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Meteoric smoke and meteor influx from global SOFIE observations

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Main Points:

1) The composition of smoke in the mesosphere is consistent with iron-rich olivine.

2) Global ablated meteoric influx is estimated to be 7.3 ± 2.0 metric tons / day, with a total influx of 25.0 ± 7.0 tons / day.

3) Hemispheric asymmetries in smoke and H_2O are consistent with stronger winter descent in the Northern polar mesosphere relative to the South.

Abstract. Measurements from the Solar Occultation For Ice Experiment (SOFIE) in both hemispheres are used to characterize meteoric smoke in the mesosphere and to estimate the meteoric flux into Earth's atmosphere. New smoke extinction retrievals from sunrise measurements in the Northern Hemisphere (NH) are presented, which complement the previously reported sunset observations in the Southern Hemisphere (SH). The sunrise observations are in good agreement with simulations from the Whole Atmosphere Community Climate Model (WACCM), for both the seasonal and height dependence of smoke in the mesosphere. The SOFIE - WACCM comparisons assumed that smoke in the mesosphere exists purely as Fe-rich olivine. This is justified because olivine is detected optically by SOFIE, meteoric ablation is predicted to inject similar quantities of the most abundant elements (Fe, Mg and Si) into the mesosphere, and olivine is anticipated by theory and laboratory experiments. In addition, the ablated and total meteoric influx determined from SOFIE assuming Fe-rich olivine is in agreement with a recent and independent investigation based on models and observations. SOFIE observations from 2007 - 2021 indicate a global ablated meteoric influx of 7.3 ± 2.0 metric tons per day (t d^{-1}), which corresponds to a total influx (ablated plus surviving material) of 25.0 ± 7.0 t d^{-1}. Finally, the results indicate stronger descent in the NH polar winter mesosphere than in the SH winter. This hemispheric asymmetry at polar latitudes is indicated by smoke and water vapor results from both SOFIE and WACCM.

1. Introduction

A layer of meteoric smoke resides in the mesosphere and stratosphere, as nanometer sized aerosol that results from the ablation of cosmic dust particles during atmospheric entry [*Plane et al.*, 2012; *Hervig et al.*, 2017a]. Smoke in the mesosphere is enhanced during polar winter and reduced in summer, due to transport by the global meridional mesospheric circulation. This behavior was first predicted by a two-dimensional model [*Megner et al.*, 2008] and later observed by the Solar Occultation for Ice Experiment (SOFIE) [*Hervig et al.*, 2009]. The annual variation in smoke occurs despite the annual variation in meteoric influx (MI), which is highest (lowest) near the fall (spring) equinox [*Fentzke et al.*, 2008]. The phase difference between smoke in the middle atmosphere and meteoric influx is due to the dominance of transport in the mesosphere, as discussed by *Bardeen et al.* [2008].

Estimates of the total meteoric influx (TMI, ablated plus surviving material) into Earth's atmosphere range from 1 to 270 metric tons per day (t d^{-1}) [e.g., *Plane*, 2012]. The most recent results, however, appear to be converging on a narrower range (30 - 60 t d^{-1}) than previously. *Gardner et al.* [2014] report a TMI of 60 ± 16 t d^{-1} based on mid-latitude lidar observations of sodium near the mesopause combined with models. *Carrillo-Sánchez et al.* [2016] derived a TMI of 43 ± 14 t d^{-1} by combining a meteoric ablation model with a solar system dust model, constrained by lidar measurements of the vertical fluxes of mesospheric Na and Fe at mid-latitudes and cosmic spherule deposition at the South Pole. Importantly, they also found that only ~18% of the incoming meteoric material is ablated (and thus resident in the middle atmosphere), far lower than previous estimates (>80%) [e.g., *Vondrak et al.*, 2008]. *Hervig et al.* [2017a] used SOFIE satellite observations of meteor smoke in the Southern Hemisphere (SH) mesosphere to derive a TMI of 30 ± 18 t d^{-1}. Most recently, *Carrillo-Sánchez et al.* [2020] report an update to the *Carrillo-Sánchez*

61 *et al.* [2016] analysis (a new chemical ablation model) which suggests TMI = 28 ± 16 t d^{-1}, and a
62 slightly higher ablated fraction (30%) than previously.

63 The present study uses SOFIE observations to examine the time and height dependence of
64 meteoric smoke in the Northern Hemisphere (NH), for the first time. This advance comes from
65 new methods for calibrating the detector response drift during sunrise, which has been more
66 challenging than for the sunset measurements. The new smoke results are compared to models and
67 to SOFIE sunset observations, and subsequently used to determine meteoric influx during 2007 -
68 2021 in both hemispheres.

69 2. SOFIE Observations

70 SOFIE has observed temperature, five gases (O_3, H_2O, CO_2, CH_4, and NO), polar
71 mesospheric clouds (PMC), and meteoric smoke, from the Aeronomy of Ice in the Mesosphere
72 (AIM) satellite during 2007 - present [*Russell et al.*, 2009]. The occultation measurements are used
73 to conduct retrievals at altitudes from roughly 20 to 95 km (up to 150 km for NO), with a vertical
74 resolution of ~1.8 km. The measurement latitudes have evolved over the years, with dedicated
75 polar coverage from 2007 – 2016 and 2019 – present. The years from 2017 - 2019 had equatorial
76 coverage with some interruptions, and a change from sunsets (sunrise) in the SH (NH) to the NH
77 (SH), due to progression of the AIM orbit (Figure 1). The current SOFIE data is version 1.3 which
78 is available online (sofie.gats-inc.com).

79 The primary challenge in interpreting the meteoric smoke signals is accounting for a small
80 drift in detector responsivity, which occurs due to heating of the system during solar view. The
81 response drift is small (< 10 counts) compared to the dynamic range (2^{15} counts), but significant
82 in terms of the response due to meteoric smoke (< 20 counts). For sunset observations the drift is
83 highly linear, and is successfully removed by extrapolating a fit to measurements above the

atmosphere (exo-atmospheric) to lower heights [*Gordley et al.*, 2009]. Results for sunset smoke observations were first described by *Hervig et al.* [2009], who reported smoke extinction ($\beta(\lambda)$) at 1037 nm wavelength (λ). An updated response calibration approach [*Hervig et al.*, 2017a] provided sunset smoke extinctions at the additional wavelengths of 330 and 867 nm, which subsequently allowed the chemical composition of smoke to be identified. Sunset measurements benefit from a long period of solar observation above the atmosphere, which allows the instrument temperature to achieve a state of steady linear change, facilitating straightforward corrections to the signals. The drift in sunrise measurements is more difficult to characterize, however, because the atmosphere is observed before the instrument temperature has a chance to stabilize.

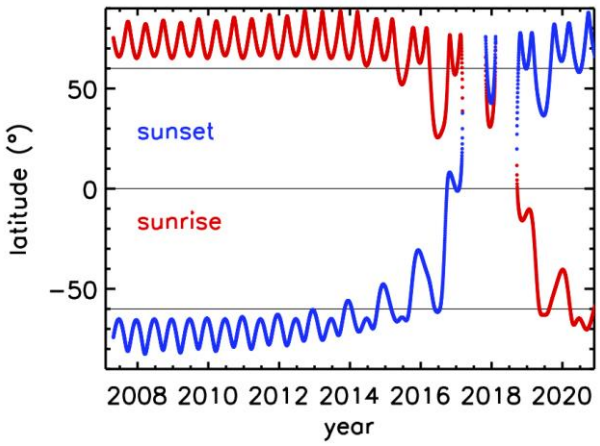

Figure 1. The latitude of SOFIE sunrise and sunset observations, from May 2007 through February 2021.

The drift in sunrise observations above the atmosphere was found to be consistent with a third order polynomial. Attempting such a high-order fit to individual measurements can be problematic, however, as variations due to noise can cause unrealistic values in the subsequent extrapolation to atmospheric altitudes. This issue is eliminated when fitting a polynomial to the average signal versus height based on multiple days (15 observations per day) as discussed in *Hervig et al.* [2017a]. The results here used 10-day averages (150 profiles), as shown in the example in Figure 2, where the response (R) minus the exo-atmospheric response (R_{EXO}) is shown

versus height. This approach was found to reduce the statistical uncertainty in the drift corrections to levels that were below both the statistical noise limit (~0.3 counts, see *Gordley et al.*, 2009) and the atmospheric response. The uncertainty in retrieved smoke extinction is defined as the root-sum-square of the measurement noise, drift correction uncertainty, and errors in removal of interference. Interference is due to O_3 absorption and Rayleigh scattering at 330 and 867 nm, and only Rayleigh at 1037 nm. As a result the 1037 nm observations have the lowest uncertainties, and are thus are used here to determine meteoric influx.

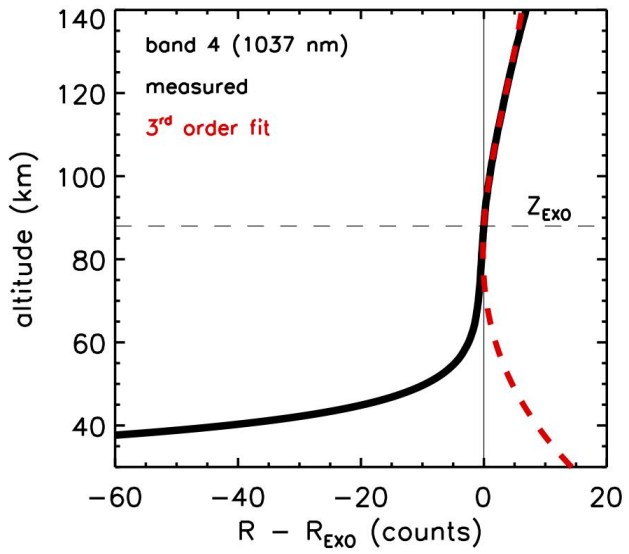

Figure 2. Example of SOFIE sunrise observations, as the response (R) minus that measured (R_{EXO}) at the exo-atmospheric height (Z_{EXO}). The profile is an average over 10 days (150 profiles) during December 1 - 10, 2010 (~70°N latitude). A third order polynomial fit at heights from Z_{EXO} to Z_{EXO} + 30 km is also shown. Note that the corrected response is the difference of the black and red curves.

For this work meteoric smoke extinctions were retrieved using 10-day averages of SOFIE signals, for observations from 2007 - 2021. The signal averages used only measurements that were free of PMCs, which are opaque enough to overwhelm the signal due to smoke. For the new sunrise (NH) observations reported here, this results in a lack of smoke extinctions during June and July when PMCs are ubiquitous at polar latitudes. Similarly, SH smoke extinctions are rarely obtained during December - January.

SOFIE measurements of smoke extinction are converted to volume density (V) using the relationship reported by *Hervig et al.* [2017a], $V = C\,\beta(1037)$, where C is a constant that varies with smoke composition. This linear relationship exists because at the SOFIE wavelengths smoke attenuation is entirely due to absorption, which is proportional to the particle radius cubed. Obtaining estimates of V from SOFIE allows direct comparison with the models, and also provides a means to determine meteoric influx. SOFIE multi-wavelength observations show that the most likely (>60% detection probability) smoke compositions are magnesiowüstite ($Mg_xFe_{1-x}O$, x = 0, 0.1, 0.2, and 0.6) and iron-rich olivine ($Mg_{0.8}Fe_{1.2}SiO_4$) [*Hervig et al.*, 2017a]. Note that values of C span roughly 250 to 1900 ($\mu m^3\ cm^{-3}$ km) for the potential smoke compositions. Furthermore, the different smoke compositions can be identified simultaneously in the SOFIE multiwavelength measurements, due to their spectral similarity combined with SOFIE uncertainties. Of the compounds indicated by SOFIE, only olivine has an elemental makeup that is similar to the relative elemental abundances of ablated meteoric material (see Table 1). Furthermore, laboratory and theoretical studies suggest that iron-rich olivine should result from the recombination of meteoric ablation products in the mesosphere [*Saunders and Plane*, 2011]. Taking these clues, the SOFIE extinctions were analyzed below assuming that smoke consists only of $Mg_{0.8}Fe_{1.2}SiO_4$. The first consequence is that the conversion of extinction to volume density becomes $V/\beta = 1512 \pm 1\ \mu m^3\ cm^{-3}$ km. This is in contrast to the previous interpretation which used the average V/β for the possible compositions ($687 \pm 470\ \mu m^3\ cm^{-3}$ km), and accepted the large standard deviation as an experimental uncertainty [*Hervig et al.*, 2017a]. Note that the resulting SOFIE V (and MI) are increased here by a factor of ~2 compared to previous results that assumed the average optical properties for a range of smoke compositions. The second consequence of assuming $Mg_{0.8}Fe_{1.2}SiO_4$ is that the SOFIE ablated influx has an elemental breakdown consistent with that

predicted by combining chemical ablation and solar system dust models with observations [*Carrillo-Sánchez et al.,* 2020]. This in turn provides a straightforward relationship between the ablated meteoric influx determined from SOFIE (see Section 5) and total meteoric influx (ablated plus surviving material).

Table 1. Relative abundance of the top five meteoric elements, listed for incoming meteoroids, and for the top three smoke compositions identified by SOFIE.

Element	Ablated Influx[1] ($t\ d^{-1}$)	Influx Fraction[1] (% by wt.)	Olivine[2] $Mg_{0.8}Fe_{1.2}SiO_4$ (% by wt.)	Magnesiowüstite[2] $Mg_{0.6}Fe_{0.4}O$ (% by wt.)	Wüstite[2] FeO (% by wt.)
Fe	2.8	34	38	42	78
O	2.7	32	36	30	22
Si	1.2	14	16	-	-
Mg	1.0	12	11	27	-
Na	0.3	3	-	-	-

[1]According to *Carrillo-Sanchez et al.* [2020].
[2]Composition identified using SOFIE multiwavelength smoke observations [*Hervig et al.,* 2017a]. The detection probabilities were 68% for olivine, 75% for magnesiowüstite, and 71% for Wüstite.

3. WACCM Model

This work used a model description of meteoric smoke based on a first principles representation in the Whole Atmosphere Community Climate Model (WACCM), as originally described by *Bardeen et al.* [2008]. The model begins with meteoric ablation products as metal-rich molecular clusters of 0.25 nm radius, and simulates the evolution of smoke particles due to growth by agglomeration, sedimentation, and transport. The model includes annual and latitudinal variations in meteoric influx [*Fentzke et al*., 2008], with the ablated meteoric influx (AMI) specified as the annual global mean. Note that the model only considers the ablated fraction of incoming meteoroids, since the surviving material falls quickly to the surface [*Plane et al.*, 2012]. Later model adaptations used the original smoke component of *Bardeen et al.* [2008] incorporated in the specified dynamics (SD) version of WACCM [*Bardeen et al.*, 2010]. The smoke simulations were later integrated into NCAR Community Earth System Model (CESM) version of WACCM

[*Marsh et al.*, 2013a; 2013b], along with new descriptions of the gas-phase chemistry of meteoric metals and interactions between smoke and trace gases [*Saunders et al.*, 2012; *Plane et al.,* 2015; *Frankland et al.*, 2015; *James et al.*, 2017]. Finally, the model is nudged with the Modern-Era Retrospective Analysis for Research and Applications (MERRA2) [*Molod et al.*, 2015; *Gelaro et al.*, 2017]. This is the version used here, which is maintained at the University of Leeds, and was previously used in comparisons with SOFIE by *Hervig et al.* [2017a]. WACCM results for 2007 - 2020 were used here to determine daily zonal means which were sampled to the SOFIE latitude versus time.

4. Meteoric Smoke

The new SOFIE NH (sunrise) smoke V profiles are compared to SOFIE observations in the SH (sunset) in Figure 3a, where the results are averages for polar latitudes during winter months when smoke is highest. The NH and SH V profiles are generally similar; however, note that SOFIE shows greater smoke volume density in the NH middle mesosphere. Results from WACCM are also shown in Figure 3a. The WACCM results are for 8 t d^{-1}, and were scaled slightly to match SOFIE (factor of 1.2). Note that this is equivalent to adjusting the ablated influx in the model (see Section 5 for detail). SOFIE is systematically greater than WACCM in the lower mesosphere (P > ~0.5hPa). This difference was explored by *Hervig et al.* [2017b], who found that it was consistent with a layer of neutralized sulfate mixed with smoke at altitudes above the nominal sulfate layer during autumn - winter, when temperatures are low. SOFIE indicates a larger hemispheric (NH vs. SH) difference in the middle mesosphere (~0.2 - 0.01 hPa) than is shown by WACCM. These differences are further illustrated in Figure 3b, where the NH / SH V ratios are shown versus height. This rendition shows that SOFIE and WACCM both indicate a similar height dependence in the hemispheric difference, but that SOFIE differences (~65% at 0.1 hPa) are much larger than

177 WACCM (~12% at 0.1 hPa). The seasonal variation in smoke is largely driven by the global
178 mesospheric meridional circulation, where the polar winter maximum is due to transport of smoke
179 from across the globe. The larger hemispheric differences indicated by SOFIE could thus be the
180 result of a stronger circulation in the NH winter (or weaker in SH winter) than is contained in the
181 model. Another possibility is seasonal variability in the global meteoric input function. However,
182 the variation that is currently in WACCM (based on dust sources at 1 AU in the solar system)
183 indicates a symmetric distribution with respect to latitude and season [*Feng et al.*, 2013] because
184 the Earth's orbit has a small eccentricity and inclination to the invariant plane of the solar system.
185 At pressures lower than ~0.01 hPa, SOFIE results are increasingly affected by noise, and the NH
186 - SH differences at these heights are not considered at this time. Examining smoke versus height
187 in terms of volume density is relevant here because V is proportional to the retrieved extinction,
188 which is in turn proportional to the measured signal. It is also useful to look at smoke in terms of
189 mass mixing ratio (MMR) versus height, as is shown in Figure 3c. MMR is relevant because it
190 illustrates that the relative abundance of smoke increases with height, which is a result of its
191 extraterrestrial source. It is also useful when visualizing transport, because MMR is conserved
192 during both horizontal and vertical advection.

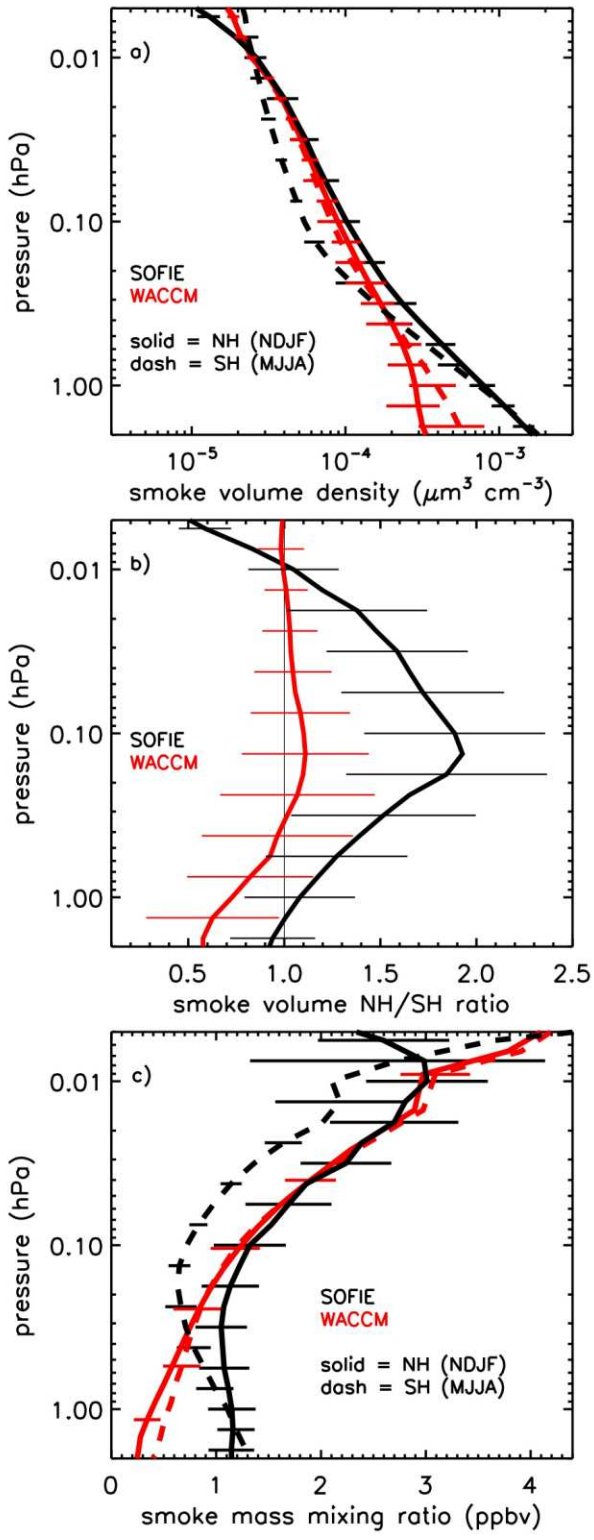

Figure 3. a) Meteor smoke volume density from SOFIE and WACCM, as averages during polar winter in the SH (~70°S, May - August) and NH (~70°N, November – February). The results are for 2007 - 2015 (before the SOFIE orbit change), when SOFIE NH (SH) measurements were from sunrises (sunsets) only (see Figure 1). The WACCM results were sampled to the SOFIE latitude vs. time. b) the ratio of NH / SH volume density from SOFIE and WACCM. c) Smoke mass mixing ratio versus height, from SOFIE and WACCM during polar winter in both hemispheres. The WACCM results are for 8 t d^{-1} influx and were scaled slightly to match SOFIE. Error bars indicate the standard deviations for the included years.

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Time series of the new SOFIE sunrise (NH) smoke volume densities are compared to WACCM in Figure 4a, as the average V for 0.2 - 0.01 hPa (V′). The SOFIE - WACCM agreement is rather good, where both indicate similar annual variability and even a twin peak during winter. The seasonal variation in smoke is shown in greater detail in Figure 4b, where the annual time series are based on averages including 2007 - 2013. Recall that SOFIE smoke observations in summer are generally not useful due to contamination by PMCs. The agreement is very good concerning the timing and depth of the annual smoke variation, with the exception that WACCM shows a later start to the autumn - winter enhancement than SOFIE. This difference is most likely due to different timing of the seasonal transition in WACCM compared to the real atmosphere.

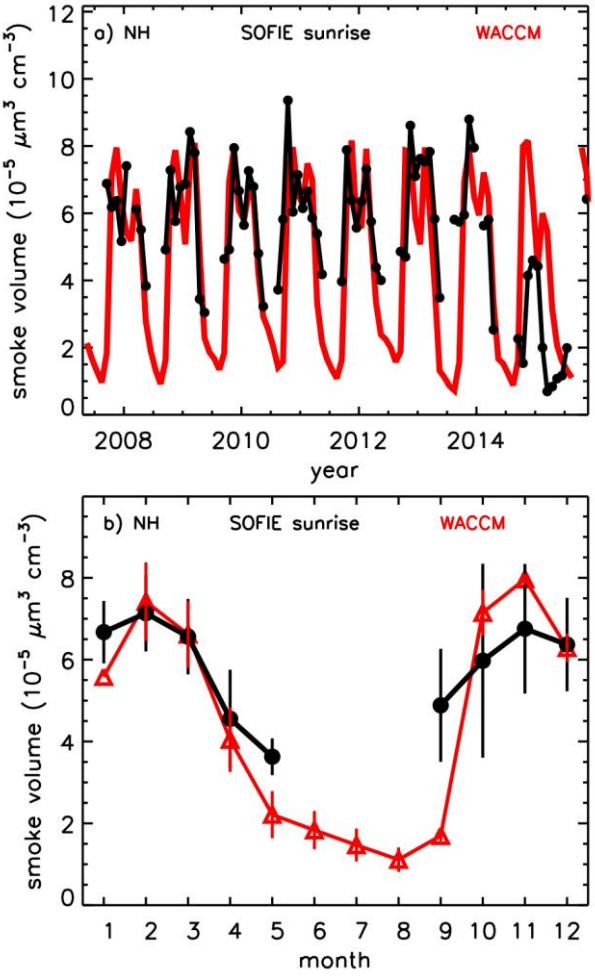

Figure 4. Time series of smoke volume density near 70°N latitude, for the vertical average of V over 0.2 to 0.01 hPa (V′). a) Time series of monthly zonal means from SOFIE and WACCM for 2007 - 2015 (before the SOFIE orbit changed). Error bars were omitted for visual clarity. b) Annual time series as monthly zonal means for 2007 - 2013, from SOFIE and WACCM. Error bars indicate the standard deviations for the included years. The WACCM results are for 8 t d^{-1} influx and were scaled to match SOFIE.

The year-to-year smoke variations were examined further using winter averages. The latitude of SOFIE observations in winter was consistently near ~70° in both hemispheres, with the exception of 2017 - 2018 when lower latitudes were sampled due to the changing AIM orbit (Figure 5a). The comparison of smoke V′ (Figure 5b) highlights the hemispheric asymmetry indicated by SOFIE (NH > SH), that is also present (although weaker) in WACCM (e.g., Figure 3). The SOFIE NH observations show greater interannual variations than the SH measurements, which is consistent with greater variability in NH polar winter dynamics relative to the SH [*Schoeberl and Newman,* 2015]. WACCM also shows greater year-to-year variability in the NH compared to the SH, although variability in SOFIE is typically greater than in the model. Some of the interannual variability is due to the changing SOFIE latitudes after 2017, and this is captured in WACCM because the model was sampled to the SOFIE latitude vs. time. It is noteworthy, however, that SOFIE indicates more smoke in the NH not only during 2007 - 2018 when the NH was observed by sunrise occultations, but also in later years when the NH was observed by sunsets. This suggests that the hemispheric asymmetry is not due to a bias between the sunrise and sunset operational modes in SOFIE, but rather is a real characteristic of smoke in the polar mesosphere.

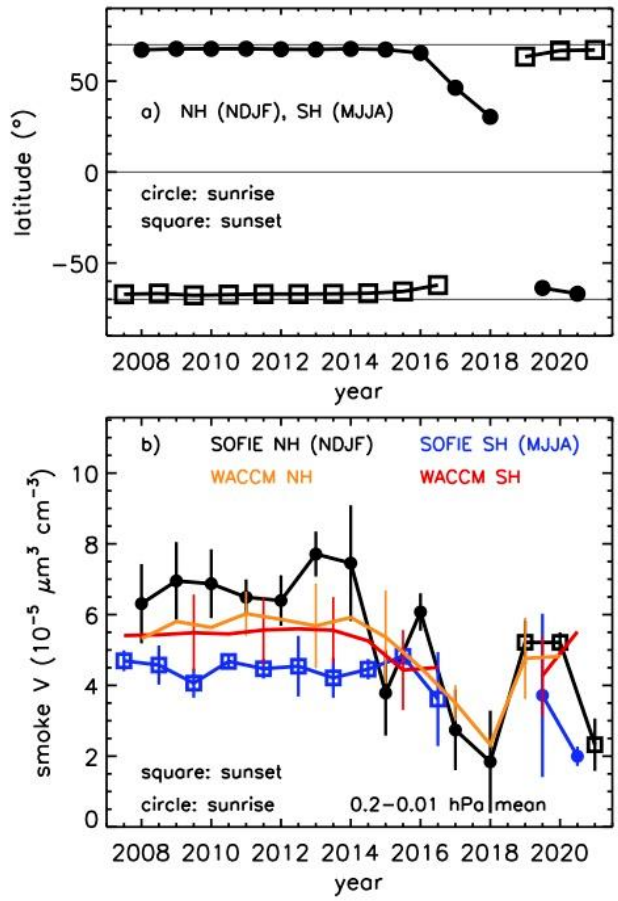

Figure 5. a) Time series of SOFIE measurement latitudes as winter means in the NH (November - February) and SH (May - August). b) The winter mean smoke volume density from SOFIE and WACCM, as the average for 0.2 to 0.01 hPa (V′). The results correspond to the latitudes in Figure 5a. Error bars indicate the standard deviation during the winter months. The WACCM results are for 8 t d^{-1} influx and were scaled slightly to match SOFIE.

The hemispheric difference in smoke was further explored by looking at water vapor in the upper mesosphere. Because H_2O behaves as a transport tracer and has a sharp vertical gradient in the mesosphere, it could indicate hemispheric differences that can confirm those in meteoric smoke. SOFIE and WACCM H_2O were examined as winter means in the upper mesosphere (0.2 - 0.01 hPa average, as for smoke). The results (Figure 6) show that there is less H_2O in the NH polar winter than in the SH polar winter, in both SOFIE and WACCM. *Lossow et al.* [2009] were the first to observe this hemispheric asymmetry in water vapor, and speculated that the underlying cause was differences in dynamics and diffusion. Water vapor decreases with height to very low values near the mesopause, so that descending air in the polar winter mesosphere causes seasonally low H_2O [*Orsolini et al.*, 2010]. The hemispheric difference in winter H_2O is therefore suggestive

of stronger winter descent in the NH than the SH. This difference is qualitatively consistent with the hemispheric differences in smoke volume density (Figure 5b), where more smoke in the NH winter compared to the SH is indicative of stronger transport in the NH. Recall that the polar winter increase in smoke is due to meridional transport, in addition to descent from meteoric ablation heights (e.g., smoke MMR increases with height; Figure 3c). Note that SOFIE and WACCM agree on the hemispheric differences in winter H_2O (SH is ~10% > NH), but that the magnitude of the hemispheric differences in smoke are much larger in SOFIE (20 to 80%) than in WACCM (<10%) (Figure 5b). Nevertheless, it is too simplistic to infer a one-to-one correspondence between different tracer profiles and pure advective transport, as noted by *Ryan et al.* [2018]. Other factors such as chemistry or diffusion need to be considered [*Smith et al.*, 2011], and it is reasonable to assume that these would behave differently for smoke and H_2O. Differences in any one of these factors between WACCM and the observations could explain the differences in the smoke and H_2O hemispheric asymmetries that are detected at polar latitudes.

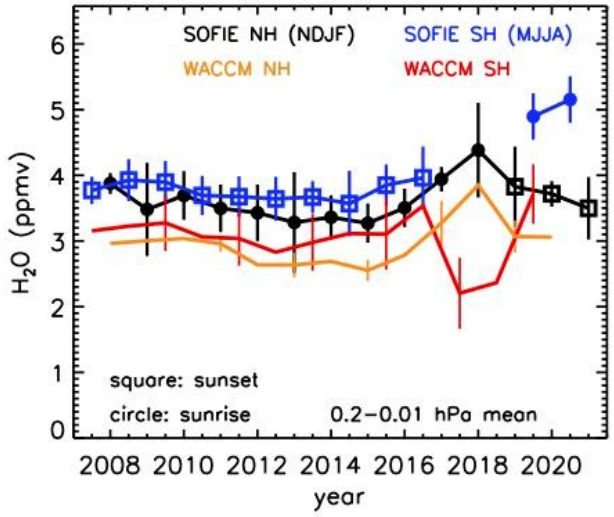

Figure 6. Time series of the winter mean water vapor from SOFIE and WACCM, as the vertical average for 0.2 to 0.01 hPa. The results correspond to the latitudes in Figure 5a. Error bars indicate the standard deviation during each winter.

5. Meteoric Influx

Ablated meteoric influx (AMI) was derived through comparisons of SOFIE smoke volume density with WACCM runs conducted for different AMI values, as discussed in detail by *Hervig et al.* [2017a]. WACCM shows that when AMI is changed, smoke V changes by nearly the same fractional amount at heights throughout the mesosphere. This is illustrated in Figures 7a - 7b, where the modeled V′ (average V for 0.2 - 0.01 hPa) is shown versus month and latitude from WACCM runs with different AMI. The approach determines AMI vs. V′ based on linear regression to the model results, AMI = $A + B$ V′, where A should be zero. WACCM results for AMI = 2, 8, and 11 t d^{-1} were used in the regressions (Figures 7a and 7b), with the additional constraint that the point (V′ = 0, AMI = 0) was included to encourage A to approach zero. Values of A have only small departures from zero (< 3%), which reflect the uncertainties in the approach (not shown). Because the SOFIE latitudes have changed over time (Figure 1), the regression to WACCM results was carried out for monthly zonal means over a complete range in latitude. Values of B at polar latitudes are found to change dramatically with season, with similar values during winter in both hemispheres (Figures 7c - 7d). High values of B in summer occur because smoke is depleted due to transport by the meridional circulation, while the regression was to the same annual global mean AMI values. The results are also found to vary with latitude (Figure 7d), where the variation is again driven by smoke transport.

The uncertainties in derived influx are a combination of the SOFIE observational errors (~9% for monthly means), and the statistical uncertainty in the WACCM representation of V′ vs. AMI (~3% in polar winter). The AMI uncertainties (δAMI) are the root-sum-square of these terms, and the average δAMI for either hemisphere is ~10% during 2007 - 2021. Recall also that the SOFIE V and influx values are based on that assumption that smoke is composed of Fe-rich

olivine. While this assumption is justified in numerous ways, the ramifications of considering other smoke compositions are briefly considered. Previous SOFIE results indicate various smoke compositions, and an alternate approach here would be to consider the mean optical characteristics for the range of compositions, as was done in *Hervig et al.* [2017a] (see also Section 2). Taking that approach would cause a ~45% reduction in smoke V, and the subsequently derived AMI. In addition, the resulting V and AMI uncertainties would increase from ~10% to ~55%, due to the variability in optical properties for the different smoke compositions. Nevertheless, the results here are supportive of smoke existing as Fe-rich olivine, and we proceed under that assumption.

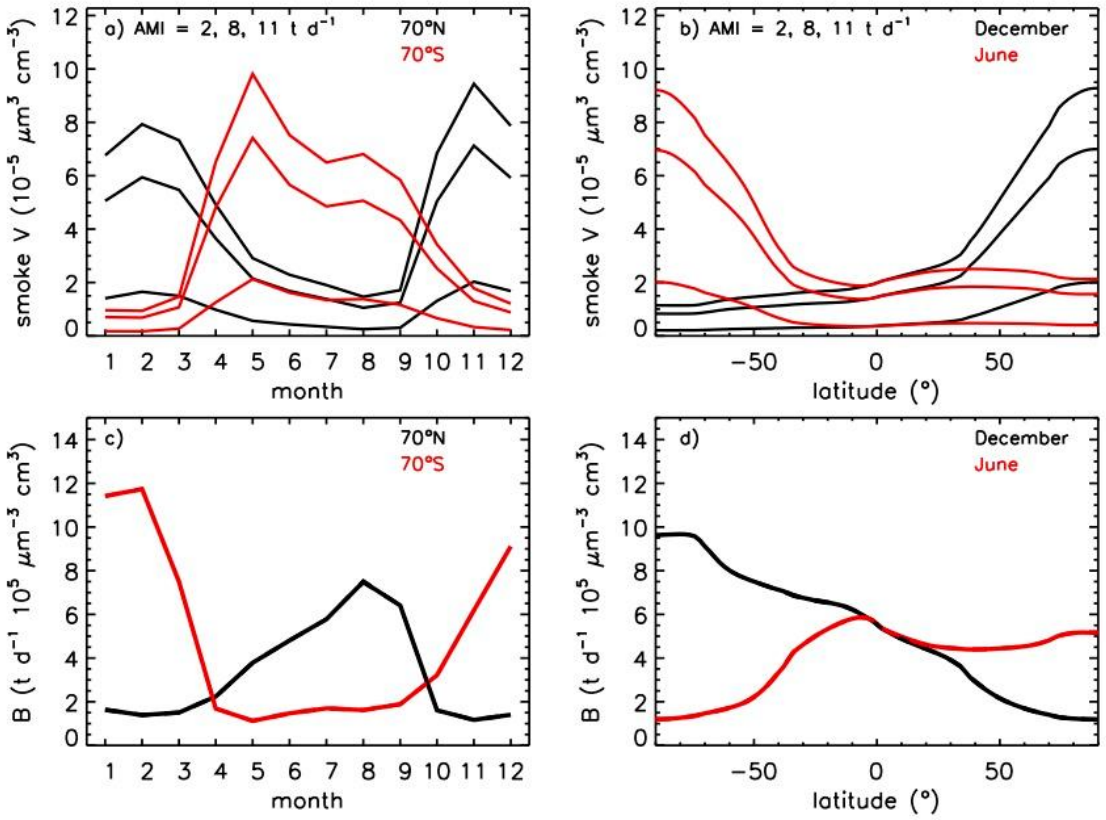

Figure 7. WACCM smoke volume density (V′, the 0.2 - 0.01 hPa average) as monthly zonal means from runs with meteoric influx of 2, 8, and 11 t d^{-1} (V′ increases with AMI). Results are shown a) versus month for 70°S and 70°N latitude, and b) versus latitude for December and

June. The slope (B) for linear regression to WACCM AMI versus V′ is shown c) versus month at 70°S and 70°N, and d) versus latitude for December and June. B was determined from monthly zonal means for 2007 - 2015 (before the SOFIE orbit changed). Uncertainties in B during high latitude winter are ~3%.

Ablated influx is shown versus month in Figure 8 during autumn through spring when meteoric smoke is most abundant (e.g., Figure 4b). The AMI estimates have additional errors during the transitional months when the SOFIE - WACCM agreement is poorer (e.g., September in the NH, see Figure 4b), although this is not captured in the current uncertainty estimates. Recall also that SOFIE smoke observations are typically not obtained in high latitude summer due to signal contamination by PMCs. The results in Figure 8 are for 2007 - 2017 when sunrise (sunset) was in the NH (SH). The average NH AMI is ~30% greater than for the SH, which is statistically significant in terms of the AMI uncertainties (~10%). If SOFIE and WACCM contained the exact same seasonal variation in mesospheric smoke, however, then the AMI derived here should be constant throughout the year (by definition). Thus, the monthly variations in AMI can be interpreted as a byproduct of SOFIE - WACCM differences in the seasonal variation of smoke, as apparent in Figure 4b. The best AMI estimates from the SOFIE - WACCM comparisons will therefore be from multi-month averages, preferably during winter when smoke is elevated and relatively stable in time.

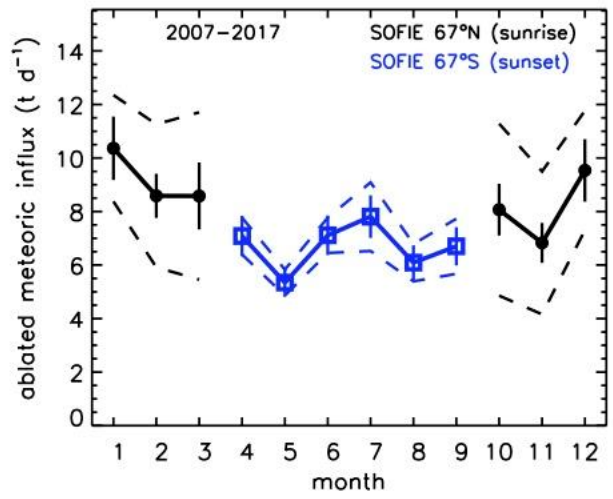

Figure 8. Ablated meteoric influx as monthly averages of SOFIE results during 2007 - 2017 when sunrise (sunset) was near 67°N (67°S). Vertical bars indicate the AMI uncertainty (δAMI, see text). Dashed lines indicate the standard deviation for the included years.

Ablated meteoric influx during 2007 - 2021 is shown as winter averages in both hemispheres in Figure 9, where the results are mostly for polar latitudes. AMI in the NH is typically greater than in the SH, with averages during 2007 - 2021 of 8.4 ± 2.0 t d^{-1} in the NH, and 6.2 ± 1.4 t d^{-1} in the SH (± standard deviation of 14 years). For both hemispheres combined AMI is 7.3 ± 2.0 t d^{-1}. The above standard deviations for 2007 - 2021 are ~22%, while the AMI uncertainty based on SOFIE and WACCM errors combined is ~10%, for either hemisphere. The results indicate inter-annual variations in meteoric influx that are often statistically significant. Other observation of meteoric influx have shown year-to-year variability, including radars [e.g., *Janches et al.*, 2004] and satellite instruments [*Malaspina et al.*, 2016]. It is thus possible that the SOFIE inter-annual variations indicate real variability in meteoric influx, but this will be the topic of future studies.

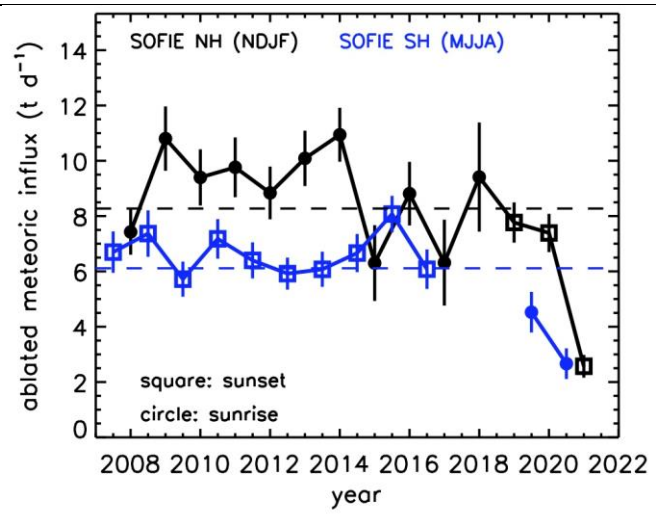

Figure 9. Time series of SOFIE AMI as winter means in the NH (November - February) and SH (May - August). The results correspond to latitudes as in Figure 5a. Note that sunrise (circle) and sunset (square) latitudes switched hemispheres in ~2018. The average AMI in the NH (8.4 t d^{-1}) and SH (6.2 t d^{-1}) are indicated by dashed lines. Error bars indicate the standard deviation for each winter.

The AMI derived here from the SOFIE-WACCM comparisons were anticipated to be equal in both hemispheres, yet hemispheric differences (NH > SH) exist during most years (Figure 9). This is due in part to hemispheric differences in SOFIE smoke volume density, that are weaker in WACCM (Figure 5b). Indeed, if WACCM had the same hemispheric differences in smoke V′ as SOFIE, then the resulting AMI would be equal in both hemispheres. Biases between the SOFIE sunrise and sunset observational modes were dismissed because the hemispheric difference persists after 2018 when sunrise switched from the NH to SH (see Section 4). Transport in the model was dismissed because hemispheric differences in SOFIE and WACCM wintertime mesospheric H_2O are similar (Section 4). Another explanation might be a hemispheric asymmetry in the interaction of smoke with an atmospheric constituent which changes the optical properties of the particles. The most likely candidate is H_2SO_4-H_2O (sulfate) droplets in the mid-stratosphere, since these can entrain smoke particles to produce sulfate droplets with a smoke core (*Brooke et al.*, 2017). Dissolution of the Fe in smoke to form Fe^{2+}/Fe^{3+} ions in the droplets is rapid under stratospheric conditions (~20 hrs. at 235 K, see *Saunders et al.*, 2012), and these droplets may have

317 different optical properties to pure smoke. The model results of *Brooke et al.* [2017] indicated that
318 mixed smoke-sulfate particle formation should only be significant below 35 km. *Hervig et al.*
319 [2017b], however, used SOFIE observations with models to show that when sulfuric acid is
320 neutralized by mixing with smoke, that a sulfate-smoke aerosol can form at heights reaching into
321 the lower mesosphere. In any case, sulfate - smoke interactions are not included in the present
322 WACCM model runs and thus could be a candidate for the observed asymmetries. A final
323 possibility is that the hemispheric difference in SOFIE smoke is due to an asymmetry in meteoric
324 influx that is not included in WACCM. *Malaspina et al.* [2016] report meteoric flux observations
325 from the Wind satellite operating roughly 10^6 km from Earth, showing a seasonal variation in MI
326 with a maximum in March and a minimum in September. This annual variation was traced to
327 interstellar particles, which flow into the Earth's orbital direction in March. While interstellar
328 particles may comprise too little mass to explain the observed asymmetries, the question is posed
329 here as there may be unexplored characteristics of the interstellar flow. The Wind dust observations
330 are not considered in the *Fentzke et al.* [2008] description of meteoric influx variations used in
331 WACCM, and thus could be a component in the SOFIE - WACCM disagreement concerning the
332 hemispheric differences in mesospheric smoke.

333 The final consideration is derivation of total meteoric influx (TMI) from the SOFIE ablated
334 meteoric influx results. The present study treats meteoric smoke as Fe-rich olivine, which has an
335 elemental abundance nearly identical to that of the ablated meteoric source (see Section 2). As a
336 result, the conversion from AMI to TMI can be taken directly from the *Carrillo-Sánchez et al.*
337 [2020] results, which give TMI / AMI = 28 ± 16 t d^{-1} / 8.3 ± 4.7 t d^{-1} = 3.4. The resulting TMI
338 values from this work are 28.4 ± 6.8 t d^{-1} in the NH and 21.0 ± 4.9 t d^{-1} in the SH. For both
339 hemispheres combined TMI is 25.0 ± 7.0 t d^{-1}. The stated uncertainties are the standard deviation

of the winter values for 2007 - 2021 (e.g., Figure 9). Note that uncertainties in the SOFIE TMI estimates reported above are the standard deviations over 14 years, and that the experimental errors represent an additional 10% uncertainty. It is furthermore arguable that the SOFIE TMI uncertainties could be increased due to propagation of the *Carrillo-Sánchez et al.* [2020] errors (~57%).

6. Summary

An improved SOFIE sunrise signal calibration has produced meteoric smoke extinction retrievals in the Northern Hemisphere, for the first time. The new observations are in good agreement with WACCM simulations concerning both the time and height dependence of smoke in the mesosphere. Comparing the SOFIE extinction measurements to WACCM requires knowledge of the smoke composition, to describe the optical properties that relate extinction to volume density. The present study assumes that smoke in the mesosphere exists purely as Fe-rich olivine ($Mg_{0.8}Fe_{1.2}SiO_4$) with the justification that 1) it is detected optically by SOFIE [*Hervig et al.*, 2017a], 2) it has the same elemental abundance of Fe, Mg and Si as predicted from meteoric ablation, and 3) it is anticipated by theory and laboratory experiments [*Saunders and Plane*, 2011]. With the assumption of olivine, SOFIE results indicate a global mean ablated meteoric influx of 7.3 ± 2.0 t d^{-1} (total influx of 25.0 ± 7.0 t d^{-1}), based on averages for both hemispheres during 2007 - 2021. The new SOFIE influx results agree with *Carrillo-Sánchez et al.* [2020] (within 11%) who used models and observations to derive an ablated influx of 8.3 ± 4.7 t d^{-1} (total influx of 28.0 ± 16 t d^{-1}). This closure provides further support for mesospheric smoke existing as olivine. Additionally, these new results reconcile previous differences between SOFIE influx estimates from *Hervig et al.* [2017a] (AMI = 3.3 t d^{-1}; TMI = 30 t d^{-1}) and *Carrillo-Sánchez et al.* [2016] (AMI = 7.9 t d^{-1}; TMI = 43 t d^{-1}).

Both SOFIE and WACCM show ~10% hemispheric differences in wintertime mesospheric H_2O (SH > NH), that are consistent with stronger transport in the NH winter vs. the SH. This difference in transport is also apparent in both the SOFIE and WACCM mesospheric smoke results, which show less smoke in the SH polar winter compared to NH winter. The open issue is that the hemispheric smoke difference is greater in SOFIE (~36%) than in WACCM (~2%). Because the meteoric influx estimates rely on comparisons of SOFIE and WACCM, a hemispheric difference emerges in the SOFIE influx values (~30%). While this difference is close to the combination of experimental uncertainties (~10%) and geophysical variability during the 14 years of observations (~20%), it is persistent in time and bears some thought. Sunrise - sunset biases in the SOFIE observations were dismissed because the hemispheric difference persists after 2018 when sunrise switched from the NH to SH (vice versa for sunset). Transport in WACCM was dismissed because the hemispheric differences in H_2O are the same in WACCM and SOFIE. The parting ideas in this regard are incomplete chemistry or microphysics in the smoke simulations, or asymmetries in meteoric influx that are not represented in the model.

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