Climate and stratospheric ozone during the mid-Holocene and Last Interglacial simulated by MRI-ESM2.0

By Yasuto Watanabe, Makoto Deushi, and Kohei Yoshida

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 spin-up model-specific biases.

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.

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."

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.

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

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

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

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

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

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-sea-ice-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 sea-ice 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.

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)."

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

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 ozone-climate feedbacks.

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

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.

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.

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

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.

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

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

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.

L240: Change "operate" to "occur."

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.

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

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.).

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.

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

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.

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

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.