Three recommendations to improve ICAR

Three recommendations to improve simulations with the Intermediate Complexity Atmospheric Research (ICAR) model

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INTRO

The Intermediate Complexity Atmospheric Research (ICAR) model is a simplified 3D atmospheric model (based on linear mountain-wave theory), accounting for a detailed vertical structure of the atmosphere, that advects atmospheric quantities (e.g. temperature and moisture) and incorporates microphysical processes (e.g. Thompson MP).

While evaluating ICAR, Horak et al. (2019) found a strong dependence of ICAR performance on the model top height (z_{top}) and numerical artifacts in the topmost vertical levels, leading to three key questions:

What is the influence of the ...

1) ...Brunt-Väisälä frequency (*N*) calculation method?
2) ...model top on processes in the domain?
3) ...boundary conditions imposed at the upper boundary on processes in the domain?

METHODS

A sensitivity study with almost 650 idealized ICAR simulations was conducted covering the parameter space spanned by **(i)** six topographies given by Witch of Agnesi ridges (heights from 0.5 km to 3 km at 40 km width, and widths of 20 km to 80 km at 1 km height), **(ii)** nine combinations of boundary conditions (BCs) imposed at the model top on potential temperature Θ and the mixing ratios of water vapor q_v, suspended hydrometeors q_{sus} and precipitating hydrometeors q_{prc} and **(iii)** model top heights between 4.4 km and 14.4 km (plus a 20.4 km reference run). **Sounding:** U = 20 m/s, N = 0.01 s^{-1}, $\Theta(z=0)$ = 270 K, RH = 100 % and $p(z=0)$ = 1013 hPa.

This study then investigated the distribution and total mass of water vapor and hydrometeors in cross sections. Differences in the spatial distributions to a reference run were quantified with the sum of squared errors (SSE). Total mass and SSE were used as a proxy to determine the influence of the model top and the boundary conditions on the physical processes within the domain.

The effect of the suggested adaptions on 24h accumulated precipitation was demonstrated with a case study conducted for the South Island of New Zealand during strong north-westerlies throughout the troposphere.

RESULTS

1) A comparison of the ICAR wind field to the analytically calculated wind field for a linear hydrostatic mountain wave (Fig 1a) showed that *N* should be, as stated by linear theory, calculated from the unperturbed base state (Fig 1b) instead of the perturbed temperature field predicted by ICAR (Fig 1c) to avoid unphysical artefacts in the wave field.

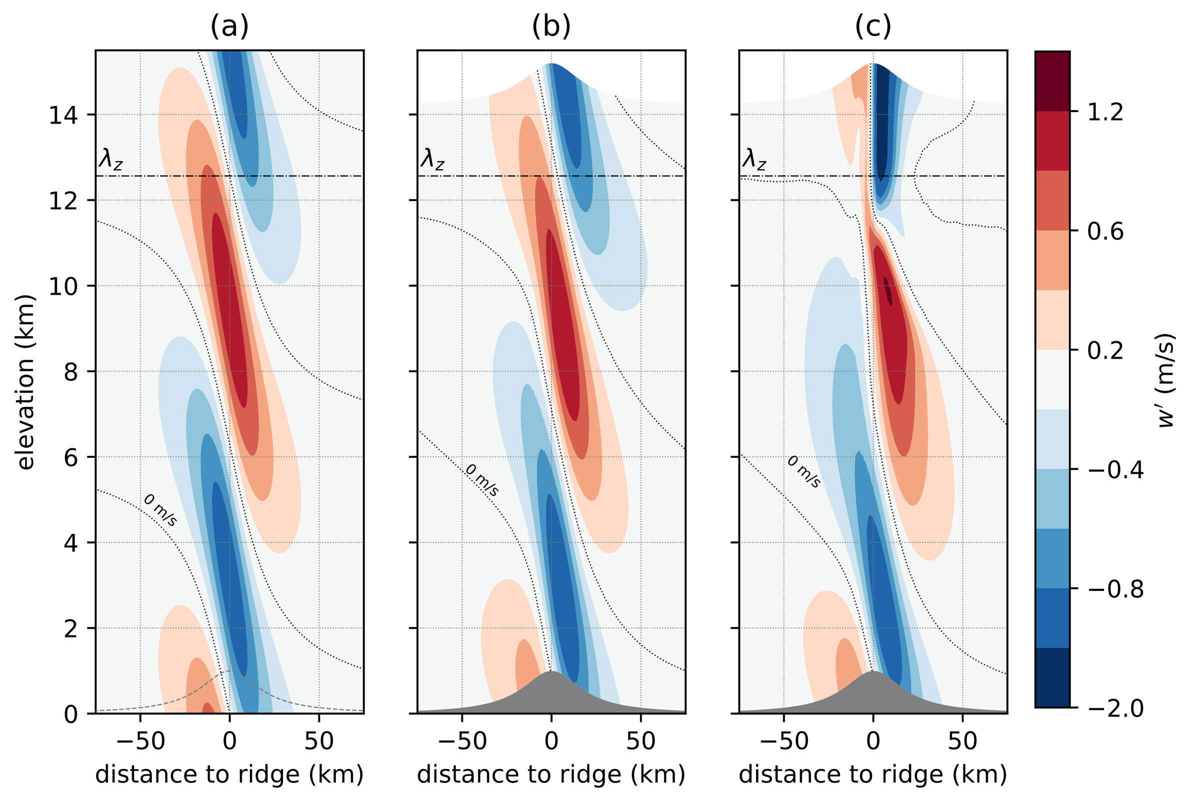

Figure 1 – The vertical wind field calculated **a)** analytically, **b)** by ICAR when calculating *N* from the unperturbed base state (e.g., provided by a reanalysis forcing dataset) **c)** by ICAR when calculating *N* from the perturbed state.

2) For the idealized simulations ICAR was found to require a minimum model top height z_{min} to allow for sufficient decoupling of processes within the domain from the model top (Figure 2). Further increases of z_{top} above z_{min} only resulted in minimal changes of the total masses and distributions of the investigated quantities. The procedure to estimate z_{min} was extended to a real world application of ICAR.

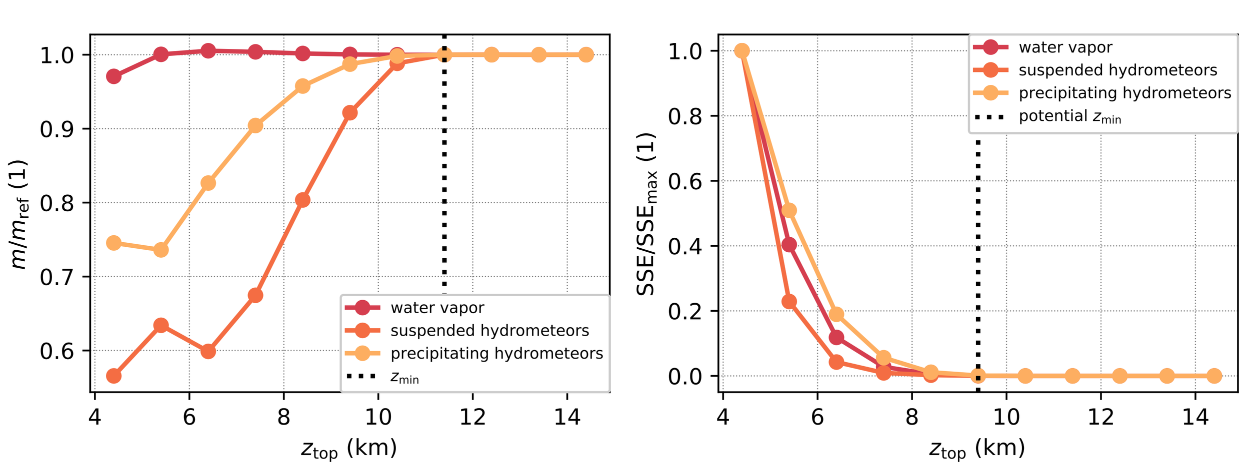

Figure 2 – **(left panel)** Total mass of water vapor and hydrometeors averaged over 24 hours and normalized by the reference simulation with z_{top} = 20.4 km. **(right panel)** SSEs of the 24h averages of the spatial distributions of water vapor and hydrometeors normalized by the maximum SSE in the cross section in dependence of the model top height. The dotted vertical line indicates the minimal necessary model top setting above which only minor improvements are found for the respective fields. Plotted for a ridge of 1 km height and 40 km width and an ICAR simulation employing constant gradient BCs at the upper boundary.

3) In the idealized simulations, a constant gradient upper BC imposed on all quantities performed best and outperformed in particular the default ZG BC when applied to all quantities. The influence of the BCs on processes within the domain was found to be neglectable once z_{top} exceeded a threshold height z_{th}. However, $z_{th} < z_{min}$ for the parameter space investigated in this study. Nonetheless, the results indicated that z_{th} dependeds on the topography with the clearest dependance on the ridge height (Fig. 3).

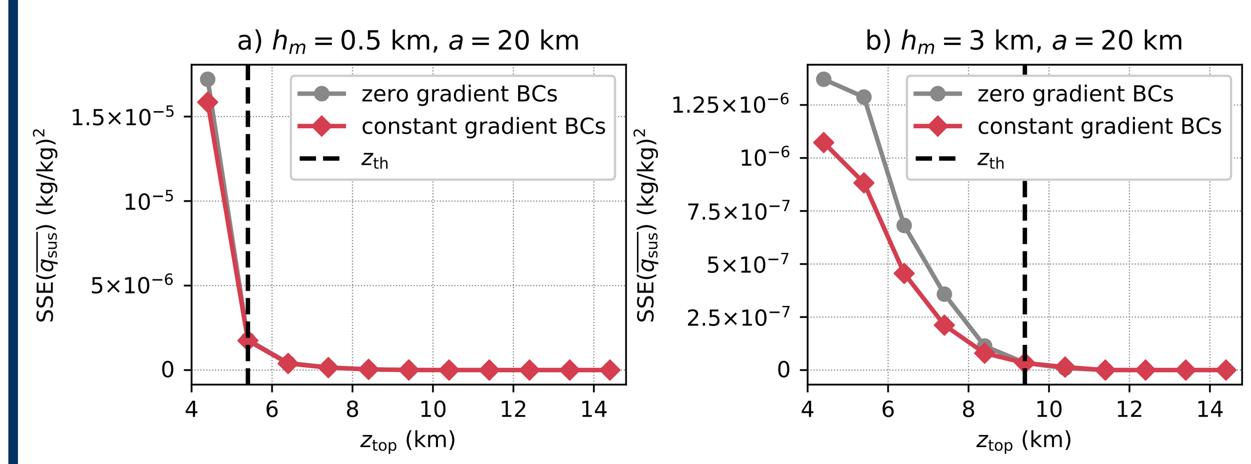

Figure 3 – The SSE of suspended hydrometeors for two ICAR simulations employing either a zero gradient BC (red curve) or a constant gradient BC to all quantities for a 500 m high ridge **(left panel)** and a 3 km high ridge **(right panel)** of equal width. The vertical dashed curve indicates the model top height threshold above which the choice of BCs does not affect the q_{sus} field anymore.

The results additionally suggested a dependence of z_{th} on the atmospheric background state, since convergent downdrafts in the topmost model levels increase the importance of the BCs (not shown).

The case study conducted for the South Island of New Zealand revealed that a simulation employing the proposed adaptions (ICAR-N) shifts the precipitation pattern upwind in comparison to the ICAR simulation setup as in Horak et al. (2019, ICAR-O) . Note that ICAR-O produces more precipitation downwind and above 1000 m due to numerical artifacts introduced by the low model top and the ZG BC.

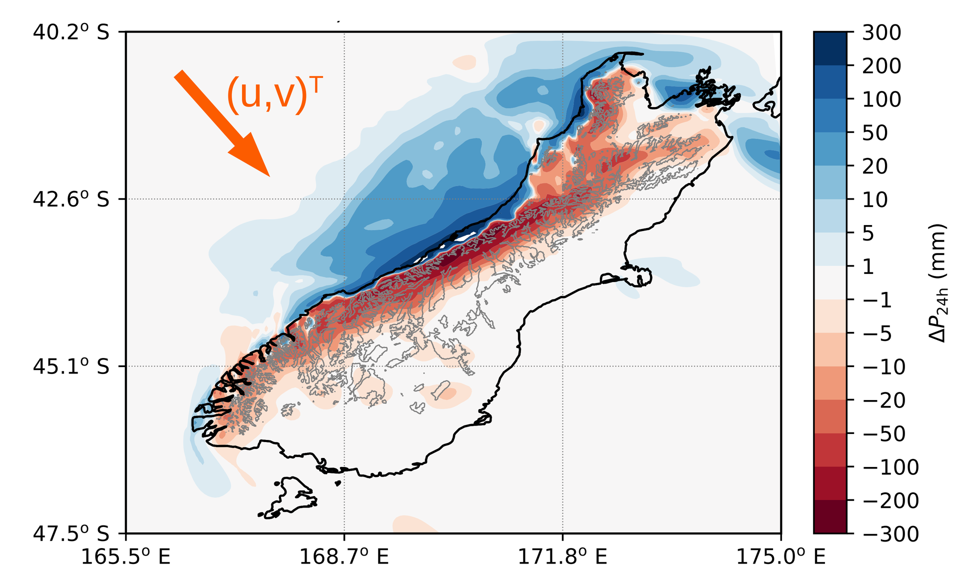

Figure 4 – Difference in 24 h accumulated precipitation between ICAR-N and ICAR-O The arrow indicates the wind direction throughout most of the troposphere and the gray outline the 1000 m m.s.l. contour line of the topography.

CONCLUSIONS / RECOMMENDATIONS

1) N should be calculated from the forcing data set
2) ICAR requires a minimum model top height z_{min} which may be determined by simulating a representative portion of a study period for increasing values of z_{top}. Above z_{min} the masses and SSEs of water vapor and hydrometeor fields only show marginal improvements.
3) Imposing constant gradient BCs on water vapor and hydrometeors may potentially avoid the introduction of errors into these fields.

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Reference
Horak et al., *Assessing the added value of the Intermediate Complexity Atmospheric Research (ICAR) model for precipitation in complex topography*, Hydrol. Earth Syst. Sci., 23, 2715–2734, https://doi.org/10.5194/hess-23-2715-2019, 2019.