

Reviewer #1

Comments on the paper on the relationship between the mesospheric sodium layer and the meteoric input function.

The paper is a study of a new sodium chemistry model using the continuity equation without making any steady-state assumption. The model includes all sodium-bearing species and runs at a high temporal resolution of millisecond. The study shows the meteor input functions (MIF) from the meteor radiant and derived from the new sodium model. The study could contribute to simulations of sodium concentration in the MLT region.

Some comments that need to be addressed:

We sincerely thank the reviewer for their valuable feedback. Please find our point-to-point response below:

1) The authors compared the meteor input functions (MIF) obtained between two types of meteor input function in Figure 6. They should provide more comparison of sodium species between the model and the Colorado State University (CSU) and the Andes Lidar Observatory (ALO), which can present the performance of the model.

Response:

The model directly utilizes the lidar measurements to estimate the sodium sink. Consequently, the sodium vertical profiles in the model are precisely aligned with the lidar observations. The ingestion of the lidar observations into the model's estimation process eliminates any variability or differences that would typically arise in a comparison scenario.

2) The authors mentioned the variation by atmospheric dynamics in the discussion. The diurnal sodium profile is the mean of observations of thousands of days, thus the variation by atmospheric dynamics should be much less prominent. As I didn't see comparison of sodium species between model and lidar observations, the influence of meridional transport of metallic sodium ions and atoms on the seasonal variability of sodium number density in the model cannot be considered less prominent.

Response:

As mentioned earlier, the model directly utilizes the lidar observations as reference profiles, as shown in Fig. 2, to guide the simulation for estimating the number of sodium atoms removed from the atmosphere. This estimation, in turn, calculates the amount of meteoroid material input required to maintain the presence of the sodium layer. The reference profiles are obtained directly from the lidar measurements, which inherently include diffusion and other dynamic effects on the sodium species in the Mesosphere and Lower Thermosphere (MLT).

3) How long could the model run steadily since the model is not a self-consistent dynamical transport model? What is the global distribution of the sodium species?

Response:

The total number of sodium atoms is conserved in the model. Therefore, it can run indefinitely with the sodium sink turned off. This study utilizes lidar measurements obtained from the Colorado State University Lidar (CSU) and Andes Lidar Observatory (ALO) to estimate the meteor input function at each site. Subsequently, the global meteoroid material input is estimated based on the relative meteoroid material input derived from the micro-meteor radiant source distribution, as illustrated in Fig. 5. Note that studying the global distribution of sodium species is beyond the scope of the current study.

4) How did the authors conclude that the uptake of sodium species onto meteoric smoke particles removes approximately three times more than the dimerization of NaHCO_3 ?

Response:

The MIF(s) is validated by matching the amplitude/relative ratio of MIF(m). The uptake is found to be approximately three times more than the dimerization of NaHCO_3 so that the seasonal variation of MIF(s) would align best with the amplitude of MIF(m).

Reviewer #2

General comments

This study employs lidar observations of Na in the MLT region in combination with a novel Na chemistry model to estimate the meteoric mass influx into the Earth system. The topic is interesting and suitable for *Annales Geophysicae*. The paper is in my opinion also relevant for the MLT community and should eventually be published. There are, however, numerous little inconsistencies and unclear statements that should be corrected first (see below)

We would like to express our sincere gratitude to the reviewer for conducting a very thorough review of our work. We have carefully considered and incorporated your valuable feedback into the revised manuscript. We believe the revised version has addressed your comments. Please find our point-to-point response below:

Specific comments

Line 17: "the MIF inferred from the meteor radiant"

I think something is missing here, "meteor radiant" appears incomplete.

Response:

The "meteor radiant" has been changed to "meteor radiant distribution."

Line 35, key point 2: Can you provide error estimates for the daily meteoric input estimates? It's not clear, whether it makes sense to provide 2 digits after the decimal point.

Response:

We agree with the reviewer that having 2 digits after the decimal point does not make sense. The corresponding daily meteoroid material input numbers are rounded to their nearest integer in the key points and in the text.

The error of the daily meteoric material input cannot be accurately determined, as the estimation is largely based on the distribution of meteor radiant sources, which currently lacks an error estimation.

Line 37: key point 3: wording not precise. The reader does not fully understand what this sentence means. Please rephrase.

Response:

Key point 3 has been rephrased to read “The frequency of meteor occurrences might not provide a precise reflection of the mass of meteoroid material input.”

Line 49: “Julia et al., 2022”

This reference is missing in reference list. I’m not aware of a colleague with the last name „Julia“. Do you perhaps mean “Julia Koch”, i.e. this paper:

Koch, J., Bourassa, A., Lloyd, N., Roth, C., and von Savigny, C.: Comparison of mesospheric sodium profile retrievals from OSIRIS and SCIAMACHY nightglow measurements, *Atmos. Chem. Phys.*, 22, 3191–3202, doi.org/10.5194/acp-22-3191-2022, 2022.

Response:

We appreciate the reviewer for pointing out the error. The references have been updated accordingly.

Line 58: “neutral chemistry”

Response:

We appreciate the reviewer for pointing out the typo. The typo has been corrected.

Line 63: „the Meteoroid Input Function (MIF) plays a crucial role“

It would be good to explain in simple words what the MIF is. This may not be clear to all readers.

Response:

A brief explanation of the MIF has been added after the sentence, which reads “The MIF is a function designed to comprehend the impact of the temporal and spatial variability of the meteoroid on the atmosphere (Pifko et al., 2013).”

Line 69: “It’s” -> “It is”

Response:

Done.

Line 77: “ as evidenced by Arecibo Observatory (AO, 18N 66 W) detecting about 20 times more meteors per unit area per unit time than the Jicamarca Radio Observatory”

A factor of 20 is not "several orders of magnitude", so this does not seem to be a good example.

Response:

We acknowledge that the example mentioned in the manuscript is insufficient to substantiate the point. Therefore, the sentence has been revised to offer more illustrative examples. The modified sentence reads:

“The detection sensitivity varies significantly among different facilities. For instance, the Arecibo Observatory (AO) at 18° N, 66° W detects approximately 20 times more meteors per unit area per unit time than the Jicamarca Radio Observatory (JRO) at 12° S, 77° W, and at least 800 times more meteors than the Resolute Bay Incoherent

Scatter North (RISR-N) radar at 75° N, 95° W, despite all being HPLA facilities (Li et al., 2020, 2023a; Hedges et al., 2022). Of note, meteor flux varies with time and latitude, but the variations cannot account for such a large difference.”

Line 80: “Consequently, the radiant mass distribution of the meteors”

Please explain, what the “radiant mass distribution” is, this is not fully clear to me and I think the wording is not very precise.

Response:

The concept of radiant mass distribution is introduced as an alternative to radiant distribution. While the radiant distribution counts the number of meteors entering the atmosphere, the radiant mass distribution represents the mass of meteors entering the atmosphere. The ‘radiant mass distribution’ is indeed unnecessary and may cause confusion. The sentence has been changed to:

“Consequently, the total mass of the meteors entering the Earth's atmosphere is subject to significant uncertainties.”

Line 86: “One of the limitations is that the model cannot reproduce the velocity distribution of the meteors in observations”

Does this mean that a velocity distribution is not considered at all in the model, or that it just cannot be reproduced in a realistic way?

Response:

The meteor velocity distribution is a function of both velocity and time. While the velocity distribution was considered in the flux curve model, the implementation is relatively simple, limiting the model's ability to reproduce the diurnal variation of the meteor velocity distribution, i.e., the meteor velocity distribution is not a function of time in the flux curve model. Meteor velocity distribution can be found in Figure 2 of Li and Zhou (2019).

Reference:

Li, Y., & Zhou, Q. (2019). Velocity and orbital characteristics of micrometeors observed by the Arecibo 430 MHz incoherent scatter radar. *Monthly Notices of the Royal Astronomical Society*, 486(3), 3517-3523.

Line 93: "Additionally, we compare the MIF obtained from the new sodium chemistry model"

The model alone does not provide the MIF, you also need Na measurements right?

Response:

Yes, that is correct. The sentence has been modified to include Na measurements. It now reads:

"Furthermore, we compared the MIF derived from the new sodium chemistry model and lidar measurements from CSU and ALO, against the results of the high-resolution meteor radiant distribution recently deduced from the observations conducted at the AO."

Line 110: "Throughout the rest of the paper, the MIF estimated from the sodium chemistry numerical model will be referred to as MIF(s)."

The nature of MIF should be explained in more detail. What is its unit? How many independent variables does it have?

Response:

The definition of the MIF has been added after the said sentence, which reads:

"MIF is a function of time and represents the mass of meteoroid material entering the Earth's atmosphere."

Line 142: "The exponential integrator, expressed in Equation 1, provides the solution to the continuity equation, with the exception of reaction 25 listed in Table 1."

The text is not explicit here: is then the Euler integrator used for reaction 25? Can you briefly explain why you didn't use the same integrator for all reactions? Perhaps I'm missing a point here.

Response:

Reaction 25 is carried out using the Euler integrator because its continuity equation is organized differently from the other reactions. As a result, the exponential integrator shown as Equation (1) does not provide a solution for it. The corresponding sentence has been modified to clarify the point. It now reads:

"The exponential integrator, as expressed in Equation (1), provides the solution to the continuity equation. Notably, reaction 25, listed in Table 1, is an exception and was carried out using an explicit Euler integrator in the simulation. The continuity equation of this reaction contains an additional loss term because it represents the only mechanism apart from the uptakes of sodium species that removes Na atoms from the chemistry simulation."

Line 145: "that either the exponential integrator or explicit Euler integrator produces nearly identical results"

I think this is not the correct usage of "either ... or"

Response:

We believe that the use of 'either... or' effectively conveys the intended meaning. Nevertheless, it has been modified for clarity. It now reads:

"Our testing indicates that both the exponential integrator and explicit Euler integrator yield nearly identical results. However, for numerical stability, the explicit Euler integrator requires a step size of $\sim 1\mu\text{s}$, which is several orders of magnitude smaller than the exponential integrator."

Line 169: "formerly known as Utah State University (USU) Lidar"

I think it is the other way around. The lidar was first operated at Fort Collins, CO and then in Utah, right?

Response:

That is correct. Thanks for spotting it. The corresponding sentence has been changed to:

“the Colorado State University (CSU, 41.4°N, 111.5°W) Lidar, also known as Utah State University (USU) Lidar”

Line 171: “..”

Response:

We thank the reviewer for spotting the error. The extra period has been removed.

Line 171: “It contains a total of 27,930 hours”

“It” here wrongly refers to ALO, because of the previous sentence. Please adjust.

Response:

The sentence has been rephrased to:

“The CSU data comprises 27,930 hours of lidar observations between 1990 and 2020, whereas the ALO data consists of 1872 hours between 2014 and 2019.

Line 184: “The general seasonal trend of the sodium vertical profile retrieved from the CSU lidar observations is similar to the estimation by simulation made by Marsh et al. (2013), whereas the results of ALO lidar observations differ from the Marsh et al. results.”

Can you show a Figure to back this up? This statement is quite vague, what is similar, what is different? Or does this refer to Fig. 2?

Response:

The statement does indeed refer to Fig. 2. The sentence has been rephrased for clarity, which reads:

“As depicted in Figure 2, the overall seasonal trend of the sodium vertical profile derived from the CSU lidar observations closely aligns with the simulation-based estimate by Marsh et al. (2013). In contrast, the results of ALO lidar observations deviate from the findings reported by Marsh et al. (2013).”

Line 196: “Finally, we further smooth the profiles by fitting them with a skew-normal distribution using the least squares error method”

What kind of distribution is it? How symmetrical is the actual Na profile?

Response:

The skew-normal distribution is a family of distributions including the normal, but with an extra parameter to regulate skewness (Azzalini & Valle, 1996). The result of fitting the skew-normal distribution closely mirrors the original Na profile. This fitting process is employed to remove noise.

The figure below shows an example of atomic sodium vertical profile from the CSU lidar. The actual Na profile normally exhibits a degree of symmetry.

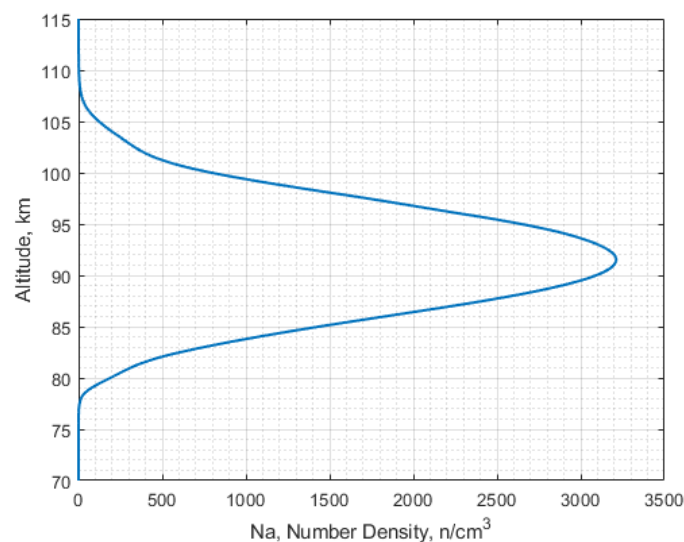


Fig. 2, both panels, y-axis label: "Km" -> "km"

Response:

Done.

Line 201: "then fitted by a normal distribution that mitigates atmospheric dynamics"

So, is it a Gaussian distribution? Above you wrote "skew-normal"?

Response:

We appreciate the reviewer for pointing out the inconsistency. It should be "skew-normal". The aforementioned text has been updated accordingly.

Lien 206: "The reference profiles used in the NaChem sodium chemistry numerical model inherently account for the effects of diffusion of sodium species as these observational data are the snapshots of sodium in diffusion at any given time."

I read this sentence several times and I don't fully understand its meaning. What does "reference profiles" refer to? The Na "profiles" (measured?) or the background species? If Na: why are Na profiles "used" in the model. The model will simulated Na, right? I suggest rephrasing the statement.

Response:

Although the model is capable of simulating Na, it does not simulate Na in the configuration presented in this work. Instead, the model directly uses measured Na number densities as reference profiles to estimate the sodium sink, i.e., the number of sodium atoms removed by NaHCO_3 dimerization (reaction 25 in Table 1), and uptake in the numerical simulation.

The reference profiles are Na lidar measurements fitted using a skew-normal distribution, smoothed by 15-day running average, and subjected to a linear 2-D interpolation across time and altitude. The lidar measurements have an altitude resolution of 500m for ALO and from 75m to 140m for CSU. These measurements are interpolated to a 100m resolution as inputs to the NaChem model. The time resolution is 0.1 seconds.

For clarity, the aforementioned paragraph has been rewritten. It now reads:

“Figure 2 displays the processed annual sodium vertical profiles from the lidar measurements, referred to as reference profiles hereafter. These profiles serve as references to guide the numerical simulation of the NaChem model. The reference profiles are Na lidar measurements fitted using a skew-normal distribution, smoothed by a 15-day running average, and processed through linear 2-D interpolation across time and altitude. The lidar measurements have an altitude resolution of 500m for ALO and from 75m to 140m for CSU. These measurements are interpolated to a 100m resolution as inputs to the NaChem model. The time resolution is 0.1 seconds. The reference profiles inherently include diffusion and other dynamic effects on the sodium species in the MLT, as these observational data represent snapshots of sodium diffusion at various times.”

Lines 221 – 223: Isn't this essentially the same statement as two sentences before? I think this is redundant.

Response:

Yes, the sentences are a summary of the previous statements. For a better flow, the sentences have been rephrased to read:

“In summary, the sodium that we can detect does not necessarily provide an accurate representation of the total sodium content or the overall count of sodium-bearing species, as unobservable species such as Na^+ and NaHCO_3 could constitute a substantial portion of the total sodium content.”

Line 224: "impact .. to" -> "impact .. on"

Response:

Done.

Line 224: "to the share of Na atom to the total sodium content"

This statement is misleading and I'm not sure, what the profiles in Fig. 3 actually show. Here you write "the share of Na atoms to the total sodium content" and below you write "total sodium content". This should be clearly explained.

It would also be interesting to mention what the ratio of Na atoms to the concentration of all Na species is.

Response:

The statement and the profiles in Fig.3 refer to the total sodium content. The corresponding sentence has been modified to read:

"Understanding the impact of each background species, i.e., species listed in Figure 3., on the total sodium content is essential to study the underlying mechanism of the chemical reactions."

Fig. 3 has been redone to display the ratio of Na atoms to the concentration of all Na species, referred to as Na number density ratio in the figure. The figure caption has also been modified.

Line 229: "The simulation is kept running until all the numbers are stable."

Are diurnal variations considered here? The WACCM background species will have a diurnal variation, right? Did you stop the simulations at a fixed local solar time? For how many days did the simulation run? Please provide more details here.

Response:

The purpose of this test is to analyze the response of sodium species to individual background species, achieved by isolating variables. Diurnal variation has not been taken into account in the sensitivity test as it introduces unnecessary complexity. The initial conditions are provided by WACCM with time set at 3:00 am on May 24, 2014. This specific time was chosen arbitrarily.

The relevant paragraph has been rewritten for clarity. It reads:

“The sensitivity test is done by altering the number density of background species in question by two orders of magnitude, i.e., with a factor of 0.1 and 10, while keeping the number densities of other background species and the atomic sodium fixed. The simulation is kept running until all the numbers are stable. The diurnal variations of the sodium and background species are not considered in the sensitivity test as they introduce unnecessary complexity.”

Line 235: “The total sodium content vertical profile f”

So the relative profile of the total concentration of all Na-species is shown? And not the “share” of Na to all species, as mentioned above?

Response:

The total concentration of all Na-bearing species is shown, not the ‘share’ of Na to all species.

Line 246: “specie” -> “species”

Response:

Done.

Line 263: “species that converts” -> “ species that convert”

Response:

Done.

Line 267: “That being said, the works of the background species are in a rather complex pattern”

Grammar? Sentence incomplete?

Response:

The sentence has been rephrased to:

“That being said, the interaction between sodium and background species is rather complex.”

Line 268: “The scope of the sensitivity test in the present paper was limited to column density.”

Well, you show profile information in Fig. 3.

Response:

We intended to express that the scope of the sensitivity factor as shown in Eq. 2 was limited to column density. The wording has been changed from ‘sensitivity test’ to ‘sensitivity factor’.

Line 269: “As a result of such, variations and behaviors of the sodium chemicals by altitude are overlooked.”

What about Fig. 3?

Response:

The intension was to discuss the limitations of sensitivity factor. The previous sentence has been adjusted accordingly.

Line 281: “and the uptake of the sodium species”

This means uptake on meteoric smoke particles, right? I think this should be mentioned to avoid misunderstandings.

Response:

We thank the reviewers for bringing up the missing information. The sentence has been adjusted to:

“During the simulation, the NaHCO₃ dimerization and the uptake of the sodium species on meteoric smoke particles, which can be turned on or off, create a deficit of sodium atoms.”

Line 283: “matches the reference profiles”

The reference profiles are the observed profiles, right?

Response:

The reference profiles are lidar measurements processed by skew-normal distribution fitting, running average, and interpolation in altitude and time. A description of the reference profile has been added to the end of section 3.2 Data processing and can be found in one of the replies.

Line 288: “infused”

Correct word? I’m not familiar with this word in this context.

Response:

The sentence has been rephrased for clarity. It reads:

“The simulation circumvents this uncertainty by directly incorporating the observational sodium vertical profile, given that diffusion is already inherently in the measurements.”

Lines 291 and 303 : “AO observations”

Please explain / spell out what “AO” means.

Response:

AO means Arecibo Observatory. It is spelled out in line 78.

Line 292: "The result is in the Earth Reference Frame (ERF)"

I'm not really familiar with this frame. What does the longitude in the plot correspond to? I would have expected more or less the same values for all longitudes, but this is apparently not the case?

Response:

The latitude of the ERF is centered (0°) on the ecliptic plane. The longitude of the ERF is centered to the Apex direction, the moving direction of the Earth, where the highest number of meteors encounters Earth. While in some publications the ERF's longitude is centered on the Helion direction, we have chosen to center it on the Apex direction to maintain consistency with the publication we are referencing.

Fig. 4 has been reworked with a different colormap for better presentation. A description of the ERF has been added to the caption. The caption now reads:

Meteor radiant source derived from the AO observations. The result is in the Earth Reference Frame (ERF), equivalent to ground-based observations. The latitude of the ERF is centered on the ecliptic plane. The longitude of the ERF is centered to the Apex direction, the moving direction of the Earth, where the highest number of meteors encounter Earth. The radiant distribution is derived from the number of meteor events. Figure reproduced from Li et al. (2022).

Fig. 6: Why can the MIF with uptake off be lower than the one with uptake on? Does the uptake work in both direction, i.e. is there positive and negative uptake?

Response:

The curves depicting 'uptake on' were adjusted downward to align with the 'uptake off' curves. This adjustment is aimed to demonstrate the difference of amplitude between these curves. We agree that the initial presentation of the figure lacks proper captions and is misleading. Fig.6 has been reworked and now displays separate curves of uptake on and off. The caption of Fig. 6 has also been revised accordingly.

Lines 304 and 306: "Kg" -> "kg"

Response:

Done.

Line 305: "the limiting meteor mass"

What is the "limiting meteor mass"? Something like a detection threshold?

Response:

Yes. Limiting mass is the smallest mass a meteoroid must have to generate sufficient ionization to be detected by radar.

Line 311: "Nesvorn'y"

Response:

done

Line 314: "The relative seasonal and latitudinal meteoroid input by the number of events inferred from the new radiant distribution is depicted in Figure 5."

Is this an approach (to get the „new“ radiant distribution) not affected by the issue mentioned in the previous sentence? Or does it suffer from the same problem? This is not clear to me.

Response:

Nearly all radar meteor studies encounter this common issue, including the methodology utilized to derive Figure 5.

Line 324: "uptakes" -> "uptake"

Response:

Done.

Line 337: "in (Li et al., 2022)" -> "in Li et al. (2022)"

Response:

Done.

Line 342: "Assuming the relative sodium elemental abundance in meteoroid material is 0.8%"

The relative mass ratio is relevant here, not the relative sodium elemental abundance, right?

I'm not able to reproduce the mentioned masses, please explain in more detail how you got these numbers.

Response:

We concur that the term 'relative sodium elemental abundance' is potentially misleading. As a result, we have revised the phrase to read 'relative abundance of sodium in chondritic meteorites.'

The specific ratio of 0.8%, as mentioned in Section 2.4 of the work by Vondrak et al. (2008), is referenced to the book by Mason (1971). The relevant references have been added to this manuscript.

References:

Vondrak, T., et al. "A chemical model of meteoric ablation." *Atmospheric Chemistry and Physics* 8.23 (2008): 7015-7031.

Mason, B.: *Handbook of Elemental Abundances of the Elements in Meteorites*, Gordon and Breach, Newark, USA, 1971.

Line 346 and line 354: "It's" -> "It is"

Response

Done.

Line 347: "Nesvorn`y"

Response:

Done.

Line 349: "given that the daily input rate is derived from combinations of chemicals that can fluctuate by several orders of magnitude"

What species exactly do you mean here? The Na concentration does certainly not vary by orders of magnitude, right? In this context it would again be interesting to know the ratio of elemental Na to the total Na in all species.

Response:

We are referring to ion-species such as NO^+ , O_2^+ , and electron density, all of which participate in sodium chemistry. The following sentence has been added after Line 349 (now 366) for clarity, which reads:

"For example, the NO^+ , which exhibits the highest sensitivity factor according to the sensitivity test, undergoes diurnal variations of approximately three orders of magnitude."

The ratio of elemental Na to the total Na in all species are shown in the revised Fig. 3.

Line 357: "The mass of the meteoroids, which constitute the metal layers"

This statement is not really correct, please rephrase.

Response:

The sentence has been rephrased to read “The mass of the meteoroids has been estimated and measured by various methods”

Line 358: “e.g., ballistic parameter (Mathews et al. 2001); plasma by meteor ablation model, radar cross-section (Close et al., 2005; Sugar et al., 2021), flux rate (Zhou and Kelley, 1997), and spacecraft observations (Leinert and Grun, 1990), to name a few”

I suggest rephrasing this part of the sentence to make the methods more understandable. What is „plasma by meteor ablation model“, e.g. ? This is unclear to me. Or „flux rate“ ? The meaning is not evident. Does „spacecraft observations“ refer to in-situ observations, or, e.g. Na remote sensing measurements from a satellite together with modelling?

Response:

The spacecraft observations were in-situ measurements carried out by NASA’s Long Duration Exposure Facility (LDEF). However, due to the complexities of meteoroid orbits, the in-situ measurements could be highly biased. This bias is also applicable to other approaches.

The sentence has been rephrased to read:

“The mass of the meteoroids has been estimated and measured using various methods. These include the ballistic parameter derived from meteor deceleration (Mathews et al., 2001), estimation of meteor head echo plasma distribution through a combination of meteor ablation models and radar cross-section measurements (Close et al., 2005; Sugar et al., 2021), flux rate determination (Zhou and Kelley, 1997), as well as spacecraft in-situ measurements (Leinert and Grun, 1990), among others.”

Lines 363, 364 and 365: the given mass ranges apply to a single meteor, right?

Response:

Right. The given mass ranges are possible mass of a single meteor.

Line 402: "was consistent"

Consistent in what way?

Response:

The sentence has been rewritten for clarity. "In this study, the MIF(s) derived from the NaChem simulation, based on the CSU lidar measurements with uptake turned on, was able to match the amplitude of MIF(m) obtained from the meteor radiant distribution."

Line 404: "diffusion would have been implicitly included"

"would have been" or "is"?

Response:

It should be "is". The sentence has been modified to read: "Although the model does not directly incorporate any dynamical processes, the vertical transport by diffusion is implicitly included."

Line 408: "The lidar data of both sites (CSU and ALO) indicate that the sodium column density consistently increases by about 20% from 22:00 to 4:00 LT the next day"

Good point! At what LST do you determine MIF(s)? How do you deal with the 20% variation?

Response:

The MIF is determined by the average value between 22:00 to 4:00 LT, which corresponds to the time window of the lidar measurements. The 20% variation was averaged into one altitude profile for each day in the reference profiles as shown in Fig. 3.

Line 413: "This number is obtained by turning the sodium sink off and keeping the total number of sodium in the system conserved."

I'm not sure this is an apples-to-apples comparison?

Response:

The sentence has been changed to:

“The value is obtained by maintaining a constant total number of sodium-bearing species by turning off the sodium sink.”

Line 434: “During our testing, the CPU time to simulated real-time ratio is about 1 to 100 using a 10-millisecond time step.”

But this high time resolution was not used here, right? Above you wrote that the default time step is 0.1 seconds.

Response:

That is correct. The high-time resolution was not used here. The sentence has been changed to “is about 1 to 1000 using a 0.1 second time step” for consistency.

Line 436: “The model simulation was able to reproduce the seasonal variation of the sodium layer in the MLT by simulations of chemical reactions. The simulation results at the CSU's latitude capture the general trend of the seasonal variation at the location.”

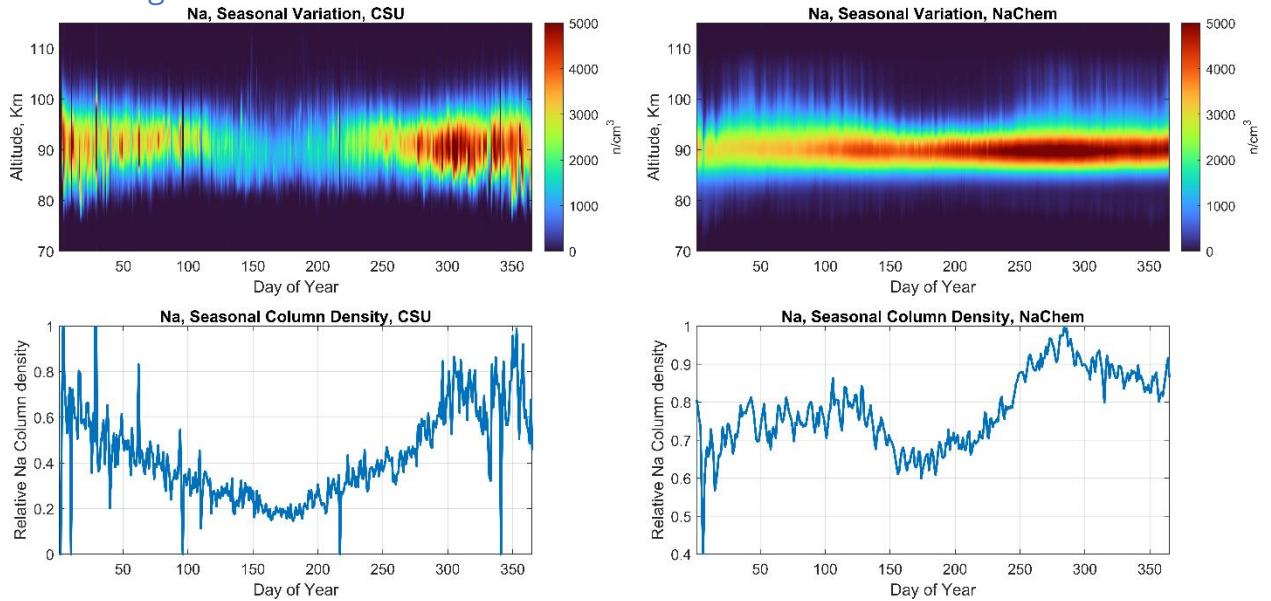
Please include a Figure showing that.

Response:

The NaChem model was able to capture the general trend of the seasonal and diurnal variation using simulations of chemical reactions as shown in the figures below. However, we do not include these figures in the manuscript for the following reasons:

- a. Simulations of seasonal and diurnal variations were conducted for the purpose of model validation. The results are depicted in the figures below. The initial conditions were given by lidar measurements, and the background conditions were obtained from WACCM data. These simulations do not incorporate vertical or meridional transport. Furthermore, due to the absence of active meteoroid material input in the model, the simulation was run with the sodium sink turned off. As such, with no sodium production and sink, this configuration and its results are not realistic.

- b. The simulation that produced the results presented in Fig. 6 was guided by Na reference profiles obtained from lidar measurements. Displaying results, e.g., the figures below, that were not guided by such reference profiles could be misleading.

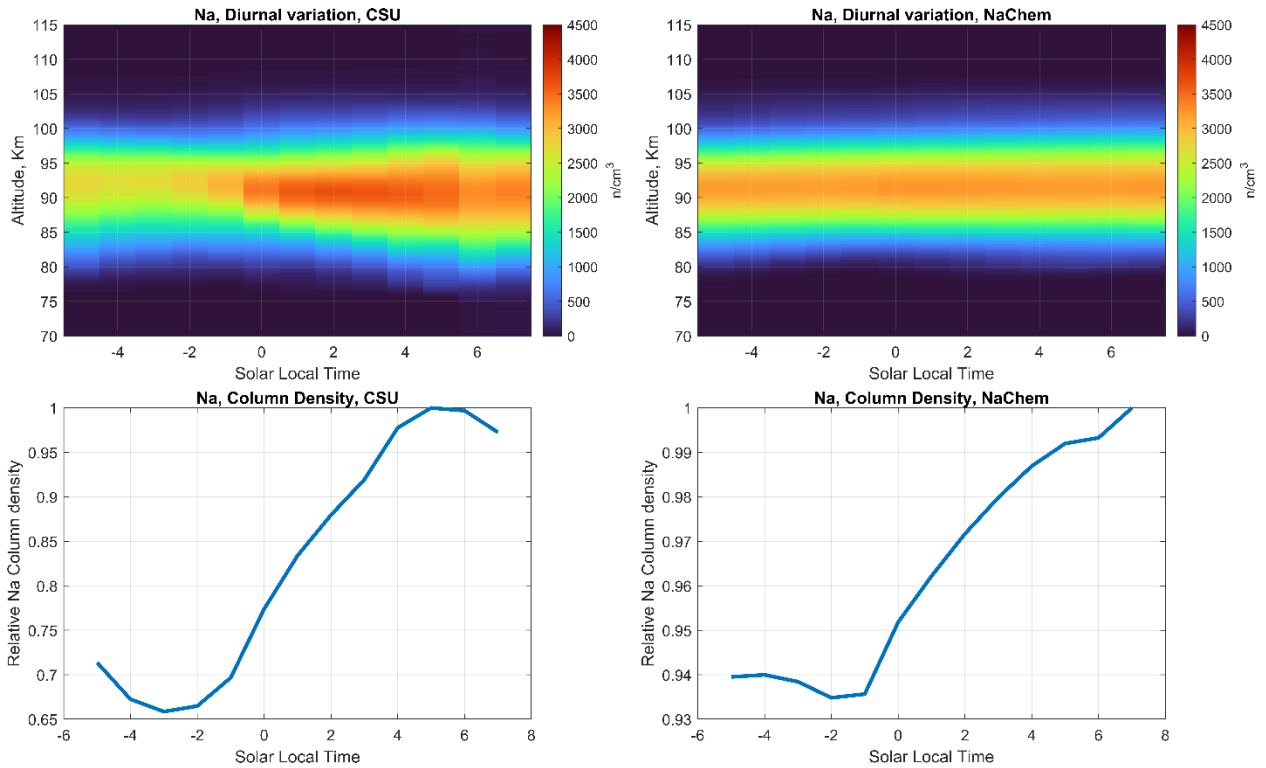


Line 442: “The numerical simulation by NaChem could reproduce the general trend of diurnal and seasonal variation of the sodium layer compared to the observations by the CSU Lidar.”

This should also be backed up by showing a figure.

Response:

Please refer to the figure below. We chose not to include these figures for the same reasons mentioned in the previous comment.



Line 467: "All authors have equal contributions to the work."

I suggest being more specific here. Probably not all authors contributed equally to the data processing, analysis, writing etc.

It has been updated in the manuscript.

Reference list: References not in accordance with Ann. Geo. standards, please update. The list also contains several typos. Please check carefully.

We have updated the reference list.