RADIATIVE FORCING BY DUST IN SNOWMELT-DOMINATED HYDROLOGIC SYSTEMS USING COUPLED SATELLITE AND IN SITU MEASUREMENTS

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ABSTRACT

Snow is the primary source of fresh water in the western United States. With the highest albedo of any naturally occurring surface on earth, pure snow reflects roughly 90% of incident solar radiation. The addition of dust to snow decreases the albedo, increases the melt rate of snow, and spurs a decline in total snow extent, which in turn leads to increased heating of the troposphere (the snow-albedo feedback). Although dust has had an enduring presence in snow, land-use change in semi-arid regions around the world has increased dust deposition to mountain regions in the past 200 years. This paper describes the MOD-DRFS model, which leverages the MODIS surface reflectance for snow grain size and radiative forcing from dust in snow. The model has been initialized using the past 10 years of MODIS data nadir to the Colorado River Basin. MODIS data coupled with in situ data, provide insight into the relationship between dust concentration in the optically-relevant portion of the snowpack and a spatially comprehensive dataset of basin scale (and larger) dust-induced energy inputs to the snowpack. Further, this paper shows there is heterogeneity of dust deposition throughout the study region and that the 2008/2009-snow year had significantly more dust radiative forcing than other years in the record. The products of this research will inform hydrologic modeling in the western US and lay the foundation for understanding how radiative forcing by dust on snow and the snow-albedo feedback can affect the global hydrologic cycle and climate. (KEYWORDS: MODIS, radiative forcing, dust deposition, snowmelt, albedo)

INTRODUCTION

This paper will demonstrate a method to asses the radiative forcing of desert dust on mountain snow cover in the western United States through the analysis of time series MODIS surface reflectance data, coupled with in situ measurements of snow spectral albedo and total dust concentration per unit volume snow. Such analysis is of growing importance as those who manage, utilize, and consume water in the western United States are impacted by the variability of dust deposition on the snowpack. This research will ultimately lay a foundation from which to directly address the notions of variability, response, consequences, and prediction as they relate to dust/snow/water dynamics in the western United States.

Dust on Mountain Snow

Dust deposition on mountain snow cover around the globe has occurred throughout history as demonstrated by annual dust layers in high elevation ice cores, with greatest deposition during the spring when snow cover begins melting (Thompson, et al., 2000). Current research has found that dust deposition on snow cover in southwest Colorado has accelerated melt and reduced snow-cover duration by approximately one month (Painter et al., 2007). Neff et al. (2008) showed with analysis of lake sediments that dust deposition in the San Juan Mountains (Colorado River Basin) is presently 500% greater than prior to the extensive population and settlement of the western US in the late 1800s. Dust deposition peaked in the period between 1900-1930, coinciding with the maximum number of grazing animals but retreated to present day levels after the Taylor Grazing Act of 1934. McConnell et al. (2007) found that dust concentrations had increased in the snow and ice of the Antarctic Peninsula by a factor of 2.5 since the 1930s when sheep were introduced to the semi-arid lands of Patagonia. In the ice core of Dasuopu, Tibet, dust increased in concentration by as much as a factor of 4 since the 1860s with the increased agriculture on the Himalayan plains (Thompson et al., 2000).

Optical Properties of Dust on Snow

Snow has the highest albedo of any naturally occurring surface on Earth. When impurities such as dust or soot are present however, snow albedo decreases through direct absorption by the impurity and the indirect grain growth associated with the direct absorption (Conway et al., 1996; Warren and Wiscombe, 1980). In a dust-laden snowpack, albedo can drop from ~0.85 to ~0.45, representing a nearly factor of 4 increase in absorption of shortwave radiation (Painter et al., 2007).

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Ice is highly transparent in the visible wavelengths, so albedo of snow is sensitive to small amounts of absorbing impurities. The spectral albedo in the near infrared is primarily sensitive to grain size because ice is more absorptive in these wavelengths (Wiscombe and Warren, 1980). As absorption by dust increases, grain growth rates increase and further suppress snow albedo. The efficacy of dust to sustain shortwave radiative forcing after deposition comes from two major factors (i) particles tend to accumulate near the snow surface as ablation advances (Conway, et al., 1996), and (ii) dust arrives and concentrates during the spring when solar irradiance is increasing.

The relationship between snow grain-size, particle accumulation at the snow surface, and timing of dust events is key to the global snow-albedo feedback loop, where the radiative forcing of dust in snow is considered in terms of its direct and indirect effects. The direct effect is absorption or solar radiation by dust. The 1st indirect effect is enhanced absorption by larger grain size due to accelerated grain growth from direct effect. The 2nd indirect effect is enhanced absorption a darker sub-surface, which is exposed earlier due to the direct and 1st indirect effect (Hansen and Nazarenko, 2004). For this research, we use the term "radiative forcing" to mean the instantaneous surface enhanced absorption due to dust through the combination of the direct effect and the 1st indirect effect.

The primary focus of this paper will be to present methods to assess the spatial distribution of dust on snow radiative forcing and in situ measurements for the 2009 snow year. This research will display that there is a heterogeneous nature to dust radiative forcing on snow and that the MOD-DRFS model is capable of identifying such a phenomena. Further, this paper will speak to the validity of continuing this type of research both in the realm of remote sensing and in situ data collection.

SITE DESCRIPTION

This research was conducted in the Rocky Mountains in Western Colorado. The Colorado Rocky Mountains are part of the larger Rocky Mountains that stretch from New Mexico to British Columbia. This fieldwork is particularly relevant to the Colorado portion of the Rocky Mountains because of their proximity to the arid American southwest. The fieldwork for this research was conducted in late April 2009 (repeated in April 2010), which corresponds to the time when the majority of dust events have been deposited onto the snowpack and when there has not been a significant loss of snow water equivalent (SWE) relative to peak SWE. There were 11 sites sampled, all of which are in proximity to a Snow Course or SNOTEL site, to better establish a longer-term understanding of site conditions.

METHODS

In Situ Data Collection

In both April 2009 and April 2010, 11 field locations were visited with the goal of collecting field spectroscopy measurements and snow samples. At each study site, the intended snowpit location was determined first. At this location, an ASD Field Spectrometer was used to take albedo measurements (these measurements will be integrated into a future study). Depending on sky conditions, albedo measurements where integrated over longer/shorter time periods, i.e. if there was a mix of sun and cloud, up-looking and down-looking measurements were taken with the intent of capturing the various magnitudes of incoming irradiance. Once albedo measurements were taken, a full snowpit was dug at the site of the albedo measurements. In each snowpit, snow samples were taken every 10 cm using a Kelly-Cutter sampler of 100 cm^3. Each snow sample was placed in a high-grade plastic bag and stored in a cooler for the duration of the field mission. Consequent measurements of temperature, hand hardness, and grain size are also taken.

To determine total dust mass, each snow sample collected while in the field was melted and run through a 0.45-micron filter. Once complete, each "dusty" filter was then dried and weighed (the clean filter mass is subtracted). Once the mass of each filter was determined, both total pit mass and dust loading of individual dust layers can be determined. These data speak to both the dust loading of individual events and the spatial variability of loading between study sites.

Remote Sensing Methodology

MODIS imagery has enabled the analysis of snow properties in remote-mountain environments because its dynamic range in the visible wavelengths accommodates the large radiances measured from snow without saturation. Because of the high reflectance in the near-infrared (MODIS band 4) and low reflectance in the short-wave infrared (MODIS band 6), snow is easily differentiated from other surfaces. Beyond the detection of snow, the sensitivity to grain size in the near-infrared band enables the retrieval of grain size from MODIS.

The algorithm used for this research, MODIS Dust Radiative Forcing in Snow (MOD-DRFS), determines the per pixel radiative forcing by dust on snow from a coupled radiative transfer model that infers the reflectance difference between clean snow spectra and dust-laden snow spectra according to a grain size matching in the NIR and SWIR wavelengths that are not affected by dust absorption. MOD-DRFS first uses the Normalized Difference Snow Index (NDSI) to differentiate snow from other surfaces:

$$NDSI = \frac{MODIS_{b4} - MODIS_{b6}}{MODIS_{b4} + MODIS_{b6}}$$

Based on the sensitivity of the slope of the spectral reflectance of snow in the shortwave infrared, we then use a normalized difference grain size index that is determined from:

$$NDGSI = \frac{MODIS_{b4} - MODIS_{b5}}{MODIS_{b4} + MODIS_{b5}}$$

As describe above, snow spectral albedo is largely insensitive to impurities in the NIR and SWIR, so we can use an estimate of grain size from those longer wavelengths to determine the clean-snow reflectance spectrum modeled for that grain size with the discrete ordinates solution to the radiative transfer equation. In turn, the MODIS measured spectrum is scaled to the clean snow spectrum by a fit to the longer wavelengths. These spectra are then splined to a high spectral resolution to match that of modeled spectral irradiance to a range of slopes and aspects on a range of elevations of the modeled-mountain range. The difference between these spectra is then convolved with the irradiance spectrum specific to each pixel according to the spectral irradiance determined with the Santa Barbara DISORT Atmospheric Radiative Transfer model for the range of elevations, slopes, and aspects of the particular mountain range.

Although researchers have acknowledged for several decades that impurities in the snow change the rate of snowmelt in mountain environments, the spatial and temporal dynamics of dust radiative forcing in snow has never been quantified at the mountain range to continental scale. Mesoscale, general circulation, and hydrologic modeling have seen recent improvements to accommodate simulation of impurity effects on snow cover (Flanner and Zender, 2006; Qian et al., 2008), but a lack of driving data and validation data at spatial scales commensurate with the modeling grids have left enormous uncertainties as to the quality of representation by these models.

RESULTS

MOD-DRFS has shown there is a heterogeneous distribution of dust on snow in the Colorado Rocky Mountains over the 10-year record and that the 2008/2009-snow year demonstrated the highest radiative forcing values over this record (Figure 2).

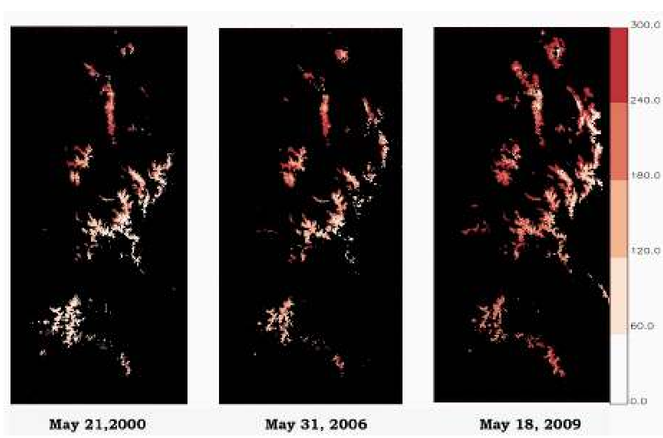

Figure 2. Three MOD-DRFS outputs that span the data record, which demonstrate heterogeneity of radiative forcing. The scale is in W/M^2. Though we have confidence is some range of values, many of the highest values are biased from vegetation.

However, because the model is showing consistent biases in areas of low snow cover (i.e. the bare ground is visible through shallow snow giving the appearance of a "darker" surface) and also areas of vegetation, quantitative statements to the exact forcing values produced by the model would be cursory. These preliminary results suggest however, relative to the 10-year MODIS record, 2009 demonstrated the highest mean radiative forcing values. The basin-mean forcing values for all 10 years of MOD-DRFS outputs were compared in a basic statistical test and 2009 demonstrated a higher-than-normal dust loading in Colorado.

H_o: The mean radiative forcing values for the MOD-DRFS study region in 2009 are not statistically significant than the 10-year record.

α=0.05
T-Test = 0.49

The null hypothesis is rejected, thus 2009 does have mean radiative forcing values that are significantly higher than each other year on record. Spatially, the highest radiative forcing values in 2009 were modeled in the San Juan Mountains of southwestern Colorado. There appears to be a strong relationship between the cumulative dust mass measured at the 11 study sites and the MOD-DRFS radiative forcing values (Figure 3). However, at this stage of research, that relationship is purely qualitative based on visual comparison. In the future, spatial statistical techniques such as Moran's I will be used to determine clustering of high/low values, which will allow more targeted monitoring of stream flow response to radiative impacts of dust on snow.

DISCUSSION

These results will provide an important contribution to the literature relating radiative impacts to contaminants on snow. Qian et al., (2008) indicated with mesoscale modeling that soot from industrial sources may alter snowmelt runoff in the western US but did not include data on dust because these data are not available. Unlike soot-induced radiative forcing however, which has been listed as one of the important anthropogenic forcings affecting climate change (Hansen and Nazarenko, 2004; Hansen et al., 2005; IPCC, 2007; Qian et al., 2008), the influence of dust on surface shortwave radiative forcing, snow cover duration, and hydrology in areas of seasonal snow cover have been relatively under quantified. Moreover, we believe that dust deposition may represent a markedly greater forcing potential than soot because of its substantially heavier loading and, unlike soot, its propensity to stay near the snow-atmosphere interface where it can absorb sunlight. Further, whereas soot comes primarily from urban centers, dust is emitted from distinctively arid environments with a source of unconsolidated material. The Colorado Rocky Mountains are in proximity to such a landscape.

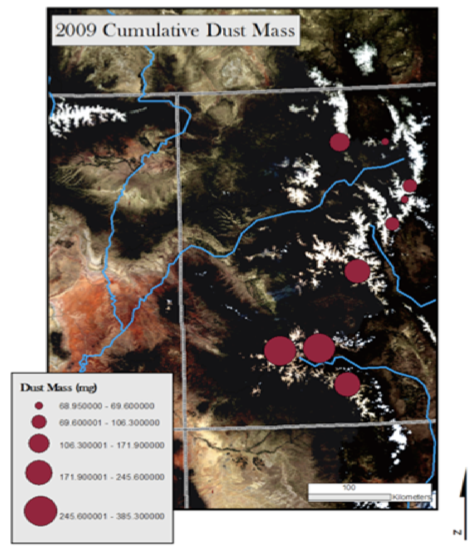

Figure 3. Dust concentration per snowpit for the April 2009 field campaign demonstrates similar patterns to the April values for MOD-DRFS.

There are several potential reasons for the heterogeneous nature of dust deposition. The total dust mass entrained, the type of wind pattern, and particle size are some of the factors that will determine the extent of a dust event. Relative to dust deposited in regions of the world like the Himalaya, where dust from the Middle East has traveled hundreds of miles, dust in the American southwest has a relatively larger grain size. It is the proximity to source region and dust grain size that leave the south/western portion of the mountains particularly vulnerable to receiving a larger mass of dust than other regions in the Colorado Rocky Mountains. Further, the synoptic pattern of wind events are more likely to track from the southwest promoting dust emission from the four-corners region and other southwest/westerly point sources. For these dust events that track from the southwest, the San Juan Mountains are the first major abrupt topographic interruption that fosters both a wet or dry deposition event.

Several factors had to come together to make 2009 such a significant year for dust events. However, these empirical relationships have not been studied enough to make a definitive statement as to "why" 2009 was so dramatic. Like any series of dust events, timing of the constituents that produce such events are a major factor. Timing of synoptic patterns, "green up" date, and surface dryness are some of the components. On the short-term temporal scale, it is the coalescence of these physical properties that can spur an enhanced dust emission year.

Over the longer time scale, major changes in land use coupled with climatic shifts could change the dust emission regime in the southwestern United States.

SUMMARY

The MOD-DRFS model was developed to determine per-pixel radiative forcing by dust on snow. The MOD-DRFS model has shown inter and intra-annual variability of dust radiative forcing. Over the 10-year MODIS record, 2009 had the highest forcing values for the MOD-DRFS study area, as well as highest values from the San Juan Mountains. However, as the model is in developmental stages, we have yet to apply robust statistical methods to the radiative forcing data.

Annual timing of snowmelt runoff is neither trivial nor stagnant. It is a dynamic system, whereupon massive sums of money and effort go into monitoring. The various stakeholders put tremendous confidence in runoff forecasts, as the livelihood of nearly all those in the west depend on this water. It has been documented that dust on snow can have an impact on the timing of snowmelt runoff and, therefore, a spatially comprehensive understanding of dust radiative forcing will be another tool forecasters could use in their predictions.

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