EGUSPHERE PAPER REVIEW

Temperature and Cloud Condensation Nuclei (CCN) sensitivity of orographic precipitation enhanced by a mixed-phase seeder-feeder mechanism

By Thomas et al.

General comments:

Motivated by the rise in water vapour capacity of a globally warmer atmosphere, and the increasing frequency of extreme rainfall events, in this article, Thomas et al. evaluate the microphysical response of mid-latitude orographic rainfall to perturbations of temperature and CCN concentration. This study applies the use of "piggybacking" (Grabowski 2014) sensitivity experiments of rainfall from mixed-phase orographic clouds which, to the authors' and this reviewer's knowledge, is the first study to do so. This reviewer agrees that the piggybacking method is a robust technique to isolate the effects of warming and CCN concentrations on orographic precipitation. Interesting findings are presented in this article such as:

1. Rainfall increase in a warming climate is significantly less than increase in precipitable water.
2. A surface rain budget analysis reveals that the negative temperature sensitivity of the condensation ratio and the increase of sub-cloud rain evaporation dampen the rainfall enhancement in a warmer climate.
3. Decreasing the CCN concentration speeds up the microphysical processing, esp. rain growth by collision-coalescence, which leads to an increase in total rainfall. This is consistent with previous model sensitivity studies, such as Chen et al. (2010), which have shown that decreasing CCN number in mixed-phase clouds results in fewer but larger cloud droplets, but also fewer ice crystals; its effect on surface precipitation depends on the interplay between the increased warm-rain production and the decreased or increased ice-phase precipitation. Precipitation responds nonlinearly to CCN number change, causing precipitation decrease in high CCN concentration environments but showing no clear tendency in low CCN concentration environments (Chen et al. 2010).
4. In clean air (low CCN concentration) the sensitivity of rainfall to temperature is systematically smaller. In fact, the CCN and temperature sensitivities are to a large extent independent, and additive.

As is clearly stated in the section titled Limitations and Potential Solutions, this study lacks more robust conclusions that could be derived from a larger statistical ensemble of various orographic rainfall events, including different cloud depths, stability profiles, and wind profiles. Since this project was particularly based on a specific flood event in the UK (the Cumbria flood which occurred in December 2015), we suggest modifying the title to add ": a case study"

Overall, this paper deserves publication.

Major Comments:

1. The statements on **Ln35** "where low mountain ranges would otherwise not efficiently produce precipitation", and on **Ln41** "nor do they have to be in the same thermodynamic state" miss a key point. Surely deeper clouds in which only warm rain processes operate experience orographic

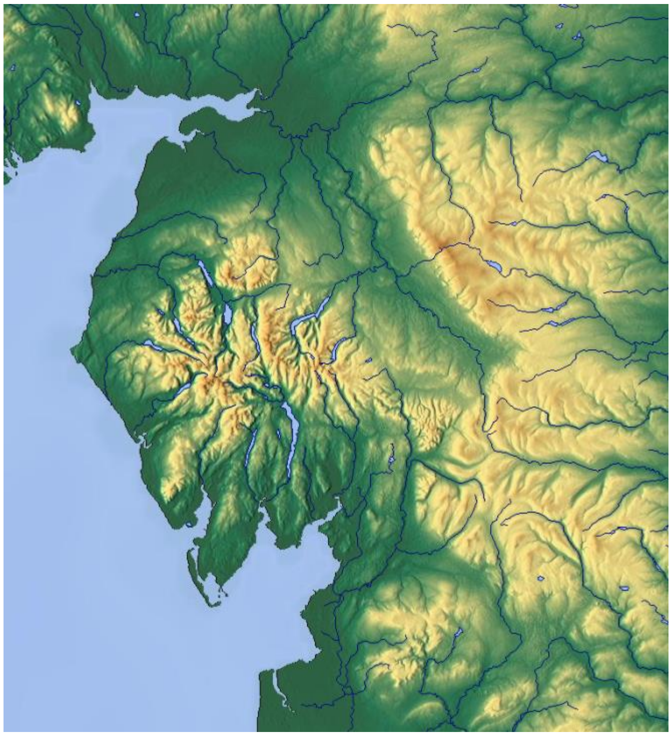
enhancement, as low-level lifting enhances low-level cloud LWC. But that is not a seeder-feeder effect. The older literature was vague about this for lack of in situ observations, but the key to the seeder-feeder mechanisms as described in many more recent observational and modelling papers is *the lack of ice crystals in the shallow supercooled cloud layer*. In other words, the seeder-feeder mechanism is a mixed-phase process. See, for instance, Houze (2014, Cloud Dynamics 2nd Edition), p. 148-152. How do you define “cloud layer” in the statement on **Ln40** “The seeder-feeder mechanism does neither require the two cloud layers to be vertically separated”? You are correct if you refer to the water-saturated layers (those containing cloud droplets). But a defining aspect of the seeder-feeder mechanism is that falling ice particles (ice or snow in your model) reach the lower liquid-saturated layer, which is the case in your simulations (Fig. 6a and c). In other words, vertical continuity of ice particles is required. Please clarify/correct the text in the Introduction and elsewhere. For instance, in Section 5.1. And the last sentence of the Summary should be omitted.

2. Examination of the effect of a warmer climate on precipitation is done in an unconventional way. Why not uniformly change the Θv and qv (to maintain constant RH) at the lateral and surface boundaries? By changing the temperature only for the microphysics scheme (as mentioned on **Ln127**), your model is dynamically inconsistent. In doing so, you underestimate LW radiation from cloud base to the surface and from cloud top to outer space and evaporation from the sea or land surface, for instance. You are not representing a true warmer climate. The piggybacking technique is intended to separate microphysical and dynamical effects of changes in microphysical properties. Dynamical effects refer to changes in buoyancy or stability that might result in convection (for instance), altering the precipitation. But radiative and surface energy processes are not dynamical. Here, you treat the temperature change as a microphysical sensitivity (the atmosphere simply carries more water vapor and saturates at a higher q value). It is OK to call this a “piggybacking” method, although that is unusual. You claim that it removes the dynamical effects. It removes not just dynamical effects, also radiative, surface, PBL, and other effects. **I am asking that you do your model sensitivity analysis also the more conventional way, i.e. changing the Θv and qv in your driver dataset**. That will include all these other effects. This will quantify the importance of all these other effects on P. Given the strong winds and the small domain, I suspect the difference will be small, as stated also around Ln420.
3. **Eqn (7)** is misleading. The first term on the RHS (dyn) is incorporated in the other terms (CR and PE). All you can say here is that the T sensitivity can be broken down into three terms (not four). Then you can quantify these terms either using the “piggybacking” method, or the convectional method, as mentioned.
4. As discussed in the text and shown quite nicely (Fig. 4, Fig. 6c, Fig. 7), warming seems to shift the precip distribution from the central valley (Eden Valley?) to the upstream mountains (the peaks of the Lakes district). This shift in precip distribution explains the main conclusion of the paper, that the enhancement of rainfall due to warming is higher over the highest altitudes than over the entire domain. This is a key take-away in my opinion, and is dependent on the detailed terrain configuration. The results may be quite different for a different terrain layout. A more general treatise warrants evaluation using idealized terrain, as suggested already around Ln434. Maybe this has been done already, if so, please add a reference. If not, than here is a suggestion for a follow-up paper.

<u>Minor Comments:</u>

- **Ln 20:** the *relative* increase is stronger for lower temperatures. The absolute increase decreases with decreasing temperatures
- **Ln 29:** RH is assumed to ***(be)**** constant... Refer to the CMIP6 ensemble mean or other reference, specifically for atmospheric rivers maybe. This is more than a hypothetical assumption, it is rooted in climate simulations under the synoptic conditions of interest, and that should be mentioned. On Ln 123, you refer to (Pörtner et al., 2022).
- **Ln 40:** The seeder-feeder mechanism ***(thus)**** neither require …
- **Ln53:** Given the focus on extreme orographic precip, I suggest referring to the many studies of atmospheric rivers impacting coastal (or inland) terrain.
- **Ln57:** Preconditions → Upstream conditions (that is, they should persist during the storm)
- **Ln59:** strong wind, moist air: why not refer to IVT? Surely Browning did not use that quantity, but science has evolved.
- **Ln63:** last bullet: suggest simplifying this to: the terrain must be sufficiently high to lift the BL air mass above its LCL

Fig. 2 Some corrections in the caption: Cross section used in (c), not (b). Also, what is “see 3”? Precip normally is expressed in depth (mm), rather than kg m^{-2}. The latter units may alienate some users. This change affects many Figs. The vertical velocity in (c) is quite coarse, it appears to be outer domain data, whereas the cross-section is entirely in the inner domain. At ~500 m grid resolution, I expect far more detail, including transient features. Also, can you please increase the figure size or plot size especially 2b. That plot should include the topo. In include an example here (screenshot from https://maps-for-free.com/), because I need it to interpret your subsequent figures.



- **Ln 68 & 69:** “both” applies to two traits, but there are three … suggest: to become more frequent and longer-lived, as well as more enriched with water vapour...

- **Ln 71:** pls quantify the integrated water vapor (PW) and integrated vapor transport (IVT), and infer that this event classifies as an atmospheric river.
- **Ln 97:** Use either (-4.2 ◦ to −1.8◦) or (4.2◦ E to 1.8 ◦ E) Longitude and from (53.5◦ N to 55.1◦ N) latitude. **NB: Longitudes are from West to East and Latitudes are from North to South.**
- **Ln 117**: Θv instead of absolute temperature is used ***(to)**** preserve static stability.
- **Ln 120-121:** Initially, qv is ***(adjusted)**** to the perturbed value of Θv...
- **Ln 167:** After the moist air ***(enters)*** LAKEDISTR (phase 1), it is forced to ***(ascend)*** **over** the mountain barrier.
- **Ln 373:** that can lead to an upwind shift ***(in)*** the distribution of precipitation.
- **Ln 380:** This discrepancy in αP may be due ***(to)*** the choice of the integration domain...
- **Ln 396:** the negative sensitivity of CR ***(yields)*** a total decrease in DR...

Tables A1 and A2: Can you account for the seemingly different temperature sensitivity trend for the PB-plus3-CCN? Sensitivity increases from just the nCCN = 50 cm^{-3} to nCCN = 200 cm^{-3}. Temperature sensitivity of average rainwater content and accretion tend to decrease as the concentration of CCN increases. Why?

Tables A3 - A8: Is there an explanation as to why temperature sensitivity of melting stays the same for nCNN = 800 cm^{-3} and nCNN = 1500 cm^{-3} at PB-plus3-CNN condition? Why are there inconsistencies in temperature sensitivities under PB-minus1-CNN and PB-plus1-CNN conditions? Why are there inconsistencies in the temperature sensitivity trends for the remaining parameters in tables A4 – A8?