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

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 ($z_{\text{top}}$) 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 $\Theta$ and the mixing ratios of water vapor $q_v$, suspended hydrometeors $q_{sw}$ and precipitating hydrometeors $q_{pw}$, and (iii) model top heights between 4.4 km and 14.4 km (plus a 20.4 km reference run).

Sounding: $U = 20 \text{ m/s}, N = 0.01 \text{ s}^{-1}, \Theta(z=0) = 270 \text{ K}, RH = 100 \% \text{ and } p(z=0) = 1013 \text{ hPa}$.

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 adaptations 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.

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

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 negligible once $z_{\text{top}}$ exceeded a threshold height $z_{\text{top}}^\text{th}$.

However, $z_{\text{top}} < z_{\text{top}}^\text{th}$ for the parameter space investigated in this study. Nonetheless, the results indicated that $z_{\text{top}}^\text{th}$ depended on the topography with the clearest dependence on the ridge height (Fig. 3).

The results additionally suggested a dependence of $z_{\text{top}}^\text{th}$ 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 adaptations (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.

CONCLUSIONS / RECOMMENDATIONS

1) $N$ should be calculated from the forcing data set

2) ICAR requires a minimum model top height $z_{\text{top}}^\text{th}$ which may be determined by simulating a representative portion of a study period for increasing values of $z_{\text{top}}$. Above $z_{\text{top}}^\text{th}$ the masses and SSEs of water vapor and hydrometeor fields only show marginal improvements.

3) Impose constant gradient BCs on water vapor and hydrometeors may potentially avoid the introduction of errors into these fields.

Reference