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From the International Indian Ocean Expedition (IIOE) to the Arabian Sea Monsoon Experiment (ARMEX) – four decades of major advances in monsoon meteorology

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सार – इस शोध पत्र में पिछले 50 वर्षों अथवा लगभग इससे भी अधिक वर्षों में मानसून को समझने, उसके निदर्शन और पूर्वानुमान लगाने की व्याख्या करते हुए बहुत अधिक संख्या में शोध कार्य किए गए हैं जिससे नए प्रेक्षणात्मक और परिकलनात्मक तकनीकों का सूत्रपात किया गया है । आई. आई. ओ. ई. (1963–1965) से प्रारम्भ हुई और आरमेक्स (2002, 2003) में चरम बिंदु पर पहुँचे पिछले 4 दशकों में राष्ट्रीय और अन्तर्राष्ट्रीय स्तर पर अति–आधुनिक समुद्र स्थल और अंतरिक्ष पर आधारित प्रेक्षणात्मक प्रणालियों का उपयोग करते हुए अनेक क्षेत्रीय प्रेक्षणात्मक कार्यक्रम आरम्भ किए गए हैं जिससे मानसून संबंधी शोध कार्य को नई चूनौतियाँ मिली हैं । इस शोध पत्र में प्रेक्षणात्मक और निदर्श के अध्ययनों का उपयोग करते हुए चार दशकों (1963–2003) के दौरान किए गए मानसून संबंधी शोध कार्यों और आगे आने वाली चुनौतियों की प्रमुख विशेषताओं का पता चलता है ।

ABSTRACT. Vast amount of researches on describing understanding, modelling and prediction of monsoon have taken place in the last 50 years or so as new observational and computational technologies have been introduced. Several field observational programs using state of the art sea-land and space-based observational systems have been undertaken nationally and internationally in the last 4 decades beginning with the IIOE (1963-1965) and culminating in the ARMEX (2002, 2003) which have given new challenges to monsoon-related research. The paper provides salient features of the research on the Indian monsoon accomplished during the four decades (1963-2003) using observational and modelling studies and the discusses new challenges which lie ahead for its further improved understanding and prediction.

Key words – ARMEX, Monsoon research, Field programs, IIOE.

1. Introduction

One of the most spectacular and dramatic atmospheric phenomena over South Asia is the summer monsoon (June to September) rains. It is known for its regularity and yet fascinates the specialists as well as the general public for the variability in timings of its arrival and its fluctuations in space and time on the intra-seasonal as well as inter-annual scales. The summer monsoon (henceforth monsoon) has been studied since the ancient times but the methodology, approach and scope of the studies have undergone tremendous changes with time. Due to progressive introduction of scientific and technological approaches in monitoring, analysing and modelling since the mid-19th century, the scientific knowledge-base on the monsoon processes has enormously increased and tools for monsoon prediction have consequently improved. India Meteorological Department (IMD), established In 1875, has played vital and dynamic roles in steadily improving observational network, data collection and transmission, development of forecasting tools and steering and promoting research programs for better understanding of monsoon phenomenology for over 120 years (IMD. 1976).

Recognizing the importance of the Indian Ocean on the monsoon, IMD in the in the very first 20 years of its existence, under the leadership of its first Director-General, John Eliot, had launched a special effort in 1893-94 to collect surface meteorological observations on the vast Indian Ocean. This resulted in an exciting observational finding by Eliot (1901) that at the time of monsoon onset a gigantic cross-equtorial clockwise wind gyre develops. Its setup brings in strong cross-equatorial wind flow across the west Arabian Sea, linking South Indian Ocean with the North Indian Ocean. This program could as well be called the first field experiment for understanding monsoon processes. Since then special field experiments with well-focused objectives have played vital role in advancing knowledge and understanding of the processes involved in the fluctuations of the monsoon. The very first international effort to understand the weather and oceanography of the Indian Ocean was implemented during 1963-65, under the International Indian Ocean Expedition (IIOE). India played a pivotal role in the IIOE. Since the IIOE, several bilateral and international field programs like Indo-Soviet Monsoon Experiment – 1973 (ISMEX-73), International

Monsoon Experiment – 1977 (Monsoon-77), the Summer Monsoon Experiment as part of the First Global GARP Experiment – 1979 (Summer MONEX-1979) and the Indian Ocean Experiment (INDEX) in 1980s were carried out between 1973-1983. India's participation in these experiments benefited the Indian atmosphere-ocean science community to better understand the monsoon jointly with the international community. Since 1970 tremendous progress has been made in India about the observational systems through improvements based on land-ocean-and-space technologies. This has encouraged the Indian atmosphere-ocean science community to launch special national field programmes for understanding monsoon processes designed and implemented by their own efforts. This has resulted in the implementation of the Monsoon Trough Boundary Layer Experiment (MONTBLEX) in 1989-90 (Sikka and Narasimha, 1995), Land Surface Processes Experiment (LASPEX) in 1995-1996 (J. Agrometeorology 2001), Bay of Bengal Monsoon Experiment (BOBMEX) in 1999 (Bhat *et al.*, 2001 and Proc. Ind. Acad. Sci., 2003), Arabian Sea Monsoon Experiment (ARMEX-I) in 2002 and the Arabian Sea Monsoon Experiment (ARMEX-II) in 2003 (Sanjeeva Rao and Sikka, 2005). The analyses of observational data collected during these experiments and efforts on diagnostic and modelling studies with the availability of new infrastructures, setting up of new research centres like the Indian Institute of Tropical Meteorology (IITM) at Pune, National Institute of Oceanography (NIO) at Goa, Centre for Atmospheric Research at IIT Delhi, Centre for Atmosphere-Ocean Studies at IISC, Bangalore and the National Centre for Medium-Range Forecasting (NCMRWF), New Delhi and introduction of courses in atmospheric sciences and oceanography at several universities, have resulted in enormous increase of research on monsoon meteorology in the last 4 decades. While during 1875 to 1900, there were only three or four prominent researchers on monsoon meteorology in the IMD (Blanford, Dallas, Eliot and Field), this number grew to over three dozens during 1920 to 1947, most of them being Indians in this period. Phenomenal growth in the number of researchers engaged in monsoon research has occurred in the post-independence era, especially after the establishment of the IITM, NIO in early 1960s and other centres, including those in the universities since 1970s. Field experimental programs, introduction of computers and launching of INSAT program in the last 4 decades have also provided specialized phenomenological data and tools for diagnostic and modelling research. The setting up of the NCMRWF, with super computing facility at New Delhi in 1988, has been chiefly responsible for not only operational dynamical weather forecast up to 5–days in advance but the Centre has also acted as a major facility for providing model-generated research data. Active participation of international science community in monsoon research, availability of specialised data on different parameters on the inter-net from international data centres and sources as well as the re-analysis products from the NCEP/NCAR and ECMWF have also provided important data sources to researchers for monsoon studies. Availability of research-ship facility (Sagar Kanya) of the Department of Ocean Development (DOD), implementation of Met-Ocean buoys and the ARGOS floating buoys between 1982-2004 by the agencies of the DOD and the thrust given to monsoon research by the Department of Science and Technology (DST) since 1985, have provided impetus for the study of ocean-atmosphere coupling in the regional monsoon system.

In this article our aim is to provide the salient aspects of the major advances in monsoon research which have been accomplished in the last four decades, in particular as a result of monsoon field programmes, introduction of space-based (satellite) and land-ocean based observing systems as well as impetus provided to modelling research. Several hundred research papers on multi-faceted aspects of the monsoon have been published since 1950s and only a selected ones are referred to in this article to save space.

2. Monsoon research prior to and during the IIOE

2.1. *Major advances prior to the IIOE*

Till about 1962, IMD was the only organisation in India devoted to monsoon research and the observing systems were only land-based surface and upper air ones. IMD's officers and staff besides performing their responsibilities for developing and providing observational, climatologically and forecasting services to the country, also devoted themselves to the analyses of data for research on understanding the weather and climate of India and neighbourhood. As the agricultural productivity of India depends on the bounty of the monsoon, long-range forecasting of the monsoon attracted the attention of Blanford (1884) in the early years of IMD. He linked it to the winter snowfall in the Himalayas and introduced the LRF of monsoon in 1884. Later Walker (1924) advanced the subject during 1905 to 1924. The sound statistical foundation to LRF of monsoon introduced by the work of Walker, has survived the passage of time as statistical methodology practiced even at present is almost the same through the parameters within the technique have undergone changes with time.

As the observational network had expanded between 1880 to 1940s, the data analyses revealed complex structure of the monsoon transient disturbances (like monsoon lows and depressions) and the active-break cycle of the monsoon. The predominant role of the monsoon trough in acting as an anchor of the monsoon rainy period, with more then normal rains when it lay near its normal or somewhat south of its normal position (active monsoon) and the lack of rains when the trough shifted northward close to the foothills of Himalayas (break monsoon), was well established by Blanford (1886) and several others since then. The role of box-like orography of India in the climatological distribution of rainfall was first suggested by Simpson (1921) and later mathematically simulated by Banerji (1930). Numerical simulation of the role of orography by an Atmosphere Global Circulation Model (AGCM) was later performed four decade later by Hahn and Manabe (1975). Work by Sir Charles Normand and his collaborators on the thermo-dynamics of moist air was extensively carried out during 1930s to 1940s. Ramanathan and Ramakrishnan (1937) examined the structure of monsoon with mostly pilot balloon data. Sawyer (1947) examined the structure of Inter-tropical Front (Monsoon Trough) as different air masses (tropical marine, tropical continental etc.) were then thought to take part in monsoon processes. Yin (1949) and others emphasised the role of shift in mid-latitude westerly regime during spring season in heralding the onset of monsoon. Pisharoty and Asnani (1957) examined the preferential distribution of heavy rain in south west such sector of a monsoon depression in a dynamical frame work. Koteswaram and his collaborators (1950, 1958a, 1958b) examined monsoon structure and formation of its transients. Flohn (1957), Staff Members of Academic Sinica (1957) and Koteswaram (1958 C) emphasised the role of mid-tropospheric sensible and latent heating over the Tibetan Plateau in the formation of the upper tropospheric Tibetan high and the outflow from it leading to the establishment of the Tropical Easterly Jet stream (TEJ). Ramaswamy (1958, 1962) brought out the role of mid-latitude troughs in initiating the break-monsoon conditions. Other important components of the mean monsoon, like the monsoon trough were the Tibetan high, the TEJ and the low-level strong cross-equatorial flow over the Arabian Sea, Rao (1962) studied the meridional circulation in the monsoon. Break monsoon was linked to typhoon activity in northwest Pacific (Raman 1955, 1967, Ramana 1969). Das (1962) dynamically examined the vertical wind circulation over the monsoon trough and showed that while in the mean, moist ascent and convective clouds dominate over eastern India subsidence prevails over the western India with mostly non-raining low-level clouds. This is the so called east-west circulation of the regional South Asian monsoon system. Thus the mean structure of monsoon circulation, its transients and active-break and revival after break remained important areas of research in the pre-IIOE period. Most of these studies were empirical and observational, except a few which were of dynamical character.

2.2. *Major advances resulting from the IIOE*

The International Geographical Year (IGY) of 1957-58 led to further development of observational infra-structures in India and even weather radars were introduced to monitor severe weather to help the expanding civil aviation sector in the country. Under the WMO, India became an important partner in international collaborative research programmes and in 1957 organised the first major symposium on ‘Monsoons of the World’ at New Delhi in which several leading monsoon meteorologists of the world presented their contributions. Monsoon research had by then become an area of active research internationally. IIOE, the first major field observational program to understand the summer and winter monsoons, was organized during 1963-65 for which India played host to the International Meteorological Centre (IMC), which was set up at Mumbai to coordinate the IIOE related operations and research. During the IIOE research aircraft of USA and several research ships of different countries participated and collected new observations. For the first time an oceanic buoy was installed over the Arabian Sea to understand the air-sea interactions during the monsoon. The first automatic picture transmission system was setup at the IMC to obtain real time satellite photographs of the clouds as the U S satellite passed over India. Srinivasan (1968) described the cloud organisation in the monsoon system. Even the first computer for monsoon research (IBM-1620) was installed at the IMC in 1964. Thus IIOE was a major watershed in advancing monsoon research on modern lines and several path-making discoveries on monsoon phenomenology were made as a result of the vast data collected during the experiment . Some of the prominent new findings of the I IOE were :

(*i*) Drop sonde data revealed the structure of the monsoon over the Indian seas. Colon (1964) discovered that the moist layer in the monsoon air is rather shallow across the west Arabian Sea due to presence of a capping inversion in the lower atmosphere. The inversion is gradually lifted upward as the air travels over the the central Arabian sea and finally disappears east of 65° - 68° E as the air approaches the convergence zone of the West Coast of India and the organized convective clouds are built up (Bunker 1965). This started a debate on the role of air-sea interactions *vis-a-vis* different air masses in the establishment of the inversion layer and the influence of the Western Ghats in forced ascent for the removal of inversions (Desai 1968, 1970).

(*ii*) Joseph and Raman (1966) stressed the role of low-level westerly flow over peninsular India. Find latter (1969, 1977) emphasized the role of low - level jet (L.L.J.) in sub-seasonal fluctuations of the rains across the West Coast. Later theoretical studies by different workers on the role of orography off the east Coast of Africa in the production of LLJ led Krishnamurti et *al.*, (1983) to successfully simulate the LLJ in a numerical dynamical model.

(*iii*) Miller and Keshvamurty (1968) established the existence of a class of new rain bearing transient disturbance – the so called Mid-Troposphere Cyclone (MTC) and revealed its complex dynamical structure after a painstaking analyses of conventional and drop-sonde data. MTC has remained a subject of research in subsequent years and its simulation and associated dynamical instability were undertaken in the work of Mak (1975) and others and its dynamical aspects were studied by Carr (1977).

(*iv*) Pisharoty (1965) focused on the evaporation over the Arabian Sea by examining the moisture budget and showed that the evaporation over the sea contributes substantially to the moisture flux across the West Coast of India. Saha (1970) and Saha and Bavdekar (1973) reinforced the earlier views on the subject that bulk of the moisture is transported across the equator by the cross-equatorial flow. Further studies on the subject were done by several other workers in India. Ramamurthy *et al.*, (1976) examined the moisture flux during active-break cycle of the monsoon using ISMEX-1973 field phase data.

(*v*) Existence of the Southern Hemisphere near Equatorial Trough (SHET) was stressed during the IIOE and its role in organisation of convective cloudiness was further examined by Saha (1971), Sikka and Dixit (1973), Prasad and Johari (1990) and De *et al*., (1995).

(*vi*) Ramamoorthy (1969) consolidated the features of the break monsoon which were further studied by Raghavan (1973), Sikka and Grossman (1981), Desai (1986) and Cadet and Daniel (1988). Break monsoon has become a subject of intense research in recent studies by De and Mukhopadhyay (2002), Gadgil and Joseph (2003) and Krishnan *et al*., (2000). Ramage (1966) described the monsoon structure over the Arabian Sea. Ramage (1971) and Rao (1976) have discussed the then existing knowledge on monsoon.

(*vii*) Air-Sea interactions during the monsoon season were examined for the first time during the IIOE and the LLJ was shown to be the main artery which feeds moisture to the monsoon. The moisture layer is built up slowly as the air traverses across the Arabian Sea over changing SST regimes of cold SST (SST < 26°) over the west Arabian Sea to the warmer waters over the east Arabian Sea (SST $\geq$ 28°) (Bunker 1965, Desai 1968). Further work on air-sea interactions was carried out as a result of the ISMEX-73, MONSOON-77, MONEX-79 and analyses of historical SST data [Shukla and Misra (1977), Rao and Goswami (1988), Gadgil *et al*., (1984)]. The data collected during the recent field programmes like the MONEX-77, MONTBLEX-1990, BOBMEX-1999 and ARMEX-I and II -2002 and 2003 (reviewed in a subsequent section) have further advanced knowledge about the ocean-atmosphere interactions in monsoon processes.

(*viii*) Raman and Ramanathan (1964) discussed the interactions between the lower and upper tropospheric circulation and role of latent heat release in maintenance of the TEJ.

Three important atlases [Ramage and Raman (1972) Hasternath and Lamb (1979) and Wyrtki (1971)], which later served as important source materials, came as a result of efforts under the IIOE impetus. The above areas of research have continued to be pursued in many many studies in the post-IIOE years and even up to the present.

2.3. *Advances during the PRE-MONEX, MONEX and POST-MONEX period (1970s to 1980s)*

Emphasis on air-sea interactions, diagnostics of monsoon dynamics, monsoon depressions, monsoon variability etc. have remained the major foci of monsoon research in this period. Anjaneyulu (1969) studied the heat and moisture budgets of the mean monsoon trough. Keshvamurty (1968) and Keshvamurty and Awade (1970) dynamically examined the seasonal maintenance of the mean monsoon circulation and the monsoon trough respectively. The pre-MONEX field programs like the ISMEX-73 and the MONSOON-77 surveyed the north Indian Ocean with the help of the Indian and the Soviet research vessels and data were collected from a variety of land-sea - and space-based platforms for the monsoon seasons of 1973 and 1977 respectively. An important understanding on the air-sea interactions during the onset of monsoon resulted from the work of Ghosh *et al*., (1978), Pant (1982), Rao (1977, 1980, 1986) and Rao *et al*. (1981) who showed the dramatic cooling of SST over the Arabian Sea within a few days after the onset of monsoon and several other aspects of air-sea interactions over the Indian seas, including of the heat budget of the Arabian Sea. Rao and Mathew (1988) investigated the same over the Bay of Bengal. They showed that there was net loss of energy during active monsoon spells under higher winds and overcast skies and the ocean surface gained energy during weak monsoon conditions under clearer skies and weaker wind conditions (less evaporation). Some of these aspects on seasonal basis have been subsequently examined by Mohanty *et al*., (1983) and others.

One of the important areas of research during 1976-1990 was the study of monsoon depressions - the primary rain producing system of the season, from different perspectives. Daggupathy and Sikka (1977), Godbole (1977), Krishnamurti *et al*., (1976, 1977), Sikka (1977), Rao and Rajamani (1970), Saha *et al*., (1981), Dhar *et al*., 1981 Sarkar and Chowdhury (1988) and Koteswaram *et al*., (1987). Sanders (1984), Rao *et al*. (1987) and others have examined the structure and the vertical motion field associated with monsoon depression. Sikka (1980), Dhar *et al*., (1981), Mooley and Shukla (1989), Chen and Weng (1999) and Jadhav (2002) emphasised on the contribution of monsoon low pressure areas (LPAs) and the number of LPA days for the activity of the monsoon rains on inter-annual scale. Singh (2001), Jadhav (2002), Jadhav and Munot (2004) have reported on the decreasing trend in monsoon depressions and their interdecadal variability has been examined further by Kumar and Dash (2001)and Patnaik *et al*., (2004). Dynamical instability of the monsoon has been studied by Shukla (1978), Mishra and Salvekar (1980) and others, and its growth is now considered as a result of barotropic-baroclinic-CISK processes. Pant (1983) used MONEX data to examine the changes in phases of monsoon in 1979 season within a physical frame work.

A major advance in the global setting of the monsoon was made by Krishnamurti (1971). who stressed upon the planetary scale organization of the summer monsoon circulation system in the upper troposphere with wave number two structure (two centres of divergence over continental regions-Tibetan high and the Mexican High and corresponding centres of convergence over the mid-oceanic regions – mid-Pacific and mid-Atlantic troughs). This was the setup of the planetary scale monsoon. With this the description of the lower, middle and upper tropospheric structure of the South Asian Monsoon was completed. An intra-seasonal biweekly oscillation was pointed out by Krishnamurti & Bhalme (1976), Krishnamurti and Ardannuy (1980) and others. On the regional scale many important analyses of the monsoon synoptic processes were reported in several studies conducted under the Forecasting Manual Project of the IMD during 1966 to 1976 which have been extensively quoted with many diagrams in the work of Rao (1976).

By the time of the MONEX, study of monsoon variability on the intra-seasonal scale had become a major topic of monsoon research with the use of conventional and satellite photographs data. Sikka and Gadgil (1980) and Yasunari (1980, 1981) made an important contribution in emphasizing the low-frequency intra-seasonal oscillation (ISO) of organized convection on 30-40 day scale in which organised convection migrates from near-equatorial warm waters toward the northern end of the east Arabian Sea and the Bay of Bengal and adjoining continental South Asian Region on 3 or 4 episodes in each monsoon season. Study of ISO was further emphasized in the work of Krishnamurti and Subramanian (1982) by analysis of wind anomalies at 850 hPa during the MONEX-1979 data sets. Chen (1990), Lau & Chan (1986), Chen and Yen (1986) studied this oscillation with OLR data. Muthuvel (1981) Singh & Kriplani (1990) and Hartmann and Michelsen (1989) found the oscillation in the station rainfall of India. Nanjundiah *et al*., (1992) provided some aspects of 30-40 day mode of the monsoon. During the active phase of ISO overlapping monsoon LPAs from and distribute rains over South Asia (Sikka *et al*., 1986) and others. This is super-synoptic scale (5-20 days) and is akin to active phase of monsoon. ISO has dominated monsoon variability studies since 1980, [Gadgil and Asha (1992) Wang and Rui (1990), Nanjundiah *et al*., (1992), Srinivasan and Smith (1996), Annamalai and Slingo, (2000), Chatterji & Goswami (2003) Krishnamurti *et al*., (2004)] Many papers have been written by different workers dealing about inter-annual variability of the ISO [Mehta & Krishnamurti (1988), Singh *et al*., (1992), Lawrence and Webster (2001), Krishnamurthy & Shukla (2000)] and its diagnosis in the dynamical models and the inability of the models to simulate this [Sperber *et al*., (2000, 2001)]. Realistic simulation of the ISO in models is considered crucial in skillful prediction of the monsoon rains on extended range scale. Goswami and Mohan (2001) and others have shown that nearly 50% of the monsoon variability is caused by the internal dynamical instability on the synoptic and ISO scales and the remaining 50% is only accounted by the surface boundary forcings as propounded by Charney and Shukla (1980) such as SST, snow accumulation and soil moisture. Earlier Hahn and Shukla (1976), using satellite snow-cover data, had revived the work of Blanford (1884) on snow–monsoon relationship. Snow-monsoon relationship has been further investigated in 1990's from observational data by Bhanu Kumar and De (1983), Bamzai and Shukla (1999), Kriplani *et al*., (1996) and Kriplani and Kulkarni (1999). Heat sources and sinks of the monsoon system were computed by several workers with data generated under the MONEX program. While Krishnamurti and Ramanathan (1982) linked their distribution to the onset of monsoon, other researchers [Luo and Yanai (1984), Chen *et al*., (1985), Yanai and Song (1992) and Bhide *et al*., (1997)] have stressed the role of convective processes and fluctuations of heat sources and sinks on synoptic and super-synoptic scales. Structure of the monsoon vortex was examined by Krishnamurti *et al*., (1981), Saha and Saha (1993) with the MONEX data and since then studied by other researchers in India. George and Mishra (1993) studied the barotropic – baroclinic energetics of the monsoon onset vertex of 1979. Pearce and Mohanty (1984) established the build-up of the moist layer over the Arabian Sea about a fortnight prior to the monsoon onset as a precursor to the establishment of the monsoon season and this was also examined by Mohanty *et al*., (1983). Study of energetics of the monsoon became an important area of monsoon research during post MONEX period and important contributions to this area of research were made by several researchers. Influence of mid-latitude systems passing across the Mozambique channel in triggering monsoonal fluctuations have been studied with MONEX and later data sets by Sikka and Gray (1981) Kumar *et al*., (1992) and Saha and Saha (2000). Rodwell (1987) also examined this aspect exhaustively in observational-modeling framework. Grossman and Durran (1984) used MONEX data to understand the processes which are responsible for organization of deep convection off the West Coast of India. While they suggested interactions of low level flow with Western Ghats was crucial, later work by Ogura and Yoshizaki (1988) emphasized the air-sea fluxes to be also important. Thus MONEX and post-MONEX studies gave a lot of boost to monsoon research during the 1980s and early 1990s using observational and modeling approaches.

Mooley and Parthasarthy (1984) consolidated the seasonal monsoon rainfall series based on 306 number of stations which has been extended by Parthsarthy *et al*., (1995). The series has become a standard marker of monsoon intra annual variability. Several important findings of the MONEX period have been reported in different conferences and received excellent reviews in the two books by Fein and Stephenson (1986) and Chang & Krishnamurti (1987). Das (1986) also provided an excellent survey of monsoon research till 1980s. Asnani (1993) and Pant and Rupakumar (1997) have also given an exhaustive account of the climate of South Asia.

2.4. *Advances during the TOGA decade*

2.4.1. *ENSO-monsoon connections and studies on sensitivity of monsoon*

Emphasis shifted to studies on Monsoon-ENSO connections, satellite-derived OLR and its annual and intra-seasonal cycles, monsoon intra-seasonal and inter-annual variations, GCM studies on dynamical prediction of monsoon on short-medium-and seasonal-scales. Among the important achievements of the FGGE and its sub-programme MONEX are the stress laid on the adoption of numerical weather prediction of the monsoon in India and the simulation of the monsoon by using (GCMs), (Fennessy *et al*., 1994 and several others). Several regional models, based on primitive equations and parameterized physics for short-and medium-range monsoon prediction were adopted and developed in different research organizations in India and abroad. The success of these efforts and the possibility shown under FGGE Program that the temporal scale of weather prediction could be extended to medium-range scale (3 to 7 days) even in the tropics, led to the establishment of the NCMRWF at New Delhi in 1988. The NCMRWF had received support from ECMWF, COLA and NCEP in applying GCMs for the purpose and operational forecasting by the Centre began in 1992. This was a major benefit to Indian meteorology which resulted from the post-FGGE era as now a tool was available in India to understand monsoon processes and dynamics through a GCM.

One of the important fallout of the international research efforts on weather and climate prediction in the two decades of 1960 – 1980 was the emphasis laid on understanding and predicting planetary scale air-sea interactions represented by the El-Nino – Southern Oscillation (ENSO) phenomenon, discovered by Bjerkenes (1969) as a result of the world-wide weather and regional climatic anomalies observed during the El-Nino of 1957. By 1980 atmospheric GCM's were available and were being used on operational basis. The ocean GCM's were round the corner by 1982, which was another year of warm El-Nino and world-wide climatic anomalies. By that time El-Nino was recognized as the biggest signal on global climatic anomalies, triggered by complex air-sea coupling in the equatorial Pacific. International science community launched a decade long Tropical Ocean – Global Atmosphere (TOGA) Programme aimed at understanding and predicting global and regional climatic anomalies on intra-seasonal to inter-annual scales. Sikka (1980), for the first time showed connection of monsoon droughts with El-Nino phenomenon in the equatorial central and east Pacific. This aspect has been extensively studied in subsequent work by Pant and Parthasarthy (1981), Rasmusson and Carpenter (1983), Shukla and Paolino (1983), Mooley and Parthasarthy (1983), Mooley and Paolino (1989), Nigam (1994), Kane (1998, 2004), Krishnamurthy and Goswami (2000) and Slingo and Annamalai (2000). These studies have shown the connections of monsoon droughts with the warming phase of the ElNino / falling phase of the Southern Oscillation Index. As only about 55 to 60% of the monsoon droughts were linked with simultaneous rise or presence of ENSO signal, Webster and Yang (1992) and later work by Kirtman and Shukla (2000) and others have shown that the ENSO-Monsoon connections are very complex. Research by Wang (1995), Kriplani and Kulkarni (1997), Krishna Kumar *et al*., (1999) and others have suggested that ENSO-Monsoon connections have weakened since 1970s. Wang (1995) and others have suggested secular variation in ENSO events. Sikka (2003) has linked the major monsoon drought of 2002 to ENSO build up and has expressed a view that there is no single regional or global parameter which could be tied with 55-60% of monsoon droughts. According to him, the build up of the ENSO signal at least completely rules out the probability of excess rain during the monsoon season. This could as well be used beneficially for managing water resources of India. Raman *et al*., (1990) ascribed the monsoon drought of 1972 and 1979 as a result of interactions with mid-latitude circulation. The drought 1972 was ENSO-related and drought of 1979 was non-ENSO related. Statistics on monsoon droughts is available in the work of Chowdhury *et al*., (1989) and Sikka (1999).

An important benefit which resulted from the application of atmospheric GCM's for understanding inter-annual variability of the monsoon was through the diagnosis of sensitivity of the monsoon to various processes like orography, SST, soil moisture snow-cover and snow accumulation using AGCMs. A vast amount of sensitivity runs of different AGCMs have been reported during the two decades 1980 to 2000 [Sud and Smith (1985), Barnett *et al*., (1988), Meehl (1994), Palmer *et al*., (1992), Dirmeyer and Shukla (1996), Vernekar *et al*., (1995), Douville and Royer (1996), Ferranti *et al*., (1999), Sperber *et al*., (2001) and others]. Similarly, understanding of ISO of the monsoon also received attention through application of phenomenological models (Srinivasan *et al*., 1993) and also diagnosed from AMIP runs of AGCMs by Ferranti *et al*., (1997) as well as by others. Webster *et al*., (1998) and Gadgil (2003) have reviewed this extensive research on monsoon modeling & sensitivity studies. Inter-comparison of the AGCM's were organized under international AMIP Project using identical SST and initial conditions. They showed that several of the models, except a few, were found wanting in proper simulation of the South Asian Monsoon rainfall and even the monsoon rainfall simulation in extreme years like the warm ElNino year of 1987 and cold LaNina year of 1988 were not very satisfactory. Similarly other recent abnormal Indian summer monsoon season of 2000 (Krishnan *et al*., 2003) and the drought of 2002 (Gadgil *et al*., 2003) could not be simulated by the models. Kang *et al*., (2002) compared the AGCMs simulated anomalies with the Monsoon of 1997-98 El-Nino, which was not associated with monsoon drought over India. Gadgil *et al*., (2003) have shown the occurrence of drought over India to be associated with higher cloudiness in the eastern equatorial Indian Ocean during the monsoon season. Use of ensemble runs has not much solved the problems of monsoon simulation on inter-annual scale resulting from initial conditions. Super ensemble technique, which picks up the best of different models for monsoon prediction, has been suggested by some researchers recently [Krishnamurti *et al*., (2000)]. Several papers in the edited book by Singh *et al*., (2003) discuss the advances in monsoon modeling. A major new focus of research has begun on what is known as the Indian Ocean Dipole Mode (IOD) [Webster *et al*., 1999, Saji *et al*., (1999), Behra and Yamaguta (2002)] is a regional scale development of ocean-atmosphere coupled mode between the eastern and the western equatorial Indian ocean. The IOD begins to appear during the monsoon season and peaks in the post-monsoon season. Its role in monsoon fluctuations has yet to be fully established.

TOGA has also resulted in promoting research in India on monsoon variability and introducing XBT surveys of the Indian Ocean by the International and Indian research groups.

2.4.2. *Annual and Intra-seasonal cycle of OLR over South Asia*

By early 1990s nearly 15 years of satellite-based OLR data were available. Analysis of this data set on pentad mean basis has revealed some interesting features of the annual cycle of largescale organized convection over South Asia and adjoining region. There is hardly any major change in convection between January to end of March as the major centre of equatorial convection lies in the near-equatorial south Indian Ocean in the region of SHET (5-15° S and 55-120° E), and the sub-tropical ridge lies close to equator along 5° N to 10° N. As the upper troposphere sub-tropical westerlies dominate most of South Asia, the convective cloudiness belt shifts close to the equator between 5° S to 5° N by April and is rather disorganized or patchy. This is slowly emerging annual cycle of monsoon circulation. By the middle of May the OLR minimum shifts from the Indonesian region northwestward and gets organized over the Andaman Sea in the Bay of Bengal. This is related to the advance of monsoon into the Andaman Sea. Upper tropospheric easterlies strengthen almost simultaneously over the region and the subtropical ridge begins to shift near 15° N. Dramatic changes occur in OLR and lower tropospheric and upper tropospheric circulation features in the next two to three pentads (mid-May to early June). With the onset of low-level strong cross-equatorial flow in the western Arabian Sea and its extension to the central Arabian Sea and Lakshadweep Sea (SE Arabian Sea) an explosive growth of low OLR band is observed which strikes the Kerala coast by end of May - early June. This is the beginning of the fast intra-seasonal cycle of monsoon which heralds the onset of monsoon over Kerala coast of India. TEJ is also fully established rather abruptly over South Bay of Bengal and South India as the circulation responds to new organization of convection by late May / early June. For the next 25 to 30 pentads (June to mid-October), the slow sub-seasonal organization of the OLR field is noticed over South Asia and the adjoining west Pacific Ocean region. By mid-June, the low OLR band, which was less than 100 longitude in extent over South Bay of Bengal / Arabian Sea at the time of monsoon onset, shifts eastward to cover the South China Sea and the Philippines Sea. The minimum OLR band now covers 70° E to 130° E along 20° N to 15° N (covering most of India, SE Asia and adjoining South China Sea upto Philippines) in which are embedded two or three low-level convergent circulation centres spaced at 2000 – 3000 km apart. This marks the spectacular organization of the Asia-Pacific Monsoon System on gigantic regional scale over the Asia-Pacific belt. This has occurred with the first northward moving episode of the ISO at the beginning of the monsoon season which lasts from mid-June to end-June. The system oscillates in activity between beginning of July and mid-August with relative increase / decrease in OLR in association with the trough-ridge organizations of two low frequency modes of the monsoon (10-20 day and 30-50 day). In some episodes the two modes may annul or enhance each other which may impact on the fluctuations in rains on the intraseasonal scale. The Sub Tropical Ridge (STR) at the upper tropospheric level lies along 30-32° N over the Tibetan and adjoining regions. Toward the later half of August, convection is rather weak over the Indian region as this is period of another climatological singularity [Ramaswamy (1973) and Anantha Krishnan & Pathan (1971)]. Convection builds up again from near-equatorial region, migrates over the north Bay of Bengal, passing through central India, it is located over western India by 10 September. Finally low OLR centre begins to withdraw from western and central India between mid-September to first week of October. Low OLR centre shifts to the central Bay of Bengal by mid-October as the upper tropospheric STR shifts southward to 15° N and weak low-level easterlies begin to appear over north Bay. This signals the end of summer monsoon and onset of NE monsoon over northern part of the north Indian Ocean. There is considerable inter-annual variability even in this slow evolutionary phase of low OLR over the Asia-Pacific region and a detailed study of this would provide interesting results on the interactions between circulation and convection, air-sea interactions on the regional and sub-regional scales, Indian Ocean – West Pacific circulation regimes on the super-synoptic scale, the ENSO – Asia – Pacific Monsoon System on planetary scale and the IOD on regional scale. Interest has been also revived on the study of monsoon onset, advance and hiatus in the advance process over India. Several studies on relationship of these processes with tropospheric circulation features, large scale build up of cloudiness in near-equatorial region, SST on regional and extensive scales (like ENSO), sub-tropical ridge in mid-troposphere and mid-latitude circulation etc. have been reported. [Ananthakrishnan and Soman (1988), Soman and Krishna Kumar (1993) Joseph *et al*., (1994), Biswas *et al*., (1998) and others].

3. MONEX to ARMEX field programs on the Indian summer monsoon under the Indian climate research program

Infra-structural facilities available with the Indian atmosphere – ocean science community had considerably improved in the post-MONEX years. The community undertook a coordinated multi-agency program of field experiments from 1989 onward to understand specific monsoon processes. These field programs have laid emphasis on monsoon atmospheric boundary layer and land–ocean atmospheric processes and modeling. Salient features of the results from these field programs are discussed in the following sub-sections.

3.1. *MONTBLEX (1989-1990) and LASPEX (1995-1996)*

Atmospheric Boundary Layer (ABL) processes had received some attention during the MONEX as a surface layer instrumented tower was used along the Orissa coast. During 1986-1988 a comprehensive multi-agency field program was planned to understand the ABL processes across the monsoon trough whose eastern end is the seat of frequent convective activity and western end is anchored in the dry sensible heating zone which at times is visited by deep convection in association with the movement of an occasional monsoon disturbance across the Gangetic Plains. MONTBLEX focused on understanding of the fluctuations of the ABL during different phases of the monsoon and interactions between eastern and western ends of the trough. Four instrumented surface layer towers were deployed across the trough region during June-September 1990 and a research ship was stationed in the north Bay of Bengal during August-September 1990 to monitor air-sea interactions. Several important papers resulted from MONTBLEX data and the first set of papers were published by 1997 (Narasimha *et al*., 1997). ABL research from MONTBLEX data continues to be published even to the present. Air-sea interactions during the MONTBLEX were studied by Singh (1991), Sunil Kumar *et al*., (1994), Sarma *et al*., (1997) and Seetaramaya *et al*., (2001). These studies confirmed the results of the MONEX period [Seetaramaya and Master, (1984) and Rao & Mathew (1988)] that synoptic variability (besides diurnal variability) in cloudiness, wind, air atmosphere and SST modulate the air-sea fluxes. The studies also showed that the north Bay of Bengal looses net heat during the cloudy and strong wind episodes of the disturbed or active monsoon phase and gains energy during the cloud-free and low wind regime of the weak monsoon phase.

MONTBLEX was followed by another field program LASPEX organized during 1995-96 over the western Indian (Gujarat) region in the Sabarmati river basin. LASPEX focused on the study of land surface interactions with ABL. The region of the experiment is known for its sharp contrast in convective organizations on the annual cycle and intra-seasonal monsoon activity basis. Five surface layer instrumented towers were deployed. Four towers were placed along the corners of a quadrilateral (100-150 Km apart) and the fifth tower was close to its centre. Along with the ABL studies over bare soil, vegetation - ABL (crop canopy) interactions have been also studied. A number of interesting papers have been recently published collectively in the Journal of Agricultural Meteorology (2003) which showed the role played by land - vegetation - atmosphere interactions on intra-seasonal basis.

3.2. *Bay of Bengal Monsoon Experiment (1999) and Arabian Sea Monsoon Experiment (2002 and 2003)*

Encouraged by the success of MONTBLEX and LASPEX and also by the introduction of ocean observational systems in the Indian seas, the Indian ocean-atmosphere science community have organized three major field programs during 1998-2003 to understand ocean-atmospheric processes considered important for monsoon. These experiments have been carried out under the Indian Climate Research Programme (DST 1995).

3.2.1. *Bay of Bengal Monsoon Experiment (BOBMEX-1999)*

BOBMEX-1999 was organized with a focus on understanding the ocean-atmosphere coupled processes over one of the most convectively active regimes of the tropical oceans over the Bay of Bengal. Introduction of new ocean observing system in the form of Met-Ocean buoys in the north Indian Ocean in mid-1990s (Prem Kumar *et al.*, (2000) stimulated the BOBMEX field phase. Bhat *et al.*, (2001) have presented the first results of the research based on BOBMEX data. Several important papers on different aspects of BOBMEX related studies have appeared collectively in Proc Indian Academy of Sciences, Earth & Planetary Sciences (2003) as well as in other journals. Sanjeeva Rao & Sikka (2005) have also reviewed the major findings of BOBMEX which are focused on :

(*i*) Atmospheric moisture modulation in active-break cycle with moisture extending upto middle upper troposphere under active monsoon conditions and moisture restricted within the lower troposphere in weak monsoon conditions (Bhat *et al.*, 2002)

(*ii*) ISO-scale variability is prominent in the season and convective clouds move from near-equatorial warm ocean toward northern part of the Indian shores. SST fluctuations on the ISO scale is 2-3° C, which is higher than on the inter-annual scale. [Sengupta and Ravichandran (2001)] SST changes on the synoptic scale are usually restricted within 0.5 to 1.0° C.

(*iii*) Convection over the central and north Bay of Bengal fluctuates almost simultaneously as evident from OLR data analyses on the ISO scale. It fluctuates over the south Bay of Bengal in opposite phase. Warming of the north Bay of Bengal in weak monsoon phase and corresponding cooling over the cloudy south Bay leads to build up of SST gradients in north-south direction over the area. Thermodynamic coupling of the ocean-atmosphere which cools (warms) the ocean beneath the region of active convective cloudiness (clear area) and warms over north (south) Bay of Bengal during active (weak) monsoon spell, plays a crucial role in regulating the intra-seasonal fluctuations in the monsoon. Convection develops over the south Bay and weakens over north Bay in the weak monsoon spell. Warming of SST in the north Bay in the weak phase of the ISO cycle could be responsible for the northward movement of convective cloudiness band, resulting in re-establishment of another active monsoon phase over north Bay of Bengal in the mid-season. Surface processes on land-ocean interface may also help in this process (Sanjeeva Rao and Sikka, 2005).

(*iv*) Net heating cycle of the Bay of Bengal surface waters is modulated by monsoon disturbances on synoptic and ISO scales with reduction of solar radiation by cloudiness, higher transfer of latent and sensible heat leading to cooling under active monsoon spells and the reverse occurs (5-20 days) in the weak spells. Overlapping formation of monsoon low pressure systems on super-synoptic scale are the crucial elements in ocean-atmosphere coupling of the monsoon.

(*v*) Surface salinity changes on ISO and synoptic scales in north Bay of Bengal could be also substantial (>2.0 psu) after a locally heavy rainfall spell or heavy rainfall over coastal regions of Orissa, West Bengal and Bangladesh which bring plumes of low-salinity waters through river-water discharges and local rains. This process plays an important role in creating a barrier layer just below the ocean mixed layer which may be responsible for the stability of the ocean layer leading to rapid warming of the north Bay of Bengal at surface as the weak monsoon phase is set-up. This would explain the maintenance of rather warm SST on the seasonal scale in the north Bay of Bengal [Vinachandran *et al*., (2002) Sanjeeva Rao & Sikka (2005)].

Where as several of these findings strengthened the results of earlier studies in IIOE, post IIOE, MONEX and MONTBLEX field programs, new findings on salinity changes and formation of barrier layers have added a new dimension to monsoon research.

3.2.2. *ARMEX-I (Off-shore trough) and ARMEX-II (dynamics of warm pool over SE Arabian Sea and onset of monsoon over Kerala)*

ARMEX-I, which was conducted in June-August period of 2002, was focused on understanding the processes which lead to the formation of off-shore trough near the surface off the West Coast of India and possible existence of meso-scale vortices within the trough. The presence of off-shore trough and embedded meso-scale vortices was first suggested by George (1956) and later studied by Grossman and Durran (1984), Mukherjee *et al*., (1984) with MONEX data. During the ARMEX-I phase, four episodes of the off-shore trough - related vortices occurred. The two active episodes were during 26-28 June and 06-11 August 2002. Meso-scale models have been used by Bhaskar Rao *et al*., (2003) and Mohanty *et al*., (2003) to simulate these episodes. The results showed that additional observations mounted during ARMEX-I resulted in more realistic simulation of the heavy rainfall associated with them along the West Coast. Shyamala (2003) has given observational evidence of these off-shore vortices during the ARMEX-I.

ARMEX-II, which was conducted in March-June 2003, was focused on (*i*) the buildup of the mini-warm pool over the SE Arabian Sea (Lakshadweep Sea) and the onset phase of the monsoon. Presence of a mini-warm pool over SE Arabian Sea was first shown by Seetaramayya & Master (1984) in the MONEX observational data and later confirmed by Rao and Sivakumar (1999) and Shenoi *et al*., (1999). Rao and Shiv Kumar (1999) have also provided a framework on the occurrence of the mini-warm pool over SE Arabian Sea through advection of the low salinity waters from the Bay of Bengal during November to January period, enhanced near surface stratification and net surface heating. They have further shown the coincidence of monsoon onset variation with this mini warm pool in some years. The warm pool develops every years, though its intensity at surface and sub-surface may differ from year to year. The monsoon onset vortex does not form every year as it depends on the development of atmospheric instability, inspite of the necessary conditions of the environment in terms of the warm ocean surface. Theoretical basis for the formation of this warm pool, as a consequence of exchange of low salinity waters of the Bay of Bengal toward SE Arabian Sea and southern west coast of India (under westward moving Rossby waves after reflection of the Kelvin Waves from the eastern coastal margins of the Bay of Bengal) was provided by the work of Vinay Chandran and Shetye (1991) and Shankar and Shetye (1997). This was an important problem of the ocean-atmosphere system over the Bay of Bengal for the winter and over SE Arabian sea for the pre-monsoon seasons respectively. ARMEX-II data have provided confirmatory evidence for the existence of low salinity waters over the SE Arabian Sea during December to March, the existence of inversion layers in the 30-80 m depth below the surface waters and their westward propagation during January to March [Shankar *et al*., 2004 and Sanjeeva Rao and Sikka (2005)]. Durrand *et al*., (2004) have even dynamically simulated the inversion layers in a modeling study and expressed a view that these inversions could contribute to the preferential warming of sea surface over SE Arabian Sea during March-April period. However, since the strength of the inversion is rather weak (0.5° C to 0.7° C), its predominance over net surface heating under clear skies and low wind condition, could be debatable.

The period of March to mid-May 2003 was unusually cloud-free over SE Arabian Sea and ARMEX data analyses (Sanjeeva Rao and Sikka 2005) have shown that the warming began by mid-March and peak SST values exceeding 30.5° C were observed over the area during April to mid-May 2003. Inspite of such high SSTs convection remained rather suppressed as no atmospheric disturbance formed or moved through the SE Arabian sea region. Monsoon onset vortex also did not form and the onset was delayed by about 10 days. Gnanaseelan *et al*., (2003) have examined the evolution and collapse of the warm pool during 2002 and 2003 within a modeling framework and found that the forcing by the observed Quickscat winds could broadly produce the changes in the warm pool. ARMEX results highlight the following aspects :

(*i*) The atmosphere over the Arabian Sea remains decoupled from SST warm zone during March to Mid-May unless atmospheric instability is initiated. As the ITCZ begins to appear in equatorial Arabian Sea after Mid-May, the atmosphere gets coupled with the sea and the SSTs begin to decrease though still holding at near 29° C (above the threshold for convection).

(*ii*) By end of May-early June, with the onset of monsoon over SE Arabian Sea, SSTs fall to 28.5° C over the region while they continue to rise above 29.5° C over the NE Arabian Sea. The setting up of this north-south SST gradient with cooler temperature beneath the active cloudiness regime over SE Arabian Sea and warming continuing over the NE Arabian Sea, may promote northward advance of monsoon along the West Coast. Formation of a synoptic scale disturbance in the form of off-shore trough / MTC / onset vortex, depending upon the dynamic instability mechanism operating then in the atmosphere, heralds the onset and advance of monsoon along the West Coast of India.

(*iii*) While the atmospheric dynamical instability during the monsoon season is responsible for the triggering of monsoon onset and formation of transient disturbances on synoptic and ISO scales within the season, the warm surface of the north Indian Ocean regulates the monsoonal fluctuations by providing energy for feeding the disturbances. Thus air-sea coupling processes play crucial roles in regulating the monsoon on the ISO and synoptic scales rather then initiating atmospheric instability changes and bringing in active/weak/suppressed convective episodes on different temporal and spatial scales. ISOs display their own life cycle of formation, intensification peaking and decay.

There could be large inter-annual variability in ocean atmospheric processes. For example, the monsoon onset and the cooling of the central and SE Arabian Sea was delayed in 2003 season but it occurred earlier in the 2004 season with the formation of a tropical cyclone over the SE Arabian Sea in the first week of May 2004 and early onset of monsoon over Kerala by 23 May 2004. Understanding of this inter-annual variability, whether it is caused by the ocean or atmospheric processes, still remains a challenging area of research.

4. Concluding remarks

Monsoon meteorology has tremendously advanced since 1950s from purely descriptive and empirical approaches to more dynamical and modelling approaches for diagnosing its mean structure, its variability on synoptic and ISO and inter-annual scales and its prediction on meso, short-medium and long-range scales using dynamical models. A comprehensive account of the models from meso-scale to GCMs used in the prediction process, is available in different papers. Many modelling and observational studies have been undertaken using various international, bilateral and national monsoon-related field programs in the last 4 decades, from IIOE to ARMEX. These have provided a great stimulus to Indian scientists to advance monsoon meteorology in a cohesive and multi-agency partnership basis. Several important findings have resulted and the regional monsoon system is now recognized as a complex interacting land-biosphere ocean-atmosphere system. Its linkages with the neighbouring regions (West Pacific, northern mid-latitudes, southern mid-latitudes) on intra-seasonal scales as well as with remote snow cover/snow depth and ENSO-type forcing on inter-annual and decadal basis and with Indian Ocean Mode type forcing on regional basis have been suggested and even examined using a variety of models. There is great hope that the system's interactive dynamics would be further understood in the next decade as a result of future field programs such as the on going International Climate Variability and Predictability (CLIVAR), Continental Tropical Convergence Zone Experiments (CTCZ) planned by India during 2006 - 2007 and the International Observation Research and Prediction Experiment (THORPEX) during 2004-2010 and the Climate System Observations and Prediction Experiment. (COPE). Another phase of exciting monsoon research combining observations, theory and modelling approaches, is on the horizon during 2005-2015, It is hoped that this Climate System Predictability Decade (CSPD) would further promote understanding and prediction of monsoon variability on different scales.

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References

Ananthakrishnan, R. and Pathan, J. M., 1971, "Rainfall patterns over India and adjacent seas", IMD *PPSR*. No. 144, IITM, Pune.

Ananthakrishnan, R. and Soman, M. K., 1988, "The onset of monsoon over Kerala", *J. Climatol*., **8**, 283-296.

Anjaneyulu, T. S. S., 1969, "On the estimates of heat and moisture budgets over the monsoon trough" *Tellus*, **21**, 64-74.

Annamalai, H, and Slingo, J. M., 2000, "Active-break cycle diagnosis of the intra-seasonal variability of the Asian Summer Monsoon" , *Climate Dynamics*, **18**, 85-102.

Asnani, G. C., 1993, "Tropical Meteorology" noble printers, Pune.

Bamzai, A. and Shukla, J., 1999, " Eurasian snow cover and snow depth and Indian summer monsoon - An observational study", *J. Clim*., **12**, 3112-3117.

Banerji, S. K., 1930, "The effect of the Indian mountain ranges on air motion", *Ind. J. Phys*., **5**, 699-745.

Barnett, T. P., Dumenil, U., Schlesse, F., Roecknev and Latif, M., 1988, "The effect of Eurasian snow cover on regional and global climate variation", *J. Atmos. Sci*., **46**, 661-685.

Behra, S. K. and Yamagata, T., 2002, "Influence of the Indian Ocean Dipole on the Southern Oscillation", *J. Meteor. Soc. Japan*, **81**, 169-177.

Bhanukumar, O. S. R. U. and Dey, B., 1983, "Himalayan winter snow cover area and summer monsoon rainfall over India", *J. Geophy. Res*., **88**, 5471-5474.

Bhaskar Rao, D. V. and Hari Prasad, D., 2003, "The impact of ARMEX-I on the simulation of west coast off-shore trough and heavy precipitation events", paper presented at ARMEX workshop, Chennai, 22-23 December 2003.

Bhat, G. S., Chakaborty, A., Nanjundiah, R. S. and Srinivasan, J., 2002, "Vertical thermal structure of the atmosphere during active and weak phases of monsoon over the north Bay of Bengal", *Current Sci*. **83**, 296-302.

Bhat, G. S., Gadgil, S., Haresh Kumar, P. V., Kalsi, S. R., Madhusudan, P., Murty, V. S. N., Prasada Rao, C. V. K., Ramesh Babu, V., Rao, L. V. G., Rao, R. R., Ravichandran, M., Reddy, K. G., Sanjeeva Rao, P., Sengupta, D., Sikka, D. R., Swain, J. and Vinaychandran, P. N., 2001, "BOBMEX – the Bay of Bengal Monsoon Experiment", *Bull. Amer. Meteorol. Soc.* **82**, 2217-2243.

Bhide, U. V., Muzumdar, R., Ghanekar, S. P., Paul, D. K., Chen, T. C. and Rao, R. V., 1997, "A diagnostic study on heat sources and moisture sinks in the monsoon trough area during active-break phase of the Indian Monsoon of 1979", *Tellus*, **49A**, 455-473.

Biswas, N. C., De, U. S. and Sikka D. R, 1998, "The role of Himalayan massif – Tibetan plateau and the mid-tropospheric tropical ridge over north India during the advance phase of the southwest monsoon", *Mausam*, **49**, 2, 285-298.

Bjerkenes, J., 1969, "Atmospheric teleconnections from the equatorial Pacific", *Mon.Wea. Rev.*, **97**, 163-172.

Blanford, H. F., 1884, "On the connection of the Himalaya snowfall with dry winds and season of drought in India", *Proc. Roy, Soc.*, London, **87**, 3-22.

Blanford, H. F., 1886, "Rainfall of India", *Memoir Ind. Met. Dept.*, **3**, p668.

Bunkar, A. F., 1965, "Interaction of the summer monsoon air with the Arabian Sea", *Proc. Met. Results of IIOE, Bombay*, 1965, 3-16.

Cadet, K. L. and Daniel, P., 1988, "Long-range forecast of the break and active summer monsoon", *Tellus*, **40A**, 133-150.

Carr, H.F., 1977,"Mid-tropospheric cyclones of the summer monsoon", *Pure and Appld Geophys*., **115**, 1383-1412.

Chang, P. and Krishnamurti, T. N. (Eds), 1987, "Monsoon Meteorology", *Oxford Monographs in Geology and Geophysics.* No.7., Oxford Univ. Press.

Charney, J. G. and Shukla, J., 1980, "Predictablity of Monsoon", in *Monsoon Dynamics*, (Eds. J. Lighthil and R. Pearce.) Cambridge Univ. Press.

Chatterji, P. and Goswami, B. N., 2003, "Structure, genesis and scale selection of the tropical biweekly mode" *Q. J. R. Meteor. Soc.* 128, p7.

Chen, L., Reiter, E. R. and Faig, Z., 1985, "The atmospheric heat sources over the Tibetan plateau: May – August 1979", *Mon. Wea. Rev*., **113**, 1771-1790.

Chen, T. C., 1990, "Effect of the 30-50 day oscillation on the life cycle of the Indian monsoon", *Mausam*, **41**, 169-176.

Chen, T. C. and Weng, S. P., 1999, "Inter-annual and intra-seasonal variation in monsoon depression and their westward propagating predecessor", *Mon. Wea. Rev*., **127,** 1005-1020.

Chen, T. C. and Yen, M. C., 1986, "The 40-50 day oscillation of the low level monsoon circulation over the Indian ocean", *Mon. Wea. Rev*., **114**, 2550-2570.

Chowdhury, A. M., Bavedkar, M. and Raut, P. S., 1989, "Variability in drought incidence over India – a statistical approach", *Mausam*, **40**, 207-214.

Colon, J. A., 1964, "On interaction between the southwest monsoon current and the sea surface over the Arabian Sea", *Ind. J. Met. Geophys*., **18**, 217-226.

Daggupathy, S. M. and Sikka, D. R., 1977, "On the vorticity budget and vertical velocity distribution associated with life cycle of a monsoon depression", *J. Atmos. Sci.,* **33**, 773-792.

Das P. K., 1962, "Mean vertical motion and non-adiabatic heat sources over India during the monsoon", *Tellus*, **14**, 212-220.

Das, P. K., 1986, "Monsoon", 5th WMO Lecture, *WMO*, **613**, p155.

De, U. S. and Mukhopadhyay, R. K., 2002, "Breaks in monsoon and related precursors", *Mausam*, **53**, 309-318.

De, U. S., Prasad, O., and Vaidya, D. V., 1995, "The influence of southern hemisphere equatorial trough on rainfall during southwest monsoon", *Theor. Appl. Climatol.*, **52**, 171-181.

Desai, B. N., 1968, "Interaction of the summer monsoon current in the water surface over the Arabian Sea", *Ind. J. Met. Geophys*., **19**, 159-166.

Desai, B. N., 1970, "Nature of low-level inversions over the Arabian sea and the role of Western Ghats in modifying air masses stratification within 500km of the west coast of the peninsula", *Indian J. Met. Geophys.,* **21**, 653-655.

Desai, D. S., 1986, "Study of thermodynamic parameters in strong and break monsoon", *Theor. Appl. Climatol*., **52**, 177-181.

Dhar, O. N., Rakhecha, P. R. and Mandal, B. N., 1981, "Influence of tropical disturbances on monthly rainfall of India", *Mon. Wea. Rev*., **109**, 188-190.

Dirmeyer, P. A. and Shukla, J., 1996, "The effect of regional and global climate expansion of the world's deserts", *Q. J. R. Meteor. Soc*., **122**, 481-492.

Douville, H. and Royer, J. F., 1996, "Sensitivity of the Asian summer monsoon and autonomous Eurasian snow cover within the Meteo. - France G.C.M.", *Climate Dynamics*, **12**, 440-466.

DST, 1995, "Indian Climate Research Program – Science Plan", Deptt. of Science & Tech., New Delhi.

Durrand, F. S. R., Shetya, S. R., Vialand, J., Shankar, D. Shenoi, S. S. C., Ethe, C. and Modec, G., 2004, "Impact of temperature inversion as SST evolution during the pre-summer monsoon season", *Geophys. Res. Lett.*, **31**, doc.10:1029/2003gl018906, L01305.

Eliot, J., 1901, "Handbook of cyclonic storms a the Bay of Bengal", Govt. of India Printing Press, *Calcutta experiment Proc. Ind. Acad. Sci. (Earth & Planetary Sci)* **104**, 157-187.

Fein, J. S. and Stephenson, P. L., 1987, (Eds) Monsoons, *John Wiley and Sons*, p 632.

Fennessy, M. J., Kinter III, Kirtman, B. and Marx, L., Nigam, S., Schneider, E., Shukla, J., Straus, D., Vernekar, A., Xue, Y. and Zhou, J., 1994, "The simulated Indian monsoon, AGCM Sensitivity Study", *J. Climate*, **7**, 33-43.

Ferranti, L., Slingo, J. M., Palmer, T. N. and Hoskins, B. J., 1999, "The effect of land–surface feed–back on the monsoon circulation", *Q. J. R. Meteor. Soc.*,**125**, 1527-1550.

Ferranti, L., Slingo, J. M., Palmer, T. N. and Hoskins, B. J., 1997, "Relations between international and intra-seasonal monsoon variability as diagnosed from AMIP investigations", *Q. J. Roy. Meteor. Soc*., **123**, 1323-7357.

Findlatter, J., 1977, "Observational aspects of low-level cross-equatorial jet stream of the Western Indian Ocean", *Pure and Applied Geophysics*, **115**, 1251-1262.

Finldlatter, J., 1969, "A major air current near the west Indian Ocean during the summer monsoon", *Q. J. Roy. Meteor. Soc*., **95**, 1251-1262.

Flohn, H., 1957, "Large scale aspects of the summer monsoon in south and east Asia", *J. Meteorol. Soc. Japan*, 75 to the Ann. Vol. 180-186.

Gadgil, S., 2003, "The Indian monsoon and its variability", *Ann. Rev. Earth-Planet Sci.*, **31,** 429-467.

Gadgil, S. and Asha, G., 1992, "Intra-seasonal variabilities of the Indian summer monsoon–observational aspects", *J. Meteorol. Soc. Japan*, **70**, 517-527.

Gadgil, S. and Joseph, P. V., 2003, "On breaks of the Indian monsoon", *Proc. Ind. Acad. Sci (E&P Sci.)*, **112**, 529-558.

Gadgil, S. and Sajani, S. 1998, "Monsoon precipitation in the AMIP runs", *Climate Dynamics*, **14**, 659-689.

Gadgil, S., Joseph, P. V. and Joshi, N. V., 1984, "Ocean atmosphere coupling over monsoon region", *Nature*, **312**, 141-143.

Gadgil, S., Vinaychandran, P. N. and Francis, P. A., 2003, "Droughts of the Indian summer monsoon - Role of clouds over the Indian Ocean", *Current Science*, **85**, 1713-1719.

George, L. and Mishra, S. K., 1993, "An observational study on the energetics of the onset monsoon vortex, 1979", *Q. J. R. Meteorol. Soc*., **119**, 755-770.

George, P. A., 1956, "Effects of off –shore vortices on rainfall along the West Coast of India", *Indian J. Met. Geophys*., **7**, 235-240.

Ghosh, S. K., Pant, M. C. and Dewan, B. N., 1978, "Influence of the Arabian Sea on the Indian summer monsoon", *Tellus,* **30**, 117-125.

Gnanaseelam, C., Mishra, A. K., Thomson, B. and Chowdary, J. S. and Salvekar, P. S., 2003, "Mixed layer response of south east Arabian during warming phase", Paper presented at ARMEX Workshop, Chennai, 22-23 December 2003.

Godbole, R. V., 1977, "The composite structure of monsoon depression, *Tellus*, **29**, 25-40.

Goswami, B. N. and Mohan, A. R. S., 2001, "Intra-seasonal oscillation and inter-annual variability of the Indian monsoon", *J. Climate*, **14**, 1180-1198.

Grossman, R. L. and Durran, D. R., 1984, "Interaction of low-level flow with the Western Ghat mountains and off shore convection in the summer monsoon", *Mon. Wea. Rev*., **112**, 652-672.

Hahn, D. G. and Shukla, J., 1976, "An apparent relationship between Eurasian snow cover and Indian monsoon rainfall", *J. Atmos. Sci*., **33**, 2461-2462.

Hahn, D. G. and Manabe, S., 1975, "The role of mountains on the South Asian Monsoon circulation", *J. Atmos. Sci.,* **32**, 1515-1541.

Hartman, D. L. and Michelsen, M. L., 1989, "Intra-seasonal periodicities in Indian rainfall", *J. Atmos. Sci.*, **46**, 2833-2862.

Hasternath, S. and Lamb, P. J., 1979, "Climatic atlas of the Indian Ocean, Pt. I surface climate and atmospheric circulation", The university of Wiscousin Press.

Hasternath, S. and Lamb, P. J., 1979, "Climatic atlas of the Indian Ocean, Pt. II surface climate and atmospheric circulation", The university of Wiscousin Press.

India Meteorological Department (IMD), 1976, "Hundred years of Weather Service, 1875-1975", India Met. Deptt., New Delhi.

Jadhav, S. K., 2002, "Summer monsoon low pressure systems over the Indian region and their relationship with the sub-divisional rainfall", *Mausam*, **53**, 177-186.

Jadhav, S. K. and Munot, A. A., 2004, "Statistical study of low pressure system over the Indian region during summer monsoon season over the Indian region", *Mausam*, **55**, 1, 15-30.

Joseph, P. V. and Raman, P. L. 1966, "Existence of low-level westerly jet stream over Peninsular India during July", *Indian J. Met. Geophys.*, **17**, 407-410.

Joseph, P. V., Eischeid, J. K., and Pyle, R. J., 1994, "Inter-annual variability of the onset of the summer monsoon and its association with atmospheric features, El Nino and sea surface temperature anomalies", *J. Climate*, **7**, 81-105.

Journal of Agro meteorology, 2001, Special issue on Land Surface Processes Experiment (LASPEX) over the Sabarmati River Basin India, Vol. **3**.

Kane R. P., 1998, "El Nino, Southern Oscillation, equatorial eastern Pacific sea surface temperature and summer rainfall over India", *Mausam*, **49**, 1, 103-114.

Kane, R. P., 2004, "Relation of El-Nino characteristic and timings with rainfall extremes in India and Australia", *Mausam*, **55**, 257-268.

Kang, L. S., Jin, K., Lau, K. M., Shukla, J. Krishnamurthy, V., Schubert, S. D., Waliser, D. E., Stren, W. F., Satyan, V., Kitoh, A., Meehl, G. A., Kanamitsu, M., Galin, V. Ya., Sumi, A., Wu, G., Liu, Y., and Kim, J. K., 2002, "Intercomparison of atmospheric GCM simulated anomalies associated with the 1997/98 El-Nino", *J. Climate*, **15**, 2791-2805.

Keshvamurty, R. N. and Awade S. T., 1970, "On the maintenance of the mean monsoon trough over north India", *Mon. Wea. Rev.,* **98**, 315-320.

Keshvamurty, R. N., 1968, "On the maintenance of the mean zonal motion in the Indian summer monsoon", *Mon. Wea. Rev*., **96**, 23-31.

Kirtman, B. P. and Shukla, J., 2000, "Influence of the Indian summer monsoon on ENSO", *Q. J. Roy Meteor. Soc*., **126**, 213-239.

Koteswaram, P., 1958a, "The Asian Summer Monsoon and General Circulation over the Tropics", Proc. Symp. Monsoons of the World, New Delhi, 105-110.

Koteswaram, P., Rao, Poornachandra, C. and Krishnamurthy, M., 1987, "Formation and structures of monsoon revival depression over the Bay of Bengal during a weak monsoon period", *Mausam*, **38**, 1, 29-40.

Koteswaran, P., 1958c, "Easterly jet stream in the trophics, *Tellus*, **10**, 43-57.

Koteswaran, P. and George, C. A., 1958 b, "On the formation of monsoon depression in the Bay of Bengal", *Indian J. Met. Geophys*, **9**, 9-22.

Koteswaran, P., 1950, "Upper air flow in low latitudes in the Indian area during southwest monsoon breaks in the monsoon", *Indian J. Met. Geophys.* **2**, 162-164.

Kriplani, R. H. and Kulkarni, A., 1997, "Climatic impacts of El Nino / La Nina on the Indian Monsoon", *Weathe*r , **152**, 39-46.

Kriplani, R. H. and Kulkarni, A., 1999, "Climatology and variability of historical Soviet Snow depth data, some new perspective in snow-Indian monsoon teleconnections", *Climate Dynamics*, **5**, 475-489.

Kriplani, R. H., Singh, S. V. and Arakins, P. A., 1991, "Large Scale features of rainfall and outgoing long wave radiation over Indian and adjoining regions", *Contr. Atmos. Phys*., **64**, 159-161.

Kriplani, R. H., Singh, S. V., Vernekar, A. D. and Thapliyal, V., 1996, "Empirical study on Nimbus-7 snowmass and Indian monsoon rainfall", *Int. J. Climatol*., **16**, 23-24.

Krishna Kumar, Rajagoplan, K. R. and Cane, M. A., 1999, "On the weakening relationship between the Indian monsoon and ENSO", *Science*, **284**, 2156-2157.

Krishnamurti, T. N., Molinari, J. Pan, H. L. and Wong, V., 1977, "Downstream amplification and formation of monsoon disturbances", *Mon. Wea. Rev.,* **105**, 1281-1297.

Krishnamurti, T. N. and Ardannnuy, P., 1980, "The 10-20 days westward propagating mode and breaks in the monsoon", *Tellus,* **32**, 15-26.

Krishnamurti, T. N. and Bhalme, H. N., 1976, "Oscillation of a monsoon system, Pt. 1", *J. Atmos. Sci*., **33**, 10, 1937-54.

Krishnamurti, T. N. and Ramanathan, Y., 1982, "Sensitivity of the monsoon onset to differential heating", *J. Atmos. Sci.,* **39**, 1290-1306.

Krishnamurti, T. N., Chakraborthy, T. N., Cubukcu, N., Stefanova, L. and Vijay Kumar, T. S. V., 2004, "A Mechanism of the Monsoon MJO based on interaction in the frequency domain", *Quart. J. R. Met. Soc*., (Under Publication).

Krishnamurti, T. N., Kistawal, C. M., Shiv, D. W. and Welleford, C. E., 2000, "Improving tropical precipitation forecasts from a multi analysis super ensemble", *J. Climate*, **13**, 4217-4227.

Krishnamurti, T. N., Wong, V., Pan, H. L., Pasch, R., Molinari, J. and Ardanuy, P., 1983, " A three dimensional planetary model for the Somali jet", *J. Atmos. Sci*., **40**, 894-908.

Krishnamurti, T. N., Kanamitsu, M., Godbole, R., Chang, C. B., Carr, F. and Chow, J. H., 1976, "Study of monsoon depression (II) : Dynamical structure", *J. Met. Soc. Japan*, **54**, 208-224.

Krishnamurti, T. N., 1971, "Tropical east-west circulation during northern summer", *J. Atmos. Sci.,* **45**, 1304-1322.

Krishnamurty, V. and Shukla, J., 2000, "Intera-seasonal and interannual variation of rainfall over India", *J. Climate*, **13**, 4366-4375.

Krisnamurti, T. N., Ardannuy, P., Ramanathan, Y. and Pasch, R., 1981, "On the onset vortex of the summer monsoon", *Mon. Wea. Rev.,* **109**, 341-363.

Krishnamurty, V. and Goswami, B. N., 2000, "Variability and Indian Monsoon-ENSO relationship in inter-decadal time scales", *J. Climate*, **13**, 579-595.

Krishnan, R., Mujumdar, M., Vaidya, V., Ramesh, K. V. and Satyan, V., 2003, "The abnormal Indian Summer Monsoon of 2000", *J. Climate*, **16**, 1177-1191.

Krishnan, R., Chang, C. and Surgi, M., 2000, "Dynamics of breaks in the Indian summer Monsoon", *J. Atmos. Sci*., **57**, 1354-1372.

Kumar, J. R. and Dash, S. K., 2001, "Inter-decadal variation in characteristics of monsoon disturbances and their relationship with rainfall and other tropical features", *Int. J. Climatol*., **21**, 759-771.

Kumar, S., 1992, "Interaction of mid-latitude systems in the southern hemisphere with southwest monsoon", *Mausam*, **43**, 1, p37.

Kumar, P., Ravichandran, M., Kalsi, S. R., Sengupta, D. and Gadgil, S., 2000, "First results from a new observational system over the Indian seas", *Current Sci.,* **78**, 323-337.

Lao, H. and Yanai, M., 1984, "The large scale circulation and heat sources over the Tibetan plateau and areas during the early summer of 1979, Pt. II Heat and moisture budgets", *Mon. Wea. Rev*., **112**, 966-989.

Lau, K. M. and Chan, P. C., 1986, "Aspects of 40-50day oscillation during the northern summer as inferred from out going long wave radiation", *Mon. Wea. Rev.*, **114**, 1354-1357.

Lawrence, D. M. and Webster, P. J., 2001, "Inter-annual variations of the intra-seasonal oscillation in the South Asian Summer Monsoon regime", *J. Climate*, **14**, 2910-2922.

Mak, M. K., 1975, "The monsoon mid – tropospheric cyclogensis", *J. Atmos. Sci*., **32,** 2246-2253.

Meehl, G. A., 1994, "Compled land-ocean-atmosphere process and south Asian Monsoon variability", *Science*, **266**, 263-267.

Mehta, V. M. and Krishnamurti, T. N., 1988, "Inter-annual variation of 30-40 day wave motion", *J. Met. Soc. Japan*, **66**, 532-540.

Miller, F. R. and Keshvamurty, R. N. 1968, "Structure of an Asian Summer Monsoon System", *IIOE Metrological Monograph*, *East-West Centre Press*, Hawaii USA 1983.

Mishra, S. K. and Salvekar, P. S., 1980, "Role of baroclinic instability in the development of monsoon disturbances", *J. Atmos. Sci*., **37**, 384-394.

Mohanty, U. C., Dube, S. K. and Singh, M. P., 1983, "A study of the heat and moisture budgets over Arabian Sea and their role in the maintenance of the summer monsoon", *J. Met. Soc. Japan*, **61,** 208-221.

Mohanty, U. C., Sam, N. V. and Dash, S., 2003, "A study on the convective structure of the atmosphere over the west coast of India, during ARMEX-I", Paper presented at ARMEX workshop, NIOT, Chennai, 22-23 December 2003.

Mooley, D. A. and Parthasarthy, B., 1983, "Indian summer monsoon and El-Nino", *Pure Appl. Geophys*., **121**, 339-352.

Mooley, D. A. and Parthasarthy, B., 1984, "Fluctuations in all India summer monsoon rainfall during 1871-1978", *Climate Change*, **6**, 287-301.

Mooley, D. A. and Paolino, D. A., 1989, "The response of the Indian Monsoon associated with changes in SST over eastern and south equatorial Pacific", *Mausam*, **40**, 4, 369-380.

Mooley, D. A. and Shukla, J., 1989, "Main features of the westward moving low pressure systems which form over the Indian region during the monsoon season and their relationship with the monsoon rainfall", *Mausam*, **40**, 2, 137-152.

Mukherjee, A. K., De, U. S. and Sinha Ray, K. C., 1984, "The dynamics of an off-shore vortex in east Arabian Sea and the associated rainfall", *Mausam*, **35**, 2, 233-234.

Muthuvel, C., 1981, "Short period oscillations in outgoing long wave radiation over the summer monsoon region", *Proc. Ind. Acad. Sci. (E&P. Sec.)*, **90**, 125-140.

Nanjundiah, R. S., Srinivasan, J. and Gaddgil, S., 1992, "Intra-seasonal variation of the Indian summer monsoon –II, Theoretical aspects" , *J. Met. Soc. Japan*, **70**, 529-549.

Narashima, R., Sikka, D. R. and Prabhu, A., 1997, "The Monsoon Trough Boundary Layer", *Indian Acad. Sci*. Bangalore, p422.

Nigam, S., 1994, "On the dynamical basis for the Asian summer monsoon rainfall El Nino relationship", *J. Climate*, **7**, 1750-1771.

Ogura, Y. and Yoshizaki, M., 1988, "Numerical study of precipitation over the eastern Arabian Sea and ghat mountains during the summer monsoon", *J. Atmos. Sci*., **45**, 2097-2122.

Palmer, T. N., Brankovic, Viterbo, P. and Miler, M. J., 1992, "Modelling interannual variations of summer monsoon", *J. Climate*, **5**, 399-417.

Pant, G. B. and Parthasarthy, B., 1981, "Some aspects of an association between the Southern Oscillation and Indian summer monsoon", *Arch. Meteor. Geophy., Bioklim*., **1329,** 245-252.

Pant, G. B. and Rupakumar, K., 1997, "Climate of South Asia", John Wiley and Sons. Cambridge.

Pant, M. C., 1982, "Some characteristics of the low level jet field over the Arabian Sea during the Indian summer monsoon", *Mausam*, **33**, 1, 85-90.

Pant, P. S., 1983, "A physical basis for changes in the phases of the monsoon over India" *Mon. Wea. Rev*., **111**, 487-495.

Parthasarthy, B., Munot, A. and Kothawale, D. R., 1995, "Monthly and seasonal rainfall series for all India and homogeneous regions and meteorological subdivisions", *IITM Res. Rept., NO RR-060*, IITM, Pune.

Patnaik, D. R. Lamba, B. S. and Thapliyal, V., 2004, "Decadal trends in westward movement of monsoon depression over India", *Mausam*, **55**, 355-359.

Pearce, R. P. and Mohanthy, U. C., 1984, "Onset of the Asian summer monsoon 1979-82", *J. Atmos. Sci.*, **41**, 1620-1639.

Pisharoty, P. R. and Asnani, G. C., 1957, "Rainfall around monsoon depression in India", *Indian J. Met. Geophys*., **7**, 333-338.

Pisharoty, P. R., 1965, "Evaporation over the Arabian Sea and the Indian Southwest monsoon", *Proc. IIOE*, (Ed. P.R. Pisharoty), 43-54.

Prasad, O. and Johari, A. P., 1990, "Interaction of southern hemisphere equatorial trough with the southwest monsoon circulation during severe drought years", *Mausam*, **41**, 597-603.

Proc. Indian Acad. Sci. (Earth and Planetary Sci.), 2003, "Special Issue on BOBMEX, Vol. **112**.

Ragavan, K., 1973, "Break monsoon over India", *Mon. Wea. Rev*., **101**, 33-43.

Ramage, C. S., 1971, "Monsoon Meterology", *Academic Press* , p296.

Ramage, C. S. and Raman, C. R. V., 1972, “Meteorological atlas of the International Indian Ocean Expedition (Upper Air)”, National Science Foundation, USA.

Ramage, C. S., 1966, “Summer atmospheric circulation over the Arabian Sea, *J. Atmos. Sci.*, **23**, 144-150.

Ramamoorthy, K., 1969, “Monsoon of India – Some aspects of the break in the Indian Southwest monsoon during July and August”, *Forecasting Manual No. IV, 18.3, India Met. Dept., Poona,* India.

Ramamurthy, K., Jambunathan, R. and Sikka, D. R., 1976, “Moisture distribution and water vapour during an active and weak spell of southwest monsoon”, *Indian J. Met. Hydrol. Geophys.*, **27**, 127-140.

Raman, C. R. V. and Ramanathan, Y., 1964, “Interaction between lower and upper tropical troposphere”, *Nature*, **201**, 31-35.

Raman, C. R. V., 1955, “Breaks in the Indian southwest monsoon and typhoons in northwest Pacific”, *Current Sci.,* **24**, 219-220.

Raman, C. R. V., 1967, “Breaks in the Indian monsoon and typhoons in the northwest Pacific”, *Current Sci.,* **24**, 219-220.

Raman, C. R. V., Rao, Y. P. and Alvi, S. M. A., 1990, “The role of interaction with mid-latitude circulation the behaviour of the southwest monsoon of 1972 and 1979”, *Current Sci*., **49**, 123-129.

Ramana, G. R., 1969, “Relationship between depressions of Bay of Bengal and tropical storms of the China Seas”, *Indian J. Met. Geophys*., **20**, 148-150.

Ramanathan K. R. and Ramakrishna, K. P., 1937, “The Indian southwest monsoon and the structure of depressions associated with it”, *Mem. India Met. Dept*., **26**, 15-36.

Ramaswamy, C., 1958, “A preliminary study of the behaviour of the Indian south west monsoon in relation to the westerly jet stream”, *Geophysica*, **6**, 455-476.

Ramaswamy, C., 1962, “Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and westerly jet stream”, *Tellus*, **14**, 337-349.

Ramaswamy, C., 1973, “A normal period of large scale break in the south west monsoon season over India”, *Current. Sci*., **42**, 517-523.

Rao, K. V. and Rajamani, S., 1970, “Diagnostic study of a monsoon depression by a geostrophic baroclinic model”, *Indian J. Met. Geophys.,* **21**, 187-194.

Rao, R. R. and Mathew, B., 1988, “On the observed synoptic variability in the thermal structure of the upper northern Bay of Bengal during MONEX – 79”, Proc. Ind. Acad. (Earth & Planetary Sci.), Soc. **971**, 31-34

Rao, R. R., Gopalakrishna, U. V. and Babu, S. V., 1981, “A case study of the influence of surface thermal structure and ocean mixed layer depth in relation to surface energy exchange processes during MONSOON-77”, *Mausam,* **32**, 1, 85-92.

Rao, R. R., 1986, “The observed thermal response of the upper north eastern Arabian sea to the onset of the summer monsoon during ISMEX-73”, *Mausam*, **37**, 4, 429-434.

Rao, R. R., Somanatham, S. V. S., Ramakrishna, S. S. V. S. and Ramanadham, R., 1987, “A case study on the genesis of a monsoon depression in the northern Bay of Bengal during MONSOON-77 experiment”, *Mausam*, **38**, 4, 387-394.

Rao, Y. P., 1962, “Meridional circulation associated with the monsoon of India”, *Indian J. Met. Geophys.,* **13**, 157-166.

Rao Y. P., 1976, “South West Monsoon, Met. Monograph (Synoptic Meteorology), No. **1**, India Met. Dept., New Delhi.

Rao, K. G. and Goswami, B. N., 1988, “Interannual variation of sea surface temperature over the Arabian sea and the Indian monsoon - a new perspective”, *Mon. Wea. Rev*., **116**, 558-568.

Rao, R. R. 1980, “Cooling and depending of the mixed layer in the central Arabian sea during monsoon”, *Deep Sea Res.,* **33**, 1413-1424.

Rao, R. R., 1977, “On the thermal response of the upper eastern Arabian sea to the summer monsoonal forcing during monsoon – 77”, *Mausam*, **37**, 77-84 .

Rao, R. R. and Sivakumar, R., 1999, “On the possible mechanism and evolution of a mini-warm pool during the pre-summer monsoon season and onset vortex in the south-eastern Arabian sea”, *Q. J. R. Met. Soc*., **125**, 787-809.

Rasmusson, E. M. and Carpenter, T. H., 1983, “The relationship between the eastern Pacific sea surface temperature and rainfall over India and Sri Lanka”, *Mon. Wea. Rev.,* **111**, 354-384.

Rodwell, M. J., 1987, “Asian Monsoon, “ The influence of the southern hemisphere weather systems on monsoon *J. Atmos. Sci.,* **54**, 2597-2611.

Saha, K. R., Sanders, F. and Shukla, J., 1981, “Westward propagating predecessors of monsoon depressions, *Mon. Wea. Rev.,* **109**, 330-343.

Saha, K. R. and Bavdekar, S. N., 1973, “Water vapour and precipitation over the Arabian Sea during the northern summer *Q. J. R., Meteor. Soc*., **99**, 273-278.

Saha, K. R. and Saha, S., 2000, “On the onset of summer monsoon over India in relation to Interaction of monsoon stationary wave with transient baroclinic wave leading to monsoon cyclogensis”, *Mausam*, **51**, 1, 1-16.

Saha, K. R., 1970, “Air and water vapour transport across the equator in Western Indian Ocean during northern summer, *Tellus*, **22**, 681-687.

Saha, K. R., 1971, “Cloud distribution over equatorial Indian Ocean and revealed by satellite”, *Ind. J. Met. Geophys*., **22**, 3, 389-396.

Saha, S. and Saha, K. R., 1993, “A diagnostic analysis of MONEX-1979 onset vortex over the Arabian Sea, *Mausam*, **44**, 4, 321-328.

Saji, N. H., Goswami, B. N., Vinay Chandran and Yamagata, T., 1999, “A dipole mode in the tropical Indian Ocean, *Nature*”, **401**, 360-363.

Sanders, F., 1984, "Quasi-geostrophic diagnosis of the monsoon depression, 5-8, July 1979", *J. Atmos. Sci*., **41**, 538-552.

Sanjeeva Rao, P., and Sikka, D. R., 2005, "Intra-seasonal variability of the summer monsoon over north Indian ocean as revealed by the BOBMEX and ARMEX field programs, *Pure and Appl. Geophys*., Vol. **162**, (under publication).

Sarkar, R. P. and Choudhary, A., 1988, "A diagnostic study of monsoon depression", *Mausam*, **39**, 9-18.

Sarma, Y. V. B., Seetaramayya, P., Murty, V. S. N. and Rao, D. P., 1997, "Influence of the monsoon trough in the head Bay of Bengal during the southwest monsoon of 1990", *Boundary Layer Meteorology*, **821**, 517-526.

Sawyer, J. S., 1947, "The structure of Inter-tropical front over NW India during the southwest monsoon", *Q. J. R. Met. Soc*., **73**, 346-369.

Seetaramayya, P. and Master, A., 1984, "Observed air sea interface conditions and a monsoon depression during MONEX 1979", *Arch. Met. Geoph. Biomet. Ser.* A., **33**, 61-67.

Seetaramayya, P., Nagar, S. G. and Mullar, A. H., 2001, "Response of the Head Bay of Bengal (Head Bay) to monsoon depression during MONTBLEX-90", *The Global Atmos. Ocean System*, **7**, 325-345.

Sengupta, D. and Ravichandran, 2001, "Oscillation of the Bay of Bengal Sea surface temperature during the 1998 summer monsoon", *Geophys. Res. Lett*. **28**, 2033-2036.

Shankar, D. and Shetye, S. R., 1997, "On the dynamics of Lakshadweep high in the south east Arabian Sea", *J. Geophy. Res.*, **102 (C-6)**, 12551-1562.

Shankar, D., Gopalakrishna, V. V., Shenoi, S. S. C., Durand, F., Shetye, S. R., Rajan, C. K., Jonhson, Z., Araligidad and Michael, G. S., 2004, "Observational evidence for westward propagation of temperature inversions with south eastern Arabian sea", *Geophy. Res. Lett.*, 31(8), (10-1029Doc/2004 L 08305 GL 019652).

Shenoi, S. S. C., Shankar, D. and Shetye, S. R., 1999, "On the sea surface temperature high in the Lakshadweep Sea before the onset of the southwest monsoon", *J. Geophys. Res.*, **104 (C-7)** 15703-15712.

Shukla, J. and Misra, B. M., 1977, "Relationship between sea surface temperature and wind speed over the central Arabian Sea and monsoon rainfall over India", *Mon. Wea. Rev*., **105**, 998-1002.

Shukla, J., 1978, "CISK, barotropic and and baroclinic instability of the growth of monsoon depression", *J. Atmos. Sci.*, **35**, 495-500.

Shukla, J. and Paolino, D. A., 1983, "The Southern Oscillation and long-range forecasting of the summer monsoon rainfall over India", *Mon. Wea. Rev*., **111**, 1830-1837.

Shyamala, B., 2003, "Observational study on off-shore vortices during ARMEX 2002", Paper presented at ARMEX workshop, Chennai, 22-23 December 2003.

Sikka, D. R., 1999, "Monsoon Droughts in India", COLA/CARE Rept. No.2.

Sikka, D. R., 1977, "Some aspects of the life history, structure and movement of monsoon depressions, *Pure and Appl. Geophys*., **115**, 1501-1529.

Sikka, D. R., 1980, "Some aspect of the large scale fluctuations of summer monsoon rainfall over India in relationship to fluctuations in the planetary and regional scales circulation parameters", Proc. Ind. Acad. Sci. (Earth & Planetary Sci.), **89**, 179-195.

Sikka, D. R. and Gadgil, S., 1978, "Large scale rainfall over India during the summer monsoon and its relationship with the lower and upper tropospheric vorticity", *Indian J. Met. Hydrol. Geophys.*, **29**, 1&2, 219-223.

Sikka, D. R. and Gadgil, S., 1980, "On the maximum cloud zone and the IICZ over Indian longitude during the southwest monsoon", *Mon. Wea. Rev*., **108**, 1840-1853.

Sikka, D. R. and Grossman, R. L., 1981, "Large Scale features associated with the evolution and intensification of break monsoon over India during August 1979", *Int. MONEX Conf. Tallahassee, Flo.*, 1-67 to 1-70.

Sikka, D. R. and Gray, W. M., 1981, "Genesis of monsoon disturbances in north Indian Ocean with the passage of baroclinic waves across the southern Indian Ocean", Proc. Int. Conf. on Scientific Results of the Monsoon Experiment, Bali, Indonesia, WMO, Geneva, 4-29 to 4-34.

Sikka, D. R. and Dixit, C. M. 1973, "A study of the satellite observed cloudiness over the equatorial Indian Ocean during the monsoon season", *J. Marine Bio. Ass. India*, **14**, 805-818.

Sikka, D. R. and Narasimha, R., 1995, "Genesis of the monsoon trough boundary layer, Experiment Proc. Ind. Acad. Sci GE and P. Sci.) 104,4.

Sikka, D. R., 2003, "Evaluation of Monsoon monitoring and forecasting of summer monsoon over India and a review of monsoon drought of 2002", Proc. Ind. Nat. Sci. Acad., BA, 479-504.

Sikka, D. R., Paul, D. K., Deshpande, V. R., Majumdar, R. and Purranik, P. V., 1986, "Sub-seasonal scale fluctuations of ITC over the Indo-Pacific region during summer monsoon .Pt. I ; Features over the Indian region", Proc. Ind. Acad. Sci (Earth& Planetary Sci) **94**, 47-74.

Simpson, G. C., 1921, "The South West Monsoon", *Q. J. Roy. Meteor. Soc*., **47**, 151-172.

Singh, O. P., 2001, "Long term trends in the frequency of monsoonal cyclonic disturbances over the north Indian Ocean", *Mausam*, **52**, 4, 655-658.

Singh, S. V., Basu, S. and Krishnamurti, T. N., 2003, "Weather and Climate Modelling, *New Age International Pub.* , New Delhi", p231.

Singh, O. P., 1991, "Surface fluxes and cyclogensis over north and central Bay of Bengal during the MONTBLEX–1990, *Mausam*, **43**, 399-402.

Singh, S. V. and Kriplani, R. H., 1990, "Low frequency intra-seasonal oscillation in Indian rainfall and outgoing long wave radiation", *Mausam*, **41**, 217-222.

Singh, S. V., Kriplani, R. H. and Sikka, D. R., 1992, "Intenannual variability of the Maddin Julian oscillation in the Indian summer monsoon rainfall", *J. Climat*, **5**, 973-978.

Slingo, J. M. and Annamalai, H. 2000, "The El-Nino of the century and response of the Indian summer monsoon", *Mon. Wea. Rev*., **128**, 1778-1797.

Soman, M. K. and Krishna Kumar, K., 1993, "space-time variations of meteorological features associated with the on set of the Indian summer monsoon" *Mon. Wea. Rev.*, **121**, 1177-1194.

Sperber K. R, Brankovic C., Deque, Frederiksan, C. S., Graham, R., Kitoh, A., Kobayashi, C., Palmer, T., Puri, K., Tennant, W. and Volodin, E., 2001, "Dynamical seasonal predictability of the Asian Summer Monsoon", *Mon. Wea. Rev.*, **129**, 2226-2248.

Sperber, K. R., Slingo, J. M. and Annamalai, 2000, "Predictability and the relationship between sub-seasonal and inter-annual variability during the Asian summer monsoon" *Q. J. R. Met. Soc.*, 126, 2545-2574.

Srinivasan, J. and Smith, G. L., 1996, "Meridional migration of tropical convergence zones", *J. Appld. Met.* **35**, 1189-1202.

Srinivasan, V., 1968, "Some aspects of the broadscale cloud distribution over Indian Ocean during Indian southwest monsoon", *Indian J. Met. Geophys*. **19**, 39-45

Srinivasan, J., Gadgil, S. and Webster, P. J., 1993, Meridional propagation of large scale convective zones", *Meteor. Atmos. Phys*., **52,** 15-35.

Staff Members Academica Sinica, 1957, "On the general circulation over eastern Asia (I), *Tellus*, **9**, 432-446.

Sud, Y. C. and Smith, W. E., 1985, "Influence of local and land surface processes on the Indian monsoon, A numerical study", *J. Climatol. & Appl. Meteor*., **24**, 1015-1036.

Sunil Kumar, K. V., Mohan Kumar, N., Joseph, M. X. and Rao, R. R., 1994, "Genesis of meteorological disturbances and thermohaline variability of the upper layer in the Head Bay of Bengal during MONTBLEX 1990", *Deep Sea Res*., **41**, 1569-1581.

Vernekar, A. D., Chou, J. and Shukla, J., 1995, "The effect of Eurasian snowcover on the Indian monsoon", *J. Climate*, **8**, 248-260.

Vinaychandran, P. N. Murty, V. S. N. and Ramesh Babu, V., 2002, "Observation of barrier layer formation in the Bay of Bengal during summer monsoon 2002", *J. Geophys., Res.*, **107**, 1029/ 2000 JC.00083.

Vinaychandran, P. N. and Shetye, S. R., 1991, "The warm pool in the Indian ocean, Proc Ind. Acad. Sci (Earth & Planetary Sci.), **100**, 165-175.

Walker, G. T., 1924, "Correlations in seasonal variation of weather", *Memoir India Met. Dept*., **24**, 333-345.

Wang, B., 1995, " Interdecadal changes in El Nino onset in the last four decades, *J. Climate*, **8**, 167-285.

Wang, B. and Rui, H. 1990, "Synoptic climatology of transient tropical intra-seasonal convective anomalies", *Meteor. Atmos. Phys*. **44**, 43-61.

Webster, P. J. and Yang, S., 1992, "Monsoon and ENSO, Selectively interactive systems", *Q. J. R. Meteor. Soc*., **118**, 877-926.

Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Tomas, R. A, Yanai, M. and Yasunari, T., 1998, "Monsoon processes, predictability and prospects for prediction", *J. Geophys. Res.*, **103**, 14451-14510.

Webster, P. J., Moore, A. M., Loschinigg, J. P. and Leben, R. R., 1999, "Evidence of coupled oceanic-atmospheric instabilities", *Nature*, **401**, 356-360.

Wyrtki, K., 1971, "Oceanographic atlas of the International Indian Ocean Expedition", National Science Foundation, USA.

Yanai, M., Li, C. and Song, Z., 1992, "Seasonal heating of the Asian summer monsoon", *J. Meteor. Soc. Japan*, **70**, 189-221.

Yasunari, T., 1980, "A quasi-stationary appearance of the 30-40 day period in the cloudiness fluctuations during the summer monsoon over India", *J. Meteor. Soc., Japan*, **58**, 225-229.

Yasunari, T., 1981, "Structure of an Indian summer monsoon system with around 40 day cycle", *J. Met. Soc., Japan*, **59**, 336-354.

Yin, M. T., 1949, "Asymptotic aerological study of onset of the summer monsoon over India and Burma", *J. Met. Soc.*, **6**, 393-400.