Mesospheric Anomalous Diffusion During Noctilucent Clouds

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Abstract. The Andenes specular meteor radar shows meteor-trail diffusion rates increasing on average by about 10% at times and locations where a lidar observes noctilucent clouds (NLCs). This high-latitude effect has been attributed to the presence of charged NLC after exploring possible contributions from thermal tides. To make this claim, the current study evaluates data from three stations, at high-, mid-, and low-latitudes for the years 2012 to 2016 to show that NLC influence on the meteor trail diffusion is independent of thermal tides The observations also show that the meteor-trail diffusion enhancement during NLCs exists only at high-latitudes and near the peaks of NLC layers. This paper discusses a number of possible explanations for changes in the regions with NLCs and leans towards the hypothesis that the relative abundance of background electron density plays the leading role. A more accurate model of the meteor trail diffusion around NLC particles would help researchers determine mesospheric temperature and neutral density profiles from meteor radars at high-latitudes.

1 Introduction

The motion and diffusion of meteor trails depend sensitively upon the properties of the neutral atmosphere where they ablate. Measuring meteor properties with radars enables researchers and weather modelers to estimate the state of the lower thermosphere and upper mesosphere. Meteor radars most often observe underdense meteors in which the radar frequency exceeds the plasma frequency set by the peak meteor plasma density. Typically they have life-times that vary from 0.01-0.3 s at altitudes below 110 km. Studies of the meteor trail decay-time and effort to derive ambient temperatures from them have a long history (e.g., Greenhow and Neufeld, 1955; Murray, 1959), but even today there exist several subtle difficulties.

Theoretically the meteor trail diffusion (hereafter we refer it as MTD or D_a should increase exponentially with altitude. However, the MTD derived from echo fading times measured by meteor radars deviate away from exponential behavior at altitudes below about 85 km. Using chemistry based numerical simulation, Younger et al. (2014) reported that the deionization of the meteor trail by three-body attachment (a chemical process) at altitudes below 90 km could be responsible for the deviation. But, they were open to contributions from background dusts, such as meteor smoke particles and noctilucent cloud (NLC). Moreover, in a recent study Hocking et al. (2016) argued that the chemical processes are more important for the long lived (non-underdense) meteors, where the importance of ozone chemistry has been discussed. A study by Singer et al. (2008) showed different behavior of the MTD coefficient profiles during NLC and non-NLC cases. They also noted that the strong and weak meteor based separation does show a partly similar behavior, so they could not conclude clearly the contributions from NLC. Also, the NLC occurrence has a local time or tidal dependence (Fiedler et al., 2011; Fiedler and Baumgarten, 2018; Gerding et al., 2013), which could bias the MTD segregration based on it. Here we investigate multiple years of NLC and MTD from different latitudes to investigate the lack of understanding in identifying the role of NLC and atmospheric dynamics.

Altitudinal profiles of temperature are essential for improved modeling of upper atmosphere dynamics at mesospheric heights. However, uninterrupted measurement of this parameter is not possible using traditional optical techniques due to cloud cover. If it were possible to derive temperature from MTD estimates, continuous temperature measurement could become a reality. Currently there are several difficulties in the deriving temperatures from meteor diffusion measurements as there are several unknown and anomalous variabilities. Nevertheless, there are couple of techniques in use (e.g., Hocking et al., 1997; Hocking, 1999; Holdsworth et al., 2006; Stober et al., 2012; Holmen et al., 2016), which provide temperature estimates roughly at a cadence of about a day, but with their own merits and demerits.

2 Experimental Data

The primary data used for this investigation are from the specular meteor radars (SMRs) at Andenes (69°N,16°E) in Northern Norway, Juliusruh (55°N,13°E) in Northern Germany, and Biak (1°S,136°E) in Indonesia. All the three radars are all-SKy interferometric METeor (SKiYMET) systems. Elaborate technical details and working principle of this type of systems can be found in Hocking et al. (2001). Specific technical details of the Biak system can be found in Batubara et al. (2018). In this study we use the decay time information estimated from underdense meteor trails as described in Hocking et al. (2001). Although, the method is fairly robust, it does not account for meteor fragmentation, or other effects that might cause a deviation in the signal morphology deviating from a typical underdense trail. Further, we have to mention that the radars did undergo a change of the experiment settings for the Juliusruh and Andenes SMR. In the years 2014 and 2015 we changed the pulse repetition frequency from 2144 Hz (Juliusruh) and 2094 Hz (Andenes) to 625 Hz and the mono pulse was replaced by a 7-bit Barker code. The lower pulse repetition frequency together with a off-zenith filtering of angles larger than 65° eliminates a potential aliasing due to range ambiguity of the meteor altitudes. The Biak SMR kept the experiment settings with a pulse repetition frequency of 2144 Hz and used a wide meteor layer causing many ambiguous meteor positions. Thus, the data at the upper and lower edge of the meteor layer might be more prone to range aliasing issues. Other than these three radars, NLC data from a Rayleigh-Mie-Raman (RMR) lidar in Andenes are also used to study the characteristics of meteor radar diffusion during NLC presence and absence.

2.1 Specular Meteor Radar Based Diffusion Coefficients

The most commonly observed meteors using a 32 MHz meteor radar are of the underdense type, for which the amplitude profile $A(t)$ decays approximately as per the following relation:

$$A(t) = A_0 \exp\{-(16\pi^2 D_a t)/\lambda^2\} = A_0 \exp\{-\ln 2\, t/\tau_{1/2}\} \tag{1}$$

where, t is time, D_a is ambipolar diffusion coefficient, λ is wavelength of radar signal, and $\tau_{1/2}$ is the decay time to reach half of maximum amplitude (A_0):

$$\tau_{1/2} = \lambda^2 \ln 2/(16\pi^2 D_a) \tag{2}$$

Thus, knowing the decay rate $\tau_{1/2}$ from the meteor echo received, the ambipolar diffusion coefficient can be estimated. As the number densities of the electrons in the meteor trail plasma are several orders of magnitude (at least 3 orders) greater than the background plasma, the trail diffusion could be assumed as an approximation of the mesospheric neutral diffusion. This is because the movement of the trail positive ions are governed by neutrals through collisions.

We have estimated diffusion coefficient from such meteor decay rates for all the available years of meteor detections. But for the current study, based on the avilability of NLC data, 4 years (2012-2016, excluding 2014) are investigated in details. Figure 1 shows the yearly composite (daily binned) D_a values for all the available years of data obtained using the meteor radars located at low-, mid-, and high-latitudes. It can be seen here that, in general, the diffusion decreases with altitude until about 85 km, above which it starts increasing again. In the current study, meteors qualifying the following selection criteria are considered: (i) zenith angle less than 65 degrees, (ii) those during AE index less than 400 nT, and (iii) those having signal-to-noise-ratio (SNR) greater than 5 dB.

2.2 NLC data

The NLC data are obtained using the RMR lidar located at the Andoya (69°N,16°E) island in Northern Norway (Baumgarten, 2010), which is very close to the Andenes meteor radar site. Spectral and spatial filtering capability of this lidar enables continuous observations of NLC even during daylight conditions. Though the instrument existed for a long time, it had experienced several technical developments over the years. Since the year 2011 a pressure controlled single Fabry Perot etalon is used to filter out the background, which increased the SNR of the system (Fiedler et al., 2017). So, the NLC data used here are from the years 2012 to 2016 during clear sky hours of June-July-August over Andenes. The presence or absence of NLC are identified from integrated measurements, over about every 15 minutes intervals, during all the clear sky days.

3 Results

Figure 2 shows diffusion coefficients estimated from Whole Atmosphere Community Climate Model Data Assimilation Research Testbed (WACCM+DART) (Pedatella et al., 2014) temperature profiles over the stations for the year 2007. Since

WACCM+DART assimilates observations, temperatures are believed to provide not only close to realistic values as compared with satellite observations (e.g., Pedatella et al., 2014), but also a better local time coverage. The conversion from temperature to diffusion is done using the simple relation $D = 6.39\times10^{-2}T^2K_0/p$, where p, T, D, and K_0 are respectively pressure, temperature, diffusion, and zero field mobility factor. The value of the factor K_0 is debatable (e.g., Cervera and Reid, 2000; Hall et al., 2004) and we use K_0=2.5×10^{-4} $\mathrm{m^2s^{-1}V^{-1}}$ (e.g., Meek et al., 2013; Younger et al., 2014). Here it may be noted that the diffusion derived from model temperature follows the theoretically expected exponential law. But as mentioned above the observed diffusion from meteor radar based fading time shows deviation away from exponential behavior. Some investigations attributed such deviation to be due to deionization of the trail by three-body chemistry (Younger et al., 2014; Lee et al., 2013). But it may also be possible that the assumption of the ambipolar diffusion and Gaussian profile of meter trail radial plasma distribution are too simple approximations, which need further investigations.

From a comparison of Figures 1 and 2, one can say that the broad seasonal features showing altitude shift of constant value surfaces are similar, but the increased values at lower altitudes in summer differ in the datasets. This suggest that additional physical processes are responsible for the MTD variability during summer.

In the high-latitude summer mesosphere there occurs upwelling and the maximum of the upward motion lies close to the mesopause level (e.g., Smith, 2012; Laskar et al., 2017, and references therein). Due to such upward motion the summer mesosphere is the coldest region in the atmosphere. Under such cold condition the saturated water vapor present and/or transported in the mesosphere freezes up and produces NLCs. NLCs are expected to remove free electrons and thus produce negatively charged ice particles. An earlier study by Singer et al. (2008) used 6 days of meteor trail diffusion data and reported that the diffusion profiles have different behavior if separated based on the NLC presence or absence. In order to systematically investigate the role of NLC for larger datasets and for greater number of years, we have used Andenes RMR-lidar based NLC observation times to segregate the diffusion values. The leftmost column of Figure 3 shows such an NLC presence (yNLC) and absence (nNLC) based grouping for the measurements during clear sky days of June-July-August of the years 2012-2016, excluding the year 2014 wherein we had many data gaps for the high-latitude station, Andenes. The horizontal histograms in the leftmost column represent the occurrences of NLC (total number of 15 minute intervals with NLC-presence) at a particular altitude for a particular summer. The middle and right columns in Figure 3 are for the MTD data from Juliusruh (mid-latitude) and Biak (low-latitude) SMRs, but they were segregated and then grouped based on the NLC sampling at Andenes. As the meteor trail diffusion at a particular altitude is distributed log-normally, the solid (for yNLC) and dashed (for nNLC) lines here are the geometric mean, $\bar{x} = exp[\overline{logX}]$, (e.g., Ballinger et al., 2008) profiles and the shaded regions represent their 95% confidence intervals. As there are reports that neutral density and thus MTD are influenced by geomagnetic activity (e.g., Yi et al., 2018), we have considered only those meteors that had occurred during relatively quiet geomagnetic conditions (AE index less than 400 nT).

From the grouping based on NLC occurrence, as shown in Figure 3, it can be seen clearly that there are differences between diffusion profiles in the presence and absence of NLC at high-latitude. Physical causes of such anomalous behavior are discussed below.

4 Discussion

NLC particle sizes are of tens of nanometers and thus they are much heavier compared to ambient constituents. In the presence of such heavier particles, one may expect that a direct interaction with them, if any, would result in relatively smaller diffusion compared to their absence. Also, from the fact that NLCs are more probable during the cold phase of thermal tide one would expect lower values of MTD in presence of NLC. But what we see from the leftmost column of Figure 3 is the reverse, i.e., in the presence of NLC the SMR-radar measured diffusion coefficient gets enhanced. Here we present a list of possible mechanisms through which NLC may influence/modulate MTD to give rise to the unexpected anomalous behavior. In the following paragraphs we discuss about their role in explaining the anomaly. The list includes, (i) by capturing trail electrons thereby making the trail vanish faster in the eye of radar, (ii) by radiative heating due to presence of semi-transparent NLC-layer, (iii) since NLC occurrence time shows a thermal tidal behavior, it may introduce a systematic artifact in our time sampling, (iv) neutral turbulences may persist longer during the relatively colder NLC occurrence durations, which could help to diffuse the trail faster. (v) the NLC particles could absorb background free electrons thereby changing the electrodynamics of trail and background-plasma.

For (i), in the presence of NLC it may be expected that ice-particles absorb the trail electrons, which can lead to shorter life-time of the trail plasma. But the time constant of electron capture rate (order of seconds) (Rapp and Lübken, 2000) is longer than the typical life-time of the underdense trails (order of milliseconds). Also the abundance of NLC particles are at least 3 orders of magnitude less than trail electrons. Thus this process is very unlikely the cause for the enhanced diffusion. For (ii), the radiative influence on the background atmosphere due to changes in the optical properties in the presence of NLC could increase the NLC particle temperature by 1 to 2°K (e.g., Espy and Jutt, 2002). As the number of NLC particles are negligible compared to background neutral densities such rise in particle temperature would not contribute to the background temperature or diffusion.

To check if the anomaly during NLC could be occurring due to thermal tides, possibility (iii), we have used two additional stations; Juliusruh at mid-latitude and Biak at low-latitude. For the investigation of the tidal behavior in MTD, an hourly composite of the June-July 2012-2016 diffusion coefficient data for the high-, mid-, and low-latitude are shown in Figure 4. Here it can be seen that the dominant variations are a semi-diurnal tide at high-latitude, a diurnal tide at low-latitude, and both at mid-latitude. A tidal behavior was also reported in the histogram of the local time occurrence of NLC and no-NLC during June-July-August months (Fiedler et al., 2011; Fiedler and Baumgarten, 2018). Thus the tidal behavior in both MTD and NLC indicate that the difference between MTD's during NLC and no-NLC may arise from tides.

In order to investigate the tidal variability of the NLC data used here, those NLC observation durations in which simultaneous MTD data over Andenes are present are used to make histogram as presented in Figure 5. Since the MTD data at other two stations have different durations of data availabilty, the histograms for them are different but the shape of the local variability is nearly alike. So they are not shown here but are added in the supplementary information figure S1. Because of the different availabilty of MTDs at different latitudes, the total intervals of NLC (yNLC) or no-NLC (nNLC), as depicted in Figure 3 are different for different stations. For example, for the year 2012 the yNLC durations are 89, 110, and 116 hrs for the Andenes, Juliusruh, and Biak stations, respectively. From Figure 5 one can see that, except in the year 2013, there are no significant tide like daily variability, thus the sampling of MTDs based on NLC would have no tidal bias in those years. Which, however, does not conflict with the Fiedler et al. (2011) and Fiedler and Baumgarten (2018), where they showed a tidal dependence, as the time samplings here are different based on the common observations. Though in 2013 there are some diurnal variations in sampling, which do not introduce any significant difference in diffusion even at low-latitude where the diurnal tide is dominant. Moreover, the separations between NLC and no-NLC diffusion profiles at high-latitudes (as seen in Figure 3) are of higher magnitude near the peak of NLC layer.

To test if the NLC related differences could arise from some unknown systematic processes, say for example higher NLC occuring during first part of the summer, we made two random samples using MTD during just the lidar observation durations. Such random samples do not show any difference between the average profiles between two groups (interested readers can see supplementary information Figure S2). Similar test by making two random samples using whole summer MTD data does not show such difference. From these results we hypothesize that the difference observed between MTD profles during NLC and no-NLC at high latitude are predominantly due to NLC influence.

About the role of background turbulence, possibility (iv), Hall (2002) investigated the influence of neutral turbulence to explain the observed deviations of diffusion away from the exponential behavior. However, in a later report (Hall et al., 2005) they ruled out such mechanism for radars having frequencies close to 30 MHz. They also estimated that the turbulence diffusion in fact is lower in magnitude during summer than in winter. Using 10 rocket flights that were capable of high-resolution measurements of neutral density Lübken et al. (2002) argued that neutral turbulences are very weak during summer and the adiabatic lapse rate condition to support persistent turbulence is hardly reached near the NLC layer. These earlier results imply that neutral turbulence is unlikely to be the cause for the enhanced diffusion during NLC.

For (v), in the absence of NLC the electrons in the trail could be short circuited by the background free electrons and thus this would reduce the effective ambipolar diffusion as the lost electrons would no longer contribute to the diffusion. But, when there is NLC they could absorb background electrons to reduce the density of the background free electrons, making a deficit to short-circuit the trail electrons. Under such condition the ambipolar diffusion of the meteor trail would be higher due to additional pressure from the electrons that are not short circuited as the background medium is less conductive. A schematic illustration for the background situation is depicted in Figure 6, where the background electrons are less available in the NLC case (in right). This kind of explanation also suggest that the ambipolar diffusion assumption of the MTD is valid only when the background charges are very low compared to the trail electrons, similar to the situation as observed during the yNLC scenario. The possibility of such short-circuiting of the trail plasma by background free electrons was discussed both analytically and numerically by Dimant and Oppenheim (2006). This also suggest that for proper retrieval of the mesospheric diffusion we would need an estimate of background electron density.

Changes in the background chemistry could also have an influence but at lower-altitudes where the reaction rates of the three body reactions are comparable to the life-time of meteor trail. This kind of explanation was used earlier to explain the reversal or turn around and then enhancement of MTD coefficient at lower altitudes (e.g., Lee et al., 2013; Younger et al., 2014). But, they did not rule out completely the importance of aerosols, such as NLC, meteor smoke.

For the high-latitude summer time data, Singer et al. (2008) had used the assumption of presence of neutral and charged dust, as was proposed by Havnes and Sigernes (2005), to explain the slower decay rate (i.e., higher diffusion as per Equation 2) in the presence of NLC. They also expected that the strong and weak meteors would be affected differently by the presence or absence of NLC. With their limited data from only 6 days, they showed that NLC and non-NLC diffusion behavior is, to some extent, similar to diffusions during weak and strong meteor echoes. To investigate that if the enhancement during NLC are affected by strong and weak meteor bias, we also have carried out a test in which all those meteors with SNR greater than 12 dB (strong meteors) were used and it was found that the NLC and non-NLC difference scenario still persist as in Figure 3, though they get narrower as the error limit increases due to lesser number of meteors. The test case figure is provided in the supplementary information Figure S3. This test also implies that the diffusion from weaker meteor could be more anomalous and it adds credence to our hypothesis presented in the previous paragraph.

From this anomalous behavior of the meteor radar diffusion during NLC occurrence it is clear that some of the temperature profile estimation methods which uses standard pressure levels will yield misleading results at lower altitudes in presence of NLC. It also indicates that the use of MTD reversal altitude as constant density surface would not be valid under NLC conditions, unless the NLC contribution has been deciphered. Further, for the derivation of temperature at NLC altitudes from SMR-diffusion measurements, proper retrieval algorithm considering the NLC related anomaly is very important. Such retrieval would need information about background electron density, the size of NLC particles, their charge state (Chau et al., 2014) and is a subject of future studies.

5 Conclusions

Meteor trail diffusion variations measured by SMRs at high- (Andenes), mid- (Juliusruh), and low- (Biak) latitude stations, have been used to investigate the mesospheric diffusion variability during summer season. The Andenes SMR based diffusion coefficient during NLC has been found to be enhanced compared to over non-NLC periods. From a local time composite, overall, the SMR based diffusion has been found to be is dominated by the semidiurnal tide at high-latitude and the diurnal tide at low-latitude. Also, since the NLC occurrences have a well known tidal modulation, the meteor sampling based on this may be biased. However, applying the high-latitude NLC and non-NLC occurrence based local time durations to sample the mid- and low-latitude SMR based diffusions we found no significant difference, which thus delineate tidal influence. Moreover, it has been observed that for the high-latitude station the enhancements in diffusion during NLC are of higher magnitude at NLC peak altitudes. This implies that the NLC influences SMR based diffusion rates.

The NLC particles could absorb many of the background free electrons to create lesser conducting background medium. Based on current results it is hypothesized that under such background electron deficit situation, created by the presence of NLC particles, the trail diffusion would be enhanced as there are lesser number of free electrons to short-circuit the trail electrons. But in the absence of NLC the relatively higher number of background free electrons would help to short circuit electrons from trail thereby reducing the ambipolar diffusion. From this statistical study of the anomalous behavior of SMR based diffusion measurements we conclude that the temperature estimations from them would need a detailed retrieval algorithm to account for the influence of background electrons, ice particles and other dusts/aerosols.

Data availability. The meteor mpd data of the Andenes and Juliusruh systems can be made available online at ftp://ftp.iap-kborn.de upon request. The Biak system data are available at IUGONET (http://www.iugonet.org). The RMR-lidar based NLC data can be obtained from JF. WACCM+DART-2007 data can be obtained from NP. The National Center for Atmospheric Research is sponsored by the U.S. National Science Foundation.

Author contributions. FIL and GS conceived the preliminary idea. FIL analyzed most of the presented data in coordination with GS, JLC, and JF. JLC also contributed by comparing the results with data from another independent analysis. MMO helped in the interpretation of the results and provided useful comments on presentation of the results. NMP provided the WACCM+DART data. DP, MT, and TR participated in discussions related to interpretation and presentation of the results. All authors read and approved the final version of the manuscript.

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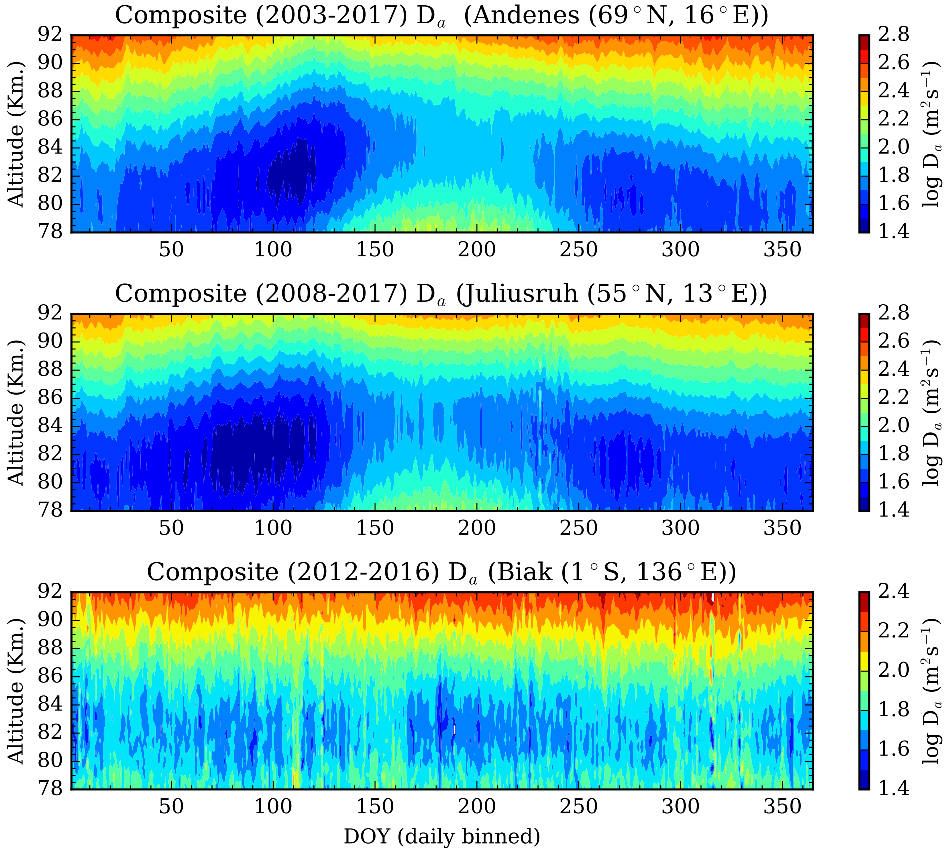

Composite (2003-2017) D_a (Andenes (69°N, 16°E))

Composite (2008-2017) D_a (Juliusruh (55°N, 13°E))

Composite (2012-2016) D_a (Biak (1°S, 136°E))

Figure 1. Diffusion coefficient (D_a) measured by SMRs located at high- (Andenes, 69°N, upper), mid- (Juliusruh, 55°N, middle), and low-latitude (Biak, 1°S, bottom) are shown. Notable features like increased D_a at lower altitudes are protruding out in the mid- and high-latitude stations during summer.

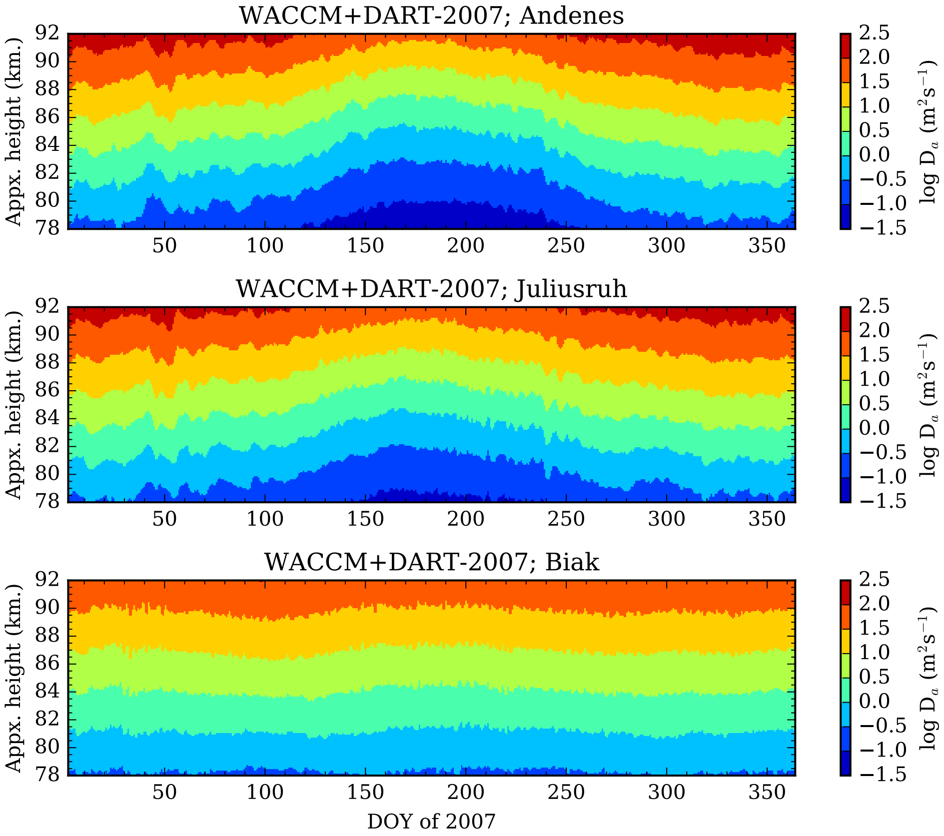


Figure 2. Representative yearly diffusion values obtained by directly converting the WACCM+DART 2007 temperatures over the 3 stations. They show nearly similar seasonal variability, except the increased meteor trail diffusion at lower altitudes seen in Figure 1. Also the summer enhancement seen in Figure 1 is not visible here. This implies that the enhanced diffusionis related to factors that are other than temperature variability.

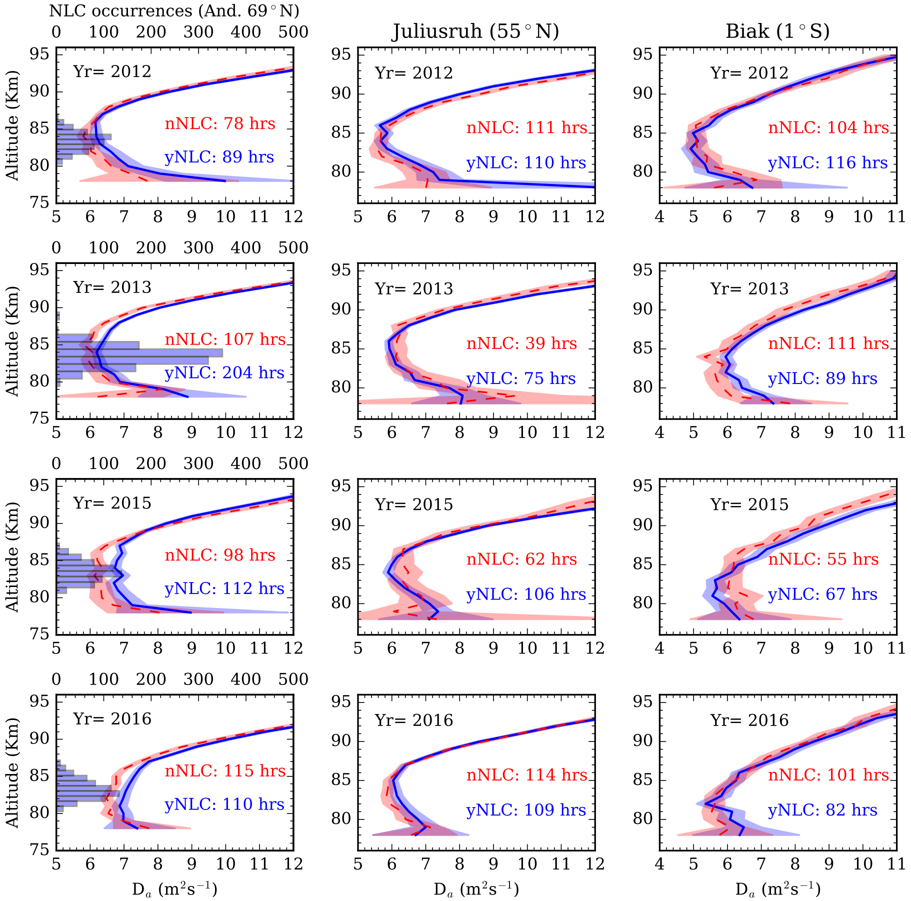
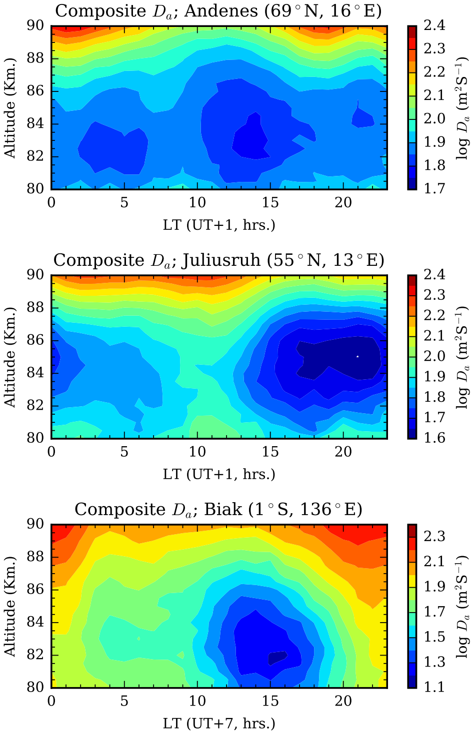


Figure 3. Mean meteor trail diffusion coefficients after segregating them based on presence of NLC (yNLC, blue) and no-NLC (nNLC, red) over Andenes station (leftmost column) are shown. Using the time sampling from NLC occurrences at Andenes, the D_a measurements at mid-latitude, Juliusruh (middle column) and low-latitude, Biak (right column) are also grouped. The shaded regions around the averaged vertical profiles, dashed for nNLC and continuous for yNLC, are the 95% confidence intervals. The histograms in the top axes of leftmost column show the altitude variability of NLC occurrences measured using RMR-lidar at Andenes during June-July-August months. Notable features are: (i) D_a during yNLC is enhanced compared to nNLC, (ii) NLC based grouping does not show separations/enhancements at mid- and low-latitudes, and (iii) the high-latitude enhancements are are predominantly at NLC peak altitudes.


Composite D_a; Andenes (69°N, 16°E)

Composite D_a; Juliusruh (55°N, 13°E)

Composite D_a; Biak (1°S, 136°E)

Figure 4. Composite D_a during June-July of the years 2012-2016, excluding the year 2014, over the three stations. It clearly shows that the semi-diurnal tide is the dominant tide at high-latitudes and diurnal is dominant at low-latitude, while at mid-latitudes seems mixed. This signifies that MTD variation has a strong tidal variability.

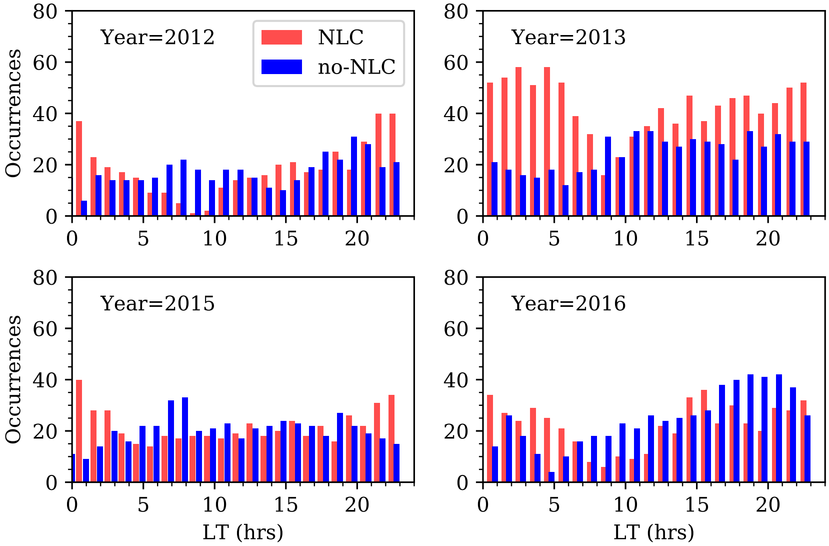


Figure 5. NLC and no-NLC occurrences (number of 15 mins. intervals) over local time during the observation years from Andenes are shown. Similar figures for other stations are shown in supplementary information figure S1. These samplings show that though the NLC and no-NLC occurrence/sampling are not uniform over local-time hours they do not vary significantly, except in the year 2013 where a diurnal tide like variability may be recognized.

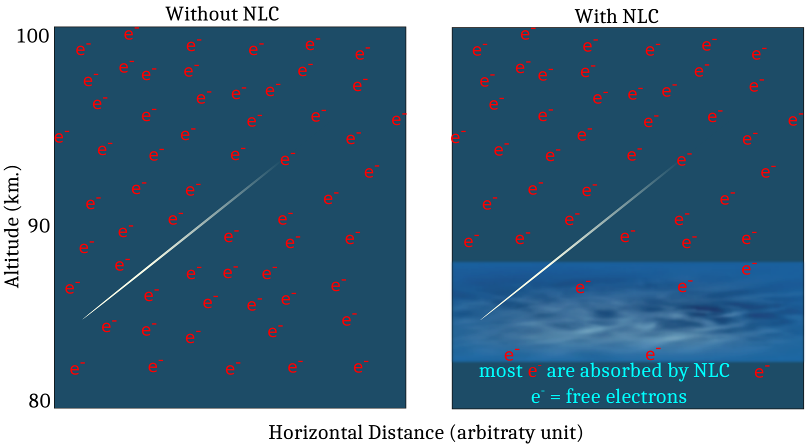


Figure 6. A schematic illustration for the background state without-NLC (in left) and with-NLC (in right) is shown. In the with-NLC case background electrons at lower altitudes are mostly taken up by the NLC particles creating a deficiency of electrons, which therefore cannot take part in short-circuiting the trail electrons and thus the meteor radar measured diffusion appears to be enhanced.