summer monsoon domain (30° E–120° E; 15° S–45° N). Based on the onset dates of the Indian summer monsoon over southwest Kerala coast (Ananthakrishnan and Soman 1988, 1989), we have categorized the onset phase into three sub-phases, viz. the pre-onset, onset, and post-onset periods in each annual cycle. Two days before and 2 days after the reported date of onset (5 days) are considered the onset period. The pre-onset and post-onset periods are considered respectively for 5 days before and 5 days after the onset period. The basic meteorological fields considered for the study include geopotential height (Z), horizontal wind (u and v), temperature (T), and specific humidity (q) at 12 pressure levels (1,000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, and 100 hPa). In order to avoid the problems with the divergent wind, the vertical velocity fields in this study have been computed from horizontal wind components (u and v) by using the kinematic method as suggested by O'Brien (1970). The vertical velocity distribution obtained from the kinematic method delineates realistic Hadley circulation over the monsoon domain, compared with the archived field. In this technique, the divergence is adjusted to its vertically integrated value zero in the entire column of the atmosphere. The budget equations obtained from the prognostic and diagnostic equations of the atmospheric model are based on simple mathematical transformations and represented in the flux form with pressure as the vertical coordinate (Mohanty and Ramesh 1994). The vertical integration of the budget equation with the boundary condition that vertical motion vanishes at the bottom and the top of the atmosphere leads to the elimination of all the terms representing vertical flux divergences of various quantities.

3 Results and discussion

Using the rainfall from a dense network of raingauge stations over south and north Kerala, the date of the onset of the summer monsoon has been derived on the basis of subjective criteria by the Indian Meteorological Department (IMD). Table 1 represents the onset date of the summer monsoon over India. The onset dates are taken from published material of the IMD. Over a 52-year period (1948–1999), the mean onset date was 1 June with a standard deviation of 8 days. The earliest and most delayed onset dates were reported as 17 May (1962, 1969) and 18 June (1972) respectively. Based on the analysis of SST fields, Joseph et al. (1994) hypothesized that the delay in monsoon onset is due to the warm anomalies over the equatorial central Pacific Ocean causing delay in the shifting of convection from the equatorial western Pacific to the north Indian Ocean.

3.1 Interannual variability

The interannual variability of onset features of the summer monsoon were examined over the Arabian Sea (50° E–72.5° E; 5° N–15° N), the Bay of Bengal (82.5° E–97.5° E; 5° N–15° N), and the Indian landmass (72.5° E–82.5° E; 5° N–15° N) based on certain dynamical and thermodynamical budget terms. Figure 1 illustrates the kinetic energy at 850 hPa for the pre-onset, onset, and post-onset periods over significant sectors. The evolution of the onset of monsoon over India took place with a sharp increase in low-level kinetic energy (850 hPa). It shows that there was a significant difference in low-level kinetic energy over the Arabian Sea and the Indian peninsula from the pre-onset to the onset and post-onset periods. The clear contrast was also noticed over the Bay of Bengal in the pre-onset and post-onset periods. The interannual variability of the volume-integrated (1,000–100 hPa) generation of kinetic energy in various sectors are represented in Fig. 2. Over the Arabian Sea, a large difference in the adiabatic generation of kinetic energy was noticed from the pre-onset to the onset and post-onset periods. The Bay of Bengal sector demonstrated a clear difference in the pre-onset and post-onset periods. On the other hand, the Indian peninsula showed no such significant changes in the generation of kinetic energy during the monsoon onset process. It is emphasized that the Arabian Sea sector showed dramatic increase during the onset phase over India. Over a 52-year

Table 1 Onset date over the Kerala coast

Year	Onset date	Year	Onset date	Year	Onset date	Year	Onset date
1948	11 June	1961	18 May	1974	26 May	1987	02 June
1949	23 May	1962	17 May	1975	31 May	1988	25 May
1950	27 May	1963	31 May	1976	31 May	1989	03 June
1951	31 May	1964	06 June	1977	30 May	1990	19 May
1952	20 May	1965	26 May	1978	28 May	1991	02 June
1953	07 June	1966	31 May	1979	13 June	1992	05 June
1954	31 May	1967	09 June	1980	01 June	1993	28 May
1955	29 May	1968	08 June	1981	30 May	1994	28 May
1956	21 May	1969	17 May	1982	28 May	1995	08 June
1957	01 June	1970	26 May	1983	12 June	1996	03 June
1958	14 June	1971	27 May	1984	31 May	1997	09 June
1959	21 May	1972	18 June	1985	28 May	1998	02 June
1960	14 June	1973	04 June	1986	04 June	1999	25 May

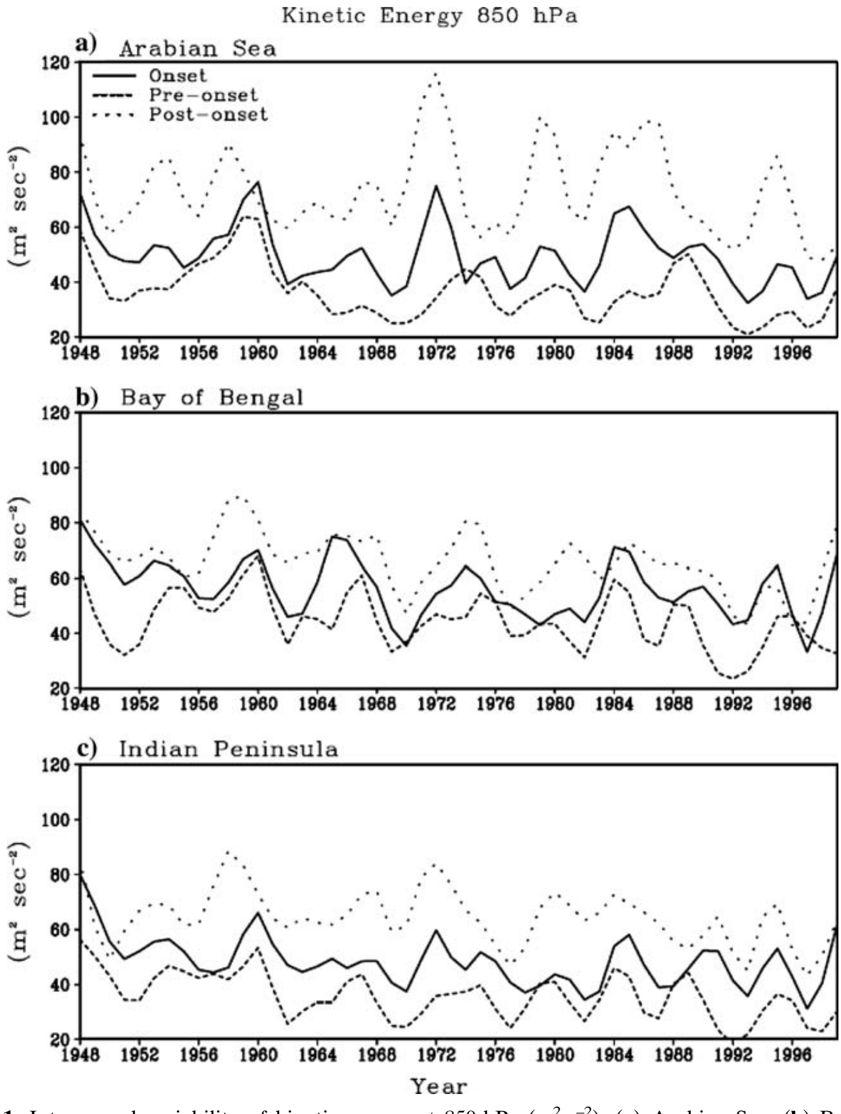

Fig. 1 Interannual variability of kinetic energy at 850 hPa ($m^2\ s^{-2}$). (**a**) Arabian Sea. (**b**) Bay of Bengal. (**c**) Indian peninsula

period (1948–1999), 11 years depicted a sudden jump in the low-level kinetic energy and generation of kinetic energy over the Arabian Sea. This was due to the strong westerly flow (low-level jet) over the Arabian Sea during the onset phase over Kerala. This low-level jet (Findlater 1969; Rao 1976) was an indicator of monsoon onset, was responsible for cross-equatorial flow, and carried moisture from the equatorial region toward the Indian subcontinent.

The evolution of the onset processes of the summer monsoon were examined by considering time and area averages over various regions such as the Arabian Sea (50° E–72.5° E; 5° N–15° N), the Bay of Bengal (82.5° E–97.5° E; 5° N–15° N), the

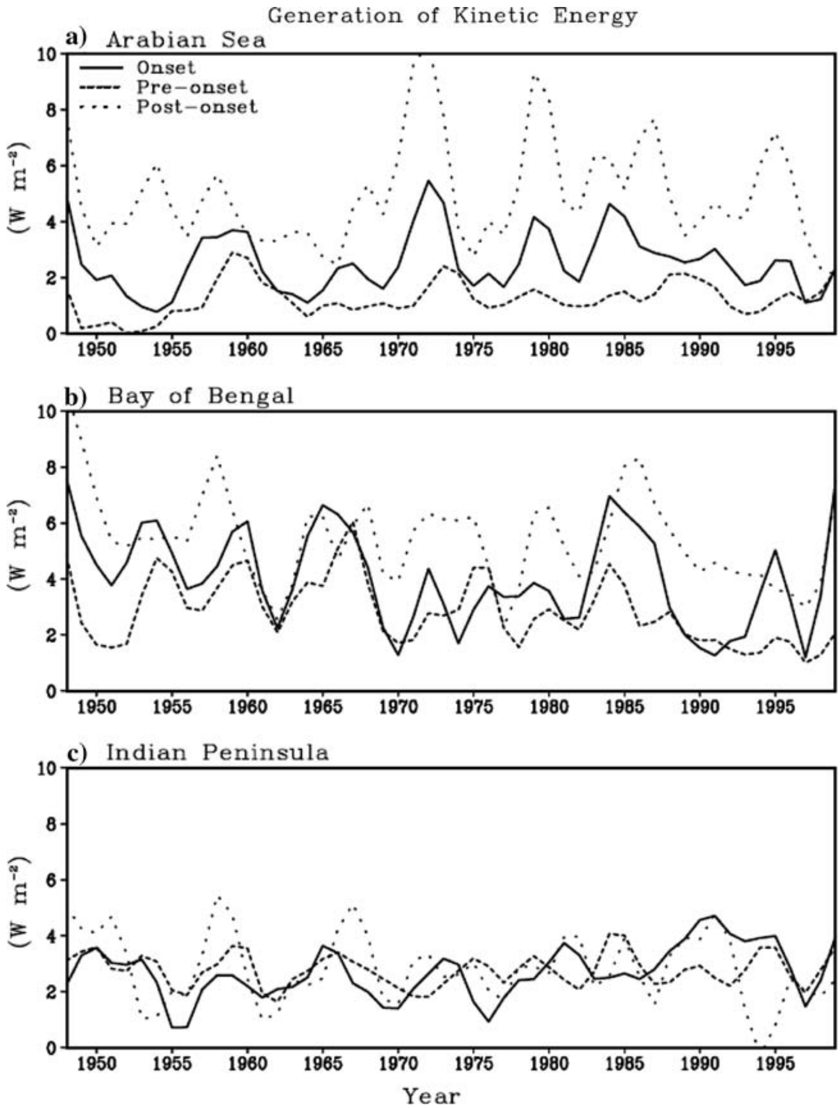

Fig. 2 Interannual variability of adiabatic generation of kinetic energy (W m^{-2}). (**a**) Arabian Sea. (**b**) Bay of Bengal. (**c**) Indian peninsula

Indian landmass (72.5° E–82.5° E; 5° N–15° N), the southwest equatorial Indian Ocean (42.5° E–75° E; 15° S–0° N), and the southeast equatorial Indian Ocean (75.5° E–100° E; 15° S–0° N). The kinetic energy budget term for the pre-onset, onset, and post-onset periods is illustrated in Table 2. The threshold value of low-level kinetic energy (850 hPa) for the onset phase was above 40 $m^2 s^{-2}$ in all these sectors. The kinetic energy further intensified over these regions in the post-onset period. It was noticed that the Arabian Sea, the Indian peninsula, and the Bay of Bengal are signified with intense low-level circulation from the onset to the post-onset periods compared with the other regions. The volume-integrated kinetic

Table 2 Volume-integrated kinetic energy budget terms during the onset phase of the summer monsoon over Kerala

Region	Kinetic energy (850 hPa) (m^{-2} s^{-2})			Generation of KE (W m^{-2})			Horizontal flux of KE (W m^{-2})		
	Pre-onset	Onset	Post-onset	Pre-onset	Onset	Post-onset	Pre-onset	Onset	Post-onset
Arabian Sea	36.5	49.7	73.2	12.6	25.5	49.9	–4.1	–2.4	4.7
Bay of Bengal	44.3	56.4	66.0	28.7	40.9	54.6	6.3	15.1	29.2
Indian peninsula	35.8	48.4	64.6	27.9	27.0	28.4	–3.0	5.6	–7.0
West equatorial Indian Ocean	35.9	41.3	47.2	13.7	15.0	11.0	–1.3	–4.1	–7.6
East equatorial Indian Ocean	36.3	40.2	39.7	19.8	20.5	18.8	3.5	2.4	1.0

energy generation over the Arabian Sea and the Bay of Bengal indicated strong generation from the pre-onset to the onset period and was further intensified in the post-onset period. Over the Indian landmass and the south equatorial Indian Ocean no significant changes in the generation of kinetic energy were depicted during the onset phase over Kerala. The volume-integrated horizontal flux divergence of kinetic energy demonstrated some interesting features. Over the Indian peninsula and the southwest equatorial Indian Ocean a flux convergence of kinetic energy was noticed that increased with the progress of the monsoon over India. On the other hand, over the Bay of Bengal and the east equatorial Indian Ocean a flux divergence of kinetic energy was noticed. However, the flux divergence increased over the Bay of Bengal and decreased over the southeast equatorial Indian Ocean from the pre-onset to the post-onset periods. In the Arabian Sea, the flux convergence was replaced by flux divergence in the post-onset period. However, the magnitudes of the Bay of Bengal region were stronger compared with those of the Arabian Sea. It was noted that the divergence flux of kinetic energy over the southeast equatorial Indian Ocean was shifted to the Bay of Bengal region and the flux convergence of kinetic energy was shifted from the southwest equatorial Indian Ocean to the Arabian Sea and Indian peninsula during the onset phase over India (Kerala coast).

The interannual variability of net tropospheric moisture and vertically integrated diabatic heating for three significant regions are presented in Figs. 3 and 4. The net tropospheric moisture (Fig. 3) over the Arabian Sea and the Indian landmass depict the build-up of net moisture in the evolution of the summer monsoon over India. The moisture gradually increased from the pre-onset phase to the post-onset phase. The moisture build-up over the peninsula was more indicative than that over the Arabian Sea. The Bay of Bengal region also showed the increase in net moisture from the pre-onset and onset periods. The diabatic heating (Fig. 4) over the Arabian Sea, the Indian landmass, and the Bay of Bengal showed that the convective activity increased during the evolutionary process of the summer monsoon over India. Interestingly, the Bay of Bengal experienced a higher magnitude of diabatic heating compared with the other regions. The onset features at various sectors were examined with the volume-integrated heat and moisture budget terms and are presented in Table 3. The net tropospheric moisture received above 40 mm in all five sectors during the onset phase over India (Kerala coast). Noteworthy changes with the evolution of the monsoon were noticed over the Arabian Sea, Bay of Bengal, and Indian peninsula. Over the equatorial Indian Ocean no significant

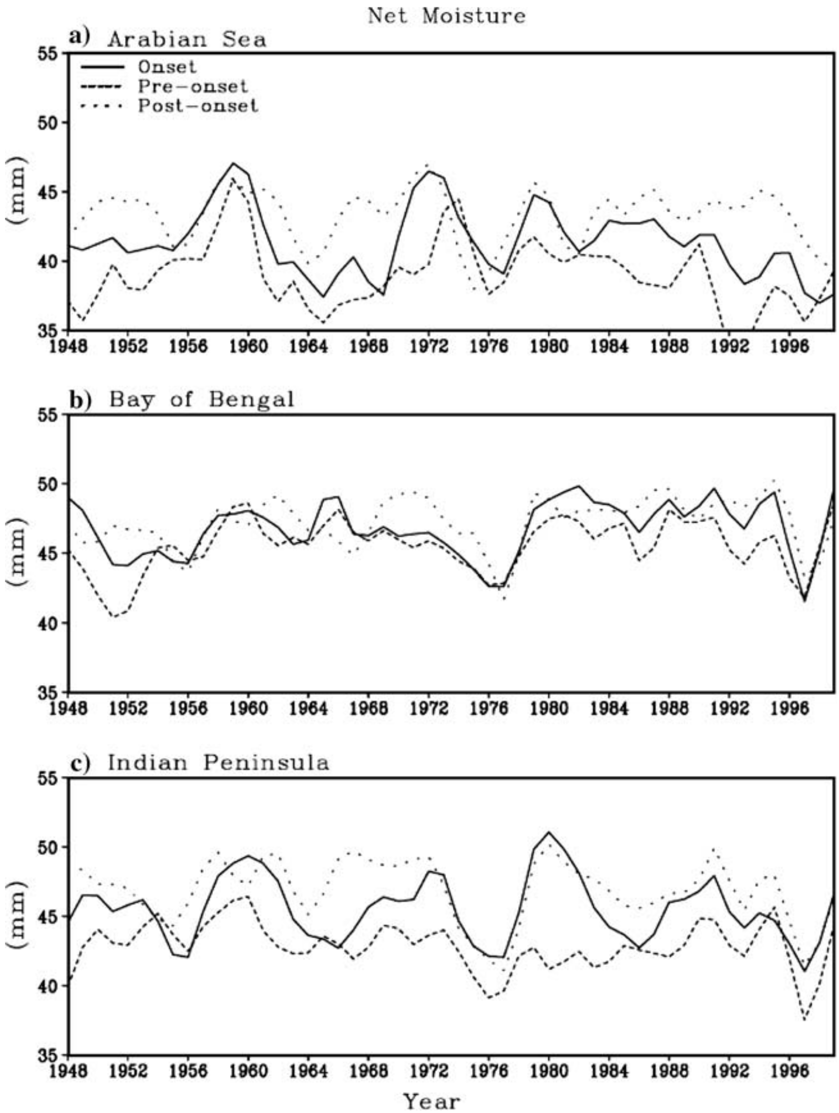

Fig. 3 Interannual variability of net tropospheric moisture (mm). (**a**) Arabian Sea. (**b**) Bay of Bengal. (**c**) Indian peninsula

changes occurred from the pre-onset to the post-onset period. It is expected that the south equatorial Indian Ocean, well before the onset over India, the net tropospheric moisture build-up takes place. After the intensification of low-level cross-equatorial flow, leading to the transport of moisture flux from this region to the Arabian Sea and finally to the Indian landmass, the net tropospheric moisture decreased in the onset and post-onset period. The diabatic heating pattern depicted that there was a sharp rise in the Arabian Sea, Bay of Bengal, and Indian peninsula from the pre-onset to the onset period. Overall, the Bay of Bengal received higher diabatic heating than the other sectors. Interestingly, there was a decrease in the trend

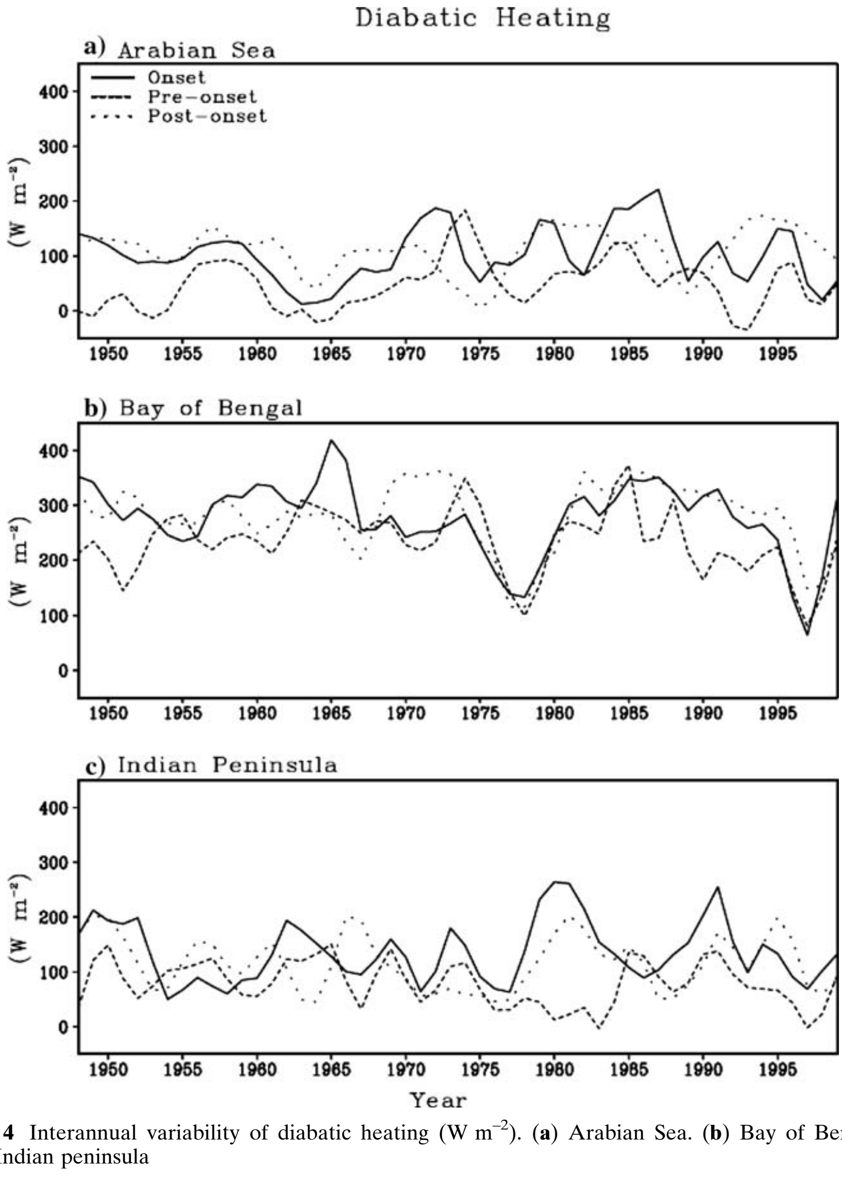

Fig. 4 Interannual variability of diabatic heating (W m^{-2}). (**a**) Arabian Sea. (**b**) Bay of Bengal. (**c**) Indian peninsula

toward diabatic heating from the pre-onset to onset period over the equatorial Indian Ocean and then an increase in the post-onset period. The horizontal flux divergence of heat showed a significant increase in flux convergence of heat from the pre-onset, onset, and post-onset periods over the Arabian Sea and Bay of Bengal. However, in the south equatorial Indian Ocean a decrease in the flux convergence of heat was demonstrated from the pre-onset to the post-onset period. The strong heating enhances the low-level cross-equatorial flow, and they may have be augmented further by precipitation and latent heat release over the Arabian Sea. These characteristics indicate the complexity of the diabatic forcing and the additional role

Table 3 Volume-integrated heat and moisture budget terms during the onset phase of the summer monsoon over Kerala

Region	Net moisture (mm)			Diabatic heating (W m^{-2})			Horizontal flux of heat (W m^{-2})		
	Pre-onset	Onset	Post-onset	Pre-onset	Onset	Post-onset	Pre-onset	Onset	Post-onset
Arabian Sea	40.0	41.4	43.3	47.0	103.7	110.1	–130.8	–276.4	–321.7
Bay of Bengal	45.6	46.8	47.2	233.8	276.2	280.2	–495.8	–590.5	–600.6
Indian peninsula	42.9	45.5	46.9	79.2	135.7	116.7	–148.7	–172.6	–94.3
West equatorial Indian Ocean	40.6	39.8	39.7	66.8	49.7	51.1	–95.1	–51.8	–54.5
East equatorial Indian Ocean	42.7	42.8	42.3	81.7	81.1	64.5	–135.4	–141.4	–107.2

of dynamic factors that influenced the summer monsoon. The Bay of Bengal sector denoted a gradual increase with the advance of the monsoon over India. The evolution of the monsoon onset processes started with the tropospheric moisture build-up that took place as a consequence of the intensification of low-level cross-equatorial flow, which enhances the surface moisture over the Arabian Sea. The convergence of moisture preceded heat over the Arabian Sea. Both, in turn, gave rise to profound cumulus convection and an increase in tropospheric diabatic heating. This led to the formation of a strong thermal gradient and enhanced the cross-equatorial flow regime, which manifested as an increase in low-level kinetic energy (Pearce and Mohanty 1984).

3.2 Onset prediction: hindcast skill

The statistical forecast equation was constructed based on multiple regression analysis with the stepwise elimination technique (Drapper and Smith 1981) for forecast of the monsoon onset date over India. The stepwise forward screening procedure is one of the most widely used techniques for selecting the predictors in the regression analysis, although principle component analysis can be used in identifying the suitable predictors. However, the disadvantage of this method is that it eliminates variables rather arbitrarily (there is no statistical test for the significance of the factor loadings) without ever having them in a position to determine their usefulness in explaining the variation in the dependent variable. The stepwise regression procedure combines forward selection with backward elimination. In the stepwise regression technique the predictors that explain maximum variance are selected from the set of potential predictors. Based on the subjective criteria by IMD, the onset dates of the Indian summer monsoon that have been reported over the Kerala coast (Table 1) were considered for the development of the regression equation. In the development of the forecast model, the value of the predictand (Y) is considered 1 in the event of the onset date occurring, otherwise 0. Hence the value of the predictand, Y, varies between 0 and 1. Based on this theory, the Y values were estimated for all the observations of the developmental sample. To develop the regression equation, the upper air parameters and energetics of 42 years (1948–1989) were used. For verification of the regression model, the independent data sets of 10 years (1990–1999) were considered. The re-estimated Y values were grouped into intervals of 0.1. For each group the probability of occurrence and non-occurrence of

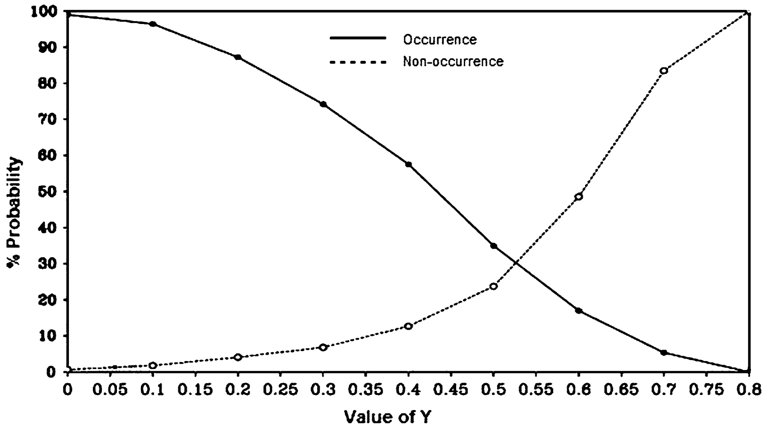

Fig. 5 Probability of the occurrence/non-occurrence of onset date over the Kerala coast using the regression model

onset dates over the Kerala coast were evaluated. The results are presented in Fig. 5, showing the forecast model with the best fitting curve. A cut-off point (where the curves representing occurrence and non-occurrence intersect) were chosen between 0 and 1 as given in Fig 5. The objective was to find the threshold Y value for deciding the cut-off value of Y for converting the probability forecast into a categorical forecast of occurrence or non-occurrence of onset dates. Thus, based on this critical value, the probability forecast was converted into a categorical Yes/No forecast. If the Y value was less than 0.54 the forecast was 'non-occurrence' (NO) and if Y was greater than or equal to 0.54 the forecast was considered as 'occurrence' (YES).

For the development of the statistical forecast model, the upper air parameters and energetics were utilized for the objective screening procedure to select the most appropriate predictors. For forecasting the onset date over the Kerala coast, area-averaged predictors for five significant regions such as west equatorial Indian Ocean, south Arabian Sea, north Arabian Sea, Indian peninsula, and Bay of Bengal were also used. In this study, a total of 285 potential predictors (Table 4) were subjected to screening in the forecasting of the onset dates over the Kerala coast. It was noted that nine significant parameters were selected in the formulation of the equation for the probability of onset date prediction over the Kerala coast. The predictors that are selected in the prediction equation and the correlations are given in Table 5. The multiple correlation coefficients are 0.60.

The regression equation is

$$\begin{aligned} \mathrm{Y} = {} & 0.3803 + 0.00839 * X_1 + 0.048622 * X_2 - 0.07435 * X_3 + 0.014596 * X_4 \\ & + 0.030492 * X_5 + 0.043827 * X_6 - 0.01769 * X_7 - 0.025369 * X_8 \\ & + 0.013686 * X_9 \end{aligned}$$

where X_1, X_2, X_3, X_4 … are the significant predictors given in Table 5.

The first predictor selected was the zonal wind at the 850-hPa level over the south Arabian Sea and the predictor contributed positively to occurrence. This indicates that a higher value of westerly flow over this region was responsible for the occurrence of the predicted onset date. The second predictor was the vertically integrated

Table 4 List of predictors used in this study

Predictors	Levels (hPa)	Regions
Basic parameters		North Arabian Sea,
Zonal wind	1,000, 925, 850, 700, 600,	south Arabian Sea,
Meridional wind	500, 400, 300, 250,	Indian peninsula, Bay of Bengal,
Temperature	200, 150, 100 (12 levels)	west equatorial Indian Ocean
Specific humidity		
Diagnostic parameters		
Kinetic energy	850	
Generation of kinetic energy	1,000–100	
Horizontal flux of kinetic energy	1,000–100	
Net tropospheric moisture	1,000–100	
Enthalpy	1,000–100	
Horizontal flux of heat	1,000–100	
Conversion of available potential energy to kinetic energy	1,000–100	
Diabatic heating	1,000–100	
Horizontal flux of moisture	1,000–100	

Table 5 Correlation coefficient by the selected predictors for the prediction of onset date over Kerala

Predictors	Region	Levels (hPa)	Correlation coefficient
Zonal wind (X_1)	South Arabian Sea	850	0.12
Generation of kinetic energy (X_2)	South Arabian Sea	1,000–100	0.23
Divergence of kinetic energy (X_3)	Western Indian Ocean	1,000–100	–0.17
Net tropospheric moisture (X_4)	North Arabian Sea	1,000–100	0.20
Meridional wind (X_5)	Bay of Bengal	700	0.23
Meridional wind (X_6)	Indian peninsula	1,000	0.14
Net tropospheric moisture (X_7)	Western Indian Ocean	1,000–100	0.13
Meridional wind (X_8)	Bay of Bengal	300	0.12
Zonal wind (X_9)	South Arabian Sea	1,000	0.21

Multiple correlation coefficient = 0.60

adiabatic generation of kinetic energy over the south Arabian Sea, which contributed positively to occurrence. The positive generation of kinetic energy and with a sudden increase over the Arabian Sea (Fig. 2) was the indication of onset over the Kerala coast. The third predictor in the regression equation was the vertically integrated (1,000–100 hPa) horizontal flux divergence of kinetic energy over the western Indian Ocean. It contributed negatively to occurrence. The negative value showed that the flux convergence over the western Indian Ocean associated with the stronger cross-equatorial flow favored the occurrence of onset over India. The next predictor is the net tropospheric moisture over the North Arabian Sea, which contributed positively. This region is the main source of moisture for the monsoon activity over the Indian subcontinent. The low-level wind increased over the Indian Ocean during the second half of May, which enhanced the surface moisture flux and the moisture content of the air increased, reaching a level sufficient to produce deep cumulus convection and latent heat release. This provided an additional heat source and the whole circulation continued to intensify through positive moisture feed-back leading to the onset of the monsoon over the Indian subcontinent (Mohanty et al.

Table 6 Validation of onset date over Kerala with independent data

Years	Onset date	
	Observed (by the IMD)	Predicted
1990	19 May	18 May
1991	02 June	01 June
1992	05 June	27 May
1993	28 May	23 May
1994	28 May	25 May
1995	08 June	07 June
1996	03 June	30 May
1997	09 June	29 May
1998	02 June	03 June
1999	25 May	23 May

1983). It was also noted that the net tropospheric moisture over the western Indian Ocean contributed positively to the prediction of onset over India. Furthermore, the meridional wind at 700 and 300 hPa over the Bay of Bengal, and over the Indian peninsula at 1,000 hPa contributed positively to the occurrence of the predicted onset over India.

The performance of the regression model for forecasting the onset date over the Kerala coast was evaluated using the independent data sets of May and June from the NCEP reanalysis for the period 1990–1999. Table 6 shows the onset dates observed and predicted by the model over the Kerala coast from 1990 to 1999. It is noticed that in six out of ten cases, the predicted onset dates were fairly in agreement with the dates observed by the IMD.

4 Conclusion

The study broadly addresses the significant aspects of the interannual variability of the onset of the summer monsoon and its prediction over the southern tip of India. In the Arabian Sea, the low-level kinetic energy (850 hPa), and the vertically integrated generation of kinetic energy shows significant differences in the pre-onset, onset, and post-onset periods. The threshold value of kinetic energy (850 hPa) during the onset period is 40 $m^2 s^{-2}$ over the summer monsoon domain. The interannual variability of the net tropospheric moisture over the Arabian Sea and the Indian peninsula depicted the build-up of net moisture in the evolution process of the summer monsoon over India. Furthermore, the large convective activity was noticed over the Bay of Bengal compared with the Arabian Sea and the Indian peninsula. The study delineates that in addition to a sufficient level of the net tropospheric moisture (above 40 mm) a minimum strength of low-level flow was needed to trigger the convective activity over the Arabian Sea and the Bay of Bengal.

The present study revealed that the low-level kinetic energy, generation of kinetic energy, and net tropospheric moisture can be used as potential predictors for the possible onset of the summer monsoon over India. The regression technique has been developed with the data from the months of May and June over 42 years (1948–1989) and tested with independent data sets of NCEP analysis for 1990–1999. The results indicated that the predicted onset dates were in good agreement with the onset dates reported by the IMD.

Acknowledgements The authors sincerely acknowledge the NCEP/NCAR for providing the reanalysis data sets for this study. The authors are grateful to the anonymous referees for their constructive comments, which helped to improve the quality of this work.

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