

***Interactive Comment on “Arctic temperature and precipitation extremes in present-day and future storyline-based variable resolution Community Earth System Model Simulations” by René R. Wijngaard et al.***

We gratefully acknowledge the reviewer for his/her remarks and suggestions, which improved the quality of the manuscript significantly. We have carefully considered the suggestions of the reviewer and we provide a point-by-point response to the reviewer’s comments. For clarity, the reviewer’s comments are given in bold italics and the responses are given in plain text. References that do not refer to those in the main manuscript are listed below. The manuscript will be modified according to the responses that are given to the comments.

***This article examines changes to mean and extreme metrics of temperature and precipitation in VR CESM simulations, where mesh refinement is over the poles. Comparisons are made with standard resolution CESM output. Simulations of present day and of two storylines of future change based on other work are performed with and without mesh refinement over the region of interest. They find that high extremes of temperature and precipitation will increase in many of the study regions encompassing high latitude land and ocean.***

***This is a well written and thorough paper. I think that the application of different storylines of future change within a high-resolution model is a novel and interesting way to use high-resolution modelling at a lower computational cost. Throughout there is thought put into trying to physically understand the results, and with trying to square these results with past studies, placing it nicely within the larger body of literature. Figures are high quality and contain a lot of information that is well presented.***

***I have mainly minor comments I’d like to see addressed before publication.***

We thank the reviewer for his/her evaluation of the manuscript. We have tried to address all concerns.

### **General:**

***In terms of readability, using capital letters to refer to simulation names (e.g. POLARRES), regions (e.g. ECG, SCA.), and metrics of extremes (e.g. WSDI, CSDI) did at times make it a bit difficult to understand. Using bolding, italics, or perhaps single quotation marks to differentiate between them (depending on what the journal might allow), or even simply spelling out the whole name of, for example, a region, would improve ease of reading.***

We will improve the readability of the manuscript by spelling out the abbreviations that are related to the temperature and precipitation extreme metrics and the regions as these are used most throughout the manuscript. For example, WSDI will then become warm spell duration and SIC will become the sea ice region.

***The Data & Methods are very comprehensive but probably a bit more specific and detailed than is necessary for this paper, more suited toward a paper published in a journal about geophysical model development. For example, details of CLM5, computational costs, parameter tuning, where reanalysis data is retrieved from, an unused dataset, etc could be pared down to the necessary information not available in other published work.***

We will shorten the *Data and Methods* section by shortening the subsections related to the model description (especially the model description of CLM5) as most of the details described in these subsections can also be found in other published work. As for the other parts of the Data and Methods section we will have a thorough look onto which parts of the main text can be shortened.

***I think it's important to keep in mind that agreement/disagreement between a reanalysis product and a model over regions of sparse observations should always be taken with a grain of salt, and that reanalyses are not equivalent to observations. Treatment of differences between a model and a reanalysis product in some regions is akin to comparing model and model, and reanalyses themselves have many biases. Perhaps a bit more discussion to this end would be beneficial.***

We agree with the reviewer that the differences between the CESM model output and reanalysis data need to be interpreted with care as reanalysis data can also contain many biases, especially in regions with sparse observations where reanalysis fields can be strongly influenced by the underlying forecast model. For example, in L319-328 of the original manuscript, we already indicate that the cold temperature differences in CESM is partly related to large warm near-surface temperature biases that have been found over sea ice during winter (clear sky) conditions in reanalysis datasets, such as ERA5 and JRA55 (the predecessor of JRA-3Q). These warm biases are mainly caused by a poor representation of snow on top of the sea ice and the sea ice thickness itself and can exaggerate the cold temperature differences in CESM. To understand the magnitude of cold temperature differences, validation of near-surface temperature against meteorological observations are therefore recommended in future research.

As the reanalysis data can be strongly influenced by the underlying model in regions with sparse observations, we have chosen to describe model-related differences, such as those between CESM and ERA5, in terms of differences rather than errors and biases. We will therefore replace “root-mean-square-error (RMSE)” and “Bias” with “root-mean-square-difference (RMSD)” and “average difference (AVGD)”, respectively, and we will adjust the wording in the main text following this terminology (e.g. cold temperature bias becomes cold temperature difference). Additionally, we will add an extra sentence to Section 2.3 *Model evaluation* to mention that the reanalysis fields can be strongly influenced by the underlying model in regions with sparse observations. We will also add an extra sentence to the *Discussion and Conclusions* section to emphasize that comparisons with meteorological observations are beneficial for a better understanding of the temperature and precipitation differences in CESM model output.

### **Specific/Technical**

***L 13 & elsewhere: ‘SST warming’ should either say ‘sea surface warming’ or ‘SST increase’ because a temperature can’t warm.***

We will replace “SST warming” with “sea surface warming” throughout the manuscript.

***L30-32: I don’t think this is a complete treatment of the literature on whether cold extremes are becoming more common in the mid-latitudes, as more recent studies (e.g. Cohen et al 2023, Van Oldenborgh 2019, Blackport 2024) have not come to the conclusion that cold extremes are occurring more often. Additionally, it’s not particularly relevant to the regions discussed later in the paper so probably best to just not include it.***

We agree with the reviewer that the treatment of the literature in this sentence is not complete since recent studies (e.g., van Oldenborgh et al., 2019, Cohen et al. 2023, Blackport & Fyfe, 2024) as mentioned by the reviewer indeed indicate that there is no clear trend (Cohen et al., 2023) or decreasing trend (van Oldenborgh et al., 2019; Blackport & Fyfe, 2024) in the occurrence of winter cold extremes in the mid-latitudes. As our study mainly focusses on the Arctic, we therefore will follow the reviewer’s suggestion by not including this sentence in the manuscript.

***Paragraph beginning at line 81: Might want to add references to Morris et al papers from 2023-2025 using VR CESM to look at wind extremes. They find that sometimes the low resolution CESM gets a different sign of response than VR CESM for extreme winds, and perhaps it's something worth looking into for the Arctic region as well.***

We will include the references to the work of Morris et al. (2023, 2024) and Morris and Kushner (2025) in the manuscript. Regarding wind extremes in the Arctic region, we believe that investigating the impact of regional grid refinement on the projection of future wind extremes would be interesting as well. However, as the manuscript is already quite lengthy, this could be a topic for future studies.

***L95: I'm curious why there is an enhancement of resolution over the Antarctic as well?***

The POLARRES grid is originally designed for Work Package 2 of the PolarRES project (<https://polarres.eu>). The project itself studies the interactions between the atmosphere, oceans, and sea ice in the Arctic and Antarctica using global climate models and regional climate models, amongst others. In Work Package 2 of the PolarRES project, three global variable-resolution climate models (CESM, ICON, and MPAS) are used to improve our understanding of atmospheric teleconnections in both the northern and southern hemispheres, regional climate impacts over the Arctic and Antarctic, and how polar climate systems affect and are affected by lower latitudes. The CESM simulations performed for this study also contribute to the research conducted in this work package. As the focus is also on Antarctica in this work package, there is an enhancement of resolution over the Antarctic as well.

***L283-285: difficult sentence to understand, I'd suggest re-writing to clarify.***

We will rewrite the sentence to “The cold temperature differences are largest relative to ERA5, with average differences of -1.32 °C and -1.72 °C for NE30 and POLARRES, respectively (Figs. 3a-b). The differences are smaller relative to RACMO, with average differences of -1.24 °C and -1.64 °C for NE30 and POLARRES, respectively (Figs. 3e-f), and to JRA-3Q, with average differences of -0.54 °C and -0.95 °C for NE30 and POLARRES, respectively (Figs. 3c-d)”.

***L353: missing comma before ‘as for example’***

We will add a comma in the main text before “as for example”.

***L408: I think here and below should read ‘cold’ anomalies and not ‘cooling’ anomalies.***

We agree. We will replace “cooling” anomalies with “cold” anomalies.

***L471: I find this sentence a bit confusing. Do wet regions become more variable?***

The sentence “This means that relatively dry regions will become wetter, while relatively wet regions will become wetter and experience longer periods of drought.” can be explained as follows. Relatively dry regions are very high-latitude regions with cold winters, in which daily precipitation above 1 mm is relatively rare. This can explain why these regions have a high present-day number of consecutive dry days. With increased warming, these regions experience an increase in precipitation and a decrease in consecutive dry days, suggesting that these regions will become wetter. Relatively wet regions (i.e. the regions with a lower present-day number of consecutive dry days) are found in the warmer southern parts of the Arctic (i.e. at lower latitudes) and experience more precipitation. These regions might experience longer periods of drought in summer in a warmer climate, resulting in an increase in the number of consecutive dry days. However, at the same time, these regions will also become wetter, as the mean precipitation and precipitation extremes will increase in intensity and frequency. This results in a higher precipitation variability, particularly over regions, such as Scandinavia and over lower latitudes. We will rephrase the sentences in the manuscript to clarify our findings.

**L500: comma after regimes, remove ‘as well’ from end.**

- We will add a comma after “regimes” and remove “as well”.

**L532: Does POLARRES produce more storms/more strong storms than the reanalyses do for this region?**

Although we did not examine the frequency and intensity of storm systems in POLARRES, a research project is currently investigating the impact of regional grid refinement on the Northern Hemisphere extra-tropical storm tracks in three global models, which are CESM, ICON and MPAS (personal communication from Kajsa Parding at the Norwegian Meteorological Institute). The initial findings of this project indicate that, compared to ERA5, the NE30 grid underestimates the number of extra-tropical storms. The POLARRES grid generates more extra-tropical storms than the NE30 grid, particularly over the North Atlantic region. On average, the POLARRES grid also generates more extra-tropical storms than ERA5 in summer, with positive differences observed over Greenland, the North American mid-latitudes, and (north)eastern Asia. The latter two regions overlap with those where larger differences in the highest 5-day precipitation sum are observed. However, these regions also show more storm tracks than ERA5 in NE30. This suggests that the higher frequency and intensity of storm systems with increasing resolution cannot fully explain the larger highest 5-day precipitation sum differences in POLARRES. Therefore, we will adjust the text in lines 368-369 of the original manuscript as follows:

“The larger differences in POLARRES may partly be the result of a higher frequency and intensity of storm systems, which bring significant amounts of precipitation over a period of several days (Zarzycki and Jablonowski, 2014). However, more research is needed to understand the impact of regional grid refinement on the frequency and intensity of storm systems and its effect on precipitation extremes in CESM.”,

and in lines 531-532 as follows:

“The larger highest 5-day precipitation sum differences in POLARRES may partly be related to a higher frequency and intensity of storm systems bringing significant amounts of precipitation over a period of several days.

**L547-549: Is this sentence at odds with that at L471?**

The sentence here is not at odds with that at L471. What we suggest here is that regions with a high number of present-day consecutive dry days show a decrease in the number of consecutive dry days. These regions are relatively dry with cold winters in which daily precipitation above 1 mm is relatively rare. Under a warmer climate, precipitation will increase, resulting a in lower number of consecutive dry days. This means relatively dry regions will become wetter. Regions with a low present-day number of consecutive dry days – located in the southern part of the Arctic – can be considered as relatively wet and show an increase in the number of consecutive dry days, which is presumably related to prolonged periods of drought during summer. However, these regions will also become wetter under a warming climate, which is indicated by the increase in intensity and frequency of precipitation means and extremes. We will rephrase this sentence in the manuscript to clarify our findings.

**Figure 2 caption & elsewhere: ‘outputted’ -> ‘output’**

We will replace “outputted” with “output” here and elsewhere in the manuscript.

## **References**

Blackport, R., Fyfe, J.C. Amplified warming of North American cold extremes linked to human-induced changes in temperature variability. *Nat Commun* **15**, 5864 (2024). <https://doi.org/10.1038/s41467-024-49734-8>.

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