SHORTWAVE RADIATIVE FORCING BY DUST DEPOSITION IN MOUNTAIN SNOW COVER

Thomas H. Painter*
National Snow and Ice Data Center, Boulder, CO
Institute for Computational Earth System Science, UCSB, Santa Barbara, CA

Andrew P. Barrett
National Snow and Ice Data Center, Boulder, CO

Chris Landry
Center for Snow and Avalanche Studies, Silverton, CO

ABSTRACT: Regional, intracontinental, and intercontinental dust emission events frequently deposit in mountain snow cover. Winter and spring storms entrain radiatively absorbing dust from desert regions and redistribute optically thick layers to the snow cover in the San Juan Mountains of Colorado as wet and dry deposition. Dust loading in the atmosphere temporarily decreases the surface irradiance through scattering and absorption. However, dust loading at the snow surface, which persists well beyond the atmospheric presence of the dust event, positively forces tropospheric temperatures through direct and indirect effects. Absorption by dust in the snow increases near-surface snowpack temperatures, decreasing the column cold content of the snowpack and increasing the energy available for melt. Enhanced absorption represents the direct effect of dust deposition on the regional radiative budget. Indirect effects occur as associated increases in snow grain size (further lowering albedo) and the more rapid snowpack ablation that reveals a darker substrate.

We observed several significant dust deposition events per year during the mountain snowcover season in the years 2002-2006. Our monitoring of surface radiative fluxes commenced in winter 2005 at an alpine meteorological tower and a subalpine meteorological tower in the San Juan Mountains. In this work we describe the breadth of research that comprises this project. The research consists of analyses of detailed in situ measurements of broadband and spectral shortwave radiation, field measurements of the hyperspectral shortwave radiation, and coupling of the above measurements with remotely sensed multispectral and hyperspectral imagery to estimate the impact of dust deposits on regional radiative forcing. Given the regional extent of dust deposition, direct and indirect effects of dust in snow may provide a positive forcing of tropospheric temperatures that would significantly outweigh the negative forcing of dust loading in the atmosphere at the regional scale.

KEYWORDS: Dust deposition, snow, albedo, radiative forcing, snowmelt

1. INTRODUCTION

Regional, intracontinental, and intercontinental dust emission events frequently deposit in mountain snow cover. Winter and spring storms entrain radiatively absorbing dust from desert regions and redistribute optically thick layers to the snow cover in the San Juan Mountains of Colorado as wet and dry deposition. Dust loading in the atmosphere temporarily decreases the surface irradiance through scattering and absorption. However, dust loading at the snow surface, which persists well beyond the atmospheric presence of the dust event, positively forces tropospheric temperatures through direct and indirect effects. Absorption by dust in the snow increases near-surface snowpack temperatures, decreasing the column cold content of the snowpack and increasing the energy available for melt.

The literature describing the effects of dust on snow albedo and melt is relatively sparse. A few studies have reported the effects of dust layers on snow radiative properties and melt (Jones, 1913; Conway, 1996; Dirmhirn, 1960). Jones (1913) reported

* *Corresponding author address:* Thomas H. Painter, National Snow and Ice Data Center, University of Colorado at Boulder, Boulder, CO 80309;tel: 303.735.3743; fax: 425.740.9260; email: tpainter@nsidc.org

that in 1913 dust mixed with snowfall advanced spring snowmelt nearly one month ahead of normal at Wagon Wheel Gap, Colorado. deQuervain (1947) observed major dust deposition in the Swiss Alps that increased net solar radiation by 20% in May and ablated snow cover completely 1.25 months earlier than normal. Conway et al. (1996) found that ablation was 50% greater with residual concentrations of ash and soot (albedos ~ 0.41) relative to natural snow cover (albedo = 0.61). Blöschl et al. (1990) found that a decrease in albedo from 0.75 to 0.65 (not explicitly due to dust deposition) resulted in an average increase in melt of 30% over a six-day period in a high relief basin in the European Alps.

We began observing dust deposition events in 2003 and in winter 2005 initiated measurements of the complete energy balance and detailed radiation that facilitates determination of the direct and indirect effects of dust on radiative forcing in snow. The direct effect of dust on radiative forcing in snow is given by the enhanced absorption directly by

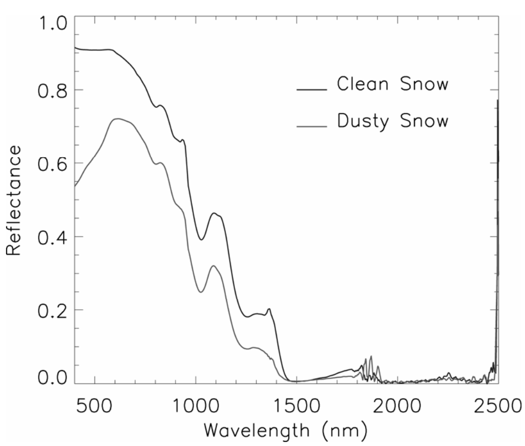

Figure 1 Spectral albedo of dust-laden and dust-free snow, Senator Beck basin, April, 2004, as measured with an Analytical Spectral Devices field spectroradiometer.

the dust (Hansen and Nazarenko, 2004) (Figure 1). The first indirect effect is given by the enhanced absorption from coarser grain size due to the direct effect reinforcement of snow metamorphism. The second indirect effect is the enhanced radiative absorption by the darker substrate (e.g. soil) that is exposed earlier due to earlier snowmelt.

2. STUDY SITE

This project has developed extensive instrumentation in the Senator Beck Basin, western San Juan Mountains, Colorado, USA (N37°54', W107°43'), performed detailed field campaigns to determine the spatial distribution of snow properties as related to dust absorption, and has also secured multi-spectral and hyperspectral remote sensing data at a range of scales from basin to region. The San Juan Mountains cover 32,000 km^2 with 6900 km^2 above treeline at ~3400 m a.s.l. The range lies contiguous to and generally east of the Colorado Plateau and acts as the first topographic obstacle to dust entrained from the desert regions of the Colorado Plateau.

The basin infrastructure is maintained and operated by the Center for Snow and Avalanche Studies (CSAS) in Silverton, Colorado (http://www.snowstudies.org). We measure the complete energy balance at two towers, one in the alpine zone at 3719 m and one in the subalpine zone at 3368 m. The basin has a generally easterly aspect and ranges in elevation from 3341 to 4118 m, discharging into Red Mountain Creek. Seasonal maximum snow accumulations generally occur during mid to late April and average 0.70-0.80 m in snow water equivalence, with winter storms primarily coming from the northwest-to-southwest quarter, crossing the Colorado Plateau and the Mojave Desert.

3. MEASUREMENTS

3.1 In situ measurements

The Senator Beck Study Site is operated by the Center for Snow and Avalanche Studies (CSAS) based in Silverton, Colorado, 5 miles from the site. The alpine study site is at 3658 m on a slightly northeast-sloping bench. The local surface is characterized by alpine tundra. The subalpine study site lies at 3368 m in a sheltered, open meadow and slopes slightly eastward.

Solar broadband and near-infrared/ shortwave infrared irradiances and reflected fluxes are measured with Kipp&Zonen CM21 pyranometers. Diffuse broadband irradiance is measured with a Kipp&Zonen CM21 under configuration with a shadowband consistent with those in the Alpine Surface Radiation Budget (ASRB) network in Switzerland (Figure

2). Longwave irradiance is measured with Kipp&Zonen CG4 pyrgeometers. Longwave exitance from the snow surface is inferred from the Stefan-Boltzmann law with measurement of snow temperature from the AlpuG SnowSurf infrared sensor, assuming snow emissivity of 0.98.

Figure 2 Broadband solar (K&Z CM21) and longwave (K&Z CG4) sensors at alpine tower, Senator Beck basin.

Air temperature, relative humidity, and wind speed are measured at two heights above the snow surface for determination of turbulent fluxes of sensible and latent heating. Barometric pressure is measured with a Vaisala PTB101B at the subalpine tower. Snow temperatures at multiple depths are measured with a thermister chain that is adjusted manually after precipitation or ablation. Soil heat flux is measured at 3 cm depth with a REBS HFT-3.1 thermopile, soil temperatures are measured at depths 0, 10, 20, and 40 cm with Campbell Scientific 107 sensors, and soil volumetric water content at 10 cm depth with a Campbell Scientific CS616.

All data are logged with Campbell Scientific CR10X coupled with multiplexers AM16/32. Data are retrieved through radio telemetry using phone-to-RF base station.

At the subalpine site, the National Snow and Ice Data Center operates a CIMEL sunphotometer to continuously monitor aerosol optical depths. The sunphotometer has been integrated into the NASA AEROsol Robotic NETwork (AERONET) and the data from the site can be found at the AERONET webpage (http:// aeronet.gsfc.nasa.gov/) under site name *Red_Mountain_Pass*. A single day's aerosol optical depths during a dust deposition event are shown in Figure 3.

Precipitation is measured at the Swamp Angel Study Site. Discharge and electrical conductivity are measured at the flume at the broad-crested weir located at the outlet of the Senator Beck Basin. Two additional stream monitoring arrays, measuring water temperature and water depth are deployed in the primary channel draining the Basin, one in the alpine area at aprox. 3,660 m and the other near treeline, at aprox. 3,450 m.

3.2 __Field Sampling__

Beginning in April, we sample the spatial distribution of snow water equivalence in the basin. Field teams measure snow depth and density, grain size, temperature, and dust concentration in snow pits. Snow depth is measured using snow probes in gridded transects. Maps of snow water equivalence (SWE) are interpolated from snow pit and probe measurements. These maps of SWE are then constrained by maps of snow-covered area from remotely sensed imagery and routine digital photography to provide best estimates of SWE distribution.

In snow pits at the two instrumented study sites, we sample dust concentration, concentration stratigraphy, particle size, optical properties, and mineral type on the same sampling schedule as that used for the snow physical properties. This analysis, along with the mineral element characterization is carried out in a biogeochemistry laboratory at CU- Boulder.

These measurements of concentration

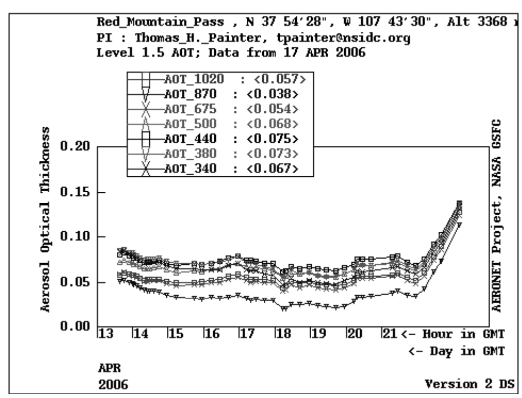

Figure 3: Aerosol optical depths at individual wavelengths during a dust deposition event on April 17, 2006 at Senator Beck basin (AERONET site Red_Mountain_Pass).

and optical properties are being compared with field measurements of integrated albedo and spectral albedo using the instrumentation arrays at the alpine and subalpine meteorological towers in Senator Beck Basin. It is important to note that the position of dust layers within the snowpack will determine the temporal effect on the variation of snow albedo as those layers emerge at the snowpack surface.

At regular intervals through the accumulation and ablation seasons, we measure snow depth, snow density, snow grain size, stratigraphy, snow grain morphology, snow morphology associated with aerosol impurities, and snow liquid water content in a time series of snowpits in undisturbed snow at both study sites in the Senator Beck Basin using standard sampling procedures. During the accumulation season (approximately October through March) we sample these variables on a monthly basis. During the ablation season (approximately April 1 through July 1), we sample these variables at the study sites on a weekly basis to capture what can at times be a rapid modification of snow morphology and stratigraphy. These variables are also measured on a monthly basis during the snowmelt season at five additional snowpit sites distributed throughout the Basin.

3.3 Remote Sensing Data

Snow-surface albedo and snow covered area will be obtained from AVIRIS scenes at a 3 m resolution and SPOT data at 10 m resolution using a spectral mixture model (Painter et al., 2003) and radiometric adjustments to broadband albedo from radiation measurements in the basin. The resolution of the remotely sensed data will be degraded to 10 m to match that of the digital elevation model. These acquisitions will be performed with gain setting appropriate for spring snowcover in order to avoid saturation and will span the period May 1 – July 1 twice weekly. The data are analyzed for snow covered area and albedo at the University of California, Santa Barbara and distributed from UCSB webservers. Additionally, the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) imaged the basin several times from April 26 through May, 2006. SPOT imaged the basin through May and June, 2006.

4. DISCUSSION

The data described above are being prepared for point and spatially distributed hydrologic modeling to understand the impacts of desert dust on snowmelt generation and river discharge. With the inferences of the radiative forcings of dust on shortwave radiation described above, we can remove these effects from spatially distributed fields of radiation in the hydrologic model to compare ensembles of runs with and without dust presence.

This project provides the springboard for wider scale projects at the scale of the Rockies and other ranges of the globe where dust deposition impacts snow cover.

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