Response letter to Referee Reviewer 1

REVIEWER COMMENTS

Referee Reviewer 1

I appreciate the time the authors took to address my concerns and increase the robustness of their findings. Overall, I find that the manuscript has been greatly improved and thus I have mostly minor comments to suggest.

Dear reviewer, thank you very much for your suggestions which were very helpful in improving the presentation of this work. For the gravity wave section, we have opted to keep most of the content, as it is important to understand gravity waves in PGW runs. Our use of hourly animations and magnitude spectrum can provide some clarity on this issue since previous studies only used mean fields to infer the absence of gravity waves. However, to address your concern, we have rewritten the paragraph to clarify our explanations and interpretations of the results. We have also modified the paper following your comments in our point-by-point responses below.

General:

• *I am confused about the point of Section 3.3 "Gravity wave noise" because the authors contradict the claims they make in this section with other parts of the paper. In this section, they attribute the appearance of gravity waves to storm development, which I believe is accurate and not noise especially because in the introduction they state that spurious gravity waves could be generated from the boundary of the domain if the perturbation upsets geostrophic balance (lines 61–63). Clearly, these are not just "spurious" gravity waves, but rather real artifacts due to storm intensification upon watching the animations sent by the authors. In the conclusions (lines 356–358), they contradict Section 3.3 and state that all experiments produce spurious waves. You cannot state that these are both spurious and storm-generated gravity waves, they must be one or the other (unless there are other gravity waves I did not see).*

From this point, I think there is too much speculation around the appearance of waves and I would recommend simply stating that they exist, and could be due to stronger storms in the PGW simulations due to the warmer temperatures. Or you could just state that they exist and are stronger with some perturbed variables but not others. If these figures are just averaged over the time period of the flood (including when it is raining), again, you are introducing mesoscale modifications of the perturbations, including mesolows, outflows, and cool pools. It is impossible to evaluate these figures and what the changes in pressure, temperature, and CAPE mean if they are already being contaminated by the presence of storms.

Sorry for the confusion and thank you for urging us to clarify our key points on gravity waves in the simulations. Here we would like to further clarify the gravity waves discussed in subsection 3.3. First, as stated in the manuscript and our previous response letter, the storm development contributes to and magnifies the gravity waves; however, storm development is not necessarily the dominant or the only deterministic source of the obvious gravity waves in the PGW simulations. As shown in Figures R1 and R2, the magnitude and frequency of gravity waves are negligible or much lower in the historical run compared with the PGW runs. The more obvious gravity waves in the PGW runs may be due to the development of a stronger storm under warming, geostrophic imbalance caused by the perturbed boundary conditions, and/or the interactions between the two factors. If the most significant gravity waves are solely caused by stronger storms in the PGW simulations and are due to the warmer temperatures, then the magnitude increase of gravity waves should be comparable to the storm intensification (e.g. the increased precipitation and associated increased latent heating). However, the magnitude and frequency of gravity waves in the historical run are much lower compared with those in the PGW runs. That is, the gravity waves are amplified far more than can be explained by the intensification of the storms.

Additionally, we can see from Figure R3 that the gravity waves during the 2006/2056 March dry periods are not obvious in both the historical/PGW runs, which suggests that storms can magnify the gravity waves in the presence of geostrophic imbalance in the boundary conditions. In other words, the gravity waves in the PGW runs are contributed by the inconsistencies and imbalances between the outer and inner domains due to the PGW perturbations and magnified by the occurrence of storms. This behavior not only increases the magnitude of gravity waves but also increases the imbalance between the boundary conditions and the inner domain. With that said, we admit that the analysis of gravity waves is still not comprehensive so further studies are needed to deepen our understanding.

We recognize that the paragraphs in the manuscript do not convey this clearly. We have modified them, instead of shortening them, as we believe that the discussion of gravity waves in PGW experiments is important for the regional modeling community. Specifically, many PGW studies preferred to add a regional mean warming signal to reduce the gravity waves caused by unrealistic adjustments to geostrophic imbalances (Hill and Lackmann, 2011; Yates et al., 2014; Mallard et al., 2013b; Ullrich et al., 2018). Their assumption is that, by modifying the temperature at each grid point according to the GCMs' projections instead of using regional mean perturbations, the temperature gradient and geostrophic balance in the control run based on reanalysis boundary conditions will no longer hold, so gravity waves will be excited due to adjustments needed to restore the geostrophic balances. But here we can see that in both PGW_T_regional and PGW_T_gp, the magnitudes of the gravity waves are comparable and are both much larger than the waves in the historical run, demonstrating that PGW_T_regional does not obviously reduce the gravity waves as suggested. Also, several previous papers (e.g. Lackmann (2013) and Mahoney et al. (2018)) concluded that gravity waves were not found in their PGW runs, even though they only analyzed the period mean fields, which mask the appearance of gravity wave noise, and do not provide animations or magnitude spectrum as provided in this study. The appearance of gravity waves is a crucial question in PGW studies so we hope our work can shed some light on this issue and call for more attention to this phenomenon in future work.

The corresponding paragraph is modified as follows:

In WRF, boundary conditions are specified based on the input forcing (here the historical reanalysis data with climate perturbations) and the numerical solutions are nudged towards the imposed boundary conditions within the buffer zone of the outer-most domain (Skamarock et al., 2008). Within the inner domain, except for the most peripheral grid points, meteorological fields are much less constrained by the boundary conditions and can significantly depart from the forcing data (Skamarock et al., 2008). This can induce inconsistencies among the meteorological fields in the outer and inner domains and explain why the wave-like noise also appears in PGW_T_regional (refer to the animations at Xue and Ullrich (2022)), even though the geostrophic balance holds in the initial and boundary conditions. From the animations of SLP during the October flood event (Xue and Ullrich, 2022), we can infer that the gravity wave is not solely excited by the storms, as the magnitude of the gravity wave is negligible in the historical run compared to the PGW run even though the storm is also present in the historical run. Furthermore, gravity waves are amplified in the PGW run more than expected from the difference in the precipitation between the PGW and historical runs. Similar results can be observed in the magnitude spectrum of SLP (Fig. S15). Storms also play an essential role in magnifying the gravity waves through significant advection of energy and momentum, as it is apparent that gravity waves are much stronger during storms than during periods with nearly no precipitation (refer to the animations at Xue and Ullrich (2022)). We conclude that the amplified gravity waves in the PGW run during storm events reflect the interactive effect of inconsistency between the meteorological fields in the outer and inner domains and the excitation of gravity waves by the storms. Although gravity waves in the PGW simulations are inspected through hourly animations and magnitude spectrum, the analysis of gravity waves could be the basis of its own standalone study.

Please refer to https://zenodo.org/record/6544880#.Y0YyQuzMJ9s

Figure. R1 The animation of sea level pressure during the 2005 October Flood and returned 2055 October Flood

The Sea Level Pressure Field and Its Magnitude Spectrum after Fourier Transform

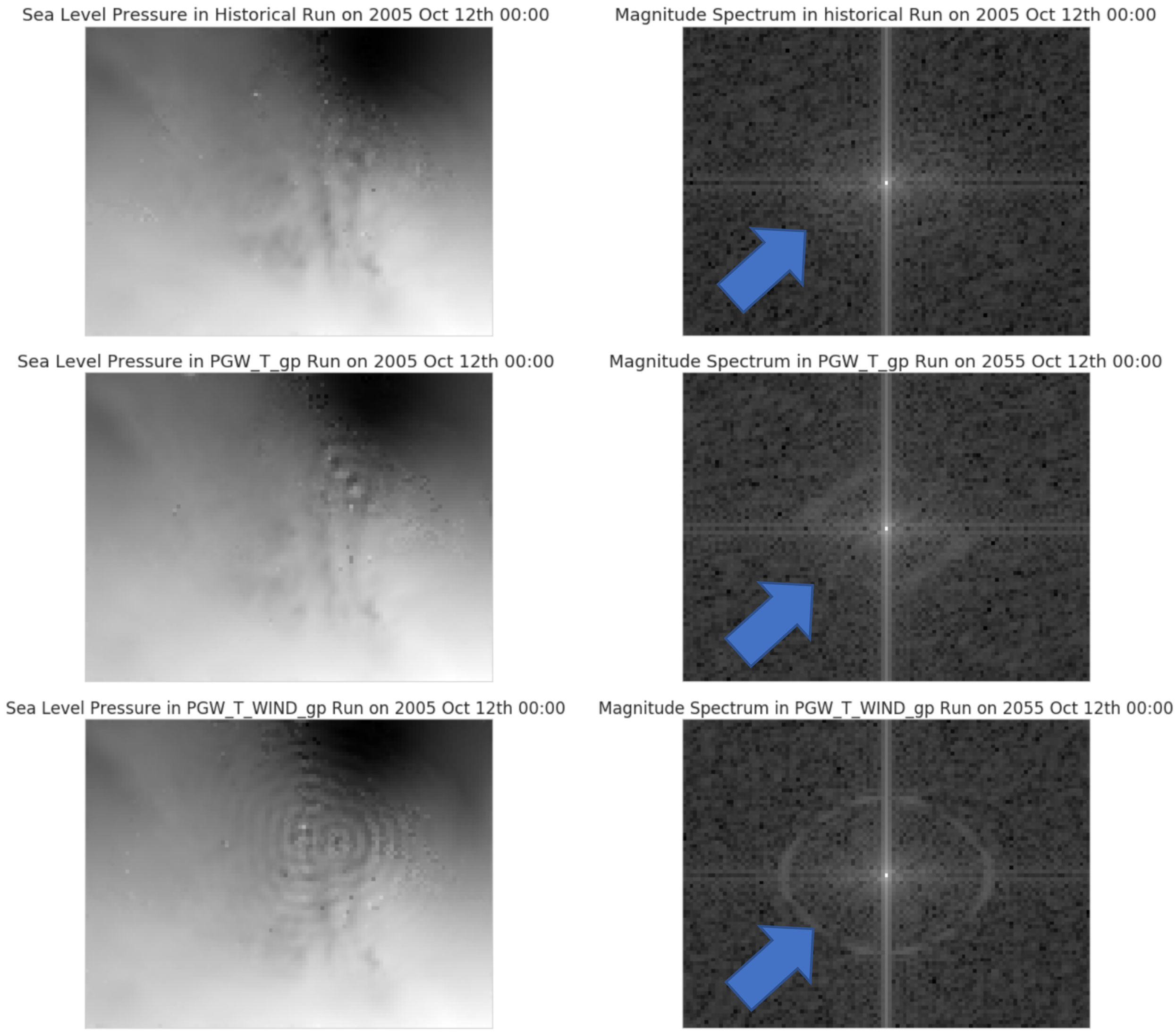

Figure. R2 The sea level pressure field and its magnitude spectrum after Fourier transform

Please refer to https://zenodo.org/record/6544880#.Y0YyQuzMJ9s

Figure. R3 The animation of sea level pressure during the 2006 March dry period and returned 2056 March dry period

Specific comments

• Lines 12–13: I do not think you can state the preservation of geostrophic balance does not hold, given my comment about gravity waves.

Please refer to our response to the general comment. It's apparent in Figures R1 and R2 that the gravity waves are much stronger in the PGW runs compared with the historical run and the difference is much larger than expected from the difference in precipitation between the two runs, suggesting that both inconsistencies and imbalances between the inner and outer domain brought by the PGW perturbations and the intensified storm development in the PGW runs contribute to the amplified gravity waves in the PGW runs. We have modified the paragraph to provide clearer explanations and mentioned that our analysis is still not comprehensive and further analysis is needed.

• Line 48, starting with "In these first PGW", I recommend starting a new paragraph since the one you have is already quite long.

Thanks a lot for your suggestions. We started a new paragraph as suggested.

• Line 136: How are perturbations linearly interpolated? Do you mean the perturbations between months?

Yes, we have added "(between the middle of two consecutive months)" after "and linearly interpolated in time" to clarify it.

• Line 138–140: Are you taking the CESM 40-member ensemble mean for your future forcing? If so, that should be stated here.

Sorry for the misunderstanding, and we did state that the CESM ensemble mean is used to provide perturbations in the subsection – Methodology and modified forcings – "For our PGW simulations of the future, the initial and boundary conditions are adjusted by adding long-term monthly mean of the ensemble mean climate perturbations from the Community Earth System Model (CESM1) Large Ensemble (LE) dataset" (Line 132).

• Figure 2 caption: I don't see a column with the difference with IMERG. Please remove this from the caption or include figures showing this difference.

Thanks for pointing out the typos. We have deleted the mention of IMERG from the caption.

• *Line 189–191: I understand how regional vs gridpoint perturbations in T would cause an impact in the October case due to the reduced land-sea contrast in the regional perturbation, but I don't understand why regional vs. grid point perturbations would affect the frontal system? Do you think it's due to a reduced horizontal temperature gradient using the regional perturbations? If so, these sorts of interpretations would be helpful to discuss in order to make sense of your results.*

We have added "Additionally, as the frontal system's intensity is highly dependent on the horizontal temperature gradient (Sawyer, 1956; Bosart, 1975; Reeder et al., 2021), it's intuitive that the first flood event is sensitive to the different spatial scales of temperature perturbations applied to the boundary conditions." But to confirm whether using regional perturbations reduces the horizontal temperature gradient and hence the strength of frontal systems requires additional analysis which is out of the scope of this study."

Instead, In Lines 189-191, we attributed the larger precipitation increase in the first event to two factors. We know that the scaling of extreme precipitation with temperature can be decomposed into two factors: vertical pressure velocity and the vertical derivative of the saturation specific humidity (Pfahl et al., 2017). As the first event has a more intense uplift (Fig. S10), it will have a larger response to the increasing humidity under warming. Also, this event has a stronger on-shore flow (Fig. S9) which means it can transport more precipitable water from the ocean to the coastal area where precipitation mainly occurs.

• *Figure 3: Please state that all precipitation products are regridded to the same grid-spacing and what that grid-spacing is.*

Thanks for the advice. We have added "All datasets have been interpolated to the resolution of our inner domain (10km)." to its caption.

• *Figure 4: Please add "difference" after "PGW_T_gp" in the figure headings in the right column to make it clear that this is a difference plot.*

Since our current title and captions already point out which columns are different plots and we follow the same layout in all similar plots (e.g. Figures 7 - 12), we'd prefer not to add "difference" to the figure headings to prevent them to be too long (e.g. PGW_T_WIND_ZG_SLP_gp difference).

• *Figure 6: The titles overlap between the two columns, so I recommend using a smaller font to make sure they do not overlap.*

We have adjusted the plot following your advice.

• *Lines 240–241, 246–247: Are you referring to Fig. S6 and S7 here? If so, please add those citations.*

Thanks for pointing out the need to add citations. We have added the corresponding citations and clarifications.

• *Lines 283–284/ "Note that precipitable water is defined as the depth of water in a column of the atmosphere instead of precipitable water in the surface atmosphere": I am well aware of how precipitable water is defined. I was simply pointing out that the reduction in precipitable water for the PGW_T_SLP_gp experiment mostly appears over the sea rather than the land (except for the 2056 May case), which is worth stating in your results.*

Sorry for the misunderstanding. That's an interesting observation which may be because in the second event SLP increases less over the sea (Figure 9), which further illustrates the impact of SLP perturbations on surface temperature. We have added "The reduction in precipitable water over the sea is stronger than over the land, except for the 2056 May flood period, probably because the SLP increase over the sea is smaller during this event (Fig. 9)."

• *Line 292: I recommend reordering the figures so that Fig. 9 comes after Fig. 13 since this is the first time you mention it.*

Thank you for your suggestions. We have reordered these two figures.

• *Lines 297–300: It is well known that CESM-LE tends to have a very strong warming signal in RCP8.5 compared to other GCMs, so what if the inclusion of SLP perturbations helps to ameliorate those biases?*

CESM-LE projects a stronger warming signal under RCP8.5 compared to other GCMs, but the stronger warming is not a model bias that should be corrected because climate sensitivity is an emergent behavior of climate models. CESM1 has been demonstrated to be a high-quality model and using CESM-LE helps reduces uncertainties due to internal variability (Kay et al., 2015; Swann et al., 2016; Sillmann et al., 2013; Karmalkar et al., 2019). Therefore CESM-LE is widely used in climate studies (Labe et al., 2018; Zheng et al., 2018; Bellomo et al., 2018; Peings et al., 2017).

To reduce model uncertainties in projections due to model biases, the multi-model mean may be used to produce the climate perturbations as adopted in some previous studies instead of including SLP perturbations to counter the model biases. As we stated in the manuscript, the warming induced by the SLP perturbations is more likely due to unrealistic adjustments made within WRF according to the hypsometric equation because we can clearly see from Figure 13 and 14 that the warming signals in PGW_T_SLP_gp deviate from the projections of CESM-LE and are inconsistent at the surface level.

• *Supplementary Table S1: you are missing a citation after CLM4*

We have added the corresponding citation.

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