Impact of disturbed desert soils on duration of mountain snow cover

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[1] Snow cover duration in a seasonally snow covered mountain range (San Juan Mountains, USA) was found to be shortened by 18 to 35 days during ablation through surface shortwave radiative forcing by deposition of disturbed desert dust. Frequency of dust deposition and radiative forcing doubled when the Colorado Plateau, the dust source region, experienced intense drought (8 events and 39–59 Watts per square meter in 2006) versus a year with near normal precipitation (4 events and 17–34 Watts per square meter in 2005). It is likely that the current duration of snow cover and surface radiation budget represent a dramatic change from those before the widespread soil disturbance of the western US in the late 1800s that resulted in enhanced dust emission. Moreover, the projected increases in drought intensity and frequency and associated increases in dust emission from the desert southwest US may further reduce snow cover duration.
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1. Introduction

[2] Dust is commonly found in the surface layer of late season snow and on glacier surfaces in the world's mountain ranges [*Franzén et al.*, 1994; *Schwikowski et al.*, 1995; *Wake and Mayewski*, 1994]. Dust deposition on mountain snow cover has occurred throughout much of recent history as demonstrated by annual dust layers in high elevation ice cores [*Thompson et al.*, 2000], increasing with prolonged or intense drought and land disturbance in source regions. It is well known that dust in snow enhances absorbed solar radiation and melt rates [*Conway et al.*, 1996; *Warren and Wiscombe*, 1980], but the degree to which dust influences radiative forcing and snow cover duration in a natural system is not quantified. Early studies [*de Quervain*, 1947; *Jones*, 1913] suggested from simple observations that dust may shorten snow cover duration by as much as a month. However, unlike soot, which has received much attention as a potential climate forcing in snow cover [*Hansen and Nazarenko*, 2004; *Hansen et al.*, 2005], the influence of dust on surface shortwave radiative forcing and snow cover duration in mountain regions has been relatively ignored [*Hansen and Nazarenko*, 2004]. Until now, the detailed radiation and energy balance measurements needed to partition dust's influence on radiation and snow cover duration have not been available.

[3] Snow has the highest albedo of any naturally occurring surface on Earth. However, when impurities such as dust or soot are present, snow albedo decreases (particularly in visible wavelengths) [*Conway et al.*, 1996; *Warren and Wiscombe*, 1980] (Figure 1). With enhanced absorption by dust, grain growth rates increase and further depress snow albedo. Dust has high potential to sustain shortwave radiative forcing after deposition because particles tend to accumulate near the snow surface as ablation advances [*Conway et al.*, 1996]. Deposition in mountain ranges comes primarily in the spring when frontal systems entrain dust particles from disturbed and loose soils [*Wake and Mayewski*, 1994], coinciding with solar irradiance approaching its annual maximum.

[4] Mountain snow cover is a critical resource as these high elevation mountain regions provide the majority of fresh water supply in arid and semi-arid environments to more than a billion of the Earth's population [*Bales et al.*, 2006]. The duration of snow pack in mountain regions critically controls the timing and magnitude of water supplies, power generation, agriculture timing, and forest fire regimes [*Westerling et al.*, 2006], as well as the duration over which glacial ice is exposed to absorption and enhanced ablation. Some studies already suggest that climate change has induced earlier snowmelt-fed runoff [*Mote*, 2003; *Stewart et al.*, 2005].

[5] The radiative forcing of dust in snow is considered in terms of its direct effect (absorption by dust, Figure 1a), 1st indirect effect (enhanced absorption by larger grain size due to accelerated grain growth from direct effect), and the 2nd indirect effect (enhanced absorption by darker substrate exposed earlier due to direct and 1st indirect effect) [*Hansen and Nazarenko*, 2004]. In this work, we use the term 'radiative forcing' to mean the instantaneous surface enhanced absorption due to dust through these effects. Here we perform the first coupled determination of the radiative forcing of dust in mountain snow and its impact on snow cover duration through detailed radiation measurements that isolate the effects of dust from other controls.

[6] The simulations show that radiative forcing by desert dust deposits shorten snow cover duration by order 1 month in the San Juan Mountains. That the dust originates in disturbed desert sources rather than locally suggests that this mechanism of increasing radiative forcing and shortened snow cover duration is widely active where the world's mountains receive dust from disturbed lands. Moreover,

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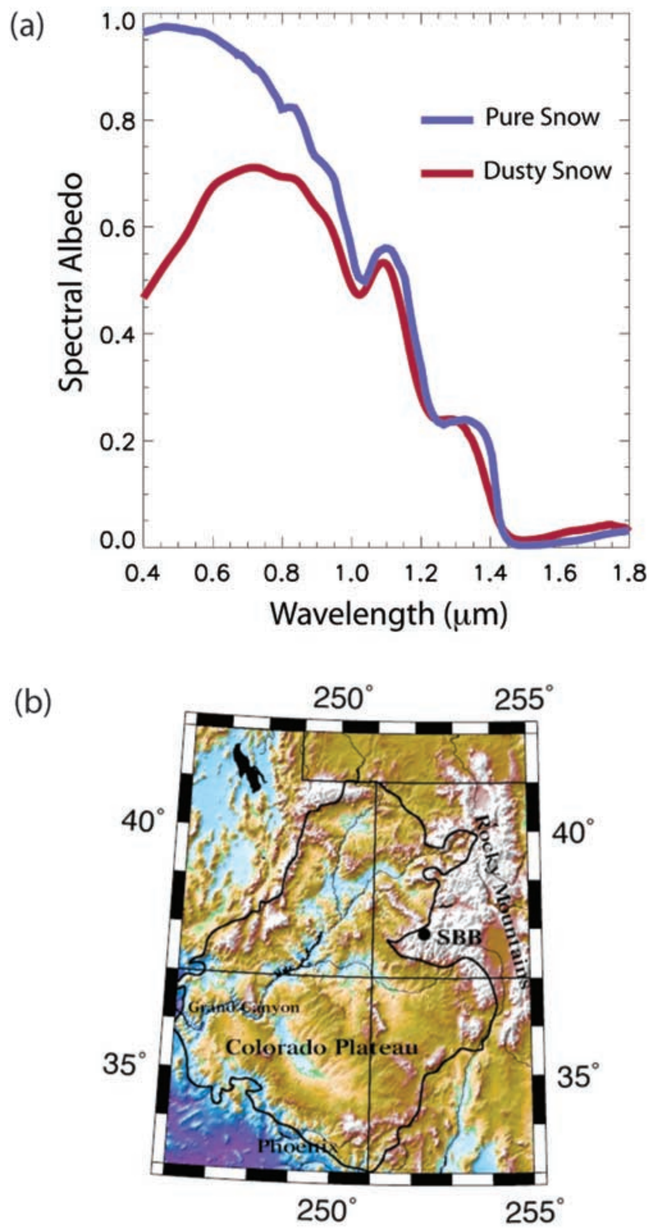

Figure 1. Spectral albedo of dust-laden snow and Colorado Plateau/San Juan Mountains. (a) Spectral albedo of pure snow (modeled with same grain size as that measured in the field) and snow with concentrated dust in surface layer (0.37 mg dust per g snow water equivalent) measured with an Analytical Spectral Devices FieldSpec FR spectroradiometer. (b) Colorado Plateau in southwestern US and Senator Beck study site (SBB) indicated in San Juan Mountains of southwest Colorado.

under global warming and associated desertification, the process could threaten snowmelt-fed water resources to arid and semi-arid regions.

2. Site and Methods

[7] We estimate radiative effects of dust and changes in snow cover duration in the San Juan Mountains, Colorado (Figure 1b) in two dramatically different dust deposition years, 2005 (4 dust events) and 2006 (8 dust events). The San Juan Mountains cover 32,000 km^2 (6900 km^2 above tree line at ~3400 m) and have a strong continental climatic regime. Headwaters for major western US rivers including the Rio Grande and the Colorado lie in the range. According to anecdotal evidence, historical research, and recent observations presented here, the San Juan Mountains receive multiple dust deposition events annually in February through May, arriving before and during the snowmelt period (Auxiliary Material Table S1).

2.1. Radiative Forcing

[8] Incident and reflected broadband shortwave and near-infrared/shortwave infrared (NIR/SWIR) radiation, along with standard meteorological variables, were measured at two towers, one in the alpine zone at 3719 m and one in the subalpine zone at 3368 m of the Senator Beck Basin. From these measurements, we determine the range of potential radiative forcings due only to dust. Minimum surface radiative forcing $F_{d\min}$ (W m^{-2}) is calculated as

$$F_{d\min} = E_{VIS}\Delta_{VIS} \tag{1}$$

where E_{VIS} is the visible irradiance (W m^{-2}) determined from the difference between the broadband and NIR/SWIR irradiances, Δ_{VIS} = 0.92 − α_{VIS}, α_{VIS} is calculated visible albedo and 0.92 is the mean visible albedo for dust-event-free snow.

[9] Maximum surface radiative forcing $F_{d\max+i1}$ is calculated as

$$F_{d\max+i1} = 0.5\left(E_{VIS}\Delta_{VIS} + E_{NIR}\alpha_{NIR}\left(\frac{1}{\xi} - 1\right)\right) \tag{2}$$

where

$$\begin{array}{ll} \xi = 1 - 1.689\Delta_{VIS}; & \Delta_{VIS} \in [0, 0.17] \\ \xi = 0.67; & \Delta_{VIS} > 0.17 \end{array},$$

E_{NIR} is the NIR/SWIR net shortwave flux, and α_{NIR} is NIR/SWIR albedo. The latter relationship gives the proportion of the change in NIR/SWIR albedo due to presence of dust versus grain coarsening in the absence of dust (see Auxiliary Material).[1]

2.2. Snowmelt Modeling

[10] Snow cover duration was simulated for observed net surface shortwave fluxes (K^*) and for the observed net surface shortwave fluxes minus $F_{d\min}$ ($K^*_{d\min} = K^* - F_{d\min}$) and $F_{dmax+i1}$ ($K^*_{d\max+i1} = K^* - F_{d\max+i1}$), respectively, using the snow energy balance model SNOBAL [*Marks et al.*, 1998]. SNOBAL uses a two-layer snowmelt approach with an active 25 cm surface layer and the remainder of the snow pack as a second layer. Initial conditions for snow pack properties came from detailed weekly measurements in the field at each site. SNOBAL is driven with hourly averages of observed and estimated dust-free net shortwave, and

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl030284. Other auxiliary material files are in the HTML.

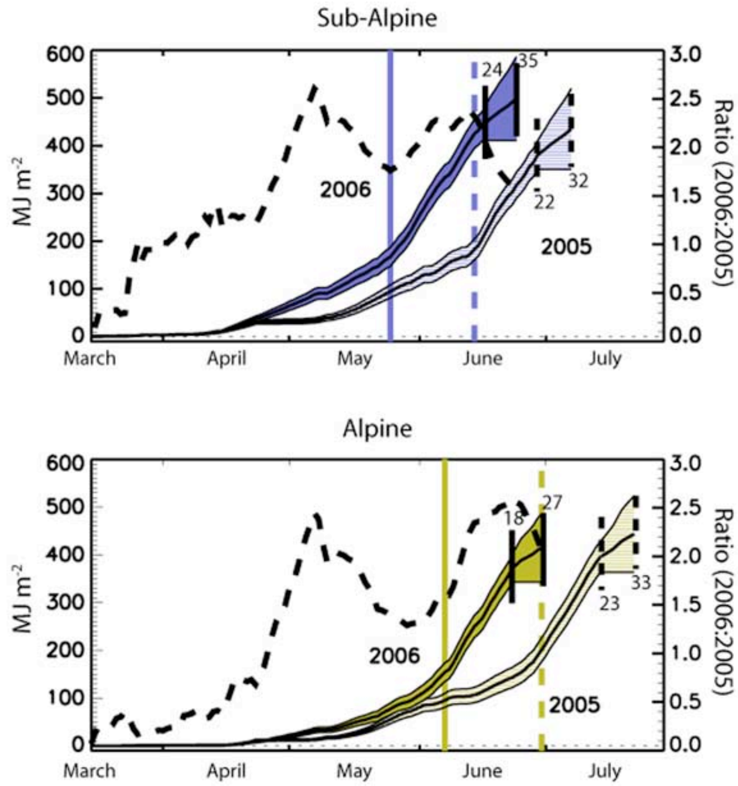

Figure 2. Cumulative surface radiative forcing by dust (MJ m^{-2}) for subalpine and alpine. The full-length vertical lines indicate observed date of disappearance of snow whereas the shorter vertical lines indicate the modeled date of disappearance of snow in the minimum and maximum forcing cases, with differences from observed date in number of days indicated. Dashed lines show the ratios of daily mean forcing in 2006 with respect to 2005.

observed incident longwave radiation, and air temperature, relative humidity, and wind speed measured at known heights above the snow surface at the respective meteorological towers.

[11] The difference between observed and simulated snow melt out-date for the measured scenario provides a measure of the accuracy of SNOBAL. In all simulations, complete snow ablation occurred within 1 day of observed ablation except in the 2005 subalpine case (2 days), due to discrimination between rain and snow near the end of snow cover.

[12] The second indirect effect for the minimum and maximum cases is the difference between simulated net shortwave radiation for snow free conditions (post ablation) and the net shortwave radiation for snow cover for minimum and maximum forcing scenarios. We add the respective 2nd indirect effect to the minimum and maximum radiative forcings after observed melt-out to obtain total forcings.

2.3. Isotopic Analysis

[13] Each dust event was collected from the mountain snow pack by excavating dust layers of snow, melting the snow into HDPE collection vessels and then refreezing the sample until analysis. The samples were freeze-dried to a powder. Resulting solids were dissolved in concentrated HF and $HCl0_4$. Rb and Sr were separated from the solution using SrSpec® resins, while Sm and Nd were obtained using conventional reverse phase chromatographic techniques [*Farmer et al.*, 1991]. Isotope dilution concentration and Sr and Nd isotopic determinations were obtained using a Finnigan-MAT thermal ionization mass spectrometer. $\varepsilon_{\mathrm{Nd}}$ represents a comparison of the $^{143/144}$Nd of the measured sample to a ratio for CHUR (chrondritic uniform reservoir) where

$$\varepsilon_{\mathrm{Nd}}(0) = \left[\left(\left({}^{143/144}\mathrm{Nd}\right)\mathrm{Sample}\left({}^{143/144}\mathrm{Nd}\right)\mathrm{CHUR}\right)/\left({}^{143/144}\mathrm{Nd}\right)\mathrm{CHUR}\right] \quad (3)$$

all at the present time (t = 0).

3. Results

[14] Between 2003 and 2005, three to four significant dust deposition events occurred in winter and spring of each year, whereas in 2006, eight significant deposition events occurred (Auxiliary Material Table S1). Broadband albedo (α_{BB}) of new, dust-free snow was 0.85 ± 0.01 but declined between snow events through grain size increase when dust was not exposed (Auxiliary Material Figure S1). Once dust emerged near or at the surface, α_{BB} decreased more rapidly due to the additional decrease in α_{VIS} from its dust event-free value of 0.92 ± 0.01.Dust events led to large increases in the daily averaged absorption of incident radiation at the surface in 2005 and 2006 (Figure 2 and Auxiliary Material Figures S2–S3).

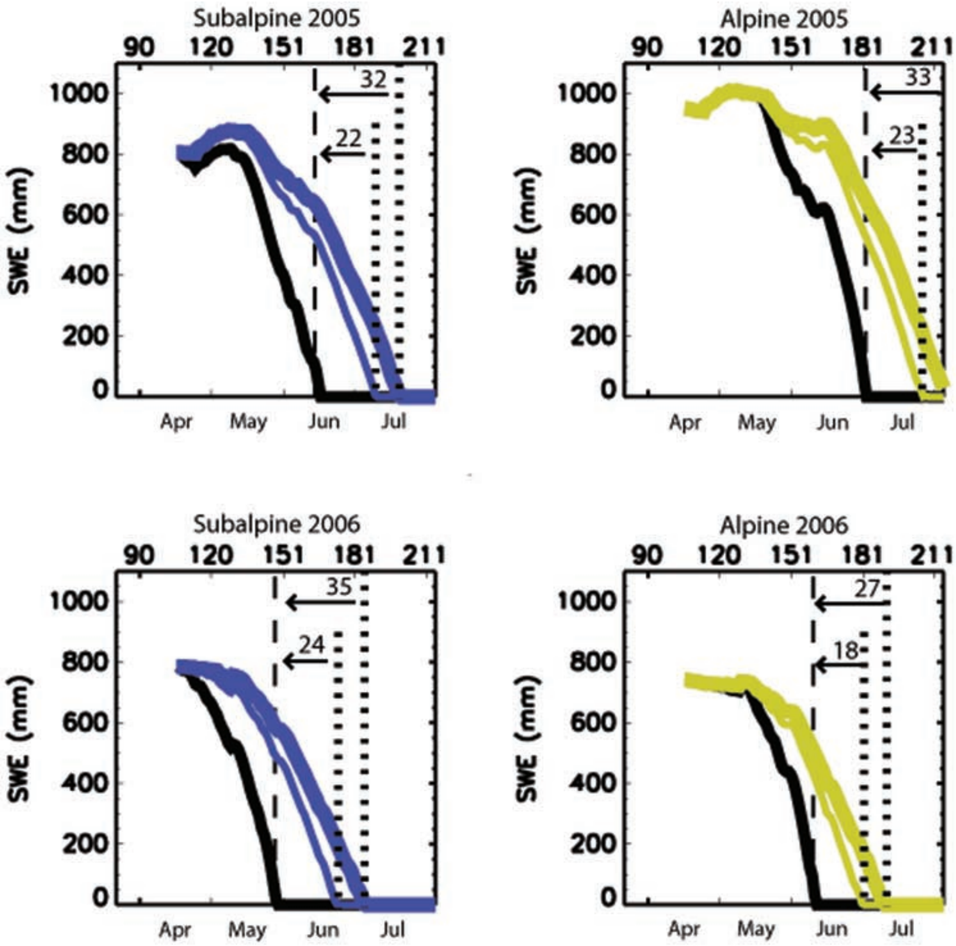

Figure 3. Time series of snow water equivalent scenarios with number of days difference from observed indicated: snowmelt model results for subalpine 2005 in measured case (black), dust free $K^*_{d\min}$ (thin), and dust free $K^*_{d\max+i1}$ (thick), where differences in snow cover duration are indicated for respective cases above the horizontal arrows; subalpine snowmelt in 2006; alpine snowmelt in 2005; and alpine snowmelt in 2006.

[15] During the winter/spring 2005, α_{BB} dropped in two periods from 0.85 (subalpine and alpine) to 0.45 (subalpine) and 0.51 (alpine), respectively, and α_{VIS} dropped in the same periods from 0.92 to 0.50 and 0.61, respectively, due to the accumulation of dust at the snow surface (Auxiliary Material Figure S1). In 2006, α_{BB} dropped quasi-monotonically from 0.85 to 0.40 and 0.46, respectively, and α_{VIS} dropped likewise from 0.92 to 0.45 and 0.58, respectively (Auxiliary Material Figure S1).

[16] In 2005, the radiative forcing had two periods of mean forcings of 30–50 (subalpine) and 20–40 (alpine) W m^{-2} as dust layers were exposed at the surface, covered by snowfall and exposed again through melt (Auxiliary Material Figure S2). In 2006, the radiative forcing increased steadily from early April to maxima of 80 (subalpine) and 60 (alpine) W m^{-2} later in ablation despite frequent but small snowfalls (Auxiliary Material Figure S3). For the period March 21 to June 21 (spring), mean daily radiative forcing in 2005 ranged from 31 to 37 W m^{-2} (subalpine) and 14 to 19 W m^{-2} (alpine), respectively, and in 2006 ranged from 56 to 64 W m^{-2} and 36 to 42 W m^{-2}, respectively. Radiative forcings in the alpine are generally lower than those in the subalpine because dust concentrations were consistently lower at the wind-exposed alpine tower. However, other slopes and aspects in the alpine collect scoured dust and have higher concentrations.

[17] The combination of more frequent and heavy dust events, less post-event snowfall and thus greater exposure, and clearer skies in 2006 compared with in 2005 resulted in distinctly larger radiative forcing and shorter snow cover duration in 2006 than in 2005. Figure 2 presents the cumulative radiative forcings and the time series of the ratios of daily mean forcings for year 2006 to 2005 for both sites. The ratio generally increased at both sites lying between 1.5 and 2.5 for most of the ablation season, indicating that the net shortwave energy made available by dust for melting was approximately doubled in 2006. Ratios less than 1 result from small but non-zero dust forcing before late April 2005.

[18] SNOBAL snowmelt simulations indicate that in 2005 the subalpine melted out 22 to 32 days earlier relative to the dust free cases and the alpine snow cover melted out 23 to 33 days earlier (Figure 3). In 2006, the subalpine melted out completely 24 to 35 days earlier and the alpine melted out 18 to 27 days earlier. Far smaller peak snow water equivalents in 2006 relative to 2005 (67% in alpine, 85% in subalpine) resulted in the small differences between 2005 and 2006 with respect to snow cover duration despite

the doubling in shortwave radiative forcing. This gave less snow cover duration over which the differences in melt rates could be manifested. Therefore, the associated melt rates were greater in 2006 by up to 40%. In the period after snow cover disappears, the 2nd indirect radiative forcing from enhanced absorption was relatively constant between the two years and sites at 147 ± 8 W m^{-2} in 2006.

[19] Dust is generated by several processes and can originate from a spatial range of sources. We determined provenance of deposited dust through a combination of isotopic analysis, back-trajectory analyses, and remote sensing. For dust from the snow pack, strontium isotope ratios, $^{87/86}$Sr, and a comparison of the neodymium isotope ratios with a ratio for chrondritic uniform reservoir, $\varepsilon_{\mathbf{Nd}}\mathbf{(0)}$, were compared with the isotopic compositions of exposed surface rocks within the Senator Beck Basin. Sr and Nd isotopic values for the deposited dust were significantly different from the surrounding surface rocks (Auxiliary Material Table S2) and therefore a local, volcanic rock origin for the dust samples taken from the snow pack was highly unlikely.

[20] Precambrian basement rocks in western North America, and sedimentary rocks derived thereof, have geographic variations in their Nd isotopic compositions that constrain the sources of dust found in the San Juan Mountains snow cover. The dust samples have Nd isotopic compositions that overlap those of Paleoproterozoic intermediate to silicic compositions rocks that comprise much of the Mazatzal Province in Arizona and New Mexico (Province 3 of *Bennett and Depaolo* [1987] which lies to the west and south of Senator Beck Basin), indicating that dust deposited in the San Juan Mountains originated in the SW US.

[21] Backtrajectory analysis of atmospheric transport and remotely sensed imagery further narrowed the likely source of the dust. The Stochastic Time-Integrated Lagrangian Transport model (STILT) [*Lin et al.*, 2003] with archived data from the Eta Data Assimilation System (EDAS) 40 km weather analysis produces ensembles of 48-hour back-trajectories from the time of dust deposition. Auxiliary Material Figure S4 shows the mean back-trajectories for the 18 dust events that we have documented since 2003. With the exception of a single event with northwesterly flow (February 22, 2003) across southeast Utah, the remaining events had southwesterly flow across northeastern Arizona and northwestern New Mexico. Clear-sky data from the Geostationary Operational Environmental Satellite 10 (GOES-10) consistently show rising dust plumes from northeastern Arizona and northwestern New Mexico close to the time of dust deposition (Auxiliary Material Figure S5, April 2–3, 2003, as example).

[22] These data are consistent with the combination of trajectories determined by the STILT analyses and isotopic data in showing that dust deposited in the San Juan Mountains comes primarily from the Colorado Plateau. Precipitation in the fall 2005/winter 2006 on the Colorado Plateau was the lowest on record and contributed to the doubling of the number of deposition events over those in 2003–2005. We conclude then that snow cover duration across the San Juan Mountains is reduced by 18–35 days due to the deposition of dust from the disturbed deserts of the Colorado Plateau and not from sources local to the mountain basins.

4. Discussion

[23] Expansion and intensification of grazing, recreational use and agriculture over the past ~140 years has increased the dust emission from the Colorado Plateau and other desert regions of the western US [*Belnap and Gillette*, 1997; *Neff et al.*, 2005; *Reynolds et al.*, 2001]. Therefore it is likely that the above changes in snow cover duration and surface radiative forcing increased significantly with human activity in the late-1800s, as desert surface crusts were disturbed and dust was more freely emitted to the Rocky Mountains and other mountain ranges of the western US that are downwind of disturbed soils. Analyses similar to those performed for the San Juan Mountains and an analysis of time series of dust deposition from mountain lake sediments across the western US will provide a clearer understanding of the spatial and temporal extent of this shortening of snow cover duration.

[24] The phenomenon of increasing dust emission exists beyond the western US and is global in nature with the potential to continue to perturb resource-critical mountain snowmelt systems. Dust emission frequency in China from the Taklimakan and Gobi deserts (proximal to the Tien Shan and Altai ranges) has increased from one event in ~35 years for the period AD85-1949 to annual since 1990 [*Liu and Diamond*, 2005]. A four-fold increase in dust deposition over the previous two centuries was found in the Dasuopu glacier ice core at elevation 7200 m in Tibet [*Thompson et al.*, 2000], with the continuum increase attributed to increased land usage whereas the interannual variability attributed to interannual changes in precipitation. The drying of the Aral Sea has affected enormous increases in dust emission that frequently deposits in the Tien Shan, Pamir, Himalaya, and Altai Mountains [*Waltham and Sholji*, 2001]. Dust deposition to the Antarctic Peninsula has doubled in the 20th Century due to the coupled effects of changing climate and land degradation [*McConnell et al.*, 2007].

[25] Under global warming, increased drought is projected for the southwest US, Middle East, and the expanding Sahel [*Cook et al.*, 2004; *Hansen et al.*, 2005; *Intergovernmental Panel on Climate Change*, 2007]. All of these deserts are known dust sources for winter and spring deposition to mountain snow cover in the Rocky Mountains (this work), Central Asia (Pamir Mountains, Hindu Kush, Karakoram) [*Wake and Mayewski*, 1994], and the Alps [*Franzén et al.*, 1994; *Schwikowski et al.*, 1995], respectively. Future drying in desert regions [*Cook et al.*, 2004; *Hansen et al.*, 2005] and projected expansion and intensification of use of arid and semi-arid lands [*Asner et al.*, 2004] could cause regional dust emission to increase in frequency and magnitude. Therefore, earlier snowmelt and its effects on mountain water resources and glacial extent is a likely scenario in many of the world's mountain ranges under enhanced dust deposition.

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