Global Variation of Meteor Trail Plasma Turbulence

L. P. Dyrud • J. Hinrichs • J. Urbina

Abstract We present the first global simulations on the occurrence of meteor trail plasma irregularities. These results seek to answer the following questions: when a meteoroid disintegrates in the atmosphere will the resulting trail become plasma turbulent, what are the factors influencing the development of turbulence, and how do they vary on a global scale. Understanding meteor trail plasma turbulence is important because turbulent meteor trails are visible as non-specular trails to coherent radars, and turbulence influences the evolution of specular radar meteor trails, particularly regarding the inference of mesospheric temperatures from trail diffusion rates, and their usage for meteor burst communication. We provide evidence of the significant effect that neutral atmospheric winds and density, and ionospheric plasma density have on the variability of meteor trail evolution and the observation of non-specular meteor trails, and demonstrate that trails are far less likely to become and remain turbulent in daylight, explaining several observational trends using non-specular and specular meteor trails.

Keywords meteor trail · plasma· turbulence · simulation

1 Introduction

The daily occurrence of billions of meteor trails in the Earth's upper atmosphere presents a powerful opportunity to use remote sensing tools to better understand the meteoroids that produced them, and the atmosphere and ionosphere in which their trails occur. One of the most promising tools employed in this endeavor are high-power-large-aperture (HPLA) radars. Such radars routinely observe two distinct types of meteor echoes, head echoes and non-specular meteor trails. Head echoes are the radar reflection from targets with short durations, usually less than 1 millisecond at a given range, and moving at apparent meteoroid velocities [Close et al., 2002; Janches et al., 2000; Mathews et al., 2001, Janches et al. 2008, Chau and Galindo, 2008, Dyrud et al.. 2008]. When radars are pointed perpendicular to the magnetic field, head echoes are often, but not always, followed by echoes lasting seconds to minutes [Dyrud et al., 2005; Zhou et al., 2001, Malhotra et al., 2007]. Because these echoes occur simultaneously over multiple radar range gates, the term non-specular echoes has been adopted by many authors in order to differentiate them from the meteor echoes from specular meteor radars, which require a trail to align perpendicular to the radar beam [Ceplecha et al., 1998; Cervera and Elford, 2004]. It is now understood that non-specular trails are reflections from plasma instability generated field aligned irregularities (FAI) [Chapin and Kudeki, 1994a, Oppenheim et al., 2000, Zhou et al., 2001, Dyrud et al., 2001, Dyrud et al., 2002, Dyrud et al., 2007, Close et al., 2008]. However, the influence that turbulent trails has on specular observations of meteor trails has only been briefly studied [Hocking, 2004,

L. P. Dyrud (✉)
Communications and Space, Sciences Laboratory, Pennsylvania State University, University Park, PA, USA. E-mail: Lars.Dyrud@jhuapl.edu

J. Hinrichs • J. Urbina
Applied Physics Laboratory, John Hopkins University, Columbia, MD, USA

Galigan et al., 2004], and we do not yet understand the degree to which meteor trails are inherently plasma unstable. This paper seeks to address some of these unknowns.

We focus on the role that neutral atmospheric wind and density, and ionospheric plasma density has on the development of meteor trail turbulence and evolution. Our goal is to understand how regional, diurnal and seasonal variability in these background parameters will influence the role that plasma turbulent meteor trails has on various applications and scientific studies. Most prominently, turbulent trails are thought to have a diffusion rate that can exceed the nominal cross-field ambipolar diffusion rate by up to an order of magnitude, significantly altering trail evolution, duration and reflectability [Dyrud et al., 2001]. The effects of this turbulent evolution are important for specular radar derivations of diffusion rate and therefore neutral temperature (T_n) [Hocking et al., 1999, Kumar, 2007], meteor burst communication [Fukuda et al., 2003], and scientific studies involving non-specular trail observations in general [Dyrud et al., 2005, 2007, Malhotra et al., 2007].

In order to understand the global variation of meteor trail turbulence, we expanded a model of the evolution of an individual meteor from atmospheric entry to trail instability and diffusion (See Dyrud et al. [2005, 2007] for a detailed description of the model) by incorporating climatological models for the relevant ionospheric and atmospheric parameters. For readers interested in the global modeling of the incoming meteor flux see Janches et al., [2006] and Fentzke and Janches [2008].

Our model was originally used to simulate artificial radar Range-Time-Intensity (RTI) images for comparison with facilities like the 50 MHz Jicamarca Radar and other coherent radars [Chau et al., 2008, Oppenheim, 2007, Dyrud et al. 2004, Dyrud et al., 2007, Hinrichs, 2008]. This program simulates head echoes and non-specular trails for meteoroids of a chosen velocity, mass, and composition, entering the Earth's atmosphere. Our new program runs this individual meteor model, and then measures several key parameters pertaining to trail plasma instability, with this paper focusing on the duration of trail plasma instability. Instability duration is closely associated with the duration of an individual non-specular trail observation. Further, duration also acts as a guide for researchers interested in specular meteor trail observations, and meteor burst communication, by indicating when, where and to what degree they can expect turbulent versus laminar meteor trail evolution. By analyzing trail variation on a global scale, we show that properties of the atmosphere and ionosphere play a critical role in the observation and interpretation of meteor trails observations, and that as a result, the characteristics of meteor trail evolution are considerably more variable then previously expected.

2 Model Description

The model used here simulates meteoroid entry into the atmosphere, including ablation, ionization, thermal expansion and plasma stability based upon the meteor Farley-Buneman Gradient-Drift (FBGD) instability [Dyrud, 2001, 2002, Oppenheim, 2000, 2003a,b]. We have now enhanced the capability of this program by automating location and time specific ionospheric and atmospheric data from three main climatological models: Cospar international reference atmosphere (CIRA) [CIRA, 2005], the International Reference Ionosphere (IRI2000) [Bltiza, 2001], and the Horizontal Wind Model (HWM) [Hedin et al., 1996]. The parameters required from these models include electron density, atmospheric mass density, neutral temperature and wind speed, and from these we also derive ion and electron collision frequencies based upon the formulas from Banks and Kockarts, [1972] for a given location and time. This information is used to make location specific meteor simulations, which are then called multiple times to build up global maps of the meteor trail characteristics. While we recognize that these climatological models do not capture the full variability of aeronomical and ionospheric parameters, they do allow for an examination of the resulting climatological and global variation expected for meteor trail evolution. An aspect which previously has never been explored in light of the known influence of plasma turbulence.

An example meteoroid comparison to model results from an individual meteoroid simulation, for a single location and local time are displayed in Figure 1a. We display the results of this model as a simulated Range-Time-Intensity image of a head echo and non-specular trail, similar to those produced by a coherent radar observations [Chapin et al. 1994, Close et al. 2002, Oppenheim et al. 2007, Dyrud al. 2005, Malhotra et al. 2007]. This figure displays the head echo trace as diagonal colored line, with color corresponding to electron line density per meter divided by 10^6, such that it may appear on the same color bar as FBGD growth rate. We have worked on numerous head echo models (See Dyrud and Janches, [2008]) but have opted to plot a parameter which is related to head echo strength, but is also of direct physical relevance to the development of plasma instability. To the right of the head echo, this plot displays the calculated, non-negative, FBGD growth rate as a function of time and altitude for a diffusing meteor column. Examination of Figure 1a reveals that only a limited altitude portion of the trail is immediately plasma unstable, with the width of this unstable portion decreasing in time. The total duration of plasma instability for this example is approximately 15 seconds, which is defined as the time from trail generation at a given altitude to the time the growth rate becomes negative at that same altitude. In order to test our model, data comparison was done with trail observations from Fort Macon North Carolina with simulated meteors. This comparison is shown in Figure 1b. We continue with a presentation of the duration of trail turbulence if such a meteor where to occur simultaneously across the globe.

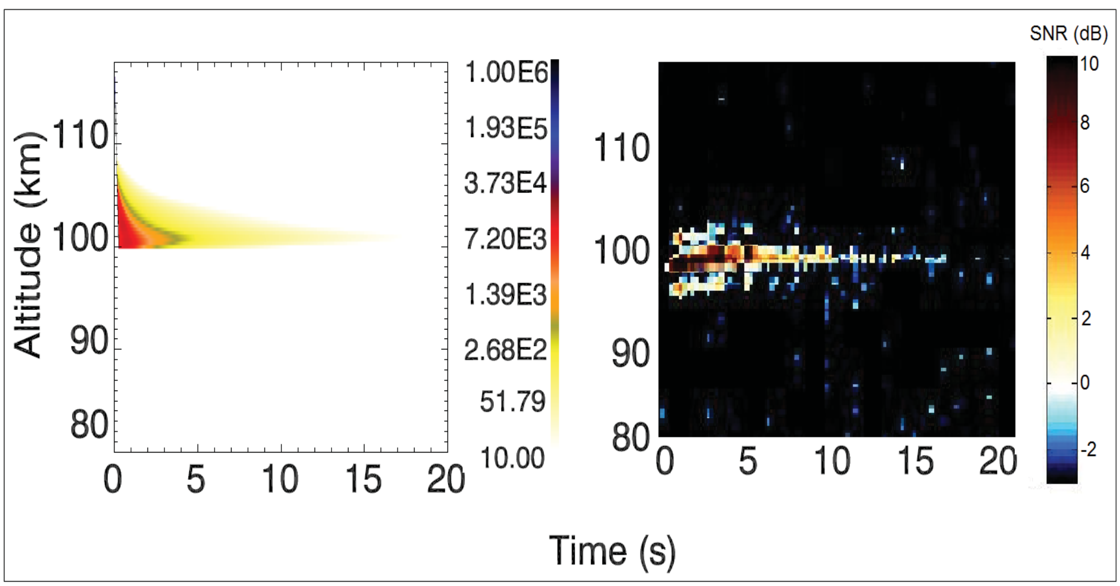


Figure 1a. A simulated RTI simulation for a meteoroid near North Carolina compared to a observed meteoroid in North Carolina (Latitude = -35^o and Longitude = -55^o) conditions for 00:00 UT, on June 27th . The simulated meteoroid mass is 10 μg, traveling at a velocity of 70 km/s, composed of an atomic mass of 30 AMU. The duration of the trail turbulence is approximately 15 seconds. The color bar shows instability growth rate in s^{-1} for the trail, and the simulated head echo displays electron line density per meter divided by 10^6 (units chosen such that they appear on the same scale).

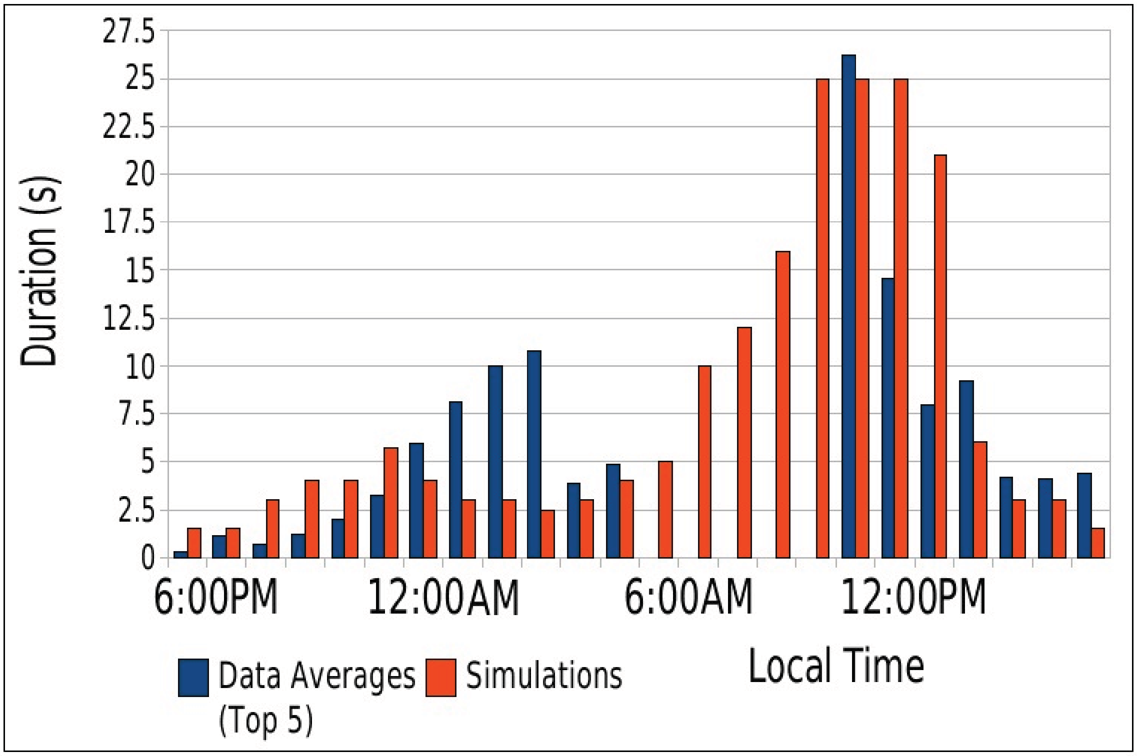


Figure 1b. A bar graph comparing meteor trail simulations from North Carolina with data observed at Fort Macon North Carolina. The data was obtained by taking the average of the top 5 largest meteors at each hour and comparing it with meteor simulations from the model previously described. Data was not taken for 6 hours, starting at 6am, because the radar was not on. Notice how much of the data points compare well with the simulated data, yet some outliers occur in the data.

3 Global Model Results

Here we examine the duration of meteor trail turbulence as function of location, for a trail produced by a 10 microgram meteor traveling at 70 km/s on June 27th at 00:00 UT, with a zenith angle of 45^{o}. These characteristic meteoroid parameters were chosen because this is a commonly measured size class of meteoroids among the billions of daily meteors [Mathews, 2001, Chau, Dyrud and Janches, 2008]. The meteor simulation of the type shown in Figure 1a, is repeated several hundred times across a 2^{o} latitude and longitude grid, with the analyzed results displayed in Figure 2a. This plot shows, in color, the duration of plasma instabilities within the meteor trail for each location, which are seen to vary between 9 seconds and 0, where 0 indicates no trail turbulence is generated. The first striking observation from this figure is the dramatic global variation of meteor trail evolution, even for trails produced by the very same meteoroid. Some of the features shown are: a clear day to night variation, i.e. that duration is significantly longer in the dark regions of the globe, and since we show a January day one can see that more of the Northern hemisphere contains longer turbulent durations than the more sunlit southern hemisphere. We also see that that duration is in general longer near equatorial regions with enhancements that appear in the Northern Atlantic Ocean, over South America and Africa. The variation in this figure is caused by variation in the main drivers for instability, which are primarily background ionization levels, and the magnitude of the neutral wind blowing both perpendicular to the trail and the geomagnetic field.

We point out here that only the HWM was used for determination of meteor zone winds, and therefore these results will likely not to apply near the equator and at the highest latitudes where ionospheric drifts due to electrojets dominate the neutral winds. Hinrichs et al. [2008], has specifically analyzed a 24 hour meteor simulation for the Jicamarca radar location with inclusion of an electrojet drift model to show that the magnitude of the electrojet drift strongly modulates trail duration. We expect to incorporate climatological models for the high and low latitude electrojets into this global simulator in the future. We continue with a presentation of both the meteoric and atmospheric parameters responsible for variability in meteor trail evolution.

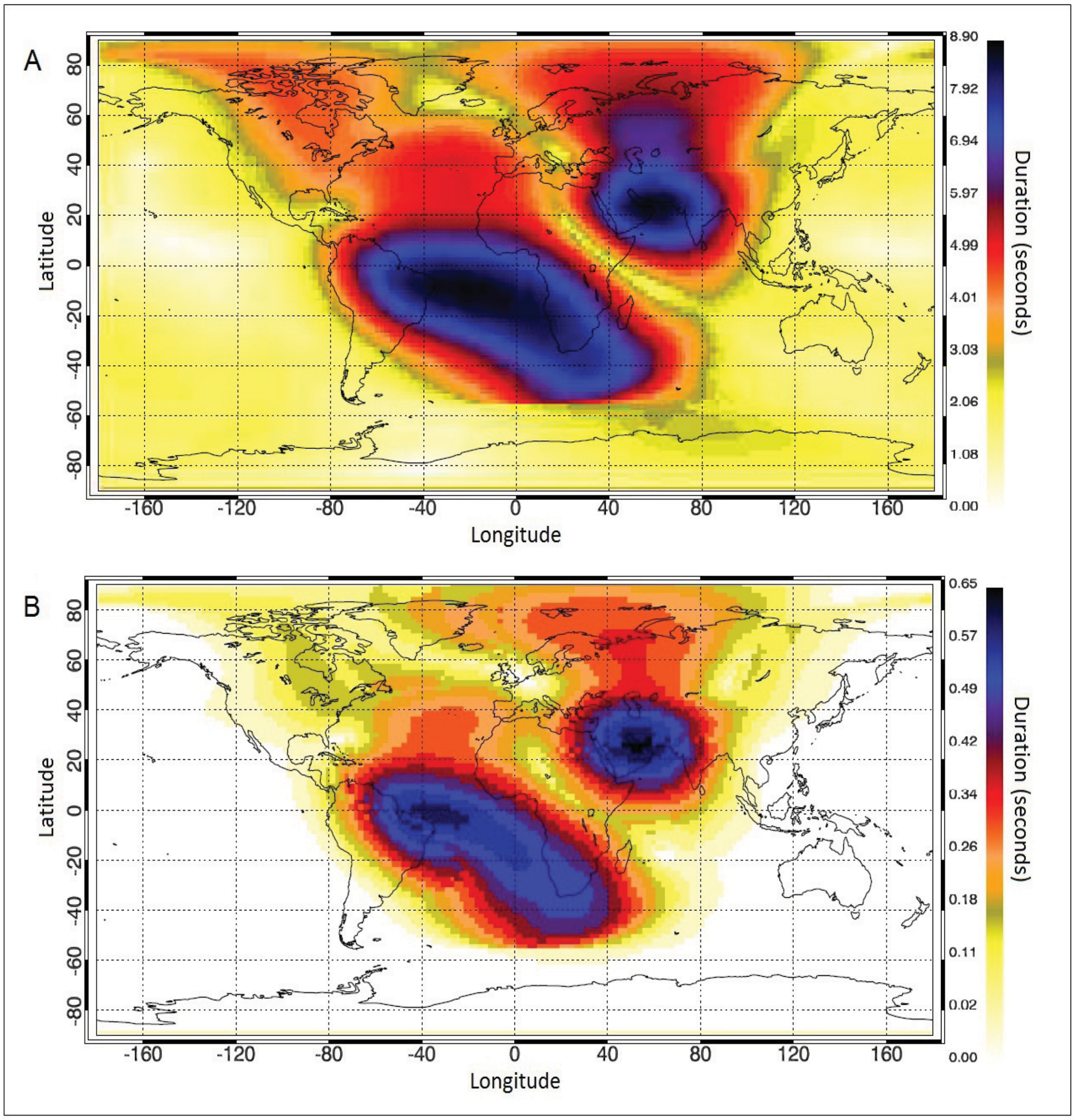
4 Meteor Properties

We now investigate meteoric properties and their influence on meteor trail duration. Two meteoric properties that have the greatest effect on meteor trail duration are mass and velocity. Figure 2b is a global simulation with identical parameters as 2a except the mass of the meteor has been decreased from 1.0 µg to 0.1 µg in order to investigate the effect of mass. As seen by comparing Figures 2a and 2b, a meteor with a mass of 1.0 µg will produce longer duration meteor trails compared to a smaller massed meteor. A more massive meteor produces steeper plasma density gradients, and penetrates to lower altitudes where polarization fields are the strongest. Not only do meteors of larger mass produce longer duration meteor trails at night, but during the daytime meteors of higher masses are now turbulent in regions where 0.1 µg meteors were not.

Unlike mass, an increased meteoric velocity doesn't always have a complementary effect to meteor trail duration. Yet, velocity has a significant impact on meteor trail duration. Figure 3 shows the drastic effect velocity has on meteor trails duration. A slow meteor traveling at 15 km/s has less ablation and ionization, which produces a relatively short lived meteor trail, if any trail at all. A very fast meteor traveling at 75 km/s has so much energy that all of its mass becomes ionized at such high altitudes that short trails are produced, due to weak polarization fields above ~100 km. The longest meteor trails observed are created by meteors of speeds in between both extremes. A velocity ranging from 35-40 km/s allows the meteor to reach lower altitudes where polarization electric fields become stronger, yet still generates steep density gradients. The impact that meteor velocity has on global meteor trail variability is shown by comparing Figure 2b and Figure 4. Figure 4 shows a global simulation of a 0.1 µg meteoroid, identical to that in Figure 2b, but with a velocity of 35 km/s. One may see that the slower velocity results in longer duration trails and more daytime trails.

5 Atmospheric Properties

In order to understand the atmospheres role in meteor trail evolution we investigate the parameters which have profound effects on trail evolution. We find that these parameters are electron density present in the ionosphere and the horizontal winds that a meteor experiences. Small changes in atmospheric properties result in dramatic global variability. Since electron density and winds effect meteor trail duration we must further investigate the variability seen in these parameters to understand a global meteor trail outlook.



Figures 2. (a) A global simulation of the duration of meteor trail turbulence of a single 1 μg meter simulated across the world traveling a 55 km/s at 00:00 UT on January 1st. The units of the color bar are in seconds after meteor trail creation. Each pixel results from the measured duration of a simulation of the type shown in Figure 1a. The location of the meteor presented in Figure 1 is denoted by a (*) near North Carolina. Figure 2a illustrates the effect that the atmospheric properties electron density and horizontal wind speed have on a meteor's trail duration. (b) A global simulation of the duration of meteor trail turbulence of a single 0.1 μg meter simulated across the world traveling a 55 km/s at 00:00 UT on January 1st. The units of the color bar are in seconds after meteor trail creation. Each pixel results from the measured duration of a simulation of the type shown in Figure 1a. Notice that a meteor of lesser mass meteor experiencing the identical atmosphere as Figure 2a will produce meteor trails of shorter duration or no meteor trail at all depending on the location.

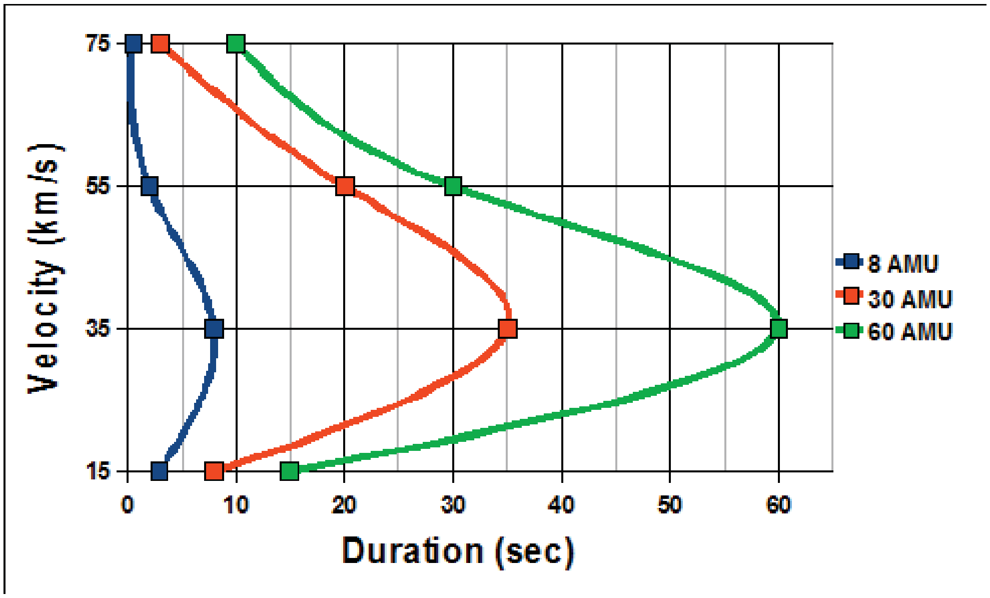


Figure 3. The duration of 3 meteors of different atomic masses (8, 30 and 60) and how its velocity effects meteor trail duration. The duration of a meteor trail is plotted in seconds and the meteors velocity is in km/s. Notice how slow and fast traveling meteor will produce short duration meteor trails in comparison with mid range meteor velocities. A velocity of 35-40 km/s has the right amount of energy to create a long duration trail.

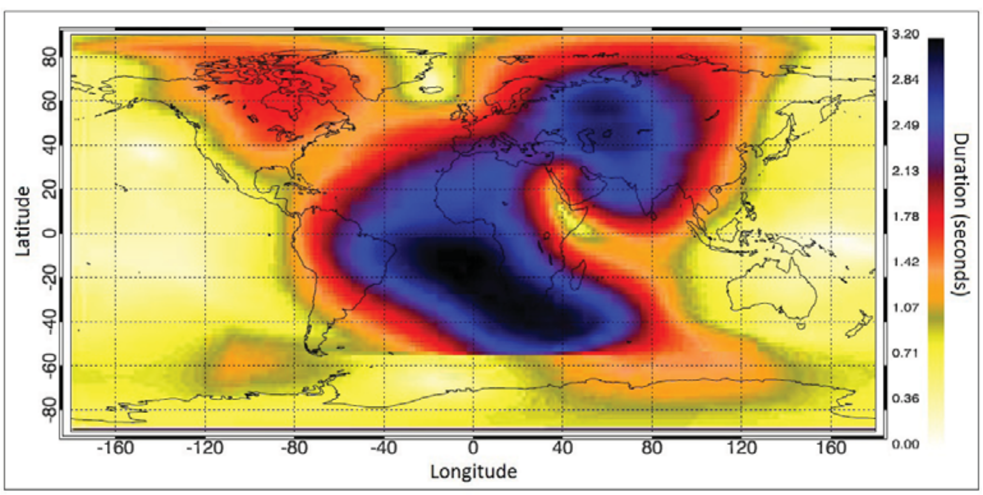


Figure 4. A global simulation of the duration of meteor trail turbulence of a single 0.1 μg meter simulated across the world traveling a 35 km/s at 00:00 UT on January 1st. The units of the color bar are in seconds after meteor trail creation. Each pixel results from the measured duration of a simulation of the type shown in Figure 1a. Notice the impact that a meteors velocity has on meteor trail evolution and trail duration. In comparison with Figure 2b which has a speed of 55 km/s, a meteor traveling at 35 km/s has a preferred velocity for producing a long duration meteor trail. Not only are longer duration trails produced but also trails in areas where they were absent in Figure 2b.

Electron density is the first atmospheric property we look at since its effect on trail duration is quite evident. Electron density is important because densities in the day differ from nighttime densities by a factor of two and electron density directly effects meteor trail evolution and duration. A meteor subject to high electron densities will produce a shorter plasma turbulent trail than if lower densities were present. Figure 5 shows the diurnal cycle of electron density at 0:00 UT on January 1st. The global structure of present electron density determines the area across the globe in which conditions favor meteor trail evolution.

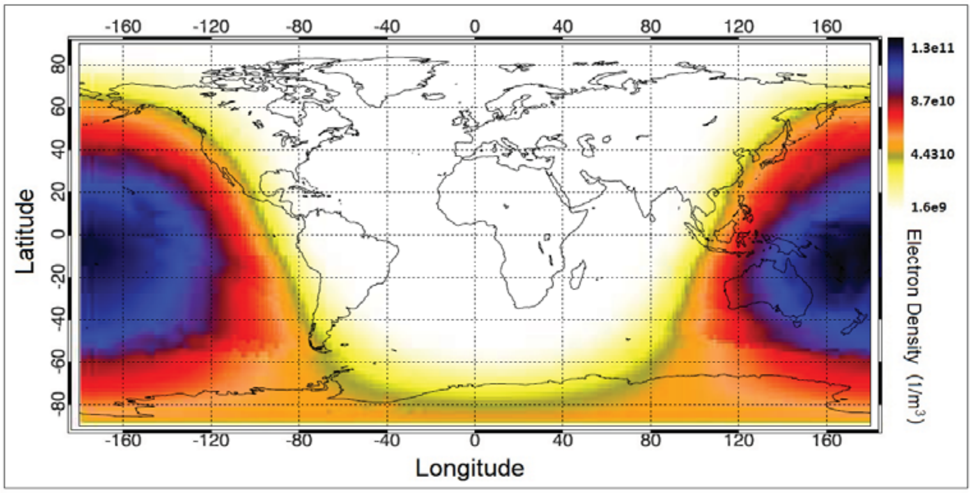


Figure 5. The electron density of the Earth's ionosphere that is present in Figure 2a and b. Density is measured in 1/m³ at 0:00 UT on January 1st. The color bar shows densities that range from high density present during daytime hours and low densities present at night. Notice the distinct diurnal cycle of high density daytime located at the east and west and the nighttime low density area located at the center of the world. Higher electron densities inhibits meteor trail evolution.

Electron density is an important factor in meteor trail evolution, but identical meteors that encounter constant electron density still have variability in trail duration around the globe. This is attributed to the winds that a meteor encounters. A meteor that is exposed to high winds will have a longer duration than the same meteor that is exposed to lower wind speeds. The impact that wind speed has on trail duration of meteors of different speeds is shown in Figure 6. To demonstrate the effect that global winds have on meteor trail duration we examined the horizontal wind speed at the altitude where maximum duration of the meteor trail occurs, this is shown in Figure 7. In the figure wind speeds vary from 0.5 m/s to 107 m/s. Although this is not the total wind that a meteor encounters, the wind speed at the altitude of maximum duration gives a good picture of the winds that directly influence a meteors plasma trail. Both the distinct global structure of winds at the altitude of maximum duration and the diurnal cycle of electron density are essential in understanding the global variability presented in this paper.

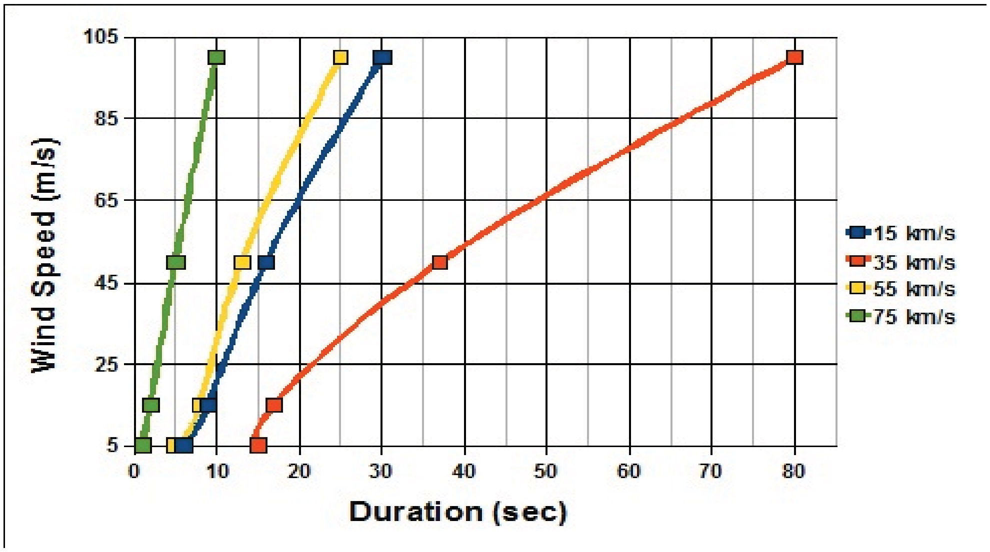


Figure 6. A plot of trail duration versus wind speed for 4 different velocities of 1.0μg meteors. The influence that the increased magnitude of horizontal wind speeds have on a meteor's plasma trail and its duration. The plot used data from simulations of the meteors trail durations of 4 identical meteors traveling at different speeds (15, 35, 55 and 75km/s). These meteors are simulated at different wind speeds. Notice that meteor trail duration is directly linked to wind speeds.

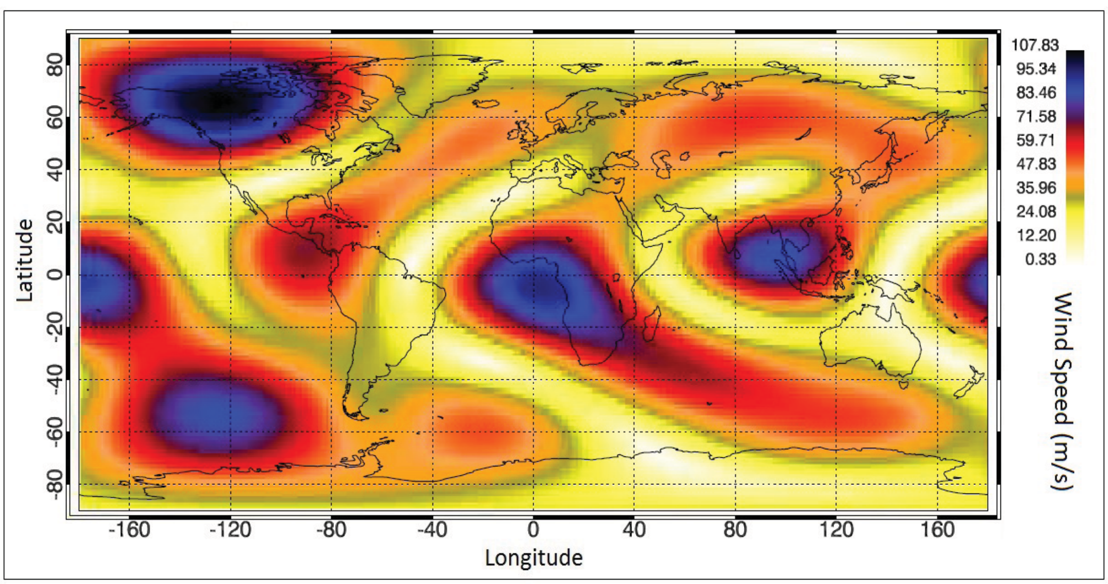


Figure 7. A global plot of the magnitude of horizontal wind speed present on January 1st at 0:00 UT at the altitude at which the simulated meteor has maximum trail duration in Figures 2a and b. The color bar shows wind speed in m/s. The wind pattern shown here is present throughout the day and is fixed in local time. Notice the large variations in the magnitude of horizontal wind speed which effects trail evolution.

6 Seasonal Variability

The effects of the atmosphere on meteor trail evolution can be seen not only globally, but seasonally as well. We now look as seasonal variability of meteor trails since the atmospheric properties we presented vary seasonally. We investigate seasonal variation by inspecting simulations near the equinoxes and solstices. Seasonal variability in meteor trail duration can be seen by comparing Figure 2b and 8. Differences in the global plots of meteor trail duration of identical meteors on January 1st and March 20th are the result of subtle yet key changes in the atmosphere throughout the seasons.

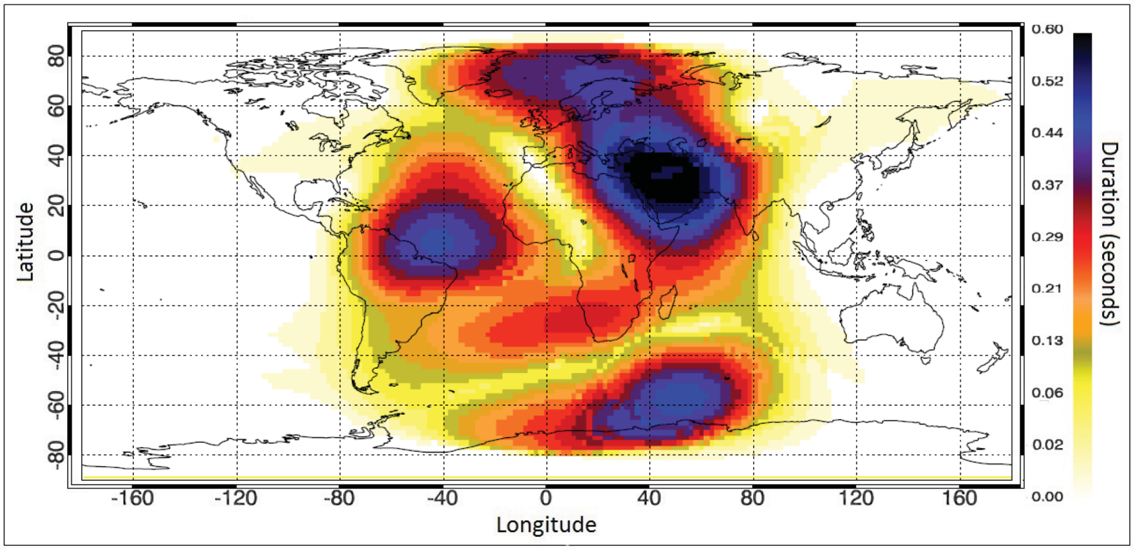


Figure 8. A global view of the duration of a meteor's trail. This simulation is of a 0.1 μg meteor traveling at 55 km/s on March 20th at 0:00 UT, measured in seconds. The units of the color bar are in seconds after meteor trail creation. Each pixel is a simulated meteor as seen in Figure 1a. Figure 8 takes place on March 20th, otherwise it is the identical conditions that is simulated in Figure 2b. Notice the differences in the global structure of trail duration compared to Figure 2b, which is simulated on January 1st. The differences are caused by the changes in the atmosphere throughout the seasons.

One difference in atmospheric properties is the structure of the present electron density. Figure 5 showed winter in the northern hemisphere. The shape of this structure varies throughout the seasons and is based on the amount of sun present throughout the day. For example June's electron density is a horizontally flipped version of Figure 5 since the night is present longer in the southern hemisphere. Since both hemispheres experience roughly the same amount of sunlight during the months near equinox, electron density will reflect accordingly. The other change in atmosphere throughout the seasons is the horizontal winds that a meteor experiences. The structure of the magnitude of horizontal wind at the altitude of maximum duration changes throughout the year.

The combination of electron density and winds along with the meteors own parameters help the understanding of the great differences seen in both day/night observations and seasonal variability of meteor trials. With this understanding we now have a better idea of the scope that small variations in atmosphere has on worldwide variability of meteor trail evolution.

7 Discussion

This paper presents a drastic global and seasonal variability in plasma turbulent meteor trail duration. We find that variations in trail duration are caused by two atmospheric properties, electron density of the ionosphere and the magnitude of horizontal winds. While the observational studies of meteor trail turbulence and non-specular meteor trails remain sparse in terms of geographical and local time coverage, several observational trends have been reported in the literature. The model we constructed is critical for placing data from individual sites in the context of a global meteor flux into a local atmosphere and ionosphere. Here we review some observations on diurnal trends.

[Chapin and Kudeki, 1994a] and [Chapin and Kudeki, 1994b] published some of the first observations of non-specular trails from the Jicamarca radar. While it was not the focus of their paper, the difference in trail occurrence and duration before and after sunrise can was clearly shown in their Figure 4. The figure shows two distinct periods of meteor observations; the first half contains over 125 meteor echoes before sunrise near 6:20 LT, followed by an abrupt decrease in the number trails observed. After 6:20 only 20 meteor echoes are seen throughout the second half of observation.

Recently, Oppenheim et al. 2008 drew specific attention to the diurnal variability of non-specular echoes at Jicamarca. Before dawn, 341 non-specular trails were observed for 1288 head echoes and only 81 trails for 1240 head echoes after dawn. They suggested that this was evidence of a previously published theory by Dimant and Oppenheim [2006a, b] that predicted stronger zeroth order ambipolar fields at night, and therefore an enhanced driver for instabilities. In contrast, we provide an alternative explanation for this day night variability, which involves not just background electron density but the presence of background electric fields or winds that drive polarization fields within the meteor trail [See Dyrud et al. 2007]. The results presented here show that day/night variability is a global phenomenon, and not limited to electrojet regions.

Zhou et al. [2001] presented observations of head echoes and non-specular trials from the MU 50 MHz radar in Japan. This experiment was conducted with the radar pointing both perpendicular, and off -perpendicular to the geomagnetic field. They noted that essentially all head echoes had a corresponding non-specular trail in the perpendicular to **B** geometry, while the off- perpendicular had essentially no trails, but similar counts of head echoes. Their data were collected from 00:00 to 08:30 LT over 4 nights, but made no comment on pre and post sunrise differences. These results cemented the view that non-specular echoes result from plasma instability induced FAI. While not the primary focus Close et al. [2008] recently demonstrated that larger meteoroids are more likely to produce non-specular echoes than smaller.

Simek [2005] examined the seasonal and diurnal variability of specular meteor trail durations to show that mean sunlit durations were 2.27 - 0.11 seconds, but that night durations were 1.95 - 0.06 seconds. These general trends fit what we expect and report here, that enhanced diffusion as a result of trail turbulence during predominantly night-time meteors will reduce trail duration. However, the values reported here include a number of influencing factors such as changing echo altitude as a function of local time. However, specular echo duration as a function of altitude, which helps isolate the effects of trail turbulence, has been examined by Singer et al. [2008]. They showed that low altitude decay times decreased at high latitude in summer, and that strong echo trails had longer decay times than weaker echo trails (stronger echoes likely typify higher electron line densities produced by larger meteoroids). However, examination of this author's Figure 2 shows that these trends are reversed at the highest altitude of observation (94 km). The results reported here explain this seasonal and meteor size trend reversal at higher altitudes. In the summer hemisphere trails are more likely to be produced in a sunlit ionosphere, and therefore remain turbulent for shorter periods of time or not at all. If turbulent decay rates are faster than laminar decay rates as reported by Dyrud et al. [2001] we expect summer trails to possess, on average, longer decay times. Since larger meteoroids produce larger plasma density gradients we also expect larger trails (or stronger echoes) to possess faster decay times. Further, these effects of turbulent diffusion are more pronounced at higher altitude as also discussed by Dyrud et al. [2001].

In a study of specular trail diffusion as a function of radar pointing to **B,** Hocking [2004] suggested that " … future theoretical analysis need to include externally imposed electric fields in order to produce accurate simulations of diffusion rates..". This is what we have included in this study. Hocking [2004] examined decay times as a function of radar azimuth angle and time of day, and found that there was far stronger anisotropic diffusion at greater altitudes above 93 km, and that winds and electric fields appear to influence the diffusion rate in general, and the overall anisotropy.

As the above summary of studies show, the existing non-specular and specular trial observations do support a day to night variation in the occurrence of meteor trail plasma turbulence. The studies also show that larger meteoroids are more like to produce turbulent trails. Further, our simulations here indicate that this day/night occurrence variation is one that is predicted to be global. However, the detailed variability is a result of the altitudinal wind profiles and magnitude. Understanding this variability will require substantially increased observations, both in terms of geographical and local time coverage, and comparison with data from other instruments. We conclude by noting that the driving factors accounting for meteor trail turbulence are many and complexly intertwined, thus it is not the focus of this short letter to describe all the competing forces but to publicize the predicted dramatic variability to researchers in various meteor related fields. We are working on a detailed analysis of the various contributions and expect to report them in an upcoming publication, but can summarize the general trends here. The primary drivers for turbulence duration are background ionization: turbulence lasts longer at night, wind or drift velocity: higher winds or drifts produce longer turbulent durations, meteoroid mass: larger meteoroids produce longer turbulent durations, velocity: velocities near 35 km/s (with some modification with entry angle and a particular mass) longer lasting turbulence because they deposit their mass at preferred altitudes for turbulence, between 90-105 km altitude.

We expect that a complete understanding and characterization of all the driving forces behind meteor trail turbulence will improve our understanding of non-specular trails, but also dramatically improve our ability to use specular trail observations to derive atmospheric temperature and other parameters, by isolating decay rates from the influence of turbulence.

Acknowledgments

Lars Dyrud and Jason Hinrichs' work was supported by NSF grants ATM-0613706 and ATM-0638912.

References

Banks, P. M., and G. Kockarts (1973), Aeronomy: Part A, Chapter 9, *Academic Press*.

Bilitza, D., International Reference Ionosphere 2000, Radio Science 36, #2, 261-275, 2001.

Ceplecha, Z., et al. (1998), Meteor Phenomena and Bodies, *Spa. Sci. Rev.*, *84*, 327-471.

Cervera, M. A., and W. G. Elford (2004), The meteor radar response function: Theory and application to narrow beam MST radar, *Planetary and Space Science*, *52*, 591-602.

Chapin, E., and E. Kudeki (1994a), Radar interferometric imaging studies of long duration meteor echo observed at Jicamarca, *Journal of Geophysical Research*, *99*, 8937-8949.

Chapin, E., and E. Kudeki (1994b), Plasma-wave excitation on meteor trails in the equatorial electrojet, *Geophysical Research Letters*, *21*, 2433-2436.
Close, S., et al. (2002), Scattering characteristics of high-resolution meteor head echoes detected at multiple frequencies, *Journal of Geophysical Research (Space Physics)*, *107*, 9-1.
Close, S., T. Hamlin, M. Oppenheim, L. Cox, and P. Colestock (2008), Dependence of radar signal strength on frequency and aspect angle of nonspecular meteor trails, J. Geophys. Res., 113, A06203, doi:10.1029/2007JA012647.
Committee on Space Research (COSPAR). The COSPAR International Reference Atmosphere (CIRA-86), [Internet]. British Atmospheric Data Centre, 2006-, *Date of citation*. Available from http://badc.nerc.ac.uk/data/cira/.
Chau, J. L., Galindo, F., First definitive observations of meteor shower particles using a high-power large-aperture radar, Icarus, Volume 194, Issue 1, p. 23-29, 2008
Dimant, Y. S., and M. M. Oppenheim (2006), Meteor trail diffusion and fields: 2. Analytical theory, *J. Geophys. Res.*, 111, A12313, doi:10.1029/2006JA011798, 2008a
Dimant, Y. S., and M. M. Oppenheim (2006), Meteor trail diffusion and fields: 1. Simulations, *J. Geophys. Res.*, 111, A12312, doi:10.1029/2006JA011797., 2008b
Dyrud, L. P., M. M. Oppenheim, and A. F. vom Endt (2001), The Anomalous Diffusion of Meteor Trails, *Geophys. Res. Lett.*, 28(14), 2775–2778.
Dyrud, L. P., Meers M. Oppenheim, Sigrid Close and Stephen Hunt, Interpretation of Non-Specular Radar Meteor Trails, Geophys. Res. Lett., 2002GL015953, 2002
Dyrud, L., et al. (2005), The meteor flux: it depends how you look, *Earth, Moon \& Planets*, *95*, 89-100, 2005a
Dyrud, L. P., E. Kudeki, and M. M. Oppenheim, Modeling long duration meteor trails, J. Geophys. Res., doi:10.1029/2007JA012692, Vol. 112, No. A12, A12307, 2005b
Dyrud, L. P., E. Kudeki, and M. M. Oppenheim, Modeling long duration meteor trails, J. Geophys. Res., doi:10.1029/2007JA012692, Vol. 112, No. A12, A12307, 2007
Dyrud, L. P., and D. Janches, Modeling the meteor head echo using Arecibo radar observations, *J. of Atmos. And Solar-Terr. Phys.*, 70, 2008a, 1621-1632
Fentzke, J. T., and D. Janches (2008), A semi-empirical model of the contribution from sporadic meteoroid sources on the meteor input function in the MLT observed at Arecibo, *J. Geophys. Res.*, 113, A03304, doi:10.1029/2007JA012531.
Fukuda A., K. Mukumoto, Y.Yoshihiro, M. Nagasawa, Y. Yamagishi-, N. Sato-, H. Yang., M. W. Yao, and L. J. Jin, Adv. Polar Upper Atmos. Res., 17, 120-136, 2003
Galligan, D. P., G. E. Thomas, W. J. Baggaley, On the relationship between meteor height and ambipolar diffusion, Journal of Atmospheric and Solar-Terrestrial Physics Volume 66, Issue 11, , July 2004, Pages 899-906.
Hedin, A.E., Fleming, E.L., Manson, A.H., Schmidlin, F.J., Avery, S.K., Clark, R.R., Franke, S.J., Fraser, G.J., Tsuda, T., Vial, F., Vincent, R.A. Empirical wind model for the middle and lower atmosphere. J. Atmos. Terr. Phys., 58, 1421–1447, 1996
J. Hinrichs, Dyrud, L. P., and, J. Urbina, Annales Geophysicae, Diurnal Variation of Non-Specular Meteor Trails, 2008.
Hocking, W. K. (1999), Temperatures Using Radar-Meteor Decay Times., *Geophys. Res. Lett.*, 26(21), 3297–3300.
Hocking, W. K. Experimental Radar Studies Of Anisotropic Diffusion Of High Altitude Meteor Trails., Earth, Moon, and Planets (2004) 95: 671–679
Janches, D., et al. (2000), Micrometeor Observations Using the Arecibo 430 MHz Radar, *Icarus*, *145*, 53--63.
Janches, D., C. J. Heinselman, J. L. Chau, A. Chandran, and R. Woodman (2006), Modeling the global micrometeor input function in the upper atmosphere observed by high power and large aperture radars, *J. Geophys. Res.*, 111, A07317, doi:10.1029/2006JA011628.
Malhotra, A., J. D. Mathews, and J. Urbina (2007), Multi-static, common volume radar observations of meteors at Jicamarca, *Geophys. Res. Lett.*, 34, L24103, doi:10.1029/2007GL032104.
Mathews, J. D., et al. (2001), The micrometeoroid mass flux into the upper atmosphere: Arecibo results and a comparison with prior estimates, *Geophysical Research Letters*, *28*, 1929.
Oppenheim, M. M., A. F. vom Endt, and L. P. Dyrud (2000), Electrodynamics of Meteor Trail Evolution in the Equatorial E-Region Ionosphere, *Geophys. Res. Lett.*, 27(19), 3173–3176.
Oppenheim, M. M., G. Sugar, E. Bass, Y. S. Dimant, and J. Chau (2008), Day to night variation in meteor trail measurements: Evidence for a new theory of plasma trail evolution, *Geophys. Res. Lett.*, 35, L03102, doi:10.1029/2007GL032347.
Oppenheim, M. M., L. P. Dyrud, and L. Ray (2003a), Plasma instabilities in meteor trails: Linear theory, *J. Geophys. Res.*, 108(A2), 1063, doi:10.1029/2002JA009548.
Oppenheim, M. M., L. P. Dyrud, and A. F. vom Endt (2003b), Plasma instabilities in meteor trails: 2-D simulation studies, *J. Geophys. Res.*, 108(A2), 1064, doi:10.1029/2002JA009549.

Singer, W. R. Latteck, L. F. Millan, N. J. Mitchell, J. Fiedler, Radar Backscatter from Underdense Meteors and Diffusion Rates,Earth Moon Planet (2008) 102:403–409, DOI 10.1007/s11038-007-9220-0

Urbina, J., E. Kudeki, S. J. Franke, S. Gonzales, Q. Zhou, and S. C. Collins, Geophys. Res. Lett., 27, 2853-2856, 2000.

Zhou, Q. H., et al. (2001), Implications of Meteor Observations by the MU Radar, *Geophysical Research Letters*, *28*(7), 1399.