MAUSAM, **55**, 1 (January 2004), 123-134

551.511.61 : 551.510.522

Quantification of atmospheric turbulence close to ground level in Satna region : I - Rainy season

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(*Received 30 May 2002, Modified 29 July 2003*)

सार – इस शोध पत्र में चार विभिन्न सिद्धांतों (ह्रास दर, Ri, σ_θ और टर्नरस् टेबल) के माध्यम से वायुमंडल के प्रक्षोभों की विशिष्टताओं का निर्धारण करने के लिए 106 एम. लंबे ए.बी.बी. (एसिया ब्राउन बोवेरी लि.,ज्यूरिख)– यूनिवर्सल टॉवर, सतना (म.प्र.) में पूरी वर्षा ऋतु के दौरान विभिन्न उच्चताओं पर लगातार मापे गए सूक्ष्म मौसम वैज्ञानिक विचलनों (तापमान, पवन गति, पवन दिशा और पवन दिशा में उच्चावचन) का विश्लेषण किया गया है। इस अध्ययन से यह पता चलता है कि 60 एम. तक धरातल के निकट की परत कुछ घंटों को छोडकर (0900 बजे से 1300–1500 बजे प्रतिदिन) उर्ध्वाधर होने के साथ ही साथ पार्श्व भ्रमिलता के साथ अत्यंत अवरूद्ध होती है। वर्षा ऋतु के दौरान दिन और रात की पूरी अवधि में ऊपरी सतह 60 एम. से 106 एम. तक प्रक्षुब्ध पाई गई है। दो परतों के स्पष्ट व्यवहार के इस तथ्य को उष्मा और प्रदूषक स्थानान्तरण को समझने और उनके निदर्श तैयार करने के लिए काफी महत्वपूर्ण माना गया है। इस अध्ययन में यह भी संकेत दिया गया है कि प्रक्षोभ के उर्ध्वाधर और क्षैतिजीय घटकों को अलग–अलग ढंग से समझने की आवश्यकता है। पहला ह्रास दर, Ri, एस.ओ.डी.ए.आर. और यहाँ तक कि टर्नरस् टेबल के आधार पर हो सकता हैं किंतु दूसरा σ_θ पर ही निर्भर होता है।

ABSTRACT. In this study micro-meteorological variables (Temperatures, wind speed, wind direction and wind direction fluctuations) measured at various elevations on continuous basis throughout the rainy season at 106 m tall ABB (Asea Brown Boveri Ltd., Jurich) - Universal tower, Satna (M.P.) have been analysed to determine the turbulence characteristics of atmosphere through four different approaches (Lapse rate, Ri, σ_θ and Turner's Table).The study shows that the layer close to ground, up to 60 m is severely constrained in respect of vertical as well as lateral eddies except for a few hours (between 0900 hrs or to 1300-1500 hrs or everyday). The upper layer from 60 m to 106 m was found to be turbulent throughout the day and night period during rainy season. This fact of different apparent behaviour of the two layers is considered to be of significant importance to understanding and modeling of heat and pollutant transport. Also the study indicates that vertical and horizontal components of turbulence need to be treated separately. The former could be based on Lapse Rate, Ri, SODAR or even Turner's Table, but the latter has to depend on σ_θ.

Key words – Turbulence, Pasquill stability classes, SODAR, Turner stability scheme.

1. Introduction

Characterisation of turbulence of the lower layer of atmosphere close to ground level (say upto 200 m above ground) is important from the point of view of dispersion of heat as also of pollutants generated or moderated by anthropogenic activities and of significant interest for health and well being of living species. IMD use radio sonde for their scientific studies of profiles (Temperature and wind) but due to fast rise of balloon the data for the most important few hundred meters closest to the ground is lost (say up to 200m from ground level).

Earlier studies of turbulence in India limit their concern only with the upper atmospheric layers to predict the happenings of meso-scale meteorological disturbances, clouds and storms etc. An intensive study of ground based turbulence can provide better understanding of pollutant and heat dispersion, formation of smog, fog and dew and the reduction in atmospheric visibility in urban as well as rural areas.

Comparison between profile derived and measured from fluxes (Businger *et al.,* 1971) is important from turbulence point of view in the lower layer of the atmosphere. In current practice turbulence indices used in pollutant dispersion modeling are derived from empirical relations and assumptions (Kumari and Sharma, 1987) rather than micrometeorological study of a site on a continuous basis. This study attempts to do this for Satna.

TABLE 1

Lapse Rate, (σ_θ) and SODAR based criterion to determine the level of atmospheric turbulence (from A to F)

Turbulence Class	Pasquill's class	Limits given by slade		Tarapur σ_θ (°)	SODAR Structure
		(σ_θ) (°)	$\nabla T/\nabla z$ (°C/100m)		
Highly turbulent	A	25°	< –1.9	10°	Clear thermal plumes > 300 m
Moderately turbulent	B	20°	–1.9 to –1.7	7°	Thermal plumes going between 200 & 300 m
Slightly turbulent	C	15°	–1.7 to –1.5	5°	Thermals going up to < 200 m
Neutral	D	10°	–1.5 to –0.5	3.5°	No structure or feeble structure
Slightly anti-turbulent	E	5°	–0.5 to 1.5	2.5°	Surface based layers with spiky structures
Anti-turbulent	F	2.5°	1.5 to 4.0	1.5°	Flat top surface based layers

TABLE 2

Turner's turbulence classification scheme (in terms of A to F class)

Surface Wind Speed (at 10m) (m/s)	Day time solar insolation			Night time conditions	
	Strong	Moderate	Slight	Thin overcast or ≥ 4/8	≤ 3/8 Cloud cover
Less than 1	A	A – B	B	F	F
Less than 2	A – B	B	C	E	F
Less than 4	B	B – C	C	D	E
Less than 6	C	C – D	D	D	D
More than 6	C	D	D	D	D

2. Turbulence - Definition and indices

2.1. The micro-scale motions in atmosphere are frequently chaotic, with dimensions from a centimeter to several hundred meters and with time scale from a second to several minutes. This particular (random and chaotic) class of fluctuating motion is called turbulence. Turbulence can produce rapid fluctuations in temperature and wind.

2.2. Indices used to define turbulence are briefly discussed below :

2.2.1. *Vertical temperature gradient,* $\left(\frac{\nabla T}{\nabla z}\right)$ *method*

This method would require temperature data at two elevations. It would be the direct and theoretical indicator for thermal turbulence. On the basis of extensive studies, Slade categorised the values of $\left(\frac{\nabla T}{\nabla z}\right)$ in terms of turbulence levels as given in Table 1 (Slade, 1968).

2.2.2. *Wind direction fluctuations* (σ_θ) *method*

The intensity of turbulence is reflected in the magnitude of wind direction fluctuations. The standard deviation of wind direction fluctuations (σ_θ) has also been used as an indicator of turbulence. Slade gave criterion to represent the degree of turbulence (A to F) based on (σ_θ) values (in column 3 of Table 1). The criterion can not be applied universally and should be modified according to the local geo-climatic conditions (Sadhuram and Vittal Murthy, 1983). For the coastal site of Tarapur near Bombay (India), modified (σ_θ) based criterion was proposed by BARC and is given in Table 1 (in column 5).

Note : (σ_θ) values are to be considered as centre values of the particular class. Line of demarcation between two classes may be taken to be the arithmetic mean of the two values.

2.2.3. *Turner's method*

Turner (1964) modified the Pasquill's classification (Pasquill, 1961) of turbulence or "Stability" (which was based on wind speed, solar insolation and time of the day) by adding the influence of clouds and proposed a classification system in terms of A to F class (Table 2). The system was primarily developed to describe the urban pollution related problems. The method is still most commonly adopted in India for modeling urban and industrial pollution.

Note 1 : For (A–B) uses average of A and B similarly proceeds for B – C and C – D.

Note 2 : 'Moderate' insolation implies the amount of incoming solar radiation when sky is clear and solar elevation is between 35° and 60°. The terms 'Strong' and 'Slight' insolation refer to solar elevations of more than 60° and less than 35° respectively.

Note 3 : Solar elevation may be obtained for a given date, time and latitude from astronomical tables. Since cloudiness reduces insolation, it should be considered along with solar elevation in determining the Pasquill's category. Insolation that would be 'Strong' may be expected to be reduced to 'Moderate' with broken (5/8 to 7/8 cloud cover) middle and to 'Slight' with broken low cloud cover respectively.

Note 4 : Where data from solar radiation measuring instruments are available; the values of insolation corresponding to 35° and 60° on clear days may be obtained and used in classification irrespective of cloudiness data.

Note 5 : Neutral class D should be assumed for overcast conditions during day or night.

2.2.4. *Richardson number (Ri) method*

Ri (Richardson, 1926, Batchelor, 1953) depends on the vertical temperature and wind speed profiles and is defined as

$$\mathrm{Ri} = \frac{\left(\frac{g}{T}\right)\left[\frac{\partial T}{\partial z} + \Gamma\right]}{\left(\frac{\partial \bar{u}}{\partial z}\right)^2} \quad (1)$$

Where g - acceleration due to gravity (9.8 m/s^2), T- temperature in °K at height z meter height above GL (ground level), $\partial z = z_2 - z_1$ (z_2 and z_1 are upper and lower heights), $\partial T = T_2 - T_1$ (T_2 and T_1 are temperatures at z_2 and z_1 levels respectively) and $\partial \bar{u} = u_2 - u_1$ (u_2 and u_1 are mean wind speeds at z_2 and z_1 levels).This is considered appropriate to characterise turbulence (Irwin, 1981) where data are available.

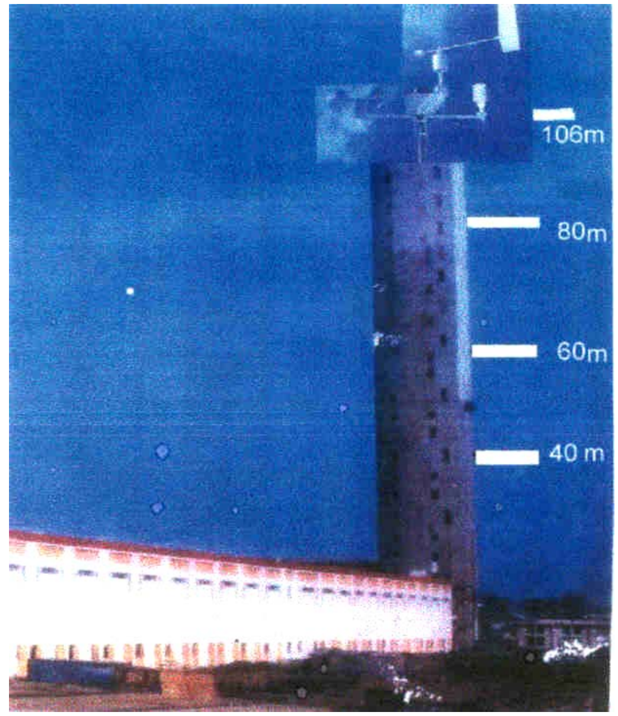


Fig. 1. Tower photograph where sensors at various heights (m) were mounted

2.2.5. *SODAR technique*

Remote sensing instruments like Sodar, Lidar and Radar have been found to provide useful meteorological information in the lower atmosphere on wind and thermal profiles. Amongst these techniques, Sodar (Sound detection and ranging) has been found to be more powerful, appropriate and inexpensive to probe the lower atmosphere (Singhal and Gera, 1982). It has the capacity to give wind velocity and thermal structure. The thermal structure provides information on thermal profile indirectly on a continuous basis. The suitability of acoustic (sound) waves over electromagnetic waves for probing the lower atmosphere is based on the fact that the interaction of sound waves with in-homogeneities of the lower atmosphere is very much stronger than that of the electromagnetic spectrum (Little, 1969). Once appropriately calibrated to interpret the echograms in terms of quantitative thermal profiles, Sodar could be the best suited to be installed at site to provide required information (Singhal and Gera, 1982) for all hours of the day and for all periods relevant to critical conditions, trends and variations (for criteria see Table 1).

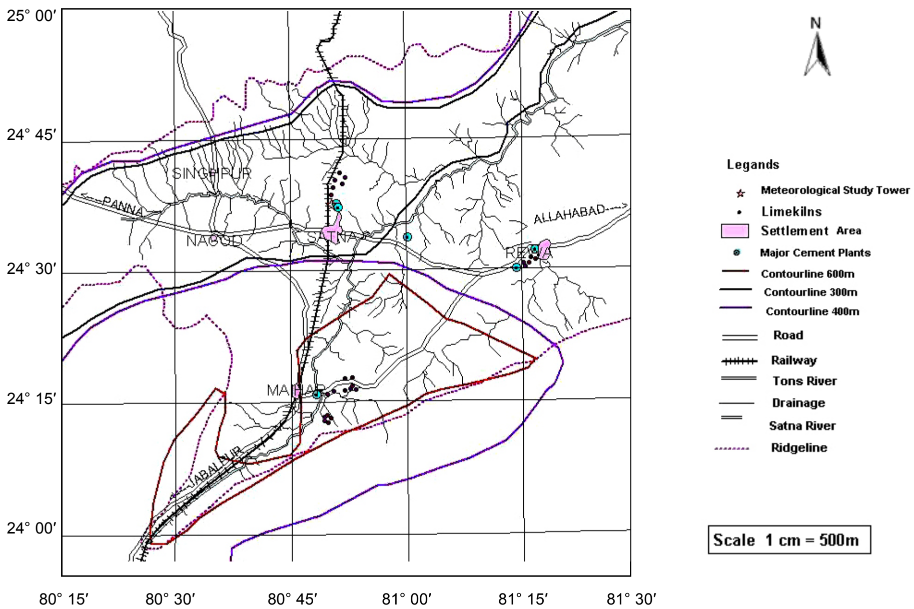


Fig. 2. Topographical map of Satna region

3. Site and methodology

3.1. *Study site*

Geographically Satna is located on Long. of 80° 50' E and Lat. of 24° 34′ N and is 317 m above mean sea level. In the pre-independence era Satna was well known for the production of lime and today it is known for both lime and cement manufacturing. Besides, there are more than 100 medium and small industries as well as numerous brick and lime kilns. The area presently is a notified industrial area of M.P. as notified by Town and Country Planning Board, Govt. of M.P.

For obtaining the temperature and wind profiles to study the lowest part of the atmospheric boundary layer upto a few hundred meters above GL a 106 m tall tower (Fig. 1) of M/s ABB-Universal (Pvt.) Ltd. was available at Satna and this was used for mounting the meteorological sensors to get the temperature and wind profiles.

Within a radius of 2 km, less than 5% of the area around the proposed instrumented-tower was occupied by building structures and the average height of the existing buildings was around 10 m. There are no hillocks, mounds or other topographical features to cause major roughness, nor any thick tall vegetation in the surrounding area.

TABLE 3

Positions of various sensors on ABB- Universal tower at Satna

S. No.	Elevation of WM-200	Effective Height of Sensors
1	At 10 meter	(a) Temperature sensor at 10 meter
		(b) Wind direction sensor at 10 meter
		(c) Wind speed sensor at 10 meter
2	At 40 meter	(a) Temperature sensor at 40 meter
		(b) Temperature sensor at 60 meter
		(c) Wind speed sensor at 40 meter
3	At 106 meter	(a) Temperature sensor at 106 meter
		(b) Temperature sensor at 80 meter
		(c) Wind direction sensor at 106 meter
		(d) Wind speed sensor at 106 meter

Probably the "Roughness Length" shall be less than a meter. Thus, the results based on data observed at ABB-Universal Tower may be valid over the entire air-shed. Topographical map of Satna region is given in Fig. 2.

3.2. *Instrumentation*

The ENVIROTECH WM-200 Wind-Monitor used in this study has been designed to provide ambient

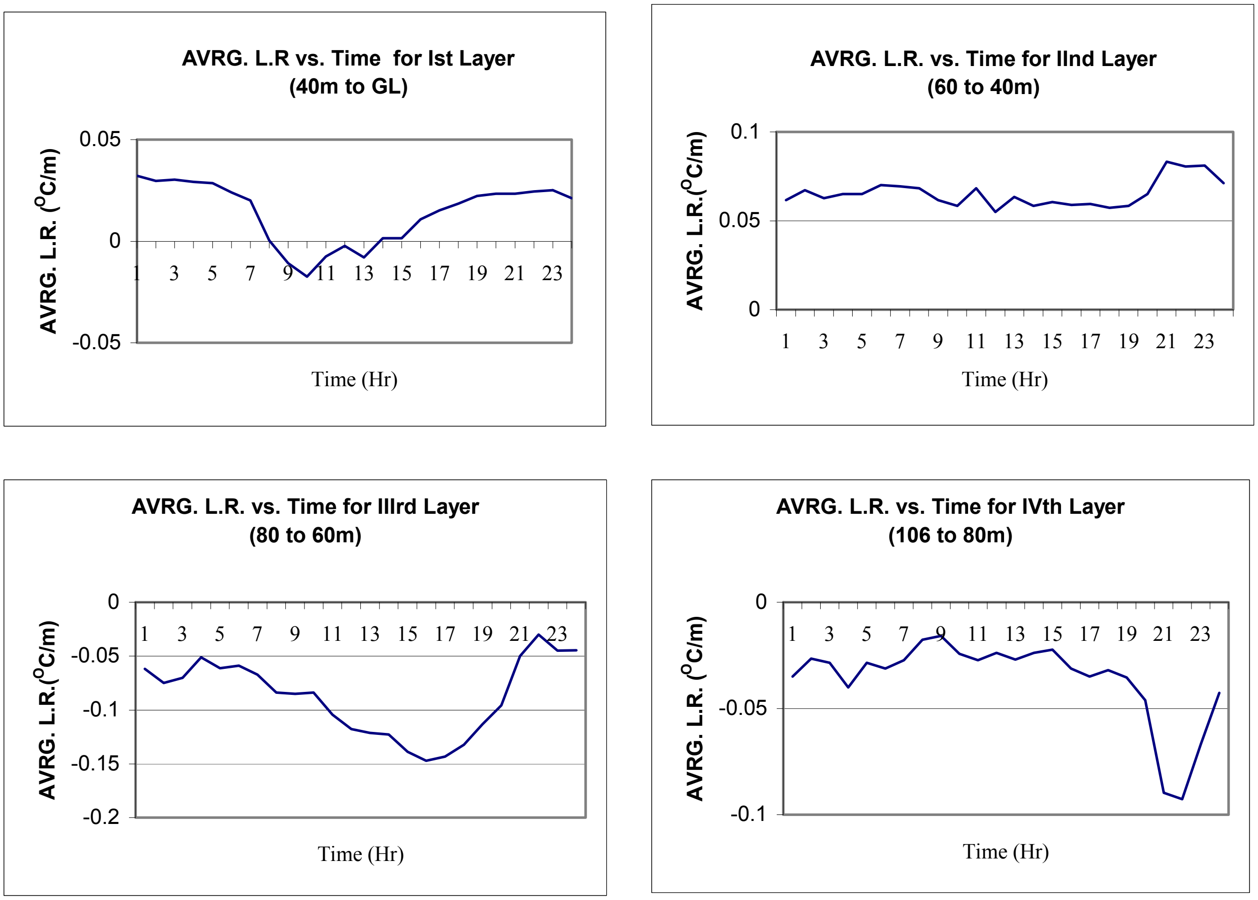


Fig. 3. Plot between average L.R. and time of four layers above GL in rainy season of year 2000

temperature in degree centigrade, wind speed in km/h and wind direction in degrees from north. The data logger of the system computes hourly averages of the three parameters and also standard deviations of the wind direction fluctuations on a Real-Time basis. The hourly data is stored in the logger memory and can be retrieved at appropriate intervals.

The WM-200 system uses specially designed digital sensors to measure wind speed, wind direction and temperature. The direction sensor uses a four bit gray code to resolve wind vane position into sixteen sectors. The wind speed sensor uses non-contact photo choppers to sense shaft rotations.

Using old wind monitoring systems wind speeds and directions were recorded in the chart form but WM-200 has a microprocessor memory as well as an inbuilt interface which makes it possible to transfer stored data to a computer system.

3.3. *Methodology*

If two WM-200 systems are installed at two different heights, the two height data would enable computation of vertical velocity gradient, temperature gradient, Richardson-Number. σ_θ measured at various heights, itself would be a measure of an aspect of turbulence.

In the present study three wind monitors were mounted at three different heights (10, 40 and 106 meters) on the tower of ABB-Universal Ltd. Sensors connected to these three WM-200 data loggers were as given in Table 3.

Fortunately a thin 106 m tall tower existed at ABB-Universal Ltd. which provided facility to install sensors at different levels. Also a SODAR was operative at this site during the period August 1999 to July 2001 and echograms from this were available.

TABLE 4 (a)

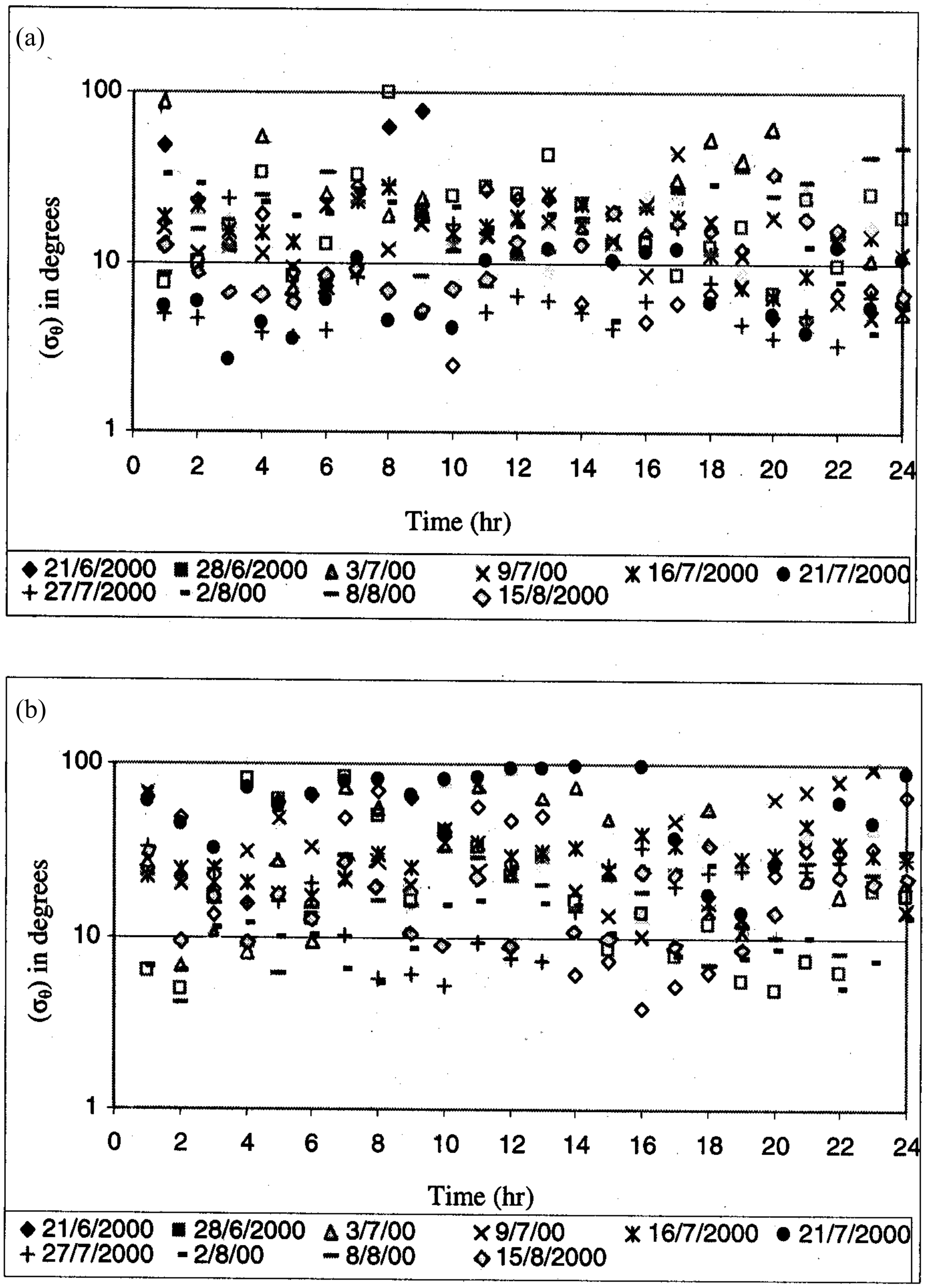
Hourly Ri values for upper layer (between 40 and 106 m above GL) on examined days of rainy season of year 2000

Time	Date								
	21 Jun	28 Jun	3 Jul	16 Jul	21 Jul	27 Jul	2 Aug	8 Aug	15 Aug
0100	-3.42	-4.11	0.403	-0.28	0.0042	-0.074	0.086	0.107	0.047
0200	-1.24	-3.72	0.122	-0.133	0.0115	0.036	0.068	0.074	0.009
0300	-1.25	-2.71	0.188	-0.127	0.0027	-0.541	0.0210	0.088	0.021
0400	-0.254	-3.58	0.272	-0.095	-0.031	-0.297	0.044	0.049	0.004
0500	-0.683	-4.45	0.740	-0.097	-0.038	-0.186	0.032	-0.056	0.124
0600	-1.638	-1.11	1.549	-0.080	-0.049	-0.159	0.065	0.107	0.030
0700	-2.524	-5172	1.384	-0.129	-0.020	-0.216	0.050	0.058	0.0186
0800	-5.31	-511.6	3.947	-0.271	-0.038	-0.113	0.041	0.1030	0.484
0900	-9.28	-2.035	0.773	-0.201	0.081	0.223	0.015	-0.650	0.404
1000	-3.89	-14.56	-0.669	-0.434	0.058	0.1157	0.011	-1.55	3.823
1100	-37.70	-31.54	-1.738	-0.278	0.348	-0.040	-0.0065	-7.28	0.474
1200	-16.48	-3.038	-0.72	-0.418	0.119	0.173	-0.083	-36.90	0.034
1300	-3.93	-1264	-0.176	0.455	-0.043	0.098	-0.091	-9.21	-0.08
1400	-13.77	-774.2	-0.162	-0.378	0.0401	-0.034	90.116	-0.77	-0.008
1500	-600.33	-3.962	-0.432	-0.405	0.110	-0.298	-7.029	-3.90	-0.030
1600	-8.309	-1.057	-1.250	-0.68	0.165	-0.244	-0.154	-0.62	-0.055
1700	-47.01	-0.358	-6.50	-0.87	-0.089	0.0982	-0.135	-0.90	0.0062
1800	-5.37	-0.281	-18.16	-1.83	0.045	-0.0417	-0.137	-0.68	0.110
1900	-1.77	-0.170	-38.96	-1.38	0.033	0.042	-0.035	-0.96	32.77
2000	-12.25	-0.207	-31.39	-2.17	0.672	-0.192	0.037	-0.36	0.087
2100	-1.34	-0.367	-21.22	-3.28	131.76	0.042	0.032	-25.69	0.307
2200	-0.258	-0.624	-3.175	-0.534	0.156	0.180	0.035	-0.123	0.045
2300	-0.430	-0.352	0.968	-0.250	0.853	0.137	0.200	0.0810	0.118
2400	-0.734	-39.59	411.99	-0.534	-0.122	0.389	0.079	2.881	2.1883

TABLE 4(b)

Hourly Ri values for lower layer (upto 40m above GL) on examined days of rainy season of year 2000

Time	Date								
	21 Jun	28 Jun	3 Jul	16 Jul	21 Jul	27 Jul	2 Aug	8 Aug	15 Aug
0100	7.89	1.49	11.34	27.98	0.041	0.17	16.44	1.33	5.15
0200	7.91	1.63	91.19	0.57	0.034	0.27	1773.2	0.423	0.23
0300	31.07	2.81	1.356	0.21	-0.0009	1.16	20.33	0.516	0.24
0400	5.94	1.30	6.31	0.23	0.052	3.11	9.42	1.083	0.105
0500	4.12	28.86	0.843	0.28	0.072	1.107	2.15	5.89	0.08
0600	∞	45.09	22.79	0.081	0.060	0.24	1.91	0.88	0.091
0700	95.18	3.68	23.16	0.154	0.062	5.09	∞	69.99	0.091
0800	-389.51	69.59	0.151	0.094	-0.185	0.22	-0.064	2.07	6.23
0900	-1147.89	5.83	-2.08	0.083	-0.69	-0.25	-0.081	24.27	2.24
1000	-7.45	1.39	-0.09	0.076	-1.001	-2.33	-0.051	1.71	-0.17
1100	999.01	-0.46	0.57	-0.001	-0.02	-2.01	-0.073	13.7	-0.17
1200	123.93	1.030	2.42	0.023	-0.57	-0.81	-0.047	-0.46	0.045
1300	-1.89	0.14	0.29	-0.019	∞	-651.7	0.036	-10.29	0.119
1400	0.06	0.307	0.24	0.035	7.449	-86.57	-0.021	0.019	0.023
1500	0.21	4.291	0.31	-0.018	-99.42	-0.089	-0.075	0.390	0.044
1600	0.13	34.53	0.29	0.024	-10.57	-0.084	0.101	0.664	0.055
1700	0.12	0.47	0.88	0.056	-0.08	-0.69	-0.03	6.86	0.060
1800	0.37	0.40	1.72	0.177	-0.46	-1.35	0.277	4.78	0.184
1900	4.20	0.49	1.63	0.271	-0.124	-29.33	0.518	4.51	0.82
2000	9.74	0.39	72.58	0.73	-3.75	3.07	1.302	109.11	0.139
2100	5.47	5.39	69.43	1.19	-1.11	-3.77	4.48	0.557	0.711
2200	25.73	35.28	55.69	0.39	0.44		86.94	133.74	0.75
2300	11.43	3.106	48.69	0.33	0.851	-66.1	7.90	26.44	0.33
2400	4.37	1.137	2264.7	0.19	0.619	-5.44	5.08	6.54	1.303



Figs. 4(a&b). Variations of σ_θ with time in the (a) lower layer and (b) upper layer in rainy season at Satna

To characterise and quantify the atmospheric turbulence in Satna region during the Rainy season of year 2000 which are being presented in this paper, 10 different dates are being selected between 15 June to 15 August of year 2000 for the analysis. The period between 15 June and 15 August (about 2 months) covers the majority of monsoon season. In selecting these dates 6-7 days gap has been kept between two successive selected dates. The dates thus are 21 June, 28 June, 3 July, 9 July, 16 July, 21 July, 27 July, 2 August, 8 August and 15 August all in the year 2000.

Hourly average values of temperatures (5 levels), wind speeds (3 levels) and wind direction fluctuations (2 levels) are used as basic variables to compute the various turbulence parameters. Comparison of the hourly

TABLE 5(a)

Hourly (σθ) based turbulence classes for the lower layer on examined 10 days of year 2000

Time	Date									
	21 Jun	28 Jun	3 Jul	9 Jul	16 Jul	21 Jul	27 Jul	2 Aug	8 Aug	15 Aug
0100	A	E	A	C	C	B	E	E	A	D
0200	A	D	B	D	D	B	E	E	A	C
0300	C	C	C	D	D	C	F	A	D	D
0400	B	A	A	D	D	C	E	E	B	A
0500	D	D	E	D	D	C	F	E	B	E
0600	E	C	A	E	E	B	E	E	B	A
0700	A	A	A	D	D	A	D	D	A	B
0800	A	A	B	D	D	A	E	A	B	E
0900	A	B	A	C	C	B	E	B	C	D
1000	F	A	C	C	C	C	E	C	B	D
1100	A	A	C	C	C	C	D	E	C	E
1200	A	A	B	B	B	B	D	E	C	D
1300	A	A	B	C	C	A	A	E	B	D
1400	E	B	C	C	C	B	C	E	B	C
1500	D	D	C	C	C	B	D	E	E	B
1600	E	C	C	D	D	B	D	E	A	B
1700	E	D	A	A	A	B	D	C	A	A
1800	E	D	A	C	C	D	E	D	A	D
1900	D	C	A	D	D	E	D	E	A	A
2000	E	E	A	B	B	E	E	E	A	A
2100	E	A	A	E	E	D	E	E	D	A
2200	E	D	C	E	E	C	D	F	D	C
2300	E	A	D	E	E	C	E	E	E	A
2400	E	B	F	D	D	E	D	E	E	A

TABLE 5(b)

Hourly Turner's table based turbulence classes for the lower layer on examined 10 days of year 2000

Time	Date									
	21 Jun	28 Jun	3 Jul	9 Jul	16 Jul	21 Jul	27 Jul	2 Aug	8 Aug	15 Aug
0100	D	D	F	D	D	E	D	D	E	F
0200	F	E	E	F	F	D	D	D	E	F
0300	E	E	E	E	E	D	D	D	E	F
0400	E	F	E	E	E	D	D	D	D	F
0500	E	E	D	E	E	D	D	D	D	F
0600	F	F	D	D	D	D	D	D	D	F
0700	B	B	C	C	C	C	D	D	C	B
0800	B	B	C	C	C	C	D	D	C	C
0900	B	C	C	C	C	C	D	D	D	C
1000	A-B	B	B-C	B-C	B-C	C-D	D	C-D	D	B-C
1100	B	B-C	C-D	B-C	B-C	C-D	D	C-D	D	C-D
1200	B-C	B-C	C-D	C-D	C-D	C-D	C-D	C-D	D	C-D
1300	C	B	C	C	C	C		C	C	B
1400	C	C	C	C	C	C	C	C	C	B
1500	C-D	C-D	C-D	C-D	C-D	C-D	D	C-D	D	B-C
1600	C-D	C-D	C-D	D	D	C-D	C-D	C-D	C-D	B-C
1700	D	C	C	C	C	D	D	D	C	C
1800	C	D	C	C	C	D	D	D	C	C
1900	D	D	D	D	D	D	D	D	D	F
2000	D	D	F	D	D	D	D	D	D	F
2100	D	E	D	D	D	D	D	D	D	D
2200	E	F	D	D	D	D	E	D	D	F
2300	D	D	D	D	D	D	D	D	D	F
2400	D	D	D	D	D	D	D	E	D	F

TABLE 5(c)

Hourly lapse rate based turbulence classes for the lower layer on examined 9 days of year 2000

Time	Date								
	21 Jun	28 Jun	3 Jul	16 Jul	21 Jul	27 Jul	2 Aug	8 Aug	15 Aug
0100	F	F	F	F	E	D	F	F	F
0200	F	F	F	E	E	D	F	F	F
0300	F	F	F	E	E	E	F	F	F
0400	F	F	F	E	E	E	F	F	E
0500	F	F	F	E	E	E	F	F	E
0600	F	F	F	E	E	D	F	F	E
0700	F	F	F	E	E	E	F	F	E
0800	A	F	D	E	A	D	C	F	E
0900	A	F	D	E	A	A	A	E	E
1000	A	E	D	E	A	A	A	E	D
1100	F	D	E	E	D	A	A	E	D
1200	E	F	E	D	A	B	A	E	E
1300	D	E	E	D	A	A	E	C	E
1400	E	F	E	E	F	A	D	D	D
1500	F	F	E	D	A	D	D	E	E
1600	F	F	E	D	C	C	E	F	E
1700	F	F	F	E	D	A	D	F	E
1800	F	F	F	E	D	A	E	F	E
1900	F	F	F	E	D	C	F	F	F
2000	F	F	F	F	D	E	E	F	E
2100	F	F	F	F	D	D	F	F	E
2200	F	F	F	E	E	C	F	F	E
2300	F	F	F	F	E	C	F	F	E
2400	F	F	F	E	E	D	F	F	E

TABLE 5(d)

Hourly SODAR based turbulence classes for the lower layer on examined 9 days of year 2000

Time	Date								
	21 Jun	28 Jun	3 Jul	16 Jul	21 Jul	27 Jul	2 Aug	8 Aug	15 Aug
0100	-	E	F	F	E	E	E	F	F
0200	-	E	F	F	F	E	E	F	F
0300	F	E	F	F	E	E	E	F	F
0400	F	E	E	E	E	F	E	E	F
0500	F	E	F	F	E	F	E	E	F
0600	F	E	C	F	E	F	E	E	F
0700	B	E	B	B	E	E	E	E	E
0800	B	B	A	B	B	C	B	E	B
0900	B	A	A	B	B	C	B	B	C
1000	B	A	A	B	B	B	A	B	B
1100	B	-	A	B	B	C	B	B	B
1200	B	A	A	-	B	B	B	B	B
1300	B	A	A	A	B	B	B	A	B
1400	C	A	A	A	B	B	B	B	B
1500	F	A	A	A	D	C	B	B	B
1600	F	B	B	A	D	D	B	B	C
1700	F	B	B	B	D	E	E	B	C
1800	F	B	C	D	D	E	E	B	C
1900	D	E	D	F	D	-	E	F	E
2000	-	E	-	F	-	-	E	F	E
2100	-	E	F	F	F	-	E	F	F
2200	-	E	E	F	F	F	E	F	F
2300	E	E	E	F	F	F	E	F	F
2400	F	E	F	F	E	E	E	E	F

turbulence classes (Demarrais, 1978) based on σ_θ, Lapse rate, Turner's table and Sodar technique is done.

4. Results and discussion

4.1. *Variations of hourly average lapse rate with time*

Due to availability of temperatures at five different heights we have considered four separate layers of atmosphere above ground level. These layers are between 10-40 meters, 40-60 meters, 60-80 meters, 80-106 meters above ground level. Hourly lapse rates are calculated separately for the four layers and these hourly lapse rates are averaged for the 10 selected dates to represent the whole season and plotted against time of the day in Fig. 3.

Temperature gradient for Ist layer (between 10-40 meters) is negative for only a few hours 0900-1400 hours. Rest of the time it is positive. It means that this layer warms up due to convection from earth surface and by this some thermal turbulence is created during the period 0900-1400 hrs. Rest of the time the layer would be thermally non-turbulent and stable. Layer IInd (40-60 meters) shows positive thermal gradient for all the 24 hours. This layer almost blocks the transfer of thermal energy or pollutants from the layer just above it to its adjacent lower layer, or *vice versa* during almost the entire day during rainy season and have extremely low turbulence.

The plots of IIIrd (60-80 m) and IVth (80-106 m) layer show a very different situation. Through-out the day and night period, there is continuous turbulent situation in these layers and could be treated as a single layer. It clearly indicates that there is a kind of discontinuity between lower and upper layers almost all the 24 hours. This situation has significant practical importance from heat and dispersion point of view.

4.2. *Richardson number (Ri)*

Ri is the measure of resultant turbulence caused due to wind and temperature profiles. For the two layers the hourly values of Ri_{106-40} show a similar pattern as was observed for lapse rate values since Ri largely depends on the lapse rate. Calculated values of Ri are given in Tables 4(a&b). Magnitude wise there are certain unusual values. From the table we draw the following inferences :

(*i*) Around 80 % Ri_L (Ri_L- Richardson number value for the lower layer) values are positive, indicating high resistance to turbulent dispersion.

(*ii*) Around 16 % Ri_L values are very high (more than 25)

(*iii*) There is no definite trend behind the occurrence of high positive or high negative Ri_L values.

(*iv*) Most of the Ri_U (Ri_U- Richardson number value for the upper layer) values are negative throughout the day and night periods indicating good turbulence and dispersion.

From above data and discussion we can say that on the basis of Ri in rainy season the lower layer was turbulent only for a very short period of a day. On the other hand the upper layer was mostly and significantly turbulent. The reason of upper layer turbulence was high wind speed and super-adiabatic lapse rate all the 24 hours in the upper layer. The reason of high Ri values (both positive and negative) is related to the very low values of Δu between 40 and 10 meter or 106 and 40 meter height.

4.3. *Variations of σ_θ with time*

σ_θ is a measure of lateral component of turbulence. The measured values of σ_θ at 10 m and 106 m height above GL [Fig. 4(a&b)] show that

(*i*) From 1800-0600 hours there a relatively non-turbulent situation whereas neutral situation also sometimes occurs during these hours but its percentage is very less compared to the non-turbulent or least turbulent situation period.

(*ii*) From 0700-1500 hours there exists a relatively turbulent situation, since during this period the wind direction fluctuations are high enough as compared to the rest of the day.

(*iii*) Turbulence even during night which helps in lateral dispersion unlike the largely barred vertical dispersion.

(*iv*) Wind direction fluctuations (σ_θ) values measured at 106 meter height were very high throughout the day and night periods. Thus there is high level lateral turbulence which helps in dispersion of pollutants in the upper layer.

4.4. *Pasquill's turbulence or stability classes*

Comparison among hourly turbulence classes by four different approaches for the lower layer (up-to 40 m above GL) is given in Tables 5(a-d). General conclusions regarding the comparison of turbulence classes are as follows :

(*i*) *By Turner's Table* - The lower layer is neutral for most of the hours in a day. From 0200-0600 hours this neutral situation is partially shifted towards non turbulent situation. On the other hand from 0700 to 1600 hours it is shifted towards turbulent situation.

(*ii*) *By Lapse rate based criteria* - This layer is completely non-turbulent for all the 24 hours. Only during noon period (1100 to 1500 hours) this non-turbulent nature partially shifted towards neutral situation.

(*iii*) *By σ_θ values* - From 1800-0600 hours majority of hours are occupied by non turbulent situation and partially by neutral situations. During 0700 to 1600 hours this layer is turbulent from σ_θ value criteria.

(*iv*) *By SODAR based criteria* - SODAR observations show turbulent situation from 0800 to 1600 hrs. Rest period is completely non-turbulent.

Comparing the results we can say that

(*i*) Turner's Table based turbulence class is by and large invariable throughout the day and night periods.

(*ii*) Lapse rate based turbulence class shows non-turbulent nature for the entire day and night periods for this layer.

(*iii*) Turner's Table and SODAR criteria show common turbulent hours throughout the day and night periods.

5. Conclusions

The layer close to ground level is non-turbulent for majority of hours. Due to rain sometimes there is continuous negative lapse rate. From sunrise (0700) to afternoon (1400) hours lower layer has effect of convective heat transfer from earth surface and becomes turbulent. Upper layer is turbulent throughout the day and night period due to high wind speed and high σ_θ values.

The experimentation could identify the discontinuous behaviour of atmosphere close to earth surface. From pollution dispersion point of view in rainy season pollutants should not be released below 60 meter height from GL. Combination of σ_θ for lateral turbulence and lapse rate for vertical turbulence based criteria to compare hourly turbulence class would be suitable. SODAR or even Turner's Table could replace the lapse rate based characterization of vertical turbulence but none of these would cover lateral part of turbulence, for which σ_θ appears the only criteria available.

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