INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2015)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4531

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Why are the Indian monsoon transients short-lived and less intensified during droughts vis-à-vis good monsoon years? An inspection through scale interactive energy exchanges in frequency domain

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ABSTRACT: The interannual variability of Indian summer monsoon rainfall (ISMR) is largely dictated by the continental tropical convergence zone (CTCZ), characterized by the frequent cyclogenetic tendency associated with the transitory low pressure systems (LPS(s) or monsoon transients) such as lows, depressions, cyclonic storms etc. A good monsoon is characterized by more intense and sustainable transients having longer westward propagation in comparison with the LPS(s) during weak monsoon. Now the questions arise from the energetics aspects – how does the energy favour the CTCZ to be more cyclogenetic during the good monsoon years? From where the monsoon transients are gaining energy to intensify and to sustain for longer durations during good monsoons compared with those in weak monsoons? The non-linear scale interactions may possibly be the dynamical reason for the intensification and maintenance of LPS(s), but, the quantification of non-linear interactions among the seasonal mean, low frequency oscillations, and synoptic scales are not revealed so far in previous studies. First time, the scale interactive energy exchanges in frequency domain have been explored to unravel the causes of weak LPS(s) during droughts vis-à-vis good monsoon years. It may be inferred from this study that the seasonal mean may play a crucial role for the generation of low and high frequency oscillations through mean–wave interaction whereas the wave–wave interactions have a significant contribution in intensification as well as the maintenance of monsoon transients. The dominant transfer of kinetic energy from the low frequency oscillations to synoptic scale observed over the large region of CTCZ favours the synoptic systems to intensify, survive for longer duration over that region before dissipation causing CTCZ to be more cyclogenetic during the good monsoon period with respect to those in weak monsoons attributing to the rainfall variability over the Indian landmass in contrasting monsoon seasons.

KEY WORDS CTCZ; frequency domain; Indian monsoon; mean–wave interaction; monsoon transients; scale interactions; wave–wave interaction

Received 10 February 2015; Revised 28 August 2015; Accepted 15 September 2015

1. Introduction

The interannual variability of Indian summer monsoon rainfall (ISMR) is largely dictated by the continental tropical convergence zone (18–30°N, 69–96°E), hereafter referred as CTCZ, characterized by high cyclonic vorticity at 850 hPa and the frequent cyclogenetic tendency due to the organized deep moist convection associated with the transitory low pressure systems [abbreviated as LPS(s)] such as lows, depressions, cyclonic storms etc. (Sikka, 1980). These LPS(s) (referred as monsoon transients) follow the locus of CTCZ whose longitudinal extent starts from warm water of Head Bay of Bengal (BoB) of its eastern end to dry convective area of western India and adjoining Pakistan of its western end (Ding and Sikka, 2006). The authors described the CTCZ as monsoon trough to denote the moist convective regime during the Indian summer monsoon (ISM) period. With the advent of the synoptic weather chart, monsoon transients have been the intriguing subject of profound research potential to the meteorological community. There is a strong legacy of the research focussed on climatology, genesis mechanism, instability, westward movement, rainfall potential, and duration of LPS(s), probably starting from the year 1960 through the edited book of the symposium ‘Monsoon of the World’ and a meteorological monogram prepared by Miller and Keshavamurty (1968) based on the first United States collaborated International Indian Ocean Expedition during 1963 monsoon period over the north-east Arabian sea along the west coast of India. Anomalous features of monsoon in terms of dynamical and thermodynamical abnormalities during the normal (1965) and drought year (1972) were documented in the study of Keshavamurty and Awade (1974) elucidating weaker north-south temperature gradient, stronger east-west walker circulation, and reduced north-south Hadley circulation during drought year compared to the normal year. The same feature

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Table 1. Number of short, medium, and long life LPS during drought, normal, and excess monsoon years.

Type of year	No. of the short life LPS (1–4 days)	No. of the medium life LPS (5–9 days)	No. of the long life LPS (≥10 days)	Total no. of LPS	Total no. of LPS days
Drought year (20 years)	122.4	82.45	7.65	212.5	922.25
Normal year (17 years)	103	110	13	226	1174
Excess year (17 years)	128	100	9	237	1097

The drought years' value is normalized by 17 to compare with normal and excess years.

was confirmed by Kanamitsu and Krishnamurti (1978) examining 200 hPa flow regime in the perspective of global tropics. Composite analysis of strong and weak monsoon year by Sikka (1980) underscored some subtle differences in contrasting seasons with higher number of 'low' and 'low days', 2.5 times more 'double LPS(s) days' and less number of days without any systems in normal and excess monsoon years compared with the deficient monsoons. The stronger lower tropospheric cyclonic vorticity with the frequent cyclogenetic character of monsoon trough embedded with the monsoon transients might be responsible to remain the trough to the south of its normal position for more number of days during good monsoon years and subsequently attributed to higher rainfall compared to in deficient years. A comprehensive study of the westward propagating monsoon disturbances in contrasting monsoon seasons using large dataset of 96 years during 1888–1983 was first documented by Mooley and Shukla (1987, 1989). Later, this study was extended by Sikka (2006) with an additional 20 years dataset of 1984–2003. It was revealed from 116 years data that there was no significant change in number of LPS(s) but, the LPS(s) days, and the total longitudinal extent of westward displacement of LPS(s) are more(less) in normal and excess (deficient) monsoon years. This implies that the higher and widespread rainfall are largely attributed to the longer path travelled with the larger LPS(s) days of monsoon transients during normal and excess monsoons compared with the deficient one (Mooley and Shukla, 1987). Moreover, Table 1 shows the statistics of LPS(s) of different life span during drought, normal, and excess years based on 116 years data during 1888–2003. It clearly indicates that the monsoon transients of medium life duration (5–9 days), shown more in numbers during normal and excess years compared with deficient monsoons, contribute maximum to the total number of LPS(s) days and hence, the interannual variability of ISMR that ultimately determines the good (normal and excess) as well as deficient Indian monsoons. Now the questions arise from the energetics aspects – how does the energy favour the CTCZ to be more cyclogenetic during good monsoon years? From where the synoptic scale disturbances are getting energy to intensify and to sustain for longer durations with the larger westward displacement during the good monsoon events compared with those in droughts?

In search of dynamical reasons for the longer duration and intensification of synoptic scale transients, Shapiro (1977) established that the non-linearity in advection was crucial for organization and maintenance of mature tropical disturbances. Similar to Shapiro (1977), McBride (1981), McBride and Zehr (1981) inferred that the non-linearity of the flow in terms of the Rossby number attributed significantly to intensify the synoptic systems at lower troposphere. Ooyama (1982) in the conceptual model of tropical system illustrated that the evolution of tropical disturbances from the individual cloud cluster was the process of many levels of non-linear multiscale interactions. Similar type of conclusion was drawn by Hack and Schubert (1986) where they demonstrated that the non-linear terms in governing equations played a crucial role in the development of tropical vortex at the very early stage of its evolution. They also concluded that the linear approach to the problem of tropical vortex development could not portrait a complete picture of important dynamical processes attributing to its structure and intensification. Strong evidence of non-linear interactions between the seasonal mean and low frequency oscillation and between low frequency oscillation and transient disturbances was underscored by Murakami *et al.* (1986) on the boreal monsoon region applying the harmonic analysis to outgoing longwave radiation data of 8 years. Anticipating the strong relations among seasonal mean, low frequency, and high frequency modes based on Murakami *et al.* (1986) study, Goswami *et al.* (2003) showed that the clustering (disorganizing) of the tracks of monsoon transients over the CTCZ/monsoon trough area was modulated by the positive (negative) epoch of intraseasonal oscillations during the active (break) phase of Indian monsoon. The number of generation of monsoon transients was more (less) during positive (negative) half cycle of intraseasonal oscillations. This indicates strong interactions between intraseasonal oscillations (ISOs) and monsoon transients and that may be one of the key factors for the generation and intensification of tropical systems. During the same period, Maloney and Hartmann (2001), Maloney and Dickinson (2003) documented the strong interactions between synoptic eddies and ISOs at north west Pacific region that favoured the enhancement of tropical depression type disturbances during the active phase compared with the suppressed phase of ISOs. Moreover, the interannual variability of ISM is partly dictated by the internal dynamics of monsoon (Goswami, 1998; Kulkarni *et al.*, 2011). One of the major sources of the internal dynamics is the non-linear interactions between ISOs and synoptic scale oscillations in the presence of annual mean (Goswami, 1995). But, the quantification of the much discussed non-linear interactions among the seasonal mean, ISOs, and synoptic scales have not been revealed so far in above papers.

Table 2. The number of synoptic scale systems of different category during summer monsoon season as per India meteorological division observations.

Year	Seasonal rainfall (%)	Systems				
		LPA/WMLPA	Depression	Deep depression	Cyclonic storm (CS)	Total
1987 (drought)	83	7	3	–		10
2002 (drought)	81	10	–	–	–	10
2009 (drought)	78	5	2	2	–	9
2007 (normal)	106	6	1	4	2 1 (super CS – 1–7 June, 25–26 June)	13
2010 (normal)	102	14	–	–	1 very severe CS (31 May–7 June)	15
2011 (normal)	102	10	3	1	–	14
1983 (excess)	114	10	2	2	–	14
1988 (excess)	117.4	15	4	–	–	19
1994 (excess)	114.4	15		1	1 severe CS	17

As the strong (weak) monsoon season is characterized by prolonged active (break) phase in intraseasonal mode (Mooley and Shukla, 1987; Kulkarni *et al.*, 2011), an explicit computation of energy exchanges among the seasonal mean, low frequency, and high frequency oscillations through the non-linear scale interactions during the contrasting monsoon seasons may reveal the answer of the questions raised in the previous paragraph as well as in the title of the paper. Data and computation are described in Section 2. Section 3 deals with the synoptic description of monsoon transients of different years chosen as per India Meteorological Department (IMD) observations. Results are described in Section 4 and the conclusions are summarized in Section 5. The detail mathematical formulation of non-linear scale interactions in frequency domain has been explained in Appendix.

2. Data and computations

The 6-h reanalysis data of horizontal winds at 850 hPa of the National Centre for Environmental Prediction (NCEP) and the ECMWF reanalysis (ERA) for the years 1987, 2002, and 2009 as the drought years and 2007, 2010, and 2011 as the normal monsoon years and 1983, 1988, and 1994 as the excess years are used for June, July, August, and September (122 days) period covering the monsoon trough area for ERA (0°–30°N, 60°–100.5°E) with grid interval $1.5° \times 1.5°$ and for NCEP (0°–30°N, 60°–100°E) with grid interval $2.5° \times 2.5°$. The four prominent oscillations viz. 30–60, 10–20, 3–5 days and the diurnal (ranging from 0.5 day to less than 1 day) oscillations along with the seasonal mean are chosen for this study. In Indian monsoon two prominent low frequency oscillations 30–60 and 10–20-day are important as the first one controls the northward propagation of monsoon trough/tropical convergence zone (Sikka and Gadgil, 1980; Krishnamurti and Subrahmanyam, 1982) and the other is responsible for the westward propagation of monsoon transients with the genesis over warm water of BoB controlling the active and break spell of ISM (Krishnamurti and Ardanuy, 1980; Kripalani *et al.*, 2004; Sikka, 2006; Preethi *et al.*, 2011). The synoptic scale disturbances represented by 3–5-day and the diurnal scale are considered as the high frequency oscillations in this study. Two types of scale interactions are computed here.

- The interaction between the seasonal mean and the above oscillations are computed through the mean–wave interaction.
- The non-linear energy exchanges among the 30–60, 10–20, 3–5-day and diurnal oscillations are computed in terms of the wave–wave interactions.

A temporal Fourier analysis is used to separate the low frequency transients, high frequency transients, and the seasonal mean flow from the wind fields. The non-linear kinetic energy (hereafter referred as k.e.) transfer into frequency '*n*' by interaction among different frequencies (excluding time mean) denoted by $<Km.Kn>$ is the sum of energy transfers by all possible individual triad interactions $L(n, r, s)$ among three frequencies n, r, s where n, r, and s are related following some trigonometric selection rules as $n = r + s$ and $n = |r - s|$ (Saltzman, 1957). Therefore, $<Km.Kn> = \sum L(n, r, s) = <L(n)>$. The non-linear k.e. transfer spectra among different frequencies i.e. wave–wave interaction $<Km.Kn>$ has been computed following Equation (A1) shown in Appendix whereas the k.e. transfer spectra between time mean flow and the time transients i.e. mean–wave interaction $<K0.Kn>$ is computed following Hayashi (1980). All energy transfer spectra are obtained by neglecting the baroclinic terms.

3. Synoptic description of LPS(s) as per the IMD observations

Following Table 2, the LPS(s) of different category observed in the drought (1987, 2002, and 2009), normal (2007, 2010, and 2011) and excess (1983, 1988, and 1994) years during the summer monsoon period are depicted in tabular form based on the end of season report published every year by IMD. The drought, normal, and excess monsoon years are described in the Tables 3–5, respectively. The synoptic description of monsoon transients is procured

Table 3. Synoptic features of drought years (1987, 2002, and 2009) as per IMD end of season report.

Year	Systems	Initial formation	Direction of movement	Dissipation	Duration of the systems
1987	LPA	North Bay and neighbourhood	WNWly direction	Dissipated in Bihar, NE Rajasthan, and adjoining MP	9–11 June, 17–24 July, (3–8, 13–17, and 18–27 August, 23–25 September One LPA (18–27 August) showed long westward propagation generated from NE and adjoining east Central Bay
	LPA	East central Arabian sea	Westerly direction	Dissipated east central Arabian sea	25–29 September
	Depression/Land Depression	LPA formed over North Bay and adjoining Bangladesh. Other depression formed over Bihar plateau and neighbourhood and North MP	Moved westerly direction and dissipated in North west MP	Intensified into land depression over Bangladesh	LPA on 24, 26–30 August (11–12 and 15–17) September
2002	LPA/WMLPA	Northwest Bay off Orissa coast, Gangetic West Bengal coasts	Moved WNWly directions. Large westward propagation	Dissipated on over SE Rajasthan and adjoining NW MP	20–28 June, 15–19 July, 31 July–1 August, (7–9, 15–18, and 22–27), August, 29 August–1 September, (8–12, 19–26, and 27–28) September Two out of 10 LPA (20–28 June and 22–27 August) showed large westward propagation
2009	LPA/WMLPA	Northwest Bay of Bengal and neighbourhood	Westerly	NE Bay of Bengal and neighbourhood	4–7 June, (6–7 and 13–16) July, 25–29 August and 28 September–3 October
	Depression	East central Arabian Sea and neighbourhood. Another depression Formed NE Arabian sea	Northerly	Saurashtra and Kutch	(23–24 and 25–26) June
	Depression/DD	NW Bay of Bengal off Orissa coast	West northwesterly	North Chattisgarh and neighbourhood	20–21 July and 5–7 September (DD)

LPA, WMLPA, DD, and WNWly stand for low pressure area, well-marked low pressure area, deep depression, and west north westerly, respectively.

from the end of season report published by India Meteorological Department in the journal 'Mausam' during the years 1988, 2003, 2010, 2008, 2011, 2012, 1984, 1989, and 1995 for the years 1987, 2002, 2009, 2007, 2010, 2011, 1983, 1988, and 1994, respectively. The tracks of depression, cyclonic storms, and severe cyclonic storms are delineated in Figures 1–3 for drought, normal, and excess years, respectively taken from IMD cyclone e-atlas available in http://www.rmcchennaieatlas.tn.nic.in.

It has been observed from the description of synoptic scale transients in Tables 3–5, and from the tracks of the depressions and cyclones in Figures 1–3 that (a) the life of LPS(s) exhibit longer duration during good (normal and excess) monsoon years compared to that in deficient monsoons. (b) The LPS(s) during good monsoons intensify more than those in weak monsoon periods. (c) Synoptic scale disturbances during good monsoons show longer westward propagation and more sustenance before dissipation causing wide spread rainfall over the larger region in comparison to those in drought years. It is quite understandable from the energetics aspects that the LPS(s) require more energy for intensification, to sustain for larger life span and to travel a longer distance during good monsoons vis-à-vis weak years. Therefore, the result section will explore the possible quasi-linear and

Table 4. Synoptic features of normal years (2007, 2010, and 2011) as per IMD end of season report. LPA, WMLPA, DD, and WNWly stand for low pressure area, well-marked low pressure area, deep depression, and west north westerly, respectively.

Year	Systems	Initial formation	Direction of movement	Dissipation	Duration of the system
2007	LPA/WMLPA	Northwest Bay off Orissa, West Bengal coasts	Moved NWly direction	East UP and adjoining Bihar	13–18 July, (10–14 and 18–21) August, (1–3 and 13–15) September
	WMLPA	East central Arabian sea off south Gujarat and north Maharashtra coasts	Northerly	South Gujarat region and neighbourhood	23–26 September
	Depression/DD	Northwest Bay of Bengal	Westnorthwestly	Northwestly MP and adjoining east Rajasthan	21–23 June, 26 June–4 July, 4–9 July, 5–7 August. 21–24 September Two depression (26 June–4 July, 4–9 July) showed long westward propagation from Bay of Bengal to SE Rajasthan and its neighbourhood
	Super cyclonic storm	Formed East Central Arabian Sea. A LPA formed over the east central AS on 1 June. It became well marked and concentrated into depression. Then it moved eastwards and intensified into DD/cyclonic storm (CS) on 2. Again it moved northwards and intensified into super cyclonic storm on 3. It moved further northwestward and then weakened into very severe cyclonic storm (VSCS) on 4. It crossed Oman coast on 6 and weakened subsequently into SCS and then into cyclonic storm on 7 June	Northwesterly direction	Iran	(1 –7 and 25–26) June
2010	LPA	Northwest Bay of Bengal adjoining Orissa region	West-northwesterly direction	Gangetic West Bengal, West MP and adjoining SE Rajasthan north Gujarat regions	(9–13 and 24–26) June, (2–5, 6–8 and 24–26) July, 28 July–1 August, (4–8, 12–13, 23–27 and 30–31) August, (3–6 and 17–20) September 4–8 August (long period)
	LPA	Formed in Vidarbha, Chattisgarh and SE MP	Northwesterly	NE Rajasthan and adjoining Haryana	8–13 September
	LPA	SE Arabian Sea and neighbourhood	North of north west	SE and adjoining east central Arabian sea	29 September–3 October (long journey)

Table 4. continued

Year	Systems	Initial formation	Direction of movement	Dissipation	Duration of the system
	Very severe cyclonic storm	LPA formed over the east central and adjoining west central Arabian Sea on 31 May. Concentrated into depression, then DD	Further intensified into cyclonic storm on 1 June moving northwestward direction. Again intensified into very severe CS and move westward on 2 June	Weakened into CS moving northward on 5. Then again weakened into depression moving east north eastward direction over west Rajasthan and then WMLPA over east Rajasthan on 7 June	31 May–7 June
2011	LPA	Formed over land i.e. East UP and adjoining north MP	Northwesterly	East UP, Rajasthan, and neighbourhood	29–30 June, 6–7 July, 8–11 August, (6–13 and 13–19) September
	LPA/WMLPA	Formed west central and Gangetic West Bengal	WNWly direction	Dissipated in south UP and adjoining north MP, Pakistan, SW Rajasthan	8 June, 13–16 July, (11–17 August and 29 August–10 September) – long journey
	LPA	NE Arabian sea off north Gujarat coast	Stationary	*In situ*	30 August–4 September
	Depression	NE Arabian sea	North north east	Saurashtra and adjoining NE Arabian sea	11–12 June
	Deep depression	Formed in NW Bay of Bengal off Orissa–West Bengal coasts	Northward and then west northwest	Gangetic West Bengal and adjoining areas of Jharkhand	16–23 June, 22–23 September. 16–23 June – travelled maximum distance. Initially formed as LPA over NW Bay of Bengal on 14 June, intensified into DD on 16–22 June, then it moves WNW direction and weakened into LPA over west MP on 23 June
	Land depression	NW Jharkhand and neighbourhood	West northwest	North MP and neighbourhood	22–23 July

Table 5. Synoptic features of excess monsoon years (2007, 2010, and 2011) as per IMD end of season report.

Year	Systems	Initial formation	Direction of movement	Dissipation	Duration of the systems
1983	LPA	NW/NW central/North Bay of Bengal and adjoin Orissa	WNWly direction	Dissipated over NE MP (Madhya Pradesh) and adjoining SE UP (Uttar Pradesh) on 31	31 May–4 June, 22–24 June, 28 June– 1 July, (1–6, 8–15 and 18–22) July, 31 July–4 August, (7–17 and 27–31 August) Among the above systems, three systems travelled maximum distance (8 –15 July, 31 July–4 August and 7–17 August)
	LPA	SW MP and adjoining North Madhya Maharashtra	Moved westnorthwest wards	Merged over SE Pakistan and adjoining NE Arabian Sea	21–24 July
	Depression	LPA formed over East central Arabian Sea and adjoining Maharashtra Coast on 15 June	It moved northwards, North Maharashtra, Saurashtra and Kutch and concentrated into depression on 17	It persists on 24 June	17–24 June
	DD	LPA developed over NW and adjoining west central Bay. Then it concentrated into depression.	It moved WNWly and became DD over Orissa coast. System continued to move WNW wards upto SE MP and then northwards. It became WMLPA and moved WNWly direction	Merged into NE Arabian Sea	(22–28 June and 1–9 August) over Bay of Bengal. One over land region i.e. Bihar plateau during (4–12 September) One system travelled upto Gujarat state during 1–9 August. Initially developed as a LPA over north Bay on 1 August, became WMLPA on 3 August, moved northwards and concentrated into depression on 4 and into DD on 5 August over Bangladesh. It moved westwards across south MP and Gujarat state and emerged into NE Arabian Sea on 9.
1988	LPA	NW Bay and adjoining West Bengal	Moved WNWly direction	it dissipated SE UP and adjoining Bihar Plateau and NE M.P	21–25 June, 27 June–1 July, (1–4, 21–23) July, 28 July – 1 August, (7–11, 17–21, 30–31) August, (16–22 and 21–24) September (Among these one LPA, 27 June–1 July showed long journey from Gangetic West Bengal to Rajasthan)
	LPA/WMLPA	East central Arabian sea and adjoining north Maharashtra coast	It moved WNWly direction	Dissipated in south Gujarat	(17–19, 1–5, and 18–26) September. One LPA showed long duration from east central Arabian sea to Himachal Pradesh (18–26 September)

Table 5. Continued

Year	Systems	Initial formation	Direction of movement	Dissipation	Duration of the systems
	LPA	Land region of South Vidharba and neighbourhood	It moved WNWly direction	It dissipates coastal areas of north Maharashtra	(10–13 and 16–19) September
	Depression	Formed west central and adjoining NW Bay off north AP	It moved in WNWly direction	Dissipated over Bihar Plateau and adjoining Gangetic West Bengal and north Orissa	8–10 June, 17–21 July and 2–7 August Among these systems, two depressions moved WNWly direction upto SE Rajasthan and Pakistan. Depression formed off north Andhra-south Orissa coast on 17 July. It moved WNWly direction and dissipated on 21 July over Northwest MP and adjoining southeast Rajasthan. Another one, initially LPA, formed on 28 July over Northwest Bay and intensified into deep depression on 2 August over NW Bay and adjoining NE Bay moved to WNWly direction and dissipated on 7 August over Pakistan
	Depression	Formed east central Arabian Sea	It made a big loop over there.	Dissipated over the sea	9–13 June
1994	WMLPA	Formed over the east central Arabian Sea off south Gujarat, North MP	Quasi-stationary	South Gujarat region merged with seasonal trough	14–16 June
	WMLPA		Northwesterly direction		14–17 July
	WMLPA	NW Bay and adjoining Gangetic West Bengal, Bihar Plateau, and neighbourhood	Westnorthwesterly directions	Dissipated in Arabian sea or Pakistan region	14–20 June, 25 June–4 July, 30 June–2 July, (3–6, 8–15 and 15–25) July, (2–7, 9–14, 21–24 and 25–29) August, 26 August–6 September, (1–11 and 15–19) September. Four systems of life span 25 June–4 July, 9–14 August, 25–29 August and 26 August–6 September. originated from NW Bay or Gangetic West Bengal and dissipated in Arabian sea or Pakistan region showing long westward propagation
	Depression/ severe cyclonic storm	Depression formed over south Maharashtra coast and adjoining Arabian Sea on 5 June	It moved in NWly direction, intensified into CS on 6 over east central Arabian Sea. Then, it intensifies into SCS on 7 June	It weakened into depression On 9 June at Oman coast	5–9 June
	DD	A depression formed over NW Bay off north Orissa–West Bengal coast on 17 August	It moved WNWly direction and intensified into DD. The system laid as DD on 18, moved NWly direction	It weakened into depression then into LPA on 21 over SE Pakistan	17–20 August

LPA, WMLPA, DD, and WNWly stand for low pressure area, well-marked low pressure area, deep depression, and west north westerly, respectively.

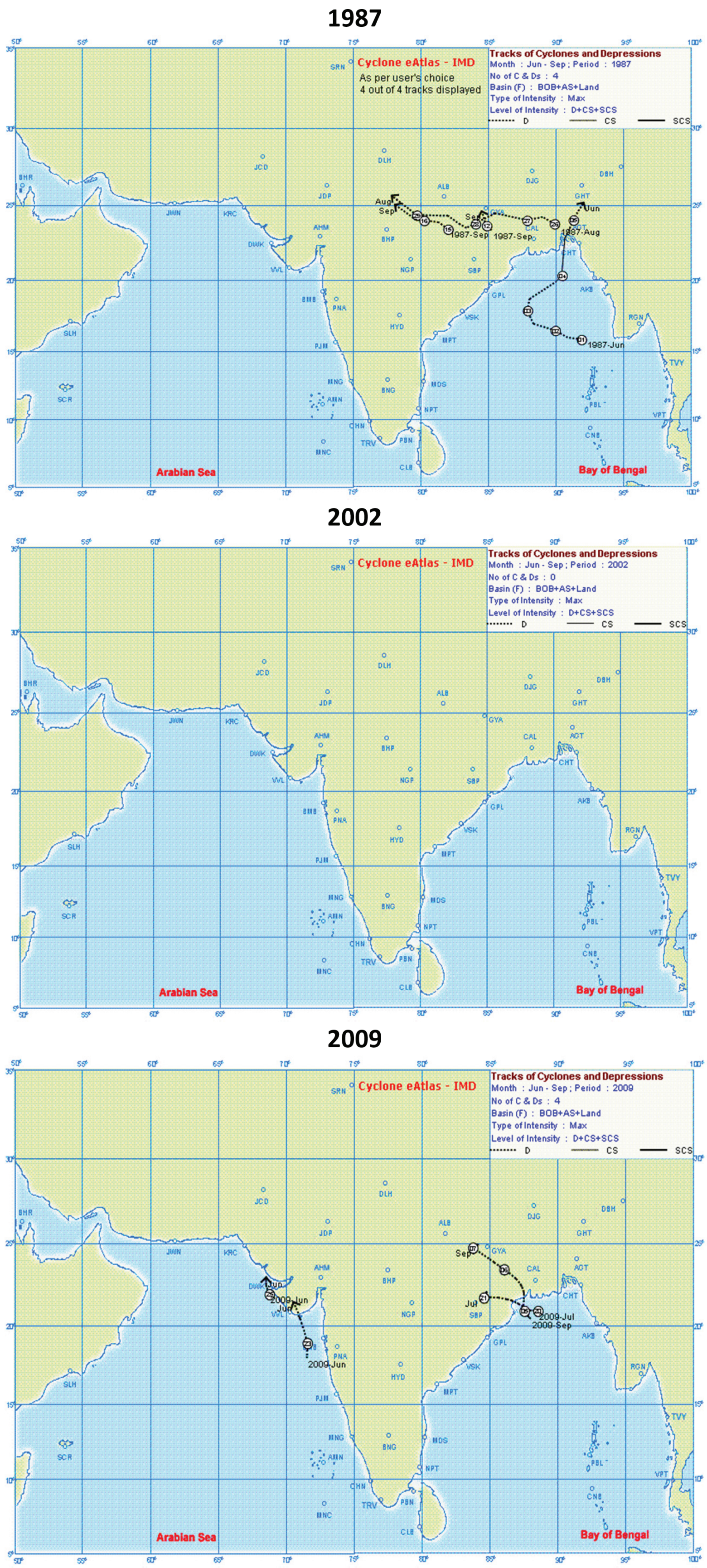


Figure 1. Tracks of depressions (D), cyclonic storms (CS), and severe cyclonic storms (SCS) during the drought years as per India Meteorological Department (IMD) cyclone Atlas available from IMD e-atlas at http://www.rmcchennaieatlas.tn.nic.in.

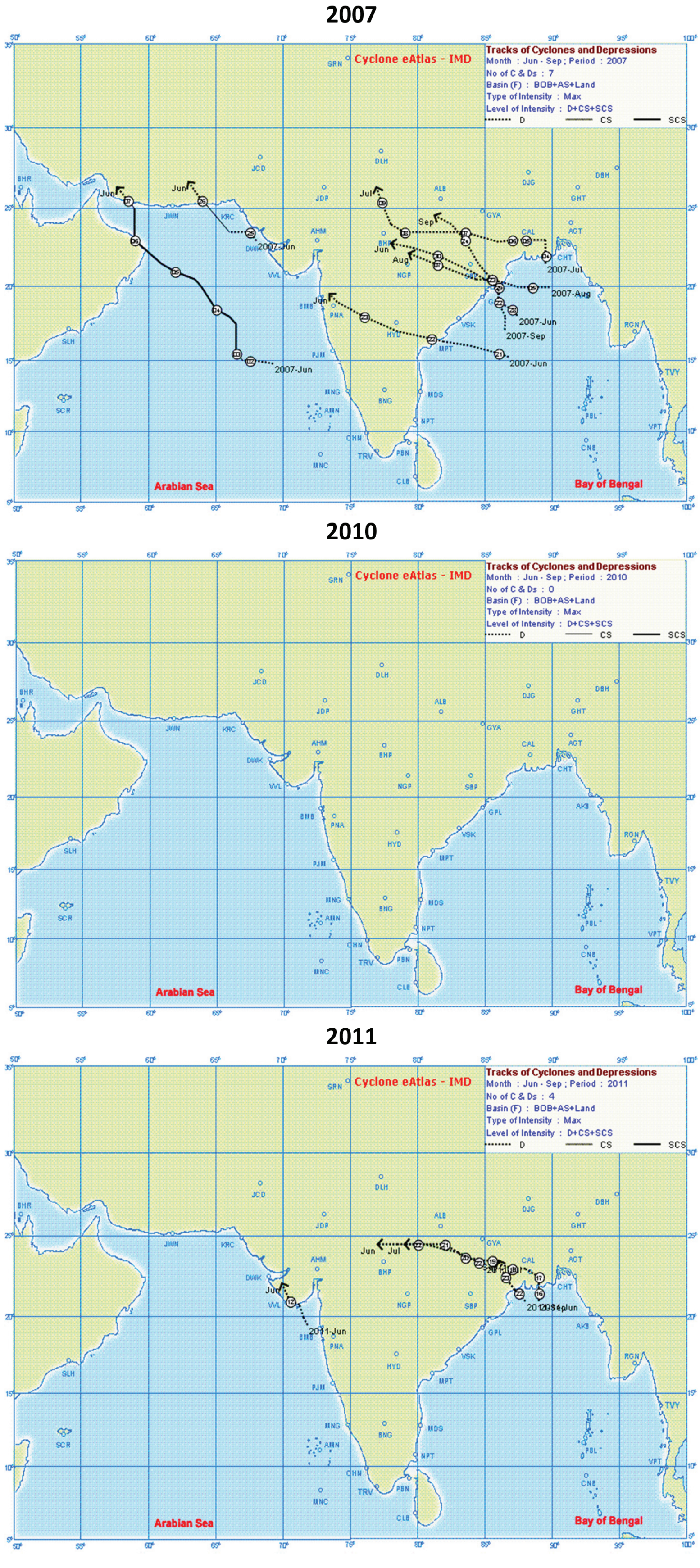


Figure 2. Tracks of depressions (D), cyclonic storms (CS), and severe cyclonic storms (SCS) during the normal years as per India Meteorological Department (IMD) cyclone Atlas available from IMD e-atlas at http://www.rmcchennaieatlas.tn.nic.in.

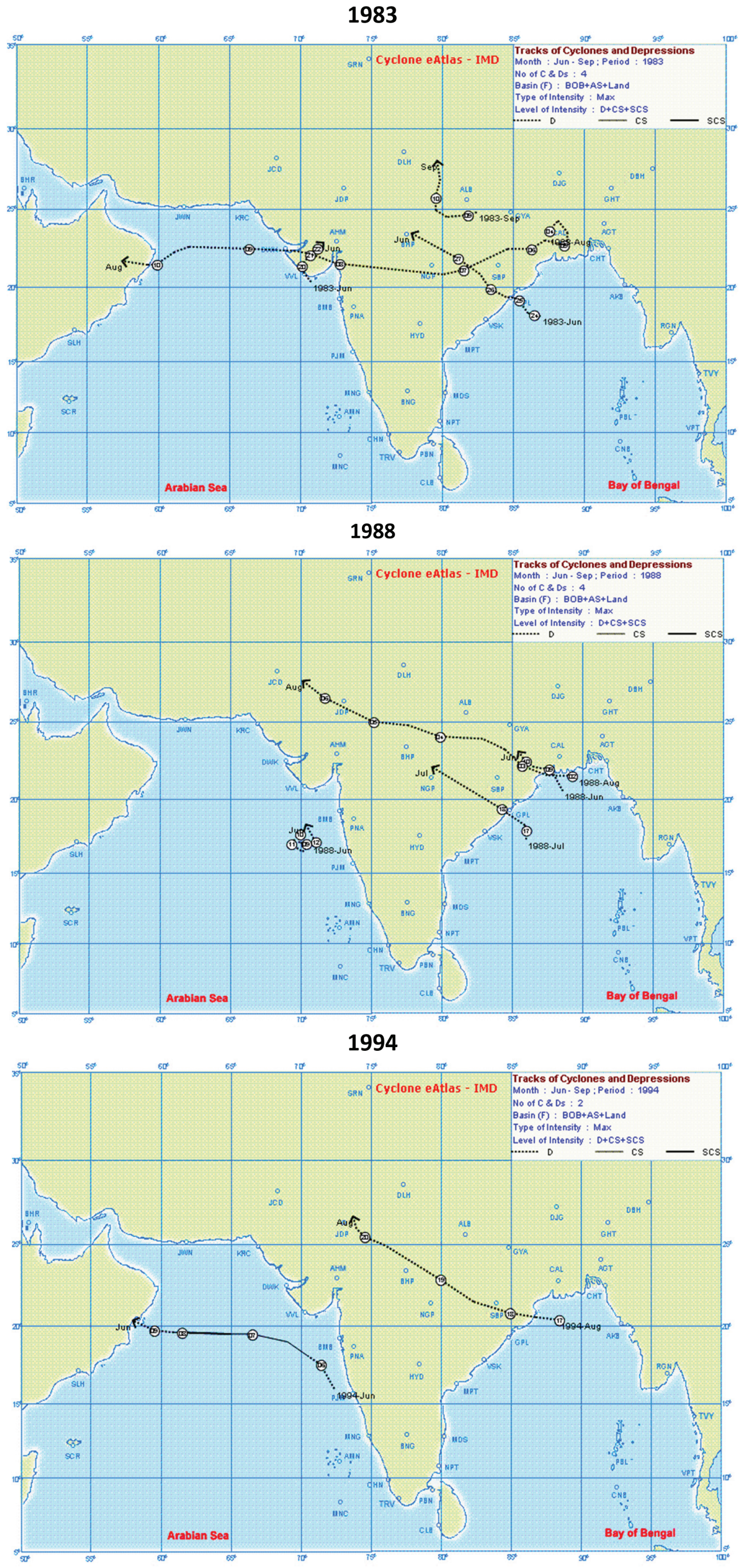


Figure 3. Tracks of depressions (D), cyclonic storms (CS), and severe cyclonic storms (SCS) during the excess years as per India Meteorological Department (IMD) cyclone Atlas available from IMD e-atlas at http://www.rmcchennaieatlas.tn.nic.in.

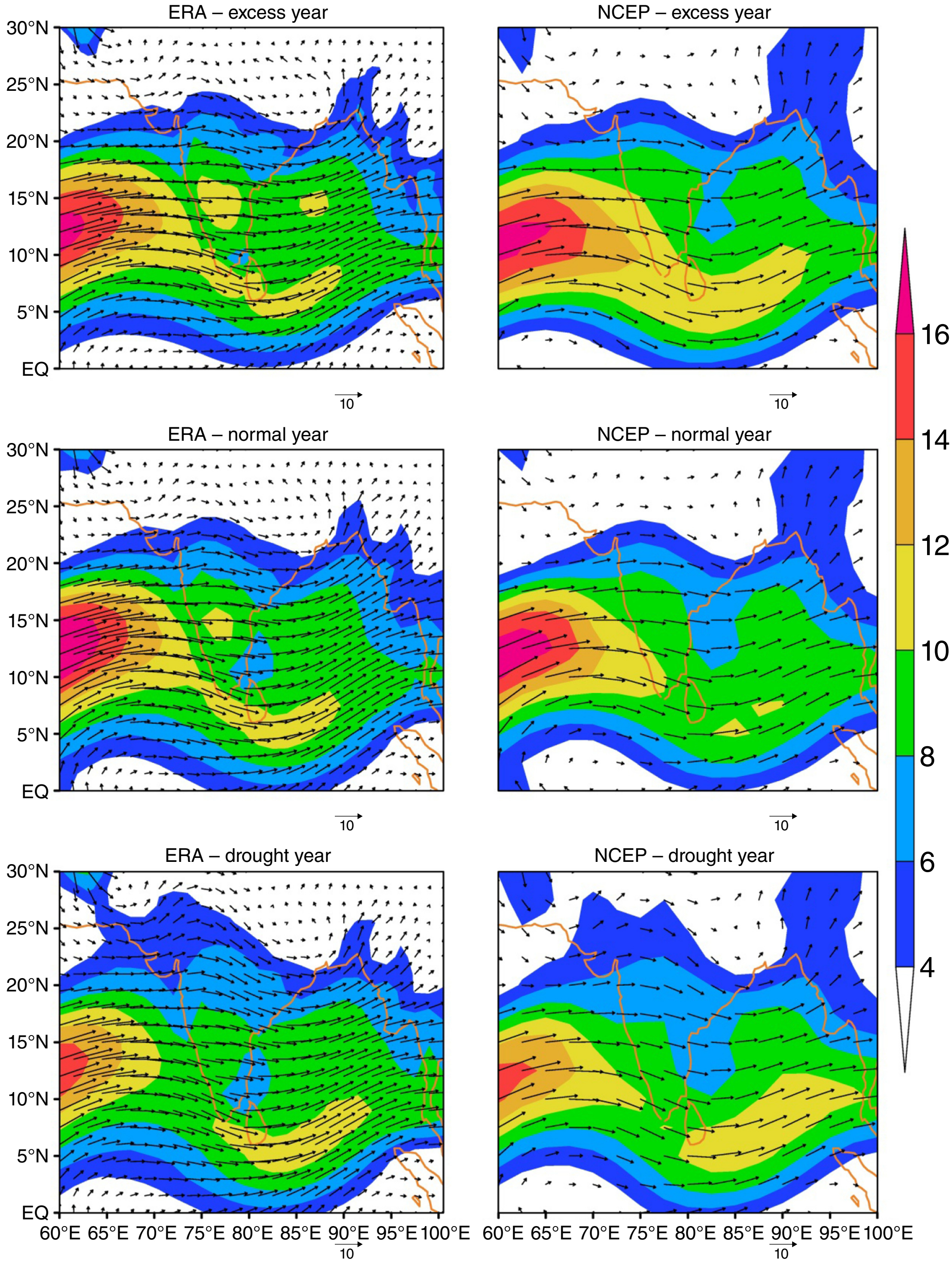


Figure 4. Seasonal mean 850 hPa wind field of ECMWF (ERA) and NCEP reanalysis averaged over the drought (1987, 2002, and 2009), normal (2007, 2010, and 2011), and excess (1983, 1988, and 1994) years.

non-linear sources of energetics of monsoon transients and compare among the contrasting years.

4. Results and discussions

As the whole study is based upon the analysis of the lower tropospheric horizontal wind field, the seasonal mean of 850 hPa wind of ECMWF and NCEP reanalysis are shown in Figure 4 for drought, normal, and excess years. It has been clearly observed from the figure that albeit the mean structures are same, the low level jet is stronger in good (normal and excess) monsoons compared with deficient monsoon years in both the ECMWF and NCEP winds. The magnitude of the wind is more over Indian landmass during good monsoons with respect to the weak ones. Hence, it is expected that the energy exchanges between any two scales are supposed to be more in normal and excess monsoons with respect to drought years.

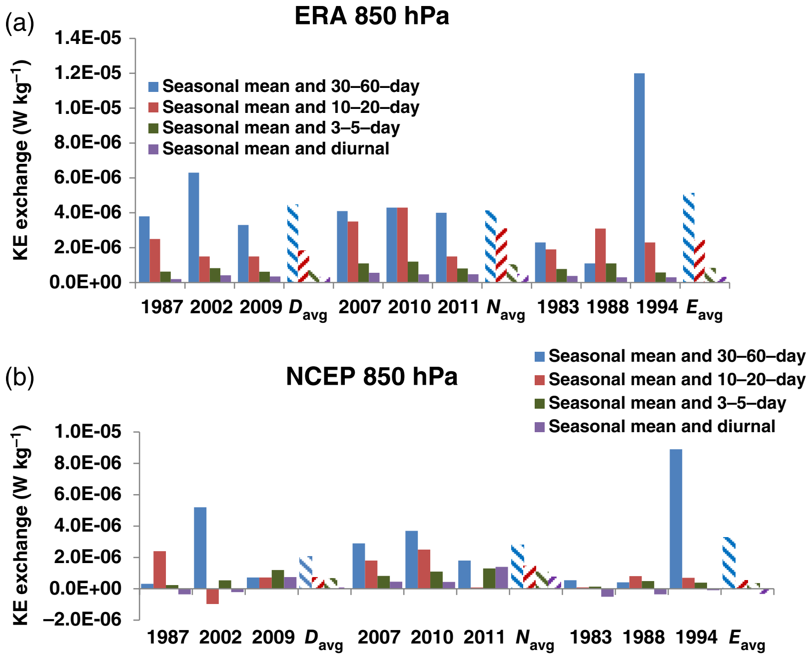


Figure 5. Kinetic energy exchanges through scale interactions between seasonal mean, high frequency (3–5-day) and seasonal mean, low frequency (10–20 and 30–60-day) oscillations (a) for ECMWF and (b) for NCEP lower tropospheric winds. Hatched pattern represents the average value of energy exchange during drought, normal, and excess years denoted as D_{avg}, N_{avg}, and E_{avg}, respectively.

4.1. Mean–wave interactions

The mean–wave interaction is a quasi-non-linear interaction comprising seasonal mean and different scale of waves. In a seasonal mean and wave interactions the positive interactions imply the energy flows from seasonal mean to high and low frequency oscillations whereas the negative interactions represent the k.e. flows in opposite direction i.e. from different waves to seasonal mean. Figure 5 describes the mean–wave interactions at different weak, normal, and excess monsoon years for ECMWF (Figure 5(a)) and NCEP (Figure 5(b)) wind fields. 'D_{avg}', 'N_{avg},' and 'E_{avg}' represent the average value of the interactions during the drought, normal, and excess years chosen above, respectively. The analysis reveals that

(1) Almost all the oscillations are gaining k.e. from seasonal mean irrespective of drought, normal, and excess years. This is observed in both ECMWF and NCEP lower tropospheric wind fields. This implies that the seasonal mean plays a main source of k.e. of low frequencies such as 30–60, 10–20-day, and high frequencies such as 3–5-day and diurnal oscillations during monsoon seasons.
(2) The amount of k.e. gain by different oscillations is proportional to the time period of oscillation indicating more energy gain by waves of larger time period. It is quite understandable from Lorenz (1969) study that the energy exchanges proportionate to the scales of the wave.
(3) As far as the interactions in individual year are concerned, the 30–60-day mode is receiving maximum amount of k.e. from the seasonal mean during the excess year 1994 as observed in both ECMWF and NCEP reanalysis winds. Now the question arises that why does the 30–60-day mode show strongest in 1994 in comparison with other years? It is well known that the 30–60-day intraseasonal mode controls the latitudinal position of monsoon trough (Sikka and Gadgil, 1980; Krishnamurti and Subrahmanyam, 1982; Kripalani *et al.*, 2004). It was observed from the end of season report (India Meteorological Department, 1995) that the monsoon trough was remained maximum period in its normal position with its eastern end to the south of the normal position (i.e. Northwest Bay) during the whole monsoon season of 1994 causing the LPS(s) to be more aligned with larger westward propagation along the monsoon trough (Sikka, 2006) in comparison with the other excess monsoon years of 1983 and 1988. Therefore, the 30–60-day oscillation in 1994 is appeared to be strong by taking the maximum amount of k.e. from the seasonal mean which is the largest source of energy.
(4) Although, the low- and high-frequency waves in particular the synoptic scale systems (3–5-day) are receiving comparable amount of energy during droughts, normal, and excess monsoons, the LPS(s) in droughts are not appeared to be as strong and sustainable as those in normal and excess years (analysing Tables 1–5). This implies that the seasonal mean may be responsible for the generation of monsoon transients but not to intensify and maintain the systems.

Hence, to unravel the reasons behind the stronger monsoon transients with the longer life span in good monsoon years compared with in deficient monsoons, the non-linear

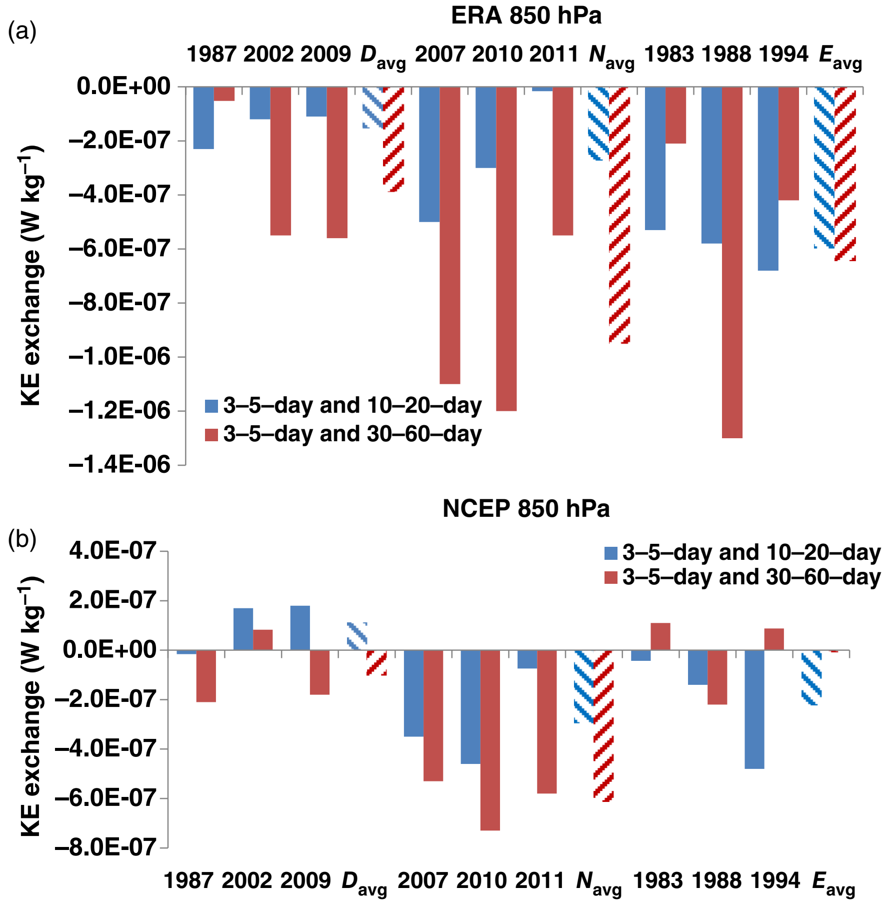


Figure 6. Non-linear scale interactions between high and low frequency oscillations for (a) ECMWF and (b) NCEP winds. Hatched pattern stands for average value of interactions in drought, normal, and excess years represented by D_{avg}, N_{avg}, and E_{avg}, respectively.

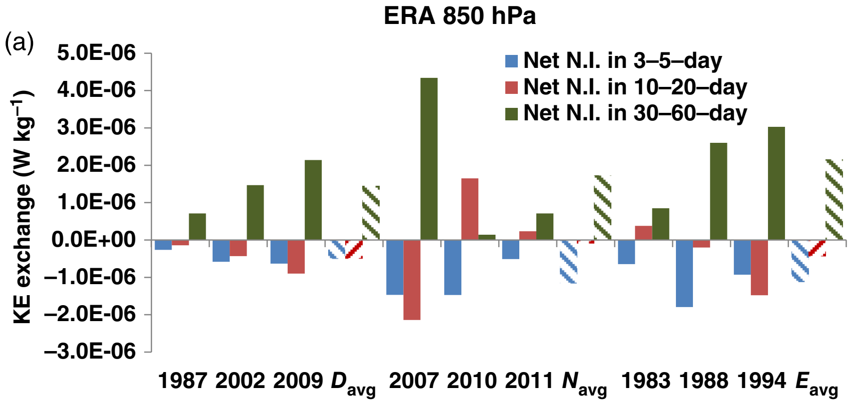
wave–wave interactions of synoptic systems (3–5-day) with low frequency and diurnal scales are to be explored in the following section.

4.2. Wave–wave interactions

The wave–wave interactions are purely non-linear interactions where three participating waves of different frequencies are interacting among each other and exchange k.e. between one wave (whose interactions are looking for) and other two waves in the form of different triads following some selection rules discussed in the data and computation chapter. As per the objective of the study, the non-linear interactions of the monsoon transients (3–5-day) with the two low frequency oscillations – 10–20 and 30–60-day and the diurnal oscillations (time period less than 1 day) are examined in this section. Figure 6 delineates the wave–wave interactions between the synoptic scale systems (3–5-day) and the low frequency oscillations for the 3 years of each of the drought, normal, and excess monsoon. The hatched line bar in the figure represents the average value of interaction for drought, normal and excess monsoons denoted by ‘D_{avg}’, ‘N_{avg}’, and ‘E_{avg}’, respectively. The positive interactions represent the k.e. transfer from 3 to 5-day to low frequency waves whereas the negative interactions stand for the k.e. flow in opposite direction i.e. from low frequency to 3–5-day. The figure reveals the following points:

1. The 3–5-day oscillations are gaining k.e. from both 10–20 and 30–60-day periods as observed from ECMWF wind field. The maximum gain of k.e. by synoptic scale is shown from 30 to 60-day period during normal monsoon years shown in ‘N_{avg}’ whereas the 10–20-day wave transfers maximum amount of k.e. to 3–5-day during excess years observed in ‘E_{avg}’ of Figure 6(a).
2. The maximum amount of energy transfer to synoptic scale is exhibited during normal monsoon years from the low frequency oscillations analysing NCEP wind field (Figure 6(b)). The 3–5-day waves are losing k.e. to 10–20-day shown in the average value of drought years ‘D_{avg}’. However there is no transfer of k.e. between 3–5 and 30–60-day during excess monsoons as revealed from ‘E_{avg}’ of NCEP winds. In general, NCEP wind also exhibits more gain of k.e. by 3–5-day wave from low frequency oscillations during excess and normal monsoon periods compared with weak monsoons.

It has been understood from the analysis of non-linear wave–wave interactions that the monsoon transients



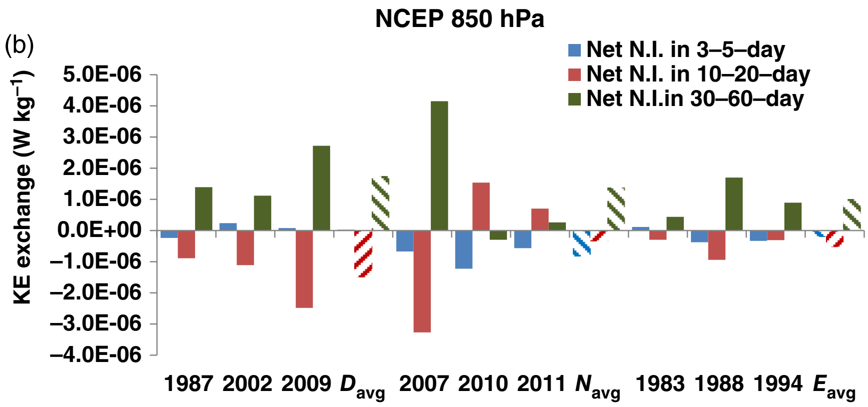


Figure 7. Net kinetic energy exchange in non-linear interactions for high and low frequency oscillations. (a) for ECMWF wind and (b) for NCEP wind. Hatched bar indicates for average value of drought, normal, and excess years denoted by D_{avg}, N_{avg}, and E_{avg}, respectively.

receive smaller amount of k.e. or sometimes losing k.e. to low frequency waves during the drought years leading to the synoptic scale systems to be weaken and dissipate faster attributing subdue rainfall activity with respect to those in good monsoon seasons. The net non-linear interactions in 3–5, 10–20, and 30–60 are elucidated in Figure 7. When a particular wave interacts with all waves, the sum of all the interactions represents the net interaction associated with that wave. The objective of this figure is to quantify the total loss/gain of k.e. of a wave while interacting non-linearly with all other waves. The positive (negative) value stands for the net loss (gain) of energy. The most interesting result is that the synoptic scale disturbances is gaining more k.e. during the normal and excess monsoon years compared to in deficient monsoons observed in both the ECMWF and NCEP winds. The 30–60-day is losing k.e. to all other waves irrespective of weak and strong monsoons implying that this intra-seasonal oscillation (30–60-day) is a potential source of k.e. such as the seasonal mean. It may be concluded from the net non-linear interactions that the synoptic scale transients receive distinguishably larger amount of k.e. from low frequency and other waves at the lower troposphere that may attribute to more sustainability and intensification of LPS(s) during good monsoons compared with those in drought period. The diurnal oscillations are always gaining one order smaller amount of k.e. from the low and high frequency oscillations irrespective of strong and weak monsoons (figures are not shown) in comparison with the interaction between 3–5-day and low frequency oscillations. Hence, the diurnal waves have no positive contribution to intensify as well as maintain the synoptic transients.

It has already been discussed in the introduction that the LPS(s) are largely bunched up in the core monsoon zone causing the area of CTCZ to be more cyclogenetic during good monsoon years compared with in deficient monsoons and this may be one of the important factors for the inter-annual variability of ISMR. Now, the question arises from the energetics aspects that why the area of CTCZ is the most preferred zone for LPS(s) to be aligned during the strong monsoons? The spatial distribution of the non-linear scale interactions over the Indian region may give some explanations for the affinity of the LPS(s) to be accumulated along the monsoon trough/CTCZ area during good monsoons.

4.3. Geographical distribution of non-linear energy exchanges

Figures 8 and 9 describe the spatial distribution of scale interactions between synoptic scale 3–5-day and low frequency oscillation 30–60-day in ERA and NCEP lower tropospheric winds, respectively. Similarly the Figures 10 and 11 elucidate the same but between 3–5 and 10–20-day for ERA and NCEP winds, respectively. The positive (negative) values of contours imply the loss (gain) of k.e. by

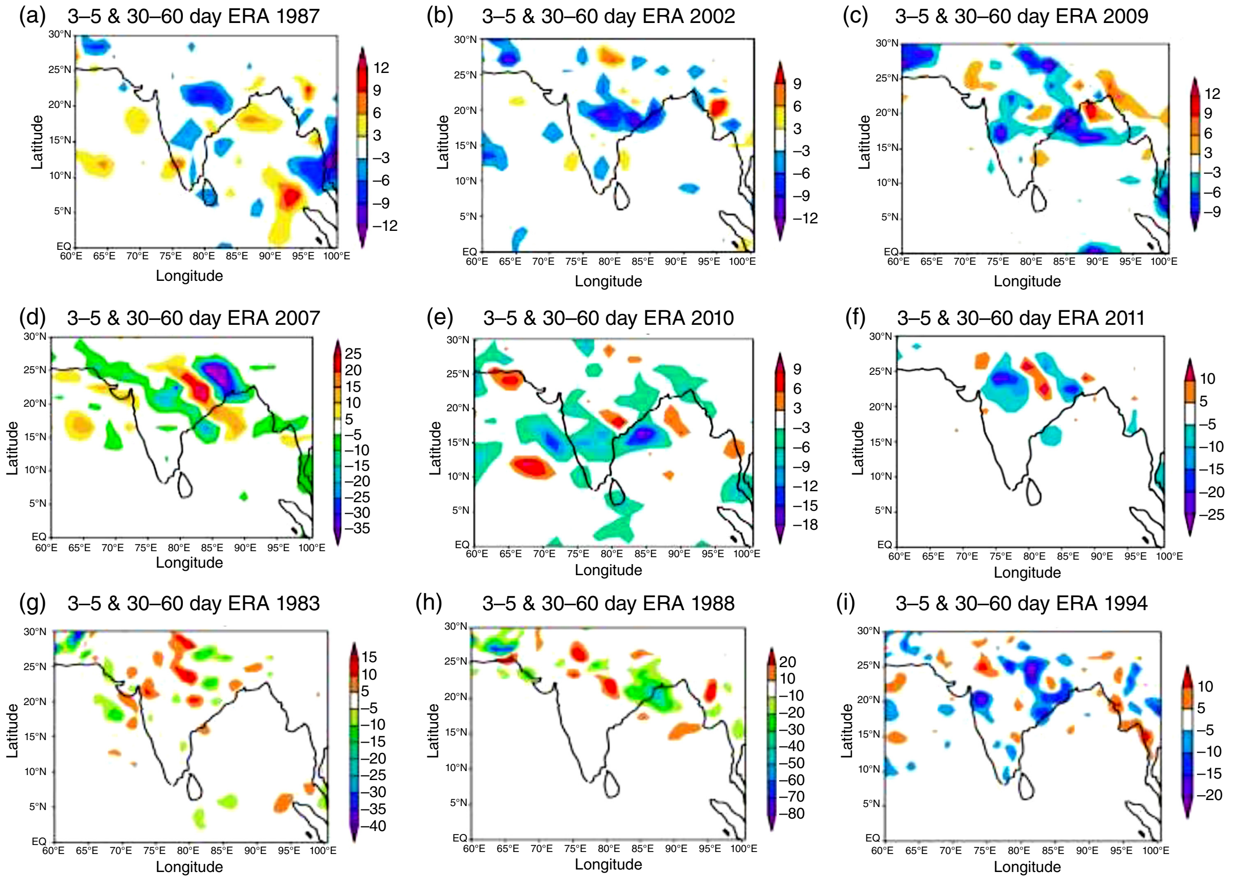


Figure 8. Non-linear interactions between synoptic scale (3–5-day) and low frequency (30–60-day) oscillations for drought (a–c), normal (d–f), and excess (g–i) monsoon years computed from ECMWF reanalysis 850 hpa wind fields during the monsoon period. The unit is watt kg^{-1} and the value is obtained after multiplication with 10^{-6}.

3–5-day to (from) low frequency modes. The followings are the major findings revealed from above figures.

- Major scale interactions are observed from the Northwest Bay and its adjoining region upto the Arabian sea, Gujarat, and adjoining Pakistan region i.e. the region of CTCZ (18°–30°N, 69°–96°E) particularly during most of the normal and excess monsoon years as observed from ERA (Figure 8) and NCEP (Figure 9) winds. The magnitude of the non-linear scale interactions during drought years are generally less than that in good monsoon years which is prominently observed in ERA winds. The negative value contours are more than the contours of positive value. Hence, after combining, there is a net negative interaction implying the gain of k.e. by 3–5-day from 30 to 60-day during normal and above normal monsoons compared with drought years.
- On the contrary, the weak interactions between 3–5 and 30–60-day are observed over Indian landmass during the deficient monsoons shown in Figures 8 and 9. In ERA wind, the magnitude of negative value contours are almost comparable with that of contours of positive value resulting the net weak interactions after combining all the interactions in deficient years, whereas there is hardly an interaction observed over the Indian landmass particularly in monsoon trough region as revealed from NCEP 850 hPa wind of deficient seasons. These may possibly be some of the reasons for the monsoon transients to be shorter life span because of not getting enough k.e. to intensify and to move further westward after entering the Indian landmass. Unlike the below normal years, the good monsoons show strong net negative interactions over the land region starting from east coast and adjoining north BoB upto the west coast of India, Gujarat, and adjoining Pakistan region. This implies that the LPS(s) receive adequate amount of k.e. from the 30–60-day oscillations over a large region of monsoon trough/CTCZ that favour them to propagate, sustain, and to intensify more causing wide spread homogeneous rainfall during normal and excess monsoon period with respect to in weak monsoons.
- There is a weak interaction of LPS(s) with the 10–20-day oscillations (Figures 10 and 11) during the drought years in respect of normal and excess monsoons particularly shown in ERA wind field as was noted in Figures 8 and 9. Dominant scale interactions are confined into the CTCZ region. Similar to the Figures 8 and 9, weak negative interactions and a strong positive interactions (i.e. the net positive interaction after combining all the contours) are exhibited over the Indian landmass during drought years

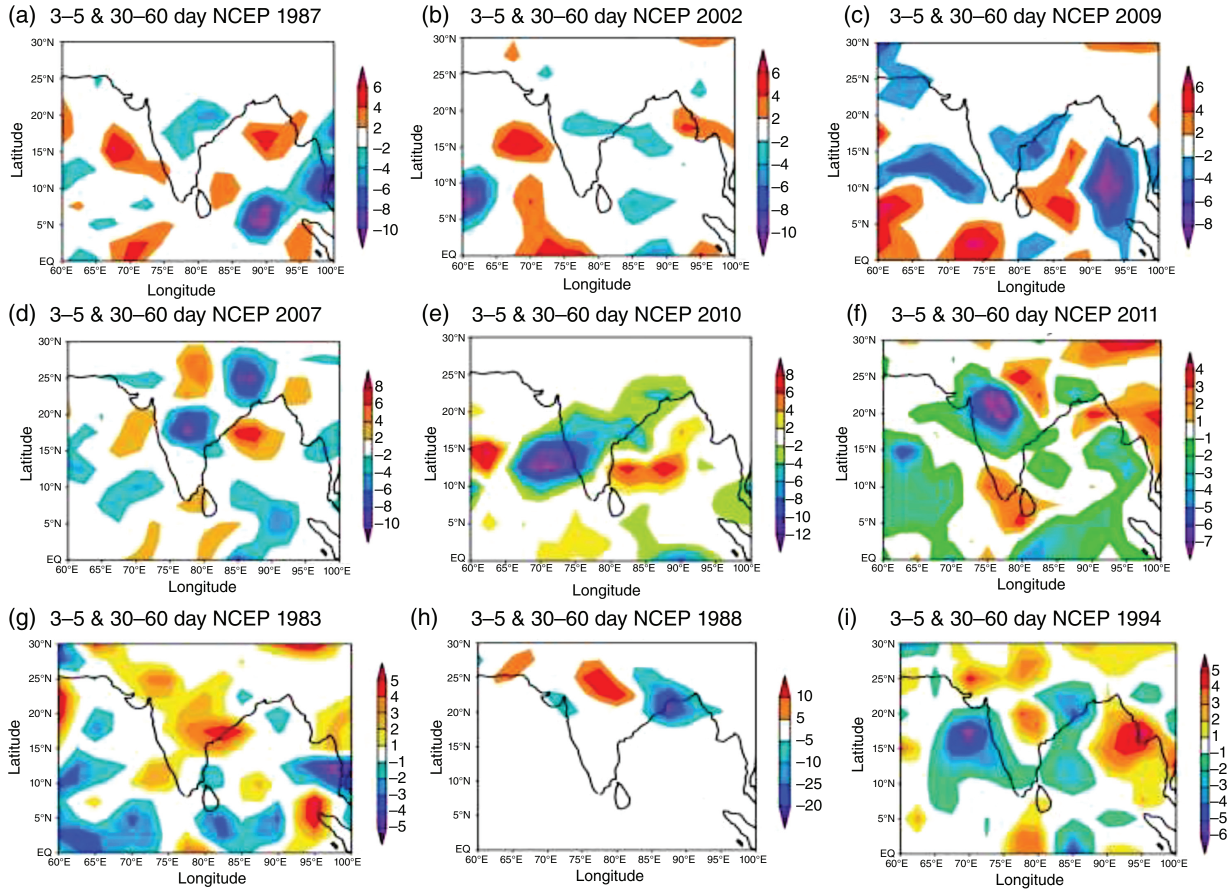


Figure 9. Non-linear interactions between synoptic scale (3–5-day) and low frequency (30–60-day) oscillations for drought (a–c), normal (d–f), and excess (g–i) monsoon years computed from NCEP reanalysis 850 hpa wind fields during the monsoon period. The unit is watt kg^{-1} and the value is obtained after multiplication with 10^{-6}.

in ERA 2009, NCEP 1987 and 2002 winds whereas equivalent amount of positive and negative value contours (resulting weak net negative interactions) are appeared in ERA 1987, 2002 and NCEP 2009 winds. This implies that either the monsoon transients are losing k.e. to the 10–20-day because of net positive interaction or the k.e. transfer to 3–5 from 10–20-day is insignificant for weak negative interaction during Indian monsoon droughts that in turn may attribute to weak, short-lived, and less propagating monsoon systems. These may be some of the key factors for subdue rainfall activity over the Indian landmass during the deficient monsoon seasons. Unlike the drought years, good monsoons exhibit strong non-linear interactions between synoptic scale and 10–20 day oscillations over the core monsoon zone (CTCZ). The negative value of interactions are appeared to be stronger than positive interactions leading to the net gain of k.e. by synoptic transients from the 10–20-day low frequency oscillations during normal and excess monsoons. Hence, as the 30–60-day, the 10–20-day waves support the LPS(s) to intensify with longer life span and to travel a longer journey before dissipation over the land region in good monsoon periods compared with the LPS(s) in deficient monsoons.

It may be revealed from the above study that the interannual variability of the cyclogenesis over CTCZ/monsoon trough region during the contrasting years which measure the interannual variability of ISMR is largely attributed due to the non-linear wave–wave interactions. Therefore, the wave–wave interaction may be treated as a measure of internal dynamics of ISM following Goswami (1995).

5. Conclusions

Indian monsoon transients have large attribution to ISMR, its intraseasonal and interannual variability. The rainfall for a LPS depends upon its life span, intensification, and its longitudinal journey before dissipation. It has been observed from the 116 years (1888–2003) dataset that the LPS(s) are likely to be short lived, less intensified, and moving a small distance before dissipation during drought years, perhaps causing subdue rainfall activity during monsoon. The statistics of the monsoon transients of different life span during the strong and weak monsoon years (analysing those 116 years data) exhibits that the transients having medium life span (5–9 days) attribute significantly to the seasonal rainfall and its variability during the contrasting monsoons. It is quite understandable from the energetics perspective that the k.e. is required

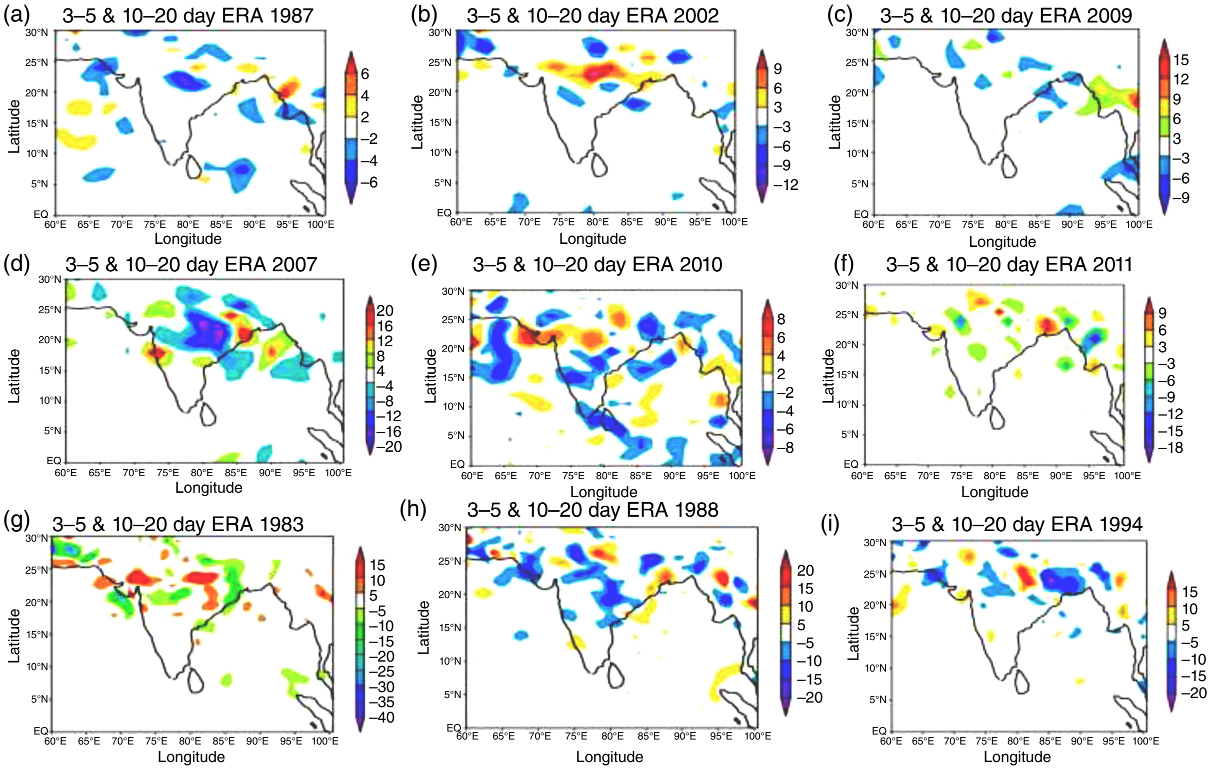


Figure 10. Non-linear interactions between synoptic scale (3–5-day) and low frequency (10–20-day) oscillations for draught (a–c), normal (d–f), and excess (g–i) monsoon years computed from ECMWF reanalysis 850 hpa wind fields during the monsoon period. The unit is watt kg^{-1} and the value is obtained after multiplication with 10^{-6}.

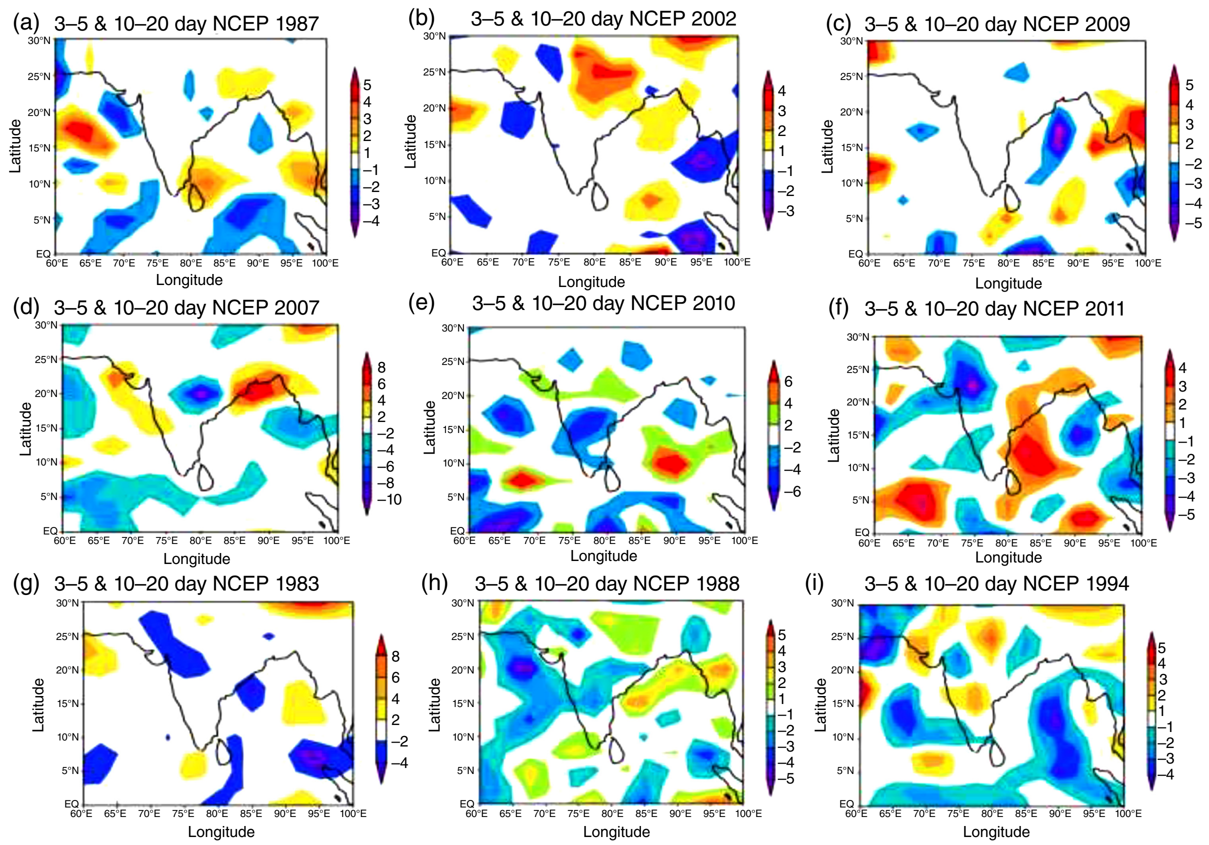


Figure 11. Non-linear interactions between synoptic scale (3–5-day) and low frequency (10–20-day) oscillations for draught (a–c), normal (d–f), and excess (g–i) monsoon years computed from NCEP reanalysis 850 hpa wind fields during the monsoon period. The unit is watt kg^{-1} and the value is obtained after multiplication with 10^{-6}.

for intensification, maintenance, and the large movement of synoptic systems. The previous literatures showed that the non-linearity of the flow and its multiscale interactions at lower troposphere might be the possible dynamical reason for the growth of the tropical disturbances from the individual cloud cluster. In this view, strong interactions among seasonal mean, low, and high frequency oscillations were also documented in the previous studies but, the quantification of the interactions were not so far revealed in those works. Hence, for the first time, the scale interactive energy exchanges in frequency domain have been explored to unravel the causes of weak LPS(s) during droughts vis-à-vis good monsoon years. The following inferences may be underscored after the comprehensive analysis of non-linear energy exchanges among the seasonal mean, high, and low frequency oscillations.

1. The seasonal mean is the main source of k.e. of low frequency (30–60 and 10–20-day) and high frequency (3–5-day and diurnal) oscillations.
2. The seasonal mean plays a key role for the generation of monsoon transients but, the same is not attributing to intensify and sustain the transients as analysed from mean–wave interactions.
3. The non-linear wave–wave interactions have shown that the 3–5-day (synoptic scale) waves gain distinguishably larger amount of k.e. from 30–60 and 10–20-day waves at lower troposphere that may attribute to more sustainability and intensification of monsoon transients during normal and excess monsoon years compared to those in deficient monsoons. The NCEP wind shows the k.e. loss of 3–5 to 10–20 day that may be one of the causes for weak monsoon transients during drought years.
4. The 30–60-day intraseasonal oscillation is another potential source of k.e. other than the seasonal mean as revealed from non-linear wave–wave interactions.
5. The drought years are characterized by weak interaction between high and low frequency oscillations over the Indian landmass shown in the spatial distribution of scale interactions. On the other hand, the dominant transfer of k.e. to 3–5-day mode from the low frequency oscillations are observed over a large region of CTCZ/monsoon trough that favour the synoptic systems to intensify, survive for longer duration, and to travel larger distance over that region before dissipation during the normal and excess monsoon period with respect to the LPS(s) in weak monsoons attributing to the rainfall variability over the Indian landmass in contrasting monsoon seasons.
6. The internal dynamics of ISM can be quantified by evaluating the non-linear wave–wave interactions between intraseasonal oscillations and synoptic scale waves.

Acknowledgements

The above work has been performed under the CTCZ project (project no. PC3/project 2 as a part of large scale component) sponsored by Ministry of Earth Sciences, Government of India. The authors thank to the Director, IITM for executing the project. Authors are grateful to NCEP and ECMWF for making the data available freely. Thanks are due to Brain Doty, COLA for GrADS software. Anonymous reviewers' comments are also gratefully acknowledged.

Appendix A

Mathematical Formulation of the Non-Linear Kinetic Energy interaction in the Frequency Domain

Following Chakraborty and Agarwal (1996), the equation for non-linear exchanges of k.e. among different frequencies r, s, and a frequency n can be written as:

$$
\begin{aligned}
\langle L(n)\rangle = -\Bigg[\frac{1}{2}&\begin{bmatrix} +\sum\limits_{r+S=n} \\ +\sum\limits_{r-S=n} \\ +\sum\limits_{r-S=-n} \end{bmatrix} \\
&\mathrm{UOC}n\cdot\mathrm{UTC}r\cdot\left(2\cdot\frac{\partial}{\partial x}\mathrm{UTC}s+\frac{\partial}{\partial y}\mathrm{VTC}s\right. \\
&\qquad\left.+\frac{\partial}{\partial p}\mathrm{WTC}s-\frac{\tan\phi}{a}\cdot\mathrm{VTC}s\right) \\
&+\mathrm{UOC}n\cdot\left(\frac{\partial}{\partial y}\mathrm{UTC}r\cdot\mathrm{VTC}s+\frac{\partial}{\partial p}\mathrm{UTC}r\cdot\mathrm{WTC}s\right) \\
&+\mathrm{VOC}n\cdot\mathrm{UTC}r\left(\frac{\partial}{\partial x}\mathrm{VTC}s-\frac{\tan\phi}{a}\cdot\mathrm{UTC}s\right) \\
&+\mathrm{VOC}n\cdot\mathrm{VTC}r\left(2\cdot\frac{\partial}{\partial y}\mathrm{VTC}s+\frac{\partial}{\partial p}\mathrm{WTC}s\right) \\
&+\mathrm{VOC}n\left(\frac{\partial}{\partial x}\mathrm{UTC}r\cdot\mathrm{VTC}s+\frac{\partial}{\partial p}\mathrm{VTC}r\cdot\mathrm{WTC}s\right)
\end{aligned}
$$

$$
\begin{aligned}
+\frac{1}{2}&\begin{bmatrix} -\sum\limits_{r+S=n} \\ +\sum\limits_{r-S=n} \\ +\sum\limits_{r-S=-n} \end{bmatrix} \\
&\mathrm{UOC}n\cdot\mathrm{UTS}r\cdot\left(2\cdot\frac{\partial}{\partial x}\mathrm{UTS}s+\frac{\partial}{\partial y}\mathrm{VTS}s\right. \\
&\qquad\left.+\frac{\partial}{\partial p}\mathrm{WTS}s-\frac{\tan\phi}{a}\cdot\mathrm{VTS}s\right) \\
&+\mathrm{UOC}n\cdot\left(\frac{\partial}{\partial y}\mathrm{UTS}r\cdot\mathrm{VTS}s+\frac{\partial}{\partial p}\mathrm{UTS}r\cdot\mathrm{WTS}s\right) \\
&+\mathrm{VOC}n\cdot\mathrm{UTS}r\left(\frac{\partial}{\partial x}\mathrm{VTS}s-\frac{\tan\phi}{a}\cdot\mathrm{UTS}s\right)
\end{aligned}
$$

$$
\begin{aligned}
&+ \mathrm{VOC}n \cdot \mathrm{VTS}r \left(2\frac{\partial}{\partial y}\mathrm{VTS}s + \frac{\partial}{\partial p}\mathrm{WTS}s \right) \\
&+ \mathrm{VOC}n \cdot \left(\frac{\partial}{\partial x}\mathrm{UTS}r \cdot \mathrm{VTS}s + \frac{\partial}{\partial p}\mathrm{VTS}r \cdot \mathrm{WTS}s \right) \\
&+ \frac{1}{2}\begin{bmatrix} +\sum\limits_{r+S=n} \\ -\sum\limits_{r-S=n} \\ +\sum\limits_{r-S=-n} \end{bmatrix} \\
&\mathrm{UOS}n \cdot \mathrm{UTC}r \cdot \left(2 \cdot \frac{\partial}{\partial x}\mathrm{UTS}s + \frac{\partial}{\partial y}\mathrm{VTS}s \right. \\
&\qquad \left. + \frac{\partial}{\partial p}\mathrm{WTS}s - \frac{\tan\phi}{a} \cdot \mathrm{VTS}s \right) \\
&+ \mathrm{UOS}n \cdot \left(\frac{\partial}{\partial y}\mathrm{UTC}r \cdot \mathrm{VTS}s + \frac{\partial}{\partial p}\mathrm{UTC}r \cdot \mathrm{WTS}s \right) \\
&+ \mathrm{VOS}n \cdot \mathrm{UTC}r \left(\frac{\partial}{\partial x}\mathrm{VTS}s - \frac{\tan\phi}{a} \cdot \mathrm{UTS}s \right) \\
&+ \mathrm{VOS}n \cdot \mathrm{VTC}r \left(2 \cdot \frac{\partial}{\partial y}\mathrm{VTS}s + \frac{\partial}{\partial p}\mathrm{WTS}s \right) \\
&+ \mathrm{VOS}n \cdot \left(\frac{\partial}{\partial x}\mathrm{UTC}r \cdot \mathrm{VTS}s + \frac{\partial}{\partial p}\mathrm{VTC}r \cdot \mathrm{WTS}s \right) \\
&+ \frac{1}{2}\begin{bmatrix} +\sum\limits_{r+S=n} \\ +\sum\limits_{r-S=n} \\ -\sum\limits_{r-S=-n} \end{bmatrix} \\
&\mathrm{UOS}n \cdot \mathrm{UTS}r \left(2 \cdot \frac{\partial}{\partial x}\mathrm{UTC}s + \frac{\partial}{\partial y}\mathrm{VTC}s \right. \\
&\qquad \left. + \frac{\partial}{\partial p}\mathrm{WTC}s - \frac{\tan\phi}{a} \cdot \mathrm{VTC}s \right) \\
&+ \mathrm{UOS}n \cdot \left(\frac{\partial}{\partial y}\mathrm{UTS}r \cdot \mathrm{VTC}s + \frac{\partial}{\partial p}\mathrm{UTS}r \cdot \mathrm{WTC}s \right) \\
&+ \mathrm{VOS}n \cdot \mathrm{UTS}r \left(2 \cdot \frac{\partial}{\partial x}\mathrm{VTC}s - \frac{\tan\phi}{a} \cdot \mathrm{UTC}s \right) \\
&+ \mathrm{VOS}n \cdot \mathrm{VTS}r \left(2 \cdot \frac{\partial}{\partial y}\mathrm{VTC}s + \frac{\partial}{\partial p}\mathrm{WTC}s \right) \\
&+ \mathrm{VOS}n \cdot \left. \left(\frac{\partial}{\partial x}\mathrm{UTS}r \cdot \mathrm{VTC}s + \frac{\partial}{\partial p}\mathrm{VTS}r \cdot \mathrm{WTC}s \right) \right]
\end{aligned}
\tag{A1}
$$

where 'a' is the earth's radius, 'ϕ' is the latitude, and n, r and s are the frequency indices. The wind fields U, V and W represent the zonal, meridional, and vertical wind, respectively. Here (UOC, UOS), (VOC, VOS) are the temporal Fourier cosine and sine coefficients of the observed U, V fields, respectively associated with frequency n, whereas (UTC, UTS), (VTC, VTS), and (WTC, WTS) are the same except for transient U, V, and W fields, respectively associated with frequencies r and s. Most of the terms for non-linear interactions in Equation (A1) involve triple products.

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