The Impact of Direct Aerosol Radiative Forcing on Surface Insolation and Spring Snowmelt in the Southern Sierra Nevada

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(Manuscript received 19 September 2005, in final form 1 February 2006)

ABSTRACT

To understand the regional impact of the atmospheric aerosols on the surface energy and water cycle in the southern Sierra Nevada characterized by extreme variations in terrain elevation, the authors examine the aerosol radiative forcing on surface insolation and snowmelt for the spring of 1998 in a regional climate model experiment. With a prescribed aerosol optical thickness of 0.2, it is found that direct aerosol radiative forcing influences spring snowmelt primarily by reducing surface insolation and that these forcings on surface insolation and snowmelt vary strongly following terrain elevation. The direct aerosol radiative forcing on surface insolation is negative in all elevations. It is nearly uniform in the regions below 2000 m and decreases with increasing elevation in the region above 2000 m. This elevation dependency in the direct aerosol radiative forcing on surface insolation is related to the fact that the amount of cloud water and the frequency of cloud formation are nearly uniform in the lower elevation region, but increase with increasing elevation in the higher elevation region. This also suggests that clouds can effectively mask the direct aerosol radiative forcing on surface insolation. The direct aerosol radiative forcing on snowmelt is notable only in the regions above 2000 m and is primarily via the reduction in the surface insolation by aerosols. The effect of this forcing on low-level air temperature is as large as −0.3°C, but its impact on snowmelt is small because the sensible heat flux change is much smaller than the insolation change. The direct aerosol radiative forcing on snowmelt is significant only when low-level temperature is near the freezing point, between −3° and 5°C. When low-level temperature is outside this range, the direct aerosol radiative forcing on surface insolation has only a weak influence on snowmelt. The elevation dependency of the direct aerosol radiative forcing on snowmelt is related with this low-level temperature effect as the occurrence of the favored temperature range is most frequent in high elevation regions.

1. Introduction

The impact of aerosol radiative forcing on the energy and water cycle is an important concern in understanding regional climate, but the details of its spatiotemporal variability remain uncertain. Aerosols influence the energy and water cycle primarily via scattering and absorption of solar radiation (direct effect) and via their impact on the characteristics of clouds and precipitation (indirect effect). In climate modeling and long-range forecasts, uncertainties in aerosol radiative impact on the energy and water cycle translate directly into uncertainties in atmosphere–land interaction, which is important for understanding the physical processes involved in the climate system and for calculating hydrologic information, for example, the seasonal projection of water resources and soil moisture. The impact of aerosols on climate and the environment has become an important scientific issue, especially in relation to the climate change induced by the emissions of anthropogenic greenhouse gases (Mitchell et al. 1995; Houghton et al. 2001).

Aerosol radiative forcing has been investigated in a number of global and regional model studies (e.g., Boucher and Anderson 1995; Pan et al. 1997; Giorgi et al. 2002). In an analysis of the changes in summer climate, air pollution, and clear-sky solar radiation in China, Xu (2001) found that increases in sulfate aerosols and the associated local albedo increases may have played an important role in the summer climate pattern characterized by "north drought/south flooding" in eastern China. Luo et al. (2000) analyzed the direct insolation in four southern China urban areas to find that direct insolation has decreased by over 20% com-

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pared to that in the period from 1960 to 1980. In a general circulation model study, Menon et al. (2002) reported that the absorbing aerosols can significantly affect the atmospheric circulation and water cycle, and hence regional climate, via atmospheric heating that alters the static stability and vertical motions. Gueymard et al. (2000) also reported that dust originating from China has affected the surface insolation in the United States, and may have altered the regional circulation and water cycle. In a regional model study over East Asia, Giorgi et al. (2002) reported that anthropogenic sulfates can induce a negative radiative forcing at the top of the atmosphere (TOA) by as much as -15 W m^{-2}.

The aerosol radiative forcing on spring snowmelt in the Sierra Nevada watershed is an important concern in California as the amount and timing of snowmelt in these high elevation regions are among the most crucial factors that determine warm-season water resources (e.g., Dettinger and Cayan 1995; Kim 1997; Kim et al. 2002). In addition, high elevation snow fields can amplify local climate variations via snow–albedo feedback. The response of surface energy and the water cycle, especially the snow budget, to external forcing such as the radiative forcing by aerosols and atmospheric greenhouse gases depends strongly on local climate shaped by geographical characteristics (Giorgi et al. 1997; Kim 2001). In the mountainous Sierra Nevada region in which surface elevations vary from near sea level to over 3000 m, large variations in terrain height can cause large spatial variations in the net impact of aerosol radiative forcing on the snow budget due to large variations in low-level temperatures. Spatial variations in the aerosol radiative forcing on important components of surface energy and the water cycle in this region as well as the associated physical processes have not been investigated so far despite their importance in understanding and long-term projections of surface energy and water cycle.

The main objective of this study is to understand the geographical variation in the direct aerosol radiative forcing on surface insolation and snowmelt during spring associated with extreme terrain variations in the southern Sierra Nevada. Section 2 presents the regional climate model employed for this study and the design of the experiment. The simulated impact of direct aerosol radiative forcing on surface insolation and snowmelt in different elevation ranges are presented in sections 3 and 4, respectively. These are followed by conclusions in section 5.

2. Experimental design

We have employed the latest version of the Mesoscale Atmospheric Simulation (MAS) model (Soong and Kim 1996; Kim 2004; Kim et al. 2005) coupled with the Noah land surface scheme (Kim and Ek 1995; Chang et al. 1999) in this study. This coupled MAS–Noah regional climate model has been used successfully in a number of numerical weather forecast and regional climate modeling studies for the western and continental United States and East Asia (e.g., Soong and Kim 1996; Kim 1997, 2001, 2004, Kim et al. 2002, 2005; Kim and Lee 2003). The MAS model is a primitive equation, limited-area atmospheric model written on σ coordinates in the vertical (Soong and Kim 1996). The advection equation is solved using a third-order-accurate finite difference scheme of Takacs (1985) that is characterized by minimal phase errors and numerical dispersion. A four-class version of the bulk microphysics scheme of Cho et al. (1989) and the simplified Arakawa–Schubert scheme (Pan and Wu 1995; Hong and Pan 1998) are used to compute grid scale and convective precipitation, respectively. The radiative transfer within the model atmosphere is computed using the δ-2/4-stream Fu–Liou scheme (Fu and Liou 1993; Gu et al. 2003) in which the optical properties of 18 types of atmospheric aerosols are incorporated based on the Optical Properties of Aerosols and Clouds (OPAC) database (d'Almeida et al. 1991; Tegen and Lacis 1996; Hess et al. 1998). Although uncertainties may exist in the OPAC database, especially for dust and smoke particles as found in recent remote sensing studies (e.g., Kaufman et al. 2001; Dubovik et al. 2002; Eck et al. 2003), these uncertainties are not expected to influence our study critically considering that we focus on providing qualitative information by prescribing a simple aerosol optical thickness (AOT) value. In our judgment, the OPAC database is so far the best data source for determining the single-scattering properties of spherical aerosols for broadband radiative flux calculations. The single-scattering albedo inferred from remote sensing data can be used to calibrate the existing database once these data are comprehensively evaluated.

A four-layer version of the Noah land surface model (Kim and Ek 1995) is coupled with MAS to compute the land surface processes. Noah predicts the soil moisture content, both frozen and unfrozen, and soil temperature within model soil layers, canopy-water content, and snow-water equivalence. The temperature and specific humidity for calculating the surface sensible and latent heat fluxes, the outgoing longwave radiation, and ground heat fluxes are calculated by iteratively solving a nonlinear form of the surface energy balance equation. For more details of the MAS and Noah models, as well as the Fu–Liou scheme, readers are referred to Mahrt and Pan (1984), Pan and Mahrt

(1987), Kim and Ek (1995), Soong and Kim (1996), Fu and Liou (1993), and Gu et al. (2003).

The impact of the direct aerosol radiative forcing is calculated as differences between the two seasonal simulations, the control (CNTL) and aerosol (AERO) runs. The CNTL run assumes no atmospheric aerosols, hence no direct aerosol radiative forcing. In the AERO run, a simple aerosol field is prescribed by spatiotemporally uniform column-integrated AOT of 0.2 at the wavelength of 530 nm based on the mean AOT for the region derived from satellite measurements (http://photojournal.jpl.nasa.gov/catalog/PIA04333; Torres et al. 2002). This AOT value is subsequently redistributed vertically assuming an aerosol scale height of 3 km and the total depth of the aerosol layer of 15 km, as well as spectrally according to the spectral single scattering properties calculated for each aerosol type and atmospheric humidity based on the OPAC database (Charlock et al. 2004).

We further assume that the prescribed aerosols consist of 90% continental and 10% black carbon on the basis of offline calculations of the radiative effect of several aerosol types including continental, maritime, and sea salt for a clear-day condition in a midlatitude region. These offline calculations show that both continental aerosols and sea salt yield negative direct aerosol radiative forcing with similar magnitudes of -20 and -27 W m^{-2}, respectively, at the surface. We also found that the radiative forcings produced by large dust particles and black carbon are similar. Both generate significant absorption of solar radiation, resulting in a positive radiative forcing at TOA but negative radiative forcing at the surface. Based on these offline calculations, we assume further that the total aerosol AOT is associated with 90% continental type and 10% black carbon to represent the effects by background aerosols and those generated by a variety of combustion processes in the region, respectively. Note that the preceding aerosol fields do not represent the details of the spatiotemporal variations in the aerosol concentration and types in the region due to the lack of data. Thus the simulation results presented below should be taken as qualitative. Changes in snow albedo due to aerosol deposition are not included in this study since reliable formulations to relate these two parameters are not available. Both runs include the radiative effects of the ice- and liquid-phase cloud particles based on the bulk cloud microphysics scheme of Cho et al. (1989) and the Fu–Liou radiation scheme. However, the indirect aerosol effect due to the impact of aerosols on cloud characteristics and precipitation is not included.

Both CNTL and AERO runs are performed for the 3-month period March–May 1998 using the initial and lateral boundary data derived from the National Centers for Environmental Prediction (NCEP) reanalysis 2 (R2). The model domain covers California and Nevada with a grid mesh of 18-km horizontal resolution (Fig. 1), 20 atmospheric layers, and 4 soil layers. For investigating the direct aerosol radiative forcing on surface insolation and snowmelt in different elevation ranges, the southern Sierra Nevada region (marked with a box in the middle of the domain) is subdivided into six elevation bands (Table 1) following Kim (2001), who showed that the elevation dependency of the response of surface water cycle to external forcings can be well presented by the averages within the elevation ranges used here.

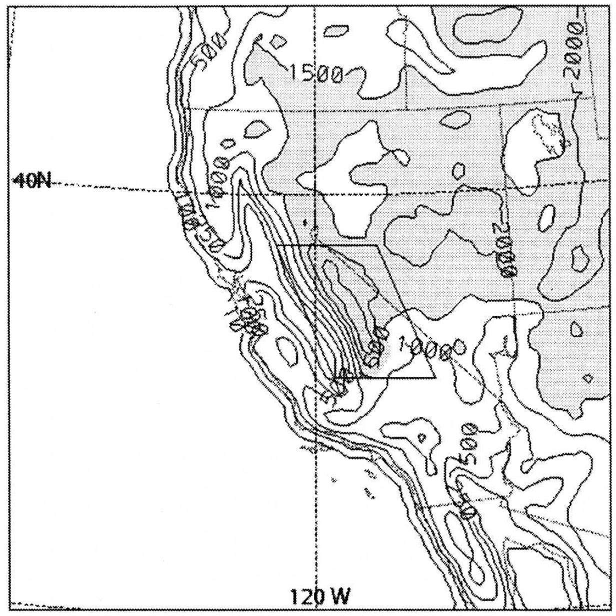

FIG. 1. The model terrain represented at an 18-km resolution. The regions above the 1500-m level are shaded. The inner box indicates the southern Sierra Nevada region.

3. The direct aerosol forcing on surface insolation

The direct aerosol radiative forcing on surface insolation is negative at all elevations with a maximum of

TABLE 1. The elevation ranges represented by individual elevation bands.

Band	Range (m)
1	0–1000
2	1000–1500
3	1500–2000
4	2000–2500
5	2500–3000
6	>3000

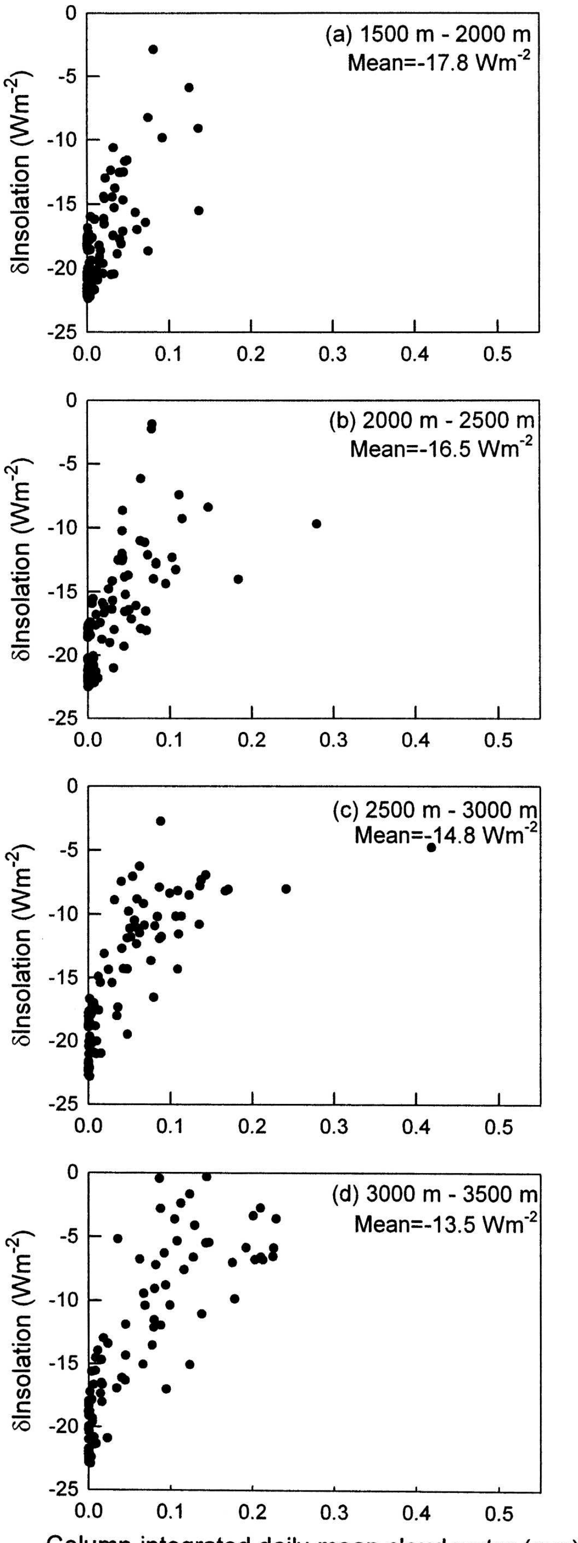

Fig. 2. The direct aerosol radiative forcing on daily mean surface insolation and the ICW in the four elevation bands above 1500 m.

about -18 W m^{-2} in the regions below 2000 m. It is nearly uniform below the 2000-m level but decreases monotonically with increasing elevation (Fig. 2). Note that the relationship between the insolation change and the column-integrated cloud water (ICW) for the 0–1500-m range is similar to that in the 1500–2000-m range (Fig. 2a). This elevation dependency of the direct aerosol radiative forcing on surface insolation is associated with the elevation dependency of the ICW. Below the 2000-m level, the ICW is smaller (Fig. 2) and cloud formation, measured by the number of cloudy days, is less frequent (Fig. 3) than in the regions above 2000 m. Figures 2 and 3 show that, in the regions above 2000 m, the ICW and the frequency of cloud formation increase with increasing terrain elevation. The relationship between the direct aerosol radiative forcing on surface insolation and the frequency/amount of clouds in different elevation ranges also suggests that clouds can effectively mask the direct aerosol radiative forcing on surface insolation.

The effect of clouds on the direct aerosol radiative

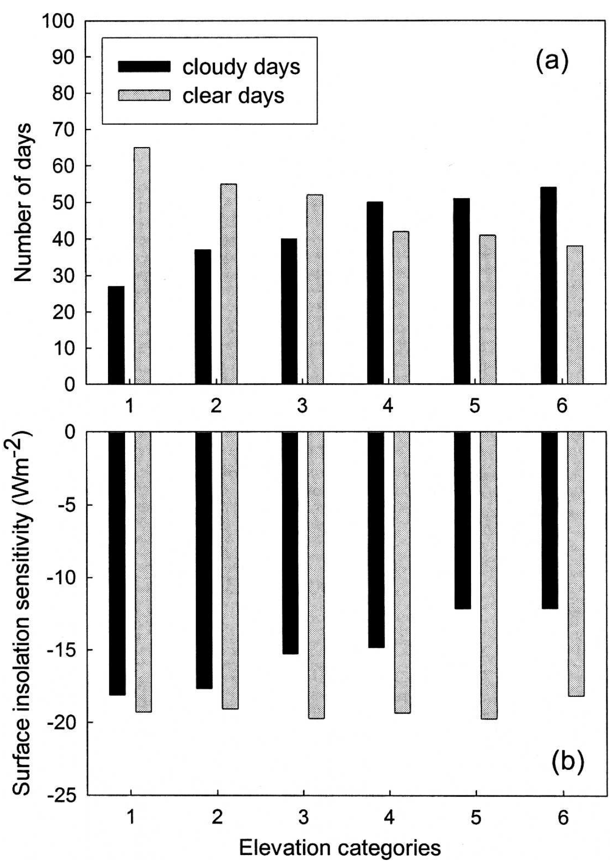

Fig. 3. Season-total (a) number of cloudy (black) and clear (gray) days and (b) the direct aerosol radiative forcing on surface insolation averaged over cloudy (black) and clear (gray) days within each elevation band.

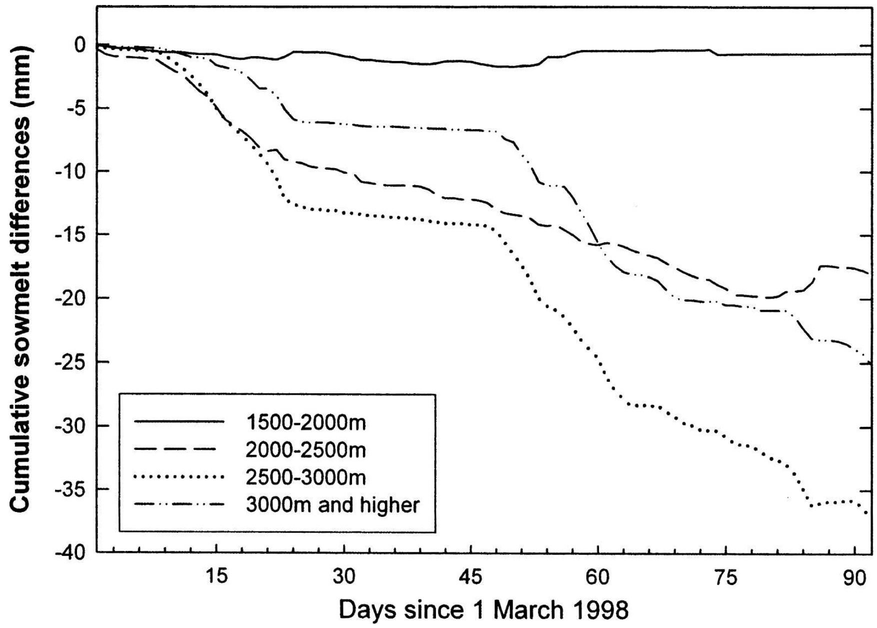

FIG. 4. The direct aerosol radiative forcing on the cumulative snowmelt within the elevation bands 3–6 (above 1500 m).

forcing on surface insolation is clear, as shown in Fig. 3, which presents the number of cloudy and clear days (Fig. 3a) and the direct aerosol radiative forcing on surface insolation averaged over cloudy or clear days (Fig. 3b). A cloudy day is defined by the threshold ICW value of 0.01 mm. The number of cloudy (clear) days increases (decreases) monotonically with increasing terrain height (Fig. 3a), indicating more frequent cloud formation in higher elevation regions. Figure 3b also shows that the cloudy-day-mean direct aerosol radiative forcing on surface insolation decreases with increasing elevation, indicating that the ICW increases with increasing elevation. The clear-day direct aerosol radiative forcing on surface insolation is nearly uniform across all elevation ranges, as expected from a spatiotemporally uniform AOT value prescribed in the AERO run (Fig. 3b).

4. Impact on snowmelt

The direct aerosol radiative forcing on the cumulative snowmelt starting from 1 March 1998 (Fig. 4) also depends clearly on terrain elevations. Snowmelt in the region below 1500 m is very small as most precipitation in these regions is rainfall (not shown). In the region between 1500 and 2000 m (solid line in Fig. 4), the direct aerosol radiative forcing on snowmelt is also small despite significant snowfall and snowmelt occurrence during the simulation period. Hence, the direct aerosol radiative forcing on snowmelt is noticeable only in the regions above 2000 m. At the end of May, the three-month total snowmelt is reduced by the direct aerosol radiative forcing effect by 20–40 mm or by 4%–9% of that in the control run (Table 2), with the largest reduction of snowmelt in the elevation range between 2500 and 3000 m. Hence, one of the important impacts of the direct aerosol radiative forcing in the region is to extend snowmelt and the snowmelt-driven runoff further into the warm season. The elevation dependency of the direct aerosol radiative forcing on snowmelt discussed above is somewhat peculiar as its impact on surface insolation decreases with increasing elevation in the regions above 2000 m (section 3). The changes in the amount of precipitation and its partition between rainfall and snowfall due to the direct aerosol radiative forcing is small (not shown); hence, they are not expected to have caused the elevation dependency of the forcing on snowmelt.

TABLE 2. The direct aerosol radiative forcing on cumulative snowmelt at the end of the three-month period.

Band (range)	Snowmelt change (mm)	Snowmelt change (% of CNTL)
3 (1500–2000 m)	−0.7	−0.95
4 (2000–2500 m)	−18.1	−4.36
5 (2500–3000 m)	−37.3	−7.43
6 (3000–3500 m)	−25.1	−9.03

TABLE 3. The monthly mean low-level air temperature and freezing-level height over the southern Sierra Nevada region from the CNTL run, CRU data, and R2.

	Low-level temperature (°C)		Freezing-level height (m)	
Month	MAS	CRU	MAS	R2
Mar	7.81	6.56	2310	2240
Apr	8.57	8.20	2338	2247
May	10.48	10.84	2611	2627

To understand the cause of this elevation dependency of the direct aerosol radiative forcing on snowmelt, we examine the relationship between the direct aerosol radiative forcings on snowmelt, low-level air temperature, and surface insolation. The simulated low-level temperature and freezing-level height compare reasonably with available observations. The low-level temperature bias, compared against the monthly data of the Climate Research Unit (CRU) at the University of East Anglia (New et al. 2000), is as large as 1.3°C in March, but largely disappears in April and May (Table 3). The simulated monthly mean freezing level height also agrees well with that inferred from R2 with differences less than 100 m throughout the three-month period (Table 3). Although more detailed evaluation of the low-level temperature variations could not be performed due to a lack of station data, these limited evaluations suggest that the simulated low-level temperature is reasonably accurate for examining the impact of low-level temperature on snowmelt sensitivity discussed above. The monthly mean low-level temperature in the AERO is lower than those in the CNTL by 0.1°–0.3°C. The magnitude of the sensible heat flux changes associated with the direct aerosol radiative forcing is 1–4 W m^{-2} (positive downward) in the high elevation regions where snowmelt is significant. The amount of sensible heat flux changes due to the prescribed aerosols is much smaller than that of insolation. In addition, the sensible heat flux changes are directed downward, that is, tend to enhance snowmelt, indicating that the sensible heat flux changes tend to compensate the reduced insolation at the surface in the high elevation ranges. Hence, the snowmelt differences between the CNTL and AERO runs should be primarily through the reduction of surface insolation by direct aerosol radiative forcing.

A further examination of low-level temperature and the direct aerosol radiative forcing on daily snowmelt and insolation shows that the changes in snowmelt are poorly correlated with the insolation changes (Fig. 5a), but are closely related to the low-level temperature (Fig. 5b). Note that the positive forcings on daily snowmelt in Fig. 5 are due to the delayed snowmelt in the presence of aerosols as snow lasts longer in the AERO run than in the CNTL. Figure 5b shows that the direct aerosol radiative forcing on snowmelt is largest when the low-level temperatures are between −3° and 5°C, that is, around the freezing point. This close relationship between direct aerosol radiative forcing on snowmelt and low-level temperature is due to the fact that, when the latter is well above the freezing point, the snowmelt is controlled primarily by sensible heat flux, primarily from the atmosphere. Low-level temperatures well below 0°C would prohibit snowmelt as well, reducing the impact of aerosol radiative forcing on snowmelt. As a result, the direct aerosol radiative forcing on surface insolation can have noticeable effects on snowmelt only when the low-level temperatures are near the freezing point. This dependence on ambient temperature explains the elevation dependency of the direct aerosol radiative forcing on snowmelt. As terrain elevations vary over 3000 m in the southern Sierra Nevada region, the low-level air temperatures can vary over 20°C between the lowest and the highest regions (Kim 2001). The freezing level in the region is located

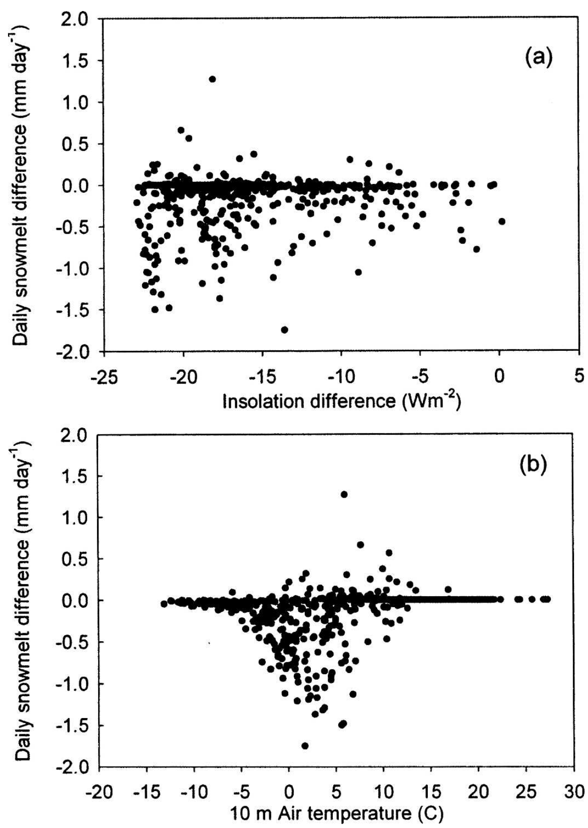

FIG. 5. The relationship between (a) the direct aerosol radiative forcings on snowmelt and surface insolation and (b) low-level temperatures and the direct aerosol radiative forcing on snowmelt, in all elevation ranges.

around 2300 m in March and moves to higher elevations in April and May following the seasonal temperature cycle (Table 3); hence, the largest impact of the forcing on snowmelt appears in the elevation range where the freezing level is located.

5. Conclusions

The direct aerosol radiative forcings on surface insolation and spring snowmelt in the southern Sierra Nevada has been investigated in a regional climate model study in which a uniform AOT value is prescribed. It is found that these forcings on surface insolation and snowmelt vary systematically according to surface elevations. The direct aerosol radiative forcing on surface insolation is negative at all elevation ranges. It is almost uniform below 2000 m but decreases monotonically with increasing terrain elevation above this level. This elevation dependency of the forcing on surface insolation is related to increases in the frequency of cloud formation as well as the amount of cloud water with increasing elevation in the higher elevation ranges.

The direct aerosol radiative forcing on snowmelt is significant only in the regions above 2000 m. The changes in low-level air temperature and sensible heat flux due to direct aerosol radiative forcing show that this forcing on snowmelt is mainly through reduction in insolation by aerosols. Although the direct aerosol radiative forcing on surface insolation decreases with increasing elevation above 2000 m, this forcing on snowmelt increases with elevation with maximum amounts in the 2500–3000-m-elevation range. Further examination of the changes in snowmelt and surface insolation due to the direct aerosol radiative forcing and the low-level temperature indicates that the direct aerosol radiative forcing on snowmelt is largest when the low-level temperatures are near the freezing point, between $-3°$ and 5°C, and is generally more closely related to low-level air temperature than the forcing on surface insolation. Hence, the elevation dependency of the direct aerosol radiative forcing on snowmelt in the region is due to the large variations in the low-level air temperature associated with extreme elevation variations in the region.

The close relationship between the direct aerosol radiative forcing on surface insolation and the amount of clouds and frequency of cloud formation shows that this forcing on surface insolation is largely masked by cloud radiative forcing. As atmospheric aerosols also influence cloud formation and precipitation, the indirect aerosol radiative forcing on snowmelt and high-elevation surface hydrology could be comparable to or larger than the direct aerosol radiative forcing studied in this paper. As uncertainties in spatiotemporal variations in regional-scale atmospheric aerosols can cause significant uncertainties in simulating surface energy and the water budget as well, a quantitative investigation of aerosol radiative forcing on the high elevation energy and water cycle should include both direct and indirect effects as well as spatiotemporal variations in the atmospheric aerosols, a subject requiring further study.

Acknowledgments. This work was performed with the grants from NOAA-GAPP (NA03OAR4310012), NOAA-PACS (NA00AANRG0201, NA06GP0376), NASA-SENH (NAG5-13248), NASA-ESE/IDS (NAG5-11363), PRRP 3TPRRP4-64, and NSF Grant ATM-0437349.

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