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

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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 $3.58 \times 10^{-12}$ 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.
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 (\( \lambda_c \)) at the limit between the inertial domain and the viscous dissipation range of the atmospheric turbulence. Strauch et al. (1984) proved that \( \lambda_c \) 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 Gematronic 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 temperate and sub-tropical areas have observed, in general, that the height of enhanced population is maximum during some specific season (say summer) since 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 an 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.

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.,

\[N = \frac{(77.6/T)}{(P + 4810 e / T)}\]  

(1)

where \(N = (n-1) \times 10^9\), \(n\) 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 Znic, 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

| 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)     | Potential Temp (°K) |
| 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 \(\partial \phi / \partial z\), \(\partial \theta / \partial z\) and \(\partial P_{Ae} / \partial Z\) are from the immediate lower level to the level where values have been furnished.
evaporation taking place. Hence a parameter that is conserved, \( \text{viz.} \), potential refractive index in \( N \) units has been defined by Bean and Dutton (1966) as

\[
\varphi = \left( \frac{77.6}{\theta} \right) \left( P_o + 4810 P_{wo} / P \right)
\]

where \( \theta \) 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. \( \varphi \) is conserved as \( \theta \) 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 \( \varphi, \theta, \) 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 \( \varphi \) with height (\( \partial \varphi / \partial z > 0 \)) in the layer adjacent to surface. More over, as \( \varphi \) varies directly with \( P_{wo} \) and inversely with \( \theta \), opposite gradients of these two terms (\( \text{viz.} \), \( \partial \theta / \partial z \) and \( \partial P_{wo} / \partial z \)) contribute to increased \( \varphi / \partial z \) in that particular layer (Doviak and Zrnic, 1993). The opposite gradients of \( P_{wo} \) and \( \theta \) (Table 1) re-confirms that \( \varphi \) has increased in the first layer (immediately above the surface). In view of weak turbulence / stability prevailing in the higher layers (positive \( \partial \theta / \partial z \)), \( \varphi \) was decreasing with height above the first layer.

5.1.1. Vertical gradients of \( \varphi \) and \( \theta \)

As has been mentioned earlier, since \( \varphi \) depends linearly on humidity and inversely on stability, opposite gradients of \( P_{wo} \) and \( \theta \) 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 (\( T_d \)), \( \varphi \) and \( \theta \) 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 (\( \text{i.e.,} \), \( \partial \theta / \partial z < 0 \)), 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 \( -157 \) unit/km, there was no super-refraction or ducting taking place in the first layer and there was no abnormality in the magnitude of \( \partial \varphi / \partial z \) 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 (\( \text{i.e.,} \), \( -\partial T_d / \partial z \)) was negative (\( \text{i.e.,} \), 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 |
|              | $\partial \phi / \partial z$ | -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 |
|              | $\partial \phi / \partial z$ | -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 |
|              | $\partial \phi / \partial z$ | -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 |
|              | $\partial \phi / \partial z$ | 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),
- $\partial \phi / \partial z$ = 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 $\phi$, 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$^{-1}$)

| Month     | 0000 UTC, Temperature inversion | 0000 UTC, Temperature lapse rate |
|-----------|---------------------------------|---------------------------------|
| NLR1      | NLR2 | NLR3 | NLR4 | NLR5 | NLR6 | Total | LR1 | LR2 | LR3 | LR4 | LR5 | LR6 | 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   |     |      |

1200 UTC Temperature inversion 1200 UTC Temperature lapse rate

| Month     | 0000 UTC, Dew point inversion | 0000 UTC, Dew point lapse rate |
|-----------|---------------------------------|---------------------------------|
| NLR1      | NLR2 | NLR3 | NLR4 | NLR5 | 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    | 0    | 1    | 3    | 11  | 8   | 7   | 30   |      |
| Feb 2003  | 0    | 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$^{-1}$; 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 | LR4 | LR5 | LR6 | 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   |     |      |

1200 UTC Temperature inversion 1200 UTC Temperature lapse rate

| Month     | 0000 UTC, Dew point inversion | 0000 UTC, Dew point lapse rate |
|-----------|---------------------------------|---------------------------------|
| NLR1      | NLR2 | NLR3 | NLR4 | NLR5 | 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    | 0    | 1    | 3    | 11  | 8   | 7   | 30   |      |
| Feb 2003  | 0    | 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$^{-1}$; 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(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 $\phi$ since $\phi$ depends linearly on humidity. As such the increased frequencies of humidity inversion explain positive gradient of $\phi$ 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 $\phi$ in view of active turbulence (Richardson number being negative on these days) transporting water vapour and causing fluctuations/inhomogeneity in number being negative on these days) transporting water.

Enhanced $\phi$ in view of active turbulence (Richardson UTC during March 2003 could have contributed to enhanced $\phi$ 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 $\partial P_w/\partial z$), 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 $\phi$ in the first layer since opposite gradients of $P_w$ and $\theta$ increases $\partial \phi/\partial z$. However the increase in $\phi$ 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$^{-1}$) 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 $> 10 \mu m$) and RDPs (of size $< 10 \mu m$) 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 ($\eta$) from turbulent scatterers by

$$C_n^2 = \frac{\eta}{0.38}$$

where $\lambda$ 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

$$Z_e = \frac{\lambda^4 \eta}{(\pi^2 |K|^2)}$$

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

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

for $\lambda = 10.43$ 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.)

$$C_n^2 = a^2 \alpha \lambda \text{ m}^{4/3}$$

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

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

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 $0.131 \times 10^{-12}$ m$^{-2/3}$ at 210 m, $0.763 \times 10^{-13}$ m$^{-2/3}$ at 554 m and $0.469 \times 10^{-13}$ m$^{-2/3}$ at 913 m based on 1125 UTC RS/RW data of 18th January with $L_o = 10$m. The corresponding values derived using $L_o = 5.5$m are $0.590 \times 10^{-13}$ m$^{-2/3}$, $0.344 \times 10^{-13}$ m$^{-2/3}$ and $0.211 \times 10^{-13}$ m$^{-2/3}$ respectively. A comparative plot of $C_n^2$ based on $L_o = 10$m and $L_o = 5.5$m with that derived from DWR data using Eqn. 3c, for an independent

| Month & Year | Mean layer height at 0000 UTC | Mean layer height at 1200 UTC |
|-------------|-------------------------------|-------------------------------|
| 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            |

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

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 $0.188 \times 10^{-9}$ m$^{-2/3}$ which has exceeded the highest value of $0.24 \times 10^{-10}$ 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

![Table 4](image-url)
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.

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

February and 5th March respectively. The magnitude of $C_n^2$ in the ABL increased by two to four orders of 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               |                                      | Begin Peak End               |
| January | AT 2345 NT 0012 CT 0038 SR 0101        | 0008 0043 0252              | SS 1224 CT 1247 NT 1313 AT 1339    | 1232 1256 1331              |
| Jan 11  | AT 2349 NT 0015 CT 0042 SR 0104        | 0000 0100 0200              | SS 1229 CT 1252 NT 1318 AT 1344    | 1240 1254 1410              |
| Jan 21  | AT 2351 NT 0017 CT 0043 SR 0106        | 0100 0210 0100              | SS 1235 CT 1257 NT 1323 AT 1349    | 1240 1300 1410              |
| Jan 31  | AT 2352 NT 0018 CT 0043 SR 0106        | 0000 0045 0203              | SS 1239 CT 1302 NT 1327 AT 1353    | 1253 1303 1430              |
| Feb 10  | AT 2351 NT 0016 CT 0042 SR 0103        | 0000 0045 0145              | SS 1243 CT 1305 NT 1330 AT 1355    | 1253 1314 1429              |
| Feb 20  | AT 2348 NT 0013 CT 0038 SR 0100        | 0000 0030 0033              | SS 1246 CT 1308 NT 1333 AT 1357    | 1300 1323 1430              |
| Mar 02  | AT 2344 NT 0009 CT 0033 SR 0055        | 0000 0030 0033              | SS 1248 CT 1309 NT 1334 AT 1359    | 1300 1323 1430              |
| Mar 12  | AT 2338 NT 0003 CT 0028 SR 0049        | 2345 0034 0200              | SS 1249 CT 1310 NT 1335 AT 1400    | 1301 1324 1331              |
| Mar 22  | AT 2332 NT 2357 CT 0021 SR 0042        | 2345 0034 0200              | SS 1250 CT 1311 NT 1336 AT 1401    | 1304 1330 1443              |
| Apr 01  | SR 0036 AT 2325 NT 2350 CT 0014        | 2334 0034 0145              | SS 1241 CT 1312 NT 1337 AT 1402    | 1304 1330 1445              |
| Apr 11  | AT 2318 NT 2343 CT 0008 SR 0029        | 2334 0034 0204              | SS 1241 CT 1313 NT 1338 AT 1403    | 1304 1330 1445              |

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 cm² at 10.43 cm wavelength.

Since the Rayleigh approximation is not applicable for these scatterers, the effective or equivalent reflectivity factor \( Z_e = \frac{\eta \lambda^2}{(\pi^2 |K|^2)} \), where \( \eta \) is the volume reflectivity which is the summation of radar cross sections of all scatterers in a unit volume (cm² km⁻³) and \( Z_e \) has the standard reflectivity units, viz., mm⁶ 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 cm² cross section per bird since 0.04159 * 2393 * 40 = 3981 mm⁶ m⁻³ which corresponds to 36 dBZ. According to Chennai based
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 \(\pi \times \left(\frac{0.262}{2}\right)^2 \times \left(\frac{0.30}{2}\right)\) (i.e.) \(8.09 \times 10^{-3}\) km³ 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 \(\pi \times \left(\frac{0.262}{2}\right)^2 \times 0.50\), (i.e.) \(26.95 \times 10^{-3}\) km³. Hence at least 19 birds of 40 cm² cross section must be present to return a reflectivity of 36 dBZ at 15 km range in a pulse volume of \(8.09 \times 10^{-3}\) km³ or 64 birds in a scan resolution volume of \(26.95 \times 10^{-3}\) km³. By a similar calculation, 60 birds km⁻³ or 2 birds of 40 cm² 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 cm² cross section or 129 birds of 20 cm² or 64 birds of 40 cm² cross section may be sufficient to give a 36 dBZ radar return. The total number of birds, (mostly of 40 cm² 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
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 cm² 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°
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 $7.3 \times 10^{-14}$ m$^{-2/3}$, $2.0 \times 10^{-14}$ m$^{-2/3}$ and $5.0 \times 10^{-12}$ 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 $0.2 \times 10^{-9}$ 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 $0^\circ - 6^\circ$, $6^\circ - 12^\circ$ and $12^\circ - 18^\circ$ 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 m s⁻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 m s⁻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 m s⁻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 m s⁻¹ with a maximum of 2.5 m s⁻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 (Cₙ²), 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 10⁵ 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 (Cₙ²) 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 Cₙ² (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 up to 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, 0.2, 1.0, 0.2, 3.0, 4.0, 0.2, 1.0, 0.2, 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