We would like to thank the Reviewers for their constructive comments and suggestions for the improvement of our manuscript. We have carefully revised the manuscript following these comments and suggestions. Below we have listed the referees' comments in black and our response in blue.

Reviewer 2

This paper uses the WRF-Chem regional model at 4km resolution to attempt to diagnose the effects of aerosols from different sources upon temperature, precipitation, snowfall and cloud properties over the California region. Simulations are run for 10 months for two different years.

There are some interesting results, but there are also some issues that need addressing before publication. My main concern is whether the "CLEAN" low aerosol case has too few aerosols (see below), which would lead to overestimates of the aerosol effect. But there are numerous others listed below. There are also a number of grammatical mistakes – I picked out a few, but there are more. Hopefully these will be picked up by the proof reader.

Response: We appreciate the reviewer's valuable comments. We have addressed these comments in the revised manuscript. Point-to-point responses are given below. We have done our best to correct grammatical mistakes.

Overall comments

Model setup – I'm a bit confused by the CLEAN case. Do you set all the lateral boundaries to zero for all aerosols? Or just anthropogenic ones? If it is all aerosols and there are no local sources then I would imagine this would soon lead to there being very little or no aerosol at all in the domain (local nonanthropogenic aerosol only?)? If so, then what does the model do in zero aerosol situations in terms of droplet activation (since this may be the case for regions near the inflow boundary)? It would make more sense to allow non-anthropogenic aerosols into the lateral boundaries, so that what comes in is more like a clean background case. Or is this what has been done? It should be made clear in the manuscript.

Response: In the CLEAN case, we set all the lateral boundaries to zero for all aerosols, while we keep all the transported chemical species. Aerosols are low in the simulation, but not zero, possibly due to aerosol chemistry. The CCN concentration at supersaturation of 0.1% is on the order of 10 cm^{-3} at most time of the CLEAN simulation. The distribution of liquid water path and ice water path in the CLEAN simulation is also similar to that in the CTRL simulation, with differences in magnitude. So we think it is reasonable to use this setting to represent a clean background case. It is clarified in the manuscript (lines 248-254).

There is a comparison of the model to observations in terms of the meteorology, but not for the aerosol properties. Since this is key to the results, it would be good to give some details of the comparison of the aerosol properties to observations rather than referring to the previous paper.

Response: We have taken the reviewer's suggestion. A figure (Fig. 4a) is added for the comparison of model simulated AOD with observations from MIS (also shown below, Figure 1). We can see that the model simulation well captures the spatial distribution of AOD in California, including the maximum over the southern part of the valley area and the larger AODs over the lower lands to the southeast of the Sierra Nevada. Note that the smoother contour in MISR is due to the coarser horizontal resolution (0.5 °) of the MISR data (lines 327-331).

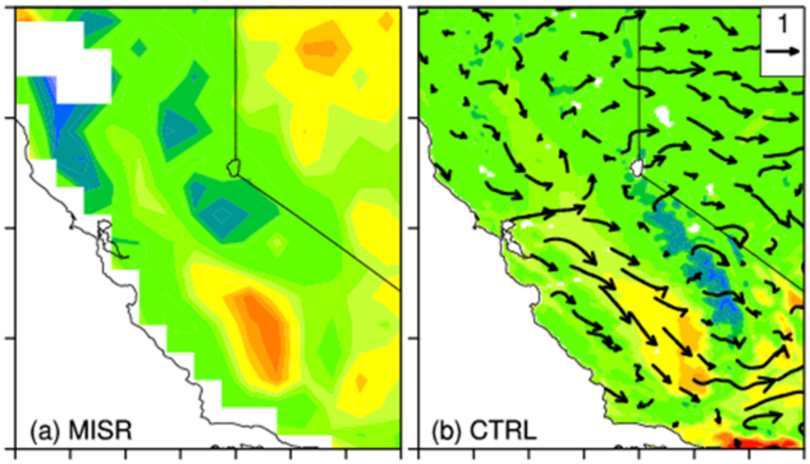

Figure 1. Spatial distribution of aerosol optical depth (AOD) averaged over October 2012 to June 2013 for (a) MISR observations, and (b) all aerosols in the CTRL simulation. 10-m wind vectors from the CTRL simulation is shown in (b).

It would be good to mark/list the observational sites that are used.

Response: Following the Reviewer's comments, the observational sites that are used are marked in Fig. 1, in which 991 DWR sites are represented by black dots; 138 CIMIS stations are represented by red dots; 32 SNOTEL sites are represented by magenta dots. The figure is also shown in the following Figure 2.

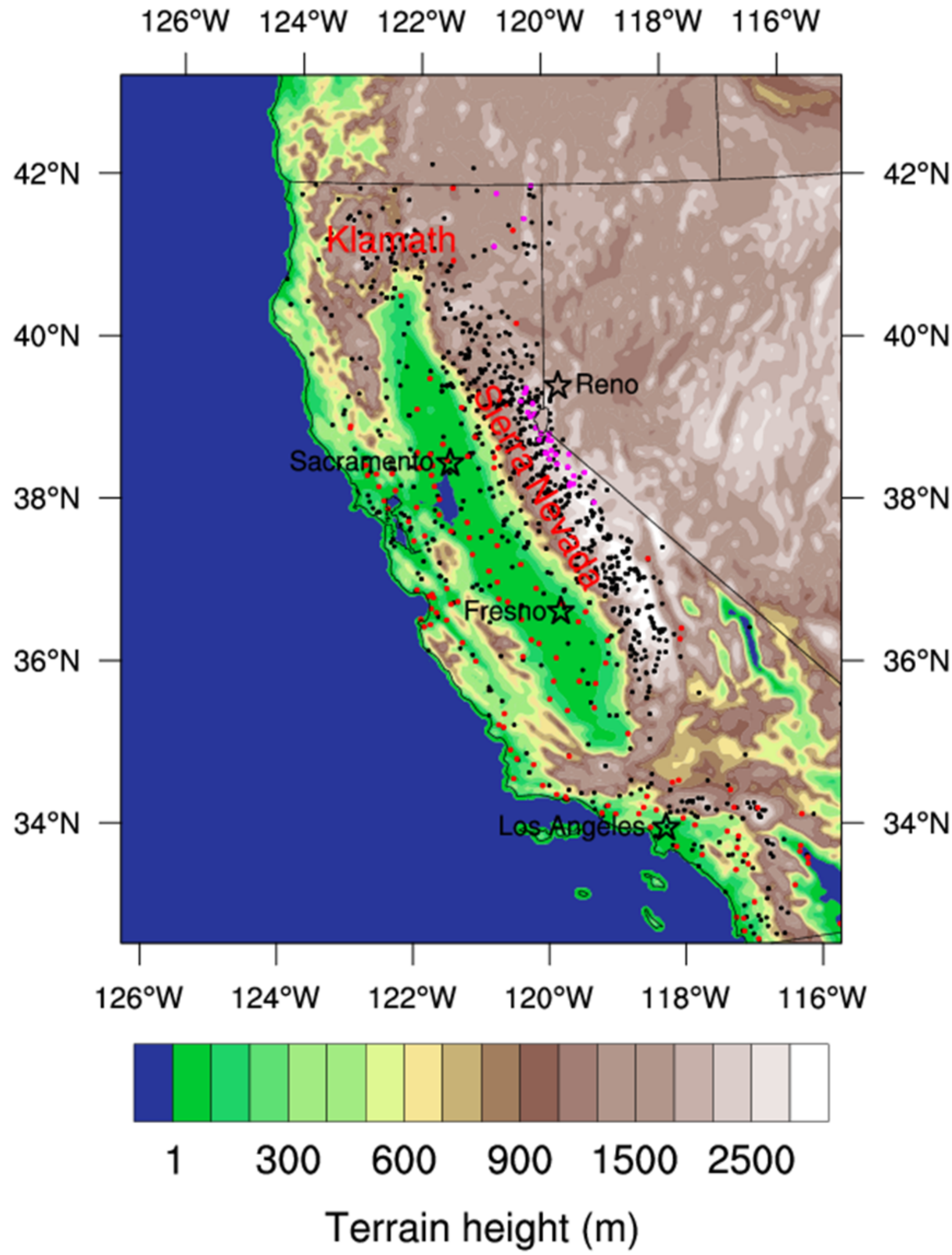

Figure 2. Model domain and terrain height (m). 991 DWR sites are represented by black dots; 138 CIMIS stations are represented by red dots; 32 SNOTEL sites are represented by magenta dots.

It mentions that there is no effect of aerosol upon ice in the model - can you discuss the potential impact of this? E.g., more aerosol might lead to more ice nucleating particles, which could affect snowfall/ice production, etc. Perhaps a sensitivity test could be done whereby the number of ice nucleating particles (INP) are enhanced. Is an INP scheme used, and if so which one?

Response: In the current WRF-Chem model, the aerosol effect on ice clouds is not included. ACI associated with ice clouds are more complex than that with liquid clouds. For example, a few studies have shown that negative Twomey effects may occur with aerosols and ice clouds, in which increased aerosols (and thus ice nuclei) lead to enhanced heterogeneous nucleation that is associated with larger and fewer ice crystals as compared to the homogeneous nucleation counterpart (DeMott et al., 2010; Chylek et al., 2006, Zhao et al. 2018). A recent study shows that the responses of ice crystal effective radius to aerosol loadings are modulated by water vapor amount in conjunction with several other meteorological parameters. While there is a significant negative correlation between ice effective radius and aerosol loading in moist conditions, consistent with the "Twomey effect" for liquid clouds, a strong positive correlation between the two occurs in dry conditions (Zhao et al. 2018). Despite numerous studies about the impact of aerosols on ice clouds, the role of anthropogenic aerosols in ice processes, especially over polluted regions, remains a challenging scientific issue. The effect of anthropogenic aerosols on ice formation and cloud radiative properties may be a critical pathway through which anthropogenic activities affect regional climate and present the opportunities for further studies using observations and models.

Following the Reviewer's comment, we have added the above discussion about the possible influence of the INP effect in the revised manuscript (lines 568-583).

Do the precipitation rates that are quoted include ice phase precipitation or just liquid? It would be helpful to try to separate the liquid and ice phase precipitation.

Response: In this study, the precipitation rate is for the total precipitation, including both liquid and ice phases (lines 284-285). Although we can separate the liquid and ice phase precipitation in the model, there are no reliable observational dataset to validate this partition. Thus we don't discuss the liquid and ice phase precipitation separately in this study.

Is it really the case that the transported aerosol comes from East Asia rather than more local sources? E.g. there seems to be a region of high AOD in Fig. 4d close to where Los Angeles is. Since the transported aerosol seems to be one of the biggest contributors the source regions for this should be examined more carefully. Wind arrows showing the mean flow are also needed for Fig. 4 (or Fig. 1).

Response: In this study, the transported aerosols refer to aerosols transported outside of the model domain, including aerosols from East Asia and other regions. It is clarified in the revised manuscript (lines 245-246). The mean flow from the CTRL simulation is included in Fig. 4b in the revised manuscript and Figure 1 in the response.

What causes the fairly large increases in SWE NW of the mountains?

Response: ARI causes fairly large increases in SWE NW of mountains. The ARI induced surface cooling over the Sierra Nevada, although not as strong as over the central valley, leads to reduced snowmelt and hence slight increase in SWE, opposite to the overall aerosol effect on SWE (Fig. 6b, lines 366-369).

It would be good to comment on the fact that the anth+dust+tran effects do not seem to add up to total effects – i.e., the overall combined effect seems to be greater than the sum of the parts.

Response: We agree with the reviewer that the anth+dust+tran effects do not seem to add up to the total effects. Following the reviewer's suggestion, we have added the following discussion in the revised paper (lines 224-230):

Since the model explicitly considers different sources and types of aerosols and contains the physical processes to represent various aerosol effects (ARI, ASI, and ACI), it is useful to decompose the aerosol effects based on aerosol sources/types and pathways. Note that the overall aerosols effects are not a simple sum of different aerosol sources/types, nor a linear combination ARI, ASI, and ACI effects. Differences between various simulations, however, help to identify the effect of a single source or pathway and the decomposition approach is a common practice in the experiment design of modeling studies.

Line-by-line comments

Abstract – you should mention the study period before you start to talk about the results.

Response: The reviewer's comment is well taken. The study period has been added in the abstract (line 50).

L37 – "snow water equivalent (SWE)," – it is never explained what is meant by this. It sounds like it is the accumulated amount of snow that has fallen to the surface expressed as mm of water equivalent. But over the time period is never given. Presumably it is over the whole study period? This should be explained more thoroughly in the text before it is used.

Response: Snow Water Equivalent (SWE) is a common snowpack measurement. It is the amount of water contained within the snowpack and can be regarded as the depth of water over unit flat surface that would theoretically result if the entire snowpack melted instantaneously.

Following the reviewer's comment, we added the definition of SWE in the revision (lines 273-275).

L238 – Does the CPC rain rate product include only rain (and not snow)? This should be mentioned for clarity.

Response: The precipitation rate is for the total precipitation, including both rainfall and snow. It is clarified in the revised manuscript (lines 284-285).

L245 – "For SWE, daily mean SWE simulations are compared with measurements collected at Snow Telemetry" – should this be daily accumulated measurements rather than a mean?

Response: Thanks. It is corrected.

L251 – "Model data are sampled onto observational sites before the comparison is conducted" – This information needs to come before the results are discussed (and put in the caption too). Does it apply to all of the observational data? Where are the observational sites? They should be listed or marked on the map, or at least some information on how many there are and their distribution, etc.

Response: Yes, it applies to all the observations used in Fig. 3. Following the reviewer's comment, this information has been moved before the results are discussed and added in the caption. The observational sites haven been added in Fig. 1 and its caption in the revised manuscript (also in Figure 2 of the response).

L258 – "Therefore, the WRF-Chem model that we employ in this study is a reliable tool for examining the impact of aerosols on the seasonal variations of precipitation and snowpack in California, especially over the Sierra Nevada"

The results show a good representation of the meteorology and precipitation/snow, but it is a bit of an extrapolation to say that this means that it can reliably be used for aerosol-cloud interactions. E.g. we don't know how well it captures the aerosol and how its interaction with clouds. Better to say that the model represents the meteorology in a realistic manner. Or move the sentence to after you have explained how WRF compares for aerosol in the next paragraph.

Response: Following the reviewer's comment, we moved this sentence to the end of this section after the evaluation of WRF-Chem AOD and snow albedo which is related to the direct effect of ASI (line 344-347).

L283 – "Transported aerosols, including dust and biological aerosols from East Asia (Creamean et al., 2013), are carried into the domain by atmospheric circulation and widely distributed, with more over the central valley due to the trapping of aerosols by the surrounding mountains (Fig. 4d)."

Is it really the case that the transported aerosol comes from East Asia rather than more local sources? E.g. there seems to be a region of high AOD in Fig. 4d close to where Los Angeles is. Since the transported aerosol seems to be one of the biggest contributors the source regions for this should be examined more carefully.

Response: The transported aerosols refer to all aerosols transported from outside of the model domain, not just from East Asia. It is clarified in the revised manuscript (lines 245-246).

Also, can you explain how you made these plots? E.g. are they from runs with just the particular emissions included (anth, dust, trans), or did you have to do some differencing between the CTRL case and the e.g. no transport simulation?

Response: We use the difference between the CTRL simulation and the corresponding experiment (NoLocAnth, NoLocDust and NoTran), respectively, to represent the simulated AOD for local anthropogenic aerosols, local dust aerosols, or transported aerosols. It is clarified in the revised manuscript (lines 324-327).

L305 – you don't talk about the effect on SWE here even though it appears stronger than for the ARI where you did discuss it.

Response: It is discussed as follows.

The main effect of ASI is to increase the temperature (Fig. 7c) over the snowy area of the Sierra Nevada through the reduction of snow albedo (Fig. 7d) and hence more absorption of solar radiation at the surface, contributing to the reduced SWE over the Sierra (Fig. 7b) (lines 369-373).

L318 - can you elaborate on why there is less SWE due to ACIs? What is the proposed mechanism and do you have evidence for it? Is it related to their being less liquid precipitation (e.g. less raindrop freezing, smaller droplets and so less droplet freezing)? Or does precipitation here include that from snow/ice? It might be argued that the higher LWPs might allow more liquid water to become frozen giving more SWE. Later on (L408) you say that the extra clouds from the ACI effect lead to less surface melt and more SWE for the lower elevation regions – can you explain/show whether the precipitation (or other) effect dominate over the temperature effect for the mountain tops, but not the lower elevations?

Likewise, can you please elaborate on why the albedo decreases and why the surface temperature increases. Is it due to the lack of fresh snow so that there is more exposed aged snow (although , or perhaps there are regions with no snow at all (at the start of the season perhaps)?

Response: In this study, precipitation includes rainfall, snow, and ice. Generally, precipitation increases with elevation due to orographic forcing and hence most precipitation occurs on the mountain range. Due to ACI, precipitation (including snow) over mountain range decreases, leading to reduced SWE over a large area of the Sierra Nevada. Surface snow albedo is proportional to the amount of snow on the ground. When SWE reduces, snow albedo decreases and hence the surface reflects less but absorb more solar radiation, resulting in warmer surface temperature over mountain tops.

For lower elevations, combined effect of ACI and ARI helps to cool the surface and result in less snowmelt.

L343 – "It is shown that transported aerosols also reduce the precipitation through ACI (Fig. 12a),"

Response: We are not sure what this question is about.

L432 – "the impact of aerosols is to speed up snowmelt at mountain tops." – This sentence should be removed since it suggests that aerosol enhance overall snowmelt when actually they reduce the runoff overall. There is a small effect of speeding up the onset, but this has already been mentioned and does not need to be said again since it ignores the snowmelt reduction effect (through the precipitation decrease).

Response: Following the reviewer's comments, we rephrase the text to better explain this (lines 496-508):

For lower elevations where there is not much snow, surface runoff is mainly associated with precipitation and the changes present a similar pattern to those in precipitation (Fig. 17c). Changes in surface runoff for the whole area present similar patterns to those of the lower elevations because of the larger area of lower elevations (Fig. 17a). However for mountain tops, changes in surface runoff are also associated with changes in snowmelt. Surface runoff over mountain tops shows a slight increase in spring, and then a decrease after April (Fig. 17b). The increase can be explained by the effect of dust aerosols deposited on the snow, which reduces the snow albedo through ASI and warms the surface, leading to more and earlier snowmelt than normal, consistent with negative changes in SWE. The decrease after April is a combined effect of less snowpack available for melting caused by earlier snowmelt due to dust aerosols and reduced precipitation caused by transported and anthropogenic aerosols through ACI. Thus, the impact of aerosols is to speed up snowmelt at mountain tops in spring and modify the seasonal cycle of surface runoff.

Conclusions/L441 – "Temperature: Dust aerosols warm the mountain top surfaces through ASI (0.12 K)," – would be good to say that the numbers in brackets are domain mean changes. Also, you should reiterated the abbreviations ASI, etc. in the text at the start of the conclusions and refer to Table 4.

Response: Following the reviewer's comment, the abbreviations ARI, ASI , and ACI have been reiterated, and a brief clarification for the numbers in the brackets have been given and referred to Table 4 (lines 515-516).

L468 – "Therefore, one of the important impacts of aerosols is to speed up the snowmelt at mountain tops." Is this really one of the most important aspects? Since the effect on runoff then goes on to be dominated by the reduction in the precipitation. And you can't be sure how much effect the earlier snow melt is having on that – most of the effect could be coming from the precip reduction?

Response: We agree with the reviewer that changes in runoff are dominated by changes in the precipitation. However, snowmelt also plays an important role in warm and dry season (lines 495-508). The earlier snowmelt at mountain tops induced by aerosols is important for water management since California depends heavily on snowmelt for water use in dry seasons.

Tables/Figures

Table 3 – perhaps it is worth mentioning that these experiments use the CTRL aerosol emissions.

Response: Done (Table 3).

Fig. 1 – It would be useful to label the valley, big cities and other regions of interest in Fig. 1. Also, the colorbar is a bit strange since the colors around 150m and 600m seem to repeat.

Response: Following the reviewer's suggestion, the indicators for mountains and big cities have been provided in Fig. 1. The colorbar in Fig. 1 is also changed. It is shown in Figure 2 of the response.

Fig. 2 – it is confusing to say that the SWE is averaged over the time period since presumably it is the accumulated snow amount?

Response: Here the model simulated SWE is the mean value of the accumulated SWE from 3-hourly model outputs. It is clarified in the revised manuscript (lines 276-277).

Fig.3 – should state the region being considered here and in the text – is it the whole model domain? It would be good to also use a dashed line for the model to help distinguish it for colorblind readers.

Response: It is the mean values at the corresponding observational sites. It is clarified in the caption. Sites are identified in Fig. 1 in the revised manuscript. Dashed line is used for the model results as the reviewer suggested.

Typos

L230 – "in CTRL experiment" -> "in the CTRL experiment"

Response: Corrected (line 272).

L233 - "in the northern California" -> "in northern California"

Response: Corrected (line 279).

L235 – "while colder temperature is found" -> "while colder temperatures are found"

Response: Corrected (line 281).

L314 - "because aerosol effect" -> "because the aerosol effect"

Response: Corrected (line 378).

L316 - "associated with ACI effect" -> "associated with the ACI effect"

Response: Corrected (line 381).

L358 – "contributes to the increase (1.88%)." – "contributes to an increase (1.88%)." (since overall there is a decrease).

Response: Corrected (line 424).

L484 – ”importance” -> “important”

Response: Corrected (line 563).