Dear Editor and Reviewers,

We thank you for your time in reviewing the manuscript. Responses to the comments are provided in the following pages. We refer to the line numbers corresponding to the track changes document.

Some of the main changes/additions include:

An appendix has been added to show that the distributions of meteoroid detections between the years for the same time period have similar zenith angles and velocities, which will correspond to those meteoroids being from the same source region. Meteoroids from the same source region are expected to have similar characteristics, such as size and mass.

We have also added an appendix investigating the bin size of the data for the analysis. After consideration, the bin size has been modified to be 6 days, with a 2 km altitude resolution. This does smooth some short time scale density variations, but also provides a robust statistical sampling of the incoming meteoroid population, further strengthening the argument that the overall meteoroid population characteristics should be similar in the analysis for the same time period between years.

The text and figures have been modified to correspond to the 6-day, 2 km bin size.

Further, we agree with the reviewers that 40% density variations are relatively rare in the data set, and have changed the text to correspond to this fact. The majority of the density variations determined with this method are within -20% to +20%.

Best regards,
The Authors

Editor

Dear Dr. Huyghebaert,

first of all, I apologize for the delay in getting back to you. The reviews of your initial manuscript were quite controversial such that I decided to ask for an additional reviewer to look at the manuscript. While this additional reviewer (referee #3) has generally rated your manuscript very well, it does not really speak to the critical arguments by referee #2. In addition, the second review of referee #2 remains extremely critical and I had to make up my mind to decide how to proceed.

I have now spent some time on your manuscript myself and think that there are indeed some critical points in the review of referee #2 that are not yet compellingly addressed.

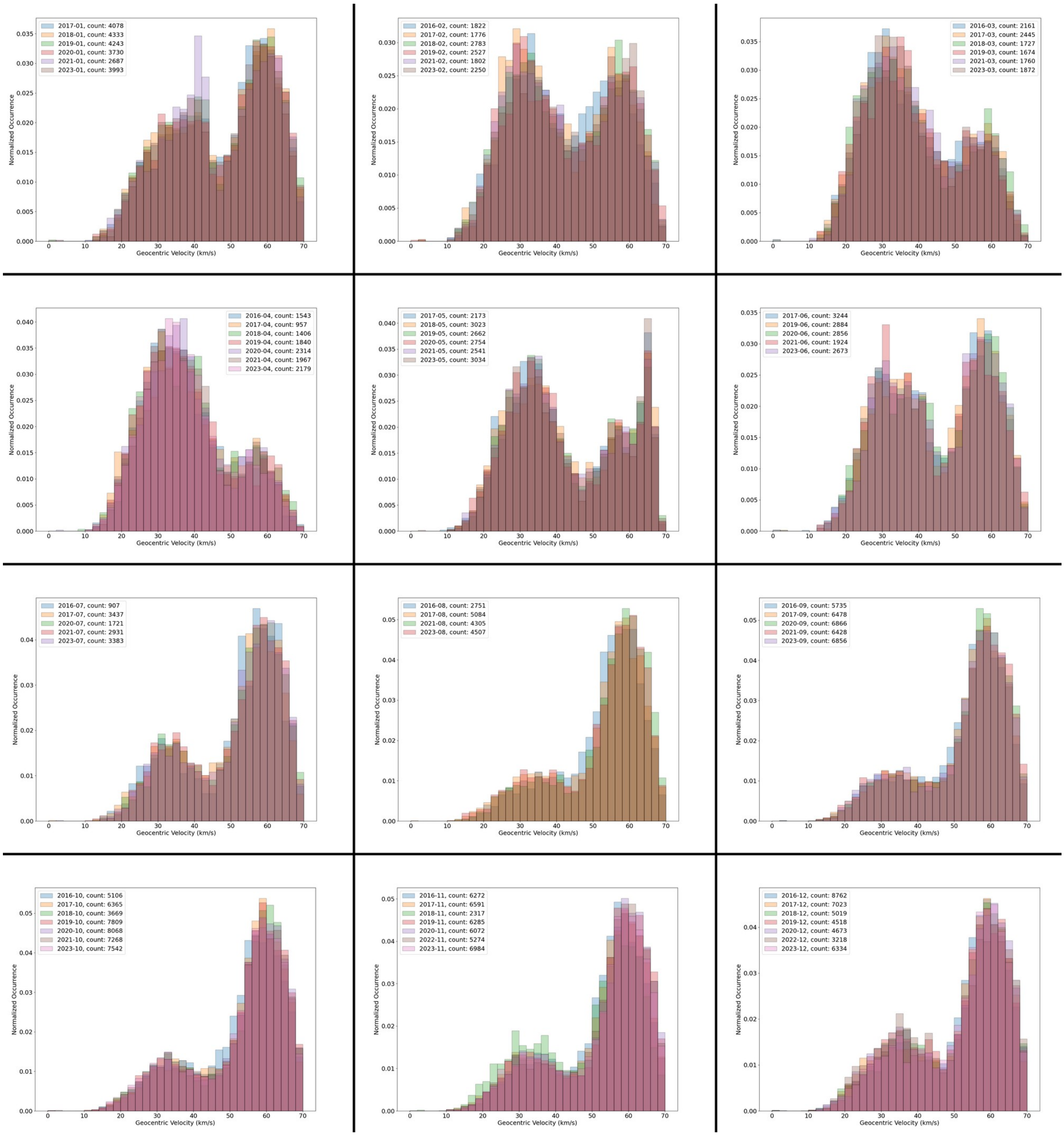
Let me start with saying that we do not need to discuss whether the manuscripts fits the scope of AMT - it clearly does. So this is not the point.

However, I nevertheless think that referee #2 makes a valid argument in pointing out that you need to demonstrate that the density ~ v^3-relation more rigorously. You argue that since you only compare density variations for the same day of year that other contributions to the scattering cross section can be neglected. This is a hypothesis that might be true, but I think more quantitative arguments need to be provided to make this a compelling starting point for your density analysis. Can this be achieved for example with a sensitivity analysis of the scattering cross section versus the involved parameters?

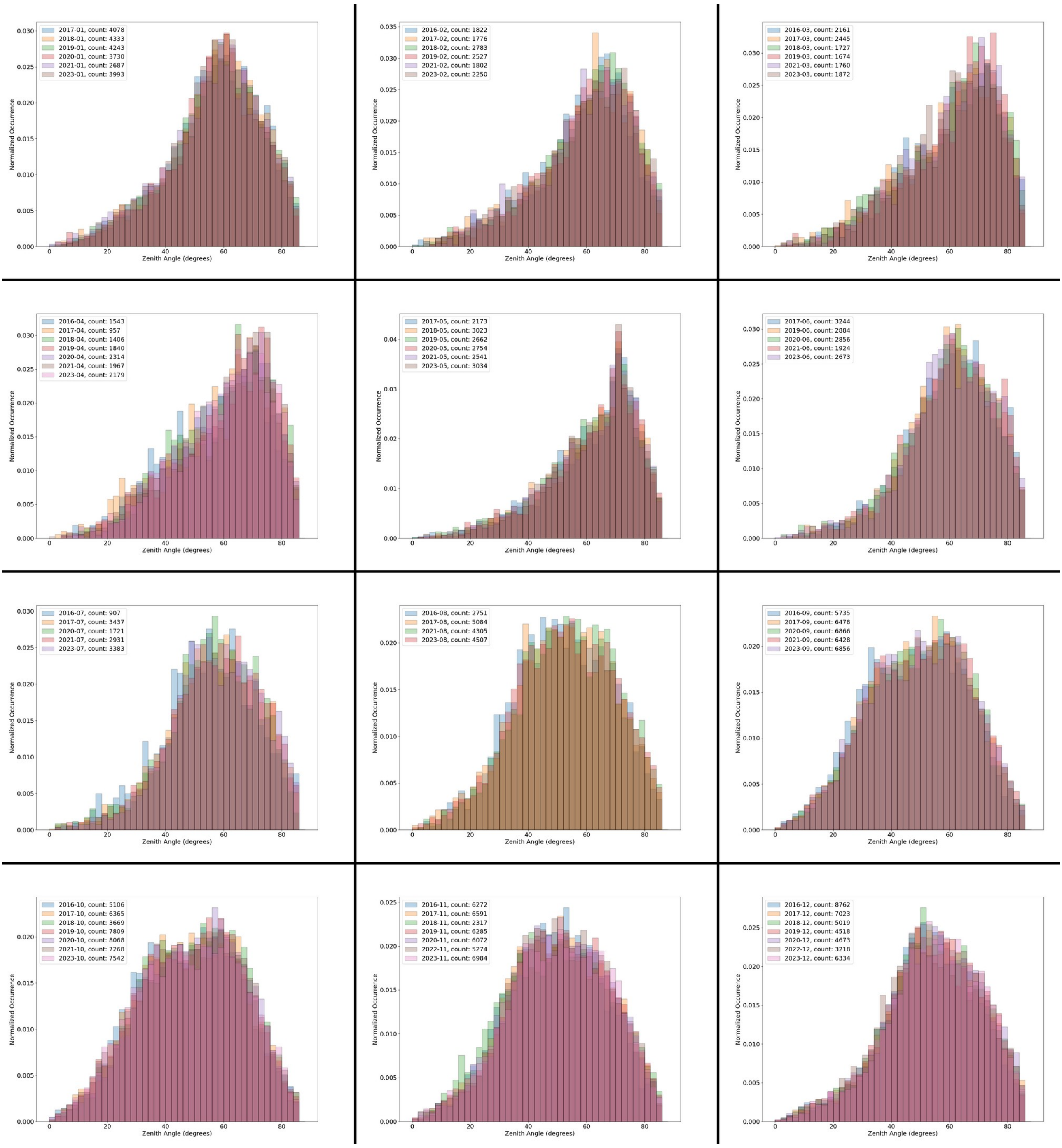
Response:

The geocentric velocity and zenith angle data for the first 6 days of each month are given in the below histogram figures and added to an appendix for the manuscript. Previous studies have already shown that the sources of meteoroids have similar characteristics regarding, e.g., mass indices (Blauuw et al., 2011) for the same solar longitude. Based on the previous research and the zenith and geocentric velocity distributions, it is reasonable to assume that the bulk meteoroid population measured during the same DOY between years will have similar characteristics. It has to be again emphasized that we are not considering single meteoroids, but rather the bulk population for the same time interval between years when determining the neutral density variations. Further emphasis with this argument in mind has been provided in the manuscript on lines 126-132.

Blaauw, R. C., Campbell-Brown, M. D., and Weryk, R. J.: Mass distribution indices of sporadic meteors using radar data, Monthly Notices of the Royal Astronomical Society, 412, 2033–2039, https://doi.org/10.1111/j.1365-2966.2010.18038.x, 2011



The geocentric velocity distributions can be seen to be consistent from year to year.



The zenith angle distributions can also be seen to be consistent from year to year.

Based on the fact that the zenith angle and velocity distributions are relatively consistent from year to year for the same 6-day period, we can consider that the source regions should also be similar. Meteoroids from the same source region should have similar characteristics, which has been investigated by previous studies.

As for the validation of the inferred density variations by comparison with UA-ICON simulations, I must say that at the moment I do not find the comparison compelling beyond the statement that variations of similar size are seen in both data sets. Can't this be done more quantitatively? If yes, this would greatly enhance the quality of the paper. Also, I am wondering if there aren't even more straight forward ways for validating the density estimates. If I am not mistaken there are colocated specular meteor radars at the same site. Wouldn't it be possible to derive density variations from these more established measurements and use them for comparison - at least in the very limited altitude range of overlap? Again, if some agreement would be found here, this would make the study much more compelling.

Response: The difficulty with validation is that there are very few measurements of the atmospheric density at these altitudes with km-scale altitude resolutions, which is why this work is important. We have used the high resolution UA-ICON model to show that the variation magnitudes are within expected values, and the structure of the variations is similar to the model. While there are specular meteor radars nearby, we wish to emphasize, as reviewer #2 is keen to highlight, these specular meteor radars use different analysis for the determination of a bulk iso-density contour – this specular meteor density contour is an integrated change in the density over the full altitude range of meteor trail detections. Those measurements also rely on meteor consistency assumptions, similar to the present study with meteor head echoes. We also wish to highlight that we are obtaining height resolved neutral density variations, a significant improvement over the previous data from meteor trail iso-density contour variations.

To go into more detail about the meteor trail radar neutral density measurements:

a) There is no single method to determine neutral density variability, e.g.,
- Stober et al. (2012) uses the mean peak flux altitude to determine a representative neutral density variability around the peak altitude, which varies as a function of time and meteor population (e.g., showers). The given relation between altitude variation and neutral air density is only valid for the meteor properties shown in their Figure 3, i.e., meteor velocity of 23-25 km/s, entrance angle of 45 degrees, and minimum mass of 5x1e-7 kg.

- Younger et al. (2015) determines the height of a constant density surface at altitudes of 78-85 km from the change of slope of the diffusion vs altitude at the lower altitudes. Their estimates present variability of altitude for a constant density. Indirectly, their Figure 2 supports our observed density variability on short-time scales.

- Yi et al. (2018), they estimated the daily mean density at 90 km using the ambipolar diffusion coefficients from the meteor radar and temperatures from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument. They also found a strong correlation between the meteor radar density and the velocity-corrected peak height indicates that the meteor radar density estimates accurately reflect changes in neutral atmospheric density and that meteor peak detection heights, when adjusted for meteoroid velocity, can serve as a convenient tool for measuring density variations around the mesopause.

b) The estimation procedures are not trivial and don't provide neutral densities as a function of altitude.

c) In future efforts, one can combine our procedure with SMR estimates to complement each other.

References

- Stober et al., 2012, "Neutral air density variations during strong planetary wave activity in the mesopause region derived from meteor radar observations", JASTP.
- Yi et al., 2018, "Estimation of Mesospheric Densities at Low Latitudes Using the Kunming Meteor Radar Together With SABER Temperatures", JGR Space Physics.
- Younger et al., 2015, "A method for estimating the height of a mesospheric density level using meteor radar", GRL.

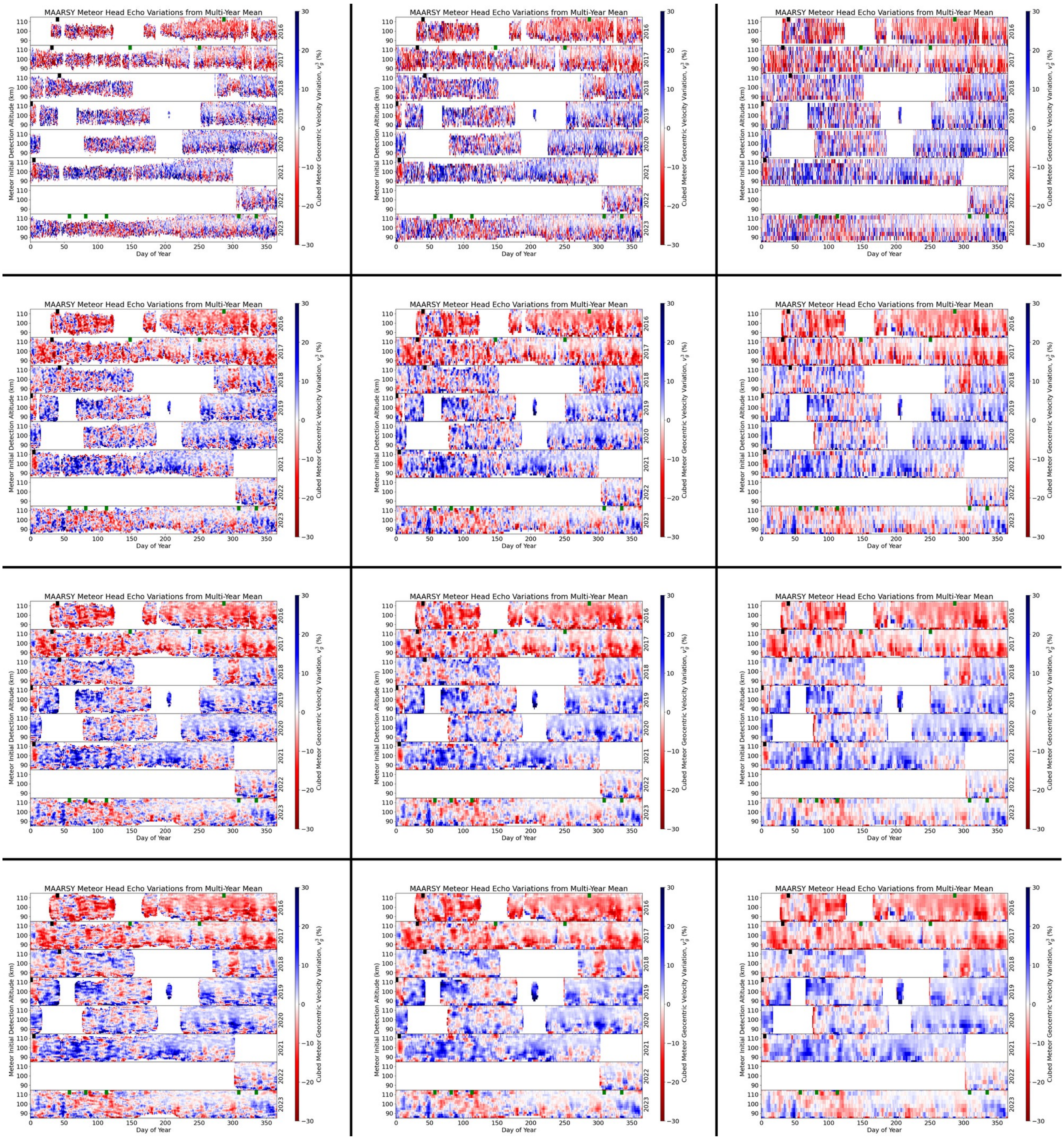
In conclusion, this study needs a major revision for being publishable - including of course, a point by point response to the refree comments as well as the comments indicated ini this letter above.

Sincerely,
Markus Rapp
Assoc. Editor

Reviewer #3

This is a well-written paper with a novel topic that seeks to extract neutral densities from meteor measurements. The authors are missing some citations, including references to more rigorous modeling that better maps the RCS to size (and mass). Also, the authors need to address how sensitive the results are to bin size and smoothing window when talking about the statistical robustness.

Response: We thank the reviewer for the positive review. The relevant literature and information has been added to the manuscript, and can be viewed in the track changes document. Regarding the bin size and smoothing window, an appendix has been added to the manuscript with the following figure and some discussion. Ultimately, we have decided to increase the averaging window to 6 days so that a large statistical sampling of the incoming meteoroid population is obtained for each variation comparison period between the years.



From the top to bottom rows, the averaging period in time is 2, 4, 6, and 8 days. From the left to right panels, the averaging bin size in altitude is 1, 2, and 4 km. Based on this data, it has been decided to use a 6-day time and 2 km altitude window for the density analysis.

Line 25-30:
Another type of reflection that needs to be included is the range-spread trail echo or non-specular trail. This one does not require perpendicular condition with the trail, but instead relies on the perpendicular condition with the background magnetic field. Please include this and cite:
Dyrud et al., “Plasma and Electromagnetic Wave Simulations of Meteors” (2008)
Dyrud et al., “Modeling high-power large aperture radar meteor trails” (2005)
Close et al., “Dependence of radar signal strength on frequency and aspect angle of nonspecular meteor trails (2008)

Response: Thank you for pointing this out. The manuscript text has been modified to include mention of this type of meteor echo on lines 34-36.

Line 30-35:
The HPLA head echo measurements are quite accurate, though agreed that it is diVicult to extract neutral densities without assumptions. Please make sure to add a more thorough description of head echoes and cite:
Close et al., "Determining meteoroid bulk densities using a plasma scattering model with high-power larger-aperture radar data" (2012)
Tarano et al, "Inference of meteoroid characteristics using a genetic algorithm" (2019)

Response: The first reference and corresponding discussion have been added to lines 40-43.

Line 50: What is the polarization? (please see Close et al., "Polarization and scattering of a long-duration meteor trail" (2011)

Response: MAARSY transmits a left circularly polarized signal, and receives a right circularly polarized signal. This information has been added to the manuscript on lines 61-62.

Figure 1: Was the range cutoV at 130 km? (70-130 km?)

Response: The range was cutoff at 130 km, correct. This information has been added to the text.

Line 95: I'm assuming you mean at each radar facility. Altitude will depend upon the polarization and frequency of the radar, as well as (slightly) the angle of the head echo with respect to the background magnetic field. Please clarify.

Response: Correct, we are stating that the meteor input function is expected to be relatively consistent from year to year for the same DOY and the same radar site. This clarification has been added to the text on lines 114-115.

Line 113 - 115: The RCS depends upon the incident frequency and the altitude as well as the velocity. There are models that are more rigorous to correlate RCS with size. Please read and cite:
Marshall et al., "Plasma distributions in meteor head echoes and implications for radar cross section interpretation",
Close et al., "A technique for calculating meteor plasma density and meteoroid mass from radar head echo scattering" 2004

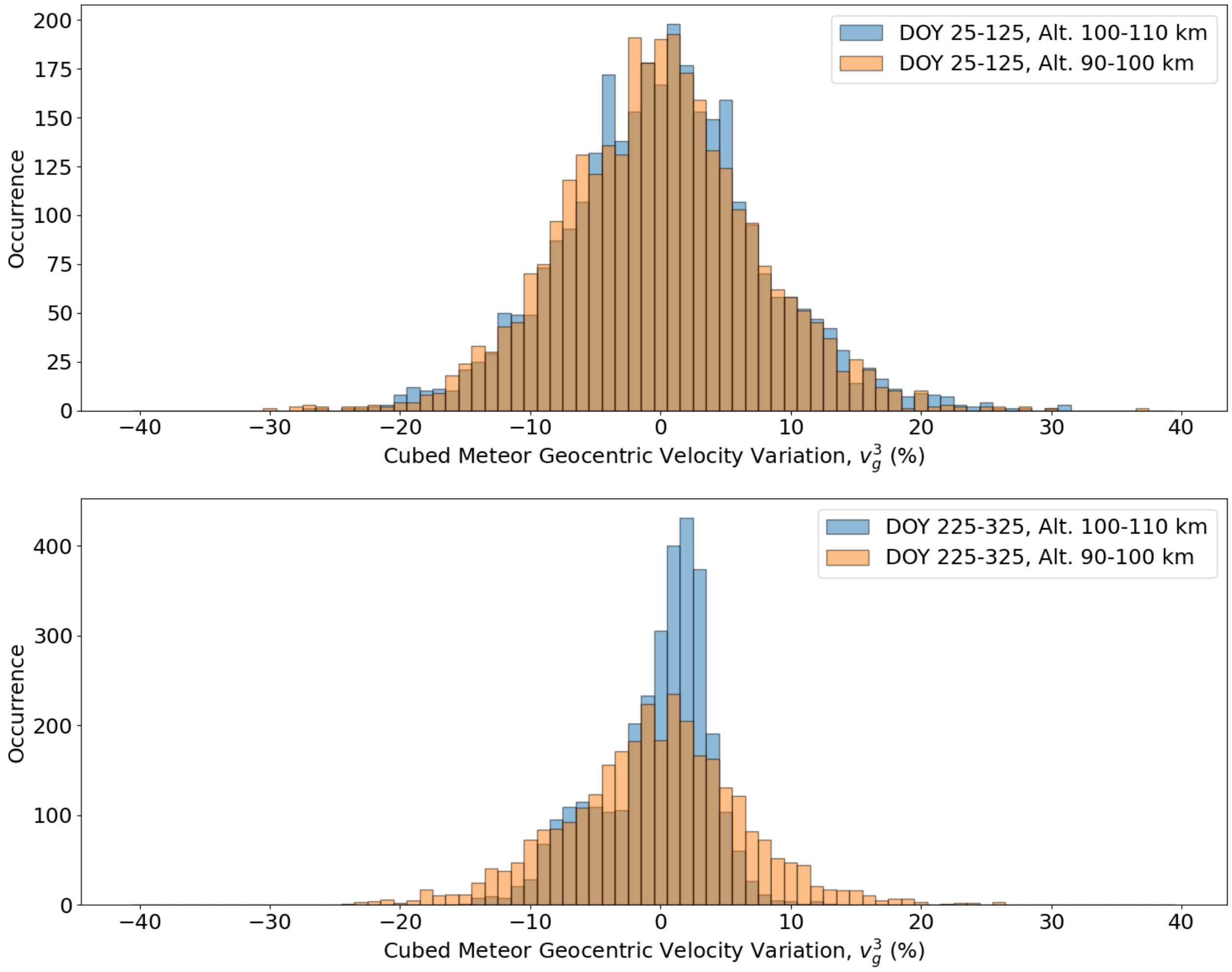
Response: We have added a further description of the RCS and the citations provided on lines 144-147.

Line 120: Ablation depends on composition, emissivity and thermal state (may not average out year-to-year) and detection depends on plasma production and radar sensitivity (not just mass loss). Please add a few sentences clarifying this.

Response: We have added a few sentences with the important information on the ablation dependencies on lines 95-102.

Line 145: 40% density changes in this region are a bit high – add a quantitative comparison and clarify that this is due to the upper-tail events (not typical)

Response: We agree that 40% changes are high, and actually quite rare in our data set. The discussion surrounding the percentage changes has been changed to state that density variations up to 20% are relatively common, with some rare cases exceeding these variation values. This can be further observed in Figure 5 (also shown here).



Reviewer #2...

Reviewer Follow-Up Comments

While I appreciate the authors' additional clarifications, the fundamental concerns raised in the original review remain unresolved. The manuscript continues to rely on assumptions that are not physically justified for the MAARSY head-echo dataset and presents results that are inconsistent with established models and climatologies. The following points elaborate on these issues.

1. Applicability of the trajectory model

The manuscript references the energy equation from Vondrak et al. (2008) and uses CABMOD as its physical foundation. To clarify, when the entry angle is measured with respect to the zenith, CABMOD is applicable to trajectories between 0° and ~85°, with 90° corresponding to a horizontal path. Thus, the concern is not that CABMOD disallows shallow entries per se, but that the simplified form of Eq. (1) used here does not capture the relevant physics of low-elevation, long-path meteoroid entries, which constitute a significant portion of MAARSY head-echo detections (Schult et al., 2017).

At such shallow geometries, several effects become first order and must be treated explicitly:

Extended atmospheric path length: Energy deposition depends on the evolving thermospheric temperature and density along the trajectory, not on velocity alone.

Gravitational curvature and deceleration: The long flight path alters both ablation timing and altitude of maximum ionization.

Variable heating history: Shallow entries experience significant pre-heating before main ablation, shifting RCS peaks independently of neutral density.

Differential ablation and fragmentation: Extended residence times amplify selective element release (especially alkalis) and fragmentation, changing radar cross-section and mass-loss functions.

Without validating Eq. (1) for these geometries, applying it directly introduces systematic bias in derived ablation heights and neutral-density retrievals. The analysis should therefore (i) demonstrate validity through simulations, (ii) restrict analysis to an angular regime where assumptions hold, or (iii) incorporate a trajectory-dependent treatment that accounts for long-path and heating effects.

Response: A histogram of the zenith angle of arrivals for the first 6 days of each month is now provided in Appendix A. We only use zenith angles between 0 and 86 degrees, thereby fulfilling the '(ii) restrict analysis to an angular regime where assumptions hold' request. The fact that we only use these zenith angles has now been provided in the text.

2. Flight physics and differential ablation

Differential ablation governs the radar cross section (RCS) and detection altitude but is largely absent from the manuscript's discussion. For shallow entries, the extended atmospheric path leads to unique heating–cooling cycles. The low heat capacity of most meteoroids allows ambient thermospheric temperatures to preheat the surface, altering the onset of ablation. The release of alkali metals (Na, K) at higher altitudes can generate strong echoes with minimal mass loss, collapsing the core assumption that detection altitude traces neutral density.

Moreover, the organic compounds present in meteors act as a glue-like matrix which binds the various mineral phases together (Flynn et al., https://doi.org/10.1016/j.gca.2003.09.001). Although the organic phases may undergo some degree of thermal degradation or pyrolysis during atmospheric – particularly for particle diameters below 200 microns (Bones et al., https://doi.org/10.1029/2021EA001884) – larger bodies may experience fragmentation (Subasinghe et al., https://doi.org/10.1016/j.pss.2016.12.009), generating multiple fragments whose combined plasma cross section differs substantially from a single solid body. The manuscript neither discusses nor quantifies how these processes impact the results, leaving a major gap in the physical interpretation.

Response: We have added some text on differential ablation. The differential ablation effect corresponds to the material of the meteoroid and goes into our assumption that similar compositions of meteoroids are occurring at the same time of year between years.

3. Physical consistency and claimed accuracy

The manuscript claims to infer neutral density variations with accuracies of several percent, despite presenting variability amplitudes of 20–40 %. Given that meteoroid mass, density, and atmospheric density contribute comparably to the kinetic energy budget, such precision is unrealistic without modeling each parameter.

Additionally, the number of head echo detections per solar longitude is limited, and a large fraction correspond to retrograde orbits (OCC or HTC), while specular radar detections—typically used for such studies—are dominated by JFC meteors. These populations differ in speed, angle, and composition, all of which influence detection altitude.

Since the relevant processes follow power-law and exponential dependencies (e.g., velocity^3, density^4), reliable uncertainty quantification requires simulations using multiple ablation and scattering models (e.g., 10.1029/2021JA029525). Even advanced models yield substantial uncertainty in mass estimates (10.1029/2023JA032281). Without such modeling, the precision claimed here is not supported.

Response: Again, we must emphasize that we analyse thousands of meteor head echoes per same time integration period between years to obtain similar compositions, speeds, and angles from a statistical perspective. This is further highlighted in the figures comparing the zenith angle and geocentric velocity distributions of the meteor head echo populations between yearly time periods in Appendix A. Previous studies have already shown that the meteoroids for a similar solar longitude have similar characteristics regarding, e.g., mass indices (e.g., Blaauw et al., 2011). We must also mention that 40% variation cases are rare in the dataset, and the bulk density variations fall between -20% to 20%, in line with previous models and predictions. The text has been modified to further highlight this fact.

Blaauw, R. C., Campbell-Brown, M. D., and Weryk, R. J.: Mass distribution indices of sporadic meteors using radar data, Monthly Notices of the Royal Astronomical Society, 412, 2033–2039, https://doi.org/10.1111/j.1365-2966.2010.18038.x, 2011

4. Data provenance and acknowledgement

The dataset used is part of the Meteor Shower Catalogue by Peter Jenniskens (Meteor Showers and Their Parent Comets). This provenance should be explicitly stated when introducing the observations. The authors should also acknowledge funding by the Deutsche Forschungsgemeinschaft (DFG) under grant STO 1053/1-1 (AHEAD), as noted in the same source.

Response: The data for this manuscript has been analyzed independently of the Meteor Shower Catalogue. We have analyzed the data from data retention algorithms that were developed before and without the DFG funding source mentioned.

5. Neutral density variability and consistency with prior work

The revised manuscript presents neutral air density variations that diverge sharply from prior studies. Vida et al. (Icarus, https://doi.org/10.1016/j.icarus.2020.114051) derived neutral density variability using NAVGEM-HA, validated against temperature and wind observations. The variability amplitudes and spatial patterns in the current manuscript are neither comparable nor physically consistent with those results or any established climatology of the mesosphere and lower thermosphere.

Response: The DOI provided appears to be incorrect (https://doi.org/10.1016/j.icarus.2020.114051). Perhaps the reviewer meant to reference this DOI: https://doi.org/10.1016/j.icarus.2020.114097 ? In this publication by Vida et al., Figure 13 actually shows very similar amplitudes of 20-30% for the short-term density variability. The citation has been added to the manuscript with some discussion on lines 185-186.

This inconsistency indicates a fundamental flaw in the analysis, as the underlying assumptions appear invalid for this type of retrieval. The authors neither acknowledge nor reconcile these discrepancies. Given the extensive validation of NAVGEM-HA, any alternative climatology would require compelling physical evidence and quantitative justification.

Response: As stated above, the results from NAVGEM-HA actually agree quite well with our results here. To quote Vida et al., when referring to Figure 13, "From the plots, it is apparent that the mass density at meteor heights can vary by up to ±25% on short time scales."

The citation of Kunze et al. (2024) as showing similar structures in UA-ICON is also inaccurate; that paper does not present seasonal neutral density variations. The authors must clarify which aspects of Kunze et al. are being invoked and provide physical reasoning for the differences.

Response: We use the UA-ICON model to validate the amplitude of density variations between years, and the structure of the density variations. The citation of Kunze et al. (2024) is a reference to the model, where we provide an independent UA-ICON model run for the current analysis.

6. Neutral density retrieval from specular meteor radars versus meteor head echoes

The inference of neutral density variability from meteor head echoes is not physically equivalent to that from specular meteor radars, yet the manuscript conflates the two. Specular radars measure underdense trails, providing direct access to velocity and electron line density, which define the leading-order terms of the ablation energy equation. Radiative heating/cooling, fusion heat, and velocity can thus be constrained, while the heat capacity term can be solved iteratively—yielding statistically valid density retrievals.

Head-echo detections, by contrast, provide only speed and an approximate radar cross section, leaving all other energy-balance terms unknown. The manuscript's claim that velocity^3 dominates neglects higher-order terms—especially the temperature dependence (T^4) and the exponential vaporization term governed by the Clausius–Clapeyron relation.
These are not secondary corrections but primary controls of ablation behaviour.

Therefore, the assertion that neutral density can be retrieved with 20–40 % accuracy is mathematically unsupported. Achieving such precision would imply knowledge of meteoroid mass, shape, and composition to within 10 %, which is unrealistic without detailed modeling. A defensible approach would require coupling head-echo observations to a complete ablation–scattering model for each meteor and propagating uncertainties accordingly.

Response: We refer the reviewer to the response to the editor on using meteor trail measurements as a tracer of neutral densities. Further, while we do not have the mass

information of the meteoroid population, it is expected that for the same DOY, if we have thousands of meteoroid detections and they have similar source regions, the mass, velocity, and angle of arrival distributions will be consistent between years. Again we must emphasize, it is due to the continuous operations of the MAARSY radar and the large number of meteor head echo detections that this present analysis is possible.

Summary

In summary, the revised manuscript remains misaligned with the physical and methodological standards expected for Atmospheric Measurement Techniques. The analysis employs simplified assumptions that are not valid for the geometry and physics of the dataset, lacks comparison with established climatologies, and overstates the precision of its results without adequate modeling or uncertainty analysis. To render the study publishable, substantial revision would be required—either incorporating a rigorous ablation–scattering framework or explicitly limiting the scope of claims to reflect the methodological constraints.

Response: We respectfully disagree with the reviewer. We have further provided evidence that the assumptions and dataset we use are valid for the analysis performed, and also show that the model cited by the reviewer supports our results with short-term density variations of +/- 25% (NAVGEM-HA, Figure 13 in Vida et al., 2021, https://doi.org/10.1016/j.icarus.2020.114097). Further, we show that the zenith angle and meteor geocentric velocity distributions for the same DOY between years are similar, and provide reference to the fact that the source regions of meteoroids have similar compositions (e.g., Blaauw et al., 2011).

Vida, D., Brown, P. G., Campbell-Brown, M., Weryk, R. J., Stober, G., and McCormack, J. P.: High precision meteor observations with the Canadian automated meteor observatory: Data reduction pipeline and application to meteoroid mechanical strength measurements, Icarus, 354, 114 097, https://doi.org/https://doi.org/10.1016/j.icarus.2020.114097, 2021.