

Response to Reviewer #1

Fan et al. report on an aerosol-cloud-precipitation process modeling study regarding two cases from CalWater 2011. The advantage of this work over FAN2014 is based on the comparison of variable cloud phase conditions (WMOC versus CMOC), providing an added level of detail. One of the more surprising findings is the increase in snow precipitation when CCN concentrations are high in the CMOC case through changes in local circulation, due to invigoration of mixed-phase clouds from latent heat release. Although the results from this study are interesting and worthy of placement in the literature, there are a few issues that need to be resolved prior to publication in ACP.

Although containing pertinent information, the introduction is somewhat difficult to follow. I suggest reordering and refocusing the introduction such that there are four paragraphs to guide the reader in a more efficient manner: 1. An abridged, broad background on aerosol-cloud-precipitation interactions, cloud phase, etc.

- Thanks for the helpful suggestions to improve the paper. Please see our point-by-point responses as below.

General comments:

Some of this information is already provided in the beginning of the introduction. Much of the information in the paragraph starting on p 5, 73 could be placed in the first paragraph. 2. Introduce the concept behind CalWater and briefly describe previous relevant results, including the main findings from Ault et al. (2011), Creamean et al. (2013, 2014, 2015), White et al. (2015), Rosenfeld et al. (2013, 2014), and of course FAN2014. 3. Discuss what is missing from those previous works, as motivation for the current study. For instance, has anything been previously done regarding WMOC versus CMOS simulations? This seems to be a new approach that could be emphasized. 4. Clearly list the objectives for the current study and what is novel about it. The information on p23, 492-494 would be suitable for the list of objectives. Further, the authors state this is a follow up on FAN2014, but should specifically discuss what is new and why this is an improvement versus serving only as an extension (i.e., the information on p 9, 168-172 and p 23, 489-492 is an improvement that should be mentioned in the introduction).

Creamean, J. M., Lee, C., Hill, T. C., Ault, A. P., DeMott, P. J., White, A. B., Ralph, F. M., and Prather, K. A.: Chemical properties of insoluble precipitation residue particles, J Aerosol Sci, 76, 13-27, 2014.

Creamean, J. M., Ault, A. P., White, A. B., Neiman, P. J., Ralph, F. M., Minnis, P., and Prather, K. A.: Impact of interannual variations in sources of insoluble aerosol species on orographic precipitation over California's central Sierra Nevada, Atmos Chem Phys, 15, 6535-6548, 2015.

Rosenfeld, D., Chemke, R., Prather, K., Suski, K., Comstock, J. M., Schmid, B., Tomlinson, J., and Jonsson, H.: Polluting of winter convective clouds upon transition

from ocean inland over central California: Contrasting case studies, Atmos Res, 135, 112-127, 2014.

White, A. B., Neiman, P. J., Creamean, J. M., Coleman, T., Ralph, F. M., and Prather, K. A.: The Impacts of California's San Francisco Bay Area Gap on Precipitation Observed in the Sierra Nevada during HMT and CalWater, J Hydrometeorol, 16, 1048-1069, 2015.

- The Introduction generally follows the line that the reviewer suggested but starts with a general background about California precipitation and cloud properties that this study focuses on. Then the factors – AR and aerosols that impact cloud properties and precipitation are introduced in the second paragraph. The third and fourth paragraphs basically follow the second one to give a more detailed literature survey about aerosol impact on orographic clouds and supercooled water. After that, we discuss what is missing from those previous studies, and introduce FAN2014, and state the objectives of this study following FAN2014. All authors are in agreement that the Introduction of this paper is organized in a logical fashion to introduce the topic and goals of this study.
- We have included the references that the reviewer suggested except White et al. (2015), which we think is not much related (see L75-77 and L90). We have also slightly modified the text to more specifically discuss what is missing from the previous studies and what is new in this study (i.e., the text at L100-102, L122-123, and L129-130).
- The text on p23, L492-494 in the original manuscript was already stated in our objectives #2 and #3 (i.e., the current L147-150), and the information on p 9, L168-172 was also already included in the introduction (i.e., the last sentence of the Section 1).

Even though the conditions for each case are described in FAN2014, they could be reiterated here. Some characteristics are presented on p 10, 194-199, but what were the average cloud top and base heights? What was the frequency of occurrence for each cloud phase type and were the particular days chosen extremes? On p 10, 192-193, I am assuming these averages for the case days only, but it would be interesting to provide information on if these are conditions that were anomalous or typical of this region. Additionally, the description of the cases on p 23 494-497 would be better suited earlier on when describing the cases.

- The averaged cloud top height for each cloud case is described on P5-6 when the cases are introduced for the first time. Now we have reiterated here (p10 L209-211). The cloud base information has been added as well (L212-213). Those two cases correspond to anomalous conditions as they are influenced by both AR and long-range transported dust/bio (L214). The description of the cases later on p 23 494-497 (the original version) is just a short version of the description here but with a little different wordings. Now we have added the same wordings (L217-218).

While a wide range of information is yielded from this more elaborate study, it is somewhat difficult to follow due to the nature in which the results are presented. As an example, the results quickly transition to comparing the CMOC to the WMOC case even before the basic results from the WMOC case are presented (p 17, 1 356-366). I recommend reordering section 3 such that the CMOC results are presented first (section 3.1, without the subsections), WMOC second (section 3.2), followed by comparison of

the microphysical changes from each case (i.e., section 3.1.3), and lastly a comparison on the disparate effects on precipitation from each case (i.e., section 3.1.2). Another option would be to condense and fold the comparison of the cases in terms of microphysical and precipitation effect differences in the discussion and conclusions. The authors could still focus on the CMOC case since it affords surprising results, but should be bolstered in the discussion. As a result, the figures would need to be restructured such that they are easier on the eye and align with the recommended reordering of section 3. For instance, Fig. 2 could instead be a combination of the current Fig. 2 and Fig. 3 panels, and Fig. 3 could be a combination of the current Fig. 4 and Fig. 5 panels for CMOC. The subsequent new figures (4 and 5) would then be the same structure, but for the WMOC case. The current Fig. 11 should be introduced with the WMOC case section (3.2). The current Figs. 6, 7, 8, 9, 10, and 12 would be pushed back to when the microphysical and precipitation accumulation differences are discussed. If restructured such that the results are reordered to enable better flow, the novelty of the work will be more apparent to the reader.

- Section 3 is already organized in the way that the reviewer suggests: CMOC is discussed first (Section 3.1) and then WMOC (Section 3.2). Within each case, we discuss the basic results first and then look into the mechanisms. We do not quite understand the reviewer's comment "the results quickly transition to comparing the CMOC to the WMOC case even before the basic results from the WMOC case are presented". The place that the reviewer pointed out (p 17, L356-366 in the previous version) only contains one sentence that mentions a sensitivity test done based on WMOC to confirm a factor in the mechanism we presented, but that is after all the basic results and the mechanisms for the CMOC have been presented and discussed. We discussed that sensitivity test here in order to give a whole picture of the mechanism at the same place. The WMOC is chosen for this test because of less mixed-phase regime compared with CMOC, so the factor would have a more significant role in the CMOC if it plays a role in the WMOC. This has been clarified further on P17 L377-381 in the current manuscript. The subsection titles are useful for the readers to follow the result section clearly.
- The sequence of the figures is also already presently constructed around the logical discussion of research findings: starting from the significant results/concerns in precipitation (Fig 2), then looking into how they are related to cloud microphysical properties (Fig 3), which are determined by major microphysical process rates (i.e., budgets; Fig 4, and 5.). After that, then we present the physical mechanisms leading to the significant changes (Fig. 6-Fig. 10). So, they are separately presented in their natural ways, e.g., Fig.2 is about precipitation and Fig. 3 is about cloud microphysical properties. Besides, each of the figures has multiple panels already. We prefer not to combine the figures as the reviewer suggested.
- Moving Figures 6, 7, 8, 9, 10, and 12 to the end does not align with the flow of the presentation in the paper, as these follow the discussion logically. In addition, it is quite common to introduce figures with comparative results prior to completing their discussion (i.e., they are referred back to), and this goes along naturally with the manner of discussing CMOC first and WMOC second.

Publishing the new findings is key. To emphasize that this study entails new findings and is not a just a slight modification of FAN2014, the authors should consider providing

specific statements as to how and why the results here vary from FAN2014 throughout the results section.

- All the results discussed in the result section are new from FAN2014. We do not think that it is necessary to say it throughout the results section. The only thing that we can compare is that the significant CCN impacts on precipitation was not seen in FAN2014, which was simply because we only increased CCN by 3 times based on the baseline cases in FAN2014, making CCN concentrations of ~ 160 and 720 cm^{-3} in the high CCN cases for CMOC and WMOC, respectively. They are smaller than 1000 cm^{-3} where the significant effect is seen in this study. In addition, CCN and IN are set to be uniform and increased uniformly over the domain, while in FAN2014, only CCN over the central valley and coastal urban area were increased. This discussion has been added to the last section (P25,L551-556).

Along these lines, the fact that snow increases with increasing CCN is surprising. The authors present some comparison with previous work (i.e., Saleeby et al. (2011)) and what key differences may have led to the disparities between the studies. First, this should be done throughout the discussion: are the results (besides this one) surprising or expected in the context of previous work? Second, what other studies contradict this finding and why? The authors state that this result, "...is different from previous modeling studies in the literature..." but which studies specifically and for what reasons?

- Such comparisons with literature studies were already presented in the Discussion section in two places (starting from L572 on P25 and the last paragraph of the paper). For the sentences that the reviewer pointed out, we have provided the possible reasons and modified that text as "different from previous modeling studies in the literature such as Lowenthal et al. (2011). Many possible reasons could lead to the differences including different cloud cases and different model parameterizations especially for riming processes" (P26 L575-577). In addition, we have provided more detailed discussion by comparing with other previous studies brought up by another reviewer as shown in L583-596.

The authors do show the spatial heterogeneity in several resulting parameters in a couple figures, but are the main conclusions based upon the results time-dependent as well? For instance, CCN increasing snowfall, is that after (X) hours of simulation? Does this occur immediately? Or is this an average over the entire simulation time period, which could be highly variable over time? The authors could consider showing a figure of key parameters over time, which would be interesting.

- Yes, time evolution is important to look at the mechanism responsible for the changes. But we already considered this information and discussed when the precipitation (or snow) enhancement starts, and then looked at the related variables at the start time and how they evolve in the subsequent 1-2 hours as shown in Fig. 6-10. The corresponding text to discuss this starts from "Since the precipitation enhancement begins at 1400 UTC, which is a couple of hours into the simulations, we focus on the time period of 14-1600 UTC" (L342-344 in the current manuscript).

It is not initially clear that the simulation parameters, namely CCN and INP concentrations, chosen are of realistic values to what is observed in the Sierra Nevada or if these are idealized situations. It is not until much later in the conclusions and discussion section that the authors mention CCN of $> 1000 \text{ cm}^{-3}$ is considered an extreme for this region (p 26 l 554-555). This should be clearly delineated much earlier, in the methods. Also, what is “normal” versus extreme for the INP concentrations at the temperatures observed for each case?

- We agree that it is useful to further frame the INP concentration range used and have added Table 2 and text to the present discussion of how dust/bio particle concentrations relate to INP concentrations as a function of temperature. This discussion has been added on P9 L196-205. The extreme conditions for CCN and INP were mentioned when the simulation setup was introduced (now L190-191).

There are several typos and grammatical mistakes throughout the manuscript, which the authors should take care in correcting for the revision. Some examples include: (1) “INP” is used in several instances where the plural form should be used (INPs), (2) CCN are plural but are commonly referred to as a singular, and (3) “Mountains” is typically capitalized mid-sentence. Also, please write in past tense when describing the results from the simulations.

- We have carefully checked these places and corrected the typos and grammatical mistakes throughout the paper.

Abstract: It is not apparent that the comparison of the WMOC and CMOC case are conducted under the same INP and CCN concentrations. Please clarify.

- We have modified a sentence in Abstract to clearly say it, i.e., to “We quantify the CCN and INP impacts on supercooled water content, cloud phases and precipitation for a WMOC and a CMOC case with sensitivity tests using the same CCN and INP concentrations between the WMOC and CMOC”

Specific comments:

P 2, l 28: Please clarify the type of deposition (i.e., in-cloud nucleation, in-cloud scavenging, etc.).

- By deposition we are referring to the depositional ice growth process.

P 2, l 30: “...WMOC *with* low INP *concentrations.*” Also provide the INP concentration used here for reference.

-As we have clarified in the current version, INPs are dependent of temperature besides dust/bio concentrations. So, it is not just one value that can be put there. .

P 2, l 30-31: Remove the sentence starting with “However” as this is redundant to the following sentence, which is better because it provides more detail. Once removed, the following sentence can be started with “*However*, we find a new mechanism...”

- Since the new mechanism is to explain the sentence “this reverses strongly for CCN > 1000 cm⁻³”, we think putting the word “however” before this sentence better conveys what we want to say here.

P 2, l 33: “...concentrations are > 1000 cm⁻³.”

- We have revised it as “for CCN of 1000 cm⁻³ and larger”.

P 2, l 34: Please clarify that this is the Central Valley and foothills west of the range.

- Done.

P 2, l 33-37: There is quite a bit of information presented in this one sentence, making it appear as a run-on. The authors should consider breaking up into two sentences.

- We have re-constructed the sentences by breaking into short pieces. And now it reads as “In this situation, more widespread shallow clouds with greater amount of cloud water form in the Central Valley and foothills west of the mountain range. The increased latent heat release associated with the formation of these clouds strengthens the local transport of moisture to the windward slope, invigorating mixed-phase clouds over the mountains, and thereby producing higher amounts of snow precipitation.” (P2 L34-38).

P 2, l 37: The beginning of this sentence is vague. What concentration of INPs? With what concentration of CCN? Some more context is needed.

- This is a generalized summary of details that can only be understood through reading the paper. We have added “under all CCN conditions” to the sentence.

P 2, l 39: “However, *an increase in precipitation occurs* in both cases...”

- Changed.

P 4, l 51: The Ralph et al. article on CalWater would be a great citation for this statement.

Ralph, F. M., Prather, K. A., Cayan, D., Spackman, J. R., DeMott, P., Dettinger, M., Fairall, C., Leung, R., Rosenfeld, D., Rutledge, S., Waliser, D., White, A. B., Cordeira, J., Martin, A., Helly, J., and Intrieri, J.: Calwater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating Us West Coast Precipitation in a Changing Climate, B Am Meteorol Soc, 97, 1209-1228, 2016.

- Added.

P 4, l 51-52: This sentence is redundant to that below, could simply remove.

- Removed.

P 4, l 54: Please clarify that this is over the Sierra Nevada mountains.

- Done.

P 4, l 57: Cloud *phase* (should be singular). Please correct here and throughout.

- Since cloud has different phases (liquid, mixed, and ice phases) and it has been used as plural commonly as well.

P 4, l 65: Remove “in the atmosphere”.

- Done.

P 5, l 73: Be more specific by clarifying that these are aerosol *climate* impacts that depend on aerosol properties *such as number, size, and composition*.

- Added “such as number, size, and composition”.

Table 1 does not seem necessary. The information on the concentrations used are already provided in the text.

- Table 1 more clearly and intuitively shows what kind of simulations we have conducted for this study than text.

All figures: Why are two markers (circles) listed in the legend for INPs?

- We listed two markers to show the legend more clearly.

Fig. 2: Please place the panels in the order in which they are discussed in the text. Also, provide what the arrows are in the caption for clarity.

- Fig. 2b and 2c follow the conventional presentation on warm and ice precipitation respectively. To be consistent with Fig.14 that is the same type of figure, we would like to keep it this way. This is allowed in scientific papers (i.e., Fig. 2c is referred before Fig. 2b). We have added the description of the two arrows to the Figure caption now.

Fig. 6: Why are there no ice nucleation rates for levels where nucleated ice particles were found?

- Fig. 6c is in logarithm scale and the nucleation rate is too low below 2.5 km altitude, so it is not shown.

Figs. 8 and 9: Why is this only shown for CMOC and not WMOC? I get that the CMOC case presents interesting results, so at the very least, the authors could provide the WMOC spatial figures in a supporting document and allude to them in the text.

- Fig. 8-9 are parts of the figures illustrating the mechanism leading to the drastic CCN impacts on precipitation in the CMOC. Since very similar mechanisms are seen in the WMOC, there is no need to present similar figures but in the text we clearly discuss the similarity starting from L490 on P20, “We have done the same investigation as in Section 3.1.1, and found the mechanism causing the increased cloud water and the snow

production is similar as that in CMOC, that is, ...". Furthermore, the key part of the mechanism for the WMOC is shown in Fig. 10b, which is the change of local circulation that increases the zonal transport of moisture to the windward slope of the mountains.

Fig. 9: It would be easier on the eye if a color scale much different than the previous figure were used, since these are differences and not absolute values. Perhaps red to white to blue?

- Right now it is red to green to blue, not much different from what the reviewer suggested (i.e., red to white to blue), and we feel that it shows the positive and negative data clearly.

Response to Reviewer #2

General Comments:

The response of cloud microphysical processes and precipitation to changes in aerosol particle concentration is still uncertain. This article presents numerical sensitivity tests on how the cloud processes and precipitation from mixed-phase orographic clouds are changed due to changes in the concentration of cloud condensation nuclei and ice forming nuclei. The results are interesting and are generally well presented. It should be publishable in ACP if the following specific issues could be considered in revision.

- Thanks for the helpful suggestions to improve the paper. Please see our point-by-point responses as below.

Specific Comments:

1) Line 51-53: Remove “Supercooled liquid occurred commonly in clouds over the Sierra Nevada during the cold season (Rosenfeld et al., 2013)”, since the similar sentence also appears in line 54-55.

-Done.

2) Line 67: "pollution aerosols" may be replaced by "anthropogenic aerosols".

-Done.

3) Change Line 73-74 to “The impacts of aerosols on clouds not only depend on aerosol properties, but also on the dynamics and thermodynamics of the clouds”.

- Changed to “Aerosol impacts on clouds not only depend on aerosol properties, but also dynamics and thermodynamics”.

4) Line 146: “which is referred to as INP concentration”: this notation may not be proper, because the concentration of aerosol particles with diameter larger than 0.5 μm is not the concentration of INP, just as a factor.

- We apologize for the confusion in using the term of INP. Besides deleting “which is referred to as INP concentration” here, we have clarified at L156-158, “...so in this paper we vary the constant $n_{a>0.5\mu\text{m}}$ over a range of relevant conditions to investigate the impacts of varied INP concentration”.

5) Line 166: The scheme for deposition nucleation should also be briefly described, since it dominates ice formation in the cold case.

- FAN2014 detailed why deposition/condensation freezing is not included. Adding deposition/condensation freezing produces large amount of small ice particles that are not observed for those cases. We have added the sentence “Adding deposition/condensation freezing produces large amount of small ice particles, which is not consistent with

observations, thereby deposition/condensation freezing is not included, as discussed in FAN2014” (P8 L164-166).

6) Line 185: “. . .with the initial INP concentration of 0.1, 1, 10, and 100 cm⁻³, respectively”: these are concentrations of coarse mode aerosol particles, not IN. This should be clarified.

- Yes, we have changed to dust/bio (or INP proxy) throughout the paper. We have also further frame the INP concentration range used and have added to the present discussion of how dust/bio particle concentrations relate to INP concentrations as a function of temperature (P9 L196-203).

- In addition, in our model, INP proxy concentration is a single prognostic variable separately from CCN. For the simulation of the observed case in FAN2014, it is initiated with the concentrations of clear-sky aerosol particles with diameter larger than 0.5 μm in the dust layer. Since our model does not have full aerosol simulations and INP proxy concentration in our model is not a factor from the predicted aerosol simulations, saying “they are the concentrations of coarse mode aerosol particles” would confuse people. We have added text to clarify, i.e., “As described in FAN2014, dust/bio particle concentration (i.e., IN proxies) is a single prognostic variable separate from CCN. For the simulation of the observed case in FAN2014, dust/bio concentration is initiated with the concentration of clear-sky aerosol particles with diameter larger than 0.5 μm in the dust layer” (L172-175).

7) Line 192: “. . . are around 30 (2) and 120 (4) cm⁻³, respectively”: the concentrations of INPs should be the coarse mode aerosol particles. When we talk about the concentration of INP, we must indicate at which temperature.

- This comment is the same as #6. Please see our response above.

8) Line 237-239: This is most likely caused by the treatment of snow particles in the model. Since most of the droplets transferred to snow when INP was high, the concentration and mass of water droplets must be lower. How the large drops are treated when they are frozen? Are they also transferred to snow?

- It could be. But even the ice nucleation forms mainly cloud ice, the large amount of ice could lead to lower rain concentrations due to conversion through WBF and riming. Yes, large droplets are transferred to snow when immersion freezing occurs (cloud ice and snow are represented with one set of size bins and distinguished with a radius of 150 microns).

9) Line 296: “. . .have ice nucleation occurring (Fig. 6b)”: through which nucleation mechanism?

- Only immersion freezing from DeMott et al. 2015 is considered in the simulations, as stated in the model setup and mentioned in the paragraph above. We have also mentioned specifically here (L348 in the current manuscript).

10) Line 372: “Atmospheric rivers” are mentioned several times, but it is not a commonly known concept. It should be explained at the beginning.

- In fact, the terminology is commonly known and is the dynamical and thermodynamic environment for precipitation events over the western US. This is explained at the beginning (L72-74).

11) Line 401-404: It should not be the upper limit, if deposition nucleation and condensation freezing are not included.

- As we discussed in FAN2014 and earlier in this paper, deposition/condensation nucleation should not be the case for those clouds since it forms a great amount of small ice crystals that were not observed by aircraft measurements. In addition, deposition/condensation nucleation does not directly convert liquid to ice, and it competes for INPs with immersion freezing (less immersion freezing will occur if deposition/condensation nucleation occurs). So, the largest effect on the SCW and cloud phase should be through immersion freezing with a given INP condition.

12) Line 405-406: the CCN effect is much more significant than INP when the concentration of CCN is 1000 cm⁻³ or above.

- That was for precipitation. For the liquid fraction discussed here, we do not see that as shown in Fig. 12, although the more significant CCN effect is seen for CCN > 300 cm⁻³, but it is still smaller compared with the INP effect.

13) Line 438-439: Remove “in our model simulation with the fast version of SBM in which ice habits are not considered”.

- In fact this was added to address one of the comments from a coauthor because the HM processes are sensitive to ice habits in nature but this fast version of SBM does not consider this in the HM processes.

14) Line 441-442: Remove “in the model simulation”.

- We prefer to keep it since recent observations suggested secondary ice nucleation could be significant but the model might not be able to simulate it. There might be additional secondary ice nucleation mechanisms besides HM processes, or the parameterization of HM processes is not adequate.

15) Page 42: The ordinates should be provided for Figure 10.

- The ordinates have been refined.

16) Page 43: The ordinates of the left panel should be provided for Figure 11.

- The ordinates have been refined.

17) Page 44: The unit of temperature in the figure should be corrected.

- Sorry we forgot to mark that the grey contour lines are the geophysical height in meters. They are not temperatures. It has been noted in the current figure caption.

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)

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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”.

1 **Effects of Cloud Condensation Nuclei and Ice Nucleating Particles on Precipitation**
2 **Processes and Supercooled Liquid in Mixed-phase Orographic Clouds**

3

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21 **Abstract**

22 How orographic mixed-phase clouds respond to the change of cloud condensation nuclei
23 (CCN) and ice nucleating particles (INPs) are highly uncertain. The main snow production
24 mechanism in warm and cold mixed-phase orographic clouds (referred to as WMOC and CMOC,
25 respectively, distinguished here as those having cloud tops warmer and colder than -20°C) could
26 be very different. We quantify the CCN and INP impacts on supercooled water content, cloud
27 phases and precipitation for a WMOC and a CMOC case with sensitivity tests using the same
28 CCN and INP concentrations between the WMOC and CMOC. It is found that deposition plays a
29 more important role than riming for forming snow in the CMOC, while the role of riming is
30 dominant in the WMOC case. As expected, adding CCN suppresses precipitation especially in
31 WMOC and low INPs. However, this reverses strongly for CCN of 1000 cm^{-3} and larger. We
32 find a new mechanism through which CCN can invigorate mixed-phase clouds over the Sierra
33 Nevada Mountains and drastically intensify snow precipitation when CCN concentrations are
34 high (1000 cm^{-3} or higher). In this situation, more widespread shallow clouds with greater
35 amount of cloud water form in the Central Valley and foothills west of the mountain range. The
36 increased latent heat release associated with the formation of these clouds strengthens the local
37 transport of moisture to the windward slope, invigorating mixed-phase clouds over the
38 mountains, and thereby producing higher amounts of snow precipitation. Increasing INPs leads
39 to decreased riming and mixed-phase fraction in the CMOC but has the opposite effects in the
40 WMOC under all CCN conditions, as a result of liquid-limited and ice-limited conditions,
41 respectively. However, precipitation in both cases is increased by increasing INPs due to an
42 increase of deposition for the CMOC but enhanced riming and deposition in the WMOC.
43 Increasing INPs dramatically reduces supercooled water content and increases the cloud
44 glaciation temperature, while increasing CCN has the opposite effects with much smaller

45 significance.

46

47 **1. Introduction**

48 Snowpack in the Sierra Nevada Mountains is California's largest source of fresh water.
49 Understanding the factors contributing to snow precipitation over the mountains has important
50 implications to predicting the hydrology and local climate of the western U.S. This has motivated
51 a series of CalWater field campaigns carried out since 2009 to improve understanding of
52 processes influencing precipitation and water supply in California ([Ralph et al., 2016](#)). Closely
53 linked to precipitation is the distribution of cloud liquid and ice phases, which may be influenced
54 by supercooled liquid commonly occurring in orographic clouds [over the Sierra Nevada](#)
55 [Mountains](#) (Rosenfeld et al., 2013). Besides precipitation, cloud radiative forcing and cloud
56 feedback in the climate system are also highly dependent on cloud phases because of the very
57 different radiative effect of liquid and ice particles. Hence understanding the key processes and
58 factors impacting cloud phases is critical, but our lack of understanding and ability to model
59 supercooled liquid and cloud phases is limiting skillful predictions at weather and climate time
60 scales.

61 Many factors such as large-scale dynamics, solar heating, and aerosol particles can
62 impact cloud properties and precipitation over the Sierra Nevada Mountains (Shen et al., 2010;
63 Rosenfeld et al., 2008). Atmospheric rivers (ARs) are one of the primary large-scale dynamical
64 features that bring large amount of water vapor from tropics to the U.S. west coast, and can
65 create extreme rainfall and floods (Bao et al 2006; Ralph et al. 2011; Neiman et al. 2010).
66 Aerosols can modify cloud microphysical processes and potentially alter the location, intensity,
67 and type of precipitation (Tao et al., 2012) by acting as cloud condensation nuclei (CCN) or ice
68 nucleating particles (INPs). In California, [anthropogenic](#) aerosols from the densely populated

69 coastal plains and the Central Valley may be incorporated into the frontal airmass before
70 orographic ascent and influence precipitation in the Sierra Nevada Mountains (Rosenfeld and
71 Givati, 2006). Long-range transported aerosols (mainly dust particles) have also been found to
72 have a potential influence on clouds and precipitation in the winter and spring seasons (Uno et al.,
73 2009; Ault et al., 2011; Creamean et al., 2013).

74 | Aerosol impacts on clouds not only depend on aerosol properties such as number, size
75 | and composition, but also dynamics and thermodynamics. Rosenfeld et al. (2014) showed
76 | significantly different supercooled water (SCW) and precipitation processes in two contrasting
77 | cloud cases with air masses containing maritime and continental aerosols, respectively. Many
78 | studies have shown that CCN can reduce warm rain precipitation from orographic clouds by
79 | reducing the efficiency of cloud droplets conversion into raindrops (e.g., Lynn et al., 2007;
80 | Rosenfeld and Givati, 2006; Jirak and Cotton, 2006) and can reduce snowfall precipitation due to
81 | reduced riming efficiency (Lowenthal et al., 2011; Rosenfeld et al., 2008). However, some recent
82 | studies show a possibility of increased precipitation by CCN in orographic mixed-phase clouds
83 | (Fan et al., 2014; Xiao et al., 2015). Other studies have shown that CCN may not have significant
84 | effect on the total precipitation, but rather shift precipitation from the windward to leeward
85 | slope; a so-called “spillover effect” (Lynn et al., 2007; Saleeby et al., 2011; 2013). By acting as
86 | INPs, aerosols can enhance ice growth processes such as deposition and riming and thereby
87 | significantly increase snow precipitation (Fan et al., 2014). Both observational and modeling
88 | studies have shown that long-range transported dust and biological particles can enhance
89 | orographic precipitation in California by serving as INPs (Ault et al., 2011; Creamean et al.,
90 | 2013, 2014, 2015; Fan et al., 2014).

91 | Besides precipitation, aerosols may have significant impacts on cloud phase and SCW in

92 the mixed-phase clouds, which directly change cloud radiative forcing and Earth's energy
93 balance. Modeling studies have shown that CCN tend to increase SCW via the processes such as
94 suppressed warm rain and/or reduced riming efficiency (Khain et al., 2009; Iltoviz et al., 2016;
95 Saleeby et al., 2013). A recent observational study corroborated that increasing CCN decreases
96 the cloud glaciation temperature and thus increases the abundance of the mixed-phase regime
97 (Zipori et al., 2015). With abundant INPs such as dust particles, cloud glaciates at a much
98 warmer temperature (Rosenfeld et al., 2011; Zipori et al., 2015). It is found that commonly
99 occurring supercooled water in the clouds near the coastal regions of the western U.S. is
100 associated with low CCN and limited INP conditions (Rosenfeld et al., 2013). Models generally
101 have difficulties to simulate SCW and cloud phases. For example, recent evaluation of the
102 Community Atmosphere Model version 5 (CAM5) with satellite data showed that the model has
103 insufficient liquid cloud and excessive ice cloud from the mid-latitudes to the polar regions, and
104 liquid deficit bias maximizes over the Southern Ocean where supercooled water is prevalent
105 (Kay et al., 2016). For cloud model simulations with cloud-resolving models, ice nucleation
106 parameterizations often need to be modified in order to produce the mixed-phase clouds in the
107 Arctic region (Fan et al., 2009; Fridlind et al., 2007). Considering many microphysical processes
108 are sensitive to aerosol types (CCN or INP), temperature, and/or supersaturation (e.g., deposition
109 growth), aerosol impacts on cloud phase and SCW can be complicated, depending on cloud
110 dynamics and thermodynamics. Our current understanding of cloud microphysical processes
111 impacting SCW and cloud phase in different meteorological environments is poor. Therefore, it
112 is important to conduct process-level studies to improve our understanding.

113 Fan et al. (2014) conducted a study for two mixed-phase orographic cloud cases with
114 different cloud temperatures and showed different significance of the CCN and INP impacts on

115 | precipitation between the two cases with much more significant impacts of INPs. The two cases
116 | are February 15-16, 2011 (FEB16), and Mar 1-2, 2011 (MAR02). FEB16 has a cloud top
117 | temperature as cold as -32°C while the cloud top temperature of MAR02 is generally warmer
118 | than -20°C. The temperature differences at the same altitude between the two cases are about 6-
119 | 10°C. For these reasons, we will herein refer to them as cold mixed-phase orographic clouds
120 | (CMOC) and warm mixed-phase orographic clouds (WMOC), respectively. The main snow-
121 | forming mechanism in warm and cold mixed-phase orographic clouds could be very different
122 | and lead to different precipitation response to changes of CCN and INPs, which has not been
123 | studied so far. Following Fan et al. (2014) this study aims to (1) understand the dominant ice
124 | growth processes in these two mixed-phase cloud systems; (2) quantify the response of
125 | precipitation to the changes of CCN and INPs over a wide range from extremely low to
126 | extremely high concentrations, and (3) examine CCN and INP impacts on SCW and cloud
127 | phases. The same WRF model with the spectral-bin microphysics (SBM) as used in Fan et al.
128 | (2014) is employed. Ice nucleation is parameterized in dependence on mineral dust/biological
129 | particle concentrations on the basis of observational evidence. To provide a better process-level
130 | understanding and better realize our science goals, the simulation resolution is further increased
131 | to be 1-km and the simulations are driven with the 2-km resolution baseline simulation from Fan
132 | et al. (2014).

133

134 **2. Model Description and Simulation Design**

135 **2.1 Model description**

136 | As in Fan et al. (2014), simulations are performed using WRF version 3.1.1 developed at
137 | the National Center for Atmospheric Research (NCAR) (Skamarock et al., 2008) coupled with a

138 spectral-bin microphysics (SBM) model (Khain et al., 2009; Fan et al., 2012). The SBM is a fast
139 version of the full SBM described by Khain et al. (2004), in which ice crystal and snow
140 (aggregates) in the full SBM are calculated based on one size distribution with separation at 150
141 μm . ice crystal and snow are referred to as low-density ice. Graupel and hail in the full SBM are
142 grouped as high-density ice, represented with one size distribution without separation. More
143 details about SBM that we used in this study can be found in Fan et al. (2014).

144 As discussed in Fan et al. (2014), hereafter referred to as FAN2014, the ice nucleation
145 parameterizations in the SBM used for this study have been modified. A new ice nucleation
146 parameterization of DeMott et al. (2015; cited as DeMott et al., 2013 in FAN2014 before the
147 parameterization was published) was incorporated to SBM to investigate the impacts of dust as
148 INPs. The parameterization connects nucleated ice particle concentration under a certain
149 atmospheric condition with aerosol particle number concentration with diameter larger than 0.5
150 μm ($n_{a>0.5\mu\text{m}}$ in Eq. 2 of DeMott et al., 2015). In FAN2014, the aerosol particles that are
151 connected with the DeMott et al. (2015) parameterization are referred to as “dust/bio” (from
152 single particle mass spectral composition measurements), and are based on observations from the
153 Passive Cavity Aerosol Spectrometer Probe (PCASP) for particles with diameter larger than 0.5
154 μm from clear-sky aircraft data. Note that the actual INP number concentration in the DeMott et
155 al. (2015) parameterization includes an exponential temperature dependence that acts on aerosol
156 concentration, and that the exponent on aerosol concentration is 1.25, [so](#) in this paper we [vary](#)
157 [the constant \$n_{a>0.5\mu\text{m}}\$ over a range of relevant conditions to investigate the impacts of varied INP](#)
158 concentration. It should also be noted that the parameterization is designed and implemented as
159 immersion freezing, that is, a pre-existing liquid particle (droplet or drop) is consumed for each
160 formed ice crystal determined by the parameterization (at the same time, an ice nucleus is

161 removed from the INP category). An added feature of the implementation is that when
162 immersion freezing occurs, freezing starts from the largest drops first, followed by the smaller
163 ones over the size spectrum of water drops. This implementation yielded the majority of large ice
164 particles as observed by aircraft measurements (FAN2014). Adding deposition/condensation
165 freezing produces a large amount of small ice particles, which is not consistent with observations,
166 so deposition/condensation freezing is not included, as discussed in FAN2014. The assumption
167 that the largest drops freeze first also acknowledges the expectation that the largest droplets
168 should have a higher probability of containing an INP active at a given temperature. For contact
169 freezing, we adopt the implementation of Muhlbauer and Lohmann (2009) for the
170 parameterizations described in Cotton et al. (1986) and Young (1974) to connect with INPs. The
171 contribution from the contact freezing with this parameterization is negligible. As described in
172 FAN2014, dust/bio particle concentration (i.e., IN proxy) is a single prognostic variable separate
173 from CCN. For the simulation of the observed case in FAN2014, dust/bio concentration is
174 initiated with the concentration of clear-sky aerosol particles with diameter larger than 0.5 μm in
175 the dust layer. Over-nucleation is prevented by applying an upper limit of ice particle
176 concentration.

177 **2.2 Design of numerical experiments**

178 In FAN2014, simulations were done for the two nested domains with a horizontal grid-
179 spacing of 10 and 2 km, respectively. To focus on the orographic clouds over the Sierra Nevada
180 Mountains and provide a better process-level understanding, we conduct new simulations using a
181 smaller domain of 300 km \times 280 km with a grid-spacing of 1 km (the yellow box in Fig. 1a)
182 nested within the 2-km grid-spacing domain of FAN2014 (the blue box). The domain grid points
183 are 301 \times 281 horizontally with 51 vertical levels. The initial and lateral boundary conditions are

184 produced from the baseline simulations of the 2-km grid-spacing in FAN2014 that were
185 validated by various observational data. The lateral boundary data are updated every 3-hours.
186 The RRTMG shortwave and longwave radiation schemes are used to account for aerosol-cloud-
187 radiation interactions based on the droplet effective radius calculated by SBM.

188 CCN in the model [are](#) represented by a spectrum with 33 size bins with prognostic CCN
189 number concentration for each bin. As stated above, dust/bio particle number concentration
190 [serves as a proxy for INP concentration](#) in this region. For the purpose of this study, we conduct
191 sensitivity tests by varying CCN and INP [proxy](#) (i.e., dust/bio particle) concentrations over a
192 wide range from the extremely low to extremely high concentrations as shown in Table 1. The
193 initial CCN concentrations for the sensitivity simulations are set to be 30, 100, 300, 1000, and
194 3000 cm^{-3} (referred to as CCN30, CCN100, CCN300, CCN1000, and CCN3000 respectively).
195 For each CCN condition, simulations are conducted with the initial [dust/bio particle](#)
196 concentration of 0.1, 1, 10, and 100 cm^{-3} , respectively, referred to as IN0.1, IN1, IN10, and
197 IN100. [Note that the conversion of \$\text{cm}^{-3}\$ dust/bio to INPs per liter is shown in Fig. 10 of DeMott](#)
198 [et al. \(2015\). We also include a table \(Table 2\) in this study to clearly show the corresponding](#)
199 [INP concentrations under different dust/bio particle concentration at a certain temperature. For](#)
200 [example, \$0.1\text{ cm}^{-3}\$ dust/bio means \$\sim 0.02\text{ L}^{-1}\$ nucleated ice particles at \$-20^\circ\text{C}\$ and \$\sim 0.2\text{ L}^{-1}\$ at \$-25^\circ\text{C}\$.](#)
201 [These numbers of INPs are akin to the number concentrations of INPs found in the natural](#)
202 [marine boundary layer \(DeMott et al., 2016\). In contrast, \$10\text{ cm}^{-3}\$ dust/bio, common within some](#)
203 [transported dust layers, means \$\sim 5\text{ L}^{-1}\$ nucleated ice particles at \$-20^\circ\text{C}\$ and \$\sim 50\text{ L}^{-1}\$ at \$-25^\circ\text{C}\$ \(Table](#)
204 [2\).](#) The vertical profiles of CCN and INP [proxy](#) concentrations at the initial time are uniform
205 below 6 km since observations do not show significant vertical variations as discussed in
206 FAN2014. Simulations are conducted for both cases, and start at 12:00 pm UTC and run for 12

207 hours since the majority of the convective orographic clouds occur during this period. Note the
208 observed CCN ([dust/bio](#)) concentrations for CMOC and WMOC are around 30 (2) and 120 (4)
209 cm^{-3} , respectively.

210 [As described earlier](#), the CMOC case on FEB16 has cloud top temperatures [of about -](#)
211 [32°C](#), [which are](#) about 10 degrees colder than the WMOC case on MAR02, and has higher
212 relative humidity (RH) due to the lower temperature although the water vapor mixing ratio is
213 much smaller (Fig. 1b-1d). [The temperatures of cloud bases over the mountain slope are about](#)
214 [0°C for the CMOC and about 6°C for the WMOC](#). Both cases are under the influence of [both](#)
215 atmospheric rivers that provide ample water vapor supply [and the long-range transported](#)
216 [dust/bio](#). We note however that the lower-level wind directions in the two cases are different,
217 with prevailing westerly and northwesterly on FEB06, and southerly and southwesterly on
218 MAR02. [Therefore, the two mixed-phase cloud cases have contrasting thermodynamics and](#)
219 [dynamics](#).

220

221 **3. Results**

222 **3.1 CMOC – FEB16**

223 **3.1.1 Precipitation and microphysical processes**

224 Fig. 2a shows the accumulated surface precipitation averaged over the domain for the
225 CMOC case (FEB16). Increasing INPs generally enhances the domain-averaged precipitation
226 except at extremely high CCN concentration (i.e., 3000 cm^{-3}), as a result of increased snow
227 precipitation (Fig. 2c). The sensitivity to INP concentration gets much smaller when INP [proxy](#)
228 [aerosol concentrations](#) are 10 cm^{-3} and larger. Under the low INP condition where the liquid
229 regime is dominant, the precipitation is first suppressed as CCN increase up to a polluted

230 condition of 1000 cm^{-3} (grey arrow). This behavior is similar to the CCN effects on shallow
231 warm clouds. As INPs [are](#) further increased and mixed-phase clouds are increased, the decreased
232 trend of precipitation with the increase of CCN is changed to a monotonic increasing trend as
233 shown by the brown arrow in Fig. 2a. The most significant feature of Fig. 2a is the sharp
234 increase of surface precipitation from CCN of 1000 to 3000 cm^{-3} , even at the [lowest](#) INP
235 condition. This is inconsistent with our previous understanding for deep mixed-phase clouds that
236 precipitation should be significantly suppressed under the extremely polluted conditions because
237 droplets get too small to grow efficiently and the riming also becomes very inefficient (Fan et
238 al., 2007; Li et al., 2008). From Figs. 2b and 2c showing the liquid and snow mass
239 concentrations near the surface (i.e., at the lowest model level of ~ 40 m above the ground),
240 respectively, we see that (1) snow dominates the precipitation for the CMOC case and the ratio
241 of warm rain to total precipitation is very small; and (2) the dramatically enhanced snow explains
242 the sharp increase of precipitation from CCN of 1000 to 3000 cm^{-3} . Note that increasing CCN
243 enhances snow precipitation under any INP condition (Fig. 2c), and warm rain is totally shut off
244 when CCN are 1000 cm^{-3} or larger [for the IN0.1 condition](#) (Fig. 2b) due to the much smaller
245 sizes of droplets.

246 By looking at the in-cloud microphysical properties as shown in Fig. 3, increasing CCN
247 enhances snow number concentration and mass mixing ratio (N_s and Q_s , respectively). Especially,
248 we see a large increase of snow mass from CCN1000 to CCN3000. Cloud ice number
249 concentration and mass mixing ratio (N_i and Q_i , respectively) is also increased. Note ice and
250 snow are represented with a single size spectrum and a threshold size of $150 \mu\text{m}$ in radius is used
251 to separate them. As discussed in Section 2, the major ice nucleation is through the immersion
252 freezing of DeMott et al. (2015), and with a specification that the largest droplets freeze first

253 when ice nucleation occurs. Therefore, most of the newly-formed ice particles should be large
254 and fall into the snow bins, and so N_s and Q_s contribute more significantly to ice number and
255 mass increase with the increase of CCN than do N_i and Q_i . As CCN increase, not only cloud
256 droplet number concentration (N_c) is increased, but also cloud mass mixing ratio (Q_c). The large
257 increase of Q_c when CCN are high, which corresponds to the large increase of Q_s , will be
258 scrutinized a little later. The decrease of raindrop number concentration and mass mixing ratio
259 (N_r and Q_r , respectively) is very sharp and warm rain becomes negligible when INP [proxy](#)
260 [aerosol concentrations are](#) 1 cm^{-3} or larger (Fig. 3).

261 From the process rates of the major microphysical processes shown in Fig. 4, we see that
262 the increase of Q_c with the increase of CCN and the decrease of Q_c with the increase of INPs are
263 well explained by the condensation rate (Fig. 4a), although the changes of evaporation have the
264 same trends as well. As shown in Figs. 4c and 4e, deposition is a more significant process than
265 riming except in the case of [very](#) low INPs ([IN0.1](#)) in this CMOC. Increasing CCN enhances
266 deposition but only enhances riming when CCN are high. The sharp increase of deposition and
267 riming rates from CCN1000 to CCN3000 explains the sharp increase of snow with a major
268 contribution from deposition. How deposition and riming are enhanced so significantly in this
269 case will be elucidated in Section 3.1.2

270 At [very](#) low INP [concentrations](#) ([IN0.1](#)), the riming rate is similar to the deposition rate in
271 this CMOC (Figs. 4c and 4e). As INPs increase, the contribution of riming is reduced
272 significantly because of the reduction of supercooled droplets resulting from increased ice
273 particles in the mixed-phase zone. Thus, the riming process is liquid-limited in this CMOC. As a
274 result of increased ice particles, deposition is enhanced significantly, and it becomes 3-4 times
275 larger than riming [in IN10](#). In the observed condition (i.e., CCN are between $30\text{-}300 \text{ cm}^{-3}$ and

276 INP [proxies](#) range between 1-10 cm⁻³), both deposition and riming contribute to the snow growth
277 but deposition is the major player. When INP [concentrations](#) are extremely high ([IN100](#)), clouds
278 glaciate very fast and liquid droplets that are available for riming are limited, [so their](#)
279 contribution is negligible (red line in Fig. 4e).

280 The Wegener–Bergeron–Findeisen (WBF) processes refer to ice depositional growth at
281 the expense of liquid through evaporation in mixed-phase clouds. So the mixed-phase cloud
282 regime where vapor pressure falls between the saturation vapor pressure over water and ice is
283 defined as the WBF regime. As CCN increase, the WBF processes get stronger as shown in Figs.
284 5a and 5b. The ratio of the evaporation through WBF to the total evaporation is larger than 0.92
285 in all simulations (Fig. 5a), meaning that drop evaporation in this CMOC occurs predominantly
286 in the WBF regime. There is generally only 50-70% of deposition occurring in the WBF regime
287 even when INP [concentrations are in a range \(IN0.1 to IN1\) that is typical for this region in](#)
288 [winter](#) (Fig. 5b), so a significant portion of deposition occurs outside of the WBF regime, and the
289 portion increases as [INPs](#) increase. Therefore, increasing INPs generally reduces the WBF
290 regime because of the reduced liquid due to enhanced depositional growth. In this CMOC, the
291 ratio of riming occurring in the WBF regime to the total riming is small (generally around 0.2-
292 0.4 in Fig. 5c), meaning that riming mainly occurs outside of the WBF regimes under any CCN
293 and INP conditions. The ratio is increased by CCN but generally decreased by INPs as a result of
294 the increase/decrease of liquid regime, respectively (Fig. 5c).

295 We see that all major microphysical processes (condensation/evaporation,
296 deposition/sublimation, and riming) are highly sensitive to INPs, while generally having much
297 lower sensitivity to CCN when CCN are below 1000 cm⁻³. The sensitivity of all the major
298 microphysical processes to CCN gets much more significant when CCN are 1000 cm⁻³ and larger

299 (Fig. 4), associated with significant changes in dynamics and thermodynamics and will be
300 discussed in detail below.

301

302 **3.1.2 Mechanism of enhanced snow precipitation by highly elevated CCN concentrations**

303 Since the results of significant enhanced precipitation from CCN1000 to CCN3000 are
304 unusual, besides verifying the use of identical initial and boundary meteorological conditions in
305 all the experiments to eliminate simulation differences arising from inadvertent factors, we also
306 conducted sensitivity tests by restoring the ice nucleation mechanisms to the default
307 parameterizations (i.e., Meyers et al., 1992 for condensation/deposition and Bigg (1953) for
308 immersing freezing) in the SBM but this yielded a similar conclusion. So, the significantly
309 increased snow precipitation associated with elevated CCN concentrations is not the result of the
310 particular ice-forming parameterization or the implementation approach of the parameterization.

311 Since the precipitation enhancement begins at 1400 UTC, which is a couple of hours into
312 the simulations, we focus on the time period of 14-1600 UTC and use the simulations of
313 different CCN concentrations [for the IN1 case](#) to examine the mechanism. By taking a close look
314 at ice nucleation (using model outputs every 6 min), we find that the total nucleated ice particle
315 number concentration is increased as CCN increase and there is a large jump from CCN1000 to
316 CCN3000 (Fig. 6a). The increase is caused by more cloudy points that have ice nucleation [\(i.e.,
317 immersion freezing\)](#) occurring (Fig. 6b) and the enhanced nucleation rate (i.e., the nucleated ice
318 particles per liter [of](#) air volume within a hour) in the lower altitudes (Fig. 6c). Considering that
319 the major ice formation mechanism is immersion freezing in this study, which requires the
320 existence of drops for primary nucleation of ice, it means that there is much more supercooled
321 liquid cloud area/volume available for nucleation in the lower altitudes as CCN increase (Fig. 6e).

322 As shown in Fig. 6d, the increase of cloud water (Q_c) that is supercooled, since the warmest
323 cloud temperature is below 0°C in this case, is very significant, with a big jump from CCN1000
324 to CCN3000, corresponding to the large increase of snow precipitation. From CCN1000 to
325 CCN3000, the increase of the supercooled liquid area is especially drastic (Fig. 6e).

326 What causes the drastic increase of Q_c and a more widespread supercooled liquid cloud
327 regime that is available for ice nucleation? We know that the increased drop surface area with the
328 increased CCN can increase condensation, but it cannot explain such a drastic increase of the
329 condensation rate averaged over the entire domain as shown in Fig. 6f. We find that over the
330 domain the updraft area (i.e., grid points with $w > 1 \text{ m s}^{-1}$) is increased significantly with CCN
331 with a jump from CCN1000 to CCN3000 as well (Fig. 7a), but the averaged updraft velocity
332 does not change significantly (Fig. 7b), suggesting that much more [widespread](#) convection
333 occurs to form more clouds in the domain as CCN increase, especially in CCN3000. From the
334 spatial distribution, we see that the increase of clouds is most prominent around the valley and
335 foothills (i.e., the lower-part of the windward slope of the [mountains](#)). The cross sections of
336 cloud water, rain and ice/snow mass mixing ratios at 1400 UTC clearly show that more clouds
337 form over the valley and foothills in CCN3000, while in CCN30 [there are fewer](#) clouds over the
338 valley and clouds are shallower over the valley and foothills (Fig. 8a). [We](#) see much more
339 invigorated mixed-phase clouds in CCN3000 compared with CCN30. The mixed-phase clouds
340 start from the foothills in CCN3000 (Fig. 8c), while CCN30 does not have the mixed-phase
341 clouds present until the regions above the middle and upper part of the mountain slope. This
342 explains the increased ice nucleation rate [in the domain](#) at the lower altitudes as shown in Fig. 6c.

343 [The](#) changes of cloud fields described above must involve dynamic and thermodynamic
344 changes. By examining the differences of dynamic and thermodynamic fields between CCN3000

345 and CCN30 (Fig. 9), we clearly see that a band of increased water vapor and relative humidity
346 (RH) from the valley/foothills to the mountain at the higher altitudes (Fig. 9a-b). The
347 corresponding temperature is only slightly decreased (Fig. 9c), which should not affect the
348 saturation water pressure and ice nucleation efficiency by much. So, the increased RH is mainly
349 caused by the increased water vapor, and this increase can be up to 8% in RH (e.g., from RH of
350 70% to 78%). The large increase of Q_v and RH is mainly a result of changed local circulation as
351 shown in Figs. 9d-e: the wind blowing to windward slope (zonal wind) gets stronger from
352 CCN30 to CCN3000 (within ~ 2 km above the ground) over the slope. In the cases of
353 atmospheric rivers, the stronger zonal wind transport means an increase of moisture transport to
354 the [mountains](#).

355 The changes of winds are only significant at the slope of the [mountains](#) and occur only
356 after 2 h of the simulations (Fig. 10a), suggesting that [they](#) stem from more latent heat release as
357 a result of more clouds over the valley and foothills (feedbacks of radiation and precipitation
358 take much longer time especially considering the two-hour time is 4- 6 am LST). The clouds at
359 the valley/foothill locations are generally shallow. Many literature studies, including both
360 observations and model simulations, have shown that CCN enhance shallow cloud formation and
361 deepen shallow clouds (e.g., Chen et al. 2015; Yuan et al. 2011; Pincus and Baker 1994; Koren
362 et al. 2014), which can be due to various reasons such as cloud lifetime effect, enhanced
363 turbulent convection by larger entrainment rates as a result of stronger evaporation, and greater
364 latent heat release due to larger drop surface area for stronger condensation. We find that
365 condensation is indeed much enhanced over the valley/foothills from CCN30 to CCN3000 [under](#)
366 [IN1](#) (Fig. 9f), which results in much reduced supersaturation with respect to water
367 (supersaturation around the cloud base in CCN30 at 1300 UTC is about 0.28% while only 0.04%

368 in CCN3000). The enhanced condensation as well as the cloud lifetime effect (i.e., conversion of
369 smaller droplets into rain is slow and cloud can be sustained for a longer time) contributes to
370 more shallow clouds at the valley/foothills. The more latent heat resulting from enhanced
371 condensation leads to the change of local circulation, which transports more moisture to the
372 windward slope of the mountain, resulting in more active mixed-phase clouds and snow
373 precipitation through enhanced deposition and riming. In addition, over the mountains more
374 supercooled liquid would be lifted to the higher altitudes in the polluted condition, forming
375 ice/snow more efficiently through immersion freezing at the colder temperature, which
376 contributes to more snow precipitation as well.

377 It should be noted that the mixed-phase clouds over the mountains are the key to the
378 enhanced precipitation by CCN. This is confirmed by sensitivity tests based on the WMOC case
379 where ice-related microphysics is turned-off in CCN30IN1 and CCN3000IN1. We chose the
380 WMOC for this sensitivity test because the similar mechanism is present and the WMOC has
381 less mixed-phase regime compared with CMOC, so the factor would have a more significant role
382 in the CMOC if it plays a role in the WMOC. As shown in Fig. 11a, precipitation is dramatically
383 suppressed from CCN of 30 cm^{-3} to 3000 cm^{-3} (Fig. 11a) and there is almost no precipitation at
384 the valley and windward slope in CCN3000 due to extremely small droplets. However, we still
385 see the change of the local circulation over the slope as a result of enhanced condensation (Fig.
386 11b). Therefore, the presence of ice is a necessary condition for such a large increase of
387 precipitation by CCN. Without ice processes (e.g., under the warm season with warm clouds
388 only), precipitation over the mountains can not form efficiently in such a polluted condition even
389 with the increased moisture. But the added latent heat from condensation of vapor to water is still
390 the main energy source of the invigoration.

391 In summary, increasing CCN forms more clouds at the valley and foothills (generally
392 shallow) through much enhanced condensation, which induces a local circulation change due to
393 more latent heat release that enhances the zonal transport of moisture, leading to the invigoration
394 of the orographic mixed-phase clouds and drastically increased snow precipitation in this CMOC
395 case. Therefore, aerosol impacts on orographic mixed-phase clouds can be extraordinary in
396 extremely polluted conditions, especially under the influence of atmospheric rivers. Besides the
397 the key role of ice processes for leading to greatly enhanced precipitation, orographic dynamics
398 is another important factor since we do not see such impacts in the sensitivity tests where the
399 terrain height is set to be 600 m for the locations with a terrain height > 600 m (precipitation
400 becomes very small in those sensitivity tests and the increase from CCN30 to CCN3000 is small
401 as well).

402 The increases of Q_v and RH are the most significant from CCN1000 to CCN3000 due to
403 non-linearity of aerosol-cloud interactions, explaining the large increase of snow precipitation. It
404 is worth noting [that](#) in CCN3000, warm rain is completely shut off (left column in Fig. 8b), [so](#)
405 much more cloud water can be transported to higher altitudes for more immersion freezing,
406 which further enhances the snow precipitation. This likely contributes to the steep increase in
407 precipitation when CCN reach 3000 cm^{-3} .

408

409 **3.1.3 Supercooled water content (SCW) and cloud phase**

410 [By](#) changing the microphysical process rates, CCN and INP impact the cloud phases and
411 supercooled water content (SCW). Fig. 12 shows that INPs have the most striking impact on
412 SCW. Increasing INPs enhances ice particle formation, and then facilitates the deposition and
413 riming processes in this CMOC as discussed in Section 3.1.1. The enhanced deposition in the

414 WBF regime, along with riming, leads to a faster conversion of liquid to ice in the mixed-phase
415 and glaciates the clouds faster. Therefore, SCW is substantially reduced as INPs increase (Fig.
416 12a). For example, in the case of CCN300, a significant amount of liquid mass fraction (0.1)
417 exists at the temperature of -30°C [for the IN0.1 case](#). Such temperature is increased to -20 , and $-$
418 10°C as [dust/bio INP proxies](#) are increased to 1 and 10 cm^{-3} , respectively. In the extremely high
419 INP case ([INP100](#)), there is nearly no supercooled water. As a result, the fractions of cloud
420 phases are dramatically changed (Fig. 13a). As expected, higher INP concentrations decrease the
421 fractions of liquid and mixed phases [as](#) the fraction of ice phase [increases](#). In this CMOC, the
422 cloud phases are most sensitive to INPs at relatively low concentrations. For example, [for the](#)
423 [IN0.1 to IN1 range that](#) is likely common for this region [in winter](#) based on observations in the
424 past field campaigns, the liquid phase fraction is reduced by nearly half and the ice phase
425 fraction is increased by 2 times or larger (Fig. 13a). Note that the effects of INPs on cloud phase
426 and SCW presented in this study may represent the upper limit because ice formation is mainly
427 through immersion freezing that transforms the large liquid particles to ice particles when ice
428 forms.

429 Compared with the effects of INPs, the magnitudes of CCN effects on SCW and cloud
430 phases are much smaller but still significant (the lines with same color but different line styles in
431 Fig. 12). Moreover, the sign is opposite. Increasing CCN generally increases SCW slightly (Figs.
432 12a). The impact of CCN on cloud phases is generally small, except when INPs are very low, i.e.,
433 [IN0.1](#) (Figure 13a). In this low INP case, increasing CCN increases ice phase fractions and
434 reduces the mixed-phase fraction when CCN are relatively low. This is because liquid clouds are
435 dominant so such clouds are sensitive to the CCN-enhanced ice nucleation as discussed in the
436 section 3.1.2.

437

438 3.2 WMOC – MAR02

439 For this warm mixed-phase cloud case, the surface accumulated precipitation is
440 suppressed by increasing CCN when CCN are lower than 1000 cm^{-3} (Fig. 14a), which is
441 different from the case of CMOC where the sign of CCN impact on precipitation depends on INP
442 concentration. This is because the clouds in this WMOC behave similarly as warm clouds due to
443 less efficient ice nucleation at the warm cloud temperatures. When CCN are lower than 1000 cm^{-3} ,
444 the large decrease of warm rain (Fig. 14b) overpowers the slight changes of snow precipitation
445 (Fig. 14c). Similar to the CMOC case, we see a drastic increase of surface precipitation from
446 CCN1000 to CCN3000, also due to drastic increase of snow precipitation. Increasing INPs
447 enhances surface precipitation in a more significant manner than that in CMOC. In other words,
448 the WMOC is more sensitive to INPs than the CMOC.

449 The in-cloud microphysical properties also show similar results as for the CMOC: the
450 steep increases of the snow mass and cloud water mixing ratios from CCN1000 to CCN3000
451 (Fig. 15). We have done the same investigation as in Section 3.1.1, and found the mechanism
452 causing the increased cloud water and the snow production is similar as that in CMOC, that is,
453 increasing CCN forms more shallow clouds at the large area of valley and foothills, which
454 induces a change of local circulation significantly through more latent heat release, which in turn
455 increases the zonal transport of moisture to the windward slope of the mountains. Additionally,
456 more abundant warm rain is present at the wide valley area in this case when CCN are low (30
457 cm^{-3}) compared with the CMOC. The suppression of warm rain as CCN increase is very
458 significant as shown in Figs. 14b and 15. Over the mountain, this suppression increases Q_c and
459 allows more cloud water to be transported to the higher altitudes along the slope where

460 immersion freezing is able to occur at lower temperatures. Ice multiplication through the Hallet-
461 Mossop parameterization (Hallet and Mossop, 1974) in this WMOC contributes to ice particle
462 concentration by 10-15% when CCN are 30 cm^{-3} and INP [proxy aerosol concentrations](#) are 1 cm^{-3}
463 ³ in our model simulation with the fast version of SBM in which ice habits are not considered.
464 Therefore, as more ice particles form from immersion freezing when CCN increase, the ice
465 multiplication processes would further increase ice crystal formation although the contribution is
466 relatively small in the model simulation. Past observation studies suggested that ice
467 multiplication through rime-spintering does occur in the orographic mixed-phase clouds of this
468 region (Marwitz 1987; Rauber 1992). We do not yet have a clear understanding of the
469 importance of this process in contributing to ice formation in reality. After more ice particles
470 form, the subsequent ice depositional and riming growth processes form efficient snow
471 precipitation. The CCN impact on local circulation change is more significant in this case
472 compared with the CMOC, probably due to much more shallow warm clouds in the valley.

473 Different from the CMOC case, riming is a more efficient ice growth process to form
474 snow than deposition in this case except when INP concentrations are extremely high ([IN100](#))
475 where both riming and deposition contribute in a similar magnitude (Fig. 16). In addition, the
476 riming rate is increased as INP concentrations increase, which is opposite to that of CMOC. This
477 is because the WMOC is ice-limited and there are not enough ice particles to collide with liquid
478 particles when INP numbers are low, therefore, increasing INPs boosts ice particles and allows
479 more riming to occur. In contrast, the CMOC case is liquid-limited, so increasing INPs reduces
480 liquid particles available for riming due to ice depositional growth. We also see that
481 condensation and evaporation rates are generally more than 2 times larger in this case compared
482 with CMOC and both rates increase more significantly with CCN concentration in this WMOC.

483 This is related to the dominance of liquid clouds in the WMOC. The more significant increase of
484 condensation by increasing CCN compared with the CMOC is likely a result of the more
485 significant change of the local circulation that is associated with more shallow clouds forming at
486 the valley. Increasing INP number concentrations reduces evaporation simply because of the
487 reduction of liquid due to the increased deposition and riming.

488 Similarly as in the CMOC, increasing CCN enhances the WBF process for this WMOC
489 as more droplet evaporation and ice deposition occur (Figs. 17a and 17b). With the increase of
490 CCN, the domain-mean riming rate is not changed much until CCN of 1000 cm^{-3} (Fig. 16e), but
491 the riming rate in the WBF regime is increased (Fig. 17c), possibly due to larger ice particles
492 resulting from stronger deposition growth in the WBF regime.

493 Similar results regarding [the](#) CCN and INP impact on supercooled water content are
494 obtained in the WMOC case as in the CMOC case: increasing INPs dramatically reduces SCW
495 and increases cloud glaciation temperature, while increasing CCN has the opposite effect with
496 much smaller significance (Fig. 12b). Compared with the CMOC, the effects of INPs on SCW
497 are a little smaller but CCN effects are a little larger. The liquid phase fraction (number fraction
498 of cloudy grid points for which the liquid represents 99% or more of the condensate mass)
499 decreases significantly as INPs increase (Fig. 13b). Correspondingly the fractions of the mixed-
500 phase and ice phase cloud volumes increase due to increased ice nucleation. Similar to the
501 increased riming as INPs increase, the mixed-phase fraction is increased as well in the WMOC,
502 which is opposite to the case for CMOC, as a result of the ice-limited condition in the WMOC
503 versus the liquid-limited condition in the CMOC. Note that INP effects are more significant at
504 higher INP concentrations in this case, while in CMOC the sensitivity decreases as INP increases,
505 suggesting that the optimal INP concentration for the maximum INP impact is higher in warmer

506 clouds than colder clouds, because ice formation at the warmer cloud temperatures [is less](#)
507 [efficient](#). The CCN impacts on cloud phase are more significant in this WMOC compared with
508 those in CMOC. The decreased liquid cloud fraction with the increase of CCN is a consequence
509 of the large increase of ice phase fraction resulting from more active cold-cloud processes, since
510 the total cloud fraction sums up to 1 (Fig. 13b).

511

512 **4. Conclusions and Discussion**

513 Extending the previous study of Fan et al. (2014), we conducted new simulations at
514 higher resolution and further sensitivity studies based [on](#) the same two [cases of](#) mixed-phase
515 orographic clouds forming on the Sierra Nevada barrier under the influence of atmospheric rivers
516 [during the](#) CalWater 2011 field campaign to quantify the response of precipitation to changes of
517 CCN and INPs and to examine CCN and INP impacts on SCW and cloud phases. The two
518 mixed-phase cloud cases have contrasting thermodynamics and dynamics: FEB16 has cold cloud
519 temperatures and northwesterly wind flow at lower-levels (i.e., CMOC), while MAR02 has about
520 10 °C warmer cloud temperatures and southerly wind flow (i.e., WMOC).

521 It is found that, in the CMOC case, deposition contributes more significantly to snow
522 production than riming because deposition process is efficient at the cold cloud temperatures
523 (from -22 to -32 °C) in this case. In the WMOC, riming generally contributes more significantly
524 because the deposition growth process is less efficient at the warmer temperatures (generally
525 warmer than -20 °C in this case), except in the extremely high INP case where both riming and
526 deposition contribute similarly.

527 We find that increasing INP concentrations enhances snow precipitation on the windward
528 slope of the Sierra Nevada Mountains in both CMOC and WMOC cases. With the increase of

529 INPs, the increased ice nucleation via immersion freezing enhances snow formation by
530 intensifying depositional growth of ice in the CMOC while both deposition and riming
531 contribute in the WMOC. Increasing INPs reduces riming in the CMOC, because of the liquid-
532 limited condition in which more efficient depositional growth at higher INP number
533 concentrations glaciates clouds and reduces liquid particles available for riming. However, in the
534 ice-limited conditions of WMOC, increasing INPs boosts ice particle concentrations so that more
535 riming can occur in a liquid-rich condition. For the same reason, increasing INPs suppresses the
536 WBF processes due to reduced liquid particles.

537 The CCN impacts on precipitation are complicated, depending on cloud temperature and
538 concentrations of CCN and INPs. When CCN are lower than 1000 cm^{-3} , boosting CCN
539 concentrations slightly increases snow precipitation, but the total precipitation can be increased
540 or decreased depending on [the](#) INP concentrations in the CMOC. In contrast, in the WMOC,
541 increasing CCN suppresses the total precipitation due to the large suppression of warm rain
542 production. We find a drastic increase of snow precipitation by increasing CCN when CCN are
543 high (1000 cm^{-3} or larger), consistently in both CMOC and WMOC, as a result of increased
544 deposition and riming rates. The mechanism by which this occurs is through more shallow
545 clouds [that form](#) at the wide valley area and foothills [with increasing CCN](#), which induces a
546 change of local circulation through more latent heat release and increases the zonal transport of
547 moisture to the windward slope of the [m](#)ountains. This results in much more invigorated mixed-
548 phase clouds with enhanced deposition and riming processes and therefore much more snow
549 precipitation. Additionally, over the mountains, the suppression of warm rain as CCN increase
550 allows more cloud droplets to be transported to the higher altitudes where immersion freezing is
551 able to occur efficiently, contributing to the enhanced snow as well. This effect is most

552 significant when warm rain is completely shut off at CCN of 1000 cm^{-3} and higher. Note that
553 this significant CCN impact on precipitation for CCN of 1000 cm^{-3} or larger was not seen in
554 FAN2014, because the CCN concentrations prescribed in that study are smaller than 1000 cm^{-3} .
555 Another difference is that CCN are set to be uniform and increased uniformly over the model
556 domain in this study, while in FAN2014 only the CCN over the Central Valley and coastal urban
557 area were increased.

558 Increasing INP concentrations dramatically reduces supercooled water content and
559 increases cloud glaciation temperature, while increasing CCN has the opposite effect but with
560 much smaller significance. As expected, the fraction of liquid phase clouds is decreased and the
561 ice phase fraction is increased by increasing INP in both cases. However, we see a decreased
562 fraction of mixed-phase clouds by INP in the CMOC but increased in the WMOC, relating to the
563 liquid-limited condition in the former where increasing ice formation enhances cloud glaciation,
564 while the ice-limited condition in the latter in which more liquid clouds are converted to mixed-
565 phase clouds as INPs increase. Compared with the effects of INPs, the magnitudes of CCN
566 effects on SCW and cloud phases are much smaller and the signs are opposite. Increasing CCN
567 generally enhances SCW in both cases. The relative fractions of cloud phases are not much
568 impacted by CCN in the CMOC, except when INPs are very low (i.e., [IN0.1](#)). However, in the
569 WMOC, increasing CCN evidently decreases liquid cloud fraction but increases ice phase
570 fraction. Thus, cloud phases in the WMOC have a large sensitivity to CCN compared with
571 CMOC.

572 This study provides a better understanding of the CCN and INP effects on orographic
573 mixed-phase cloud properties and precipitation. The result that CCN dramatically increase snow
574 precipitation over the mountains when CCN are high (1000 cm^{-3} or larger) as a result of modified

575 cloud properties at the valley and foothills is different from previous modeling studies in the
576 literature such as Lowenthal et al. (2011). Many possible reasons could lead to the differences
577 including different cloud cases and different model parameterizations especially for riming
578 processes. The mechanism for the drastic increase of the snow precipitation on the upwind slope
579 by CCN at the very polluted condition is new, and it suggests a strong impact of the shallow
580 clouds at the valley and foothills on the mixed-phase clouds and precipitation over the mountains.
581 It is worth noting that we do not see such a significantly increased precipitation by CCN in the
582 sensitivity tests without ice-related processes or without topography, suggesting that ice
583 processes in the mixed-phase clouds and orographically-forced dynamics are the key factors for
584 such CCN effects. Lynn et al. (2007) also showed that increasing small aerosol particles led to an
585 increased in-cloud snow mass content as a result of more ice particles formed from droplet
586 freezing due to suppressed warm rain formation and thereby more collisions between those ice
587 particles. But different from our study, the total precipitation on the windward slope in Lynn et al.
588 (2007) was decreased as the snow particles had smaller size with lower fall speeds, and they
589 were advected to the lee-side of the mountain, resulting in more precipitation there. The similar
590 mechanism as Lynn et al. (2007) was presented in Noppel et al. (2010) that showed a shift of
591 precipitation from the Mediterranean sea to the land downwind by increased small aerosols
592 because the delayed warm rain formation fostered the formation of extra ice particles with low
593 settling velocity, which were then advected and enhanced precipitation inland. It should be noted
594 that the primary ice nucleation mechanism implemented in the SBM for this study is based on
595 observations and is totally different from those used in Lynn et al. (2007) and Noppel et al.
596 (2010). This could be the reason leading to the different results of aerosol impact on precipitation
597 over the windward slope in our study.

598 The mechanism leading to the enhanced precipitation over the windward slope by
599 increasing CCN is seen in the two cases with very different cloud temperature, wind direction
600 and RH. However, the efficiency of the mechanism could depend on dynamics (wind speed) and
601 thermodynamics (RH). As examined in Lynn et al. (2007), aerosol impact on orographic
602 precipitation is reduced when RH is very high and increased as wind speed is reduced. Over the
603 region of Sierra Nevada Mountains, CCN of above 1000 cm^{-3} would be an extreme condition.
604 Therefore, this mechanism would not occur usually and the change of precipitation would not be
605 much when CCN are less than 1000 cm^{-3} as shown in Fig. 2a and 14a in the normal conditions
606 over this region. We show a precipitation suppression by CCN in the relatively warm situations,
607 in agreement with the observations of Rosenfeld and Givati (2006). However, for many polluted
608 regions such as China and India where CCN of above 1000 cm^{-3} are quite common, this
609 mechanism may have very important implications for orographic precipitation extremes and
610 water cycles.

611 It should be noted that our results of CCN and INP impacts on precipitation and
612 supercooled water content may represent an upper limit since the major ice nucleation in the
613 simulations is through immersion freezing that converts the largest liquid drops into ice or snow
614 directly when ice nucleation occurs, leading to very efficient conversion of liquid to ice/snow
615 and then strong ice growth processes to form snow.

616 In our study, we do not see significant spillover effect of snowfall (i.e., decrease at the
617 windward slope and increase at the leeside slope by increasing CCN) as found in Lynn et al.
618 (2007) and Saleeby et al. (2011). Precipitation mainly forms on the windward slope of the Sierra
619 Nevada Mountains and the increase of the snow precipitation is more significant on the
620 windward slope than on the lee side in both cases. The different results between our study and

621 Saleeby et al. (2011) could be related to different locations of the clouds over the mountain
622 and/or different mountain topography, or the presence of a low-level barrier jet in the
623 atmospheric river environment that reduces the cross barrier flow.

624

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632

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784 Table 1 Model simulations that are run for different CCN and [INP proxy aerosol concentrations](#).
 785 Please note that [INP proxy aerosol concentrations](#) denote dust/bio particle number concentrations
 786 with particle size > 0.5 μm for use in the parameterization of DeMott et al. (2015), as described
 787 in FAN2014.
 788

	INP proxy aerosol concentrations (cm^{-3})			
	0.1	1	10	100
30	x	x	x	x
100	x	x	x	x
300	x	x	x	x
1000	x	x	x	x
3000	x	x	x	x

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 794 **Table 2 INP concentrations (L^{-1}) calculated based on DeMott et al. (2015) under different INP**
 795 **proxy aerosol concentrations (i.e., dust/bio particles in this study) at the various temperatures.**
 796

Dust/bio (cm^{-3})	Temperature ($^{\circ}\text{C}$)						
	-5	-10	-15	-20	-25	-30	-35
0	0.00	0.00	0.00	0.02	0.15	1.52	15.19
1	0.00	0.00	0.03	0.27	2.71	27.08	270.05
10	0.00	0.05	0.49	4.84	48.27	481.47	4802.27
100	0.09	0.87	8.63	86.06	858.40	8561.88	85397.75

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Figures



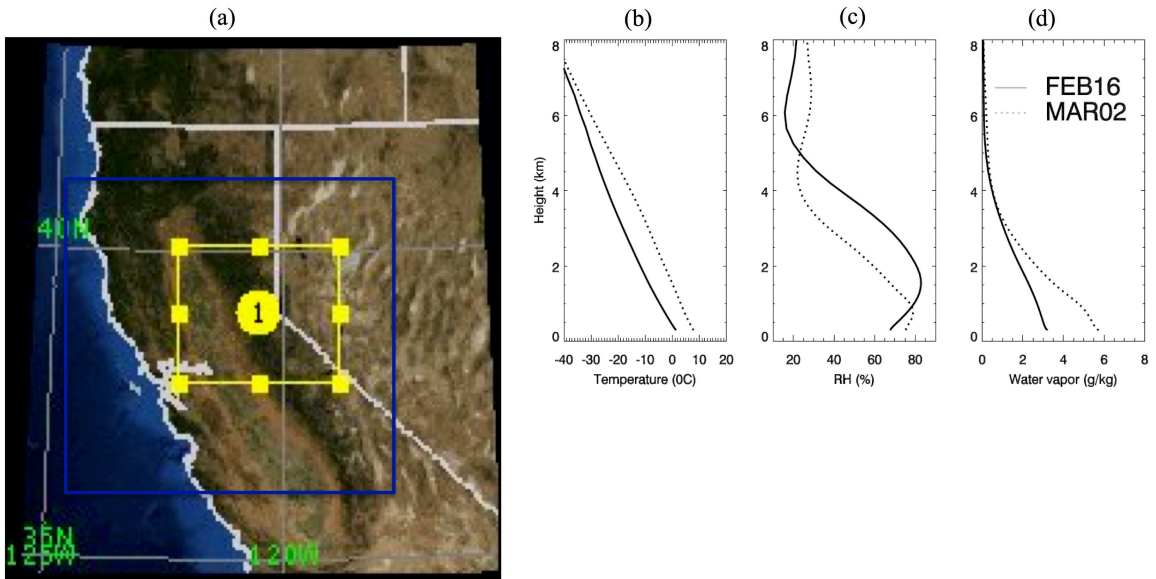


Fig. 1 (a) The simulation domain (yellow box), and the vertical profiles of (b) the temperature, (c) RH, and (d) water vapor for CMOG (FEB16) and WMOG (MAR02). (b)-(d) are domain mean values during the model simulation time period. The blue box in (a) denotes the domain of 2 km resolution simulations done in FAN2014.

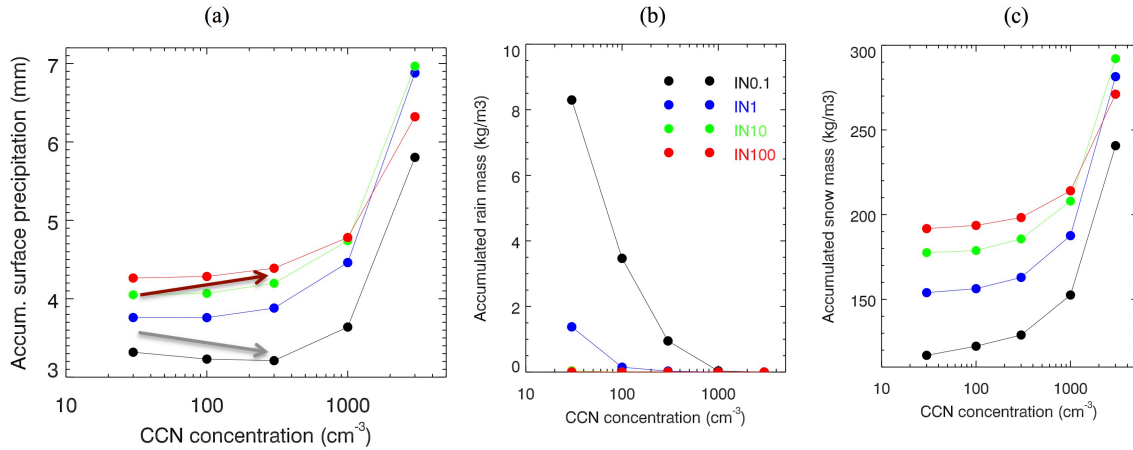


Fig. 2 (a) The domain-mean accumulated surface precipitation, and the accumulated (b) rain and (c) snow mass concentrations at the lowest model level (~ 40 m above the surface) during the simulation time period for CMOC. All domain-mean calculation excludes the lateral boundary grid points in this study. The grey arrow indicates the decrease trend under low INP proxy concentrations and the magenta arrow is for the increase trend under high INP proxy concentrations.

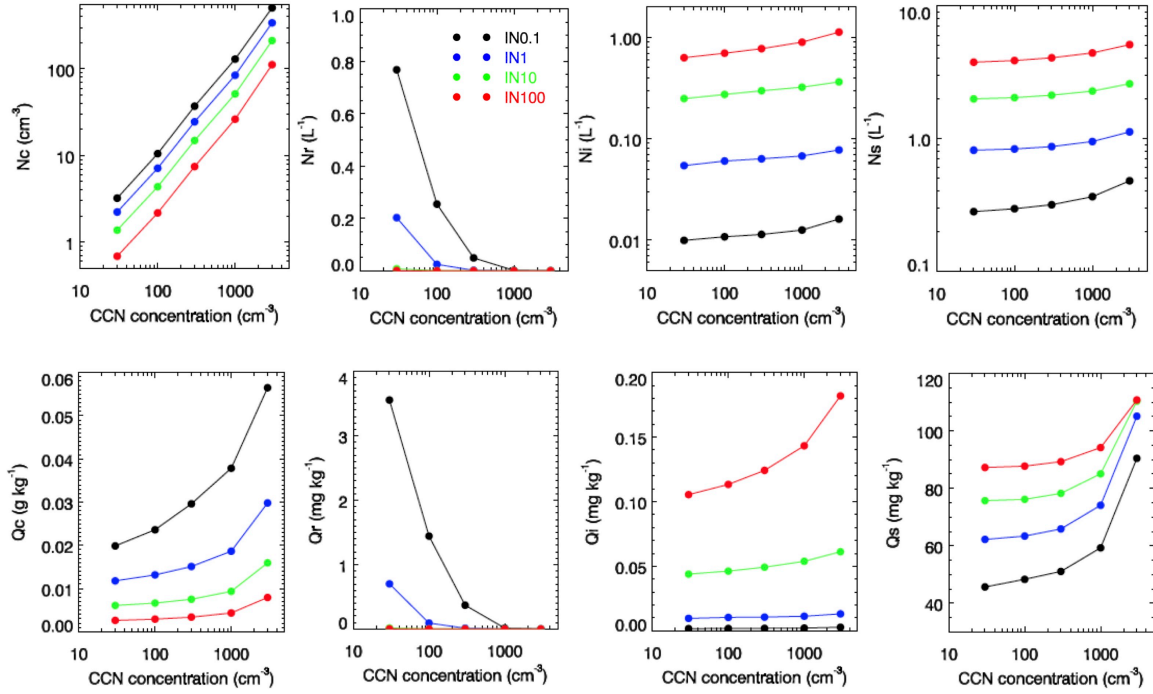


Fig. 3 The number concentrations (top row) and mass mixing ratios (bottom row) of droplet (1st column), rain (2nd column), cloud ice (3rd column), and snow (4th column) for CMOC. The data are averaged over the grid points over the domain by excluding the lateral boundary grid points below the 7 km altitude and over the simulation time by excluding the initial two hours.

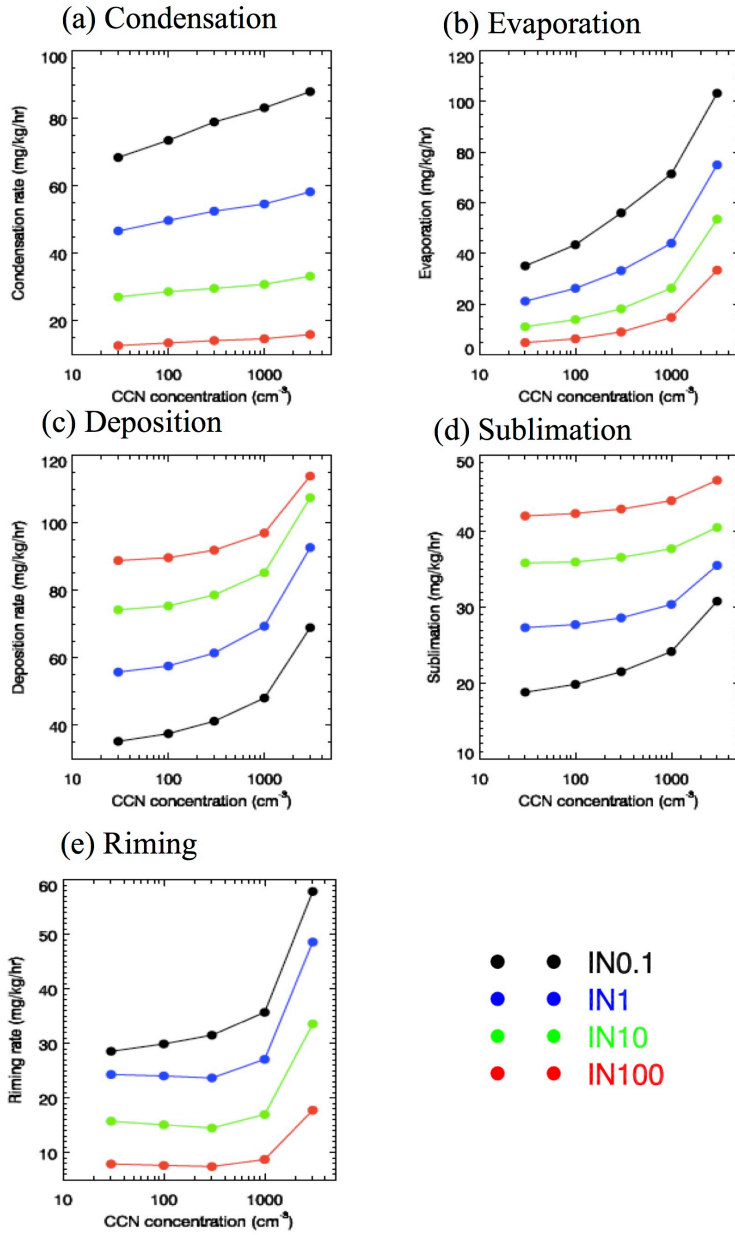


Fig. 4 The microphysical process rates of (a) condensation, (b) evaporation, (c) deposition, (d) sublimation, and (e) riming for CMOC. The model outputs for the process rates are in every 6 min frequency, and the data shown in the plots were processed in the same way as Fig. 3.

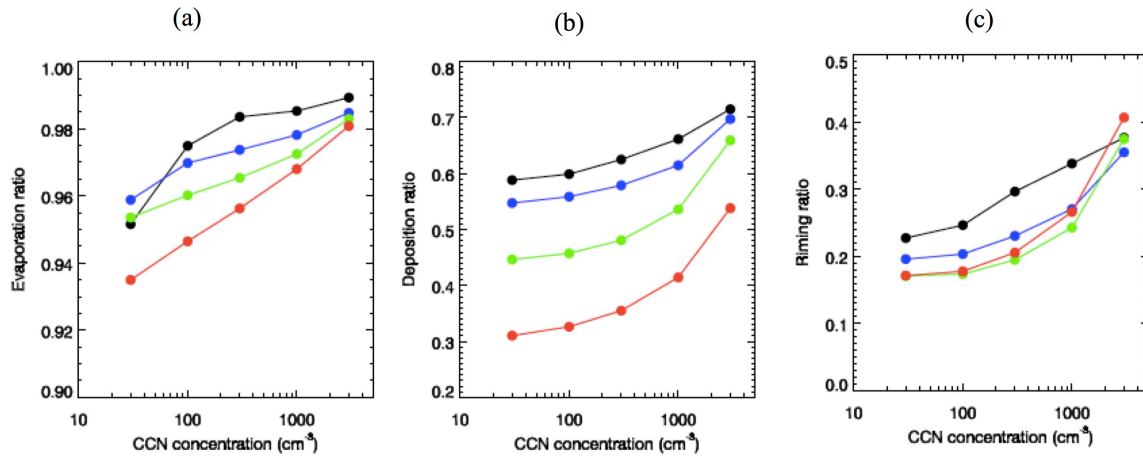


Fig. 5 (a) The ratio of evaporation occurring in the WBF regime (that is defined as the grid points where the WBF processes occur) to the total evaporation for the CMOC case. (b) and (c) are the same as (a), except for deposition and riming, respectively. Data were processed in the same way as Fig. 3. [Lines and symbols follow Fig. 3.](#)

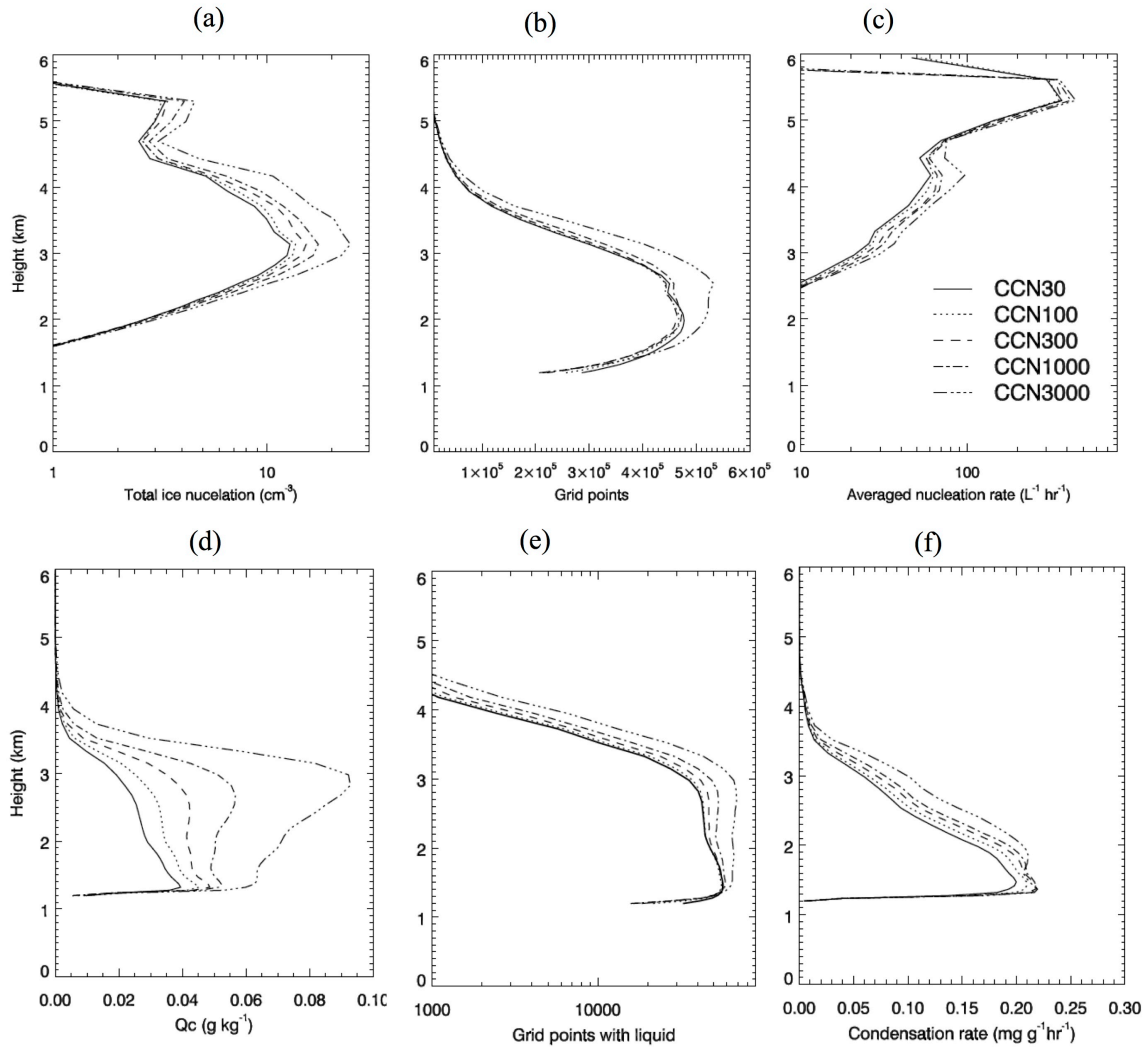


Fig. 6 Vertical profiles of (a) total nucleated ice particles, (b) the total grid points where ice nucleation occurs, (c) the ice nucleation rate averaged over the total ice nucleation grid points, (d) domain-mean cloud water content (Q_c), (e) the total grid points that have liquid (i.e., the liquid water mixing ratio is larger than $1 \cdot 10^{-5} \text{ kg kg}^{-1}$), and (f) the domain-mean condensate rate during 1400-1600 UTC for the CMOC case.

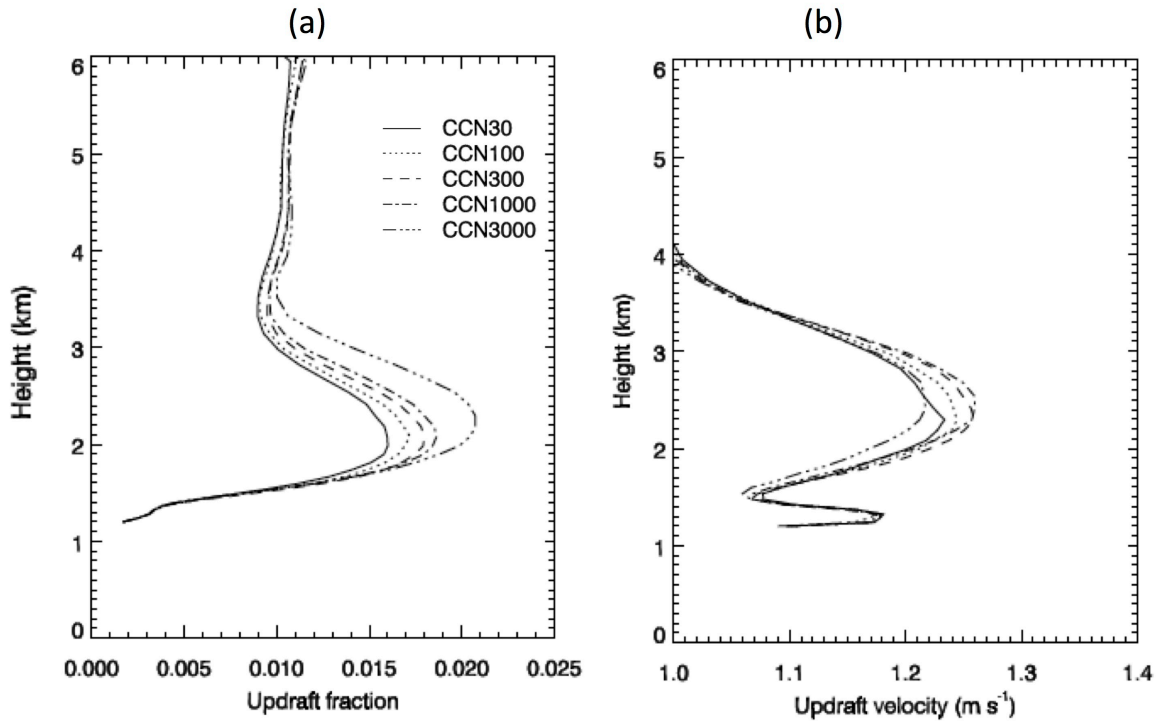


Fig. 7 (a) The fraction of updraft grid points with vertical velocity larger than 1 m s^{-1} relative to the total domain grid points, and (b) the mean updraft velocity for the grid points larger than 1 m s^{-1} over 1400-1600 UTC for the CMOC case.

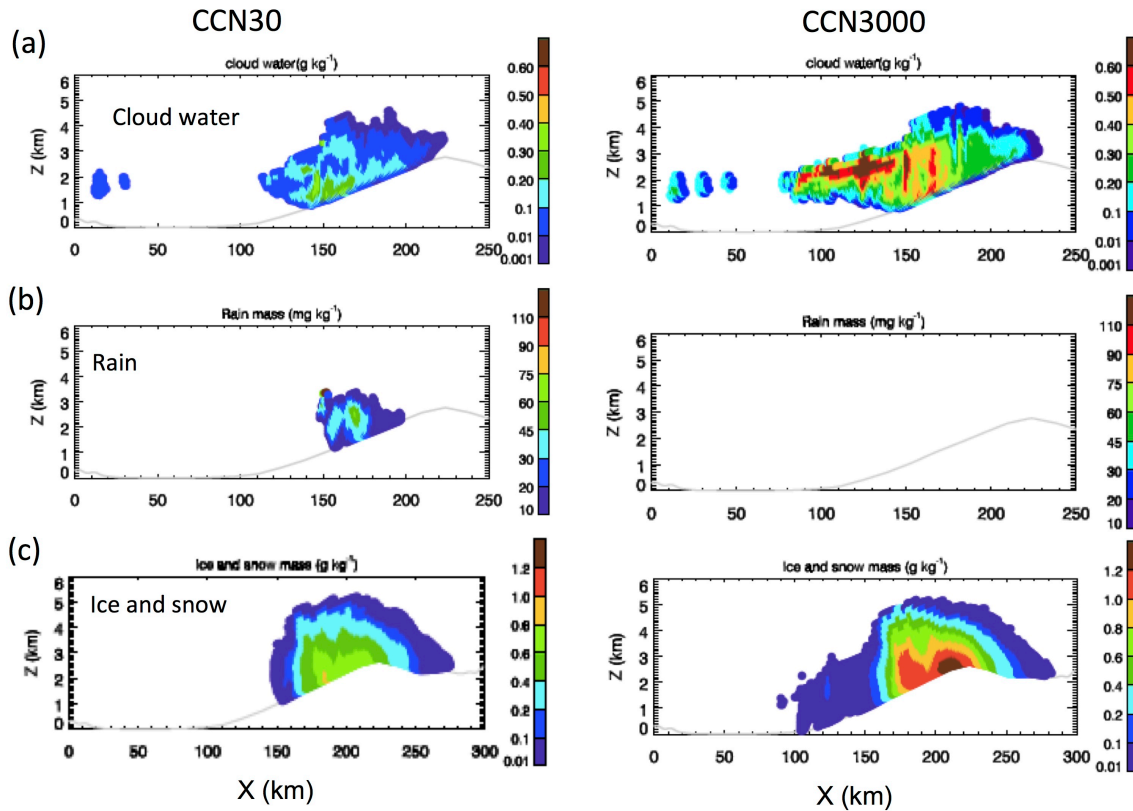


Fig. 8 The west-east cross section of (a) cloud water content, (b) rain water content, and (c) ice and snow water content for CCN30 (left) and CCN3000 (right) with INP [proxy concentrations](#) of 1 cm^{-3} at 1400 UTC averaged over the 20 km wide area zonally for the CMOC.

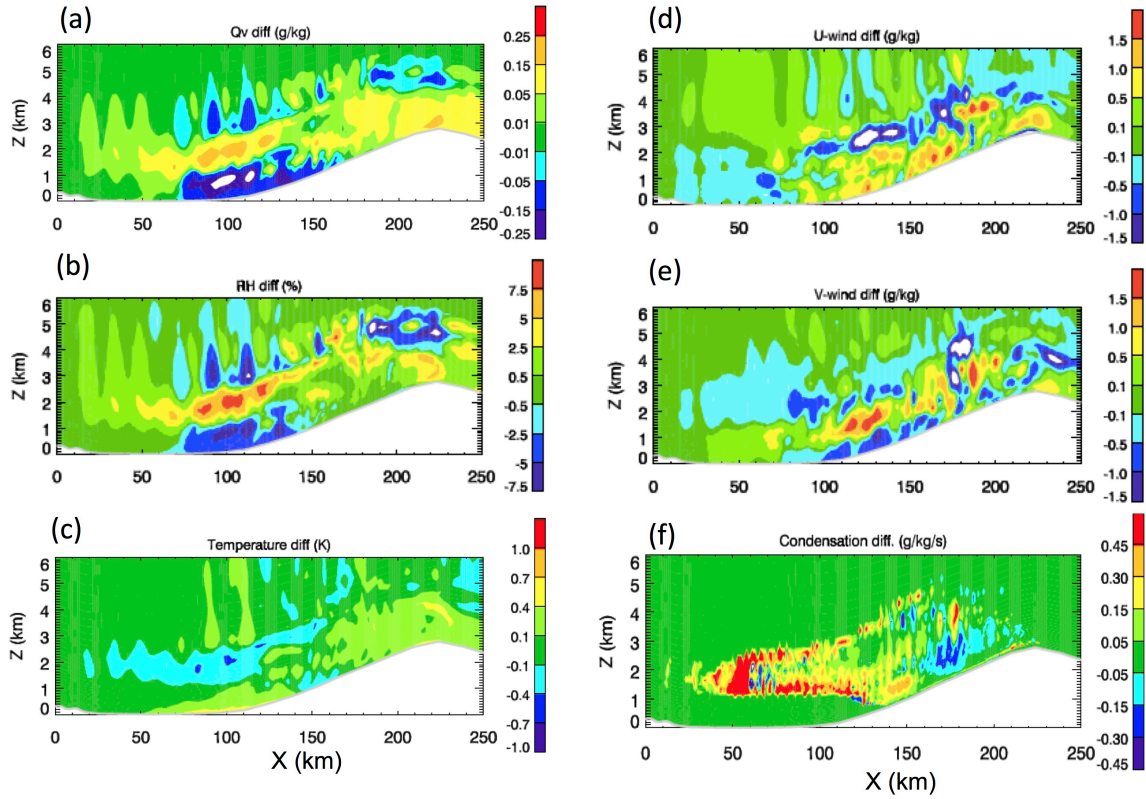


Fig. 9 Differences of (a) water vapor, (b) RH, (c) temperature, (d) U-component of the wind, (e) V- component of the wind, and (f) condensation rate between CCN3000 and CCN30 with INP proxy concentration of 1 cm^{-3} for the CMOC. The cross section area is same as Fig. 8. The time is at 1400 UTC except that the condensation rate used for the difference calculation is the sum of that from 1300-1400 UTC to show an accumulated value over 1-hour period before 1400 UTC.

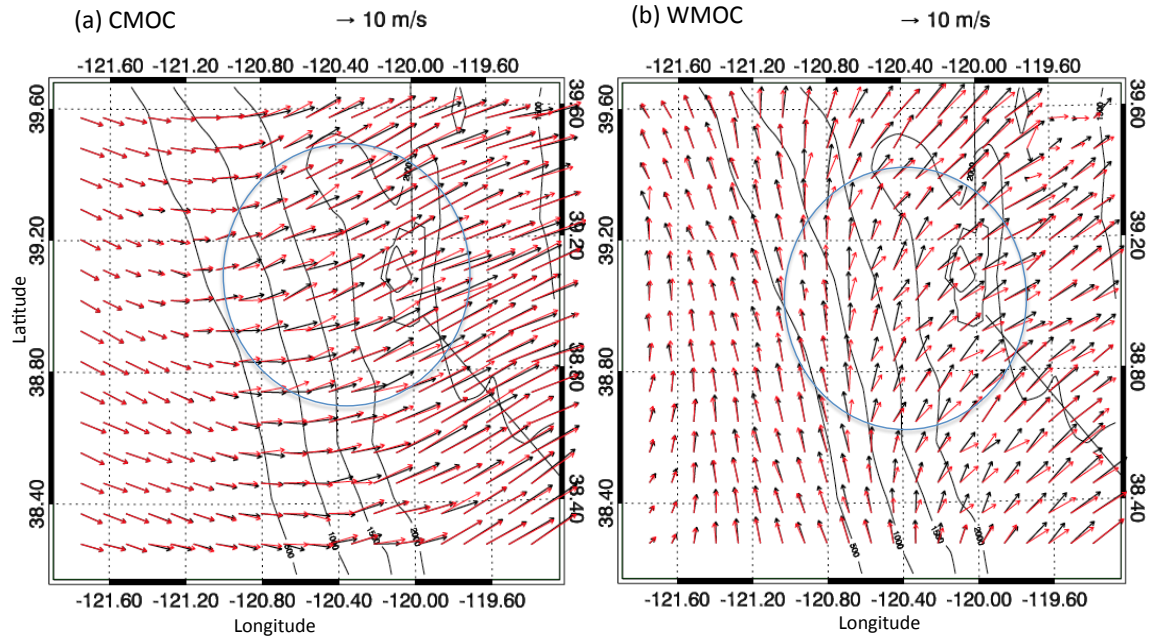


Fig. 10 The spatial distribution of wind field at about 1.7 km above the ground for (a) CMOC and (b) WMOC at 1400 UTC. The red color denotes CCN3000 and black color denotes CCN30 with IN1. The grey contour lines are the geophysical height in meters. The blue cycle is to mark the area with significant changes of wind (i.e., over the wind ward slope of the mountain).

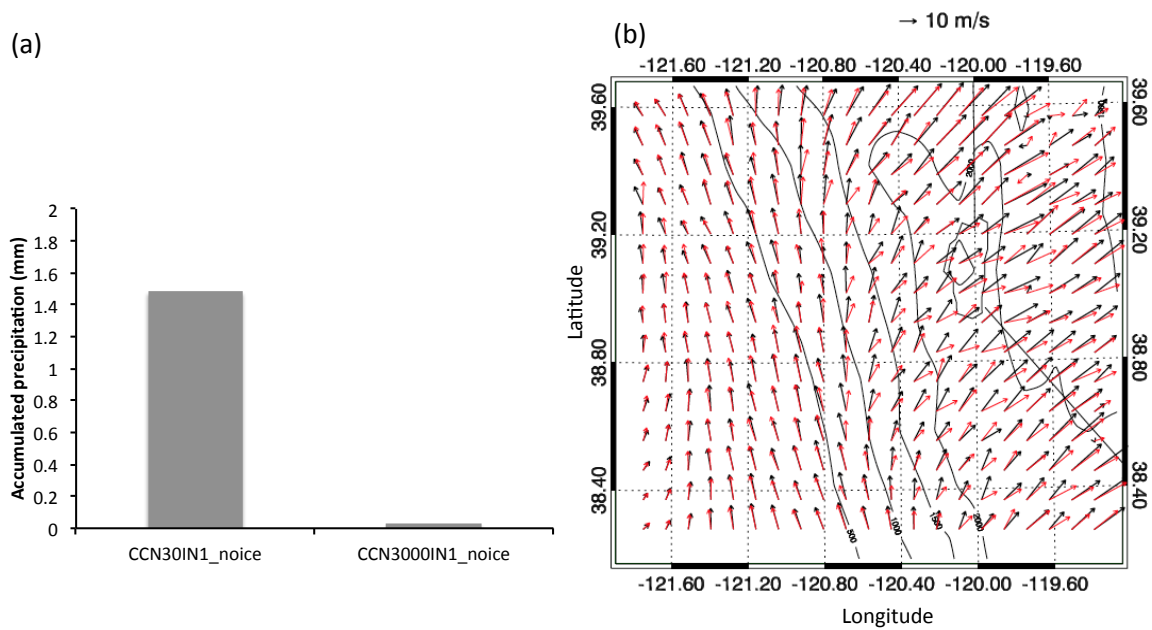
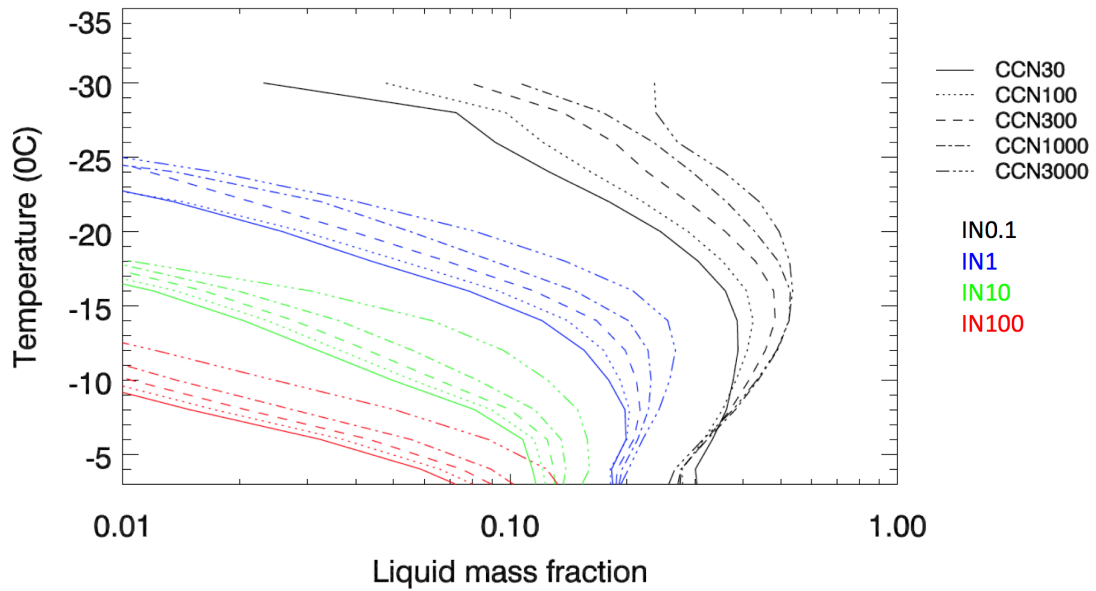


Fig. 11 Results for the two simulations without ice-related microphysics, i.e., CCN30IN1_noice and CCN3000IN1_noice, which are based on CCN30IN1 and CCN3000IN1, respectively, for the WMOC case: (a) the domain averaged accumulated precipitation, and (b) the spatial distribution of wind field at about 1.7 km above the ground at 1400 UTC. The red color on (b) denotes CCN3000IN1_noice and black color denotes CCN30IN1_noice.

(a) CMOC



(b) WMOC

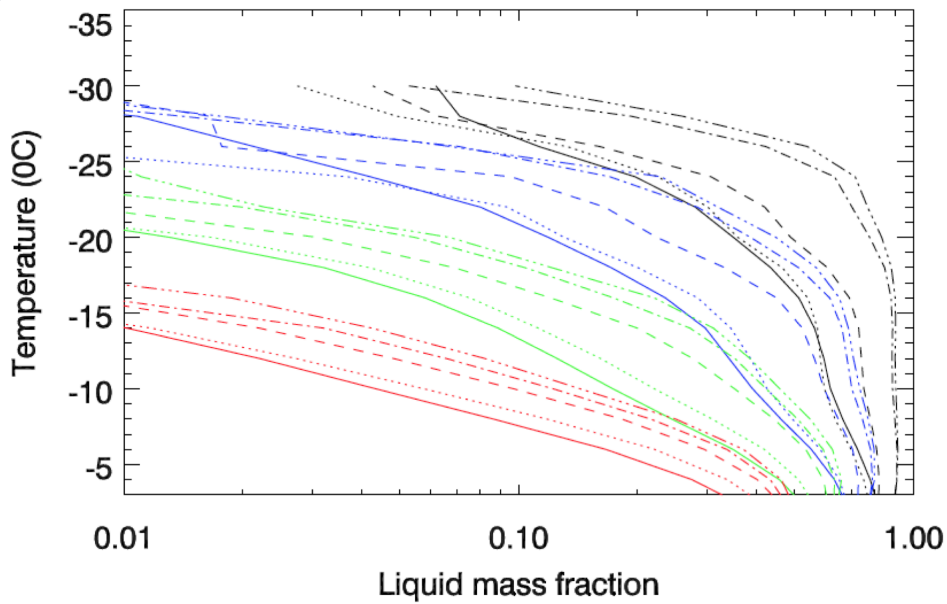


Fig. 12 The liquid mass fraction vs. temperature for the (a) CMOC and (b) WMOC over the simulation time by excluding the initial two hours. The liquid mass fraction is calculated for each temperature bin of a 2 K interval based on the total liquid water mixing ratio (droplets + raindrops) divided by the total condensate mixing ratio. The different line styles denote different CCN concentrations and different colors denote different INP concentrations.

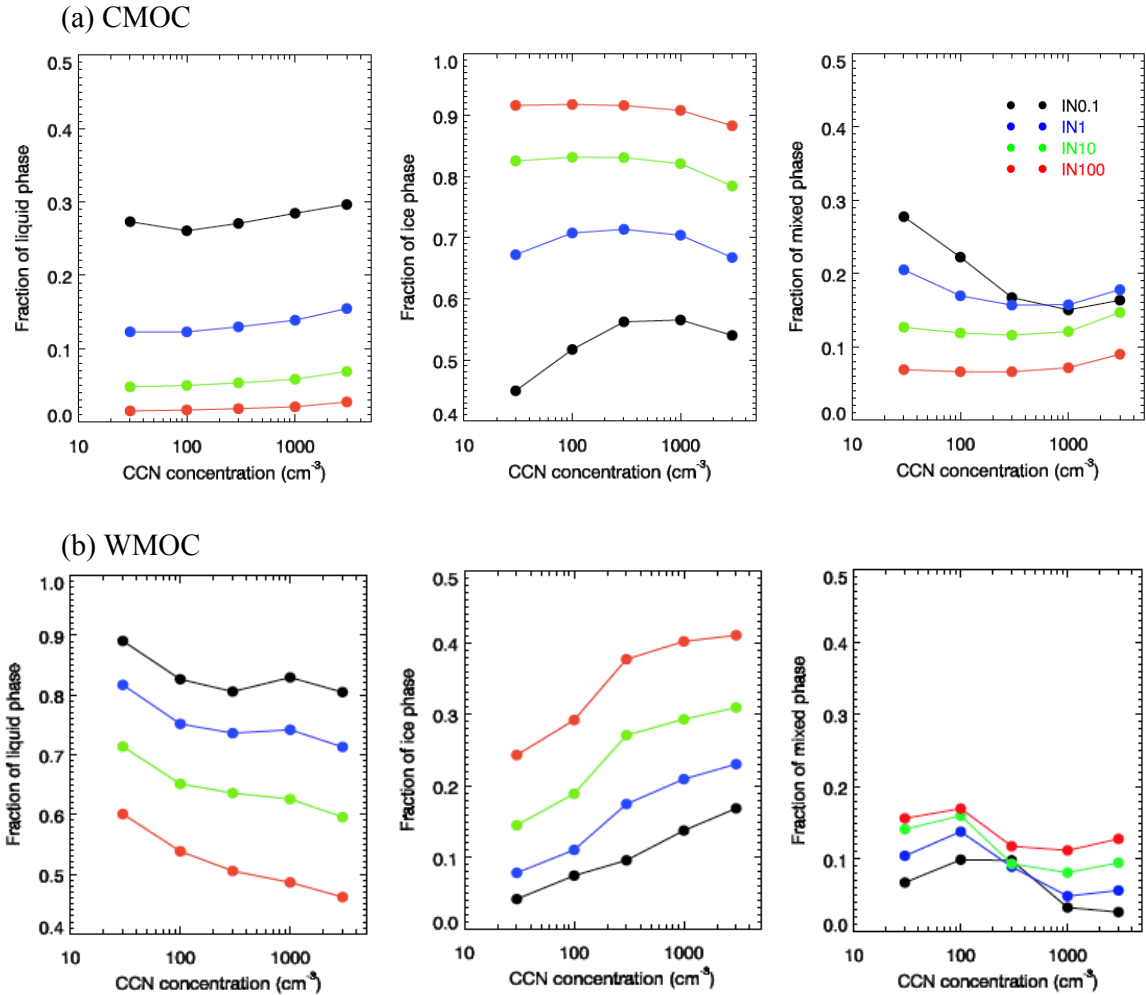


Fig. 13 The fraction of the liquid phase (left), ice phase (middle), and mixed-phase (right) for the (a) CMOC and (b) WMOC over the simulation period by excluding the initial two hours. The cloud phase for each cloud grid point that has a total condensate mass of larger than $1 \times 10^{-5} \text{ kg kg}^{-1}$ is identified based on the ratio of liquid to ice water mixing ratios. If the ratio is larger than 0.99 or smaller than 0.01, the grid point is identified as liquid phase or ice phase, respectively. Between these values is identified as mixed-phase. The fraction for each cloud phase is calculated by the number of grid points identified for the phase divided by the total number of the grid points of all three phases. So, the fractions of all three add up to 1 for each simulation case.

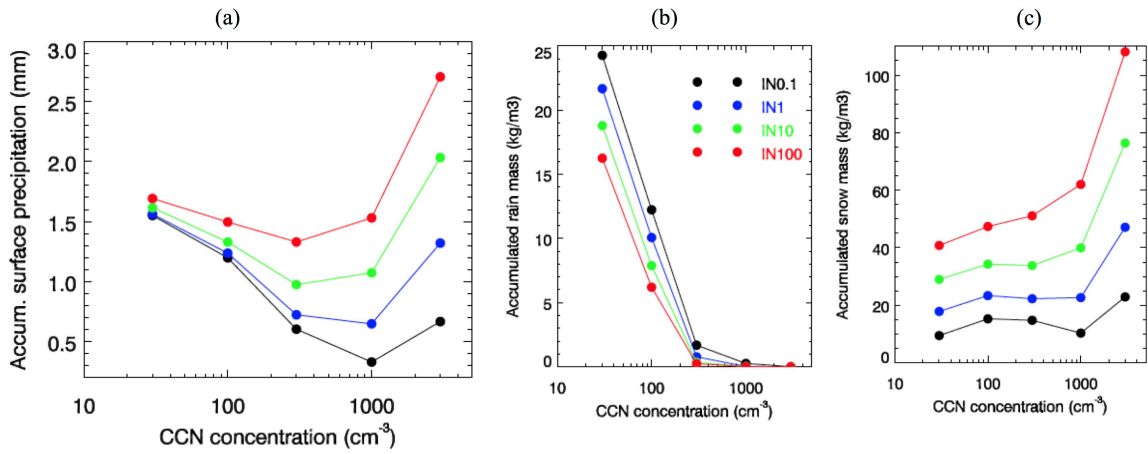


Fig. 14 Same as Fig. 2, except for the WMOC case.

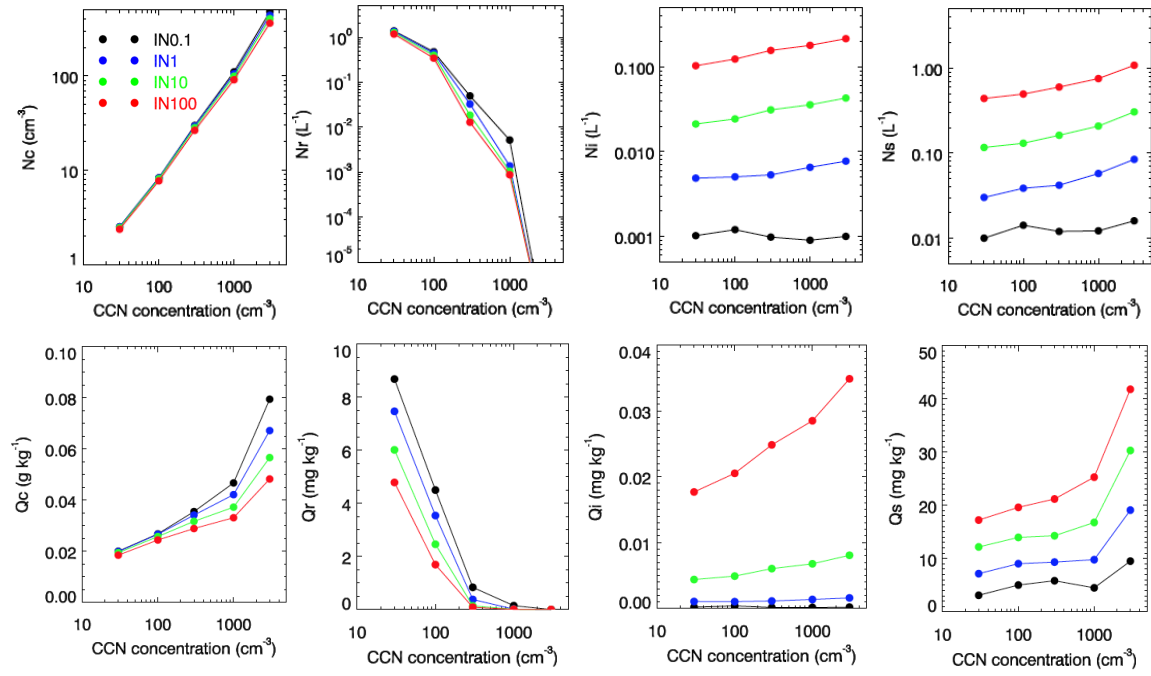


Fig. 15 Same as Fig. 3, except for the WMOC.

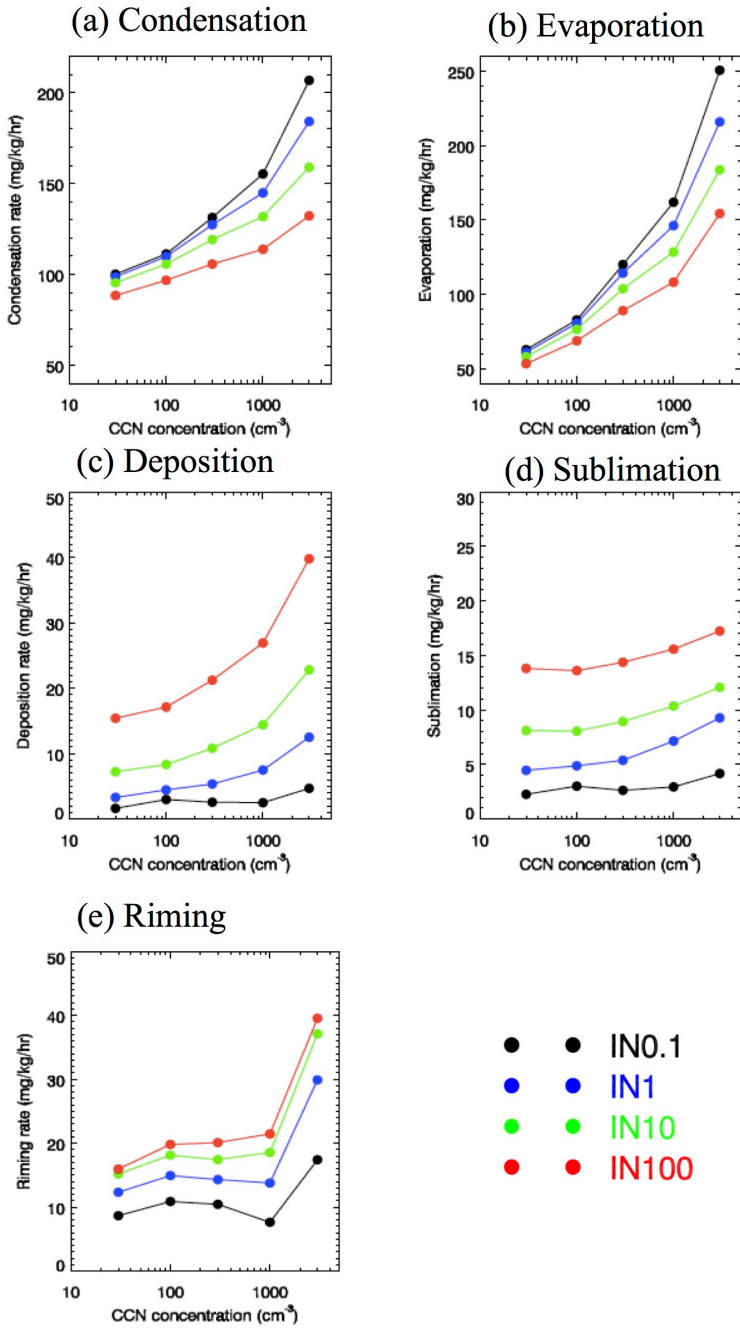


Fig. 16 Same as Fig. 4, except for the WMOC.

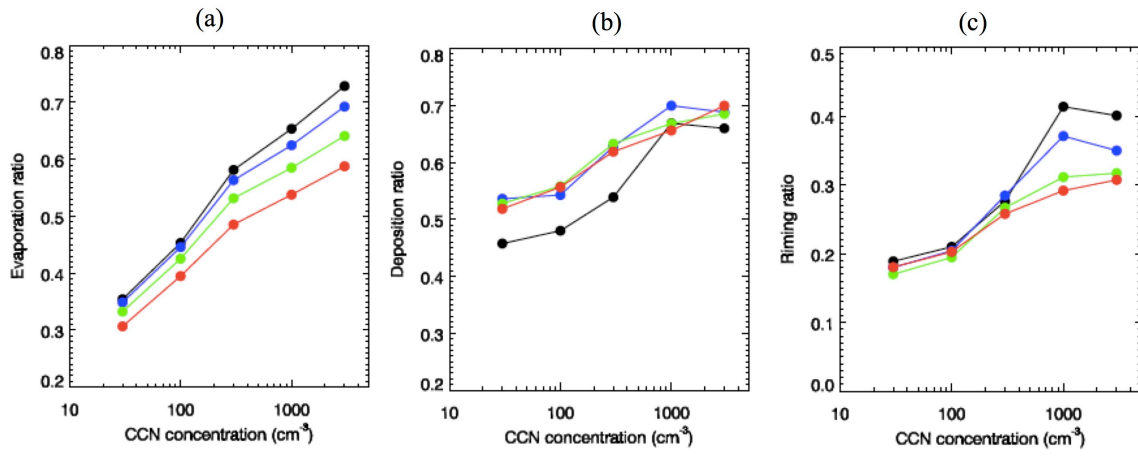


Fig. 17 Same as Fig. 5, except for the WMOC.