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Cold fronts/ upper air troughs and low level subtropical anticyclones in South Indian Ocean and Indian summer monsoon rainfall

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ABSTRACT
The movement of cold fronts with associated westerly waves from west coast of South Africa (10°E: even from 40°W) to west coast of Australia (120°E) during south west monsoon season influences Indian summer monsoon rainfall significantly.Moderate/ deep cold fronts have been observed in southern hemisphere east of 30°E and north of 30° south/ 25° south, during normal/ excess Indian summermonsoon months. Feeble cold fronts, which are observed during deficient monsoonmonths, do not penetrate north of 30°south. Westerly waveshave been observed from 850 hPa to 200 hPa or even up to 150 hPa pressure heights. It is well known thatcold fronts are closely associated with low pressure systems, normally lying at the leading edge of high pressure systems. They tend to move towards the equator and eastward. It is also well known that low and medium clouds such as Cumulus (CU), Cumulonimbus (CB), Altocumulus (AC) and Altostratus (AS) are observed at the cold front. In the rear of a cold front AC and AS clouds are observed. Because of presence of high pressure area, in the rear of a cold front, strong pressure gradient is observed from South Indian Ocean to north of the equator. Moisture generatedby the low level westerly waves/ troughs, in South Indian Ocean, can be observed by presence of thick AS clouds in the rear of cold fronts. Moisture generated (cold air mass), below 8000 feet (base of AS clouds) is transported to Indian Seas by low level subtropicalanti cyclones (from 850 hPa onwards) located between 40°W to 120°E, through southeasterly trades.This has been confirmed by 850hPa relative humidity (RH) and winds anomalies, for 21 normal/ excess and 20 deficient monsoon months for 31years period. So, the region from 40°W-120°E and north of 30°S in southern hemisphere is most vital for Indian Summer Monsoon Rainfall.

INTRODUCTION

Indian Summer Monsoon Rainfall (ISMR) failed thrice during first decade of 21st Century (2002, 2004 and 2009) and remained undetected (Gadgil et al., 2005; Francis and Gadgil, 2009). El Nino conditions and excess cyclone genesis over North West Pacific (NWP) during summer monsoon were mainly considered for failure of ISMR over India by many authors (Rajeevan, 1993; Kalsi et al., 2006; Francis and Gadgil, 2009). All India monthly rainfall during the month ofJune 2009 (85.7 mm) and July 2002 (146.2 mm) were the lowest during the period 1901-2009. Kumar et al. (2011), have observed that excess cyclone genesis over NWP during summer monsoon is not the cause of monsoon failure. They have mentioned that when an NWP system (tropical depression and above) after reaching west of 140°E, follows westerly to northwesterly track, the depth of ITCZ extends upwards up to 500 hPa in constant pressure charts over India and neighborhood and monsoon rainfall activity gets enhanced due to increased convergence along the trough line. They have further observed that out of 6 NWP systems, which crossed 30°N during the month of July 2002, one re-curved after reaching 32.0°N, two each after reaching 25.0°N and 20.2°N, respectively. One system did not re-curve (12w) and dissipated near 34.9°N/ 122.3°E. So, out of seven NWP systems, which remained east of 120°E during July, only one system did not appear to have influence on ISMR at all, because of its movements in north east direction from the very beginning. Attempts have been made to find a common cause for failure of south west monsoon rainfall over India.In this study, percentage departure of ISMR has been considered as excess for +11% and more, as normal for +10% to -10% and deficient for -11% and less.

DATA

Satellite clouds pictures (IR) for 12 years period from 2002 to 2013, 850hPa synoptic weather charts, synoptic weather surface charts for three years 2009 to 2011 and World Area Forecast Centre, London upper air charts from 2009 to 2013 have been used. Anomalies of 850 hPa RH and winds for 16 normal/ excess (1956, 1959, 1961, 1970, 1971, 1975, 1976, 1978, 1980, 1983, 1988, 1994, 1997, 2005, 2011 and 2012) and 15 deficient monsoon years (1951, 1962, 1965, 1966, 1968, 1972, 1974, 1979, 1982, 1986, 1987, 1992, 2002, 2004 and 2009) consisting of 41 months have been prepared by using NOAA Earth System Research Laboratory (USA) web site.

Previous studies

Preethi et al. (2011), have observed that presence of El Nino likes conditions in the Pacific and warming over the equatorial Indian Ocean during 2009 altered the circulation patterns and produced an anomalous low level convergence and ascending motion over the Indian Ocean region and large scale subsidence over the Indian land mass. Furthermore, the cross equatorial flow was weak, the monsoon was dominated by the slower 30-60 day mode, and the synoptic systems, which formed over the Bay of Bengal and the Arabian Sea, did not move in land. It is mentioned under Weather in India (Mausam, 2010) for the year 2009 that cross equatorial flow along the equatorial belt (equator to 5°N/ 5°S over Arabian Sea) was stronger than normal by about 5-10 knots, during the first week of June and first week of July. It was below normal by about 5 knots during second week of June. Except these, the cross equatorial flow along the equatorial belt was close to normal during the entire monsoon period, June-September. The cross equatorial flow along the equatorial belt (equator to 5°N/ 5°S over the Bay of Bengal) was stronger than normal by about 5-10 knots, during the first and second week of June, first and third week of July, first week of August and second week of September. The cross equatorial flow was almost normal for the remaining period during the season. Monthly wind anomaly features were also observed. Anomalous cyclonic and anti cyclonic circulations during June (anomalous cyclonic circulations was seen at 850 hPa over Arunachal Pradesh, adjoining Assam and Meghalaya and anomalous anticyclonic at 850 hPa over Maharashtra, Madhya Pradesh and East Gujarat extending up to 500 hPa), anomalous cyclonic circulations in July, anomalous cyclonic and anti cyclonic circulations in September, east southeasterly winds over the peninsula up to 500 hPa in August and anomalous anticyclonic circulation over central India at 850 hPa extending up to 500 hPa were observed. Gadgil et al. (2005), have mentioned that the country experienced a deficit of 13% in the summer monsoon of 2004. As in 2002, this deficit was not predicted either by the operational empirical models at IMD or by the dynamical models at national and international centres. Francis and Gadgil (2009) have mentioned that a drought was not expected from the predictions generated by the leading centres in the world using complex models of the coupled Ocean-atmosphere system. Models had generally predicted above average rainfall for June-July-August 2009 over most of the Indian region, which is almost the opposite of what was observed. They have further mentioned that for assessing the chance of drought, we have to rely either on past history or on the links with phenomena which can be predicted, such as El Nino and Southern Oscillation (ENSO). For June 2009, ENSO and Equatorial Indian Ocean Oscillation (EQUINOO) were both unfavorable but the magnitudes of the indices were not as large as in 2002. Rajeevan (1993) have observed that All India Monsoon Rainfall and number of typhoon days over NWP from June to September are significantly and negatively correlated. Khole (2008) has mentioned that during 2002, the eastward mode of the Madden Julian Oscillation and associated propagation of the convection eastwards was dominant over the northward propagation of the convection. This led to major breaks in Indian summer monsoon, particularly in the month of July. However, during 2006 the northward propagation of the convection zone was favored as compared to the eastward propagation of the convection. She has further mentioned that in 2002, there had been a significant eastward displacement of the west Pacific warm pool during the northern hemispheric summer months. The Sea Surface Temperatures (SSTs) over the Indian Ocean were above normal. In contrast, during 2006, the west Pacific warm pool was confined over that region; it did not extend east of International Date Line (IDL). Kalsi et al., (2006) have mentioned that SST anomalies over Nino 4 region of Pacific Ocean have played an important role in ISMR variation in recent years and one of the main causes for occurrence of drought 2002 may be attributed to such high abnormal warming over western Pacific. They have further mentioned that in monsoon 2002, very high number of tropical storms formed over NWP Ocean and most of these systems intensified into typhoon. Also, none of them moved towards west of 120°E in July and emerged into Bay of Bengal. Number of days of typhoon is also very high, which is one of the causes for deficient ISMR in 2002. They have further added that the daily analysis of cloud pictures from INSAT shows the whole cloud system from equatorial Indian Ocean had a tendency to move towards north western Pacific during the month of July rather than moving towards Indian region. It is mentioned in Weather in India (Mausam, 2003) that the intensity of Mascarene High at 30ºS/ 060ºE was above normal in all the months (June to September 2002) and a highest of +4.0 hPa was noticed during August. Joseph et al. (2001), had stated that when monsoon sets in over Kerala a strong cross equatorial current gets established in the lower troposphere over the Indian Ocean and south Asia at about 850 hPa. They further stated that this monsoon current transports moisture generated over the Indian Ocean to the monsoon rain area. A Low Level Jet (LLJ) is embedded in it. Sijji Kumar and Joseph (2001) had stated that while the LLJ axis crosses the equator as a southerly current in a geographically fixed and narrow longitude band close to the east African coast, the LLJ axis passes through peninsular India as a westerly current, but its axis can be anywhere from very low latitudes to almost 25º north. Mohanty and Dash (1994) observed that the flow entering the northern hemisphere during the summer monsoon months is concentrated at three regions at about 045°-055°E, 080°-090°E and 100°-120°E, corresponding to the three branches of monsoon viz., Arabian Sea, Bay of Bengal and South China Sea. They further observed that the peaks of the flow are at 050°E, 080°E and 105°E. Sikka and Gray (1981) pointed out that the sub-tropical Mascarene High undergoes short period intensity fluctuations due to passage of extra-tropical westerly waves of the southern hemisphere. The intensification of the Mascarene High strengthens the cross equatorial flow in the form of east African low level jet, and the corresponding monsoon current over the Arabian Sea. Joseph (1978) observed that in 1965 and 1966, monsoon depressions behaved erratically. Monsoon depressions formed during these two years in head Bay of Bengal and central Bay of Bengal and in 1966 even in south Bay of Bengal and had more northerly tracks than normal. These factors contributed to monsoon deficiency over central and northwest India. He had further stated that, in contrast during the monsoon season of 1967 depressions formed in central and south Bay of Bengal and moved predominantly in west-northwest direction. Asnani (1993) had observed that out of five depressions/ storms which formed over North Bay of Bengal during 1979 (June to September) only two followed near normal course, one had a short life and two moved away to northeast India. Godbole and Ghosh (1975) have observed that easterlies to the north of ITCZ are warm and dry while the westerlies to its immediate south are cool and moist. Dash and Mohanty (1999) observed that westerly wind maxima at 850 hPa were lowest along Somalia coast during 1987 (June to September) where as in the excess year 1988, it was large compared to normal and deficient monsoon years. Parsu Ram et al., (1999) have examined the cumulus activities and structure of Troposphere in a good and subdued monsoon activity periods on the western sector of the monsoon trough. They observed that moisture convergence is found up to 600 hPa in a good monsoon activity period and maximum moisture convergence is observed at 850 hPa. Here again they have highlighted the importance of 850 hPa winds. Asnani (2005) has mentioned that a good proportion of total moisture content of the air is below 800 hPa level. Kumar et al., (2011) have observed that anomalies of 850 hPameridional winds show that positive anomalies of winds are observed during normal/ excess monsoon months (July 2009, June, August and September 2011) all along the west coast and negative anomalies during deficient monsoon months (July 2002 and 2004, June 2009 and July 2011). Sakai et al., (2005) have mentioned that cold fronts are sloping transition zones extending from the surface to the troposphere wherein a cold air mass replaces a warm air mass. Kumar (1980) mentioned that the cold fronts with associated westerly waves in the lower levels move across the southern parts of the subcontinent (Africa) throughout the year. These rarely extend north of latitude 25ºS during summer season as the subtropical high pressure systems restrict their equator-ward penetration. Saha et al., (2007) have mentioned the inter-annual variability of the ISMR is due to a number of factors and hence it is difficult to derive a one-to-one relationship with any particular factor. On a global scale the ENSO has been observed to strongly affect the Indian monsoon rainfall. However, in recent years, interaction of the Indian monsoon with the ENSO appears to have undergone a change.

Kumar et al., (1983) has mentioned that the absence of frontal systems (across Southern Africa and adjoining southwest Indian Ocean) of moderate and strong intensity in 2^{nd} fortnight of May can lead to a delay in the onset of monsoon.In the year 1971 three cold fronts passed across southern Africa and adjoining southwest Indian Ocean in the 2^{nd} fortnight of May (up to 25^{th} May) and the monsoon set in earlier by 7-10 days along the west coast. In the year 1972, however, there was a conspicuous absence of cold fronts in May and up to 7 June and the monsoon was delayed by 15-20 days. They have further mentioned that the passages of cold fronts across Southern Africa and adjoining oceanic areas exercise marked influence on the strength of the cross equatorial flow which in turn leads to the organization and intensification of ITCZ and its northward advancement causing the onset of southwest monsoon. This association can be used as an aid in forecasting the onset of southwest monsoon along the west coast of India 4 to 7 days in advance. Kumar (1992) has mentioned that Feeble/ moderate cold fronts (high of intensity of 1024/ 1030 hPa in their rear) generally do not penetrate north of 25ºS and are seen slipping southeastwards between longitudes 35ºE and 45ºE. In the rear an elongated ridge from Atlantic Ocean anticyclone extends up to south Mozambique Channel and invariably forms a new anticyclonic cell. He has further mentioned that the deep/ very deep cold fronts (high of intensity up to 1035 hPa/ more than 1035 hpa in their rear) generally move further eastwards across Mozambique Channel. Along with it the Mascarene high also moves eastwards from its normal position 50ºE-60º E. As the frontal system further moves eastwards beyond 45ºE-50ºE, the Atlantic Ocean anticyclone crosses into south west Indian Ocean and stagnates over Oceanic area south of Malagasy (Madagascar) establishing the pressure ridge again. This causes southerly surge of cold air through the Mozambique Channel and increase in cross equatorial flow in Arabian Sea. This in turn leads to strengthening of equatorial westerlies and increase in horizontal shear. It is also mentioned that the most noteworthy surface synoptic feature over Southern Africa is the rhythmic eastward movement of troughs and ridges across the south and east coasts of Africa. The normal variation of pressure at 25ºS along the southeast coast over periods of 4 to 7 days is from 1010 to 1025 hPa, but in extreme cases in a variation of about 30 hPa can also occur once in a month or two.

METHODOLOGY

After examining satellite clouds picture (METEOSAT: IR) for all weeks of July 2002 (Fig-1 to Fig-4), it has been noticed that shallow layers of Alto Stratus(AS) clouds are seen in south Indian Ocean south of 10ºS/ 20ºS/ 30ºS. However, on 13^{th} July 2003, thick and bright AS clouds (more ice crystals) are seen between 50ºS-10ºS (Fig-5). The condition of south Indian Ocean (IO) was same during June 2009 as it was during July 2002. Occasionally, thick layers of AS clouds have been observed south of 30ºS prior to 26^{th} June. The condition in south IO started improving after 25^{th} June. Thick AS clouds have been noticed in July 2009 (2^{nd} July: Fig-6) when monsoon revived over the country from 1^{st} July. Generation of thick AS clouds in south IO south of 25ºS/ 10ºS shows generation of sufficient moisture in lower troposphere which is pumped into Indian Seas by the moderate/ strong cross equatorial flow ($\geq$ 30 knots). For generation and uplift of moisture some synoptic situations, like trough/ circulation is needed. Cold fronts are observed as upper air trough in south IO. The trough/ circulation is observed from 850 hPa to 200/ 150 hPa constant pressure charts from 30ºS/ south of 30°S. They start moving from 010ºE and may dissipate at 050ºE/ 120ºE (west coast of Australia: Fig-5). Sometimes cold fronts have been also seen moving from 040ºW/ 30ºS (from Atlantic Ocean: AO) and they dissipate near 010ºE/ 040ºE. In the rear of a cold front High Pressure is observed with central pressure of 1024 hPa to 1036 hPa or even more. Strong pressure gradient is created from

Figure 1. Meteosat satellite clouds picture (IR) 2nd July 2002, 1200 UTC

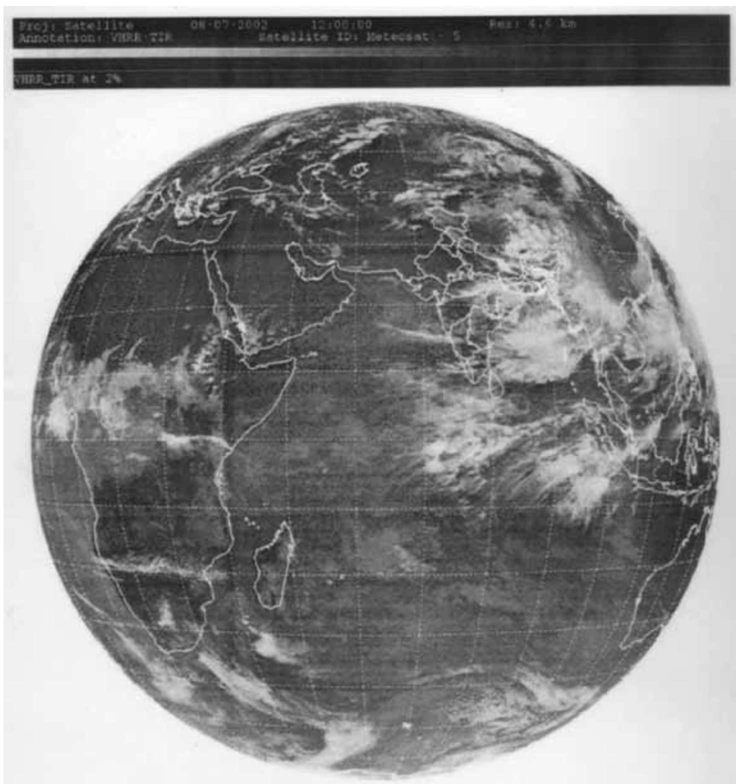

Figure 2. Meteosat satellite clouds picture (IR) 8th July 2002, 1200 UTC

Figure 3. Meteosat satellite clouds picture (IR) 13th July 2002, 1200 UTC

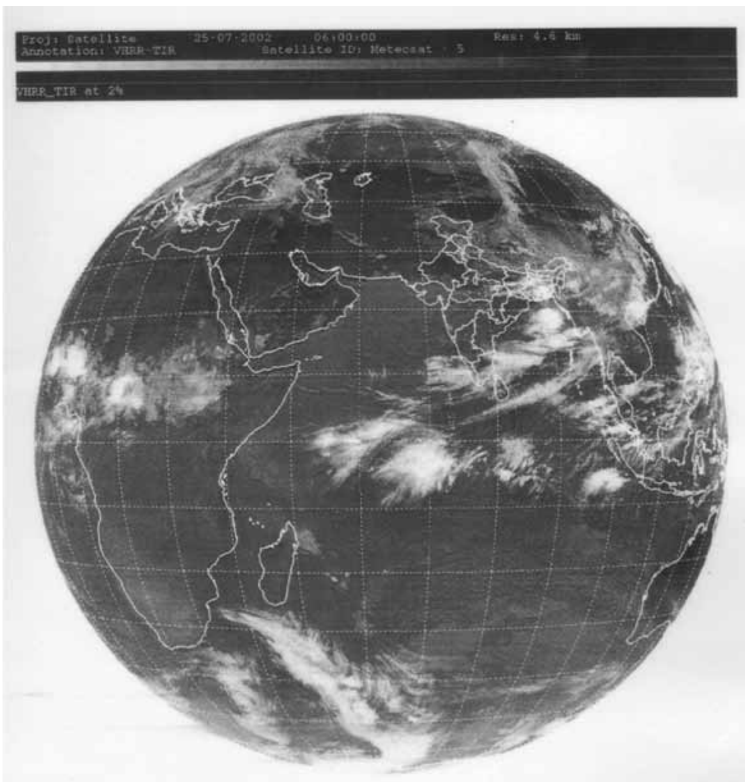

Figure 4. Meteosat satellite clouds picture (IR), 25th July 2002, 0600 UTC

30ºS to north IO in a limited area (030°E-050°E i.e., up to Madagascar Islands). In case of moderate/ deep cold front AS clouds are observed up to 25ºS/ 10ºS. During deficient monsoon years, cold fronts are mainly observed up to 30ºS. To verify these facts 850 hPa RH and winds anomalies for the region 0°E-100°E/ 30°S-25ºN for 21 normal/ excess and 20 deficient monsoon months have been considered. In a few cases the region from 40ºW-120ºE has been considered for anomalies of 850 hPa RH and winds (Annexure IA, Annexure IB and Annexure II).

Being a worst ENSO year, + RH and winds anomalies from June to September for 1997 have been also studied (Annexure IB). RH and winds anomalies over the country, AO and IO have been examined during normal/ excess or deficient monsoon months.

Cold fronts/ upper air trough in South Indian Ocean

Some important examples of cold fronts/ upper air troughs, which were observed between 2009 and 2013, have been discussed. Prior to 25thJune 2009 not even a moderate cold front was observed in South Indian Ocean during the month. An upper air trough at 850 hPawas observed over Mozambique Channel up to 20°S on 25th June. Winds and temperatures reported along 30°S by three grid points (World Area Forecast Center Chart, Washington) between 35°E-45°E have been given under Table 1 for 24th, 25th and 28th June, which confirm the gradual strengthening of westerly trough at 850 hPa (not at the cold front but in the rear) associated with the low of the cold front from 25th onwards (28th June data, Table 1, wind direction of 190/30 appears to be an observational error). This aspect is more clearly seen in Fig-11 and Fig-13. Cross equatorial flow at lower levels started improving in terms of wind speed from 27th June onwards up to 17.7°N between 55°E-72.5° (Table 2). Winds speed up to 50 knots was observed up to 15°N on 1st July at 850 hPa over Arabian Sea. A very deep cold front was observed from 1st July 2009 in South Indian Ocean. Satellite clouds picture of 2nd July 2009 (Fig-6) shows a deep cold front east of 60°E and AS clouds can be seen in the rear of the cold front up to 10°S. High Pressure Area was restricted even on 3rd July at 1800 UTC east of Madagascar Islands (Kumar, 1992). In the rear of the cold front High Pressure Area of 1032 hPa magnitude was observed (Fig-7) on 3rd July. A ship observation had reported 50 knots surface wind north of 10°N between 55°E-60°E. The cold front moved up to the east coast of Australia. In another case, a deep cold frontwas observed on surface chart of 15th June 2010. However, this cold front slipped towards south east from 17th June onwards after reaching east of 45°E. This type of feature is noticed very often and upper air trough is observed only up to south of 30°S. On many occasions upper air trough becomes deeper after reaching east of 60°E-70°E and moisture feeding to Indian seas becomes more prominent, which can be noticedon 15th July 2013 at 1200 UTC, when an upper air trough at 850 hPa is seen between 30°-40°E and up to 30°S. On 18th July at 0000 UTC, the trough is more marked and is observed between 60°-70° E and up to 20°S and intensity of Low Level Jet (LLJ) at 850 hPa strengthened further also to higher latitudes over Arabian Sea. In satellite clouds picture, AS clouds are seen moving up to northern latitude after 15th July and up to the existing trough latitudes. On 18th July (1245 UTC) clouds along the west coast were more marked than 15 July. This upper air trough moved to western coast of Australia on 21st July.

In absence of a moderate/ deep cold front, monsoon hiatus was observed from 19th to 30th June 2010. On 29th June AS clouds are observed up to 25ºS/ 70ºE in association with a cold front and further advance of monsoon started from 1st July (A prolonged hiatus occurred in the further advancement till 30th June: Weather in India, Mausam, 2011). A low (1010 hPa) on surface chart was observed on 19th May 2011 near 30°S/ 02°E and on 25th it was

Table-1: Winds (knots) and temperatures (C) at 850 hPa in June 2009 between 35°E-45°E/30°S at 0000 UTC

Date	Winds	Temp.	Winds	Temp.	Winds	Temp.
24.06.2009	230/05	+11	300/35	+15	320/30	+13
25.06.2009	220/40	+3	240/25	+4	300/35	+10
28.06.2009	200/35	+2	190/30	+3	280/45	+8

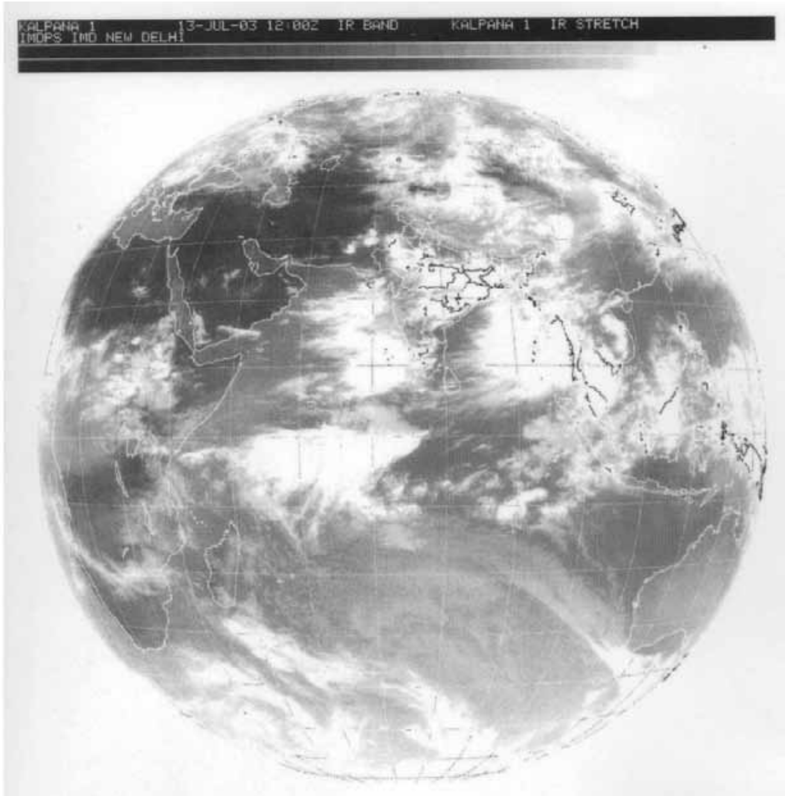

Figure 5. Kalapana 1 satellite clouds picture (IR), 13th July 2003, 1200 UTC

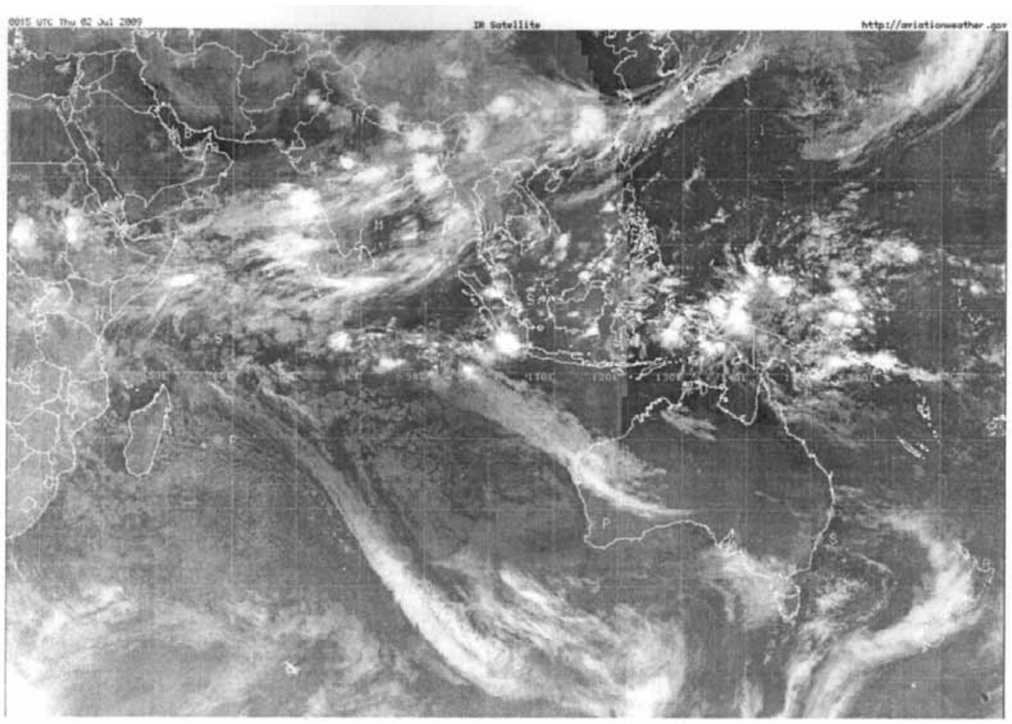

Figure 6. NOAA satellite clouds picture (IR) 2nd July 2009, 0015UTC

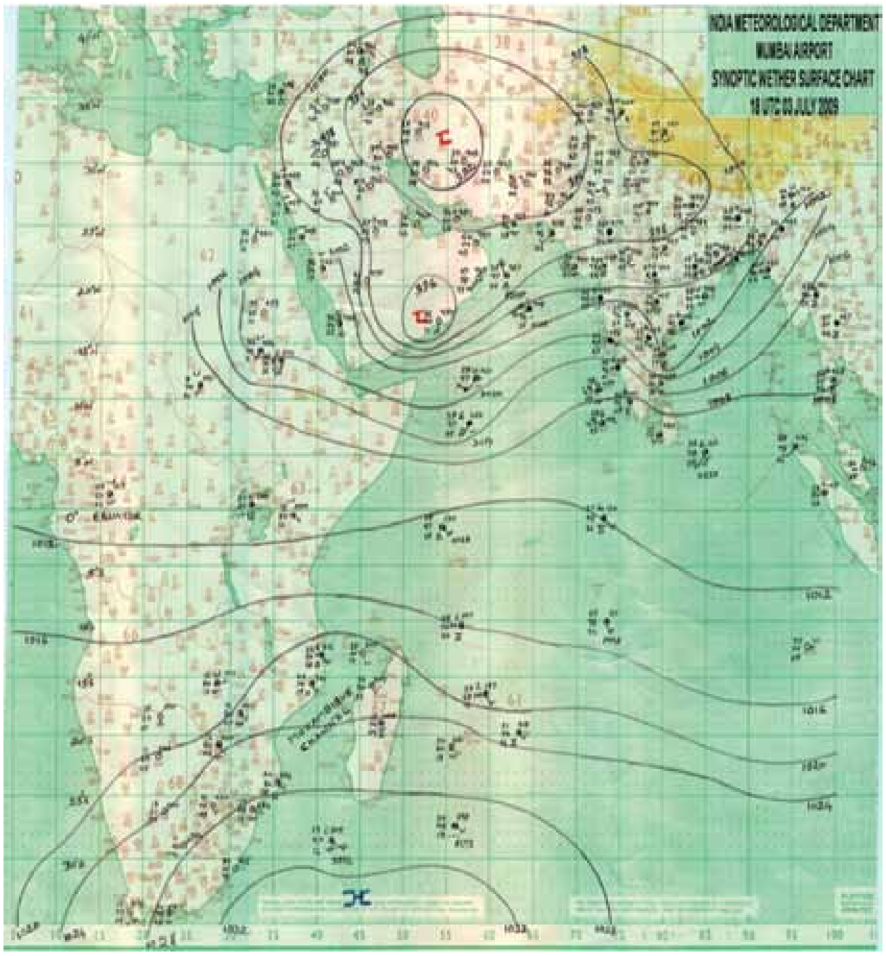

Figure 7. Synoptic weather surface chart 3rd July 2009, 1800 UTC

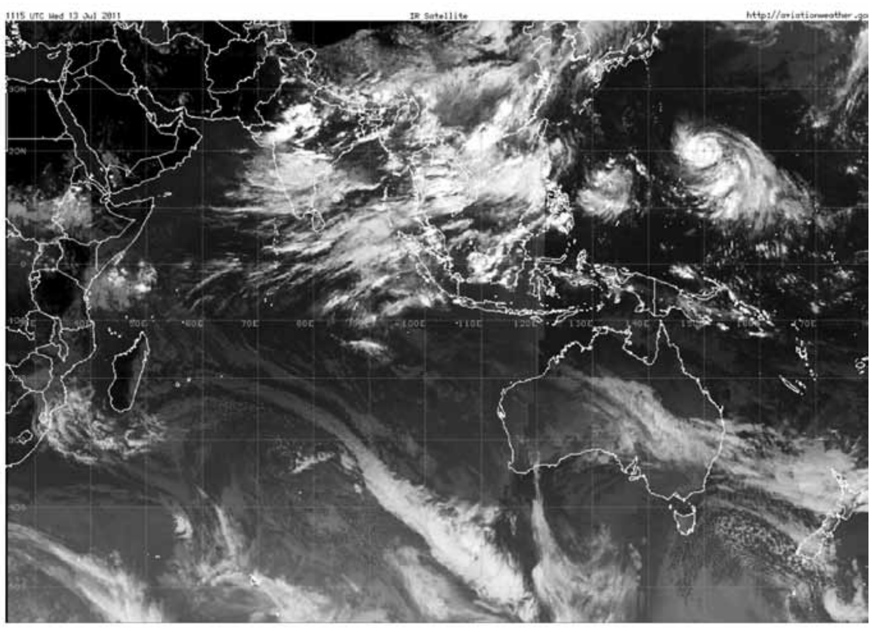

Figure 8. NOAA Satellite clouds picture (IR) 13th July 2011, 1115 UTC

near 30°S/ 30°E-40°E at 0000UTC. A moderate cold front was located between 30°E-40°E at 0015 UTC (NOAA satellite clouds picture). An upper air cyclonic circulation from 700 hPa constant pressure height (trough at 850 hPa) to 200 hPa heights was observed between 30°E-40°E. A High Pressure Area of 1028 hPa was located to rear of the cold front. On 28th the cold front was located between 50°E-60°E with northward extension up to 25°S. Monsoon set over Kerala and some other parts of the country on 29th May. Again a low (1008 hPa) was observed on surface chart near 30°S/ 30°E on 9th June at 1800 UTC. There was a short hiatus in further advance of monsoon along the west coast during 6th-10th June as no cold front was observed after the first one.An upper air cyclonic circulation was observed from 700 hPa on 10th July at 0000 UTC, near 25°S/ 10°E-20°E (trough at 850 hPa) to 200 hPa constant pressure chart. It was observed as an upper air cyclonic circulation from 850 hPa to 200 hPa constant pressure chart on 13th July between 20°S-25°S/ 40°E-50°E. Moisture generated by the circulation over Mozambique Channel is clearly seen in the satellite clouds picture (Fig-8). But no low was observed on surface chart. An anticyclone was observed just below the upper air cyclonic circulation at 850 hPa south of 30°S (Fig-9). Ridge line at 850 hPa continued up to 70°E-80°E between 30°S-35°S. Another upper air trough is seen between 80°E-100E up to 25°S (as AS clouds are seen up to 25°S), which is visible in satellite clouds picture (Fig-8). A High Pressure Area on surface chart (1028 hPa) was located between 30°E-50°E near 30°S at 1800 UTC on 13th July.Temperature gradient at 850 hPa constant pressure chart from 30°S (+07°C) to 10°N (+19°C) has been found as 12°C on 13th July 2011 (Fig-9) at 0000 UTC. Strong pressure and temperature gradients help in development of strong cross equatorial flow. Moisture generated

Table-2: Winds (knots) at 850hPa between 55°E-72.5°E from 10°N-17.5°N during 26th June to 3rdJuly 2009

Date	Lat.	55.0E	57.5E	60.0E	62.5E	65.0E	67.5E	70.0E	72.5E
26.06	10°N	250/30	230/40	240/20	260/20	280/20	280/20	290/20	290/25
27.06	10°N	260/30	250/40	260/35	250/30	260/30	270/30	280/25	280/20
28.06	10°N	260/35	250/40	250/35	260/35	260/30	270/25	270/25	280/25
29.06	10°N	260/40	260/45	260/45	260/40	250/35	250/30	260/30	270/30
30/06	10°N	260/35	260/45	260/45	26045	260/35	260/35	270/35	270/30
01.07	10°N	250/45	250/50	260/45	260/45	260/40	270/35	270/35	270/35
02.07	10°N	250/55	250/55	250/50	25045	260/45	260/40	260/40	270/35
03.07	10°N	250/55	250/55	250/55	250/45	260/40	260/40	270/35	270/35
26.06	15°N	050/15	060/20	090/15	050/10	270/10	270/10	280/15	280/15
27.06	15°N	270/15	260/20	260/25	260/30	270/30	270/30	270/30	270/20
28.06	15°N	270/30	270/20	270/20	260/30	260/30	270/30	270/25	270/20
29.06	15°N	270/30	270/30	270/35	270/35	270/35	270/35	270/35	270/30
30.06	15°N	260/30	270/45	270/45	270/45	260/45	260/40	260/35	26025
01.07	15°N	260/40	260/40	260/45	260/50	260/50	260/45	270/40	270/30
02.07	15°N	250/40	250/45	260/50	260/60	270/55	270/50	270/45	270/40
03.07	15°N	260/35	260/45	270/45	270/50	270/50	270/45	270/45	270/40
26.06	17.5°N	030/15	050/15	030/10	010/10	340/15	300/10	260/10	250/10
27.06	17.5°N	340/05	300/05	270/05	270/10	270/20	270/25	270/20	270/20
28.06	17.5°N	180/05	230/05	290/05	270/10	270/25	270/25	270/20	270/15
29.06	17.5°N	280/05	280/05	290/10	280/20	270/30	270/20	270/15	260/15
30.06	17.5°N	300/10	340/05	290/10	260/30	260/35	260/30	260/25	260/15
01.07	17.5°N	270/05	270/05	270/20	260/30	260/35	260/35	270/30	260/20
02.07	17.5°N	290/10	270/10	270/20	270/35	270/45	270/40	270/40	270/30
03.07	17.5°N	270/05	270/05	270/15	270/30	270/35	270/30	270/30	270/30

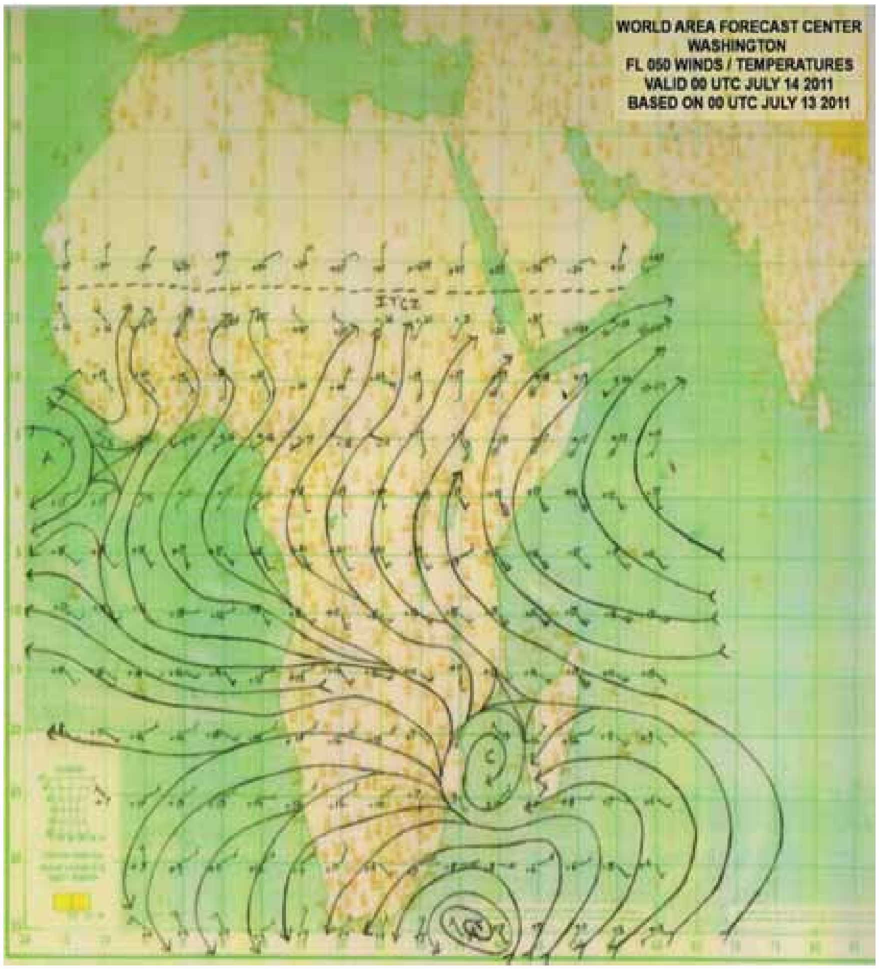

Figure 9. 850 hPa constant pressure chart 13 July 2011, 00UTC

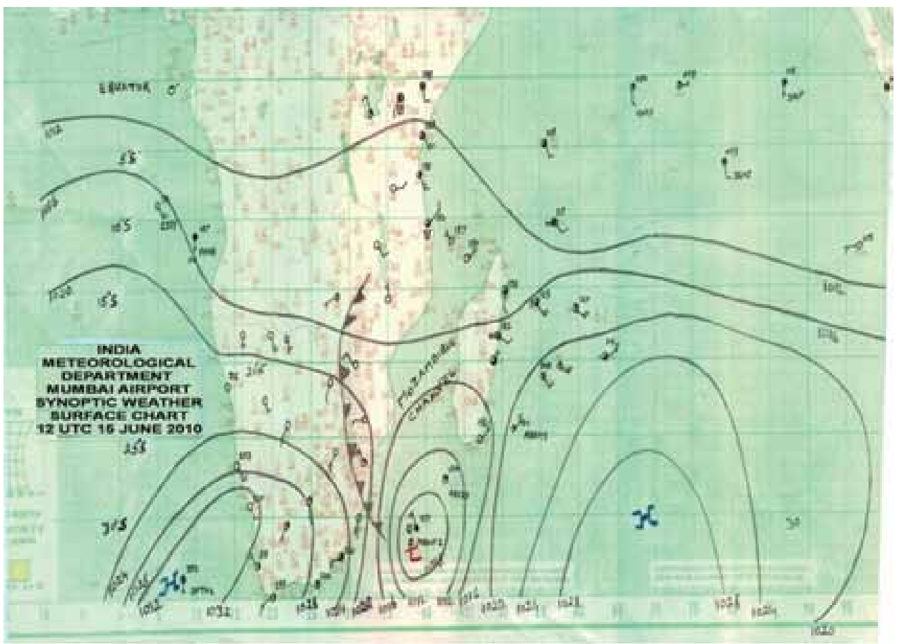

Figure 10. Synoptic weather surface chart 18th June 2010, 1200 UTC

in the rear of a cold front is pumped by moderate/ strong cross equatorial flow in the lower troposphere in the monsoon rain area (Fig-8). Low level cross equatorial flow became stronger and stronger from 14th Julyonwards. Wind distribution observed over Arabian Sea, from 14th-21st July up to 17.5°E, was almost similar to June-July 2009 wind distribution, as given under Table-2. It has been mentioned in end season report for south west monsoon 2011 that In July 2011 the weekly rainfall anomalies were negative during all the weeks except during third week (14-20 July) . It has been mentioned in Weather in India (Mausam, 2012) that cross equatorial flow along the equatorial belt (equator to 5°N-5°S) over Arabian Sea was stronger than normal by about 5 knots during 2nd week of June and 3rd week of September. It was also stronger than normal by about 5-10 knots during 1st week of September and by more than 10 knots during 3rd week of July. Synoptically, a low pressure area was observed over West Central and adjoining Northwest Bay off Andhra Pradesh-South Orissa coast on 13th July. It moved in northwest direction and became less marked over South Uttar Pradesh and adjoining North Madhya Pradesh on 17th. So, cross equatorial flow over Arabian Sea was strong during 3rd week of July and positive anomaly of weekly rainfall during 3rd week of July had occurred only because of presence of cold air mass over Mozambique Channel.

The upper air cyclonic circulation of 13th July 2011 was observed asa feeble low (1016 hPa) on surface chart on 16th July at 1200 UTCnear 24°S/ 35°E. It remained there till 18th July. It started moving eastward from 19th July and Mascarene High was shifted eastwards and weakened (1020 hPa on 20thJuly). After 21st July intensity of 850 hPa winds started weakening over Arabian Sea. Moisture feeding to Indian Seas has been also done by the upper air cyclonic circulation (13th July) having cold air mass temperature as +07°C at 850 hPa to -46°C at 300 hPa constant pressure chart (colder than surroundings). But clouds pattern of a cold front was not seen in this case. Whenever a moderate/ deep cold front (upper air trough) approaches over a station along 30°S, temperature at 300 hPa is observed as less than –40°C/ -45°C by other nearby stations also. Temperature at 300 hPa is very much marked in case of a moving cold front/ upper air trough along 30°S from 40°W to 120°E.

In a similar situation, a cyclonic circulation was observed at 850 hPa pressure chart between 25°N-30°N/ 30°-40°E on 11th August and no anti cyclonic flow was observed below it. No temperature gradient was observed at 850 hPa from 30°S. Nothing significant impact of this cold air mass was noticed on cross equatorial flow. It may be considered just a feeble upper air cyclonic circulation. From 25th May onwards one deep (13th July) cyclonic circulation and 11 cold fronts/ upper air troughs were observed during south west monsoon season 2011 in South Indian Ocean (May-1, June-3, July-3, August-2 and September-3).

In August 2012, an upper air trough was observed over Mozambique Channel on 2nd August up to 23°S and it moved in south east direction after 5th August. A deep cold front was observed on 8th August between 30°E-50°E up to 10°S. It also moved in south east direction after 10th August. This front became deeper from 15th onwards after reaching east of 60°E and its impact was seen up to 20th. On 15th August another feeble front was observed south of 30°S. Againon 21st August 2012 a feeble cold front was observed between 40°E-60°E/ South of 38°E. It remained South of 30°S from 23rdand was observed between 70°E-100°E/ South of 30°S on 26th. A new cold front was observed on 26thbetween 30°E-50°E/ South of 30°S. This cold front became deeper on 29th, as an upper air trough at 850 hPa, World Area Forecast Center Chart, Washington at 0000UTC, is seen between 75°E-100°E up to 25°S. In satellite clouds picture of 29th Aug 2012, 1245 UTC, AS clouds are seen between 50°E-90°E, south of 25°S (Fig-11). Anticyclone at 850 hPa is seen between 50°E-70°E/ 25°S-35°S with center at 30°S. In ECMWF analyzed Surface and 850 hPa chart of 29th August (Africa), 0000UTC a high of 1024 hPa is seen near 50°E/30°S (Fig-12) and a trough on surface chart between 60°E-90°E up to 30°S (Fig-12 and Fig-13). Clouds along the west coast and east coast became very prominent from 29th onwards. It is mentioned in the End Season Report for 2012 that under the influence of five low pressure areas that formed during successive weeks of August (3rd -9th August, 12th-14th August, 17th-22nd August, 25th-27th August and 30th-31st August) the rainfall activity over monsoon trough zone got enhanced. Again it is mentioned that towards the end of August, the systems and their remnants caused active to vigorous monsoon conditions over major parts of the country. In a satellite clouds picture of 6th July 2012, 0915 UTC, (Fig-14) two cold fronts are seen. One is located west of 70°W and another one is located west of 0°.

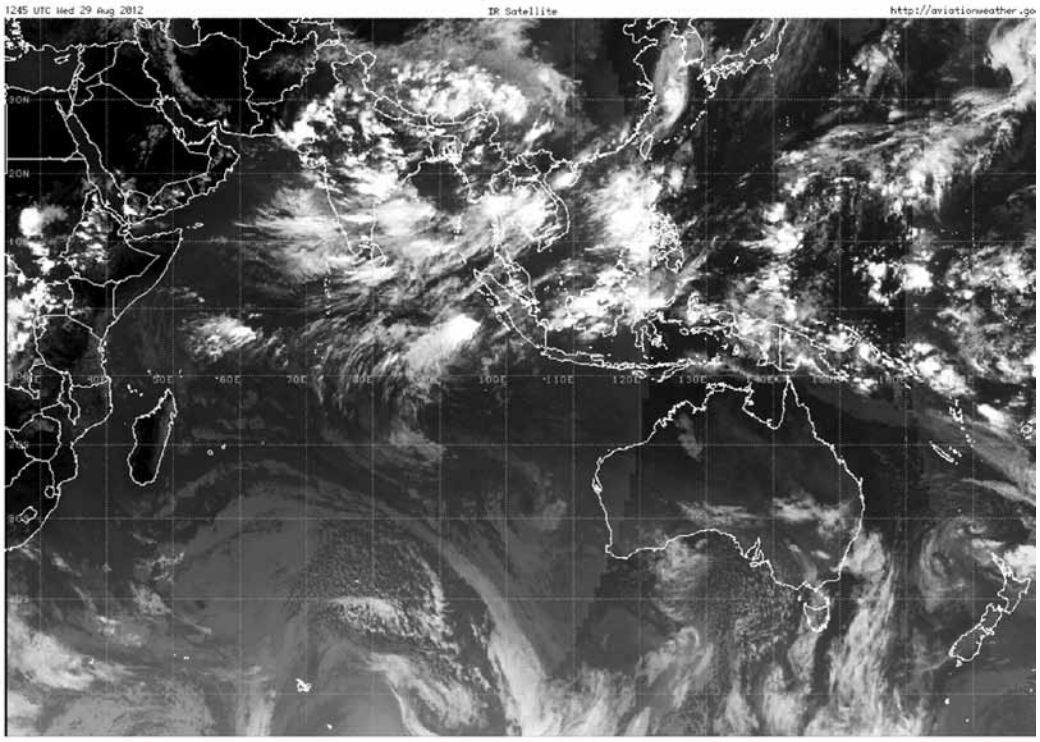

Figure 11. Satellite Clouds picture (IR) 29th August 2012, 1245 UTC

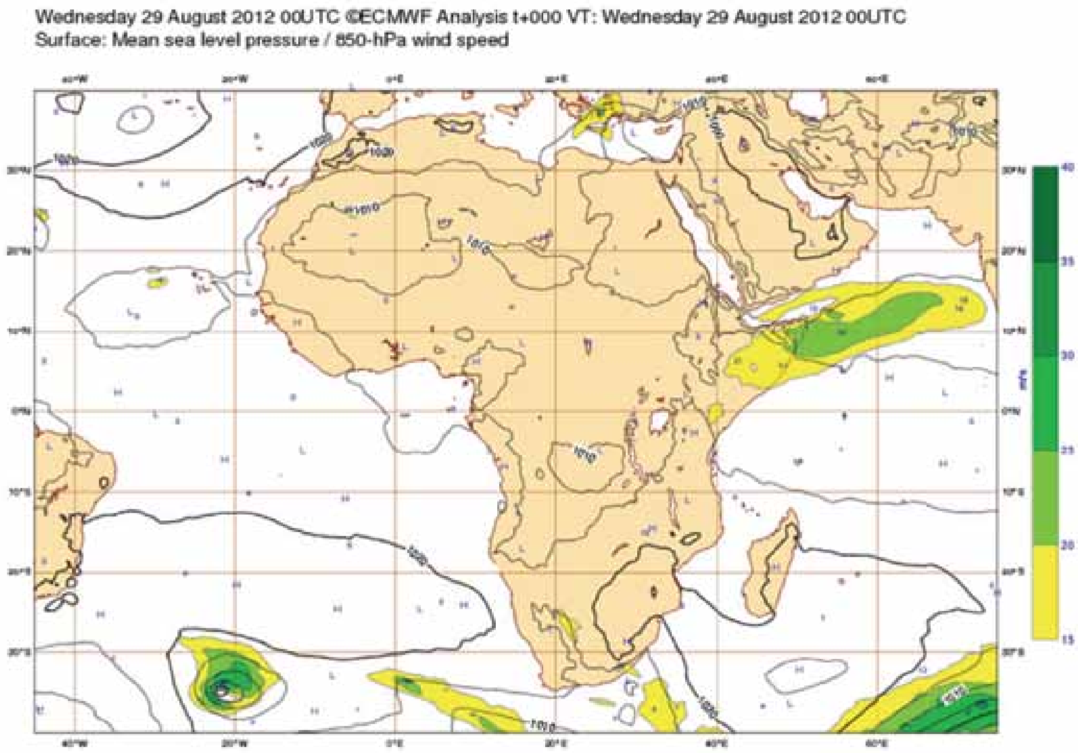

Figure 12. ECMWF analysed MSL/ 850 hPa winds chart (Africa) 29th August 2012, 00 UTC

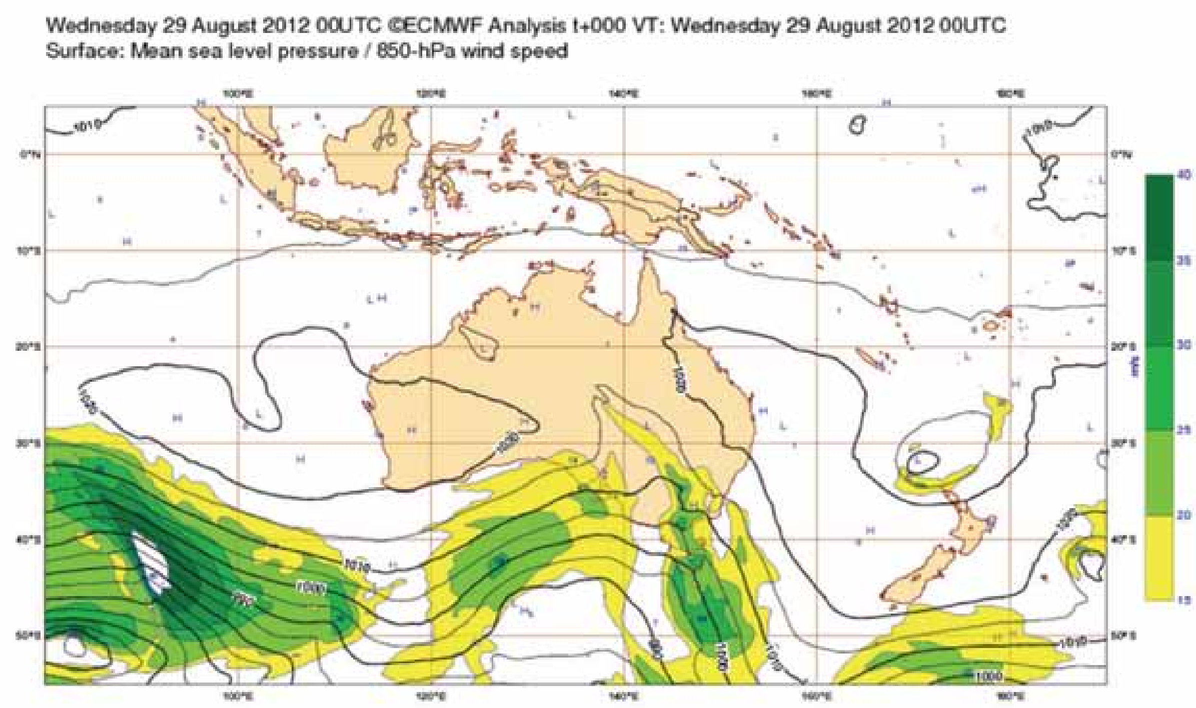

Figure 13. ECMWF MSL/850 hPa wind speed chart (Australia) 29th August 2012, 00 UTC

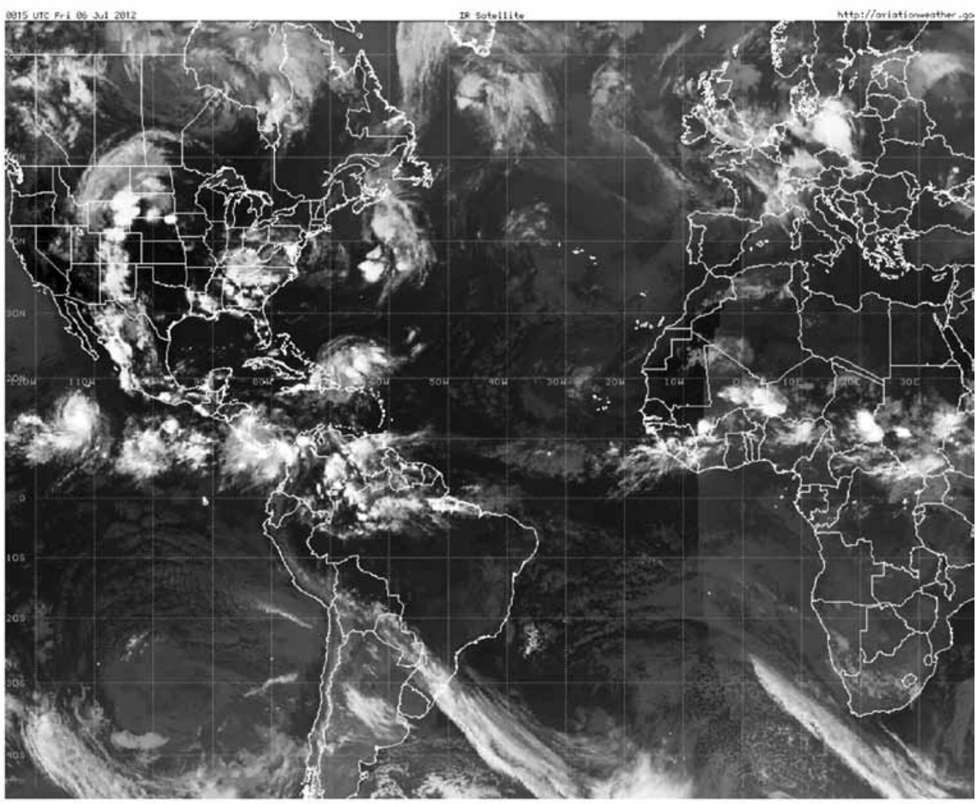

Figure 14. NOAA Satellite clouds picture (IR), 6th July 2012, 0015 UTC

In both cases moisture has been generated up to 10°S. These cold fronts feed moisture to the ITCZ, which is seen near 5°N. So formation and movement of cold fronts/ upper air troughs in South Indian Ocean east of 30°E (also from east of 40°W) and north of 30°S is a major parameter which influences ISMR.These observations have been well supported by RH and winds anomalies at 850 hPa over AO, IO, Indian Seas and India for normal/excess and deficient monsoon months discussed under next item.

RH and winds anomalies at 850 hPa in Indian Ocean for normal/ excess and deficient monsoon months

For examining RH and winds anomalies, 15 excess and 6 normal (1997: Jun-Sept, 2009-Jul and 2011-Aug) and 20 deficient monsoon months have been considered (Annexure- IA, Annexure-IB and Annexure-II). After going through these anomalies, details observations have been made under Table-3 and Table-4, respectively. Moisture, generated by moving upper air westerly troughs/cold fronts from 40°W-120°E and north of 30°S, is pumped to the north of equator by low level subtropical anticyclones through south easterly trades.In July 1956, + RH anomaly over the country is marked but - winds anomaly over the country has been marked. So, – winds anomaly over the country did not harm much as moisture has been pumped over monsoon rain area with the available wind field. During 6 years (7 months) of the respective months + RH and + winds anomalies were prominent over the country: 1959 (Jul), 1961 (Jul and Sep), 1971 (Jun), 1978 (Jun), 1980 (Jun) and 2011 (Aug). During 5 years 1970 (Aug), 1975 (Aug), 1983 (Aug), 1988 (Jul) and 1994 (Jul), + RH anomalies were prominent and + winds anomalies were observed in some parts. In the years 2009 (Jul) and 2012 (Sep), + winds anomalies were prominent over the country and + RH were observed in some parts. During 1997 (Jun and Sep), + winds anomalies were prominent over the country. However during August 1976, 1997 (Jul-Aug), Jul 2005 and Sept 2012, neither + RH nor + winds anomalies were prominent over the country. In August 1976 three depressions formed over the Bay (1^{st}, 12^{th} and 27^{th}: all became deep depression) which were mainly responsible for excess rainfall (28.4%) during the month. That is why + winds anomaly is seen from Bay of Bengal during the month. During 1997, 4 depressions (Jul-1, Aug-3: 3 deep depressions) and 2 low pressure areas (Jul-1, Aug-1) formed over Bay. So, influence of the Bay during Jul and Aug is very much marked. During July 2005, two low pressure areas (7^{th}-9^{th} and 23^{rd} -28^{th}) and one deep depression (29^{th} -31^{st}) formed over the Bay, which were mainly responsible for excess rainfall (14.7%) during the month. Here again marked + winds anomaly from the Bay is seen during the month. Similarly during September 2012, two well marked low pressure areas (3^{rd}-11^{th}, 27^{th}) over the Bay and one low pressure area (10^{th}-12^{th}) over Chhattisgarh and adjoining Odisha were observed, which were mainly responsible for normal rainfall (11%) over the country. However, marked + winds anomaly is seen from IO over the country during the month. During 21 normal/ excess monsoon months, –RH anomaly was not prominently observed during any month over thecountry.Moisture generation and feeding have been observed from (i) Atlantic Ocean (AO): 1956 (July), 1988 (July): (ii) AO and IO: 1959 (Jul.), 1961 (Jul. and Sept.), 1997 (Jun) and 2011 (Aug.); (iii) AO, IO and Bay of Bengal: 1994 (Jul) and 2012 (Sept.) (v) IO including western coast of Australia and Bay of Bengal: 1970 (Aug.), 1978 (Jun), 1997 (Sept: wind), 2005 (Jul.: also + wind) and 2009 (Jul) and from IO: 1971 (Aug), 1975 (Aug.), 1980 (Jun) and 1983 (Aug).

After examining RH anomaly for 850 hPa (Annexure-II) for 20 deficient monsoon months, these are the following observations: both – RH and – winds anomalies were prominent over the country doing 2002 (July: marked –RH anomaly from IO to Indian Seas and region) and 2004 (July). During 5 months of the respective years –RH anomalies were prominent over the country: 1982 (July), 1987 (July), 1992 (July), 2009 (June) and 2012 (June). However + winds anomaly were very prominent along the west coast during 1982 (Jul) but marked – winds anomaly is seen from 30°S to 10°S just below the + winds anomaly. - Winds anomaly were prominentduring 1962 (Jun: marked continuous – anomaly from IO to India), 1974 (Jun: west coast) and 1986 (Jul: marked continuous – anomaly from IO to the whole country) were prominent. Neither RH (both + or -) nor winds (+ or -) anomalies were observed prominent over India during the respective months of the years: 1951 (Jul), 1965 (Jun), 1966 (Jul), 1968 (Aug), 1972 (Jun and Jul), 1979 (Jun and Jul), 1992 (Jun) and 2011 (Jul).

Moisture generation in AO and IO (+ RH

Table-3: Observation on RH and winds anomaly at 850 hPa during normal/excess monsoon months (Annexure-I)

Year	Month	All India rainfall in % departure	Remarks
1956	Jul	22.5	Continuous positive (+) RHanomaly is seen from 10°W/5°N through 40°E/20° to Indian latitudes, maximum moisture generation and feeding from Atlantic Ocean (AO).Continuous + anomaly of winds from 30°S/10°E-25°E through 20°N/40°E to Arabian Sea, +winds anomaly from IO to the Bay. - Winds anomaly over the country has got less importance as + RH anomaly is seen.
1959	Jul	23.0	Marked + RH anomaly from 0°/10°N through 30°E-40°E, continuous + RH anomaly mainly from Indian Ocean (IO) to Indian Seas and Indian region. No – RH anomaly over the country. Continuous + anomaly of winds along the west coast.
1961	Jul	18.4	Marked + RH anomaly from 40°W/20°N through 10°E-40°E. Continuous + RH anomaly over the country also through IO. + Winds anomaly from IO over the country. Moisture feeding from AO and IO.
1961	Sept	48.8	Marked + RH anomaly from 10°W, north of equator. Marked continuous + RH anomaly over the country from IO. Marked + anomaly of winds from AO and IO. Moisture feeding from AO and IO.
1970	Aug	26.0	Marked continuous + RH anomaly over the country mainly from IO including west coast of Australia. + Winds anomaly from IO to Arabian Sea and the Bay.
1971	Jun	43.1	Marked continuous +RH anomaly over the country from IO. Continuous + anomaly of winds from IO over the country through west Coast.
1975	Aug	21.0	Continuous + RH anomaly over the country from IO. + winds anomaly through. Almost no – winds anomaly over the country.
1976	Aug	28.4	No continuous+ RH anomaly from IO. Continuous – RH anomaly from AO. – winds anomaly along Somalia coast. Continuous + anomaly of winds from Bay of Bengal.
1978	Jun	30.8	Continuous + RH anomaly from west coast of Australia. Continuous + anomaly of winds along the west coast.
1980	Jun	37.7	Marked continuous + anomaly of RH over the country from IO. + Winds anomaly from IO to the country.
1983	Aug	23.8	Marked continuous + RH anomaly from IO, + anomaly of winds along Somalia and east coasts. No – anomaly of winds along west coast.
1988	Jul	26.6	Marked + RH anomaly from 10°E/ 5°N to Indian latitudes. Continuous + anomaly of winds from AO, along Somalia coast and from Bay of Bengal.
1994	Jul	20.8	Marked continuous + RH anomaly from AO, IO and Bay of Bengal. –Winds anomaly along Somalia coast from IO. + winds anomaly along west coast up to 15°N.
1997	Jun	6.4	Marked continuous – RH anomaly from IO up to 10°N along the west coast and 25°N along the east coast. Continuous + RH anomaly from 20°E/10°N to north of 12°N and west of 80°E. Continuous + anomaly of winds over the country. Moisture feeding from AO/IO.
1997	Jul	-1.6	+ RH anomaly along the west coast, almost no - RH anomaly over India and neighborhood. + RH anomaly south of equator between 0°-80°E. + Winds anomaly from IO between 40°E-60°E/100°E-120°E, + winds anomaly from 20° N along west coast. – Winds anomaly over land north of 15°N
1997	Aug	9.3	–RH anomaly over very small area of the country. +Winds anomaly from 5°S to 18°N along west coast. – winds anomaly in a small region, NNW over Rajasthan.
1997	Sept	-6.1	- RH anomaly from IO to southern most Indian region. + Winds anomaly from east of 100°E from IO over India.
2005	Jul	14.7	Continuous +RH anomaly from IO to Indian seas. Marked + anomaly of winds from Somalia coast and Bay of Bengal. Marked – winds anomaly along west coast.
2009	Jul	-4.3	Continuous +RH anomaly mainly from IO and Bay of Bengal. Marked + anomaly of winds from IO along the west coast.
2011	Aug	10.0	Marked continuous + RH anomaly from AO, IO and from Bay of Bengal. Marked + RH anomaly from 0°/5°N. Marked + anomaly of winds from IO over the country.
2012	Sept	11.0	Continuous + RH anomaly from AO, IO and from Bay of Bengal. Continuous marked + anomaly of winds from IO along west coast of India.

Table-4: Observation on RH and winds anomaly at 850 hPa during deficient monsoon months (Annexure-II)

Year	Month	All India rainfall in % departure	Remarks
1951	Jul	-18.9	No continuous positive (+) RH anomaly from Indian Ocean (IO), Marked +RH anomaly from $0^o/10^oN$ through$35^oE/20^oN$ to Indian latitudes. No problem in moisture feeding from AO. Marked negative (-) winds anomaly along Somalia and east coast up to 15^oN + anomaly of winds along west coast only up to 14^o N.
1962	Jun	-34.4	Marked + RH anomaly from $0^o/ 12^oN$ to Arabian Sea. Moisture feeding also from IO. Marked - winds anomaly from IO along Somalia, west and east coasts.
1965	Jun	-33.3	No continuous + RH anomaly from AO/ IO to Indian Seas. – Winds anomaly along east coast.
1966	Jul	-15.9	No continuous + RH anomaly From IO to Indian Seas. Continuous + RH anomaly from 0 to 45 E/north of 10N. Moisture feeding from AO.
1968	Aug	-17.3	No continuous + RH anomaly from AO. Inadequate moisture generation in IO, marked - winds anomaly along Somalia and east coasts. + winds anomaly only up to 15^oN.
1972	Jun	-26.7	Continuous +RH anomaly from IO to Indian Seas. Marked - winds anomaly along Somalia coast, - winds anomalies east coast to central India. + winds anomaly north of 18 N.
1972	Jul	-31.2	Continuous +RH anomaly from IO to Indian Seas, marked – winds anomaly along Somalia and east coasts. + Winds anomaly along west coast up to 15^o N and over Gujarat.
1974	Jun	-25.6	Continuous + RH anomaly from 0 to Somalia Coast, equator and eastward. No continuous + RH anomaly from IO. Marked – winds anomaly along Somalia and West coasts and over NE India.
1979	Jun	-15.5	Continuous +RH anomaly from AO to Indian Seas. – RH over parts of India. Marked - anomaly of winds along Somalia coast, + marked winds anomalies along west coast up to 17 N from IO, - anomalies over parts of India.
1979	Jul	-16.0	RH continuous + anomaly from AO/ IO, + and – RH over parts of India, marked – anomaly of winds along Somalia coast. + and - anomalies of winds over parts of India.
1982	Jul	-23.1	Continuous – RH anomaly from AO/ IO to Arabian Sea, marked – RH anomaly over India. Marked – winds anomaly along Somalia coast. Marked +winds anomaly along west coast from IO.
1986	Jul	-14.2	-RH anomaly over AO. + RH anomaly from 15^o S/110^o E towards south of Indian latitudes in a narrow region. Marked – winds anomaly from IO to east of Somalia coast to Indian Seas and Indian region.
1987	Jul	-28.8	Only - RH anomaly from AO/IO to Indian Seas and Indian region. Marked – winds anomaly from IO along Somalia Coast, + and– winds anomalies over parts of India.
1992	Jun	-22.0	Continuous + RH anomaly from 10^oS to 10^oN from IO. – RH from north of 11 N over India. Inadequate moisture generation in IO/ AO. – Winds anomaly from Somalia coast to north Indian latitudes from 15^oN. + Winds anomaly in parts of India.
1992	Jul	-19.1	Continuous – RH anomaly from IO to Indian Seas and Indian region, inadequate moisture generation over AO/IO. – Winds anomaly along Somalia coast, + and - winds anomalies over parts of India.
2002	Jul	-54.2	Marked continuous– RH anomaly from AO/ IO to Indian Seas and region, marked - winds anomaly along west coast and over the country.
2004	Jul	-19.9	– RH anomaly in IO Indian Seas and over India, marked – winds anomaly along west coast. + winds anomalies along Somalia and east coasts from IO.
2009	Jun	-47.2	Marked continuous – RH anomaly from IO to Indian Seas and region, + winds anomaly only up to 10^o N. – Winds anomaly over parts of India.
2011	Jul	-15.0	Marked continuous + RH anomaly from IO to Indian Seas, + RH anomaly over a small region. + Marked winds anomaly along west coast, slightly away after 12^o N,- and + winds anomalies over parts of India
2012	Jun	-28.0	Marked – RH anomaly over AO/ IO, Indian seas and region. Marked + anomaly of winds from IO to Indian Seas, slightly away from west coast from 10N-15 N. – winds anomaly over pars of north and NE India.

anomaly above 30S and north of 25S) has been affected (Annexure-II) during the following years: 1987 (Jul), 1992 (Jun and Jul), 2002 (Jul), 2004 (Jul), and 2009 (Jun) as cold fronts did not penetrate north of 25°S. Low level subtropical anticyclones in south AO/ IO were not strong enough to pump adequate RH over the country through Arabian Sea and the Bay of Bengal branches of monsoon currents (eastward from AO through SE trades) during the following years: 1951 (Jul), 1962 (Jun), 1965 (Jun), 1966 (Jul), 1968 (Aug), 1972 (Jun and Jul), 1974 (Jun), 1979 (Jun and Jul), 1982 (Jul), 1986 (Jul), 2011 (Jul) and 2012 (Jun).

EL-Nino, cold fronts and low level anticyclones in AO/ IO

It is known that (Asnani and Verma: 2007) SST-anomalies in Eastern Pacific are directly and visibly connected to anomalies in the position and intensity of low-level subtropical anticyclones. It is also known that these low-level subtropical anticyclones in the eastern pacific form a chain of low-level subtropical anticyclones throughout the global subtropics; if one anticyclone has anomalous position or intensity, the whole global chain of low-level subtropical anticyclones manifests anomalies in position and intensity. Many authors have observed that there is some relationship but not one to one correspondence between El Nino (SST anomaly in region Nino 3.4: 5°N-5°S, 170°W-120°W, be 0.4°C or more for at least 6 consecutive months (April-September), Asnani-2005) / La Nina events and Indian summer monsoon rainfall. NOAA (2012) Oceanic Nino Index (NOI) for: AMJ 1973-JJA 1974: -2.0, OND 2005-FMA 2006:-0.9 and ASO 2011-FMA 2012: -1.0 shows that 1974, 2005 and 2011 were La Nina years. Also 1966, 1979 and 2012 (MJJ: -0.0, JJA: 0.1 and JAS: 0.3) are not El-Nino years. But deficient rainfall has occurred in the respective months, as mentioned, because of position and intensity of low level anticyclones in AO/ IO. The year1988 was a La Nina Year, but marked- winds anomaly is seen in from IO to the west coast of India up to 10°N during July. It is well known that frontal systems are major weather system during winter for Southern Western Australia. Grains Research and Development Corporation, Australia (2008-2011: climetkelpie@ econnect.com.au) has mentioned that impact of ENSO has got very little impact on the climate of Western Australia. Saha et al., (1994) have mentioned that, in 1994, during the strongest EL-Nino of the century, the rainfall was above normal (12.5%). During 1994 (Jul), excess rainfall (20.8%) occurred over India, marked + RH anomalies can be seen over the country and Indian Seas (Annexure-IA). Again during 2009 (Jul) a very deep cold front was observed in IO (Fig-6), and 2009 was also an El Nino year. All India rainfall during the month was observed as normal (-4.3%).So, impact of ENSO on movement of cold fronts is not much affected. Cold fronts have been observed as a major constituent of ISMR. Its movement can be helpful for day to day and short range forecasts.Moisture generation in AO/ IO was not adequate during 6 deficient months and low level subtropical anticyclones were not strong enough during 14 deficient monsoon months.

CONCLUSIONS

The movement of cold fronts with associated westerly waves from west coast of South Africa (10°E: even from 40°W) to west coast of Australia (120°E) during south west monsoon season influences Indian summer monsoon rainfall significantly. Moderate/ deep cold fronts (upper air troughs) have been observed in southern hemisphere east of 010°E and north of 30°S/ 25°S during normal/ excess Indian summer monsoon months. Feeble cold fronts/ upper air troughs, which are observed during deficient monsoon months, do not penetrate north of 30°S. Shallow layers of AS clouds or no AS clouds are seen in south IO north of 30°S during deficient monsoon months. Thick AS clouds are seen in association with upper air westerly trough/ cold front (rear) even up to 10°S if the trough extends up to 10°S. Moisture feeding from South Indian Ocean to Indian Seas is also done by upper air cyclonic circulation from 850 hPa to 200 hPa constant pressure height. Its impact on cross equatorial flow has been observed very prominent if it is located near 20°N-25°N/ 30°-50°E. Whenever a moderate/ deep cold front (upper air trough) approaches over a station along 30°S, temperature at 300 hPa is observed as less than –40°C/ -45°C by other stations also along the route. Temperature at 300 hPa is very much marked in case of a moving cold front/ upper air trough/ upper air cyclonic circulation along 30°S from 40°W to 120°E. Presence of an upper air trough at 850 hPa at least up to 25°S and less than -40°C temperature at 300 hPa along 30°S almost over the same region confirm the presence of moderate cold front/ upper air trough at first glance. A few upper air troughs at 850 hPa become more deep (south of 30°S-20°S) after reaching east of 60°E during a monsoon season.Absence of moderate/ deep cold fronts (upper air troughs) in south Indian Ocean during south west monsoon season is the most common cause of deficient monsoon in a year.

+ RH and + winds or + RH or + winds anomalies over the country are observed prominently during normal/ excess monsoon months in most of the cases. During 21 normal/ excess monsoon months, –RH anomaly was not prominently observed during any month over the country. Moisture feedings were prominent from AO, IO (including western coast of Australia) and Bay of Bengal. – RH and – winds, - RH or – winds anomalies were prominently observed during 10 deficient monsoon months. During the remaining 10 deficient monsoon months neither RH (+ or -) nor winds (+ or -) anomalies were prominently observed over the country.

There is no one to one relationship between El Nino/ La Nina years over deficient/ normal/excess monsoon months.

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