Response to Reviewer 1

Abbreviations and the use of colors in this response:

AR Author Response (Johannes Horak)

RC Reviewer Comment

Note that in this response orange bold text**, such as this,** or a red equation, indicates a change in the manuscript text (either an addition or some rephrasing). Blue or crossed out text ~~(example)~~ indicates the removal of text. Additionally, each modification in the manuscript is complemented by the respective page number and line where the modification occurred (e.g. **P01L01**). In the case where a table was altered, the respective modification is highlighted by an orange box around the modification. A modified figure is indicated by an orange border.

RC: In this paper, the authors present a detailed investigation of the upper boundary within the ICAR model, as well as a well-supported correction to the calculation of the BruntVäisälä frequency for linear theory calculations. They perform rigorous comparisons of their improved model (ICAR-N) with the old model (ICAR-O), the analytic solution to the underlying equations of ICAR, and to a more complex atmospheric model, WRF. The questions posed, methodologies employed to answer them, and final conclusions reached, are of value to the development community of ICAR. In the test case, these results support their conclusion that some model top height exists which reduces errors to the advected quantities and microphysics of the model which maximizing computational efficiency.

AR:

We thank the reviewer for the time and effort they took to evaluate the manuscript and provide constructive feedback. We thoroughly went through every comment and revised the manuscript accordingly where appropriate.

Please find a detailed response to every comment below.

RC: However, after testing a number of boundary conditions (BC) for the upper boundary, they fail to provide a clear recommendation for which combination of upper BC is most favorable. Such a determination would surely strengthen their conclusions, and be of great value to the community using ICAR. The demonstrated lack of dependence between minimum model top height (Zmin) and combination of BCs seems to contradict the hypothesis that Zmin is chosen to avoid errors in the assumed downward fluxes. The authors should explain this discrepancy and, if possible, provide evidence in support of a combination of upper BCs to be used as default in ICAR going forward.

AR: We agree that a recommendation for a set of BCs would be preferable, however, our study has shown that the main strategy to avoid errors in the q_v, q_{sus} and q_{prc} fields is to employ a high model top setting that covers at least the troposphere. The only quantity where a BC may yield significant improvements even at higher model top settings is potential temperature. However, our study has shown that a CG BC on Theta leads to potential problems with the numerical stability of simulations. While this did not affect the idealized studies it was an issue for the real case scenario. Therefore, we chose to avoid a general recommendation. We rephrased the relevant section in the discussion in order to better clarify that a higher model top is our recommendation.

Concerning the discrepancy – please refer to the answer to RC comment concerning P34:L3 (farther below).

Adjustment to the manuscript

> **P38L21:** It seems unlikely that any boundary condition is able to accurately represent the effect of cloud and precipitation processes above the model domain and the resulting interaction with the corresponding processes in the model domain (e.g. the seeder-feeder mechanism). Therefore, in order to capture all relevant cloud and precipitation processes**, it is recommended that** the vertical extension of the domain should at the very least encompass the entire troposphere."

RC: P7:L10-11: Why use a constant dz spacing for ICAR, but not for WRF? ICAR v1 supports this.

AR: While ICAR v1 does indeed support variable vertical layer thicknesses, these are, nonetheless, horizontally constant. The WRF setting was, except for the amount of vertical levels, left at its default, resulting in variable dz spacings. For quantitative comparability WRF cross sections were linearly interpolated to the ICAR grid.

RC: P7:L23-24: How did you test Thompson MP code to see that ICAR and WRF produce the same results? This sounds like you have ICAR producing identical output to WRF. This would be exceptional, but unlikely.

AR: We rephrased to better indicate the code review and WRF 3.4 simulations employed to rule out differences in the Thompson microphysics implementation.

We went through the Thompson MP code and compared the definitions of the variables definable in the ICAR options and the values of the constants defined in the first 386 lines of code. The only difference found was for the value of C_sqrd where ICAR Thompson uses 0.3 and WRF Thompson 0.15. We then ran simulations with the C_sqrd value set to 0.15 but this only yielded negligible differences in the simulation results for the idealized default scenario. Additionally, we checked the ICAR Thompson MP code for differences made since it was forked from the WRF repository. Where we found differences we undid the changes and tested whether the idealized simulations were affected – we did not find any indication that the functionality of ICAR Thompson differed from WRF Thompson. As an additional check we simulated the idealized default scenario with the WRF version from which the ICAR Thompson code was forked from (WRF-3.4) and noticed only negligible differences to the results obtained with the WRF 4.1.1 version.

Adjustment to the manuscript

> **P09L23:** The Thompson microphysics scheme as described in Sect. 2 is employed in all models. The **ICAR implementation of the Thompson MP was forked from WRF version 3.4. Preliminary tests were conducted, showing that WRF 3.4 and WRF 4.1.1 yielded the same results for the default scenario, with only negligible differences. Additionally, the** code of the Thompson MP implementation in ICAR and WRF **4.1.1** was reviewed and tested to ensure that ~~both implementations produce the same results for the same input~~ **differences between the implementations did not affect the results**. All input files and model configurations are available for download (Horak, 2020).

RC: Section 2.2.2 – Please also state explicitly that upward fluxes result in quantities being lost (no longer tracked) by ICAR. This would motivate the use of a downward flux BC that seeks to balance this, and may explain why the current downward flux BC in ICAR does not produce drastically unrealistic simulations on first pass.

AR: We revised Section 2.2.2. to explicitly state this potential issue.

Adjustment to the manuscript

P8L01: **While the effect described above is related to downdrafts at the model top, note that updrafts, on the other hand, may cause moisture to be transported out of the domain, leading to a mass loss. However, for k=N_z and $w^t_{Nz+1/2}$ > 0 and $w^t_{Nz+1/2}$ > 0, the discretization of the vertical flux divergence in Eq. (9) yields**

$$\frac{\partial(w\psi)}{\partial z} \approx \frac{1}{\Delta z}\left(\psi^t_{N_z-1} w^t_{N_z-1/2} - \psi^t_{N_z} w^t_{N_z+1/2}\right)$$

Therefore, this issue cannot be addressed by applying different boundary conditions, since Eq. (17) does not depend on ψ_{Nz+1}.

Adjustment to the manuscript

P8L16: Therefore, this study investigates whether the application of computationally cheaper alternative boundary conditions is able to reduce errors caused by, e.g., the unphysical mass influx **and loss** described above.

RC: Section 3.4 – I could use some discussion of the different BC's, what they try to represent, and why you chose them. Not too much, perhaps just a sentence or two for BC's1-4. Especially prior to where you refer to them on P9:L26.

AR: For clarification we added the equations corresponding to the respective BCs to Table 3. Furthermore, as requested, the introductory paragraph in Section 3.4. now gives some brief additional information for each of the BCs.

Adjustment to the manuscript

P11L24: To this end several alternative BCs to the existing zero gradient boundary condition are added to the ICAR code, their abbreviations**, mathematical formulation** and their numerical implementation are summarized in Table 2. **All BCs constitute Neumann BCs except for the zero value Dirichlet BC.** Per default ICAR imposes a ZG BC at the model top to all quantities**, corresponding to the assumption that, e.g. the mixing ratio of hydrometeors q_{hyd} above the domain is the same as in the topmost vertical level. A ZV BC imposed on, e.g., q_{hyd} avoids any advection from outside of the domain into it. The CG, CF and CFG BCs assume that a either the gradient, flux or flux gradient of ψ, respectively, remains constant at the model top, representing different physical situations. The respective discretizations of the equations given in Table 2 then determine the value of ψ_{Nz+1}.**

Please note that in order to show the adjustment right below, we inserted a screenshot of the updated table and highlighted the changes to the caption and table itself with orange rectangles.

Adjustment to the manuscript

P12:

Table 2. Overview of all types of boundary conditions that were imposed at the model top of ICAR in the sensitivity study. The table lists the ID number, the abbreviation used in this study, the full name and equation of the BC evaluated at $z = z_{\text{top}}$, and the resulting equation for ψ_{N_z+1} required to calculate the flux at the top boundary of the domain in equation (16). Note that the zero gradient BC is a special case of the constant gradient BC and that the constant c is chosen as $\psi_{N_z} - \psi_{N_z-1}$. Due to the upwind advection scheme each BC is only applied if $w_{N_z} < 0$.

ID	abbreviation	boundary condition		ψ_{N_z+1}
0	ZG	zero gradient	$\frac{\partial\psi}{\partial z} = 0$	ψ_{N_z}
1	CG	constant gradient	$\frac{\partial\psi}{\partial z} = c$	$\max(0, 2\psi_{N_z} - \psi_{N_z-1})$
2	ZV	zero value	$\psi = 0$	0
3	CF	constant flux	$\frac{\partial(w\psi)}{\partial z} = 0$	$\frac{w_{N_z-1}}{w_{N_z}}\psi_{N_z}$
4	CFG	constant flux gradient	$\frac{\partial^2(w\psi)}{\partial z^2} = 0$	$\frac{1}{w_{N_z}}(2\psi_{N_z-1}w_{N_z-1} - \psi_{N_z-2}w_{N_z-2})$

RC: Section 4.1 **–** Do you think ICAR should be considering wave amplification as a result of decreased density with height? This seems to be the cause of a major difference between ICAR-N, the analytical solution, and WRF. EQ7 seems to suggest that such a correction is not too difficult to implement, but this may just appear deceptively simple.

AR: While such a modification was not the focus of the presented manuscript, the authors agree that it could be beneficial for ICAR. We added this aspect to the corresponding paragraph in the discussion section.

Adjustment to the manuscript

P39L21: This could have drastic consequences for the results of studies relying on ICAR to provide precipitation fields for, i.e. applications in hydrology or glaciology. **Future work could implement and investigate whether the amplification of perturbations due to the vertical density gradient yields ICAR-N results closer to those of WRF.**

RC: P18: L6-7: “If ztop is set high enough these deviations therefore do not affect the cloud processes below” Would you expect these deviations to be advected down into the model where cloud processes occur? Please provide some discussion for why the errors in potential temperature remain in the upper most layers and are not advected elsewhere in the domain.

AR: We provided additional discussion to clarify this point.

Adjustment to the manuscript

P21L05: As shown in Fig. 4, for simulations with higher model tops these are mainly confined to the topmost kilometer of the model domain. If z_{top} is set high enough these deviations therefore do not affect the cloud processes below. **A potential reason for this behavior is that air that is either too warm or cold, depending on the error introduced by the BC, is advected into the topmost vertical level. From there it is redistributed by vertical and horizontal advection until an equilibrium is reached, effectively confining the introduced errors to the topmost vertical levels of the domain.** While the results indicate that a CG BC effectively reduces errors in θ, it is found to be problematic for atmospheres with stronger stratifications.

RC: P19:L5-6: If all of the BC combinations are similar, why do you decide on BC code 111 in the end? Is this the most physical? The simplest computationally? Provide some support for this choice. Do you think that this should be the upper BC by default for ICAR?

AR: We rephrased the corresponding sentence to provide support to the choice, see below. However, it should not be the default boundary condition in ICAR due to the potential numerical instabilities caused by placing a constant gradient BC on Theta. Furthermore, a general statement about which BC is the most physical is difficult to make since it effectively depends on the specific scenario that is investigated.

Adjustment to the manuscript

P22L04: To reduce the parameter space in the following analysis, and since the results for each BC combination are very similar, the idealized simulations from here on focus on CG BCs imposed at the model top (BC code 111). **This combination is chosen over the others for its computational simplicity, the larger REs observed for θ and q_v, as well as the potential to reduce $z_{min}(\theta, BCs)$ in the idealized simulations.**

RC: Section 4.5 I would restructure/rewrite this section. If WRF and ICAR are using the same MP schemes, then all differences in the hydrometeor, water vapor, and precipitation fields should be due to the wind field and advection code. Indeed, this seems to be the main conclusions of sections 4.5.1 and 4.5.2. So, I would just approach this section by way of differences in the ICAR and WRF wind fields, and then use those differences to explain the observed differences in ICAR and WRF hydrometeor, water vapor, and precipitation fields. This way it is organized cause!effect instead of effect!cause.

AR: The authors agree that this is a possible restructuring of Section 4.5. However, in this case the intent specifically was to emphasize and identify differences between the fields (effects) and trace them back to their causes. In the context of the manuscript the authors feel that this approach is more instructive since it, overall, focuses on the effects brought on by the proposed modifications and the limitations of linear theory.

RC: P 28:L5: This point should be reflected in your conclusions.

AR: Please refer to our AR on page 1 as to why we chose not to recommend a specific boundary condition (AR starting with "*We agree that a recommendation for a set of BCs would be preferable, …*"). Additionally, the authors think that their main finding with regards to the boundary conditions is reflected in the discussion and conclusions, see:

P38L17: *"Boundary conditions imposed on q_v and the hydrometeors at the upper boundary are found not to influence the value of Z_{min} for the investigated parameter space despite potentially mitigating errors in the potential temperature and water vapor fields. In particular, the cloud formation and precipitation processes within the domain are shown to almost exclusively depend on the model top elevation z_{top} and not on the chosen set of boundary conditions, and only stabilize for $z_{top} \geq Z_{min}$. It seems unlikely that any boundary condition is able to accurately represent the effect of cloud and precipitation processes above the model domain and the resulting interaction with the corresponding processes in the model domain (e.g. the seeder-feeder mechanism). Therefore, in order to capture all relevant cloud and precipitation processes, it is recommended that the vertical extension of the domain should at the very least encompass the entire troposphere."*

and

P41L09: *"While most of the tested boundary conditions (in comparison to the default zero gradient boundary condition) are suitable to reduce the errors in the water vapor and potential temperature fields, no tested combination of these boundary conditions can achieve a lower value for Z_{min}."*.

RC: P29:L14-15: I do not agree with this statement. Horak et al. 2019 did not test model top heights up to the Zmin of 15.2 km. It has not been shown that comparing simulation output with measurements leads to an incorrect result – you would have to show me the comparison with measurements for ICAR-O with a model top of 15.2 km for me to believe that statement. Your background information on the MSE of ICAR-O with the mentioned measurements given on P35:L21-23 clarifies your statement though – perhaps you could move some of this to the earlier reference.

AR: We agree that the statement may be considered misleading without the additional context. Since the discussion on P40:L23 addresses this issue and the statement is, overall, better located there, we removed the statement.

Adjustment to the manuscript

P33L15: This indicates that ~~determining the optimal model top elevation solely by comparing simulation output to measurements may lead to an incorrect result. The~~ the cloud formation processes in the ICAR-O simulation with the low model top elevation are likely unphysical and strongly disturbed by the model top.

RC: P29:L15: This difference in model top heights between the two simulations (ICAR-N and ICAR-O) seems unfair. ICAR-N represents an altered model. However, the model top height is chosen to minimize errors relative to an ideal model setup. This choice of the model top height is a user parameter given to ICAR, not a feature of ICAR-N itself. I can see why you do this though, to show the "best-case" setup following your procedure. Still, I would like to see an "ICAR-O/N" simulation in this section with ICARO run with a model top of 15.2 km. If you also wanted to compare these simulations to the measurement dataset used in Horak et al. 2019, it would make this section much stronger.

AR: We agree that strictly the comparison is not the same, and, as correctly stated, the intention was rather to compare the best-case setup to the setup chosen in Horak 2019 and to highlight the resulting differences. We included an adapted version of Figure 13 and Figure 14 that includes ICAR-O (BCs 000) with ztop = 15.2 km in the middle column and adjusted the paragraph discussing these results accordingly. Please refer to **Section 4.6** in the updated manuscript, additionally, please find the key results from that Section below.

Adjustment to the manuscript

P36L17:

Note that for this case study the effect of raising the model top elevation is mainly the removal of artificial clouds in the topmost model levels (compare Fig. 14a and b) and a weakening of the updrafts upwind of the initial peak in the topography (not shown), yielding a lower concentration of $\overline{q}_{prc}$ (compare 14d and e). Calculating the Brunt-Väisälä frequency from the atmospheric background state instead of the perturbed state of the domain, on the other hand, results in stronger updrafts and increased amounts of $\overline{q}_{prc}$ and P_{24h} (compare Fig. 14e and f, as well as Fig. 14h and i).

AR (continued):

However, we consider a comparison to measurements, such as performed in Horak 2019, as outside of the scope of the manuscript since it would require additional multi-year simulations for the South Island of New Zealand with ICAR-O(ztop=15.2 km).

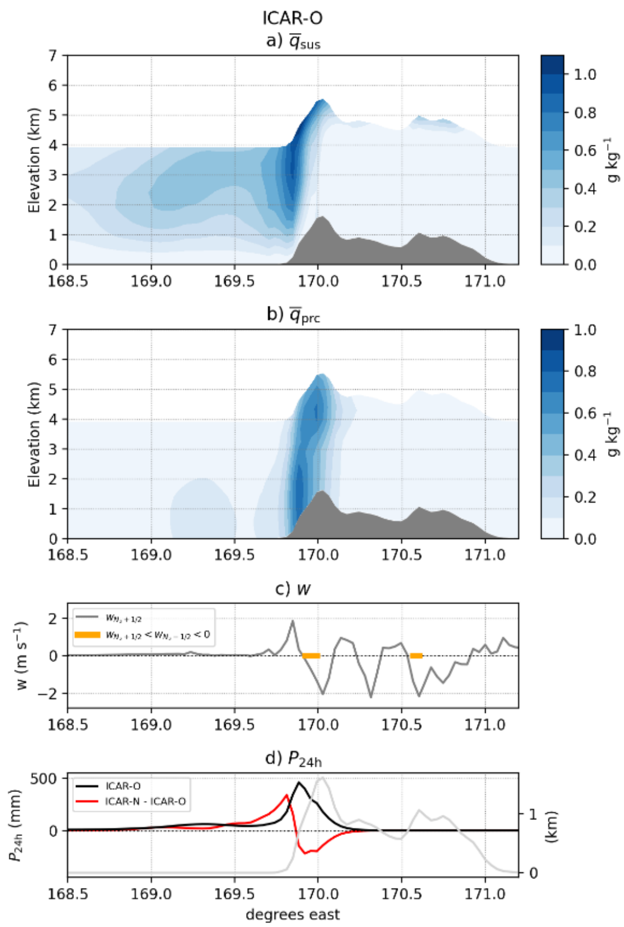
RC: P 31:L3: To support this statement of the upper BC in ICAR-O causing the excess hydrometeor concentration, I would like to see the vertical wind field for the model top of ICAR-O, or some evidence of strong downward fluxes.

AR: Please find below an additional panel for ICAR-O that shows the vertical wind velocity w in the topmost half level of ICAR-O. Furthermore, the additional panel c shows the regions where the mass influx is triggered due to the mechanism described in 2.2.2 (orange regions). This requires not only a downward flux (which does not necessarily have to be strong) but rather a strong negative vertical gradient in w and nonzero amounts of a quantity ψ. Overall the conditions

$\psi > 0$ and

$w_{Nz+1/2} < w_{Nz-1/2} < 0$

must be satisfied. We adjusted the respective paragraphs accordingly to clarify the two conditions.



Adjustment to the manuscript

> **P07L28:** In case of downdrafts, **$\psi_{Nz} > 0$** and vertical convergence in the wind field across the topmost vertical mass level $w_{Nz+1/2} < w_{Nz-1/2}$, this results in a negative vertical flux-gradient and an associated increase in ψ (see equation 16).

Adjustment to the manuscript

> **P19L11:** The choice of an alternative BC over the standard ZG BC has the largest potential for a reduction of error when **(i)** the grid cells of the uppermost vertical level coincide with ~~(i)~~ regions of vertical convergence where $w < 0$ and $dw/dz < 0$ and (ii) ~~when~~ the vertical flux gradients ϕ_z in these regions are negative (see Sect. 2.2.2). **Note that this particularly requires $\psi > 0$.**

RC: P34:L3: You suggest that the model top height has an effect on the model mainly by controlling if the model top cuts through up and down drafts. To me, this suggests that the presence of negative fluxes, as you discuss in Section 2.2.2, and the elimination of these fluxes, should be dictating where the model top is. Following this logic, different upper boundary conditions should then also have an effect on the model top height. However, in figure 5, you demonstrate that this is only the case for potential temperature using a CG vs a ZG. Can you explain this inconsistency? Isn't it strange that there was 0 effect on Zmin by changing the upper BCs? Especially given that you conclude in section 4.6 that the ICAR-O simulations are affected by the upper BC used.

AR:

Whether the model cuts through a "trigger-region" where $w_{Nz+1/2} < w_{N\_z-1/2} < 0$ is satisfied is one of the two necessary conditions. The other is that $\psi > 0$. In our scenarios and the real case, water vapor q_v, suspended hydrometeors q_{sus} and precipitating hydrometeors q_{prc} generally tend towards zero with increasing elevation while potential temperature increases with elevation.

Therefore, for q_v, q_{sus} and q_{prc} the location of the trigger-regions becomes less important once the model top is at a sufficiently high elevation. This in contrast to θ which, in trigger regions, is always affected by the mechanism described in Sect. 2.2.2. Consequently, alternating the BC for θ has an effect on Z_{min} but less so for q_v, q_{sus} and q_{prc} (and, by extension, precipitation P).

Figure 5 essentially reflects this behavior. While the BCs may reduce some error in q_v, q_{sus} and q_{prc} and P_{12h} at lower model tops (but not nearly enough as to closely approximate the fields in the reference simulation and lower Z_{min}) they do not or much less so once the model top is high enough since concentrations of q_v, q_{sus} and q_{prc} are very low. As described above for θ the situation is different and here Z_{min} is affected by the choice of the BC.

Due to the very low model top used in ICAR-O the boundary conditions do play a bigger role and cause the influx of additional water into the domain. Just using a higher model top elevation for ICAR-O would mostly alleviate this issue (compare the updated Figure 14). However, in that case ICAR-O still calculates the Brunt-Väisälä frequency from the perturbed state of the domain.

We clarified the text in Sect. 2.2.2 to emphasize $\psi > 0$ and added a third condition in the analysis of why microphysics species and potential temperature respond differently to the choice of boundary condition.

Adjustment to the manuscript

P07L28: In case of downdrafts, **$\psi_{Nz} > 0$** and vertical convergence in the wind field across the topmost vertical mass level $w_{Nz+1/2} < w_{Nz-1/2}$, this results in a negative vertical flux-gradient and an associated increase in ψ (see equation 16).

Adjustment to the manuscript

P19L11: The choice of an alternative BC over the standard ZG BC has the largest potential for a reduction of error when **(i)** the grid cells of the uppermost vertical level coincide with ~~(i)~~ regions of vertical convergence where w < 0 and dw/dz < 0 and (ii) ~~when~~ the vertical flux gradients ϕ_z in these regions are negative (see Sect. 2.2.2). **Note that this particularly requires $\psi > 0$.** For potential temperature, in case of the specified sounding, **all** conditions are always satisfied in some region no matter at what elevation the model top is chosen,

RC: P5:21 – sentence needs to be fixed for clarity

AR: We modified the sentence accordingly.

Adjustment to the manuscript

P07L15: In the following the mass levels are indexed from 1to N_z and the half levels bounding the k-th mass level~~, i.e. the levels where~~ **are denoted as k-1/2 and k+1/2. Note that** the vertical wind components ~~is defined as k-1/2 and k+1/2~~ **are calculated at half levels with Eq. (8) and that, in particular, no boundary condition is required to determine w at the model top.**

RC: P6:L30-31: This description of ICAR-N, "calculates N from the perturbed state of the atmosphere predicted by the ICAR-O" should be somewhere in section 2.2.1. It makes clear the differences between ICAR-N and ICAR-O, I could have used it earlier.

AR: We rephrased parts of Section 2.1 and 2.2.1 to better clarify and introduce the difference between ICAR-O and ICAR-N.

Adjustment to the manuscript

P05L03: Note that ICAR employs quantities from the perturbed state of the domain to calculate N even though in linear mountain wave theory N is a property of the background state (e.g. Durran, 2015).

Adjustment to the manuscript

P6-P7:

2.2.1 Calculation of the Brunt-Väisäla frequency

From the initial state of θ and the microphysics species fields at t_0 (see Eq. 12), ICAR calculates the (moist or dry, Eq. 6 and 7) Brunt-Väisälä frequency N for all model times t_m smaller than the first forcing time t_{f1}. During each model time step, the θ and microphysics species fields in the ICAR domain are modified by advection and microphysical processes. Therefore, for model times $t_m > t_0$, θ and all the microphysics species q represent the perturbed state of the respective fields, denoted as

$$\theta = \Theta + \theta' \text{ and}$$

$$q = q_0 + q'.$$

Note that in this notation, the perturbed water vapor field is denoted as q_v, the background state water vapor field as q_{v0} and the perturbation field as q_v'. Consequently, during all intervals $t_{fn} \leq t\_m < t_{fn+1}$, where t_{fi} are subsequent forcing time steps, N is based on the perturbed states of potential temperature and the microphysics species at t_{fn}. More specifically, all atmospheric variables ICAR uses for the calculation of N with Eqs. (6) and (7) are represented by the perturbed fields.

However, in linear mountain wave theory N is a property of the unperturbed background state (e.g. Durran, 2015), an assumption that is not satisfied by the calculation method employed by the standard version of ICAR. This study therefore employs a modified version of ICAR that, in accordance with linear mountain wave theory, calculates N from the state of the atmosphere given by the forcing data set if

the corresponding option is activated. In the following, the modification of ICAR basing the calculation of N on the background state is referred to as ICAR-N, while the unmodified version, that bases the calculation on the perturbed state of the atmosphere, is referred to as the original version (ICAR-O). If properties applying to both versions are discussed, the term ICAR is chosen.

RC: P9: L22: "to as [a] set of boundary conditions"

AR: We inserted the missing "a".

RC: P12:L29: "This section", please give section number of case study results.

AR: We rephrased to "**Section 4.6** additionally investigates..."

RC: Figure 6, Figure 13 caption should read: "Reduction of error (RE)"

AR: We modified the caption as suggested.

RC: Figure 13: I feel that this should preceded figure 12. Figure 13 supports your model configuration as discussed in the third paragraph of section 4.6, while figure 12 provides results relevant to paragraph 4. I see that they are ordered this way since you refer to the South Island DEM first, but the order ends up illogical when the whole figures are taken into consideration.

AR: We agree and have changed the order of the Figures.

RC: P36:L1: should read " possible model top elevation Zmin to produce"

AR: We corrected the sentence as suggested.

RC: P36:L8-9: This is not a finding or a recommendation. It should be removed from the list

AR: We rephrased the corresponding item to fit the list.

Adjustment to the manuscript

P41L07: ~~In a proof of concept, the~~ **The** method described in this study to determine Z_{min} ~~is~~ **may be** applied to idealized simulations and a real case alike. **This was demonstrated as proof of concept.**