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 providing many valuable comments. In the course of revision, we will clarify that our model does not consider the human-induced effect on tropospheric ozone in numerical experiments conducted in this study. We will further clarify the distribution of the sea ice during the PI, MH, and LIG and also compare our sea-ice distribution to the ones estimated by other climate models. We will also enrich our mention of the abundance and distribution of atmospheric ozone during the MH and LIG. We will take 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 will revise 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 will rewrite the sentence as suggested.

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 will add sentence as follows:

> *“These results are 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.

Following the suggestion, we will remove the last sentence.

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

We will change the expression as suggested.

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

We will rewrote 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 will remove the sentence in the revised manuscript.

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

We will rewrite 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 out this. We will enrich our explanation of the current understanding of the importance of sea ice distribution in the MH and LIG in the revised manuscript, while referring to the previous studies mentioned by the reviewer.

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 will revise the sentence in the revised manuscript as suggested by the reviewer.

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

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

"Although this mechanism was proposed for the human-induced ozone depletion at the poles, a similar ozone-climate mechanism may work in response to the different astronomical forcing in the past interglacials (Noda et al., 2017)."

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.

We will enrich our explanation about the present-day ozone change based on previous studies such as Son et al. (2010) while mentioning the magnitude of the ozone changes.

Son, S. W., Gerber, E. P., Perlwitz, J., Polvani, L. M., Gillett, N. P., Seo, K. H., ... & Yamashita, Y. (2010). Impact of stratospheric ozone on Southern Hemisphere circulation change: A multimodel assessment. Journal of Geophysical Research: Atmospheres, 115(D3).

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

We will enrich our explanation about the magnitude of the changes in stratospheric ozone simulated by Noda et al. (2017) in the revised manuscript.

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 will enrich 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 on the response of stratospheric ozone. For this purpose, we employed MRI-ESM2.0 and simulated…"

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 out this. The *PIcontrol* experiment was started the calculation from the well-spun-up PI condition submitted to CMIP6, while the *MHcontrol* and *LIGcontrol* experiments was started from the MH simulation submitted to CMIP6/PMIP4. We will clarify this while mentioning the potential effect of the length of the spin-up duration for polar regions in the revised manuscript.

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

We expect that some of the three-months-mean-temperature would be strongly affected by the calendar adjustments. We will add a brief comment mentioning that this would be affected by the calendar adjustment in the revised manuscript. We also note here that we will move these mentions to Appendix, following the comments from another reviewer.

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 pointing out this. We will add a 15% SIC line in each figure. We also note here that the 15% SIC line for the PI condition was also shown in Yukimoto et al. (2019) (See their Figures 9 and 10). Yukimoto et al. stated as follows:

> *"The Southern Hemisphere wintertime sea-ice extent (Fig. 9b) is slightly excessive in both models, particularly in MRI-ESM2.0. Both models simulate austral summer minimum sea-ice extents that coincide well with the observations" (From Yukimoto et al., 2019)*

and also as follows:

> *"The sea-ice edge distribution of the Antarctic sea-ice distribution simulated by MRI-ESM2.0 (Figs. 10c, d) is reproduced fairly well." (From Yukimoto et al., 2019)*

As already mentioned in Yukimoto et al. (2019), the overall reproducibility of southern sea ice in the present-day condition by MRI-ESM2.0 is good. On this basis, we will further enrich our discussion about the impact of the sea ice distribution simulated by the model on the simulated MH and LIG climates. For example, in the LIG, 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). Our model also does not simulate the loss of sea ice in the Arctic region, which may affect the strength of the ozone-climate feedback. For this reason, we will enrich our discussion about the sea ice distribution in PI, MH, and LIG simulated by our model, comparison with the reconstruction of the past temperature and sea ice distributions, and the potential impact of sea ice distributions to the ozone-climate feedback in both hemispheres in the revised manuscript.

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., ... & Ishii, M. (2019). The Meteorological Research Institute Earth System Model version 2.0, MRI-ESM2. 0: Description and basic evaluation of the physical component. Journal of the Meteorological Society of Japan. Ser. II, 97(5), 931-965.

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

We will add references following the reviewer's comment in the above.

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 will restructure the whole paragraph as suggested.

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

We will rewrite the sentence as follows:

> *"The decrease in the ozone concentration would work in the direction to suppress the warming in the upper stratosphere, but the temperature increased as a result of the increase of shortwave radiation in austral winter during 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 agree with the reviewer. We will reorganize the sentence so the result of the present study and difference from the previous study become clear.

L240: Change "operate" to "occur."
Following the suggestion, we will change the wording here in the revised 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 will add a sentence explaining this in the Abstract, as follows:

> *"These results are 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 will rewrite the sentence following 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 will enrich our discussion regarding the LIG and MH sea ice distributions and changes.

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 will enrich our explanations about the magnitudes of the ozone change itself and its impact on air temperature in the revised manuscript.

L276: Spell out "mean annual" and "globally"—for example, large seasonal Arctic changes exist.
Following the suggestion, we will revise 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.
We agree with the reviewer. We will decrease the amount of our explanation about the climate state simulated by MRI-ESM2.0 (following the comments by another reviewer) and remove the discussion regarding the global mean temperature and non-polar changes. Instead, we will enrich our discussion about the reproducibility of the reconstructions of temperature and sea-ice distribution around polar regions in our model in MH and LIG, and their potential impact on the climate-ozone feedback in the revised manuscript.

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

We will clarify that the response of ozone is robust between the previous study and our result, while the responses of wind patterns and surface air temperature can be dependent on models. We will enrich our explanation while mentioning the biases of the model, following the previous study (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.

We appreciate the reviewer for pointing out this. 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 NOx and CH4. We will rewrite the paragraph in the revised manuscript.