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 #3 comments (RC1):

Understanding the global metallic ions transport in the thermosphere is important for the field. There is no doubt that WACCM-X is one of the excellent global-scale models to study metallic ions’ transport. Overall, the work on this subject is worthy for publication. However, there are a few points that are not clear enough in the manuscript. I would like to suggest to the authors do a minor revision to clarify all the comments. Here are the detailed comments,

Major Comments:

First and foremost, the ambipolar diffusion velocity in equation 2 of the ion velocity equation adopts the equations (5.54) and (5.70) in Schunk and Nagy (2000), which include the effects of the neutral collision, the number density gradient, and temperature gradient, the gravity force, and the viscous stress along with the magnetic field line. Since the equation 5.54 is derived from the momentum equations 5.51 and 5.52, the neutral-ion momentum transform has been already taken into account. If the authors directly use equation 5.54 in Schunk and Nagy (2000), that could lead to double counting neutral wind effects in equation 2 in the manuscript. The ambipolar diffusion equation shows up as different formulas in various literature. It has to be careful to use them directly, and a strict mathematical derivation is required.

Response: We very much agree with the reviewer that a strict mathematical derivation is required. For this reason, when we used equation (5.54) in Schunk and Nagy (2000), we removed the field-aligned neutral wind in equations (5.54). In the model, metallic ions should be treated as minor ionic species at higher altitudes ($\geqslant$150 km), and their movement will be influenced by the major species. In our formulation, we separate the bulk motion transport (neutral wind and various drifts) from those due to kinetic effects (pressure balance, including gravity). In order to avoid a misunderstanding, we have changed "given by" to "derived from" in the revised manuscript.

In section 3.1, the peak altitude of Mg+ is ~10 km higher in the summer hemisphere, and the authors suggest that it is caused by the summer to winter neutral wind that transports the metallic ions along with the magnetic field line. Although the vertical drift velocity is provided, the evidence is not enough to support this inference. Firstly, the authors need to clarify the contributions of electric field and neutral wind to the upward drift velocity of ~5 m/s in line 98. Does it mean the ~5 m/s upward drift velocity is only driven by neutral wind? Secondly, since the magnetic field line is roughly symmetric on both sides of the dip equator, we would expect the downward drift velocity on the other side. Some features in Figure 1 may indicate the downward drift, however, more clear evidence should be provided. Thirdly, due to lack of collision, the weak ion-neutral collision may lead to less effect of neutral wind in higher altitudes, but the upward drift velocity somehow increases with respect to altitude in Figure 1. If it is caused by the increasing winds, related evidence should be provided.

Response: Thank you for this comment. “The upward drift velocity of ~5 m/s” in line 98 of the previous manuscript is only driven by the neutral-ion collision-induced ion motion along the magnetic field lines. Indeed, the downward drift velocity is on the other side (see the second line of panels in Figure R1). Previously, Figure 1 mainly showed the upward drift velocity, but in the revised manuscript we illustrate both the upward and downward drift velocity. Please see the response to Reviewer #2 where this figure appears.

Compared with Figure 1, Figure 2 shows the Mg+ is barely above 100 km at 10 LT for all months, and much lower than those in Figure 1. It is skeptical because the wind and electric field show no upward effects at all, especially, the diurnal variations of Mg+ in section 3.2 show the Mg+ ions are easily transported to higher altitudes by the fountain effect around the local noon. Is there any explanation, and further investigation on this feature?

Response: The pronounced difference in Fig. 2 is due to the diurnal variation of ion electro-dynamical transport. Figure 4e in the revised manuscript shows the diurnal variation of Mg^+ number density near the dip equator as a function of local time. The Mg^+ drifts down towards the main layer at 10 LT. The figure shows that the fountain effect transports metal ions upward from 12 LT. The dominant chemical reactions at different heights are different, in particular the rapid neutralization of Mg^+ at lower heights (below 100 km, neutralization occurs with a time constant < 1 hour (Whalley et al., 2012)). In addition, as mentioned above, tides and other dynamic processes also play an important role in ion transport, and these vary with latitude.

In section 3.3, sentence “…, the ions at subtropical latitude (orange line) are transported upward to a small extent at midday, but transported downward to a lower height (~1 cm−3 at ~100 km) at March …, which is in reasonable agreement with the downward drift of the fountain effect along the magnetic field lines at midnight.” is questionable. The dynamo effect originates from the strong ion-neutral coupling in the lower E region, and the electric field produced by the dynamo effect could have substantial effects on the vertical transport of ions in higher altitudes. In the mid and low latitude region, the electric field may not be that important below 120 km, compared with neutral winds. In other words, neutral winds could be the dominant factor that determines in the vertical motion below 120 km in the mid and low latitude region. I would like to suggest the author examine the wind and electric field at March Equinox and June Solstice, and calculate the vertical drift velocities driven by neutral wind and electric field, respectively. In addition, it is hard to judge what factors determine the Fe+ profile shape for the orange and green lines. It’s better to extend the discussion on the role of electric field and neutral winds.

Response: This is a good suggestion. The vertical drift velocity due to terms 1 - 4 of Equation 2 in the manuscript, the sum of the drift velocities, and the neutral vertical velocity at 12 LT at March Equinox and June Solstice are shown in Figure R5. 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 third term is the Coulomb-force-induced ion drift along the E direction, and the fourth term is the E×B drift. Figure R5 shows that the drift velocity has a significant latitudinal distribution, in which V×B drift and Coulomb-force-induced drift are most significant from 110 km to 140 km (1st term and 3rd term), and transport along the magnetic field line and E×B drift are most significant above ~130km (2nd term and 4th term). At 12 LT, in general, the vertical ion velocity driven by electric field (which is responsible for the fountain effect) plays a dominant role at low latitudes, while the vertical ion velocity due to neutral winds is dominant at mid-latitudes.

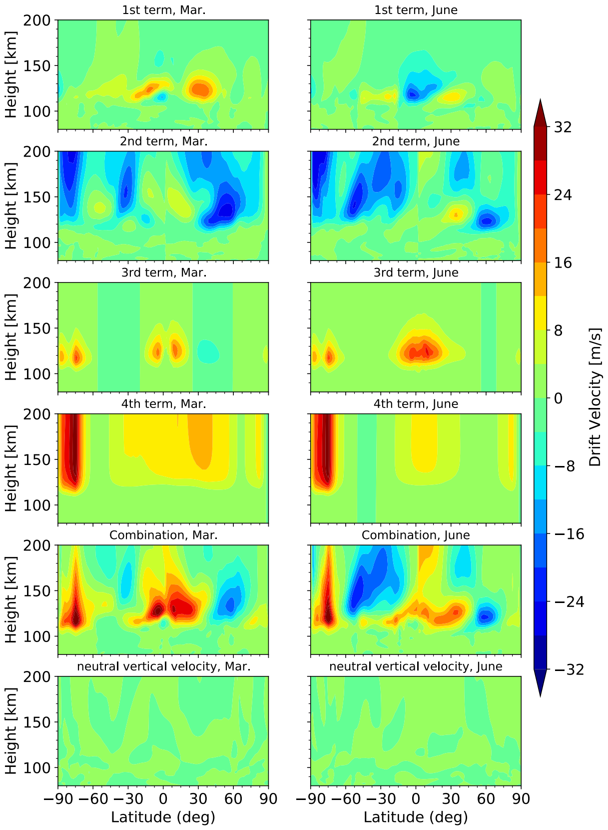

Figure R5: The vertical ion velocity due to terms 1-4 of Equation 2, the sum of the ion velocities, and the neutral vertical velocity at midday (12 LT), at March Equinox and June Solstice.

In section 3.4, what are the initial global number densities and distributions of Fe+, Mg+, and Na+? The studies in Huba et al (2019) show that there is not much difference between the transports Fe+ and Mg+, please refer to Figures 1 and 2 in Huba et al (2019). To clarify this issue, it's better to compare the vertical drift velocities of Fe+ and Mg+.

Response: The metal atoms and ions were initialized from a long-term simulation of WACCM-metals (e.g., Feng et al., 2017) and interpolated to the WACCM-X vertical grids with zero metal neutral/ions values above 6×10^{-6} hPa. Their initial distributions are roughly Gaussian-shaped layers with peak heights between 90 and 100 km, similar to the Fe and Fe^+ from the control run in Figure 5 (dotted/dashed lines).

Figure R6 shows the altitude dependence of several transport coefficients (α defined in the same way as in equation 3 of Huba et al. (2019)). The coefficients of Mg^+ and Fe^+ are pretty similar, so that our conclusion is similar to Huba et al (2019): “There is more than a factor of 2 difference in the masses of Fe^+ and Mg^+, the difference in the α factors is only ∼10%”

The mass separation in WACCM-X is caused by the mass-dependent transport terms, particularly, molecular diffusion which does not appear to have been included in Huba et al. (2019) and should not be ignored above the turbopause. The WACCM-X molecular diffusion coefficient for minor species is described in the first WACCM-X paper (Liu et al. (2010), equation 5).

$$D_j = \frac{\sqrt{T}}{\rho}\overline{m}\sqrt{\left(\frac{1}{\overline{m}}+\frac{1}{m_j}\right)\frac{1}{Av}}1.52\times10^{20}\ \mathrm{m^2s^{-1}} \qquad (5)$$

Molecular diffusion will displace the species heavier than the background atmosphere (i.e., 29 amu.) downward.

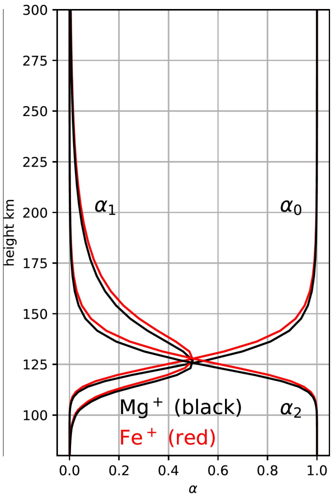

Figure R6: α defined same as the equation 3 in Huba et al. (2019). The figure is similar to Figure 1 of Huba et al. (2019).

Feng, Wuhu, Bernd Kaifler, Daniel R. Marsh, Josef Hoffner, Ulf-Peter Hoppe, Bifford P. Williams and John M. C. Plane, Impacts of a sudden stratospheric warming on the mesospheric metal layers, J. Atmos. Sol.-Terr. Phys., http://dx.doi.org/10.1016/j.jastp.2017.02.004, 2017.

Minor Comments:

Line 35, “thermospheric metal atom” -> “the thermospheric metal atom”

Response: Corrected.

Line 43, “affects of ion” -> “effects of ion”

Response: Corrected.

Line 80, “a major sources” -> “a major source”

Response: Corrected.

Line 86, “Na^+, Fe^+ and Mg^+”->” Na^+, Fe^+ , and Mg^+”

Response: Corrected.

Line 102, “which shows a minimum” -> “which show a minimum”

Response: Corrected.

Line 115, “The modelled” -> “The modeled”

Response: ACP uses UK English so we have not made this change.

Line 120, “Diurnal variation of” -> “Diurnal variations of”

Response: Corrected.

Caption Figure 3. “… The white dashed lines indicates the position of the the dip equator.” -> “… The white dashed lines indicate the position of the dip equator.”

Response: Corrected.

In Figure 4, the caption says the time is UT, but the titles of all subplots are LT. It is confusing. Please make a consistent statement.

Response: Although UT and LT are the same at latitude 0°, we agree this is confusing. We have changed them to UT in Figure 4.

Line 170, “is thought to be related” -> “are thought to be related”

Response: Corrected.

Line 173, “Figure 7 and 8 compares” -> “Figure 7 and 8 compare”

Response: Corrected.

Line 184, “charge transfer of” -> “the charge transfer of”

Response: Corrected.

The axes of all figures are not friendly. Please add minor ticks in y-axis. Please add ticks from the low limit to the up limit of every axis.

Response: Thanks for this suggestion. We've updated the axes of all the figures to make them more user-friendly.

The x-axis of Figure 4 and Figure 8 better shows from 0 to 24 with 2 or 4 hours step.

Response: Thanks. Now changed.