Responses to Referee #2

The work by Paik et al. studies the volcanic imprint on surface climate in the CESM Last Millennium ensemble (Otto-Bliesner et al., 2016) dependent on the latitude of eruption. A topic, which has been addressed by several authors before. This particular study concentrates on the influence of tropical, northern, and southern volcanic eruptions on the surface climate, specifically on the role of El Niño–Southern Oscillation, monsoonal precipitation and the Northern Hemisphere stratospheric winter climate. The results suggest that volcanic eruptions modulate surface climate by warming the sea surface temperature over the equatorial eastern Pacific and strengthening the stratospheric polar vortex but with diverse patterns depending on eruption latitudes. El Niño-like responses tend for example to amplify summer monsoon drying, which is stronger after tropical eruptions compares to northern and southern ones. After tropical and southern eruptions a strengthened Arctic polar vortex is found that, is accompanied a positive Arctic Oscillation response in boreal winter, while northern eruptions only weekly influence the Arctic polar vortex and associated surface responses.

I recommend major revisions as I have a couple of major concerns:

General comments:

The CESM Last Millennium ensemble has been widely studies with respect to volcanic eruption of different season and latitudes (e.g. Stevenson et al., 2016; Zuo et al., 2018, 219a;b,;2021). In particular, the work on the volcanic impact on tropical hydroclimate is therefore repetitive. Zuo et al. published four papers on this topic in the last four years using the same model simulations and the same volcano classification. While the authors cite the 1st three papers of Zuo and co-workers, a citation of the recent work by Zuo et al. (2021) on the dependence of global monsoon response to volcanic eruptions on the background oceanic states is missing. This is in particular important as the current paper has a complete session 3.2 on it.

Hence, I ask myself with respect to tropical hyroclimate what do we learn from this study what we did not know beforehand. Are there are any new insights? I miss a thorough and careful comparison of your results with respect to Zuo et al in the discussion section. In addition, there are also many other papers on the hydro climate impact of volcanic eruptions dependent on their latitude (e.g. Liu et al, 2016; 2018; Zhuo et al. 2021; Pausata et al., 2015. At the end of the paper in the discussion session, it would be also important to discuss how your results fit into the broader picture. Is this consistent or are there differences/uncertainties, which we need to understand and address further

The aim and the purpose of this paper is not really clear to me. I would like to see a much better motivation of the current study, e.g. what is your driving question? I recommend to narrow down the subject of the study and to focus on one or two specific questions e.g. the impact of the eruption of latitude on the NH winter response. Maybe it would make sense to distinguish even a bit further between the latitude of the eruptions. NH hemisphere eruptions could lead to very different forcing pattern see for example Toohey et al. (2019, their supplementary Figure 3). Hence, their impact on atmospheric circulation and surface climate could be quite different.

Thank you very much for your thoughtful and constructive comments. The main purpose of this study is to understand how volcanic eruption latitudes can diversify surface climate responses through altering natural variability modes. In this respect, we focus on ENSO and polar vortex variations and their influences on surface temperature and precipitation. We understand your concern on the novelty in our study given many previous studies based on the same model simulations. In the revised manuscript, we will clarify new findings by comparing our results with those from previous studies from the same model as well as different models. Specifically, we plan to provide a table summarizing consistency and difference in models, methods, and main findings between studies on eruption latitude influences on climate. The latter will be divided into ENSO-monsoon and polar vortex-

AO responses and the associated in-depth discussion will be provided, which will help highlight the novelty in our analysis. This will include a careful comparison with Zuo et al. (2021) results as you suggested. Regarding ENSO-monsoon responses, our study provides the first analysis of much detailed temporal variations of ENSO from tropical, northern and southern eruptions with new possible physical mechanisms discussed (e.g., role of delayed oscillation following southern eruptions). Further, we provide a first quantification of ENSO-induced global monsoon drying responses to different latitudes of volcanic eruptions. As for polar vortex-AO responses, there have been no studies systematically evaluating the influence of eruption latitudes. Our study demonstrates diverse polar vortex and associated AO responses depending on eruptions latitudes and examines associated physical mechanisms driving those diverse responses. Agreeing to your suggestion, we will consider dividing NH eruptions further into a couple of subgroups and check their different influences on atmospheric circulation and surface climate focusing on winter seasons.

I have difficulties with the criteria for the classification of tropical northern and southern eruptions. This selection criterion, which was introduced by Samantha Stevenson in her study in 2016, is related to the atmospheric aerosol load and mostly used in the context of the CESM Last Millennium ensemble.

Looking to Figure S1, one can clearly see that the pattern of the southern eruption is quite similar to the tropical one while the pattern of the northern eruptions looks quite differently. The peak aerosol mass of the southern eruption is still located in the inner tropics and close to the equator. This also explain why southern and tropical eruption have a similar influence on the NH winter hemisphere in the CESM Millennium runs. The term "southern" is quite misleading here in particular if one compare the response to other studies, which make a clear separation between tropical and extratropical eruption e.g. Zhuo et al. (2021). This might also explain some of the literature difference with respect to the ENSO response.

I recommend to revise/reevaluate the applied classification criteria. Does it really makes sense for your study or would another criteria e.g. tropical and extratropical eruption much more appropriate? If there are statistically not enough southern hemisphere extratropical eruptions one can either focus on tropical and NH extra tropical only or use a multi-model approach by including PMIP3 or PMIP4 simulations.

Thank you for the good point and useful suggestion. Agreeing with your concern on the small number of samples for SH eruptions, in the revised manuscript, we will consider applying different criteria which allow for more appropriate classifications of volcanic eruptions based on eruption latitudes and revise our results accordingly. One way would be to focus on tropical and NH extratropical eruptions as you suggested. In this case, we can show results from SH eruptions in the supplement and discuss its possible influences distinct from tropical eruptions, considering the large uncertainty due to limited samples. The other way would be to keep tropical, northern, and southern eruptions in the main paper and showing tropical-SH combined results in the supplement. In that case, we will clearly explain the separation criteria employed with showing detailed patterns of aerosol forcings between SH and tropical eruptions. As we mentioned above, we will compare our results with previous studies based on different models including Zhou et al. (2021) that applied idealized eruption latitudes (30N, 30S). In this respect, we will attempt to divide our NH eruptions into lower and higher latitudes and evaluate differences in atmospheric circulation and surface climate responses although uncertainty can increase due to the reduced sample size.

Specific comments:

Introduction: Some recent literature is missing:

- Tropical hydroclimate e.g. Zuo et al., (2021); Zhuo et al. (2021); Predybalo et al (2020), Ward et al (2021)

- NH winter response: Zambri et al. (2017), Dalla Santa et al (2021) and references therein, Coupe and Robock (2021)

Thank you. We will cite these papers and include them in our discussion as appropriate.

Page 14, line 295 ff: The paragraph about the Laki eruption has to be revised. The spatial distribution looks completely weird, see for comparison Zambri et al (2019). Laki is an Icelandic fissure eruption, which erupted on 8 June 1783 and lasted for 8 months. It is located at 64 N so it could be easily included in the polar vortex. It might be that not only the timing but also the spatial distribution of the Laki eruption is wrong in the CESM Millennium ensemble. Please check this carefully and adapt your interpretation.

Thank you for notifying this. We will revise the related paragraph carefully in comparison with Zambri et al. (2019) and other related papers.

Page 10- 12: How consistent are your results with Zuo et al. (2021) in particular Figure 5 with their Figure 8?

As we mentioned above, we will compare our results with Zuo et al. (2021) and add a discussion about the differences in the revised text. Some differences are noticeable. For example, Zuo et al. (2021) suggested the opposite sign of contributions from volcanic induced direct response and ENSO variation following tropical eruptions when oceanic initial condition is neutral. This difference seems to be due to different samples and methods used. Zuo et al. (2021) divided volcanic samples according to oceanic initial conditions and quantified ENSO contribution based on piControl simulations. In our analysis, we focused on eruption latitude influences on ENSO contribution to drying responses and used all years when ENSO has significant positive phases (e.g., YR0 following northern eruptions). We also derived ENSO contribution by linearly regressing regional monsoon precipitation variations onto ENSO index.

Page 19, line 391-391: "First study" is not correct in particular with respect to the ENSO response, see general comment above . So please revise this accordingly

We will clarify this issue. See our response above.

Page 20, line 406: the southern eruptions considered here are not high latitude eruptions

Indeed, the southern eruptions have relatively weaker asymmetric aerosol loadings. This issue will be considered. See our response above.

Page 20, line 421: Your classification is too coarse to really have an important impact for the volcanic impact on decadal predications. Looking to the different spatial distribution for NH mid and high latitude extratropical eruptions, see e.g. Toohey et al. (2019), you will expect quite different surface climate responses although both would be quantified in your classification as northern.

We will consider this issue. See our responses above.

Table 1: Please refer here to the original table by Stevenson et al. (2016).

Will be done.

Figure 1: The surface temperature plots are not readable at all.

We will revise them for better readability.

Figure 3: Why are there are significant dots in the years prior to the eruptions in panel c) and e).

This might be due to other influences from external forcings and previous eruptions. We will mention this in the revised text after further checking.

Figure 8: The panels a) and c) look quite similar, are they are the same? What does the black dots show in panels b) and d)? I also do not completely understand if you have values only at four levels, then the distinct maximum between 10 and 200 hPa would not make sense.

The panel a) and c) look quite similar but there are some differences. Black dots in panels (b) and (d) are just dots associated with x-axis. Actually, the vertical layers between the levels are supposed to be filled with upper or below level. It seems confusing due to the use of shading. We will revise the figure considering your points.