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Thermal and wind structure of the monsoon trough boundary layer

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Abstract. Radiosonde data from Jodhpur, taken at 0530, 1730 and around 1100 hr IST during MONTBLEX 1990, reveal that the distribution of virtual potential temperature θ_v below about 500 hPa has a structure characterized by up to three layers each of approximately constant gradient. We are thus led to introduce a characterization of the observed thermal structure through a sequence of the symbols N, S and U, standing respectively for neutral, stable or unstable conditions in the different layers, beginning with the one closest to the ground. It is found that, of the 29 combinations possible, only the seven classes, S, SS', SNS', NS, NSS', USS' and UNS are observed, where S' stands for a stable layer with a different gradient of θ_v than in the layer S. It is also found that, in 90% of the launches at 0530 hr, 48% of the launches at 1730 hr and 69% of the launches around 1100 hr, the first radiosonde layer near the ground is stable; the classical mixed layer was found in only 11% of the data set analysed, and, if present on other occasions, must have been less than 250 m in height, the first level at which radiosonde data are available. Supplementing the above data, sodar echograms, available during 82% of the time between June and August 1990, suggest a stable layer up to a few tens of metres 48% of the time. A comparative study of the radiosonde data at Ranchi shows that the frequent prevalence of stability near the surface at Jodhpur cannot be attributed entirely to the large scale subsidence known to be characteristic of the Rajasthan area. Further, data at Jodhpur reveal a weak low level jet at heights generally ranging from 400 to 900 m with wind speeds of 6 to 15 m/s. Based on these results, it is conjectured that the lowest layers in the atmosphere during the monsoons, especially with heavy clouding or rain, may frequently be closer to the classical nocturnal boundary layer than to the standard convective mixed layer, although often with shallow plumes that penetrate such a stable layer during daytime.

Keywords. Atmospheric boundary layer; monsoons; thermodynamic structure.

1. Introduction

The classical picture of the convective boundary layer in the lower atmosphere suggests the following pattern (see e.g., Stull 1988). In the lowest hundred meters or less from the surface, in the region called the surface layer, the fluxes and the stresses vary by less than 10% of their value at the surface. A super-adiabatic temperature lapse rate and strong wind shears are not uncommon here. Above this layer is a mixed layer where the turbulence is convectively driven, and heat, moisture and momentum are well mixed. The mixed layer grows with time over the day and reaches its maximum height late afternoon. Usually the top of the mixed layer is a stable inversion layer in which the virtual potential temperature increases with height. This layer acts as a lid to thermals rising from the ground. At this height entrainment into the mixed layer occurs. Towards the evening transition the mixed layer collapses, and at night a stable nocturnal boundary layer develops near the surface.

Previous work on the height of the mixed layer at Indian stations has been largely based on radiosonde data, generally available only at 0000 GMT (0530 IST) and 1200GMT (1730IST). The data consist of temperature, dewpoint and wind direction and speed, at various pressure/height levels. By plotting the virtual potential temperature profile, the boundary layer height is estimated as extending to the base of the capping inversion above the zero gradient region indicating the neutral or well-mixed layer. To define neutrality a threshold gradient is usually set; this value was chosen as $2\,K\,km^{-1}$ by Parasnis and Goyal (1990) over land, and about $1\,K\,km^{-1}$ by Holt and Raman (1985) over the oceans. During daytime, when radiosonde data are not available, mixed layer heights were estimated following Holzworth (1962) using the morning 0530 hr radiosonde ascent and the surface temperature data at the given time (e.g., Padmanabhamurty and Mandal 1979). The mixed layer heights so estimated over Indian stations are listed in table 1.

The present work examines the structure of the lower atmosphere especially over the western side of the monsoon trough region, based largely on radiosonde and sodar data. Some studies have also been made of data from Ranchi and Delhi to provide comparisons. Although the accuracy of Indian radiosonde data has sometimes been questioned (e.g., Ananthakrishnan and Soman 1992), it is noted that there has been no suggestion of errors at the low altitudes we are considering here.

Table 1. Mixed layer heights from various studies over Indian stations.

Investigators	Site	Mixed layer height
Gamo *et al* (1994)	New Delhi	3000 m during premonsoon. 5000 m during monsoon. 2000 m during postmonsoon. < 1000 m during winter season.
Holt and Raman (1987)	MBL over northern Bay of Bengal	400 m to 500 m.
Holt and Raman (1985)	East central Arabian Sea	800 m to 1500 m.
Padmanabhamurty and Mandal (1976)	New Delhi	1000 m (December). 2000 m (March).
Parasnis and Morwal (1994)	Kharagpur	100 m (0600 am). 900 m (1200 pm).
Parasnis and Goyal (1990)	Pune	850 mb (active monsoon). 780 mb (break monsoon).
Raman *et al* (1990)	Bangalore Delhi Delhi	900 m (convective conditions). 2500–3000 m (maximum). 4700 m (with a weaker inversion at 2500 m).
Raman (1982)	Raichur	2800 m (during NE monsoon).
Kusuma *et al* (1991)	Monsoon trough region	approximately 500 m and 3000 m during active and break monsoon respectively.

The data used for the study are from radiosondes over Jodhpur (26·18N, 73·08E) taken during MONTBLEX-90. The data are available at intervals of 50 hPa usually and 20–30 hPa during intensive observation periods (IOP). The weather during such periods is summarized in table 2. The data were available up to 200 hPa, but in the present study only data up to 500 hPa are considered. Using these data the virtual potential temperature has been computed using the standard methods (Iribarne and Godson 1973). In analysing these distributions, it has been useful to identify two special weather conditions that we shall call dry and wet situations, defined as follows. A dry situation is said to occur when at least five preceding days go without receiving any rain. When more than 10 mm rainfall occurs each day for two or more days continuously, we term it a 'wet' situation. (The soil may be expected to be respectively dry and wet during these situations.) Jodhpur was an ideal station for this study since there were days with all the following situations occurring sometime or other during the season (indeed we had eight samples for each case): **(i)** days when the wet situation prevailed, **(ii)** days when the dry situation prevailed, **(iii)** days when the trough was over the station and **(iv)** days when it was more than 500 km from the station. The days so selected for analysis are listed in table 3. Jodhpur may of course be considered representative of the western side of the monsoon trough region.

As the radiosonde data are available only at specific hours during the day, the need was felt to supplement the present analysis with an examination of sodar data, which were

Table 2. Weather situation during intensive observation periods.

Period	Weather system
29th June to 3rd July	Monsoon onset phase.
17th July to 22nd July	Weak monsoon in that area.
4th August	Passage of well-marked low across south Rajasthan, organized clouds.
18th August to 20th August	Period of monsoon depressions/ low pressure systems.

Table 3. Days selected for analysis as representing various weather situations.

Weather situations	Periods
Heavy rain	July: 2, 3, 4, 5, 6. August: 2, 3, 4, 5, 6 and 20.
No rain	June: 18, 19, 20, 21, 28, 29, 30. July: 26, 27, 28, 29.
Trough very near/ over the station	July: 4, 5, 24. August: 6, 17, 23, 31.
Trough far from station	June: 7, 8, 24, 30. August: 25. September: 2, 10.

available on a virtually continuous mode at Jodhpur. The instrument was a monostatic sodar designed and developed at the National Physical Laboratory (Singal and Gera 1982). Sound pulses of 80 ms duration were sent every 4 s and the backscattered signal, after proper amplification, filtering and detection, was displayed on a facsimile recorder as an 'echogram'. The operating frequency was 2200 Hz and the maximum range was 700 m. In an earlier study of the monsoon boundary layer over Jodhpur (Singal *et al* 1993) the following echo patterns were observed in the echograms recorded by the sodar: shear echo, thermal echo, and multiple/elevated layered structures. During the three months June – August, shear echoes corresponding to a stable layer were seen 46% of the time, thermal echoes corresponding to an unstable layer were seen 36% of the time and 18% of the time no echoes were received. However this analysis was not segregated into the different weather situations mentioned above and no direct correlation with radiosonde data was attempted. We have therefore re-examined the data again in detail.

2. Method of analysis

In general our experience has been that the classical mixed layer (convective boundary layer capped by an inversion) is not often revealed by radiosonde ascents at a place like Jodhpur. To demonstrate that there are such cases, figure 1 shows one instance at 1100 hr on 18th August 1990 over Jodhpur where a mixed layer, with constant virtual potential temperature, is observed up to a height of about 900 hPa. Also shown in figure 1 are data from a Kytoon ascent at Kharagpur (1700 hr, 3rd June 1990), showing a mixed layer (height ~450 m) with an overlying stable layer.

However, while mixed layers like those in figure 1 are rare, an extensive examination of the available radiosonde data at Jodhpur shows that the distribution of virtual potential temperature can almost always be characterized as consisting of up to three layers of approximately constant gradient in each layer (figure 2). In all of the charts in figure 2, the first point in the profile is the surface air temperature at screen height. As the second point from the radiosonde (i.e., the first above screen height) is usually at a height of 950 hPa, it is of course not possible to resolve a mixed layer that is shallower than this height. Nevertheless, it is clear from the profiles shown in figure 2 that the

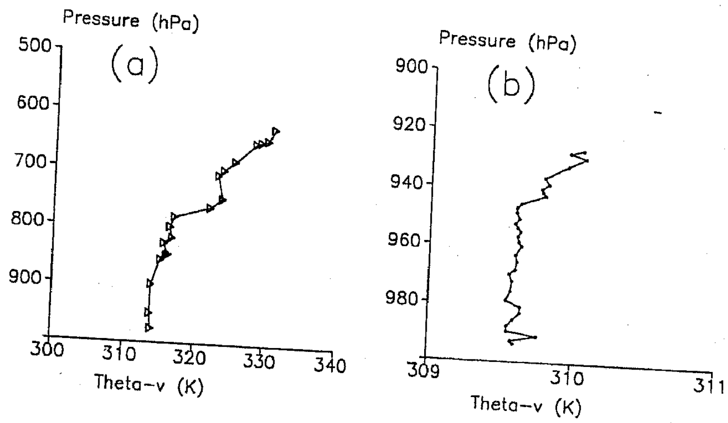

Figure 1. Virtual potential temperature profiles showing mixed layer heights on (**a**) 1100 hr, 18th August 1990 at Jodhpur using radiosonde data, (**b**) 1700 hr, 3rd June 1990 at Kharagpur, using Kytoon data.

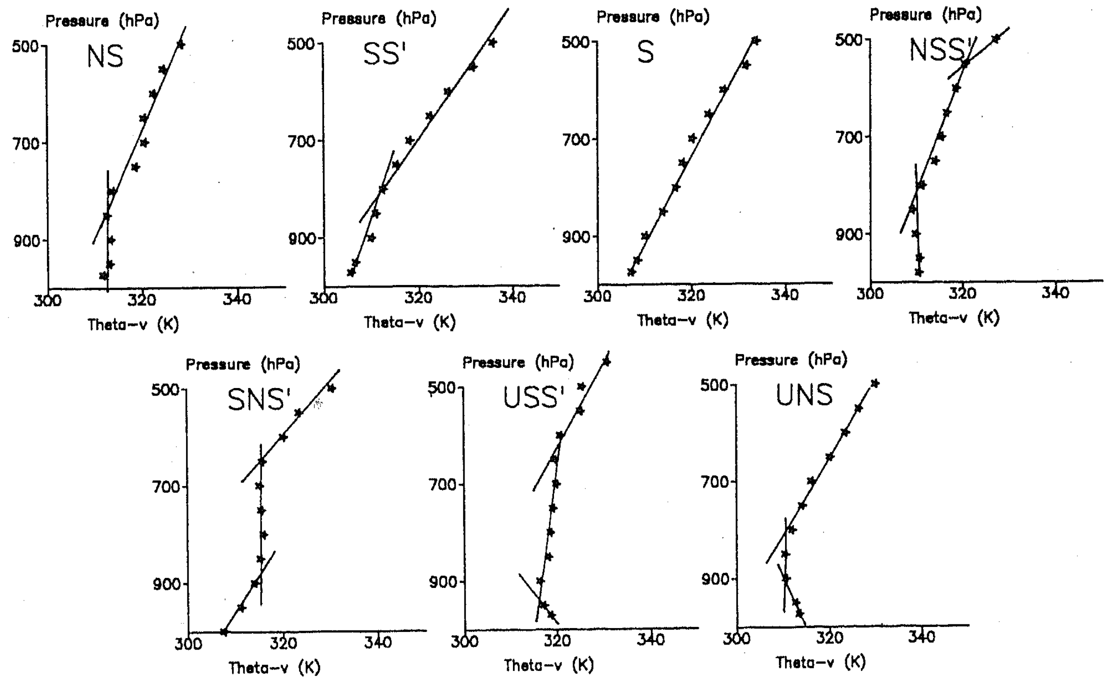

Figure 2. Seven types of virtual potential temperature profile observed over Jodhpur during 1990. Clockwise from top left: 1700 hr, 28th July; 1730 hr, 5th August; 1730 hr, 6th August; 1730 hr, 10th September; 1730 hr, 4th August; 1730 hr, 19th June; 1730 hr, 23rd August.

simplest way to describe the thermal structure of the lower troposphere (up to 500 hPa) is that it consists of up to three layers in each of which the gradient of the virtual potential temperature θ_v is approximately constant (to within $2\,\mathrm{K\,km^{-1}}$). We may designate each such structure by a set of three symbols S, N, U, standing respectively for stable, neutral and unstable conditions; if there is more than one layer belonging to the same stability category but with a distinctly different potential temperature gradient, we denote it by a primed symbol (thus SS' denotes two stable layers with different θ_v gradients). A major finding of the analysis is that all the available data can be classified into one of the seven types shown in figure 2. In the system of classification proposed here, these types are designated as S, SS', SNS', NS, NSS', USS' and UNS; the symbols are arranged in the order of their occurrence with increasing height from the surface. Of a total of 29 combinations possible, as many as 22 (namely $SS'S''$, $SS'N$, $SS'U$, SN, SNU, SU, SUS', SUN, SUU', N, NSN', NSU, U, US, USN, USU', UN, UNU', UU', $UU'S$, $UU'N$, and $UU'U''$) were not seen in the data examined here. (We are of course not in a position to assert that these structures are not possible, but they certainly seem rare during the monsoons.)

In this study we look at the first two layers from the surface. A probability distribution of their occurrence is computed during wet and dry situations, as well as when the trough is either over the station or away from it. The wind velocity has also been plotted during the various situations.

Also the sodar echograms taken in Jodhpur have been examined in detail to derive information about stability (Singal *et al* 1983; Singal 1990), since within its limited range (700 m), the resolution of the sodar is much better than that of the radiosonde. At any given time, one of the following structures could be observed: (i) stable, (ii) neutral, (**iii**) plumes, (**iv**) elevated stable layers, (**v**) rain or (**vi**) dust. For each day a chart was then prepared, indicating the echogram type at different times of day; a sample is shown in figure 3. The symbol 'na' (not available) indicates periods when the data were not available or the echoes were not legible.

An attempt was then made to identify the stability class appropriate to each echogram. This subject has received considerable attention in the literature. Singal (1989, 1993) describes efforts made to associate an appropriate Pasquill stability class with the echogram type. It turns out however that such a scheme correlates with tower data only about 50% of the time. On the other hand, a less elaborate classification into just three types, namely stable, neutral and unstable, produces excellent correlation between sodar and tower data. We have therefore opted for this simple scheme.

In general, thermal plumes indicate the presence of an unstable layer; surface based shear echoes a stable layer; and no echoes a possible neutral layer. There was hardly any observation of neutral echoes at Jodhpur. Among the other types of echoes observed were the elevated stable layer and waves, both of which could be clearly seen on the echograms. They represent stable layers. There is some ambiguity in interpreting dot echoes from an echogram alone, but it probably represents water vapour clusters (Singal *et al* 1985). The presence of continuous echoes in the echograms, from top to bottom of the chart, usually indicates drizzle or rain, since the scattering of sound waves by the water droplets would extend throughout the scanned area. On most such

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dd=date        mm=month          sb=stable;       nt=neutral;       pl=plume;
~~=elevated stable layer         ||=rain;         ::=dust;          na=not available

dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
01 06 ..sb.)(.............na.............)(.pl.)(...sb..)(.....na...)(....sb...

dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
02 06 ....sb.....)(.............na.............(pl.)(............na...........

dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
03 06 ...........na........)(.........nt..........)(::::pl::::)(........na........

dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
12 06 .......sb..............)(.........pl........)(............na.............
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dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
20 06 ...........sb............)(...na...)(.......pl.......)(........sb........
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dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
21 06 ............sb............)(..na...)(::::::pl:::::)(..........sb.........
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dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
22 06 ...........sb................)(:::::::::::::pl:::::::::::::)(.....sb.....
      ~~~~~~~~~~~~~~~~~~~~~~~~~

dd mm 0 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
23 06 .............sb..............)(......na.....)(.pl.)(:::::::::sb::::::::::
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Figure 3. A sample representing identification of echogram types during different times of day.

occasions (e.g., 3rd, 15th, 21st–23rd June), plumes can be clearly seen almost immediately after the cessation of the continuous rain-like echoes. These occasions are therefore classified as unstable. However on 4th and 6th June continuous rain-like echoes were seen but with no plumes; furthermore the Indian Daily Weather Report does not mention any rain at Jodhpur on those days. On the other hand the weather summary prepared by the MONTBLEX team on site (Rudra Kumar *et al* 1991) recorded the occurrence of a sand storm. Since the presence of denser particles suspended in the atmosphere tends to have a stabilizing effect on the flow (Wamser and Lykossov 1995), such instances have been classified as stable.

Using the interpretations described above, we have classified all available data into one of three conditions, stable (S), neutral (N) or unstable (U), at any given time.

4. Results and discussion

4.1 *Radiosonde data*

The results obtained during the different weather situations mentioned in section 2 are listed in table 4. Among the days when dry and wet situations prevailed, the frequency of occurrence of the various stability classes in the first two layers of the lower atmosphere is examined. When it was wet both layers were stable during morning 0530 hr and evening 1730 hr, whereas around noon the layer close to the surface was stable and the layer above that was neutral (SN). During dry situations in the morning the lowest layer is usually stable, and the layer above that is either stable or neutral (SS' or SN). In the evenings it is usually unstable or neutral capped by a neutral or stable layer (US or NS). Around noon the lowest layer was again stable but the layer above that is often neutral (SN). Unfortunately data were available only for 13 days during daytime, and this might at first seem to be a biased sample, as the daytime radiosonde launches occurred only during IOPs. However, as the IOP were determined based on weather towards the eastern region of the monsoon trough, the weather at Jodhpur was often undisturbed on these days; in fact on 9 of these 13 days, there was no rain. We believe that the results presented here do therefore indicate the general trend, but clearly more data and analysis are required to draw firm conclusions.

The thermal structure has also been examined when the trough was over the station and when it was away by more than 500 km. As can be seen from table 4, no clear pattern seems to emerge. When the trough is over the station, during the mornings the first layer from the surface is usually stable and the second neutral or stable; during the evenings all the stability classifications are observed in the first layer, whereas it is mostly stable in the second layer. When the trough is far away, the first layer is again stable during the mornings in most of the cases studied, whereas in the evenings the second layer is neutral or stable even though the first layer can be unstable, neutral or stable.

To summarize, it appears as if, irrespective of the weather situation being wet or dry, and the monsoon trough being over the station or far away from it, the lowest layer is almost always stable. Considering the data from 76 radiosonde launches which includes all the weather situations mentioned before, the lowest layer of constant gradient from the surface is stable 90% of the time in the morning at 0530 hr, 69% during daytime (around 1100 hr) and 48% during the evenings at 1730 hr (figure 4).

Table 4. Stability classes of the first two layers of constant gradient during various weather situations using radiosonde data over Jodhpur.

Weather	Time of radiosonde flight	Stability classes				
		US	*NS*	*SN*	*SS'*	*S*
Dry situation	0530		1	5	3	1
	1730	5	3	1	1	
Wet situation	0530		1	2	4	2
	1730	1	1	2	4	2
Trough over Jodhpur	0530		1	2	3	1
	1730	2	1	1	2	1
Trough far from Jodhpur	0530		1	4	3	4
	1730	2	3	3		

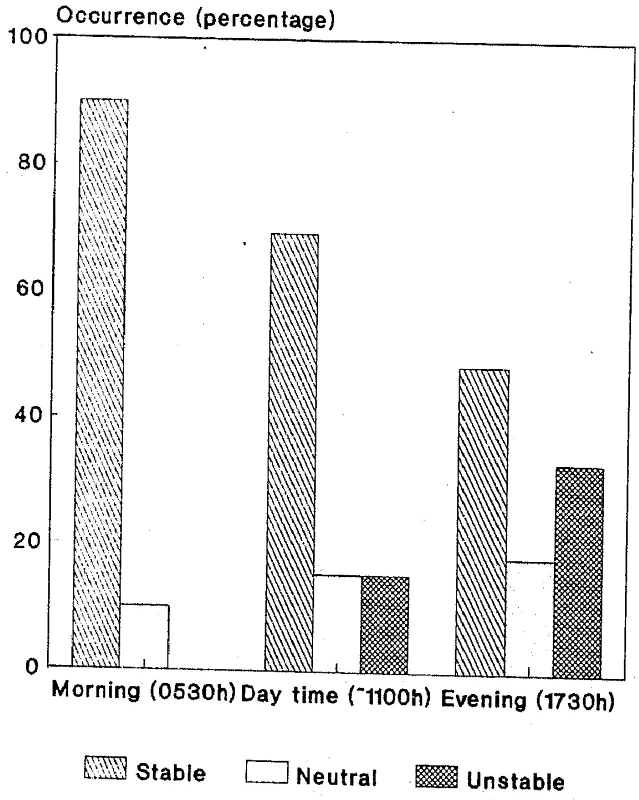

Figure 4. Percentage occurrence of the different types of stability of the lowest layer of constant gradient from the surface in Jodhpur.

Mixed layers have been observed at Jodhpur only during 11% of the time, and when observed they have a depth between 400 and 900 m.

The general prevalence of a stable layer near the ground at Jodhpur may at first appear to be related to the large-scale subsidence of air characteristic of the northwest of India (see e.g., Das 1962; Rao 1976, pp. 86–88). To ascertain whether the stable layer over Jodhpur is due to this subsidence, data over Ranchi, (23·21N, 85·20E) a station much further to the east where mild convergence is believed to occur at the surface, are considered. Ranchi has the advantage of being an elevated region (606 m above mean sea level), and would be free from the effects of other advective flows such as the sea breeze that may affect stations not so well inland. Here again, using radiosonde data, virtual potential temperature profiles are plotted. The stability of the first layer of constant gradient is noted. Frequency distributions of different stability conditions are derived at 0530, 1100 and 1730 hr. As can be seen from figure 5, the frequency of stable conditions in the lowest layer was 85% in the morning, 60% around noon, and 80% during the evening. These results over Ranchi strengthen the observations from Jodhpur that during the monsoon season a stable layer near the surface is observed more often than was expected.

A similar analysis at Delhi shows that the frequency of a stable first layer is 95·8%, 26·3% and 52·2% at 0530, 1100 and 1730 hr respectively.

Typical profiles of wind speed and direction observed at Jodhpur at 0530 and 1730 hr are shown in figures 6 and 7 respectively. It is seen that there is a maximum in the wind speed at around 950–850 hPa level, and that there is a change in wind direction by only ±20 degrees as wind speed changes from about 12 to 5 m/s through the maximum. Judging by the criteria used by Joseph and Raman (1966) this is a low level jet, although relatively weak as wind speeds are generally lower than 15 m/s. More specifically, the low level jet has the following characteristics. The jet axis is at heights varying from 950 to 850 hPa during a dry situation, and the maximum velocity varies from 6 m/s to

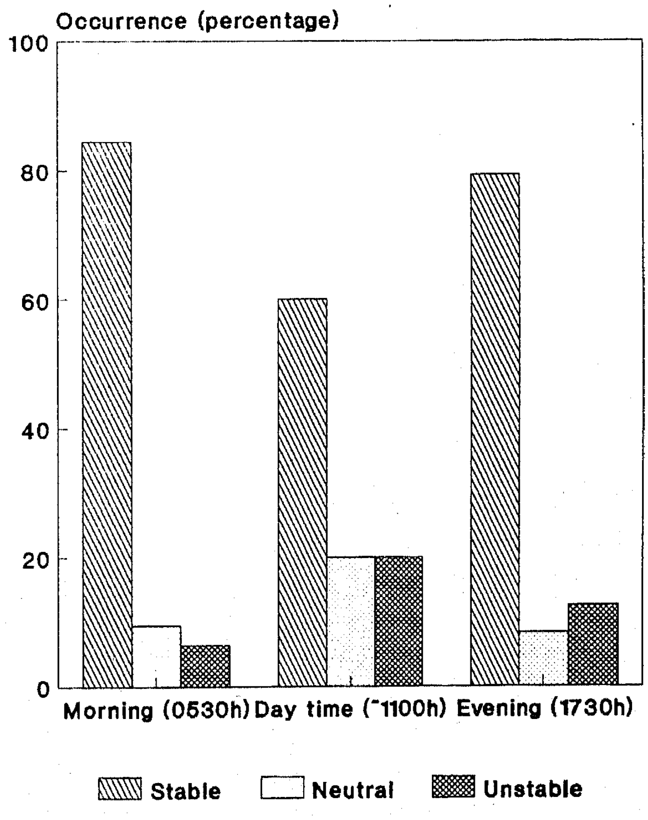

Figure 5. Percentage occurrence of the different types of stability of the lowest layer of constant gradient from the surface in Ranchi.

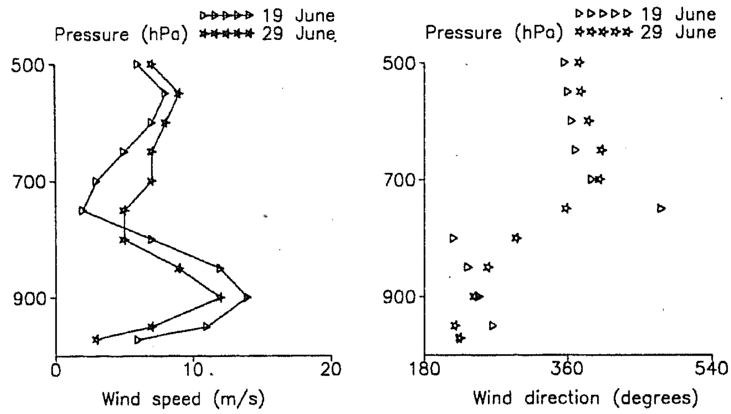

Figure 6. Typical profiles of wind speed and direction at 0530 hr over Jodhpur, during 1990.

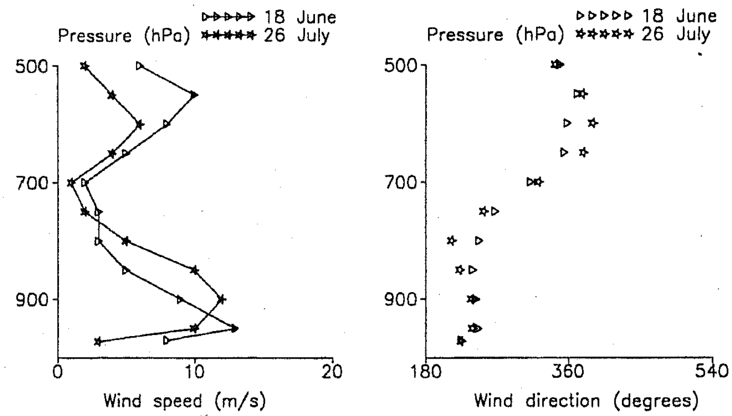

Figure 7. Typical profiles of wind speed and direction at 1730 hr over Jodhpur, during 1990.

15 m/s. But during wet situations the jet is found to be better organized; its axis is around the 950 hPa level, and the velocities are between 4 and 8 m/s both morning and evening (figures 8a and b). It is well known that a low level jet occurs over peninsular India during the monsoons (Joseph and Raman 1966; Rao 1976), as an extension of the Findlater jet (Findlater 1969) over the Arabian Sea; this jet, usually located around 15°N, is generally observed at central and southern stations south of 20°N. Although the presence of such a jet at latitudes beyond 20°N does not appear to have been studied, it is possible to interpret the data, such as from figure 3 in Sikka and Narasimha (1995), as indicating a westerly jet over Jodhpur, especially during a break in the monsoon. There was no classical 'break' in 1990 (Srivastav 1995); at any rate it is generally considered that at the latitude of Jodhpur such a jet, even if present, will be weak. At higher altitudes, the wind over Jodhpur changes direction, from approximately southwesterly to northeasterly, with a very weak wind maximum of 5–10 m/s. It is essential to study whether these characteristics of the wind seen at Jodhpur are local or extend over a wider region. While this question is outside the scope of the present paper, it appears that, in the light of the present observations, the low level jet of figure 8 could be different from the well-known low level jet over the peninsula.

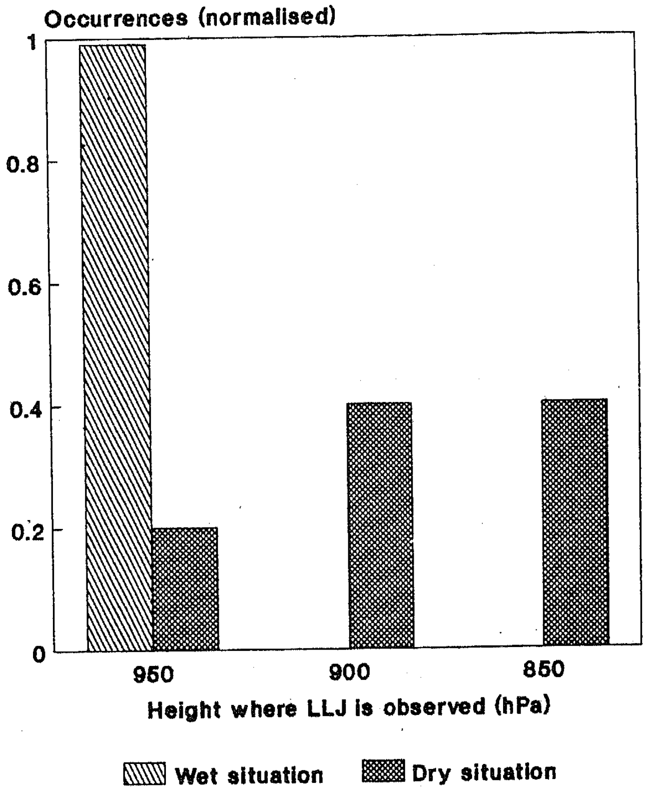

Figure 8(a). Height of low level jet during wet and dry situations.

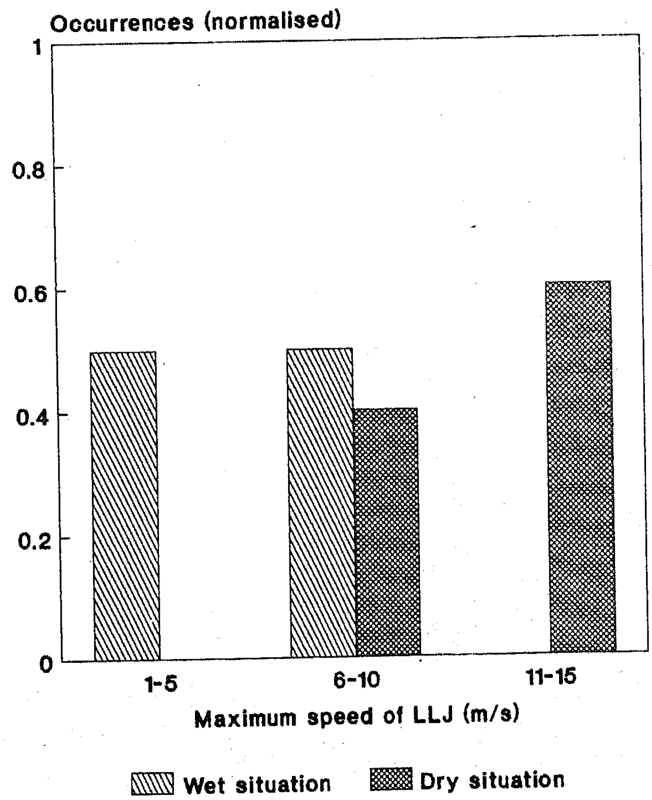

Figure 8(b). Maximum wind speed in the low level jet during wet and dry situations.

4.2 *Sodar data*

The echograms for the month of June, July and August 1990 have been examined using methods following Shaw (1974), Brown and Hall (1978) and Singal (1990) for the various structures mentioned elsewhere. Two distinct time intervals were considered: (i) 1000 to 1600 hr, when usually thermal plumes are expected, and (ii) times other than (i) i.e., from 1600 to 1000 hr when stable, neutral and even unstable conditions can be expected. The situation considering the whole day from 0000 to 2400 hr is also examined. Table 5 shows the frequency of occurrence of stable and unstable conditions for the above time periods during the individual months June, July and August 1990, and also during the whole season from June to August. Figure 9 shows an analysis of the data (considering the whole day) for the entire period June to August 1990. An analysis based on the weather situation indicates that, during wet-situation days 74% of the available data shows the region near the surface to be stable. Even when the situation is dry and less than half the sky is covered with cloud, as much as 60% of the data available shows stable stratification (figure 10).

Considering the entire monsoon season in the year 1990, stable layers occurred during 48·3% of the time according to the sodar data, whereas the radiosonde data (from all daytime launches during a variety of weather situations listed in section 2),

Table 5. Frequency of occurrence of various stability situations during different time periods over Jodhpur as observed from SODAR echograms (*S* – stable; *U* – unstable; *NA* – data not available).

Time period	10–16 hours			00–10 hours and 16–24 hours			00–24 hours		
	S	*U*	*NA*	*S*	*U*	*NA*	*S*	*U*	*NA*
June	7·2	57·8	35·0	56·5	10·6	32·9	40·1	26·3	33·5
July	9·1	81·2	9·7	76·9	16·9	6·2	54·3	38·3	7·4
August	9·1	76·3	14·5	71·1	16·5	12·5	50·4	36·4	13·3
June to August	8·5	71·9	19·6	68·3	14·7	17·0	48·3	33·8	17·8

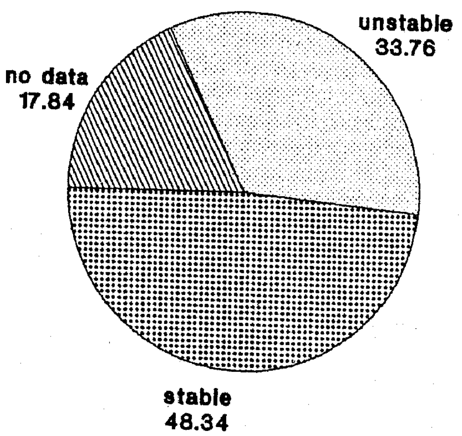

Figure 9. Stability classifications using echograms, monthwise and for the entire period (June–August, 1990) over Jodhpur.

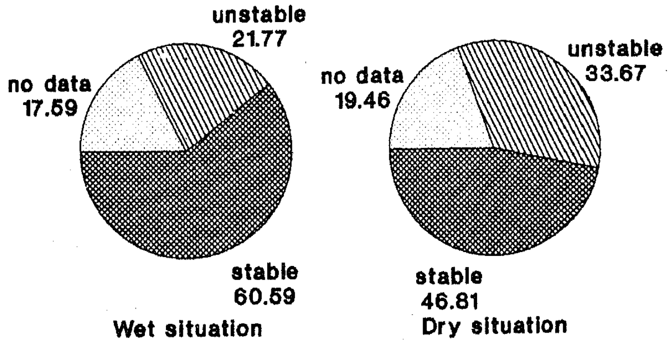

Figure 10. Stability shown by the echograms for wet and dry situations.

indicated a stable layer during a larger percentage (66%) of the time. In order to examine this difference, θ_v profiles from radiosonde data and the sodar echograms both taken at the same time have been compared in detail for two cases. Figures 11(a and b) show the sodar echogram and θ_v profile at 1235 hr on 17th July 1990 over Jodhpur. The θ_v profile belongs to the *SN* class, and shows the lower atmosphere to be stable up to 250 m and neutrally stable from 250 to 1200 m above the surface. Data are not available between screen height (1·2 m) and 250 m, so the presence of an unstable layer below 250 m cannot be ruled out. Plumes are seen on the echogram up to nearly 400 m. At 1135 hr during 20th July 1990 (figure 12b), the θ_v profile (again *SN*) shows the lower atmosphere to be stable up to 720 m (900 hPa) and neutral above. At the same time the sodar echograms (figure 12a) show the presence of plumes up to 200 m. Although it is difficult to draw firm conclusions without knowing the temperature distribution below the first level of observation provided by the radiosonde, figure 12 provides some indication that, even if plumes are present in the echogram, the lower atmosphere appears stable from the radiosonde data. A possible explanation is the following. During daytime the ground temperature can go very high, up to 5 to 10° warmer than the temperature at screen height at Jodhpur. This temperature gradient, which is up to two orders of magnitude higher than that elsewhere in the lower atmosphere, can initiate strong plumes. From figures 11(a) and 12(a) it seems that such plumes will penetrate into a possibly stable layer above, to a height that depends on the intensity of the plume and the stability of the overlying layer. The presence of plumes underneath a statically stable layer suggests that the height of plumes cannot be unambiguously converted into the height of a mixed layer, as the latter may be shallow in spite of indications of some buoyant transport above it by sodar echograms.

5. Conclusions

The structure of the lower atmosphere over Jodhpur has been studied using radiosonde and sodar data. Depending on the rainfall over the station dry and wet situations are defined. When the situation was wet the atmosphere was predominantly stable during mornings and evenings; whereas during afternoons there is often a stable layer underneath a neutral layer. During a dry situation the picture is almost the same during mornings, in the first layer from surface; during evenings it is neutral or unstable in both the layers, and during afternoons the second layer above the ground is usually

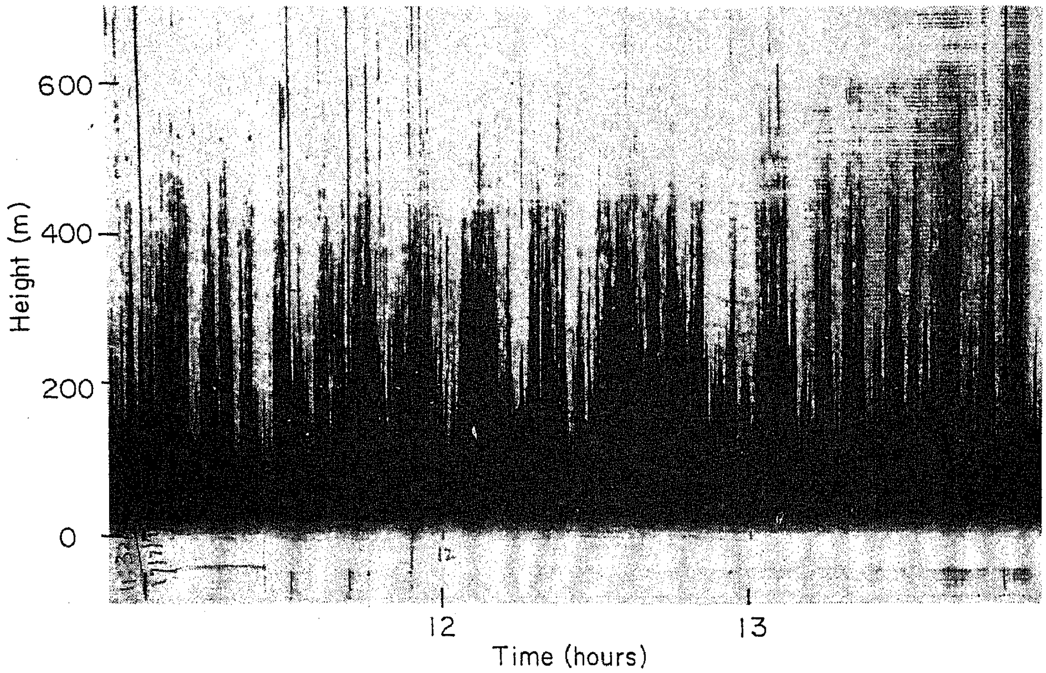

Figure 11 (a). Echograms showing plumes on 17th July 1990 over Jodhpur.

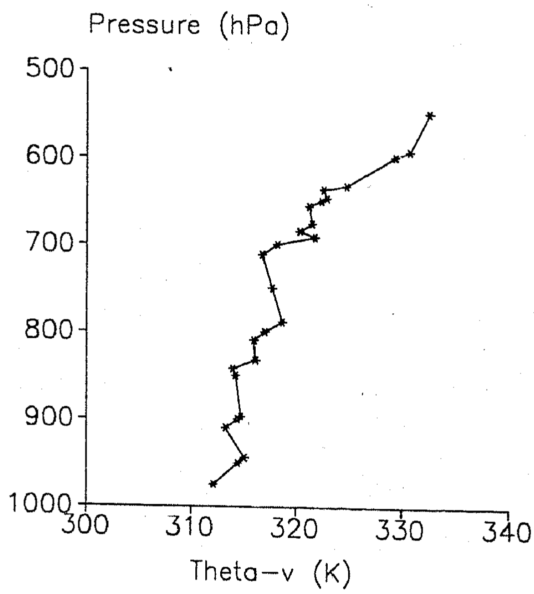

Figure 11 (b). Virtual potential temperature profile at 1235 hr, 17th July 1990 over Jodhpur showing stable layer up to 250 m.

neutral.

The classical mixed layer was rarely found; given that the available radiosonde data have a resolution of only 50 hPa it is possible that a mixed layer existed within the first reported level of radiosonde data, implying that, if present, it must generally be shallow (less than 250 m). Occasionally, however, the mixed layer was found to extend up to 900 m at noon.

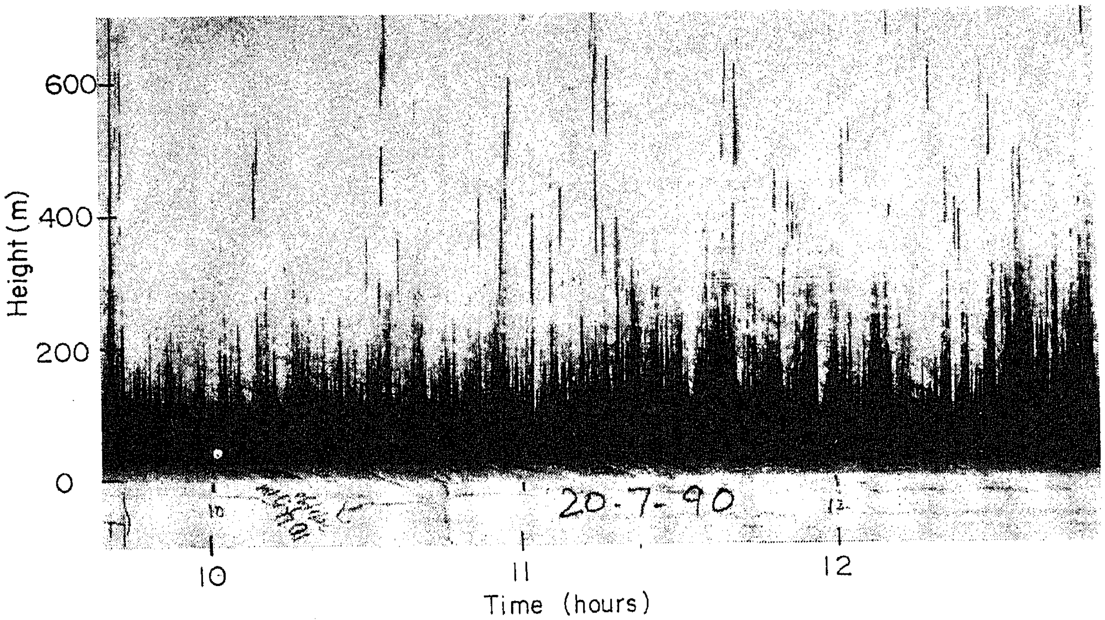

Figure 12(a). Echograms showing shallow plumes on 20th July 1990 over Jodhpur.

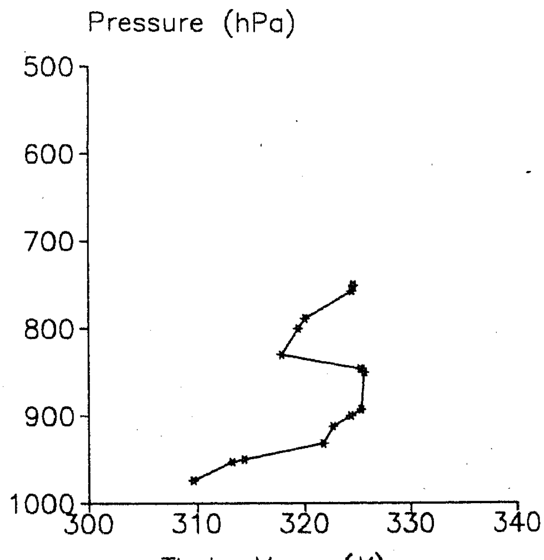

Figure 12(b). Virtual potential temperature profile at 1135 hr, 20th July 1990 over Jodhpur showing stable layer near the surface.

A low level jet is observed at Jodhpur even though the latitude is north of 26°N, to be compared with the Findlater jet which is generally considered to occur mostly south of 20°N. During dry situations the jet was stronger, and occurred at a height varying from 950 to 850 hPa.

A detailed examination of sodar records showed that, during wet situations, the lowest layer was stable nearly 75% of the time; even on dry situations without cloud, it is most often stable. A critical comparison with radiosonde data shows the presence of plumes even when the lowest radiosonde layer indicates stability. It is conjectured that the high temperature gradients very near the surface (100 times that of rest of the boundary layer) can give rise to shallow plumes which penetrate an otherwise stable layer above.

Thus the presence of stable conditions most of the time in the lower most part of the atmosphere (first layer of constant gradient), as inferred from radiosonde and sodar data, and of the low level jet, suggests that the typical monsoonal boundary layer may be closer to a nocturnal boundary layer rather than to the classical well-mixed layer, especially when the ground is wet and the sky is overcast.

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