MAUSAM, **73**, 4 (October 2022), 957-962

MAUSAM

DOI: https://doi.org/10.54302/mausam.v73i4.3727
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 502 : 551.553

Wind profile in the atmospheric boundary layer during morning hours over a tropical semi-arid station

M. N. PATIL, T. DHARMARAJ*, R. T. WAGHMARE and S. D. PAWAR

Indian Institute of Tropical Meteorology, Ministry of Earth Sciences, Pune – 411 008, India

(*Received 8 November 2021, Accepted 8 July 2022*)

***e mail : dharam@tropmet.res.in**

सार – ऊष्मा और गति से जुड़ी भूमि की सतह प्रक्रियाएं सुबह के समय में वायुमंडलीय सीमा परत (ABL) के ऊष्मण को नियंत्रित करती हैं। वर्तमान अध्ययन में, हम सुबह के समय में पवन की संरचना और एबीएल के ऊष्मण में इसकी भूमिका की जांच करने का प्रयास किया है। इस प्रयोजन के लिए, उष्णकटिबंधीय स्टेशन आनंद, भारत के ऊपर भूमि सतह प्रक्रियाओं के प्रयोग (लास्पेक्स) के दौरान एकत्रित रेडियो सॉन्डे/रेडियो विंड प्रेक्षणों का उपयोग किया गया है। यह देखा गया है कि वायु घुर्णन और एक प्रमुख निम्न स्तर जेट (Llj) धारा के रूप में वायुमंडलीय सीमा परत (ABL) पवन प्रोफाइल को एक मौसम से दूसरे मौसम में बदल दिया है। मानसून ऋतु के दौरान डबल मिक्सिंग लाइन स्ट्रक्चर और एलिवेटेड विंड-बैकिंग लेयर की स्थापना में निम्न स्तर जेट धाराओं ने महत्वपूर्ण भूमिका निभाई है।

ABSTRACT. The land surface processes associated with heat and momentum govern the heating of the atmospheric boundary layer (ABL) in the morning hours. In the present study, we investigate the structure of wind in ABL depicted in the morning hours and its role in establishing the heating of ABL. For this purpose, the Radiosonde/ Radiowind observations collected during the Land Surface Processes Experiment (LASPEX) over the tropical station Anand, India, have been used. It is observed that the ABL wind profiles have been changed from one season to another in the form of wind rotation and a prominent Low Level Jet (LLJ) stream. LLJ played a significant role in establishing the double mixing line structure and elevated wind-backing layer during the monsoon season.

Key words – Wind veering, Wind backing, Low level Jet, Double mixing line structure, LASPEX.

1. Introduction

After sunset, the land surface starts to cool due to longwave radiation emission, and consequently, the atmospheric boundary layer (ABL) becomes stably (nocturnal) stratified. The nocturnal ABL will change into a convective one due to an input of solar radiation that instigates at the time of sunrise. The strong thermal convection in the morning (around 0530 UTC) induces the rapid growth of ABL (Vernekar *et al*., 1991; 1993). At this time, entrainment of air mass into the ABL (Van Ulden and Wieringa, 1996; Angevine *et al*., 2001) takes place by various processes, such as the temperature and wind gradients (including wind rotation), surface heat fluxes etc. The wind tends to rotate (veer or back) due to decreased frictional force with height (Hess, 1959). In the morning hours, the positive wind shear plays an important role (Lapworth, 2006; Angevine *et al*., 2001; Alberty, 1969) in the ABL growth by enhancing dynamical vertical motion. Similarly, the wind direction shear or a veering (backing) wind is associated with warm (cold) air advection and dynamic lifting (sinking). Over the Indian subcontinent, numerous investigators have studied the diurnal and synoptic aspects of wind (Paul *et al*., 1995; Murthy *et al*., 1996; Luhar, 2002; Patil, 2006); studies on wind rotation (veering and backing) are very few. On the other hand, in the context of air pollution dispersion and evolution of ABL, the wind veering and backing phenomenon was investigated thoroughly over the mid-latitudinal region (Perez *et al*., 2006; Dayan *et al*., 2002). In the present study, the seasonal feature of wind veering, wind backing and Low Level Jet (LLJ) that are observed at 0000 UTC (0530 hrs IST) has been elucidated. The observations taken during the experiment have been discussed in the next section.

2. Data and methodology

From January 1997 to December 1998, over a semi-arid region of the Gujarat state in western India, the Land

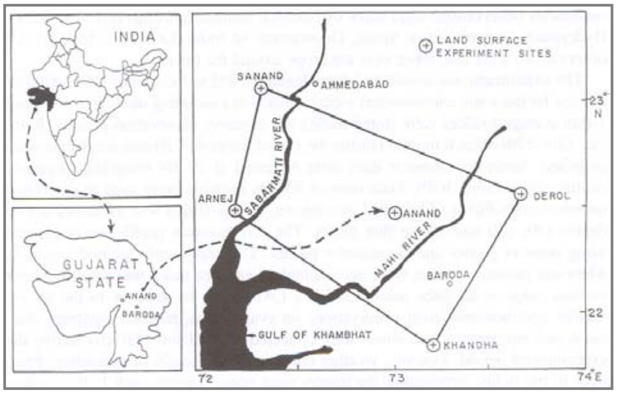


Fig. 1. Observational site of LASPEX program

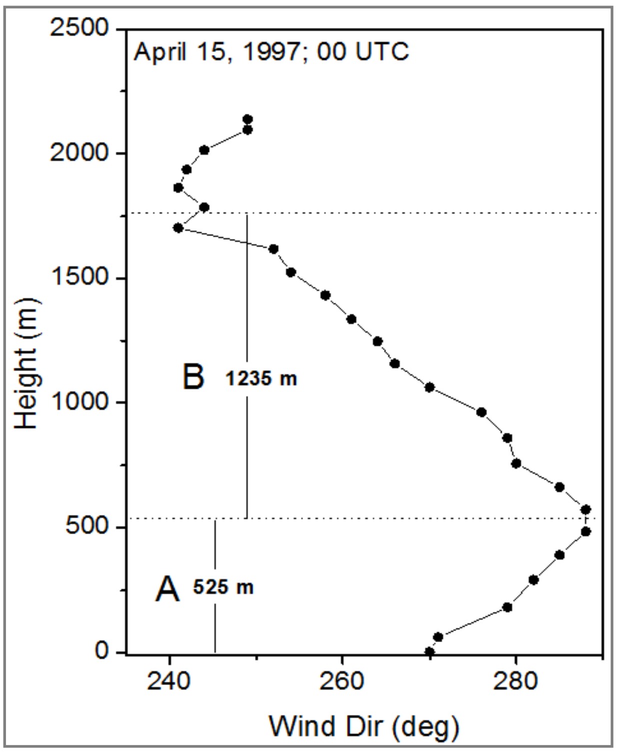
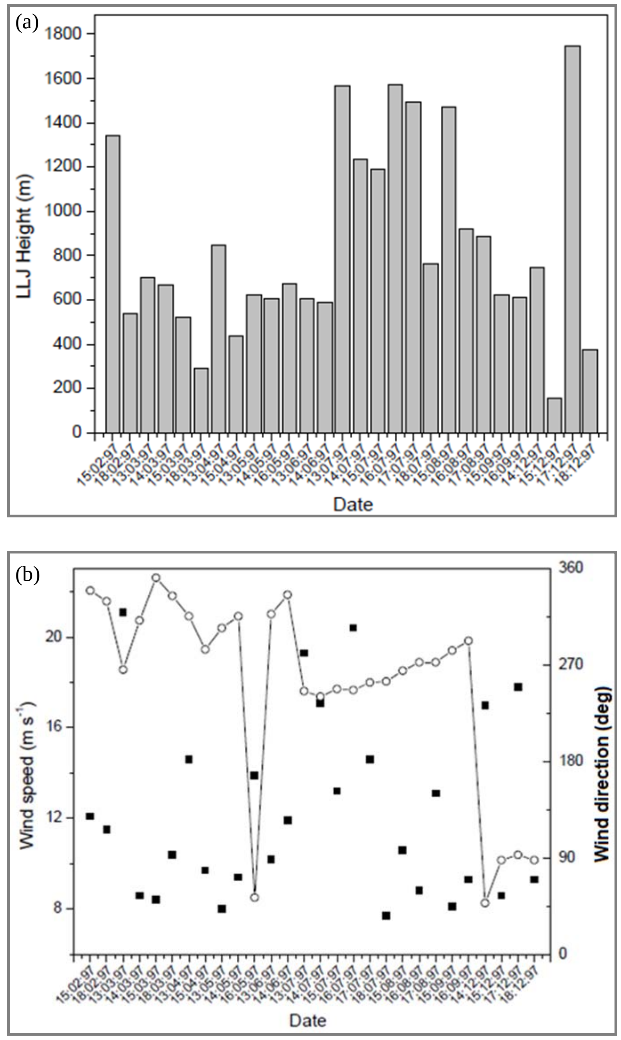


Fig. 2. Observed typical wind direction profile on 15 April, 1997 at 0000 UTC over Anand



Figs. 3(a&b). (a) Low level jet height observed at 0000 UTC on different days. Southwest monsoon onset was on 17 June, 1997 over Anand and retrieval at the end of September and (b) Wind speed (solid square) and wind direction (open circle) at low level jet height observed at 0000 UTC

Surface Processes Experiment (LASPEX) (Vernekar *et al*., 2003) was conducted. The stations indicated in Fig. 1 have different soil and vegetation properties. The dates of 13 to 18 in each month were selected as the intensive observational period (IOP). For example, the observations were taken from 13 to 18 April in April. Over the central station, Anand (22° 35' N, 72° 55' E), during the IOP, the Radiosonde / Radiowind (RS/RW) and sonic anemometer observations were recorded. Vernekar *et al*. (2003) have reported more details on the experimental set-up. The wind (speed and direction) and temperature profiles were obtained from RS/RW using a slow rising balloon (with an ascent rate of about 2.5 ms^{-1}) tracked by thedolite. Total thirty-nine qualified soundings at 0000 UTC in 11 - IOP months (February 1997 to December 1997) were available for analysis. Some investigations using LASPEX data related to land surface interactions by model simulations (Satyanarayana *et al*., 2000; Murthy *et al*., 2004; Patil *et al*., 2011) were carried out. The meteorological observations recorded on the micrometeorological tower included atmospheric pressure, wind speed, wind direction, air temperature, humidity, radiation (short wave and net) etc. At various depths, the sub-surface soil temperatures were measured. In addition to this, evaporation, precipitation and soil moisture were also recorded daily.

TABLE 1

Potential temperature, relative humidity, wind speed and wind direction by RS/RW system at 0000 UTC in the wind veering boundary layer. (Subscripts 1 and 2 denote the base and top of the veering layer, respectively)

Date 1997	Z1 (m)	Z2 (m)	U1 (ms^{-1})	U2 (ms^{-1})	WD1 (deg)	WD2 (deg)	θ_1 (°K)	θ_2 (°K)	RH_1 (%)	RH_2 (%)	ΔZ (m)	$\Delta U/\Delta Z$ (s^{-1})	$\Delta(WD)/\Delta Z$ (deg m^{-1})	$\Delta\theta/\Delta Z$ (°K m^{-1})	$\Delta(RH)/\Delta Z$ (% m^{-1})
15-2	2	590	2.0	9.3	270	350	290.6	300.9	65	38	588	0.013	0.137	0.018	-0.046
18-2	2	900	2.0	10.2	315	339	288.8	301.6	100	59	898	0.009	0.027	0.014	-0.046
13-4	2	810	3.0	14.6	224	316	292.1	303.7	80	47	808	0.014	0.115	0.014	-0.041
15-4	2	575	2.0	6.4	270	288	296.1	296.9	83	81	571	0.008	0.032	0.002	-0.004
16-4	2	625	2.0	3.9	270	383	292.2	300.5	82	24	623	0.003	0.182	0.013	-0.094
14-5	2	565	2.2	9.4	248	316	295.7	305.4	80	37	563	0.013	0.121	0.017	-0.077
14-6	2	2145	1.0	5.4	210	101	306.2	312.1	89	64	2143	0.002	0.117	0.003	-0.012
15-8	2	820	2.0	8.2	225	270	299.5	304.3	80	94	818	0.008	0.055	0.006	0.017
16-8	50	705	2.7	8.3	216	276	299.1	302.7	81	81	655	0.009	0.092	0.006	0
17-8	2	710	2.0	11.8	225	275	299.9	301.0	95	100	708	0.014	0.071	0.002	0.007
15-9	2	713	3.0	7.6	225	285	299.8	300.3	92	80	711	0.006	0.085	0.001	-0.017
16-9	95	705	4.5	8.4	264	294	299.5	302.5	92	94	610	0.006	0.049	0.005	0.003
17-9	75	655	4.6	6.0	267	297	300.8	304.3	93	100	580	0.002	0.052	0.006	0.012
17-10	2	515	1.0	2.4	45	59	295.1	303.0	85	57	513	0.003	0.027	0.015	-0.054
15-12	2	980	3.0	8.0	90	123	287.3	294.4	90	60	978	0.005	0.034	0.007	-0.030
17-12	135	1485	9.3	16.2	65	95	288.5	297.0	95	48	1350	0.005	0.022	0.006	-0.035
18-12	2	765	4.0	3.2	70	107	287.6	292.0	85	78	763	-0.001	0.049	0.006	-0.010

3. Results and discussion

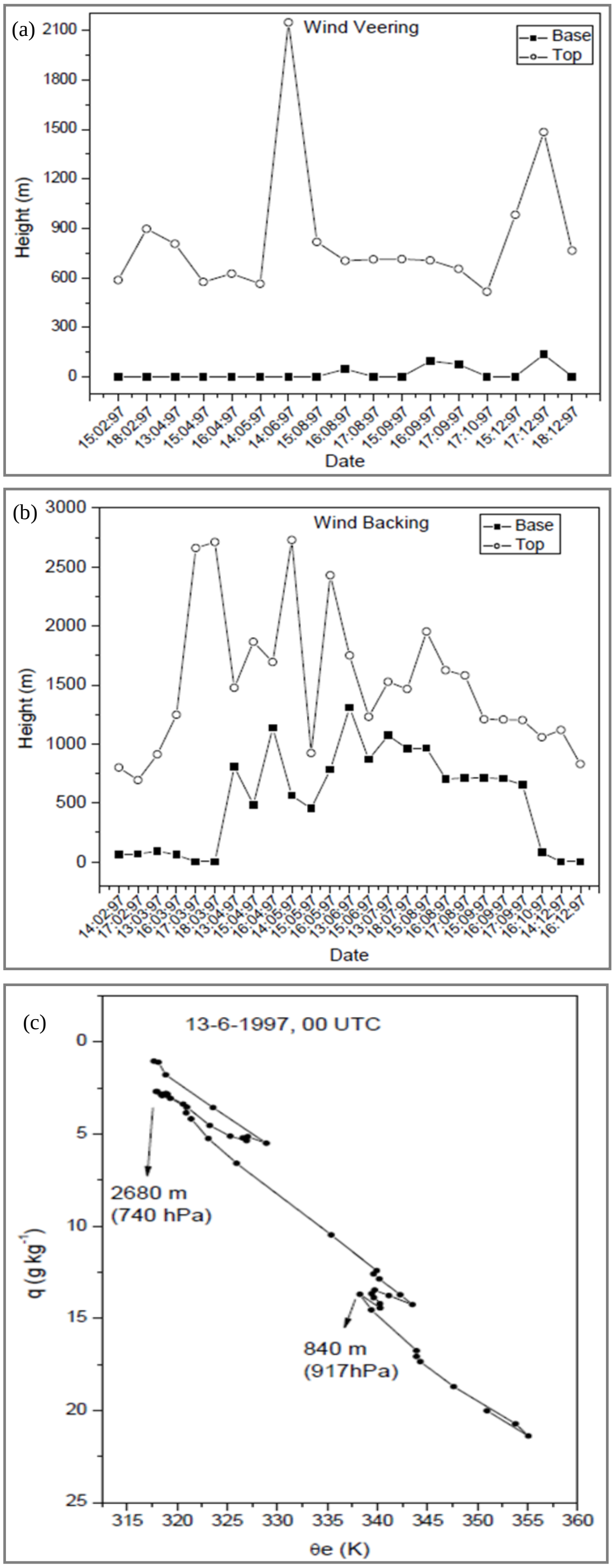
Fig. 2 shows the typical wind direction profile observed on 15 April, 1997 at 0000 UTC over Anand. The wind direction, which was 270 degrees at the surface, became 290 degrees at 525 m. This wind direction steadily changed to 243 at 1760 m. The wind-veering layer (marked with A) was established from the ground to 525 m, and the wind backing layer was found from 525 to 1760 m (marked as B). The wind-veering feature in 22% and the wind backing feature in 47% of the total soundings were depicted. Both types of wind rotation (wind backing above wind veering, as shown in Fig. 2) are exhibited in 31% of total soundings. The base of the wind-veering (backing) layer represents the first height at which the wind begins to veer (back), and the top represents the height up to which it veers (backs). The following sub-sections describe the complete wind structure such as LLJ, wind veering and wind backing observed over Anand.

3.1. *Low Level Jet (LLJ)*

The ABL wind maxima or LLJ is a mesoscale phenomenon that has importance to thunderstorm development, monsoon cyclogenesis, air pollutant transport etc. In the LLJ height analysis, we adopted two conditions: (*i*) A height where the first wind-maxima was observed and (*ii*) a height at which the wind speed is greater than 8 ms^{-1}. Throughout the available dataset (11 months) at 0000 UTC, 69% of wind profiles exhibited LLJ stream, whereas, in the monsoon season, 100% exhibited LLJ. Fig. 3(a) shows the observed LLJ height at 0000 UTC on different days. The mean LLJ height was observed to be 850 ± 430 m. Similarly, the mean wind speed at LLJ height was 12.3 ± 4 ms^{-1}. Over the observational station, the southwest monsoon arrived over Anand on 17 June 1997 and withdrew in the last week of September. During the monsoon period, the LLJ height increased to 1122 ± 377 m with a wind speed 12 ± 4.5 ms^{-1}. The wind direction at the LLJ height was 270-315 degrees during the monsoon season [Fig. 3(b)]. This wind sector is towards the Arabian Sea, and the observed LLJ brings the moisture (water vapour) from the Arabian Sea in the monsoon season. In the winter season, the wind direction of LLJ changed to 45-90 degrees, which is from the continental region.

3.2. *Wind veering*

Fig. 4(a) shows the observed base and top of the wind-veering layer at 0000 UTC over Anand. The base of the wind-veering layer was near the ground, whereas the



Figs. 4(a-c). (a) The base and top of the wind-veering layer observed over Anand, (b) The base and top of the wind-backing layer observed over Anand and (c) Conserved variable diagram observed on 13 June, 1997 at 0000 UTC over Anand

top was at the height of 839 ± 404 m. Table 1 shows the wind speed, wind direction, air temperature, and relative humidity observed at the base and top of the wind-veering layer. The thickness (top height – base height) of the wind veering layer was 817 ± 398 m. In the monsoon season, this thickness was reduced to 680 ± 85 m. During the pre-monsoon (April-May) and monsoon (June-September) periods, the wind direction at the surface was southwest, while in the winter (October-January) season, it was from the northeast. The wind speed was low (high) at the base (top) of the wind-veering layer. As seen from Table 1, in 94% of cases, the wind shear was positive, with the mean magnitude of 0.0075 ± 0.0042 s^{-1}. The mean wind rotation was observed to be 7.4 ± 4.6 deg per 100 m. It is also evident that there was always temperature inversion with the strength of 8.3 ± 5.6 K km^{-1} in the wind veering layer (Table 1). During the monsoon season, relative humidity increased at the top of the wind veering layers.

3.3. *Wind backing*

Fig. 4(b) shows the observed base and top of the wind-backing layer at 0000 UTC. It is seen that the base of the wind-backing layer was near the ground in the winter season and was at an elevated height (807 ± 236 m) in the pre-monsoon (April-May) and monsoon (June-September) months. The thickness (top height - base height) of the wind-backing layer was observed to be 985 ± 661 m which was reduced to 660 ± 224 m in the monsoon season (Table 2). In this layer, the wind direction shear of magnitude 8.4 ± 10.1 deg per 100 m was observed. During the monsoon season, at the base of an elevated wind-backing layer, the relative humidity was 72 ± 28 %, loaded with a large amount of moisture (water vapour) brought by the LLJ from the Arabian Sea. Thus, due to cold and heavy air in this layer compared to the surface, there was a sinking motion, as shown in Fig. 4(c) as a double mixing layer structure. Therefore, observed elevated wind-backing layer in the monsoon season attributed to the presence of LLJ. Table 2 shows the observed wind speed, wind direction, air temperature and relative humidity at the base and top of the wind-backing layer. During the monsoon season, the wind direction at the base was from the southwest. The wind speed always showed variable features with low wind shear. For the wind backing layer, 44% of cases only witnessed positive wind shear of 0.0042 ± 0.003 s^{-1} magnitude and 56% of cases witnessed negative wind shear of -0.0031 ± 0.0017s^{-1}. The negative wind shear supported for sinking motion. The observed wind rotation (8.4 ±10.1 deg per 100 m) was found to be well compared to the mid-latitudinal observations (6-12 deg per 100 m) by Dayan *et al*. (2002). The potential temperature (Table 2) showed an inversion of the strength of 5.8 ± 3.6 K km^{-1} in the wind backing layer.

TABLE 2

Potential temperature, relative humidity, wind speed and wind direction by RS/RW system at 0000 UTC in the wind backing boundary layer (Subscripts 1and 2 denote the base and top of the wind backing layer, respectively)

Date 1997	Z1 (m)	Z2 (m)	U1 (ms^{-1})	U2 (ms^{-1})	WD1 (deg)	WD2 (deg)	θ_1 (°K)	θ_2 (°K)	RH_1 (%)	RH_2 (%)	ΔZ (m)	ΔU/ΔZ (s^{-1})	Δ(WD)/ΔZ (deg m^{-1})	Δθ/ΔZ (°K m^{-1})	Δ(RH)/ΔZ (% m^{-1})
14-2	65	800	4.1	0.3	55	308	293.1	302.3	45	14	735	-0.005	-0.146	0.013	-0.042
17-2	70	695	3.0	1.9	326	317	290.7	299.4	74	41	625	-0.002	-0.014	0.014	-0.054
13-3	95	915	8.4	16.4	30	243	298.8	308.4	70	37	820	0.010	-0.180	0.012	-0.039
16-3	60	1250	3.5	5.2	343	269	298.1	307.8	72	47	1190	0.001	-0.062	0.008	-0.021
17-3	2	2660	1.0	9.5	135	284	292.1	306.1	78	51	2658	0.003	-0.079	0.005	-0.010
18-3	2	2710	2.0	9.1	360	260	293.1	303.8	62	52	2708	0.003	-0.037	0.004	-0.004
13-4	805	1475	14.6	13.7	316	291	303.5	306.5	49	34	670	-0.001	-0.037	0.004	-0.024
15-4	485	1865	8.2	13.6	288	241	296.5	303.3	87	31	1380	0.004	-0.034	0.005	-0.041
16-4	1140	1695	3.4	1.9	12	298	301.3	301.9	27	31	555	-0.003	-0.133	0.001	0.008
14-5	565	2730	9.4	3.9	316	131	305.3	311.0	37	38	2165	-0.003	-0.086	0.003	0.001
15-5	455	925	5.6	5.2	327	300	305.4	308.9	44	30	470	-0.001	-0.058	0.007	-0.030
16-5	785	2430	12.9	4.6	53	2	309.0	309.2	16	23	1645	-0.005	-0.031	0.000	0.004
13-6	1310	1750	2.4	1.4	351	281	305.8	307.5	80	83	440	-0.002	-0.159	0.004	0.005
15-6	870	1230	2.5	3.4	273	92	309.3	310.8	65	62	360	0.003	-0.504	0.004	-0.007
13-7	1075	1525	14.3	19.3	248	246	304.5	306.5	95	91	450	0.011	-0.004	0.004	-0.009
18-7	960	1465	7.4	5.6	267	249	303.9	305.2	97	97	505	-0.004	-0.036	0.003	0
15-8	965	1955	8.5	10.4	270	256	305.1	308.9	95	89	990	0.002	-0.014	0.004	-0.006
16-8	705	1625	8.3	9.9	276	239	302.6	305.3	81	66	920	0.002	-0.040	0.003	-0.016
17-8	710	1580	11.8	7.4	275	253	300.9	304.8	100	82	870	-0.005	-0.025	0.004	-0.021
15-9	715	1210	7.6	7.5	285	266	300.3	301.4	80	83	495	0	-0.038	0.002	0.007
16-9	705	1205	8.4	6.3	294	279	302.5	303.9	94	99	500	-0.004	-0.030	0.003	0.010
17-9	655	1205	6.3	3.3	297	273	304.3	306.6	100	99	550	-0.005	-0.044	0.004	-0.002
16-10	80	1060	3.0	4.8	20	221	296.4	303.9	87	70	980	0.002	-0.163	0.008	-0.018
14-12	2	1120	4.0	9.8	90	32	288.9	293.7	83	54	1118	0.005	-0.052	0.004	-0.026
16-12	2	830	3.0	0.5	45	318	288.6	296.5	88	69	828	-0.003	-0.105	0.009	-0.023

The conserved variable diagram (Betts, 1982; Betts and Albrecht, 1987) constituted a plot of equivalent potential temperature (θ_e) *vs* mixing ratio (q) and the line connecting these points is referred to as a mixing line structure. Such double mixing line structure is the phenomenon observed in convective boundary layer. We found such ABL structure at the transition time in 69% of profiles in pre-monsoon and monsoon months. Fig. 4(c) shows a conserved variable diagram for a day on 13 June 1997 at 0000 UTC. On this day, the wind-backing layer was within 1310-1750 m. One can see a stable layer immediately above the ground (see the first two points) as a descending motion. This stable layer is up to 227 m, as seen from the data. The potential temperatures (Fig. not shown) at 2, 227 and 346 m were 302.1, 303.1 and 301.4 K respectively. These values also suggested a ground-based stable layer of 227 m thickness. The first marked kink was at 840 m in ABL (below the wind-backing layer) but close to LLJ height (700 m), and the second was at 2680 m (above the wind-backing layer), which shows the double mixing line structure. Thus, whenever there was an elevated wind-backing layer, a double mixing line structure was observed. The complete wind structure in the monsoon season, during the time of morning hours, shows that there were two mixed layers separated by a stable layer (which is within the wind-backing layer). A similar double mixing line structure was observed in pre-monsoon and monsoon conditions over a continental region (Murthy and Parasnis, 2002) as well as over the oceanic area of the Arabian sea (Parasnis and Morwal, 1993a; 1993b) and the Indian ocean (Morwal, 2000). Thus, the existence of the double mixing line structure in the monsoon season was attributed to the presence of LLJ, which is a seasonal monsoon phenomenon in India.

4. Conclusions

The RS/RW wind and temperature profiles and the surface turbulence observations over the tropical station, Anand, located in the western part of India were analyzed to investigate the ABL wind structure in the morning hours. The well-depicted LLJ in the monsoon season helped to moisture incursion over the western region of India. The ABL exhibited veering (anticyclonic) and backing (cyclonic) winds characteristics. The wind veering layer is always established near the surface in all seasons. The base of the wind-backing layer was observed to be near the ground in the winter season (October to March), whereas it was at an elevated height (807 ± 236 m) in the pre-monsoon (April-May) and monsoon (June to September) seasons. The observed elevated wind-backing layer is attributed to the LLJ that brings moisture from the Arabian Sea and promotes sinking motion. Also, the double mixing line structure (which is a convective boundary layer phenomenon) was observed whenever there was an elevated wind backing layer. The observed magnitude of the wind rotation was consistent with the observations from the mid-latitudinal region.

Acknowledgements

The authors express their gratitude to the Director, Indian Institute of Tropical Meteorology, Pune, for his inspiration in the research. India Meteorological Department conducted the RS/RW observations over the observational site. The Department of Science and Technology, Govt. of India, funded the LASPEX program.

Disclaimer : The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Alberty, R. L., 1969, “A proposed mechanism for cumulonimbus persistence in the presence of strong vertical shear’’, *Monthly Weather Review*, **97**, 8, 590-596.

Angevine, W. M., Baltink, H. K. and Bosveld, F. C., 2001, “Observations of the morning transition of the convective boundary layer”, *Boundary Layer Meteorology*, **101**, 209-227.

Betts, A. K. and Albrecht, B. A., 1987, “Conserved variable analysis of the CBL Thermodynamic structure over the tropical oceans”, *Journal of Atmospheric Science*, **44**, 83-99.

Betts, A. K., 1982, “Saturation point analysis of moist overturning”, *Journal of Atmospheric Science*, **39**, 1484-1505.

Dayan, U., Lifshitz-Goldreich, B. and Pick, K., 2002, “Spatial and structural variation of the atmospheric boundary layer during summer in Israel-Profiler and Rawinsonde measurements”, *Journal of Applied Meteorology*, **41**, 447-457.

Hess, S. L., 1959, “Introduction to Theoretical Meteorology”, Henry Holt and Co., New York, 362 pp. (Ch. 18, "Viscosity and Turbulence.").

Lapworth, A., 2006, “The morning transition of the nocturnal boundary layer”, *Boundary Layer Meteorology*, **119**, 501-526.

Luhar, A. K., 2002, “The influence of vertical wind direction shear on dispersion in the convective boundary layer and its incorporation in coastal fumigation models”, *Boundary Layer Meteorology*, **102**, 1-38.

Morwal, S. B., 2000, “Convective boundary layer structure over the equatorial Indian oceanic region”, *MAUSAM*, **51**, 169-176.

Murthy, B. S. and Parasnis, S. S., 2002, “Observation of double mixing line structure in the convective boundary layer during summer monsoon season”, *Pure and Applied Geophysics*, **159**, 1345-1357.

Murthy, B. S., Dharmaraj, T. and Vernekar, K. G., 1996, “Sodar observations of the nocturnal boundary layer at Kharagpur, India”, *Boundary Layer Meteorology*, **81**, 201-209.

Murthy, B. S., Parasnis, S. S. and Ek, M., 2004, “Interaction of the land-surface with the atmospheric boundary layer: case studies from LASPEX”, *Current Science*, **86**, 1128-1134.

Parasnis, S. S. and Morwal, S. B., 1993a, “Thermodynamic structure of the marine boundary layer over the Arabian sea as revealed by the MONSOON-77 data”, *Boundary Layer Meteorology*, **63**, 365-380.

Parasnis, S. S. and Morwal, S. B., 1993b, “Radiatively driven subsidence over the eastern Arabian Sea with MONSOON-77 data”, *Indian Journal of Radio and Space Physics*, **22**, 235-238.

Patil, M. N., 2006, “Aerodynamic drag coefficient and roughness length for three seasons over a tropical western Indian station”, *Atmospheric Research*, **80**, 280-293.

Patil, M. N., Waghmare, R. T., Halder, S. and Dharmaraj, T., 2011, “Performance of Noah land surface model over the tropical semi-arid conditions in western India”, *Atmospheric Research*, **99**, 85-96.

Paul, D. K., Ghanekar, S. P., Murthy, B. S. and Vernekar, K. G., 1995, “Wind profiles in the boundary layer over Kharagpur associated with synoptic scale systems”, *Proceeding of Indian Academy of Science*”, (Earth & Planet. Sci.), **104**, 317-326.

Perez, I. A., Garcıa, M. A., Sanchez, M. L. and Torre, B. de., 2006, “Analysis of wind data in the low atmosphere from a RASS sodar”, *Annals in Geophysics*, **24**, 415-426.

Satyanarayana, A. N. V., Lykossov, V. N. and Mohanty, U. C., 2000, “A study of atmospheric boundary layer characteristics at Anand, India using LSP experimental data sets”, *Boundary Layer Meteorology*, **96**, 393-419.

Van, Ulden, A. P. and Wieringa, J., 1996, “Atmospheric boundary layer research at Cabauw”, *Boundary Layer Meteorology*, **78**, 39-69.

Vernekar, K. G., Sadani, L. K., Brij Mohan, Saxena, S., Debaje, S. B., Pillai, J. S., Murthy, B. S. and Patil, M. N., 1991, “Structure and growth of atmospheric boundary layer as observed by a tethered balloon payload”, *Indian Journal of Radio and Space Physics*, **20**, 312-315.

Vernekar, K. G., Brij Mohan, Saxena, S. and Patil, M. N., 1993, “Characteristics of the atmospheric boundary layer over a tropical station as evidenced by tethered balloon observations”, *Journal of Applied Meteorology*, **32**, 1426-1432.

Vernekar, K. G., Sinha, S., Sadani, L. K., Sivaramakrishnan, S., Parasnis, S. S., Brij Mohan, Saxena, S., Dharmaraj, T., Patil, M. N., Pillai, J. S., Murthy, B. S., Debaje, S. B. and Bagavathsingh, A., 2003, “An overview of the Land Surface Processes Experiment (LASPEX) over a semi-arid region of India”, *Boundary Layer Meteorology*, **106**, 561-572.