We thank the reviewers for making very useful suggestions to improve the paper. Our point-by-point responses to the reviewers' comments and corresponding changes with line numbers are detailed below in blue text, and the changes are shown in the version of the manuscript with track changes.

Reviewer #2 comments (RC3):

This work is an implementation of transports of metallic ions (Mg^+, Fe^+, and Na^+) in WACCM-X for the purpose of understanding the effects of atmospheric motions on their distributions. The work lacks sufficient description of the implementation as well as scientific insights.

The implication of the transport effect, mainly described by equation (2), is questionable. There are terms missing as compared with Chu and Yu (2017), 2nd and 6th term in their eq(6). This is not explained. The effect of neutral wind (6th term) is especially important in the E region.

Response: The ion transport velocity described in equation 2 is an additional metal ion velocity term which has been added to the standard WACCM-X model. The 6th term of eq (6) in Chu and Yu (2017) is already included in the dynamical core of the WACCM-X model, and so is not included in equation 2 for simplification. We have therefore added the following sentence at Line 80 to make this clear: "Note that the term corresponding to transport is omitted from Equation 2, because advection by the neutral wind is already included in the dynamical core of WACCM-X."

The second term of eq (6) in Chu and Yu (2017) is the field-aligned term of the drift in electric field. We include this term in our model, but classify it as one of the ambipolar diffusion terms. This is consistent with Chu and Yu (2017), who stated: "The E•B term is not negligible, because it is important for field-aligned diffusion. This term is proportional to the electron pressure gradient along B. The electron and ion pressure gradient terms act in the same direction, **producing ambipolar diffusion**."

"Self-consistency" appears in numerous places but there is no explanation of what "self-consistency" really means, and what was not consistent in any previous model works. The difference of this work from that by Langowski et al. (2015) is not clear, except that the model used is WACCM-X instead of WACCM.

Response: see the response to reviewer #1.

Almost all conclusions were drawn based on comparisons of the distributions from model simulations with observations or other model runs. This is a poor way to gain much insight into any physical/chemical processes. Most of the conclusions are speculative, without any quantitative assessments. The benefit of modeling is to enable the examination of individual effects associated with different processes. If only the final results are examined, the value of modeling is not utilized much. Several examples are listed below:

Response: The main purpose of the present paper is to describe a new global thermospheric metal model with the ability to simulate the global transport of metallic ions. This is a challenging task in itself because of the very different time-scales of the various transport processes. Therefore, we mainly present here comparisons of the model with/without electrodynamic transport to illustrate the importance of including electrodynamic transport of the long-lived metallic ions, and then evaluate the model performance by comparing with the existing observations and simulations. We are grateful to the reviewer for the suggestions and ideas they have provided, which will doubtless form part of our further work with the new model. We now address the specific points in turn.

1. The authors argue that the "upward transport of Fe+ does not significantly contribute to changes of Fe," (line 152). To prove this, the contributions of Fe+ transport to the time tendency of Fe need to be calculated separately and compared with other effects.

Response: We have modified the relevant sentence in the revised manuscript to: "In general, changes in Fe (at densities > 1 cm^{-3}) do not appear to be synchronized with the upward transport of Fe^+, so that the vertical distribution of Fe in the transport run is similar to that in the control run."

Fe/Fe^+ ion-neutral coupling is important in the formation of thermospheric iron layers, as shown particularly by the work of Xinzhao Chu's group at UC Boulder. At present, there are many unsolved mysteries about this, which partly inspired us to develop the new model. However, as we stated above, this article mainly introduces our new global thermospheric metal model and its ability to simulate the global transport of metallic ions. As stated in the Conclusions Section of the manuscript "In the future, this new version of WACCM-X can be used to better investigate the effect of lower atmospheric dynamical processes on the formation of thermospheric neutral metal layers, by using the "specified-dynamics" version of the model (SD-WACCM-X)."

2. The authors argue that "uplift of metal ions" is "driven by "meridional wind," (line 196-197). This could be supported if the authors can demonstrate that the magnitude of uplift due to the meridional wind is indeed much larger than other wind components.

Response: The vertical ion velocity due to terms 1 - 4 of Equation 2 in the manuscript, and due to the neutral wind (term 1 + term 2) are shown below in Figure R1 for March and June. The first and second terms are the Lorenz force-induced V×B drift and the neutral-ion collision-induced ion motion along the magnetic field lines, respectively. The lowest panels in Figure R1 show the drift velocity resulting from the combined effect of the first and second terms. Figure R1 shows that the drift velocity caused by the neutral wind has a significant latitudinal distribution, in which V×B drift mainly operates from 110 km to 140 km, and transport along the magnetic field line mainly works above ~130km. Therefore, from the continuity equation, the uplift in the mid-latitudes of the summer hemisphere is mainly driven by the vertical ion velocity due to the neutral wind.

We have rephrased the sentence in the revised manuscript to: "This appears to be caused by the vertical ion velocity due to the neutral wind (first and second terms in Eq. 2), with the monthly mean drift velocities shown in Figure 1".

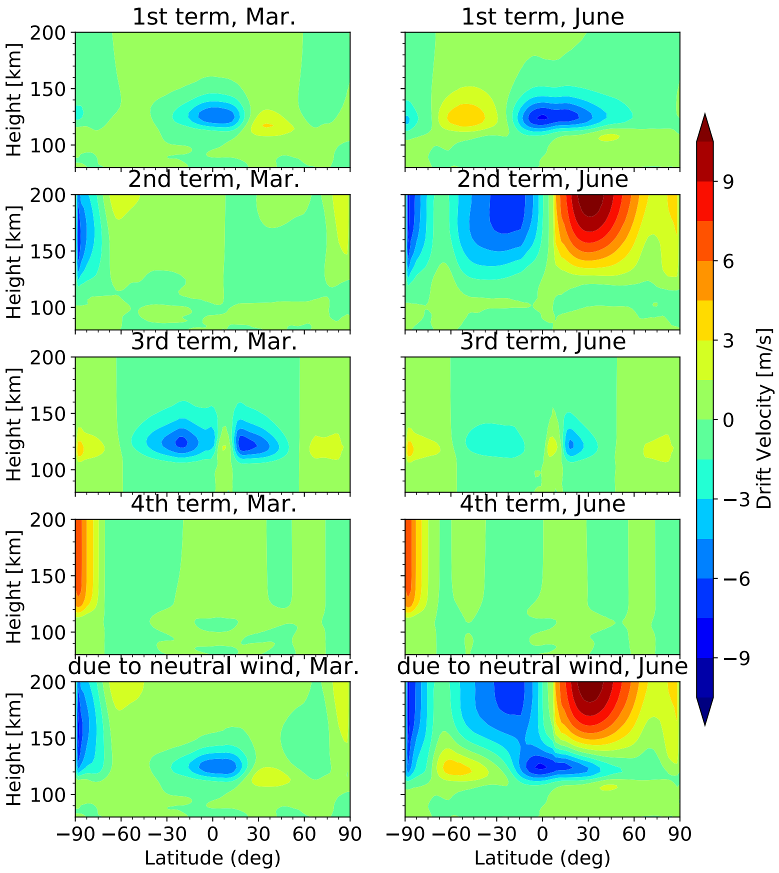

Figure R1: The monthly and zonal mean of vertical ion velocity due to terms 1-4 of Equation 2, and due to neutral wind in March and June.

3. The authors believe that this uplift can "explain the summer maximum occurrence of thermospheric sodium layers." If that were the case, then the contribution of the uplift term to the production of neutral sodium would show being much larger than others. Furthermore, the authors did not even show that the model actually produced a summer maximum of Na in the thermosphere. In addition, it is not true that thermospheric Na appears mostly in summer. As Cai et al. (2017) stated, the thermospheric sodium appeared at this Southern Hemisphere site mostly in spring and fall and rarely in summer and winter.

Response: The model simulations show that the peak altitude of Mg^+ in the summer hemisphere at ~40° is ~10 km higher than at other latitudes, which is very similar to the SCIAMACHY observations (Langowski et al. 2015). The Beijing and Utah State University lidar stations are located at ~40° N. Both stations report that the occurrence of high-altitude sporadic Na layers (Nas) and lower thermospheric Na layers peak during summer, which is consistent with the latitudinal distribution of the metal ions we simulated. So we express it as "this is in good agreement with the summer peak occurrence of lower thermospheric neutral Na layers observed by mid-latitude lidars (Wang et al., 2012; Dou et al., 2013; Yuan et al., 2014; Xun et al., 2020).".

Cai et al. (2017) used model simulations to investigate the summertime Na variations at mid-latitudes, in particular the occurrence peaks of the high-altitude Nas during summer at Utah State University lidar station. Cai et al. (2019) used simulations to investigate thermospheric sodium layers (TSLs) at Cerro Pachón, Chile ((30.25°S, 70.74°W). Indeed, they found that TSLs appeared at Andes Lidar Observatory (ALO) mostly during equinox. However, ALO is located at 30.25°S (20°S in magnetic latitude), which is different from the phenomenon described by the present paper. At the same time, this shows the diversity of TSL formation mechanism. Further work on the geophysical mechanisms of their formation is clearly required.

As stated in the Conclusions Section in the manuscript "Previous research has established that thermospheric neutral metal layers are modulated by dynamics (e.g. gravity waves, atmospheric tides). In the future, this new version of WACCM-X can be used to better investigate the effect of lower atmospheric dynamical processes on the formation of thermospheric neutral metal layers, by using the "specified-dynamics" version of the model (SD-WACCM-X)."

Most of the thermospheric Na observed showed a downward phase progression similar to that of diurnal or semidiurnal tides. Since tides are well resolved in WACCM-X, this feature should be reproducible if the model results are to be believed. On the other hand, the thermospheric Fe at high latitude showed variations on much shorter timer scales (Chu and Yu 2017). Comparison with Fe observations with a model that cannot resolve the short-time scale dynamics (gravity waves) is not meaningful.

Response: We have not proposed that the present model is appropriate for studying the effects of short-wavelength gravity waves on the thermospheric Fe layers. For that, a higher resolution (both horizontally and vertically) version of WACCM-X will be needed. For example, Liu et al. (2014) developed the first mesoscale-resolving whole atmosphere general circulation model (high-resolution WACCM), which can simulate mesoscale gravity waves. A combination of our metal ion transport model and this regionally refined general circulation model should be available in the near future for studying metallic layers.

Liu, H.-L., McInerney, J. M., Santos, S., Lauritzen, P. H., Taylor, M. A., and Pedatella, N. M. (2014), Gravity waves simulated by high-resolution Whole Atmosphere Community Climate Model, Geophys. Res. Lett., 41, 9106– 9112, doi:10.1002/2014GL062468.

The reviewer is correct that a tidal influence is observed in the model. Figure R2 shows the vertical ion velocity due to terms 1-4 of Equation 2 in the manuscript, and due to neutral wind (term 1 + term 2). The first and second terms are related to the background wind, that is, the neutral wind tides, and the tidal influence on the vertical ion velocity is clear in the figure. Figure R3 shows the diurnal variation of Mg^+, demonstrating that atmospheric tides strongly influence the distribution and transport of the metal ions. The corresponding Mg diurnal variation is shown in Figure R4. The topside of the Mg layer shows significant diurnal variation.

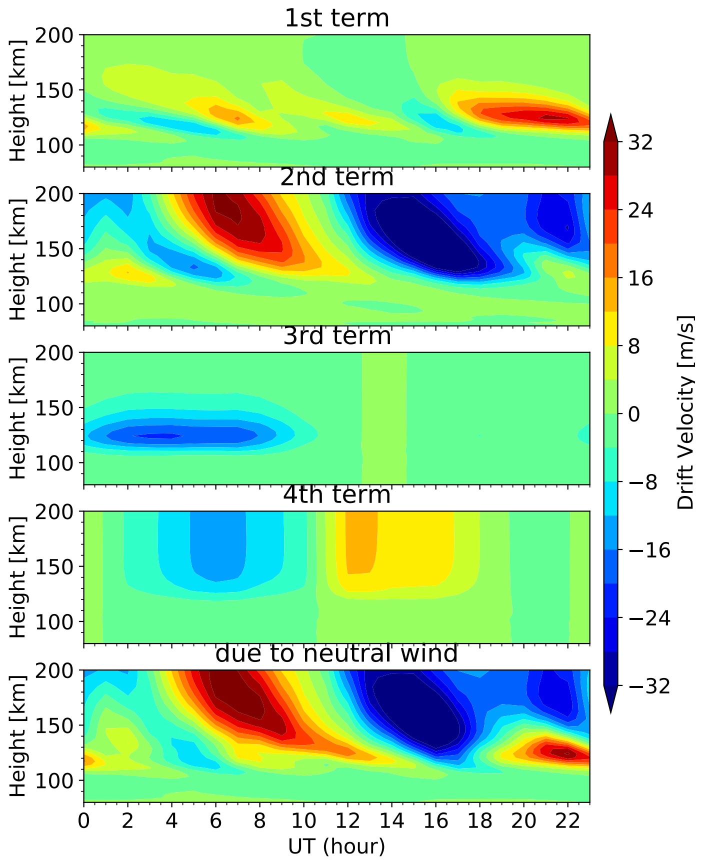

Figure R2: The vertical ion velocity due to terms 1-4 of Equation 2, and due to neutral wind.

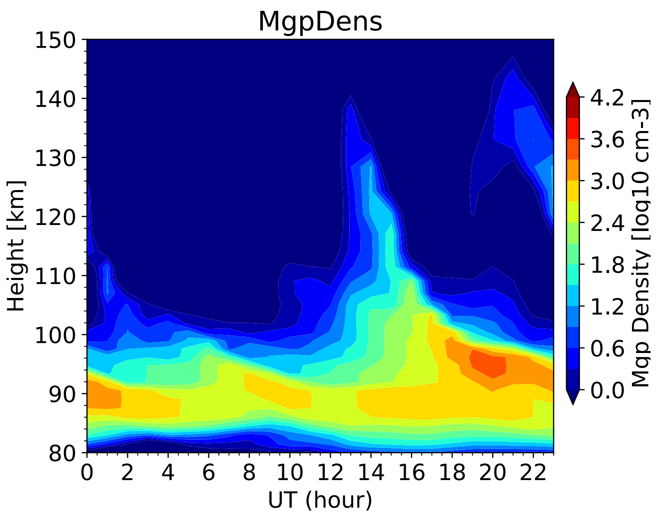

Figure R3: Time and altitude distributions of Mg^+ number density.

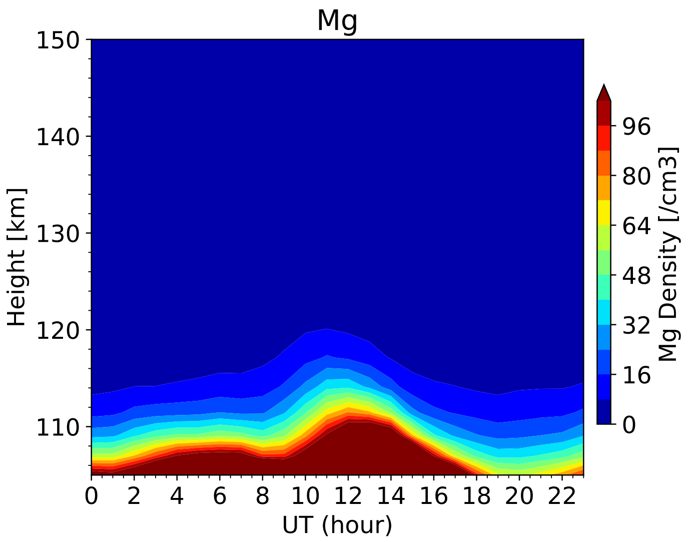

Figure R4: Time and altitude distributions of Mg number density above 105 km.

Other minor points

According to Liu et al. (2018), WACCM-X "neglects the influence of ion-neutral collisions on ion motion perpendicular to B," which is significant "in the E-region where the O+ lifetime is short and transport is unimportant." Since E-region is an area of focus in this study, how does this neglected effect influence the simulation result?

Response: As described in Section 2.2.2 of Liu et al. (2018), it is reasonable to keep O^+ in chemical steady-state equilibrium in WACCM-X because the O^+ lifetime in the E region is short (because of its rapid reaction with N_2), and transport is less important. Note that transport of metal ions in our model includes ion motion perpendicular to B (refer to equation 2 in the manuscript).

169-170: TIFe and TINa are not defined. In fact, there is no point in using such acronyms as they are mentioned only once and they are not widely accepted.

Response: Suggestion incorporated.

Figure 3e needs to adopt a different color range to show more structure.

Response: Thanks for this suggestion. We have updated Figure 3 using different color ranges.

I suggest that the authors cite the following paper, which is the first report of thermospheric Na in the southern hemisphere. Furthermore, the temperature and wind reported in this paper is a rare dataset that can be used to validate model simulations trying to reproduce the thermospheric Na.

Liu, A. Z., Guo, Y., Vargas, F., and Swenson, G. R. (2016), First measurement of horizontal wind and temperature in the lower thermosphere (105–140 km) with a Na Lidar at Andes Lidar Observatory, Geophys. Res. Lett., 43, 2374– 2380, doi:10.1002/2016GL068461.

Response: This reference has now been added.