

Vertical thermal structure of the atmosphere during active and weak phases of convection over the north Bay of Bengal: Observation and model results

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Owing to the lack of atmospheric vertical profile data with sufficient accuracy and vertical resolution, the response of the deep atmosphere to passage of monsoon systems over the Bay of Bengal had not been satisfactorily elucidated. Under the Indian Climate Research Programme, a special observational programme called 'Bay of Bengal Monsoon Experiment' (BOBMEX), was conducted during July–August 1999. The present study is based on the high-resolution radiosondes launched during BOBMEX in the north Bay. Clear changes in the vertical thermal structure of the atmosphere between active and weak phases of convection have been observed. The atmosphere cooled below 6 km height and became warmer between 6 and 13 km height. The warmest layer was located between 8 and 10 km height, and the coldest layer was found just below 5 km height. The largest fluctuations in the humidity field occurred in the mid-troposphere. The observed changes between active and weak phases of convection are compared with the results from an atmospheric general circulation model, which is similar to that used at the National Centre for Medium Range Weather Forecasting, New Delhi. The model is not able to capture realistically some important features of the temperature and humidity profiles in the lower troposphere and in the boundary layer during the active and weak spells.

THE rainfall is not uniform throughout the Indian summer monsoon season (June–September period). There are spells of rainfall over a large area (referred to as active phase of monsoon) during which extensive, deep convective clouds occur (active phase of convection), separated by periods of little or no rainfall (weak phase of monsoon or break monsoon) during which extensive, deep convective clouds are absent (weak phase of convection). Associated with the active phase of the monsoon, many places along the Indian coast and over land in the main monsoon belt receive very heavy rainfall, often exceed-

ing 10 cm day^{-1} . Rain is an outcome of several processes in the atmosphere, and the most important one is the condensation of water vapour in cumulonimbus clouds (i.e. deep convective clouds), and the phenomenon is known as deep convection. Condensation is an exothermic process, and the latent heat released corresponding to 10 cm rainfall is sufficient to increase the temperature of a column of air between the surface and 16 km height by more than 25°C . However, such large temperature increases are never observed in the atmosphere, because, most of the heat released during condensation is utilized in overcoming the adiabatic cooling of the air ascending in clouds, and only a small fraction actually goes towards increasing the air temperature at any given height. These temperature changes, though small, maintain the large-scale circulation of the tropical atmosphere, and the manner in which the large-scale atmospheric circulation responds depends on the vertical distribution of temperature change following deep convection¹. The vertical distribution of heating and temperature change, including the level of maximum heating are observed to be different in different regions². Therefore, details pertaining to the response of the atmosphere to convection need to be established from observations for each region.

Most of the rainfall over the Indian region during the monsoon season occurs in association with convective systems over the Bay of Bengal, which propagate or extend onto the subcontinent. Therefore, what happens over the Bay is very important for understanding the Indian monsoon. However, owing to lack of atmospheric vertical profile data with sufficient accuracy and vertical resolution, we are yet to satisfactorily address the problem of response of the atmosphere to passage of monsoon systems over the Bay. There have been two major field campaigns over the Bay prior to 1999 that involved detailed atmospheric observations during the monsoon period. The first experiment, namely monsoon experiment carried out in the year 1977 (known as MONSOON-77), involved four USSR ships forming a polygon over the Bay centred around 17°N and 89°E during 11–19 August

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1977. During the second experiment, namely the monsoon experiment (referred to as MONEX-79), four Russian ships formed a stationary polygon during 11–24 July 1979 centred around 16.2°N and 89.5°E in the north Bay³. The analysis of data from these experiments has shown that during the convective period, maximum upward motion occurred in the evenings, and that the peak heating was located between 500 and 450 mb⁴.

One of the main limitations of earlier experiments is that the observation period over the Bay was less than two weeks, and the active and weak phases of monsoon could not be adequately captured. Further, these experiments were carried out more than 20 years ago. There has been significant progress in ocean–atmosphere observation techniques and numerical modelling of the atmosphere during the past 20 years. A detailed field experiment that takes advantage of the recent developments in atmospheric and oceanic observations was required over the Bay, in order to address some of the outstanding issues concerning the formation of monsoon systems as well as maintenance of high frequency of deep convection over the Bay. Under the Indian Climate Research Programme, a special observational programme called ‘Bay of Bengal Monsoon Experiment’ (BOBMEX), was conducted during July–August 1999. BOBMEX was a national experiment and involved the participation of about 80 scientists from 15 different institutions in India. The major objectives and design of BOBMEX are given in Bhat *et al.*⁵. The emphasis in BOBMEX was on time series observations at fixed locations in the northern and southern Bay, so as to capture a complete cycle of active and weak phases of monsoon. The BOBMEX field experiment was carried out during 16 July to 30 August 1999 on-board two research ships. Figure 1 shows the cruise tracks and time series (TS) observation positions

during BOBMEX. The time series position TS1 (13°N, 87°E) was occupied by INS *Sagaradhwani* belonging to the Naval Physical and Oceanographic Laboratory, DRDO, Kochi. At the second position TS2 (17.5°N, 89°E), ORV *Sagar Kanya* belonging to the Department of Ocean Development, Government of India and managed by the National Centre for Antarctic and Ocean Research, Goa was deployed.

The present paper describes the observed changes in the vertical structure of the atmosphere between active and weak phases of convection at TS2 in the north Bay (Figure 1). The corresponding behaviour simulated in an atmospheric general circulation model (GCM) is also presented. We briefly describe the field data and the GCM used, followed by results from the field phase, and the model performance.

Data and the numerical model

The field results presented here are mainly based on the radiosonde data collected on-board ORV *Sagar Kanya* in the north Bay during BOBMEX. A Vaisala radiosonde receiver system with GPS upper-wind capability 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 in 25–40 m range up to heights exceeding 16 km. More than 100 radiosondes were launched from the ship during BOBMEX. The frequency of radiosonde launch varied between 2 and 5 per day depending on the synoptic conditions and weather advice. During each launch, the radiosonde temperature, humidity and pressure readings were compared with the ground truth. Radiosonde temperature, humidity and pressure readings were within 0.2°C, 2% and 0.5 mb respectively, from the ground truth. These values are within the manufacturer-specified accuracy of these measurements. Hence, no corrections are required for the radiosonde data.

We have used a version of the global spectral model of the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi. This model has a horizontal resolution of approximately 140 km (spectral resolution of 80 modes with triangular truncation). The vertical profiles in the radiosonde data have a very fine structure. To ensure that the model captures the vertical structure reasonably, we have conducted simulations with an enhanced number of levels (28 sigma levels) corresponding to an approximate grid spacing of 1 km in the vertical (instead of the 18 vertical levels normally used in this version of the model). The modelling of cumulus-scale convection (i.e. the modelling of clouds and its effects on the larger scale) is done using the parameterization scheme of Grell⁶, commonly known as the simplified Arakawa–Schubert scheme. A detailed docu-

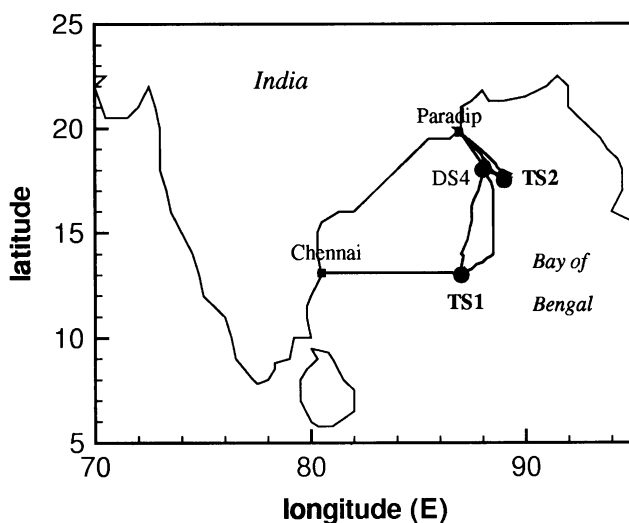


Figure 1. Cruise tracks and time series observation stations (TS1 and TS2) during BOBMEX period: 16 July–30 August 1999. TS1, 13°N, 87°E (INS *Sagaradhwani*); TS2, 17.5°N, 89°E (ORV *Sagar Kanya*).

mentation of the model can be found in Kanamitsu *et al.*⁷. The simulations were conducted with an initial condition from NCEP/NCAR reanalysis corresponding to 00 GMT 01 March 1998 and integrations were carried out till 31 August 1999. The seasonally varying sea surface temperature (SST) was prescribed from March 1998 to August 1999 as the lower boundary condition over the ocean, as obtained from the data set of Reynolds and Smith⁸.

Observational results

Synoptic and surface conditions

Both active and weak phases of monsoon were encountered during BOBMEX. An active phase of monsoon was observed during 25 July to 8 August, with the development of two depressions and a low over the Indian region⁵. Another deep convective system developed in the northern Bay during 14–16 August which produced about 200 mm rain at TS2. However, this system did not intensify further and decayed over the Bay itself.

Figure 2 shows hourly rainfall rate, SST, INSAT-derived OLR for a $2.5^\circ \times 2.5^\circ$ grid box, wherein TS2 was located and wind speed measured at TS2. Substantial

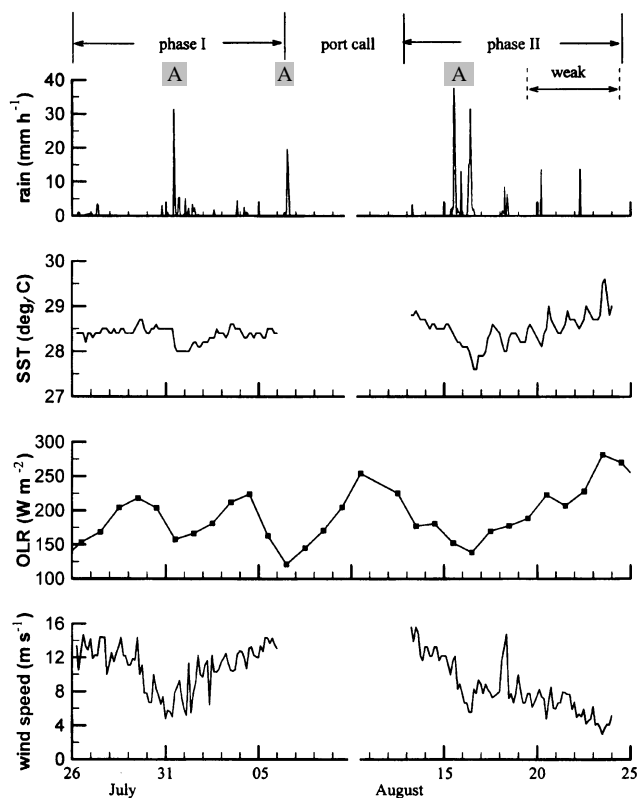


Figure 2. Daily rainfall, OLR, SST, wind speed and CAPE at TS2. The OLR shown is from INSAT satellite for the $2.5^\circ \times 2.5^\circ$ box containing TS2. 'A' refers to the convectively active days that together constitute the convective period CP and weak refers to weak convective period.

rainfall occurred during 31 July–1 August, 6 August, and 15–16 August. (Since the ship moved away from TS2 on 6 August, rainfall data for that day are incomplete.) SST remained around 28.5°C during phase I and showed a larger variation (from less than 28°C to more than 29.5°C) during phase II. SST remained above the convection threshold value of about 28°C (ref. 9) throughout, except for a brief period on 16 August. It is observed from Figure 2 that SST decreased rapidly when it rained. During 31 July–1 August, the TS2 station received about 100 mm of rainfall and SST decreased by about 0.4°C . A larger decrease ($\sim 0.9^\circ\text{C}$) was observed during 15–16 August when the TS2 station received about 200 mm rainfall. Wind speeds varied from 3 to 15 m s^{-1} (short-period gust winds exceeded 18 m s^{-1} on few occasions), with the average wind during phase I ($\sim 10\text{ m s}^{-1}$) higher than that during phase II ($\sim 7\text{ m s}^{-1}$).

Convection was more active during phase I of BOBMEX compared to that during phase II. During phase I, OLR was below 225 W m^{-2} and the sky was generally cloud-covered even when it was not raining. During the period marked weak in Figure 2, values of OLR increased to 280 W m^{-2} , winds were low and SST increased to 29.5°C . The solar radiation was intense and SST showed a prominent diurnal variation during the weak convective period. For the purpose of comparing and contrasting the changes in the atmosphere during the active and weak phases of convection, the days with substantial rainfall are together considered as the convective period (CP, Figure 2). The daily rainfall exceeded 25 mm on days belonging to CP category. During the weak convective period, the sky was generally free of large deep clouds, and there were no prolonged rain spells. During this period, the entire region was having a weak phase of convection and there were no prominent convective systems in nearby places. (It may be noted that few isolated cumulonimbus clouds formed during the weak period also. However, the duration of these cloud systems was not more than an hour.) Thus, weak is representative of break monsoon conditions.

Vertical sections

To start with, let us consider the average sounding for the entire period at TS2 (referred to as the average sounding), and the departures from the average during active and weak phases of convection. As already stated, the frequency of radiosonde launch varied between 2 and 5 per day. In order to remove the bias of the average sounding towards days with more frequent soundings, the average sounding is calculated by considering the morning (00 UTC) and evening ($\sim 12\text{ UTC}$) soundings for each day. The average soundings for the active and weak periods of convection are averages of all available soundings for the respective periods. The average sounding is

an average of 24 days of radiosonde data, and CP and weak soundings are averages of five days each.

Figure 3 shows the vertical profiles of average air temperature and relative humidity, and Figure 4, the anomalies (i.e. departure from the average) of temperature and water vapour mixing ratio during active and weak convective periods. Maximum departure of temperature from the average was less than 1.5°C (Figure 4); this change is small compared to more than 110°C decrease observed between the surface and the tropopause (Figure 3). Therefore, temperature profiles appear more or less identical in Figure 3. On the other hand, changes in the humidity field are more prominent. Relative humidity increased particularly in the middle troposphere during the convective period, and the entire troposphere became drier during the weak phase; the largest changes occurred between 600 and 300 mb levels (Figure 3). There is a clear difference in the temperature and humidity changes between CP and weak periods (Figure 4). During the convective period, the average temperature in the lowest 6 km (below 490 mb) decreased, that in the 6 to 13 km (490 to 185 mb) layer became warmer, and above 13 km the temperature decreased. During the weak period, lower troposphere was warmer, mid-troposphere was colder and

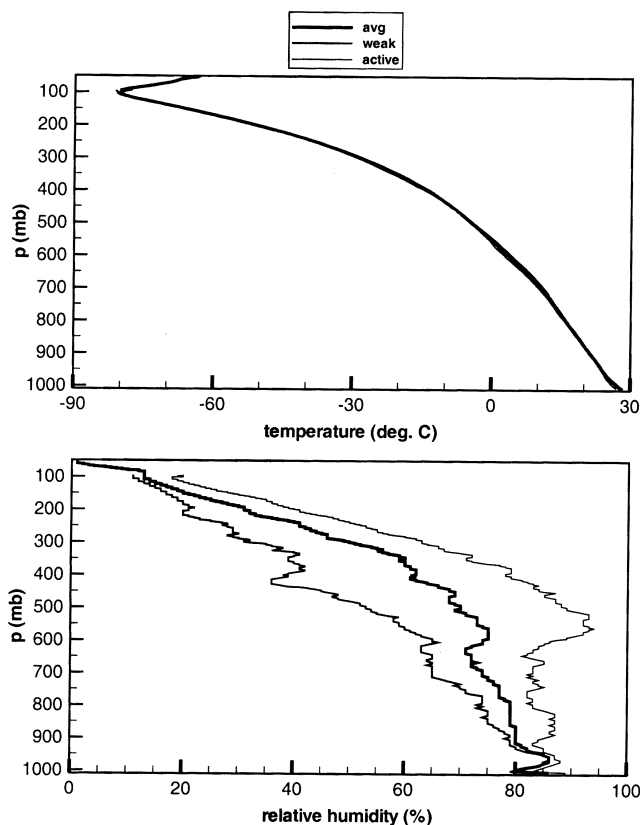


Figure 3. Vertical profiles of average temperature and relative humidity for the observation period at TS2 (referred to as average), for the active period (active) and weak phase of convection. The left vertical axis is in pressure coordinate and the corresponding height is shown on the right.

a warmer layer near the tropopause was present. These features are in agreement with the general features of tropical convection reported previously^{10,11}.

It may be noted here that the variation of saturation vapour pressure with temperature¹⁰ is such that more than 60% of the moisture that enters the (deep convective) cloud at its base condenses below 5.5 km; however, the atmosphere here became colder when clouds and precipitation formed. The reason is as follows. The ascending air, in which moisture condenses, has a positive buoyancy and rises further. Also, above the freezing level (around 500 mb or 5.8 km height) water freezes, and the latent heat of freezing acts like a buoyancy booster enabling the rising air in the cloud to reach greater heights (~ 13 to 16 km)¹². When precipitation from deep clouds (in the form of ice crystals) falls below the freezing level, ice particles melt absorbing the latent heat of melting. This produces a cold temperature region around 5 km height, and cooler and denser air moves down (down draughts), wherein air from around 5 km level is brought down, sometimes even to the surface¹³. Down draughts reduce relative humidity of the surface air, and the evaporation from falling rain drops tends to increase the relative humidity and in the process cools the air near the surface. Thus, the lower troposphere cools due to melting and evaporation as a result of deep convection and precipitation. The cooling above 13 km level could be a consequence of overshooting of the rising air in cumulonimbus clouds above the level of neutral buoyancy¹⁴ and radiative cooling of the cloud top.

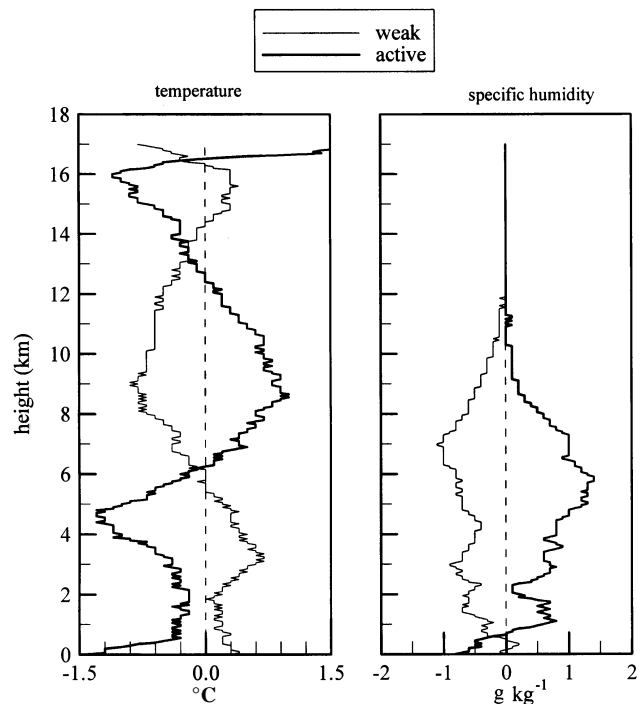


Figure 4. Anomalies of temperature and water vapour mixing ratio during active and weak phases of convection.

Model simulations of convective events

A rich and interesting variation between the active and weak phases of convection was observed earlier. There are significant differences in the vertical profiles of temperature and moisture between these phases. Here we investigate whether numerical model simulations of active and weak convective phases over the Bay of Bengal also show similar differences. The daily simulation results of July–August 1999 at a model grid situated at 17.5°N and 88.6°E, which is closest to the TS2 location (17.5°N, 89.0°E) were chosen to compare with the field observational results.

In Figure 5, time series of precipitation and sea-level pressure at the chosen location along with the wind speed at the lowest model layer are shown for the period July–August 1999. Four spells of high precipitation can be noticed within this 62-day period when precipitation was above 19 mm day⁻¹. All these four phases were associated with low sea-level pressure and high wind speed. Therefore these phases can be identified as strong convective phase or active phase of monsoon. We chose eight days (marked by asterisks in Figure 5) from the above-mentioned ones with high precipitation as the days representing the active phase of convection in model simulation. Daily precipitation values also show considerably low amount of precipitation on 5 to 7 consecutive days during the second and fourth week of August 1999. These spells are associated with high sea-level pressure and low wind speed, and therefore can be identified as the break phase or weak phase of monsoon. We chose 12 days (marked by open circles in Figure 5) with low precipitation to represent the model behaviour during weak phase of convection. It may be remarked here that in the observations (Figure 2) and in model simulations (Figure 5), the 20–25 August period was a weak phase of convection.

Figure 6 shows the anomaly of temperature and specific humidity (which is approximately equal to mixing ratio to a first approximation) profiles with height, for active and weak phases of convection at the location described above. The anomalies were computed by combining all days of active and weak convective activity (separately) and subtracting the mean value for July–August 1999. Comparison between Figures 4 and 6 brings out the similarities and differences between observations and simulations. In the observation, the entire lower troposphere cools during the convective period, whereas the model simulation shows a warmer atmosphere from the surface up to 15.5 km level. The largest change in the temperature field between active and weak phases occurs around 9 km height, while in the model simulation the corresponding change is observed around 11 km height.

The model shows better ability in simulation of the moisture profiles. The increase in moisture in the lower troposphere during the active period and its reduction

during the period of weak convection are simulated realistically. During the weak phase, the maximum reduction in moisture occurs below 2 km in the simulation. The increase in moisture around 1–2 km altitude during the active phase is also captured by the model. However, the reduction of moisture in the lowest 1 km layer of the atmosphere (i.e. the boundary layer) during the active period is not simulated. The inability of the model to realistically simulate both temperature and moisture profiles in the boundary layer suggests some shortcomings in the modelling of the boundary layer or in the specification of the cloud downdraft physics. Also the model cannot realistically simulate the moisture profile above 6 km compared to the observation. This may be due to the inability of the cumulus convection scheme to pump moisture above a certain pressure level.

In Table 1 we compare various atmospheric variables during active and weak phases as seen in BOBMEX observations and as simulated by the NCMRWF model. We notice that while the actual values (between simulations and observations) are different, the simulated variations of most of these quantities are qualitatively correct, e.g. precipitable water is higher during convective spells both in observations and simulation. An important difference is seen in the average daily rainfall. While the observed average rainfall for the convective

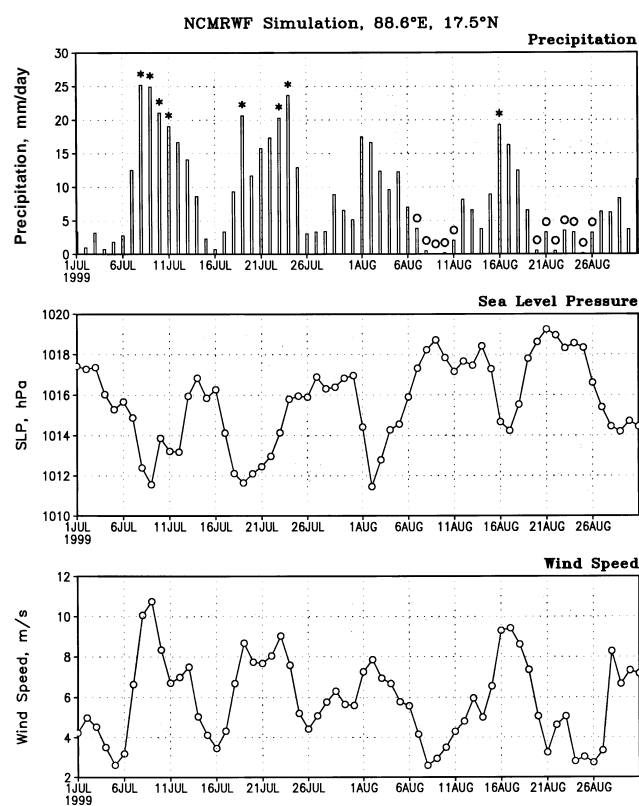


Figure 5. Time series of precipitation, sea-level pressure and wind speed at the lowest model layer from NCMRWF simulation in the grid location centred at 17.5°N and 88.6°E.

period is 68.6 mm day^{-1} , that produced by the model is 21.8 mm day^{-1} . One reason could be that ship observation represents a point measurement of rainfall, whereas that of the model corresponds to an average over a larger area ($140 \text{ km} \times 140 \text{ km}$). The other reason could be that in nature, rainfall is highly intermittent with most of it occurring on few active convective days. On the other hand, the precipitation produced in a model is sensitive to the cumulus parameterization scheme used. The simplified Arakawa–Schubert scheme used in the present simulations has the tendency to rain very frequently. With a

version of the Kuo scheme (results not shown) we observed more intermittent rainfall.

Also the change in the near-surface specific humidity between active and weak periods is incorrectly simulated. This could be related to the shortcomings of the boundary layer physics or in the specification of cloud downdraft physics. We believe that the problem lies with the model cloud downdraft physics. In precipitating cloud systems, the direct negative buoyancy due to the drag of the condensed water, the negative buoyancy resulting from the evaporation of condensed water (when rain falls through an unsaturated layer of air below the cloud base) and melting of frozen water all add up to generate downward moving air currents (downdrafts)¹⁰. Melting can be a very strong effect just below the 0°C isotherm, and the observed mid-tropospheric cooling in Figure 4 is predominantly due to this. When the rate of precipitation is strong, downdrafts originating from above the boundary layer (sometimes even from the melting level) can reach the surface¹². Cooling and drying of the boundary layer seen in Figure 4, basically represents this process. In the model simulations of the active phase, both mid-tropospheric cooling and boundary-layer drying are not similar to the observations. This suggests that the model cumulus cloud parameterization lacks proper downdraft physics. Also heating of the mid- and lower-troposphere

Table 1. Comparison of observed and model-simulated surface variables

Variable	Active		Weak	
	BOBMEX	Model	BOBMEX	Model
Precipitation (mm day^{-1})	68.6	21.8	5.8	1.8
Precipitable water (kg m^{-2})	62.2	57.3	55.3	47.6
Air temperature (near surface, $^\circ\text{C}$)	28.1	30.7	28.7	30.0
Specific humidity (near surface, g kg^{-1})	20.2	20.0	21.3	17.8
Wind speed (near surface, m s^{-1})	8.4	8.0	5.6	2.4
Sea level pressure (hPa)	1002.6	1013.4	1005.1	1018.2

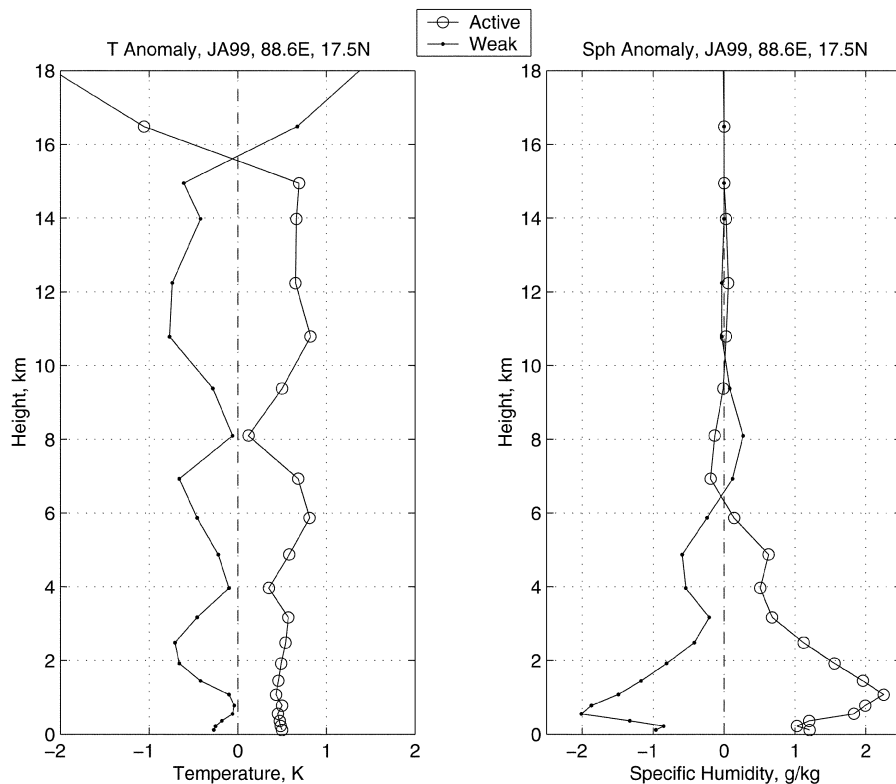


Figure 6. Model-simulated anomalies of temperature and specific humidity for active and weak convective periods.

might be due to considerable amount of shallow convection produced by the model.

Conclusions

The high-resolution radiosondes launched during BOBMEX provided data to study the variations in the vertical structure of the atmosphere in the north Bay of Bengal during the active and weak phases of convection during the peak monsoon months of July–August. It has been observed that: (1) During the convective period, the atmosphere cooled below 6 km and became warmer between 6 km and 13 km height. The amount of cooling/warming was less than 1.5°C relative to the observation period average temperature profile. The warmest layer was located between 8 and 10 km height, and the coldest layer was found just below 5 km height; (2) The largest fluctuations in the humidity field occurred in the mid-troposphere; (3) The NCMRWF model is not able to realistically capture important features of the vertical profiles of temperature anomaly in the lower troposphere during the active and weak phases of convection. The humidity field is somewhat better simulated.

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