Impact of Enhanced EUV Flux Impact on Upper Atmosphere of Earth-like Planets Using GITM

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Abstract

Exoplanet habitability is one of the focuses of modern astronomy, with a number of future missions dedicated to this field. A key aspect in the evolution of planetary atmospheres is the ability of exoplanets to retain their atmosphere over their lifetime. We use the Global Ionosphere and Thermosphere Model (GITM) to study the impact of enhanced EUV flux on the upper atmosphere of close-in Earth-like planets. As orbital distance between a planet and a host star decreases, the EUV radiation experienced by the planet increases. GITM is used to solve for various state variables that describe the conditions of the upper atmosphere, including O^+, N^+, & e^- densities, ion velocities, Pedersen conductance, and joule heating. We discuss the response of these state variables to the enhanced EUV flux, as well as loss rates of O^+ in the ionosphere. Evidence of an inflated atmosphere due to enhanced EUV flux is presented. The results of this study are beneficial to understanding how habitable atmospheres may exist and evolve for close orbit exoplanets.

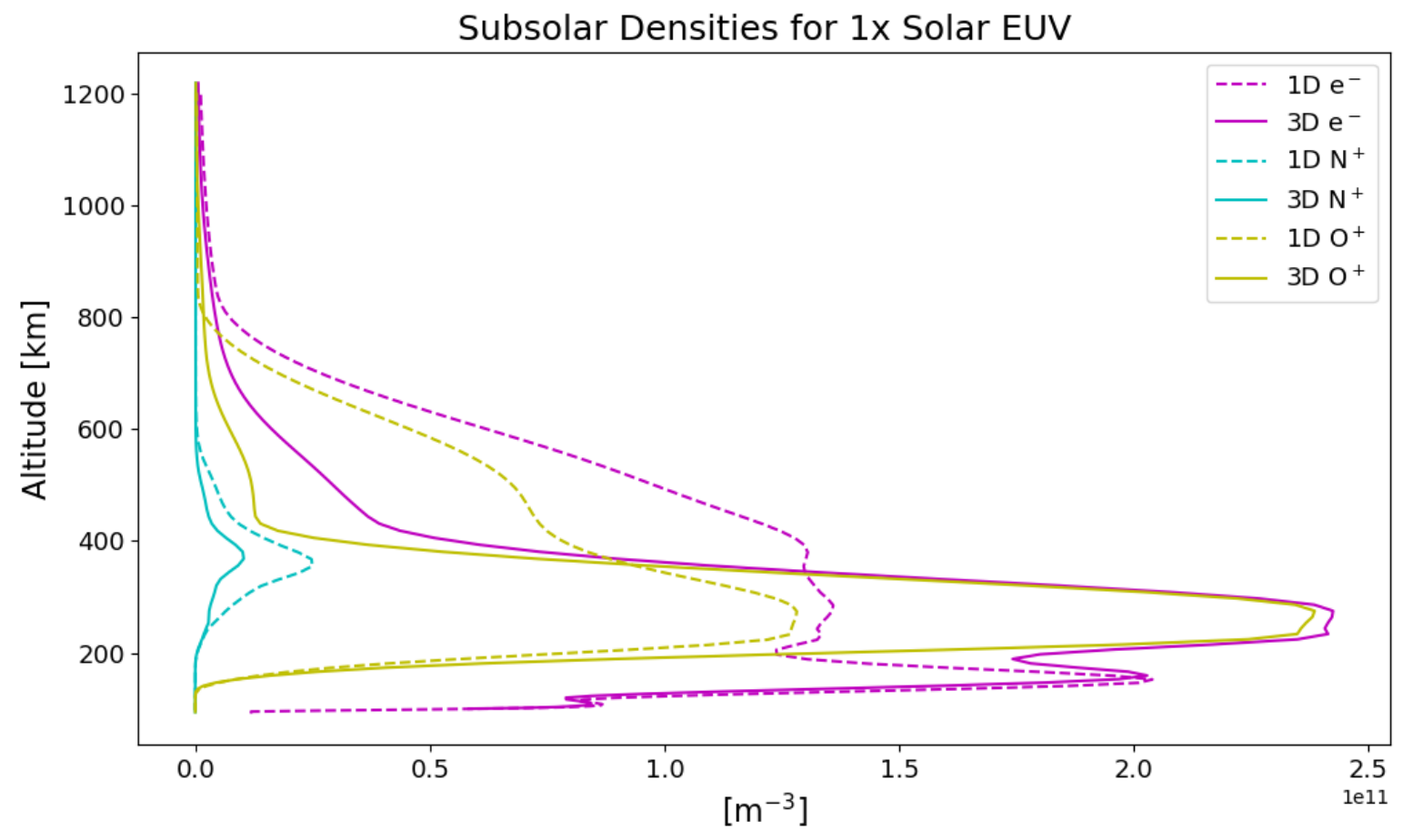
Methods

- GITM is a self-consistent, multifluid, 3D model for the upper atmosphere. It is also capable of modeling 1D cases
- Uses a spherical grid, horizontal resolution is 11.25° longitude by 5.625° latitude. Altitude resolution varies with scale height, given by:

$$h = \frac{k_b T}{mg}$$

- Lower boundary is assumed to be typical of Earth's ionosphere. Input EUV flux determines how system evolves
- We compare 1D and 3D cases to demonstrate a need to explore 3D models more deeply
- Baseline $F_{10.7}$ flux = 150 sfu (10^{-22} $Wm^{-2}Hz^{-1}$)
- Scale this value by the following factors: 1, 5, 7, 8, 9, 10, 50, 100

1D vs 3D



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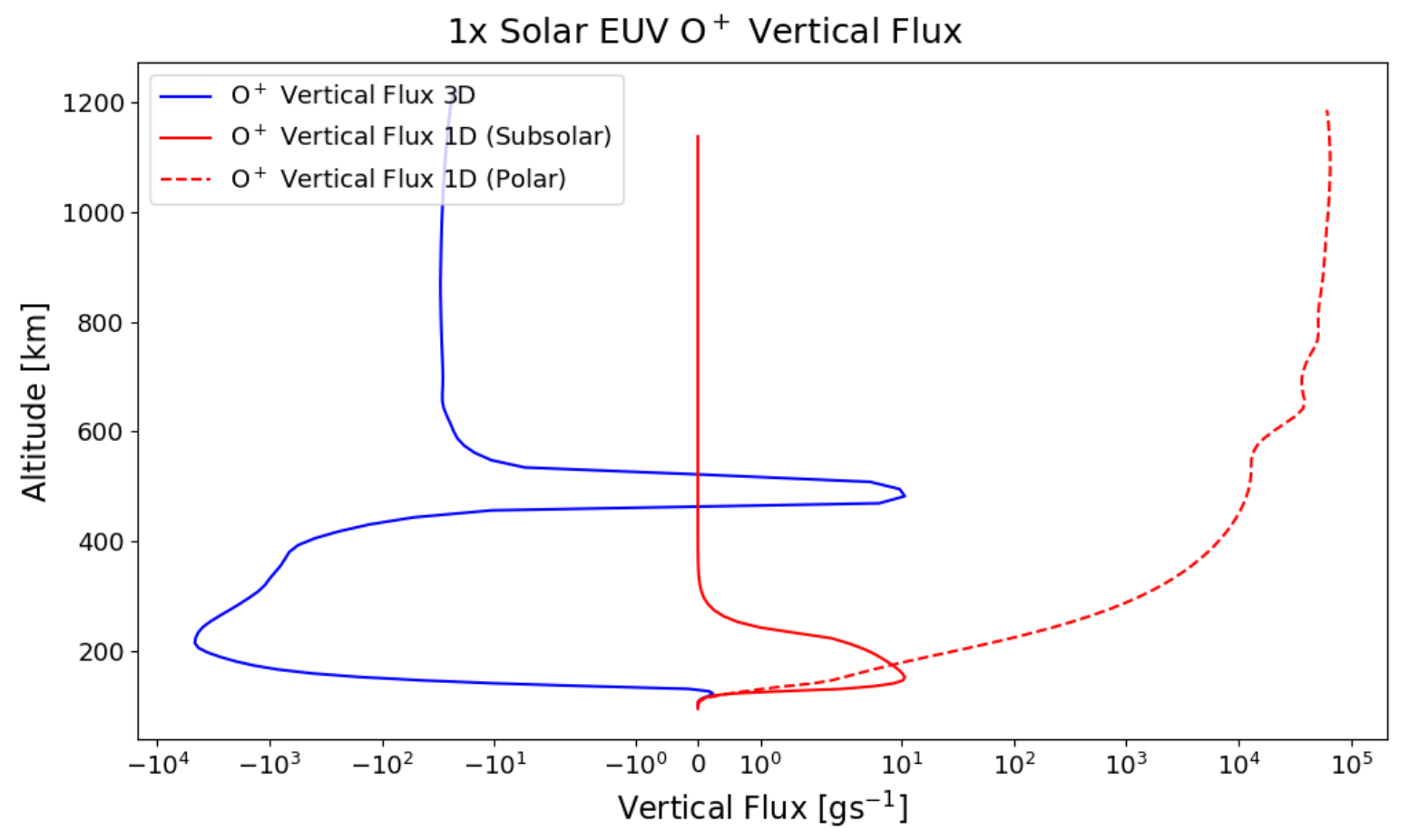

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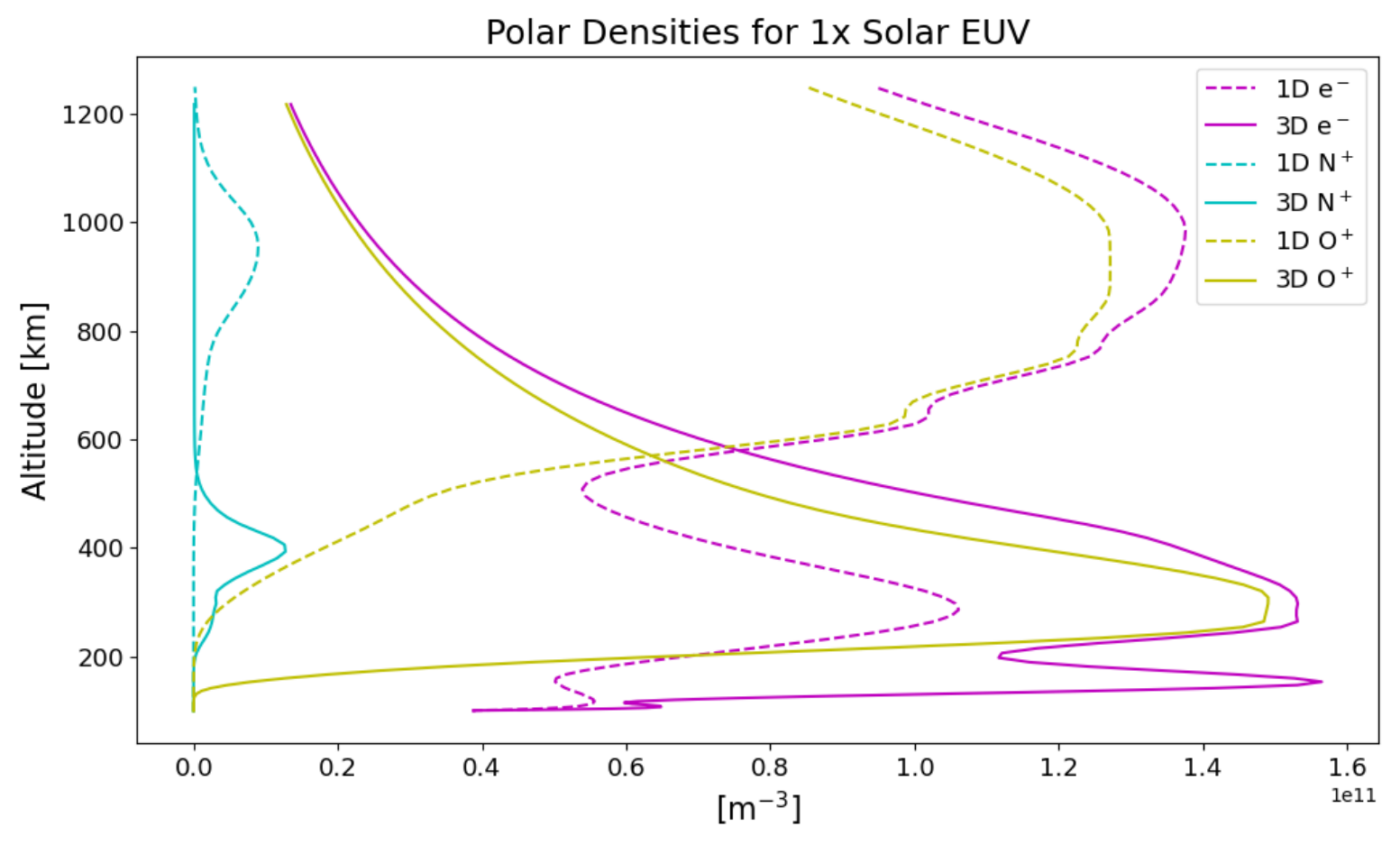
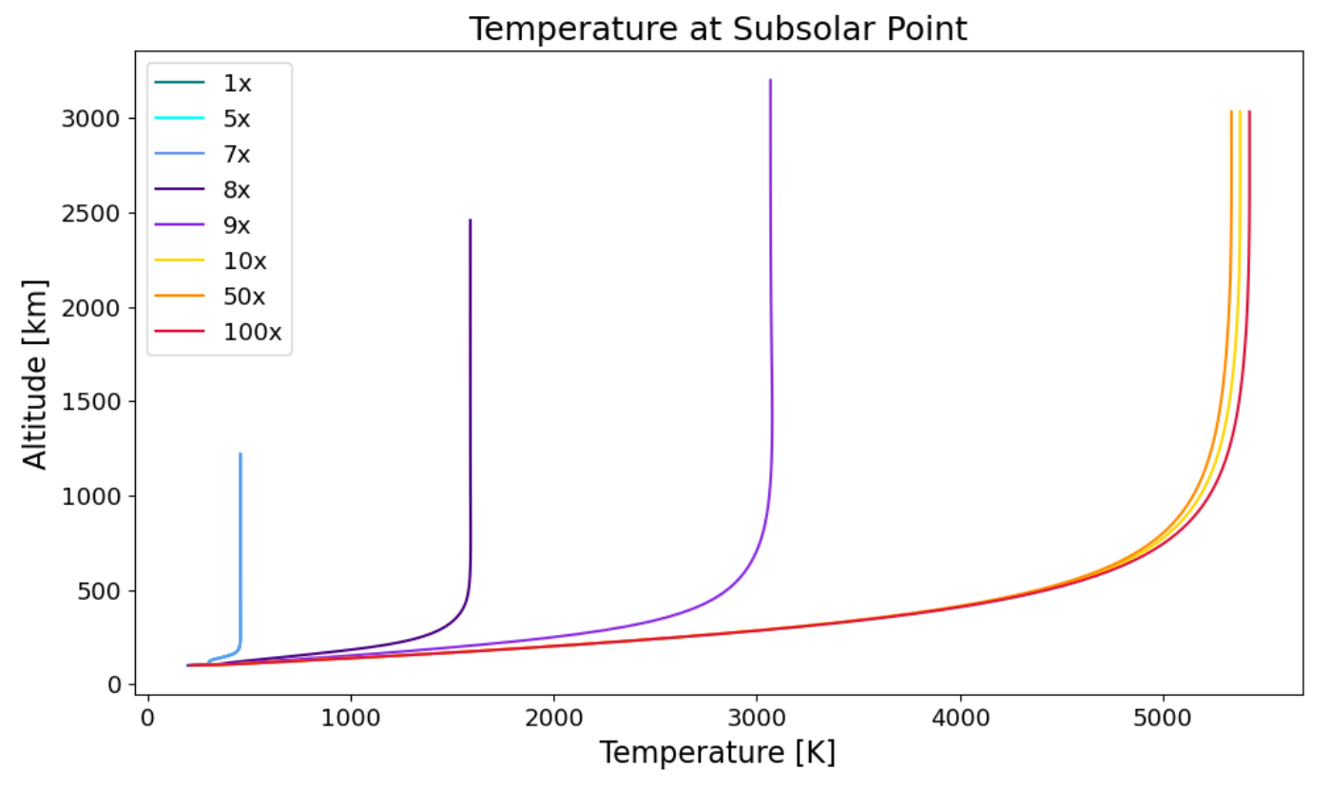


(2)

We compare the results of 1D and 3D simulations. Figures (1) and (2) show important species densities at subsolar and polar locations. Figure (3) shows the vertical O^+ flux: in blue, the 3D simulation, in red, the vertical flux calculated using subsolar vertical motion as a global average (solid), and using polar vertical motion as the global average (dotted). The same comparisons were made for a scale factor of 8 with similar results.

Subsolar Profiles



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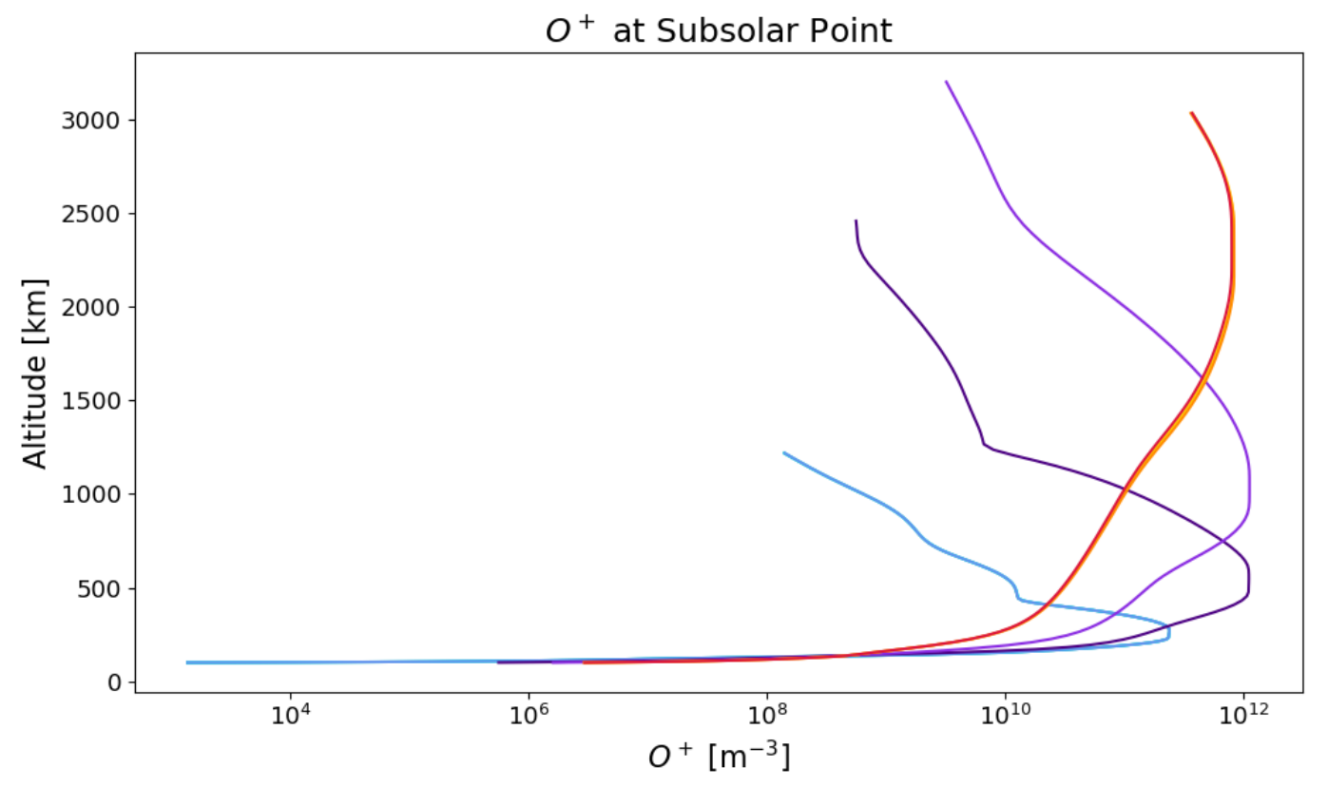

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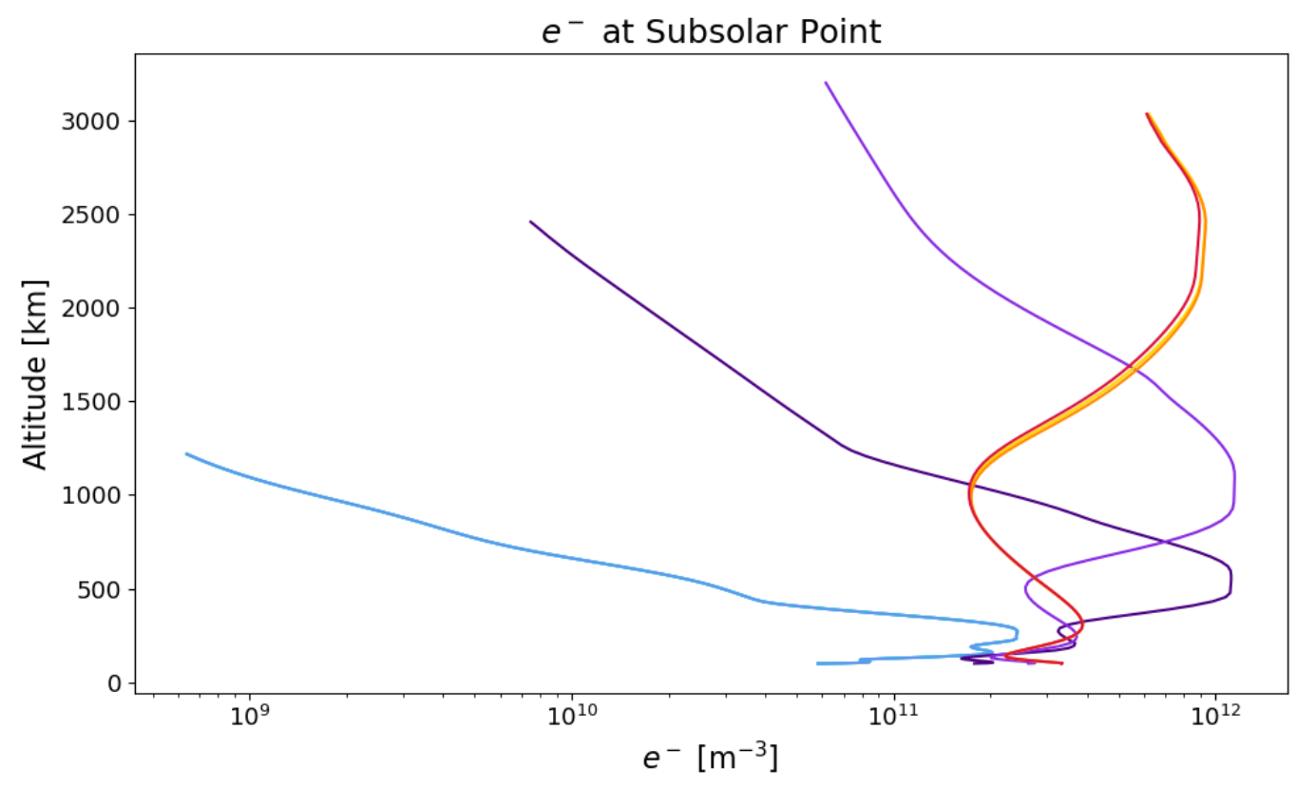


(3)

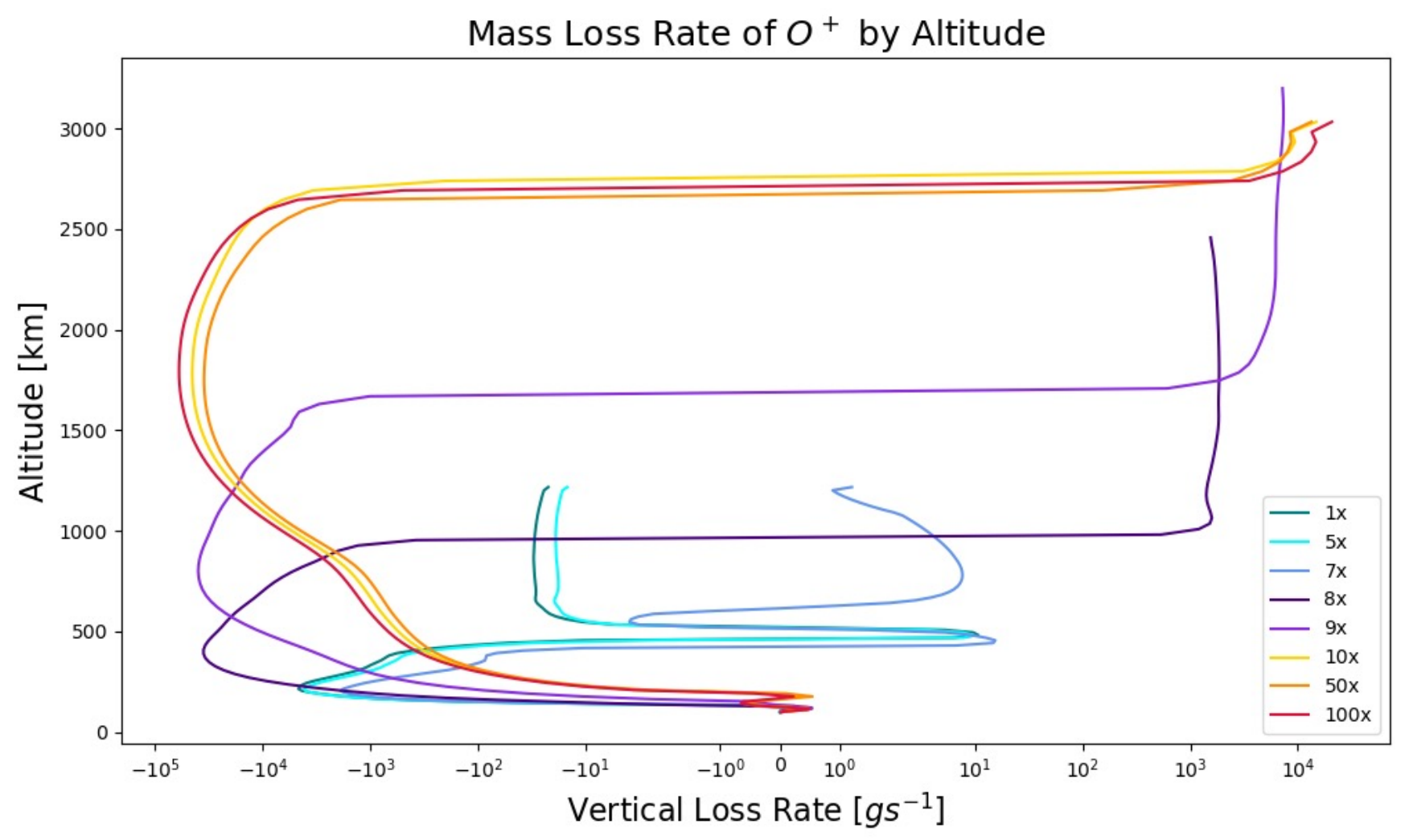
Figure (1): Temperature variation by altitude for each enhanced EUV flux. Scale factors 1, 5, and 7 are overlapped on top of each other. Scale factors 10, 50, and 100 appear similar but not identical.

Figure (2): O^+ number density variation by altitude for each enhanced EUV flux. Scale factors 1, 5, and 7 are overlapped, 10, 50, and 100 produce similar but not identical results

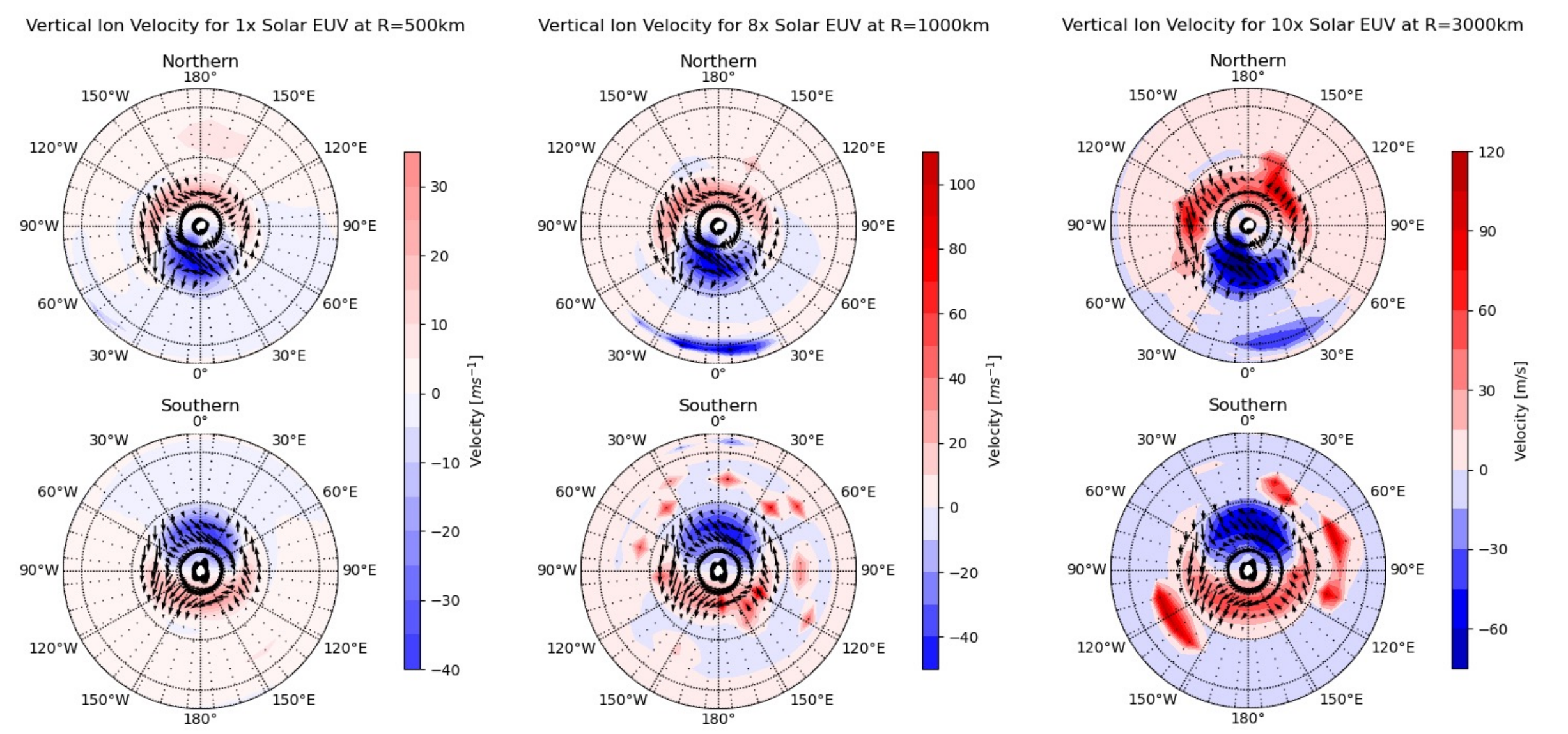
Figure (3): e^- number density variation by altitude for each enhanced EUV flux. Scale factors 1, 5, and 7 are overlapped, 10, 50, and 100 produce similar but not identical results

It is observed that the ionosphere expands with increasing EUV flux, with peak electron density and O^+ ion production occurring at higher altitudes. However, the number density appears to be maximized for enhanced flux scale factors greater than 7. The 1, 5, and 7 scale factors being identical in these data is of concern and being re-examined for potential issues.

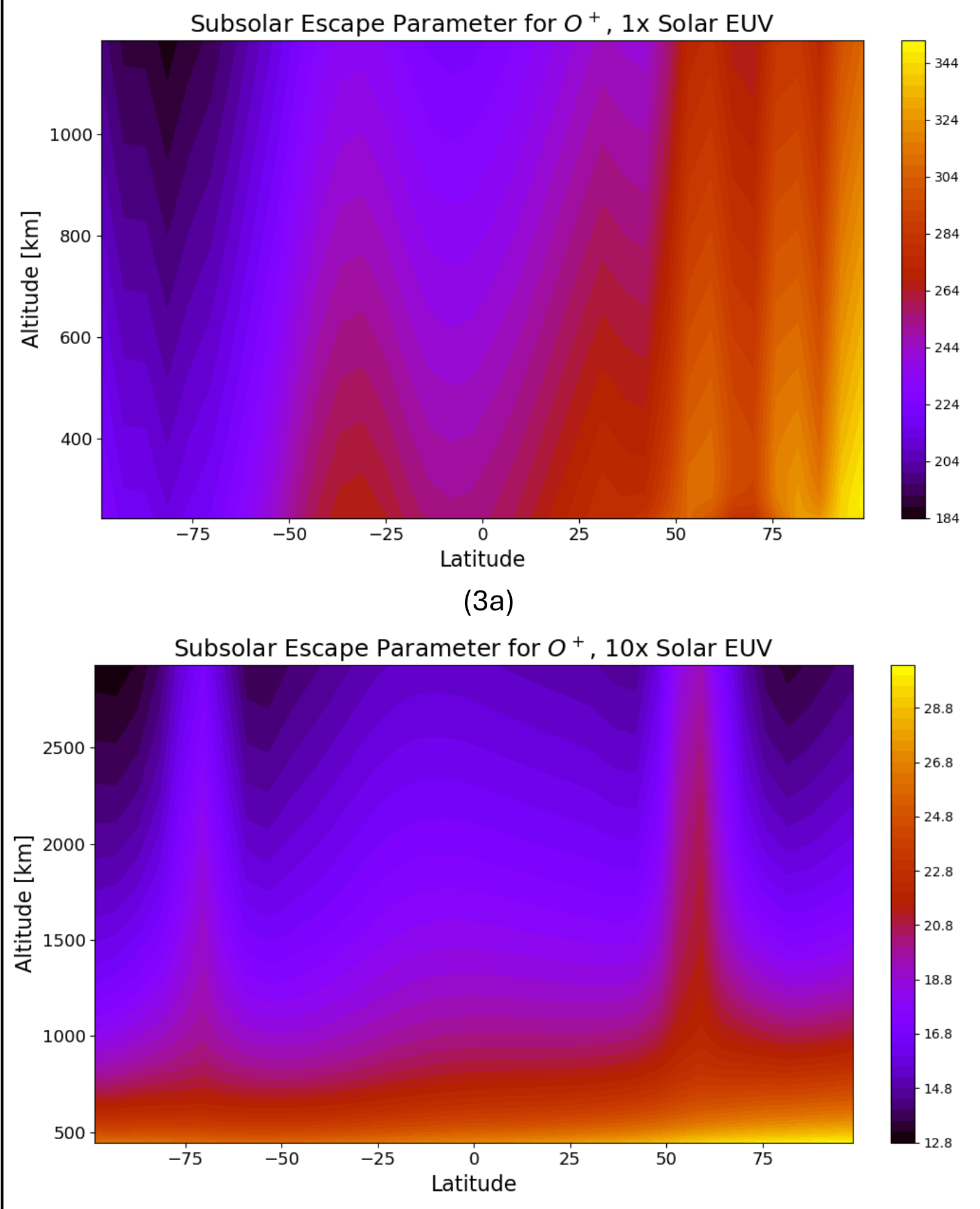
O⁺ Escape



(1)



(2a) (2b) (2c)



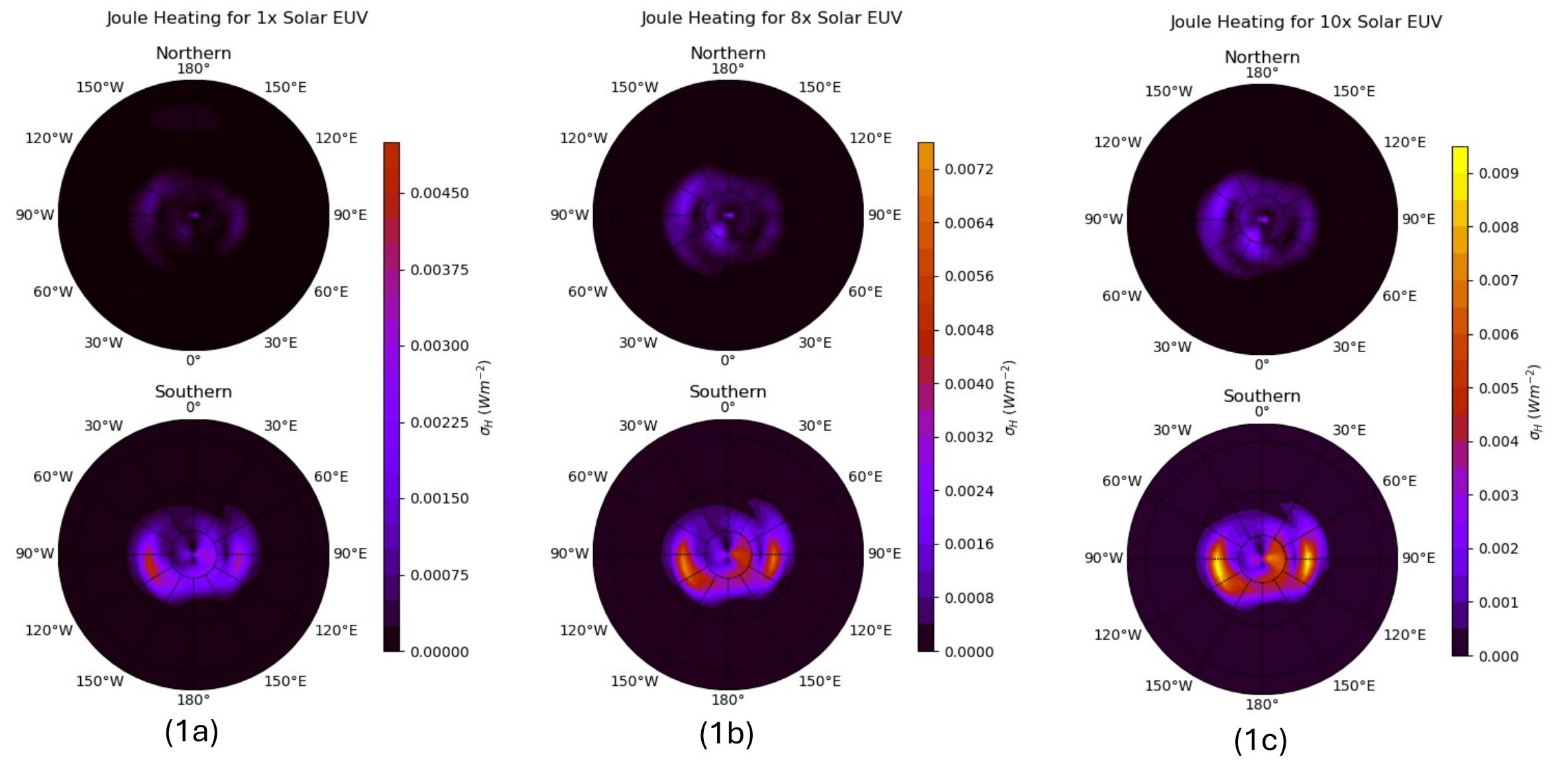
(3a) (3b)

Figure (1): Vertical O+ flux for each EUV scale factor. We observe positive vertical motion at the top of the ionosphere for the lower scale factors, although the 7x case also shows another peak higher up. For the higher scale factors we observe a larger peak that extends vertically to the top of the simulated region, with these peaks all occurring just above the location of the inflated ionospheres.

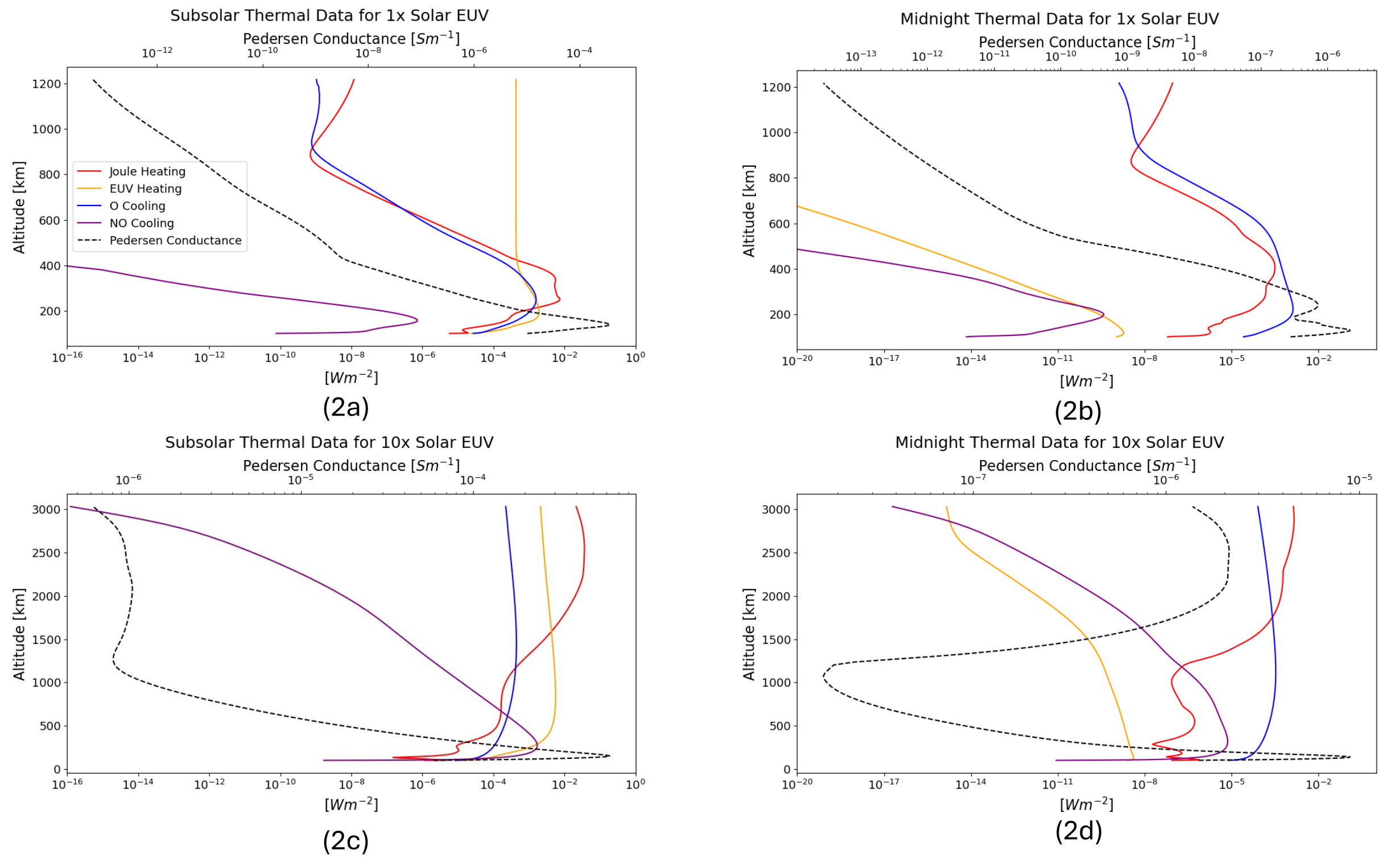
Figure (2a-c): Global O^+ vertical velocity, shown at approximately the region of global peak upward motion, for scale factors 1, 8, and 10. Majority of the upward motion occurs in the polar regions on the dayside (subsolar point is along 180° longitude). The peak velocities increase roughly 3-4 times compared to the base case of 1x scale factor. Also shown is horizontal flow of O^+ ions, once again with the majority of the motion occurring near the poles.

Figure (3a-b): We calculate the Jeans escape parameter for O^+ for the scale factors of 1 and 10. A parameter closer to 1 means that a particle is more likely to escape thermally. The 10x scale factor data show an escape parameter in the range of 12 near the poles, which is not a high probability on its own, however, observations on Earth show that there is a small amount of O^+ thermal escape occurring on our planet, so the significant increase in the escape parameter compared to the baseline scale factor of 1 suggests that there is a meaningful increase in escape at this enhanced EUV radiation level.

Heating & Cooling



(1a) (1b) (1c)



(2a) (2b) (2c) (2d)

Figure (1a-c): Global joule heating for scale factors 1, 8, and 10. Peak joule heating occurs in the polar regions, coinciding with peak vertical O^+ motion.

Figure (2a-d): (2a) and (2c) show subsolar heating and cooling for scale factors 1 and 10 respectively. Peak joule heating occurs at a much higher altitude for the 10x case. O^+ cooling and NO cooling drop of a considerably lower rates with altitude compared to the baseline case, and the NO cooling is orders of magnitude greater for the 10x case. (2b) and (2d) depict the same data on the nightside, where we observe similar trends but also note that the Pedersen conductance swells considerably in the ionosphere of the 10x case, a feature that isn't present in the baseline case.

Conclusions & Future Work

- Enhanced EUV flux results in inflation and elevation of the ionosphere of Earth-like planets.
- While it is unclear specifically how much O^+ escapes from the atmosphere in these enhanced EUV cases, we believe that the escape rate is increased, which may be significant for the evolution of habitable atmospheres for close-in exoplanets.
- There are issues to address within the current modeled data, primarily over the scale factors of 5 and 7 which produced surprising results
- Future modeling may use Mars or Venus as exoplanets to explore how different atmospheric compositions respond to the enhanced EUV radiation.

Selected References

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