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Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin

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[1] Accurate prediction of snowmelt runoff is critical in the US Intermountain West, where water demand is increasing and snow patterns are shifting. Here, we show that errors in the National Weather Service Colorado Basin River Forecast Center's operational streamflow predictions are correlated with the interannual variability of dust radiative forcing in snow. With data from 2000–2010, we show that errors in snowmelt period streamflow prediction for the southern Colorado Rockies are linearly related to melt period dust radiative forcing in snow as inferred from NASA Moderate Resolution Imaging Spectroradiometer data, which ranged interannually from 20 to 80 W m^{-2}. Each 10 W m^{-2} change of melt period dust forcing resulted in a corresponding change in runoff prediction bias of 10.0% ± 1.5% and a 1.5 ± 0.6 day shift in runoff center of mass. Accounting for bias introduced by dust forcing could improve streamflow prediction in regions prone to dust deposition in the snowpack. **Citation:** Bryant, A. C., T. H. Painter, J. S. Deems, and S. M. Bender (2013), Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin, *Geophys. Res. Lett.*, *40*, 3945–3949, doi:10.1002/grl.50773.

1. Introduction

[2] The mountain snowpack of the Upper Colorado River Basin (UCRB) is the primary water source for the Colorado River, which supplies water to seven states and Mexico for agriculture, industry, and domestic consumption [*Barnett and Pierce*, 2009]. Recent studies have shown that dust from the Colorado Plateau shortens snow cover duration at sites in the UCRB by 25–50 days [*Painter et al.*, 2007; *Skiles et al.*, 2012]. Modern dust deposition in the mountains of the UCRB is 5 times greater than prior due to the disturbance of biological and physical crusts in the lowlands of the Western US in the mid nineteenth century [*Neff et al.*, 2008]. By accelerating snowmelt and extending the snow-free season, this impact may have shifted peak normalized runoff at Lee's Ferry, AZ to more than 3 weeks earlier and reduced the total annual runoff of the Colorado River by an average of more than 5% [*Painter et al.*, 2010].

[3] The National Weather Service (NWS) Colorado Basin River Forecast Center (CBRFC) produces operational streamflow forecasts for the Colorado River Basin. The forecasts are produced using the coupled SNOW-17 [*Anderson*, 1976] and Sacramento Soil Moisture Accounting (Sac-SMA) [*Burnash et al.*, 1973] models. Each decade, the coupled models are calibrated to a 30 year historical record of observed streamflow, initiated with mean areal precipitation and mean areal temperature forcings, which are based on observed historical station data. The forcing data are used to build the basin snow water equivalent (SWE) over the snow accumulation period and determine melt volume over the snow ablation period. During the calibration process, model parameters for hundreds of individual forecast points are adjusted so that predicted streamflow most closely matches observations, thus minimizing bias by balancing overestimates and underestimates.

[4] Temperature-index-based models such as SNOW-17 are the central component of operational hydrologic forecasting systems where snowmelt is the dominant influence on regional streamflow [*Franz et al.*, 2008]. Temperature index models assume empirical relationships between air temperature and snowmelt [*Hock*, 2003]. Their low data requirements and simplicity make them the most common tool for snowmelt modeling. However, considerable research dedicated to measuring and modeling snow cover energy and mass balance [*Marks and Dozier*, 1992; *Painter et al.*, 2007] has shown that solar radiation fluxes frequently dominate snowmelt. The temperature index melt factor used by SNOW-17 is a seasonally dependent index of the relative proportions of energy balance components for each elevation zone within a modeled basin [*Anderson*, 2006]. However, the frequency, spatial extent, and mass flux of dust deposition in the UCRB vary annually [*Kavouras et al.*, 2007; *Painter et al.*, 2012; *Steenburgh et al.*, 2012], strongly modifying snow albedo from year to year. As snow surface albedo deviates from the calibration period mean, so does the fraction of incoming shortwave radiation absorbed by the snowpack, directly influencing snowmelt timing and runoff and rendering the melt index less representative.

[5] We know that dust radiative forcing and snowmelt acceleration have considerable interannual variability in the UCRB [*Skiles et al.*, 2012] and hypothesize that this variability affects the accuracy of the CBRFC SNOW-17 predictions. Here, we explore the sensitivity of CBRFC prediction errors to dust radiative forcing as inferred by remote sensing using the NASA Moderate Resolution Imaging Spectroradiometer (MODIS).

Additional supporting information may be found in the online version of this article.

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Figure 1. The Upper Colorado River Basin with the four gage catchments and their respective 8 digit hydrologic unit code (HUC-8) river basins and stream gages; counterclockwise from the northeast are the Upper Gunnison, Uncompahgre, Upper Dolores, and Animas Basins. DRGC, Animas River at Durango; DRRC, Dolores River below Rico; UCRC, Uncompahgre River near Ridgeway; LFGC, Lake Fork at Gateview.

2. Background

[6] Clean snow has the highest albedo of any naturally occurring Earth surface. When light-absorbing impurities (primarily mineral dust, carbonaceous particles, and organics) are present, snow spectral albedo decreases primarily in the visible wavelengths (VIS), with the effect extending into the near-infrared wavelengths (NIR) as concentration and/or particle single-scattering co-albedo increases [*Painter et al*., 2007]. We define radiative forcing by dust and/or other light-absorbing impurities in snow in terms of a direct effect and two feedbacks [*Hansen and Nazarenko*, 2004; *Painter et al*., 2012].

[7] The direct effect comes from the enhanced absorption of solar irradiance by the impurities themselves, primarily in the VIS and to a lesser degree in the NIR [*Warren and Wiscombe*, 1980] and subsequent conductance of that energy directly to the contacting snow grains. The first feedback comes from the enhanced absorption in the NIR and shortwave infrared (SWIR) wavelengths by larger snow grains grown by melt-freeze metamorphism, a process enhanced by the direct effect. This process affects the entire spectrum by reinforcing the direct absorption in the visible wavelengths along with the increased absorption in the NIR through SWIR. The second feedback comes from an extended period of greater absorption of solar radiation by the darker substrate (i.e., soil, rock, and/or vegetation) that is exposed earlier due to the direct effect and first feedback.

[8] Snowpack energy balance and detailed radiation fluxes from micrometeorological stations in southwestern Colorado have provided important insights into the drivers of snowmelt, including how dust changes snowmelt timing [*Painter et al*., 2007; *Skiles et al*., 2012; *CSAS*, 2013]. However, there are only three stations throughout the UCRB that provide such measurements and only one other in the western United States with the necessary instrumentation with which to calculate dust radiative forcing. To make up for the paucity of such data, remote sensing data are needed to enable the integration of dust effects with operational hydrologic prediction efforts. Specifically, MODIS data have enabled analysis of snow properties in remote mountain environments [*Painter et al*., 2009], due to the sensor's dynamic range in the visible wavelengths [*Dozier and Painter*, 2004]. *Painter et al*. [2012] used MODIS data and a coupled radiative transfer model to create the MODIS Dust Radiative Forcing in Snow (MODDRFS) product, which provides per-pixel (463 m) radiative forcing by dust in snow attributed to the "direct effect." Estimates of surface radiative forcing (W m^{-2}) from MODDRFS are determined by multiplying local potential spectral irradiance by the albedo differences between the measured MODIS spectrum and the modeled clean snow spectrum for the same optical grain radius (OGR).

[9] In snowmelt-dominated basins, operational streamflow prediction relies on calibrated relationships between measured air temperature and snowmelt. The strong influence of variable dust loading on absorption of solar radiation and snowmelt rate can cause actual conditions to deviate substantially from these calibrations, potentially reducing prediction skill. This research explores sensitivities of streamflow prediction errors to radiative forcing by dust in snow in the southeastern portion of the UCRB from 2000–2010. Specifically, we (1) quantify prediction errors between observed streamflow and the CBRFC-predicted streamflow data produced for the 1981–2010 calibration of the SNOW-17 and Sac-SMA models and (2) present results that suggest that radiative forcing by dust in snow drives first order uncertainty in the predicted streamflow produced by the coupled SNOW-17 and Sac-SMA system. This analysis indicates that runoff predictions in parts of the UCRB could be markedly improved under current implementation if forecasters had spatially extensive dust radiative forcing in snow data that could inform manual adjustments to runoff forecasts. Ultimately, the remotely sensed retrievals can constrain the physically based hydrologic forecast models that are currently under development by the research community and being considered for potential use at NWS River Forecast Centers.

3. Data and Methods

[10] We performed our analysis in the San Juan Mountains of Colorado (Figure 1), where considerable research and monitoring have been conducted on dust radiative forcing and snowmelt acceleration [*Painter et al*., 2007; *Skiles et al*., 2012; *Center for Snow and Avalanche Studies* (*CSAS*), 2013], ecosystem response [*Steltzer et al*., 2009], and long-term changes in dust deposition

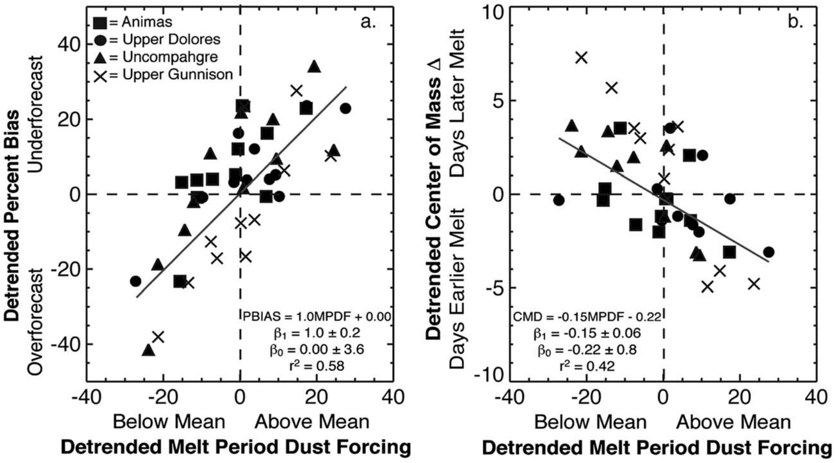

Figure 2. Least squares linear fit of melt period dust forcing and (a) percent bias and (b) center of mass delta with their respective regression coefficient (β_0 and β_1) values.

[*Neff et al.*, 2008]. We used streamflow records from four headwater gages that have no recorded diversions or other obstructions above the gage site. At each gage location, the four rivers have distinct snowmelt-driven peak flows in spring and baseflow for the remainder of the year, often punctuated by small peaks from summer convective precipitation. The catchments for each gage have a maximum elevation near 4000 m and range in area from 272 to 1792 km^2. We refer to each gage catchment by the name of its respective eight digit hydrologic unit code (HUC-8) basin [*Seaber et al.*, 1987]. Lastly, in only one of the basins has forest health been affected by beetle infestation and with markedly minor extent relative to other regions in the UCRB [*United States Forest Service*, 2013], where beetle infestations have altered snow accumulation and melt patterns [*Pugh and Small*, 2012].

3.1. Streamflow Data

[11] We use observed and predicted daily mean streamflow data for each gage between 1 January and 30 September for water years 2000–2010. This span covers the overlapping data record between MODIS and the most recent SNOW-17 and Sac-SMA calibration period. Observed streamflow data were acquired from the US Geological Survey (http://water.usgs.gov) and predicted data were contributed by the CBRFC. Hereafter, we refer to the predicted flows as a product of SNOW-17, acknowledging that predicted snowmelt was input to the Sac-SMA model prior to reaching the basin outlet as predicted streamflow.

3.2. Dust Radiative Forcing in Snow Data

[12] The MODDRFS algorithm [*Painter et al.*, 2012] infers per-pixel radiative forcing by dust in snow using MODIS surface reflectance data and a coupled radiative transfer model for snow. MODDRFS forcings are derived from the spectral differences between the spectral albedo inferred from the measured MODIS spectrum and the modeled clean snow spectral albedo for the same OGR, simulated using the discrete ordinates solution to the radiative transfer equation, all splined to a spectral resolution of 0.01 μm. The spectral difference is multiplied by terrain-corrected local spectral irradiance to obtain surface radiative forcing. The radiative forcing estimate, F, is retrieved from the following:

$$F = \sum_{\lambda=0.35\mu\text{m}}^{\lambda=0.876\mu\text{m}} E_{\text{corrected},\lambda}\left(\alpha_{\text{clean},\lambda} - \alpha_{\text{MODIS},\lambda}\right)\Delta\lambda, \qquad (1)$$

where $E_{\text{corrected},\lambda}$ is topographically corrected irradiance at wavelength λ, $\alpha_{\text{clean},\lambda}$ is modeled clean snow spectral albedo of the equivalent OGR, $\alpha_{\text{MODIS},\ \lambda}$ is spectral albedo of the MODIS pixel, and $\Delta\lambda$ is 0.01 μm. The retrieved radiative forcings are instantaneous measurements of dust forcing at the time of MODIS Terra overpass, around 10:30 A.M. local solar time. The root-mean-square error for the MODDRFS retrievals is 32 W m^{-2} with a mean absolute error of 25 W m^{-2} [*Painter et al.*, 2012]. In the Western US, retrieved radiative forcing ranges from 0 to over 400 W m^{-2}.

[13] Each MODDRFS output is masked for cloud cover using a combination of the MODIS cloud mask (embedded in the MOD09GA file) and a user-defined mask, which defines a pixel as cloudy if band reflectances exceed predetermined thresholds. We averaged the MODDRFS outputs to create a daily mean radiative forcing time series for each catchment, $\overline{F_b}$, from

$$\overline{F_b} = \frac{\sum\limits_{\text{pixels}_b} F_i}{n_b}, \qquad (2)$$

where F_i is the per-pixel instantaneous forcing, pixels$_b$ are all of the forcing pixels within a given gage catchment, and n_b is the number of forcing pixels within the gage catchment. Lastly, we then averaged the dust forcing for each year and catchment over the rising limb of the hydrograph (starting 1 April, which is the approximate date of peak SWE in the region) to produce the melt period dust forcing (MPDF):

$$\text{MPDF}_b = \frac{\sum\limits_{n=\text{April1}}^{n=\max(Q\text{obs})} \overline{F}_b}{n}, \qquad (3)$$

where $max(Q_{\text{obs}})$ is the date of peak observed discharge at each respective stream gage and n is the number of days between 1 April and peak observed streamflow.

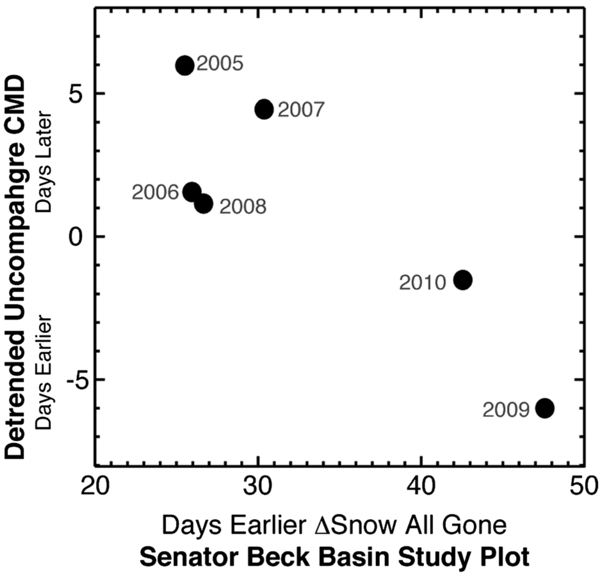

Figure 3. Senator Beck Basin Study Area ΔSAG and center of mass delta for the Uncompahgre gage from 2005 to 2010.

3.3. Statistical Methods

[14] We calculated two metrics to compare the timing and magnitude of predicted relative to observed runoff: percent bias (Pbias) and runoff center of mass (Figure 2). Pbias is a measure of accuracy of a predicted time series [*Franz et al.*, 2008]:

$$\mathrm{Pbias} = \left[\sum_{t=1}^{n} \left(Q_{\mathrm{obs}}(t) - Q_{\mathrm{sim}}(t)\right) \Big/ \sum_{t=1}^{n} Q_{\mathrm{obs}}(t) \right] \bullet 100. \qquad (4)$$

[15] Pbias describes the average tendency of predicted data to be larger or smaller than their observed counterparts, where positive values indicate that the predicted data have an underestimation bias and negative values indicate an overestimation bias. We calculated Pbias over the same interval as MPDF (1 April through peak observed discharge). The runoff center of mass (CM) is the date when half of the total discharge passes the stream gage, accumulated from 1 January to 30 September. The difference between the dates of observed and predicted CM created the variable center of mass delta (CMD), where negative values indicate observed CM occurred earlier than predicted and positive values indicate observed CM occurred later than predicted.

[16] We used simple linear regression techniques to compare radiative forcing by dust in snow (MPDF) to each of the prediction error variables (Pbias and CMD). Pearson's correlation coefficient (r) describes the strength of the linear relationship between MPDF and prediction error. The coefficient of determination (r^2) indicates the proportion of prediction error variance explained by MPDF. Before statistical analysis was performed, however, we removed outliers (z scores greater than 3.0) and any linear trend in MPDF, Pbias, and CMD using the least squares mean line for each variable. The results describe interannual variability over any monotonic change in dust forcing or prediction errors over the analysis period. Results without trends removed are shown in Figures S1 and S2 in the supporting information.

4. Results

[17] MPDF and CMD in the four catchments have significant negative correlation ($\alpha = 0.01$). Each 10 W m^{-2} increase in MPDF results in the observed runoff center of mass occurring 1.5 ± 0.6 days earlier than predicted (Figure 2a), with an r^2 of 0.42. Further, the mean MPDF value for all catchments over the analysis period corresponds to a negligible (0.22 ± 0.8 day per W m^{-2}) difference between observed and predicted in center of mass, suggesting that SNOW-17 is empirically calibrated to the mean forcing over the MODIS record. Thus, deviation from the mean MPDF increases the likelihood that the observed runoff center of mass will not match the predicted.

[18] MPDF had a significant positive correlation with Pbias ($\alpha = 0.01$) and explained the majority of Pbias variance (r^2 of 0.58) in the four catchments, where each 10 W m^{-2} increase of MPDF resulted in a corresponding streamflow prediction bias of 10.0% ± 1.5% (Figure 2b). Consistent with CMD, the mean MPDF over all catchments resulted in a negligible Pbias difference (0.0% ± 3.6%) between predicted and observed runoff, where values above the mean resulted in runoff underprediction and runoff overprediction below the mean. Pbias errors in the four catchments ranged from −32% to +49% over the analysis period. Thus, when treated empirically, remotely sensed measurements of dust radiative forcing in snow could potentially allow the CBRFC to reduce the magnitude of prediction errors in these basins to ±20%.

[19] CMD results for the Uncompahgre gage are consistent with snowmelt acceleration attributed to dust on snow in the Senator Beck Basin Study Area (SBBSA), a headwater catchment of the Uncompahgre River [*Painter et al.*, 2007; *Skiles et al.*, 2012; *CSAS*, 2013] (Figure 3). *Skiles et al.* [2012] used the SNOBAL energy balance model [*Marks and Dozier*, 1992] to determine the change in Snow All Gone date (ΔSAG) between modeled clean and dust-influenced snowpacks at SBBSA. CMD at the Uncompahgre gage has a significant relationship (at $\alpha = 0.05$) with ΔSAG from SBBSA, with an $r^2 = 0.75$. With only 6 years of data for a single basin, we proceed cautiously with this relationship. However, it indicates that the 11 year mean MPDF translates to an actual earlier melt of ~25–30 days relative to a clean snowpack and MPDF one standard deviation above the mean translates to ~40–50 days earlier melt.

5. Discussion and Conclusions

[20] The complexity of modeling and measuring snowpack properties in the study basins induces a baseline level of uncertainty in predicted runoff. Changes in basin vegetation from the calibration period, errors in the measurement and interpolation of SNOW-17 input parameters, and limitations of temperature-index-based snowmelt models are all potential sources of error in CBRFC-predicted runoff. Uncertainty is further compounded by the interannual variability in dust deposition that modifies ablation period snow surface albedo, which directly affects snowmelt acceleration [*Painter et al.*, 2007; *Skiles et al.*, 2012]. This research found that SNOW-17 runoff prediction errors are significantly correlated with variability in dust radiative forcing.

[21] Under the current temperature-index-based forecasting paradigm used by the CBRFC, however, the MODDRFS product could be used as a qualitative tool to inform

manual adjustments to runoff forecasts. As we move toward physically based snowmelt runoff models for operations [*National Operational Hydrologic Remote Sensing Center*, 2004], these products can begin to constrain the energy balance components, and variability in radiation fluxes in forested and nonforested regions can be simulated explicitly. Further, MODDRFS retrievals indicate equivalent radiative forcings by dust in other snowmelt- and glacier-melt-dominated hydrologic systems around the world [*Painter et al*., 2012], such as the mountain snowpacks of Central to South Asia that provide water to over a billion people [*Immerzeel et al*., 2010]. Future work will include a focus on the hydrologic implications of dust in snow in the Greater Himalaya.

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