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THE BAY OF BENGAL MONSOON EXPERIMENT : BOBMEX

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Despite its economic and scientific importance, *in situ* observations providing accurate data for studying the properties of the atmosphere, ocean and their coupling has been lacking over the Bay of Bengal during the monsoon period. Detailed observations of the atmosphere and ocean were carried out in the Bay of Bengal during the peak monsoon months of July-August in 1999 under the Indian Climate Research Programme. This paper describes the motivation, objectives and field phase of this experiment along with some initial results. High resolution radiosondes, launched for the first time in the North Bay, provided the differences in the atmospheric characteristics between active and weak phases of monsoon. A strong diurnal dependence of convection is observed. Also, a major difference is noted in the near surface characteristics between the North Bay and other tropical oceans, the West Pacific in particular. The sea air temperature and specific humidity differences are significantly smaller in the North Bay compared to that observed over the tropical West Pacific.

Key Words: Monsoon; Tropical Convection; Air-Sea Coupling; Planetary Boundary Layer

1 Introduction

The Bay of Bengal (hereafter referred to as the Bay) is a fertile breeding ground for several monsoon systems that produce rainfall over the Indian subcontinent. The Bay has certain features that combine to make it unique. For example, the sea surface temperature (SST) over the Bay during the boreal summer is among the warmest over the tropical oceans, and the frequency of occurrence of deep convective systems is also one of the highest. Further, the head Bay receives a large quantity of fresh water through river discharge in addition to local precipitation, resulting in very low values of surface salinity which is not the case in the southern parts of the Bay. The freshwater layer makes the top layer of the water column very stable for vertical mixing. This essentially limits the wind driven mixing (stirring) of the upper layer of the ocean to a very shallow layer at the top even at strong monsoon winds, and prevents the SST from getting colder by mixing with the water from below. Thus, we can expect the response of the ocean to a given wind forcing to be different in the northern and southern Bays.

Several observational studies have been carried out over the seas around India in the past. The International Indian Ocean Expedition (IIOE carried out in mid 1960s), the Indian Summer Monsoon Experiment (ISMEX, carried out in 1973), MONSOON-77 (carried out in 1977), Monsoon Experiment (MONEX, carried out in 1979) and the Monsoon Trough Boundary Layer Experiment (MONTBLEX, carried out in 1990) are some important studies during the monsoon period. Except for MONTBLEX, the experiments mentioned above were carried out with international collaboration with the initiative also coming from out side. These studies were generally biased towards the Arabian Sea (again MONTBLEX is an exception) and the Bay has not received the attention that it merits. Prior to 1998, mainly three observational studies have been carried out over the Bay. The first major experiment, namely MONSOON-77, involved four USSR ships forming a polygon over the Bay centred at 17° N 89°E during 11-19 August 1977. A trough formed over the head Bay on August 16 which developed into a depression on August 19. The MONSOON-77 experiment provided data that enabled the study of the changes in the horizontal wind fields, vertical velocity and large scale heat and moisture budgets between disturbed and undisturbed conditions over the Bay. It has been found that during the disturbed period, maximum upward motion occurred in the evenings,

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and that the peak in the apparent heat source was located between 500 mb and 450 mb[1]. During MONEX-79[2], four Russian ships formed a stationary polygon (11-24 July 1979) centered at 16.2°N 89.5°E in the North Bay[2]. However, this period happened to be break/weak monsoon period over the region, and therefore, disturbed conditions could not be documented. In addition to the ships, an aircraft equipped with dropwind sondes was used for the study of a monsoon depression during August 1979 as part of MONEX-79. This data showed large horizontal temperature gradients at 850 mb and 700 mb in the southward sector of the depression, and also across the equatorial trough in the latitudinal belt 10°N to 15°N during the break monsoon situation[3]. It was not known whether there was an associated gradient in SST. MONEX-79 brought out the large scale flow features of the Indian Summer Monsoon[4]. Apart from these two major international experiments, observations using a single ship were made from 18 to 31 August and 9 to 19 September during the Monsoon Trough Boundary Layer Experiment in 1990 (MONTBLEX-90)[5]. This experiment enabled the study of the response of the ocean to a monsoon depression and changing characteristics of water in the North Bay as the monsoon progressed[6].

Past experiments over the Bay had certain limitations. The time series from these experiments were either too short (less than 2 weeks, e.g., MONSOON-77 and MONEX-79) or the observations were of limited nature and important variables such as radiation not measured (e.g., MONTBLEX-90). Monsoon exhibits a strong variation on intraseasonal timescales of 2-4 weeks characterized by active and weak spells. Active spells are characterized by a high frequency of genesis of synoptic scale systems over the Bay and are accompanied by wide spread (and often heavy) precipitation over a large area in the region. During the weak spells or breaks, suppressed convective conditions prevail in the region. However, the precise nature of the ocean-atmosphere coupling on intra-seasonal timescales has not been understood over the Bay owing to lack of accurate observations. Further, the soundings had typical vertical resolution of 50 mb, which is not sufficient to study the structure of the marine boundary layer or to calculate parameters such as CAPE (Convective Available Potential Energy) and CINE (Convection Inhibition Energy). It has been shown by model studies that interaction between convection and the boundary layer processes can lead to intraseasonal variability of convection[7,8]. This signature in the Bay needs to be explored. Similarly an outstanding question related to air-sea interaction over the Bay is the role of the ocean in determining variability of the atmosphere, particularly of organized convective systems, on intraseasonal scales. Further, a key parameter in deep convection over the tropical oceans is CAPE. It is known that CAPE is high before the onset of deep convection[9] . When disturbances occur, precipitation, winds and downdrafts decrease the energy of the near surface air. while deep cloud activity makes the upper troposphere warmer. As a result, atmosphere becomes stable and CAPE is substantially reduced during disturbances[9]. When disturbances attenuate or move away, the sensible and latent heat fluxes from the ocean increase the energy of the surface air, radiative cooling and large-scale circulation remove the warmer air aloft, thus destabilize the atmosphere and build up CAPE. Hence the period between successive disturbances is expected to depend upon the time it takes for CAPE to build up. How the instability builds up, the changes that take place with the growth/arrival of monsoon disturbances, how much instability is consumed and the manner in which it rapidly recovers after the disturbance, are some of the basic issues that need to be clearly established and understood for the Bay.

This paper briefly describes the plan and objectives of a field campaign, called the Bay of Bengal Monsoon Experiment (BOBMEX), an inter-agency national program and entirely an Indian effort, carried out in the Bay during July-August 1999 and some initial results. For the first time, scientists from major national scientific organizations and educational institutes involved in atmospheric and oceanic research came together to carry out a very successful national experiment. About 80 scientists from 15 different institutions in India collaborated during BOBMEX to make observations in most hostile conditions of the raging monsoon. The organizations involved in BOBMEX included Indian Institute of Science, Bangalore; National Institute of Oceanography,

Goa; Naval Physical and Oceanographic Laboratory, Kochi; India Meteorological Department, New Delhi; Space Application Centre, Ahmedabad; National Institute of Ocean Technology, Chennai; National Centre for Antarctica and Ocean Research, Goa; Space Physics Laboratory, Trivandrum; Andhra University, Visakhapatnam; Cochin University, Cochin; National Centre for Medium Range Weather Forecasting, New Delhi; Indian Institute of Tropical Meteorology, Pune and Indian Institute of Technology, New Delhi.

The results presented here are of very limited nature and are mainly based on the atmospheric data collected by the author's group in the North Bay. Section 2 describes the objectives, Section 3 results, Section 4 discussion and Section 5 concludes the paper.

2 BOBMEX Objectives and Field Phase

Because of its economic and scientific importance, a field experiment aimed at accurate observations of the ocean and the atmosphere during a summer monsoon season was required in the Bay. Hence, BOBMEX, the first field program under the Indian Climate Research Programme (ICRP) was planned in the Bay. BOBMEX had the following main objectives.

i) The vertical stability of the atmosphere during different phases of convection

ii) Variability of upper ocean currents in relation to changing wind and thermohaline forcing

iii) The surface fluxes and atmospheric and oceanic boundary layer characteristics during different phases of convection.

iv) Air-sea coupling on synoptic and intraseasonal timescales.

The data from recently deployed met-ocean buoys in the Bay showed that the variation in SST of 1°C to 2°C on intra-seasonal time scales (20-40 days) is much larger than the inter annual variation of 0.5°C[11]. These intra-seasonal variations in turn influence the seasonal and interannual variations. Therefore, it is important to understand the atmosphere, ocean and their coupling covering at least one complete intra-seasonal cycle. Hence it was decided to aim for time-series observations for about six weeks. Two locations - one each in the southern and northern Bay were chosen for the time-series observations (henceforth referred to as TS1and TS2 respectively, see Fig.1). The choice of these two locations was based on the following consideration. The occurrence of organized convection is high at both the locations. During the northward propagation of the tropical convergence zone, the systems tend to move across the Bay from south to the north[12]. Hence, it is important to document the gradients in atmospheric variables and SST between these two regions. Also, there are marked differences in the freshwater fluxes at these two locations and hence in the thermohaline structure of the upper layers of the ocean. The differences, if any, in response of the ocean to convection at these locations could provide further insight into coupling.

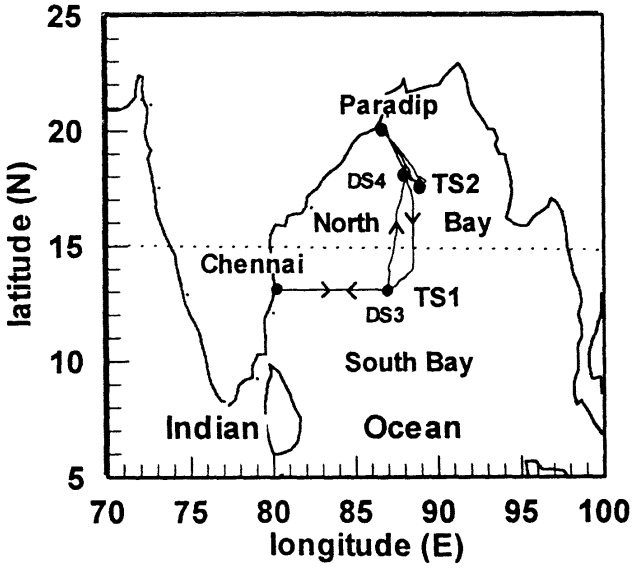

Fig.1 Cruise tracks, time series observation stations (TS1 & TS2) and met-ocean buoys locations (DS3 and DS4) in the Bay of Bengal during BOBMEX. Observation positions : TS1 – 13°N & 87°E; TS2 – 17.5°N & 89°E; DS3 – 13°N & 87°E; DS4 – 18°N & 88°E. INS Sagardhwani was stationed at TS1 and *ORV Sagar Kanya* occupied TS2. Apart from time series observations at TS1 and TS2, data along the ship tracks were also collected

The BOBMEX field experiment was carried out during the period 16 July to 30 August 1999 on board two research ships. The first station TS1 at 13°N & 87°E was taken by *INS Sagardhwani*, belonging to NPOL (Naval Physical and Oceanographic Laboratory, DRDO, Cochin). The second station TS2 at 17.5°N & 89°E was occupied by *ORV Sagar Kanya*, belongs to the Department of Ocean Development (DOD) and managed by the National Centre for Antarctica and Ocean Research (NCAOR), Goa. In addition, two met-ocean buoys

located at 13°N & 87°E and 18°N & 88°E were specially equipped for BOBMEX by NIOT (National Institute of Ocean Technology, Chennai) to provide surface meteorological and oceanographic data for the BOBMEX period at regular 3 hour intervals. The ship cruise tracks and buoy positions are shown in Fig.1.

On board *ORV Sagar Kanya*, micro-meteorological sensors were mounted on a tower fixed to a horizontal 7 m long boom, at a height of 11.5 m from the sea surface at the bow of the ship. The sensors on the tower included sonic and Gill anemometers, IR hygrometer (measures water vapour concentration), temperature and relative humidity instruments, long-wave and short-wave radiation instruments, accelerometers and tilt sensors (to measure the velocity induced by ship's rolling and pitching motions). A GPS based Vaisala radiosonde receiver system was specially procured for BOBMEX and was installed on *ORV Sagar Kanya*. This provided information on the vertical thermal structure of the atmosphere and upper winds at vertical resolutions between 25-40 meters up to heights exceeding 16 km. Oceanographic measurements included ocean currents (using Acoustic Doppler Current Profiler, ADCP and lowered ADCP) up to a depth of 1000 m, CTD (conductivity, temperature and depth probe) that sampled water column temperature and salinity upto 1000 m depth. These were supplemented by manual observations at synoptic hours. Measurements of certain chemical species were also made. Important measurements on board *INS Sagardhwani* included surface meteorological parameters (manually collected and automatically measured by sensors mounted on a tower fixed to a boom), ocean currents and CTD up to 500 m depth. Buoys provided data on surface wind speed and wind direction, air temperature, pressure, SST and sea surface salinity and currents every 3 hours. These observations are supplemented by satellite data, enhanced observations by India Meteorological Department at island/coastal stations in/near the Bay and reanalysis data from numerical models.

One of the emphasis from the very planning stage of BOBMEX was on obtaining high quality data. The selection of the sensors/instruments for the surface observations, wherever possible, was made considering the latest international trends. Sensors were calibrated before and after the field phase. Further, two inter-comparison experiments were carried out at TS1 location for about 12 hours duration at the start and end of the BOBMEX field phase to assess the relative accuracies of the data collected on two ships and the buoy DS3. The inter-comparison results showed good agreements for wind speed, SST, shortwave and longwave radiation, and mainly air temperature data showed differences exceeding the instrument accuracies[13].

3 Results

Monsoon was active during the BOBMEX period. A depression developed over the head Bay on 27 July 1999 and moved over land. Three more monsoon systems were observed over the Bay and North Indian region during the BOBMEX period, namely, a low during 2-4 August, a depression during 6-8 August and again a low during 24 August - 4 September. Another deep convective system, that produced about 200 mm rain at TS2 developed on 15-16 August in the North Bay. However, this system did not intensify further and decayed.

Preliminary analysis of the data collected during BOBMEX and results of two inter-comparison experiments carried out at TS1 indicate that BOBMEX data set is of high quality and suitable for scientific investigations. The initial results shown next are mainly based on the meteorological data collected on board *ORV Sagar Kanya* at TS2.

3.1 Surface Conditions

Fig. 2 shows the surface meteorological variables at TS2. Surface pressure and SST measured by the met-ocean buoy DS4 for the corresponding period in 1998 are also shown. (The discontinuity in data during 6-13 August 1999 corresponds to a port call at Paradip for supplies.) The average surface pressure was 999 mb during the first leg (July 27-August 6) compared to 1006 mb during the second leg (13-24 August). The surface pressure variations during the second half of August were somewhat similar during 1998 and 1999, whereas, SSTs were different with average SST during BOBMEX about 1°C lower compared to what prevailed during the corresponding period in 1998. Now, compared to SST, air temperature exhibited larger fluctuations with its values varying in 25°C to 29°C range. Large decreases in air temperature

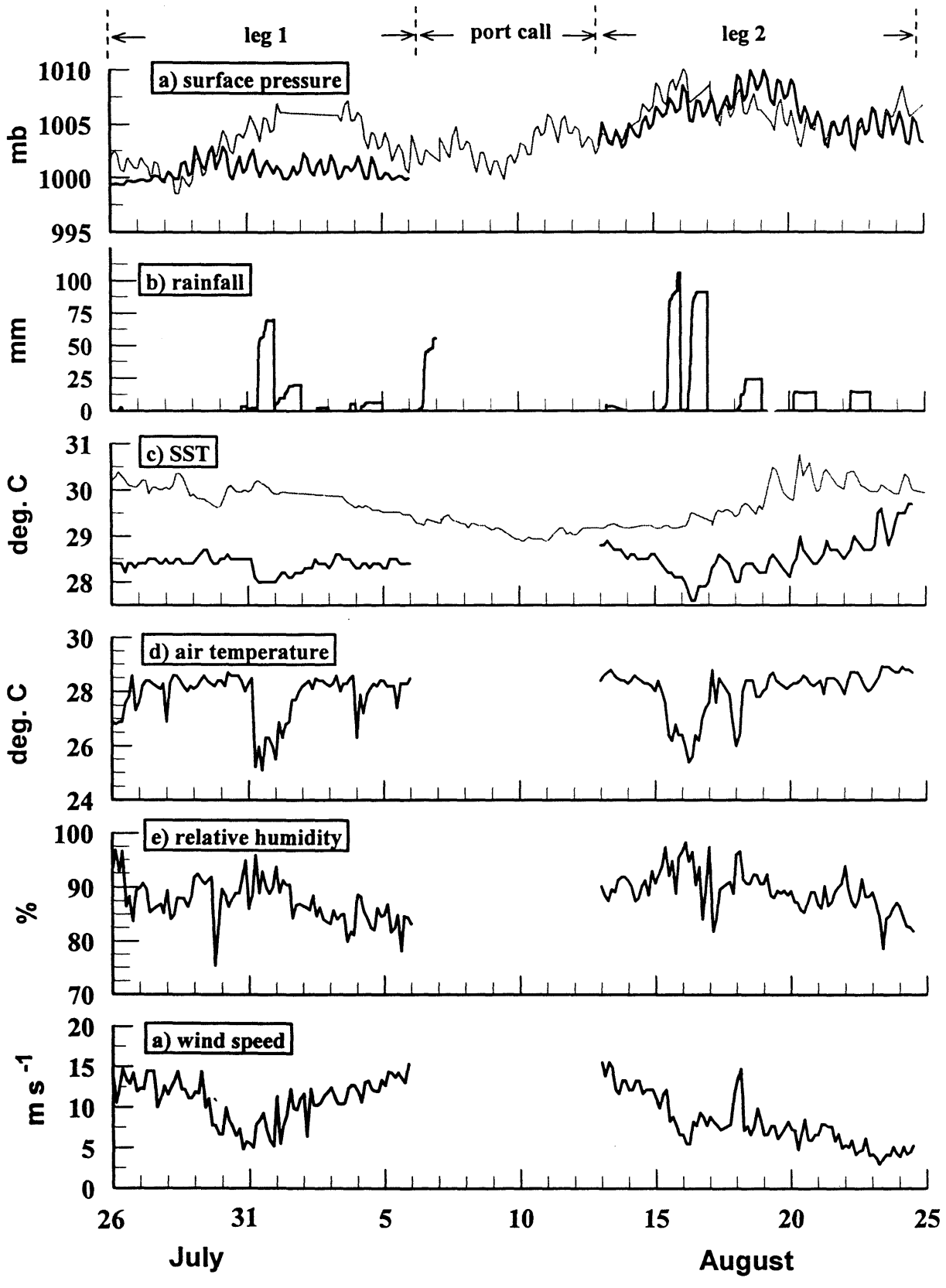

Fig. 2 Near surface variables measured at TS2 station. Also shown are surface pressure and SST measured by the met ocean buoy DS4 for the corresponding period in 1998 (light continuous lines)

were associated with precipitation. Very often, air temperature decreased by more than 3°C during heavy rains and recovered within 12-24 hrs after rains subsided. When it was not raining, SST and air temperature were very close to each other, with their differences often less than 0.5°C. Relative humidity was high, with its values typically varying in 80% to 95% range. Wind speed varied from less than 3 m/s to 15 m/s with short term gust winds exceeding 18 m/s.

3.2 Vertical Sections

About 100 radiosondes were launched from *ORV Sagar Kanya* with a frequency between 2 and 5 per day depending on the weather advice. In the tropical atmosphere, temperature is nearly steady and the difference between convectively active and weak atmospheres is typically less than 2°C at upper levels. This was observed during BOBMEX also. On the other hand, humidity and wind fields can exhibit larger fluctuations. Therefore, here we consider the time-height variation of relative humidity and winds during BOBMEX. Fig. 3 shows the time-height variation of relative humidity at TS2 station. It is observed from Fig. 3 that the relative humidity was generally high throughout the troposphere during the first leg as compared to that during the second leg. During 20-24 August period (weak phase of convection), low humidity regime gradually moved down from around 350 mb level (~9 km) to 600 mb (~4 km), and the mid troposphere gradually dried up.

Upper winds are available for the second leg of BOBMEX only. Fig. 4 shows the vertical variation of wind from 13 to 30 August. When a convective system was present nearby (e.g., 13-16 August and 25-28 August), wind speed increased around 900 mb level (~1 km above the surface) and in the upper troposphere near 200 mb level (Fig. 4a). During the weak convective period (20-24 August), maximum winds were in 25-30 m/s range, whereas, winds in 35-44 m/s range prevailed during convectively active periods. Normally low winds prevailed around 500 mb level on all occasions. It is also seen from Fig. 4a that during weak convective conditions, low wind speed (<10m/s) prevailed from surface to 350mb level. Fig. 4b shows the wind direction. At low levels, southwesterly winds prevailed, exception being the period around August 26 when it became southerly. At upper levels (~200 mb), easterly winds are always present. During active period, south westerly winds penetrated beyond 300 mb height, whereas, as the weak convective conditions continued, easterly winds gradually migrated down to 600 mb level. In general, the change from south westerly to easterly wind direction took place abruptly, that is, the transition is sharp.

3.3 Diurnal Variation

Studies based on satellite data have shown strong diurnal dependence of cloudiness over the Bay. Over the Bay and Arabian sea, convection is found to be more active around noon and late

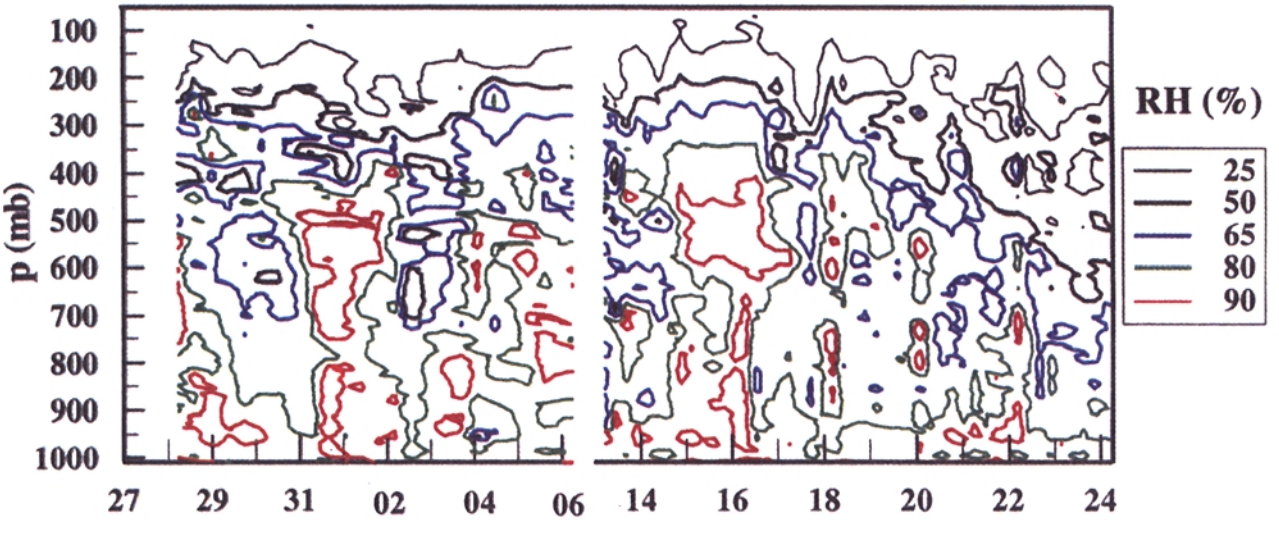

Fig. 3 Time-height section of the relative humidity (RH) at TS2

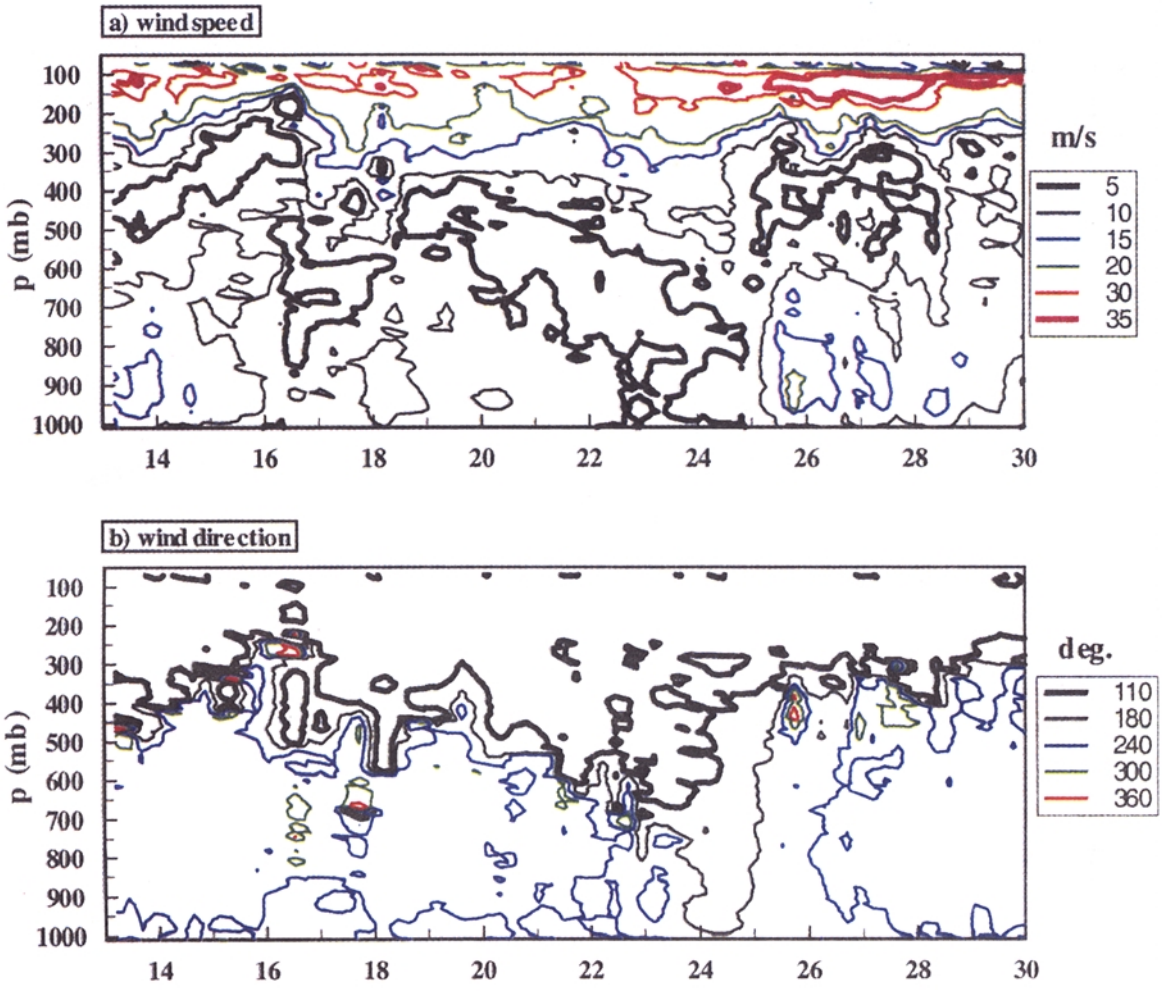

Fig. 4 Time-height section of (a) wind speed and (b) wind direction. Ship moved away from TS2 on 24 August. During 24-27 August, ship moved from TS2 to TS1 and provided a North-South section of the atmosphere along the cruise track. During 28-30 August period, ship moved from TS1 to Chennai

afternoon hrs (1200 to 1800 LST), while early morning peaks are more frequent over the tropical South Indian Ocean[14]. BOBMEX provided *in situ* data to examine the diurnal nature of precipitation over the Bay. Fig. 5 shows the daily cumulative rainfalls measured at TS1 and TS2 starting from local midnight. Clear preference for morning to noon hours is seen in Fig. 5, in particular, when the daily rainfall exceeded 20 mm. A salient feature of Fig. 5 is the near absence of precipitation during 2000-0400 LST even when the area was convectively active. For example, on 15 August, it started raining around noon, followed by a lull in activity between 2200-0700 LST, and then picked up again in the morning on 16 August. At TS1, rainfall is observed to be preferred during 0900-1400 LST. Thus, there is a strong diurnal pattern to precipitation over the Bay.

4 Discussion

The surface pressure and wind speed shown in Fig. 2, and the vertical sections shown in Figs. 3 and 4 suggest the presence of an intra-seasonal oscillation (ISO). The surface pressure was about 7 mb lower during leg 1 (mean 999 mb) compared to that during leg 2 (mean 1006 mb). The periods 26 July to 9 August and 9-24 August can be considered to belong to the active and weak phases of ISO respectively. During the period 26 July to 9 August, India Meteorological Department declared 3 monsoon systems in the region, while no monsoon system formed over the Bay during leg 2. During the weak phase of ISO, winds throughout the troposphere weaken and the mid troposphere became relatively dry. During the active phase of ISO, winds are stronger and the mid troposphere is more moist.

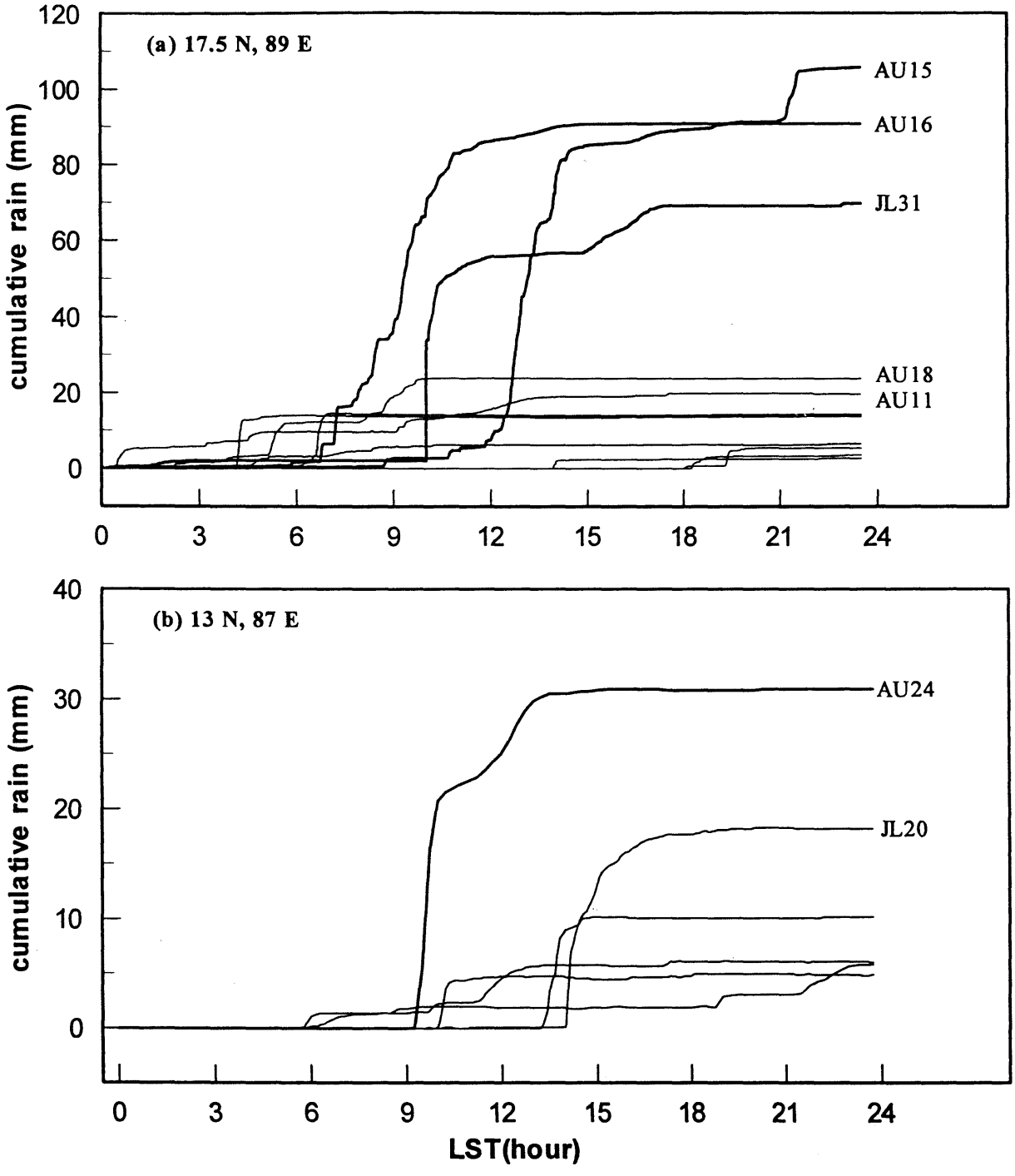

Fig. 5 Diurnal variation of the precipitation at (a) TS2, and (b) TS1. Days with more than 15 mm rainfall are identified

One question that naturally arises is how different is Bay compared to other tropical oceans. This aspect is being explored at present and here the author presents one specific example to show that conditions over the Bay are different from that over other warm tropical oceans. Let us consider the similarities and differences between the North Bay and the tropical West Pacific. In the tropical West Pacific Ocean, SSTs are very warm, it supports a high frequency of convection like the Bay and accurate surface data are available. The Tropical Ocean Global Atmosphere – Coupled Ocean Atmosphere Response Experiment (TOGA-COARE)[15] carried out over the West Pacific Ocean

during 1992-1993 has provided extensive data on the coupled ocean-atmosphere system over the West Pacific[16,17]. The measurements in the North Bay at TS2 covered a time period of about a month compared to the four months duration of TOGA-COARE (1 November 1992 to 28 February 1993). Therefore, the range of synoptic conditions that could be covered over the Bay is limited. Nevertheless, BOBMEX, carried out during the peak monsoon months of July-August captured both the active and weak phases of convection and enables us to explore if there are any special features of the atmosphere over the North Bay during the peak monsoon months.

The average SST at TS2 was around 28.5°C, 0.5° to 1°C lower compared to the SSTs that prevailed during TOGA-COARE[16]. There is observational evidence that the average SST over the Bay can also be higher than that observed during BOBMEX during the monsoon period. For example, the buoy data indicates that SST was warmer by about a degree Celsius during July-August 1998 compared to that during the BOBMEX period in the North Bay (Fig. 2). Therefore, the lower value of average SST observed at TS2 during BOBMEX could be associated with the inter-annual variations of the ocean-atmosphere system in the North Bay. The air temperatures at TS2 and TOGA-COARE are comparable (typically 28°-29°C range). The relative humidity varied from 70% to more than 95% at TS2, and this range is comparable to that observed during TOGA-COARE. The average specific humidity was 20-21 g kg^{-1} at TS2 compared to 18-20 g kg^{-1} range observed over the West Pacific[16]. Thus, despite a lower SST, the water vapour content in the air was very high at TS2.

The major difference between the North Bay and tropical West Pacific (and perhaps other tropical oceans as well) is observed in the sea air temperature and specific humidity differences. The average values of ΔT (SST-T_a, where T_a is the air temperature at 10 m height above the sea surface) are in 0.2°C to 0.5°C at TS2 during non-raining periods (Fig. 6a). These values are significantly lower than the values of around 1.5°C observed during TOGA-COARE[16] and 1°-2°C over open tropical oceans in general[18]. The differences in ΔT between North Bay and other tropical oceans are well above the measurement uncertainties. The average values of Δq ($=q_s-q_a$, q_s being the saturation specific humidity at SST corrected for water salinity and q_a is specific humidity of the air at 10 m height above the sea surface) were about 4 g kg^{-1}. This quantity is again much smaller compared to 6-7 g kg^{-1} range observed during TOGA-COARE[16].

5 Conclusions

BOBMEX brought together different research organizations and educational institutes in India engaged in atmospheric and oceanic research, and demonstrated that the community can work together as a team. With the successful implementation of BOBMEX, a beginning has been made in India in conducting special observational experiments over

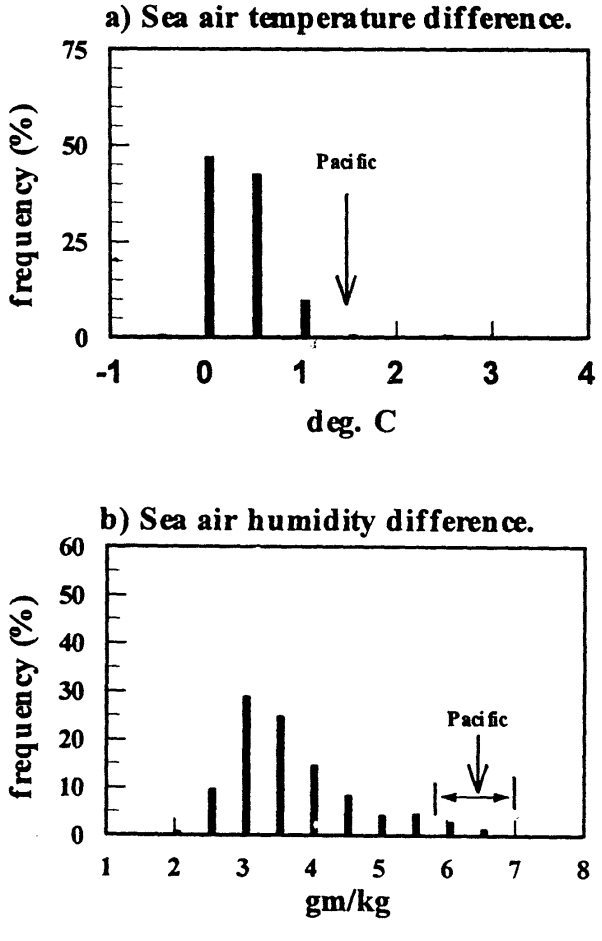

Fig. 6 Histogram of sea-air temperature (ΔT) and specific humidity difference (Δq) at TS2 excluding days with significant rainfall. Mean values observed over the tropical West Pacific Ocean during TOGA-COARE are indicated.

the seas around India. Such programmes are expected play a critical role in understanding the variability of the Indian monsoon.

Preliminary analysis of the data show that the Bay has some special features. Except during rains, the average sea-air temperature difference was less than 0.5°C, much smaller than the typical range of 1°C to 2°C observed over other tropical oceans. Similarly, the sea air specific humidity differences were also much smaller compared to that normally found over the tropical oceans. The relative humidity increased at all heights upto 300 mb during convection and gradually decreased as the weak convective conditions continued. Precipitation showed a strong diurnal dependence with the period between 2100 LST and early morning hours as the least preferred time.

The results shown here cover only a small portion of the data collected during BOBMEX. With several groups analysing the atmospheric and oceanographic data collected during BOBMEX, more exciting results are expected in the next couple of years.

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