Response to Reviewer 3

Abbreviations:

AR Author Response (Johannes Horak)

RC Reviewer Comment

RC: Overview This well-written manuscript details a comparison between ERA-Interim and ICAR at generating precipitation over New Zealand's south island. They find that ICAR adds value over ERA Interim at most alpine locations, but not at coastal stations. They additionally tease apart ICAR performance during different flow regimes (identified by the Froude number) and during different weather regimes (identified through synoptic patterns). The work is useful and complete, and I have only minor comments, enumerated below.

AR:

We thank the reviewer for her or his time and the detailed comments and criticism of our manuscript! We reflected on each point and modified the manuscript accordingly, please find the detailed answers below!

Correction to the manuscript independent of the RCs:

P5L8: We found that the list of fields contained in the forcing file was incomplete. We added the two missing fields, the sentence now reads:

"The assembled ICAR forcing file contains ERAI zonal and meridional winds U and V, potential temperature Θ, pressure p, specific humidity q_v , **cloud liquid water mixing ratio q_c , cloud ice water mixing ratio q_i** and surface pressure p_0 at each 6 h forcing time step and every grid point within the domain."

P32L14: The list of employed open-source libraries was incomplete. We added the missing library. The sentence now reads:

"numpy (van der Walt et al., 2011), pandas (McKinney et al., 2010), xarray (Hoyer and Hamman, 2017), matplotlib (Hunter, 2007), cartopy (Met Office, 2010) **and salem (Maussion et al., 2019)**."

Specific Comments

RC: P. 3, l. 27-29: During my first read through of the manuscript this sentence made me question how this replacement of unstable locations/times with weakly stable locations/times impacts ICAR's performance (since it's very unphysical). Some comment here or perhaps in the introduction about application of ICAR during unstable conditions (referring to section 2.6, which is how it is handled in this manuscript), and how/where this factor limits ICAR's use, is warranted.

AR: We agree that an analysis of how ICAR performs under unstable/near stable conditions is necessary. For this reason, we conducted a detailed analysis of ICAR performance in dependence of the flow regime and atmospheric stability in Section 4.6. To avoid unnecessary zig-zagging as suggested by Mensh (2017) we did not include a forward reference since the Abstract and

Introduction both mention the conducted analysis and the corresponding results (P1L14 and P3L6).

We also corrected the erroneously given value of 10^{-7} s^{-1} at P3L29 for the lower limit of N. The correct value now shown in the manuscript is **3.2 10^{-4} s^{-1}**.

RC: P. 5, l. 10: '6 h h' the second h is a mistake

AR: We removed the additional h

RC: P. 5, l. 21-24: I found the way this is notated to be somewhat confusing. I think the reason the authors are using the nomenclature 'ICARcp' to replace P(t) (i.e., ICAR precipitation added to ERA Interim convective precipitation regridded through bilinear interpolation to the 4km grid) is because it's basically ICAR plus convective precipitation. But this seems more complicated than necessary – why not use P(t) and Pi(t) throughout the text? If the authors insist on keeping ICARcp and ICAR then they should use this nomenclature in equation 1 and include a sentence explaining the nomenclature after the equation.

AR: We employed the variables P(t), $P_{CP}(t)$ and $P_I(t)$ in equation (1) to conform to Journal guidelines where the use of multi-letter variables is discouraged where possible. (see Section Mathematical requirements, Symbols and Equations, index b). However, the nomenclature $ICAR_{CP}$ and ICAR was chosen to allow a reader skipping parts of the introduction to immediately identify the data source of a time series or precipitation map. Additionally, due to the length of the manuscript, choosing the nomenclature $ICAR_{CP}$ over P(t) and ICAR over $P_I(t)$ avoids having to reestablish the variable definition all over again to remind the reader of the meaning of the variable.

RC: P. 7 l. 12: 'In case of the coastal weather stations,...' is awkward.

AR: We rephrased the sentence. Please note that the corrected version includes another adaption due to a comment by reviewer 4 (orange, non-bold text). The sentence now reads: "**At** coastal weather stations, records from the New Zealand National Climate Database (NCD, https://cliflo.niwa.co.nz) were employed."

RC: P. 8, caption of Table 1, last sentence: 'north respectively south' should read 'north and south, respectively'

AR: We rephrased the sentence to: "Δ was not considered for coastal weathers stations and no values were assigned for Mahanga and Larkins since they lie **north and south, respectively,** of the main alpine crest."

RC: P. 12, l. 4: 'performs very similar' should read 'performs very similarly'

AR: We rephrased accordingly and fixed a spelling error in precipitation: "Since only small negative scores are found and the median score is 0.01 for all alpine stations, this indicates, that at this threshold $ICAR_{CP}$ performs very similar**ly** to ERAI, and that $ICAR_{CP}$ does not improve on modeling the frequency of precipitat**i**on."

RC: P. 13: Fig 3 panel b: coastal is misspelled in title.

AR: We corrected the spelling.

RC: P. 14, table 2 caption, last sentence, asterisk is misspelled.

AR: We corrected the spelling.

RC: P. 16, l. 16-17: It's unclear to me exactly what this sentence is describing since the figure is not shown; does this mean that the amplitude of the seasonal cycle is too small in ICAR or more generally that ICAR underestimates climatological precipitation at some locations? More discussion is warranted and perhaps this figure should be included in the manuscript.

AR:

We included an additional figure and rephrased for clarity. P16L4 now more specifically indicates that this paragraph is about the seasonal precipitation patterns, while the paragraph starting at P16L13 is concerned with results at the weather station level. Answering the reviewer's questions: Both statements are true for the alpine weather stations investigated. On average $ICAR_{CP}$ understimates the amplitude of the seasonal cycle and the climatological precipitation at the weather stations situated in the Southern Alps. However, in contrast to ERAI, which predicts spring to be the wettest season and autumn as the driest, $ICAR_{CP}$ is able to reproduce the characteristics of the measured seasonal cycle (e.g., winter as the driest season and summer and spring similarly wet).

P16L4 now reads: "The seasonal variations of precipitation **patterns** as derived from the VCSR data set (Fig. 5b-e) are best reproduced by $ICAR_{CP}$ (Fig. 5l-o)."

P16L13 now includes a reference to the additional Figure added to the Appendix instead of 'not shown': "Seasonal averages of daily accumulated precipitation $\overline{P_{24h}}(\mathrm{se})$ derived from measurements at the alpine weather stations show winter as the driest season, summer as the wettest and the transitional seasons in between (**see Fig. A1**)."

Additional Figure and caption:

Appendix A

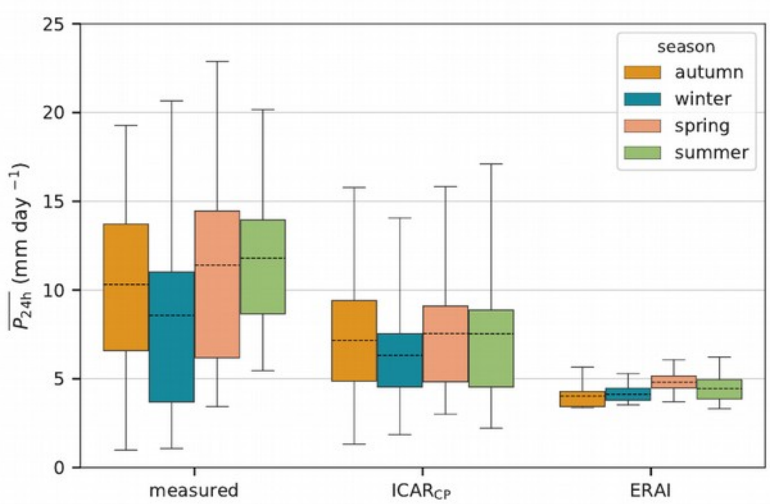

Figure A1. Box and whisker plot of the mean daily precipitation (y-axis) for each season $\overline{P_{24h}}(\mathrm{se})$ at alpine weather stations as measured or calculated by $ICAR_{CP}$ and ERAI (x-axis). All amounts were calculated using the entire P_{24h} time series available at each weather station. The lower boundary of the box indicates the 25th percentile, the upper boundary the 75th percentile and the horizontal dashed line the mean. Whiskers show the minimum and maximum values of the data set.

RC: P. 16, l 23-24: Is there any reason to think that the correspondence in seasonal errors between ICAR and ERA-I (i.e., that both have largest errors in summer and smallest in winter) is causal? That is, since ERA-Interim provides lateral boundary conditions for ICAR?

> **AR:** While this is a possibility we are of the opinion that, at least for winter, this correspondence is mostly due to a characteristic of the mean squared error. E.g. since ICAR and $ICAR_{CP}$ generally underestimate measured precipitation it follows that the potential magnitude of the MSE is reduced for winter since it is the driest season. During summer, however, it seems feasible that convective events that are missed by ICAR (which cannot model convective precipitation) and by ERAI alike (which potentially misses them due to the coarse grid spacing) contribute to the increase. This would apply to $ICAR_{CP}$ as well since it incorporates convective precipitation from ERAI.

RC: P. 17, Figure 5: masking the ICAR and ERAI values over the ocean would be less distracting (since there is no 'truth' over the ocean, anyways).

> **AR:** While it is not possible to compare ICAR precipitation over the ocean to the VCSR, we still see value in showing the precipitation patterns over the ocean. It showcases the behavior of the model there, i.e. that precipitation is indeed generated even though there is no topography present. To reference this behavior and the choice not to mask values above the ocean in the manuscript we added an additional sentence to the paragraph starting at P15L8:
>
> "**While above the ocean no data is available for the VCSR, the results clearly show that ICAR is able to generate precipitation with seasonal variation above the ocean where no topography is present (Fig. 5f-j).**"

RC: P. 19, l. 11: What percentage of the crest of the southern Alps is over 1500m?

> **AR:** If the elevations of all points used for the definition of the Alpine Crest in Figure 1 are extracted from the SRTM digital elevation model (3 arcsecond grid-spacing), approximately 97% of the crest lie above an elevation of 1500 m MSL.

RC: Based on Fig. 1 it seems closer to 1000m would be a somewhat more appropriate height to use in the calculation of Froude number;

> **AR:** The average elevation of the Southern Alps is 1100 m MSL if the area east and west of the alpine crest up to a distance of 0.5° is averaged over (corresponding to the approximate width of the Southern Alps of 60 km referenced in Section 3.1).

RC: are the results pertaining to the Fr<1 and Fr>1 cases sensitive to this mountain height?

> **AR:** Choosing a lower value for H would shift days from the $Fr < 1$ regime to the $Fr >= 1$ regime (see equation 4) and vice-versa for higher values of H. The observed characteristics of ICAR remain the same even if instead of $H = 1500$ m, $H = 1000$ m or $H = 1750$ m is chosen. However,

for H = 1750 m the number of cases in the Fr >= 1 regime is too low to calculate meaningful scores.

RC: P. 25, second sentence in Fig 9 caption: This sentence is poorly worded.

AR: We reworded the first two sentences in the caption: "Box and whisker plot of SS_{MSE} calculated for all alpine weather station in dependence of the synoptic weather pattern (**x-axis;** Kidson, 2000). **The regime associated with each weather pattern is indicated by color shadings in the lower part of the plot.**"

RC: P. 26, l. 12-13: This sentence is poorly worded.

AR: We rephrased and split the sentence in two: "**Furthermore, at Ivory, the trend found in the measurements is correctly reproduced by $ICAR_{CP}$ and ERAI. The absolute amounts of precipitation are, while underestimated, better modeled by $ICAR_{CP}$.**"

RC: P. 29. L18-23: Can the authors speculate why there is this sensitivity to model top height?

AR: The authors are currently investigating this sensitivity and hope to present answers in a follow-up study. We currently speculate that the behavior may be caused by divergences and convergences in the forcing wind field (see Section 5. discussion P31L10-12) and, at lower model top settings, by numerical artifacts due to the way the model top is treated. However, further research is necessary.

RC: P. 29, L. 21: 'estimation the model' is missing 'of'

AR: We inserted the missing 'of'.

RC: P. 30, L. 9-13: This paragraph should be expanded for clarity (i.e., rather than saying 'solution to issue (iv) it would be helpful to repeat the description of the issues).

AR: We restated issue (iv) in the referenced paragraph (P31L9-13) and added reference to the relevant Figures.

"**At a model top setting of 4 km above topography, seeder-feeder interaction between synoptic clouds and orographically lifted moist air may mostly be eliminated. Increasing the model top is an apparent solution to this issue.** However, the sensitivity study in Sect. 4.3 showed, that this does not lead to a decrease in the MSE of ICAR or $ICAR_{CP}$ **(Fig. 2a), nor does it increase model skill for time series at the alpine weather stations (Fig. 2b).**"

References

Mensh, B., & Kording, K. (2017). Ten simple rules for structuring papers. *PLoS computational biology*, *13*(9), e1005619.