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ORIGINAL ARTICLE

Anisotropic diffusion of meteor trails due to the geomagnetic field over King Sejong Station (62.2°S, 58.8°W), Antarctica

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Abstract We analyzed meteor decay times measured by a VHF meteor radar at King Sejong Station, Antarctica (62.22°S, 58.78°W) to study diffusion processes of the meteor trails above the altitude of ∼93 km. Above this altitude, where the atmospheric density is so dilute that collisions between trail ions and ambient molecules become rare, diffusion of a meteor trail can be greatly affected by the geomagnetic field, resulting in anisotropic distribution of measured decay times over the azimuthal and elevation angles. Our preliminary analysis confirm the anisotropic nature of meteor decay times due to geomagnetic field.

Keywords Meteor trail · Anisotropic diffusion · Antarctica

1 Introduction

A meteor trail, which is an ionized plasma tail from a meteor, is formed at the altitude of 70–110 km due to the collision with atmospheric particles as a meteor enters the Earth's atmosphere. A meteor trail is decayed at a low altitude approximately below 93–95 km due to the ambi-polar diffusion process, and the trail plasma diffuses away slowly as the frequency of collisions between the trail plasma and surrounding atmosphere becomes large due to increasing atmospheric density with lower altitudes. In contrast, the collision frequency decreases with altitudes, resulting in fast diffusion.

Above the altitude of approximately 93–95 km, a meteor trail in a plasma state is diffused at a faster rate along the earth's magnetic field than the perpendicular direction to the magnetic field so that anisotropy of diffusion is expected to occur (Cervera and Reid 2000). In recent years, theoretical studies have taken into account the earth's magnetic field with regard to the decay time of meteor trails (Dyrud et al. 2001, 2002; Oppenheim et al. 2000; Robson 2001). However, most studies have focused only on theoretical viewpoints and few studies have been conducted on an experimental basis to verify the theories. Although observational studies have been attempted before, most studies employed short-term data obtained during the meteor shower period, and the number of meteor samples used in data analysis was small so that data reliability was not sufficient to prove or disprove the theoretical results (Heritage et al. 1962; Zhou et al. 2001). Thus, an analysis based on actual long-term observation data is needed in studies on diffusion of meteor trails in consideration of the earth's magnetic field.

Radio waves emitted from the meteor radar are reflected to the meteor plasma trail, and the signals are detected at the ground receiving antenna. The detected echo signals contain various items of information that allows to acquire atmospheric physical parameters around the meteor trail. Among these items of information, the decay time of the meteor trail has been used in studies on atmospheric characteristics at an altitude of 70–110 km, the altitude region where most meteors ablaze.

Thus, the present study analyzes the altitude distribution of the meteor trail decay time that occurred at an approximate altitude of 80–110 km using data during March to May

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in 2009 (fall in the southern hemisphere) obtained from the meteor radar at King Sejong Station in the Antarctic to study the diffusion process of meteor trails at a high altitude approximately above ∼93 km. The anisotropy of meteor trail diffusion is noticed from the decay time of the meteor trail above ∼93 km, and the main factors of anisotropic diffusion are investigated through the analysis on diffusion coefficient values of meteor trails as a function of altitude.

2 Radar experiments

A VHF meteor radar has been operated since March 2007 at King Sejong Station (KSS; 62.22°S, 58.78°W), Antarctica for observations of the MLT region (Kim et al. 2012). The antenna system of the radar consists of one transmission antenna and five receiving antennas. The transmitter emits 33.2 MHz frequency radio waves at 8 kW power with the maximum duty cycle of 8.4%. The receiving antenna is an interferometer that has an array of "cross (+)" shapes. The five receiving antennas were configured so that four receiving antennas were arranged with a distance of two times and 2.5 times the wave length (λ) around the center receiving antenna along the antenna array lines. This antenna array pattern can increase the accuracy of the echo position (angle of arrivals) by minimizing interference (antenna coupling) between antennas (Jones et al. 1998). The operation parameters of the radar are summarized in Table 1. The entire raw data analysis is done by the built-in raw data analysis software developed by the manufacturer (ATRAD). We only have an access to the analyzed data named "met" file which include all necessary information on meteor itself and background atmospheric condition. Holdsworth et al. (2004) briefly describes above raw data analysis such as meter detection procedure and decay time estimation.

Table 1 Operating parameters of the meteor radar at King Sejong Station

Parameters	Values
Frequency (MHz)	33.2
Frequency agility (kHz)	±100
Transmit power (kW)	8
Transmit polarization	Circular
EPW (m/μs)	7200/47.95
PRF (Hz)	440
Duty cycle (%)	8.4%
Receiver-filter width (kHz)	18.1
Pulse code type	4-bit complementary
Pulse shape	Gaussian
Range (km)	80–307
Range sampling resolution (km)	1.8
Coherent integrations	4
Effective sampling time (s)	0.009
Number of samples	12650
Acquisition length (s)	115

The meteor radar at King Sejong Station has observed 15000–18000 meteors a day on average. The number of observed meteors varies with season; the number increases in summer and decreases in winter. A meteor trail is not fully ionized but passes through the atmosphere above ∼100 km due to low ambient density, whereas most of meteors are blazed away before 70 km altitude. The meteor radar is thus designed to detect meteors between 70 and 100 km. The present study employed only data gathered during March to May in 2009 (southern fall) to avoid seasonal variation of atmosphere and meteor influx.

3 Background theories

The amplitude of the radio signal that was reflected by a meteor plasma trail decreases with time instantly after the detection, as the meteor trail is diffused away. Assuming that ambi-polar diffusion is the main diffusion mechanism of a meteor trail, a temporal change in amplitude (A) of the received signal can be expressed in the following equation (1) (McDaniel and Mason 1973; Hocking 1999).

$$A(t) = A_0 \exp\left[-\frac{16\pi^2 D_a t}{\lambda^2}\right] = A_0 \exp\left[-\ln 2 \frac{t}{\tau_{1/2}}\right] \quad (1)$$

Here, t refers to time after the detection, λ and D_a are a wavelength of the meteor radar and the ambi-polar diffusion coefficient of the meteor trail, respectively. A_0 refers to the maximum amplitude immediately after the meteor trail is observed, and $\tau_{1/2}$ is the meteor trail decay time, which is defined as the time for the amplitude of the received signal to be reduced to half the maximum. Note that the diffusion coefficient is proportional to the inverse decay time ($1/\tau_{1/2}$). Once meteor echo is recognized by pre-determined meteor selection criteria (Holdsworth et al. 2004), the meteor decay time can be calculated by fitting an exponential function to the received power series from the meteor echo peak to the position where the meteor echo power falls to the noise level. The decay time can be readily converted into the diffusion coefficient using a simple equation given by

$$D_a = \frac{\lambda^2}{32\pi^2 \tau} \quad (2)$$

where τ is a decay time observed from the meteor radar. According to Hocking (1999) and Hocking et al. (1997), for data obtained from the meteor radar whose frequency is in the range of 30–50 MHz, $\tau_{1/2}$ is in the range of 0.01–0.3 second in the case of a meteor trail whose density is low enough to be diffused efficiently.

Orientation of the meteor trail and the Earth's magnetic field can be expressed using Cartesian coordinates (Elford and Elford 1999; Jones 1991; Robson 2001). As illustrated in Fig. 1, the direction along the meteor trail is taken as Z-axis direction and the Earth's magnetic field is placed in the XOZ plane with an angle θ toward X axis from the entrance direction of the meteor trail. The radar signal, as indicated with a wavenumber vector K_0, is back-scattered by the meteor trail on the XOY plane which is perpendicular to the meteor trail. The Y axis is a component that is perpendicular to the XOZ plane that includes both meteor trail and Earth's magnetic field direction vectors. Then, μ refers to an angle between the Y-axis and the radar signal (the line of sight) and ϕ is an angle between the line of sight of the radar signal and the Earth's magnetic field.

Theoretical studies including Kaiser et al. (1969), Jones (1991), Elford and Elford (1999), and Robson (2001) expressed the diffusion coefficients along two directions with respect to the Earth's magnetic field. The diffusion parallel to the Earth's magnetic field can be considered along the OX direction, defined as D_{parall}, and the diffusion perpendicular to the Earth's magnetic field, D_{perp}, is along the OY direction (Elford and Elford 1999). Then the effective diffusion coefficient (D_{eff}) is given by,

$$D_{eff} = D_{parall} \sin^2 \mu \sin^2 \theta + D_{perp} \left(1 - \sin^2 \mu \sin^2 \theta\right) \quad (3)$$

as in Eq. (12) in Robson (2001). Since $\cos \phi = \sin \theta \sin \mu$, Eq. (3) can be expressed as:

$$D_{eff} = D_{parall} \cos^2 \phi + D_{perp} \sin^2 \phi \quad (4)$$

In Elford and Elford (2001), diffusion coefficients were inferred using collision cross-sections obtained in the laboratory. As a result, D_{parall}/D_{perp} has approximately the size of 10 at an altitude of 95–96 km, and 2 at an altitude of around 93 km. However, they argued that the ratio of D_{parall}/D_{perp} is closer to one at an altitude below 93 km. Thus, they predict that the speed of diffusion should be significantly different for the parallel and perpendicular directions to the magnetic field at an altitude above 93 km; anisotropic diffusion. Since diffusion will occur at a slower rate in the perpendicular direction to the Earth's magnetic field, observed diffusion of meteor trails above 93 km should reveal anisotropic distribution of decay time, depending on observing directions according to their relative direction to Earth's magnetic field. By contrast, the anisotropic effect is not expected to be displayed below 93 km.

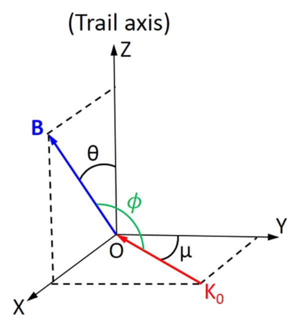

Fig. 1 Geometry of the meteor trail, the Earth's magnetic field B, and the meteor radar radio wave vector K_0

4 Horizontal distribution of inverse decay time of meteor trails

4.1 Anisotropy above 93 km

Figure 2 shows the horizontal distribution of the inverse decay time (IDT) of meteor trails during daytime in fall (March to May in 2009) in the southern hemisphere. The left and right figures present the distributions at altitudes

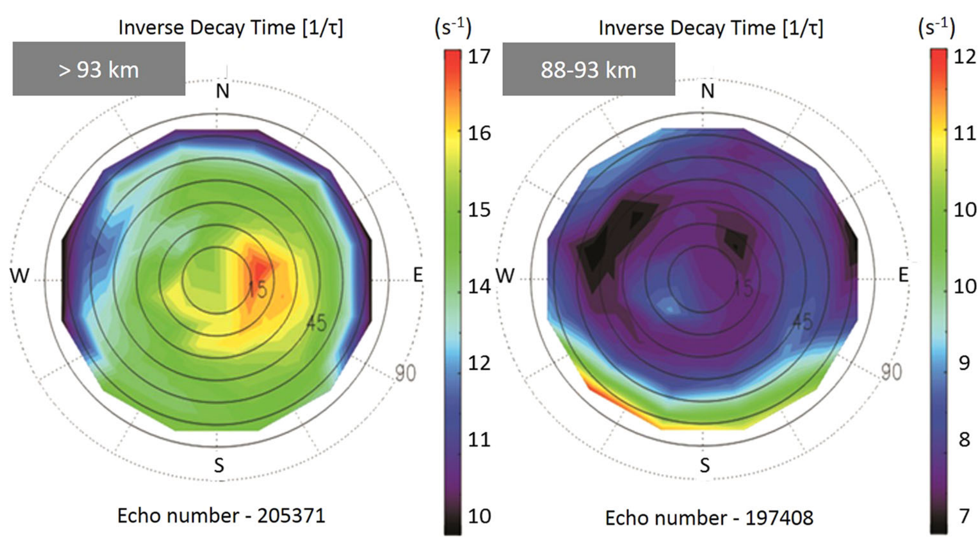

Fig. 2 Contour maps of median IDT($1/\tau_{1/2}$) as a function of zenith and azimuth angles for daytime (09–15 LT) for fall season (from March to May). The left and right panels are for 93 km or higher and for 88–93 km, respectively. Concentric circles show zenith angles with 10° step

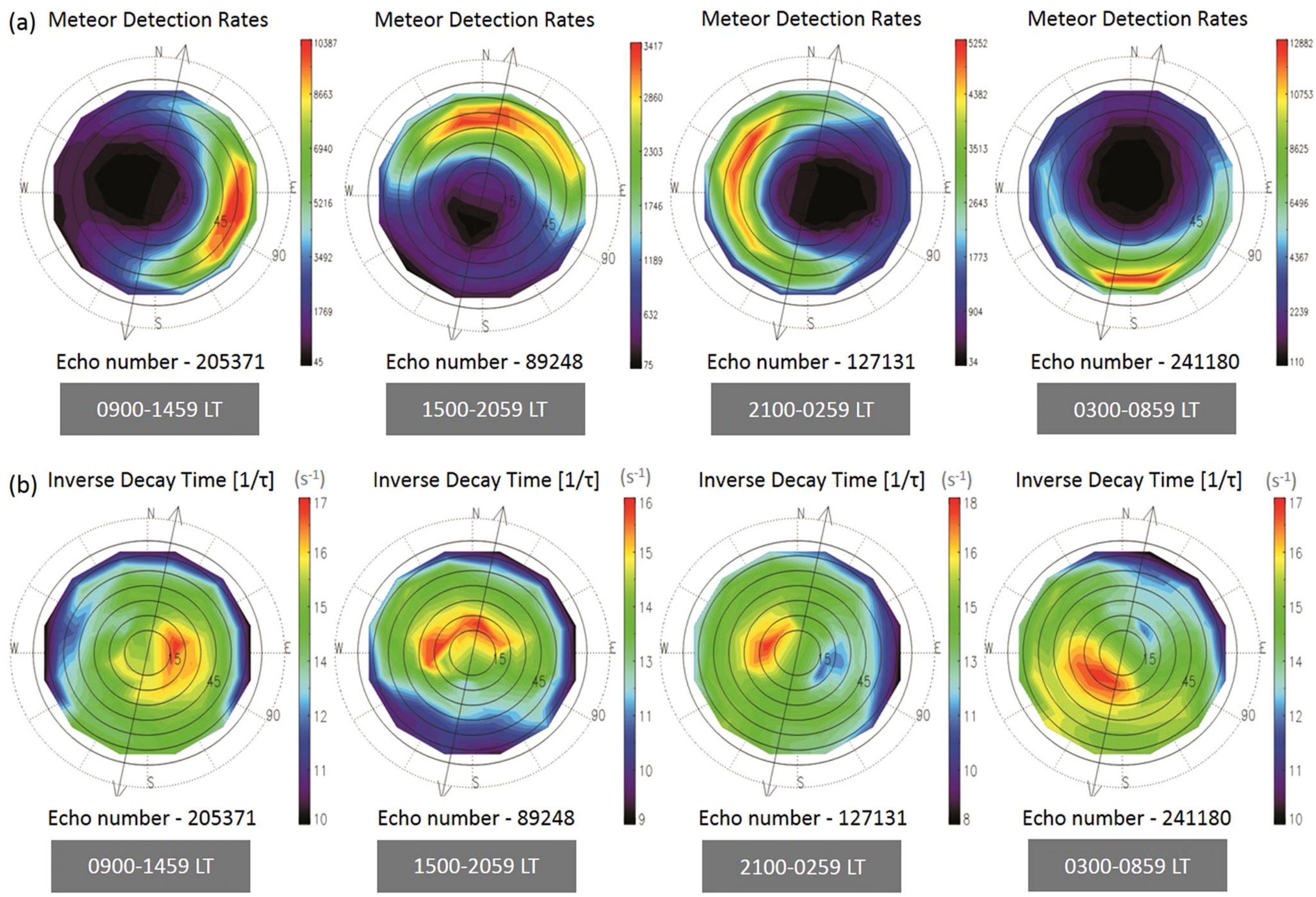

Fig. 3 (**a**) Median MDR plotted on a sky map for fall season (from March to May). The large arrows near median indicate magnetic field direction. (**b**) Median IDT($1/\tau_{1/2}$) plotted on a sky map for fall season (from March to May). The large arrows near median indicate magnetic field direction

above 93 km and 88–93 km, respectively. The upper direction refers to the north direction and the concentric circle in the figure refers to the zenith angle, the innermost circle being 15° and each circle representing 10° increase of zenith angle up to 75°. The azimuth angle was divided every 30° to show the IDT distribution. Median IDT values were shown for 72 zones; 12 azimuth angles by six zenith angles.

For the low altitude distribution, the range of the IDT median values is 7–12 s^{-1} and no significant variation with the azimuth angle is present except near the southern edge. The high IDT values near the southern edge can be understood by considering the fact that the lines of sight for meteor detection there are more aligned with the magnetic field line ($\mu \rightarrow 90°$) and thus parallel diffusion is dominant as in Eq. (3). This indicates that some of meteor trails even below 93 km are affected by anisotropic diffusion when the trail geometry relative to the magnetic field line is matched. In contrast, the distribution above 93 km shows clear anisotropy with a maximum value values around 90° of azimuth angle. The eastward maximum direction is consistent with the fact that the lines of sight for detected meteor are more aligned to the magnetic field whose declination angle of 10.57° east at King Sejong station. Again the parallel diffusion is dominant for the detected meteors in the east region. The IDT values are in the range of 10–17 s^{-1}, which is larger than those for the low altitude distribution. This is because the low atmospheric density allows faster diffusion at high altitudes. Thus, Fig. 2 provides clear observational evidence for anisotropic diffusion that the theory has predicted. The next analysis employed data only above 93 km, which are suitable for the study of the anisotropic diffusion of meteor trails—the purpose of the present study.

4.2 Local time variation of IDT distributions

Most meteors are expected to enter from the direction of the Earth's orbital motion (apex direction), and the radar observes the meteor at the opposite side of the apex because of backscattering detection from the trail plasma. The entry direction of the meteor changes with local time due to the Earth's rotation. Figure 3(a) shows distributions of meteor detection rates (MDR) in time intervals of 6 hours. It is evident from Fig. 3(a) that the area where maximum number of meteors were detected were consistent with the theoretical expectation that it rotates in a counter-clockwise direction around the zenith. In the same format, we plotted IDT distributions in Fig. 3(b). The long arrow passing through the center of the polar contour indicates the direction of the magnetic field, which was determined using the magnetic declination angle. The red-color area is where the IDT values are larger than that of other areas, meaning that the meteor trail is diffused at a faster rate. One can note immediately that the areas where the meteor trail is diffused rapidly change over time very reminiscent of the MDR's local time variation shown in Fig. 3(a). Since the direction of the Earth's magnetic field at a given location is fixed regardless local time, the local time variation of IDT distribution is not consistent with previous theoretical studies in which the anisotropic diffusion of a meteor trail would occur at a faster rate in the parallel direction to the Earth's magnetic field but at a slower rate in the perpendicular direction.

However, the present result shown in Fig. 3(b) is similar to the observational study result by Hocking (2005), in which meteor radar data in the northern hemisphere were used in the analysis. Hocking (2005) investigated four 3-hour time intervals and found that the area of the maximum IDT value of a meteor trail was not constant over time but moved in a clockwise direction around the zenith in the northern hemisphere in the same manner as in the southern hemisphere. Hocking (2005) proposed that the reason for the rotation of the maximum area was due to the effect of atmospheric tides. More specifically, Hocking (2005) argued that the anisotropic diffusion of meteor trails at an altitude above 93 km could be more affected by an electric field formed by the atmospheric tide, which changes periodically, than by the direction of the Earth's magnetic field.

It is not clear whether or not atmospheric tides affect the diffusion of meteor trail. No theoretical model or observational evidence has been presented for this scenario. Instead, we argue here that the similar behavior of local time variation in IDT and MDR may be due to the sampling effect of meteor data. The more meteors are detected, the shorter decay time would be derived because the median value of decay time tend to decrease in its distribution at high altitudes. In order to investigate further the effect of the Earth's magnetic field on the decay time, we analyze the vertical distribution of the diffusion coefficient in the next section.

5 Vertical distribution of diffusion coefficient of meteor trails

Elford and Elford (1999) presented a relationship between meteor trails and the Earth's magnetic field considering molecules and atoms in relation to the altitude at the ground laboratory as shown in Fig. 2 of their paper. The figure explains that as the angle (θ) between the meteor trail and the

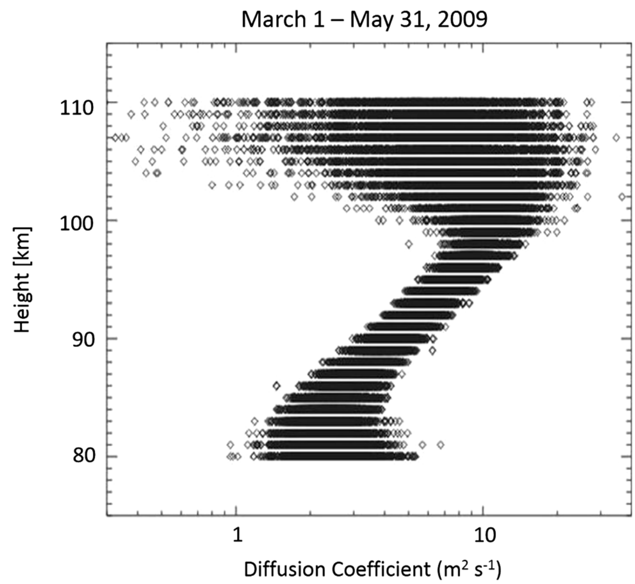

Fig. 4 Height profiles of the observed meteor diffusion coefficient from March to May, 2009 at King Sejong Station in Antarctic. Each point represents a 30-min average of the observed values

Earth's magnetic field at an altitude approximately above 100 km was closer to 90°, meteor trails were not diffused well due to the effect of the Earth's magnetic field. The above interpreted results were similar to the analysis results of the diffusion coefficient according to altitude using the meteor radar data at King Sejong Station in Antarctic as shown in Fig. 4. Each point in Fig. 4 represents the average of the data in 30-minute increments. At altitudes between 80 and 100 km, the diffusion coefficient increased steadily as altitude increased, and at altitudes above 100 km, various diffusion coefficient values were revealed.

The meteor radar at King Sejong Station observes the movement of the meteor as a single point for all-sky. Although the direction of movement of a meteor cannot be predicted accurately, the angle (ϕ) between the radio wave direction of the meteor radar and the Earth's magnetic field can be inferred considering the entry direction of meteor, the Earth's rotation, and the dip angle of the Earth's magnetic field. Figure 5 shows a schematic diagram of the magnetic field line near King Sejong Station, the line of sight of King Sejong Station's meteor radar, and meteor trails. The dip angle at King Sejong Station is −57°. The left side of Fig. 5 shows the south direction whose azimuth angle is 120°–260° and the right side shows the north direction. Due to the radar's characteristics, the entry direction of meteor trails and the line of sight of radar waves become perpendicular. Thus, in an area where the zenith angle is 57° in the southern sky, ϕ is closer to 90°. Around this area, entries of meteor trails will be observed at various angles with regard to the Earth's magnetic field. In particular, entries of meteor trails in the parallel direction to the Earth's magnetic field

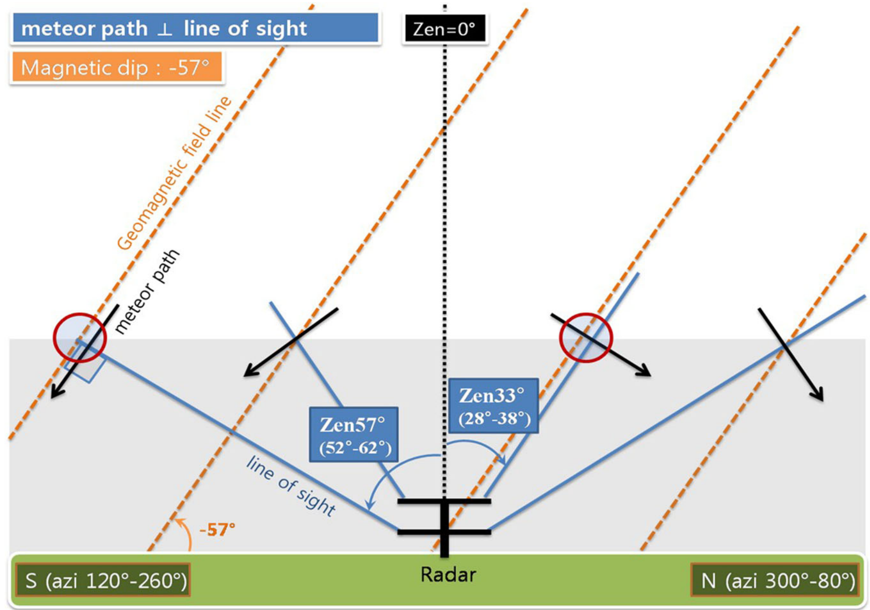

Fig. 5 Schematic diagram of magnetic field line near the King Sejong Station, line of sight of King Sejong Station's meteor radar, and meteor trails

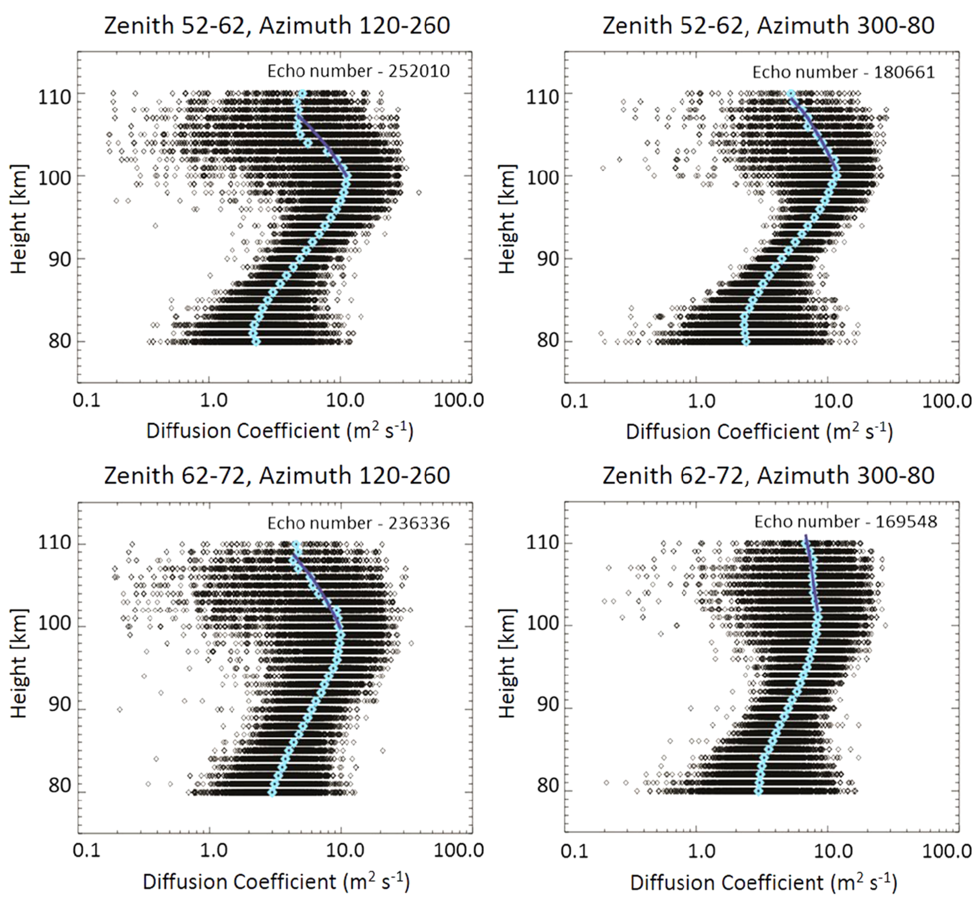

Fig. 6 Height profiles of 30-min averaged diffusion coefficient for all local times from March to May, 2009 at King Sejong Station in Antarctic

can be observed. In contrast, in an area where the zenith angle is 33° in the northern sky, ϕ is closer to 0°. Around this area, most entries of meteor trails observed by the radar will be observed in the perpendicular direction to the magnetic field. Thus, since θ is mostly 90° in the northern sky whereas θ has various values in the southern sky, meteor trails that entered parallel to the Earth's magnetic field at $\theta = 0°$ will be observed only in the southern sky.

The left two figures in Fig. 6 show diffusion coefficients according to altitude of meteor trails in the southern direction where the azimuth angle is 120°–260° in the meteor radar observation, and the right two figures show diffusion coefficients according to the altitude of meteor trails in the northern direction where the azimuth angle is 300°–80°. The upper and lower figures are divided according to the zenith angle. The zenith angles in the upper and lower figures are 52°–62° and 62°–72°, respectively. A blue-colored point refers to a median of diffusion coefficients at each altitude, and the dark blue-colored line refers to a line that links the median values of diffusion coefficients at an altitude above 100 km. In the southern direction where the azimuth angle is 120°–260°, extremely small diffusion coefficient values are observed at an altitude above 100 km in contrast with the northern direction where the azimuth angle is 300°–80°. In the northern direction where the azimuth is 300°–80°, an increasing trend of diffusion coefficients is well revealed with higher altitudes. The reason for this was because there were meteor trails in parallel to the Earth's magnetic field in areas where the zenith angle was 62°–72° and the azimuth angle was 120°–260° in terms of geometrical consideration. Here, since θ is $\sim 0°$ and ϕ is $\sim 90°$, many of the observed effective diffusion coefficients are diffusion coefficients that are perpendicular to the Earth's magnetic field according to Eq. (4). However, in areas where the zenith angle is 62°–72° and the azimuth angle is 300°–360° and 0°–80°, most meteor trails are perpendicular to the Earth's magnetic field. In such a case, since θ is $\sim 90°$ and ϕ is $\sim 0°$, most effective diffusion coefficients are diffusion coefficients in parallel to the Earth's magnetic field. The reason for the above distinctive difference in altitude distribution of meteor trail IDT at an altitude above 93 km in the southern and northern directions was because the effect of the Earth's magnetic field, which was dependent on the entry direction of meteors, influenced the decay of meteor trails significantly. It is also necessary to compare the study result on temperature estimation through meteor trail diffusion in addition to meteor trail decay time and diffusion coefficients in order to understand the anisotropy of meteor trail diffusion that occurred at an altitude above 93 km.

6 Summary and conclusion

The present study analyzed the decay times of meteor trails observed at the VHF meteor radar at King Sejong Station to investigate the diffusion process of meteor trails at an altitude above 93 km. Since the meteor radar at King Sejong Station can observe more meteor trails than other radars used in previous studies, it can provide highly reliable meteor observation data. The present study analyzed IDTs of the observed meteor trails in the viewpoint of the atmospheric diffusion coefficient and in consideration of the effect of the magnetic field.

The spatial distribution of IDT of meteor trails demonstrated a clear anisotropy at an altitude above 93 km regardless of day or night as reported in previous studies. Data were divided into six-hour interval based on the fact that the main entry direction of meteors is different due to the effect of Earth's rotation and revolution. As a result, the distribution of meteor trails which were diffused rapidly at the all-sky figures revealed a rotation in a counter-clockwise direction over time. This result can be compared with the study result by Hocking (2005) in which the direction of meteor trail diffusion was in a clockwise direction in the northern hemisphere. He claimed that the effect of the electric field due to atmospheric tide was more influential on meteor trail diffusion at a high altitude than the Earth's magnetic field. However, the meteor detection rate in the same time interval showed that areas where meteor trails were diffused rapidly and areas where meteor trails were much observed were the same areas. Thus, it implies that the distribution of anisotropic IDT was affected by both the Earth's magnetic field and a meteor's entry direction. The observations at King Sejong Station actually revealed that extremely small diffusion coefficient values are observed at an altitude above 100 km in the south direction where the azimuth angle is 120°–260°, in contrast with the northern direction where the azimuth angle is 300°–80°. In the northern direction where the azimuth is 300°–80°, an increasing trend of diffusion coefficient is well revealed with higher altitude. The reason for the above distinctive difference in the altitude distribution of meteor trail IDT at an altitude above 93 km in the southern and northern directions was because the effect of the Earth's magnetic field, which was dependent on the entry direction of meteors, influenced the decay of meteor trails significantly. In future studies, a study on temperature estimation through meteor trail diffusion will be additionally conducted to better understand the anisotropy of meteor trail diffusion that occurs at an altitude above 93 km.

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