Estimating of the optical turbulence profile for clear sky over Baghdad

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Abstract:
Study of optical turbulence profile represented by refractive index structure ($C_n^2$) through the atmosphere has several effects on the propagation of light, free space optics, degradation of images taken by telescopes. Based on the routine meteorological data taken from radiosonde such as air pressure, air temperature and wind speed, this study presents $C_n^2$ profiles for clear sky four days at time 12 pm of year 2019, which are chosen at different seasons: winter, spring, summer and autumn. The results show that these profiles have large values near the ground and gradually drop to low values. Also these profiles have large values in winter and after 17 km height they drop steeply and unify to same trend and magnitudes.

Keywords: refractive index structure function, Atmospheric turbulence, optical turbulence profile, Outer length scale, Baghdad

1. Introduction

Atmospheric optical turbulence, generally, is generated by mechanical and/or thermal actions, for instance, wind shear and/or convection over a heated surface respectively and also depends on synoptic meteorology (Avila et al., 1997). It is responsible for many serious problems degradations of images obtained by means of ground-based telescopes, laser communications, free space optics and directed energy technologies. The intensity of optical turbulence can usually represented by the refraction index structure function parameter ($C_n^2$), which depends on the geographical altitude, location and time of day (Shaik, 1988; Jaber and Al-Jiboori, 2018). The values of $C_n^2$ at the lower heights (i.e. atmospheric boundary layer) are larger than those at higher heights (i.e. free atmosphere\(^1\)) whereas the largest gradients of temperatures are highest close to ground and lowest below the tropopause. Owing to the distribution of temperature during the day time, $C_n^2$ is highest around the mid of day.

\(^1\) It is the higher part of the atmosphere extending from the first kilometer above ground until the limit of the Earth’s atmosphere (i.e. towards 20 km adapted in this study).
There are various techniques to obtain the vertical profile of $C_n^2$ such as the balloon-borne microthermometer (Abahamid et al., 2004), scintillation detection and ranging (Avila et al., 1997), multi-aperture scintillation sensor and scintillation. Unfortunately, they are expensive and hard to observe in spatial –temporal field. Thus estimation of $C_n^2$ profile using models has less cost and convenient alternative, for example Tatarski and Hufnagel models. Their structures are different whereas the former was based upon regular meteorological radiosonde data, while the latter which is parametric models based on the measured data of $C_n^2$. Many studies estimated the optical turbulence profile which comparing with measurement to avoid the regional differences (e.g. Cuicui et al., 2020), but in this research we try to characterize the vertical behavior of $C_n^2$ over Baghdad based on Tatarski method. Unfortunately, there are never $C_n^2$ measurements available for comparing proposes but the result of this method examined and compared with the measured by several studies (Cuicui et al., 2020).

2. Data used:

To recover the vertical profile of refractive index structure parameter, we use reanalysis meteorological data taken from National Centers for Environmental Prediction (NCEP) and National Centers for Atmospheric Research (NCAR). These chosen centers were selected for easy accessibility (free data access) as well as the long temporal coverage. Moreover, unfortunately there are no real radiosonde data for new recent histories running at Baghdad weather station since 1990, except in 2013 at 12 GMT, which has not complete data especially at high heights.

To put into practice, the NCEP/NCAR dataset downloaded for point within Baghdad city defined by Latitude (33.25° N) and Longitude (44.25° E) for one year of 2019 and 33 m above mean sea level. These data are available every 6 hours (or 4 times per day: 12 am, 6:00 am, 12:00 pm and 6:00 pm UTC) and for 20 pressure levels. These levels have been transformed to geometric heights (H) using the equation follows as according to the International Standard Atmosphere.

$$H(m) = \left[ 1 - \frac{P(Pa)}{1013.25}^{-5.56} \right] \div 22.6 \times 10^{-6}$$

(1)

The results of this transformation for some levels are reported in Table 1.

Table 1: Geometric heights corresponding to pressure levels.

| Pressure levels (hPa) | 1000 | 850 | 700 | 500 | 300 | 200 | 150 | 100 | 50 |
|----------------------|------|-----|-----|-----|-----|-----|-----|-----|----|
| Height (km)          | 0.11 | 1.57| 3.01| 5.57| 9.16| 11.8| 13.5| 15.8| 19.3|

We chose the clear sky days at time 12:00 pm for four days during the year. The dates of these days with their seasons are shown in Table 2.
Table 2: Dates of used data with values of $C_n^2$ at surface layer in Baghdad.

| Season | Date               | $C_n^2$ (m$^{-2/3}$) | p   |
|--------|--------------------|----------------------|-----|
| Winter | 15 January, 2019   | $3 \times 10^{-15}$  | 1.43|
| Spring | 15 April, 2019     | $7 \times 10^{-15}$  | 1.45|
| Summer | 15 July, 2019      | $10^{-12}$           | 1.45|
| Autumn | 27 October, 2019   | $34 \times 10^{-14}$ | 1.45|

3. Methodology:

3.1 Tatarski Model:

According to Kolomogrov’s theory, the parameterization for calculating $C_n^2$ profile has been expressed by (Tatarski, 1961) as below

$$C_n^2 = a M^2 L_{o}^{4/3}$$  

(2)

where $a$ is a dimensionless constant that is commonly taken a value of 2.8 (Abahamid et al., 2004). $M$ is the gradient of potential refractive index which expresses as

$$M = - \left( \frac{79 \times 10^{-6} p}{T} \right) \frac{\partial \ln \theta}{\partial z}$$  

(3)

where $\theta$ is the potential temperature profile defined by

$$\theta = T \left( \frac{1000}{p} \right)^{0.286}$$  

(4)

which is conserved in adiabatic lifting or descent of an air mass. $z$ is the height above the ground, $P$ is the air pressure in mbar and $T$ is the air temperature expressed in K.

To solve Eq. (1), the outer length scale, $L_{o}^{4/3}$, for the flow is needed. There are several stochastic models to parameterize $L_{o}^{4/3}$ reported in many references (e.g. Coulman et al., 1988; Dewan, et al., 1993; Abahamid et al., 2004; Cuicui et al., 2020). These models mostly take into account the wind velocity shear and sometimes temperature lapse rate which determine for two layers of atmosphere (i.e. troposphere and stratosphere). In this study, we used the following Equation (Dewan et al., 1993) to calculate outer scale at stratosphere

$$L_{o}^{4/3} = 0.1^{4/3} \times 10^{(0.506+50S)}$$  

(5)

where $S$ is the shear of horizontal velocity defined as

$$S = \sqrt{\left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2}$$  

(6)
With $u$ and $v$ are the north-south and east-west wind components.

In general, $L_0$ at any height of atmosphere the atmospheric conditions are turbulent, so $L_0$ should be function of Richardson number which less than 0.25. Thus, the shear of horizontal wind will be more effective than actual temperature lapse rate. Using SCIDAR measurements of $C_n^2$ and $M^2$, (Coulman et al., 1988) found that values of $L_0$ range from 1 m to 5 m for heights from 2 km to 17 km. Thus, for heights from 2 km to lower heights, we use the following equation (Crabbs et al., 2012)

$$C_n^2(h) = C_n^2(h_0) \left(\frac{h}{h_0}\right)^p$$

(7)

where $h_0$ is the height of the instrument above ground and the power $p$ is parameter depending on the temporal hour of day which is computed by (Canuet, 2014)

$$p = 1.45 - 0.02(TH - 6)^2$$

(8)

where $TH$ is time hour calculated by

$$TH = \frac{T-T_{\text{sunrise}}}{T_{\text{sunset}}-T_{\text{sunrise}}}$$

(9)

with $T$ is time of observation, $T_{\text{sunrise}}$ (or $T_{\text{set}}$) is the time of sunrise (or sunset).

4. Results and Discussion:

4.1 Vertical distribution of air temperature and wind speed:

Figs. 1a-4d show the vertical profile of air temperature (solid lines) and wind speed (dashed lines) for four seasons: winter (January), spring (April), summer (July) and autumn (October), respectively. In general, it can be noticed that air temperatures drop with increasing heights whereas lapse rate deeps to height 18 km in winter, 16 km in spring and summer and 12.5 km in autumn. Over these heights, vertical profiles of temperature behave either isotherm or inversion.

In contrast, wind speeds increase with heights with different shear rates, except in summer whereas velocity value did not increase 12 m/s. High wind speed (jet stream) were found in spring and winter and slight wind speed is in autumn. The different maximum winds occurred at different heights where wind speed in spring has highest value of 70 m/s found at 11 km, 52 m/s at 13 km in winter, 17 m/s at 10 km in summer and 21 m/s at height of 16 km.
Fig. 1: vertical variations of air temperature (solid line) and wind speed (dashed lines) with heights.

4.2 Vertical variations of potential temperature lapse rate, wind shear and Richardson number

For calculation gradient of potential refractive index, $M$, which is essential parameter in computing $C_n^2$, we calculated potential temperature lapse rate, $\frac{d\Theta}{dz}$, for all days and presented in Fig. 2. All $\frac{d\Theta}{dz}$ profiles have positive values with height and they are in the same behavior, except for summer (July) in which the lowest values of $\frac{d\Theta}{dz}$ are found in heights ranging from 10 km to 16 km. It is interesting to show that after 18 km all profiles unit with the same values and behavior (see Fig. 2).
Fig. 2: Vertical variation of potential temperature lapse rate at four times at four months over Baghdad.

Also we need to see the behavior vertical wind shear which is important in calculating outer length scale. The vertical wind shear were calculated for each two levels which plotted in Fig. 3. It is clear that vertical profile of wind shear has highest positive/negative values (±0.014 s⁻¹) in spring (April), while it has also the same behavior but with less values (±0.005 s⁻¹). Finally, wind shear profiles for July (summer) and October (autumn) have the same behavior with lowest values (fluctuate about ±zero).
From the calculations above, we could computed vertical profile of Richardson number, $R_i$, for all times indicated in this study. The results are plotted and presented in Fig. 4, which show that the vertical atmosphere over Baghdad city have value $-R_i<0.25$. This indicates that the atmospheres in clear skies are instability and fully turbulent. In April (spring), the instability is to be weak somewhat especially from 8 km to 18 km. This is right because this month is transition month from cold winter to hot summer.

**4.3 Vertical profile of refractive index structure function**

To recover the vertical profile of $C_n^2$, it has been calculated for altitudes from the surface layer to 2 km (using Eq. 7) and from 2 km to 18 km (using Eq. 2). In applying Eq. (2), the values of $C_n^2$ was calculated in Baghdad based on the measurements of 3D ultrasonic anemometer set up on the roof of building with height of 19 m (see Jaber and Al-Jiboori, 2019, for more details). The values of $C_n^2$ and the power p for the days indicated in this study are reported in Table 2. The profiles of $C_n^2$ were derived for 12 pm time for 4 days of different seasons of the year 2019: winter, spring, summer and autumn. $C_n^2$ profiles over Baghdad are displayed in Fig. 5. In general, the profile have large values of $C_n^2$ near the ground, especially in summer and autumn because of high solar energy absorbed by the urban surface of Baghdad in these seasons. These profiles gradually decrease with altitudes in free atmosphere starting from 12 km to low stratosphere. The values of $C_n^2$ in winter, spring and autumn for altitudes from 8 km to 14 km are larger than those for summer. In general, after 17 km, the $C_n^2$ values drop steeply and are approximately consistent in trend and magnitude.
When comparison among $C_n^2$ profiles over the year, it is worth highlighting that $C_n^2$ profile values are large in winter in which the dynamics of synoptic pressure systems passing over Baghdad are in the best activity.

![Graph of refractive index structure function parameter, $C_n^2$](image)

Fig. 5: Vertical profile of refractive index structure function parameter, $C_n^2$

5. Conclusion:

This study present and illustrate significant characteristics of $C_n^2$ profiles at four days for 12 pm time distributed during the seasons of year 2019. Based on the radiosonde data such as air temperature, pressure and wind speed, the vertical profiles of $C_n^2$ estimated using Tatarski model for heights from 2 km and Eq. (7) for heights from surface layer to 2 km. Before deriving $C_n^2$ profile the profile of temperature, wind speed, potential temperature gradients are plotted to demonstrate their characteristics over Baghdad city. The conclusions of this study can be drawn in several points as:

1. Temperature lapse rate have different altitudes according to nature of season whereas in spring and summer, it has high altitudes while has low heights in winter and autumn.

2. Winds are significant in winter and spring.

3. Potential temperature gradient profiles have the same behavior along the heights studied in this work.

4. Wind shear were largest in spring and lowest in autumn.
5. The atmosphere over Baghdad is mostly instability and turbulent.

6. $C_n^2$ profiles have large values near the ground comparing with the free atmosphere. In other speech, $C_n^2$ values drop gradually from the surface layer to high altitudes. In addition, after 17 km, their values drop steeply and all $C_n^2$ profile over different times unify in trend and behavior. It seems that the largest values of $C_n^2$ profiles are found in winter.

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