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.

I'd like to thank authors' addressing many of my questions and comments (in RC1) by their revision and replies. I am able to better understand the logics from the revised figures and texts. Especially I gained more insights from the new off-line CLM simulations.

While the revised manuscript reads great to me, I still have a major concern about how the authors justify their using hydrostatic dynamical core (along with other configurations of CAM).

First, I appreciate the authors introducing a new study that I was not aware of, Liu et al., 2022, and also clarifies that Rhodes et al. (2018) indeed conducted CESM-VR simulation with grid spacing reined to 7 km. Going over these two studies and the authors' replies, I still feel it is misleading how the authors (and Rhodes et al., 2018) to a lesser extent) explain the applicability of hydrostatic dynamical dynamical cores to the 7-km regionally-refined grid over Tibet, with the full (moist) physics.

I also believe that making the readers aware of these limitations would not affect the main conclusions of this study nor degrades its contribution to the community. I think the way the authors should justify the current CAM configuration is not by insisting that the hydrostatic dynamical core is appropriate for the grid used in this study, but instead explaining the following:

#1 This study is experimental; it describes new capabilities and/or high-resolution dataset for CESM's cryospheric-hydrological cycles over HMA, and evaluates the impact of these capabilities.

#2 Atmospheric model configurations fully appropriate for the spatial resolution required by this study are not available in the versions of CESM used (high vertical resolutions, non-hydrostatic dynamical cores, and the authors probably want to mention scale-aware deep convection schemes as well)

#3 The focus is the land surface (glaciers) and near-surface land-atmosphere coupling, not the atmospheric dynamics

#4 most importantly, the consistency between the results from atmosphere-land coupled simulations and off-line land simulations suggest that the main findings of the study is rather insensitive to atmospheric forcing; therefore, if all simulations are switched to non-hydrostatic atmospheric model, the main conclusions are expected to hold.

For #2, the authors can further mention the following for the readers:
- non-hydrostatic version of the SE dynamical core already exists (as in Liu et al. 2022), and another non-hydrostatic dynamical core MPAS is being tested in the CESM framework (Huang et al., 2023),

- (as the authors stated in their reply) "Recent developmental versions of CESM also have the option to run with 58 vertical levels by default."

- scale-aware deep convection schemes are also being ported to CESM/CAM (e.g., Jang et al., 2022)

therefore, it is expected that future studies can utilize more appropriate CAM configurations for the regionally-refined mesh developed in this study.

With that, let me further clarify why I do not think the hydrostatic dynamical core is appropriate for the model grid used in this study. There are three reasons.

1) The general agreement within the modeling communities, especially those who focus on moist convection with meso-scale and convection permitting resolution, is that grid spacing smaller than ~ 10km should use non-hydrostatic model.

To give more context, the topic of hydrostatic vs non-hydrostatic models is not new in the weather forecasting and mesoscale modeling fields (e.g., Tag and Rosmond 1980; Martin and Pielke 1983; Dudhia 1992; Kato and Saito 1995; Jang and Hong, 2016; Qi et al., 2018)

Difference between hydrostatic and non-hydrostatic models are somewhat model-dependent, but several studies with full moist physics suggest that even > 10 km grid spacing show difference between hydrostatic and non-hydrostatic models (Kato and Saito 1995; Jang and Hong, 2016; Qi et al., 2018). Furthermore, a review article and a textbook state that simulations with grid spacing < 10 km should use non-hydrostatic dynamical cores:

Review article:
Steppeler, J., Hess, R., Schättler, U., & Bonaventura, L. (2003). Review of numerical methods for nonhydrostatic weather prediction models. Meteorology and Atmospheric Physics, 82(1–4), 287–301. https://doi.org/10.1007/s00703-001-0593-8

"Operational numerical weather prediction (NWP) models are currently close to the 10km horizontal resolution threshold, beyond which the hydrostatic approximation becomes inaccurate." (p1, Introduction)

Textbook
Satoh, M. (2014). Atmospheric Circulation Dynamics and General Circulation Models. , 2nd ed., Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-13574-3

"... As introduced in Chapter 20, however, the recent progress in computer resources has enabled us to drastically increase the horizontal resolution of global models, say, less than 10 km. For these high-resolution simulations, we need to switch the governing equations from hydrostatic equations to nonhydrostatic equations." (p608, ch.24 "Non-hydrostatic modeling")

therefore, I believe that the general consensus is that the grid spacing used in this study requires non-hydrostatic dynamical core.

2) Unrealistic, truncation-scale (below the effective resolution) vertical motions are more likely to be simulated in hydrostatic dynamical cores, especially when coupled with full moist physics.

It is recognized that hydrostatic models tend to simulate more intense vertical velocity than non-hydrostatic models (Tag and Rosmound 1980; Kato and Sato 1995,; Qi et al.,2018). Hydrostatic model does not have a term that decelerates upward motion through non-hydrostatic, perturbation pressure. In other words, the work required for a rising air parcel to push out the environmental air from its way (Davies-Jones 2003; Pauluis and Garner 2006; Morrison 2016; Jeevanjee and Romps 2016). This environmental response becomes non-linearly stronger as horizontal scale of the parcel, or grid column, becomes smaller(Jeevanjee and Romps 2016), meaning that neglection of this term in hydrostatic models become increasingly problematic at smaller scales. This limitation of the hydrostatic formulation is depicted by Pauluis et al., 2006 as follows,
"... In the atmospheric sciences, the system of equations in which the vertical momentum equation (1) has been replaced by the hydrostatic balance (6) is known as the primitive equations. ... One of the main limitations of the primitive equations lies in how they handle the kinetic energy of convective motions. ... For planetary- or synoptic-scale circulations, the vertical velocity is much smaller than the horizontal velocity, and its contribution to the kinetic energy is negligible. This is not the case for convective motions for which the use of the primitive equations leads to unrealistic values of the vertical velocity. In fact, analytic solutions of the primitive equations in a convectively unstable atmosphere yield infinite growth rate for short horizontal wavelengths."

Please note that models do response to forcing in the spatial scales smaller than the effective resolutions, usually not in a physically realistic way, and associated precipitation is termed as "grid-point" storm or "truncation-scale" storms (Held et al., 2007; Williamson 2013; section 7 in Gross et al., 2018; Marquet et al., 2019). Unphysical vertical wind is often accompanied by strong moisture convergence, condensation, and positive buoyancy production, which is mainly represented by the cloud microphysics in the CAM model. That Yang et al. (2017) and Liu et al. (2022; their section 4) showed the hydrostatic and non-hydrostatic difference become much larger with moist physics seems relevant to this limitation of the hydrostatic model. Also for this concern of grid-scale storms, the model effective resolution and its spatial scale (as used by some studies) are not relevant.

3) The present authors seem to underestimate the implication of the result from Yang et al. (2017)
First, Yang et al. (2017) reported that the difference between hydrostatic and nonhydrostatic simulations is statistically significant in the mid-latitude case, but with much less magnitude than over the tropics.
Second, while the maximum height of the mountain in Yang et al. (2017) is comparable to the topographic relief over Tibetan Plateau, the slope is far smaller than those over Tibetan Plateau. The idealized mountain in Yang et al., has the following parameters:

max height (h0) = 2km
half width (a) = 60km and 120km.

These parameters lead to the slopes of 1.9 degree with a = 60 km and 0.6 degree with a = 120km. On the other hand, slopes of > 10 degrees are common over the Tibetan Plateau (Liu-Zeng et al., 2007). Although the model input topography is usually smoothed, it is still likely that vertical wind forced by the impinging horizontal winds is stronger over the realistic Tibetan Plateau topography than over the idealized mountain in Yang et al., (2017).

I do not think the authors need to provide this much background information in their manuscript. But again please consider the above suggestions to caution the readers about the CAM configuration used in this study and introduce relevant, on-going development in CAM that enable better configuration for the scales considered in this study. Justification for using the current CAM configuration should be made in accordance with focus of the study, model development status, and robustness of the main findings regardless of the atmospheric forcing.

----

other reference:

Davies-Jones, R. (2003). An expression for effective buoyancy in surroundings with horizontal density gradients. Journal of the Atmospheric Sciences, 60(23), 2922–2925. https://doi.org/10.1175/1520-0469(2003)060<2922:AEFEBI>2.0.CO;2

Dudhia, J. (1992). A Nonhydrostatic Version of the Penn State–NCAR Mesoscale Model: Validation Tests and Simulation of an Atlantic Cyclone. Monthly Weather Review. https://doi.org/10.1175/1520-0493(1993)121<1493:ANVOTP>2.0.CO;2

Gross, M., Wan, H., Rasch, P. J., Caldwell, P. M., Williamson, D. L., Klocke, D., et al. (2018). Physics–Dynamics Coupling in weather, climate and Earth system models: Challenges and recent progress. Monthly Weather Review, MWR-D-17-0345.1. https://doi.org/10.1175/MWR-D-17-0345.1

Held, I. M., Zhao, M., & Wyman, B. (2007). Dynamic radiative-convective equilibria using GCM column physics. Journal of the Atmospheric Sciences, 64(1), 228–238. https://doi.org/10.1175/JAS3825.11

Huang, X., Gettelman, A., Skamarock, W. C., Lauritzen, P. H., Curry, M., Herrington, A., et al. (2022). Advancing Precipitation Prediction Using a New Generation Storm-resolving Model Framework -- SIMA-MPAS (V1.0): a Case Study over the Western United States. Geoscientific Model Development Discussions, 2022(June), 1–23. Retrieved from https://gmd.copernicus.org/preprints/gmd-2022-111/

Liu-Zeng, J., Tapponnier, P., Gaudemer, Y., & Ding, L. (2008). Quantifying landscape differences across the Tibetan plateau: Implications for topographic relief evolution. Journal of Geophysical Research: Earth Surface, 113(4), 1–26. https://doi.org/10.1029/2007JF000897

Kato, T., & Saito, K. (1995). Hydrostatic and Non-Hydrostatic Simulations of Moist Convection. Journal of the Meteorological Society of Japan. Ser. II, 73(1), 59–77. https://doi.org/10.2151/jmsj1965.73.1_59\Y

Jang, J., & Hong, S. Y. (2016). Comparison of simulated precipitation over East Asia in two regional models with hydrostatic and nonhydrostatic dynamical cores. Monthly Weather Review, 144(10), 3579–3590. https://doi.org/10.1175/MWR-D-15-0428.1

Jang, J., Skamarock, W. C., Park, S., Zarzycki, C. M., Sakaguchi, K., & Leung, L. R. (2022). Effect of the Grell-Freitas Deep Convection Scheme in Quasi-uniform and Variable-resolution Aquaplanet CAM Simulations. Journal of Advances in Modeling Earth Systems. https://doi.org/10.1029/2020ms002459

Jeevanjee, N., & Romps, D. M. (2016). Effective buoyancy at the surface and aloft. Quarterly Journal of the Royal Meteorological Society, 142(695), 811–820. https://doi.org/10.1002/qj.2683

Marquet, P., Descamps, L., & Bouyssel, F. (2019). A new " grid-point storm control " scheme in the ARPEGE NWP model. In Research Activities in Earth System Modelling (Vol. 49, pp. 4–11). Geneva: WMO Working Group on Numerical Experimentation. Retrieved from https://wgne.net/publications/

Martin, C. L., & Pielke, R. A. (1983). The Adequacy of the Hydrostatic Assumption in Sea Breeze Modeling over Flat Terrain. Journal of the Atmospheric Sciences, 40(6), 1472–1481. https://doi.org/10.1175/1520-0469(1983)040<1472:TAOTHA>2.0.CO;2

Qiang Sun, Y., Rotunno, R., & Zhang, F. (2017). Contributions of moist convection and internal gravity waves to building the atmospheric -5/3 kinetic energy spectra. Journal of the Atmospheric Sciences, 74(1), 185–201. https://doi.org/10.1175/JAS-D-16-0097.1

Pauluis, O., & Garner, S. (2006). Sensitivity of Radiative Convective Equilibrium Simulations to Horizontal Resolution. Journal of the Atmospheric Sciences, 63(7), 1910–1923. https://doi.org/10.1175/JAS3705.1

Pauluis, O., Frierson, D. M. W., Garner, S. T., Held, I. M., & Vallis, G. K. (2006). The hypohydrostatic rescaling and its impacts on modeling of atmospheric convection. Theoretical and Computational Fluid Dynamics, 20(5–6), 485–499. https://doi.org/10.1007/s00162-006-0026-x

Tag, P. M., & Rosmound, T. E. (1980). Accuracy and Energy Conservation in a Three-Dimensional Anelastic Model. Journal of the Atmospheric Sciences, 37(10), 2150–2168. https://doi.org/10.1175/1520-0469(1980)037<2150:AAECIA>2.0.CO;2

Williamson, D. L. (2013). The effect of time steps and time-scales on parameterization suites. Quarterly Journal of the Royal Meteorological Society, 139(January), 548–560. https://doi.org/10.1002/qj.1992

We thank the reviewer for his/her evaluation of the revised manuscript. We appreciate the reviewer for carefully explaining the reasoning for a general consensus within the mesoscale modeling community that dx~10 km grid spacing is the limit at which hydrostatic dynamics are no longer valid. It is clear that decades of research have gone into developing this consensus. As our discussion has expanded such that we are debating a variety of issues, such as whether the effective resolution provides a constraint on permitted updrafts and grid-scale storms in a hydrostatic model, we'd like to focus specifically on this consensus to streamline the review process. The reviewer states:

"The general agreement within the modeling communities, especially those who focus on moist convection with meso-scale and convection permitting resolution, is that grid spacing smaller than ~ 10km should use non-hydrostatic model."

We remain skeptical on how rigorously this dx~10 km cut-off is intended to be adhered to, and in particular for deeming grid resolutions in its immediate vicinity as inappropriate (e.g., dx=7 km) or appropriate (e.g., dx=13 km) for a hydrostatic model. It is inconceivable that the actual cut-off grid-spacing in which hydrostatic dynamics are inappropriate would not be model dependent, a point the reviewer mentions ('Difference between hydrostatic and non-hydrostatic models are somewhat model-dependent'). Similarly, studies seeking out the true cut-off grid-spacing rely on model's with a non-hydrostatic/hydrostatic "switch." These non-hydrostatic configurations are not identical to the hydrostatic version other than the non-hydrostatic terms; the model structure necessarily changes to accommodate a new prognostic variable, e.g., introducing additional filters to remove errors associated with a different vertical discretization. That different modeling studies find that different grid spacings are important for non-hydrostatic dynamics we think speaks to the importance of these model dependent structural changes.

There are studies that indicate non-hydrostatic dynamics are only important for grid spacings finer than 10 km. The modeling study of Jeevanjee (2017) illustrated that in FV3, the non-hydrostatic and hydrostatic vertical velocities only begin to diverge at dx=2 km and finer (see their Figure 4). Jang and Hong (2016) highlight prior studies indicating that non-hydrostatic dynamics are 'weak' at grid spacing courser than 5 km. Similarly, a study of the IFS model using hydrostatic and non-hydrostatic versions found very little sensitivity down to 5 km (Wedi et al. 2010):

"The tests performed ranged from seasonal climate runs at T159 (125 km) resolution to medium-range forecasts up to and including T2047 (10 km) to assess the performance of the non-hydrostatic model in the hydrostatic regime, all the way to ultra-high resolution simulations in the non-hydrostatic regime (Wedi et al., 2009). Experiments with the T2047 horizontal resolution indicate that the differences between the hydrostatic and the non-hydrostatic simulations are still not significant at this resolution. Even the highest horizontal resolution at which the IFS can be run to date (T3999, 5 km) is still too coarse to fully resolve non-hydrostatic phenomena."

We do not want to insist, based on these studies, that our configuration is optimal. As the reviewer highlights, there are studies that find non-hydrostatic dynamics important at grid spacings significantly coarser than 10 km. So even though studies with FV3 and IFS suggest that nonhydrostatic effects are of secondary importance at grid-spacings of 5-10 km, we agree that caution is warranted. Nevertheless, we believe that the spread in the literature of the grid-spacing at which non-hydrostatic dynamics becomes important indicates there is insufficient basis to deem our model configuration inappropriate. We have made adjustments in Section 2.2 *HMA-VR Grid and Performance* to emphasize this point, and that we are not insisting on our configuration as appropriate. We've also added some language in Section 3.7 *Future Directions*, using this uncertainty to motivate a future study using the same grid resolution, but with the MPAS-A non-hydrostatic dycore that was recently ported to CESM2.3.X.

The adjusted paragraph in Section 2.2 *HMA-VR Grid and Performance* (L213-233) is shown below:
"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 atmosphere (e.g., Wedi and Smolarkiewicz, 2009). This could raise the question whether it is appropriate or not to use a 7 km regionally refined grid in combination with a hydrostatic model. In literature, there is, however, a spread of the grid spacing at which non-hydrostatic dynamics becomes important. There are, for instance, studies that indicate non-hydrostatic dynamics are only important for grid spacings finer than 10 km. Jeevanjee (2017) illustrated that in the FV3 model, the non-hydrostatic and hydrostatic vertical velocities only begin to diverge at dx = 2km or finer. Jang and Hong (2016) highlighted prior studies (e.g., Dudhia, 1993, 2014; Kato, 1996; Janjic et al., 2001) indicating that non-hydrostatic dynamics are 'weak' at grid spacings coarser than 5 km. Similarly, a study of the IFS model using hydrostatic and non-hydrostatic versions found very little sensitivity down to 5 km (Wedi et al., 2010). Other studies indicate that non-hydrostatic dynamics are also important at grid spacings coarser than 10 km, which is suggested by the studies of Yang et al. (2017) and Liu et al. (2022), who show 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 the spread in literature of the grid-spacing at which non-hydrostatic dynamics becomes important, we believe there is insufficient basis to deem our model configuration inappropriate. However, we are aware that using the hydrostatic version in combination with a 7 km regionally refined grid could propagate model-related uncertainties into model outputs, such as precipitation. Nonetheless, the ability of the hydrostatic VR-CESM to simulate mountainous climate with a 7 km regionally refined grid has successfully been shown over the mountain ranges of western USA (Rhoades et al., 2018)."

The newly added paragraph in Section 3.7 *Future Directions* (L591-598) is shown below:
"In this study, the spectral-element dynamical core used by CESM is based on the hydrostatic approximation, which means non-hydrostatic vertical acceleration terms are neglected. Although we believe there is an insufficient basis to deem our model configuration inappropriate, we are aware that the hydrostatic version in combination with a 7 km regionally refined grid could propagate model-related uncertainties into model outputs, such as precipitation, wind, and cloud cover, which eventually also could affect the SEB and SMB. To address these model-related uncertainties, one potential solution could be to apply a similar regionally refined grid in combination with the newly developed MPAS (Model for Prediction Across Scales) non-hydrostatic dynamical core, which has recently successfully been applied over the western US mountain ranges (Huang et al., 2022)"

References

Dudhia, J.: A nonhydrostatic version of the Penn State-NCAR mesoscale model: validation tests and simulation of an Atlantic cyclone and cold front, Mon Weather Rev, 121, https://doi.org/10.1175/1520-0493(1993)121<1493:ANVOTP>2.0.CO;2, 1993.

Dudhia, J.: A history of mesoscale model development, Asia Pac J Atmos Sci, 50, https://doi.org/10.1007/s13143-014-0031-8, 2014.

Huang, X., Gettelman, A., Skamarock, W. C., Lauritzen, P. H., Curry, M., Herrington, A., Truesdale, J. T., and Duda, M.: Advancing precipitation prediction using a new-generation storm-resolving model framework - SIMA-MPAS (V1.0): a case study over the western United States, Geosci Model Dev, 15, https://doi.org/10.5194/gmd-15-8135-2022, 2022.

Jang, J. and Hong, S. Y.: Comparison of simulated precipitation over East Asia in two regional models with hydrostatic and nonhydrostatic dynamical cores, Mon Weather Rev, 144, https://doi.org/10.1175/MWR-D-15-0428.1, 2016.

Janjic, Z. I., Gerrity, J., and Nickovic, S.: An alternative approach to nonhydrostatic modeling, Mon Weather Rev, 129, https://doi.org/10.1175/1520-0493(2001)129<1164:AAATNM>2.0.CO;2, 2001.

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

Kato, T.: Hydrostatic and non-hydrostatic simulations of the 6 August 1993 Kagoshima torrential rain, Journal of the Meteorological Society of Japan, 74, https://doi.org/10.2151/jmsj1965.74.3_355, 1996.

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.

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.

Wedi, N., Benard, P., Yessad, K., Untch, A., Malardel, S., Hamrud, M., Mozdzynski, G., Fisher, M., and Smolarkiewicz, P.: Non-hydrostatic modeling with IFS: current status, https://www.ecmwf.int/en/elibrary/78642-non-hydrostatic-modeling-ifs-current-status, November 2010.

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.