Response to review 2

Summary

This study uses a 3-D Earth System Model (WACCM6) to investigate the effect on hydrogen escape of varying the atmospheric O2 mixing ratio. The study finds that, to first order, atmospheric warming due to increased ozone concentrations with increased O2 results in a weakening of the H2O cold trap. This allows more hydrogen to be lifted into the upper atmosphere, where it can escape to space. However, changes in O2 level alone are unlikely to have been a significant factor affecting H escape rate variations over geological time. The article ends with a comprehensive discussion of the applicability of the results to the water loss and atmospheric composition of both early Earth and other (exo)planetary bodies.

Overview

This work is a very interesting and important contribution to the field, as it thoroughly explores the effects of varying O2 levels on other atmospheric processes. The WACCM6 Earth System Model is an excellent tool to explore the research question. The simulations are well-designed and the model results explored carefully and in sufficient detail to thoroughly assess the effect of one factor (O2 mixing ratio) on another (H escape) and explain the relevant causes and effects.

For the most part, the figures are well-chosen and illustrate the key points well. The discussion section is comprehensive and relevant, and demonstrates the wide applicability and importance of the results to different aspects of the field. It achieves a great balance of evidence-based speculation without stretching too far. The abstract and conclusion summarize the study very helpfully.

The overall article is well structured and easy to follow. Key terms and ideas are well explained and defined (e.g., TTL, cold trap).

I have only minor comments and suggestions for improvement or consideration, as follows. A number of them could help the reader to match descriptions of the results in the text with the corresponding figures.

We would like to thank the reviewer for their reading of our manuscript and the helpful suggestions they have made. We have addressed each point and modified the manuscript accordingly, including the relevant figure captions. We have provided more context in the introduction and discussion to better outline the scope of the work.

1. Introduction

L34: “the GOE… has been proposed to have halted hydrogen escape.” I suggest a different word/phrase is used, e.g., “significantly reduced,” as hydrogen escape will have persisted, even if at a much smaller magnitude. If I’m mistaken and the word “halted” is kept, I suggest a reference is needed at the end of this sentence.

Thank you, this is a good point, and we have changed the phrase to ‘significantly reduced’ instead.

L41: Suggestion: “through several mechanisms, including Jeans escape…” (as I don’t think this is a fully exhaustive list).

Thank you, we have now used ‘including’ to make this clear.

L67: Typo: “thought”

Done.

L73: The comparison to the deepest point in the Earth’s ocean is helpful for providing context to the water loss rate, but I think that the global equivalent layer of the Earth’s current oceans (~3.6 km) might be an even more helpful comparison. This would also provide consistency and ease of comparison with L76.

We have included 3.6 km as an additional reference point and given a citation too.

L88-93: This is a really helpful paragraph summarizing a clear aim.

We appreciate the positive feedback, thank you.

2. Numerical methods

I think a sentence on the model’s lower boundary condition for H2O would be helpful to note, even if it is in the referenced literature; e.g., is an infinite ocean reservoir assumed?

In terms of evaporation and hydrogen feedback, an infinite water reservoir is assumed, and no water loss is explicitly simulated. We think this assumption is acceptable because we are simulating points in time rather than an evolution of the atmosphere.

We have included a new sentence stating that water vapour feedback is included through evaporation and rainout, but that water loss from the ocean is not explicitly included.

L105: “that have been estimated to have existed on the Earth over…” I suggest a very minor rewording to something like “within estimates for the Earth over…”

Thank you for the suggestion, this has been altered.

L118: suggest, for clarity and conciseness: “The diffusion-limited hydrogen escape rate (Hunten, 1973; Kasting and Catling, 2003), Φesc, is proportional to the total mixing ratio of hydrogen components at the homopause: $\Phi esc \propto fT\ (H)$, fT(H) can be written…”

We have modified this to make it more concise based on the reviewer’s suggestion.

3. Results

L162: “measured” is perhaps slightly misleading, as the text is referring to model results. Suggest “< 3K in terms of global averaged surface temperature” or something similar, instead.

This has been changed as per the reviewer’s suggestion.

L164: “PI, 1%, and 0.1% PAL

This has been added in, thank you.

L168: There is no explanation of how low and medium clouds are defined.

Medium and low cloud definitions have now been added, thank you.

L170: Suggest that “±0–60°” might be clearer than “±60°.”

This has been modified.

L171: Suggest “ice content (blue shading) and a lower amount of H2O (colored contours),” for ease of understanding Fig. 4 quickly.

Thank you, we have modified this caption to improve this.

L194: It is not clear what is meant by “visual discernment,” as this depends on the scale used on the figure. Suggest “a visual discernment on the scale of Fig. 4” or equivalent.

This has been modified in the text. Additionally, to confirm the visual discernment, we have performed a phase lag and Fourier analysis of the data which shows there is no tape recorder affect for the 0.1% PAL case, but there is a clear tape recorder effect for the pre-industrial simulation. We have now mentioned this in the manuscript.

L201: A brief explanation of the focus on 88 hPa (and also 100 hPa on L207) in particular might be helpful. In general, if there is a way to contextualize these pressure levels with altitudes or atmospheric levels (e.g., tropopause, homopause, etc.) a little more often, that might be helpful to the reader.

This pressure level is the pressure level that roughly corresponds to the top of the tropopause, so most water vapour has passed through the tropical tropopause layer by this stage. Linear regression fits show that it is also the pressure level which has the coefficient of determination (R^2) value closest to 1. In other words, the total hydrogen

mixing ratio at other pressure levels is less strongly correlated with the warmest atmospheric temperature reached at that pressure level in the tropics. We have added this explanation in and also given the approximate height that it corresponds to.

L204: "A positive correlation is not present when comparing fT(H) with global mean temperature alone." Is this referring to global mean temperature in the tropics (at all pressures) or at 88 hPa (in the tropics) or at all latitudes and pressures?

We agree this was not as well-defined as it should be in the manuscript. So, in this case, it is all latitudes and longitudes for the 88 hPa pressure level. We have now made this clearer in the manuscript.

L218-219: "Above the cold trap in the TTL… due to CH4 reacting with OH." It is unclear where the 5 ppmv value comes from and how it corresponds to Fig. 7. I suggest that some further description is given of where in Fig. 7 we see this, as I am looking at the solid black line (for H2O) in the lower left subpanel, where the maximum above 1 hPa is ~10 ppmv rather than 5 ppmv. In addition, I suggest moving this sentence to the below paragraph, after the lower panels of Fig. 7 have been introduced.

The mixing ratio of H_2O is 5 ppmv which corresponds to 10 ppmv of hydrogen atoms. Fig. 7 shows the contribution that each molecule has to the total hydrogen mixing ratio, so H_2O and H_2 are multiplied by 2 here and CH_4 by 4. But we did not make this clear, so we have now explicitly stated this in the caption of Fig. 7. The sentence has also been moved to the next paragraph.

L222: Suggest specifying in parentheses which species are being referred to, e.g., "…the lighter atmospheric constituents (H) increase…" It seems from the figure that this is only the case for H, rather than multiple species. I also suggest that this sentence is moved to the paragraph below, as it is more connected to the discussion of the different species' mixing ratios.

Other species do increase in relative abundance, such as He, N, and O, but these are not relevant to figure 7. We have kept the sentence in this paragraph because it is relevant to why H dominates at the top of the model in the PI simulation. However, we have also added a sentence in the next paragraph to say this is the case in all simulations.

Discussion

Another point that could have been discussed in Section 4 is whether there is any feedback whereby a change in H escape affects the O_2 mixing ratio (as H escape can be considered a source of oxygen).

We thank the reviewer for their suggestion and have included this towards the end of the Discussion section.

Figures and Tables:

Table 1: I think this table is unnecessary, as the mixing ratios (right hand column) are clear from the names of the simulations alone (left hand column). I suggest that the mixing ratio column is included in Table 2 between the 'Simulation' and 'fT(H)' columns instead. The text in the caption can then be folded into the main text, e.g., around line 104, such that the number of simulations, the full definition of PAL, the model surface pressure, and the information about the other boundary conditions is not lost.

Thanks for the suggestion to help reduce repetitiveness in the manuscript. We have removed table 1 and modified the methods text.

Figure 2 caption: Suggest "against the atmospheric mixing ratio of O2 at the surface in terms…"

Thank you, the caption has been modified accordingly.

Thank you for the opportunity to review this paper, and I look forward to seeing it published in due course.

Thank you for your positive and constructive feedback and taking the time to review our manuscript.