CHAPTER IV

Atmospheric turbulence parameter, $Cn^2$: its role in signal propagation and adoption as EQ precursor

4.1 Introduction

Turbulence is composed of eddies, which are nothing but patches of zigzagging, and very often swirling fluid, moving randomly around and about the overall direction of motion. The atmospheric turbulent states generally produce such eddies with spatial and temporal scales which carry turbulent kinetic energy (TKE), i.e. the energy per unit mass associated with the eddies. In the process of dissipations in the atmospheric medium, large eddies shrink to small eddies, resulting in decrease of TKE, a process known as inertial cascade process. Such transformation of large eddies to small one transferring their energy into the medium, is generally proportional to the dissipation rate. Therefore, atmospheric cascade process is associated with transfer of energy from the kinetic field leading to formation of irregularities and eddies in the fluid (Justus et al., 1969). Small scale turbulence plays an essential role in the lower atmospheric dynamics as well as in signal propagation.

The atmospheric structure constant ($Cn^2$), is a parameter that reflects random fluctuations of atmospheric refractive index. In steady conditions, this index decreases monotonically with height, but the atmospheric medium often remains in a turbulent state caused by factors such as irregular heating of the earth’s surface, forced cooling and also by natural or manmade perturbations. The size of the irregularities is defined by the parameter $Cn^2$. 
During recent years, there has been emphasis on understanding the lower atmospheric dynamics through analysis of $Cn^2$ features in diurnal and seasonal terms (Satheesan et al., 2002; Singh et al., 2008; Belu et al., 2012; Ghosh et al., 2001; Nath et al., 2010). This parameter is also used for predicting fast changing fluctuation and attenuation of radio wave while travelling through lower atmosphere (Tatarskii, 1971; Grabner et al., 2012; Ishimaru et al., 1997). Further, as lower atmospheric dynamics are highly sensitive to variations in temperature, pressure and humidity, $Cn^2$ may suffer changes with atmospheric situation, like worst weather ambiances (Singh et al., 2008; VanZandt et al., 1978). One can therefore, expect modification of this parameter by earthquake (EQ) preparatory processes when atmospheric variables get modulated by seismic induced energy sources (Dolukahnov et al., 1971; Devi et al., 2007).

Atmospheric turbulence depends mainly on the background atmospheric parameters such as wind, temperature, and humidity (VanZandt et al., 1978). By using a statistical approach, Kolmogorov (Kolmogorov, 1941) attempted to model the turbulence in the atmosphere. The Kolmogorov theory is based on the assumption that wind velocity fluctuations are approximately locally homogeneous and isotropic random fields for scales less than the largest wind eddies.

Endlich (Endlich et al., 1965) classified the turbulent layers on the basis of wind and temperature as follows:

1. The first region consists of quasi-horizontal layers of considerable wind speed and in which the wind direction changes rapidly in the vertical and horizontal directions. These conditions of flow are favorable to turbulence at the boundary of the tropopause.
2. The second type of turbulent region lies near the pronounced jet cores (on the cyclonic side of the core).

3. The third type of turbulent regions is found in anticyclonic horizontal shear below the core height.

4. The fourth type is the role of mountain waves that contain highly turbulent conditions even at the tropopause height.

The mechanism of turbulent scatter explained by many researchers (Pekeris, 1947; Booker and Gordon, 1950) and later developed by Tatarskii (1971) to explain the tropospheric radio propagation. VanZandt et al. (1978) developed a theoretical model for the determination of \( Cn^2 \) from Radiosonde (RS) balloon soundings, which has been later used by (Rao et al., 1997; Singh et al., 2008; Nath et al., 2010). By using the VHF radar measurements Nastrom et al. (1985) studied the diurnal variation of \( Cn^2 \) during summer months. They found fair correlation between the \( Cn^2 \) variation and the wind speed at tropopause. Gage et al., (1980), VanZandt et al., (1978), Smith et al., (1983), Tsuda et al., (1985) have found fair correlation between \( Cn^2 \) and large shear due to jet stream. Nastrom and Eaton (1993) used \( Cn^2 \) as a predictability parameter of humidity for the arrival of monsoon. The turbulence parameter has been measured by both in situ (Barat and Bertin, 1984; Lubken et al., 1987) and remote sensing techniques (Frisch and Clifford, 1974; Crane, 1980; Gage et al., 1980; Weinstock, 1981; Sato and Woodman, 1982; Woodman and Rastogi, 1984). Kolmogorov theory assumes local homogeneity and stationarity of the refractive index fluctuations. But Dole et al., (2001), Wilson et al., (2005) suggested that in radar experiments the assumption within the illuminated volume is hardly satisfied. Earlier studies were carried out over the observational site using the MST radar in VHF band to quantify the turbulence...
parameters in troposphere, lower stratosphere (Rao et al., 1997), height structure of $Cn^2$ for different seasons (Rao et al., 2001a) and height structure of eddy diffusivity in troposphere, lower stratosphere and mesosphere (Rao et al., 2001b). Nastrom (Nastrom et al., 2004) measures the atmospheric turbulence with dual beam width method, Satheesan (Satheesan et al., 2002) adopted the variance method and estimated the turbulence parameter and the eddy diffusivity for momentum in upper troposphere and lower stratosphere, Sasi (Sasi et al., 2001) estimated the turbulent kinetic energy dissipation rate and eddy diffusion coefficient with their seasonal variation using MST radar data. The turbulence refractivity structure constant $Cn^2$ is an important parameter to characterize the turbulence. Ghosh et al., (2001) and Rao et al., (2001a) attempted to bring out the height structure of $Cn^2$ for different seasons using four years of MST radar data. In the present thesis an attempt has been made to characterize the turbulence parameter and their role on signal propagation.

With the above background, the chapter aims at to characterize the seasonal variation of $Cn^2$ over Guwahati (26.2°N, 91.75°E) using five years of Radiosonde (RS) data available from Regional Meteorological Centre Guwahati and Wyoming University. Further, the chapter examines possible role of EQ induced effects, if any, on $Cn^2$, during a few major EQ events.

### 4.2 Data and Methodology

In this chapter, $Cn^2$ is determined by using RS data. The RS contains a radio transmitter with sensors to measure pressure, temperature, humidity as well as wind speed and direction at different heights of the atmosphere starting from the surface to around 30 km. The entire package of transmitter and sensors is carried aloft by a
spherically shaped free flying balloon released from surface, generally, two times a day, i.e. at 0000 and 1200 hrs UTC. The 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). The \( \text{Cn}^2 \) values are calculated by using the Eqs (4.1) and (4.2) with the data from above website.

The expression for \( \text{Cn}^2 \) is defined by Eq. (4.1) as (Tatarskii et al., 1971):

\[
\text{Cn}^2 = a^2 \text{e} l_o^4 M^2
\]  

(4.1)

where, \( a^2 \), is a dimensionless constant within 1.5 and 3.5 but most commonly taken as 2.8 (Monin et al., 1971); \( \text{e} \), a numerical constant, generally, taken as unity; \( l_o \), the buoyancy/outer scale length of the turbulence spectrum; and \( M \), the vertical gradient of potential refractive index fluctuations. This gradient is expressed as (Warnock et al., 1985, Doviak et al., 1993):

\[
M = -77.6 \times 10^{-6} \left( \frac{P}{T} \right) \left( \frac{\partial \ln \theta_T}{\partial Z} \right) \left[ 1 + \frac{15500}{T} \left( 1 - \frac{1}{2} \frac{\partial \ln q}{\partial Z} \right) \right]
\]  

(4.2)

where, \( T \), is the ambient temperature in K; \( P \), the pressure; \( q \), the specific humidity (SH); and \( \theta_T \), the potential temperature (PT), given as:

\[
\theta_T = T \times \left( \frac{P_0}{P} \right)^{0.3}
\]  

(4.3)

where, \( P_0 \), is the standard atmospheric pressure; and \( Z \), the height in meters.

The total turbulent energy density spectrum consists of a production region, the inertial sub-range and the dissipation region. Most of the turbulence production energy
input occurs at scale sizes between $6l_o$ and $l_o/6$, where, $l_o/6$, is defined as the onset of the inertial sub-range. The outer scale $l_o$ is presumed to be around 10 m (VanZandt et al., 1978), although no direct evidence is available on the thickness of a turbulent layer (Singh et al., 2008).

Taking RS data at an interval of 1 km height, the gradients of potential temperature ($\partial \theta / \partial z$) and specific humidity ($\partial q / \partial z$) are computed up to the height of 15 km. From the gradients so obtained, M values are calculated by using Eq. (4.2) and $C_n^2$ profile is then drawn [Eq. (4.1)] for morning and evening hours of each day taking $l_o$ to be 10 m with values of constants ‘a’ & $\infty'$ as 2.8 and 1, respectively (Singh et al., 2008, Belu et al., 2012, Monin et al., 1971). From these profiles, monthly average $C_n^2$ value is calculated. Finally, to attain the climatological variation of this parameter, the 5-years mean of monthly average $C_n^2$ profiles are averaged. In this analysis, June-August is taken as summer months, September-November as autumnal equinox and December-February as winter season while months from March-May cover vernal equinox period.

4.3 Results and Discussion

Considering the significant role played by PT and SH on $C_n^2$ (Eq (4.2)), it is essential to analyze variation pattern of these two parameters with height. Therefore, PT and SH from 1 to 15 km altitude are calculated using temperature, humidity and pressure data of RS for each day of a month. In Figure 4.1(a and b), summer time representative profiles for PT and SH, respectively are presented. The figure shows that PT increases with a constant rate up to the height of 9-10 km but beyond this altitude, a break in the PT gradient is noted. The SH profile also presents a constant decrease of its value up to a height of 6 km but its gradient changes once it crosses this altitude and
attains zero value at a height of 10 km. Next, from the SH and PT profiles, the value of M is calculated using Eq. (4.2) individually for each day from the total of 3000 such profiles covering five-year study period. Finally, Eq. (4.1) is used for evaluating $Cn^2$ profile from 1 to 15 km height by incorporating the corresponding vertical gradient of potential refractive index value (M). The profiles of M and $Cn^2$ for each month is drawn by averaging each day profile of a month and the 3-months mean is then calculated to receive the seasonal pattern.

Figure 4.1: Profiles of: (a) Potential temperature (PT); (b) Specific humidity (SH); (c) Potential refractive index gradient; and (d) Refractive index structure constant parameter ($Cn^2$) (representative pattern)

The height variation of M and log$Cn^2$ of a summer day of the year 2007 are presented in Figure 4.1 (c and d), as a representative profile of this month. The
breakdown in the slope of M profile at a height of 8-10 km [Figure 4.1(c)] is similar to that observed in the PT -variation pattern of Figure 4.1(a). It is seen that log\(Cn^2\) varies from \(-14 \text{ m}^{-2/3}\) to \(-18.8 \text{ m}^{-2/3}\) up to the height of 10 km but above this altitude, it shows an abrupt increase till it reaches the tropopause height. In general, \(Cn^2\) attains the highest value within the height interval of 1-3 km. In the middle troposphere (3-10 km), the log\(Cn^2\) value gradually decreases to reach minimum (\(-18.8 \text{ m}^{-2/3}\)) at a height of 9-11 km.

### 4.3.1 Month-to-month variation of \(Cn^2\)

From large number of individual profiles, variation of \(Cn^2\) for each month is calculated. The log\(Cn^2\)- height profile so obtained is then averaged for each month covering five-year period and the profiles so obtained are presented in Figure 4.2.

![Figure 4.2: Climatological (2006–2010) mean of log \(Cn^2\) for different months (January-December) over Guwahati (Contd.)](image)
Figure 4.2: Climatological (2006–2010) mean of log $Cn^2$ for different months (January-December) over Guwahati
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The finer features of \( \log C_n^2 \) for each month within the height range 1-15 km are presented in Table 4.1. It is seen from the table that over Guwahati, \( \log C_n^2 \) may reach a maximum value of \(-14.3 \text{ m}^{-2/3}\) and a minimum of \(-18.3 \text{ m}^{-2/3}\), which varies from month-to-month. Further, the table shows that \( \log C_n^2 \) gradually decreases with height up to 10 km in each month and then it changes its value once its crosses this altitude.

Table 4.1: Mean of \( \log C_n^2 \) for different months (January–December) over Guwahati during 2006-2010

<table>
<thead>
<tr>
<th>Height, m</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>-17.29</td>
<td>-17.29</td>
<td>-17.41</td>
<td>-16.79</td>
<td>-16.62</td>
<td>-16.43</td>
<td>-16.03</td>
<td>-16.05</td>
<td>-16.47</td>
<td>-16.73</td>
<td>-16.97</td>
<td>-17.31</td>
</tr>
<tr>
<td>8000</td>
<td>-17.28</td>
<td>-17.63</td>
<td>-17.50</td>
<td>-17.22</td>
<td>-16.95</td>
<td>-16.78</td>
<td>-16.57</td>
<td>-16.54</td>
<td>-16.64</td>
<td>-17.00</td>
<td>-17.23</td>
<td>-17.35</td>
</tr>
<tr>
<td>9000</td>
<td>-17.47</td>
<td>-17.77</td>
<td>-17.44</td>
<td>-17.37</td>
<td>-17.20</td>
<td>-17.28</td>
<td>-17.00</td>
<td>-16.97</td>
<td>-17.21</td>
<td>-17.38</td>
<td>-17.47</td>
<td>-17.65</td>
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<tr>
<td>10000</td>
<td>-17.35</td>
<td>-17.73</td>
<td>-17.33</td>
<td>-17.31</td>
<td>-17.37</td>
<td>-17.85</td>
<td>-17.46</td>
<td>-17.41</td>
<td>-17.73</td>
<td>-17.73</td>
<td>-17.59</td>
<td>-17.80</td>
</tr>
<tr>
<td>11000</td>
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<td>-17.75</td>
<td>-17.21</td>
<td>-16.93</td>
<td>-17.66</td>
<td>-18.10</td>
<td>-17.99</td>
<td>-17.59</td>
<td>-18.12</td>
<td>-18.00</td>
<td>-17.63</td>
<td>-17.85</td>
</tr>
<tr>
<td>13000</td>
<td>-17.33</td>
<td>-17.15</td>
<td>-17.54</td>
<td>-17.84</td>
<td>-18.15</td>
<td>-17.97</td>
<td>-18.12</td>
<td>-18.09</td>
<td>-18.03</td>
<td>-17.68</td>
<td>-17.66</td>
<td></td>
</tr>
<tr>
<td>15000</td>
<td>-17.28</td>
<td>-16.99</td>
<td>-17.34</td>
<td>-17.62</td>
<td>-17.79</td>
<td>-17.82</td>
<td>-17.69</td>
<td>-17.67</td>
<td>-17.54</td>
<td>-17.58</td>
<td>-17.16</td>
<td></td>
</tr>
</tbody>
</table>
Such changes in logCn² gradient in the range 1-10 km and 10-15 km are shown in Figure 4.3 (a and b), respectively. The figure shows that Cn² attains maximum value in the months of June and July up to the height of 10 km but beyond this range, Cn² abruptly decreases to reach a lowest value as compared to other months of the year.

4.3.2 Seasonal variation of Cn²

The seasonal Cn² profiles are then drawn and five years average seasonal logCn² - height variation pattern for four seasons is presented in Figure 4.4. The profiles show that up to the height of 10 km, Cn² attains higher value during summer and autumnal equinox and lowest value during winter and vernal equinox season, but above this altitude Cn² goes minimum in summer and maximum in winter and vernal equinox season as reflected in profiles of each individual month of Figure 4.2.
Figure 4.4: Seasonal variation of LogCn^2 for the summer, autumnal equinox, winter and vernal equinox season

4.3.3 Relation of Cn^2 with Earthquake (EQ)

The key parameters in modifying irregularity size is temperature and humidity, therefore, whenever there is a significant change in these parameter, its effect on Cn^2 will also be observed. One such situation is the EQ preparatory process. Because there are large number of reports on changes in temperature before and during an EQ, be it surface temperature, the sea surface temperature (SST) or surface latent heat flux (SLHF)(Alvan et al., 2012; Cervone et al., 2004; Dey et al., 2003; Goswami et al., 2014; Ouzounov et al., 2007; Qiang et al., 2007; Singh et al., 2007; Tronin et al., 2002;
Tronin et al., 2000). It is expected to see the effect in the turbulence size structure at EQ time. Therefore, Cn\(^2\) gradient is examined before a few strong EQs events (Table 4.2).

**Table 4.2: Earthquakes under consideration**

<table>
<thead>
<tr>
<th>S No</th>
<th>Date</th>
<th>Epicenter position</th>
<th>Depth, km</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Latitude, °N</td>
<td>Longitude, °E</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12.05.2008</td>
<td>31.021</td>
<td>103.367</td>
<td>33</td>
</tr>
<tr>
<td>2</td>
<td>11.3.2011</td>
<td>38.322</td>
<td>142.369</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>09.01.2013</td>
<td>25.4</td>
<td>94</td>
<td>75</td>
</tr>
</tbody>
</table>

### 3.3.1 China earthquake on 12 May 2008

The China EQ of magnitude 7.9 occurred at 31.021°N and 103.367°E on 12 May 2008. On this occasion, surface Cn\(^2\) value for each day of the EQ month May 2008 is calculated and the profile so obtained is presented in Figure 4.5. One can see that there is a drastic reduction in Cn\(^2\) by 12.5% from its average just one day prior to the EQ day. Along with the Cn\(^2\) variation for May 2008, the day-to-day variation of Cn\(^2\) is presented in Figure 4.5 for May 2009 where there was no EQ, i.e. there was no major EQ (M>7) over this region. The abnormal decrease of logCn\(^2\) reaching a value as low as -18 m\(^{-2/3}\) on 11 May 2008 suggests possible contribution of EQ preparatory processes in modifying the structure constant parameter.
Figure 4.5: Diurnal variation of $Cn^2$ profile over China for the month May of 2008 prior, during and after the China Earthquake, 12 May 2008 shown by black line and the normal days variation are shown by red line

4.3.3.2 Japan earthquake on 11 March 2011

The Japan EQ of magnitude 9 occurred at 38.322°N and 142.369°E on 11 March 2011. In this event too, log$Cn^2$ values near to the epicentre, as presented in Figure 4.6, display a 13% drop from its normal magnitude, two days before the EQ event. Such changes in log$Cn^2$ are not detected in any other day of this or other months. As an example, the log$Cn^2$ variation is also presented, for a non-EQ month of March 2010, i.e. there was no major EQ (M>7), in Figure 4.6. The figure shows that there was no abnormal variation in this parameter during the non-EQ month and the sudden drop of $Cn^2$ prior to strong EQ of Japan may be associated with EQ induced effect.
Figure 4.6: Diurnal variation of $Cn^2$ profile over Japan for the month March of 2011 prior, during and after the Japan Earthquake, 11 March 2011 shown by black line and the normal days variation are shown by red line

4.3.3.3 Myanmar Earthquake on 9 January 2013

It is also significant to note that even during EQs of moderate strength; there may be situation when marginal changes in $Cn^2$ may be detected. As an example, $Cn^2$ variation is presented during a moderate EQ of $M=5.9$, that occurred at a location $25.4^\circ N$ and $94^\circ E$, on 9 January 2013. It is seen that $Cn^2$ at the epicentre site decreases by 0.4% before the EQ, but unlike the strong EQ events, the change is marginal and recovery period of three days (Figure 4.7) from the EQ time $Cn^2$ to its average value is large.
In order to associate such changes in Cn² with the EQ events, the modification in temperature are further calculated. For this purpose the diurnal peak of temperature, i.e. T_max is extracted for each day and the average T_max value is calculated for the EQ month. The percentage deviations in maximum temperature (δT_max) is calculated from their monthly average values and the result is plotted in Figure 4.8. It is noted that in all the three EQ cases there is a significant drop in temperature near the epicenter position as marked in Figure 4.8. In the China EQ of 12 May 2008, the temperature decreased by 78% from its average value, while for Japan EQ of 11 March 2011, temperature showed a very strong dip 250% and for moderate EQ of 9 January 2013, a decrease of only 40% from the average T_max value was noted. However, more case studies on variation of Cn² at different EQ magnitudes and depths are planned to be conducted in future.
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Figure 4.8: Percentage deviations of temperature from the average magnitude for (a) China (b) Japan (c) Myanmar EQ respectively. The red arrow shows the EQ day

4.4 Conclusion

In the chapter, the monthly as well as seasonal characteristics of turbulence parameter ($C_n^2$) over Guwahati (26.2°N, 91.75°E) are analysed and the role of EQ preparatory processes in modifying this parameter is examined.

From the results, it is observed that $C_n^2$ has wide fluctuations in summer and autumn season than compared to the winter and vernal equinox months. The summer $C_n^2$ values from the surface up to the 9-11 km height are larger compared to the other seasons. A region of minimum $C_n^2$ values is observed at nearly 10 km in all seasons where the potential temperature gradients have a significant change. Due to the excess humidity present in the lower atmosphere, it is likely that $C_n^2$ shows higher values within 1-6 km height (Singh et al., 2008; Nath et al., 2010; VanZandt et al., 1978). This factor also has a control in the variation of $C_n^2$ in its seasonal pattern. In winter and vernal equinox seasons with very low humidity in the background, the $C_n^2$ attains the lowest value as compared to the summer and autumn months when humidity attains the seasonal peak over Guwahati as is seen from Figure 4.9, where five years average...
seasonal variation characteristics of humidity (RH) over this station, are shown. The significant low value of RH (40-57%) during winter and vernal equinox months (December –May) and excess of RH (60-70%) in summer and autumn equinox months (June-November) as seen from the figure, might have an effect in controlling the $C_n^2$ magnitude at different seasons.

![Image of relative humidity variation](image)

*Figure 4.9: Five years (2006-2010) average mean relative humidity variation over Guwahati for each month*

Along with humidity, temperature also plays a key role in modifying $C_n^2$. In this regard, the temperature profile over Guwahati in different seasons is presented in Figure 4.10. It is seen from the figure that temperature maintains the expected pattern up to 10 km height where summer values are higher as compared to winter and vernal equinox season. But it is interesting enough to note a break in the profile at around 10 km height, when temperature during summer shows a decrease in its value as compared to winter and vernal equinox season. This feature is similar to that observed in $C_n^2$ profile in Figure 4.4 indicating a significant role played by temperature and humidity on the
structure constant parameter. It is also observed that along with humidity, the temperature also plays a key role in modifying $C_n^2$. Therefore there may be significant change on $C_n^2$ during EQ time, as atmospheric parameters forced by its preparatory process(Chapter III). We have seen from analysis of $C_n^2$ in relation to EQ that its value decreases before and during the earthquake time ambience resulting to increase in RRI and hence favouring beyond LOS propagation. Thus, $C_n^2$ can be used as a predictive cursor parameter of an impending earthquake. This interesting finding may be used as a precursive parameter, if further studies on this finding is taken for the validation of the possibility.

![Figure 4.10: Average seasonal variation of temperature with height](image)

Figure 4.10: Average seasonal variation of temperature with height