A SPATIAL AND TEMPORAL ANALYSIS OF RADIATIVE FORCING ACROSS A REGIONAL SCALE IN THE WESTERN UNITED STATES

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ABSTRACT

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Snow is a unique land cover type, and varies significantly in reflectance from other types of surfaces on Earth. Uncontaminated, or 'clean', snow has a very high spectral albedo. This is reduced by the deposition of light absorbing particulates, like dust from arid and disturbed landscapes, which darken the snow surface and enhances the rate of snow melt. The instantaneous enhanced surface absorption of solar radiation by dust on snow is known as radiative forcing. Radiative forcing by dust on snow can be monitored at the regional scale with the MODIS Dust Radiative Forcing in Snow (MODDRFS) product. Here present results from the Western US, namely on the Rocky Mountains and Sierra Nevada Mountains. We show the effect of dust on snow has high interannual variability, and dust radiative forcing is consistently higher in the Rockies relative to the Sierra Nevada. Gaining a better understanding of the spatial and temporal patterns of dust on snow in the Western US will help in formulating effective management of water resources in a region that is dependent on snow melt to meet water demands.
(KEYWORDS: dust-on-snow, albedo, snowmelt, remote sensing)

INTRODUCTION

Dust is episodically deposited on snow in the Western US in the spring when soils dry out and wind speeds peak. When deposited in snow dust is not efficiently entrained in meltwater and individual dust layers combine at the surface as snowmelt progresses, compounding surface darkening (Skiles and Painter, 2016). Because snowmelt is mainly controlled by net solar radiation, this reduction in surface reflectance, referred to as radiative forcing enhances melt and shifts runoff timing and intensity (Skiles et al., 2012). The amount of dust transported in any given dust event varies and is dependent on the conditions of the source regions, for example wind speeds, soil moisture, and vegetation, and previous work in the Colorado Rockies (Skiles et al., 2012) has shown that dust deposition, and its impact on snow melt, exhibits interannual variability. It is of interest to monitor and better understand the influence on dust on snowmelt rates to more effectively manage water resources.

Freshly fallen clean snow, which has a visible albedo of 0.97-0.99, is the most reflective natural surface on Earth. Dust aerosols that deposit on the snow surface reduce albedo directly by darkening the surface, and indirectly be enhancing the rate of snow grain growth, which controls albedo in the near infrared (NIR) where ice is absorptive. The depth of ice absorption feature centered at 1030 nm in the NIR directly correlates to snow grain size, and clean snow albedo can be modeled based upon the retrieved optically equivalent grain size. The difference in absorption between a theoretical clean snow spectral albedo, and observed snow spectral albedo for the same grain size, is the radiative forcing due to dust (Fig. 1). An algorithm to retrieve radiative forcing by dust in snow from MODIS was developed by Painter et al., 2012, and the MODIS dust radiative forcing in snow (MODDRFS) product is distributed both historically and in near real time via the snow data system portal (NASA-JPL) over the full MODIS record. Here we assess trends in springtime radiative forcing from MODDRFS over the Western US.

Study Area

Snowmelt runoff is an important source of water for the Western United States, contributing 50% to 80% of total annual runoff in many areas (Serreze et al. 1999; Stewart et al. 2004). The Western US has both mountains, where the snow accumulates, and dry and arid regions, like the southern Colorado Plateau, that produce dust. Therefore, the mountain snowpack of the Western US is particularly prone to dust on snow deposition and hydrologic impacts. The predominant wind direction in the spring (south/southwest) leads us to hypothesize that the Rocky Mountains would receive more dust deposition and have higher radiative forcing values than the Sierra Nevada, since the Rockies are downwind from the southern Colorado Plateau and there is no similar consistent dust producer near the Sierra Nevada. The MODDRFS record allows us to assess the radiative forcing for both of these mountain ranges, and assess the interannual variability at the regional scale.

Paper presented Western Snow Conference 2017
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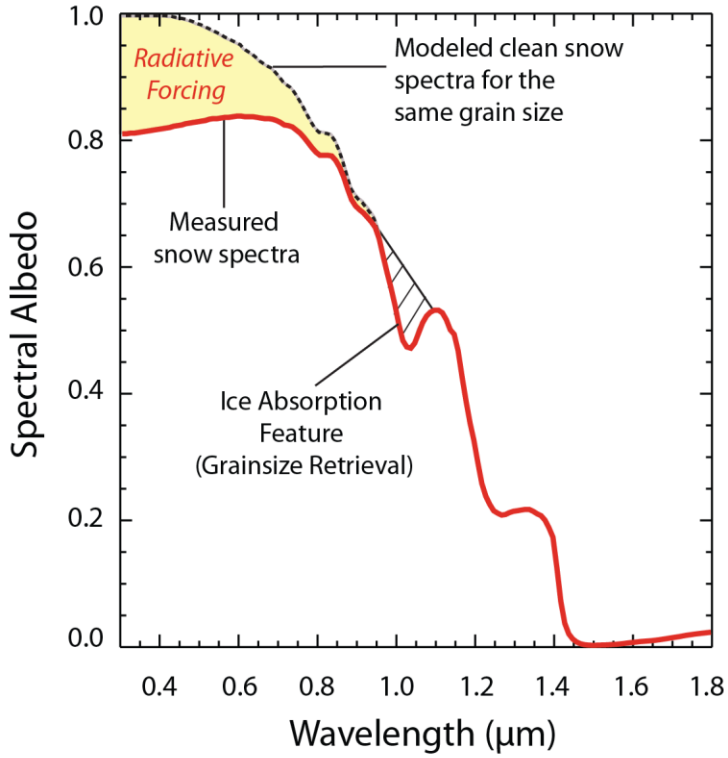

Figure 1. Demonstration of the concept of dust on snow radiative forcing. Note that this is showing spectral snow albedo, whereas MODIS has only 7 bands across the solar wavelength range.

METHODS

Patterns in springtime radiative forcing was assessed over 5 Western US tiles, as 8-day composites which are less likely to have cloud artifacts, between 2001-2012. In this initial study, radiative forcing was analyzed for the week of May 7th, which was chosen because episodic dust events are most commonly observed in the spring (Skiles et al., 2012) and have the largest impact on melt when they coincide with increasing solar radiation. Furthermore, the time frame is typically past peak snow water equivalent when melt has initiated. The MODDRFS algorithm infers per-pixel radiative forcing by light absorbing particulate in snow using MODIS surface reflectance data (Terra MODIS MOD09GA- near daily over the Western US), and a coupled radiative transfer model for snow. MODDRFS determines the spectral reflectance differences between the measured MODIS spectrum and the modeled clean snow spectrum of the same optical grain radius (as demonstrated in Fig. 1). The instantaneous at-surface radiative forcing (Wm^{-2}) is calculated via the integration of the band-wise multiplication of the spectral difference with local terrain accounting spectral irradiance (Painter et al., 2012). The data was downloaded from the NASA-JPL snow data system server, re-projected and mosaicked in ENVI, and imported into ArcGIS to be analyzed.

RESULTS

Here we present a selection of radiative forcing retrievals for the Sierra Nevada and broader Western Rockies, including the Colorado Rockies and the Wasatch and Uintah Mountains of Utah (Figures 2-3). Our analysis shows that radiative forcing tends to be stronger for mountain snowpacks in the intermountain West relative to the Sierra Nevada or mountains in the Pacific Northwest. Radiative forcing is generally most intense for the San Juan Mountains of southwest Colorado, which is the first high elevation point of contact for dust being transported from the southern Colorado Plateau. The radiative forcing then exhibits a generally decreasing northwest trend. Over the full region, radiative forcing exhibits inter-annual variability, with mean radiative forcing varying between 40 Wm^{-2} to 60 Wm^{-2}. The magnitude of the impact of dust driven radiative forcing varied, and ultimately this depends on the snow-covered area, number and timing of dust events, amount of dust deposited, and dust in snow dynamics.

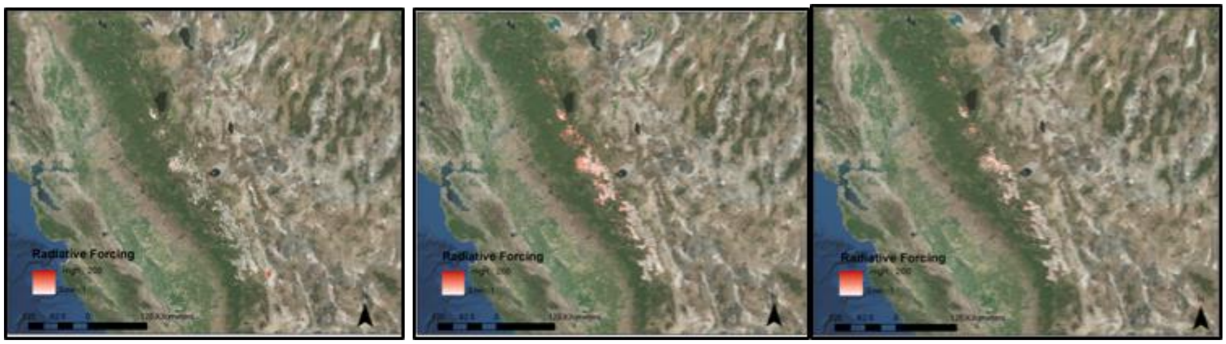

Figure 2. MODDRFS radiative forcing in the Sierra Nevada for a low snow year (2003; left), a high dust radiative forcing year (2009; middle), and an average snow/average dust year (2012; right).

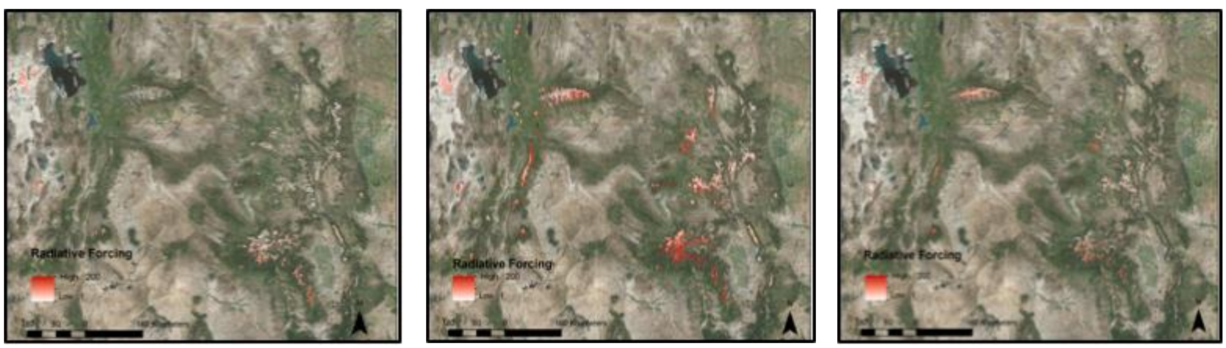

Figure 3. MODDRFS radiative forcing in the intermountain West for a low snow year (2003; left), a high dust radiative forcing year (2009; middle), and an average snow/average dust year (2012; right).

CONCLUSIONS

Our analysis indicates that mountain ranges located closer to, and downwind from, arid desert regions are more vulnerable to the effects of dust on snow. The ability to acquire dust deposition via satellite remote sensing improves our ability to monitor spatial and temporal trends of dust on snow radiative forcing, and improves our understanding of the relationship between dust and snowmelt. Dust aerosols play an important role in the prediction of snowmelt runoff but are currently not accounted for in surface runoff models. Future research will explore radiative forcing patterns over the full spring time period, and the relationship to other snow-covered products and datasets, for example, snow line elevation and rate of depletion, as shown in Figure 4. Since the analysis shows spatial variability, it will also focus on understanding trends for specific mountain ranges (e.g. the San Juans or the Sierra Nevada) as we continue to analyze the region as a whole.

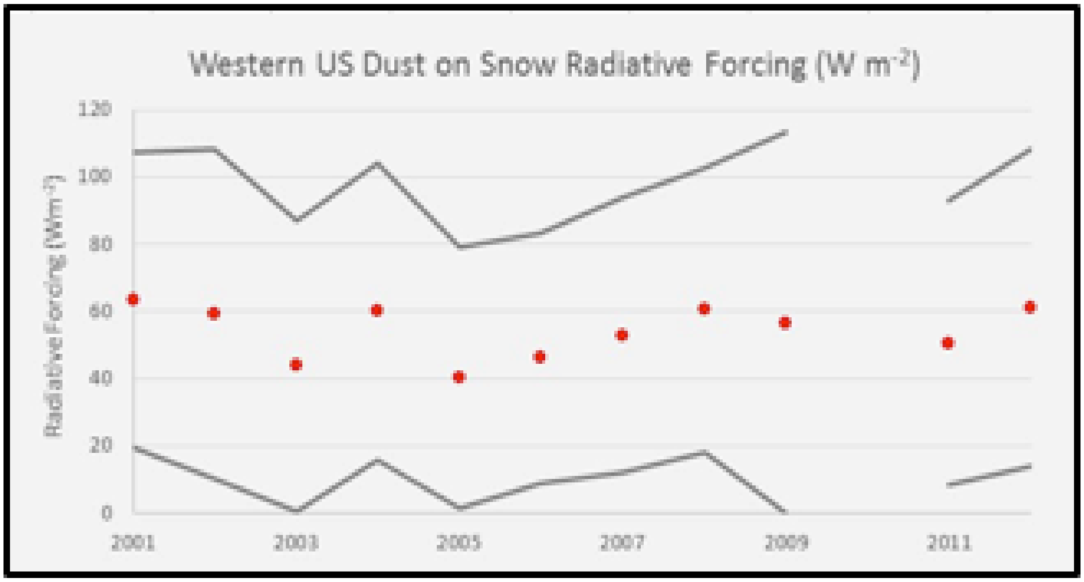

Figure 4. Regional dust on snow radiative forcing for the week of May 7th between the years of 2001 - 2012. Red dots are mean values, lines indicate (+/-) standard deviation. Data still being analyzed for 2010 as indicated by the lack of data.

ACKNOWLEDGEMENTS

We would like to the Snow Data System Team at NASA JPL (https://snow.jpl.nasa.gov/portal/data/help_moddrfs) and Utah Valley University Department of Earth Science.

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