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Role of southern hemispheric equatorial trough in the development of Indian summer monsoon

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सार – प्रस्तुत शोधपत्र में भारतीय ग्रीष्मकालीन मानसून वर्षा (आईएसएमआर) का पूर्वानुमान लगाने में दक्षिणी गोलार्ध के भूमध्यरेखीय गर्त (एसएचईटी) पर आउटगोइंग लॉन्गवेव रेडिएशन (ओएलआर) की उपयोगिता की की जांच करने का प्रयास किया गया है। एसएचईटी और आईएसएमआर के बीच विलंबित सहसंबंध के अध्ययन के लिए अध्ययन में विश्लेषण किए गए दैनिक ओएलआर डेटा की गणना जून-सितंबर में साप्ताहिक आधार पर की जाती है। आईएसएमआर के दीर्घ अवधि पूर्वानुमान और इसके सत्यापन के लिए एक मॉडल विकसित करने के लिए 30 वर्षों वर्षों (1981-2010) की अवधि के लिए ओएलआर डेटा का उपयोग किया गया है। हालांकि, एसएचईटी हमेशा 400 ई से से 1000 ई के अपने पूरे क्षेत्र में सक्रिय नहीं होता है। पूरे भारत में वर्षा की परिवर्तनशीलता पर इसके पश्चिमी और पूर्वी भागों में SHET गतिविधिकी सापेक्ष भूमिका की तुलना करने के लिए, SHET क्षेत्र को तीन भागों में विभाजित विभाजित किया गया है: पश्चिमी SHET (WSHET) (-5° से -150°, 40°-60° E), मध्य SHET (CSHET) (-5° से -15° S, 60°-80° E) और पूर्वी SHET (ESHET) (-5 ° से -15° S, 80°-100° E)। औसत OLR की गणना हर 30 साल (1981-2010) में मौसम के 20 सप्ताहों के लिए WSHET, CSHET और ESHET क्षेत्रों में औसत से की गई थी। वर्तमान अध्ययन में, WSHET और CSHET का AISMR के साथ अच्छा नकारात्मक सहसंबंध (-0.52 और -0.55) था। तीन अतिरिक्त वर्षों (1983, 1988 और 1994) में SHET की महत्वपूर्ण विशेषताएं दर्शाती हैं कि मासिक और मौसमी पैमाने पर स्थानिक और लौकिक परिवर्तनशीलता OLR में उल्लेखनीय अंतर है। कम मानसून वाले वर्षों (1982, 2002 और 2009) के दौरान, यह देखा गया कि प्रशांत क्षेत्र के साथ-साथ दक्षिणी भूमध्यरेखीय हिंद महासागर में संवहन सामान्य सामान्य से अधिक था। कमी वाले वर्षों के दौरान, पूर्वी भूमध्यरेखीय हिंद महासागर SHET (ESHET) OLR का AISMR के साथ महत्वपूर्ण रूप से नकारात्मक सहसंबंध था, जबकि पश्चिमी भूमध्यरेखीय हिंद महासागर SHET (WSHET) OLR के साथ कोई महत्वपूर्ण सहसंबंध नहीं है।

ABSTRACT. An attempt has been made in the present paper to examine the usefulness of Outgoing Longwave Radiation (OLR) over Southern Hemispheric Equatorial Trough (SHET) in foreshadowing Indian Summer Monsoon Rainfall (ISMR) qualitatively during extreme ISMR (deficient or excess) years. The daily OLR data analyzed in the study are computed on weekly basis over June- September for the study of lagged correlation between the SHET and ISMR. For developing a model for Long Range Forecasting of ISMR and its verification OLR data for a period of 30 years (1981-2010) have been used. However, SHET is not always active across its entire zone of 40° E to 100° E. To compare the relative role of SHET activity in its western and eastern parts on the variability of rainfall over India as a whole, the SHET zone has been divided into three parts: Western SHET (WSHET) (-5° to -15° S, 40° - 60° E), Central SHET (CSHET) (-5° to -15° S, 60°-80° E) and Eastern SHET (ESHET) (-5° to -15° S, 80° - 100° E). The mean OLR was computed by averaging throughout the WSHET, CSHET and ESHET regions for 20 weeks of the season every 30 years (1981-2010). In the current study, WSHET and CSHET had a good negative correlation (-0.52 and -0.55) with AISMR. The significant features of SHET in three excess years (1983, 1988 and 1994) show that there is marked difference in the spatial and temporal variability OLR in monthly as well as seasonal scale. During deficient monsoon years (1982, 2002 and 2009), it was observed that convection was more than normal over Pacific region as well as over southern equatorial Indian Ocean. During deficient years, Eastern Equatorial Indian Ocean SHET (ESHET) OLR was significantly negatively correlated with AISMR whereas there is no significant correlation with Western Equatorial Indian Ocean SHET (WSHET) OLR.

Key words – Outgoing Longwave Radiation (OLR), Southern Hemispheric Equatorial Trough (SHET), Indian Summer Monsoon Rainfall (ISMR) and ITCZ.

1. Introduction

Satellite observed cloudiness has been extensively used in the study of ISM during the past four decades (Sadler, 1969; Saha, 1971; Prasad *et al*., 1978, 1981, 1983, 1988, 2000; Sikka and Gadgil, 1980; Yasunari, 1980, 1981; De *et al.,* 1995) and several others. Studies using cloud data by (Prasad *et al.*, 1978, 1981, 1983, 1988) had identified in general, an inverse relationship between the activity of Southern Hemispheric Equatorial Trough (SHET) and the performance of summer monsoon over India. De *et al.*, 1995 observed that the major epochs of breaks in the Indian monsoon coincide with the active SHET epochs. The existence of an inverse relationship between the strength of the Inter-Tropical Convergence Zone (ITCZ) over the warm waters of the equatorial Indian Ocean and continental ITCZ in the vicinity of the monsoon trough was also supported by (Vernekar and Ji, 1999). Studies on the breaks in southwest monsoon emphasize the propagation of low-frequency modes and middle latitude interactions. There are two-timescales that modulate monsoon activity (a) the 30-50-day time scale (Madden and Jullian, 1972; Sikka and Gadgil, 1980; Chowdhury *et al*., 1988a), (b) 10-20 day oscillation (Krishnamurti and Bhalme, 1976; Murakami and Frydrych, 1974).

As mentioned above, satellite observed cloudiness data from the Indian Ocean have been studied by several workers to improve our understanding of the development of the Southwest monsoon and its different phases. In this context, two results are important: (*i*) a slowly propagating south to north mode with a period of around 40 days (Madden & Jullian, 1972; Sikka and Gadgil, 1980; Yasunari, 1981) a maximum cloud zone which develops near and on either side of equator moves to 30 N at the rate of about 1 deg. Lat. per day. However, the period of this mode has been found to vary from year to year, becoming as large as 60 days in the deficient year (1972), (Yasunari, 1980; De *et al*., 1988; Prasad *et al*., 1988). Before this, an oscillation with a period of about 30 days in the wind field at 850 hPa level during SW monsoon had been reported by Dakshinamurti and Keshavamurti (1976). (*ii*) An inverse relationship between SHET and Monsoon Trough (MT).

The SHET had been first recognized as an important element of SW monsoon circulation by Prasad (1981, 1983). Earlier, the existence of an east-west oriented double convergence zones in the equatorial Indian Ocean during the SW monsoon season over Southeast Asia had been reported by several workers (Flletcher, 1945; Flohn, 1960; Koteswaram, 1960; Raman, 1965; Saha, 1971; Asnani, 1973). Prasad *et al*., 1983, 1988 and Johri and Prasad, 1990 had further confirmed the dominating role of SHET in the development of SW monsoon and its different phases. Intense convection in the zone of SHET causes considerable reduction in the cross-equatorial flow of SE trades of the Southern Hemisphere into the north Indian Ocean leading to weak monsoon circulation over India. On the contrary, when SHET is close to the equator and weak and allows the large cross-equatorial flow of SE trades in the north Indian Ocean, the SW monsoon is active (Prasad1981, 1983).

Studies mentioned above have demonstrated an important role of interaction of two equatorial troughs in the development of the SW monsoon and its different phases. Out of these two troughs, *i.e*., the Northern Hemispheric Equatorial Trough (NHET), which gets established over plains of north India as Monsoon Trough (MT) by July and SHET, the latter is found to play a dominant role in monsoon dynamics: intense convection in the zone of SHET results in weak monsoon conditions over India. Occurrences of tropical disturbances like Depressions, Deep Depressions, etc. in the north Indian Ocean were subdued during active SHET phases (De *et al*., 1995). Observations were made for eight years and it is found that 24 (73%) of systems originated in the Bay of Bengal when SHET was absent or weak. They also made two important observations in their study: (*i*) Low-pressure systems in the Northwest Pacific were not affected due to the activity of SHET. The SHET does not affect the strength of ITCZ in the NW Pacific therefore; there is no hindrance in the formation of typhoons in that region. (*ii*) During the years with longer duration of epochs of active SHET, Cross Equatorial Flow (CEF) is considerably reduced and therefore cyclo-genesis in the Bay of Bengal is highly subdued. Consequently, ISMR remains below normal over the Indian subcontinent.

Satellite observed cloudiness and associated Outgoing Long Wave Radiation (OLR) data from Indian Ocean have been studied in an effort to improve our understanding about the development of Indian Summer Monsoon (ISM) and its different phases. The present study focuses on convection over the SHET from the southern Indian Ocean region, in improving our understanding of the Indian summer monsoon and a model developed for preparing Long Range Forecast (LRF) of ISMR, using only OLR data. The categorization of monsoon used by IMD, *e.g*., Excess (ISMR - 111% or more), Normal (110% - 90%), and Deficient (89% or less) has been used here. Seasonal (June-September) and monthly (June, July, August & September) mean OLR data of three excess monsoons (1983, 1988 & 1994), three normal monsoons (1981, 1993, & 2007), and three deficient monsoons (1982, 2002 & 2009) have been presented for illustration. For developing a model for LRF of ISMR and its verification, OLR data for a period of 30 years (1981-2010) have been used.

2. Data and methodology

2.1. *OLR data*

Outgoing Longwave Radiation (OLR) is generally treated as the proxy of rainfall and is most coherent spatially. Its temporal variation is compatible with the parameters of atmospheric circulations such as pressure, temperature, geopotential height, etc. Many researchers used most frequently the long-term satellite-derived datasets of OLR (Gruber and Winston, 1978; Gruber and Krueger, 1984) for many aspects of climatological studies of tropical convection. The datasets have been used for monitoring and understanding the tropical circulation as well as regional climate change studies (Murakami, 1980; Liebmann and Hartmann, 1982; Liebmann and Smith, 1996; Horel *et al*., 1989), the studies of the ENSO phenomena (Gill and Rasmusson, 1983; Rasmusson and Wallace, 1983; Lau and Chan, 1988), the intraseasonal (30-60 day) oscillation (Weickmann, 1983; Weickmann *et al*., 1985; Lau and Chan, 1983) and the estimates of tropical precipitation (Arkin, 1984; Morrissey, 1986; Yoo and Carton, 1988). The satellite-derived OLR data have been used extensively by atmospheric scientists as an important component of the radiation balance of the atmosphere (Ohring and Gruber, 1982) as well as study of the changes in the amount, height and, vertical extent of the clouds. It may indicate both, the warmth of the Earth's surface and the condition of the atmosphere overhead. Warm surfaces radiate more in the long-wavelength region and the values of OLR are representative of the clouds in the atmosphere. The radiation coming from below the clouds gets trapped and the temperature of the cloud top heights determines the amount of longwave radiation measured at the top of the atmosphere (TOA).

The OLR at the top of the Earth's atmosphere is modulated mainly by two factors, *viz*., the cloud characteristic and the surface temperature both of which are correlated to precipitation to some varying degrees. The surface temperature varies modestly through the annual cycle over the tropics and hence the strongest variation in the OLR is largely modulated by the changes in the amount, vertical distribution, depth of the cloud, and the temperature at the top of the clouds (Xie and Arkin 1998). Clouds in the tropical atmosphere occur in a wide range of sizes starting from isolated cumulus to mesoscale large cloud clusters. It plays a major role in the vertical transport of energy from the planetary boundary layer to the upper troposphere (Willium and Houze, 1987). Most of the precipitation over the tropical region is associated with deep convection. This direct physical connection with clouds led to the use of OLR in quantitative precipitation estimation for the tropical areas where the total OLR fluxes are strongly modulated by deep convective clouds (Lau and Chan, 1983; Xie and Arkin, 1998; Arkin, 1984; Arkin and Ardanuy, 1989; Motell and Weare, 1987; Jonowiak and Arkin, 1991). Low annual mean OLR values (< 200 Wm^{-2}) associated with deep atmospheric convection are found over the equatorial landmass, Amazon basin, and in the western equatorial Pacific Ocean. OLR < 200 $Wm^{-2}$is associated with cold temperatures in the Himalayas. High annual mean OLR values (>280 Wm^{-2}) are observed over the central and eastern Sahara and Arabian Peninsula.

Water vapor is one of the important emitters of longwave radiation, knowledge of its concentration in the atmospheric vertical profile is necessary for solving the radiative transfer equation accurately. A moist atmosphere containing a high-water concentration will have a larger value of OLR than a dry atmosphere. The thermal structure of the atmosphere also plays significant a role as the temperature at the various layers is directly used in Stephan's Boltzmann equation in computing the OLR. Satellite measures the radiances and the measured radiances are converted into brightness temperature (T_{BB}). The brightness temperature (T_{BB}) is thus converted again to flux temperature T_F. This flux equivalent to blackbody temperature (T_F) is translated to the outgoing longwave emittance, known as the outgoing longwave radiation (OLR) with Stephan's Boltzmann Law,

$$F = \sigma^{*} T_F^{4}$$

where, $\sigma = 5.67051\times 10^{-8}$ $W/m^2/K^4$,

The radiative transfer model for 99 different atmospheres covering a broad range of temperature, humidity, and cloudiness is used for different Zenith angles (sec ɵ = 1.0, 1.25, 1.5,1.66, 1.75, 2.0, 2.25 and 2.5).

2.2. *Analysis of OLR data*

OLR data covering the Indian Ocean and western Pacific regions for the period 1981-2021 have been used in the study. Daily mean OLR values at 2.5° × 2.5° lat./long. grid was downloaded from Climate Diagnostics Centre's (CDC) website (www.cdc.noaa.gov). Weekly mean OLR values were prepared for the region bounded by 40° N-30° S and 40° E-130° W, covering the Indian Ocean and western Pacific. Weekly mean OLR anomalies were prepared from the daily mean for the base period of 1981-2010. Monthly and seasonal plots of OLR anomaly, for the months of June-September for three groups of the years, namely, excess, deficient, and normal have been prepared using GrADS software developed by

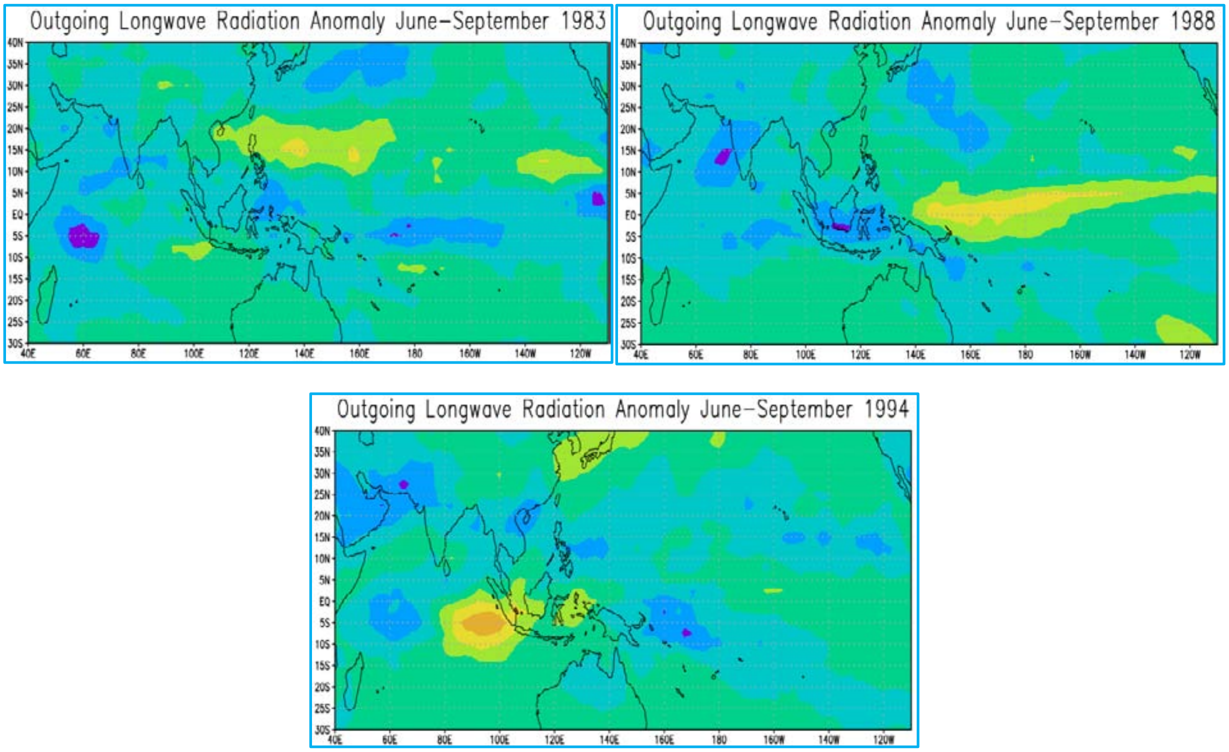

Fig. 1. Seasonal composite OLR anomaly (Wm^{-2}) for excess monsoon years. The Contour interval is 10 Wm^{-2}

COLA/IGES for analysis and plotting the data. Interpolated OLR data were provided by the NOAA/ OAR/ESRL/PSD Boulder, Colorado, USA, from their website at http:/www.esrl.noaa.gov/psd/.

3. Result and discussions

In order to find the existence of a pattern, if any, in the evolution of OLR anomaly from the zone of SHET and its relationship with ISMR, we have examined OLR anomaly in each year. The results of the analysis of seasonal and monthly OLR anomaly for nine years (three years each of Excess, Deficient and Normal monsoon) are briefly discussed below.

3.1. *Excess monsoon (1983, 1988, and 1994)*

Fig. 1 shows the seasonal OLR composite anomaly for the excess monsoon years. The significant feature is the presence of strong negative anomaly (intense convection) over the Indian subcontinent, Equatorial South Indian Ocean (ESIO) and the region extending from Indonesia to the southwest Pacific. Strong positive anomalies (suppressed convection) are seen over the equatorial central Pacific indicating suppressed convection in 1983 and 1988. The region of suppressed convection lies over the equatorial South Indian Ocean (SIO) between the equator and 10°S and east of 80° E in 1994. To the west of 80° E, anomalies are negative. Thus, for the season as a whole in 1994, a dipole structure is seen in the OLR anomaly. This feature is present in 1983 also, but not marked. This feature is absent in 1988. It appears that in 1994, the effect of El-Nino on the Indian monsoon was neutralized due to positive feedback of the Indian Ocean Dipole (IOD). There is a large variation in the OLR anomaly field from one excess monsoon to another. Similar variations are seen over the Pacific also.

Figs. (2-4) show the monthly OLR anomaly field during excess monsoon years. During June 1983, the region of IO between 15°-20° S, was dominated by the negative anomaly, indicating the presence of an active SHET. The Indian subcontinent was dominated by positive anomalies. The region of negative anomaly over SIO moved northward and the positive anomaly reduced over the Indian subcontinent. There was a considerable increase in the intensity and areal extent of negative anomaly over the Indian subcontinent during August-September and a decrease in negative anomaly over SIO, except for a small pocket between the equator and 10° S west of 70° E. The monthly OLR anomaly field shows an inverse relationship between the convection in the zone of SHET and that over the Indian subcontinent. This feature is seen during July 1988 also. The picture is slightly

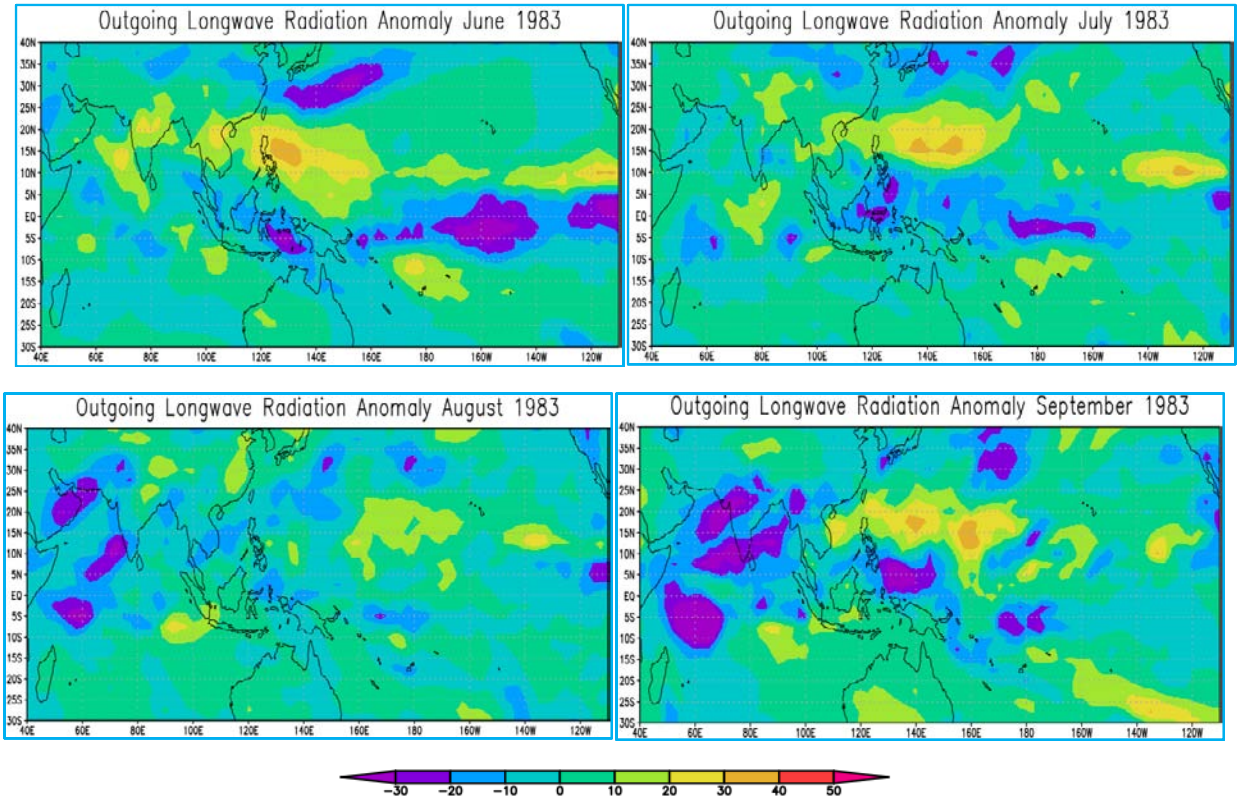

Fig. 2. Monthly composite anomaly of OLR (Wm^{-2}) for the excess monsoon year 1983. The Contour interval is 10 Wm^{-2}

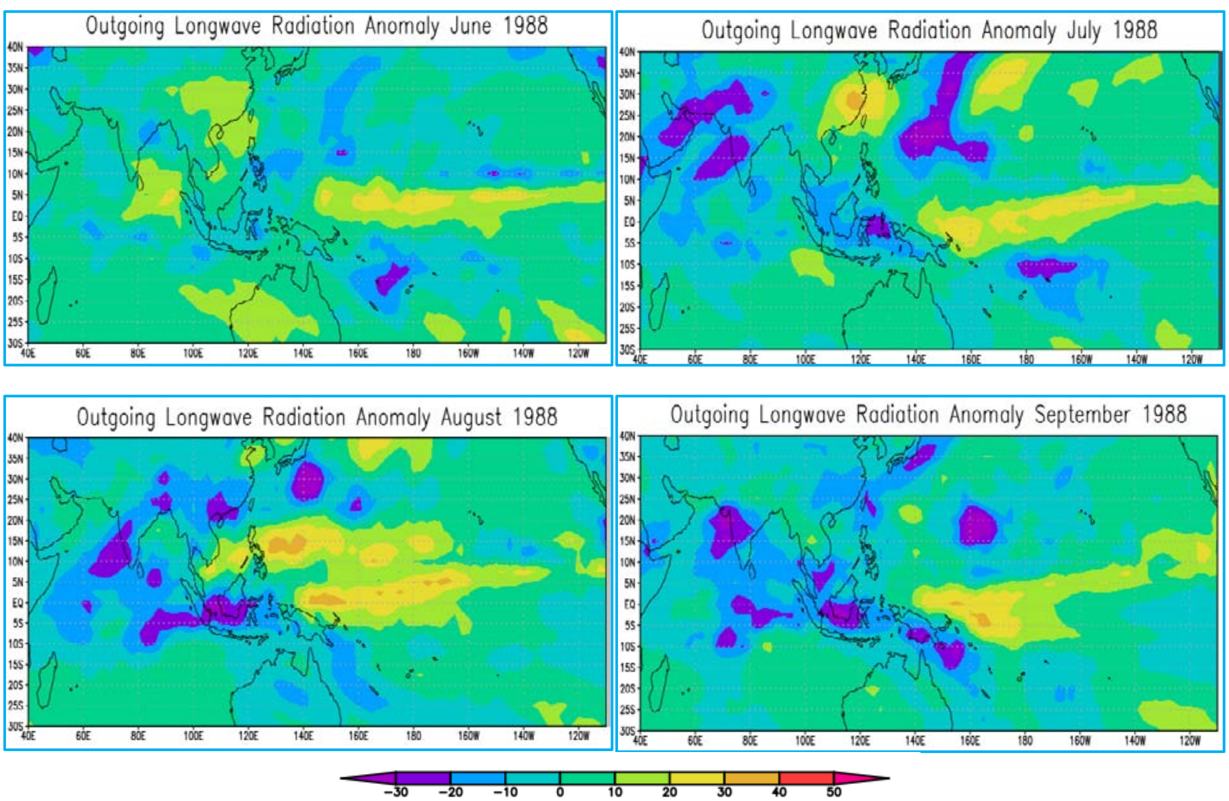

Fig. 3. Monthly composite anomaly of OLR (Wm^{-2}) for the excess monsoon year 1988. The Contour interval is 10 Wm^{-2}

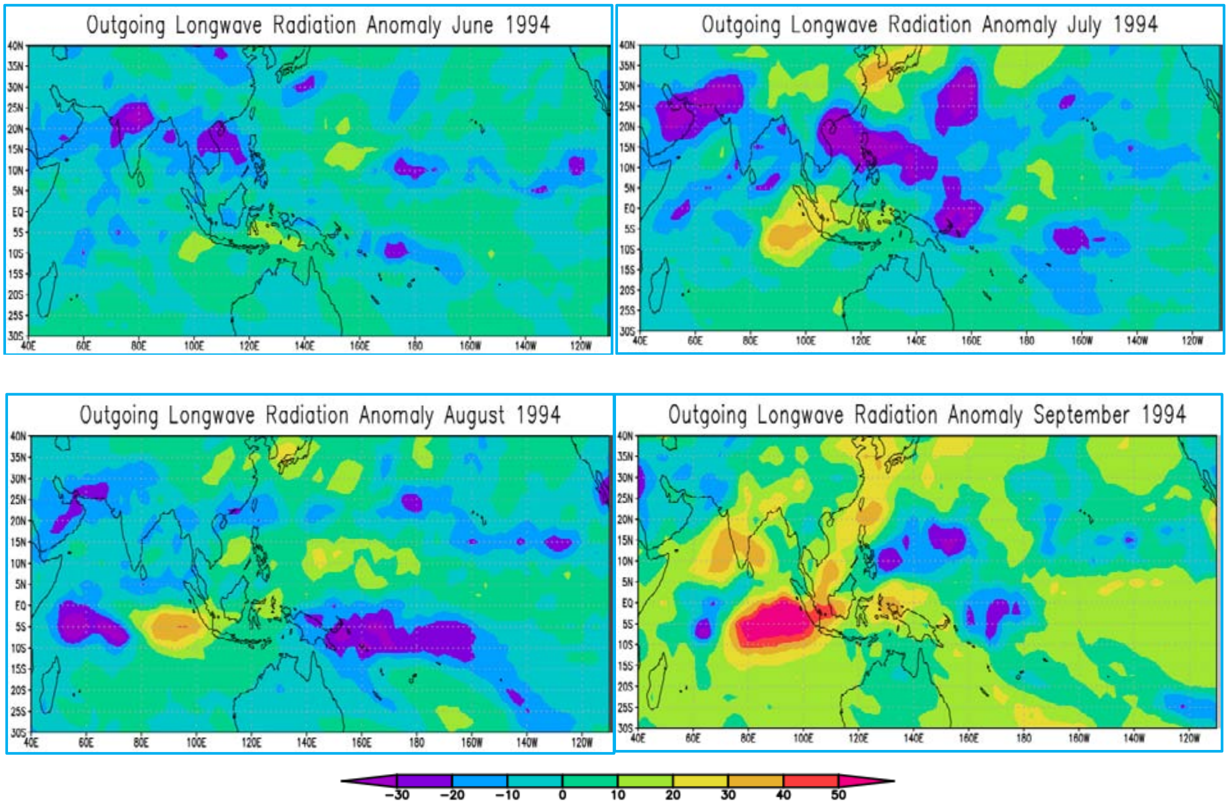

Fig. 4. Monthly composite anomaly of OLR (Wm^{-2}) for the excess monsoon year 1994. The Contour interval is 10 Wm^{-2}

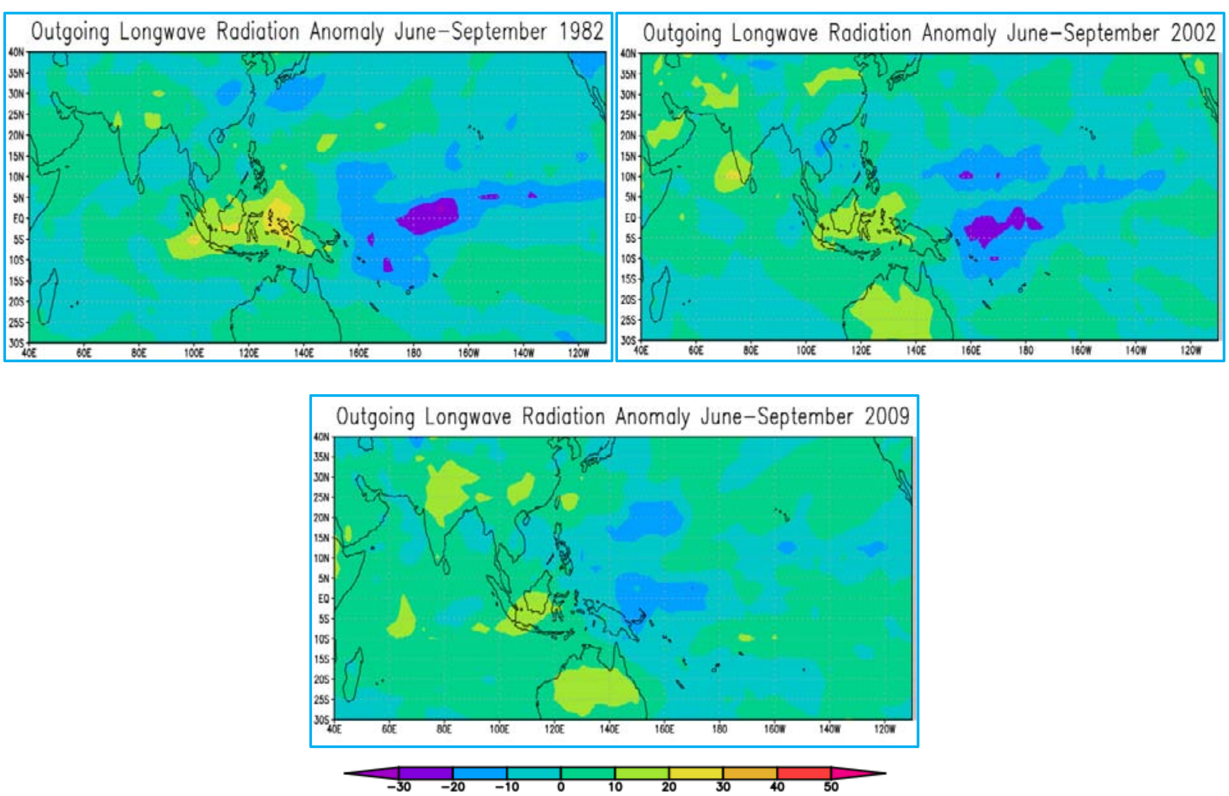

Fig. 5. Seasonal composite anomaly of OLR (Wm^{-2}) for the deficient monsoon years. The Contour interval is 10 Wm^{-2}

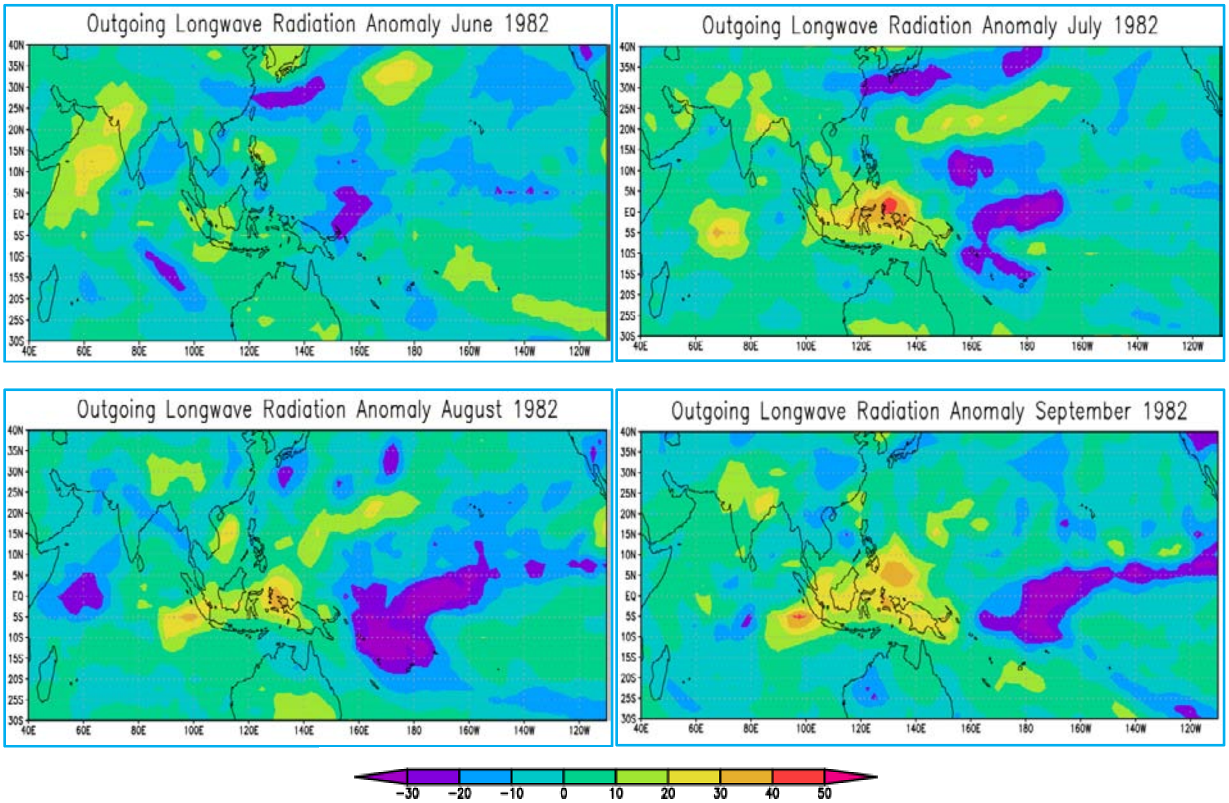

Fig. 6. Monthly composite anomaly of OLR (Wm^{-2}) for the deficient monsoon year 1982. The Contour interval is 10 Wm^{-2}

different during August-September 1988. Negative anomalies extend from around 5° S to 30° N. There is a zone of highly negative OLR anomaly field close to the equator but south of it, beginning from around 80° E to further east during August-September 1988. This indicates the presence of SHET close to the equator. This suggests that SHET is located close to the equator does not weaken the monsoon. The evolution of the OLR anomaly field was different during 1994 as compared to 1983 and 1988. The first sign of development of a Dipole mode type of positive OLR anomaly in Southeast Indian Ocean (SEIO) and negative in Southwest Indian Ocean (SWIO) was seen in June. This feature strengthened through July-August and occupied practically the whole of tropical SIO as the area occupied by negative anomaly got reduced considerably.

The significant features of SHET in excess years are that there is a marked difference in the spatial and temporal variability in monthly as well as seasonal scales. For the excess year associated with La-Nina (1988), the presence of SHET is close to the equator and does not weaken the monsoon, whereas, in the year associated with moderate El-Nino (1994), a dipole structure is seen in the OLR anomaly. This feature is also present in 1983 as well, but not marked. It appears that the effect of El-Nino on the Indian monsoon was neutralized due to positive feedback of the Indian Ocean Dipole (IOD).

3.3.2. *Deficient monsoon (1982, 2002 and 2009)*

Fig. 5 shows seasonal composite OLR anomalies for deficient monsoon years (1982, 2002 & 2009). They were all El Nino years. The negative anomaly had persisted over SIO to the south of 10°S during 1982 as well as in 2002. SHET had been active for the season as a whole, in both the years, in a more southerly location as compared to its normal location. During July 2002, India had received a record deficit rainfall of 51% below normal. SHET remained active during the month (Fig. 7) to the east of 70° E. In addition, there was enhanced convection over the equatorial Pacific Ocean and enhanced subsidence over the Indian region. Development in both the oceans had contributed to the reduction of rainfall over the Indian region during July 2002. The weakening of SHET was an important change during August. The result was an increase in rainfall during the month as the percentage departure of August rainfall became 1.7. In 2009, there was an overall reduction in convection over SIO as well as over the Indian sub-continent. Thus the

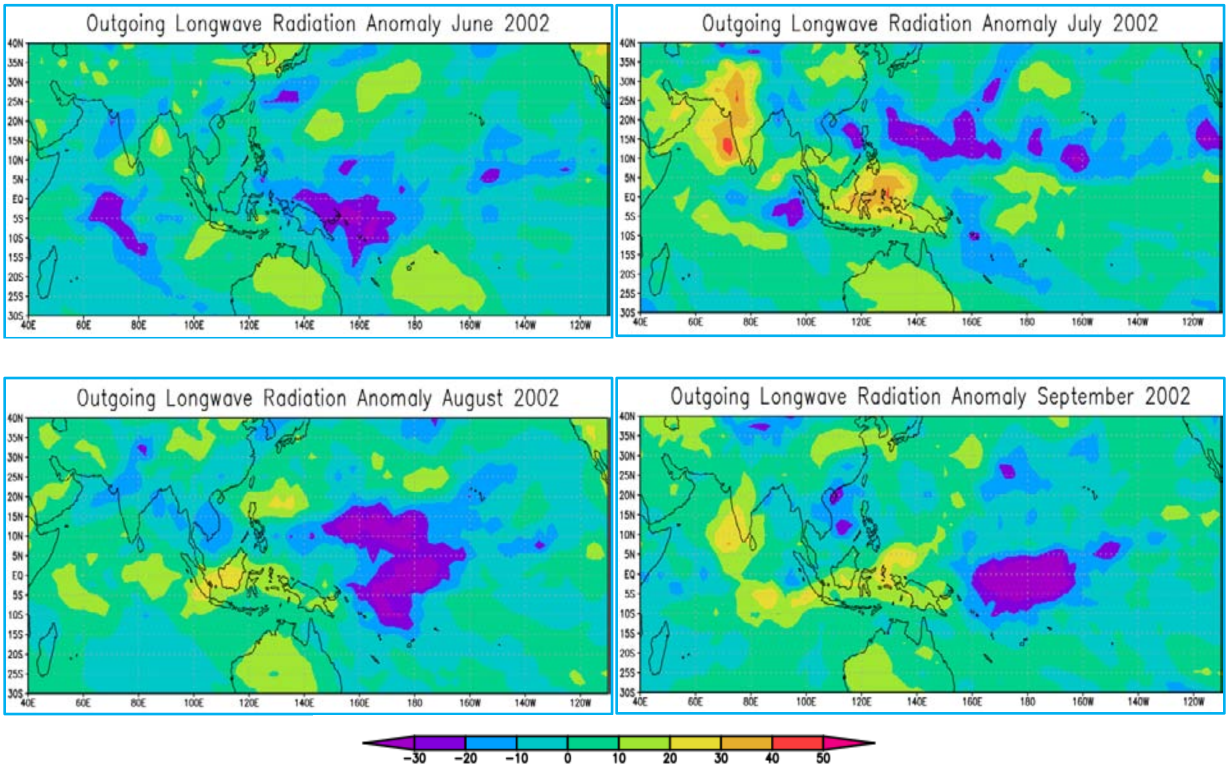

Fig. 7. Monthly composite anomaly of OLR (Wm^{-2}) for the deficient monsoon year 2002. The Contour interval is 10 Wm^{-2}

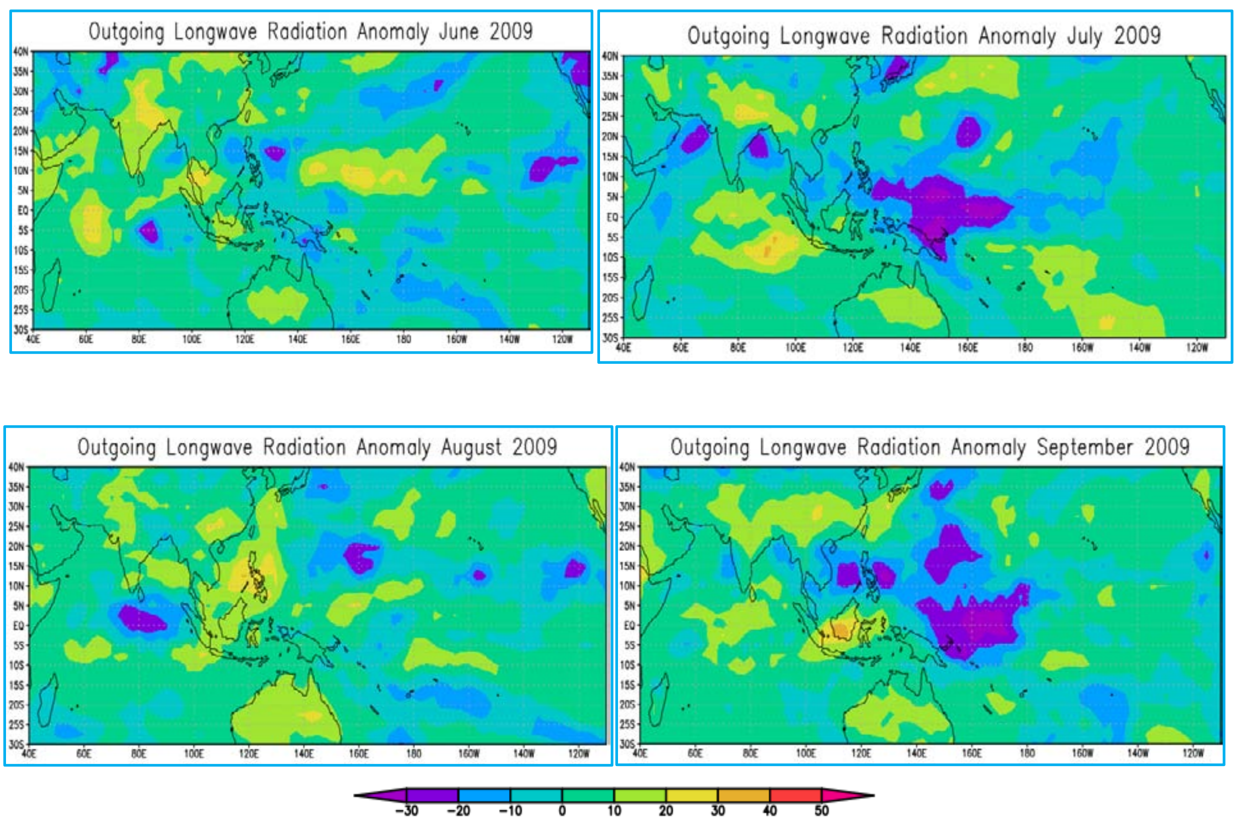

Fig. 8. Monthly composite anomaly of OLR (Wm^{-2}) for the deficient monsoon year 2009. The Contour interval is 10 Wm^{-2}

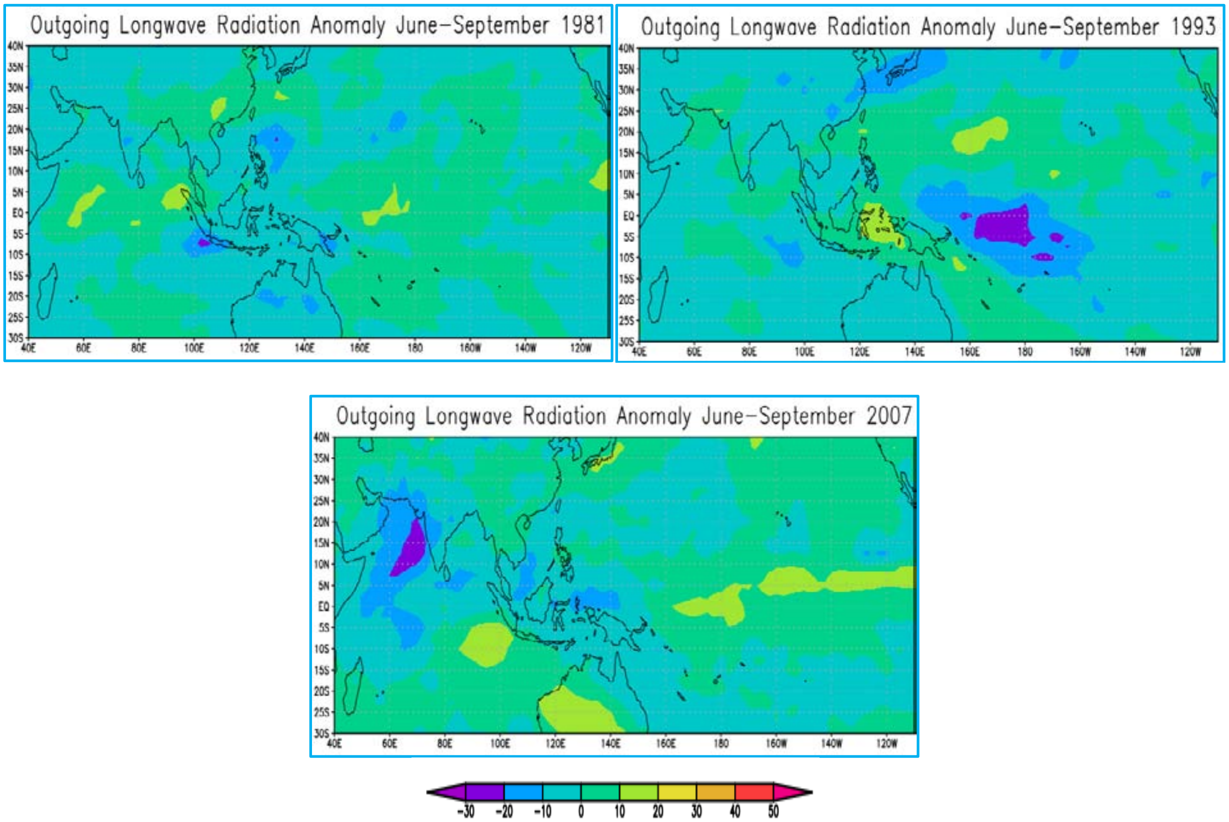

Fig. 9. Seasonal composite anomaly of OLR (Wm^{-2}) for the normal monsoon years. The Contour interval is 10 Wm^{-2}

usual dipole-like pattern (negative anomalies over the Indonesian region and positive over the equatorial central Pacific) during excess monsoon years was found to be reversed during ENSO years.

Figs. 6-8 show the monthly anomaly in individual deficient monsoon years. The negative anomaly over the equatorial Central Pacific persisted during all four months. During August 1982 (Fig. 6), negative anomalies were observed over WEIO and positive anomalies over EEIO and have positive feedback of IOD to the active monsoon rainfall over central India. During July 2002 (Fig. 7), the negative anomalies observed over the north of the entire equatorial Pacific Ocean showed enhanced convection, and simultaneously its subsidence was also observed over the Indian region resulting in one of the extremely deficient July rainfall over the country. During August, negative anomalies (convective zone) moved southwards covering the central equatorial Pacific Ocean and positive anomalies over the Indian region.

During the monsoon months, persistent positive OLR anomalies were seen over the Indian region showing below normal convective activity. Particularly in July, the positive anomalies were comparatively stronger except during the year 2009 (Fig. 8). During 2009, negative anomalies were observed over the central equatorial Pacific in July which moved northward over the entire Pacific Ocean during August resulting in deficient rainfall over the Indian region.

During deficient monsoon years, it was observed that convection was more than normal over the Pacific region as well as over the southern equatorial Indian Ocean. The eastward shift of strong convection from equatorial west Pacific to east Pacific was very much pronounced during the El-Nino years. This indicates the eastward shift of the ascending branch of Walker circulation.

3.3.3. *Normal monsoon (1981, 1993 and 2007)*

Fig. 9 shows seasonal composite OLR anomalies for the normal monsoon years (1981, 1993 & 2007). The significant feature is the presence of strong negative anomaly (intense convection) over the Indian subcontinent, Equatorial South Indian Ocean (ESIO), and the region extending from Indonesia to southwest Pacific, and strong positive anomalies (suppressed convection)

TABLE 1

Association of break monsoon situation with SHET

Year	Monsoon Activity	Period of break	Sector in which SHET was Active	Maximum anomaly zone	Anomaly Maxima (Wm^{-2})	Rainfall distribution (% departure from Normal)
1981	Normal	24-27 July	CSHET ESHET	85° E	-50	**AISMR**(-8) NWI (33) **CI (-54)** NEI (58) SPIN (-45)
		26-30 August	CHET	70° E - 80° E	-50	**AISMR** (-44) NWI (-82) **CI (-65)** NEI (-32) SPIN (-13)
1993	Normal	16-23 July	ESHET	82° E - 110° E	-50	**AISMR** (-8) NWI (-15) **CI (-26)** NEI (-13) SPIN (27)
		22-28 August	WSHET ESHET	42° E - 60° E 82° E - 110° E	-30 -60	**AISMR** (-33) NWI (-67) **CI (-34)** NEI (16) SPIN (-57)
1982	Deficient	1-8 July	WSHET ESHET	50° E - 65° E 80° E - 100° E	-50 -50	**AISMR** (-53) NWI (-40) **CI (-68)** NEI (-9) SPIN (-48)
2002	Deficient	4-17 July	CSHET ESHET	70° E - 80° E 80° E - 110° E	-50 -60	**AISMR** (-58) NWI (-44) **CI (-93)** NEI (-9) SPIN (-76)
		21-31 July	CSHET ESHET	60° E - 100° E	-30 -30	**AISMR** (-53) NWI (-79) **CI (-74)** NEI (-18) SPIN (-44)
2009	Deficient	6-12 August	CSHET ESHET	60° E - 95°E	-50 -50	**AISMR** (-55) NWI (-64) **CI (-71)** NEI (-15) SPIN (-67)
1983	Excess	8-9 July	WSHET ESHET	50° E - 60° E 80° E - 110° E	-50 -60	**AISMR** (-42) NWI (-74) **CI (-19)** NEI (-64) SPIN (-17)
		22-26 August	CSHET ESHET	60° E - 90° E	-50 -60	**AISMR** (-3) NWI (1) **CI (-30)** NEI (9) SPIN (-9)
1988	Excess	4-10 August	CSHET ESHET	75° E - 100° E	-60	**AISMR** (3) NWI (-12) **CI (-46)** NEI (50) SPIN (20)
1994	Excess	6-10 August	WSHET ESHET	45° E - 60° E 60° E - 80° E	-60 -60	**AISMR** (-61) NWI (-65) **CI (-95)** NEI (-55) SPIN (-46)

All India summer monsoon rainfall (AISMR), Northwest India (NWI), Central India (CI), Northeast India (NEI), Southern Peninsular India (SPIN) were seen over the equatorial central Pacific indicating suppressed convection in 2007. The region of suppressed convection lies over equatorial SIO between equator and 10°S and east of 80°E and enhanced convection to the west of 80°E in 2007. During 1993, negative anomalies were observed over the central equatorial Pacific whereas positive anomalies were seen over the central equatorial Pacific in 1981. Negative anomalies were observed over the Eastern Equatorial Indian Ocean (EEIO) in 1981 and 1993 whereas positive anomalies were seen over EEIO in 2007.During June 1981 positive anomalies were observed over the Indian Ocean region and negative anomalies over the south of the eastern Pacific Ocean which were extended westward to the SIO region in July. During August 1981, positive anomalies were observed over the Indian Ocean, Indian sub-continent, and Central Pacific Ocean. The negative anomaly over the equatorial Central Pacific persisted during all 4 months in 1993. During September 1993, the negative anomalies were observed over the Indian Ocean, Indian sub-continent, and Central Pacific Ocean shows enhanced convection. The positive OLR anomaly in SEO and negative in SWIO was seen in June 2007. This feature was also observed through August-September and enhanced convection over the Indian sub-continent showed that 2007 was above normal rainfall year.

The spatial patterns for the normal years were almost similar to that of the excess monsoon cases. The anomalies were comparatively weaker. Negative anomalies were observed over the Indian region, south Indian Ocean, and a region extending from Indonesia to the southwest Pacific Ocean, and positive anomalies were observed over the equatorial central Pacific Ocean. These features persisted throughout the monsoon season.

4. Association between OLR anomaly from the zone of SHET and ISMR

In the previous section, we had discussed the association between convection over the Pacific Ocean and ISMR. We now analyze the role of the Southern Hemispheric Equatorial Trough in this section.OLR anomaly from the zone of SHET has shown a close strong relationship with AISMR. However, SHET is not always active over its entire zone from 40°E to 100°E. For the sake of comparison of the relative role of the activity of SHET in its western and eastern parts on the variability of rainfall over for India as a whole, the zone of SHET has been divided into three parts, *i.e.*, Western SHET (WSHET) (-5° to -15° S, 40°-60° E), Central SHET (CSHET) (-5° to -15° S, 60°-80° E) and Eastern SHET (ESHET) (-5° to -15° S, 80°-100° E). During the nine years for which OLR and AISMR have been discussed above, 12 cases of break monsoon conditions in July and August have been analyzed in the OLR field (Table 1). Ramamurthy (1969) had cataloged the 'breaks' in July and August and made given the criterion for ‘break’ in monsoon: If the monsoon trough is not being seen on the sea-level chart as well as up to 850 hPa level and this synoptic pattern persists for more than two days, 'break' in SW monsoon may be declared. (Ramamurthy, 1969; Ramaswamy, 1962 and Raghvan, 1973) have shown that the middle of August is most susceptible to 'breaks'. The monsoon trough also seems to reach the northernmost position about the middle of August as indicated by the frequency of 'breaks'. As the break-monsoon sets in over the plains, it is seen that the rainfall decreases over Central India and increases remarkably over the Himalayan region and the southern parts of India adjoining the Indian Ocean.

The most significant feature was the occurrence of strong negative anomalies over WSHET and, in general, positive anomalies over ESHET regions throughout the season. Whenever there was a contrast in OLR anomalies over these two regions the rainfall was good over India *i.e.*, the monsoon was active and *vice versa*. In deficient monsoon years, there were strong negative anomalies over ESHET with more such epochs during the season. Mean convection over SHET regions for deficient years was less than excess years. There was a mixed type of pattern in the anomaly field during normal years. The anomaly field was more like that in excess monsoon years. Thus, inactive during weak or break monsoon conditions, with negative (positive) anomalies were observed over WSHET and positive (negative) anomalies over ESHET.

4.1. *Lagged correlations between weekly OLR anomalies from the zone of SHET and AISMR*

We have seen from the previous section that in all 9 contrasting years there is a lagged correlation between the SHET and ISMR. Thus, we have calculated weekly OLR anomaly over SHET zone and ISMR for these lagged correlations. Table 2 shows the lagged correlation of the entire SHET zone and AISMR, Central India rainfall, and the analysis of correlation coefficients between SHET OLR and AISMR has shown that there is a highly negative relationship between the two. Results of further analysis are discussed for three categories of ISM, *i.e.*, deficient, excess, and normal.

4.1.1. *Deficient years*

(*i*) In deficient years, SHET OLR anomalies are negatively correlated with AISMR at 1 to 2-week lag in the year 2002, 3 weeks lag during 2009 (at 95 % confidence level), and 6 to 7-week lag during 1982 (Table 2).

TABLE 2

Correlation between OLR SHET and summer monsoon rainfall

SHET (-5°S to -15°S & 40°E-100°E)									
All India Summer Monsoon Rainfall									
C.C	Drought			Normal			Excess		
	1982	2002	2009	1981	1993	2007	1983	1988	1994
Lag 0	0.34	0.10	0.00	0.14	-0.36	**-0.43***	-0.06	-0.35	**-0.59****
Lag 1	0.49	**-0.51****	-0.09	-0.40	-0.39	**-0.81*****	-.039	-0.20	**-057****
Lag 2	0.02	**-0.51****	-0.15	**-0.50****	-0.21	-0.23	**-0.80*****	**-0.45***	-0.27
Lag3	0.11	0.24	**-0.54****	-0.06	-0.09	0.50	**-0.43***	0.00	**-0.68*****
Lag4	0.15	0.34	0.08	-0.30	0.43	0.49	0.12	-0.15	**-0.45***
Lag5	-0.34	0.28	0.42	0.20	0.13	-0.12	-0.20	-0.06	-0.03
Lag6	**-0.52****	0.03	0.62	0.61	0.11	-0.30	0.13	-0.23	0.43
Lag7	**-0.50****	0.71	0.23	0.41	0.02	-0.11	0.57	**-0.65*****	0.51
Central India Summer Monsoon Rainfall									
Lag 0	0.11	0.12	0.20	0.23	-0.28	-0.13	0.18	0.03	-0.24
Lag 1	0.14	-0.38	0.02	-0.19	-0.21	**-0.85*****	-0.22	-0.11	-0.40
Lag 2	-0.23	**-0.50****	-0.28	**-0.55****	-0.36	-0.36	**-0.61*****	-0.35	-0.29
Lag3	0.27	-0.08	**-0.57****	**-0.58****	-0.40	0.26	-0.21	**-0.41***	**-0.61*****
Lag4	0.51	0.13	-0.11	-0.39	0.08	0.42	-0.25	-0.21	**-0.53****
Lag5	0.09	0.21	0.49	0.34	-0.09	0.09	-0.33	-0.02	-0.19
Lag6	**-0.56****	0.20	0.52	0.40	0.34	-0.10	0.42	-0.04	0.40
Lag7	**-0.60****	0.50	0.25	0.29	0.31	-0.17	0.67	-0.13	0.67
Southern Peninsular Indian Rainfall									
Lag 0	-0.05	-024	0.30	0.11	0.24	-0.43	-0.15	-0.31	**-0.51****
Lag 1	0.07	**-0.71*****	-0.17	**-0.61*****	-0.17	**-0.67*****	**-0.49****	**-0.60*****	-0.38
Lag 2	0.11	-0.32	**-0.43***	-0.40	-0.04	0.04	**-0.53****	**-0.51****	-0.21
Lag3	0.25	0.36	**-0.60*****	-0.06	0.57	0.43	-0.03	**-0.45***	**-0.48****
Lag4	0.08	0.42	0.37	0.01	-0.13	0.14	-0.07	-0.16	**-049****
Lag5	**-0.59*****	-0.14	0.58	0.17	-0.09	0.12	-0.37	-0.02	0.15
Lag6	**-0.87*****	0.09	0.24	0.02	0.05	-0.02	0.26	-0.29	0.63
Lag7	**-0.44***	0.33	0.19	0.14	-0.23	-0.30	0.74	-0.36	0.22

Significant confidence levels mentioned are (* 90%, ** 95%, ***99%)

(*ii*) Correlations with Central India rainfall (CIR) are the same as AISMR (Table 2) whereas for Southern Peninsular India (SPIN) correlation (at 99 % confidence level) lag is one week before CIR. Therefore, the impact of SHET on rainfall is moreover SPIN than over Central India.

(*iii*) All the three deficient years are El-Nino years in which 1982 is strongest as compared to 2002 and 2009.

(*iv*) During deficient, years ESHET has a significant negative correlation with CIR for the years 2002 (95%) at lag1, 1982 (90%) at lag 2 and 2009 (90-95%) at lag0, whereas there is no significant correlation with WSHET OLR (Table 4). During drought years ESHET OLR was significantly negatively correlated with AISMR (Table 3). During the year 2002 concurrent, as well as lag1 correlation coefficients, were significant at 95 % confidence level. The lag was of 3 weeks during 2009

TABLE 3

Correlation between OLR over WSHET and ESHET with All India Rainfall

	All India Summer Monsoon Rainfall					
	WSHET Zone (-5°S to -15°S & 40°E-60°E),			ESHET Zone (-5°S to -15°S & 80°E-100°E)		
C.C	Drought	Excess	Normal	Drought	Excess	Normal
Lag 0	2009**(-042*)**	1994**(-0.47*)** 1983**(-0.55**)**	2007**(-0.46*)**	2002**(-0.50**)**	1994**(-0.58**)**	-
Lag 1	-	1983**(-0.55**)** 1994**(-0.53**)**	1993**(-0.58**)** 2007**(-0.50**)**	2002**(-0.51**)**	1994**(-0.49**)**	1981**(-0.47*)** 2007**(-0.73***)**
Lag 2	-	1983**(-0.89***)**	-	-	1988**(-0.46*)**	1981**(-0.55**)**
Lag3	-	1983**(-0.63***)**	1993**(-0.44*)**	2009**(-0.65***)**	1994**(-0.69***)**	-
Lag4	-	1988**(-0.54**)**	-	-	1994**(-0.52**)**	-

Significant confidence levels (* 90%, ** 95%, ***99%) and values of CC are mentioned in brackets

TABLE 4

Correlation between OLR over WSHET and ESHET with Central India Rainfall

	Central India Summer Monsoon Rainfall					
C.C	Western SHET Zone (40°E-60°E), (-5°S : -15°S)			Eastern SHET Zone (80°E-100°E), (-5°S : -15°S)		
	Drought	Excess	Normal	Drought	Excess	Normal
Lag 0	-	-	-	-	-	-
Lag 1	-	1983**(-0.43*)**	2007**(-0.57**)**	2002**(-0.49**)**	-	2007**(-0.74***)**
Lag 2	-	1983**(-0.68***)**	-	1982**(-0.43*)**	-	1993**(-0.41*)** 1981**(-0.62***)**
Lag3	-	1988**(-0.51**)** 1994**(-0.54**)**	1993**(-0.74***)**	2009**(-0.66***)**	1994**(-0.48**)**	1981**(-0.66***)**
Lag4	-		-	-	1994**(-0.50**)**	-

Significant confidence levels (* 90%, ** 95%, ***99%) and values of CC are mentioned in brackets.

(99%). The role of WSHET is the same for CIR except that there was a weak negative correlation during the year 2009 (90%).

4.1.2. *Excess monsoon years*

(*i*) In excess monsoon years, SHET OLR anomalies were also negatively correlated with AISMR at 0 to 1- and 2-weeks lag for the year 1994 (95 % confidence level), 2 weeks lag for 1983 (99 % confidence level) and also for 1988 (90 % confidence level) (Table 2).

(*ii*) Northward propagation of convection/rainfall belt was noticed from SPIN to central India with one week lag.

(*iii*) The year 1988 was a La-Nina year. In La-Nina years, usually, the rainfall over India is in excess (1956, 1961, 1970 and 1975). The year 1983 was an exception as El-Nino conditions continued from the beginning of the year till July. The SST anomalies over the Nino 3.4 region prevailing before the commencement of the season were not indicative of excess monsoon in 1983. The year 1994 was an El-Nino year and features were not indicative of excess monsoon to follow; rather they were indicative of a weak monsoon/drought.

(*iv*) For the excess monsoon years, WSHET usually has a significant negative correlation with CIR than ESHET (Table 4). For the year 1983, WSHET had a negative

TABLE 5

Table showing details of the regions of SHET

Region	Starting longitude	Ending longitude	Starting latitude	Ending latitude	CC
WSHET	40° E	60° E	5° S	15° S	-0.5203
CSHET	60° E	80° E	5° S	15° S	-0.5512
ESHET	80° E	100° E	5° S	15° S	0.01002

correlation at 2 weeks lag with CIR (99 % confidence level), 1988 and 1994 at 3 weeks lag (95 % confidence level). ESHET has a negative correlation at 3 to 4-week lags with CIR (at 95 % confidence level) as it was an El-Nino year. Convection was observed over the eastern equatorial Indian Ocean.

(*v*) For all excess years, the role of ESHET and WSHET isalmost similar to that for ISMR in comparison with CIR (Table 3) where the correlations are good as compared to CIR.

4.1.3. *Normal monsoon years*

(*i*) In normal years, SHET OLR anomalies are also negatively correlated with ISMR at 0 to 1-week lag for the year 2007 (at 99 % confidence level), 2-week lag for 1981(at 95 % confidence level) (Table 2).

(*ii*) Northward propagation of convection/rainfall belt is noticed from SPIN to central India with one week lag during 1981 and 2007 only.

(*iii*) The year 1981 and 2007 were neutral years with small negative SST anomalies in Nino 3.4 regions. The year 1993 was also a neutral year with small positive SST anomalies in Nino 3.4 regions. The year 2007 was an active monsoon year whereas 1981 and 1993 were normal monsoon years.

(*iv*) For all the normal years (Table 4) ESHET usually has a negative correlation with CIR than WSHET for 1981 and 2007. During the year 1993, ESHET had a weak negative correlation at 2-week lag with CIR (at 90 % confidence level) as compared to the WSHET correlation at 3-week lag (at 99 % confidence level). For the year 1981, ESHET had been negatively correlated with CIR at 2 to 3-week lag (at 99 % confidence level) were no significant correlation for WSHET. For the year 2007, WSHET and ESHET have been equally negatively correlated with CIR at 1 to 2-week lag where the correlation was with ESHET.

(*v*) For all normal years the role of ESHET and WSHET were almost similar to that for ISMR in comparison with CIR (Table 3) where the correlation is poor as compared to CIR.

The OLR has been calculated by averaging out over the WSHET CSHET and ESHET regions (Table 5). It is arranged for 20 weeks for the season of every 30 years (1981-2010) periods.

In the current study, WSHET and CSHET had a good negative correlation (-0.52 and -0.55) with AISMR (Table 5). The OLR from SHET region could be used to develop a simple one parameter empirical model to forecast All India Summer Monsoon Rainfall (AISMR) in the future.

4.2. *Conclusions*

In this study, an attempt has been made to examine the usefulness of Outgoing Longwave Radiation (OLR) over Southern Hemispheric Equatorial Trough (SHET) qualitatively during extreme ISMR (deficient or excess) years. The findings are as following:

(*i*) The significant features of SHET in three excess years (1983, 1988 and 1994) show that there is marked difference in the spatial and temporal variability OLR in monthly as well as seasonal scale. For the excess year associated with La-Nina (1988), the presence of SHET is close to equator and does not weaken the monsoon. Whereas years associated with moderate El-Nino 1994, a dipole structure of SHET is seen in OLR anomaly. This feature is present in 1994 and 1983 as well, but not marked. It appears that effect of El-Nino on Indian monsoon was neutralized due to positive feedback of Indian Ocean Dipole (IOD).

(*ii*) During deficient monsoon years, it was observed that convection was more than normal over Pacific region as well as over southern equatorial Indian Ocean. During drought years, Eastern Equatorial Indian Ocean SHET

(ESHET) OLR was significantly negatively correlated with AISMR whereas there is no significant correlation with Western Equatorial Indian Ocean SHET (WSHET) OLR.

(*iii*) The spatial patterns for the normal years were almost similar to that of excess monsoon case. The anomalies were comparatively weaker. For all normal years, the role of ESHET and WSHET is almost similar to that for AISMR in comparison with CIR where the correlation is poor with AISMR as compared to CIR.

(*iv*) SHET OLR anomalies are negatively correlated with AISMR, northward propagation of convection/rainfall belt was noticed from Southern Peninsular India (SPIN) to central India with one-week lag, impact of SHET on rainfall is more over SPIN than over the Central India.

(*v*) The year 1988 was a La-Nina year. In La-Nina years, usually the rainfall over India is excess (1956, 1961, 1970 and 1975). The year 1983 was an exception as El-Nino conditions continued from the beginning of the year till the month of July. The SST anomalies over Nino 3.4 region prevailing before the commencement of the season were not indicative of excess monsoon in 1983. The year 1994 was an El-Nino year and features were not indicative of excess monsoon to follow; rather they were indicative of a weak monsoon/drought.For the excess monsoon years, WSHET usually has significant negative correlation with Central India rainfall (CIR) than ESHET.

The study revealed the role of convection over southern hemispheric equatorial trough (SHET) regions in extreme years of the period, 1981-2010. It was also suggested that the role of SHET responsible, was present in the deficient years, not only during the season but also prior to the monsoon season, which can be used in the future to forecast the deficient years across India. In future more observation as well as diagnostic studies may provide satisfactory explanations to the queries raised in the paper.

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