Indian summer monsoon experiments

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Eight major field experiments have been carried out so far addressing the Indian summer monsoon. While these experiments were international and the impetus was external till 1980, India's own monsoon programmes evolved since then. In this article, objectives and outcomes from some of these experiments are described. It is shown that monsoon experiments have contributed in several ways. Each experiment enhanced the infrastructure facilities in the country, brought together scientists from different organizations to a common platform and also injected new people in this field. A large amount of data have been generated and their analysis has led to better understanding of the summer monsoon and discovery of new phenomena.

Keywords: ARMEX, BOBMEX, MONTBLEX, monsoon.

SEVERAL observational experiments have been carried out in the last five decades targeting the Indian summer monsoon. The word 'monsoon' is of Arabic origin, coined by the Arab traders well before the time of modern science and referred to the phenomenon of seasonal reversal of winds over the Arabian Sea (AS). However, the spatial scale of the monsoon flow was not scientifically explored till India Meteorological Department (IMD), which was established in 1875, carried out a two-year intensive programme to collect surface observations from land and ocean (ship-based) in the so-called monsoon area[1] during 1893–94. These observations led to the discovery that at the time of monsoon onset, strong cross equatorial flow develops off the east coast of Africa bringing in moisture from the south Indian Ocean[1]. Then there was a gap of more than 60 years with no major monsoon experiment (perhaps the two world wars might have partly contributed to this). In the last five decades, eight major monsoon observational experiments have been carried out. When we examine the genesis of these programmes, they fall into two broad categories, namely, pre-1980 and post-1980. There were four pre-1980 monsoon experiments, namely, International Indian Ocean Expedition (IIOE) carried out during[2,3] 1960–1965, Indian Summer Monsoon Experiment (ISMEX[4], year 1973), Indo-Soviet monsoon experiment[5] of 1977 (MONSOON-77), and the monsoon experiment[6–8] MONEX-79 carried out in 1979. The post-1980 experiments are Monsoon Trough Boundary Layer Experiment[9,10] in 1990 (MONTBLEX), Land Surface Processes Experiment[11] (LASPEX) during 1997–98, the Bay of Bengal Monsoon Experiment[12] (BOBMEX) in 1999, and the Arabian Sea Monsoon Experiment[13] (ARMEX) during 2002–2005 (Figure 1). Further, an international experiment, 'Joint Air–Sea Monsoon Interaction Experiment' (JASMINE) was carried out in 1999 over the tropical Indian Ocean during the pre-monsoon (7–22 April, 1 May–8 June) and towards the end of monsoon season (2–28 September)[14].

Indians did participate in and contribute to the pre-1980 monsoon experiments, however, the initiative and

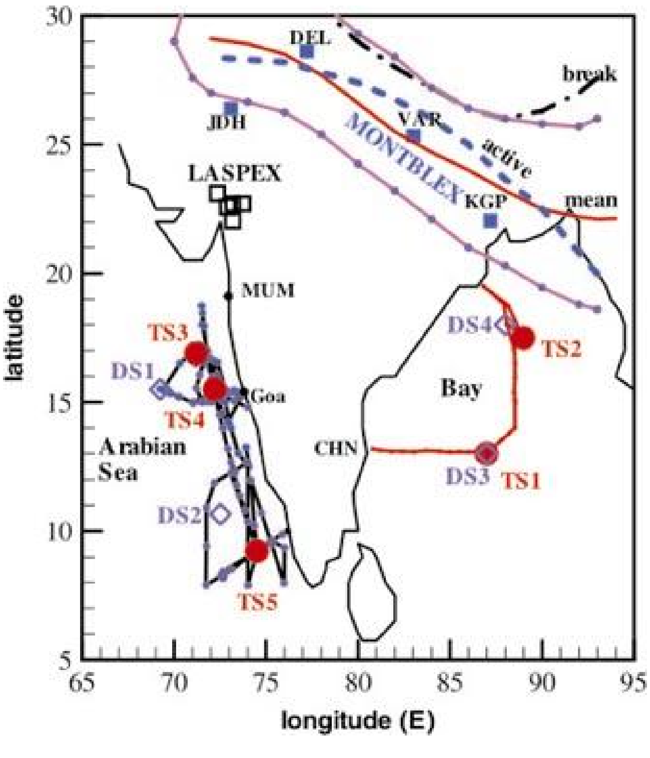

Figure 1. Study areas of recent monsoon experiments carried out by Indian scientists. The fluctuating location of the monsoon trough is shown in northern India (pink line) where MONTBLEX observations were carried out (from Rajkumar and Narasimha[29], based on data of Paul and Sikka). The filled boxes show the locations of 30 m towers operated during MONTBLEX. The open boxes in western India show the observation sites of LASPEX. The lines over the Bay of Bengal and Arabian Sea show cruise tracks of *ORV Sagar Kanya*, and the corresponding time series observation stations (TS2 to TS5) by filled circles. *INS Sagar Dhwani* was deployed at TS1 (13°N, 87°E). DS1, DS2, DS3 and DS4 (diamond) are moored buoys deployed by NIOT.

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leadership came from outside. These were international programmes and enormous amount of resources were mobilized. On the other hand, post-1980 experiments (except for JASMINE) were conceived, designed and executed by Indian scientists. These were India's national experiments with participation of a large number of Indian organizations, institutes and universities. The motivation came from a desire to identify and address outstanding issues that could lead to better prediction of monsoon. Being national experiments, the resources available were very modest compared to pre-1980 experiments but not in absolute terms. In this article, pre-1980 experiments are discussed very briefly and post-1980 experiments, where authors were directly involved, are given more space. In a recent paper, Sikka[15] has summarized major advances made in Indian monsoon meteorology during the last four decades where more information on pre-1980 field experiments and related references can be found.

Pre-1980 monsoon experiments

The first major observational programme in the Indian Ocean region was IIOE carried out during 1960–65. The Indian Ocean till then was barely explored scientifically. Three issues considered to be addressed under IIOE are as follows. First, to know the Indian Ocean potential for fishery resources, since most of the countries bordering the Indian Ocean were deficient in protein in their diet. Second, to assess the role of the north Indian Ocean in affecting the monsoonal changes, which influence agriculture on the subcontinent, ocean currents, upwelling, and productivity and the carbon dioxide cycle. Third, to determine the limits to the use of the oceans to dump anthropogenic wastes including nuclear waste. The study area was the Indian Ocean including adjoining seas. In all 20 countries participated including India, 40 ships were deployed over a six-year period from 1960 to 1965, and aircraft were flown to measure atmospheric vertical structure using dropsondes.

IIOE was a landmark experiment and revolutionized oceanographic and monsoon research in India in several ways. IIOE led to new discoveries including the low level jet during monsoon[16,17], strong atmospheric inversions over the western and central Arabian Sea[18]. The data also enabled the estimation of transport of moisture across the equator and into the Indian landmass and evaporation over the Arabian Sea[15]. IIOE resulted in the establishment of new institutes including the National Institute of Oceanography at Goa. India started getting weather data from the global network in real time (radio teletype messages) during IIOE as part of the infrastructure development, and an IBM computer (model 1620) was installed at the International Meteorological Centre established at Bombay (Mumbai) during IIOE to process data. Several (then) young scientists (e.g., R. N. Keshavamurthy, M. B. Mathur, D. R. Sikka, Suryanarayana) were introduced to monsoon research during IIOE.

MONEX-79 was a sub-programme of the First Global GARP (Global Atmospheric Research Programme) Experiment (FGGE), and a major international effort to study the Asian monsoon after IIOE[6]. MONEX-79 provided a more comprehensive dataset from a large area around India where surface and upper air networks were augmented to meet the requirements[6,8]. Two special observing periods were organized: (i) the summer monsoon experiment during 1 May to 30 June (phase I, focus – Arabian Sea side) and 1–27 July 1979 (phase II, focus – Bay of Bengal side), and (ii) winter monsoon experiment during 1 January to 28 February, 1979. About 20 ships participated and aircrafts were deployed for dropsondes. MONEX-79 provided the planetary and regional scale features of the monsoon[7], and also triggered a large number of investigations including the monsoon onset processes[19], the structure of the monsoon onset vortex[20]. It motivated studies leading to better understanding of west coast rainfall and effect of orography on rainfall[21,22]. Combining ISMEX, MONSOON-77 and MONEX-79 observations, the response of the upper ocean to atmospheric forcing during monsoon could be examined[23]. MONEX-79 also marked the beginning of atmospheric boundary layer (ABL) measurements in India[24].

Post-1980 monsoon experiments

Following the global trends, numerical models gained popularity in India during 1980s as research and weather forecasting tools. Accurate representation of the near surface processes and ABL in the models became important. Over the vast areas of the Indian landmass, there had been no organized efforts to study ABL. Surface fluxes and ABL parameterizations used in the numerical models were based on measurements carried out in mid and high latitudes and not in the monsoon region. It is not a priori clear that these relations are applicable to the Indian conditions, particularly over the monsoon trough and need to be validated[8]. MONTBLEX and LASPEX were carried out to fill this gap.

MONTBLEX

In his classic memoir of 1886 on *The Rainfall of India*, Blanford[25] noted the existence of a 'barometric trough which runs obliquely across Northern India, and is the chief seat of the convective ascent…'. The trough extends from Rajasthan and Pakistan in the west to the head of the Bay of Bengal in the east (Figure 1); its position is closely associated with rainfall patterns in India[26]. The eddy fluxes in the trough region can play a crucial dynamical role, and their proper parameterization has the potential to improve model simulations of the monsoons.

A study of ABL in the trough region therefore seemed highly worthwhile. Some experience in ABL studies had already been gained by an IISc team through an experiment carried out in Balasore as part of MONEX-79 (using what to the best of our knowledge was the first microprocessor-driven surface layer instrumentation system in the world)[24], and another in Raichur in connection with the total solar eclipse[27] of 16 February 1980. A project proposal for the field experiment MONTBLEX, involving 20 Indian institutions, was approved by DST in 1988.

The project had as its chief objectives the description of the structure of the ABL across the entire extent of the trough, the study of eddy fluxes and energetics, and the formulation of better parameterization schemes for the boundary layer for use in atmospheric general circulation models. Another objective was to understand the interactions between the moist, ascending eastern end of the monsoon trough with the dry subsidence regime at its western end. The project included observations from four 30 m surface layer masts, respectively at Jodhpur, Delhi, Varanasi and Kharagpur (Figure 1); ocean cruises by *ORV Sagarkanya*; observations over IMD network; sodar and tethersonde measurements; and extensive aircraft flights carried out by the Indian Air Force. A pilot experiment was conducted at Kharagpur in July 1989, and was followed by the full field experiment in 1990. A comprehensive account of the results from the various investigations carried out was published[28] in 1997, but there have been numerous papers published elsewhere as well, before and after that date.

One characteristic feature of the monsoon trough was obtained by a spectral analysis of its position at the two longitudes 79°E and 85°E[29]. The analysis revealed (Figure 2) significant spectral peaks (confidence level > 95%) at 2.6, 2.9, 4.5, 7.7 and 51.5 days at 85°E; at 79°E, the peaks are at 2.7, 3.7, 7.7 and 51.5 days, so there is considerable overlap. These peaks may be correlated with the average life of weather systems (~3 days, synoptic period), the time interval between such systems (~9 days), and the 40–50 day oscillation[30].

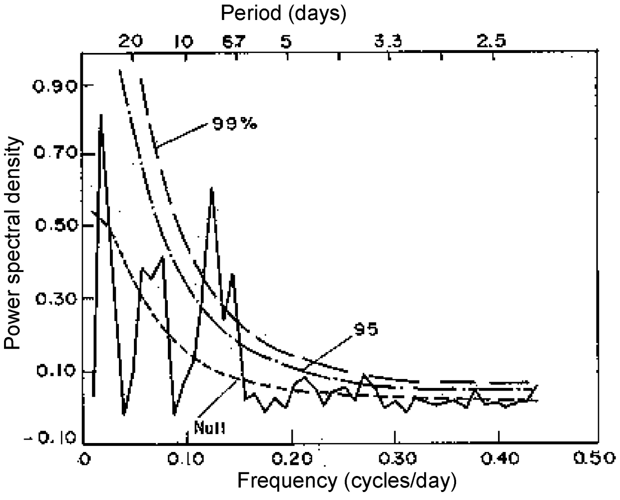

Figure 2. Power spectral estimates of the latitudinal position of the monsoon trough at 85°E, without smoothing[29].

In retrospect, the major outcome of the experiment has been the acquisition of good data on momentum and heat flux by sonic anemometers, and the effort that followed at devising new parameterizations. A preliminary report on the data was presented[31] in 1995. Of the 18 papers devoted to reporting MONTBLEX data, analysis or modelling in ref. 28, a third were connected with eddy fluxes in one way or other. MONTBLEX data also proved valuable in viewing eddy flux processes as a series of events, demanding an episodic rather than a harmonic description[32]. Both Mohanty *et al.*[33] and Rao *et al.*[34] noted that the bulk aerodynamic coefficients showed an appreciable increase as wind speed fell. A detailed study of this dependence, with the data segregated on a stability parameter like the flux Richardson number, showed that Monin–Obukhov (M–O) theory could be in considerable error at sufficiently low speeds[35]. The data from Jodhpur, where the wind velocity was mostly in the range 0.5–7 m s^{-1}, turned out to be valuable in making such detailed analyses.

Eventually, Rao and Narasimha[36] provided a new framework for parameterizing eddy fluxes in the low-wind convective regime that prevailed in Jodhpur (and is actually characteristic of much of the tropics). From a physical point of view, it is useful to introduce a flow regime that may be called ‘weakly forced convection’ (WFC) where the sensible heat flux is given by the classical free convection formula even in the presence of mild (cross) wind. An analysis of the extensive laboratory measurements reported in the engineering literature supports this view, and suggests that the wind speed V characterizing the outer limit of the regime is defined by an intrinsic Froude number F, equal to $V(gL)^{-1/2}$, where L is a characteristic length scale and g is the acceleration due to gravity[37]. Within the WFC regime the drag varies linearly with wind speed (and not as its square, as assumed in the formulation of bulk aerodynamic coefficients). The evidence for these conclusions is shown in Figure 3. Interestingly, support for these conclusions was obtained from an analysis of data from BLX83, an experiment carried out in Chickasha, Oklahoma between 26 May and 18 June 1983 and summarized by Stull[38]; about half the data points listed by Stull turned out to be in the WFC regime (Figure 4). What these results suggest is that the conventional scaling argument of M–O theory, centered around friction velocity U^* and friction temperature θ^*, needs to be replaced by one scaled by heat flux in the WFC regime. The implications of the data for the M–O parameterization have also been considered separately[39].

A new parameterization scheme based on these ideas has been introduced into an AGCM written at the National Aerospace Laboratories (NAL), Bangalore, and has

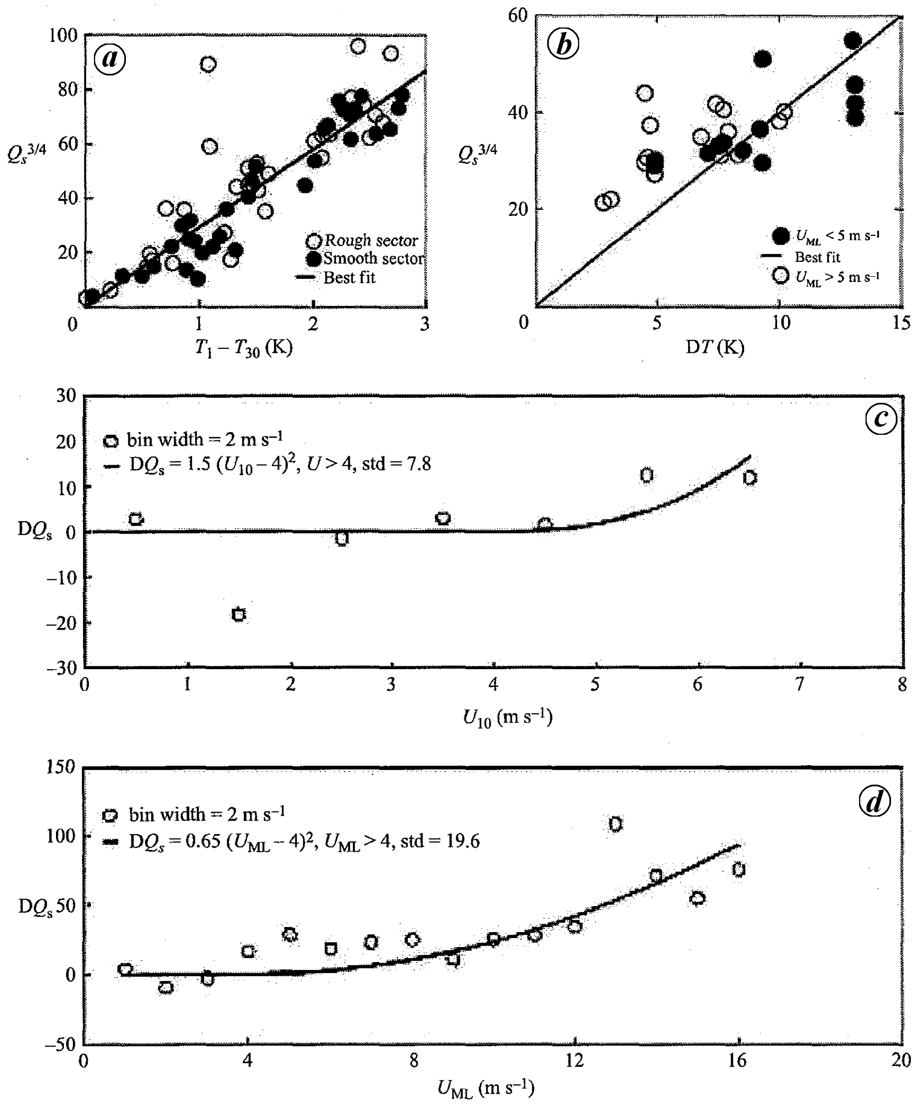

Figure 3 ***a–d*****.** Observed sensible heat flux as a function of a characteristic temperature differential to show the range of a 4/3 power dependence. ***a***, Data from MONTBLEX; ***b***, Data from BLX 83, indicating separately low and high-wind observations; ***c***, ***d***, Deviations of Q from best fit as function of wind speed; data from MONTBLEX (***c***) and BLX83 (***d***)[38].

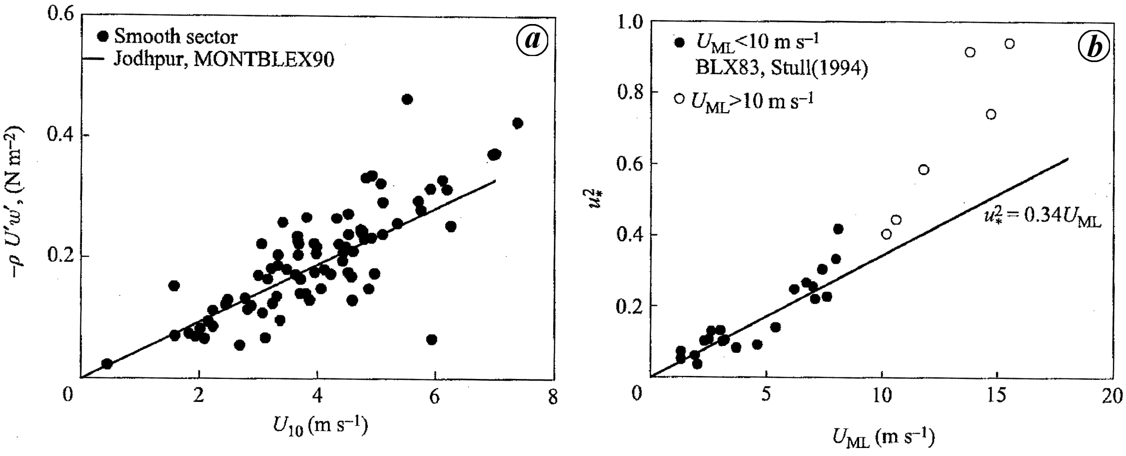

Figure 4. Observed drag as function of wind speed. In the lower diagram (BLX83 data) the linear expression is a fit only to observations with U_{ML} < 8 ms^{-1} (filled points)[36].

shown appreciable improvement in prediction skill on the track of the Orissa super-cyclone[40] as well as many others elsewhere in the world. The new parameterization scheme may be seen as an alternative to others seeking to enhance eddy fluxes above M–O values at low winds[41], and has the merit of being based on the extensive new data set on low-wind convective boundary layers over land acquired during MONTBLEX 90.

Indian climate research programme

The emphasis in pre-1980 monsoon experiments was on understanding the large-scale aspects of monsoon circulation. Since 1980, it became clear that the underlying surface (particularly the ocean) is not a mere supplier of energy and moisture to the atmosphere, but influences and is also influenced by the events in the atmosphere, and this interaction can be an important mechanism of climate variability. As the El Nino and Southern Oscillation (ENSO) phenomenon was being unravelled in the 1980s, ocean–atmosphere variations and their coupling on intraseasonal timescales and accurate estimation of surface fluxes emerged as important scientific issues[42]. New relationships were discovered between the occurrence of large cloud systems (organized convection) and the sea surface temperature (SST)[43,44]. A variety of satellite-derived data became available and numerical models were becoming powerful tools of research. Monsoon research also benefited from these developments and a number of issues were being addressed by different investigators. In early 1990s, the need to document what we know about monsoon based on all the work done till then including the Indian, and what needs to be done that will enhance our ability to understand and predict monsoon variability better, was increasingly felt within the Indian scientific community. In order to have maximum impact from the limited resources available in the country, a road map for monsoon research in the country for the coming decade with well-focused programmes was required. After several meetings within the country among people working in the areas of meteorology and oceanography, an ICRP document[45] titled *Indian Climate Research Programme Science Plan* was brought out in 1996. The major thrust of ICRP is on monsoon variability on timescales ranging from subseasonal to interannual and decadal, and its impact on critical resources. The ICRP science plan lists the following four major objectives:

1. Understanding the physical processes responsible for variability of the monsoon, the oceans (specifically the Indian seas and the equatorial Indian Ocean) and the coupled atmosphere–ocean–land system on various timescales (sub-seasonal, seasonal, interannual, and decadal).
2. Study of the space time variation of the monsoons from sub-seasonal, interannual to decadal scales for assessing the feasibility for climate prediction and development of methods for prediction.
3. Study of change in climate and its variability (on centennial and longer timescales) generated by natural and anthropogenic factors.
4. Investigation of the links between climate variability and critical resources such as agricultural productivity, and for realistic assessment of the impact of the climate change.

Meeting the objectives of ICRP required well-focussed programmes which study not only the individual components but also the interactions/feedbacks between the different components of climate. Suggested action plans to address the ICRP objectives are discussed in the ICRP Implementation Plan[46]. These include the analysis of available data, numerical modelling, and carrying out several special field experiments with focus on process studies. In the ICRP implementation plan, BOBMEX and ARMEX are given top priority. These experiments have been carried out. ICRP experiments are inter-agency national programmes with support from DST, Department of Ocean Development (DOD), Department of Space, and Ministry of Defence, and all major national institutes, research organizations and universities working in meteorology and oceanography in India participated. Atmospheric and oceanographic communities worked together during these experiments. Documents on the science issues to be addressed were brought out and the implementation plans were prepared before each experiment. The field experiments were so designed that resulting data would enable the testing of some of the hypotheses that were prevailing then regarding the monsoon onset, propagation of monsoon cloud systems, air–sea interactions, oceanic processes, etc. Available resources in the country were utilized. DOD provided its ship *ORV Sagar Kanya* and the National Institute of Ocean Technology (NIOT), Chennai (an organization under DOD) deployed additional buoys. The National Physical Oceanographic Laboratory (NPOL), Kochi participated with its ship *INS Sagar Dhwani*. Indian Navy, Coast Guard and Indian Air Force actively participated and provided their facilities for observations. IMD organized special observations from coastal and island stations in addition to hosting the Scientific Advisory Committee (that monitored the progress and advised observational strategies based on short-term weather forecasts) during the field phase. The scientific rationale, objectives and important findings from these experiments are described briefly in the following.

Buoy measurements: Indian monsoon is strongly coupled to the warm oceans surrounding the subcontinent. Most of the monsoon rainfall occurs in association with synoptic scale systems (the monsoon disturbances such as lows and depressions) which are generated over these waters and move onto the Indian landmass. In particular, the Bay of

Bengal (bay henceforth) is exceptionally fertile, with a very high frequency of genesis of these systems. However, *in situ* data, especially in the areas where monsoon systems form and/or intensify, have been lacking. Monsoon observations received a boost with the installation of moored buoys (buoys henceforth) in AS and Bay by NIOT in 1997. Buoys are floats on the sea surface anchored to the ocean floor and contain instruments for measuring near surface atmospheric and oceanic variables with satellite communication link.

Buoy measurements showed for the first time that ocean and atmosphere undergo coherent variations on intraseasonal timescales in the north Indian Ocean during monsoon[47]. Time series of SST and wind speed measured over the Bay and AS during 1998 are shown in Figure 5. Both AS and Bay show similar patterns of SST warming between March and the monsoon onset time. During the monsoon onset, SST collapsed suddenly over AS but gradually over the Bay. The dramatic decrease in SST over AS coincided with a sudden increase in the wind speed following the formation of a monsoon onset vortex and its subsequent development into a cyclonic storm. In some years AS SST does not collapse as dramatically and shows gradual cooling over a few weeks after the monsoon onset. The behaviour of SST during July–September differs between AS and head Bay with intraseasonal variability in the former dull while very strong in the latter. Wind speed also showed a larger variation over the Bay with values more than 10 m s^{-1} when organized convection (this term refers to the occurrence of large, deep convective clouds systems which show significant self-organization) occurred there[47] while wind speed decreased below 3 m s^{-1} during the weak phase of convection (condition of the atmosphere where the sky is either clear or partially covered by non-raining, shallow, scattered clouds). On the other hand, winds over AS do not drop this low during the monsoon season even when convection is in its weak phase. As a result, the latent heat loss always remains high over AS.

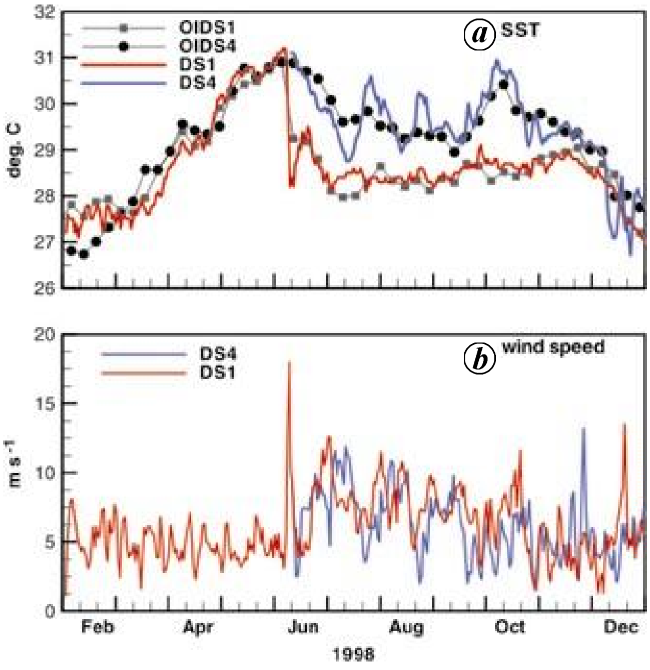

Figure 5 ***a, b***. ***a***, The variation of daily average SST measured by NIOT buoys DS1 and DS2 in the year 1998. Corresponding optimally interpolated pentad SST (earlier known as Reynolds SST) downloaded from NOAA website in February 2006 at DS1 (OIDS1) and DS4 (OIDS4) are also shown. ***b***, Daily average wind speed measured by buoys.

Figure 5 demonstrates how continuous *in situ* data can alter our thinking on intraseasonal oscillations and air–sea coupling over the North Indian Ocean during the summer monsoon. In the absence of other observations, research studies and conclusions derived are often based on Reynolds SST[48] (also called optimally interpolated SST, OISST) which merges satellite-derived SST with ground truth. Reynolds SST missed the strong intraseasonal signal over the North Bay, and the conclusions one would reach from buoy and Reynolds SST time series are entirely different (Reynolds SST shown here was downloaded in January 2007, and the earlier comparison was no better[47]). Buoy data showed that Bay is not an infinite reservoir of heat and moisture unaffected by the monsoon drama unfolding over it in the atmosphere during summer, but has a top layer that quickly responds to atmospheric forcing even on very short timescale of a few days. Since SST and deep convection relationship is highly nonlinear[49], this has strong implications for atmospheric convection. Bay SST undergoes large intraseasonal fluctuations (while remaining above the convection threshold), whereas that of AS remains nearly steady just above the convection threshold, but nevertheless supports intense high rainfall events on the west coast of India[26,50]. Thus, AS and Bay have their unique characteristics. Buoy data raised new questions and some of the objectives of BOBMEX and ARMEX were an attempt to answer them.

BOBMEX

Bay is the breeding ground for the monsoon systems. One of the outstanding problems has been, how does the Bay manage to sustain high SSTs conducive for convection for a period of more than four months despite strong winds and frequent clouding? There were several such questions regarding the Bay with no clear answer but many possibilities, and it was decided to organize the first field experiment under ICRP over the Bay. BOBMEX is the first experiment to collect observations during a peak monsoon period in the north Bay using modern surface flux sensors and high resolution radiosondes[12]. The emphasis in BOBMEX was on collecting high quality data over the Bay and the surrounding coastal areas during different phases of monsoon. Within the Bay, there are marked variations in the freshwater flux between the northern and southern parts of the Bay. The northern Bay receives a large quantity of fresh water through river discharge in addition to local precipitation. This results in very low values of surface salinity in the northern Bay which is not the case in the southern Bay[51]. The low saline water makes the top layer of the ocean very stable for vertical mixing. Thus, we expected the nature of the response of the ocean to atmospheric forcing to be different in the northern and southern parts of the Bay. The upper ocean processes in the presence of strong monsoonal winds and low surface salinity needed to be understood. Therefore, it was decided to measure energy fluxes over the Bay with sufficient accuracy, along with upper ocean temperature and salinity profiles.

BOBMEX was carried out during July–August 1999 with a pilot during October–November 1998. [Some initial results from the BOBMEX–Pilot experiment are published in the June 2000 (special) issue of the *Proceedings of the Indian Academy of Sciences* (*Earth and Planetary Sciences*)]. Long time series observations over the open sea was given high priority in BOBMEX as previous observations in the Bay were less than two weeks in duration and could not capture active and break monsoon conditions adequately. Indian research vessels *INS Sagar Dhwani* and *ORV Sagar Kanya* were deployed at TS1 (13°N, 87°E) and TS2 (17.5°N, 89°E) respectively (Figure 1). Measurements of all components of surface fluxes, the vertical profiles of atmospheric temperature, humidity and winds, and ocean temperature, salinity and current profiles were planned from both the ships. All the planned measurements could be accomplished only on *ORV Sagar Kanya* and upper air data could not be collected on *INS Sagar Dhwani*. Synoptic and upper air observations over the coastal and island stations belonging to the India Meteorological Department (IMD) were also documented. Observations covered active and break monsoon conditions[12].

ARMEX

After the successful execution of BOBMEX, ARMEX was carried out during 2002–2003 with some measurements completed in 2005. ARMEX was executed in two phases addressing different issues related to the atmosphere and ocean. It is observed from Figure 5 that SST rapidly increases during March–April, and then remains above 30°C (i.e. well above the convection threshold value of 28°C for the Indian Ocean[43]) for over a period of more than a month but organized convection rarely develops. In fact, a mini-warm pool builds up in the south eastern Arabian Sea and there have been theories about its evolution, maintenance (see the paper by Vinayachandran *et al.*[52], this issue), and its importance to the Indian monsoon rainfall. One of the objectives of ARMEX was to understand the mini-warm pool dynamics and test the hypotheses. The monsoon onset processes over Kerala and dramatic collapse of SST during the monsoon onset was another important issue. This part of ARMEX involving the study of the evolution, maintenance and the collapse of the AS mini warm pool and pre-onset and onset phases of the monsoon, formed one phase of ARMEX (phase II in chronological order and was named ARMEX-II) and was carried out during March–June 2003. Oceanographic component dominated ARMEX-II objectives and has been described in Vinayachandran *et al.*[52] (this issue).

When monsoon is active, many places along the Indian west coast receive more than 200 mm rain in 24 h[50], and such cases were designated as intense rainfall events (IREs) in ARMEX. One recent example is the Mumbai rain event of 25 July 2005 where 94 cm rainfall occurred in about 12 hours[53]. Documenting the structure of offshore vortices (whose existence was first suggested by George[54] in 1956) that produce IREs, the off shore trough and mechanism of IREs, and the monsoon rainfall of the west coast was another objective of ARMEX. The experiment to address these issues was carried out during June–August 2002 (ARMEX-I). Previous monsoon experiments over AS covered mid May to early July period, whereas ARMEX-I covered monsoon onset (mid June) to late August period with emphasis on IREs, and the revival and maintenance of monsoon on the west coast after the monsoon onset phase is over. The scientific background, experimental design and field phase of ARMEX-I along with some preliminary results can be found in the special issue of *Mausam* brought out on ARMEX[13].

The focus in ARMEX was the region within 250 km from the west coast of India. Land-based observations were enhanced by installing 10 automatic weather stations along the west coast, and ships were deployed for monitoring conditions over the AS. Surface and upper meteorological observatories belonging to IMD, Defense establishments and other agricultural and research organizations falling within the ARMEX study area were operated and data made available. The Indian Navy deployed two ships and DOD provided *ORV Sagar Kanya*.

What is new?

The questions 'Did the experiments lead to new findings?', naturally arise at the end of each experiment. BOBMEX and ARMEX did provide data to study and understand certain physical processes and test some hypotheses. For example, it was known that when organized convection occurs, boundary layer cools and convective instability of the atmosphere (which drives the formation of clouds in tropics) is destroyed. However, how long it would take for the atmosphere to recover its instability to support another active spell of rains over the Bay was not known. BOBMEX observations revealed that the recovery time is about two days[12,55]. The changes in the vertical temperature structure of the atmosphere between the active and weak convective conditions could be clearly seen with the BOBMEX upper air data[12,56]. The largest variation in the vertical between active and weak convective conditions is observed in the relative humidity (Figure 6) and wind fields[12,56]. Another interesting observation is the differences in the dependence of the latent heat flux (LHF) on wind speed over Bay and AS. At a given wind speed, the LHF is much lower (30–40%) over the Bay as compared to that over AS and the western Pacific warm pool (Figure 7).

During BOBMEX, the differences in the upper ocean structure between northern and central Bay could be clearly established[12]. The decrease of the oceanic mixed layer in the North Bay could be captured[12,57,58]. Fresh water arrived in the last week of July at the ship location (TS2, Figure 1) during BOBMEX, and following this, the mixed layer depth (MLD)[57] decreased from around 30 m to less than 15 m (Figure 8). While salinity is responsible for mixed layer decreasing in the head Bay, it destabilizes the upper layer of the ocean over the AS (Figure 8). The intra-seasonal behaviour of SST over the Bay and AS is very different (Figure 5). The data collected during BOBMEX and ARMEX helped in addressing this issue, and the SST evolution is briefly discussed next.

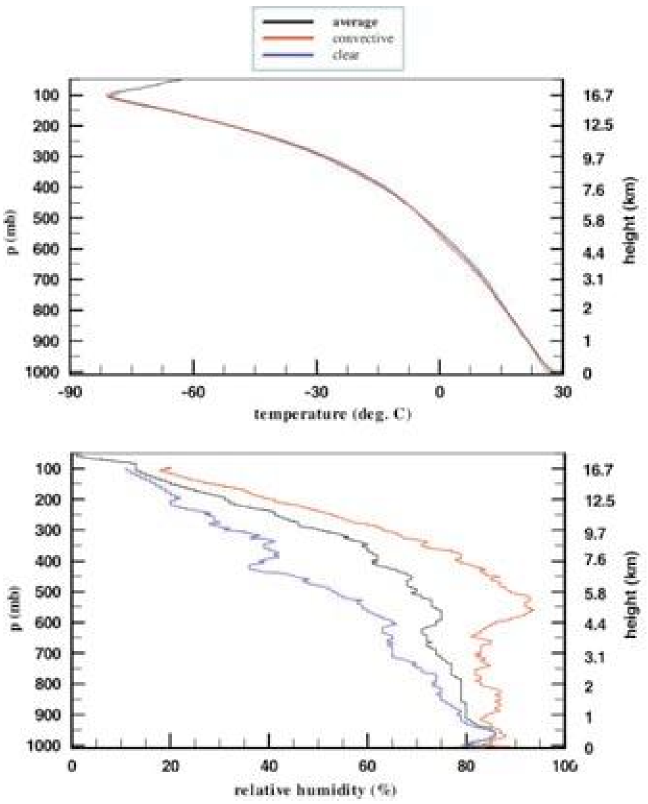

Figure 6. Vertical profiles of temperature and relative humidity measured at TS1 during BOBMEX. Convective and clear refer to average for the periods with and without organized convection.

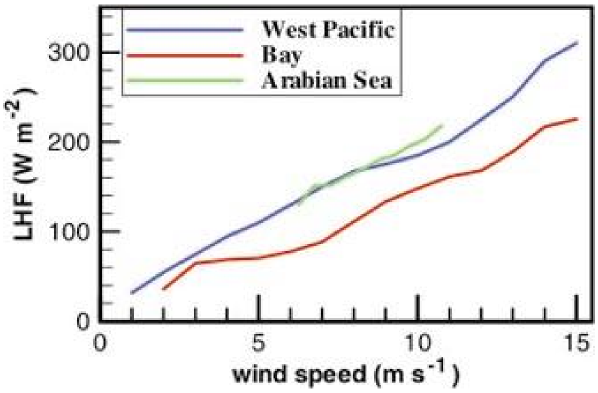

Figure 7. Variation of latent heat flux with wind speed over three warm water bodies.

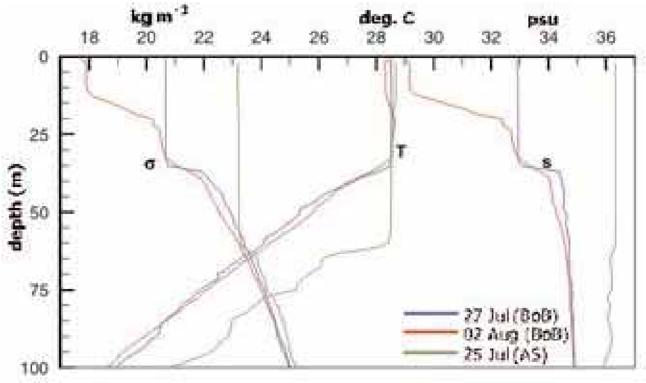

Figure 8. Vertical variation of water temperature (T), salinity (s) and water density (σ) in the head Bay of Bengal (measured during BOBMEX) and Arabian Sea (measured during ARMEX-I). The constant density layer is the mixed layer, and MLD approximately corresponds to the thickness of this layer[57].

Surface fluxes and SST evolution

The temperature is an outcome of the energy balance, and the energy balance of the mixed layer is useful in understanding SST evolution. One dimensional heat balance models have been often used to predict the evolution of the temperature of the top layer of water on short time scales[59]. Neglecting a minor contribution from the rainfall, the evolution of the temperature of the top layer of the ocean of depth h is given by[59],

$$\rho_w C_w \partial\,(hT)/\partial t = Q(t) + [\rho_w C_w\ \kappa \partial T/\partial z](h) + A_h + A_z, \qquad (1)$$

where ρ_w and C_w are the density and specific heat of water, T is the average temperature of the layer, κ is the eddy diffusivity of heat, A_h and A_z are the horizontal and vertical transport of heat by advection. The net energy flux (Q) going into the ocean at the surface is given by,

$$Q = (\mathrm{SW_d} - \mathrm{SW_u}) - (\mathrm{LW_u} - \mathrm{LW_d}) - \mathrm{SH} - \mathrm{LH}, \qquad (2)$$

$$= \mathrm{NSW} - (\mathrm{NLW} + \mathrm{SH} + \mathrm{LH}), \qquad (3)$$

where SW and LW are shortwave and longwave radiation, respectively, and subscripts d and u refer to downward and upward components of radiation, NSW and NLW refer to net shortwave and net longwave radiation respectively. SH and LH are the sensible and latent heat fluxes. When the mixed layer is shallow, part of the solar radiation escapes from its bottom (Q_{pen}) and the actual heat flux available for the mixed layer is Q–Q_{pen}. During BOBMEX, all terms in eq. (2) could be obtained from measured data except Q_{pen}, while all terms including Q_{pen} were measured during ARMEX. Here we look at the short time SST variations at the ship location driven by the surface heat flux neglecting the diffusion and advection terms. Assuming a constant value of h, the temporal evolution of T is given by,

$$T(t) = T_0 + \int_0^t (Q(t') - Q_{\text{pen}}(t')\mathrm{d}t'/(\rho_{\text{w}} C_{\text{w}} h). \qquad (4)$$

In eq. (4), T depends on three factors, namely Q, h (normally taken to be MLD) and Q_{pen}. MLD could be less than 15 m in the head Bay whereas that in the AS is more than 60 m (Figure 8). At the time of planning BOBMEX, it was thought that the large difference in MLD is primarily responsible for the rapid warming of SST in the head Bay (Figure 5). Over the head Bay, latent heat fluxes are 30–40% smaller compared to that over other warm tropical basins at a given wind speed (Figure 7). During the weak phase of convection (when ocean tends to warm), wind speed is very low over the Bay while over AS it remains high (Figure 5). Further, the atmosphere is very humid over the Bay and the net longwave radiation is around 30–35 Wm^{-2} compared to 40–50 Wm^{-2} over other oceans. The sensible heat flux is negligible in both the cases. The net result is that when all terms are added up during the weak phase of convection, the daily average value of Q is in the range of 140–180 Wm^{-2} in the head Bay, whereas over the AS, it can vary from +50 Wm^{-2} to –80 Wm^{-2} with a mean value (averaged over several days) very close to zero or slightly negative even during the weak phase of convection (Figure 9). Q_{pen} is not negligible over the head Bay, however Q is sufficiently large to provide enough heat to warm the mixed layer by more than 1°C in just four days[60] after organized convection decays. Calculations show that both the shallow mixed layer and significantly larger value of surface heat flux (compared to other warm tropical oceans) contribute almost equally to increase the SST so rapidly over the North Bay. Thus, the combination of shallow mixed layer and large net heat flux into the ocean result in the rapid increase in SST over the Bay. Therefore, in the head Bay, ocean and atmosphere cooperate to maintain high SST. The situation over the AS is just the opposite, and even during clear sky conditions, Q could be negative.

Drought of 2002

Field experiments need large lead time for planning and execution. At times, ground situation may not favour the original objectives as the weather conditions are not under experimenter's control. For example, understanding IREs was one of the main objectives during ARMEX-I. However, 2002 was a major drought year against all expectations of a normal monsoon[61,62], and the all India seasonal rainfall was about 20% below the normal. The offshore vortex did not form and IRE did not occur in the area known for propensity of IREs[50] where ARMEX-I intense observations were planned. Nevertheless, ARMEX-I data proved very valuable as July 2002 rainfall was the lowest in the recorded history and the data collected over the AS and on the west coast helped in understanding the conditions that prevailed over the eastern AS during one of the worst monsoon years. In particular, strong and persistent inversions were present in the atmosphere over the AS and west coast[63]. A sample from the radiosonde data collected during ARMEX-I is shown in Figure 10. Two inversions are seen in the AS temperature profile (around 2 km and 6 km). Such strong inversions suppress the vertical development of clouds and rain cannot occur. Specific humidity (q) is the amount of water vapour per kg of air. It is observed that q shows several minima (especially

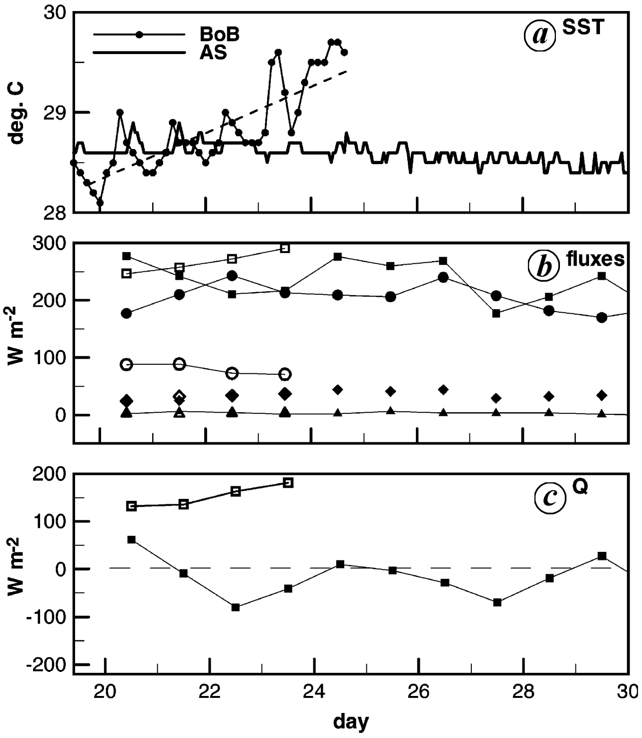

Figure 9. Variation of SST, components of surface energy flux and net heat flux into water at the air–sea interface over the Bay of Bengal and Arabian Sea during the weak phase of convection. The fluxes shown are daily average values. The period is 19–24 August 1999 for BOBMEX and 20–30 July 2002 for ARMEX. Open symbols refer to Bay in (***b***) and (***c***).

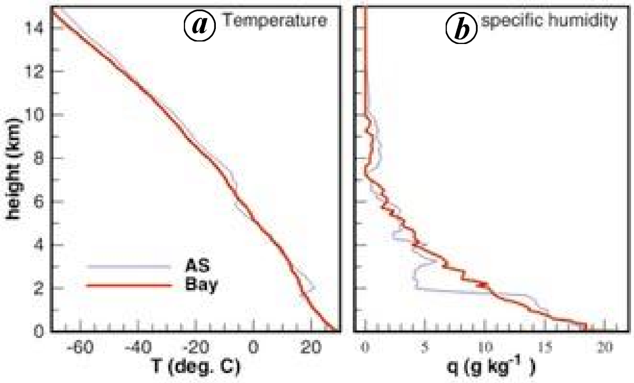

Figure 10. Vertical profiles of temperature and specific humidity. The thin line is ARMEX sounding collected on 04 July 2002 over the Arabian Sea. The thick line is 23 August 1999 profile collected during BOBMEX.

in the inversion layers), suggesting a highly stratified and laminated atmosphere where air parcels from different sources were moving in thin layers with little vertical mixing. The large-scale circulation was very different during July 2002 compared to a normal monsoon year and mid latitude air had penetrated southward of 15°N over AS during this period[63].

ARMEX-I data has been used for modelling, especially using regional models. A couple of IRE events occurred in the last week of June over Gujarat[64], i.e. slightly to the north of intense observations area during ARMEX. Numerical experiments showed that incorporating ARMEX-I observations (ship radiosonde data in particular) did have an impact in improving the simulation of systems associated with these IRE events[65].

Aerosols were not measured during BOBMEX. Following the Indian Ocean Experiment[66] (INDOEX) carried out during 1996–1999, its impact on monsoon became a highly debated topic. Measuring the aerosols and their radiative forcing was taken up as an objective of ARMEX and aerosol spectral optical depths were measured over AS as a part of ARMEX-I[67]. These are the first measurements of aerosols over northern and central AS during Indian summer monsoon season. Estimates show that sea-salt contributes about 60% to the composite aerosol optical depth[67]. The presence of aerosols over the Arabian Sea during summer monsoon season decreases the short wave radiation arriving at the surface by as much as 21 W m^{-2} and increases top of the atmosphere reflected radiation by 18 W m^{-2}. Thus, the atmosphere absorbs 3 W m^{-2}. ARMEX data also helped in quantifying the direct and indirect effects of aerosols and it was found that the magnitude of indirect effect is several-fold larger than the direct effect of sea-salt aerosols[68].

Concluding remarks and future outlook

Monsoon experiments have contributed to monsoon studies in several ways. Each experiment enhanced the infrastructure facilities in the country, brought together scientists from different organizations in the country to a common platform and also attracted new people to this field. A large amount of data have been generated and their analysis has led to new understanding and discovery of new phenomena. However, we believe that these data have a lot more potential, and there is scope for further studies using numerical models and modern data analysis techniques.

A monsoon experiment with even modest objectives requires enormous resources, and several burning issues cannot be addressed owing to the lack of required facilities or man power. For example, monsoon rain comes from clouds, but study of clouds (microphysics and dynamics) could not be taken up in Indian monsoon experiments as India does not have an instrumented aircraft needed for this purpose. Similarly, upper air data could be collected only from *ORV Sagar Kanya* as other ships did not have the radiosonde facility. One important physical process in the tropics is the interaction between organized convection and the large scale atmospheric circulation. To calculate their interaction, at least three simultaneous radiosonde profiles with temperature, humidity and wind measurements are needed over the open ocean. This means simultaneous deployment of three ships. Hopefully research aircraft and additional ships will not be a constraint in future programmes.

The next programme proposed under ICRP is the Continental Trough Convergence Zone (CTCZ) experiment. This envisages monsoon as a physical system involving interactions between land, atmosphere and ocean. Often weather does not behave the way we want it to study a given phenomenon in one year, but over a period of a few years the chances are much better. Hence, CTCZ is a multi-year programme. It is planned to be held during 2008–2010.

Weather knows no national and political barriers and monsoon is a planetary scale phenomenon. Monsoon trough over the Indian sub-continent is a part of the planetary scale system stretching eastward from the Indian longitudes to the central Pacific. The cloud systems that give rain over India are linked to Tibetan high, east China monsoon, South China Sea and Pacific Ocean. A major international monsoon research programme named MAHASRI (Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative) led by Japan is being planned by some Asian countries during 2008–2010. Another programme, the Asian Monsoon Year (AMY), which aims to study the Asian monsoon system on different spatial and timescales with coordinated simultaneous measurements in many Asian countries, is being observed during 2008–09. Clearly, a co-ordination of the CTCZ programme with AMY and MAHASRI would help in collecting observations in critical regions of Asian monsoon spread across nations. Now the time is ripe for India to collaborate with neighbouring and other countries in monsoon research with her own well-defined programmes. CTCZ could be the Indian contribution to MAHASRI and AMY.

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