Climatological study of turbulence structure constant over two tropical stations, Mumbai and Guwahati in India

S. Rambabu*, J. S. Pillai, A. Agarwal and H. J. Goswami

Society for Applied Microwave Electronics Engineering & Research (SAMEER), IIT Campus, Powai, Mumbai 400 076, India

Wind profiling radars operating at VHF and UHF bands are highly sensitive to radio-refractive index variation associated with small-scale atmospheric turbulence. The measurement of atmospheric turbulence at these radar stations may be used to estimate the range of the radar that can be achieved based on its sensitivity. Turbulence structure constant (C_n^2) is one of the basic parameters to measure turbulence. In the present study, climatological (2000–2011) variation of C_n^2 from 1 to 20 km height over Mumbai (72°51′E, 19°6′N) and Guwahati (91°34′E, 26°6′N) regions using radiosonde data has been analysed. It has been observed that the mean C_n^2 values over the two stations are in the range 10^{-18} to 10^{-12} $m^{-2/3}$. The C_n^2 values are higher in the lower troposphere where both temperature and humidity gradients contribute to refractive index variation, and lower in the middle and upper troposphere where moisture gradient is negligible. The lowest values of C_n^2 are observed just below the tropopause region between 10 and 16 km over Guwahati and 10 and 13 km over Mumbai region. As a coastal station, Mumbai shows higher values of C_n^2 (two orders of magnitude) at the surface and lower troposphere compared to Guwahati. It has been observed that over the two stations, in the lower troposphere the C_n^2 values of summer (March–May) and southwest monsoon period (June–September) are higher than post-monsoon (October–November) and winter (December–February) period.

Keywords: Atmospheric turbulence, refractive index, turbulence structure constant, wind profilers.

WIND observations taken by aircraft, radiosonde (RS) and towers have provided a wealth of information for lower atmospheric studies. However, the development of wind profilers has revolutionized the lower atmospheric studies with their excellent height and temporal resolutions[1,2]. These wind profiling radars operating at VHF and UHF bands can detect echoes from irregularities in the neutral atmosphere, which are mainly sensitive to radio-refractive index variation associated with small-scale atmospheric turbulence. The magnitude of the backscattered signal depends on the intensity of variation of turbulence at different heights. Hence the vertical structure of the turbulence variation may be useful in identifying the intensity of the backscattering echo and maximum achievable range of the radar based on its sensitivity. Turbulence is one phenomenon through which transport of momentum, heat and moisture in the atmosphere takes place. It also influences the diffusion of pollutants from near surface to higher altitudes. Several researchers[3–7] have examined the possibility of deducing turbulence parameters, viz. refractive index structure parameter (C_n^2) and turbulent energy dissipation rate (ε) from the observed Doppler spectrum of radars or with the RS/radio wind (RW) data.

It is well known that turbulence in the free atmosphere is confined to thin horizontal layers separated by non-turbulent regions[8–11]. These layers are limited in horizontal extent and time. This gross turbulence in these layers is, therefore, inherently inhomogeneous, anisotropic and non-steady. Nevertheless, in the interior of the turbulent layer, at scale lengths much smaller than the thickness of the layer, turbulence may be expected to be nearly homogeneous and isotropic. Moreover, the time for setting up the turbulent spectrum is much shorter than the time characteristic of the evolution of the layer, and then the turbulence may be close to steady state.

In homogeneous isotropic turbulence, the turbulence structure constant for the radio-refractivity is given by[12]

$$C_n^2 = \alpha^2 \alpha' l_o^{4/3} M^2, \qquad (1)$$

where α^2 is a constant = 2.8, α' the ratio of eddy diffusivities ~ 1, l_o the buoyancy/outer scale length of the turbulence spectrum and M is the vertical gradient of the potential refractive-index fluctuations. The total turbulent energy density spectrum consists of the production region, the inertial subrange and the dissipation region. Most of the turbulent energy production occurs at scale sizes between $6l_o$ and $l_o/6$, where l_o is defined as the generic buoyancy/outer scale of turbulence and $l_o/6$ is defined as the onset of inertial sub-range. In this study, the turbulent scale length (l_o) is considered to be 10 m and the value of l_o is taken as the same for both the stations, for different years and months[3]. The value of M is given by the relation

$$M = -77.6 \times 10^{-6} \left(\frac{P}{T}\right)\left(\frac{\partial \ln \theta_T}{\partial z}\right) \times \left[1 + \frac{15{,}500q}{T}\left(1 - \frac{1}{2}\frac{\partial \ln q/\partial z}{\partial \ln \theta_T/\partial z}\right)\right], \qquad (2)$$

where P is the atmospheric pressure (mb), T the absolute temperature (K), θ_T the potential temperature (K), q the specific humidity (g/kg) and z is the altitude (m).

*For correspondence. (e-mail: rametsiri@gmail.com)

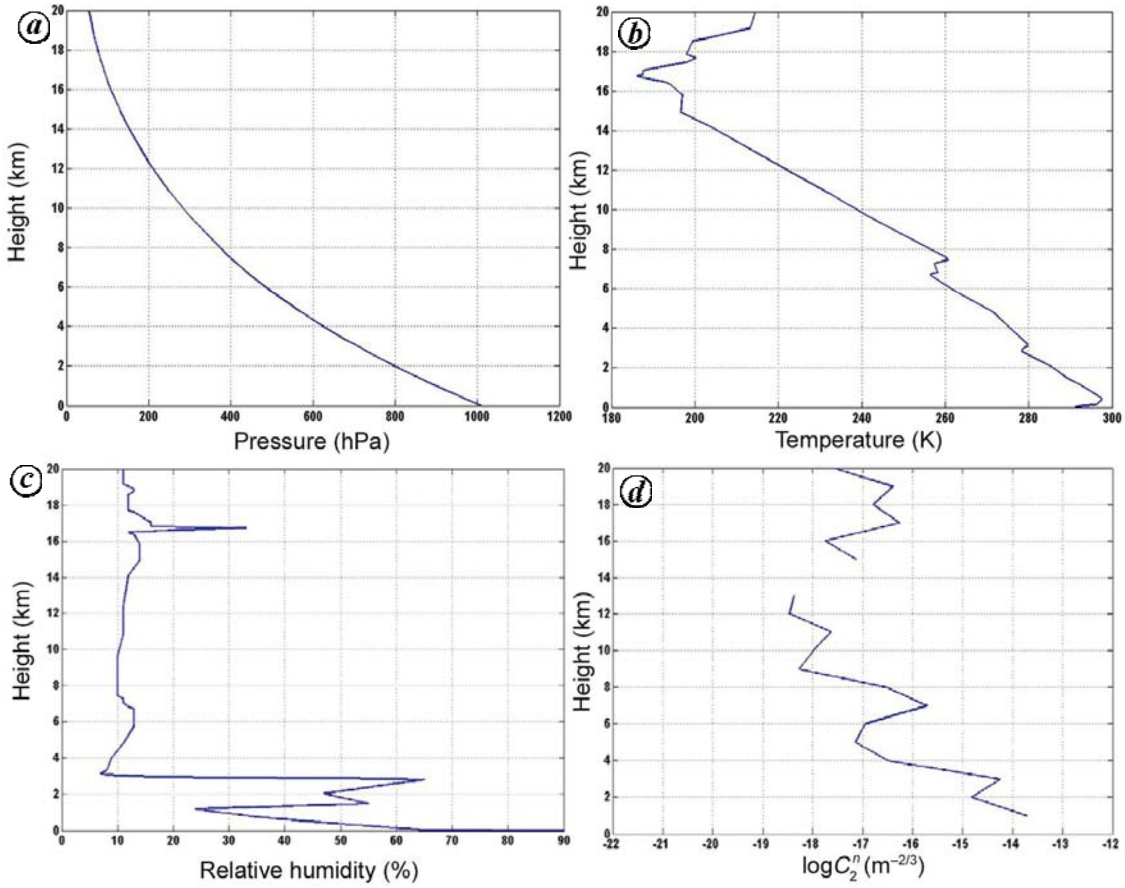

Figure 1. Vertical profiles of (***a***) pressure (hPa), (***b***) temperature (°C), (***c***) relative humidity (%) and (***d***) derived log C_n^2 ($m^{-2/3}$) values based on 31 January 2012, 00 UTC radiosonde (RS) data over Mumbai.

It may be noted that the value of M can be obtained from the RS/RW measurements of temperature, humidity and pressure for different heights in the atmosphere. One may then estimate the vertical profile of average C_n^2 from the RS/RW data. However, the turbulent layers are rather thin, separated by non-turbulent regions and hence in dealing with the radar one has to be able to estimate an average fraction of the radar beam/volume which is turbulent, to get the correct estimate[7] of C_n^2. One may therefore, write

$$\overline{C^2_{n(\text{radar})}} = \overline{c_n^2}F. \qquad (3)$$

Here F is the average fraction of the radar volume which is turbulent. The appropriate value of F is taken as 0.1 for the troposphere and 0.03 for the stratosphere, according to the model of VanZandt *et al.*[3]. The value of F is taken as the same for both the stations, for different years and months.

The daily RS data launched at different meteorological stations around the world are available to public users, provided by the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). For this study, the daily RS data from Mumbai and Guwahati stations for the period 2000 to 2011 (12 years) were collected from the above website. Since the RS data are available at non-uniform heights, it is difficult to make mean profiles. Hence, each day RS data is taken onto some common height levels (approximately 1 km interval) and the gradients of temperature ($\partial T/\partial z$), potential temperature ($\partial \theta/\partial z$) and specific humidity ($\partial q/\partial z$) are computed in the vertical up to 20 km. From these gradients the C_n^2 profiles of each day are computed using eqs (1) and (2). These daily C_n^2 values are averaged to compute monthly mean C_n^2 of different months for all the years to study the annual variability. Further, these monthly means are averaged for all the years to get the climatological mean profiles of C_n^2 for different months. However, above 6 km height, underestimation of the moisture measurements by RS may result in lower values of C_n^2. But the actual C_n^2 value could be somewhat higher. This difference of C_n^2 computed from RS and radar measurements was also noticed by Singh *et al.*[7], who reported that this may be due to the differences of balloon sounding with wind profiler (radar gives the volume reflectivity and the balloon a point observation at a particular altitude level).

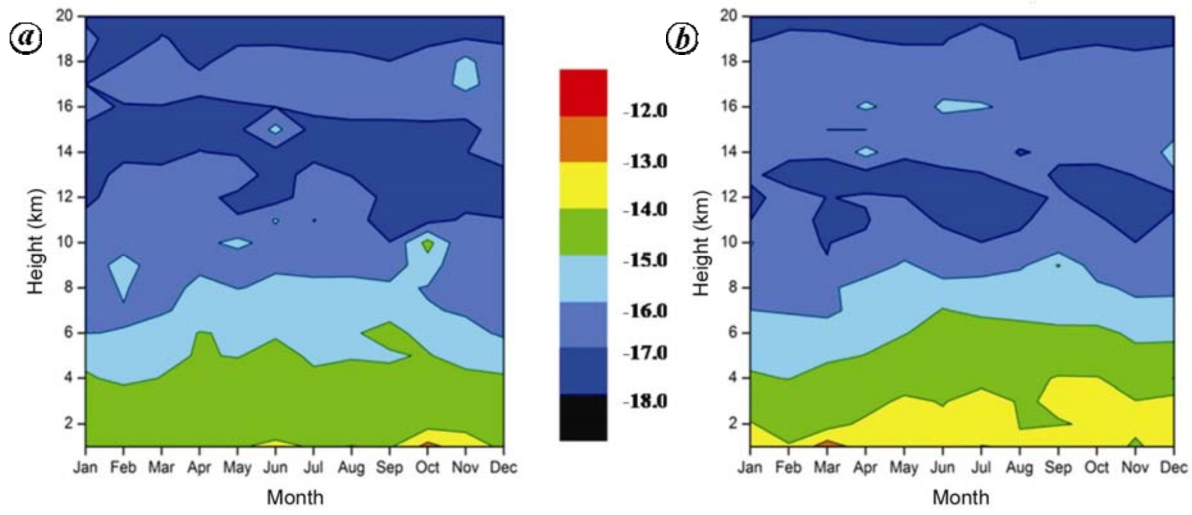

Figure 2. Climatological (2000–2011) mean annual variation of log C_n^2 profiles over (***a***) Guwahati and (***b***) Mumbai from the RS data of the respective station.

Table 1. Climatological (2000–2011) mean log C_n^2 over Guwahati

Height (m)	January	February	March	April	May	June	July	August	September	October	November	December
1,000	–14.4	–14.6	–14.3	–14.2	–14.2	–14.2	–14.2	–14.1	–14.2	–13.7	–14.0	–14.3
2,000	–14.5	–14.7	–14.6	–14.5	–14.7	–14.8	–14.7	–14.7	–14.6	–14.5	–14.5	–14.5
3,000	–14.7	–14.8	–14.8	–14.7	–14.6	–14.6	–14.7	–14.5	–14.6	–14.5	–14.8	–15.0
4,000	–15.1	–15.3	–15.1	–14.8	–14.7	–14.9	–14.9	–14.9	–14.9	–15.0	–15.0	–15.0
5,000	–15.9	–15.8	–15.7	–15.3	–15.2	–15.0	–15.2	–15.2	–15.2	–15.2	–15.7	–15.8
6,000	–16.2	–16.1	–15.9	–15.3	–15.3	–15.3	–15.3	–15.2	–15.1	–15.5	–16.0	–16.3
7,000	–16.3	–16.4	–16.3	–16.1	–15.6	–15.7	–15.7	–15.6	–15.6	–16.0	–16.4	–16.6
8,000	–16.7	–16.6	–16.8	–16.2	–16.2	–16.0	–16.0	–15.9	–16.0	–16.2	–16.9	–16.7
9,000	–16.8	–16.3	–16.8	–16.6	–16.7	–16.5	–16.4	–16.5	–16.6	–16.5	–17.0	–17.1
10,000	–16.9	–16.7	–16.8	–16.8	–16.6	–16.8	–16.9	–16.9	–17.0	–16.6	–17.1	–17.0
11,000	–17.1	–16.6	–16.8	–16.9	–17.0	–16.9	–17.2	–17.1	–17.4	–17.4	–17.1	–17.0
12,000	–17.1	–17.0	–16.9	–17.1	–17.4	–17.6	–17.5	–17.3	–17.6	–17.5	–17.4	–17.2
13,000	–17.3	–17.2	–17.1	–16.9	–17.1	–17.8	–17.2	–17.6	–17.8	–17.7	–17.6	–17.2
14,000	–17.1	–17.3	–17.2	–17.1	–17.2	–17.5	–17.8	–17.7	–17.3	–17.4	–17.1	–16.9
15,000	–17.2	–17.3	–17.4	–17.3	–17.3	–16.9	–17.7	–17.6	–17.5	–17.3	–17.2	–16.8
16,000	–16.7	–17.2	–17.1	–17.8	–17.0	–17.0	–16.8	–16.7	–16.7	–16.6	–16.8	–16.8
17,000	–17.0	–16.5	–17.1	–17.1	–16.9	–16.8	–16.6	–16.7	–16.6	–16.6	–16.2	–16.6
18,000	–17.0	–17.0	–16.8	–17.2	–16.8	–16.8	–16.8	–16.9	–17.0	–16.9	–16.2	–16.9
19,000	–16.9	–17.4	–17.0	–17.2	–17.1	–17.1	–17.3	–17.1	–17.1	–17.1	–17.1	–17.0
20,000	–17.2	–17.5	–17.1	–17.4	–17.4	–17.4	–17.4	–17.4	–17.5	–17.4	–17.4	–17.4

Initially to check the response of C_n^2 values with the respective variation in atmospheric parameters pressure, temperature and humidity, the RS profile of a winter day 31 January 2012 of Mumbai is considered. As known, the pressure pattern shows an exponential decrease from 1010 hPa at the surface to 50 hPa at 20 km height (Figure 1 *a*). The temperature profile from RS shows three shallow inversion layers in the troposphere at the surface (up to ~ 100 m), 3 km and 7 km height (Figure 1 *b*). The relative humidity shows a maximum variation up to 3 km and is nearly constant thereafter (Figure 1 *c*). The C_n^2 profile shows maximum values (10^{-15}–10^{-14} $m^{-2/3}$) in the lower troposphere up to 3 km, where large gradients of both temperature and humidity cause large refractive index variation. In the middle and upper troposphere (3–14 km), the C_n^2 values gradually decrease to $10^{-18.5}$ $m^{-2/3}$, which may be due to the small or no gradient of humidity and the refractive index variation was mostly dependent on temperature gradient. However, in the stratosphere (14–19 km), where temperature inversion exists, C_n^2 values show slight increment from $10^{-18.5}$ to $10^{-16.5}$ $m^{-2/3}$ (Figure 1 *d*).

As mentioned earlier, daily C_n^2 values are averaged to compute monthly mean C_n^2 for different months to study the annual variability of all the 12 years. From the annual variability of all the 12 years, the mean climatological

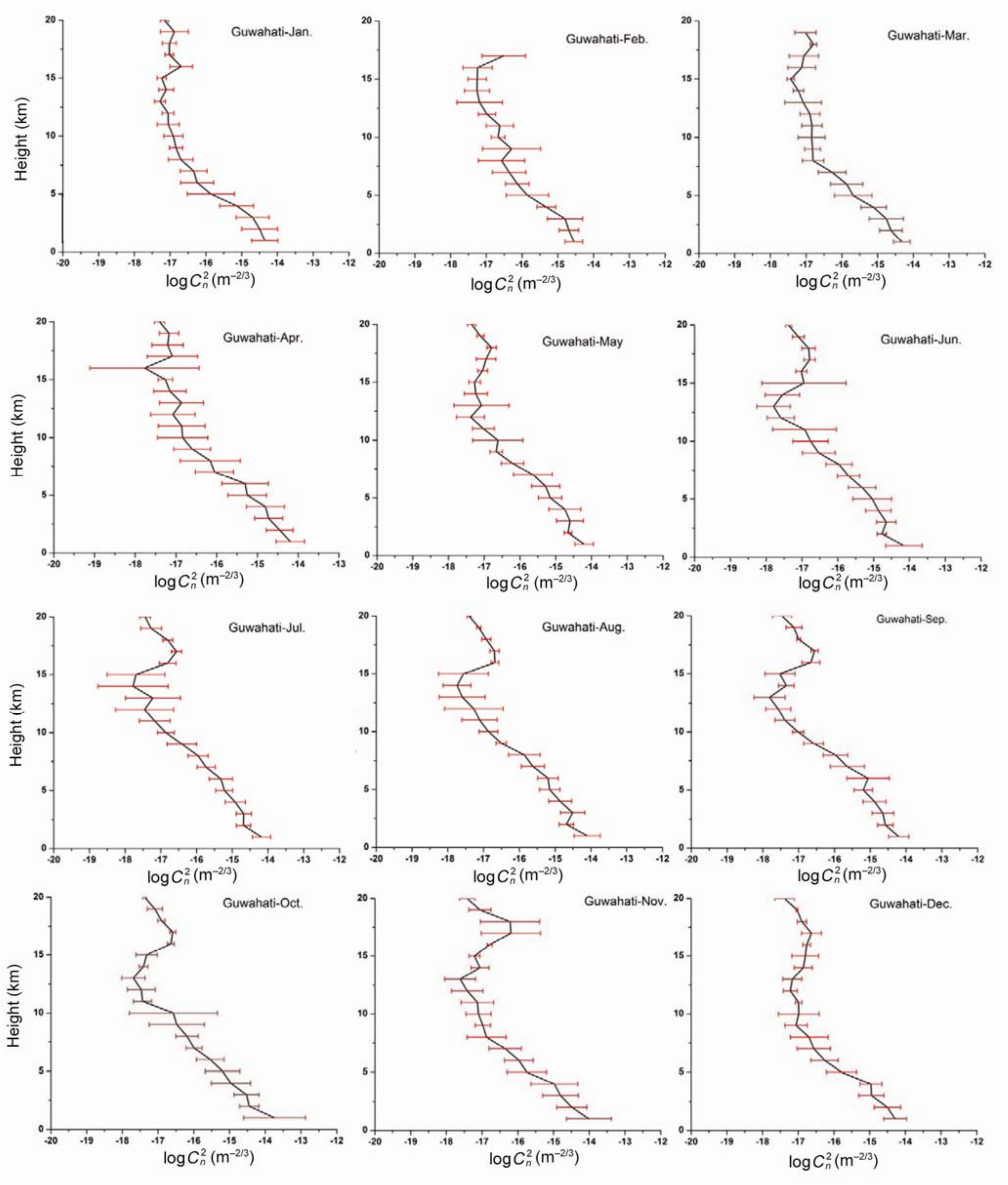

Figure 3. Climatological (2000–2011) mean and standard deviation of log C_n^2 for different months (January–December) over Guwahati.

annual variability over the station was studied by averaging over all the 12 years. This climatological pattern (Figure 2) shows that over the two stations the C_n^2 values vary between 10^{-18} and 10^{-12} $m^{-2/3}$, with maximum values at the surface and gradual decrease with height. Over both the stations, C_n^2 values in the lower and mid troposphere are higher during summer (March–May) and southwest monsoon period when more gradients in the

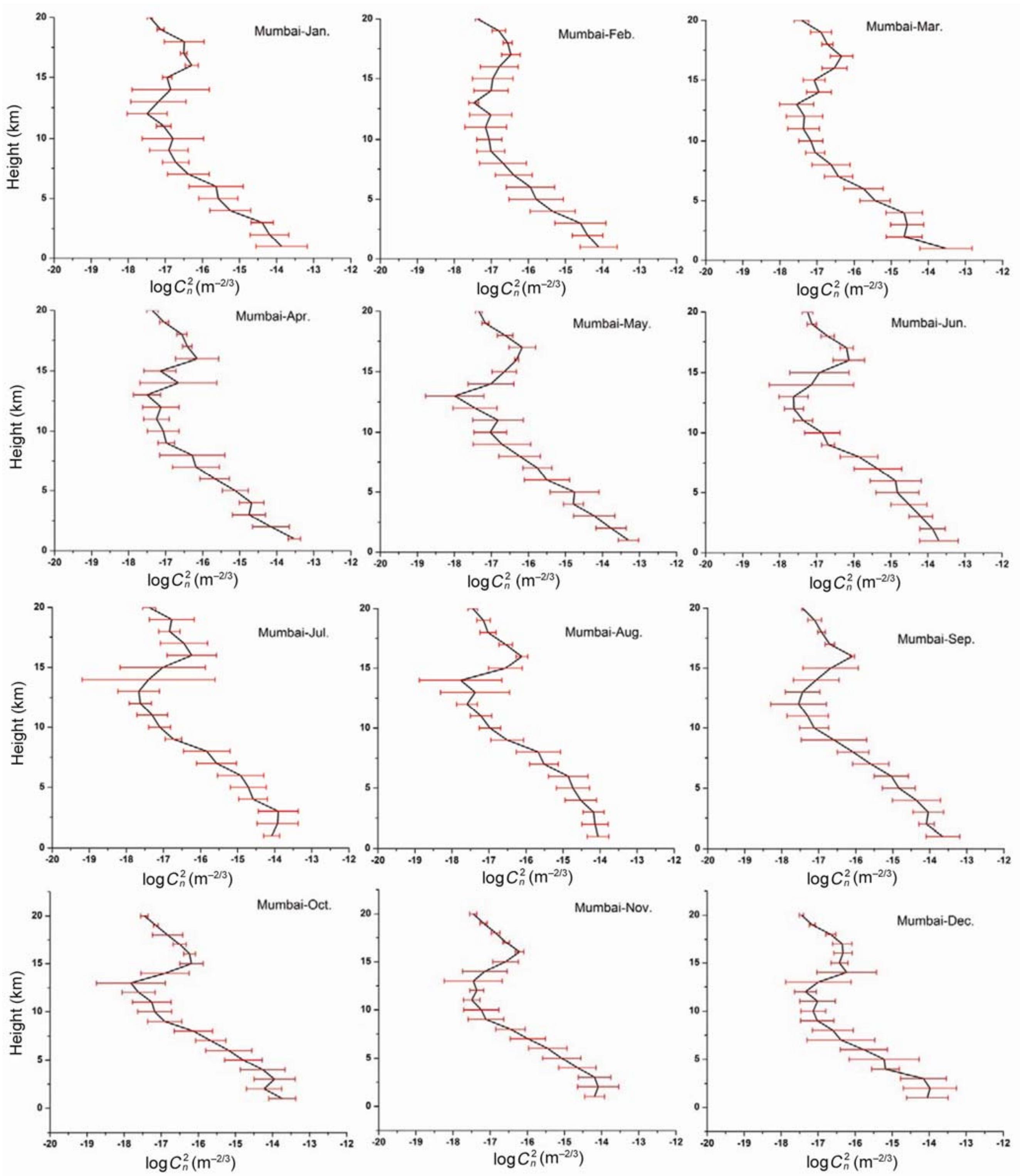

Figure 4. Climatological (2000–2011) mean and standard deviation of log C_n^2 for different months (January–December) over Mumbai.

temperature and moisture exist, compared to winter (December–February) and post-monsoon (October–November) seasons. Mumbai has shown higher values of C_n^2 at the surface and lower troposphere compared to Guwahati, which can be attributed to the advantage of moisture advection from the sea over Mumbai. A region of minimum C_n^2 values ($< 10^{-17}$ $\mathrm{m}^{-2/3}$) was observed nearly between 10 and 16 km over Guwahati and 10 and 13 km over Mumbai region. The mean climatology of these C_n^2 values for individual months along with the standard

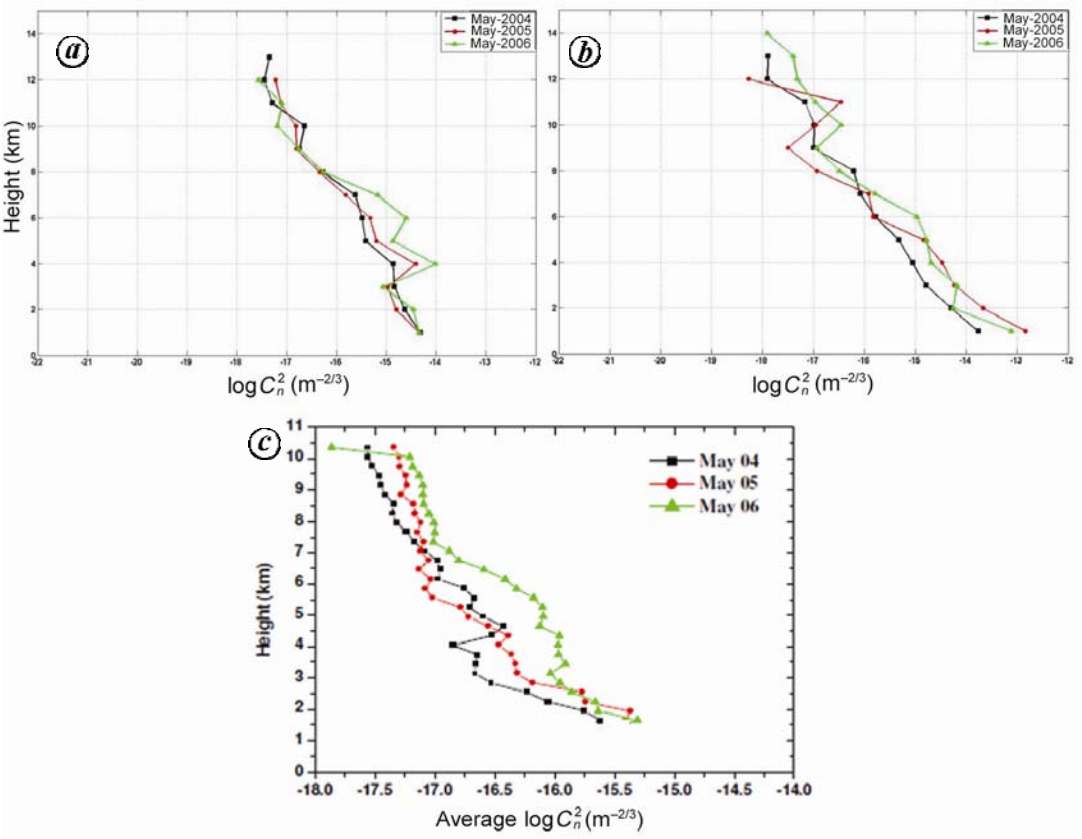

Figure 5. Comparison of mean computed (using RS) log C_n^2 values of (***a***) Guwahati and (***b***) Mumbai with measured values of (***c***) Pune wind profiler of May 2004, 2005 and 2006.

Table 2. Climatological (2000–2011) mean log C_n^2 over Mumbai

Height (m)	January	February	March	April	May	June	July	August	September	October	November	December
1,000	–13.9	–14.1	–13.5	–13.5	–13.3	–13.7	–14.1	–14.1	–13.6	–13.7	–14.2	–14.1
2,000	–14.2	–14.4	–14.7	–14.2	–13.8	–13.9	–13.9	–14.1	–14.1	–14.2	–14.1	–14.0
3,000	–14.4	–14.6	–14.6	–14.8	–14.2	–14.2	–13.9	–14.2	–14.0	–13.9	–14.2	–14.2
4,000	–15.2	–15.3	–14.6	–14.7	–14.8	–14.5	–14.6	–14.5	–14.4	–14.3	–14.7	–15.2
5,000	–15.6	–15.8	–15.4	–15.1	–14.8	–14.8	–14.7	–14.7	–14.8	–14.8	–15.1	–15.2
6,000	–15.6	–15.9	–15.7	–15.7	–15.5	–14.9	–14.9	–14.9	–15.0	–15.2	–15.4	–15.8
7,000	–16.4	–16.4	–16.4	–16.2	–15.8	–15.3	–15.6	–15.5	–15.6	–15.7	–16.0	–16.4
8,000	–16.7	–16.7	–16.6	–16.3	–16.2	–15.9	–15.8	–15.7	–16.1	–16.1	–16.5	–16.6
9,000	–16.9	–17.0	–17.0	–17.0	–16.7	–16.7	–16.7	–16.5	–16.6	–16.9	–17.1	–17.0
10,000	–16.8	–17.1	–17.2	–17.1	–17.0	–16.8	–17.1	–17.0	–17.1	–17.2	–17.2	–17.1
11,000	–17.0	–17.2	–17.4	–17.2	–16.8	–17.4	–17.3	–17.2	–17.3	–17.3	–17.5	–17.0
12,000	–17.5	–17.0	–17.3	–17.1	–17.4	–17.6	–17.6	–17.6	–17.5	–17.6	–17.4	–17.3
13,000	–17.2	–17.5	–17.6	–17.5	–18.0	–17.6	–17.7	–17.4	–17.4	–17.8	–17.5	–17.0
14,000	–16.9	–17.0	–16.9	–16.7	–17.0	–17.1	–17.4	–17.8	–17.1	–16.9	–17.1	–16.2
15,000	–17.0	–17.0	–17.1	–17.2	–16.7	–16.9	–17.0	–16.6	–16.7	–16.2	–16.6	–16.4
16,000	–16.3	–16.8	–16.5	–16.2	–16.3	–16.1	–16.2	–16.1	–16.1	–16.2	–16.2	–16.3
17,000	–16.5	–16.5	–16.3	–16.4	–16.2	–16.2	–16.4	–16.6	–16.7	–16.5	–16.6	–16.3
18,000	–16.5	–16.6	–16.7	–16.6	–16.6	–16.7	–16.8	–17.0	–16.9	–16.8	–16.9	–16.7
19,000	–17.1	–16.8	–16.9	–17.0	–17.2	–17.1	–16.8	–17.1	–17.1	–17.1	–17.2	–17.2
20,000	–17.4	–17.4	–17.4	–17.4	–17.3	–17.2	–17.4	–17.4	–17.4	–17.5	–17.5	–17.5

deviation over the two stations are presented in Figures 3 and 4, and mean values are given in Tables 1 and 2. Over both the stations the standard deviation is less in the upper levels (15–20 km) than in the lower levels.

Further, in order to check the range and pattern of variation of the computed C_n^2 values with the radar measurement values, a comparison of computed mean C_n^2 profiles of May 2004, 2005 and 2006 at Mumbai, Guwahati and measured values from wind profiler at Pune[7] is made. The range of variation in the troposphere is 10^{-18} to 10^{-13} over Mumbai, $10^{-17.5}$ to $10^{-14.5}$ over Guwahati and that of measured values at Pune is 10^{-18} to 10^{-15} (Figure 5). The pattern of variation shows a gradual decrease from the surface to the upper troposphere for both the computed and measured values.

Unlike other atmospheric radars (rain radar or cloud radar), the wind profiling radars are mainly sensitive to radio-refractive index variation in the neutral atmosphere. This variation is caused by the small-scale atmospheric turbulence in the atmosphere. The refractive index structure parameter (C_n^2) is one of the basic variables of atmospheric turbulence calculation. The C_n^2 variation can be computed from the backscattered signal[13] and also from the known atmospheric parameters[12] of RS data. In the present communication, the annual and climatological variability of C_n^2 over two tropical stations, namely Mumbai and Guwahati has been analysed.

The mean C_n^2 values over the two stations are in the range 10^{-18} to 10^{-12} $m^{-2/3}$. The C_n^2 values are higher in the lower troposphere where both temperature and humidity gradients contribute to refractive index variation, and lower in the middle the upper troposphere where moisture gradient is negligible. The lowest values of C_n^2 are observed just below the tropopause region between 10 and 16 km over Guwahati and 10 and 13 km over Mumbai region. Over the two stations, in the summer (March–May) and southwest monsoon period, the high C_n^2 values in the lower troposphere extended even into the mid-tropospheric levels. As a coastal station, Mumbai shows higher values of C_n^2 at the surface and lower troposphere compared to Guwahati. This study would provide help system designers of wind profilers/ST radars in finalizing the radar parameters to achieve the required sensitivity for targeted height over that region.

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Run-off potential assessment over Indian landmass: a macro-scale hydrological modelling approach

S. P. Aggarwal, Vaibhav Garg*, Prasun K. Gupta, Bhaskar R. Nikam, Praveen K. Thakur and P. S. Roy

Indian Institute of Remote Sensing, Indian Space Research Organisation, 4, Kalidas Road, Dehradun 248 001, India

The evolution of land–atmosphere–ocean models has resulted in the need for hydrologic models applicable to large areas and river basins. Such developments offer new challenges and opportunities for hydrologists to understand the hydrologic response of areas as large as continents. In the present study, the ability of variable infiltration capacity (VIC) hydrological model has been studied to assess run-off potential and other hydrological components for entire India. VIC is a semi-distributed macroscale hydrological model designed to represent surface energy, hydrological fluxes and states at scales from large river basins to the entire globe. It is grid-based model which quanti-

*For correspondence. (e-mail: vaibhav@iirs.gov.in)