

Anonymous Referee #1

Summary: Watanabe et al. utilize MRI-ESM2.0, an Earth system model with an ozone module, to simulate climate and atmospheric ozone changes for the preindustrial (PI), mid-Holocene (MH), and Last Interglacial (LIG). Their study explores ozone-climate feedbacks by selectively enabling and disabling the ozone-chemistry module, with a particular focus on high-latitude regions. While their results indicate that stratospheric ozone changes can influence polar surface air temperatures, they suggest a limited impact on global mean temperature. The study extends previous work by examining both MH and LIG. It raises questions about model dependency and the need for further multi-model comparisons. The manuscript requires improvement in several areas, including the need for clearer differentiation between the sizes and sources of human-induced and natural ozone changes (i.e. quantification of ozone changes in ppm), and much more careful and robust discussion of sea ice state errors and their implications. Overall the study requires that it includes findings from previous research on MH/LIG polar climate changes, particularly regarding Arctic sea ice extent and its role in driving feedbacks. Further smaller clarifications are also required on spinup model-specific biases.

We appreciate the reviewer for the thoughtful review and for providing many valuable comments. In the course of revision, we have clarified that our model does not consider the human-induced effect on tropospheric ozone in numerical experiments conducted in this study. We have further clarified the distribution of the sea ice during the PI, MH, and LIG, and also compared our sea-ice distribution to the ones estimated by other climate models. We have also enriched our mention of the abundance and distribution of atmospheric ozone during the MH and LIG. We have taken all these comments and suggestions into account in the process of revision.

Line-by-line comments:

L9: Remove: "However, understanding the role of changes in stratospheric ozone during past warm interglacial periods is limited to MH conditions," since work suggests that previous understanding was incorrect.

We agree with the reviewer. Instead of removing the sentence, we have rewritten the sentence as follows:

"However, little is known about the role of changes in the stratospheric ozone during past warm interglacial periods."

L13: Reverse clauses for better sentence construction: "We show that while ozone feedbacks may affect surface air temperature regionally, impacts on the zonal mean surface air temperature are small."

We have rewritten the sentence as follows:

"We further show that ozone feedbacks decrease the surface air temperature by ~ 0.35 and ~ 0.25 K in the high-latitude regions of the northern hemisphere in both MH and LIG, while the impact on the zonal mean surface air temperature around Antarctica was small."

L14: Add a sentence explaining that these results represent an update on previous findings or that further work using more models is needed to determine whether this indicates model dependency.

Following the suggestion, we have added the sentence as follows:

"This is the opposite of the previous finding that implies the importance of ozone in southern hemisphere climates, indicating the need to determine whether this indicates model dependency."

L14-15: Remove or rewrite the last sentence to reflect the previous comment.

Done.

L16: Change "is expected" to "can."

We have changed the expression as suggested.

L24-25: Split land-ocean versus sea ice-ocean feedbacks (Arctic versus other land) and rewrite the sentence clearly.

We have rewritten the sentence as follows:

"The warming is especially enhanced over high-latitude regions, possibly reflecting the amplification by feedback mechanisms such as sea-ice changes over the Arctic Ocean and vegetation feedback over land areas of the Northern Hemisphere ..."

L27: Remove the sentence on ice volume/GMSL changes. The authors do not address this here, and it adds nothing.

We agree with the reviewer. We have removed the sentence in the revised manuscript.

L29-L34: These lines confuse the MH and LIG and add nothing. They can be removed.

We have rewritten the sentence so that the discrepancy between temperature reconstruction and climate model exists in both MH and LIG, as follows:

"However, many climate models do not simulate the higher global annual mean surface air temperature inferred from the paleoclimate proxy during the MH and LIG (Masson-Delmotte et al. 2013; Otto-Bliesner et al., 2013; Liu et al. 2014; Brierley et al. 2020; Kaufman and Broadman 2023). The cause of this discrepancy has been vigorously debated (Liu et al. 2014, 2018; Hopcroft and Valdes 2019; Park et al. 2019; Bova et al. 2021; Zhang and Chen 2021; Thompson et al. 2022; Laepple et al. 2022; Kaufman and Broadman 2023), indicating that high-latitude processes over land and ocean are critical for further understanding the climate warming during the past interglacials."

L29-L34: Instead, provide a clear description of what is known about MH and LIG polar (sea ice and polar ocean) changes, particularly sea ice. Refer to:

- Gao, Qinggang, et al. (2025) Assessment of the southern polar and subpolar warming in the PMIP4 Last Interglacial simulations using paleoclimate data syntheses. *Climate of the Past*, 21. 10.5194/cp-21-419-2025
- Sime, Louise C., et al. (2025) More modest peak temperatures during the Last Interglacial for both Greenland and Antarctica suggested by multi-model isotope simulations. *Climate of the Past* [in review]. 10.5194/egusphere-2025-288
- Chadwick, Matthew, et al. (2023) Model-data comparison of Antarctic winter sea-ice extent and Southern Ocean sea-surface temperatures during Marine Isotope Stage 5e. *Paleoceanography and Paleoclimatology*, 38(11). 10.1029/2022PA004600
- Sime, Louise C., et al. (2023) Summer surface air temperature proxies point to near-seaice-free conditions in the Arctic at 127 ka. *Climate of the Past*, 19. 10.5194/cp-19-883-2023
- Diamond, Rachel, et al. (2021) The contribution of melt ponds to enhanced Arctic seaice melt during the Last Interglacial. *The Cryosphere*, 15(16). 10.5194/tc-15-5099-2021
- Kageyama, Masa, et al. (2021) A multi-model CMIP6-PMIP4 study of Arctic sea ice at 127 ka: Sea ice data compilation and model differences. *Climate of the Past*, 17(26). 10.5194/cp-17-37-2021
- Guarino, Maria Vittoria, et al. (2020) Sea-ice-free Arctic during the Last Interglacial supports fast future loss. *Nature Climate Change*, 10. 10.1038/s41558-020-0865-2
- Williams, Charles J.R., et al. (2020) CMIP6/PMIP4 simulations of the mid-Holocene and Last Interglacial using HadGEM3: comparison to the pre-industrial era, previous model versions, and proxy data. *Climate of the Past*, 16(22). 10.5194/cp-16-1429-2020

When constructing a paragraph about polar changes for the LIG, the Sime et al. (2025) reference summarizes much of what is required.

We deeply appreciate the reviewer for pointing this out. We have enriched our discussion and added references regarding the sea ice distribution during the MH and LIG in the revised manuscript, as follows:

"Indeed, the minimal extent of both Arctic and Antarctic regions would have been smaller than in the PI condition in the MH and LIG owing to the stronger insolation (Yoshimori and Suzuki, 2019; Brierley et al., 2020; Otto-Bliesner et al., 2020; Guarino et al., 2020; Diamond et al., 2021; Kageyama et al., 2021; Sime et al., 2023; Chadwick et al., 2023; Gao et al., 2025). Particularly, northern hemisphere sea ice may have completely melted seasonally during the LIG, which has a profound impact on the climate (Guarino et al., 2020; Diamond et al., 2021; Sime et al., 2023)."

L40: Change sentences to clarify that the focus is on ozone-climate feedbacks. Change to: "One possible factor that can affect the high latitudes is stratospheric ozone-climate feedbacks (Thompson and Wallace, 2000; Noda et al., 2017)."

We have rewritten the sentence in the revised manuscript as suggested by the reviewer, as follows:

"One possible factor that can affect the high latitudes is stratospheric ozone-climate feedbacks (Thompson and Wallace, 2000; Noda et al., 2017)."

L41: Rewrite to clarify the difference between human-generated ozone changes and the ozoneclimate feedbacks being investigated.

We have added a sentence to clarify the difference between human-generated ozone changes and the ozone-climate feedbacks in the past interglacials, as follows:

"Despite the uncertainty regarding the impact of the mechanism caused by the human-induced ozone depletion in the late 20th century, a similar ozone-climate mechanism may have worked in response to different astronomical forcing during past interglacials (Noda et al., 2017)."

Please see our reply to the next comment for further details.

L47: Add numbers to show the size of the effects: ozone changes in ppm for present-day (human-induced) versus possible ppm changes for the MH or other past climates due to ozoneclimate feedbacks.

After reassessing the impact of the mechanism in present-day conditions, we noticed that the magnitude of the ozone-climate relationship is uncertain even during the late 20th century (e.g., Langematz et al. 2018), although some idealized numerical simulations infer that this mechanism could work around Antarctica (e.g. Ferreira et al., 2015). For this reason, we have enriched our explanation to explain this, as follows:

"This has been pointed out to further affect the distribution of sea ice around Antarctica because the changes in jet strength affect the Ekman transport in the Southern Ocean (SO) and the warming of the surface ocean, while the plausibility and impact on the historical period remains still uncertain (Sigmond and Fyfe 2010, 2014; Bitz and Polvani 2012; Ferreira et al. 2015; Smith et al. 2012; Noda et al. 2017; Langematz et al. 2018). Despite the uncertainty regarding the impact of the mechanism caused by the human-induced ozone depletion in the late 20th century, a similar ozone-climate mechanism may have worked in response to different astronomical forcing during past interglacials (Noda et al., 2017)."

Instead, we have enriched our explanation about the ozone-climate impact of this mechanism during the MH (see our response to the next comment).

L49: Again, ensure the previous estimated response size in ppm from Noda et al. is explicitly stated.

We have enriched our explanation about the magnitude of the changes in stratospheric ozone simulated by Noda et al. (2017) in the revised manuscript, as follows.

"They showed that the positive ozone anomaly with a maximum value of ~0.2 ppm in the stratosphere would be caused by the different astronomical forcing during the MH. They further showed that this

would lead to the annual zonal mean surface air temperature anomaly of up to +1.7 K around the South Pole.”

L53-66: Clearly spell out that the two objectives of this study are:

1. Testing whether a newer model yields the same results as the previous MH study.
2. Extending the work on interglacials from the MH to both the MH and LIG.

We have enriched our explanation of our objectives as pointed out by the reviewer, as follows:

“In this study, we first test the response of the stratospheric ozone and its impact on climate during the MH using a state-of-the-art Earth system model. We then investigate the response of stratospheric ozone in both MH and LIG to show the impact of different astronomical forcing.”

Table 1 / Methods Section: The spin-up process is unclear. Is everything initiated from the same well-spun-up PI? Add comments on the usual spin-up duration (>250 years) and its importance for polar regions. Refer to Kageyama et al. (2021) for comments on this.

We appreciate the reviewer for pointing this out. The *Plcontrol* experiment was started with the calculation from the well-spun-up PI condition submitted to CMIP6, while the *MHcontrol* and *LIGcontrol* experiments were started from the MH simulation submitted to CMIP6/PMIP4. We have enriched our explanation as follows:

“We note that this spin-up period is relatively short compared to many of the PMIP4 experiments for these periods, and only two models have a spin-up period of 50 years (e.g., Kageyama et al., 2021). For this reason, the processes with long timescales, such as the oceanic circulation, would not have reached a steady state. Nevertheless, the response of total ozone during the MH and LIG had sufficiently reached a steady state after the spin-up period, so we consider this would not change our main conclusion.”

L110-L115: Check whether this result is dependent on calendar adjustments and comment or adjust accordingly.

Yes, we expect that some of the three-months-mean-temperature can be strongly affected by the calendar adjustments. We clarified that all the monthly output was post-processed to apply calendar adjustments.

“The calendar adjustment was conducted in all the monthly output data for MH and LIG conditions outputs to consider the changes in the length of months (Bartlein and Shafer 2018).”

Figures 4, 7, and SIC-related figures: These figures should also show the actual PI and Interglacial SIE or SIC (add a 15% SIC line for each climate to each figure), not just anomalies. See Kageyama and Sime papers for why sea ice states/errors (in the PI and MH/LIG) are critical for determining SIC-climate changes (not just anomalies). Discuss any PI or MH/LIG sea ice state errors and their likely impacts.

We appreciate the reviewer for bringing this to our attention. We have added a 15% SIC line in each figure. As previously discussed in Yukimoto et al. (2019), the overall reproducibility of southern sea ice in the present-day condition by MRI-ESM2.0 is good. On the other hand, in the LIG condition, one model (HadGEM3) reproduced the high surface temperature in the Arctic region that is consistent with reconstructions, which is associated with the loss of sea ice in summer (Guarino et al., 2020; Diamond et al., 2021), while other models did not simulate the loss of sea ice in the Arctic region in summer (Kageyama et al., 2021). This may also affect the strength of the ozone-climate interaction. During this revision, we have further enriched our discussion about the impact of the sea ice distribution simulated by the model on the ozone-climate interactions in Discussion.

“This different response around Antarctica may be related to the different biases in temperature. For example, the surface air temperature around Antarctica simulated by MRI-ESM2.0 employed in this study exhibits a cool bias, while that simulated by MRI-CGCM3, which is an atmospheric general circulation model used in MRI-ESM1 employed by Noda et al. (2017), exhibits a warm bias, especially over the Southern Ocean (Yukimoto et al., 2019). As a result, the responses of the sea ice distribution and the surface air temperature differed from those reported by Noda et al. (2017), exhibiting zonally asymmetric characteristics. In MRI-ESM2.0, the sea-ice extent around Antarctica is slightly higher than observations and MRI-CGCM3, but it reproduces the sea-ice edge around Antarctica well (Yukimoto et al., 2019). The reproduction of sea ice extent in the Arctic Ocean in MRI-ESM2.0 was much closer to the observations than that of MRI-CGCM3. These different sea-ice distributions may have also contributed to the different responses between the models. Specifically, for the case of the LIG, the sea ice may have completely melted seasonally (Guarino et al., 2020; Diamond et al., 2021; Sime et al., 2023). In this case, the ozone-induced climatic impact of the changes in sea-ice distributions in the Arctic Ocean may have been smaller than in our model.”

L133: Add more appropriate references and comments based on the MH/LIG sea ice and polar change papers listed above.

Please see our reply to the next comment.

L133-151: This section is structured backward. It is primarily direct insolation impacts on Arctic sea ice that reduce the SIE (SIC), leading to warming and subsequent climate changes. See Diamond et al., Kageyama et al., and Sime et al. for clarification. Rewrite these paragraphs accordingly.

We have reorganized the paragraph as follows, while mentioning the previous study discussing the LIG sea ice extent. We note here that this part is moved to Appendix A in the revised manuscript.

“For the LIG case, the overall patterns of the surface air temperature anomaly from the PI conditions were similar to the MH, but the signal tended to be stronger, which was similar to the previous study (Otto-Bliesner et al. 2021). The sea ice concentration during SON decreased over a wide area of the Arctic Ocean (Fig. A3g). The ice edge retreated compared with the PI in the Greenland Sea and Barents Sea. However, it did not exhibit the complete loss of sea ice simulated by previous studies (Guarino et al., 2020; Diamond et al., 2021; Sime et al., 2023) as in many other climate models (Kageyama et al., 2021). Nevertheless, significant warming was observed in JJA and SON (right panels in Fig. 2a), reflecting the higher insolation anomaly and the associated response of sea ice distribution (Figs. 3b and A3). In SON, specifically, the surface air temperature over the Arctic Ocean increases by more than ~4 K compared with the PI conditions (Fig. A4d). As a result, significant warming is observed in the annual mean temperature over the regions covering the Greenland Sea, Norwegian Sea, and Barents Sea (Fig. A1c). The warming is also observed in the central part of North America, the southern part of South America and Africa, the northern part of Australia, the western part of the Eurasian continent, and in part of the Southern Ocean. Despite the warming in these regions, the global annual mean surface air temperature did not exceed the PI value.”

L168-171: Sentence is unclear—rewrite for clarity.

We have rewritten the sentence as follows:

“The decrease in the ozone concentration would work in the direction of suppressing the warming in the upper stratosphere, but the temperature increased because of the increase in shortwave radiation during austral winter in the MH and LIG.”

L171-175: Similar to the previous comment. The mixed tenses (previous interglacial times vs. previous Noda et al. results) make these lines difficult to parse. Separate:

- Climate-to-ozone feedback processes.
- Ozone-to-climate processes.
- MH/LIG simulation changes.
- Changes in the representation of climate-ozone-climate feedbacks.
- Differences between the Noda et al. results (previous model) and the new findings.

We have reorganized the paragraph so that the results of the present study and differences from Noda et al. (2017) become clear. Please see Sections 3.1 and 3.2 in the revised manuscript.

L240: Change "operate" to "occur."

Following the suggestion, we have revised the wording in this section of the manuscript.

L243: "This contradicts the results shown by Noda et al. (2017), which suggest a warming in the Southern Hemisphere during the MH." This difference should be clearly stated in the abstract.

We have added a sentence explaining this in the Abstract, as follows:

"This is the opposite of the previous finding that implies the importance of ozone in southern hemisphere climates, indicating the need to determine whether this indicates model dependency."

L245: Change "any season" to "all seasons" and "specifically" to "particularly."

We have revised the wording according to the suggestion.

L247: Contextualize the size of the changes relative to previously identified LIG and MH sea ice changes (Guarino, Sime, Chadwick, Gao, and Kageyama et al.).

Following the suggestion, we have enriched our discussion regarding the LIG and MH sea ice distributions and changes, as follows:

"In MRI-ESM2.0, the sea-ice extent around Antarctica is slightly higher than observations and MRI-CGCM3, but it reproduces the sea-ice edge around Antarctica well (Yukimoto et al., 2019). The reproduction of sea ice extent in the Arctic Ocean in MRI-ESM2.0 was much closer to the observations than that of MRI-CGCM3. These different sea-ice distributions may have also contributed to the different responses between the models. Specifically, for the case of the LIG, the sea ice may have completely melted seasonally (Guarino et al., 2020; Diamond et al., 2021; Sime et al., 2023). In this case, the ozone-induced climatic impact of the changes in sea-ice distributions in the Arctic Ocean may have been smaller than in our model."

Figures 10 and 13: Show ozone-dependent impacts in K for pressures and latitudes (e.g. ~0.25K in the high Arctic). Explicitly state the magnitude of these numbers in the abstract and conclusions.

We have added a new figure to show the ozone-dependent impacts in K for pressures and latitudes in Figure 4. We have mentioned these numbers in the abstract and conclusions.

L276: Spell out "mean annual" and "globally"—for example, large seasonal Arctic changes exist.

Following the suggestion, we have revised the phrase as *"...higher global and annual mean surface air temperature"*.

L281-L298: Since the study focuses on ozone impacts in polar/high-latitude regions, remove the discussion on global mean temperature and non-polar changes. Instead, discuss whether either model version accurately captures known MH/LIG sea ice and surface polar ocean changes and how that affects the climate-ozone-climate feedbacks.

Following the suggestion, we have moved the discussion about the global climate states in MH and LIG to Appendix A. Instead, we have enriched our discussion about the different responses of the

ozone-induced impact between this study and the previous study (Noda et al., 2017) and the effect of the sea-ice distributions in the revised manuscript, as follows:

“This different response around Antarctica may be related to the different biases in temperature. For example, the surface air temperature around Antarctica simulated by MRI-ESM2.0 employed in this study exhibits a cool bias, while that simulated by MRI-CGCM3, which is an atmospheric general circulation model used in MRI-ESM1 employed by Noda et al. (2017), exhibits a warm bias, especially over the Southern Ocean (Yukimoto et al., 2019). As a result, the responses of the sea ice distribution and the surface air temperature differed from those reported by Noda et al. (2017), exhibiting zonally asymmetric characteristics. In MRI-ESM2.0, the sea-ice extent around Antarctica is slightly higher than observations and MRI-CGCM3, but it reproduces the sea-ice edge around Antarctica well (Yukimoto et al., 2019). The reproduction of sea ice extent in the Arctic Ocean in MRI-ESM2.0 was much closer to the observations than that of MRI-CGCM3. These different sea-ice distributions may have also contributed to the different responses between the models. Specifically, for the case of the LIG, the sea ice may have completely melted seasonally (Guarino et al., 2020; Diamond et al., 2021; Sime et al., 2023). In this case, the ozone-induced climatic impact of the changes in sea-ice distributions in the Arctic Ocean may have been smaller than in our model.”

L299-L312: Clarify which aspects are model-specific (e.g., climate biases affecting interpretation) and state the headline results.

We have enriched our discussion so that the potential impact of the model biases is mentioned, following the previous study (Yukimoto et al., 2019).

“This different response around Antarctica may be related to the different biases in temperature. For example, the surface air temperature around Antarctica simulated by MRI-ESM2.0 employed in this study exhibits a cool bias, while that simulated by MRI-CGCM3, which is an atmospheric general circulation model used in MRI-ESM1 employed by Noda et al. (2017), exhibits a warm bias, especially over the Southern Ocean (Yukimoto et al., 2019).”

L313-L327: This paragraph is difficult to parse. If the argument is that further chemistry should be included in the model, first state which chemistry is currently missing, then explain why this could be important for MH, LIG, or another past climate interval.

The intended arguments here were that the available reconstruction of the past atmospheric ozone is limited to the values near the surface and that the surface ozone concentration would be affected by processes that are not considered in the model, such as the wildfire-related supply of chemical components such as NO_x and CH₄. Because the original paragraph was misleading, we have rewritten the paragraph in the revised manuscript, as follows:

“While the reconstruction of stratospheric ozone in the past is not available, the tropospheric ozone burden during the LIG was estimated based on a record of the clumped isotope composition of O₂ in the East Antarctic ice core (Yan et al. 2022), indicating a reduction in the tropospheric ozone burden by nearly 9 % compared with the PI conditions. It has been inferred that the dispersal of modern humans had not yet occurred during the LIG (Liu et al. 2015; Malaspinas et al. 2016; Groucutt et al. 2018), which makes the LIG an ideal period for reconstructing the tropospheric ozone under a smaller impact from the influence of humans (Yan et al. 2022). However, the tropospheric ozone concentration may be affected not only by factors such as astronomical forcing, but the activity of early humans. For example, early humans could affect the supply rate of methane to the troposphere through rice cultivation. Indeed, ice core records indicate that the atmospheric methane level has increased since the MH compared with the LIG (Spahni et al. 2005; Singarayer et al. 2011), which would be associated with rice cultivation (Ruddiman 2003; Ruddiman et al. 2008) and/or natural wetland emissions (Schmidt and Shindell 2004; Sowers 2010; Singarayer et al. 2011). The early

human activity can affect the supply rate of NO_x to the troposphere by causing wildfire events (Ward et al. 2012). The magnitude of wildfire events is determined by the complex interrelationship between climate, vegetation activities, and early human activities, so it would also be affected by the different astronomical forcing. Because our model does not consider the different source fluxes of these gases, the simulated tropospheric ozone should not be compared with the reconstructions. Simulations of the last glacial cycle using a fully coupled Earth system model including the atmosphere, ocean, aerosol, ozone chemistry, and vegetation cycle would be ideal for understanding the variations in the tropospheric ozone distribution during this period.”

Anonymous Referee #2

Review. This paper explores the effect of stratospheric ozone changes – if any – on the climate of the mid-Holocene (MH) and the Last Interglacial (LIG). The question is well posed, and most interesting. To answer it the authors have performed an excellent set of model runs: 3 epochs (1850 PI control, MH and LIG) and, for each epoch, 2 runs (with PI ozone and with interactive ozone). So, they should be able to answer the question clearly.

We appreciate the reviewer for the thoughtful review and for suggesting the improvement of the structure of the manuscript. We reorganized the manuscript by moving some of the figures describing the climatic condition simulated by the model to the Appendix, so that our main results and discussion, that is, atmospheric ozone distributions during the MH and LIG, appear earlier in the manuscript. We enriched our discussion regarding the atmospheric ozone during the MH and LIG by adding some figures, such as a latitude-altitude plot of atmospheric ozone, which is crucial for understanding the dynamics of ozone. We have taken all these comments and suggestions into account in the process of revision.

Unfortunately the manuscript, in its current form, is really a mess. The authors waste 7 figures (each with many panels) discussing all manner of secondary considerations, and only show an ozone field for the first time in Figure 8. So, the narrative is completely backwards. If one is trying to tell the impact of ozone changes, one should start by showing the ozone changes. But this need to be done properly. Why are we shown ozone at the 3 hPa level in Figure 8? Is that where the ozone layer is? I would imagine the readers want to see ozone at 50 or 70 hPa. What about a latitude/height map of ozone changes in the ML and LIG? Or again, how about showing a lat/lon map of total column ozone (TCO)? Is the ozone layer thicker or thinner than under PI forcings? By how many Dobson units? I have no idea what the answer is (as I have not run the models), but none of this is shown in the paper. Again: the paper needs to start with 2 or 3 well chosen figures telling us what ozone looks like in the MH and LIG, and how it differs from the PI control.

We agree with the reviewer's suggestion. We have largely reorganized the manuscript in this revision. Now all the climate-related figures are moved to Appendix A, and the results start with explaining the total mass of ozone in these periods, as follows:

“The latitudinal-vertical plot of the zonal-mean ozone concentration anomaly for the MH and LIG conditions from the PI condition is shown in Fig. 2a. For the case of the MH, the ozone concentration was higher compared to PI in the lower stratosphere at low-latitude regions and near the South Pole, while it was lower in the upper stratosphere at low-latitude regions and near the North Pole. As a result, the 150-year mean value of total ozone was 314.7 DU, which was slightly lower than the PI value (315.4 DU). For the case of the LIG, on the other hand, the 150-year mean value of total ozone was 316.7 DU, which was slightly higher than in the PI. This is related to the positive anomaly in ozone concentration in broad regions of the lower stratosphere (Fig. 2b). These anomalies would be primarily associated with the different astronomical forcing during the MH and LIG.”

We have also added a new latitude-height map of the ozone anomaly in the MH and LIG (in the revised Figure 2). We have also added the ozone concentration in the MH and LIG using contours in this figure,

showing that the ozone layer is present in both MH and LIG. We have also added a new figure showing the latitude-height map of the air temperature anomaly and ozone-induced air temperature anomaly in the new Figure 4. We have also added a vertical-seasonal plot of ozone and temperature in tropical regions to discuss the response of the ozone distribution according to the different astronomical forcing in the MH and LIG, and the dependencies of ozone response in the tropics and the high-latitude regions of the northern and southern hemispheres (Figure 5). We believe these additions would help the readers to understand the basic responses of the ozone distributions and their potential impact on climate during the MH and LIG.

Next, the key results are at the very end of the paper, in Figures 12, 13 and 14: these show that ozone changes in the ML and LIG have basically no statistically significant impact on surface climate. So, why are the most important figures left at the end of the paper? And why are the authors not stating clearly that the effect of interactive on surface temperature are minuscule? And what about precipitation (which is not show)? I suspect ozone is also irrelevant for the that. In my mind that should be the key point of the paper: ozone changes in the ML and LIG don't matter. It is a null result, but null results are very much worth publishing. In all honesty, I am not surprised that ozone changes make no difference: this is because I suspect these changes are small. It takes something like an ozone hole over the South Pole (as we have seen in the late 20th century) to make a substantial climate impact. Hence the key figure the readers need to see: how big are the ozone changes in the ML and LIG compared to those caused by CFCs?

As in our reply to the previous comment, we have reorganized the manuscript. As a result, the original Figure 13 appears much earlier in the manuscript. After showing that the ozone-induced climate change is minor (we note, however, it affects in north of 60°N), we explained the details of the impact in the regions around the North and South poles. We have also clarified this in the abstract and conclusions, as follows:

"We further show that ozone feedbacks decrease the surface air temperature by ~0.35 and ~0.25 K in the high-latitude regions of the northern hemisphere in both MH and LIG, while the impact on the zonal mean surface air temperature around Antarctica was small. This is the opposite of the previous finding that implies the importance of ozone in southern hemisphere climates, indicating the need to determine whether this indicates model dependency."

The ozone-induced response of precipitation around Antarctica was also minor. The magnitude of the change in the total ozone in the atmosphere from PI was 2 DU even in the LIG, which is much smaller than the changes in the late 20th century. This also implies that the ozone changes to astronomical forcing are minor, as the reviewer notes here. However, another important point is that the astronomical forcing affects the ozone concentration seasonally, so the impact of ozone on the seasonal changes of the atmospheric structure is also important. For this reason, we have enriched our discussion regarding the vertical changes in ozone and temperature anomalies in different regions (the tropics and the high-latitude regions of the northern and southern hemispheres) by adding figures showing vertical-seasonal plots (Figs. 5, 7, and 12).

Recommendation. The paper – in its present form – should be rejected. However, the authors should be strongly encouraged to resubmit. They have a nice set of runs, and a very clean story to tell: the ozone changes in the ML and LIG are small, and therefore they make little difference for the surface climate. Such a paper is easy to write, as the key points can be made with a few simple figures, and no complicated mechanisms needed to be invoked. It will be a nice contribution to the literature. I look forward to it.

We appreciate the reviewer for the thoughtful comment. Yes, as mentioned above, we reorganized the structure of the manuscript so that the ozone distributions during the MH and LIG and their impact on climatic conditions are clearly shown in the manuscript.

Community comments by Jo-Jo Eumerus

A few minor observations:

We appreciate Jo-Jo Eumerus for providing valuable comments on our manuscript.

* Are there any data that identify causal mechanisms e.g are the ozone and temperature changes solely due to local insolation and sea ice or are there atmospheric circulation changes (perhaps sector-dependent) that also play a role?

We expect that the signal of local temperature anomaly caused by ozone over the southern polar region would have been caused by a complex interplay of ozone chemistry, atmospheric circulation, radiation, and/or cloud formation instead of a simple response to local insolation. For this reason, the exact mechanism would not be easy to identify clearly in this case, partly because the impact on climate would be very small (i.e., significant signal is limited seasonally and regionally in the southern hemisphere). This is in contrast to the case of the previous study (Noda et al., 2017), which showed an ozone-climate feedback caused by the wind and sea ice responses in the MH. This different response may be attributed to the biases of the model we used and the one used in Noda et al. (2017), so we have enriched our discussion regarding this in the revised manuscript in Discussion. For further quantitative constraints on the mechanism driving the climatic impact of atmospheric ozone, investigations using multiple Earth system models with interactive ozone would be important.

* In Fig3, it seems like MH and LIG have opposite temperature changes in Antarctica during JJA; any indication why?

We expect that the different temperature responses around Antarctica between MH and LIG would be associated with the different astronomical forcing (Figure 5). The seasonal timing of the onset of the positive insolation anomaly in the regions around the Southern Ocean is March-April in the LIG, which is much earlier than in the MH.

* Has ozone effects on climate just in Antarctica?

The changes in ozone may affect the temperature in the northern hemisphere in the MH and LIG, as can be seen in the difference between grey and red/blue lines in Figure 6. In this revision, we have enriched our discussion regarding the ozone impact on the northern hemisphere (Section 3.3).