Review for manuscript EGUsphere-2024-618– The presence of clouds lowers climate sensitivity in the MPI-ESM1.2 climate model

General evaluation: Major revision.

This manuscript presents a "clear-sky" modeling approach (i.e., making clouds transparent to radiation) for a more complete evaluation of clouds impacts on the equilibrium climate sensitivity (ECS). In complement to the common approach of diagnosing the cloud radiative effects from the full-sky model experiment (both the cloud direct radiative effects and the cloud masking on CO2 and water vapor radiative effects), this clear-sky approach additionally accounts for the cloud indirect effects on thermodynamics (e.g., temperature lapse rate and water vapor distribution) and dynamics (e.g., changes in circulation and the associated surface warming pattern), which are shown to significantly modulate the radiative forcing, adjustments, and feedbacks. As the result, the ECS in the clear-sky experiment is much higher than the full-sky experiments with the same climate model, which is surprising but interesting. The authors further perform a systematic decomposition of the effective radiative forcing (ERF) and feedbacks and show their spatial patterns, which helps clarify the physical mechanisms.

Overall, I think this clear-sky approach is useful in identifying the indirect cloud effects on ERF and feedbacks, which have not been emphasized much in previous studies. Unfortunately, the comparison is heavily impacted by the control climate differences between the clear-sky and full-sky run, which complicates the physical interpretation. Although the authors have tuned the global-mean temperature to be comparable by reducing insolation in the clear-sky run, the temperature spatial pattern (pole-to-equator gradient, land-sea contrast, interhemispheric contrast, etc.) is still drastically different, and many of the adjustments and feedbacks are dependent on these patterns (especially the Antarctic sea-ice cover and its associated albedo feedback). Thus, I think it is a bit far-fetched to attribute the clear-sky versus all-sky ERF and feedback differences simply to the cloud modulation of radiative adjustments and feedbacks. In the current manuscript, this complication by control climate has not been clearly presented or sufficiently discussed.

To address this issue, I think the difference between the control climate states in the clear-sky and all-sky runs should be presented and discussed in further detail. In the current manuscript, it is only mentioned briefly on L116–119 without any figures. I think spatial maps of the top-of-atmospheric (TOA) radiative imbalance and surface temperature for both clear-sky and all-sky runs and their differences should be shown. They are essential for the readers to evaluate the mean-state impacts on ERF and feedbacks (e.g., by comparing them to Figures 5 and 6). In addition, the sea surface temperature (SST) warming pattern (evaluated with the same ensemble members and time spans as Figure 5) should also be presented, so that the readers can link the feedback differences to the known mechanisms of SST pattern effects, and possibly associate them with the SST Green's function studies.

In the result discussions, it would be necessary to distinguish the mean-state induced differences from the cloud-induced differences more clearly. Especially, the impact of the larger

Antarctic ice cover in the clear-sky control climate should be more thoroughly analyzed – it not only leads to a stronger ice albedo feedback, but it is also associated with a southern ocean amplified (and tropically damped) SST warming pattern (implied from Figure 5, "planck" panel), which is known for increasing the climate sensitivity (most recently by Kang, Ceppi, Yu and Kang, 2023, Nature Geoscience). Even in clear-sky experiments without cloud feedbacks, the lapse rate feedback is still impacted by the SST pattern (e.g., Andrews and Webb, 2018, Journal of Climate). This mechanism is implied in Figure 5: the SST over the tropical convective regions in the clear-sky run does not warm as much as the full-sky run, which likely leads to the reduced free-tropospheric warming and lapse-rate feedback globally (compare the "planck" and "lapse-rate" panels). Thus, I think the authors' explanation of the lapse rate feedback differences by the direct cloud radiative heating (L155–160 and L265–266) is likely insufficient.

Additionally, I think it would be necessary to discuss how this clear-sky approach is compared with the cloud-locking approach (e.g., Medeiros, Clement, Benedict, and Zhang, 2021, npj Climate and Atmospheric Science), which can also disable all cloud-induced thermodynamic and dynamic changes in the warming climate but largely maintains the control climate state. Are there significant weaknesses of the cloud-locking approach that motivate the authors to use the clear-sky approach instead? If so, it would be helpful to discuss in the introduction and conclusion sections. If not, the different physical interpretations of these two approaches should still be discussed. It would be even better if the authors can perform cloud-locking experiments and see which of the cloud impacts on ERF and feedbacks are robust for both approaches.

Specific comments

- L13: It should be clarified that the ECS is defined by the global-mean surface temperature (GMST).
- L25: Please include the references for the "recent studies" at the beginning of this line.
- L64: It should be clarified that, while using the first 100 years for the regression may be a common approach, the resulting ECS may not be the "true" ECS in the final equilibrium state, especially for models that manifest different slopes for the Gregory plot after the first century (e.g., Winton et al. 2020, JAMES).
- L70: Does the fixed-SST run use the climatological mean SST that repeats itself every year, or does it include the observed SST interannual variabilities?
- L85: It would be helpful to break down the \xi factor into the contributions from the feedback and ERF terms.
- L112–113: This description is somewhat unclear. What does "previous version" refer to, and how is the model "fine-tuned"? And is this sentence describing only the full-sky experiment, or is the clear-sky experiment also spun up with the same initial ocean state from the "previous version"?
- L116–119: As stated in my general comments, it is essential to include a figure for the surface temperature and ice cover of the full-sky and clear-sky experiments.
- L128: It should be clarified that the "different initial conditions" are all taken from the respective control runs after equilibration.

- L142: As stated in my general comments, it should be clarified that the “strong radiative effect” of clouds can affect the other feedback mechanisms by (1) changing the control climate state or (2) changing the thermodynamic/dynamic responses to increased CO_2. The physical interpretation is very different between these two scenarios.
- L161–166: As stated in my general comments, it should be clarified (and quantified if possible) whether this damped lapse-rate feedback is due to the lack of cloud-induced upper tropospheric warming, or due to the weaker warming over the tropical convective region that reduces the free-tropical warming globally. To address this question, it may be helpful to compare the 3-dimensional temperature responses between the clear-sky and full-sky cases, and check whether the differences in warming are collocated with the cloud radiative heating (both in height and horizontally), or whether they are more extant below the cloud heating level and beyond the high cloud regions.
- L167–168: The first sentence fits better with the preceding paragraph.
- Figure 2: Please add a column to show the sum. Also, following my comment on L85, it seems that the sum of the clear-sky from full-sky feedback parameters is similar to the sum in the clear-sky experiment. What is the \xi factor and the implied ECS if equation (4) is computed with these “clear-sky from full-sky” values? Is the implied ECS (perhaps coincidentally) similar to the clear-sky values?
- L177: It should be clarified that the CO_2 forcing differs because of the cloud masking and the differences in temperature and humidity.
- L178: The hyphen after “temperature” is unnecessary.
- L186–187: The “low bias” here is not simply a problem with denser points away from the y-axis, but it essentially indicates the time-dependent (or temperature-dependent) feedback strength. If the feedback parameter is unchanged over time, all points would sit on the same straight line and no “low bias” would occur despite the denser points away from the y-axis. This comment also applies to L190 where the argument “more homogeneously distributed points reduced the effect of bending” blurs the essential issue of time-dependent feedback.
- L198–199: Why is the enhancement expected? Is it based on the assumption that cloud masking effect dominates over the cloud adjustment? Also, it would be intuitive to refer to Figure 1 here or around L215 for explaining why [G100] differs from [G20], i.e., the clear-sky case shows more “bending” than the full-sky case.
- L214–215: This “artifact” seems physical to me – the southern ocean warming and sea-ice albedo feedback occurs over the centennial timescale, so it is more pronounced in [G100].
- L219–220: The definition of local feedback by global mean temperature has some advantages as the authors describe, but it may blur the physical interpretation of lapse-rate feedback differences between clear-sky and full-sky cases, because the free-tropospheric temperature profiles (and the lapse rate) over most the tropics and subtropics roughly follow the weak temperature gradient mechanism, which is determined by the SST of the convective region rather than the global mean SST. If so, it may be helpful to check whether computing the lapse rate feedback with the tropical-mean SST, or with the precipitation-weighted SST (e.g., Zhang and Fueglistaler 2020, GRL), can help reduce the lapse rate feedback differences.
- Figure 4: Please add a column to show the sum.

- Figure 5: It would be helpful to clarify in the caption that the “total” row is the sum of the “temperature”, “water vapor”, “albedo”, and “cloud” rows, whereas the “temperature” row is approximately the sum of the “planck” and “lapse rate” rows.
- Figure 6: This figure is confusing because the stratospheric adjustments are included in the temperature adjustments. It would be better to show the tropospheric adjustments (planck and lapse rate) rather than the full temperature adjustments, so that they are not washed out by the nearly uniform stratospheric adjustments, and that the “total” row is the sum of all other rows.