Reviewer #2

Response to the reviewer

General comments:

I thank the authors for considering the comments in my previous review. I apologize, but I only realized after reading the revised version of the manuscript that there may be a fundamental problem with your basic approach. My interpretation may be wrong and if that is the case, please let me know.

In the initial version of the manuscript the MIF was not really defined (and it is still not described well in the revised version). My earlier understanding was that MIF corresponds to a model of the daily meteoric mass influx as a function of latitude (and perhaps longitude) with units of, e.g. kg / day. But this is not the case, I think? If I understand your approach correctly, you are matching (in Fig. 6) the seasonal variations of MIF(m) and MIF(s), but not the absolute values of the MIFs. These two MIFs in fact have different units. MIF(m) is dimensionless (?) and scaled to MIF(s) in Fig. 6, right? MIF(s) on the other hand has the units /cm^3/s. My initial understanding was that both MIFs have the same units and are matched here, but this apparently is not the case. Then the question is, what criterion is actually used to do the matching. I think that you are trying to reproduce the seasonal variation of the MIFs – is this correct? I'm not sure this is a really robust approach.

Another problem is related to the estimated of the total daily meteoric mass influx. As I understand it, these values cannot really be robustly estimated using your approach, because you empirically adjust the uptake factor (for the uptake on meteoric smoke particles) to obtain the "best results". It is not explained at all what "best results" means. For the reader this means, that the uptake factor is adjusted in some arbitrary way. The problem now is that your estimate of the meteoric mass influx depends directly on the chosen uptake factor. In other words, your estimated mass influx is not really robust, right?

If my interpretations are correct, then there are some fundamental flaws in the approach taken in the manuscript and it would then be very difficult to interpret the meaning of the results. If I'm wrong, please let me know.

Response:

We thank you for the opportunity to further clarify the points that were raised by you. No need to apologize. There is some misunderstanding (no fault on you). Below please find our responses to your questions. We believe they adequately address your questions or concerns. Thank you again for your input to make this article better.

The MIF(m) is a relative unitless quantity, representing the relative seasonal changes of the meteoroid material input from radar measurements. Therefore, MIF(m) provides the insights of the relative seasonal variation of the meteoroid material input. The mass of the meteoroids cannot be accurately determined from radar measurements. The uncertainties in estimating meteor mass from radar measurements are discussed between line 386 and line 402 in the revised manuscript.

On the other hand, MIF(s) derived from the chemistry model has a unit of $1/cm^3$/second of sodium atom, which can be converted to meteoroid mass input in $Kg/m^3/s$ with estimations in relative sodium elemental abundance of 0.8% (line 371) in meteoroid material.

The goal of this study is to match the amplitude of seasonal variation of the MIF(s) and MIF(m). In other words, the value of [MIF(s)/mean(MIF(s))] should be similar to MIF(m). In essence, we are comparing MIF(m) and MIF(s) but given that the former one is a relative quantity and the latter one's value can be computed, we need to scale MIF(m) by multiplying the mean value of MIF(s) so that these two quantities can be compared, and the least square error can be found. The value of MIF(s) can be determined from the numerical chemistry simulation. Fig.6 is presented as [MIF(m) x mean(MIF(s))] and MIF(s), in this form it conveys more information.

As illustrated in Panel 2 (CSU 40° N – Uptake off) and Panel 4 (ALO 30° S – Uptake off) of Figure 6, the amplitudes of MIF(s) and MIF(m) do not align without uptake. Notably, MIF(s) becomes negative around day 50 due to the faster depletion of sodium compared to the sodium sink rate caused by NaHCO3 dimerization. This is physically impossible, necessitating the consideration of uptake. We believe this approach is innovative and provides a rather robust way to infer MIF.

The amplitude of the MIF(s) can be adjusted by altering the uptake rate. Please refer to the figures attached at the end of this document. They show the matching with different uptake factors, and the results should be self-explanatory.

Specific comments:

Line 64: "to comprehend" -> "to describe" or "to model" ?

Same sentence: Thanks for adding this information. I suggest adding information on the units of the MIF and the variables it depends on (Latitude, time, longitude? .. etc.?)

Response:

"to comprehend" has been replaced by "to model".

More description on MIF and the variables has been added to line 117-122, where MIF(s) and MIF(m) are first introduced. The corresponding text reads:

"The MIF(m) is determined through a 3-D meteoroid orbital simulation, a process similar to the seeding process discussed in section 3.1 of Li et al. (2022), based on the meteor radiant distribution. MIF(m) is a relative unitless quantity. Note that the meteor mass cannot be accurately determined via radar measurements, however, the seasonal variation of meteoroid material input can be represented by MIF(m). The estimation of meteor mass is further discussed in Section 5. In contrast, MIF(s) is expressed in units of $1/cm^3$/second."

The corresponding sentence has been rephrased to:

"While meteor flux does exhibit variations based on time and latitude, these fluctuations alone cannot explain the magnitude of the observed difference."

Response:

This study obtains the value of MIF(s) from the chemistry model (NaChem) and compares the relative value of MIF(s) to MIF(m). The process has been discussed to a greater extent in the response to the general comments. The sentence mentioned in this comment has been revised for clarity:

"This study estimates the MIF in the numerical model by matching the amount of sodium atoms removed by the dimerization reaction and uptake, i.e., sodium sink, to maintain the observed sodium presence in the MLT."

Response:

MIF(m) is a unitless quantity. The sentences have been rewritten and have been included in the previous answer.

Response:

The model used was CESM2 with WACCM6. Regardless which version is used, O_3 has virtually no effect on sodium chemistry as shown in Figure 3. The WACCM version has been added to the corresponding text.

Response:

Eq. 1 is a first-order numerical exponential integrator for numerical simulation. It is a solution of the continuity differential equation, which does not have a unit. The exponential integrator is utilized to mitigate the problem of numerical instability.

Response:

Yes. In simulation, x_0 is the number density of the species.

The corresponding sentence has been expanded to: "Where x_0 is the value in the current step. In the simulation, it is the number density of the species."

As mentioned in the previous response, Eq.1 represents a numerical integrator, which does not have a unit.

Response:

There are 14 sodium species (as shown in Table 2) in the simulation. The uptake of each species is calculated independently by an additional term in their continuity equation. E.g., Eq. (2), Eq. (3) and Eq. (4) in Plane (2004).

Plane, J. M. C. "A time-resolved model of the mesospheric Na layer: constraints on the meteor input function." Atmospheric Chemistry and Physics 4.3 (2004): 627-638.

Response:

You are right. It should be absorption. The sentence has been revised to:

"The [hv] is the term that represents the loss via photoionization, which is approximately a sinusoidal function based on the Solar zenith angle of the respective local time.

Response:

It is approximately a sinusoidal function because it involves the Earth's rotation. The definition of a sinusoidal function includes both the sine and cosine function.

Response:

"local time" has been changed to "local solar time". The latitude information is represented by the solar zenith angle.

Response:

The corresponding texts have been expanded to:

"In contrast, ALO lidar observations deviate from the findings reported by Marsh et al. (2013). The ALO measurements exhibit a prominent peak around June, while the results in Marsh et al. (2013) show a double peak in March and October."

Response:

The text has been revised to:

"The time resolutions of the lidar measurements typically vary between 1 and 10 minutes, depending on the experiment. In this study, they are linearly interpolated to 0.1 seconds."

Line 249: "Additionally, the sensitivity factor and the Na number density ratio to the concentration of all sodium species .."

Is the density ratio averaged over all altitudes or given for a specific altitude? This should be mentioned.

Response:

The curves presented in Fig.3 contain altitude information. The sensitivity factor, on the other hand, is calculated with column density. This has been discussed in the text below Eq.2.

Line 256: "The factor is measured": "measured" -> "determined" or "calculated" ?

Response:

The word has been replaced by "calculated'.

Line 260: "For example, a Sensitivity Factor of 5 indicates that the total sodium content increases by five times when the respective background species increases 100 times."

This is not correct, because the sensitivity factor is not normalized by the value for a factor of 0.1, but for the reference value.

Assume, e.g., the following: NaTc10 = 5, NaTc0.1 = 1, NaTc = 2. Then there is a factor of 5 increase, but:

Sens. factor = (5 - 1)/2 = 2 !

Response:

You are correct! Thanks for spotting it. We do want to emphasize that this does not affect the outcome of the sensitivity test. The corresponding text has been changed to:

"The sensitivity factor provides a general insight into how variations in the background species correlate with sodium number density. A larger absolute value for the sensitivity factor indicates a stronger correlation. A positive sensitivity factor indicates a positive correlation between the total sodium content and the respective species, and vice versa."

Line 267: "as the altitude profile of the sodium atoms is fixed."

Response:

The altitude profile of [Na] is fixed only in the sensitivity test. In essence, this test calculates the ratio of [Na] in all sodium-bearing species (e.g., those listed in Table 2) at the equilibrium state for a given background condition. While the altitude profiles of other sodium species vary with the background condition, [Na] remains fixed, serving as an unlimited supply and sink of sodium atom.

The corresponding text has been modified to clarify:

"In the simulation, a greater total sodium content implies that a smaller percentage of the sodium chemicals are present as sodium atoms because the altitude profile of the sodium atoms is fixed in the sensitivity test."

Line 278: "is strongly correlated"; or rather "is strongly anti-correlated" ?

Response:

It should be anti-correlated. The corresponding text has been changed.

Line 298: "The diffusion coefficient is found to be highly correlated with"

Which diffusion coefficient? Not the one in your model, because you don't consider diffusion. Does this refer to WACCM? And shouldn't the diffusion coefficient be independent of some species concentration or removal rate?

Response:

It was referred to the finding in the reference provided at the end of the sentence. The diffusion coefficient is highly correlated with the sink rate because the sodium sink mostly occurs at lower altitudes (<90km). Therefore, the amount of sodium removed by [$NaHCO_3$] dimerization is strongly connected to the amount of [Na] atom transferred to lower altitude via diffusion. The corresponding text has been revised to avoid confusion:

"The diffusion coefficient is found to be highly correlated with the sodium sink due to the dimerization reaction mostly occurs at lower altitudes. (Plane, 2004)."

Fig. 4: What is shown here? What are the units of "radiant density"? The colour bar has not units. Excuse my ignorance, but I don't understand what this plot displays and it is not well explained.

Response:

The radiant density is a unitless relative quantity. The caption has been revised to:

"Figure 4. Logarithmic meteor radiant source distribution derived from the AO observations. The figure illustrates the relative frequency of meteor occurrence at different radiant directions 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 encountering Earth. The radiant distribution is derived from the number of meteor events. Figure reproduced from Li et al. (2022)."

Fig. 5: Does "meteoroid input" correspond to the mass or the occurrence?

Response:

Meteoroid input in Fig. 5 corresponds to the occurrence. The caption has been revised for clarity.

"Figure 5. Relative seasonal and latitudinal meteoroid input by meteor occurrence, inferred from the radiant source distribution shown in Figure 4."

Fig. 6: The MIF(m) curves (blue) in the top two panels should be identical, right? This is not the case?

OK, the caption says that the blue curves are linearly scaled, but why? The absolute differences are also important, right?

With this scaling, the reader does not know what the actual MIF(m) value is. The model should be judged by its agreement with the "measurement", right? Same comment for the bottom two panels.

Response:

The MIF(m) in Fig. 6 is scaled with the mean of MIF(s) by multiplying the mean of MIF(s). This procedure allows us to compare the scaled MIF(m) to MIF(s). As was mentioned several times in the previous responses, our study compares the curve of MIF(s) and MIF(m). Please refer to the figures at the end of this response.

Fig. 6, bottom panel: What are the discontinuities in MIF(s) caused by, e.g. around day 65 and around day 305? Are they expected?

Response:

The discontinuities result from missing days in lidar observations, because the ALO data is relatively sparse compared to the CSU data. As shown in Fig. 1, day 65 and day 305 are both at boundaries of the missing lidar days.

Line 323: "the estimated mass"

Which mass do you mean? The limiting meteor mass or the daily or annual meteoric mass input into the atmosphere?

Response:

The limiting mass of the Arecibo Radar. The corresponding sentence has been revised for clarity.

"Despite these estimations being based on various simplified assumptions that may lead to inaccurate results, the estimated limiting mass at AO is still at least two orders of magnitude smaller than the estimations of other facilities by similar means."

It looks like a solid line, not a dotted one.

Response:

It is indeed a solid line. The word 'dotted' has been removed.

How was this determined? What is the best result? This seems like an arbitrary scaling and I'm not sure what the results then really mean? Since the absolute value of the meteoric mass influx directly depends on the uptake factor, your mass estimates are not really robust, right? Perhaps I'm missing a point, but this seems to be a major weakness of your approach?

Response:

The optimal uptake factor is found by the value that leads to the smallest least square error between [MIF(s)/mean(MIF(s))] and MIF(m). It was not an arbitrary scaling as there exists an optimal solution, where the least square error between MIF(s)/mean(MIF(s)) and MIF(m) is minimized. Please refer to the figures at the end of this response for better illustration.

Response:

As was responded earlier, it is the optimal, but not an arbitrary, uptake factor that was found. Our approach provides a robust estimation of Na influx by comparing the relative seasonal variation of MIF derived from the modeling, lidar, and radar measurements. (MIF(s) from lidar measurements and numerical modeling; MIF(m) from radar measurements).

Response:

Since MIF(m) is a unitless relative quantity, its actual value cannot be produced. Measuring the actual value of MIF(m) might be possible, the community is still working towards this goal.

MIF(m) offers insights to the relative seasonal variation of the meteoroid material input based on radar measurements. Our study aims to reproduce this relative seasonal variation by MIF(s), which combines [NaHCO3] dimerization and uptake. Please refer to the figures at the end of this document for better illustration. As shown in Response Fig. 1 (at the end of this document), which illustrates the square difference between [MIF(s)/ mean(MIF(s))] and [MIF(m)], there exists one optimal solution.

Response:

This sentence is to indicate that the absolute value of MIF(s) is derived from the numerical chemistry model based on lidar Na measurements.

Response:

That is correct.

"Further, the WACCM, which supplied the background species to the NaChem, is an older version that does not fully incorporate the dynamics of each ion species."

Which WACCM version is it? Is there a version number?

Response:

WACCM6 in CESM2 version. The WACCM version is now specified in line 126.

"Despite our results showing good agreement between the MIF(s) and the MIF(m)"

Not in absolute terms, only regarding seasonal variations, right?

Response:

Correct. MIF(m) cannot be matched in absolute terms.

"Our results indicate that the uptake of sodium species onto meteoric smoke particles removes approximately three times more sodium than the dimerization of NaHCO3."

I don't think this really is a robust result. If you "empirically adjust" the uptake rate to get the "best results"? As I said, perhaps I am missing a point, but I think this conclusion cannot be drawn.
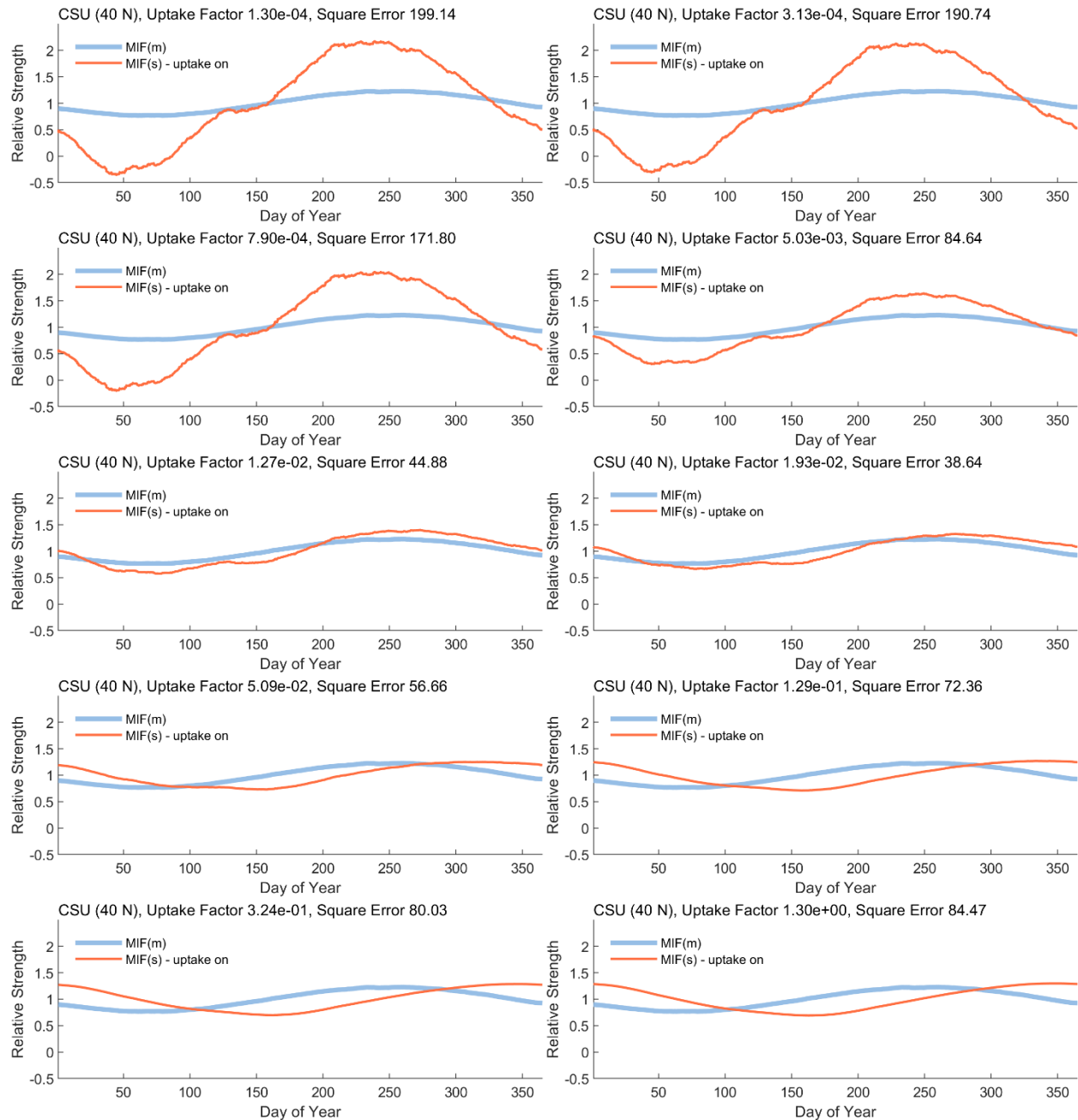
Response:

Now we understand why you think our approach is not robust because you think that we arbitrarily adjust the uptake to get the best results. This is not quite the full story or the right interpretation of our approach. As we mentioned/responded earlier, the uptake was not adjusted arbitrarily. It was found when the matching of the measured and simulated MIF has the smallest least square error. This ensures that the uptake needed for the best match is indeed the one for the best match. Please refer to the figures below for detailed illustrations.
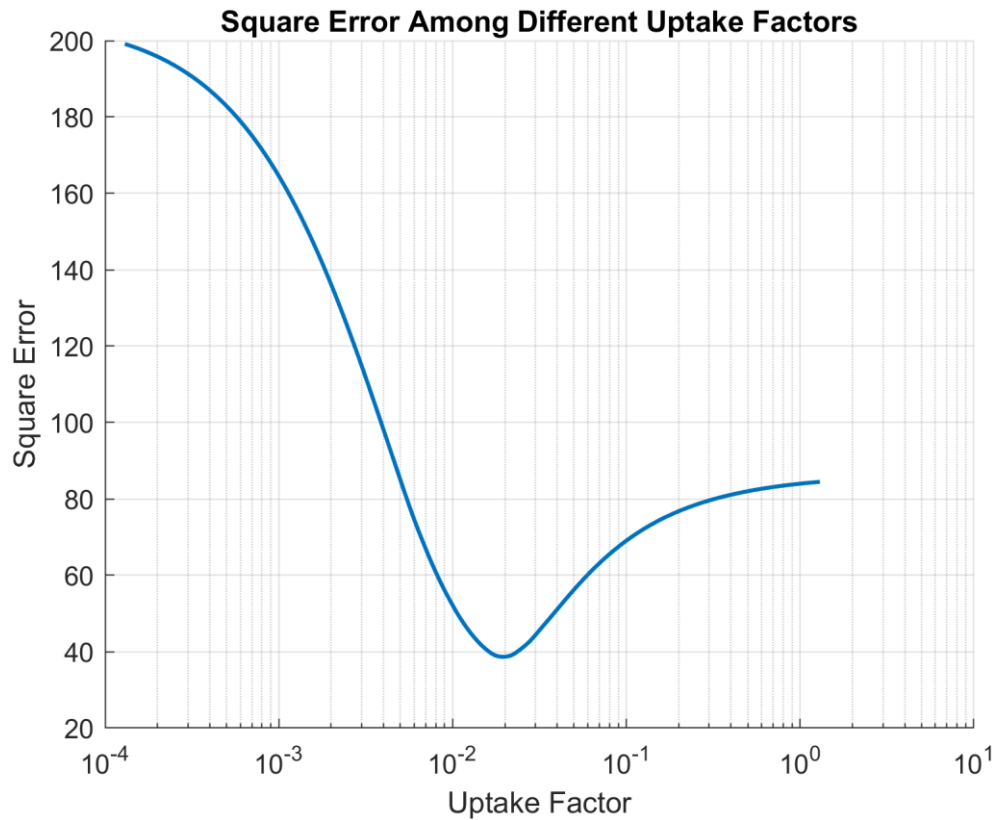
Response Fig. 1. This figure illustrates the square Error between MIF(s)/mean(MIF(s)) to MIF(m). It`s clear that there is an optimal solution at about $2x10^{-2}$. The square error is in arbitrary units.

MIF(m) is a unitless relative quantity, in other words, we are comparing the relative changes of MIF(s) and MIF(m) across different time periods. The MIF(s) is divided by its mean for easier comparison, and this operation does not affect the relative change of MIF(s) across different time periods.

To further illustrate the point, please refer to the Response Fig. 2.

Response Fig. 2. This figure depicts the comparing of [MIF(s)/mean(MIF(s))] (in orange) and [MIF(m)] (in blue) with different uptake factors. The y axis is relative strength, and the x axis is day of year. The uptake factor and the square error between MIF(m) and MIF(s) are listed on each panel. Among these figures, it's clear that when the uptake factor is 1.93×10^{-2}, the square error reaches its minimum.

After obtaining the best fits between MIF(m) and MIF(s), Fig. 6 in the manuscript is presented with mean of MIF(s) multiplied back to the curves, as the mean of MIF(s) also contains the information of the absolute values of the sodium injection rate. For example, with uptake on, the two curves on the first tile of Fig. 6 are centered at about 24000 n/cm^3/s. On the other hand, with uptake off, the two curves on the

second tile of Fig. 6 are centered at about 6000 n/cm^3/s. The absolute values of mean(MIF(m) illustrate that the sodium removal due to uptake is approximately three times the effect of dimerization.