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Latitudinal variation in vertical distribution of meteor decay time and its relation with mesospheric Ozone in the altitude range of 80-90 km

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Investigations on meteor trail decay time and its evolution in the mesosphere and lower thermosphere are very important to estimate the temperature in this region. The present study focuses on the vertical distribution of meteor decay times at three different latitudes to understand the mechanism responsible for the deviation of meteor decay time from the theoretical estimations below 90 km of altitude. The present study is based on measurements from three identical meteor radars located at equatorial (Kototabang: 0.2° S, 100.3° E), low (Thumba: 8.5° N, 76.9° E) and polar latitudes (Eureka: 80.0° N, 85.8° W). The results reveal a pronounced seasonal variation of vertical distribution of meteor decay time turning altitude (inflection point) over polar latitudes as compared to that over equatorial and low latitudes. Apart from direct estimations from meteor radar observations, the meteor decay time is estimated using temperature and pressure measurements from the SABER/TIMED. Above 90 km of altitude, decay times estimated from both methods are in good agreement. However, below 90 km of altitude, these estimations start deviating and it has been noted that the deviation increases with decreasing altitude. Further, observed meteor decay times correlated with ozone concentration at three representative altitude bins. The correlation analysis reveals a significant negative correlation at 80 - 90 km of altitude over the three latitudes indicating that an increase in ozone concentration results in decrease in meteor decay time. The significance of the present results lies in analyzing the vertical distribution of meteor decay time simultaneously from three radar locations representing equatorial, low and polar latitudes and evaluating the relation between ozone concentration and meteor decay time, quantitatively.

Keywords: Meteor radar, Meteor decay time, Ozone concentration

1 Introduction

As a meteoroid enters the Earth's atmosphere, due to collision with surrounding air molecules, its surface temperature rises rapidly so that the surface particles start to evaporate and leave behind an ionized plasma trail[1]. This ionized plasma trail from ablation occurs in the height range of 70 to 110 km with a peak occurrence range at 90 km depends on RADAR frequency, known as meteor trail, can reflect radio waves.

All sky interferometric meteor radar is an effective tool to study the several meteor parameters such as location, ablation height, radial velocity, and entry speed and meteor decay time[2]. The time taken for the radar backscattered signal amplitude to fall one half of its maximum value is known as meteor decay time. The decay time of the meteor trail is predominantly governed by the process known as ambipolar diffusion among other processes such as chemical reaction and recombination. According to the theory, ambipolar diffusion is a function of temperature and pressure and decay time is inversely proportional to the diffusion coefficient[3]. From the past decades, a number of studies have employed meteor decay times to estimate ambipolar diffusion coefficient, temperature and pressure parameters[4-13].

The method of estimating mesospheric temperature through meteor decay time has gone through several modifications in recent years. The basic assumption made for retrieving the mesospheric temperature from the meteor decay time is that it depends solely on the ambipolar diffusion. However, it is clear from the earlier studies that apart from the ambipolar diffusion, other mechanisms also govern the evolution of meteoric plasma trail, especially below 90 km of altitude[8, 14-22].

In order to understand the mechanisms responsible for deviation of radar decay time from the well-established ambipolar diffusion theory, especially below 90 km of altitude, it is necessary to consider

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what other processes that have been left out from the original theoretical framework. In the present study, we focus on decreasing decay times below 90 km of altitude and the potential mechanisms responsible for such deviation.

One of the possible mechanisms in altering the meteor decay time below this altitude is the absorption of free electrons in meteor trails by aerosols. Havnes and Sigernes[15] proposed that the meteor trail with small initial electron line density would be more prone to get decay. Singer et al.[16]verified the suggestions of Havnes and Sigernes[15] and noticed that the weak echoes usually produce shorter decay time than the strong echoes at the same height range. Younger et al.[18] extended the modelling studies of Havnes and Sigernes[15] by investigating meteor decay time using different radars of frequencies 33 MHz and 55 MHz located at Darwin (12^0 S), Buckland Park (35° S) and Davis Station (68° S). This study considered the role of aerosols in reducing the meteor decay time and conformed that the trails with low electron density are most affected. Further the authors also noticed that the effects of aerosol absorption on meteor decay time are dependent on radar wavelength under certain circumstances, particularly below 90 km of altitude. However, all the previous observations on meteor decay time are well beyond what may be expected from aerosol attachment. Moreover, an aerosol numerical model developed by Younger et al.[22] is a revised version of the model developed by Younger et al.,[18] to explore the possible effects of aerosol-electron attachment on meteor decay time for a range of radar wavelengths, trail electron line densities and aerosol conditions. They have concluded that aerosol absorption may have some effect on decay time; however, the predicted behavior was contrary to the observations, implying that aerosol absorption is not the main mechanism responsible for the observed disparities in decay time below 90 km of altitude.

The other possible mechanism responsible for deviation of meteor decay time from the ambipolar diffusion predictions is chemical processes. Baggaley and Cummack[23]and Plane and Whalley[24] listed out the number of reactions related to the formation of meteoric plasma trails. The study of Baggaley[25] has suggested that in the case of overdense meteors, recombination and attachment processes will reduce the decay time, especially at lower altitudes. Furthermore, Baggaley[26] examined recombination effects and concluded that they have negligible effects on underdense meteor decay times. However, this study was focused above 90 km of altitude. At higher altitudes, the presence of ozone causes the rapid deionization of meteoric plasma[23] through the following reaction

$$M^{+} + O_3 \rightarrow MO^{+} + O_2 \qquad \ldots (1)$$

Further, it leads to the removal of the electrons through the dissociative recombination reaction

$$MO^{+} + e \rightarrow M + O \qquad \ldots (2)$$

where, M is the meteoric ion.

Baggaley and Cummack[23] concluded that the above reactions are crucial for the lack of long duration overdense meteor trails. According to Jones et al.[27] and Cevolani and Pupillo[28], this phenomenon can be used to evaluate ozone concentration in the mesospheric region. Recently, Ye and Han[29] estimated the ozone concentration during various meteor shower periods and compared the same with the satellite measurements, and found a modest agreement. For overdense meteor trails, the effect of ozone concentration at higher altitudes (above 90 km) is very significant and well established. From model simulations, Younger et al.[22] concluded that the ozone has a significant effect on overdense echoes at higher altitudes (above 90 km), and has a modest effect on underdense echoes at low altitudes (below 90 km). However, there are no observational studies on the effect of ozone on underdense echoes. In addition, only a few investigations have been carried out on the vertical distribution of meteor decay times over equatorial and low latitudes as compared to middle and high latitudes[20, 16].

In this regard, the central objective of present study is to understand the role of ozone in reducing the underdense meteor decay times at altitudes below 90 km. The importance of the current study lies in evaluating the role of ozone in governing meteor decay times at equatorial, low and polar latitudes and comparing their seasonal variations.

2 Materials and Methods

2.1 SKiYMET meteor radars

The meteor decay time measurements used in the present study were obtained from three identical meteor radars located at equatorial (Kototabang: 0.2° S, 100.3° E), low (Thumba: 8.5° N, 76.9° E) and polar latitudes (Eureka: 80° N, 85.8°W). The archival data from equatorial and polar latitudes are for the year 2016 and from low latitude it is for the year 2015. All the radar systems are commercially procured all-SKy interferometric METeor (SKiYMET) radars, based on the original design of Jones et at.[30]. All the radar systems (except radar at Thumba, which uses four transmitting antennas) uses a single transmitting Yagi antenna of three elements and five separate receiving Yagi antennae of two-elements each oriented along two orthogonal baselines, forming an interferometric array. The operating frequencies of the radars are 37.70 MHz (Kototabang)[31], 35.25 MHz (Thumba)[12] and 33.40 MHz (Eureka)[32] with peak transmitting powers of 12 kW, 40 kW and 12 kW, respectively. The main experimental specifications of each radar system can be found in Table 1. Further technical details and data collection procedure of the SKiYMET meteor radars can be found in Hocking et al.[2].

Using these radar systems, it is possible to study the meteor decay times in the height range between 70 and 110 km. However, anomalous diffusion can influence the decay time, particularly above 100 km of altitude[13,19,33-34]. Hence, for further analysis, the maximum height range is confined to 100 km for the present study. In addition, to improve data accuracy, we chosen only unambiguous echoes with zenith angle between 10^0 and 65^0 in order to avoid the echoes that are range aliased due to statistical uncertainties in the azimuth and elevation angles. The small radial velocities given by the echoes of small zenith angle may cause large errors in determination of horizontal winds. Similarly, the echoes of large zenith angle contain significant atmospheric effects, which may leads to significant errors in range determination[2,13,19]. Further, to ensure unambiguous detection of underdense echoes at all heights, we also applied a signal to noise ratio (SNR) criteria, where the echoes with SNR $\geq$ 5 dB are considered in this study.

2.2 TIMED/SABER Satellite

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) is one of the instruments in onboard the NASA's Thermosphere-Ionosphere-Mesosphere Energetics Dynamics (TIMED) satellite, launched in December 2001. The TIMED satellite is in a 625 km orbit with an orbital inclination 74.1^0. This instrument observes limb emission in 10 broadband spectral channels ranging from 1.27 – 17 µm. In this study, version 2.0 temperature, pressure and ozone concentration data were obtained within the 5^0 x 10^0 latitude and longitude centered on the three radar locations mentioned in section 2.1. The seasonal mean values of temperature, pressure and ozone measurements from the SABER observations during the respective radar observational period are used for the study. The details of the SABER instrument and data retrieval algorithm including data quality assessment can be found in Mertens et al.[36] and Remsberg et al.[35].

2.3 Meteor decay time estimation from TIMED/SABER

Based on scattering mechanism, there are mainly three types of meteor trails that can be detected with different radar systems, known as the head echoes, specular and non-specular trail echoes. Classical radars of low transmitting power, like all-sky meteor radars mainly detect the localized specular trail echoes traveling perpendicular to the line-of-sight of the probing radar. According to the electron density of the ionized trail, specular meteor trails can be classified into two limiting cases: very

Table 1-The main experimental specifications of each radar system

Parameter (unit)	Kototabang (0.2° S, 100.3° E)	Thumba (8.5° N, 76.9° E)	Eureka (80° N, 85.8° W)
Frequency (MHz)	37.70	35.25	33.40
Peak power (kW)	12	40	12
Bandwidth (kHz)	200	1500	1500
Pulse width (µs)	13.3	13.3	13.3
PRF (kHz)	2500	2144	2144
Coherent Integrations	4	4	4
Range sampling (km)	2	2	2
Pulse code	1	1	1
Min - Max height (km)	70 - 110	70 - 110	70 - 110
Duty cycle (%)	5	15	-
Tx antenna	Single circular polarized three-element cross yagi	Four Circular polarized three-element cross yagi	Single Circular polarized three-element cross yagi
Rx antenna	Five circluar polarized two-element cross yagi	Five circluar polarized two-element cross yagi	Five circluar polarized two-element cross yagi

high electron line density (overdense) and very low electron line density (underdense). Conventionally, an electron line density of 2.4 x 10^{14} electrons per meter is considered as the limiting line density between underdense and overdense trails[37]. For underdense trail, it is assumed that the radius of the trail is far smaller than the probing radar wave length, the electron line density is constant, the trail is perpendicular to the radar pointing direction and the initial radius of the trail is zero. The radial distribution of electron concentration in the trail is assumed to be Gaussian.

By assuming ambipolar diffusion as the predominant mechanism by which the underdense meteor echo decays, Jones and Jones[38] theoretically formulated the process of meteor trail formation and expansion. And the underdense decay time ($\tau_{1/2}$) is defined as the time taken for the back-scattered radio signal power to fall one half of its maximum value[39-40], which is given by the equation

$$\tau_{\frac{1}{2}} = \frac{\lambda^2 ln2}{16\pi^2 D_a} \qquad \ldots (3)$$

where, λ is the radar wavelength. The ambipolar diffusion coeffcient (D_a) describes the rate at which meteoric plasma diffuse in a neutral background and it is proportional to atmospheric temperature (T) and pressure (P)[38] by the equation

$$D_a = \frac{2kT}{q_e}\left(\frac{\mathrm{T}}{173.16}\right)\left(\frac{1.013 \text{ x } 10^5}{\mathrm{P}}\right)\mathrm{K_o} \qquad \ldots (4)$$

where, k is the Boltzmann constant, q_e is the ionic charge and $\mathrm{K_o}$ is the zero field ion mobility factor in the meteoric plasma. From Chilson et al.[41], Hocking et al.,[3], Kumar and Subrahmanyam,[20], a typical value of $\mathrm{K_o}$ can be taken as 2.5 x $10^{-4}\mathrm{m^2s^{-1}V^{-1}}$. After substituting D_a and the other constant values in the Eq. 3, we get

$$\tau_{\frac{1}{2}} \alpha \frac{P}{T^2} \qquad \ldots (5)$$

By employing vertical profiles of mesospheric temperature and pressure from the SABER/TIMED measurements, Eq. 5 can be used to construct predicted meteor decay time vertical profiles, by assuming ambipolar diffusion alone is responsible for meteor trail decay process.

3 Results and Discussions

The meteor radar observations at equatorial, low and polar latitudes during winter, spring, summer and fall seasons are used to understand the vertical profiles of the meteor decay time over different latitudes. Figure 1 depicts the vertical distribution of radar meteor decay times during different seasons over three latitudes. This figure provides an evidence for decreasing nature of decay time below the turning altitude (inflection point, about 82 km). It is also noticed that the decay time is not exponentially

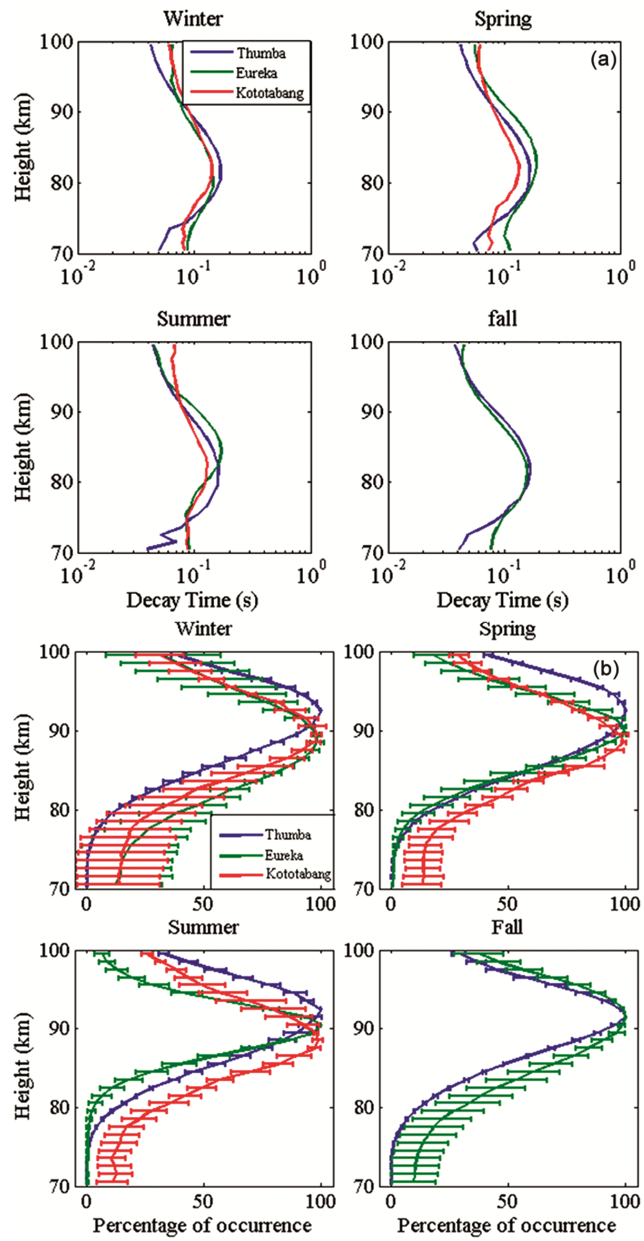

Fig. 1 — (a) Mean seasonal vertical distribution of meteor decay time, and (b) seasonal distribution of percentage of occurrence height over a km interval at three meteor radars located at equatorial (Kototabang), low (Thumba) and polar latitudes (Eureka).

decreasing with height, which demonstrates that there are other mechanisms apart from ambipolar diffusion in altering the decay time below the inflection point. Kumar and Subrahmanyam[20] found a similar decreasing trend below the 82 km of altitude from their observations at Thumba (8.5^0 N) during the winter season. At equatorial and low latitudes decay time turning occurs at a height of about 82 km and the same is observed in all the seasons of the year. At polar latitude, the turning occurs at 80 km in winter and it shifts to about 5 km higher altitude in spring and summer with a maximum turning altitude of 85 km in summer and it comes down to 82 km during fall. We also plotted seasonal distribution of percentage of occurrence height over a km interval at three radar stations, which have a similar pattern as presented in Reddy et al.[42].

From 33.2 MHz meteor radar observations at King Sejong station (62.22^0S, 58.78^0W), Kim et al.[19] found a similar variation of turning altitude which shows a lower altitude in winter and fall, higher in summer and spring. However, such variations in turning altitude are absent at low and equatorial latitudes. At polar latitude, reduced decay time is observed between the 80 km to 90 km during winter and fall as compared to spring and summer. However, no such variations are observed at low and equatorial latitudes.

To examine the role of ozone on meteor decay time, ozone concentration measurements from the TIMED/SABER satellite observations in the meteor detection height within 5^0 x 10^0 latitude and longitude, centered over the three radar sites are employed. The seasonal variations of vertical distribution of ozone concentration taken from the satellite measurements are shown in Fig. 2. The seasonal variations are relatively moderate at low and equatorial latitudes, as compared to large seasonal variations observed at polar latitude. At polar latitude the ozone concentration is relatively high in winter and fall and it is relatively low in summer and spring, with maximum concentration in winter and minimum in summer.

From Eq. 5, one can expect an approximately exponential decrease in decay time as the pressure decreases with height. To measure the decay time governed by the ambipolar diffusion only, we have used temperature and pressure values taken from SABER satellite data in the Eq. 5. Figure 3 shows the vertical profiles of decay time measured by radar observations (green line), predicted from SABER measurements (blue line) and ozone concentration (red line) in the height range of 70 to 100 km for all the seasons over three radar sites. The error bars in each case represent the standard deviation.

By comparing the vertical profile of meteor decay time constructed using radar (green line) and SABER (blue line), one can find out whether the radar measured decay time follows the ambipolar diffusion or not, which is the very important assumption made in retrieving the temperature profiles using meteor decay time. These two profiles are very much comparable above the inflection point (>90 km) at all the three radar sites, conforming that the meteor decay is governed by the ambipolar diffusion. To examine it furthermore, we also plotted seasonal variation in vertical distribution of ozone along with the deviation of observed decay times from the SABER based predicted decay times. Such variation shows a minimum at around the turning altitude throughout the seasons, except in summer at polar latitude which is occurring at high altitude where ozone has exactly opposite distribution.

However, below 90 km of altitude, a noticeable deviation observed between the radar and SABER measured decay time, but the deviation varies among the seasons and latitudes. At low and equatorial latitudes the deviation starts at about 85 km and it increases with decreasing height. At polar latitudes,

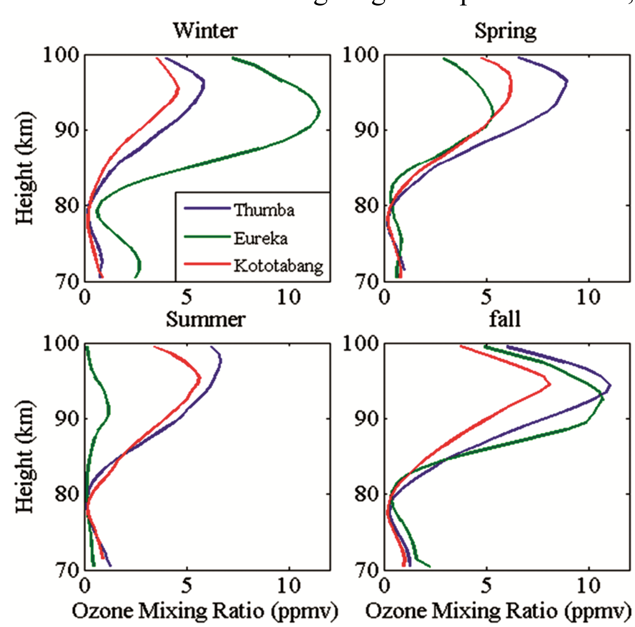

Fig. 2 — Seasonal variation in vertical distribution of ozone mixing ratio (ppmv) obtained from the SABER/TIMED satellite measurements.

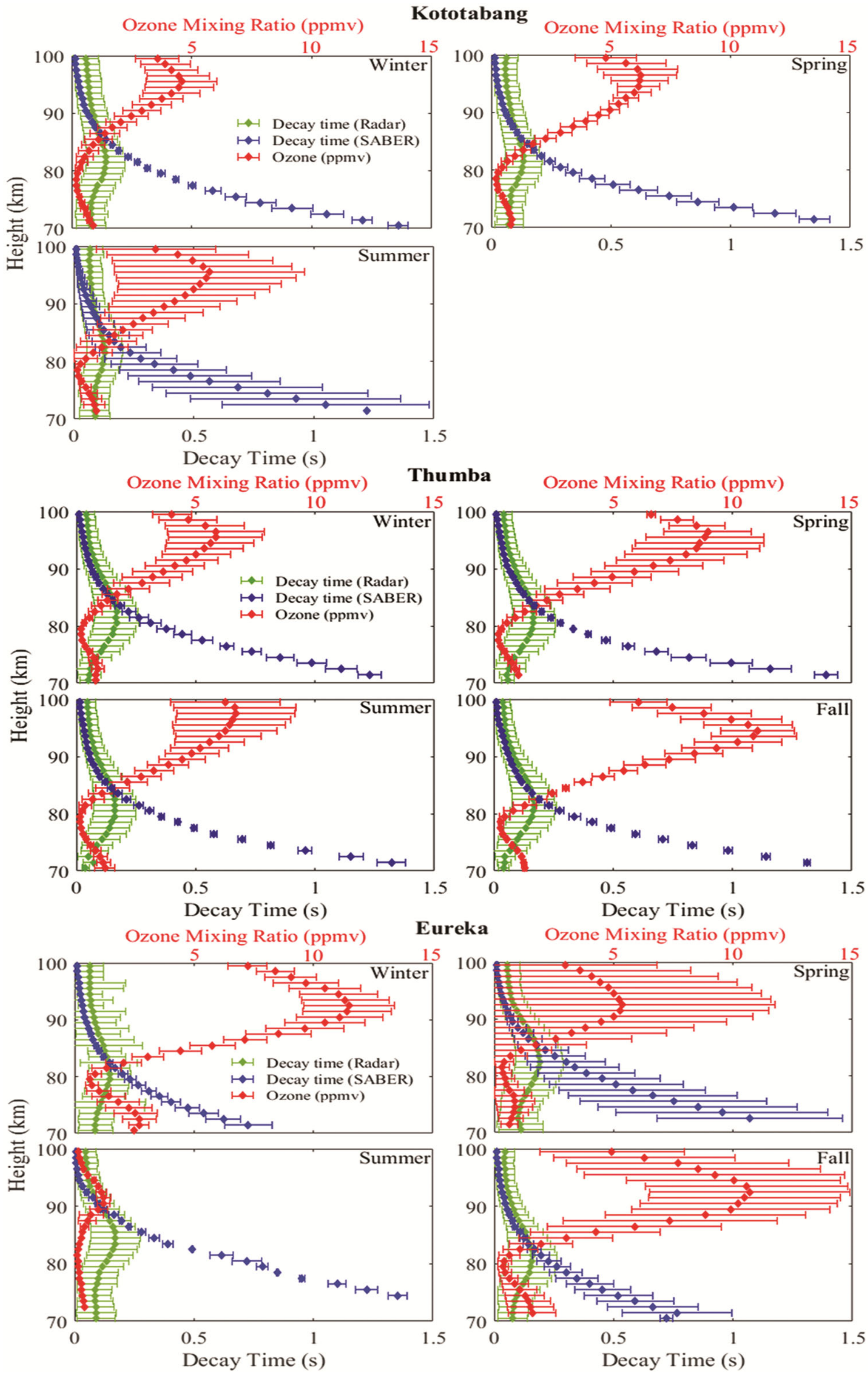

Fig. 3 — Seasonal variation in vertical distribution of mean meteor decay time measured using radar and SABER observations along with ozone mixing ratio (ppmv) profiles over three radar stations (a) Kototabang, (b) Thumba, and (c) Eureka.

The deviation height shows a significant seasonal variation, where the deviation starts at lower heights in winter and fall and it extends to higher altitudes in spring and summer. The lowest deviation height is observed in winter at 82 km and highest is observed in summer at 88 km. From the low latitude station, Thumba, Kumar and Subrahmanyam[20] observed a similar deviation in decay time below 85 km of altitude, but in winter season for the year 2006.

Further, meteor decay time estimated from radar and ozone concentration is compared quantitatively at three representative height bins of each a km height as shown in Fig. 4. These representative height bins are denoted by three colors: green, red and blue, representing turning altitude (80-90 km), above (90-100 km) and below (70-80 km) the turning altitude, respectively. A negative correlation is found between the ozone concentration and radar decay time, particularly below the turning altitude over all the three latitudes as shown in Fig. 4. There is a consistent negative correlation over the three locations particularly between 80 - 90 km with correlation coefficients of -0.59, -0.79 and -0.77, respectively. We performed a statistical test of significance (t-test) of the correlation coefficient at three radar stations indicates a significance of more than 95% at Thumba (8.5^0 N) and little less significance at other two stations, which conforms the observed relationships are significant. In addition, we also found good agreement between the meteor decay time and ozone concentration at lower altitudes (70 - 80 km) at low and equatorial latitudes, with correlation coefficients of -0.67 (Kototabang) and -0.86 (Thumba). In contrast, very poor agreement is noted at this altitude at Eureka (-0.12), and no significant correlation is found at 90 - 100 km over Thumba and Eureka, whereas a correlation coefficient of -0.35 is found over Kototabang at this altitude.

In the present study, a decreasing nature of meteor decay time below the turning altitude is observed in all the seasons of the year at polar, low and equatorial latitudes, which is contrary to the ambipolar diffusion theory. Many mechanisms have been proposed to explain the behaviour of meteor decay time below the turning altitude (inflection point). As outlined earlier, role of dust particles in the absorption of electrons

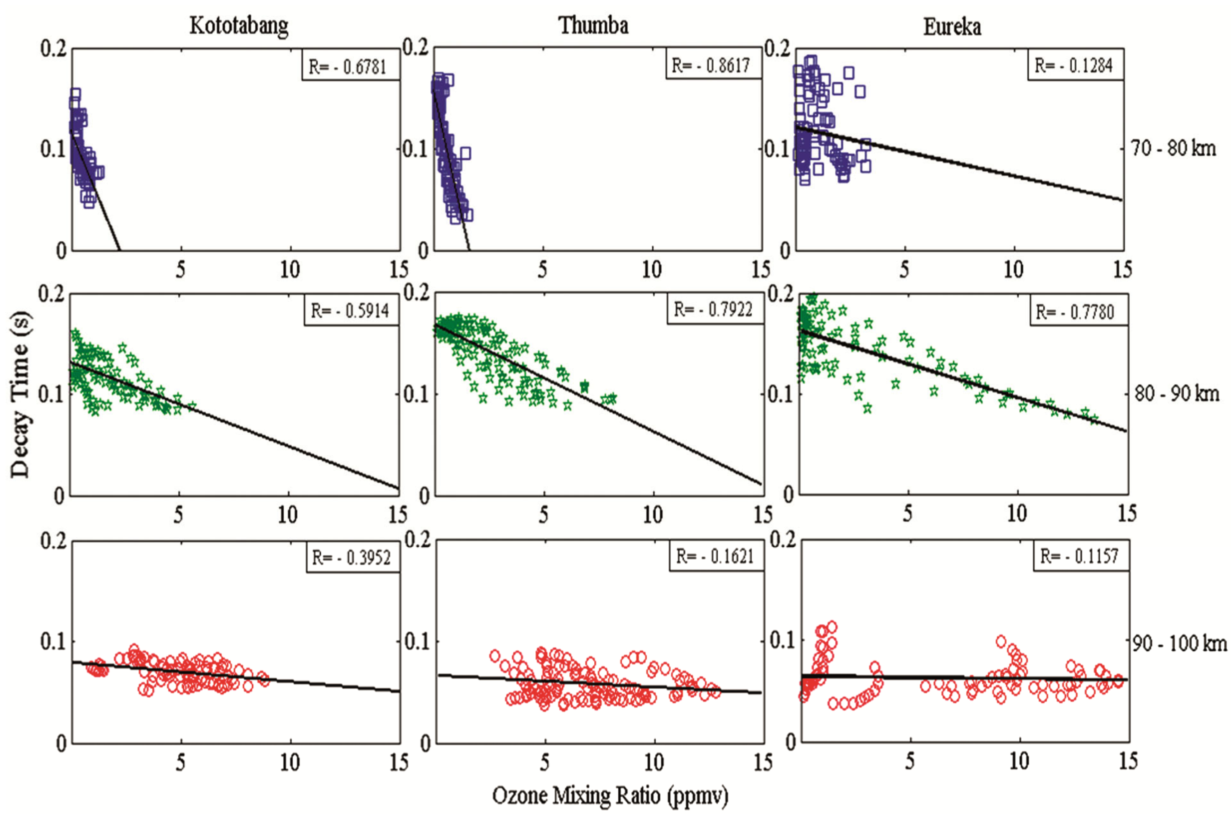

Fig. 4 — The correlation between the radar decay time and ozone mixing ratio (ppmv) obtained from SABER measurements in the height range of 70 - 80 km (Blue), 80 - 90 km (Green) and 90 -100 km (Red) over (a) Kototabang, (b) Thumba, and (c) Eureka. Solid line represents the linear fit to respective data in each panel and R is the correlation coefficient.

from the meteor trails has been proposed to explain the observed vertical distribution of meteor decay time[15,18,22]. Ballinger et al.[17] have pointed out the role of electron - ion recombination process in diffusion of meteor trails. Kim et al.[19] have investigated meteor decay time in all the seasons and explained its decreasing tendency by adopting an empirical recombination model, and proposed that the D-region chemistry may also play a role in decreasing the decay time below the inflection point. Hall[14] suggested that the neutral turbulence is also an important cause for the observed reduction in the meteor decay time. However, Kumar and Subrahmanyam[20] verified the effect of neutral turbulence and concluded that large winds can reduce the decay time, but it is not the case always. Apart from these effects, the role of ozone concentration in reducing the meteor decay time, especially for the underdense echoes below the inflection point, was reported by Younger et al.[22] using model simulations.

In the present study, the role of ozone in reducing the underdense meteor decay time is investigated by employing radar observations of meteor decay time and SABER measured ozone concentration. It is known that the underdense meteor decay time is also affected by ozone[43], since ozone chemistry may play a role in trail destruction, particularly at altitudes below the turning altitude. The present analysis showed significant negative correlation below the turning altitude over all the three observational locations, except at 70 - 80 km altitude region over the polar latitude, where a poor correlation coefficient of -0.12 is noticed.

From Fig. 1, it can be noted that the height of inflection point shows a significant seasonal variations at polar latitude, in winter it is at 80 km and at 85 km in summer. But no such seasonal pattern is noted at the low and equatorial latitudes. As decay time turning altitude varies with mesospheric density[21,44-46], the seasonal variation of inflection point is correlated to the seasonal variation of mesospheric density. Based on decay time inflection point, Younger et al.[46] estimated the mesospheric density. These density variations are relatively low over equatorial latitude[46] and are relatively high over polar latitudes[21]. Thus distinct seasonal variations in mesospheric density over equatorial and polar latitudes explain the observed seasonal variations in the height of inflection point over the present observational sites.

One of the noteworthy observations from the Fig. 1 is the reduced decay time during the summer season over polar latitude below 80 km as compared to the other seasons. However, such sharp variations are not found over low and equatorial regions. The reduction in meteor decay time over polar latitude may be due to presence of icy particles in the cold summer mesopause region which may or may not connected with the noctilucent clouds (NLC)[16,19]. More recently, Laskar et al.[47] studies mesospheric anomalous diffusion during NLC scenarios and presented a number of possible explanations for such diffusion. Their study found a remarkable influence of NLC on meteor trail diffusion which showed that on an average about 10% of enhancement in meteor trail diffusion rate during the present of NLC at high latitudes. In addition, nanoparticle size ice crystals are also thought to be present in the mesospheric region responsible for polar mesospheric summer echoes (PMSE) can influence the meteor decay time during summer seasons particularly at polar latitudes[17]. Further, in Fig. 3 (a, b, and c) the height at which radar and SABER estimated meteor decay time start deviating show very little seasonal variation over low and equatorial latitudes as compared to polar latitude. This deviation height is observed to be at 85 km during all the seasons over low and equatorial latitude. In contrast at polar latitudes, this deviation height shows strong seasonal variation with lower height in winter at about 82 km and higher height in summer at about 90 km.

4 Conclusion

The seasonal and latitudinal variations in vertical distributions of meteor decay times at equatorial (Kototabag: 0.2^{0} S, 100.3^{0} E), low (Thumba: 8.5^{0} N, 76.9^{0} E) and polar latitude (Eureka: 80^{0} N, 85.8^{0} W) have been examined in present study. The results suggest that there is a strong seasonal variation in vertical distribution of decay time turning altitude (inflection point) at polar latitude as compared with the low and equatorial latitudes. At polar latitude, the inflection point occurs at relatively higher altitude in summer, moderate in fall and spring and at lower altitude in winter, as reported by previous studies of Kim et al.[19] and Premkumar et al.[48]. The turning altitude varies between 80 - 85 km with seasons, having maximum in summer and minimum in winter at polar latitude. The observed seasonal variations in turning altitude over polar latitude is attributed to mesospheric density variations which exhibit negligible seasonality over low and equatorial latitudes as compared to polar latitudes. At polar latitude, reduced decay time is observed below 80 km (i.e., 70 - 80 km) in summer, which can be attributed to presence of icy dust particles in the cold summer mesopause region. More recently, a similar kind of anomalous decay times during NLC scenarios were reported by Laskar et al.[47]. The comparison between radar and SABER estimated meteor decay time showed that the mechanism other than ambipolar diffusion governs the meteor trail decay time below the 90 km. It is also observed that the deviation of meteor decay time away from the ambipolar diffusion assumption increases with decreasing height. Present results indicate a clear and consistent anti-correlation between the meteor decay time and ozone mixing ratio (ppmv) below the turning altitude. A significant negative correlation is found over all the three observational locations in the height range of 80 - 90 km indicating higher the ozone concentration lower is the meteor decay time. The statistical test of significance (t-test) of the correlation coefficients indicates a significance level of more than 95% at Thumba (8.5^0 N) and little less significance at other two stations. In addition, a significant correlation is also found between meteor decay time and ozone concentration over low and equatorial latitudes in the height range of 70 - 80 km. However no significant correlation is found in this height range overthe polar latitude.

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