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 1

Aerosols can induce large impacts on the regional climate and hydrologic cycles. Currently the aerosol effects are still not well understood, especially for the individual and combined effects of different underlying mechanisms (direct, indirect, and feedback).

This study presents a comparison of different aerosol effects including aerosol radiation interaction (ARI), aerosol-cloud interaction (ACI), and aerosol-snow interaction (ASI) on the regional climate in California based on WRF-Chem simulations. The study also shows the different effects induced by local dust emissions, local anthropogenic emissions, and transportation. Overall, the manuscript is well written, and most of the content is well organized. The scientific findings are significant to our understanding of climatic effects of different aerosols. This study is useful for the relevant research community on unraveling the aerosol affects in climate and hydrologic cycles.

However, some statements are not clear and some of them may need further evidence. Part of the manuscript can be better organized for easy following. I have some suggestions and comments that I would like the authors to consider before the manuscript can be accepted for publication in ACP.

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

**Major comments:**

(1) Lines 254-256, Figure 3, Lines 36-40 (Abstract): The authors states that the model simulations represent reasonable magnitude of SWE, because SNOTEL data underestimates real SWE. They deduce the underestimate of SNOTEL SWE from "The main issue with weighing-type gauges for snowfall estimation is the undercatch of approximately 10%–15% due to wind (Serreze et al., 2001; Yang et al., 1998; Rasmussen et al., 2001). " (Lines 249-251). I should mention that snowfall is not SWE. They are measured differently: snowfall referring to a solid form of precipitation is measured by gauges, while SWE is measured using a snow pillow (https://www.wcc.nrcs.usda.gov/about/mon_automate.html). Therefore, underestimation of snowfall doesn't mean underestimation of SWE. If SNOTEL SWE is not underestimated compared to the reality, the model (with aerosol effects) may have large biases in SWE (up to ~ 100 mm) (Figure 3b).

Response: We agree with the reviewer that the underestimation of snowfall does not mean an underestimation of SWE. We revised the text as following (lines 294-300):

For SWE, daily mean SWE simulations are compared with measurements collected at Snow Telemetry (SNOTEL) stations. SWE is measured using a snow pillow sensor and biases in SWE measurement could occur when temperature differences between surrounding ground cover and the pillow sensor create uneven distribution of snow (Meyer et al., 2012). Both under- and over-estimation could happen depending on the snowmelt conditions and the snow density rate of change (Serreze et al., 1999; Serreze et al., 2001; Johnson and Marks, 2004).

The authors state that inclusion of aerosol effects reduce the model biases (Abstract). Although it is generally true, it is not simply the case for a model simulation regarding the large uncertainties in current models. With aerosol effects, WRF-Chem reduces SWE biases by 0-60 mm (Figure 15), but still has the bias of ~100 mm (mentioned above, if SNOTEL SWE is not biased low). Although the authors can still get the conclusion of reduction of SWE biases with aerosol effects, discussion on other reasons for the model biases (potentially larger than the biases that can be reduced by including aerosol effects) is desirable and helpful.

Response: Discussion on other reasons for the model biases are included in the text (lines 584-586):

Our model simulation produces relative larger SWE than the SNOTEL observations. Improvement of snowpack simulation in the land surface model is needed for accurate quantification of aerosol impacts on snowpack.

In addition, model simulations are not always improved with the inclusion of aerosols effects. For example, CTRL simulation underestimates precipitation in April (Figure 3a). If the aerosol effects are removed, simulated precipitation is larger (Figure 14), which is more consistent with the observation.

Response: In the abstract, we talk about general performance of the model simulation with aerosol effects included. We agree with the reviewer that the model simulations are not always improved with the inclusion of aerosol effects in all months. The different performance of the model simulation in different months is clarified in the main text as following (lines 303-305).

In the relative dry months from February to June, the simulated precipitation has similar magnitude to the observations, with slightly overestimation or underestimation in different months.

For precipitation and temperature, there are multiple observations available for comparison with the model simulations. Without the investigations of the reliability of each observation, the selected observations may be arbitrary. Besides the CPC, DWR, and CIMIS observations used in this study, there are also other datasets (including a widely-used dataset, PRISM-Parameter-elevation Regression Independent Slopes Model) available but not included. The resolution of PRISM (4 km), much higher than CPC (0.25 degree) used, is also similar to the model resolution (4km). I am wondering how the simulation results are compared to the PRISM observation at similar resolution.

Response: Thanks for the suggestion. We have added comparison with PRISM in the revised manuscript. As shown in the following Figure 1, the CTRL simulation has better agreement with PRISM than CPC. As pointed out by the reviewer, the PRISM data is widely used and has the same resolution as the CTRL run. Thus, we replace CPC by PRISM in Fig. 2f, while including both CPC and PRISM in Fig. 3a in the revised manuscript. The text is revised accordingly.

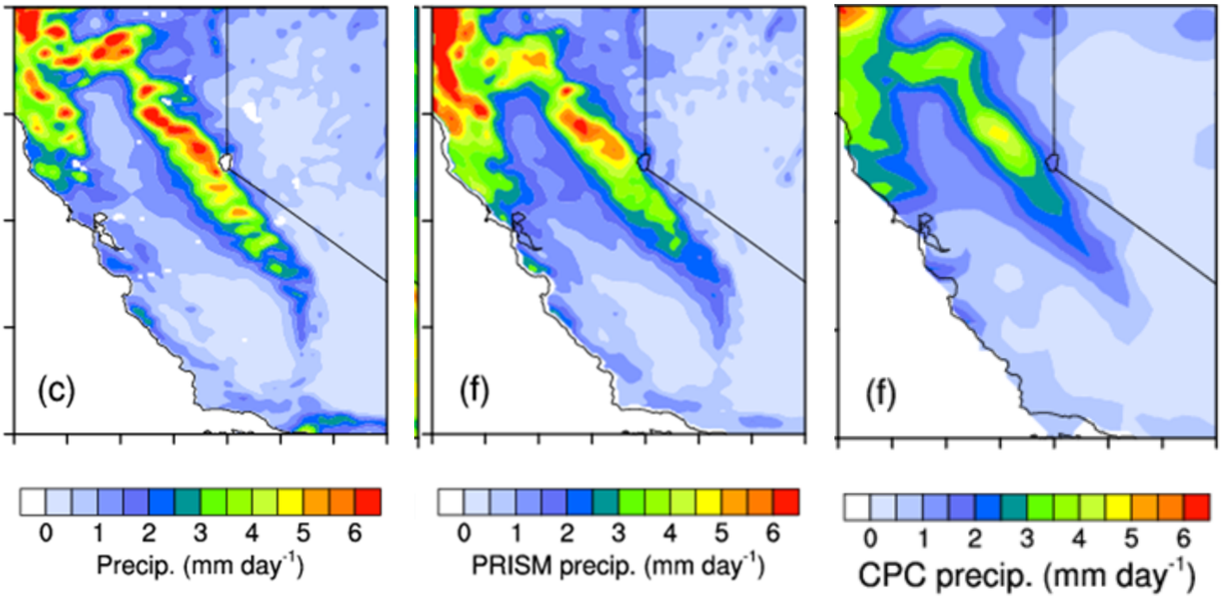

Figure 1. Mean precipitation (mm day$^{-1}$) from (left panel) CTRL, (middle panel) PRISM, and (right panel) CPC.

Overall, more investigation is needed to support the improvement of model performance when aerosol effects are included, by comparison of model results with more observation datasets and consideration of the reliability of these observations.

Response: Following the reviewers' comments, we have added more comparisons to support the improvement of model performance when aerosol effects are included. We have added comparisons with PRISM in Fig. 2 and Fig. 3a. The comparison of AOD between the MISR observation and the CTRL simulation is included in Fig. 4a and 4b. We have also added a figure in the supplementary information (Fig. S2) to evaluate the model simulations of snow albedo which is related to the direct effect of ASI.

(2) Table 3, Lines 216-223: The authors decompose the effects of ARI, ACI, and ASI from these multiple experiment. Do they assume the linear combination of ARI, ACI, and ASI? It is possible that ARI, ACI, and ASI can be interacted to generate overall effects. CTRL-NARI (CTRL-NASI) may include the interaction of ARI/ACI and ARI/ASI (ARI/ASI and ACI/ASI), which may be different from NASI-NARS (NARI-NARS). If any difference between CTRL-NARI and NASI-NARS (CTRL-NASI and NARI-NARS) is found, it is also helpful if the authors can explicitly mention this nonlinear combination of ARI/ACI/ASI. Although it is difficult to identify the interaction of ARI, ACI, and ASI, at least some discussions are needed.

Response: We agree with the reviewer that the overall aerosols effects are not a linear combination of the ARI, ASI, and ACI 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 of the 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.

(3) Section2: The authors describe the three pathways of aerosol effects in the order of ARI, ACI, and ASI in Introduction, but describe their representation in WRF-Chem in the order of ASI, ARI, and ACI in Section 2. This tends to give the readers an impression that ASI is more important than ARI and ACI and the main focus of the paper. I think this is not exactly what the authors want to show. In addition, the model version and modifications lacks some clear outlines. For example, WRF-Chem is first designed to simulate aerosol cycle, such as by MOSAIC; ASI is further included by coupling SNICAR (in CLM4) with aerosol cycles. Therefore, it would be better if this section can be re-organized as follows: brief description of model framework (WRF-Chem and WRF), representation of aerosol cycles, and aerosol effects (in the order of ARI, ACI, and ASI as in Introduction). Following the model description, some configurations for the specified simulation (such as domain, resolution, initial and boundary conditions, emission files, etc) in this study can be presented. Lines 195-223 can be kept as it is.

Response: We appreciate the reviewer's suggestion on the structure of the manuscript. The ASI pathway included in our WRF-Chem version is the major difference from the public released version. Thus we put ASI in the first order with more detailed description. ARI and ACI have been documented by many papers, such as Fast et al. (2012, 2014) and Zhao et al. (2010, 201, 2013a, 2013b). Therefore, we give a brief introduction of ARI and ACI following ASI.

(4) Table 2, Lines 199-215: I am wondering what kinds of chemical species are transported into the domain. Do these species include dust or anthropogenic aerosols? Please explicitly mention this. If they include dust, NoDust should be NoLocDust. If they include anthropogenic aerosols, NoAnth should be NoLocAnth. Since their domain only covers a small region of Southwest United States, is it possible that dust and anthropogenic aerosols are also transported from adjacent regions (California-Arizona borders, Arizona, New Mexico, and the country of Mexico)? The authors only mention the long-range transportation from Asia and Africa. Please also clarify this.

Response: The initial and boundary chemical conditions are taken from the MOZART-4 global chemical transport model. The chemical species transported into the model domain include organic carbon, black carbon, sulfate, nitrate, ammonium, sea salt, dust, etc.. Following the reviewer's suggestion, we give a brief description of the chemical species which are transported into the domain, including dust and anthropogenic aerosols. The transported aerosols investigated in this study refer to the aerosols transported from outside the model domain, including those from East Asia and other regions. It is clarified in the revised manuscript (lines 241-247).

In the NoDust and NoLocAnth experiments, only local dust or local anthropogenic aerosols are excluded. We have followed the reviewer's suggestion and change the experiment name to NoLocDust and NoLocAnth in the revised manuscript.

(5) Lines 261-273: The evaluation of model simulations are only on the atmospheric aerosol. This study lacks the evaluation of aerosol-in-snow concentrations. Reasonable simulations of airborne aerosols don't necessarily imply reasonable simulation of aerosol-in-snow distribution, as there are lots of processes going after aerosol deposition on snow. Although the observations may be limited, some basic examination of aerosol-in-snow concentrations and their evaluation (if possible) is desirable to increase the reliability of ASI in this study. The results can be put in the supplement.

Response: Since the observations on aerosol-in-snow concentrations are rather limited both spatially and temporally as the reviewer pointed out, it's very difficult to conduct direct comparisons with model simulations. Following the reviewer's suggestion, we instead added a figure in the supplementary information to evaluate the model simulations of snow albedo which is directly affected by the ASI (Fig. S2). The model simulated snow albedo is compared with the product from NASA Land Data Assimilation Systems (NLDAS) Mosaic (MOS). It is shown that model simulation provides rather reasonable estimate of the snow albedo with ASI included (Fig. S2 and the following Figure 2, lines 339-344).

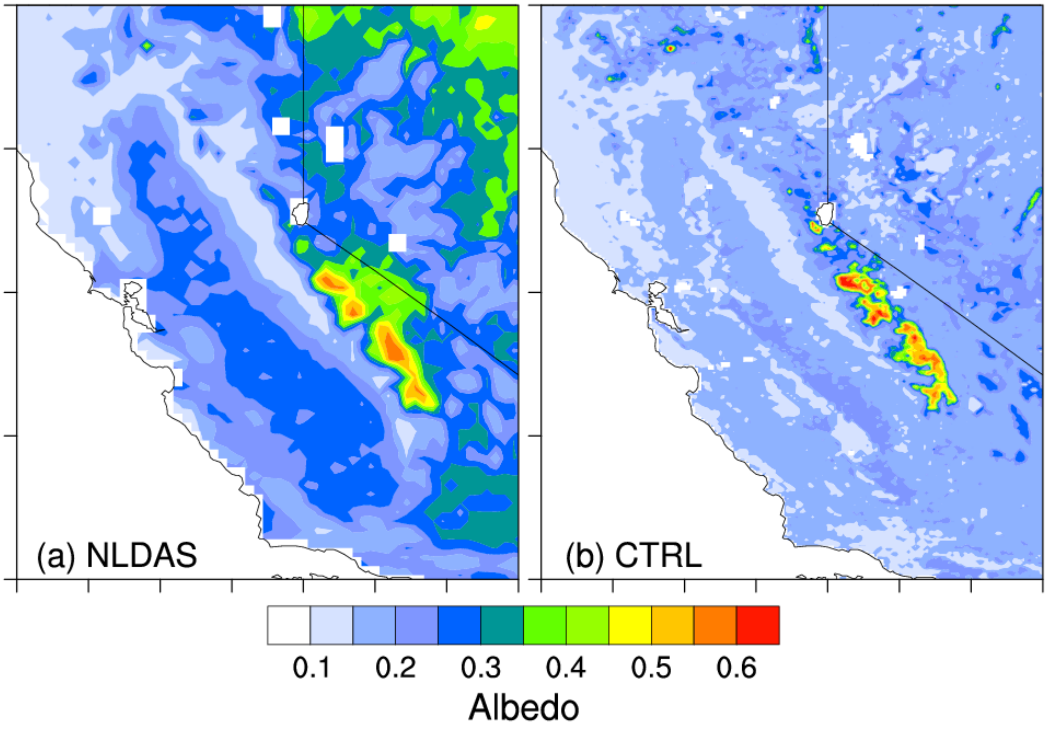

Figure 2. Spatial distribution of surface albedo averaged over October 2012 to June 2013 from (a) NLDAS data assimilation and (b) CTRL simulation.

**Specific comments:**

Title: There is a word “convection-permitting” in title, but it is not mentioned in the main text. To increase the significance, I would suggest adding some brief discussions on the benefit of convection-permitting WRF-Chem simulations in Introduction.

Response: The reviewer’s comment is well taken. A brief discussion on the benefit of convective-permitting WRF-Chem simulations has been added in the revision (lines 205-223):

One important subgrid process in climate models is the representation of deep convection. Parameterizing deep convection is challenging and the use of convection parameterization schemes leads to common errors such as misrepresentation of the diurnal cycle of convective precipitation (e.g., Dai et al., 1999; Brockhaus et al., 2008), underestimation of dry days (e.g., Bergetal., 2013) and precipitation intensity (e.g., Prein et al., 2013; Fosser et al., 2014; Ban et al., 2014), and overestimation of low-precipitation frequency (e.g., Bergetal., 2013). Although recently developed parameterization schemes lead to improvements in the simulation of precipitation intensity (Donner et al., 2011), intraseasonal variability (Benedict et al., 2013), and diurnal cycles (Bechtold et al., 2014), a promising remedy to the error-prone model simulations using convective parameterizations is the use of convection-permitting model with horizontal grid spacing of about 4 km or less (e.g., Satoh et al., 2008; Prein et al., 2013; Ban et al., 2014). Advances in high-performance computing allowed refinement of the model grids well below 10 km. At these scales, convection parameterization schemes may be switched off as deep convection starts to be resolved explicitly (e.g., Weisman et al., 1997). According to Prein et al. (2014), it seems prudent to use horizontal grid spacing of 4 km or less for convection-permitting model simulations. The 4 km simulation can also represent topography and inhomogeneous distribution of anthropogenic emission and precipitation better, leading to a better representation of aerosol distribution comparing to the 20 km simulation (Wu et al., 2017).

Lines 35-36: Please make the order of ARI, ASI, and ACI consistently throughout the paper.

Response: The order is kept in the revision.

Lines 46-47: Transported anthropogenic aerosols or transported aerosols?

Response: Here it means transported aerosols. We have change it to “Transported aerosols and local anthropogenic aerosols” (line 46).

Line 50: Please mention the year for the period (since there is only a year for comparison).

Response: Years have been added as “from October 2012 to June 2013” (line 50).

Lines 70-71: The most (moist) adiabatic structure of the atmosphere is not clear.

Response: Following the reviewer’s comment, we have revised the following sentence (lines 69-76):

Previous studies suggested that warming trends are amplified in mountains compared to lowlands (Pepin et al., 2015). The amplified warming in mountain areas, also referred to as elevation-dependent warming, is generally attributed to a few important processes (Pepin et al., 2015), such as water vapor changes and latent heat release, surface water vapor changes, radiative flux changes associated with three-dimensional rugged topography (Gu et al., 2012a; Liou et al., 2013; Lee et al., 2015; Zhao et al., 2016), and snow-albedo feedback (Leung et al., 2004). A review and assessment of the mechanisms contributing to an enhanced warming over mountain areas is given in Pepin et al. (2015).

Lines 87-88: The short atmospheric residence time can't cause geographical distributions. Compared to natural aerosols (dust), anthropogenic aerosols with smaller particles can be transported for a longer distance and a longer residence time. Please clarify.

Response: The local geographical distributions of anthropogenic aerosols over California is also related to another reason: the regional topography. Following the reviewer's comment, we have revised this sentence (lines 92-95).

"Anthropogenic aerosols are geographically distributed because of localized emission sources, the short atmospheric residence time, and regional topography. With valleys and surround mountain barriers, dispersion of air pollutants is more difficult for locally emitted anthropogenic air pollution."

Lines 191-192: Is the impact of aerosol on ice cloud formation included in the model?

Response: The impact of aerosols on ice cloud is not included in the model, and therefore there no significant changes in ice water path (IWP, Figs. 8b & 8d). This has been clarified in the model description part (lines 178-179) and results part (lines 378-379) of the original manuscript.

Line 194: How long is the timestep?

Response: The time step is 20 seconds and has been added in the revision (line 199).

Lines 197-199: If the results are similar, why are they still provided? Please clarify.

Response: It is clarified as the following (lines 202-204).

To test the robustness of the results, simulations are also conducted for year 2013-2014, and similar results are found. In the following section, our analysis focuses on year 2012-2013, while quantitative information of the aerosol impacts for year 2013-2014 is provided for comparison.

Line 222: Is NARS similar to the CTRL, except that ARI and ASI are not included?

Response: Yes, NARS is similar to the CTRL, except that both ARI and ASI are not included. We have rephrase the sentence (line 263).

Lines 237-238: Is it possible to find a reference for CPC? In addition, I cannot open the link for CPC data (Line 496).

Response: The link for the CPC data is updated:
https://www.esrl.noaa.gov/psd/data/gridded/data.unified.daily.conus.html

The following reference for CPC has been added in the revision (line 292; 647-649):

Chen, M., Xie, P., and Co-authors: CPC Unified Gauge-based Analysis of Global Daily Precipitation, Western Pacific Geophysics Meeting, Cairns, Australia, 29 July - 1 August, 2008.

Line 244: I am wondering how to get DWR data? What is the resolution? Is it gridded dataset or station measurement? It is not found in Data availability.

Response: DWR data can be downloaded at http://cdec.water.ca.gov/snow_rain.html. It is station measurement. We added the link in the Data Availability part (line 594).

Line 245: Is it possible to find a reference for CIMIS? If so, please delete "http://www.cimis.water.ca.gov/", since Data availability is the place to mention it.

Response: The following reference for CIMIS has been added in the revision (line 293; lines 833-834):

Snyder, R. L.: California irrigation management information system. Am. J. Potato Res. 61(4): 229 – 234, 1984.

Lines 249-251: Does this affect both CPC and DRW datasets? Please clarify it.

Response: This statement is removed in the revision. We are not aware of any study that investigated wind effects on CPC or DWR datasets.

Lines 291-293: what period is used for the calculation of difference and for daily data?

Response: The differences are averaged over October 2012 to June 2013 for the contour maps. This information has been added in the revision (line 355).

Lines 317-319: Probably mention that increase in temperature by reduced snow amount also overwhelms the decrease of temperature which may be caused by more clouds.

Response: The reviewer's suggestion has been well taken. The text has been revised accordingly (lines 381-384).

Line 322: I cannot find the runoff results.

Response: The runoff results are added in Supplementary Information, Fig. S3. (line 387).

Line 327: what's the aerosol-snow albedo feedback? Are you meaning snow-albedo feedback?

Response: Here it means the aerosol induced snow-albedo feedback. The text has been revised (lines 392).

Lines 328-329: Please mention that reduced SWE can also initialize the snow albedo feedback.

Response: We appreciate the reviewer's suggestion. We have revised the sentence as: "For the ACI effect, however, warming over the mountain region is a result from the reduced SWE which can also induce snow-albedo feedback and result in smaller surface albedo and more surface absorption of solar radiation." (lines 393-395).

Lines 347-348: The increased SWE can be canceled out to some extent by reduced snowfall (Lines 344-345). Please don't just mention the increased SWE and reduced snowfall separately, but consider them together (northern part of Sierra: ARI>ACI; southern part of Sierra: ACI>ARI).

Response: Following the reviewer's comment, the text has been revised as (lines 409-415):

It is shown that transported aerosols also reduce the precipitation through ACI (Fig. 12a), which exceeds the ARI effect and leads to decreased SWE and increased temperature over the southern part of Sierra Nevada (Figs. 12b and 12c). Over the central valley, as well as over the northern part of the Sierra, temperature decreases (Fig. 12c) due to the relatively larger ARI effect of the transported aerosols compared to ACI, resulting in less snowmelt and increased SWE over that region (Fig. 12b).

Lines 358-359: Please be aware that this only applies to the total runoff change, but not to the monthly change which the snowmelt change also contributes to.

Response: We agree with the reviewer that snowmelt change also contributes to the change in runoff. We revised the sentence as (lines 426-428):

Overall changes in surface runoff are similar to those in precipitation, accompanied by contributions from changes in snowmelt.

Lines 372-374: The authors are talking about the relative change here. Why is the relative change of runoff smaller when the relative change of SWE is larger? This can be partly explained by the slightly smaller change of precipitation (both liquid and solid form of precipitation are converted to runoff, soil water, and evapotranspiration eventually). Is it possible that the change of evapotranspiration also contributes?

Response: The relative change of surface runoff at the mountain tops in year 2013-2014 is smaller than year 2012-2013 because the mean surface runoff in year 2013-2014 (0.33 mm day$^{-1}$) is larger than that in year 2012-2013 (0.27 mm day$^{-1}$), possibly contributed by less SWE and faster snowmelt at the mountain tops in year 2013-2014. The corresponding changes in evapotranspiration are –0.12% in year 2012-2013 and –1.20% in year 2013-2014, respectively, which also contributes to the relatively smaller change of surface runoff in year 2013-2014 at the mountain tops.

We have added this in the revision (lines 441-447).

Line 397: what's the orographic forcing?

Response: Here we mean "precipitation due to orographic forcing". We have reworded it as "the orographic precipitation over the mountain region". Orographic lift occurs when an air mass is forced from a low elevation to a higher elevation as it moves over rising terrain. As the air mass gains altitude it quickly cools down adiabatically, which can raise the relative humidity to 100% and create clouds and, under the right conditions, precipitation. Orographic forcing is an efficient and dominant mechanism for harnessing water vapor into consumable freshwater in the form of precipitation, snowpack, and runoff. It has been estimated that about 60–90% of water resources originate from mountains worldwide, including the western slope of the Sierra Nevada range in California.

Lines 423-424: The definition of surface runoff can be put earlier in Line 352 (when it appears at the first time).

Response: We appreciate the reviewer's suggestion. The definition of surface runoff has been moved earlier when the overall changes in surface runoff are discussed (lines 425-426).

Lines 425-426: If the authors are talking about total runoff (in an annual scale), surface runoff is mainly associated with precipitation. But in a monthly scale, surface runoff is mainly associated with rainfall and snowmelt, and a portion of snowfall will become surface snow accumulation (epically for the winter season). In the melting season, precipitation is mainly in the terms of rainfall, which will mostly become runoff. Please clarify this.

Response: We agree with the reviewer that snowmelt plays an important role in surface runoff. We have revised the text following the reviewer's comment (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.

Lines 428-430: Please indicate this is consistent with change of SWE.

Response: Done (line 504).

Line 431: Please add "less snowpack available for melting caused by" before "earlier snowmelt".

Response: Done (line 505).

Lines 462-463: Again, this is for longer time scale (e.g., annual). In a shorter time scale, runoff can be generated from snowmelt. This is actually one point in this study: seasonal cycle of runoff is modified by aerosols through the impacts of aerosol on snowpack.

Response: We really appreciate the reviewer's comment. We have added the effect of snowmelt in monthly variations (lines 539-540; 546).

Line 467: Probably add "less snowpack available for melting caused by" before "earlier snowmelt". In the earlier period of snowmelt, the author can say there is more runoff due to earlier snowmelt.

But in the late period of snowmelt, it is more correct to say that less runoff is due to less snowpack available for melting to generate runoff.

Response: Done (lines 543-544).

Lines 481-486: Does underestimation of AOD imply that the aerosol effects are also biased low here? If so, please explicitly mention it.

Response: The reviewer has a very good point. We have added in the revision: "The underestimate of AOD in the model implies that the simulated aerosol effects could also be biased low." (lines 562-563).

Lines 489-492: The authors have mentioned that aerosol effect on ice cloud formation is not explicitly treated in the model (Line 314). They also mentioned the potential significance of aerosol effect on snow formation (Lines 122-124). May the limitation of the model (i.e., inexplicit treatment of aerosol effect on ice cloud formation) affect the results presented here? It will be helpful to add a brief discussion.

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).

Figures: Surface runoff is one of key variables the authors focus on. However, the authors don't present any spatial distribution and temporal evolution as other variables (precipitation, SWE, T2). I would suggest adding the spatial distribution and temporal evolution of runoff as well as spatial distribution of runoff change by aerosols. They can be put in supplement.

Response: The spatial and temporal distribution of surface runoff is included in the Figures S1, S3 and S4 in the Supplementary Information of the revised manuscript.

Figure 1: If possible, please provide some indicators for the main mountains (including Sierra Nevada and Klamath Mountains) and valleys, which can be easily referred to in the main text. This will help the general readers of the journal.

Response: Following the reviewer's suggestion, the indicators for Sierra Nevada and Klamath Mountains have been provided in Fig. 1.

Figure 3 captions, Lines 791-794: I would say "from CTRL simulations and xxx observations" instead of "simulated from CTRL and the observations from xxx". In addition, do (a) and (c) refer to a regional mean? Please clarify.

Response: Captions have been modified following the reviewer's suggestion. All the data refer to an average for the stations used.

Figure 3: X-axis in (c) is overlaid by white shaded box.

Response: Changed.

Figure 5: I am wondering how the authors do the significant test, as there is only one year simulation for each experiment.

Response: The two-tailed Student's t test, in which deviations of the estimated parameter in either direction are considered theoretically possible, is applied to the 3-hourly data for each experiment in this study to measure the statistical significance of the sensitivity simulations (lines 352-355).

Figures 6-12: Can the result of significant test be shown as in Figure 5? This is normally required as the authors mention multiple times of "significant" in the text (Lines 304, 313, 317, 326, 339, 369, 479).

Response: The figures with the result of significant test look quite noisy. So we don't show the dots as in Fig. 5. For Figures 6-12, most of the data are statistically significant at a significance level of 70%. We added this explanation in the text (lines 362-363).

Figures 14-17: Please add the "zero" line in the figures for easy viewing.

Response: Done.

## 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).

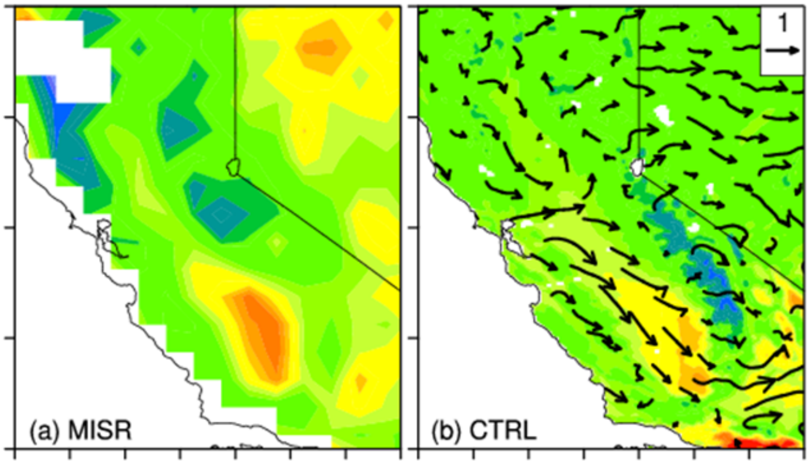

Figure 1. Spatial distribution of aerosol optical depth (AOD) averaged over October 2012 to June 2013 for (a) MISR observations, and (b) all aerosols in the CTRL simulation. 10-m wind vectors from the CTRL simulation is shown in (b).

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.

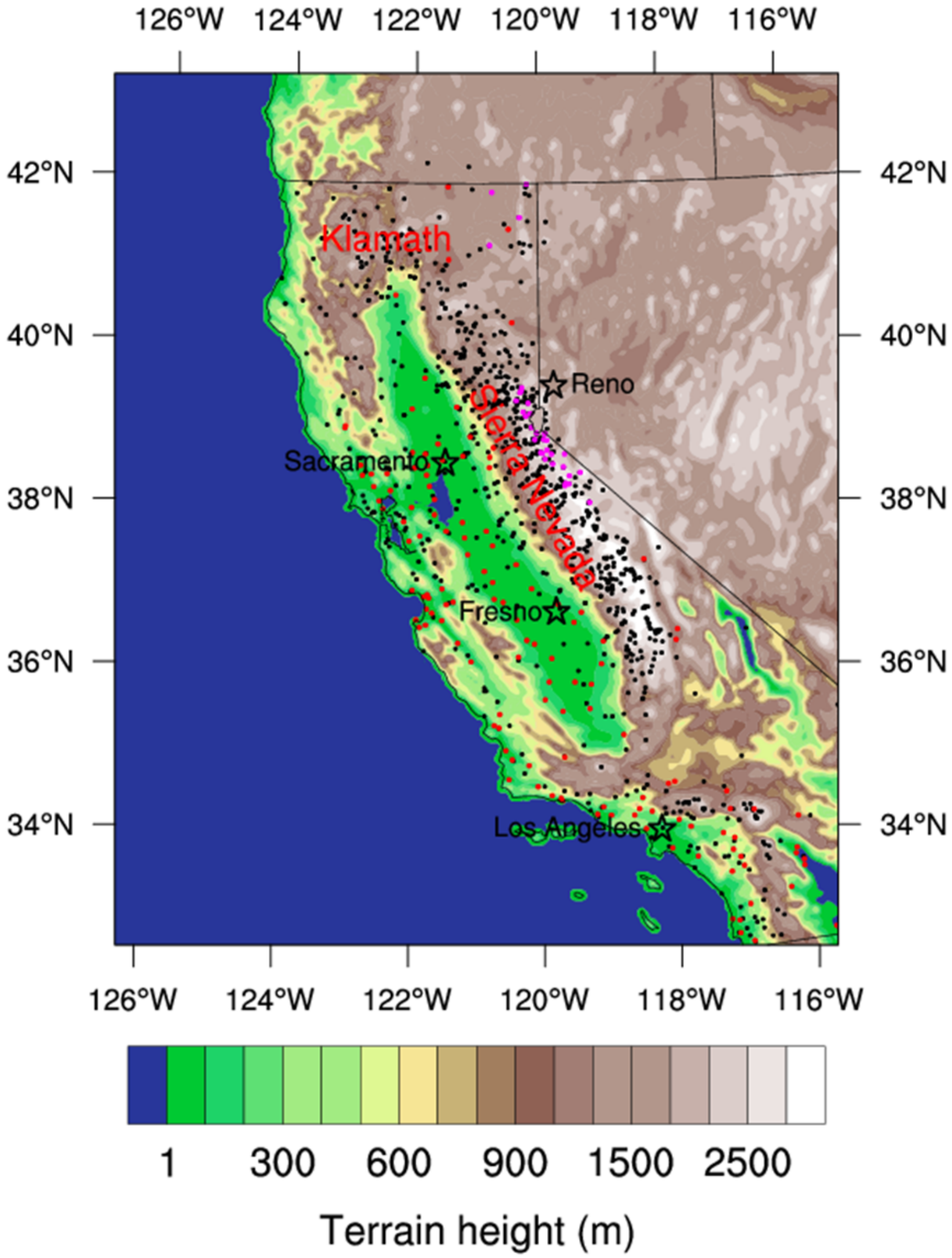

Figure 2. Model domain and terrain height (m). 991 DWR sites are represented by black dots; 138 CIMIS stations are represented by red dots; 32 SNOTEL sites are represented by magenta dots.

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).

# Impacts of Aerosols on Seasonal Precipitation and Snowpack in California Based on Convection-Permitting WRF-Chem Simulations

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(Submitted to ACP)

Highlights:

1. Aerosols warm the California mountain tops through aerosol-snow interaction by local dust but cools the lower elevation areas through aerosol-radiation interaction and aerosol-cloud interaction by transported and local anthropogenic aerosols.
2. Aerosols reduce precipitation and snowpack in California primarily through aerosol-cloud interaction by transported and local anthropogenic aerosols and aerosol-snow interaction by local dust.
3. Aerosols cause early~~ier~~ snowmelt at mountain tops through aerosol-snow interaction by local dust, ~~leading to reduced surface runoff after April~~and hence modify the seasonal cycle of surface runoff.

## Abstract

A version of the WRF-Chem model with fully coupled aerosol-meteorology-snowpack is employed to investigate the impacts of various aerosol sources on precipitation and snowpack in California. In particular, the impacts of locally emitted anthropogenic and dust aerosols, and aerosols transported from outside ~~of~~ California are studied. We differentiate three pathways of aerosol effects including aerosol-radiation interaction (ARI), aerosol-snow interaction (ASI), and aerosol-cloud interaction (ACI). The convection-permitting model simulations show that precipitation, snow water equivalent (SWE), and surface air temperature averaged over the whole domain (34-42°N, 117-124°W, not including ocean points) are reduced when aerosols are included, therefore reducing ~~the high model~~large biases of these variables ~~when~~ due to the absence of aerosol effects in the model ~~are not considered~~. Aerosols affect California water resources through the warming of mountain tops and the reduction of~~anomalously low~~ precipitation;~~,~~ however, different aerosol sources play different roles in changing surface temperature, precipitation and snowpack in California by means of various weights of the three pathways. ARI by all aerosols mainly cools the surface, leading to slightly increased SWE over the mountains. Locally emitted dust aerosols warm the surface of mountain tops through ASI, in which the reduced snow albedo associated with ~~dirty~~ dusty snow leads to more surface absorption of solar radiation and reduced SWE. Transported aerosols and local anthropogenic aerosols play a dominant role in increasing ~~cloud water amount~~non-precipitating clouds but reducing precipitation through ACI, leading to reduced SWE and runoff over the Sierra Nevada, as well as the warming of mountain tops associated with decreased SWE and hence lower surface albedo. The average changes in surface temperature from October 2012 to June 2013 ~~October to June~~ are about −0.19 K and 0.22 K for the whole domain and over mountain tops, respectively. Overall, the averaged reduction during October to June is

about 7% for precipitation, 3% for SWE, and 7% for surface runoff for the whole domain, while the corresponding numbers are 12%, 10%, and 10% for the mountain tops. The reduction in SWE is more significant in a dry year, with 9% for the whole domain and 16% for the mountain tops. The maximum reduction of ~20% in precipitation occurs in May associated with the maximum of aerosol loadings, leading to the largest decrease in SWE and surface runoff over that ~~time~~ period. It is also found that dust aerosols could cause early snowmelt at the mountain tops and reduced surface runoff after April.

## 1. Introduction

Water resources in California are derived predominantly from precipitation (mostly during the winter time) and storage in the snowpack in the Sierra Nevada. Snowpack provides about one-third of the water used by California's cities and farms. The fresh water stored in the snowpack gradually releases through runoff into river flows during the warm and dry season. The amount and timing of snowmelt are critical factors in determining water resources in this region. It is important to understand the factors influencing precipitation and snowpack on seasonal timescale for water management and hydropower operation.

The 2012-2014 California drought has been attributed to both warming and anomalously low precipitation (Griffin and Anchukaitis, 2014). Previous studies ~~have~~ suggested that warming trends are amplified in mountains compared to lowlands (Pepin et al., 2015). The amplified warming in mountain areas, also referred to as elevation-dependent warming, is generally attributed to a few important processes (Pepin et al., 2015), such as water vapor changes and latent heat release, surface water vapor changes, radiative flux changes associated with three-dimensional rugged topography (Gu et al., 2012a; Liou et al., 2013; Lee et al., 2015; Zhao et al., 2016), and snow-albedo feedback (Leung et al., 2004). A review and assessment of the mechanisms contributing to an enhanced warming over mountain areas is given in Pepin et al. (2015).

~~Previous studies have suggested that warming trends are amplified in mountains compared to lowlands because of the moist adiabatic structure of the atmosphere and snow-albedo feedback (Leung et al., 2004).~~ In addition to the warming effects of greenhouse gases, aerosols may have substantial impacts on water resources in California. Recent observational and numerical modeling studies have shown that aerosol pollutants can substantially change precipitation and snowpack in California (e.g., Rosenfeld et al., 2008a; Qian et al., 2009a; Hadley et al., 2010; Ault et al., 2011; Creamean et al., 2013, 2015; Fan et al., 2014; Oaida et al., 2015). Lee and Liou (2012) illustrated that approximately 26% of snow albedo reduction from March to April over the Sierra Nevada is caused by an increase in aerosol optical depth (AOD).

In California, aerosols can be generated locally or transported from remote sources. Among local aerosol types, dust comprises a significant fraction over California (Wu et al., 2017). Based on a four-month, high intensity record of size-segregated particulate matter (PM) samples collected from a high elevation site, Vicars and Sickman (2011) found that the mass concentration of coarse atmospheric PM in the southern Sierra Nevada, California, was dominated by contribution from dust (50-80%) throughout the study period. Dust aerosols can exert important impact on radiative forcing and regional climate in California through its interaction with radiation (e.g., Zhao et al., 2013a) as well as its role as cloud condensations nuclei for cloud formation (e.g., Fan et al., 2014). Anthropogenic aerosols are geographically distributed because of localized emission sources, the short atmospheric residence time, and regional topography. With valleys and surround mountain barriers, dispersion of air pollutants is more difficult for locally emitted anthropogenic air pollution.~~Anthropogenic aerosols are geographically distributed because of localized emission~~

~~sources and the short atmospheric residence time.~~ The anthropogenic aerosols can cause changes in atmospheric circulation and regional climate especially where the aerosol concentrations are high and the synoptic atmospheric systems are not prominent (e.g., Qian et al., 2003; Fast et al., 2006; Rosenfeld et al., 2008a; Zhao et al., 2013a).

Besides the local aerosol sources, the atmospheric transport of aerosol pollutants from the Asian continent (e.g., Jiang et al., 2007; Wang et al., 2015; Hu et al., 2016) is also a significant contributor to aerosol loading throughout the Pacific basin. Asian aerosols can reach relatively high concentrations above the marine boundary layer in the western US, representing as much as 85% of the total atmospheric burden of PM at some sites (VanCuren, 2003). Trans-Pacific dust transport has been found to be particularly relevant in high-elevation regions such as the Sierra Nevada, which typically represents free-tropospheric conditions due to the limited transport of lowland air pollutants and predominance of upper air subsidence (VanCuren et al., 2005). Observations from the CalWater campaign demonstrated that dust and biological aerosols transported from northern Asia and the Sahara were present in glaciated high-altitude clouds in the Sierra Nevada coincident with elevated ice nuclei (IN) particle concentrations and ice-induced precipitation (Ault et al., 2011; Creamean et al., 2013).

Aerosols can influence precipitation, snowpack and regional climate through three pathways: (1) aerosol-radiation interaction (ARI, also known as aerosol direct effect), which can warm the atmosphere but cool the surface, resulting in changes in thermodynamic environment for cloud and precipitation and the delay of the snowmelt (Charlson et al., 1992; Kiehl and Briegleb, 1993; Hansen et al., 1997; Koren et al., 2004; Gu et al., 2006, 2016, 2017); (2) aerosol-cloud interaction (ACI, also known as aerosol indirect effect), which is related to aerosols serving as cloud condensation nuclei (CCN) and IN. By changing the size distribution of cloud droplets and ice particles, aerosol may affect cloud microphysics, radiative properties and precipitation efficiency, thus affect the atmospheric hydrological cycle and energy balance (Twomey, 1977; Jiang and Feingold, 2006; Rosenfeld et al., 2008b; Qian et al., 2009b; Gu et al., 2012b); (3) aerosol-snow interaction (ASI). When aerosols (mainly absorbing aerosols, such as dust and black carbon) are deposited on snowpack, they can reduce snow albedo and affect snowmelt (Warren and Wiscombe, 1985; Jacobson, 2004; Flanner et al., 2007; Qian et al., 2011, 2015; Zhao et al., 2014). Numerical experiments have shown that ARI reduces the surface downward radiation fluxes, cools the surface and warms the atmosphere over California (Kim et al., 2006; Zhao et al., 2013a), which could subsequently impact clouds, precipitation and snowpack. In a 2-D simulation, Lynn et al. (2007) shows that ACI decreases orographic precipitation by 30% over the length of the mountain slope. Fan et al. (2014) showed that ACI increases the accumulated precipitation of an Atmospheric River event by 10-20% from the Central Valley to the Sierra Nevada due to a ~40% increase in snow formation. Snow impurities (ASI) increase ground temperature, decrease snow water, shorten snow duration and cause earlier runoff (Jacobson, 2004; Painter et al., 2007, 2010; Qian et al., 2009a; Waliser et al., 2011; Oaida et al., 2015).

Although recent studies showed that aerosols can substantially influence precipitation and snowpack in California, they focused only on one of the aerosol sources or on a single event or one pathway. A complete account of the aerosol impacts from different sources through three pathways on regional climate in California has not been presented yet. The objective of this study is to investigate the impacts of various aerosol sources on seasonal precipitation and snowpack in California. A fully coupled high-resolution aerosol-meteorology-snowpack model will be used. We will distinguish and quantify the impacts of aerosols from local emissions and transport, and the roles of different prevailing aerosol types in California, particularly dust and anthropogenic aerosols. In Section 2, we describe the WRF-Chem model employed and experiments designed to understand the impact of aerosols on precipitation and snowpack in California. Results from model simulations are discussed in Section 3. Concluding remarks are given in Section 4.

## 2. Model Description and Experiment Design

This study uses a version of the Weather Research and Forecasting (WRF) model with chemistry (WRF-Chem; Grell et al., 2005) improved by the University of Science and Technology of China (USTC) based on the public-released version 3.5.1 (Zhao et al., 2014). ASI is implemented in this WRF-Chem version by considering aerosol deposition on snowpack and the subsequent radiative impacts through the SNow, ICe, and Aerosol Radiative (SNICAR) model (Zhao et al., 2014). The SNICAR model is a multilayer model that accounts for vertically heterogeneous snow properties and heating and influence of the ground underlying snow (Flanner and Zender, 2005; Flanner et al., 2007, 2009, 2012). The SNICAR model uses the theory from Wiscombe and Warren (1980) and the two-stream, multilayer radiative approximation of Toon et al. (1989). SNICAR simulates snow surface albedo as well as the radiative absorption within each snow layer. It can also simulate aerosol content and radiative effect in snow, and was first used to study the aerosol heating and snow aging in a global climate model by Flanner et al. (2007). Simulated change of snow albedo by SNICAR for a given black carbon concentration in snow has been validated with recent laboratory and field measurements (Brandt et al., 2011; Hadley and Kirchstetter, 2012). More detailed description of the SNICAR model can be found in Flanner and Zender (2005) and Flanner et al. (2007, 2012).

The MOSAIC (Model for Simulating Aerosol Interactions and Chemistry) aerosol model (Zaveri et al., 2008) with the CBM-Z (carbon bond mechanism) photochemical mechanism (Zaveri and Peters, 1999) is used and coupled with the SNICAR model. The MOSAIC aerosol scheme uses the sectional approach to represent aerosol size distributions with a number of discrete size bins, either four or eight bins in the current version of WRF-Chem (Fast et al., 2006). In this study, aerosol particles are partitioned into four-sectional bins with dry diameter within 0.039-0.156 μm, 0.156-0.625 μm, 0.625-2.5 μm, and 2.5-10.0 μm. The 4-bin approach has been examined in dust simulations and proved to reasonably produce dust mass loading and AOD compared with the 8-bin approach (Zhao et al., 2013b). All major aerosol components including sulfate, nitrate, ammonium, black carbon, organic matter, sea salt, and mineral dust are simulated in the model. The MOSAIC aerosol scheme includes physical and chemical processes of nucleation, condensation, coagulation, aqueous phase chemistry, and water uptake by aerosols. Dry deposition of aerosol mass and number is simulated following the approach of Binkowski and Shankar (1995), which includes both particle diffusion and gravitational effects. Wet removal of aerosols by grid resolved stratiform clouds/precipitation includes in-cloud removal (rainout) and below-cloud removal (washout) by impaction and interception, following Easter et al. (2004) and Chapman et al. (2009). In this study, cloud-ice-borne aerosols are not explicitly treated in the model but the removal of aerosols by the droplet freezing process is considered. Aerosol optical properties such as extinction, single scattering albedo (SSA), and asymmetry factor for scattering are computed as a function of wavelength for each model grid box. Aerosols are assumed internally mixed in each bin, i.e., a complex refractive index is calculated by volume averaging for each bin for each chemical constituent of aerosols (Barnard et al., 2010; Zhao et al., 2013a). The Optical Properties of Aerosols and Clouds (OPAC) data set (Hess et al., 1998) is used for the shortwave (SW) and longwave (LW) refractive indices of aerosols, except that a constant value of 1.53+0.003i is used for the SW refractive index of dust following Zhao et al. (2010, 2011). A detailed description of the computation of aerosol optical properties in WRF-Chem can be found in Fast et al. (2006) and Barnard et al. (2010).

ARI is included in the radiation scheme as implemented by Zhao et al. (2011). The optical properties and direct radiative forcing of individual aerosol species in the atmosphere are diagnosed following the methodology described in Zhao et al. (2013a). ~~Calculation of ~~T~~t~~he activation and re-suspension between dry aerosols and cloud droplets are~~ was~~ included in the model as shown in~~by~~ Gustafson et al. (2007). By linking simulated cloud droplet number with shortwave radiation and microphysics schemes, ACI is effectively simulated in the model (Chapman et al., 2009).

The model setups (Table 1), including the physical schemes used, follow Wu et al. (2017), which showed that the model simulations reasonably captured the distribution and variation of aerosols in the San Joaquin Valley. ~~Note that convective processes are resolved in the 4 km simulations. One important subgrid process in climate models is the representation of deep convection. Parameterizing deep convection is challenging and the use of convection parameterization schemes leads to common errors such as misrepresentation of the diurnal cycle of convective precipitation (e.g., Dai et al., 1999; Brockhaus et al., 2008), underestimation of dry days (e.g., Bergetal., 2013) and hourly precipitation intensities (e.g., Prein et al., 2013; Fosser et al., 2014; Ban et al., 2014), and overestimation of low-precipitation event frequency (e.g., Bergetal., 2013). Although recently developed parameterization schemes lead to improvements of several of these common errors including the simulation of precipitation intensities (Donner et al., 2011), intraseasonal variability (Benedict et al., 2013), and diurnal cycles (Bechtold et al., 2014), a promising remedy to the error-prone model simulations using convective parameterizations is~~

~~the use of convection-permitting model with horizontal grid spacing of about 4 km or less (e.g., Satoh et al., 2008; Prein et al., 2013; Ban et al., 2014). Advances in high-performance computing allowed refinement of the numerical grids of numerical models well beyond 10 km. At these scales, convection parameterization schemes may eventually be switched off as deep convection starts to be resolved explicitly (e.g., Weisman et al., 1997). According to Prein et al. (2014), it seems prudent to use horizontal grid spacing of 4 km or less for convection-permitting model simulations. ARI is included in the radiation scheme as implemented by Zhao et al. (2011). The optical properties and direct radiative forcing of individual aerosol species in the atmosphere are diagnosed following the methodology described in Zhao et al. (2013a). Calculation of the activation and re-suspension between dry aerosols and cloud droplets was included in the model by Gustafson et al. (2007). By linking simulated cloud droplet number with shortwave radiation and microphysics schemes, ACI is effectively simulated in the model (Chapman et al., 2009).~~

The model domain covers the Western US centered at 38°N and 121°W, as shown in Fig. 1. The horizontal resolution is 4 km × 4 km together with a vertical resolution of 40 model levels. Model integrations with a time step of 20 seconds have been performed for 10 months (with the first month used for the model spin-up) starting on September 1, 2012, at 00:00UTC till the end of June 2013 to cover the major precipitation and snow seasons. To test the robustness of the results, s~~S~~imulations are also conducted ~~have also been done~~ for year 2013-2014, and similar results are found. In the following ~~result~~ section, our analysis focuses on year 2012-2013, while quantitative information of the aerosol impacts for year 2013-2014 is provided for comparison.

Note that convective processes are resolved in the 4 km simulations. One important subgrid process in climate models is the representation of deep convection. Parameterizing deep convection is challenging and the use of convection parameterization schemes leads to common errors such as misrepresentation of the diurnal cycle of convective precipitation (e.g., Dai et al., 1999; Brockhaus et al., 2008), underestimation of dry days (e.g., Bergetal., 2013) and ~~hourly~~ precipitation intensity~~ies~~ (e.g., Prein et al., 2013; Fosser et al., 2014; Ban et al., 2014), and overestimation of low-precipitation ~~event~~ frequency (e.g., Bergetal., 2013). Although recently developed parameterization schemes lead to improvements in ~~of several of these common errors including~~ the simulation of precipitation intensity~~ies~~ (Donner et al., 2011), intraseasonal variability (Benedict et al., 2013), and diurnal cycles (Bechtold et al., 2014), a promising remedy to the error-prone model simulations using convective parameterizations is the use of convection-permitting horizontal resolution ~~model~~ with ~~horizontal~~ grid spacing of about 4 km or less (e.g., Satoh et al., 2008; Prein et al., 2013; Ban et al., 2014). Advances in high-performance computing allowed refinement of the model ~~numerical~~ grids ~~of numerical models~~ well below~~eyond~~ 10 km. At these scales, convection parameterization schemes may ~~eventually~~ be switched off as deep convection starts to be resolved explicitly (e.g., Weisman et al., 1997). According to Prein et al. (2014), it seems prudent to use horizontal grid spacing of 4 km or less for convection-permitting model simulations. The 4 km simulation can also represent topography and inhomogeneous distribution of anthropogenic emission and precipitation better, leading to a better representation of aerosol distribution comparing to the 20 km simulation (Wu et al., 2017).

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 of the 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. To examine the overall aerosol effects and the roles of locally generated and transported aerosols, the following five experiments have been designed (Table 2):

1) CTRL: This is the control experiment with all aerosol emissions and transports included in the simulation.

2) NoLocDust: This experiment is performed without any local dust emission. Differences between the CTRL and NoLocDust experiments illustrate the effect of dust aerosols locally emitted.

3) NoLocAnth: This experiment is similar to NoLocDust, except that emissions of local anthropogenic aerosols are turned off. Comparison between CTRL and this experiment will elucidate the effect of local anthropogenic aerosols.

4) NoTran: The initial and boundary chemical conditions in the CTRL simulation are taken from the global Model for Ozone and Related Chemical Tracers, version 4 (MOZART-4; Emmons et al., 2010). The chemical species transported into the model domain include organic carbon, black carbon, sulfate, nitrate, ammonium, sea salt, dust, etc.. In the NoTran~~is~~ experiment, aerosols transport from outside the model domain, including those from East Asia and other regions, are~~is~~ not considered by setting the lateral boundary conditions for aerosols to zero. ~~The initial and boundary chemical conditions are taken from MOZART-4 global chemical transport model. The chemical species transported into the model domain include organic carbon, black carbon, sulfate, nitrate, ammonium, sea salt, dust, etc..~~ Differences between CTRL and ~~this experiment~~NoTran will show the effect of transported aerosols.

5) CLEAN: This experiment is performed without any local aerosol emissions or transport from outside the model domain while all the transported chemical species are kept, and therefore

represents a scenario of clean condition. Aerosols are low in the simulation, but not zero, possibly due to aerosol chemistry. The CCN concentration at supersaturation of 0.1% is ~~ino more than~~on the order of 10~~0~~ ~~on the order of 50~~ cm$^{-3}$ at ~~throughout~~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. Differences between the CTRL and CLEAN experiments would illustrate the effects of all primary aerosol types, including those locally emitted and transported from outside the domain.

In order to distinguish the pathways through which the aerosols influence the precipitation and snowpack, we also conducted a few other experiments (Table 3):

6) NARI: This experiment is similar to the CTRL run, except that ARI is not included. Comparison between CTRL and this experiment will elucidate the effect of ARI.

7) NASI: This experiment is similar to the CTRL run, except that ASI is not included. Comparison between CTRL and this experiment will show the effect of ASI.

8) NARS: This experiment is similar to the CTRL run~~In this experiment~~, except that both ARI and ASI are not included. By comparing this experiment and CLEAN, the effect due to ACI can be examined.

## 3. Model Simulation Results

### 3.1 Validation of Model Results

Since our focus is on the changes in precipitation and snowpack due to aerosol effects, we first show the spatial distribution of averaged results over the period from October 2012 to June 2013 when snow normally presents over the Sierra Nevada. Figure 2 illustrates a few important and relevant variables that the model simulates in the CTRL experiment, including liquid water path (LWP), ice water path (IWP), precipitation, snow water equivalent (SWE), and temperature at two meters (T2) above the ground. 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. Here, the model simulated SWE is the mean value of the accumulated SWE from ~~at~~ 3-hourly model outputs. It is shown that clouds (Fig~~s~~. 2a ~~&~~and 2b), precipitation (Fig. 2c), ~~and~~ snowpack (Fig. 2d), and surface runoff (Fig. S1) mostly occur over the Sierra Nevada and Klamath Mountains in ~~the~~ northern California. ~~Here, model simulated SWE is the mean value of SWE at each time step.~~ For temperature (Fig. 2e), the central valley area appears to be relatively warm with two maxima over the northern and southern part of the central valley, respectively, while colder temperatures ~~is~~ are found over the mountain ranges. The model-simulated precipitation is compared with corresponding observations from the Parameter -elevation Regression on Independent Slopes Model (PRISM, 2004) gridded data product at 4 km resolution ~~the Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Daily Precipitation product at 0.25° × 0.25° resolution~~ (Fig. 2f). Note that the ~~rain~~precipitation rate in comparison here is for total precipitation, including rainfall~~,~~ ~~snow, and ice~~ and ice-phase particles. Compared to the ~~CPC~~ PRISM observations, the model successfully captures the precipitation pattern, including the locations of the major precipitation centers, but slightly overestimates the magnitude over the Sierra Nevada.

In order to validate the simulated seasonal variations, the monthly mean model simulated precipitation and T2 are compared with observations (Fig~~s~~. 3a ~~&~~ and 3c). Model data are sampled onto observational sites before the comparison is conducted.

For precipitation observations, besides the ~~CPC~~ PRISM product, we also employ the Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Daily Precipitation product

(Chen et al., 2008) at 0.25° × 0.25° resolution and the gauge measurements from Department of Water Resources (DWR). Observed air temperature is obtained from the California Irrigation Management Information System (~~CIMIS; http://www.cimis.water.ca.gov/Snyderhttp://www.cimis.water.ca.gov/~~Snyder, 1984). For SWE, daily ~~mean~~ accumulated SWE simulations are compared with measurements collected at Snow Telemetry (SNOTEL) stations. SNOTEL ~~The use of the SNOTEL data, including known deficiencies, has been described in several studies (e.g., Serreze et al., 1999; Serreze et al., 2001; Johnson and Marks, 2004).~~ SWE is measured using a snow pillow sensor and biases in SWE measurement could occur when temperature differences between surrounding ground cover and the pillow sensor create uneven distribution of snow (Meyer et al., 2012). Both under- and over-estimation could happen depending on the snowmelt conditions and the snow density rate of change (Serreze et al., 1999; Serreze et al., 2001; Johnson and Marks, 2004).~~The main issue with weighing-type gauges for snowfall estimation is the undercatch of approximately 10%–15% due to wind (Serreze et al., 2001; Yang et al., 1998; Rasmussen et al., 2001).~~ ~~Model data are sampled onto observational sites before the comparison is conducted.~~

It is shown that the model captures the maximum precipitation in December, with the magnitude falling between the observations from CPC and PRISM/DWR during winter, which is the major rainy season in California (Fig. 3a). In the relative dry months from February to June, the simulated precipitation has similar magnitude to the observations, with slightly overestimation or underestimation in different months. For SWE, ~~given the possible underestimate of SNOTEL data,~~ the model simulations represent ~~reasonable magnitude and~~ seasonal variations of SWE with the maximum between March and April (Fig. 3b), but the model overestimates SWE amount comparing to SNOTEL. -While the model overestimates the surface temperature in magnitude, it captures the seasonal variations well, including the highest/lowest temperature in July/January, respectively (Fig. 3c). ~~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 simulated aerosols over California using this model have been validated extensively in Wu et al. (2017) by comparing to observations, such as MISR (Multiangle Imaging Spectroradiometer) and AERONET (Aerosol Robotic Network) AOD, CALIPSO (Cloud-Aerosol Lidar and Infrared pathfinder Satellite Observation) aerosol extinction, IMPROVE (Interagency Monitoring of Protected Visual Environments) and EPA CSN (National Chemical Speciation Network operated by Environmental Protection Agency) aerosol speciation. It has been shown than the model simulation used in this study reasonably captures the distribution and seasonal variation in aerosols during the cold season from October to March. The simulation of aerosols in the warm season from April to September (especially from July to September) has larger low biases than in the cold season, mainly due to poor simulations of dust emission and vertical mixing. Because the precipitation and snow mainly occur~~s~~ in October-June, we focus on the simulations from October to June with relative good performance on aerosol simulations in this study.

Here, we present the distributions of AOD averaged over October 2012 to June 2013 for the MISR (Diner et al., 1998) observation and all aerosols in the CTRL simulation, together with locally emitted aerosols and those transported from outside the model domain, derived from the difference between the CTRL simulation and the corresponding experiment (NoLocAnth, NoLocDust and NoTran), respectively, ~~together with the total aerosols from the CTRL experiment in Fig. 4~~ to facilitate the understanding of the aerosol effects in different regions and from different sources (Fig. 4). It is shown that the model simulation well captures the spatial distribution of AOD in California, including the maximum ~~of total AOD is located~~ over the southern part of the valley area and~~.~~ l~~L~~arger AODs ~~are also found~~ over the lower lands to the southeast of the Sierra Nevada (Fig. 4a and 4b). Note that the smoother contour in MISR is due to the coarser horizontal resolution (0.5-°) of the MISR data. The distribution of the locally emitted anthropogenic aerosols (Fig. ~~4b~~4c), which are mostly located over the central valley associated with the emissions from local industries and farms, presents a similar pattern to the total AOD and substantially contributes to the maxima AOD over the region. Local dust aerosols mainly reside over the lower lands to the southeast of the Sierra Nevada while substantial amounts are also seen over the central valley (Fig. ~~4c~~4d). 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~~4e).

Since the observations on aerosol-in-snow concentrations are rather limited both spatially and temporally, it's very difficult to conduct direct comparisons with model simulations. Here we evaluate the model simulations of snow albedo which is ~~the~~ directly a~~e~~ffected by the ~~of~~ ASI (Fig. S2). The model simulated snow albedo is compared with the product from NASA Land Data Assimilation Systems (NLDAS; Sheffield et al., 2003) Mosaic (MOS). It is shown that model simulation provides rather reasonable estimate of the snow albedo when ~~with~~ ASI is included. ~~Therefore~~Overall, 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.

### 3.2 Aerosol Effects on Precipitation and Snowpack

The overall aerosol effects, from all aerosol types and sources (including locally emitted and transported) through the three pathways (ARI, ASI~~ACI~~, and~~ ASI~~ ACI), can be examined from the differences between the experiments CTRL and CLEAN. The two-tailed Student's t test, in which deviations of the estimated parameter in either direction are considered theoretically possible, is applied to the 3-hourly data for each experiment in this study to measure the statistical significance of the simulations. Figure 5 shows the differences averaged over October 2012 to June 2013 in precipitation, SWE, and T2, where the dots represent differences of the ~~daily~~ 3-hourly data being statistically significant at above 90% level. Due to the aerosol effects, temperature decreases over the central valley, where most aerosols are located, while significant warming occurs over the mountain tops (Fig. 5c). Precipitation decreases over the Sierra Nevada (Fig. 5a), consequently leading to decreased SWE (Fig. 5b).

In order to understand how the aerosols affect these important variables, we examine the effects of ARI, ASI~~ACI~~, and ~~ASI~~ ACI separately.~~, where the contours are plotted only for~~In the following figures (Fig. 6 to Fig. 12), the differences ~~which~~ are statistically significant at ~~a significance level of 0.1~~70% level. It is seen that the major effect of ARI is to decrease the surface temperature over the whole domain through the scattering and absorption of solar radiation, with the maxima over the central valley where the aerosols are mostly located, contributing to the surface cooling caused by the total aerosols effects in that region (Fig. 6c). 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). The effect of ARI on rainfall is not very significant (Fig. 6a). 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 Nevada (Fig. 7b). The effect of ASI on precipitation is also minimal.

Figure 8 shows the effect of aerosols on clouds through ACI. When more aerosols are present in the atmosphere, more ~~cloud condensation nuclei (CCN)~~CCN are available for the formation of clouds with smaller cloud droplets. As a result, more non-precipitating clouds are produced when aerosol are included in the model. The enhanced LWP (Fig. 8a) is primarily produced by the ACI effect (Fig. 8c). There are no significant changes in IWP (including ice, snow, and graupel) because the aerosol effect on ice cloud formation is not explicitly treated in the model. The ACI effect leads to reduced precipitation and less SWE over the mountains (Figs. 9a ~~&~~ and 9b). Temperature decreases over the valley due to more clouds formed associated with the ACI effect. ~~Note that the negative differences shown here (Fig. 9c) are only significant at 70% level.~~ The increase in temperature over the mountain areas (Fig. 9c) is caused by the reduced snow amount, which results in weaker surface albedo (Fig. 9d) and enhanced solar absorption at the surface and overwhelms the decrease of temperature which may be caused by increased~~more~~ clouds.

Overall, aerosols affect surface temperature, precipitation, and snowpack in California through the three pathways. ACI plays a dominant role in increasing cloud water but reducing precipitation, leading to reduced SWE and surface runoff (Fig. S3) over the Sierra Nevada. ASI also reduces SWE due to the smaller snow albedo associated with dirty snow, leading to more surface absorption and snowmelt. ARI, on the other hand, slightly increases SWE through the cooling of the surface. For surface temperature, ARI and ACI contribute together to the cooling of the valley area, while ACI and ASI significantly warm the surface over the mountain tops. Note that for the ASI effect, warming of the snow cover area through aerosol induced snow-albedo~~aerosol-snow albedo~~ feedback is the cause for the reduced SWE. For the ACI effect, however, warming over the mountain region is a result from the reduced SWE which can also induce snow-albedo feedback and result in ~~and hence~~ smaller surface albedo and more surface absorption of solar radiation.

Next, we examine the roles of local anthropogenic aerosols and local dust as well as transported aerosols. The effect of local anthropogenic aerosols can be discovered from the differences between CTRL and NoLocAnth. It is shown that local anthropogenic aerosols slightly suppress~~es~~ ~~the rainfall~~ precipitation (Fig. 10a) via ACI, leading to a reduced SWE (Fig. 10b) and a warming over the mountain tops (Fig. 10c). The cooling of the valley area, where locally emitted anthropogenic aerosols are mostly located (Fig. 4b), is associated with both the ARI effect and more non-precipitating clouds produced through ACI. Dust aerosols emitted from local sources mainly warm the surface through the reduction of snow albedo (ASI, Fig. 11c), consequently enhancing the snowmelt and leading to the reduced SWE (Fig. 11b). Local dust aerosols~~, mostly generated from the area to the southeast of Sierra Nevada,~~ ~~do not seem to~~ have no significant effect on precipitation (Fig. 11a).

Note that the effects of local anthropogenic and dust aerosols do not seem to be able to explain the total effects of aerosols as seen in Fig. 5, raising the question whether the transported aerosols play an important role in the precipitation and snowpack over the Sierra Nevada. Figure 12 illustrates the impact of aerosols transported from outside the model domain. It is shown that transported aerosols ~~also~~ reduce the precipitation through ACI (Fig. 12a), which exceeds the ARI effect and leads to decreased SWE and increased temperature over the southern part of the Sierra Nevada (Fig~~s~~. 12b ~~&~~and 12c). Over the central valley, as well as over the northern part of the Sierra Nevada, temperature decreases (Fig. 12c) due to the relatively larger ARI effect of the transported aerosols compared to the ACI effect, resulting in less snowmelt and increased SWE over that region (Fig. 12b).~~It is shown that transported aerosols also reduce the precipitation through ACI (Fig. 12a), leading to decreased SWE and increased temperature over the southern part of Sierra Nevada (Figs. 12b & 12c). Due to the ARI effect of the transported aerosols, temperature decreases over the central valley, as well as over the northern part of the Sierra (Fig. 12c), resulting in less snowmelt and increased SWE over that region (Fig. 12b).~~

The overall changes induced by aerosols for surface temperature (K) and precipitation, SWE, and surface runoff in percentage averaged over October to June are given in Table 4 for the whole domain (34-42 °N, 117-124 °W, not including ocean points), mountain tops (elevation ≥ 2.5 km), and lower elevations (elevation < 2.5 km). For the whole domain in year 2012-2013, temperature is cooled by 0.19 K due to aerosol ARI (−0.14 K), as well as ACI (−0.06 K) mainly associated with transported aerosols (−0.17 K), accompanied by reduction in precipitation, SWE, and surface runoff of about 7%, 3%, and 7%, respectively. Reduction in precipitation is mainly caused by ACI (−6.26%) associated with transported (−2.97%) and local anthropogenic (−1.02%) aerosols. For SWE, reduction is attributed to ACI (−2.67%) and ASI (−1.96%), while ARI contributes to ~~the~~ an increase (1.88%). Surface runoff is defined as water from ~~rain~~precipitation, snowmelt, or other sources that flows over the land surface, and is a major component of the hydrological cycle. Overall c~~C~~hanges in surface runoff are similar to those in precipitation, accompanied by contributions from changes in snowmelt~~Changes in surface runoff are similar to those in precipitation~~. For the mountain tops, warming of 0.22 K is found attributed to ASI (0.12 K) and ACI (0.17 K) associated with local dust and anthropogenic aerosols, respectively, with 10% or more reduction in ~~the~~ precipitation, snowpack, and surface runoff. Therefore, aerosols may contribute to California drought through both the warming of mountain tops and anomalously low precipitation over the whole area. For the lower elevations, the domain averaged changes are similar to those for the whole domain, except for SWE which slightly increases by 0.42% due to ARI (2.43%) with main contribution from transported aerosols (4.01%).

The simulations for year 2013-2014 are consistent with those in year 2012-2013 (Table 4). For the whole domain in year 2013-2014, temperature is cooled by 0.21 K due to aerosols, accompanied by reduction in precipitation, SWE, and surface runoff of about 6%, 9%, and 5%, respectively. Aerosol impacts on SWE is more significant in year 2013-2014 (−8.88%) than in year 2012-2013 (−3.17%), possibly due to less precipitation and SWE in year 2013-2014 than year 2012-2013 (not shown). The changes of SWE for year 2013-2014 are −15.57% for the mountain tops and 2.66% for the lower elevations. The relative change of surface runoff at the mountain tops in year 2013-2014 ~~is~~ is smaller than year 2012-2013 because the mean surface runoff in year 2013-2014 (0.33 mm day$^{-1}$) is larger than that in year 2012-2013 (0.27 mm day$^{-1}$), possibly contributed by less SWE and faster snowmelt at the mountain tops in year 2013-2014. The corresponding changes in evapotranspiration ~~is~~are −0.12% in year 2012-2013 and −1.20% in year 2013-2014~~5.08%,~~, respectively, which also contributes to the relatively smaller change ~~ange in~~of surface runoff in year 2013-2014 at the mountain tops.

## 3.3 Seasonal Variations of Aerosol Effects

Figure 13 depicts the monthly mean AOD for total aerosols (brown solid), local anthropocentric aerosols (green dashed), local dust (blue dashed), and transported aerosols (red dashed) averaged over the whole domain, ~~the~~ mountain tops, and lower elevation area from October 2012 to June 2013. It is seen that transported aerosols contribute to about two-thirds of the total AOD. The total AOD has two maxima, one in December and one in May, mainly associated with the seasonal variations of transported aerosols and local dust aerosols. Local d~~D~~ust

AOD starts to increase in March and reaches a maximum around May, while transported aerosol AOD peaks in April (Fig. 13a). The seasonal variations of AOD over the mountain tops and lower elevations are similar to those of the whole domain (Figs. 13b ~~&~~and 13c).

The monthly mean differences in precipitation due to the total aerosols (brown solid), ARI (green solid), ASI (blue solid), ACI (red solid), local anthropocentric aerosols (green dashed), local dust (blue dashed), and transported aerosols (red dashed) are shown in Fig. 14. Reduced precipitation is seen over the whole domain, with the most contribution from transported aerosols, followed by local anthropogenic aerosols, both of which play roles in precipitation changes through ACI as previously shown. ARI, ASI, or locally emitted dust aerosols do not seem to play an important role in the monthly mean precipitation changes (Fig. 14a). Two maxima of aerosol effects are found: one in December when it is the rainy season of the California (Fig. 3a) and at the same time relatively larger AOD presents over ~~the~~ this region (Fig. 13a); the other peak reduction in precipitation due to the aerosol effects is found in May with a value of about 0.2 mm day$^{-1}$ (Fig. 13a), probably associated with the maximum aerosols (Fig. 13a) and also the orographic precipitation over the mountain region ~~due to orographic forcing over~~ during that time period (Lee et al., 2015). Given that the monthly mean precipitation in May is only about 1 mm day$^{-1}$ (Fig. 3a), the reduction caused by aerosols is about 20%. For monthly mean precipitation, changes over the mountain tops and the lower elevation area, respectively, have similar seasonal variation patterns (Figs. 14b ~~&~~and 14c).

For SWE, however, changes over the mountain tops are different from those in the lower area (Fig. 15). For mountain tops, negative changes in SWE are seen over the whole time period, with a maximum reduction of about 60 mm in May corresponding to the maximum AOD (Fig. 15b). Major contribution is from local dust aerosols through ASI, as well as transported and local anthropogenic aerosols through ACI. ARI produces small positive changes (~ 5 mm in May) in SWE due to the scattering and absorption of solar radiation by aerosols which leads to surface cooling. For lower elevation area, slightly enhanced SWE is found during the winter time, associated with the effects of transported aerosols which produce more clouds through ACI, and together with the ARI effect, lead to the cooling of the surface and hence less snowmelt~~.~~ (Fig. 15c). Over the whole domain, SWE is reduced with a maximum of about 2 mm in May, equivalent to about 2% reduction, mainly attributed to the local dust particles through ASI, and local anthropogenic and transported aerosols through ACI (Fig. 15a).

Changes in temperature also exhibit different patterns over the mountain tops and the lower elevations (Fig. 16). Warming over the mountain tops is produced by dust aerosols through ASI with a maximum around May, and by transported aerosols through ACI during winter which leads to reduced precipitation and SWE with a maximum in January (Fig. 16b). Cooling over the lower elevation areas is caused by ARI, and also induced by more clouds generated in the model simulations due to transported aerosols through ACI, with a maximum cooling of about 0.3 K in April, corresponding to the maximum AOD of transported aerosols (Fig. 16c). The average temperature changes over the whole domain are negative because of the large area of the lower elevations (Fig. 16a).

~~Surface runoff is defined as water from rain, snowmelt, or other sources that flows over the land surface, and is a major component of the hydrological cycle.~~ Surface runoff reaches~~has~~ a maximum in December for the lower elevations and the ~~the~~ whole domain, but a peak value in May for mountain tops when the temperature is warmer (Fig. S4). 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 the 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 local 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 local dust aerosols and reduced precipitation caused by transported and local anthropogenic aerosols through ACI. Thus, the impact of aerosols is to speed up snowmelt at the mountain tops in spring and modify the seasonal cycle of surface runoff.~~Surface runoff is mainly associated with precipitation and the changes present a similar pattern to those in precipitation for the whole domain (Fig. 17a) and lower elevation areas (Fig. 17c), with most contribution from transported and anthropogenic aerosols. For the mountain tops, surface runoff 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. The decrease after April is a combined effect of 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.~~

## 4. Conclusions

A fully coupled high-resolution aerosol-meteorology-snowpack model is employed to investigate the impacts of various aerosol sources on precipitation and snowpack in California.

The relative roles of locally emitted anthropogenic and dust aerosols, and aerosols transported from outside ~~of~~ the model domain are differentiated through the three pathways, aerosol-radiation interaction (ARI), aerosol-snow interaction (ASI), and aerosol-cloud interaction (ACI). In the following summary, the numbers in brackets represent the domain averaged ~~mean~~ changes (Table 4).

**Temperature**: Local d~~D~~ust aerosols warm the mountain top surface~~s~~ through ASI (0.12 K), in which the reduced snow albedo associated with dirty snow leads to more surface absorption of solar radiation. Transported and local anthropogenic aerosols warm the surface of mountain tops through ACI (0.17 K), which produces more non-precipitating clouds but reduces precipitation and hence snow amount, leading to decreased surface albedo and more absorption of solar energy. The cooling of the valley area (–0.21 K) is primarily caused by the scattering and absorption of all aerosols through ARI (–0.14 K). Transported and anthropogenic aerosols can also cool the surface over the central valley through ACI (–0.07 K) that enhances cloud amount, leading to more reflection of solar radiation.

**Precipitation and SWE**: Reduced precipitation of –6.87% is found due to the aerosol effects and is mainly caused by transported and local anthropogenic aerosols through ACI (–6.26%). The maximum of aerosol effect on precipitation is found in December during the rainy season when the aerosols loadings are also relatively large. The other peak effect occurs in May with a reduction of about 20%, probably associated with the maximum of aerosol loadings and more orographic precipitation over the mountains. Locally emitted dust aerosols represent one of the most important contributors to the reduced SWE (–3.17%) through ASI (–1.96%), with the largest reduction in May corresponding to the maximum dust emission over that time. Local a~~A~~nthropogenic aerosols can also reduce SWE through ACI (–2.67%). On the other hand, ARI (2.43%) by all aerosols, with most contributions from the transported aerosols, exceeds the effects of ASI (−0.99%) and ACI (−0.27%) and slightly enhance SWE by 0.42% over lower elevations in winter time through the surface cooling.

**Surface runoff**: As a major component of the water cycle, surface runoff is mainly generated by precipitation, but for mountain tops, the changes in surface runoff are also associated with the changes in snowmelt. We find that the seasonal-mean ~~overall~~ surface runoff is reduced by −6.58% associated with suppressed precipitation, caused by transported and anthropogenic aerosols through ACI (−6.30%). Over mountain tops, runoff slightly increases in spring due to the enhanced solar absorption by dust aerosols. Runoff decreases after April as a combined effect of less snowpack available for melting caused by earlier snowmelt due to local dust and reduced precipitation due to transported and local anthropogenic aerosols through ACI. Therefore, one of the important impacts of aerosols is to speed up the snowmelt at mountain tops in spring and modify the seasonal cycle of surface runoff.

In summary, we find that the WRF-Chem model simulations with aerosol effects included would produce lower precipitation and SWE by about 10% and colder temperature by 0.2 K over California than the simulations without aerosols. Therefore, including aerosol effects can reduce the high biases of these variables in the simulations reported previously. Aerosols play an important role in California water resources through the warming of mountain tops and the subsequent modification of precipitation and snowmelt. The total aerosol effects produce a warming of 0.22 K over mountain tops and a reduction from October to June in precipitation, SWE, and surface runoff of about 7%, 3%, and 7%, respectively, for the whole domain, with corresponding numbers of 10% or more over mountain tops. In a dry year (year 2013-2014), aerosol can have more significant impacts on SWE, with a reduction of up to 9% for the whole domain and 16% over mountain tops.

It is ~~still quite~~ challenging to accurately represent aerosol properties in the model (Fast et al., 2014). As pointed out by Wu et al. (2017), biases exist in the current model as compared to observations, for example, underestimation of AOD due to poor representation of dust emission and vertical mixing in the warm season. The underestimate of AOD in the model implies that the simulated ~~-~~aerosol effects could also be biased low. Given the important~~ce~~ role that dust plays in the California snowpack, improved dust emission and vertical mixing are needed for accurate quantification of the impact of dust. Also, the underestimation of organic matter (associated with secondary organic aerosol processes) in the model (Wu et al., 2017), which are primarily scattering aerosols, would contribute to the high bias in the simulation of surface temperature. More accurate representation and simulation of these aerosols in the model are needed. In the current WRF-Chem model, the aerosol effect ~~of aerosol~~ on ice clouds is ~~has~~ not ~~been~~ 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 ~~INP~~ice~~-~~ nuclei~~nucleating particles~~) 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 ~~most~~ recent study shows that the responses of ice crystal effective radius ~~(Rei)~~ to aerosol loadings are modulated by water vapor amount in conjunction with several other meteorological parameters. While there is a significant negative correlation between ~~Rei~~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~~ion~~ regions, remains a challenging ~~unresolved~~ scientific issue~~, which has not been considered in the model consideration on a regional scale~~. 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 ~~based on~~ observations~~al~~ and model~~ing approache~~s.

Our model simulation produces relative larger SWE than the SNOTEL observations. Improvement of snowpack simulation in the land surface model is needed for ~~more~~ accurate quantification of aerosol impacts on snowpack. Our results are based on two years of simulations. Additional simulations under different meteorological conditions will help to better assess the aerosol impacts on California hydrology quantitatively.

## Data availability

The PRISM data are available through the following link: http://prism.oregonstate.edu/recent/. ~~at:~~ The CPC data are available through the following link: https://www.esrl.noaa.gov/psd/data/gridded/data.unified.daily.conus.html~~https://www.esrl.noaa.gov/psd/data/gridded/data.unified~~. The DWR data are available through the following link: http://cdec.water.ca.gov/snow_rain.html. The CIMIS data are available through the following link: http://wwwcimis.water.ca.gov/. The SNOTEL data are available through the following link: https://www.wcc.nrcs.usda.gov/snow/. The MISR data is available through the following link: https://misr.jpl.nasa.gov/getData/accessData/. The NLDAS MOS0125 albedo data are available through the following link: https://giovanni.gsfc.nasa.gov/giovanni/#service=TmAvMp&starttime=&endtime=&variableFac

ets=dataFieldMeasurement%3AAlbedo%3BdataProductPlatformInstrument%3ANLDAS%20Model%3BdataProductTimeInterval%3Amonthly%3B.

## Competing interests

The authors declare that they have no conflict of interest.

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## List of Table

Table 1. Model configuration

| Atmospheric Process | WRF-Chem option |
|---|---|
| Microphysics | Morrison double-moment |
| Radiation | RRTMG for both shortwave and longwave |
| Land surface | CLM4 with SNICAR included |
| Planetary boundary layer (PBL) | YSU |
| Cumulus | No cumulus scheme used |
| Chemical driver | CBM-Z |
| Aerosol driver | MOSAIC 4-bin |
| Anthropogenic emission | NEI05 |
| Biogenic emission | MEGAN |
| Biomass burning emission | GFEDV2.1 |
| Dust emission | DUSTRAN |
| Meteorological initial and boundary conditions | ERA-Interim |
| Chemical initial and boundary conditions | MOZART-4 divided by 2 |

Table 2. Experiment design for various aerosol sources.

| Experiment | Anthropogenic Aerosols | Dust Aerosol | Transport | Description |
|---|---|---|---|---|
| CTRL | Y | Y | Y | Control experiment with all aerosol emissions/transports included |
| NoLocDust | Y | N | Y | Local ~~D~~dust aerosol emission is not included |
| NoLocAnth | N | Y | Y | Local ~~A~~anthropogenic aerosol emissions are not included |
| NoTran | Y | Y | N | Aerosols transported~~s~~ from outside the model~~of~~ domain are not included |
| CLEAN | N | N | N | Aerosol emissions/transports are not included |

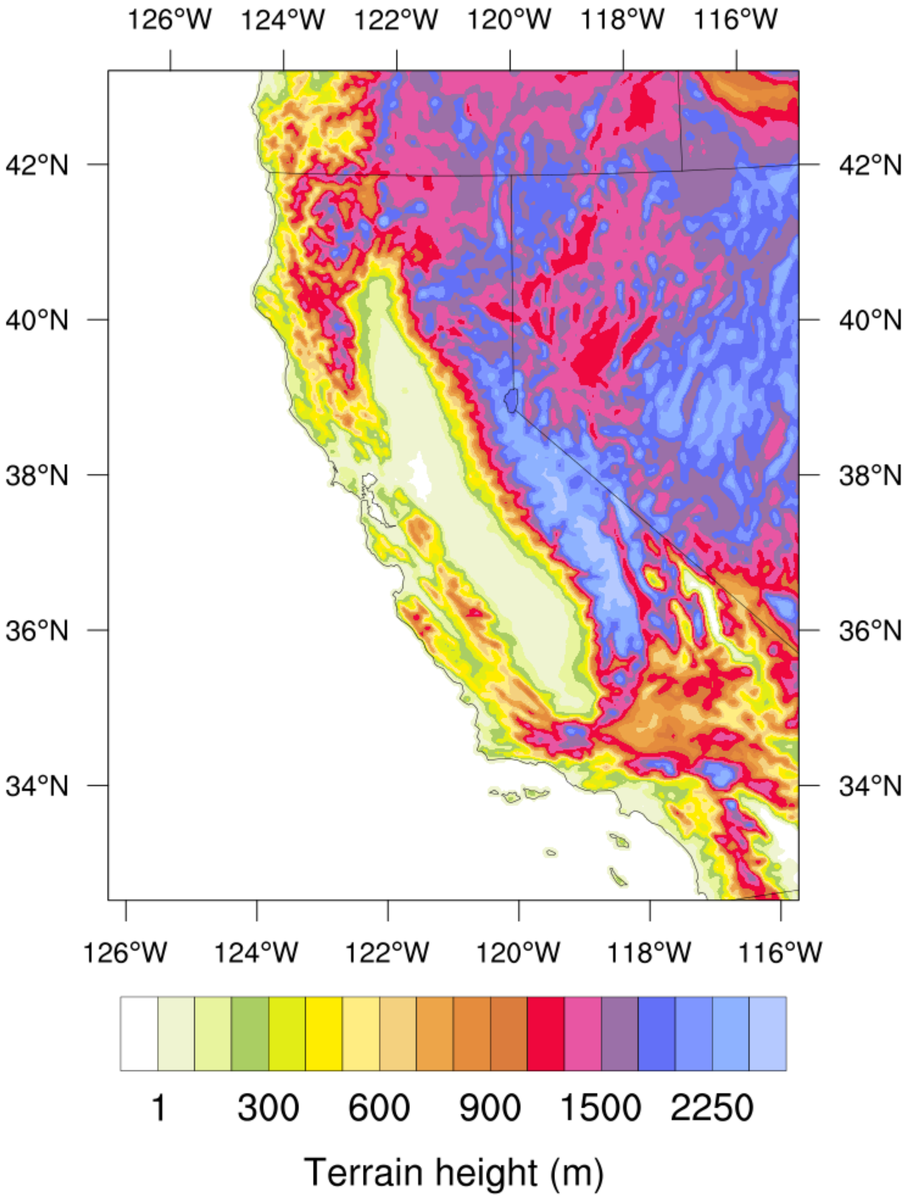
Table 3. Experiment design for various aerosol pathways, using the CTRL aerosol emissions.

| Experiment | ARI | ACI | ASI | Description |
|---|---|---|---|---|
| NARI | N | Y | Y | ARI is not included |
| NASI | Y | Y | N | ASI is not included |
| NARS | N | Y | N | ARI and ASI are not included |

Table 4. Changes in surface temperature (K) and precipitation, SWE, and surface runoff in percentage averaged over October 2012 to June 2013 due to overall and various aerosol effects for the whole domain (34-42 °N, 117-124 °W, not including ocean points), mountain tops (with elevation ≥ 2.5 km), and lower elevations ( < 2.5 km). Total impacts for the simulations from October 2013 to June 2014 are also included as “Total_13-14”.

| Region | Source/ pathway | T2 (K) | Precipitation (%) | SWE (%) | Surface runoff (%) |
|---|---|---|---|---|---|
| Whole Domain | Total | −0.19 | −6.87 | −3.17 | −6.58 |
| | Total_13-14 | −0.21 | −5.99 | −8.88 | −5.13 |
| | ARI | −0.14 | −0.47 | 1.88 | −0.21 |
| | ASI | 0.01 | −0.03 | −1.96 | 0.04 |
| | ACI | −0.06 | −6.26 | −2.67 | −6.30 |
| | LocAnth | −0.02 | −1.02 | −0.91 | −0.94 |
| | LocDust | 0.00 | −0.19 | −1.35 | 0.01 |
| | Tran | −0.17 | −2.97 | 1.89 | −2.90 |
| Mountain Tops | Total | 0.22 | −11.53 | −10.50 | −9.58 |
| | Total_13-14 | 0.15 | −9.90 | −15.57 | −3.55 |
| | ARI | −0.09 | −0.61 | 0.76 | −0.49 |
| | ASI | 0.12 | 0.26 | −3.94 | 1.10 |
| | ACI | 0.17 | −11.03 | −7.57 | −10.25 |
| | LocAnth | 0.03 | −1.75 | −1.60 | −2.06 |
| | LocDust | 0.10 | 0.31 | −2.99 | 1.49 |
| | Tran | −0.02 | −5.25 | −2.43 | −4.76 |
| Lower Elevations | Total | −0.21 | −6.62 | 0.42 | −6.42 |
| | Total_13-14 | −0.22 | −5.75 | 2.66 | −5.26 |
| | ARI | −0.14 | −0.46 | 2.43 | −0.19 |
| | ASI | 0.00 | −0.04 | −0.99 | −0.01 |
| | ACI | −0.07 | −6.00 | −0.27 | −6.09 |
| | LocAnth | −0.03 | −0.98 | −0.57 | −0.89 |
| | LocDust | 0.00 | −0.22 | −0.55 | −0.07 |
| | Tran | −0.17 | −2.85 | 4.01 | −2.81 |

# List of Figures



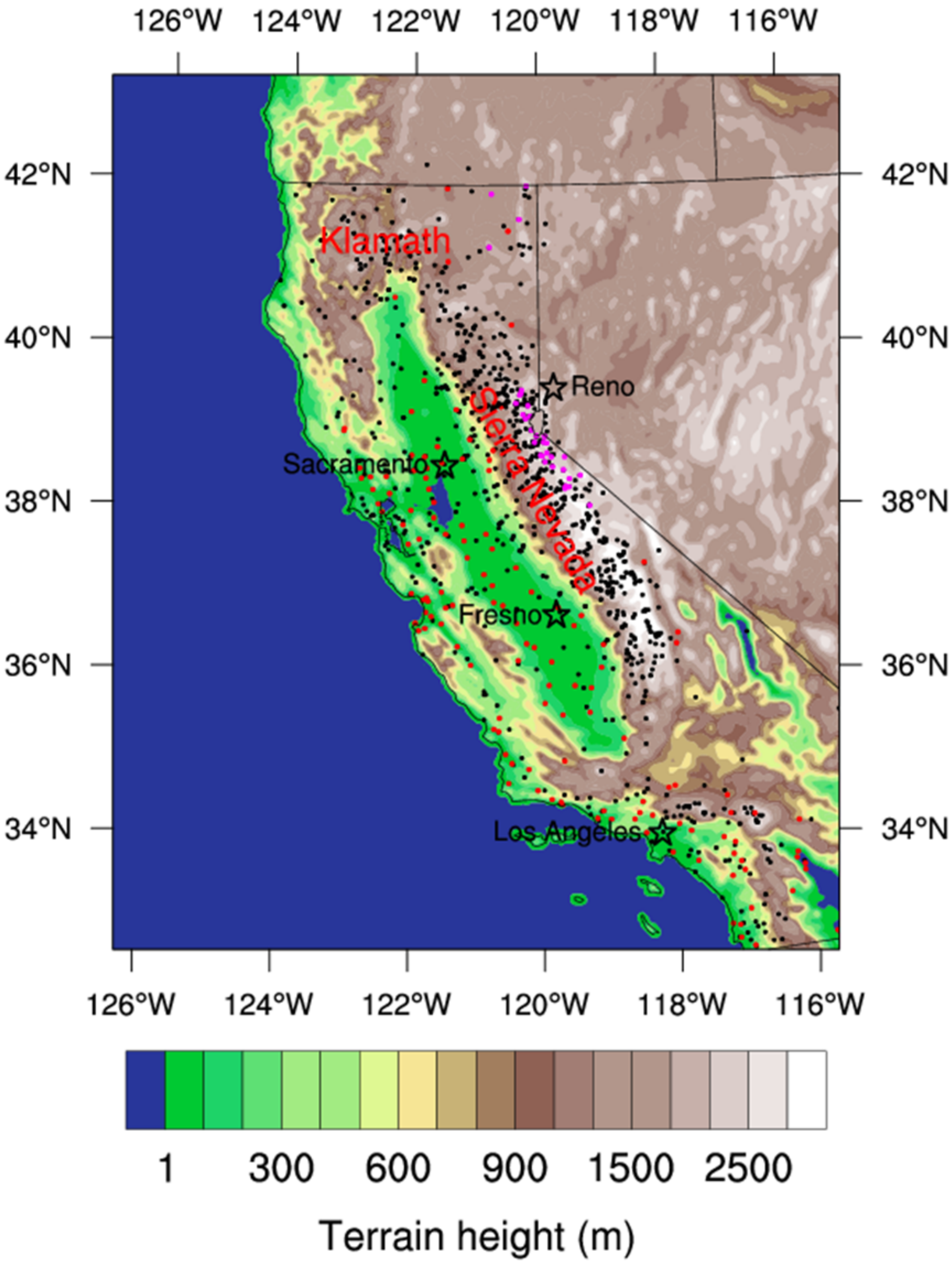
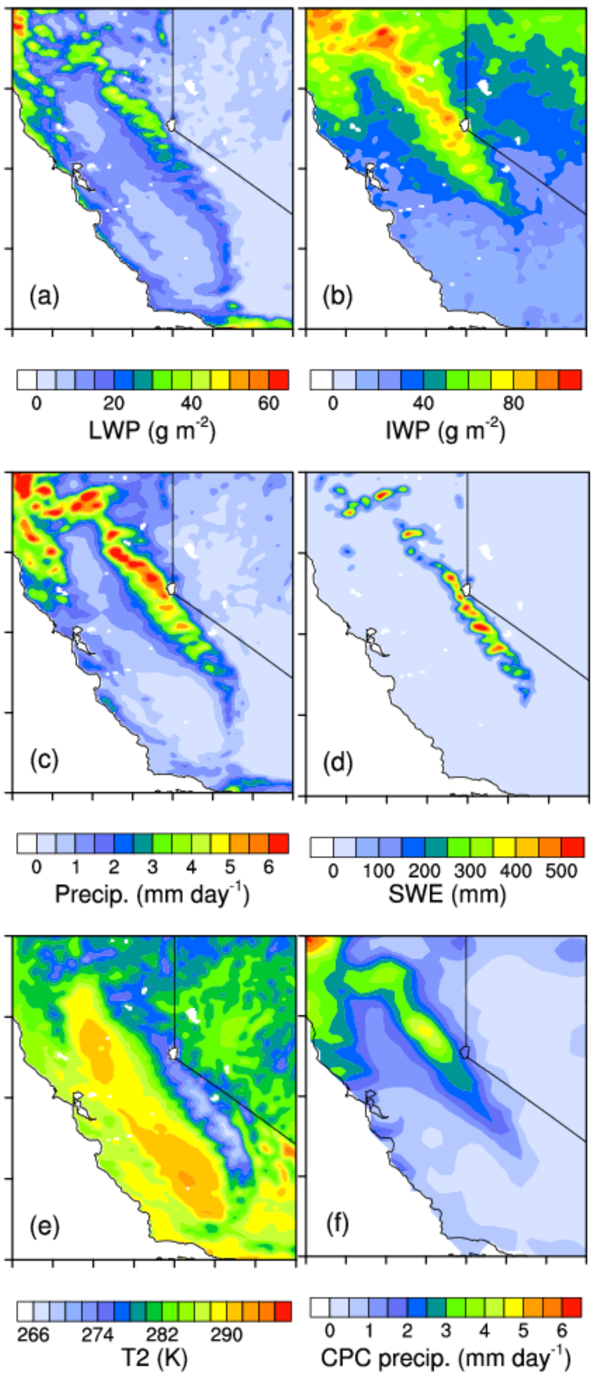


Figure 1. Model domain and terrain height (m). 991 DWR sites are represented by black dots; 138 CIMIS stations are represented by red dots; 32 SNOTEL sites are represented by magenta dots.


(a)
(b)
0 20 40 60
LWP (g m$^{-2}$)
0 40 80
IWP (g m$^{-2}$)
(c)
(d)
0 1 2 3 4 5 6
Precip. (mm day$^{-1}$)
0 100 200 300 400 500
SWE (mm)
(e)
(f)
266 274 282 290
T2 (K)
0 1 2 3 4 5 6
CPC precip. (mm day$^{-1}$)

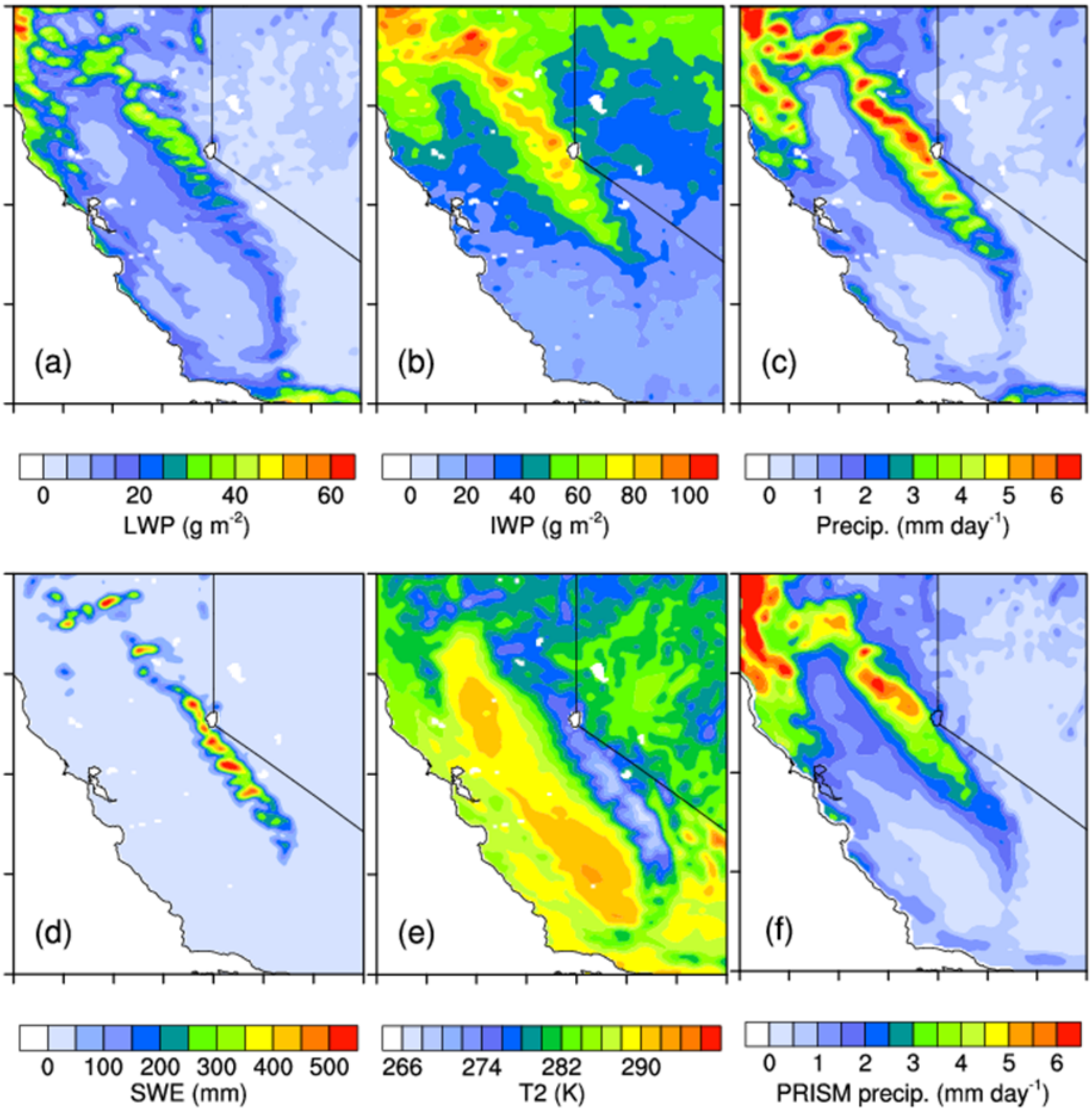
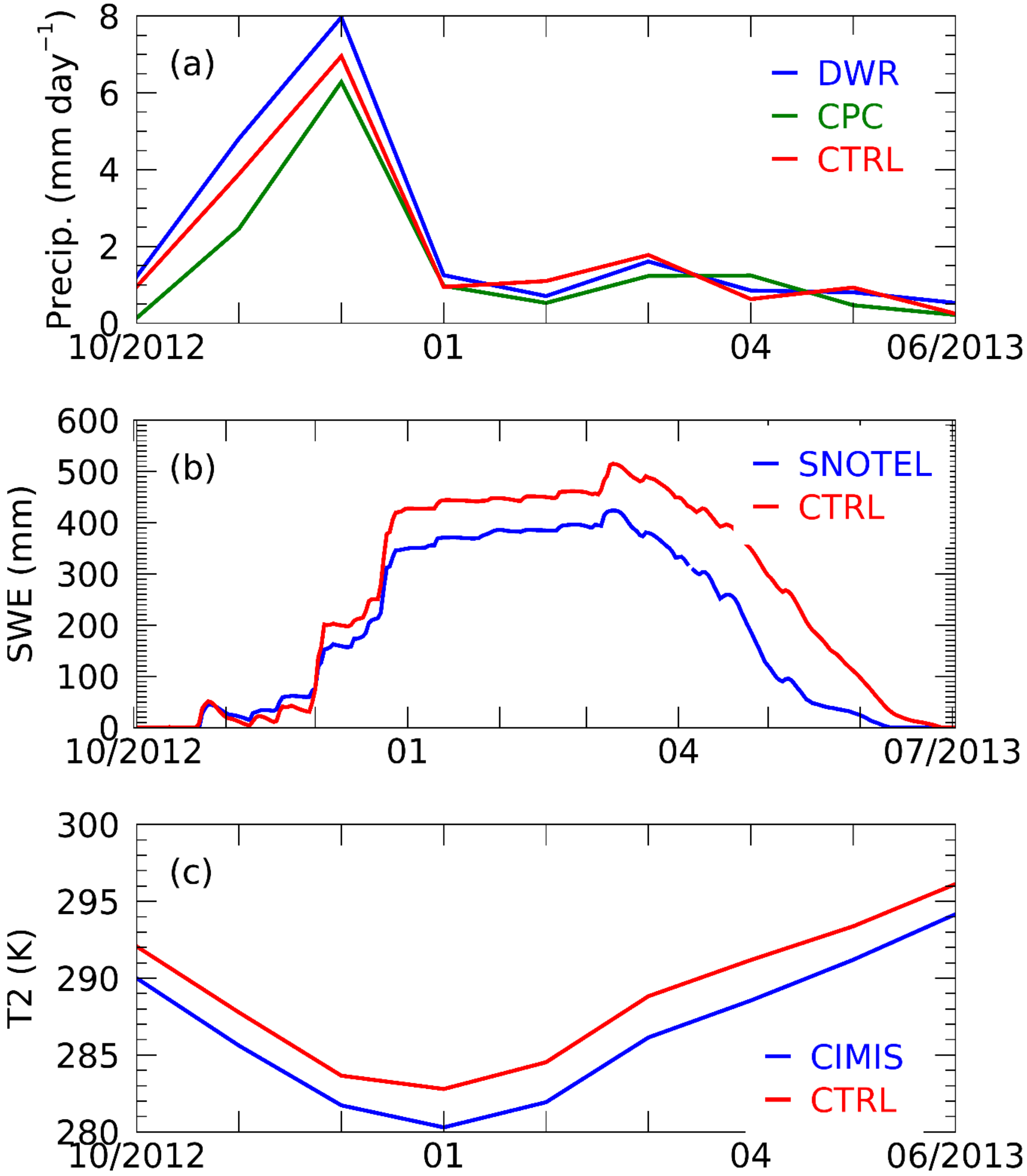


Figure 2. Model simulated (a) LWP (g m$^{-2}$), (b) IWP (g m$^{-2}$), (c) precipitation (mm day$^{-1}$), (d) SWE (mm), and (e) temperature at 2 meters, T2 (K) from ~~experiment~~ the CTRL simulation, and (f) ~~CPC~~ PRISM observed precipitation (mm day$^{-1}$), averaged over October 2012 to June 2013.


Precip. (mm day$^{-1}$)
8
6
4
2
0
(a)
DWR
CPC
CTRL
10/2012
01
04
06/2013
SWE (mm)
600
500
400
300
200
100
0
(b)
SNOTEL
CTRL
10/2012
01
04
07/2013
T2 (K)
300
295
290
285
280
(c)
CIMIS
CTRL
10/2012
01
04
06/2013

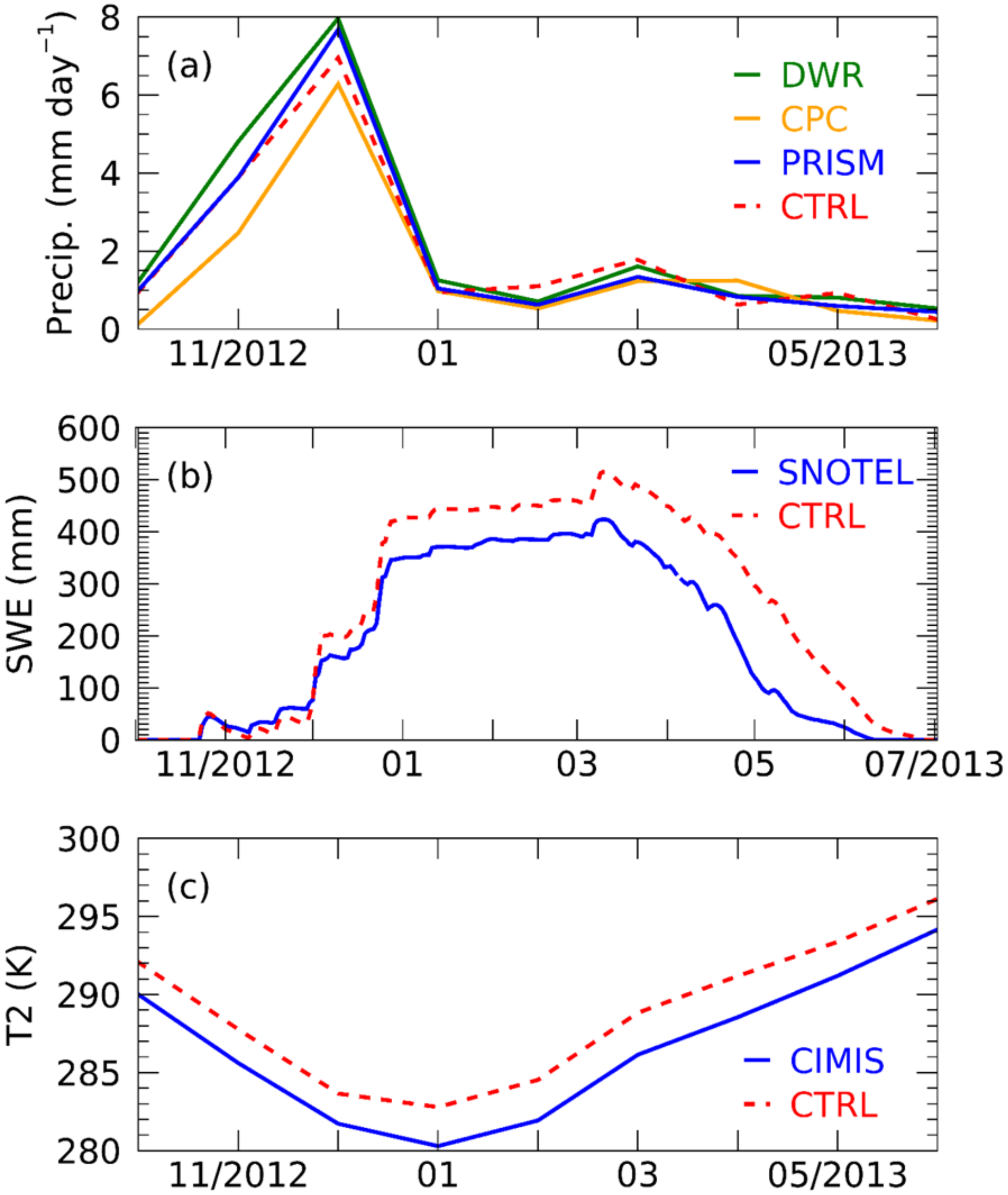


Figure 3. (a) Monthly mean precipitation (mm day$^{-1}$) ~~simulated~~ from the CTRL simulation (red ~~curve~~dashed) and ~~the observations from~~PRISM (blue), CPC (~~green~~orange) and DWR (~~blue~~green) observations; (b) Daily ~~mean~~ accumulated SWE (mm) ~~simulated~~ from the CTRL simulation (red dashed) and ~~observed at~~ SNOTEL ~~stations~~ observation (blue); and (c) Monthly mean T2 (K) ~~simulated~~ from the CTRL simulation (red) and ~~the observations from~~ CIMIS observation (blue). Model data are sampled onto observational sites before the comparison is conducted.

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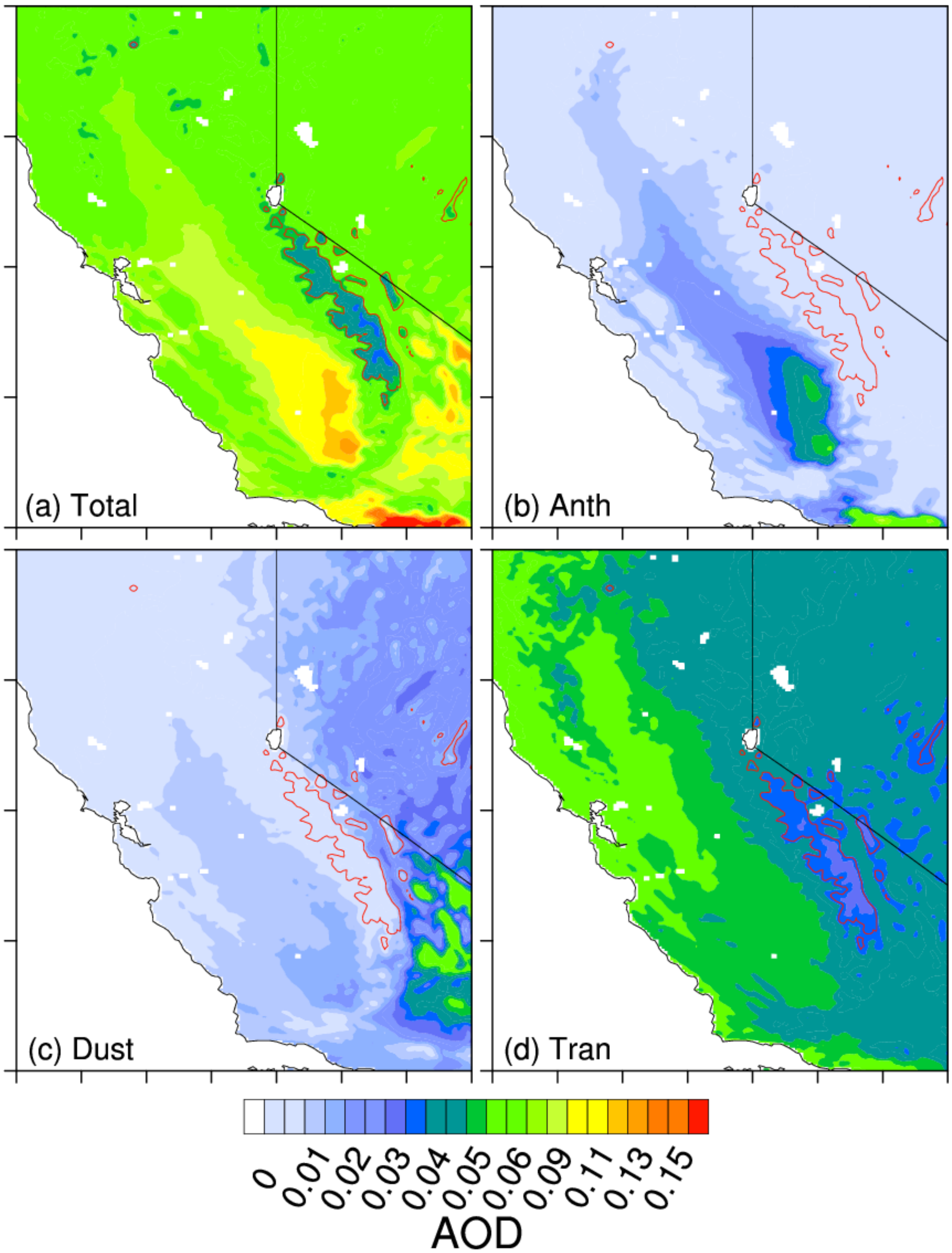

(a) Total
(b) Anth
(c) Dust
(d) Tran
0
0.01
0.02
0.03
0.04
0.05
0.06
0.09
0.11
0.13
0.15
AOD

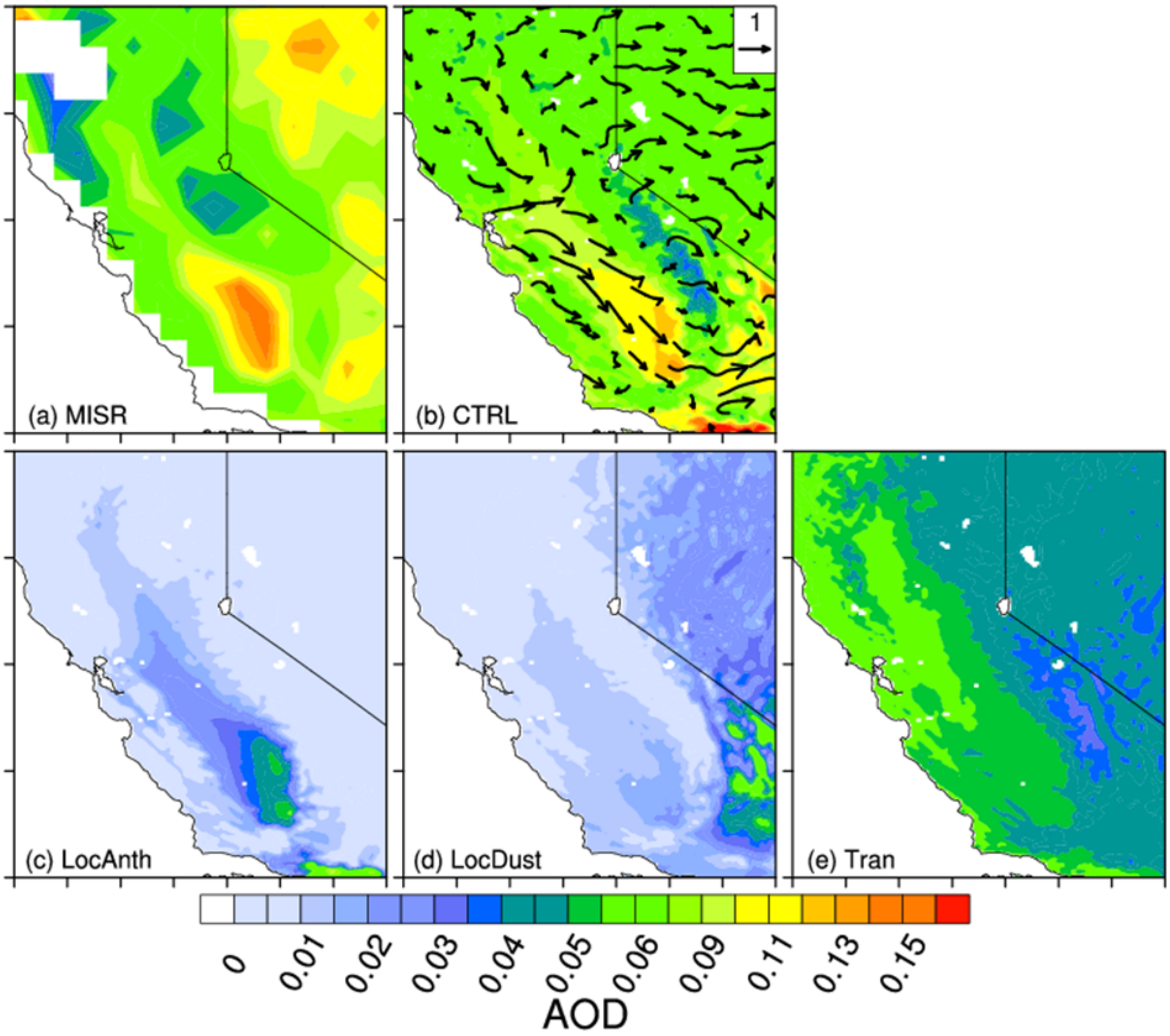


Figure 4. Spatial distribution of aerosol optical depth (AOD) averaged over October 2012 to June 2013 for (a) MISR observations, (b) all aerosols in the CTRL simulation, (c~~b~~) local anthropogenic aerosols, (d~~c~~) local dust aerosols, and (e~~d~~) transported aerosols from outside the domain, derived from the difference between the CTRL simulation and the corresponding experiment (NoLocAnth, NoLocDust and NoTran), respectively. 10-m wind vectors from the CTRL simulation is shown in (b)~~simulated from CTRL~~. ~~Red lines represent the mountain tops with elevation ≥ 2.5 km.~~

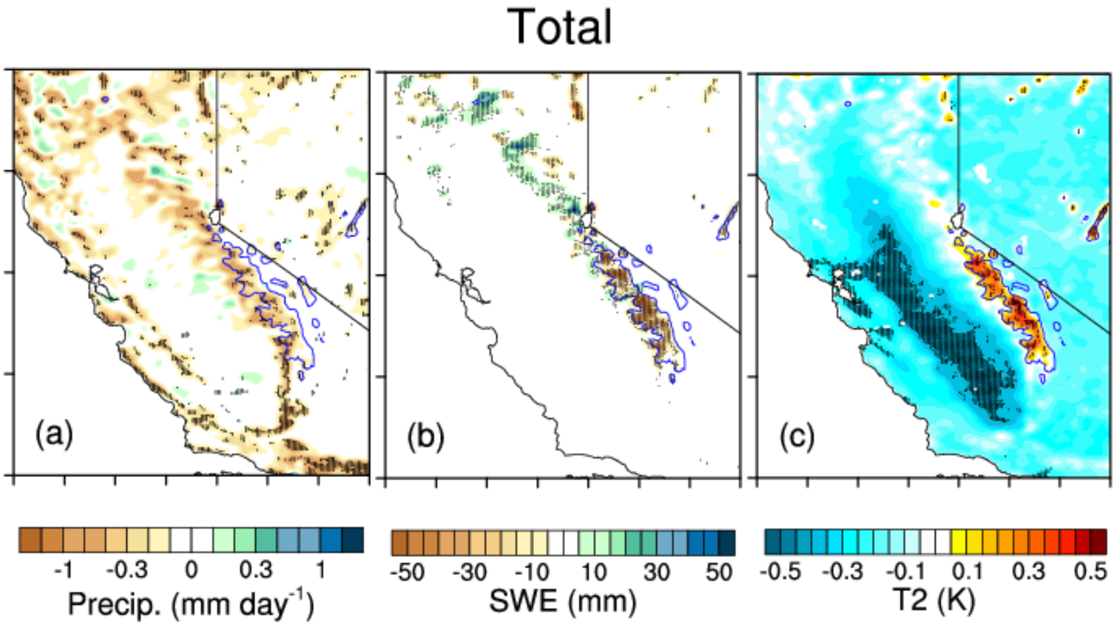


Figure 5. Total aerosol effects (CTRL – CLEAN) on spatial distribution of (a) precipitation (mm day$^{-1}$), (b) SWE (mm), and (c) T2 (K). The dotted area denotes statistical significance above the 90% confidence level. Blue lines represent the mountain tops with elevation ≥ 2.5 km.

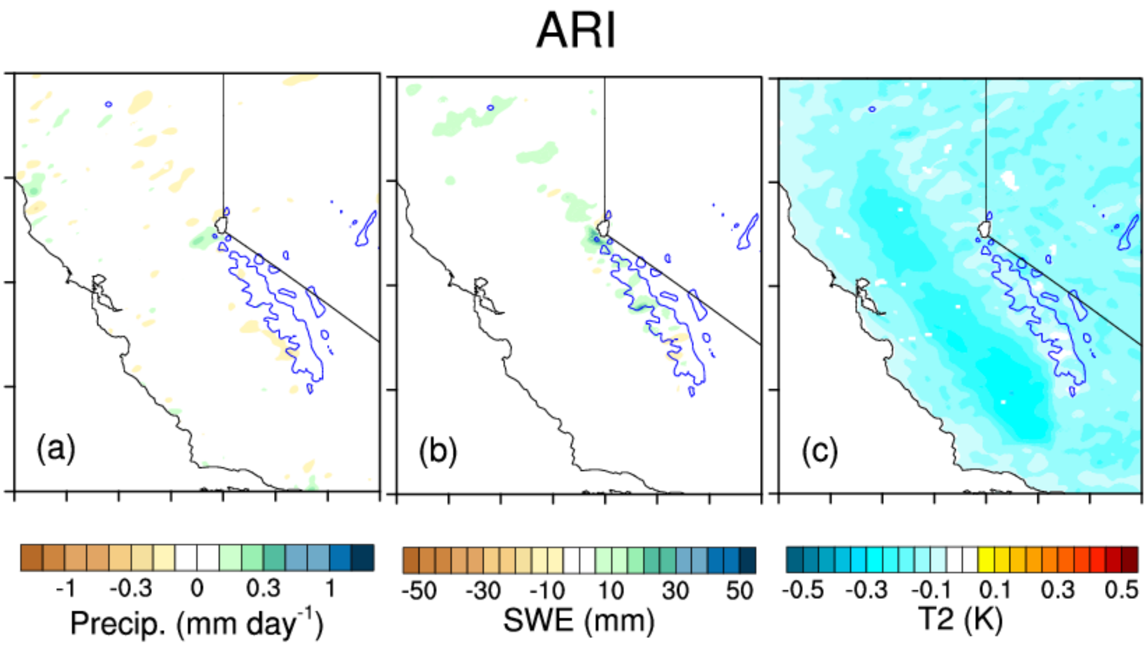


Figure 6. ARI effects (CTRL – NARI) on spatial distribution of (a) precipitation (mm day$^{-1}$), (b) SWE (mm), and (c) T2 (K). Blue lines represent the mountain tops with elevation ≥ 2.5 km.

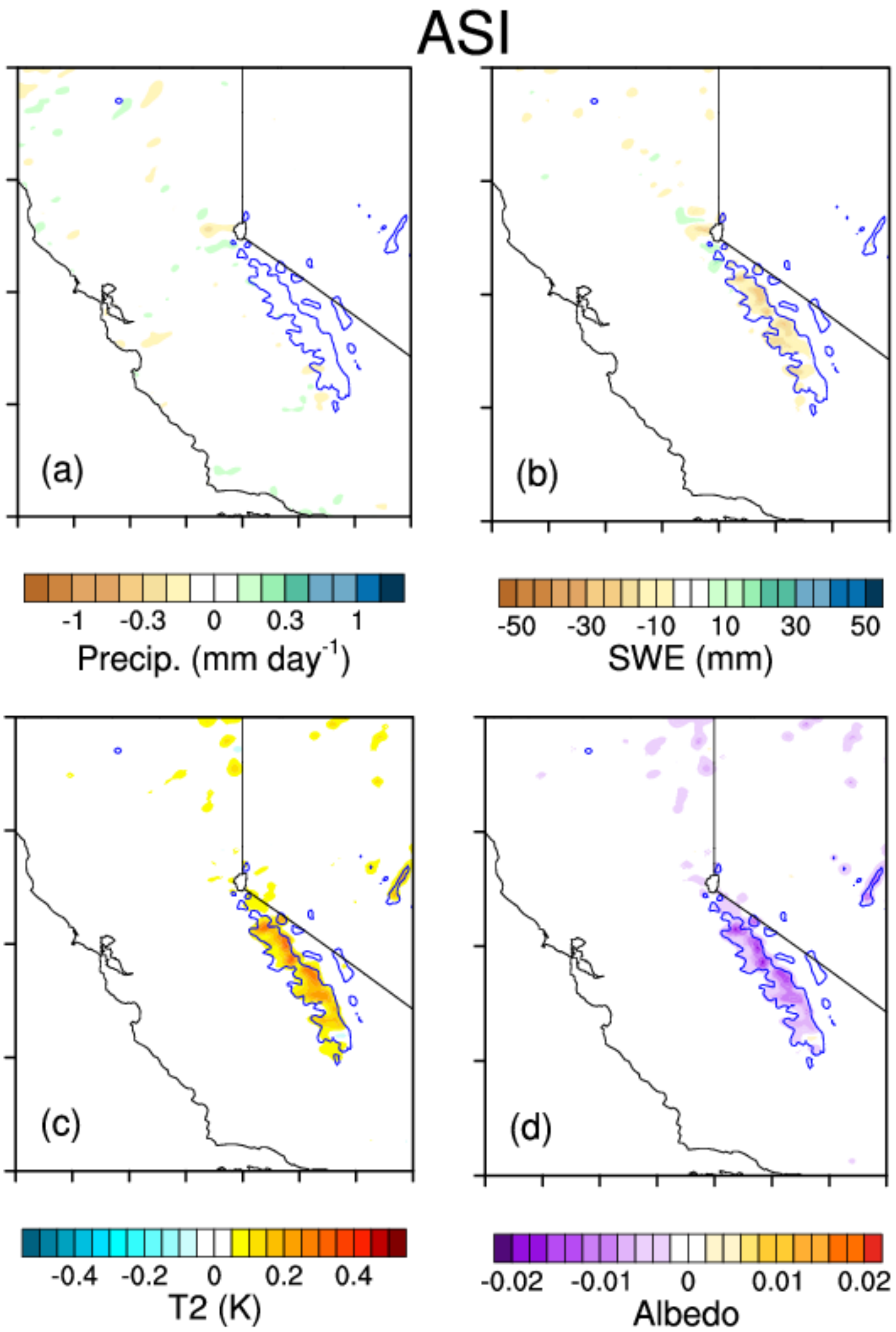


Figure 7. ASI effects (CTRL – NASI) on spatial distribution of (a) precipitation (mm day$^{-1}$), (b) SWE (mm), (c) T2 (K), and (d) surface albedo. Blue lines represent the mountain tops with elevation ≥ 2.5 km.

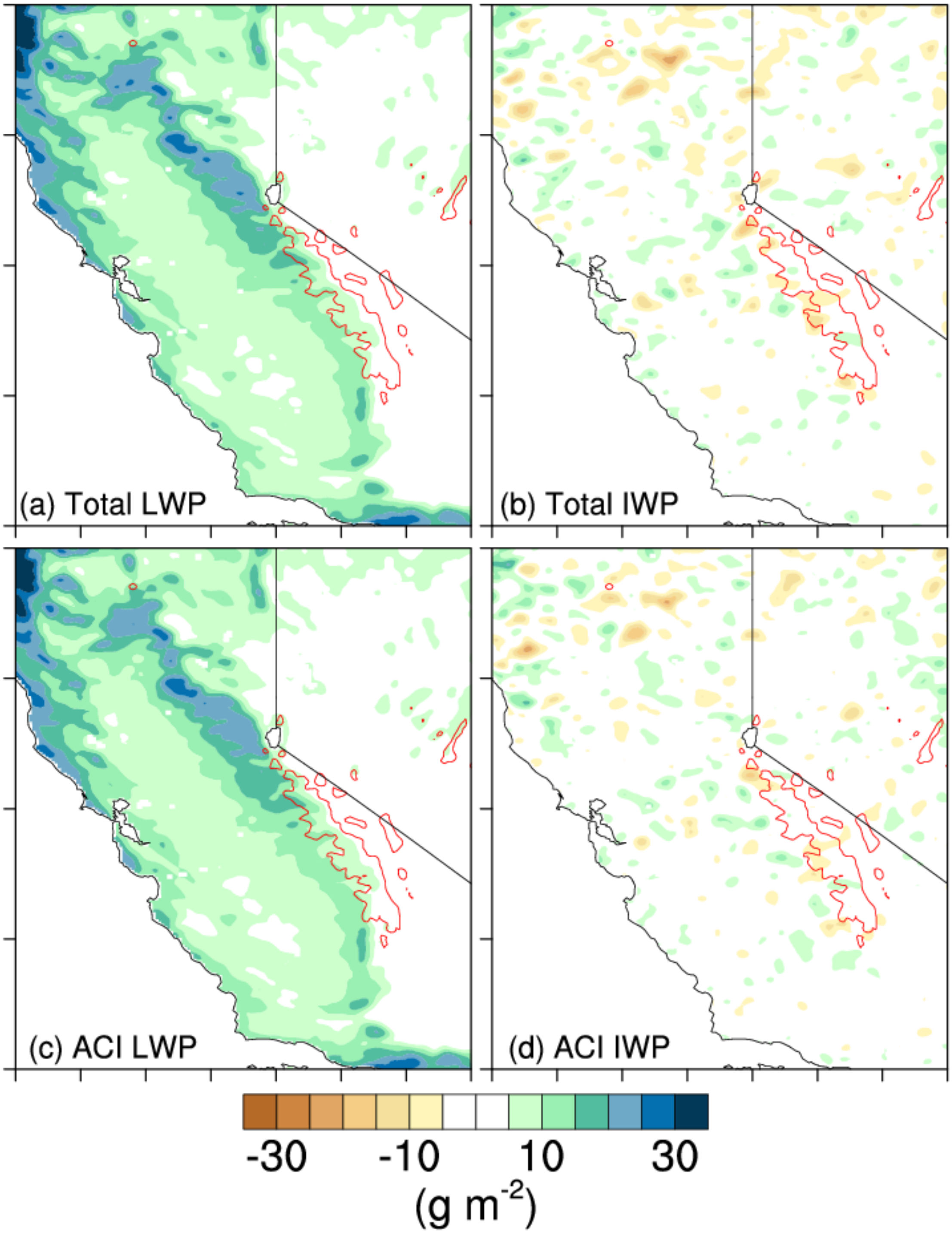


Figure 8. Differences in (a) LWP (g m$^{-2}$) and (b) IWP (g m$^{-2}$) due to all aerosol effects (CTRL – CLEAN), and (c) LWP (g m$^{-2}$) and (d) IWP (g m$^{-2}$) due to ACI effect (NARS – CLEAN). Red lines represent the mountain tops with elevation ≥ 2.5 km.

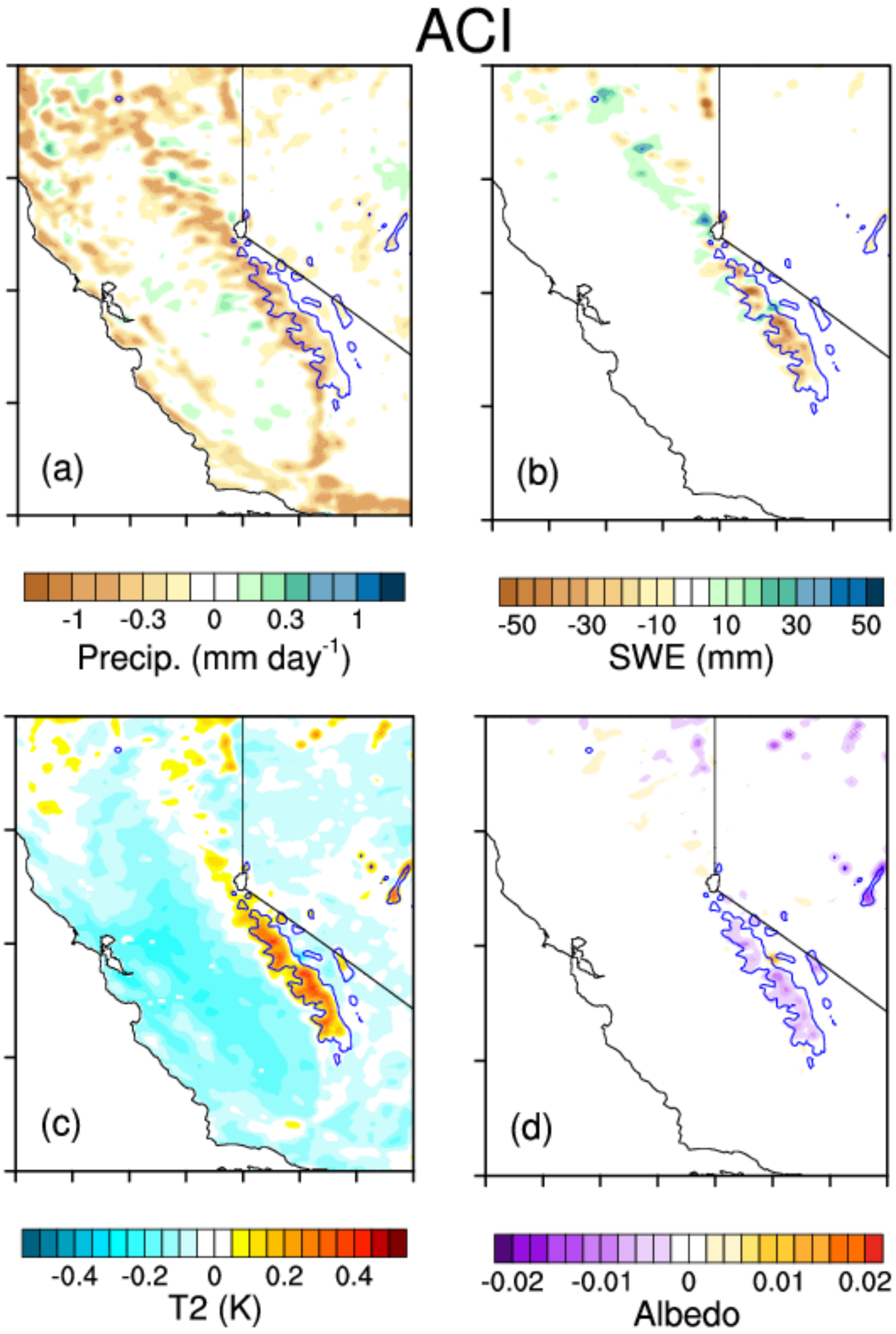


Figure 9. Same as Figure 7, but for ACI effect (NARS – CLEAN).

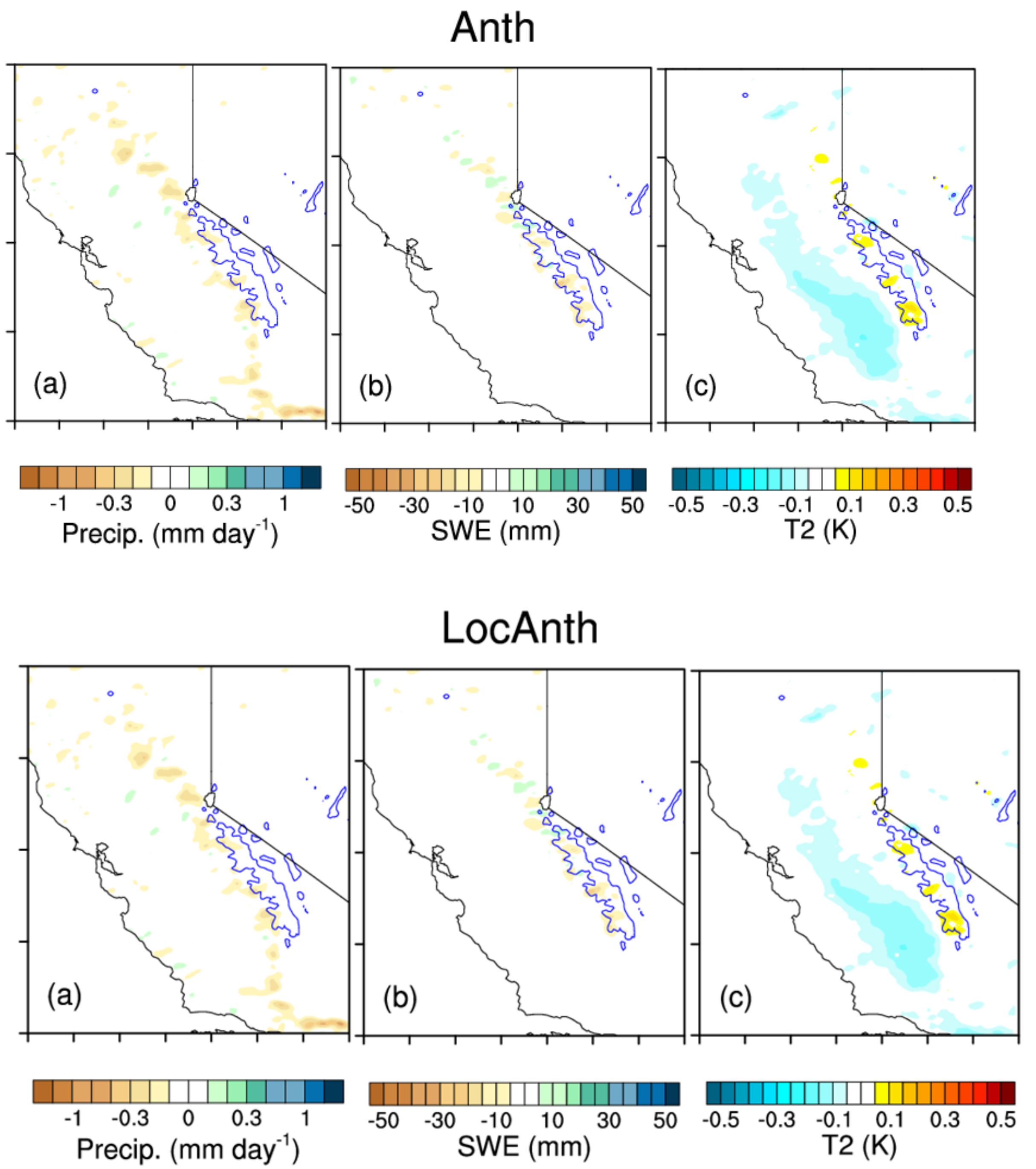


Figure 10. Effect of local anthropogenic aerosols (CTRL – NoLocAnth) on spatial distribution of (a) precipitation (mm day$^{-1}$), (b) SWE (mm), and (c) T2 (K). Blue lines represent the mountain tops with elevation ≥ 2.5 km.

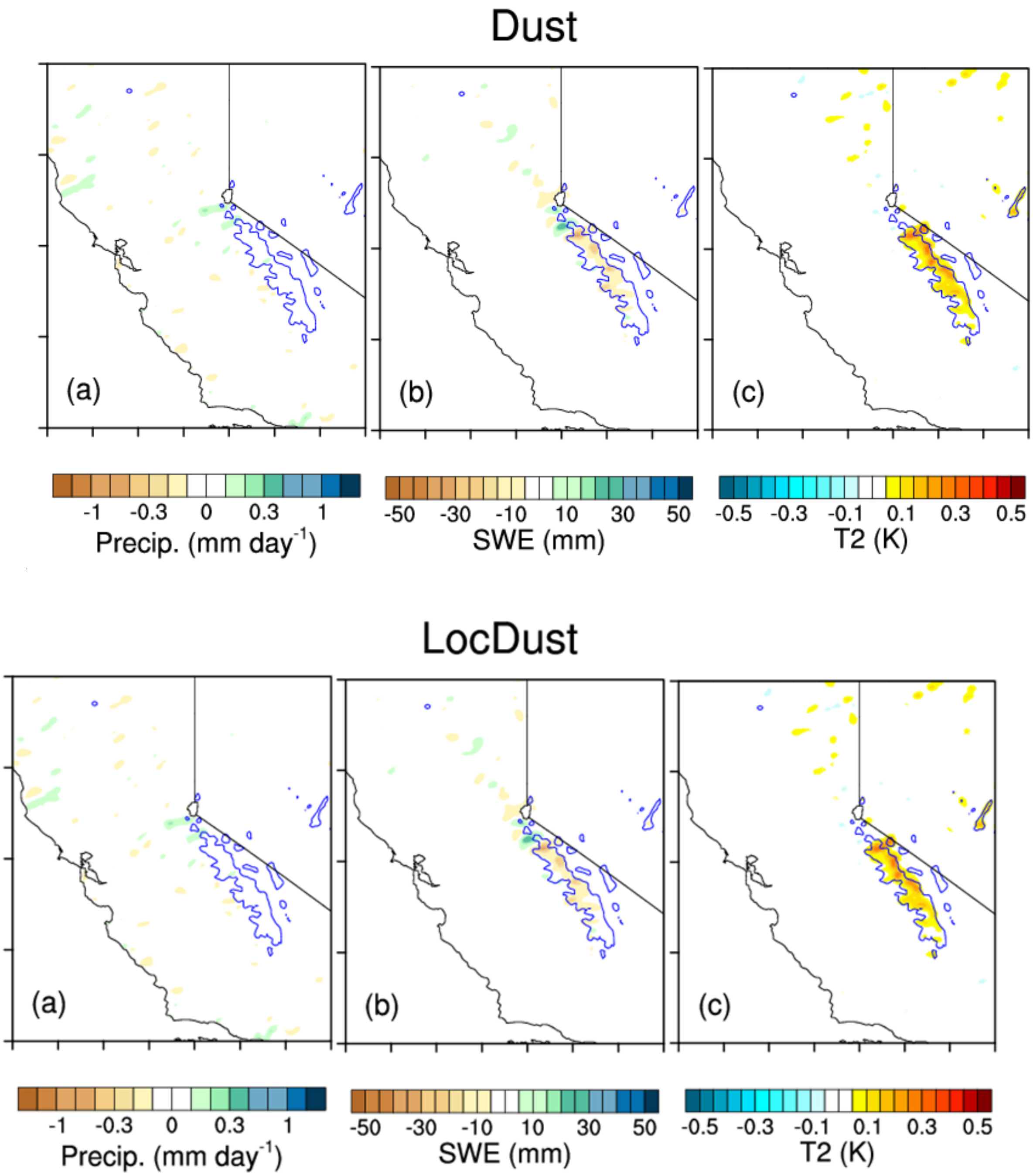


Figure 11. Same as Figure 10, but for the effect of local dust aerosols (CTRL – NoLocDust).

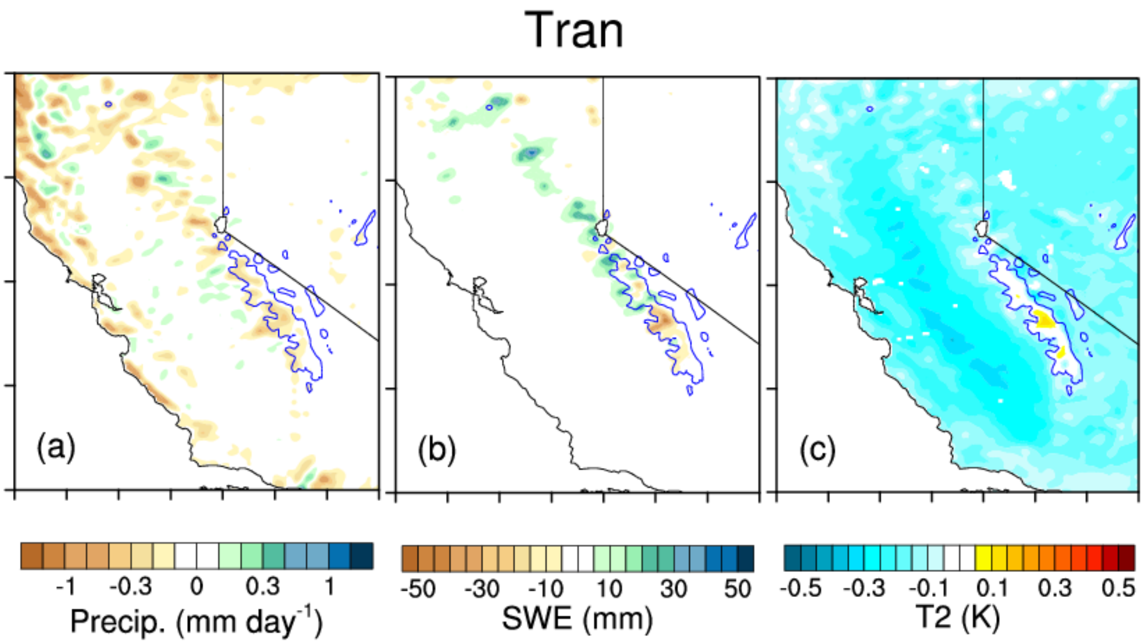
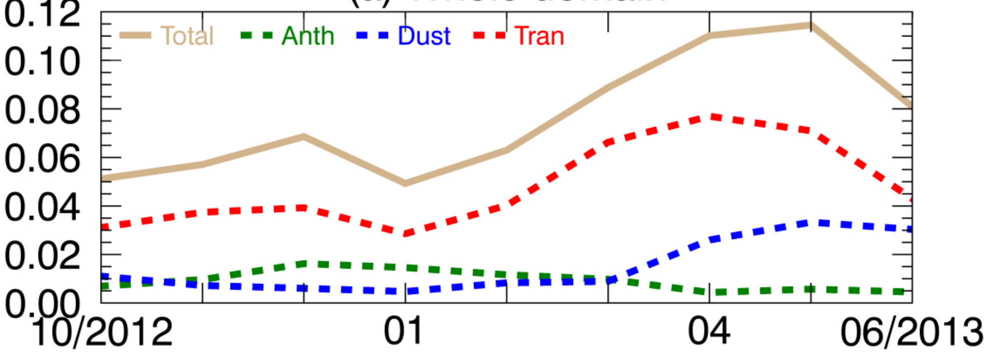
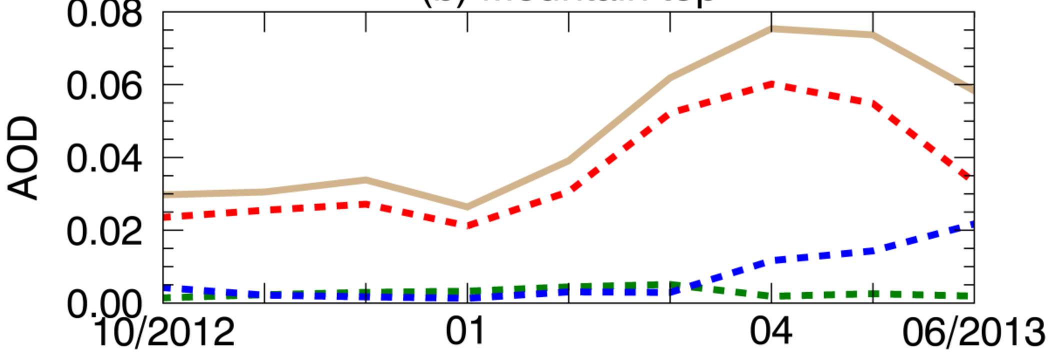


Figure 12. Same as Figure 10, but for the effect of transported aerosols (CTRL – NoTran).

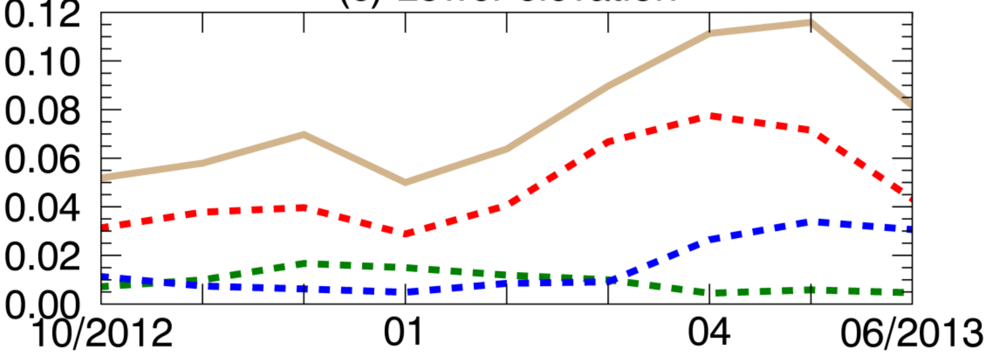
(a) Whole domain



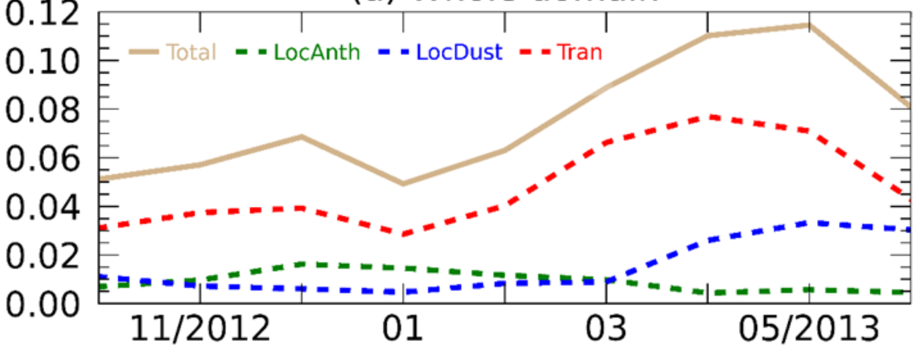
(b) Mountain top



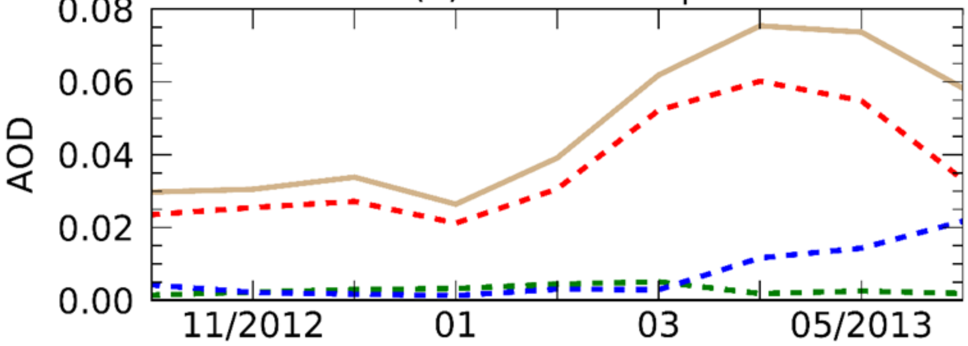
(c) Lower elevation



(a) Whole domain



(b) Mountain top



(c) Lower elevation

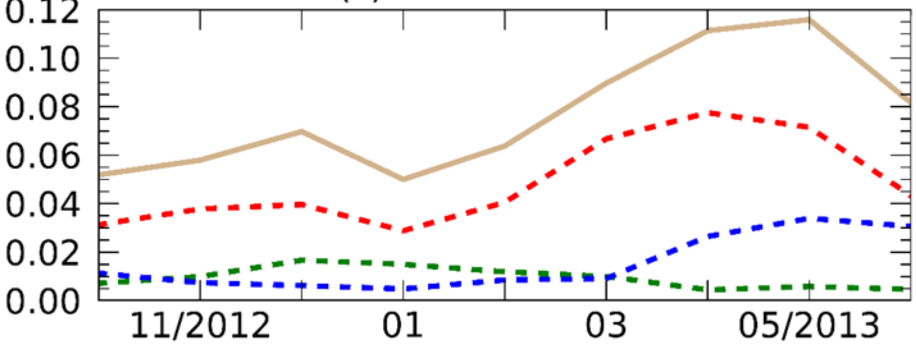
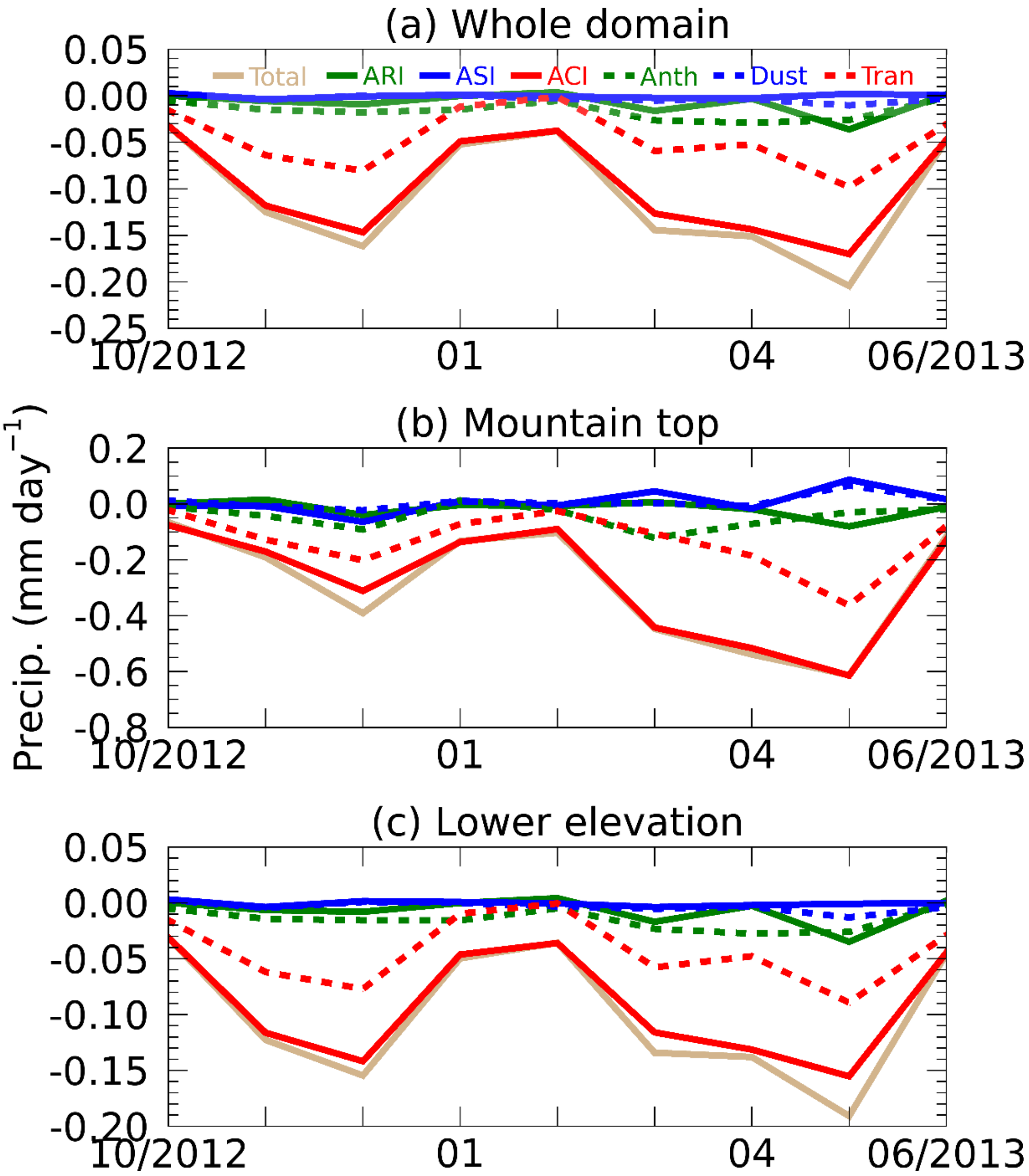


Figure 13. Monthly mean AOD simulated from CTRL for total aerosols (brown solid), local anthropocentric aerosols (green dashed), local dust (blue dashed), and transported aerosols (red dashed) averaged over (a) the whole domain (34-42 °N, 117-124 °W, not including ocean points), (b) mountain tops (with elevation ≥ 2.5 km), and (c) lower elevation area ( < 2.5 km) from October 2012 to June 2013.


(a) Whole domain
Total
ARI
ASI
ACI
Anth
Dust
Tran
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
10/2012
01
04
06/2013
Precip. (mm day$^{-1}$)
(b) Mountain top
0.2
0.0
-0.2
-0.4
-0.6
-0.8
10/2012
01
04
06/2013
(c) Lower elevation
0.05
0.00
-0.05
-0.10
-0.15
-0.20
10/2012
01
04
06/2013

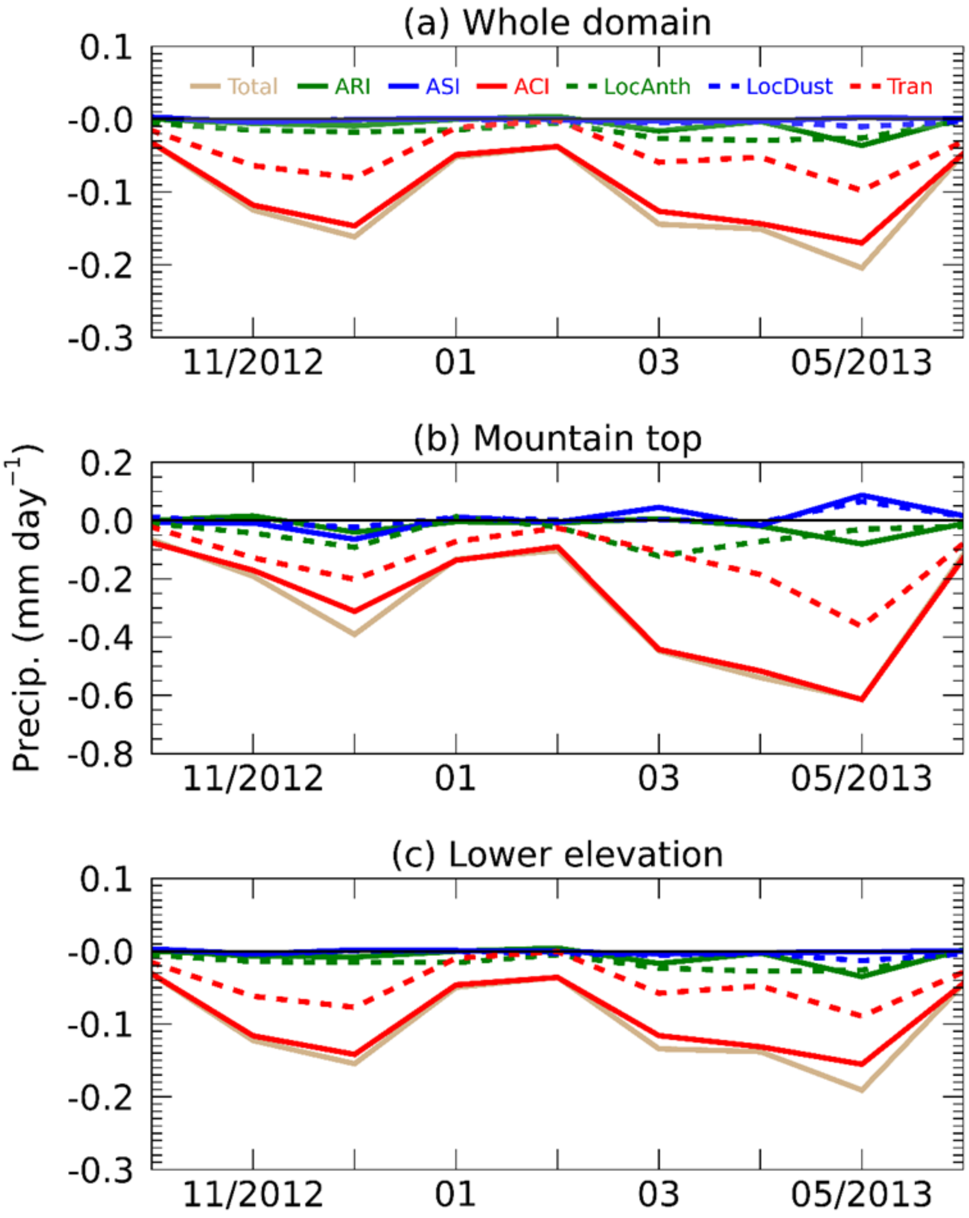
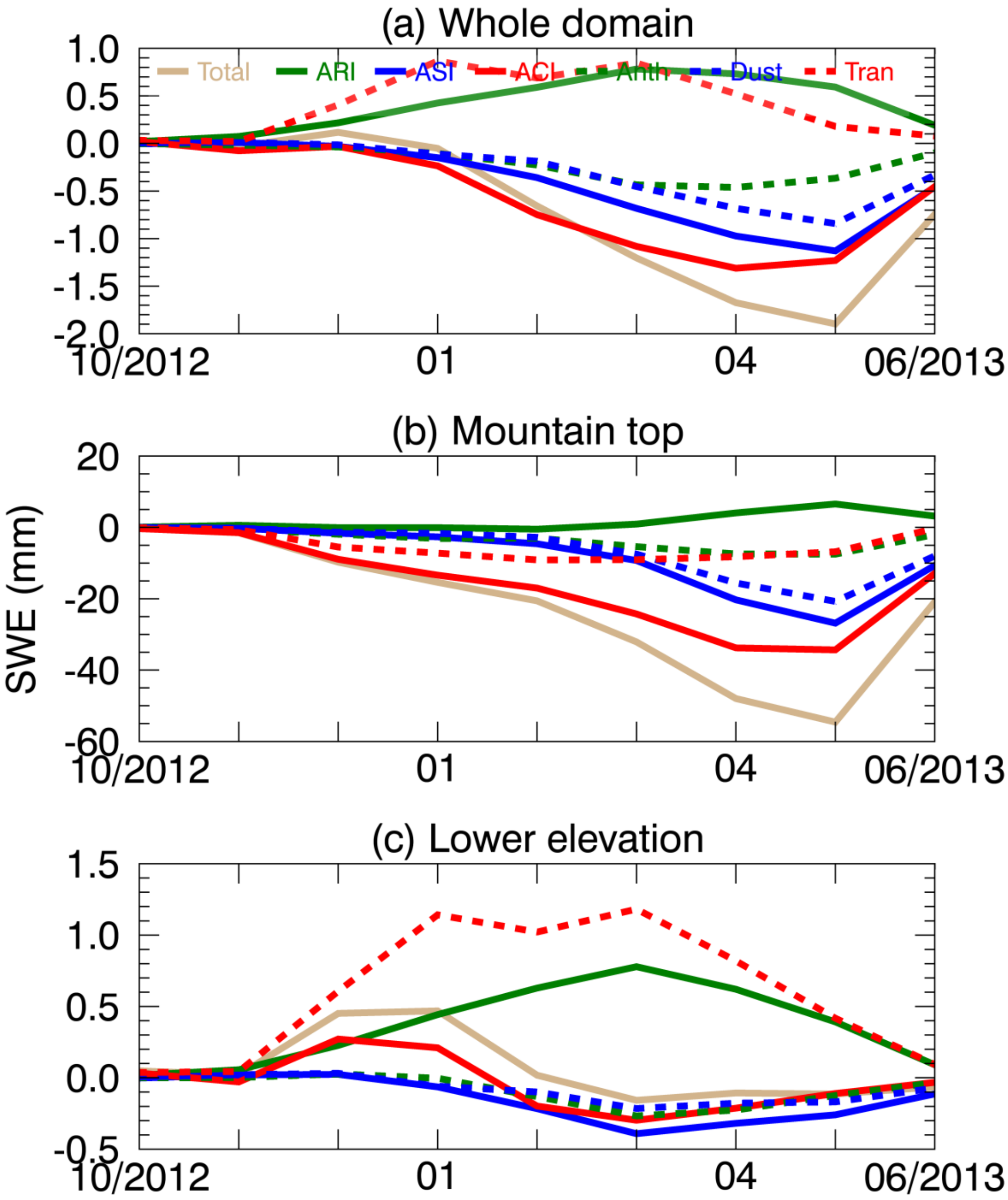


Figure 14. Monthly mean differences in precipitation (mm day$^{-1}$) due to total aerosols (brown solid), ARI (green solid), ASI (blue solid), ACI (red solid), local anthropocentric aerosols (green dashed), local dust (blue dashed), and transported aerosols (red dashed) averaged over (a) the whole domain (34-42 °N, 117-124 °W, not including ocean points), (b) mountain tops (with elevation ≥ 2.5 km), and (c) lower elevation area ( < 2.5 km) from October 2012 to June 2013. Zero line is shown as thin black line.


(a) Whole domain
Total
ARI
ASI
ACI
Anth
Dust
Tran
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
10/2012
01
04
06/2013
(b) Mountain top
SWE (mm)
20
0
-20
-40
-60
10/2012
01
04
06/2013
(c) Lower elevation
1.5
1.0
0.5
0.0
-0.5
10/2012
01
04
06/2013

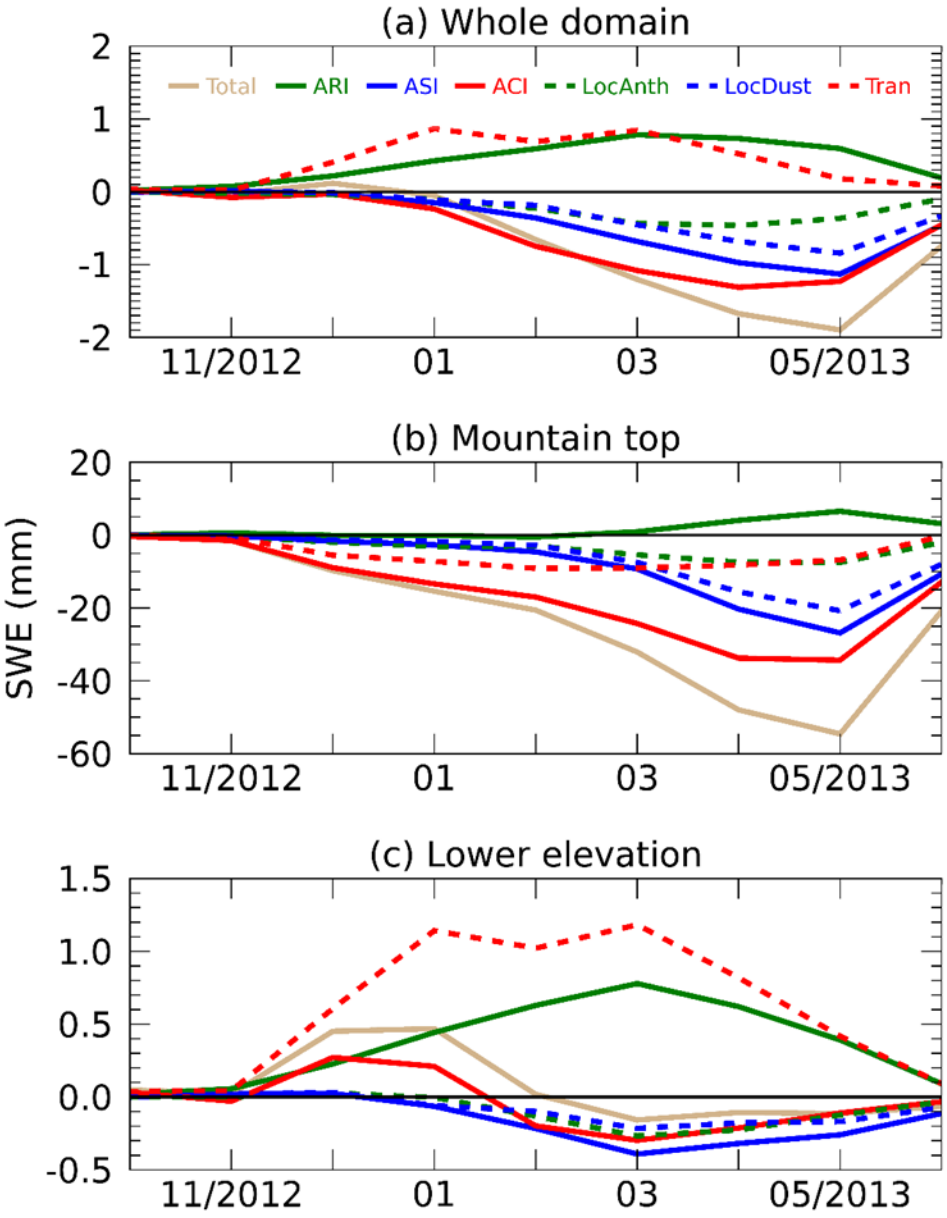
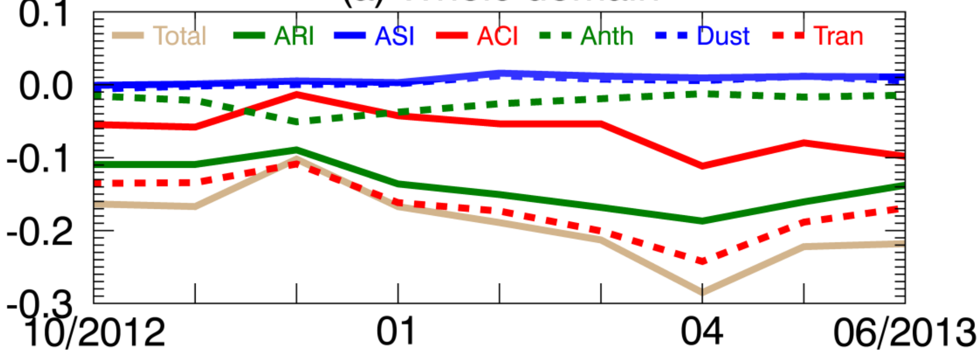
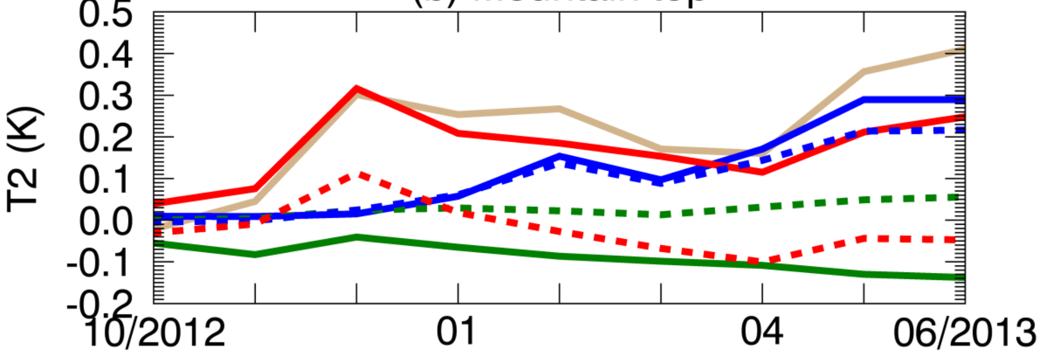


Figure 15. Same as Figure 14, but for SWE (mm).

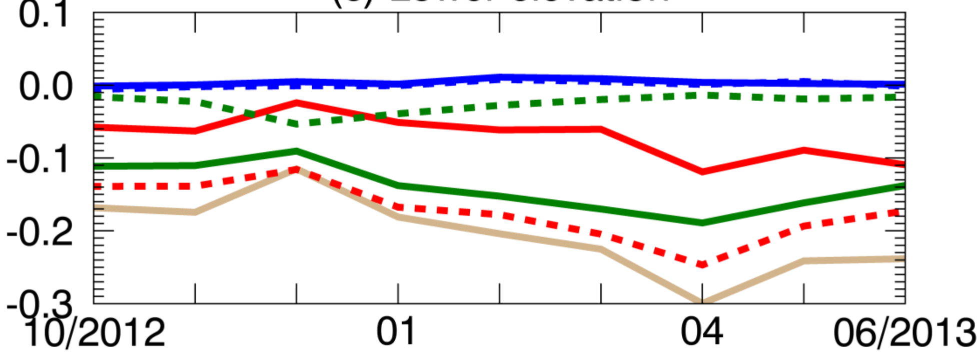
(a) Whole domain



(b) Mountain top



(c) Lower elevation



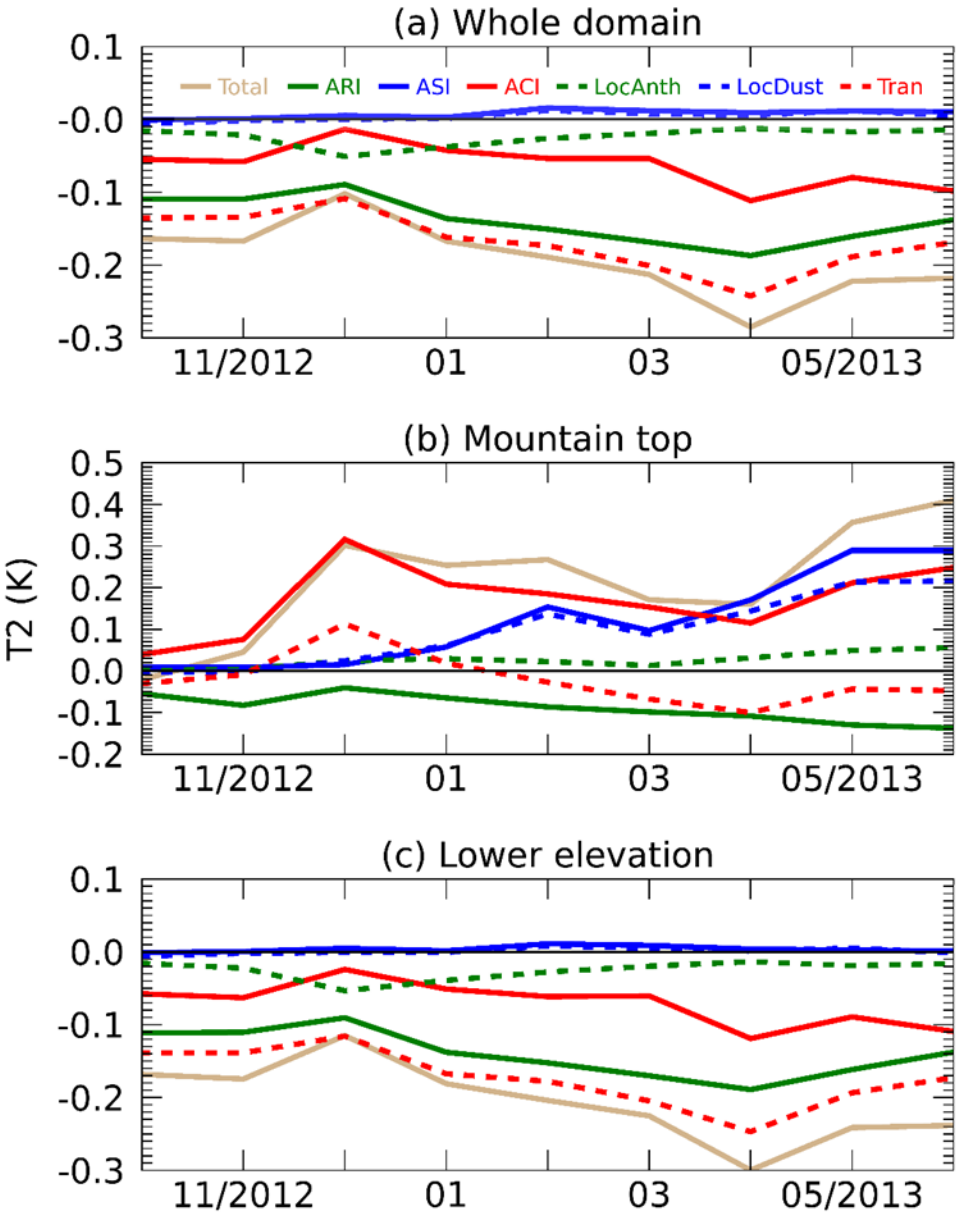
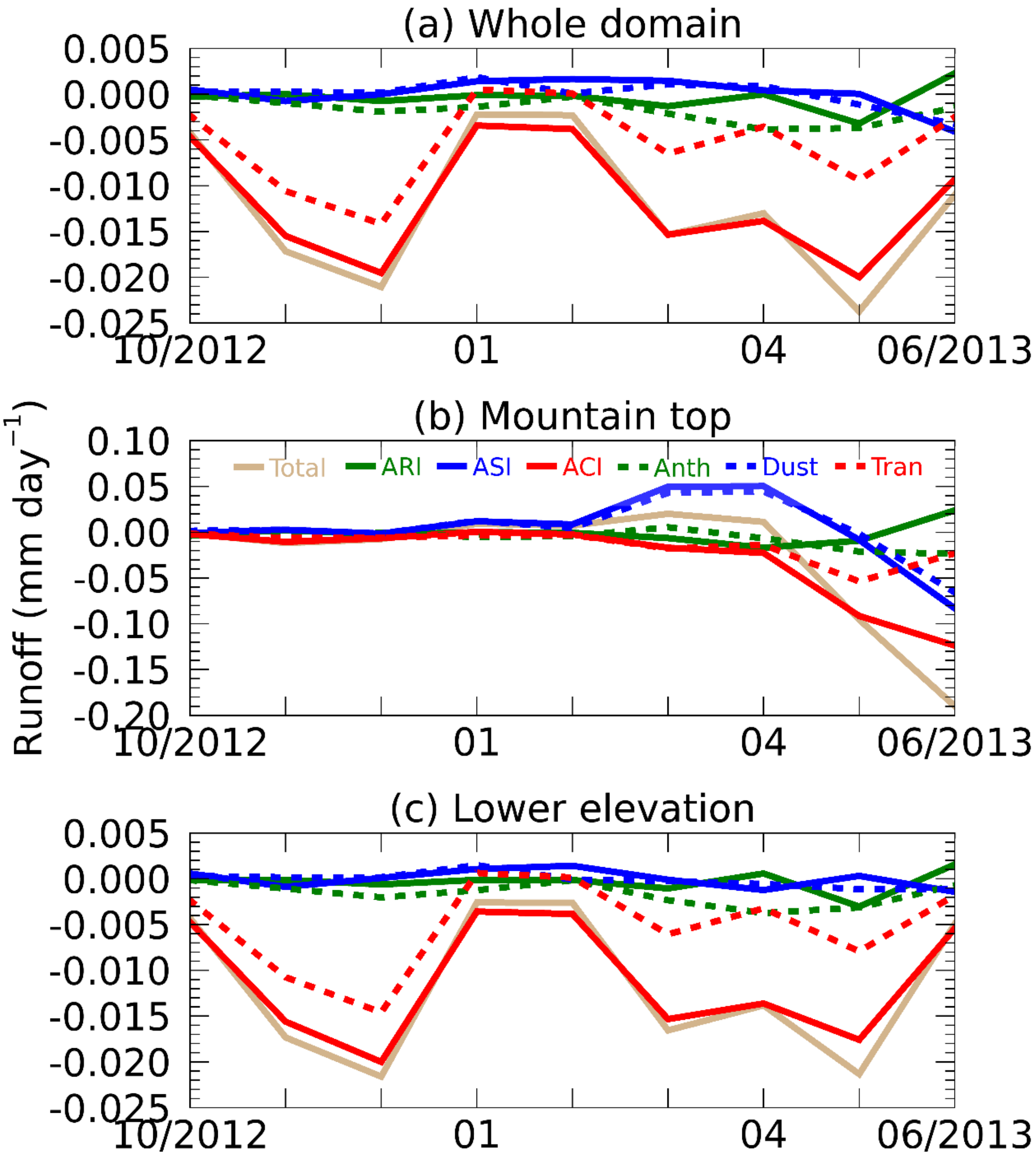


Figure 16. Same as Figure 14, but for T2 (K).


(a) Whole domain
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
10/2012
01
04
06/2013
(b) Mountain top
Runoff (mm day$^{-1}$)
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Total
ARI
ASI
ACI
Anth
Dust
Tran
10/2012
01
04
06/2013
(c) Lower elevation
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
10/2012
01
04
06/2013

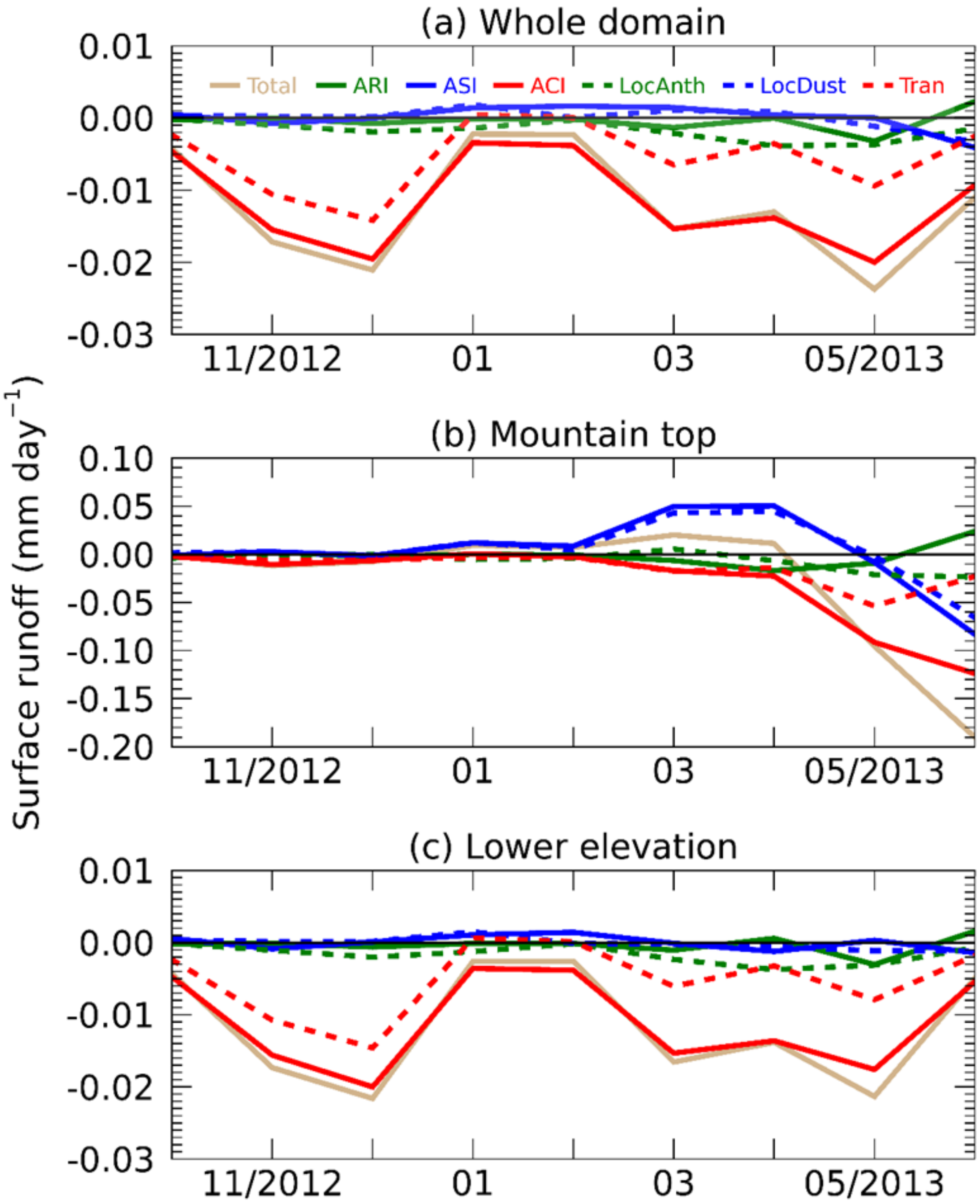


Figure 17. Same as Figure 14, but for surface runoff (mm day$^{-1}$).