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Clear air echoes from the atmospheric boundary layer over Chennai – A study using S-band Doppler Weather Radar

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सार – दिसम्बर 2002 से अप्रैल 2003 के प्रारम्भिक दिनों के दौरान, सांध्यकाल की अवधि में 2345 और 0215 यू. टी. सी. तथा 1230 और 1400 यू. टी. सी. के मध्य, चक्रवात संसूचन रेडार केन्द्र चेन्नई में संस्थापित डॉप्लर मौसम रेडार (डी. डब्ल्यू. आर.) से वायुमंडलीय परिसीमा स्तर में 28 से 38 डी. बी. जेड. तक की उँचाई से रेडार से प्राप्त हुई सूचनाओं का नियमित रूप से अवलोकन किया गया है। विश्लेषण करने पर यह पाया गया है कि रेडार से प्राप्त हुई सूचना बरसाती मेघों के संबंध में नहीं थी अपितु किसी अन्य अदृश्य स्रोतों से प्राप्त हुई थी। इतनी अधिक उँचाई से प्राप्त हुई इस सूचना को उपलब्ध कराने में सहायक क्रिया विधि का इस शोध पत्र में मौसम वैज्ञानिक और गैर मौसम वैज्ञानिक दृष्टिकोणों से विश्लेषण किया गया है। तापगतिकीय प्राचलों और संभावित रेडियों अपवर्तनांक का आकलन और विश्लेषण भी इसमें किया गया है। अपवर्तनांक संरचना स्थिरांक (C_n^2) का आकलन 0000 और 1200 यू. टी. सी. के रेडियोसोंदे/रेडियोपवन आँकड़ों और रेडार परावर्तकता आँकड़ों से किया गया है। 1200 यू. टी. सी. पर धरातल के समीप पहली परत (350 मी. ए. जी. एल. तक) में संवहनीय रूप से अस्थिर वायुमंडल और 0000 यू.टी.सी. धरातल पर रात्रिकालीन प्रतिलोमन के कारण 900 मी. ए. जी. एल. तक के स्तरों में 3.58×10^{-12} से 10^{-15} मी.$^{-2/3}$ की परिधि में C_n^2 में वृद्धि का पता चला है। इस प्रकार की उच्च C_n^2 के ब्रैग प्रकीर्णन की वजह से रेडार परावर्तकता गुणक +0.8 डी. बी. जेड तक उँचा रहा है। पिछले तीन दशकों के दौरान, अनुमानतः फंसे हुए धूल के कण और अंतःश्वसनीय धूल कण की उच्च सांद्रता के कारण चेन्नै में धरातल के रात्रिकालीन प्रतिलोमन में चिंताजनक वृद्धि हुई है। रेडार परावर्तकता गुणक में इन प्रदूषकों का अधिकतम योगदान लगभग –0.9 डी. बी. जेड तक सीमित रहा है। 10–50 से. मी.^{2} रेडार के क्रास सेक्शन से लगभग आठ से बारह हजार तक प्रवासी पक्षियों की संख्या में हुई वृद्धि और कीटों की असंख्य बढ़ी हुई संख्या के कारण परावर्तकता में वृद्धि पाई गई है।

ABSTRACT. During December 2002 – early April 2003, between 2345 and 0215 UTC and between 1230 and 1400 UTC covering the twilight period, radar reflectivities as high as 28-38 dBZ were measured in the atmospheric boundary layer by the Doppler Weather Radar (DWR) installed at Cyclone Detection Radar station, Chennai regularly. On analysis, it was found that these radar returns were not from precipitating clouds but from some other invisible source(s). The contributory mechanisms for this high order of reflectivity have been analysed from meteorological and non-meteorological angles. Thermodynamical parameters and potential radio refractive index have been computed and analysed. The refractive index structure constant (C_n^2) has been computed from the 0000 and 1200 UTC RS/RW data as well as from the radar reflectivity data. The prevalence of convectively unstable atmosphere in the first layer adjacent to the surface (upto 350 m a.g.l) at 1200 UTC and nocturnal surface inversion at 0000 UTC contribute to the enhanced C_n^2 in the range of 3.58×10^{-12} to 10^{-15} m$^{-2/3}$ in the layers upto 900 m a.g.l. This sort of Bragg scattering with high C_n^2 could have contributed to radar reflectivity factor as high as +0.8 dBZ only. During the last three decades, there is an alarming increase in nocturnal surface inversion frequencies over Chennai presumably due to high concentration of suspended particulate matters and respirable dust particles. The contribution by these pollutants to the radar reflectivity factor is restricted to a maximum of about – 0.9 dBZ only. Migratory birds of about eight to twelve thousand in number with 10 – 50 cm^2 radar cross section and possibly innumerable insects appear as sources of the enhanced reflectivity.

Key words – Doppler weather radar, Refractive index, Refractive turbulence structure constant (C_n^2) Birds, Insects, Radar ornithology, Inversion, Humidity, Boundary layer, Twilight.

1. Introduction

Weather radars measure detectable power from meteorological as well as non-meteorological targets. Clear air echoes, often known as 'angels' in radar meteorology have been studied since late 1940s. The possible cause of these clear air echoes were considered to be from insects, birds and gradient of refractive indices /

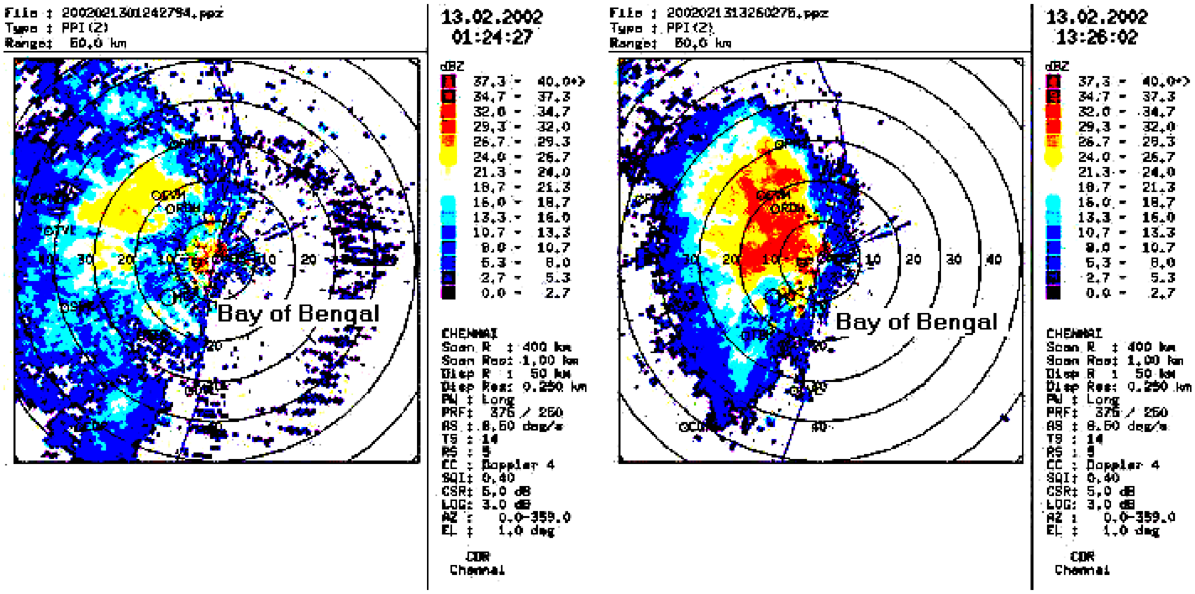


Fig. 1. Plan position indicator display of clear air reflectivity (1° elevation) at 0124 and 1326 UTC on 13 February 2002. Range circles are 10 km apart

Bragg scattering (Atlas, 1959) in the earliest studies. Careful examination and interpretation of these clear air returns help to get weather information, especially the information about winds, gust front, atmospheric stability, turbulence etc. A detailed review on clear air reflectivity studies may be seen in the celebrated publications of Gossard and Strauch (1983), Atlas (1990), Sauvageot (1992), Doviak and Zrnic (1993) and Rinehart (1999). Radar studies on lower and middle atmosphere throughout the world during late 1970s not only highlighted the necessity of studying the refractivity turbulence structure constant (C_n^2) in view of its important role in parameterising turbulent scatterers and attenuation but also stressed the importance to build its climatology (Green *et al*., 1978; Gage *et al*., 1978). A number of studies on the variability of C_n^2 have been conducted using X-band/S-band and VHF and UHF radars and a detailed review may be seen, for example, in Kropfli (1981) and Hardy and Gage (1990). Though inhomogeneities of the refractive index are ubiquitous in the atmosphere, Bragg scattering can be detected only when half the radar wavelength ($\lambda/2$) exceeds the cut-off wavelength (λ_c) at the limit between the inertial domain and the viscous dissipation range of the atmospheric turbulence. Strauch *et al*. (1984) proved that λ_c is more than 2 cm near the ground and increases with altitude. Kropfli (1981) opined that S-band radar is quite suitable for the atmospheric boundary layer (ABL) clear air studies in view of its spatial resolution and transmitted power besides its sensitivity to refractive index fluctuations. An attempt has been made in this paper to study the ABL over Chennai using the data obtained from the 10.43 cm wavelength S-band Doppler Weather Radar (DWR) of the India Meteorological Department (IMD) at Chennai. Interesting results on the variability of C_n^2 and some information about the radar ornithology have been presented in this paper.

2. Observations

A state-of-the-art DWR of M/s Gematronik GmbH, Germany make has been made operational at Cyclone Detection Radar station, Chennai (13° 05.031′ N / 80° 17.400′ E) with effect from 20 February, 2002 (Bhatnagar *et al*., 2003; Suresh, 2004). The radar has been well calibrated for all its functional components. A number of scan strategies, depending on the operational requirements, have been adopted and they are put in a cyclic loop with pre-defined repetition time varying between 20 and 30 minutes. The scan strategies which were frequently in use during February 2002 - April 2003 have been furnished in Annexure I. DWR data [radar reflectivity factor (*Z*), radial velocity (*V*) and spectrum width (*W*)] for the period December 2002 – April 2003 have been used.

During late December 2002 to early April 2003, radar reflectivity factor (*Z*) as high as 38 dBZ had been

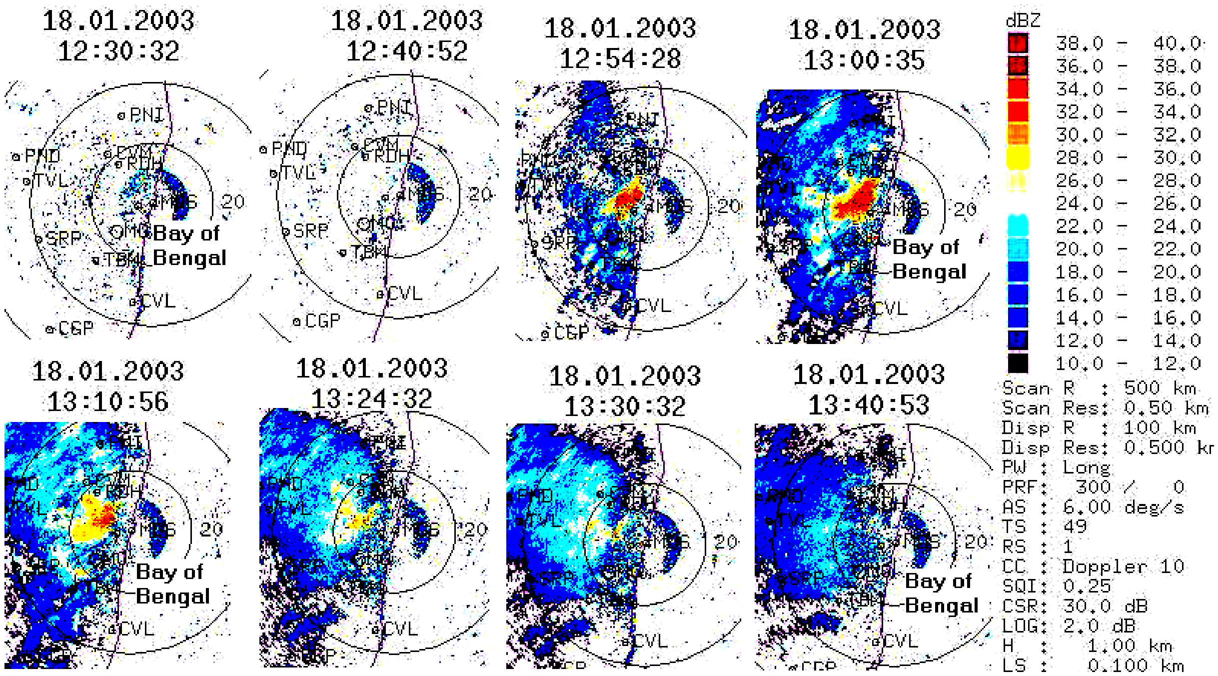


Fig. 2. Maximum display of reflectivity between surface and 1.0 km height (layer spacing 100 m) on 18 January 2003 between 1200 and 1400 UTC. The range circles are at 20 km interval

measured in the ABL by DWR, Chennai between 1230 and 1400 UTC; between 2345 and 0215 UTC, it was in the range 24 – 32 dBZ. For the sake of convenience, the *Z* is usually expressed in logarithmic form, *viz*., dBZ. During the rest of the day the reflectivity was quite normal (the reflectivity factor in dBZ was negative with occasional maximum of –4 dBZ) as that could be expected from clear air in the ABL. A typical plan position indicator (PPI) display at 1° elevation at 0124 and 1326 UTC of 13 February, 2003 (date selected at random) has been shown in Fig. 1. At 0124 UTC the maximum *Z* was 28 dBZ and it was 34 dBZ at 1326 UTC between 10 and 30 km radius in the west to northwest sector. This sort of high *Z* was measured by the DWR, Chennai on all days during the said period and there was very little change in the peak intensity on day-to-day basis. However, it may be mentioned that there was no rain over the areas where high *Z* was measured.

3. Methodology

The plausible contributory causes for the high radar reflectivity (under non-precipitation weather conditions) from cloud mantle echoes, particulate scattering including from biota (birds and insects) and Bragg scattering have been examined in-depth for the period under consideration. On a birds' eye view of the literature we have surveyed, the maximum radar return from insects and birds may not exceed 28 dBZ and that from the inhomogeneities of refractive index is restricted to a few dBZ (usually negative dBZ) only (Atlas, 1990; Doviak and Zrnic, 1993; Sauvageot, 1996; Rinehart, 1999 and a few web sites listed as "Additional references" in this paper) with an exception by Achtemeier (1991) who reported clear air echoes as high as 40 dBZ from dense cloud of large insects over North Dakota. In this paper we consider 10 dBZ as the lower limit to study the cause of the enhanced *Z* from clear air based on Gossard (1990) and Knight and Miller (1993). Clear air returns may be due to refractive index inhomogeneities, returns from suspended particulate matter (SPM), biota (insects and birds), ground clutter and anomalous propagation (AP) or from non-precipitating low clouds. We computed stability parameters, radio refractivity index (RRI), potential RRI and their gradients, refractivity structure constant for studying the clear air returns. Ornithological observations and studies over Chennai were examined to explain the cause for enhanced *Z* during specific periods of the day.

4. Data used

Climatologically and as per the weather records maintained by the Regional Meteorological Centre, IMD, Chennai the amount of low clouds is the least at 0000, 1200 and 1500 UTC during January – April and the average number of rainy days during January – April varies between 0.3 and 1.0 (IMD, 1999). As there was practically no rainfall activity from 7 December, 2002 to 15 March, 2003 over Chennai, the radar reflectivity factor from 0000 to 0300 UTC and 1200 and 1500 UTC during this period was attributed to clear air returns only. Insect population is maximum during some specific season (say summer in temperate and sub-tropical areas) since favourable flight thresholds of insects (10° – 20° C) prevail in the ABL during these periods (Russell and Wilson, 1997). Similar studies on insect population over and around Chennai are not available. However the closest temperature threshold may exist only during winter over Chennai. Hence this study has been restricted to December – early April. Moreover, according to ornithologists and naturalists, the population of migratory birds is at its peak only during December – March over Chennai (Gurusami, personal communication).

For studying the stability of the atmosphere and to compute the radio refractive index, RS/RW data (recorded at significant levels and at every minute during its flight) of Chennai for the period December 2001 – April 2003 have been used. Three hourly auxiliary synoptic observation data of meteorological observatory, Meenambakkam, Chennai and Area Cyclone warning Centre, Nungambakkam, Chennai and half-hourly current weather reports (METARs) of airport meteorological office, Meenambakkam, Chennai for the period December 2002 – April 2003 were also considered to compare the measured *Z* value with the type of clouds (fair weather or convective or rain bearing), if any, and to work out surface radio refractive index.

5. Results and discussion

Although we have critically analysed the cause of enhanced *Z* throughout the period of study, only a few cases (selected at random) have been presented in this paper for discussion. However, summary for the entire period of study has been highlighted wherever it is relevant. Fig. 2 depicts the value of maximum *Z* over each vertical column, between surface and 1.0 km height (H) with a interpolated layer spacing (LS) of 0.1 km, derived from volume scans of different scan strategies adopted on 18 January, 2003 between 1200 and 1500 UTC. The *Z* value was less than –10 dBZ at 1130 UTC (not shown) and increased to 38 dBZ at 1300 UTC and then dropped to less than 0 dBZ after 1400 UTC (not shown). The maximum *Z* value was measured between the altitudes 100 and 500 m. During December 2002 – April 2003, we have observed, in general, that the height of enhanced *Z* was restricted to less than 700 m and the peak value of *Z* was measured around 200-400 m. In the absence of precipitating clouds, the cause of this enhanced reflectivity has been analysed in-depth and presented in the following sub-sections. Since appropriate Doppler filters to remove clutter have been used in each scan strategy, the impact of ground clutter on clear air return has been ruled out in the present study and hence the ground clutter is not considered for further analysis.

TABLE 1

Variability of thermodynamical parameters and vertical gradients of potential temperature, potential vapour pressure and potential radio refractive index at 1125 UTC of 18 January 2003 over Chennai

Height (m)	Pressure (hPa)	Temp (°C)	Dew pt (°C)	θ (°K)	P_{wo} (hPa)	$\partial\theta/\partial z$ (°K/km)	$\partial P_{wo}/\partial z$ (hPa/km)	$\partial\varphi/\partial z$ (N/km)
15	1012.9	26.8	20.1	298.9	23.5	-	-	-
406	968.8	22.0	21.9	297.8	26.3	-2.59	9.96	45.8
703	936.3	20.1	20.0	298.8	23.4	3.32	-7.23	-35.7
1123	891.8	17.7	17.7	300.5	20.2	4.07	-5.38	-28.6

Note : Temp – Temperature; Dew pt – Dewpoint temperature; Gradients ($\partial\varphi/\partial z$, $\partial\theta/\partial z$ and $\partial P_{wo}/\partial z$) are from the immediate lower level to the level where values have been furnished.

5.1. *Radio Refractive Index (RRI) and potential RRI over Chennai*

In order to ascertain the possible contribution by inhomogeneities of refractive index, RRI has been computed for 1125 UTC of 18th January from the Chennai RS/RW data. We have used the well known formula for computing RRI, *viz.*,

$$N = (77.6/T)\,(P + 4810\,e\,/\,T) \qquad (1)$$

where $N = (n\text{-}1) * 10^6$, *n* is the atmospheric refractive index, *T* is the temperature (°K), *P* is the atmospheric pressure (hPa) and *e* is the water vapour pressure (hPa). Since *T* and *e* are not conserved when a parcel of air is displaced vertically, *N* is not conserved. The vertical gradient of *N* from the surface to 406 m, 406 to 703 m and 703 m to 1123 m were 19.54, –60.75 and –52.24 *N* units km^{-1} respectively. These gradients confirm that there was no super-refraction (ducting or AP) as none of the gradients was less than –157 *N* units km^{-1} (Doviak and Zrnic, 1993; Rinehart, 1999). Moreover, even had there been AP, it would have been filtered by the selected Doppler filter of notch width ± 1 ms^{-1}. Hence the measured *Z* values were real and not resulted from AP.

For the interpretation of clear air returns we are concerned with turbulence processes in which heat and moisture are conserved and assume that the parcel follows an adiabatic process with neither condensation nor

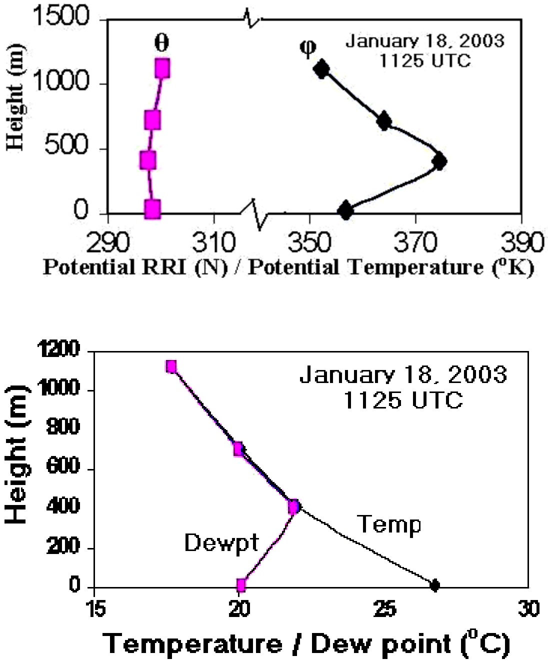


Fig. 3. Vertical profiles of temperature, dew point, potential RRI (φ) and potential temperature (θ) at 1125 UTC on 18 January 2003. Both dry bulb and dew point temperature are nearly equal in the layer between 406 and 1123 m (see Table 1 also)

evaporation taking place. Hence a parameter that is conserved, *viz.*, potential refractive index in N units has been defined by Bean and Dutton (1966) as

$$\varphi = (77.6 / \theta)\,(P_o + 4810 P_{wo} / \theta) \qquad (2)$$

where θ is the potential temperature, $P_{wo} = e\,(P_o\ /\ P)$ is the potential water vapour pressure and P_o is the reference pressure usually set to 1000 hPa. φ is conserved as θ and P_{wo} are conserved properties of air parcel. For a detailed description of potential RRI and its relative advantage over RRI, [Gossard (1990) and Doviak and Zrnic (1984 and 1993)]. Fig. 3 shows the vertical profiles of φ, θ, temperature and dew point at 1125 UTC of 18th January.

Table 1 lists the vertical distribution of the thermodynamical variables obtained from RS/RW ascent released at 1125 UTC on 18 January, 2003 at Chennai. Super adiabatic lapse rate (12.3° C km^{-1}) that prevailed between the surface and the first layer (406 m) indicates the prevalence of absolute instability in this layer. In this layer the Richardson number was negative (far less than the threshold 0.25 for the onset of turbulence) suggesting that the turbulence was quite active. Moreover, dew point was increasing with height in this layer (Fig. 3) contrary to its usual decrease with height and the relative humidity was nearly 100% from 406 to 1123 m. Hence we may conclude that the absolute instability together with dew point inversion probably explains the increase of φ with height ($\partial\varphi/\partial z > 0$) in the layer adjacent to surface. More over, as φ varies directly with P_{wo} and inversely with θ, opposite gradients of these two terms (*viz.*, $\partial\theta/\partial z$ and $\partial P_{wo}/\partial z$) contribute to increased $\partial\varphi/\partial z$ in that particular layer (Doviak and Zrnic, 1993). The opposite gradients of P_{wo} and θ (Table 1) re-confirms that φ has increased in the first layer (immediately above the surface). In view of weak turbulence / stability prevailing in the higher layers (positive $\partial\theta/\partial z$), φ was decreasing with height above the first layer.

5.1.1. *Vertical gradients of φ and θ*

As has been mentioned earlier, since φ depends linearly on humidity and inversely on stability, opposite gradients of P_{wo} and θ contribute to increase in $\partial\varphi/\partial z$ and hence to enhanced reflectivity. Hence, we worked out the potential RRI and potential temperature at 0000 and 1200 UTC for all days for the period December 2002 to March 2003 and the layer mean vertical gradients of temperature (T), dew point temperature (T_d), φ and θ have been tabulated in Table 2. Though the mean layer values mask the day-to-day variability, an overall idea about the thermodynamical parameters that contribute to the stability of the atmosphere, potential RRI and hence to the radar reflectivity can be obtained from this Table. It can be seen that at 1200 UTC the convective instability (*i.e.*, $\partial\theta / \partial z < 0$), though of less magnitude, prevails in the first layer adjacent to the surface (except during January) and convective stability aloft whereas at 0000 UTC convective stability extends throughout the boundary layer with very strong stability (because of nocturnal inversion) in the first layer adjoining surface.

This has been supported by the steep temperature lapse rate exceeding 10° C km^{-1} prevailing over the first layer at 1200 UTC (except in January during which period 8.73° C km^{-1} prevailed). But at 0000 UTC negative lapse rate (inversion) prevailed. Since the $\partial\varphi/\partial z$ has never gone below –157 N unit/km, there was no super-refraction or ducting taking place in the first layer and there was no abnormality in the magnitude of $\partial\varphi/\partial z$. However during March, we observed positive gradient of $\partial\varphi/\partial z$ in the first layer at both 0000 and 1200 UTC in contrast to negative gradients that were seen during the other months. One possible explanation for the positive $\partial\varphi/\partial z$ could be that the humidity lapse rate (*i.e.*, $-\partial T_d / \partial z$) was negative (*i.e.*, humidity inversion) at both 0000 and 1200 UTC. The magnitude of the mean dew point lapse rate was very small because it is the average of both positive and negative gradients. Nevertheless, the predominance of humidity inversion over the lapse rate is evident from this

TABLE 2

Layer mean gradients of temperature, dew point, potential RRI and potential temperature at 0000 and 1200 UTC over Chennai, December 2002 - March 2003

Month & Year	Parameters	0000 UTC			1200 UTC		
		Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
December 2002	Thick(m)	15 – 319	319 - 608	608 – 898	15 – 324	324 - 620	620 – 966
	$\partial T / \partial z$	-7.13	7.32	8.11	10.14	8.83	6.61
	$\partial T_d / \partial z$	3.37	8.14	13.0	13.19	8.06	10.5
	$\partial \varphi / \partial z$	-30.18	-32.78	-53.96	-58.13	-29.56	-35.34
	$\partial \theta / \partial z$	16.85	2.4	1.63	-0.46	0.88	3.17
January 2003	Thick(m)	15 - 338	338 - 643	643 – 946	15 - 355	355 - 663	663 – 973
	$\partial T / \partial z$	-4.46	8.01	7.61	8.73	9.17	7.50
	$\partial T_d / \partial z$	4.46	9.8	11.32	7.54	7.68	11.88
	$\partial \varphi / \partial z$	-31.38	-42.67	-46.67	-28.85	-29.22	-43.16
	$\partial \theta / \partial z$	14.17	1.71	2.14	0.96	0.54	2.27
February 2003	Thick(m)	15 - 323	323 - 603	603 – 895	15 - 340	340 - 651	651 – 955
	$\partial T / \partial z$	-2.64	7.72	5.12	12.26	8.47	5.12
	$\partial T_d / \partial z$	3.12	7.31	16.8	11.75	10.44	14.81
	$\partial \varphi / \partial z$	-24.66	-37.22	-72.83	-47.16	-40.73	-65.19
	$\partial \theta / \partial z$	12.34	1.99	4.68	-2.58	1.24	4.70
March 2003	Thick(m)	15 - 311	311 - 590	590 – 872	15 - 323	323 - 609	609 – 898
	$\partial T / \partial z$	-3.35	7.10	4.90	11.14	7.30	4.94
	$\partial T_d / \partial z$	-5.36	13.29	13.27	-0.16	17.93	15.04
	$\partial \varphi / \partial z$	32.88	-66.95	-77.73	20.36	-98.09	-64.09
	$\partial \theta / \partial z$	13.05	2.59	4.88	-1.47	2.42	4.86

Thick = the thickness of the layer in m.

$-\partial T / \partial z$ = Lapse rate of dry bulb temperature (°C km^{-1}), $-\partial T_d / \partial z$ = Lapse rate of dew point temperature (°C km^{-1}),

$\partial \varphi / \partial z$ = Vertical gradient of potential RRI (N units km^{-1}), $\partial \theta / \partial z$ = Vertical gradient of potential temperature (°K km^{-1})

averaged negative value during March 2003. In order to further enquire into the cause of this positive gradient of φ, we analysed the temperature, humidity data derived through RS/RW ascents and the results are discussed in the next sub-section.

5.1.2. *Surface temperature and humidity inversion at 0000 and 1200 UTC during December – March*

The strength of lapse rate/inversion of dew point and dry bulb temperature from surface to the layer reported at the first minute of RS/RW ascent have been computed for 0000 and 1200 UTC for the period December 2002 – March 2003. The results are summarized in Tables 3(a&b). A quick look at the Table 3(a) reveals that humidity inversion was taking place at 0000 UTC nearly on 50% of the days during December – February while during March the humidity inversion was seen in 24 out of 30 days. Also it can be seen from Table 3(b) that nocturnal surface inversion was observed on almost all days during December – January and the frequency was more than 71% during February and more than 83% during March. Table 3(c) compares the percentage frequencies of nocturnal surface inversion over Chennai during 1970-2003. A plausible contributory cause for the increased inversion frequencies during January – March, 2003 could be because of increased concentration (10^5 to 10^6 m^{-3}; 340 – 380 µg m^{-3}) of SPM of size 10 to 100 µm and respirable dust particles (RDP) of size less than 10 µm as measured on thrice weekly basis and reported by the Tamilnadu Pollution Control Board, Chennai (*Source* : The HINDU, Daily News paper, Chennai edition, January– March 2003). Surface inversion strength as high as 19.7° C km^{-1} was observed on 24th March. Turbulence, even if it is weak, traps the humidity within the inversion layer. The top of the inversion layer acts as a shield to prevent vertical transport of water vapour trapped in this layer. Layers of inversion restrain convective activity but cause fluctuations/irregularities of refractive index and

TABLE 3(a)

Monthly frequencies of gradient of dew point temperature between the surface and the first layer adjoining the surface over Chennai, December 2002 – March 2003

Month	0000 UTC, Dew point inversion (°C km^{-1})					0000 UTC, Dew point lapse rate (°C km^{-1})					
	NLR1	NLR2	NLR3	NLR4	Total	LR1	LR2	LR3	LR4	LR5	Total
Dec 2002	6	3	3	0	12	7	8	1	2	1	19
Jan 2003	7	5	0	0	12	6	6	2	5	0	19
Feb 2003	8	3	0	0	11	9	3	4	1	0	17
Mar 2003	11	10	3	0	24	5	1	0	0	0	6
	1200 UTC, Dew point inversion (°C km^{-1})					1200 UTC, Dew point lapse rate (°C km^{-1})					
Dec 2002	1	2	0	0	3	4	7	4	7	3	25
Jan 2003	8	1	1	0	10	3	7	6	1	3	20
Feb 2003	3	2	0	0	5	7	4	3	3	6	23
Mar 2003	7	1	0	1	9	4	6	1	0	0	11

NLR : Negative Lapse Rate; LR : Lapse Rate; NLR1 : 0 to –2° C km^{-1}; NLR2 : –2 to –4° C km^{-1}; NLR3 : -4 to –6° C km^{-1}; NLR4 : -6 to –8° C km^{-1}; LR1 : 0 to 2° C km^{-1}; LR2 : 2 to 4° C km^{-1}; LR3 : 4 to 6° C km^{-1}; LR4 : 6 to 8° C km^{-1}; LR5 : >8° C km^{-1}

TABLE 3(b)

Frequencies of gradient of dry bulb temperature between the surface and immediate next higher layer

Month	0000 UTC Temperature inversion							0000 UTC Temperature lapse rate			
	NLR1	NLR2	NLR3	NLR4	NLR5	NLR6	Total	LR1	LR2	LR3	Total
Dec 2002	1	2	6	5	5	9	28	1	1	1	3
Jan 2003	2	4	8	6	3	3	26	4	1	0	5
Feb 2003	2	6	6	1	1	4	20	0	4	4	8
Mar 2003	7	5	4	2	4	3	25	3	0	2	5

Month	1200 UTC Temperature inversion			1200 UTC Temperature lapse rate						
	NLR1	NLR2	Total	LR1	LR2	LR3	LR4	LR5	LR6	Total
Dec 2002	1	0	1	2	1	2	2	3	17	27
Jan 2003	0	0	0	0	1	3	11	8	7	30
Feb 2003	0	0	0	0	0	1	3	5	18	28
Mar 2003	1	0	1	1	0	0	4	2	12	19

NLR : Negative Lapse Rate ; LR : Lapse Rate,
NLR1 : 0 to –2° C km^{-1}; NLR2 : –2 to –4° C km^{-1} ; NLR3 : –4 to –6° C km^{-1} ; NLR4 : –6 to –8° C km^{-1};
NLR5 : –8 to –10°C km^{-1} ; NLR6 : < –10° C km^{-1} ; LR1 : 0 to 2° C km^{-1}; LR2 : 2 to 4° C km^{-1};
LR3 : 4 to 6° C km^{-1} ; LR4 : 6 to 8° C km^{-1}; LR5 : 8 –10° C km^{-1} ; LR6 : >10° C km^{-1}

TABLE 3(c)

Percentage frequencies of nocturnal surface inversion over Chennai

Year	January	February	March
1970-74[@]	27.0	30.0	23.0
1984-88[#]	31.0	33.1	Data not available
1995-98[#]	76.6	54.0	Data not available
2003	83.9	71.4	83.3

Source : [@] : IMD (1983); [#] : Suresh (1998 and 2002) thereby contributes to increased Z (Hennington *et al.*, 1976). Hence, we can believe that the humidity inversion in the layer adjoining the surface has contributed to the enhanced φ since φ depends linearly on humidity. As such the increased frequencies of humidity inversion explain positive gradient of φ in the first layer adjacent to the surface at 0000 UTC during March 2003. The steep lapse rate of temperature exceeding dry adiabatic lapse rate (DALR) on 12 out of 19 days [LR6 of Table 3(b)] at 1200 UTC during March 2003 could have contributed to enhanced φ in view of active turbulence (Richardson number being negative on these days) transporting water vapour and causing fluctuations/inhomogeneity in moisture field. The prevalence of humidity inversion (positive $\partial P_{wo}/\partial z$), steep lapse rate exceeding DALR (unstable stratification and negative Richardson number, negative $\partial \theta/\partial z$) in the layer adjacent to the surface and stable stratification aloft explain the enhanced φ in the first layer since opposite gradients of P_{wo} and θ increases $\partial\varphi/\partial z$. However the increase in φ does not directly indicate the possible cause for enhanced Z (*i.e.*, 24 – 36 dBZ) since the measured Z during the time of RS/RW observation (0000 and 1200 UTC) was between –10 and 4 dBZ only.

5.2. *Clouds*

Based on the three hourly auxiliary synoptic meteorological observations and half –hourly aviation current weather observations (METARs), only 2 okta Sc clouds with base at 600 m were reported at 1200 UTC and this low cloud vanished at 1500 UTC. Taking into account of maximum possible drop size distribution (drop size maximum of 27µm with a maximum concentration density of 40 cm^{-3}) of the maritime non-precipitating Sc clouds (Wallace and Hobbs, 1977), Z can never exceed –18 dBZ. Even by assuming that Sc clouds developed into fair weather Cu rapidly, the radar return can never exceed 10 dBZ (Knight and Miller, 1998). Hence it is most unlikely that Z of more than 28 dBZ could be from these innocuous clouds.

5.3. *Scattering from suspended particulate matter*

Radar reflectivity contribution from SPMs (of size > 10 µm) and RDPs (of size < 10 µm) have been computed using the formula given by Erkelens *et al.*, 1999) based on the average concentration of these pollutants as published by the Tamilnadu Pollution Control Board, Chennai ('The HINDU', daily news paper, Chennai edition). The Z could be normally of the order of - 25 to - 20 dBZ (resulting from particles of 55-68 µm and concentration of about 10^{5} m^{-3}) with a very rare possibility of peak value of –0.9 dBZ (from particulates of size 100 µm size and concentration 10^{5} m^{-3} in the volume sampled). Hence the contribution by air pollution sources to the observed level of enhanced Z (*i.e.*, $Z > 10$ dBZ) is ruled out.

5.4. *Refractivity turbulence structure constant (C_n^2)*

C_n^2 plays an important role in parameterising turbulent scatter and attenuation and it may be used to estimate the mean turbulent dissipation rate besides its dominant role in the propagation of electromagnetic waves through turbulent atmosphere (Tatarskii, 1971; Gage *et al.*, 1978). The enhancement in C_n^2 may be attributed to increased gradients of refractive index or increased turbulence intensity or both (Green *et al.*, 1978). C_n^2 is related to the radar reflectivity (η) from turbulent scatterers by

$$C_n^2 = \lambda^{1/3}\ \eta / 0.38 \qquad (3a)$$

where λ is the wavelength of the radar (Atlas *et al.*, 1966; Ottersten, 1969). If the true nature of the scatterers is not known, a quantity called effective or equivalent reflectivity factor (often denoted by Z_e) can be used (Knight and Miller, 1993; Russell and Wilson, 1997). By analogy with Z for Rayleigh scattering by particles, Z_e is defined as

$$Z_e = \lambda^4\ \eta / (\pi^5 |K|^2) \qquad (3b)$$

Z_e has standard units of radar reflectivity factor, *viz.*, mm^6 m^{-3}. Combining Eqn. (3a) and (3b), we get

$$C_n^2 = 2.976 \times 10^{-12} \times Z_e\ \text{m}^{-2/3} \qquad (3c)$$

for λ = 10.43 cm Chennai S-band DWR, assuming $|K|^2 = 0.93$ for water.

Theoretical postulation by Tatarskii (1971) states that C_n^2 depends on the outer scale of the turbulence (L_o) and the mean gradient of refractive index (M). (*i.e.*)

$$C_n^2 = a^2\ \alpha^{/}\ L_o^{\ 4/3}\ M^2 \qquad (4)$$

where q is the specific humidity, p and T are the atmospheric pressure and temperature respectively and M is given by the relation

$$M = -77 \times 10^{-6}\ (p / T) \times [(\mathrm{dln}\ \theta / \mathrm{dz}) + (15500\ q / T)\ (\mathrm{dln}\ \theta / \mathrm{dz}) - 7800\ (\mathrm{d}q / \mathrm{dz})] \qquad (5)$$

In Eqn. 4, a^2 is considered as a universal constant 2.8 and $\alpha^{/}$ which is a ratio of eddy diffusivities is normally considered as unity. In the first one or two kilometres of the troposphere, it has been established based on structure parameter data from airborne measurements and mean values measured with 10 cm radars that the lower limit of the inertial subrange is as low as a few centimetres (Gage, 1990; Doviak and Zrnic, 1993).

In an excellent historical review of clear air radar returns by Hardy and Gage (1990), the upper limit of the inertial subrange has been normally restricted between 1 and 10 m though a few higher values of L_o were also reported. VanZandt *et al.* (1981) arrived at L_o = 10 m, based on theoretical model for the computation of C_n^2 using Eqn. 4 from the archival of RS/RW data, even within the turbulent layers. In the middle and upper troposphere (between 4 and 20 km a.g.l.), C_n^2 values in the range of 10^{-16} to 10^{-20} $m^{-2/3}$ have been measured using Mesosphere - Stratosphere - Troposphere (MST) radar at Gadanki (13.45° N / 79.18° E), a place 110 km NW of Chennai, by many Indian scientists (Narayana Rao *et al.*, 1997; Ghosh *et al.*, 2001). In the absence of any previously established value for the outer scale length of turbulence spectrum for Chennai, we also considered L_o = 10 m (as this value has been used by many researchers) and computed C_n^2 based on 0000 and 1200 UTC RS/RW data for December 2002 – March 2003. These values are little higher than that have been published in Sarkar *et al.* (1985). The layer mean values of C_n^2 in the boundary layer between 100 and 900 m are of the order of 10^{-12} $m^{-2/3}$ over Chennai (Table 4). This is in agreement with a theoretical model of C_n^2 values postulated in Burk (1978) to the effect that values larger than 10^{-12} $m^{-2/3}$ is quite possible upto 1 km a.g.l. in the marine boundary layer.

Though the computed values fairly agree well with clear air studies conducted elsewhere using 10 cm DWRs in the convective boundary layers and frontal zones [Doviak and Berger (1980), Gossard (1990)], it appears that these values are on the higher side when compared to some of the boundary layer studies made in the higher latitudes/extra-tropics in stable atmospheric conditions. Hence, we wanted to look into the reason for the relatively high value of C_n^2 during the study period. By regressing C_n^2 derived from RS/RW data using Eqn. 4, assuming L_o = 10 m, with that derived from DWR data using Eqn. 3c, at collocated points (close to RS/RW observatory) for the period December 2002 – February 2003, we empirically estimated the value of L_o as 5.5 m. The layer mean C_n^2 values are 0.131×10^{-12} $m^{-2/3}$ at 210 m, 0.763×10^{-13} $m^{-2/3}$ at 554 m and 0.469×10^{-13} $m^{-2/3}$ at 913 m based on 1125 UTC RS/RW data of 18th January with L_o = 10m. The corresponding values derived using L_o = 5.5m are 0.590×10^{-13} $m^{-2/3}$, 0.344×10^{-13} $m^{-2/3}$ and 0.211×10^{-13} $m^{-2/3}$ respectively. A comparative plot of C_n^2 based on L_o = 10m and L_o = 5.5m with that derived from DWR data using Eqn. 3c, for an independent time of observation on 5 March, 2003 has been shown in Fig 4(a). It can be seen from Fig. 4(a) that these values match perfectly with the observed radar returns in the boundary layer and lower troposphere during convective cloudless conditions and we have seen that this sort of comparability was seen throughout March 2003. However, a fairly accurate L_o can be arrived at only after using a sufficiently large volume of RS/RW and DWR data in the ensuing years.

TABLE 4

Mean C_n^2 ($\times 10^{12}$ $m^{-2/3}$) values in the atmospheric boundary layer over Chennai at 0000 and 1200 UTC, December 2002 – March 2003

Month & Year	Mean layer height at 0000 UTC			Mean layer height at 1200 UTC		
	167 m	463 m	753 m	170 m	472 m	793 m
Dec 2002	0.399	0.122	0.370	0.434	0.139	0.128
Jan 2003	0.296	0.225	0.236	0.257	0.113	0.262
Feb 2003	0.218	0.166	0.560	0.635	0.237	0.362
Mar 2003	0.262	1.620	0.740	0.283	1.340	0.430

However, it may be mentioned that estimation of C_n^2 using RS/RW data may be less accurate since the humidity measurement is less precise than temperature measurement in radio sonde. Within a few tens of minutes it is not at all uncommon to have an order of magnitude variation of C_n^2 in vertical and spatial scales (Gage *et al.*, 1978) and computation from twelve hourly RS/RW data can not account for the variability of refractivity turbulence. Hence an attempt to build climatology of C_n^2 using continuously available S-band radar reflectivity data, though embryonic over Chennai, has been made to understand the morphology of turbulence. But in this process, we often encountered high Z which would require unreasonably large values of C_n^2 at some point of time during the period under study, whereas the value was quite comparable with those published elsewhere, just prior to and after this episode of high reflectivity. For example, if the Z is attributed to refractivity turbulence with high C_n^2, then the C_n^2 between 1254 and 1310 UTC on 18th January was as high as 0.188×10^{-9} $m^{-2/3}$ which has exceeded the highest value of 0.24×10^{-10} $m^{-2/3}$ measured during daytime summer conditions with 10 cm Terminal DWR (TDWR) at Denver (Doviak and Zrnic, 1993). Hence, we wanted to identify the contributing mechanism for this sort of high Z over some specific period since there was absolutely no convective cloud development during the said period to support this high C_n^2 value.

Figs. 4(b-d) show the vertical variation of C_n^2 computed from RS/RW data (with L_o = 10 m) as well as

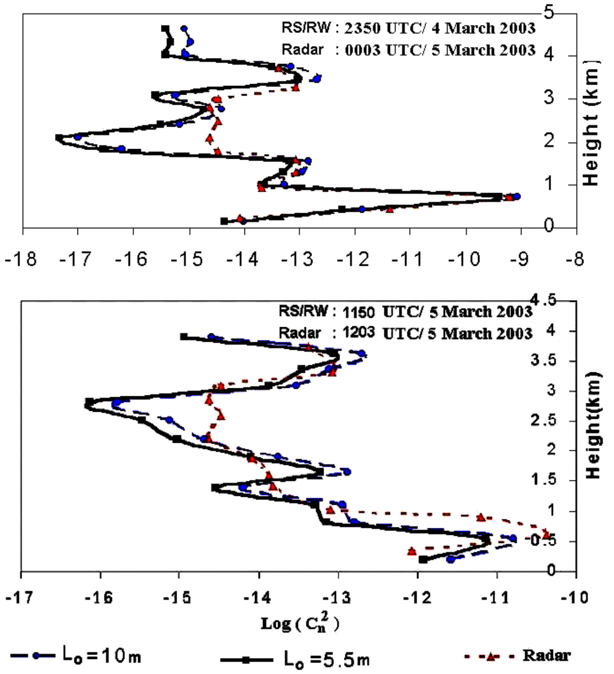


Fig. 4(a). Comparison of C_n^2 estimated from RS/RW data using outer scale length 10m and 5.5m with that estimated from radar reflectivity data on 5 March 2003

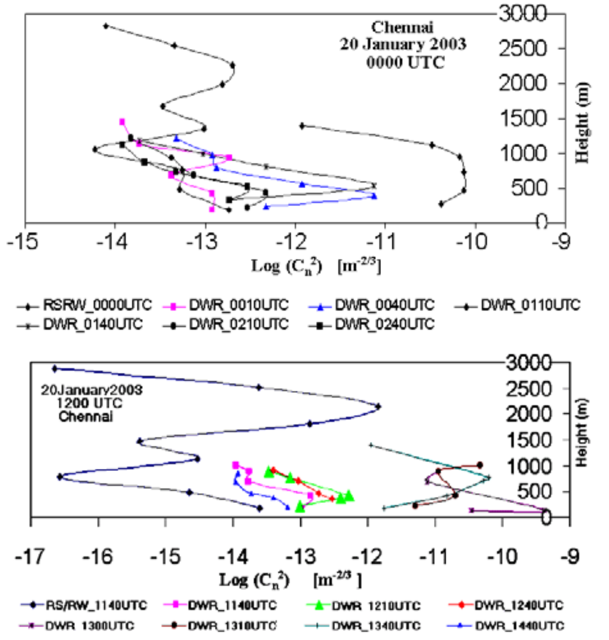


Fig. 4(b). Plot of vertical variation of refractive index structure constant C_n^2 computed from RS/RW and DWR data on 20 January 2003

February and 5th March respectively. The magnitude of C_n^2 in the ABL increased by two to four orders of

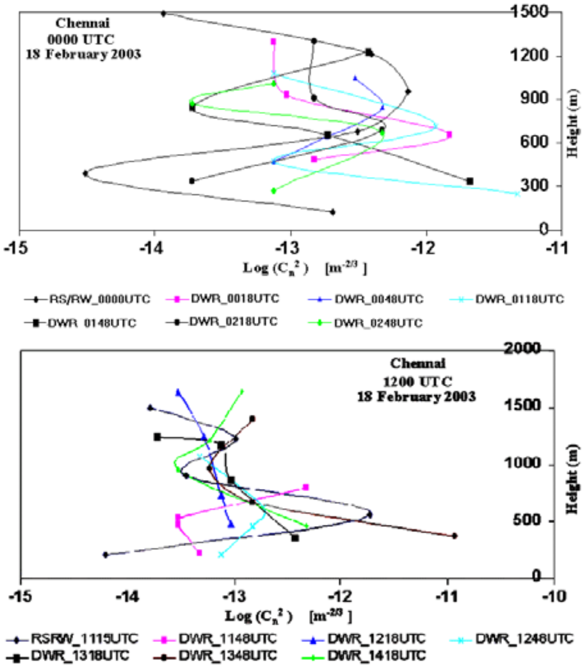


Fig. 4(c). Plot of vertical variation of refractive index structure constant C_n^2 computed from RS/RW and DWR data on 18 February 2003

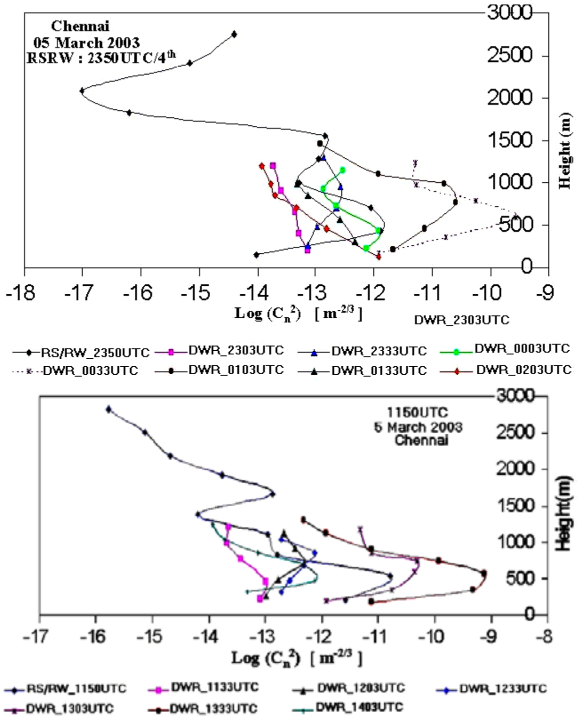


Fig. 4(d). Plot of vertical variation of refractive index structure constant C_n^2 computed from RS/RW and DWR data on 5 March 2003

estimated from the *Z* values on 20th January, 20th magnitude (> 10^{-10} m$^{-2/3}$) within an hour from the time of

TABLE 5

Activities of birds *vis-à-vis* astronomical factors over Chennai

Date	Beginning of Twilight / Sun Rise (UTC)	Ornithological Activity (UTC)			Sun Set / Ending of Twilight (UTC)	Ornithological Activity (UTC)		
		Begin	Peak	End		Begin	Peak	End
Jan 01	AT 2345	0008	0043	0252	SS 1224	1232	1256	1331
	NT 0012				CT 1247		1302	1342
	CT 0038				NT 1313			
	SR 0101				AT 1339			
Jan 11	AT 2349	0000	0040	0200	SS 1229	1240	1300	1410
	NT 0015		0100		CT 1252	1254		
	CT 0042				NT 1318			
	SR 0104				AT 1344			
Jan 21	AT 2351	0010	0040	0210	SS 1235	1240	1300	1410
	NT 0017		0100		CT 1257	1254	1310	1424
	CT 0043				NT 1323			
	SR 0106				AT 1349			
Jan 31	AT 2352	0000	0045	0203	SS 1239	1253	1303	1430
	NT 0018				CT 1302		1315	1445
	CT 0043				NT 1327			1453
	SR 0106				AT 1353			
Feb 10	AT 2351	0000	0045	0145	SS 1243	1253	1314	1429
	NT 0016			0153	CT 1305			
	CT 0042				NT 1330			
	SR 0103				AT 1355			
Feb 20	AT 2348	0000	0030	0145	SS 1246	1300	1323	1430
	NT 0013		0033	0153	CT 1308			
	CT 0038				NT 1333			
	SR 0100				AT 1357			
Mar 02	AT 2344	0000	0030	0130	SS 1248	1300	1323	1430
	NT 0009		0033	0145	CT 1309			
	CT 0033		0044		NT 1334			
	SR 0055				AT 1359			
Mar 12	AT 2338	2345	0023	0145	SS 1249	1301	1324	1431
	NT 0003		0030		CT 1310		1331	
	CT 0028		0045		NT 1335			
	SR 0049				AT 1400			
Mar 22	AT 2332	2345	0034	0200	SS 1250	1304	1330	1443
	NT 2357		0038		CT 1311			
	CT 0021				NT 1336			
	SR 0042				AT 1401			
Apr 01	SR 0036	2334	0034	0145	SS 1241	1304	1330	1445
	AT 2325				CT 1312			
	NT 2350				NT 1337			
	CT 0014				AT 1402			
Apr 11	AT 2318	2334	0034	0204	SS 1241	1304	1330	1445
	NT 2343				CT 1313			
	CT 0008				NT 1338			
	SR 0029				AT 1403			

SR : Sun Rise; SS : Sun Set; AT / NT / CT : Astronomical / Nautical / Civil Twilight.

release of RS/RW ascent. Except the peak value of C_n^2, other values are quite comparable to those values mentioned in the references cited in this paper. Interestingly, it may be mentioned here that the time of high value falls within the twilight period and close to Sun rise/Sun set (Table 5). Doviak and Zrnic (1993) attributed that larger values of C_n^2 may result from point scatterer's contribution to reflectivity at centimetric wavelengths. Possible contribution from particulate scatterers such as biota to the enhanced *Z* has been analysed by taking a field study of migratory birds.

5.5. *Radar ornithology*

Simpson Industrial Estate (SIE), Sembium located at 15 km NNW of Radar site has been listed as one of the wet lands of Asia supporting more than 20,000 wetland birds. The Asian water-fowl census (1994-96) carried out

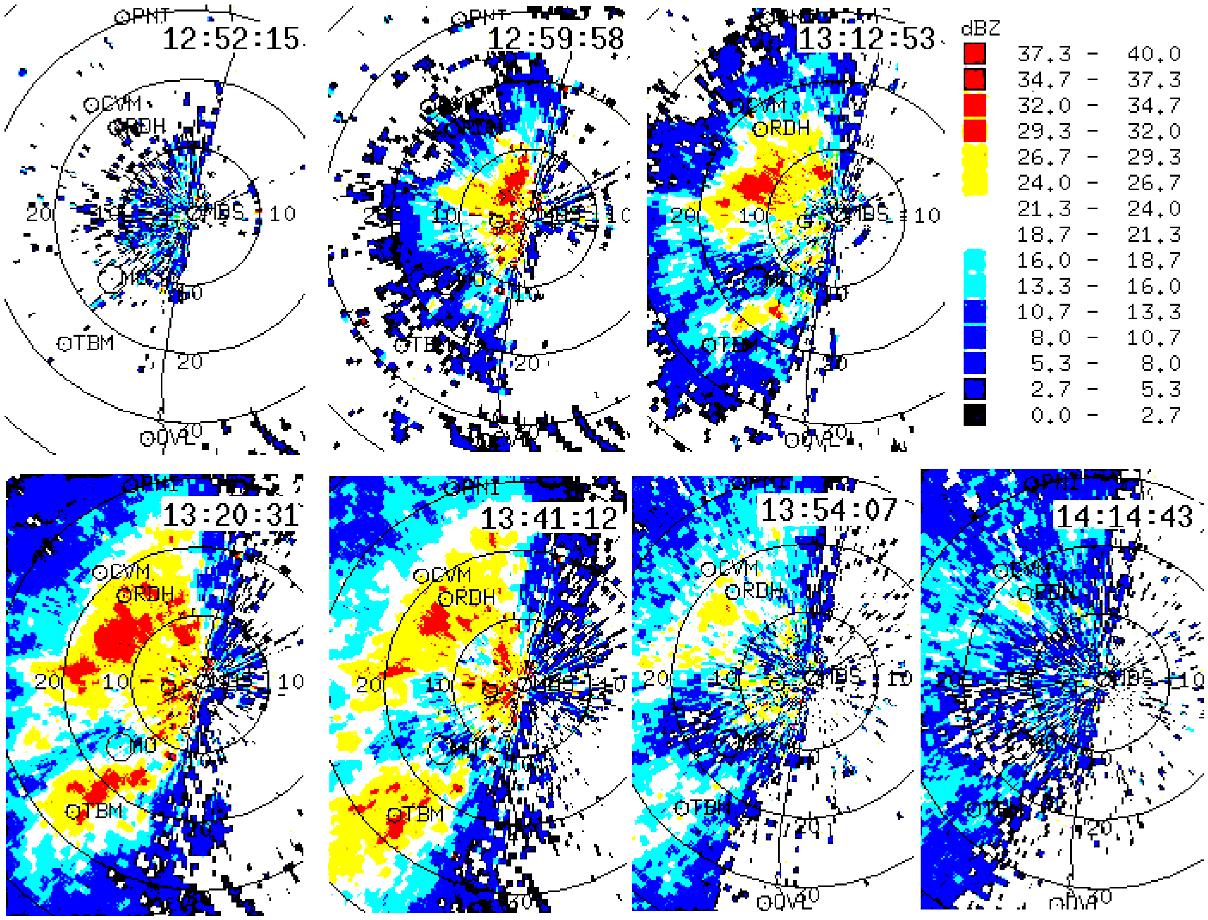


Fig. 5. PPI (*Z*) display at 1.0° elevation from 1252 UTC to 1414 UTC on 22 February 2003. The range rings are 10 km apart. The radar returns are from flock of birds when they return to their roosting site within one hour after the sunset time, *viz*., 1234 UTC (1813 hrs IST)

by Wetlands International recorded a count of 20,111 birds (of many species) in 1995 and during 2003 it was estimated as 8000 only (*Source* : The HINDU, Chennai based daily English Newspaper, dated 20 March 2003). There are other roosting places in and around Chennai such as Pallikaranai and Adayar (12 - 18 km SSW of DWR site) wherein three to four thousand birds in each roosting site were counted. Other than these places, towards 20 km NW of radar there are a few reservoirs close to which a few thousands of country birds migrate. Amongst 55 species of migratory birds, Jacanas, Egrets, Cormorants, herons and black winged Stilt (whose size are quite bigger than Starlings and Pigeons) were the most commonly seen around these roosting places during December – February and at times during March (Gurusami, 2003, personal communications).

According to Gurusami, naturalist, these birds depart from their roosting site just prior to or just after sunrise and go to the nearby *jheels* (wet lands) for their daily feeding and return after the sunset exploiting the twilight available in the atmosphere. The normal height of their flight is between 200 and 500 m. Based on the literature survey on the radar cross section of birds (Russell and Wilson, 1997; Rinehart, 1999; Dunning, 1993), it is roughly estimated that these birds will have radar cross section of 10 – 50 cm^2 at 10.43 cm wavelength.

Since the Rayleigh approximation is not applicable for these scatterers, the effective or equivalent reflectivity factor [$Z_e = \eta \lambda^4 / (\pi^5 |K|^2)$], where η is the volume reflectivity which is the summation of radar cross sections of all scatterers in a unit volume ($cm^2 \, km^{-3}$) and Z_e has the standard reflectivity units, *viz*., $mm^6 \, m^{-3}$, has been used to estimate the number of birds in each pulse volume. With suitable conversion, we get $Z_e = 0.04159 \eta$ for $\lambda = 10.43$ cm. To get a reflectivity of 36 dBZ, there must be 2393 birds km^{-3} with an average 40 cm^2 cross section per bird since $0.04159 * 2393 * 40 = 3981 \, mm^6 \, m^{-3}$ which corresponds to 36 dBZ. According to Chennai based

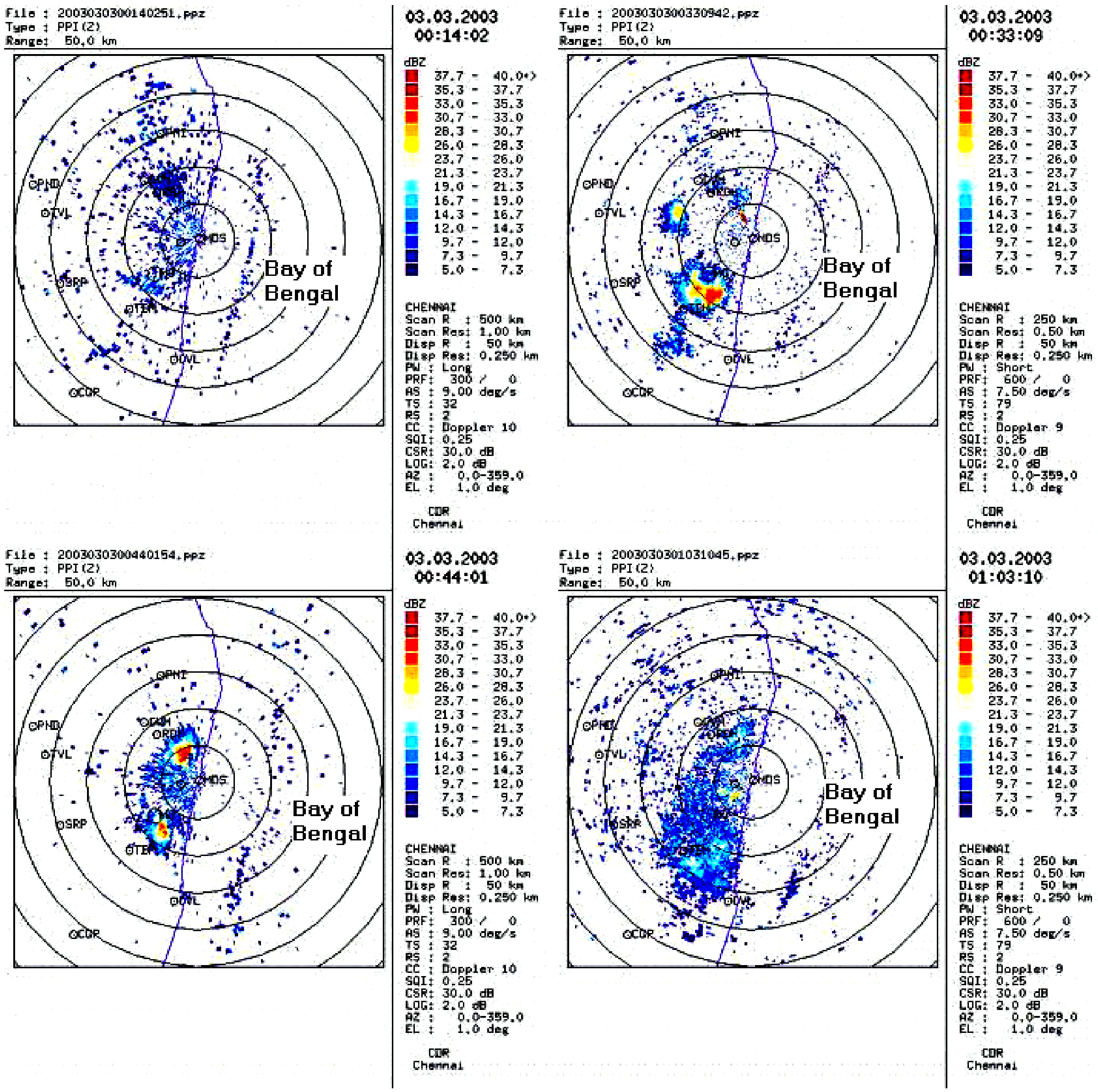
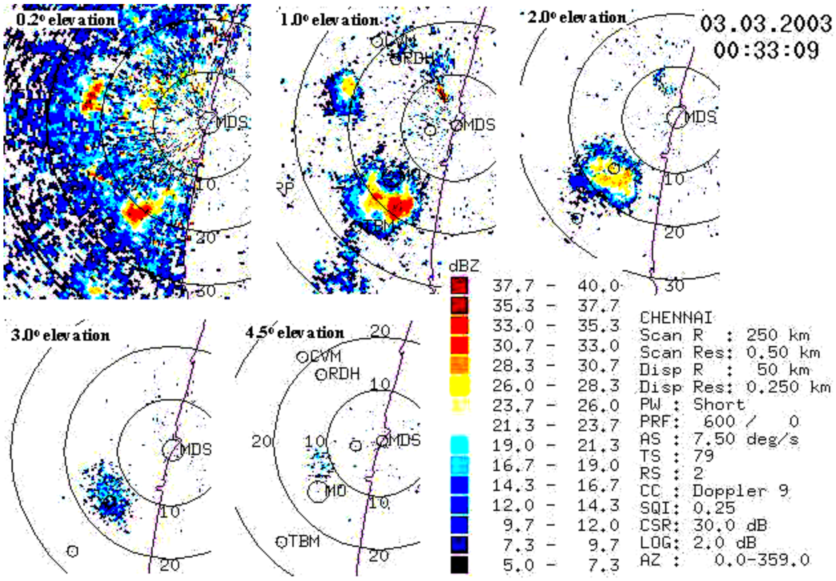


Fig. 6. PPI display of reflectivity at 1.0° elevation on the early hours of 3 March 2003. The range rings are 10 km apart

naturalists and ornithologists, this density of birds could be quite possible since the species of birds mentioned above fly in a flock of 100-200 with sufficient separation (200 – 500 m) between each flock. At 15 km range, one degree beam width has a diameter of 0.262 km. Hence for 1 μ sec pulse width (which corresponds to 0.3 km), the pulse volume is approximately [π * (0.262 / 2)^2 * (0.30 / 2)] (*i.e.*) 8.09 × 10^{-3} km^3 since we normally take half the pulse width to account for onward and return travel of the pulse. For a 0.5 km scan resolution, the scan resolution volume is [π * (0.262 / 2)^2 * 0.50)], *i.e.*, 26.95 × 10^{-3} km^3. Hence at least 19 birds of 40 cm^2 cross section must be present to return a reflectivity of 36 dBZ at 15 km range in a pulse volume of 8.09 × 10^{-3} km^3 or 64 birds in a scan resolution volume of 26.95 × 10^{-3} km^3. By a similar calculation, 60 birds km^{-3} or 2 birds of 40 cm^2 cross section each may return 20 dBZ. Confining our calculation of the density of birds to scan resolution volume at 15 km range, since the volume scan data is collected with 0.5 km scan resolution, 258 birds of 10 cm^2 cross section or 129 birds of 20 cm^2 or 64 birds of 40 cm^2 cross section may be sufficient to give a 36 dBZ radar return. The total number of birds, (mostly of 40 cm^2 cross section) that could have contributed to Z values of 20 to 36 dBZ over an area 5 km × 7 km, have been worked out to be between 8000 and 13000. This



```
03.03.2003
00:33:09

CHENNAI
Scan R  : 250 km
Scan Res: 0.50 km
Disp R  :  50 km
Disp Res: 0.250 km
PW : Short
PRF:  600 /   0
AS : 7.50 deg/s
TS : 79
RS : 2
CC : Doppler 9
SQI: 0.25
CSR: 30.0 dB
LOG: 2.0 dB
AZ :   0.0-359.0
```

Fig. 7. PPI display of Z at 0.2° to 4.5° elevation on at 0033 UTC 3 March 2003. Range rings are 10 km apart

estimation agrees well with the ornithological count made by Chennai based ornithologists.

Besides the birds, dense cloud of insects are also normally seen in and around Chennai during the winter months (December – February) during which period they breed exploiting favourable weather conditions over Chennai. In the absence of entomological studies over Chennai, we assumed the cross section of insects as 0.23 cm^2 based on Russell and Wilson (1997). The estimated concentration is about 6,60,000 km^{-3} to get a radar return of 36 dBZ based the relation $Z_e = 0.04159\ \eta$ for $\lambda =$ 10.43 cm. As such we have every reason to believe that the 38 dBZ radar return is quite feasible from these birds/insects since it is not uncommon that Z as high as 40 dBZ has been reported by Achtemier (1991) from dense clouds of large insects alone.

5.5.1. *An example of enhanced Z during evening*

Fig. 5 shows the plan position indicator (PPI) display of Z at 1.0° elevation during 1252 - 1414 UTC on 22 February, 2003. The increase in Z with time within 10 to 30 km radius over land (west of radar marked MDS in the figure) may preempt or prompt the reader to think that convective/rain bearing clouds were seen around Chennai, but in reality these echoes were from the birds returning to their roosting sites after sunset. The average time of sunset during February is 1225 UTC (1755 hr IST). Chennai based ornithologists confirmed that the birds return to their roosting within the twilight period of one hour or so after sunset and some birds like Cormorants and black winged Stilt may fly even in the evening taking advantage of the slightest light available in the atmosphere (nautical or astronomical twilight that prevails after the civil twilight). This explains the Z maxima at 1320 and 1341 UTC and sharp fall of Z immediately after the twilight period.

5.5.2. *An example of enhanced Z during morning*

Fig. 6 shows the radar returns from birds at 1.0° elevation from 0014 to 0103 UTC on 3 March, 2003. The mean time of sunrise for the month of March over Chennai is 0608 hr (IST) (0038 UTC). In the morning hours the birds usually take off for their daily food just before sunrise (during twilight period) and/or within 10-20 minutes after sunrise (Gurusami, personal communication). The enhanced reflectivity between 0033 and 0044 UTC confirms the flight of birds. We could not get doughnut (circular and annular shaped rings) echoes presumably because the roosters are at a closer range, between 10 and 20 km from DWR. Nevertheless, eye witness reports by the naturalists/ornithologists and absence of any form of precipitation clouds over the areas of enhanced Z confirm that these echoes are from birds.

5.5.3. *Flying altitude of migratory birds*

Fig. 7 shows the PPI display of Z at 0.2° to 4.5° elevation at 0033 UTC on 3rd March. The Z value decreases with height rapidly since the normal flight altitude of these birds are between 300 and 600 m, though some species may prefer high altitude flights of say 1.0 km or so. Analyses of vertical variation of Z during the entire study period (December 2002 – March 2003) revealed that the enhanced Z is usually absent beyond 4.5° elevation and mostly it is confined only upto 3.0°

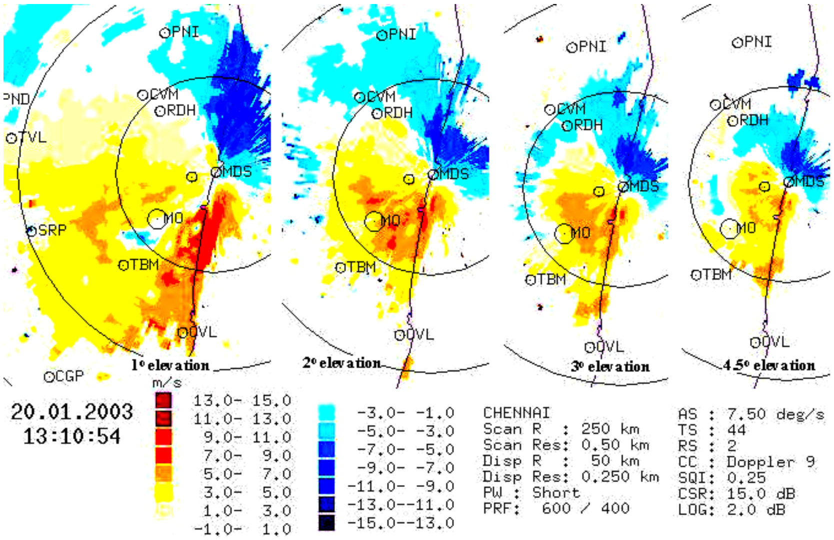


Fig. 8. PPI display of radial velocity at 1310 UTC on 20 January 2003. Range circles are 20 km apart

elevation within a range of 20 km from DWR, Chennai. This result is in confirmation with the flying altitude characteristics of the migratory birds (Konrad *et al.*, 1968; Wilson *et al.*, 1994).

Computed value of C_n^2 based on RS/RW data of 2355 UTC / 2nd March with L_o = 10 m and 0014 UTC DWR data of 3rd March were 7.3×10^{-14} $m^{-2/3}$, 2.0×10^{-14} $m^{-2/3}$ and 5.0×10^{-12} $m^{-2/3}$ at mean heights 141, 420 and 711 m respectively which are quite comparable with values furnished in the literature elsewhere (for example, Burk, 1978 and Doviak and Berger, 1980). However, C_n^2 values between 0030 and 0045 UTC / 3rd March computed from *Z* data has increased by two orders of magnitudes and C_n^2 as high as 0.2×10^{-9} $m^{-2/3}$ was estimated at a height of 361 m. The apparent increase of C_n^2 value was not because of the refractivity induced turbulence (RIT) in the ABL or from clouds as there was practically no cloud observed during this period but due to returns from flocks of thousands of birds flying at that height causing a radar reflectivity more than 36 dBZ. The wet land birds normally migrate over wet lands and not over sea/ocean and this has been observed on all days under study since enhanced *Z* are seen only over land and not over the Bay of Bengal. Similar observations of migratory insects and birds were recorded by Wilson *et al.* (1994) and Russell and Wilson (1996 and 1997). Russell and Wilson (1997) give a detailed review of characteristics of diurnal clear air radar echoes compared with spatio-temporal ecology of aerial insects.

5.5.4. *Activities of birds vis-à-vis twilight*

The period of morning and evening twilights consists of three parts, *viz.*, Civil twilight (CT), Nautical twilight (NT) and Astronomical twilight (AT) when the Sun is 0° - 6°, 6° - 12° and 12° - 18° below the horizon respectively. As has been stated earlier, the ornithological activities (commencement, peak and cessation) are usually confined to the twilight periods, we wanted to exactly pinpoint the type of twilight, *viz.*, AT, CT and NT, at which such activities are prominent over Chennai region. Table 5 summarises the Sun rise, Sunset and the beginning and ending of different twilight timings over Chennai (in the area of interest), at 10 days interval – since it is well known that the timings of astronomical events will not change appreciably on day-to-day basis or say within 10 days. From this Table, one can notice that the activities of birds commence during AT, the peak activity was seen during CT and the activity ceases about 1 - 1½ hours after sunrise in the morning. However, in the evening, the activities of birds begin during CT, the peak activity extends beyond CT but well within the NT and ceases during AT (at times seen even upto 30 to 40 minutes after AT).

5.6. *Radial velocity*

Normally, at 0000 UTC the prevailing winds are between ENE and SSE with speed varying between 2.0 and 6.0 ms^{-1} and at 1200 UTC between NE and SE with speed 3 - 7 ms^{-1} from surface upto 1.0 km a.g.l. during January – March. Birds have flying speed of 10 - 12 ms^{-1} (Rinehart, 2003, personal communication). If the prevailing wind is very light / calm and if the birds fly in the direction of radar beam, then it can be clearly distinguished from the radial velocity information obtained from a single DWR. When flocks of birds fly in the opposite direction of the radar beam and/or they cut the radar beam with an angle, the migration can be identified only with sufficient knowledge of the prevailing wind speed and direction. As the birds may return, from different directions to their roosting site, after their daily flight, migration of birds can be identified by noting the sudden change (±10 ms^{-1}) in velocities (*www.njaudubon.org/Education/oases/RadImages.html*).

On some days, spots of opposite velocities or enhanced velocities were noticed during the period under study. Prevailing wind at 1200 UTC on 20th January 2003 was northeasterly of speed 4.0 to 5.4 ms^{-1} between surface and 1100 m with maximum speed at 173 m a.g.l. Radial velocity during enhanced *Z* period between 1300 and 1330 UTC were of the order of 3 to 9 ms^{-1}. Fig. 8 shows PPI plot of radial velocity on a typical situation. The mean velocity spectrum width (W) was around 1.0 – 1.5 ms^{-1} with a maximum of 2.5 ms^{-1}. The spectrum width information does not throw any light on enhanced *Z*. As pointed out by Hooke (1990), the received power level dependence with Doppler spectrum width is yet to be established since contrasting relationships have been found between these two parameters so far. Therefore, the radial velocity and spectrum width data need to be critically analysed on meteorological as well as ornithological angles and this study will be taken up separately.

6. Conclusions

The following conclusions have been arrived at from this study.

(*i*) Enhanced radar reflectivity factor (*Z*) as high as 38 dBZ was observed over land near the times of sun rise and sun set during the period December – March around Chennai.

(*ii*) The enhancement in *Z* can not be attributed to

(a) Refractivity induced turbulence, because a maximum of +0.8 dBZ only is possible from the maximum value of refractivity turbulence structure constant (C_n^2), *viz*., 3.58×10^{-12} $m^{-2/3}$.

(b) Clouds, since there was no convective / rain bearing clouds and the prevailing Sc clouds (of 2 octa) at the maximum may contribute only –18 dBZ.

(c) The suspended particulate matter and pollutants, because a peak value of –0.9 dBZ only can be expected from a maximum concentration of 10^5 m^{-3} of 100 μm size.

(d) Convective instability or humidity inhomogeneities in the layer just above to the surface, because these contribute to radar reflectivity factor between –10 and 4 dBZ only.

(*iii*) The likely origin of enhanced *Z* was from birds (and possibly from insects) because

(a) The time of enhanced *Z* coincides with the activity of birds.

(b) The activity of birds over the area and period of study have been confirmed by Chennai based ornithologists and naturalists.

(c) Computation based on 0000 and 1200 UTC RS/RW data indicate that the refractivity turbulence structure constant (C_n^2) varies between 10^{-12} and 10^{-15} $m^{-2/3}$ from surface to 900 m a.g.l. during December – March. These values are in quite agreement with that computed from radar reflectivity data during the same period. Further computation of C_n^2 (within one hour after sunrise and sunset) shows that these values increase by more than two orders of magnitude due to enhanced reflectivity caused by the migratory birds and insects.

(*iv*) No enhancement in reflectivity was observed over Bay of Bengal indicating that the activity of birds was confined to only over the land.

(*v*) In the morning (evening), the activities of birds commenced during Astronomical twilight (Civil twilight), the peak activity during Civil twilight (beyond Civil twilight but well within Nautical twilight) and ceased about 1 - 1½ hours after sunrise (in Astronomical twilight and at times even upto 30 to 40 minutes after Astronomical twilight).

(*vi*) Knowledge of the source and time of clear air reflectivity may help the forecaster to improve his nowcasting capabilities.

(*vii*) Nocturnal surface inversion frequency has a steep increase over Chennai during 2002-03 in comparison to 1970s and 1980s presumably because of atmospheric pollution.

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ANNEXURE I

Scan strategies adopted at DWR, Chennai during November 2001 – April 2003

Item	Scan I	Scan II	Scan III	Scan IV	Scan V	Scan VI	Scan VII
Range(km)	300	500	250	120	400	250	250
Resolution(m)	500	1000	500	500	1000	500	1000
Range Sampling	2	2	2	2	5	2	2
Pulse	LP	LP	SP	SP	LP	SP	SP
PRF 1	500	300	600	800	375	600	1200
PRF 2	333	----	----	----	250	400	----
Antenna speed (°/sec)	6	9	9	9	8.5	7.5	17.9
Time Sampling	83	33	66	88	14	44	64
Elevation angles	0.2, 1.0, 2.0, 3.0	0.2, 1.0, 2.0, 3.0, 4.0, 5.0	0.2, 1.0, 2.0, 3.0, 4.5, 6.0, 7.5, 9.0, 11, 13.0, 15.5, 18.0, 21.0	0.2, 1.0, 2.0, 3.0, 4.0, 5.5	0.2, 1.0, 2.0, 3.0, 4.0, 5.5	0.2, 1.0, 2.0, 3.0, 4.5, 6.0, 7.5, 9.0, 11.0, 13.0, 15.5, 18.0, 21.0	0.2,1.0, 2.0,3.0
CSR	5.0	10.0	10.0	7.0	5.0	15	5.0
SQI	0.25	0.25	0.25	0.25	0.4	0.25	0.40
Doppler Filter	5	10	9	6	4	9	4
Doppler Filter notch width (ms^{-1})	0.4	1.0	1.5	0.8	0.25	1.5	0.8

Note : LP : Long pulse (2µ sec), SP :Short Pulse (1µ sec),

PRF : Pulse repetition frequency (PRF1 and PRF2 refers to first PRF and second PRF respectively),

CSR : Clutter to Signal Ratio, SQI :Signal Quality Index, Scan VII (250km range with 1200PRF) is meant for second trip recovery