

Response to Reviewer #3

Interactive comment on “Effects of Cloud Condensation Nuclei and Ice Nucleating Particles on Precipitation Processes and Supercooled Liquid in Mixed-phase Orographic Clouds” by Jiwen Fan et al.

A. Khain (Referee)

alexander.khain@mail.huji.ac.il Received and published: 21 October 2016

Review of the paper “Effects of cloud condensational nuclei and ice nucleating particles on precipitation processes and supercooled liquid in mixed-phase orographic clouds”, authored by J. Fan, L.R. Leung, D. Rosenfeld and P.J. DeMott.

The study presents a detailed analysis of process of ice formation and of precipitation response of orographic clouds over Sierra Nevada to the changes air temperature, CCN and IN. This study is an extension of the previous study by Fan et al. (2014). The strength of the study is the utilization WRF with spectral bin microphysics and wide use budgets to evaluate rates and efficiency of one or another microphysical processes. The paper is of interest. I recommend to accept the paper with minor (from point of view of changes of the text), but important corrections.

- Prof. Khain, thank you so much for the useful comments to improve our manuscript. Please see our detailed responses below.

1. Line 81. I suppose that reference to studies by: Lynn B., Khain, A. P., D. Rosenfeld, William L. Woodley, 2007: Effects of aerosols on precipitation from orographic clouds. Journal of Geophysical Research, 112, D10225 and to H. Noppel, A. Pokrovsky, B. Lynn, Khain, A. P., and K.D. Beheng 2010: On precipitation enhancement due to a spatial shift of precipitation caused by introducing small aerosols: numerical modeling. J. Geophys. Res.. 115, D18212, 17 PP., 2010, doi:10.1029/2009JD012645.

In both /cases shift of precipitation by changing of CCN concentration was investigated.

- Sorry that we forgot to cite Lynn et al. (2007) at this place since it was the first study showing the spillover effects. We have added it now. Noppel et al. (2010) does not fit here since we are discussing aerosol impacts on orographic precipitation here. But we have discussed this paper in the last section at L626-631 (P. 25-26).

2. Lines 152-158. Please describe the treatment of large AP clearer. Are these APs considered as CCN? Can these particles be activated to drops if $S > 0$? What is soluble fraction of these large APs? (typically soluble fraction is about 0.1-0.2). Do you keep non-soluble fraction within the nucleated drops?

- We think you might have misunderstood the statements here. These descriptions are about freezing of large liquid drops through immersion freezing, not about freezing of aerosol particles.

3. Line 160. Do you mean that you consider frozen drops as these large ice particles? Please add a more detailed explanation, even repeating some points from Fan et al. 2014. The paper should be self-consistent.

- The size of formed ice particles through immersion freezing depends on drop size. Our implementation of the immersion freezing starts from the largest drops freeze first, followed by the smaller ones over the size spectrum of water drops when immersion freezing occurs. Therefore, this implementation yields relatively large ice particles in the model simulation, which is consistent with observations. Deposition/condensation ice nucleation is not considered in this study since it produced large amount of small ice particles that were not observed. We have changed the text here and also repeated some text in FAN2014. Now it is read as “An added feature of the implementation is that when immersion freezing occurs, freezing starts from the largest drops first, followed by the smaller ones over the size spectrum of water drops. This implementation yielded the majority of large ice particles as observed by aircraft measurements (FAN2014). Adding deposition/condensation freezing produces a large amount of small ice particles, which is not consistent with observations, so deposition/condensation freezing is not included, as discussed in FAN2014. The assumption that the largest drops freeze first also acknowledges the expectation that the largest droplets should have a higher probability of containing an INP active at a given temperature” (L161-168)

4. Line 166. What is the way of description of primary ice nucleation? Was it the same as in Khain et al. 2004, where the formula of Meyers et al was used? Or do you use formula by DeMott only for large APs that you consider as IN?

- We did not consider deposition/condensation freezing, so Meyers et al 1992 is not included. The reason was discussed in FAN2014 and now has been added here in L164-166. INP is a single prognostic variable separately from CCN. For the simulation of the observed case in FAN2014, dust/bio is initiated with the concentrations of clear-sky aerosol particles with diameter larger than 0.5 μm in the dust layer. The relevant text is at L150-154 and L172-176. For examining the impacts of INP, we change the initial dust/bio particle concentration of 0.1, 1, 10, and 100 cm^{-3} , respectively, referred to as IN0.1, IN1, IN10, and IN100 (L196-198). We have also added Table 2 and some text to the present discussion of how dust/bio particle concentrations relate to INP concentrations as a function of temperature based on DeMott et al. (2015) on P9 L196-205.

5. Line 182. Do you consider these large AP as IN separately from CCN? What is size of ice particles that form on the INP after its nucleation? What do you do with these AP if supersaturation over water is larger than zero? The questions 3-5 are caused by unclear description of IN treatment.

- Our responses to Comments 3-4 should have addressed the questions here.

6. Line 548 and some places above. The statement is not correct. In the study by Lynn et al. (2007) mentioned above a dramatic increase in snow over mountains in case of high CCN concentration is reported and described in detail. In particular they presented

figures 6-8 which are, in my opinion, similar to Fig 8 in the paper under revision.

- Here we are talking about the mechanism leading to the drastically increased snow precipitation on the windward slope of the mountain, which is new indeed. For your convenience, we repeat the mechanism here as below,

Increasing CCN forms more shallow clouds at the wide valley area and foothills, which induces a change of local circulation through more latent heat release and increases the zonal transport of moisture to the windward slope of the mountains. This results in much more invigorated mixed-phase clouds with enhanced deposition and riming processes and therefore much more snow precipitation.

Lynn et al. (2007) indeed showed the increased snow water content in cloud by CCN but not snow precipitation on the windward slope of the mountain. That study showed decreased precipitation on the windward slope in the polluted case and increased precipitation over the downwind slope (with a decreased total precipitation). Their explanation for the increased snow is through collision of ice particles formed from the enhanced drop freezing due to delayed warm rain formation. So, as you can see, the results and the mechanism are different from our study. We have added the relevant discussion of Lynn et al. 2007 here, that is, “Lynn et al. (2007) also showed that increasing small aerosol particles led to an increased in-cloud snow mass content as a result of more ice particles formed from droplet freezing due to suppressed warm rain formation and thereby more collisions between those ice particles. But different from our study, the total precipitation on the windward slope in Lynn et al. (2007) was decreased as the snow particles had smaller size with lower fall speeds, and they were advected to the lee-side of the mountain, resulting in more precipitation there” (L585-590).

7. Line 550. In the study by Lynn et al. 2007 it is shown that an increase in the AP concentration decreases warm rain production and intensifies ice processes. The ice particles are advected downwind producing a substantial increase in snow and other ice precipitation over upwind slope and over the mountain peak. So the mechanism discussed in the study is not new and was described before. Besides, Lynn et al also discussed an important effect of very low relative humidity on the downwind slope. This low RH leads to evaporation of precipitating particles over downwind slope. As a result, effect of aerosols turned out to be also dependent on the wind speed because strong wind advected ice particles into zone of very low RH. So there is an “optimum” combination of APs concentration and wind speed to get maximum snow mass at the upwind slope and over the mountain peak. I propose that the authors discuss the similarities and differences of their results as compared with those reported by Lynn et al. (2007).

- Lynn et al. (2017) showed that increased CCN decreased precipitation on the upwind slope. The increased precipitation occurred over the downwind slope (not the upwind slope), which is very different from our result of drastically increased snow precipitation on the upwind slope through a mechanism of changed circulation that enhances the transport of moisture from the valley to the mountain. As discussed in our response to the comment right above, they are very different results and mechanisms. We have discussed the similarities and differences of the results between Lynn et al. (2007) and

our study and the possible reasons for the differences, as shown on P26 from L585 to L598.

- We agree that the aerosol impacts would depend on dynamics (wind speed) and thermodynamics (RH), as studied in Lynn et al. (2007). Although we did not carry out such sensitivity tests, we showed similar results and mechanisms in two cases with very different wind direction and RH. We have added discussion about this as shown in L599-603, “The mechanism leading to the enhanced precipitation over the windward slope by increasing CCN is seen in the two cases with very different cloud temperature, wind direction and RH. However, the efficiency of the mechanism could depend on dynamics (wind speed) and thermodynamics (RH). As examined in Lynn et al. (2007), aerosol impact on the orographic precipitation is reduced when RH is very high and increased as wind speed is reduced”.