Interactive Comment on **"Exploring the ability of the variable-resolution CESM to simulate cryospheric-hydrological variables in High Mountain Asia"** ***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.

The authors evaluate the performance of a variable-resolution (VR) configuration of the Community Earth System version 2 over the High Mountain Asia (HMA) region, focusing on the cryospheric-hydrological variables. A new VR mesh is produced for this study with its grid spacing refined to ~ 7 km over the HMA region from ~ 1° in the coarse-resolution domain. A new glacier-cover input data is also produced for the VR grid.

The performance of VR configuration is compared to a globally uniform ~1° grid (NE30) through 20-year long simulations (1979-1998) and also evaluated against a variety of observational dataset. While the regionally refined mesh improves some aspects of the simulation quality, such as the circulation patterns forced by the topography, other aspects are degraded from the NE30 simulation. One reason for the degradation is model sensitivity to spatial resolution and time step length, i.e., less optimal tuning. Another VR simulation with several tuning to alleviate such sensitivities showed improved performance, but model biases still remain. They also suggest several future directions to reduce the VR model bias and improve physical representations in both the atmosphere and land models, as well as their coupling method.

The study addresses questions relevant to the scope of TC. The target region (HMA) is an important natural resource for the population in the broad Asia region. The model they evaluate (CESM) is a widely used community model. The grid resolution within the regional refinement is higher than a previous study focusing on the same region using CESM, and the new glacier input data is a original product from this study. The text is well written, and figures are overall high quality, altough I have several minor suggestions. All together, I think this study can be an important contribution to the community. However, I have one major concern about their atmospheric model configuration and one suggestion of additional experiment that could strengthen the scientific quality and impact of the manuscript. Please consider the following major comments before publication.

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

Major comments

I believe the spectral element dynamical core used in this study is the hydrostatic version, which is not expected to be appropriate for the 7-km grid spacing. Several previous studies found that hydrostatic and non-hydrostatic schemes produce significantly different solutions in sub-10km grid spacings, or even larger gridcell sizes over steep topography like HMA (Wedi and Smolarkiewicz 2009, Prein et al., 2015, Yang et al., 2017). Errors would appear in vertical acceleration or unphysical propagations of gravity waves, which certainly affect moist physics behavior over HMA. No assessment of those aspects were provided in the manuscript.

Another related concern is the vertical resolution. The small horizontal grid spacing is probably not balanced by the rather coarse 32 vertical levels (Lindzen and Fox-Rabinovitz 1989, Skamarock et al., 2019). Any testing was done with different vertical levels?

Because I believe that the model is used with the resolution outside of its intended use, I strongly suggest the authors providing justifications and caveats to the readers about their results. The atmospheric model configuration used here should not be recommended as the standard for future modeling studies on the 7km VR grid.

Regarding the appropriateness of using a 7 km regional refined grid in combination with the hydrostatic VR-CESM, we understand the concerns of the reviewer. We'd like to orient this discussion by beginning with the scale analysis for non-hydrostatic dynamics invoked by Wedi and Smolarkiewicz (2009) that the reviewer has cited. Referring to their Figure 4, they state that "the results are consistent with estimates typically obtained from a heuristic scale analysis of non-hydrostatic motions in NWP, i.e. horizontal scales L = O(10 km) resolved with grid intervals dx = O(2 km)." We think it's fair to equate this scale analysis as the null hypothesis; that non-hydrostatic terms are only important at length scales below O(10km). In our 7km simulations, the smallest resolved scales are between 4 to 6 times the grid spacing (Skamarock et al., 2014; Lauritzen et al., 2018), or between 28 km and 42 km, which is greater than 10 km.

Testing this hypothesis requires experiments in which the dynamical core has a hydrostatic and non-hydrostatic "switch," and with pairs of tests performed across a range of grid spacings spanning the dx=2km transition. As discussed in Liu et al. (2022), models that support both hydrostatic and non-hydrostatic dynamics may contain design differences in addition to just the non-hydrostatic terms. For example, non-hydrostatic dynamics have one more prognostic variable, and therefore one more degree of freedom for applying the explicit damping operators, and how those operators behave in regions of steep topography matters a great deal (as does the vertical coordinate). This is not to discount the results cited in, e.g., Yang et al. (2017), but rather rejecting the null hypothesis in a single study may not be sufficient for the atmospheric modelling community as a whole to reject the null hypothesis, due to the challenges in testing this hypothesis.

Liu et al. (2022) provides a nice synthesis of studies that have cast doubt on the null hypothesis. It seems that prior to the Yang et al. (2017) study, studies showed conflicting results regarding the importance of non-hydrostatic dynamics at grid spacings between 2km and 30km. The recent studies of Yang et al. (2017) and Liu et al. (2022) do, however, provide convincing evidence to reject the null hypothesis, that non-hydrostatic dynamics are important at grid spacings up to 25 km, particularly in its representation of tropical convective systems.

But we believe that the reviewer's statement that "the atmospheric model configuration used here should not be recommended … for future modelling studies …" is too definitive given the challenges of testing this hypothesis and the relatively few studies that definitively reject the null hypothesis. However, we agree with the reviewer that this crucial discussion on the controversy of using a hydrostatic model at high resolution is missing. We will add the following discussion in the revised manuscript (under section *2.2 HMA-VR Grid and Performance*):

"The spectral-element dynamical core used by CESM is currently based on the hydrostatic approximation; non-hydrostatic vertical acceleration terms are neglected, which are important for the representation of deep convection, gravity waves, and flow over topography (Jeevanjee, 2017; Liu et al., 2022). Conventionally, the horizontal scales at which non-hydrostatic terms become important are assumed to be O(10 km), the vertical scale of the troposphere (e.g., Wedi and Smolarkiewicz, 2009). In our 7 km simulations, the smallest resolved scales are between 4 to 6 times the grid spacing (Skamarock et al., 2014; Lauritzen et al., 2018), or between 28 km and 42 km, which suggests that the hydrostatic approximation is appropriate. However, the more recently published studies of Yang et al. (2017) and Liu et al. (2022) have shown that non-hydrostatic terms are important at grid spacings up to 25 km, particularly in its representation of tropical convective systems. Due to the inherent difficulty in testing the null hypothesis (Liu et al., 2022), and that only two studies the authors are aware of have categorically rejected the null hypothesis, we do not believe this is grounds to conclude whether it is appropriate or not to use a 7 km regionally refined grid in combination with a hydrostatic model. Nonetheless, simulations with the hydrostatic VR-CESM in combination with a 7 km regionally refined grid have been performed before. Rhoades et al. (2018) have successfully shown the ability of VR-CESM to simulate mountainous climate with a 7 km regionally refined grid over the mountain ranges of western USA. Due to its location in the mid latitudes, the hydrostatic simulations with a 7 km grid spacing are still considered to be appropriate since the differences between hydrostatic and non-hydrostatic dynamics, as suggested by (Yang et al., 2017) mainly occur in the Tropics. Considering that High Mountain Asia is at about the same latitudes as the western US mountain ranges, we assume it is appropriate to apply a 7 km grid spacing over HMA in combination with a hydrostatic model."

Also, we would like to note that simulations with the hydrostatic VR-CESM in combination with a 7km regionally refined grid have been performed before. Rhoades et al. (2018) have successfully shown the ability of VR-CESM to simulate mountainous climate with a 7km regionally refined grid over the mountain ranges of western USA. Due to its location in the mid latitudes, the hydrostatic simulations with a 7km grid spacing are still considered to be appropriate since the differences between non-hydrostatic and hydrostatic dynamics, as suggested by Yang et al. (2017), mainly occur in the tropics. Considering that High Mountain Asia is at about the same latitudes as the western US mountain ranges, we think it is appropriate to apply a 7km grid spacing over HMA in combination with a hydrostatic model.

Regarding the vertical resolution, the 32 vertical level scheme was the default scheme of the Community Atmosphere Model (CAM) when the simulations were performed. Recent developmental versions of CESM also have the option to run with 58 vertical levels by default. The main reason of not performing the simulations with a higher number of vertical levels is the computational cost that increases significantly with the number of vertical levels. However, we understand the concerns of the reviewer. We expect that future simulations with the HMA_VR7 grid will also be performed with 58 vertical levels.

2) First, I appreciate the authors for not only identifying model biases but also suggesting certain model components/characteristics that contribute to the biases, e.g., tropospheric warming due to stronger vertical motion and additional heating from CLUBB at higher resolution and with a shorter time step. But some of bias attribution remain speculative/qualitative or too general (section 3.7), which I feel is limiting the impact of the manuscript.

Noting that enough materials are presented in the current draft, I'd still like to suggest conducting off-line CLM5 simulations on the same two grids, NE30 and HMA_VR, forced by observed meteorology. Off-line land simulations are much cheaper than the coupled atmosphere-land simulation and would help partition model biases in the surface/near surface variables, especially SEB and SMB, into those from the land model alone or those from erroneous forcing from the atmosphere (or from problems arising from coupling or feedback). It is also worth asking if finer grid resolution and/or the new glacier data improve the off-line CLM5 performance. Having more accurate knowledge of CLM5 performance will help strengthen the logical basis for the discussion in section 3.7.

References

Lindzen, R. S., & Fox-Rabinovitz, M. (1989). Consistent vertical and horizontal resolution. Monthly Weather Review, 117, 2575–2583.

Lu, J., Chen, G., Leung, L. R., Burrows, D. A., Yang, Q., Sakaguchi, K., & Hagos, S. (2015). Toward the Dynamical Convergence on the Jet Stream in Aquaplanet AGCMs. Journal of Climate, 28(17), 6763–6782. https://doi.org/10.1175/JCLI-D-14-00761.1

Pope, V. D., & Stratton, R. A. (2002). The processes governing horizontal resolution sensitivity in a climate model. Climate Dynamics, 19(3–4), 211–236. https://doi.org/10.1007/s00382-001-0222-8

Prein, A. F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., et al. (2015). A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. Reviews of Geophysics, 53, 1–39. https://doi.org/10.1002/2014RG000475.Received

Rauscher, S. a., & Ringler, T. D. (2014). Impact of variable-resolution meshes on midlatitude baroclinic eddies using CAM-MPAS-A. Monthly Weather Review, 142(11), 4256–4268. https://doi.org/10.1175/MWR-D-13-00366.1

Skamarock, W. C., Snyder, C., Klemp, J. B., & Park, S.-H. (2019). Vertical Resolution Requirements in Atmospheric Simulation. Monthly Weather Review, 147(7), 2641–2656. https://doi.org/10.1175/mwr-d-19-0043.1

Wedi, N. P., & Smolarkiewicz, P. K. (2009). A framework for testing global non-hydrostatic models. Quarterly Journal of the Royal Meteorological Society, 135, 469–484. https://doi.org/10.1002/qj.377

Yang, Q., Leung, L. R., Lu, J., Lin, Y. L., Hagos, S., Sakaguchi, K., & Gao, Y. (2017). Exploring the effects of a nonhydrostatic dynamical core in high-resolution aquaplanet simulations. Journal of Geophysical Research: Atmospheres, 122(6), 3245–3265. https://doi.org/10.1002/2016JD025287

Thank you for your valuable suggestions. Based on your suggestions, we performed CLM-offline simulations with the HMA_VR grid (following the HMA_VR7a and HMA_VR7b settings, referred as HMALOa and HMALOb, respectively), although the period is relatively short (3 years; 1979–1981). The relatively high computational cost of an HMALO simulation (~12,000 core hours per simulated year) limited the amount of years we could run. The HMALO simulations are driven by observation-based meteorological forcings from the Global Soil Wetness Project (GSWP), one of the default offline modes in CLM. As for the NE30 grid, we choose not to run offline CLM simulations. As we will explain later, the NE30 simulations we used for evaluation do not compute SMB over the HMA region, but only over the Greenland and Antarctic glacier regions. Therefore, we think (from the SMB perspective) that an offline CLM simulation with the NE30 grid will not have an additional value until NE30 simulations have been performed that also compute SMB over HMA.

The HMALO simulations show an increased SMB bias relative to the equivalent HMA VR simulations (Table RC1.1). The larger SMB bias (relative to HMA_VR7) can be attributed to the warmer surface climate in the HMALO simulations (Figure RC1.1), which results in less refreezing and more melt than in the HMA VR simulations. Also, precipitation volumes in HMALO simulations (46 Gt yr^{-1}) are smaller than the precipitation volumes passed by CAM in the HMA VR simulations (90-93 Gt yr^{-1}), which translates into less snowfall and less accumulation (Figure RC1.2). Compared to the observation-based WFDEI, the temperature and precipitation biases are small. However, it should be mentioned that observation-based datasets, such as WFDEI and GSWP, rely on the availability of meteorological observations, which are often poorly distributed over HMA, especially at higher altitudes. Therefore, it could result in temperature overestimates and precipitation estimates (Palazzi et al., 2015; Immerzeel et al., 2015; Gu et al., 2012; Lalande et al., 2021), which can (partly) explain the cold and wet biases that are visible in the HMA VR simulations. From a few perspectives, the HMALO simulations can still help to understand the performance of CLM/CESM over HMA better. First, the colder surface temperatures and higher precipitation volumes in the HMA VR simulations help to reduce to the SMB bias. Second, as Figure RC1.3 shows, the SMB in HMALO simulations also shows a declining trend with decreasing glacier fraction, which confirms the necessity to improve land-atmosphere coupling. We will include the presented tables and figures in the manuscript or in the supplementary information, and highlight the key points mentioned above in Section 3.7.

Table RC1.1. Mean integrated SMB mass fluxes (Gt yr^{-1}) for the period 1979–1998 (1979–1981 for HMALO simulations) in gigatons per year. The numbers in brackets denote the standard deviation in time. The integrated SMB mass fluxes have been calculated over two different areas of integration for HMA_VR7a, derived from the original and updated glacier-cover datasets, respectively. The SMB mass fluxes for HMA_VR7a (HMALOa) that are integrated over the glacier areas of the updated glacier-cover dataset are denoted as HMA_VR7a_GC2 (HMALOa_GC2). The mass fluxes of HMA_VR7b (HMALOb) are only integrated over the glacier areas of the updated dataset.

Simulation	Glacier Area (km^2)	Precipitation (Gt yr^{-1})	Ice Melt (Gt yr^{-1})	Total Melt (Gt yr^{-1})	Refreezing (Gt yr^{-1})	Runoff (Gt yr^{-1})	Sublimation/ Evaporation (Gt yr^{-1})	SMB (Gt yr^{-1})
HMA_VR7a	120,087	111 (6)	463 (33)	553 (29)	34 (2)	554 (33)	15 (1)	-459 (33)
HMA_VR7a_GC2	96,493	90 (5)	356 (26)	432 (23)	29 (2)	430 (26)	12 (0.6)	-352 (27)
HMA_VR7b	96,493	93 (4)	228 (20)	324 (18)	32 (2)	306 (21)	12 (0.5)	-224 (21)
HMALOa_GC2	96,493	47 (2)	463 (14)	501 (9)	13 (2)	492 (12)	19 (1.0)	-464 (11)
HMALOb	96,493	46 (2)	333 (19)	385 (8)	16 (5)	367 (12)	19 (0.9)	-339 (11)

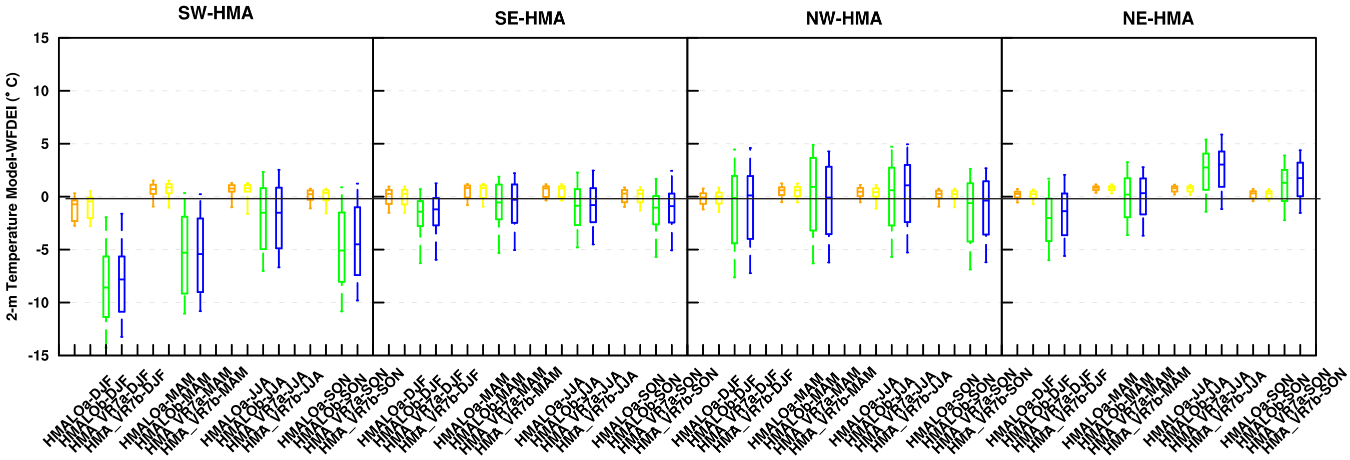

Figure RC1.1. Boxplots of 2-m temperature differences (°C) between the simulation outputs of HMALOa (orange), HMALOb (yellow), HMA_VR7a (green), HMA_VR7b (blue), and the observation/reanalysis-based WFDEI for each season and HMA subregion (shown in Figure 1b). The box represents the biases between the 25th and 75th percentile, the line in the box denotes the median, and the whiskers represent the 10th and 90th percentile of temperature differences.

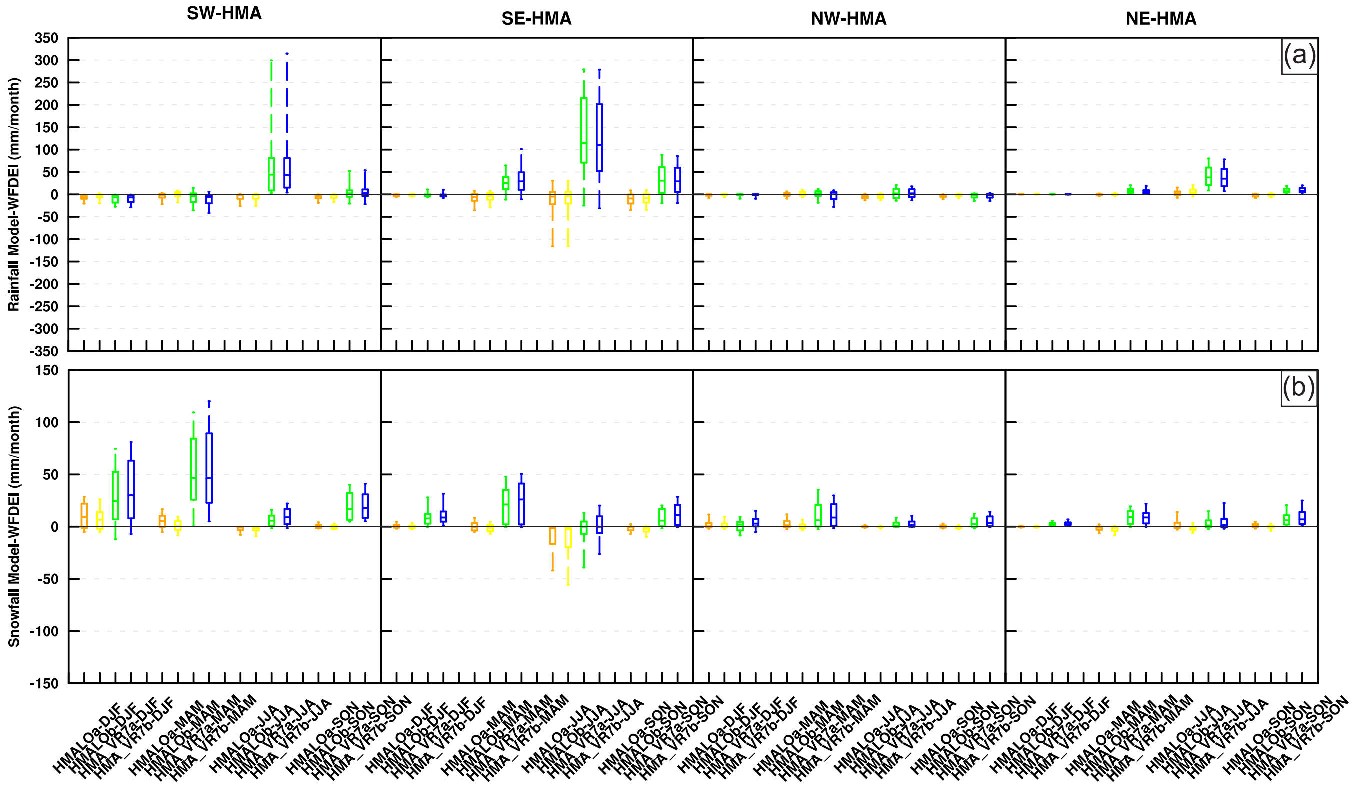

Figure RC1.2. Same as Figure RC1.1, but for rainfall (mm month^{-1}) (**a**) and snowfall (mm month^{-1}) (**b**)

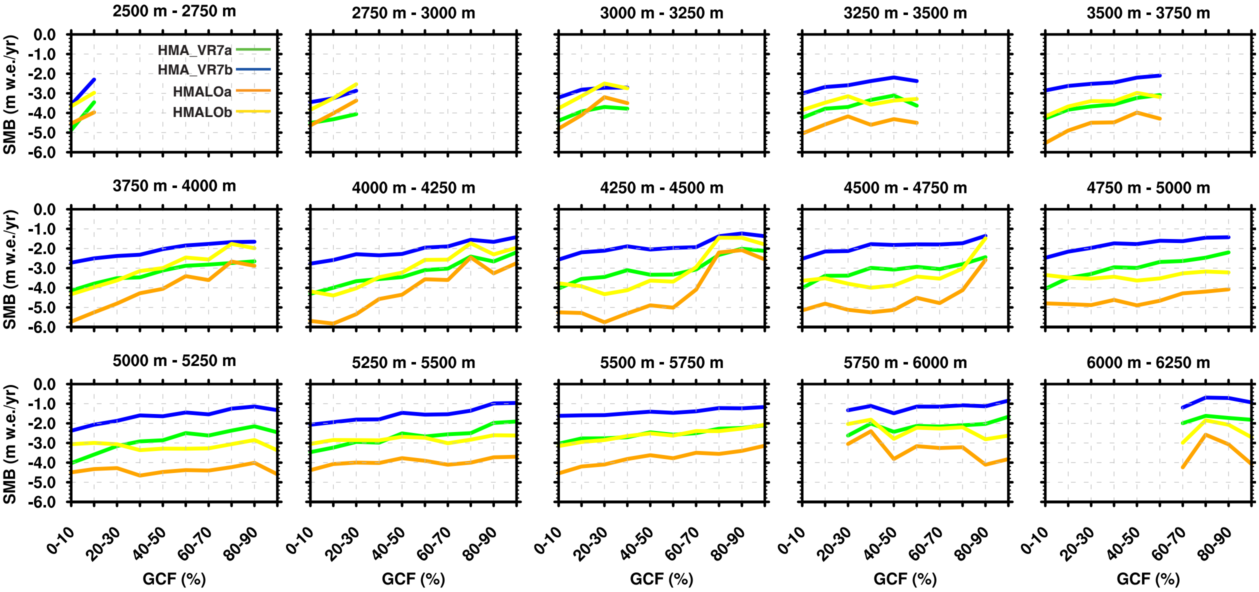

Figure RC1.3. CLM grid-cell-mean SMB-glacier fraction distributions for HMALOa (orange), HMALOb (yellow) HMA_VR7a (green), and HMA_VR7b (blue). The SMB–glacier elevation distributions are calculated for 15 different 250m elevation zones between 2500 m and 6250 m altitude, where elevation zones are based on CLM grid-cell-mean elevation distributions.

Minor comments

L98

"In the western USA and the Chilean Andes, it has been used with regional refinements up to 7 km to simulate regional climate and snowpack (Huang et al., 2016; Rhoades et al., 2016; Bambach et al., 2021; Xu et al., 2021).Also, over the Tibetan Plateau, South Asia, and East Asia, it has been applied to study the regional climate and snow characteristics (Rahimi et al., 2019; Xu et al., 2021). The application of VR-CESM to simulate glacier SMB has been limited, this far, to the Greenland Ice Sheet (van Kampenhout et al., 2019;Herrington et al., 2022)."

I do not find any of the cited studies carrying out 7-km resolution refinement with the CESM-SE or a comparable model; the finest grid spacing seems to be ~ 12km.

We will add a citation to the manuscript that refers to a study carrying out 7-km resolution refinement with the CESM-SE, which is from Rhoades et al. (2018). This study investigated the sensitivity of mountain hydroclimate simulations in VR-CESM to horizontal resolution and microphysics by applying 7-km horizontal refinement, amongst others, over the Sierra Nevada Mountain range in western US.

L127~

Deep convection parameterization is not mentioned. Was it turned off for the simulations in this study?

Deep convection in CESM2 is parameterized by the Zhang-McFarlane (ZM) convection scheme (Zhang and McFarlane, 1995) and is by default turned on. We will add an extra sentence to the Data and Methods section to cover this information.

L227

"including a new glacier region over HMA with a 36-EC scheme in CLM. The new glacier region makes it possible to simulate SMB in multiple (including virtual) ECs in HMA, while retaining the computationally cheaper default behavior of one EC per grid cell in other mountain glacier regions. "

To clarify, in the default CESM/CLM, can a user set different number of ECs for each grid column? Or is this region-dependent EC numbers is a special configuration prepared for this study?

In the default CLM, the world's glaciers and ice sheets are broken down in several glacier regions covering Greenland, the peripheral regions of Greenland, Antarctica, and all others. In this study, we added another glacier region covering High Mountain Asia. For each specific region it is possible to set the behavior of melt and runoff, and the use of ECs, which are needed to specify the use of elevation downscaling and computation of SMB. By default, 10 ECs are used over the Greenland (and peripheral) and Antarctic glacier regions, and a single EC is applied over the other mountain glacier regions. It is, however, possible to use another EC scheme within CLM, varying from 3 ECs to 36 ECs. Nonetheless the number of ECs that is chosen is fixed for all glacier regions where the use of ECs is set to multiple/virtual, which means it is not possible to set different number of ECs for each grid column. In this light, the 36 ECs we chose for this study are not only applied over HMA, but also over the Greenland and Antarctic glacier regions. We will add an extra sentence to the manuscript clarifying that the 36 ECs in this study are also applied over the Greenland and Antarctic glacier regions.

L231~

Why the difference in spin-up procedure for each VR run? I suppose spin-up procedure affect the model bias against observations, especially those of cryospheric-hydrological variables. So signals from the spin-up difference are likely to be mixed with those from the configuration/resolution differences. The authors can look at model biases of the HMA_VR7b spin-up run and compare them to those after spin-up to get some ideas of the spin-up impact on the analyzed variables.

The differences in spin-up procedures for each VR run can be explained as follows. For the first simulation (HMA_VR7a), CLM was forced with a land climatology originating from a NE120 run, which happens by default. Due to computational constraints at that time, we chose for a spin-up period of 1 year, which was assumed to be sufficiently long to equilibrate the atmosphere and land models. Following a spin-up period of 1 year, we applied a maximum allowed snow depth of 1 m w.e. (default CESM1), since a 1-year period was not assumed to be sufficiently long to reach a maximum allowed snow depth of 10 m w.e. (default CESM2).

For the second simulation, we choose to initialize the snow depth over glacierized land units to 2.5 w.e. To equilibrate the atmosphere and land model, and in particular the snowpack, a longer spin-up period was required. Since the HMA grid is expensive in computational cost, we could not afford long spin-up runs with VR-CESM. Instead, we decided to split-up the spin-up procedure into two parts: 1) an AMIP-style spin-up run of 10 years with CAM, and 2) an offline CLM spin-up run of 50 years. Offline CLM runs are computationally cheaper and therefore allow to run the model for a longer period. To initialize CLM, the coupler output of the CAM spin-up run was used, which was sub cycled over a 10-year period for 50 years. We found that a period of 50 years is sufficiently long to equilibrate the snowpack in the model (Figure RC1.4).

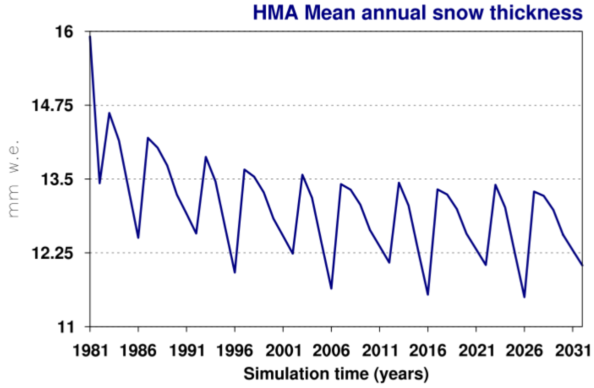

Figure RC1.4. Area-averaged annual snow thickness (mm w.e.) over the period 1981-2030 derived from the simulation outputs of CLM spin-up of HMA_VR7b. The area-averaged snow thickness is calculated for the entire HMA region.

To give an idea of the impact of the spin-up on analyzed variables, such as snow depth, Figure RC1.5 shows the snow depth differences between the CAM spin-up, the last sub cycle of the CLM spin-up (2021-2030), the transient HMA_VR7b run, and the JRA55 dataset. In most regions and throughout most seasons, the snow depth bias relative to JRA55 reduces between the CAM spin-up and the transient HMA VR run, where the largest changes occur during spring over SW-HMA (i.e., ~45 mm w.e. difference between the median snow depth biases of the CAM spin-up and the transient HMA VR run). This means that the spin-up procedure has a positive impact on the snow depth in the model. When we look at the changes in snow depth biases resulting from the configuration differences (HMA_VR7a vs HMA_VR7b; Figure 9), we see an opposite trend with increasing snow depth biases between HMA_VR7a and HMA_VR7b. Therefore, we think it is unlikely that the signals of the different spin-up procedures and configurations are mixed.

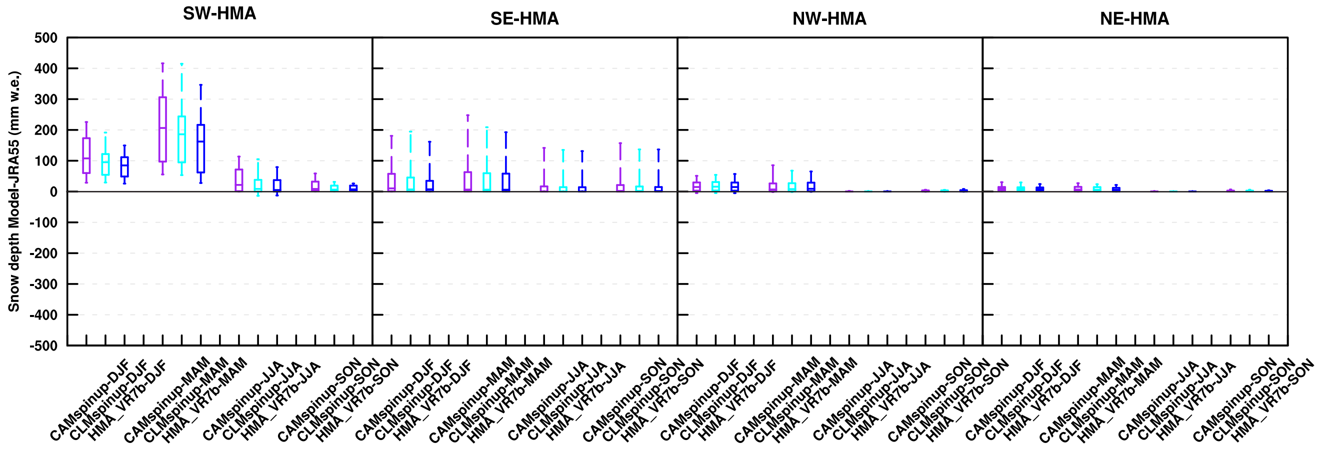

Figure RC1.5. Boxplots of snow depth differences (mm w.e.) between the simulation outputs of the CAM spinup (purple), the last sub cycle of the CLM spinup (2021–2030; cyan), HMA_VR7b (blue), and JRA-55 for each season and HMA subregion (shown in Figure 1b). The box represents the biases between the 25th and 75th percentile, the line in the box denotes the median, and the whiskers represent the 10th and 90th percentile of snow depth differences.

L344~

"The monsoonal circulation in the NE30 run has two centers, a broad region of ascent in the southern HMA region, primarily over the Indian Ocean, and a narrower region of ascent over the front range of the Himalayas." Please specify which sub-figures or rows are being discussed (e.g., "Figure 6, second row") to help readers follow the text. Maybe it's useful to add indices (a,b,c,...) to each row.

The text cited by the reviewer refers to second row and first column of Figure 6 or Figure 6d. We will add indices to each panel of Figure 6 to specify which sub-figures are discussed.

L353-356

"While the warming and drying patterns are largely the result of greater vertical velocities due to the enhanced spatial resolution in the HMA VR runs, the shorter physics timestep also contributes to this warming and drying (not shown), which is a common response to reducing the physics timestep (Williamson, 2008; Herrington et al., 2022)."

Williamson (2008) does not specifically discuss warming and drying as seen in this work. He illustrated model sensitivities to both the timestep and spatial resolution.

According to Herrington et al. (2022), shorter time step contributes only to the warming of the lower troposphere. Pope and Straten (2002) found a similar warming of the mid-latitude troposphere because of eddy flux and its convergence are enhanced with higher resolution. Although largescale feature, mid-latitude waves simulated at different resolutions converge only at 50 km or finer grid spacing according to Lu et al.(2015). An enhanced mid-latitude eddies inside regional refinement is reported by Rauscher and Ringler (2014) in their VR simulations as well, so the same processes may be occuring in the simulations here.

Figure RC1.6 shows latitude-height transects averaged over the longitude band 80˚-100˚ (same as Figure 6) for NE30 and NE30* differences relative to NE30, where NE30* represents NE30 simulations with a (shorter) physics time step of 450s. The broad warming originating on the north side of the domain (Figures RC1.6h), and the drying on the south-side of the domain (Figures RC1.6j), is evident from the figures. We agree with the reviewer that the cited studies do not specifically show a drying with reduced physics timestep. Therefore, we will remove the latter part of the sentence (L353-356) "which is a common response to reducing the physics timestep (Williamson, 2008; Herrington et al., 2022)" from the revised manuscript.

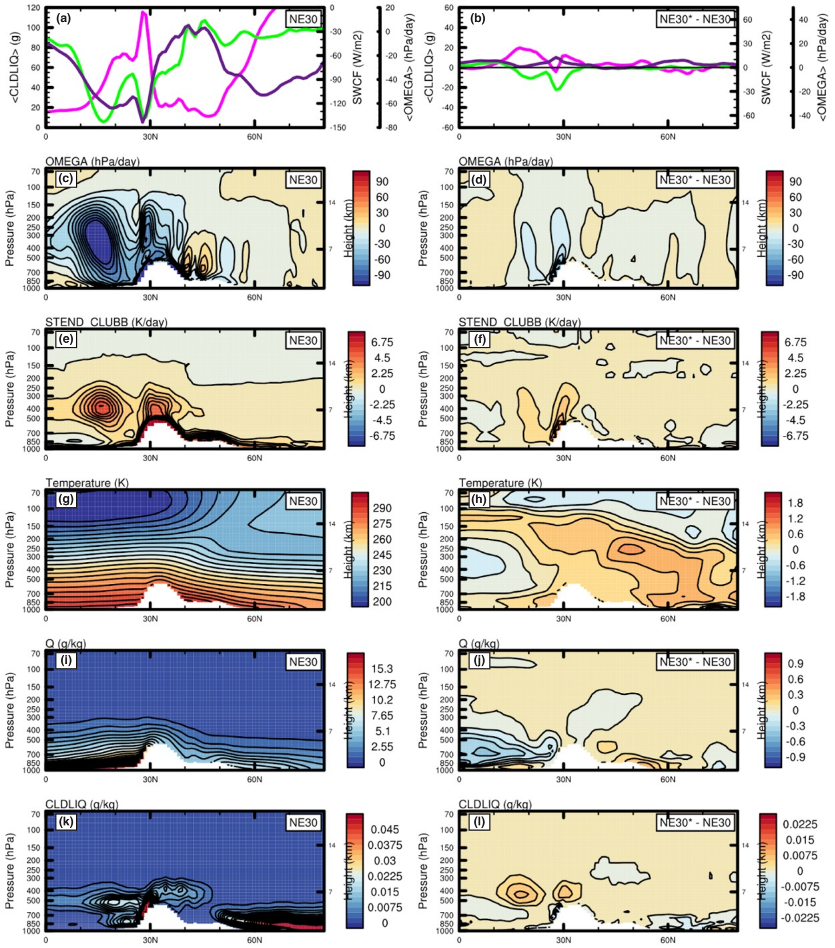

Figure RC1.6. Same as Figure 6 but comparing NE30 (control) against NE30 with a physics timestep of 450 s (NE30*). (Left column) NE30, (right column) NE30* differences relative to NE30.

Section 3.3 & 3.4
Please clarify what "absolute monthly mean xxxx (e.g., precipitation) differences" means. Precipitation, snow cover, and snow depth are positive quantities, so no need to use their absolute values.

Our aim was to make a distinction between “absolute” and “relative” changes, where “absolute” change is expressed in terms of a quantitative change and a “relative” change is expressed in terms of a percental change. To avoid further confusion, we will remove “absolute” from the manuscript text and figures’ captions.

Section 3.6
Why is the NE30 result not included in this section?

The globally uniform NE30 simulations we used in this study do not compute SMB over the HMA region, but only over the Greenland and Antarctic glacier regions. The SMB is not computed over the HMA region since the HMA region was previously part of all other mountain glacier regions, where, by default, the glacier melt water remains in place until it refreezes, which means ice melt does not result in runoff and SMB is not computed. To enable the computation of SMB over HMA, we added a new glacier region and applied a different glacier behavior setting that allows glacier melt water to runoff.

L517, typo
"Figure 15 shows the relation between grid-cell-mean SMB and glacier fraction (GCF)"
->"Figure 14 shows..."

We have changed “Figure 15 shows…” to “Figure 14 shows…”.

Figure 8
The minimum and maximum biases are not good to be used as whiskers for this figure because they push the y-axis limits so wide that we cannot see the differences in the quantile boxes. It's probably better to use 95th percentile, 3 standard deviations, or any other quantities that only moderately widens the y-axis range compared to the quantile range.

We agree with the reviewer that the minimum and maximum biases are not good to be used as whiskers. Therefore, to improve Figure 8 and other figures showing boxplots (Figures 7 and 9), we will replace the minimum and maximum values by the 10th and 90th percentiles, respectively. Using these percentiles narrows down the y-axis, which improves the visibility of the quantile boxes.

typo in the caption
"for rainfall (mm month-1) (a-b) and snowfall (mm month-1) (c-d)"
should be
"for rainfall (mm month-1) (a,c) and snowfall (mm month-1) (b,d)"

We have changed “for rainfall (mm month-1) (a-b) and snowfall (mm month-1) (c-d)” to “for rainfall (mm month-1) (a-c) and snowfall (mm month-1) (b-d)”

Figure 11, typo in the caption
Obs, blue
-> Obs, black

We have changed “Obs, blue” to “Obs, black”

Figure 12, typo in the caption
"The black box in Figure 14a denote"
-> "The black box in Figure 12a denotes"

We have changed “The black box in Figure 14a denote…” to “The black box in Figure 12a denote…”

Code and Data Availability.
"Data will be available before publication in Zenodo." What data are you referring to? Will the codes that produced the input data be publicly available?

Publicly available data will be stored in two separate data archives on Zenodo. The first archive (https://doi.org/10.5281/zenodo.7864689) will contain the model scripts and files that were used to create the updated glacier cover dataset. The second archive (https://doi.org/10.5281/zenodo.7864633) will contain the NE30 and HMA_VR7 grid variables that were used to generate most of the figures in this manuscript. The remainder of the data will be available on request. We will update the data availability statement accordingly.

Supplement material

Section S1 describes the workflow to produce the new glacier data in great detail. A critical information missing is the codes and/or applications used. Please consider sharing those information as well. Without, it is difficult for other researchers to reproduce the data or apply the same procedure to other regions.

We would like to refer to the previous response.

Figure S1
Not sure how the redbox in the inset of Figure S1b represents the outline of HMA. Do the two insets cover the same area?

The red box in both insets of Figure S1b denote the location of the glacier outlines that are shown in Figure S1b, whereas the black outline in the leftmost inset denotes the outline of High Mountain Asia. The leftmost inset shows the location of the red box within the outline of High Mountain Asia, where the rightmost inset zooms in to the region where the red box and corresponding glacier outlines are located. We realize that the visibility of the red box is in the leftmost inset is not very clear. Therefore, we will improve its visibility. Also, we will change the text in the Figure's caption as follows:

"The red box in the insets denote the location of the glacier outlines and the black outline represents the outline of High Mountain Asia, where the HMA outlines are retrieved from the Global Mountain Biodiversity Assessment (GMBA) Mountain Inventory version 1.2 (Körner et al., 2017)."

References

Gu, H., Wang, G., Yu, Z., and Mei, R.: Assessing future climate changes and extreme indicators in east and south Asia using the RegCM4 regional climate model, Clim Change, 114, https://doi.org/10.1007/s10584-012-0411-y, 2012.

Immerzeel, W. W., Wanders, N., Lutz, A. F., Shea, J. M., and Bierkens, M. F. P.: Reconciling high altitude precipitation with glacier mass balances and runoff, Hydrol Earth Syst Sci, 12, 4755–4784, https://doi.org/10.5194/hessd-12-4755-2015, 2015.

Jeevanjee, N.: Vertical Velocity in the Gray Zone, J Adv Model Earth Syst, 9, https://doi.org/10.1002/2017MS001059, 2017.

Körner, C., Jetz, W., Paulsen, J., Payne, D., Rudmann-Maurer, K., and M. Spehn, E.: A global inventory of mountains for bio-geographical applications, Alp Bot, 127, https://doi.org/10.1007/s00035-016-0182-6, 2017.

Lalande, M., Ménégoz, M., Krinner, G., Naegeli, K., and Wunderle, S.: Climate change in the High Mountain Asia in CMIP6, Earth System Dynamics, 12, https://doi.org/10.5194/esd-12-1061-2021, 2021.

Lauritzen, P. H., Nair, R. D., Herrington, A. R., Callaghan, P., Goldhaber, S., Dennis, J. M., Bacmeister, J. T., Eaton, B. E., Zarzycki, C. M., Taylor, M. A., Ullrich, P. A., Dubos, T., Gettelman, A., Neale, R. B., Dobbins, B., Reed, K. A., Hannay, C., Medeiros, B., Benedict, J. J., and Tribbia, J. J.: NCAR Release of CAM-SE in CESM2.0: A Reformulation of the Spectral Element Dynamical Core in Dry-Mass Vertical Coordinates With Comprehensive Treatment of Condensates and Energy, J Adv Model Earth Syst, 10, https://doi.org/10.1029/2017MS001257, 2018.

Liu, W., Ullrich, P. A., Guba, O., Caldwell, P. M., and Keen, N. D.: An Assessment of Nonhydrostatic and Hydrostatic Dynamical Cores at Seasonal Time Scales in the Energy Exascale Earth System Model (E3SM), J Adv Model Earth Syst, 14, https://doi.org/10.1029/2021MS002805, 2022.

Palazzi, E., Von Hardenberg, J., Terzago, S., and Provenzale, A.: Precipitation in the Karakoram-Himalaya: a CMIP5 view, Clim Dyn, 45, 21–45, https://doi.org/10.1007/s00382-014-2341-z, 2015.

Rhoades, A. M., Ullrich, P. A., Zarzycki, C. M., Johansen, H., Margulis, S. A., Morrison, H., Xu, Z., and Collins, W. D.: Sensitivity of Mountain Hydroclimate Simulations in Variable-Resolution CESM to Microphysics and Horizontal Resolution, J Adv Model Earth Syst, 10, 1357–1380, https://doi.org/10.1029/2018MS001326, 2018.

Skamarock, W. C., Park, S. H., Klemp, J. B., and Snyder, C.: Atmospheric kinetic energy spectra from global high-resolution nonhydrostatic simulations, J Atmos Sci, 71, https://doi.org/10.1175/JAS-D-14-0114.1, 2014.

Wedi, N. P. and Smolarkiewicz, P. K.: A framework for testing global non-hydrostatic models, Quarterly Journal of the Royal Meteorological Society, 135, https://doi.org/10.1002/qj.377, 2009.

Yang, Q., Leung, L. R., Lu, J., Lin, Y. L., Hagos, S., Sakaguchi, K., and Gao, Y.: Exploring the effects of a nonhydrostatic dynamical core in high-resolution aquaplanet simulations, J Geophys Res, 122, https://doi.org/10.1002/2016JD025287, 2017.

Zhang, G. J. and McFarlane, N. A.: Sensitivity of climate simulations to the parameterization of cumulus convection in the canadian climate centre general circulation model, Atmosphere - Ocean, 33, https://doi.org/10.1080/07055900.1995.9649539, 1995.