Sodar observed winds in the convective boundary layer at Kharagpur, India, during monsoon 1990

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Sodar has been installed at Kharagpur (22.2° N, 87.3° E) as a part of the Monsoon Trough Boundary Layer Experiment (MONTBLEX-90) and data were collected during the monsoon period. The monthly-mean wind field variation in the convective boundary layer (CBL) at Kharagpur during the S-W monsoon of 1990 has been studied. Monthly-mean horizontal winds were found to be westerly/north-westerly in the convective boundary layer above ~600 m in all the monsoon months. In August, mean winds near the surface have become easterly in response to the monsoon depressions formed in the north Bay of Bengal during 15-31 Aug. 1990. Two case studies of depression are studied in terms of winds and thermal structure in the convective boundary layer at Kharagpur. The variation of CBL height over Kharagpur during the onset, active and low/depression phases of the monsoon 1990 is also presented.

1 Introduction

Indian summer monsoon has always been the focus of research because of its prominent role in global circulation. Number of experiments have been conducted earlier to understand the dynamics of the monsoon. One of the experiments, viz., summer Monsoon Experiment (MONEX) in 1979, has provided an excellent data over the Arabian sea and the Indian Ocean which helped a lot in understanding the monsoon systematically. The studies covered modelling, theoretical and observational aspects of monsoon. The largest heat source of the monsoon is associated with condensation heating and it follows the course of the maximum rainfall belt. The behaviour of monsoon over India is largely dictated by the differential between the principal region of rainfall and a net cooling in the surrounding regions. The Indian monsoon can largely be viewed as a response of the circulation to the differential heating between the regions of cooling and heating. Formation of the onset vortex has been attributed to the instability arising from the explosive increase of horizontal shear of the broadscale monsoon current. The monsoon trough is the most important feature in the lower troposphere over India during the summer monsoon season. It appears on the sea-level pressure chart as a subcontinental scale feature stretching from west Rajasthan to the head of the Bay of Bengal across the entire length of the Gangetic Valley. On the seasonal and monthly mean charts, strong westerly to southwesterly winds flow to the south of the trough and weak easterly to north-easterly winds flow to its north. Lows and depressions that form in the Bay of Bengal and Arabian sea during the monsoon season play an important role in producing widespread rain over India. The conditional instability of the second kind (CISK) which is a dominant factor in the tropics and coupled with barotropic and baroclinic instability processes, is responsible for the formation of the monsoon disturbances and maintenance of the dynamic trough.

The Monsoon Trough Boundary Layer Experiment (MONTBLEX) was conducted during June-September 1990 over monsoon trough region to study the interaction of the planetary boundary layer with the mean monsoon circulation. As a part of this programme a monostatic Doppler sodar was also installed at Kharagpur (22.2° N, 87.3° E), India, to measure profiles of horizontal wind and direction up to a height of 1.5 km with a height resolution of 30 m. Over Kharagpur, one of the experimental sites of MONTBLEX and located on the eastern end of the monsoon trough, the atmospheric boundary layer is characterized by deep moist convection during the monsoon period. Sodars have been used for air quality-related boundary layer meteorological studies. Many comparison studies also have been made using tethered balloons and sodars simultaneously. Comparison studies have been done using low-level radiosonde and sodar to monitor atmospheric stability. The Doppler sodar-measured winds are very much useful to study the effect of the synoptic weather disturbances on the atmospheric boundary layer. This is the first occasion that high-
resolution winds have been measured over monsoon trough using Doppler sodar. In an earlier study wind structure at Kharagpur in the nocturnal boundary layer was brought out. In this paper, variation of the mean wind field in the convective boundary layer during the monsoon season is discussed. Day-to-day variation of wind field in the boundary layer over Kharagpur, as monsoon depressions cross the coast and move across the land, is also presented.

2 Doppler sodar and wind profiles

Sodar (Sonic detection and ranging), an acoustic remote sensing technique, is widely being used to probe the microstructure (thermal and wind) of the lowest 1 km of the atmosphere. Qualitative information about turbulent regions and their height above the sounding site can be obtained by looking at the facsimile chart of the echograms received from a backscattering sodar, while quantitative information about the structure parameters, turbulence and wind field in the scattering volume can be computed by measuring the amplitude and the Doppler shift in frequency of the received signal from a combination of the monostatic and bistatic systems. The sodar, installed at Kharagpur, is a monostatic Doppler sodar manufactured by Aerovironment Inc., USA. It measures horizontal winds up to a height of 1.5 km with height resolution of 30 m.

The sodar site at Kharagpur has a long stretch of open and flat surface towards the south (~2 km). Since Kharagpur is located about 50 km from the sea, it is very much affected by depressions in the Bay of Bengal. Sodar was operated throughout the monsoon, i.e. June-September 1990. In June and September sodar was operated only in daytime. The specifications of the monostatic Doppler sodar are given in Table 1. Measured mean hourly wind profiles are averaged over a month (~17 days) to get an average picture of the wind structure up to a height of 1.5 km. The monthly-mean daily variations of winds from June to September are presented in Fig. 1. The wind vector is plotted as an arrow, the length of which represents magnitude of wind and the direction follows normal meteorological convention. The sodar data used in computing the monthly-mean wind are shown in Table 2. It may be noted that the number of days available for average in each month range from 7 to 17 days. It is called 'monthly-mean' for the sake of convenience of presentation. Though it is not really a monthly-mean, it does represent average wind field for each month of the monsoon season. The hourly wind fields in the atmospheric boundary layer for the depression, i.e. 19-23 August, are presented in Figs 2 and 3. Wind analysis for another depression, i.e. 15-18 August, is presented in Fig. 4.

3 Results and discussion

3.1 Mean winds during monsoon

The hourly-mean sodar winds in the boundary layer over Kharagpur have been compared with instantaneous synoptic winds and it was found that they matched well up to a height of 600 m only. The monthly-mean horizontal winds at surface were southerly/south-westerly in June (Fig. 1). Winds were north-westerly above ~600 m. Winds above ~750 m are uniform in magnitude as well as direction and not varying much with height during daytime, indicating that the boundary layer is well mixed. In July, wind were westerly near the surface up to a height of ~500 m and above this height they were north-westerly. In August, winds turned easterly near the surface (up to ~600 m) and above this level they were north-westerly. In September, winds were southerly near the surface and above they were north-westerly (Fig. 1). Thus, in general, the monthly-mean horizontal wind at upper levels in the boundary layer during the monsoon season at Kharagpur were westerly/north-westerly. The magnitude of wind at surface is significantly high in July relative to that in other monsoon months. No appreciable change was observed at upper level winds from June to September. The mean position of monsoon trough during June-September 1990, determined taking in account wind direction as well as surface pressure

<table>
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<th>Table 1—Doppler sodar specifications</th>
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<tr>
<td>Made: Aerovironment Inc., USA</td>
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<tr>
<td>Mode: Monostatic, pulse mode (three antennae)</td>
</tr>
<tr>
<td>Operating frequency: 1500 Hz</td>
</tr>
<tr>
<td>Range: 1500 m</td>
</tr>
<tr>
<td>Height resolution: 30 m</td>
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<tr>
<td>Pulse width: 180 m</td>
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<td>Pulse interval: 27 s (9 s for each antenna)</td>
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<th>Table 2—Available sodar data at Kharagpur during the monsoon 1990</th>
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<td>Month</td>
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<tr>
<td>June</td>
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<td>July</td>
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<td>August</td>
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<td>September</td>
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Fig. 1 — Monthly-mean daily variation of horizontal winds in Pith during the S W monsoon 1950. (Wind vectors (arrows) represent both magnitude (length of the arrow) and direction (usual meteorological convention). The scale of wind vector is shown at the bottom-right corner.)
Fig. 3—Hourly-mean horizontal winds after the depression of 23-26 Aug 1.
Fig. 4 — Hourly-mean horizontal winds during the depression of 15-18 Aug. 1990.
has been found to be 26.9° N at 79° E longitude and 23.2° N at 85° E longitude. This is indicated in Fig. 5 as a line connecting the two points (26.9° N, 79° E) and (23.2° N, 85° E) and is extrapolated to the extreme positions assuming linearity. The position of trough (at 85° E) was located to the north Khargpur in June, July and September, whereas it was to the south in August. Hence, the position of trough determines

Fig. 5—Track of depressions in the Bay of Bengal during the monsoon 1990
the direction of wind at Kharagpur (KGP). In other words, when the trough lies to the north of Kharagpur, winds are westerly and they become easterly when the trough is to the south. The period, i.e., 15-31 August, was characterized as a period of monsoon depression/low pressure systems\(^{15}\). The observed change of mean winds near the surface to easterly in August may be attributed to the dominating wind flow associated with the depressions in the Bay of Bengal during 15-31 August.

3.2 Winds during the passage of depression

Two depressions were formed in the north Bay of Bengal in August—one during 15-18 August and another during 19-23 August. June and September have witnessed one depression each and there was no depression in July\(^{13}\). The tracks of the monsoon depressions formed in the Bay of Bengal during June-September 1990 are presented in Fig. 5. A well marked low, formed over north Bay of Bengal about 250 km south-east of Kharagpur on 19 August, concentrated into a depression by the evening of 20 August and crossed the coast near Paradeep (about 200 km south of Kharagpur) as deep depression on the morning of 21 August. This deep depression moving west laid center near Raipur on 22 August, weakened as depression and laid center near Hoshangabad on 23 August. Moving west-north-west, the depression centered near Udaipur on 24 August. Later it weakened and merged with the seasonal low. One more depression was formed on the morning of 15 August and it crossed the coast the same evening at about 250 km south of Kharagpur and weakened as a low by 18 August after penetrating much into inland\(^{13}\).

The time variations of winds in the boundary layer for the depression of 20-22 August were presented in Fig. 2. One more day when there was no significant synoptic feature, i.e., 26 July, was also presented in Fig. 2 for the purpose of comparison. This date was selected since there was one more depression during 15-18 August and no continuous data were available before 15 August. Since 18 and 19 August are associated with low-pressure systems over land and in Bay of Bengal, respectively, they are not considered suitable for comparison purpose. Winds, which were westerly/south-westerly on 26 July have become easterly/north-easterly near the surface up to \(\sim 600 \text{ m} \) on 20 August, when a depression formed in the Bay of Bengal. During the passage of depression, i.e., 20-22 August, winds near the surface turned from north-easterly to easterly and then south-easterly. Higher level winds in the boundary layer varied much in speed and direction, whereas below \(\sim 600 \text{ m} \) there was relatively a smooth easterly flow. On 23 August when the depression weakened and lied quite away from the sodar site, winds were southerly near the surface (Fig. 3). To confirm the change of direction of winds near the surface during the passage of depression, one more depression during 15-18 August was also studied (Fig. 4). This depression crossed the coast at \(\sim 250 \text{ km} \) south of Kharagpur. Similar to the other depression, during this depression also, winds near the surface turned easterly.

Since Kharagpur is located at a strategic location on the eastern end of the trough, winds in the boundary layer depend on the position of the trough relative to the station. When depression forms in the Bay of Bengal, usually the trough shifts to the south of Kharagpur and, hence, winds became easterly near the surface. After the depression when trough shifted to the north of the station, winds at Kharagpur turned back to westerly. The low-level convergence of boundary layer air into the region of depression when it lies close to Kharagpur might be the reason for turning of near-surface winds to easterly at Kharagpur. This result is tentative as it is inferred from only two case studies of depressions.

The winds have slowly turned from easterly to south-easterly as the depression weakens and move away from the station (Fig. 4). The magnitude of winds increases as the depression moves near to the station and then decreases as it moves away. It indicates that the boundary layer winds near the surface have turned from westerly to easterly when there was a depression in the north-west Bay of Bengal. The winds near the surface in the boundary layer have slowly turned to westerly/north-westerly as the depression moves away from the station and weakens.

The thermal structure of ABL can be observed on sodar echogram which gives time-height cross-section of backscattered acoustic signal of the vertical antenna. Sodar echograms for the depression period are shown in Figs 6 and 7. The intensity of darkness on echogram is directly proportional to the magnitude of scattered signal or temperature inhomogeneities in the atmosphere. The echogram represents the instantaneous picture of the thermal structure of the atmosphere. On 19 Aug. 1990 when there was a well marked low in the north west Bay of Bengal, the sodar echogram (Fig. 6) showed a rising elevater
inversion in the early morning hours and buoyant thermal plumes during 0900-1500 hrs IST. The dark thin vertical bands on the echogram represent noise from a passing train, at about ~300 m away from the sodar site. The dark bands with more width represent rain. On the day when the deep depression crossed the coast at about ~200 km south of Kharagpur in the morning of 21 Aug. 1990, the sodar echogram (Fig. 7) indicates the temperature inhomogeneities (dark patches/lines) spreading throughout the boundary layer. This might have resulted due to the convergence of two opposing wind flows, viz., easterly at the surface and north-westerly above ~700 m within the boundary layer. When compared with the echogram on 21 August (Fig. 7), the echogram on August 19 (Fig. 6) is found to be relatively free from strong temperature inhomogeneities above ~500 m. For the other depression (15-18 Aug. 1990), sodar
echogram was not available during the night of 15 August after the depression crossed the coast in the evening of 15 August.

Thus, ABL at Kharagpur was found to be associated with large temperature fluctuations when the depression in the Bay of Bengal crossed the coast south of Kharagpur.

3.3 CBL height over the monsoon trough

The monsoon trough is the seat of cyclonic vorticity in the lower troposphere, particularly, along its eastern end over the north Bay of Bengal where organized moist convection prevails during the monsoon months. In this region the upward motions carry boundary layer air away from the ground to large altitudes throughout the troposphere. It is difficult to define a boundary layer top for these situation. Cloud base is often used as an arbitrary cut-off for boundary layer studies in these cases. The atmospheric boundary layer is defined as that part of the troposphere that is directly coupled to surface processes and includes fair weather cumulus and strato-cumulus clouds\(^{14,15}\). The CBL height is usually taken as the base of an elevated inversion or a stable layer capping a well-mixed convectively driven or even neutral boundary layer. Various methods have been used to estimate the height of CBL. One of them is to find the height at which an undiluted air parcel rising from the surface would first become neutrally buoyant. This criterion has been adopted here to find the CBL height. For this, virtual potential temperature profile was used.

The radiosonde measurements at Kharagpur, the eastern end of the monsoon trough, during MONTBLEX were used to estimate the CBL height during various phases of the monsoon 1990. The onset, active and low/depression phases of the monsoon were observed during the period 1-7 June, 6-12 July and 24-30 August, respectively. The associated weekly cumulative rainfall (at Alipore, near Calcutta, \(\sim 100 \text{ km from Kharagpur}\)) are 50 mm, 235 mm and 65 mm, respectively, in these phases (IMD weather summary). Radiosonde data are not available during active phase. They are available during 26-31 July only. The 'non-local parcel movement' method has been adopted to know the static stability of the atmosphere and the CBL height is defined as the level of neutral buoyancy\(^{12,15}\). Practically, one needs only test (displace) parcels up from the relative maxima and down from the relative minima of virtual potential temperature profile in the sounding to determine the extent of mixing.

The profiles of specific humidity and virtual potential temperature are shown in Figs 8 and 9 for onset phase (6 and 7 June 1990), in Fig. 10 for active phase (26 July 1990) and in Figs 11 and 12 for low/depression phase (29 and 30 Aug. 1990) respectively. One can infer from the profiles that there was not much change in specific humidity values for different phases, but the temperature at lower levels in active phase was less by \(\sim 2\ \text{K}\) as compared to that in onset and low/depression phases. For active phase only one day profile was presented. The profile available on other few days also revealed positive gradient of temperature indicating stable atmosphere. Since the height resolution is very less (\(\sim 500\) m), one can infer that if, at all, there is a mixed layer, it should be less than \(\sim 500\) m during active phase. This can be understood from the fact that the prevailing synoptic conditions in the active phase do not favour strong turbulence generation near the surface. In the onset phase, the mixed-layer height varied between 1500 m and 4000 m for 1130 hrs and 1730 hrs IST ascent. The low/depression phase show a mixed-layer height of approximately 1 km. The results are tentative and may be considered as case studies, since a very few profiles are analyzed.

From this study, one can say that the mixed-layer height in the active phase of monsoon is very much less than that in onset phase. Frequent precipitations collapse the surface layer and the net energy available at the surface is very less because of overcast sky in active phase. So the wind-shear generated turbulence dominates in active phase. Moisture convergence in low levels results in the formation of clouds. Since the cloud formation and its dynamics are relatively less dependent on surface fluxes of heat and moisture, they are not considered to be a part of the boundary layer.

4 Summary

The variation of monthly-mean wind field Kharagpur in the convective boundary layer during the monsoon was studied. Mean winds were found to be westerly/north-westerly during the monsoon season. The westerly winds near the surface have become easterly when there was a depression in the Bay of Bengal. The winds above \(\sim 700\) m we observed to be turbulent as compared to a relative smooth easterly flow near the surface during passage of depression across the coast. It appears that low-level convergence of boundary layer air into the region of depression might have induced easterly flo
Fig. 8 — Profiles of virtual potential temperature and specific humidity at Kharagpur on June 6 for the onset phase of the Monsoon 1990.

Fig. 9 — Same as Fig. 8 but on 7 June 1990.
Fig. 10 — Same as Fig. 8 but on 26 July for the active phase of the Monsoon 1990

Fig. 11 — Same as Fig. 8 but on 29 Aug. for low/depression phase of the Monsoon 1990
near the surface at Kharagpur. It was also found that the winds in the boundary layer near the surface slowly return to their normal direction as the depression moves away from the station. The thermal structure of ABL at Kharagpur as revealed from sodar echogram was found to be associated with strong temperature inhomogeneities throughout the boundary layer when the depression in the Bay of Bengal crossed the coast south of Kharagpur. The convective boundary layer height over Kharagpur during the active phase (~500 m) was found to be much less than that during the onset phase (~1.5-4.0 km) of the monsoon.

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