Response of Colorado River runoff to dust radiative forcing in snow

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The waters of the Colorado River serve 27 million people in seven states and two countries but are overallocated by more than 10% of the river's historical mean. Climate models project runoff losses of 7–20% from the basin in this century due to human-induced climate change. Recent work has shown however that by the late 1800s, decades prior to allocation of the river's runoff in the 1920s, a fivefold increase in dust loading from anthropogenically disturbed soils in the southwest United States was already decreasing snow albedo and shortening the duration of snow cover by several weeks. The degree to which this increase in radiative forcing by dust in snow has affected timing and magnitude of runoff from the Upper Colorado River Basin (UCRB) is unknown. Here we use the Variable Infiltration Capacity model with postdisturbance and predisturbance impacts of dust on albedo to estimate the impact on runoff from the UCRB across 1916–2003. We find that peak runoff at Lees Ferry, Arizona has occurred on average 3 wk earlier under heavier dust loading and that increases in evapotranspiration from earlier exposure of vegetation and soils decreases annual runoff by more than 1.0 billion cubic meters or ∼5% of the annual average. The potential to reduce dust loading through surface stabilization in the deserts and restore more persistent snow cover, slow runoff, and increase water resources in the UCRB may represent an important mitigation opportunity to reduce system management tensions and regional impacts of climate change.

aerosols | land use change | reflectivity | snow melt

Simulations of future runoff from the Colorado River Basin project that flow will decrease by 7–20% in response to anthropogenically driven climate change by 2050 (1–4). However, these simulations have focused on changes in temperature and precipitation without consideration of the influence of radiative forcing by changes in dust and soot in mountain snow. Desert dust is a strong forcing of earlier snowmelt in the Upper Colorado River Basin (UCRB) through its enhancement of absorption of solar radiation (5), and the present levels of dust loading are markedly greater than existed prior to the mid-1800s (6). Ensemble backtrajectories, geostationary remote sensing, and isotopic analysis show that the dust loading in the UCRB comes from the disturbed soils in the Colorado Plateau and Great Basin (5).

Dramatic growth in grazing, agriculture, and resource exploration that accompanied the expanded settlement of the western United States and the political and economic marginalization of Native Americans beginning in the mid-1800s contributed to disturbance of soil surfaces in the Colorado Plateau and Great Basin (6–10). The disturbance of fragile physical and biological crusts left these surfaces more vulnerable to wind-driven dust emission. Lake core records indicate that dust accumulation in the eastern UCRB increased sixfold by the early 20th century, followed by a relaxation to fivefold over predisturbance accumulation coincident with a reduction in numbers of grazing animals (6).

Here, "radiative forcing" refers to the enhanced absorption of solar radiation at the surface by the lowering of snow albedo through dust's direct absorption and increased grain size from accelerated snow metamorphism. Present day dust concentrations cause an average March/April/May radiative forcing in snow of 25–50 W/m^2 in the east central UCRB, with instantaneous radiative forcings reaching more than 400 W/m^2 (5). For perspective, this radiative forcing at the snow surface dwarfs the global average anthropogenic greenhouse gas forcing of $\sim$2 W/m^2 but only on the snow surfaces where dust can have its impact. This additional absorbed radiation shortens the duration of snow cover by 27–35 d relative to clean snow, and drives more rapid runoff (5). However, the degree to which this modern radiative and hydrologic forcing has changed timing and magnitude of runoff from the UCRB has been unknown.

We now realize that increased dust forcing of earlier melt and the impact on runoff in the UCRB is embedded in what we have considered "normal." Stream and river runoff records in the UCRB headwaters and main stem began decades after dust deposition had already increased to peak levels and was impacting runoff. Likewise, the *Colorado River Compact* of 1922 and subsequent legal agreements, known collectively as the *Law of the River* (11, 12), have long implicitly incorporated a misunderstanding of the river's "normal conditions" because the core gauging of the river came during a period of abnormally high runoff.

Under the *Compact* and subsequent agreements, allocation of the river runoff among the Upper Basin states (9.3 bcm/y to Colorado, New Mexico, Utah, and Wyoming), the Lower Basin states (9.3 bcm/y to Arizona, California, and Nevada), and Mexico (1.9 bcm/y) is overcommitted by approximately 2.0 bcm/y relative to the historical (1916–2003) mean runoff of 18.3 bcm/y (13) and relative to the dendrochronological estimates of 17.7–18.1 bcm/y (14). The direct impacts of dust radiative forcing in snow of the UCRB are constrained to the Upper Basin where snow accumulation is greatest. However, the hydrologic impacts have socioeconomic relevance for the entire Colorado River system, due to overallocation, increases in water demand, and potential future climate impacts on availability and demand.

Radiative forcing by dust in snow shortens the snow cover duration in the UCRB by about 1 mo (5), but those results were derived from plot measurements. Here we extend the radiative forcing by dust in snow from the plot scale to the entire UCRB, using a physically based hydrology model that includes the effects of decreasing snow albedo. The extension of the process understanding to the basin scale will improve our knowledge of the

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ENVIRONMENTAL SCIENCES

regional hydrologic cycle, inform regional water and land management in the UCRB, and offer better insights as to what constitutes normal in the Colorado River Basin.

Model

We use the Variable Infiltration Capacity (VIC) hydrologic model (15) to simulate the naturalized discharge and annual runoff from the UCRB at Lees Ferry, Arizona (Fig. 1 and Figs. S1 and S2) under postdisturbance dust loading and predisturbance dust loading but with identical meteorological inputs. VIC has been applied in numerous hydroclimate studies in the western United States (2, 16–19) and globally (20, 21). For this application, we ran VIC at 1/8° resolution at a daily time step for the period 1915–2003 (18). The model state variables were allowed to stabilize over 1915 and we analyze the outputs from 1916–2003.

We refer to the control run results from ref. 18 as after disturbance dust loading (ADL), because the snow albedo parameterizations for dry and wet snow used in this run are consistent with those that we observe under current dust loading at energy balance towers in the Senator Beck Basin Study Area (SBBSA) in the east central UCRB (5) (Fig. S3). Although the parameterization was not developed in the Colorado River Basin, its resultant albedos differ from the measurements in the SBBSA only by $-1 \pm 2\%$ for the accumulation season and by $-1 \pm 3\%$ for the melt season (Fig. S3 *B* and *C*). These differences in terms of daily clear-sky, net solar radiation are respectively -2.0 ± 3.9 W/m^2 in mid-February and -4.0 ± 12.1 W/m^2 in mid-May.

The experiment run represents the cleaner snow environment that existed prior to disturbance [before disturbance dust loading (BDL); i.e., prior to ~1850]. Lake sediments show low background levels of dust deposition pre-1850 (6), indicating a baseline level of emission in the desert regions prior to the five- to sixfold increase in loading. No model is available that treats the dynamic, coupled effects of dust concentrations and snow metamorphism to determine aging of snow albedo. Therefore, we developed the albedo parameterization for BDL from a fit of the linear combination of albedo measurement time series from the Morteratschgletscher, Switzerland (22) and the Storglaciären Glacier, Sweden (23), regions that currently receive less dust loading than the UCRB and have slower albedo decay (5, 22, 23). This parameterization has 2.5 (accumulation season) to 3 times (ablation season) less dust-related absorption than does the ADL parameterization (Fig. S3). Snow albedo exhibits a nonlinear response to increases in impurities and grain size (24), with the greatest albedo reductions resulting from initial changes in impurity content or grain size. Therefore, the BDL parameterization, which represents the 5 times lower dust concentration, shows less than a fivefold decrease in solar absorption. The parameterization is conservative in its approximation of the cleaner snow surface predisturbance and therefore provides a minimum estimate of the impact of dust radiative forcing on runoff.

We evaluated the appropriateness of the albedo perturbation by comparing snow cover duration changes in the San Juan Mountains as modeled by VIC and inferred from detailed radiation and energy balance modeling (5). Fig. 1 shows the mean difference per cell in date of 90% snow depletion ($\Delta SD_{90\%}$, i.e., the change in the date at which 10% of the peak snowpack remains) between BDL and ADL scenarios for 1916–2003. We use this metric to avoid the problem of comparing dates of complete snow ablation; otherwise snowfall events after the ablation of the main snowpack introduce artifacts into the analysis. In the VIC model cell that contains the SBBSA energy balance towers, the mean $\Delta SD_{90\%}$ over 1916–2003 was 21 d. By comparison, the point model comparison of observed dusty snow to hypothetical pure snow in the SBBSA predicted a $\Delta SD_{90\%}$ of 28 d (5). The residual 7 d of $\Delta SD_{90\%}$ between the point model and the full basin simulation is caused by the background levels of dust loading under BDL (6).

The $\Delta SD_{90\%}$ is greatest in areas with the greatest snow accumulation (Fig. S4), because with more snow, the period over which dust affects melt rate is greater. $\Delta SD_{90\%}$ varies inversely with vegetation cover because the canopy controls the transmission of shortwave radiation (Fig. S5). Therefore, VIC reduces irradiance at the snowpack surface as canopy density increases. The sensitivity to vegetation cover in the simulations also indicates that projected future loss of vegetation cover because of fire, prolonged drought, or bark beetle infestation may increase the impacts of current and future dust loading.

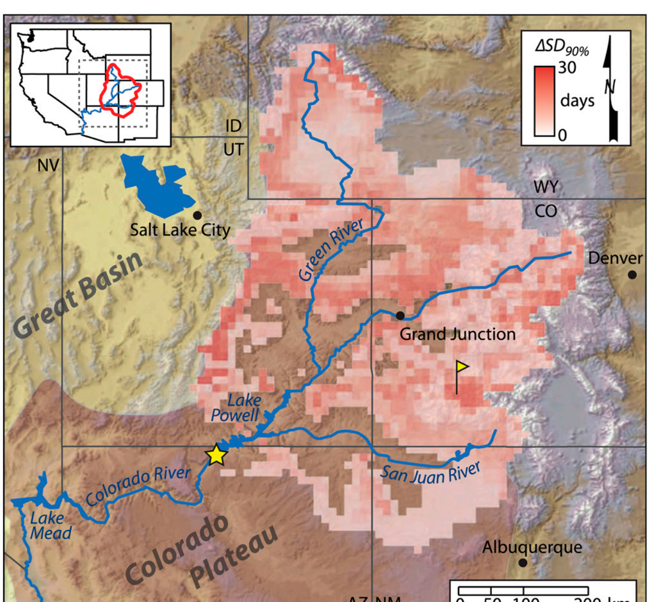

Fig. 1. Overview of Upper Colorado River Basin, and the Colorado Plateau and Great Basin physiographic provinces, overlain with change in date of $\Delta SD_{90\%}$ for elevations above 1,800 m. Star indicates Lees Ferry, AZ and flag indicates SBBSA.

Results

Fig. 2*A* shows modeled hydrographs of full natural flow (effects of water management removed from observations) at Lees Ferry averaged over 1916–2003 for ADL and BDL. The ADL mean

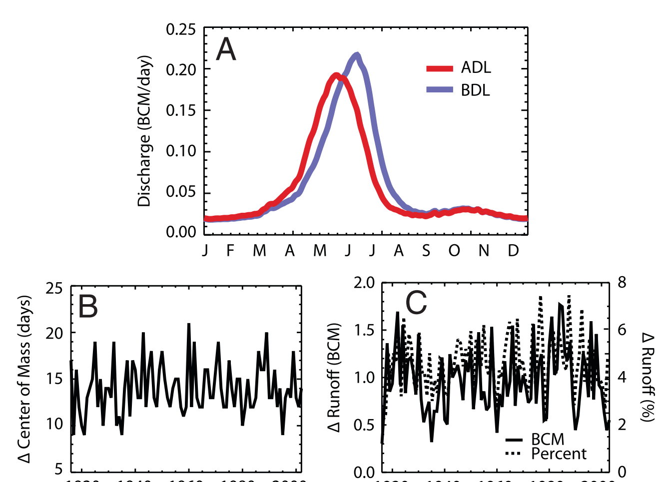

Fig. 2. Differences in runoff timing and volume between ADL and BDL dust scenarios. (*A*) Mean discharge at Lees Ferry, AZ on the Colorado River for ADL and BDL scenarios across the period 1916–2003. (*B*) Time series of BDL versus ADL Δ runoff in billion cubic meters across 1916–2003. (*C*) Time series of BDL versus ADL Δ runoff in percent of ADL runoff.

peak of 0.19 bcm/d occurs on May 29, over 3 wk earlier than the BDL mean peak of 0.22 bcm/d on June 21. The ADL mean center of mass (date of half of the annual flow) occurs on May 31, whereas the BDL center of mass occurred on average 2 wk later on June 14, with a range of differences of 9–21 d over the 88-y period (Fig. 2*B*). This change in flow has rendered water management operations more vulnerable to mistakes, and reduced the late-summer flows that are crucial for Upper Basin water delivery, riparian vegetation health, and fish survival. Fig. 2*C* shows the difference in total annual runoff between BDL and ADL (Δ runoff). The mean Δ runoff across 1916–2003 was 1.0 bcm, with a range of 0.3–1.8 bcm. In terms of percent of annual runoff under ADL, Δ runoff has a mean of 4.9% with a range of 2.3–7.6% (Fig. 2*C*).

The time series of spatial distributions of monthly average Δ runoff between BDL and ADL illustrates the spatial pattern of the hydrograph shift. The change in snowmelt generation across the mountain regions occurs primarily in April–July (Fig. 3*A*). Under ADL, runoff from snowmelt increases in April and peaks in May, whereas under BDL the mountain snowpack remains relatively intact. By June, however, the ADL runoff has dropped and the runoff under BDL reaches its peak. Even in July, the higher mountains continue to produce substantial runoff under BDL compared to ADL. By August, runoff equilibrates between the scenarios with the nearly complete removal of snow cover. The largest changes in runoff timing occur in cells with the greatest snow accumulation, as a longer melt season allows for greater temporal divergence between ADL and BDL.

The time series of change in evapotranspiration (ET) shows a seasonal asymmetry not evident in the change in runoff, increasing in magnitude from March–June (Fig. 3*B*). Only in July and August do some of the higher elevations begin to see slightly greater ET under the BDL case from a brief period of greater moisture availability. ET changes at lower monthly intensities than does runoff, but with greater duration. This asymmetry in ET losses, which is not balanced by a later positive difference, results in the decrease in total annual runoff between BDL and ADL (Fig. 2*C*).

Although the change in ET is a relatively small proportion of the total annual ET flux when averaged over the entire UCRB (1.3%, a 4.2-mm increase over the ADL ET of 323.1 mm), the change in ET as a proportion of annual runoff is much more substantial (5.1%, a 4.2-mm decrease from the ADL runoff of 81.6 mm). It is important to note that the majority of UCRB runoff is generated by a relatively small fraction of the basin area (Fig. S4*A*), because these regions receive most of cool-season precipitation (Fig. S4*C*). Although changes in ET over the full upper basin are relatively small, in the primary areas of runoff generation the ET differences represent as much as 20% of their total annual ET flux (Fig. S4*B*).

Two processes contribute to the decrease in total runoff with dust radiative forcing: (*i*) Earlier warming and wetting of the snowpack enhances snow sublimation (included in ET), and (*ii*) earlier increase in potential and actual evapotranspiration when snow cover is lost earlier (Fig. 4). A minor contribution to Δ ET comes from liquid water reaching the root system before snow cover retreats, consistent with observations in montane forests (25).

Saturation vapor pressure (SVP) over ice increases with temperature most at the highest temperatures. For example, an increase in temperature from −5 °C to 0 °C increases SVP by ~50%. Therefore, the increases in snow temperature and earlier wetting of the snow surface under ADL results in greater mass loss through sublimation (included in ET) before snow-covered area (SCA) begins to decrease (Fig. 4*A*). The majority of Δ ET however comes from the increase in ET that accompanies the additional snow-free period under ADL. This greater ET comes from the dramatic increase in potential evapotranspiration when the surface changes from snow to vegetation and soil. Fig. 4*B* illustrates this tight coupling of declining SCA and increasing ET. After both scenarios have lost snow cover, moisture provided by summer rain ensures that late-summer ET is identical under both scenarios (Fig. 4 *A* and *B*); therefore, the Δ ET is driven primarily by changes in snowmelt timing. In 10 of the 88 y, the earlier retreat occurs before mean daily temperature exceeds 0 °C. In these cases, the start of the growing season is the same for both scenarios and the differences in ET, and subsequently Δ runoff, are relatively small (Fig. 2*C*).

As mentioned above, in the UCRB, summer rains represent roughly one-third of annual precipitation, by which soil moisture equilibrates in the rooting zone in both ADL and BDL scenarios during the snow-free season. In turn, ET equilibrates after both

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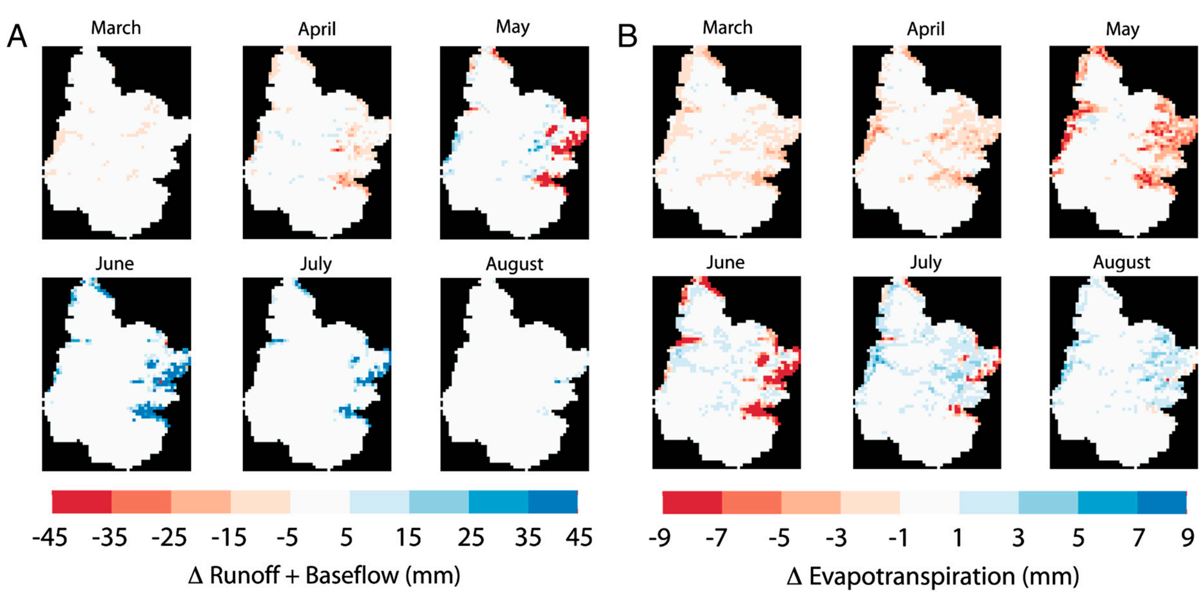

Fig. 3. Simulated spatial changes in runoff and ET in the UCRB. (*A*) Spatial change in monthly average runoff (BDL–ADL) for March–August. (*B*) Spatial change in monthly average ET (BDL–ADL) for March–August. Note the difference in scales. Representation of runoff and ET in terms of depth (mm) is traditional for these studies and can be thought of as the depth of water across the entire grid cell. Each cell's volume of runoff or ET comes from multiplying this depth by the area of the cell.

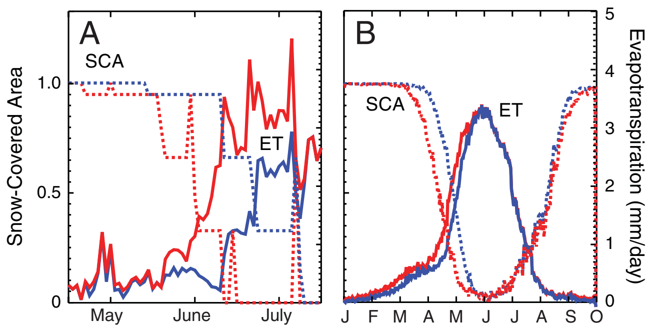

Fig. 4. Relative timing of snow cover disappearance and rapid increase in ET. (*A*) Mean time series (1916–2003) of total ET and SCA for the VIC cell containing the SBBSA. (*B*) Time series of SBBSA total cell ET and SCA for ADL and BDL scenarios for an individual year (1970), showing the acute sensitivity of ET to changes in snow-covered area.

scenarios have lost snow cover and no period occurs in which ET is significantly greater under BDL than ADL that can compensate for the earlier ET losses. However, for regions where summer rainfall is considerably lower than in the UCRB, such as the Sierra Nevada of California, early snowmelt could reduce summer ET because the water would be available when potential ET is lower, and the direction of Δ runoff could be the opposite, with less runoff under cleaner conditions. At what threshold precipitation and soil moisture the ET offset might come, as well as the role of total soil depth, is left for a work of broader scope than the present result for the UCRB. Moreover, there are no measured time series in basins other than the SBBSA of radiative forcing and changes in albedo related to dust and other light-absorbing impurities that can constrain the VIC model.

The magnitude of Δ runoff increases with the magnitude of the annual runoff (Fig. S6). Greater snow water equivalent accumulation in wet years results in a longer snowmelt season, increasing $\Delta SD_{90\%}$ and thus increasing differences in ET fluxes. Though wetter years still produce higher runoff, they do not reach their full runoff potential under the influence of dust. Hence, the potential for recovery of system storage in wet years following dry periods may be reduced.

Discussion

Although the model assumptions are relatively simple, this sensitivity study gives an initial understanding of the response of runoff timing and magnitude in the UCRB to increased radiative forcing by dust in snow and its chain of processes, constrained by detailed observations (5). If these results ultimately prove robust through modeling with more refined descriptions, a reduction of dust loading to mountain snow would then become an attractive means to prolong snow cover, reduce runoff rates, and possibly increase total runoff. Again, it is important to note that the effect on timing can be easily extrapolated to other basins globally—a darker snow surface absorbs more solar radiation and warms and melts sooner. By contrast, the direction of change in magnitude of runoff is a more complex function of timing of melt, precipitation climate, and vegetation and soil properties. In the case of the UCRB, however, these results suggest that the impact of dust radiative forcing is toward loss of runoff.

Uncertainties in the VIC modeling come from the driving datasets (air temperatures, precipitation, and wind speed), the calibration step based on modeled naturalized flows, and the static representation of vegetation cover (17, 18, 26). Moreover, the VIC model does not dynamically model the interaction between surface and atmosphere. In June and July, dynamic land–atmosphere interaction would allow the more persistent snow cover under BDL to cool the overlying atmosphere, resulting in a cooler boundary layer and lower ET in the BDL scenario. Because the lower air temperatures would further reduce snowmelt rates, reduce atmospheric PET, and increase basin runoff, the simulations of the associated change in runoff timing and magnitude are conservative.

The ADL and BDL albedo decay functions are applied uniformly across the model domain, and no attempt is made here to represent any spatial variation in dust accumulation and radiative forcing due to preferential dust emission pathways in any given year. No current field dataset or quantitative remote sensing retrieval exists that could inform this distribution, but the Colorado Dust on Snow monitoring program (http://www.snowstudies.org/codos1.html) will establish this important dataset. Planned future spaceborne instruments such as the NASA Hyperspectral Infrared Imager (27) will allow quantitative retrievals of radiative forcing by dust and other absorbing impurities in the Colorado River Basin and other critical snow- and glacier-melt hydrologic systems that are affected by dust or soot, such as the Himalaya (28), Karakoram (29), and Tien Shan (30).

The greatest uncertainty due to not treating transience in vegetation cover would come from the rates of reestablishment of mountain forests altered substantially by logging in the late 1800s (31). Further, we do not treat transience in stomatal resistance related to plant response to the observed global rise in CO_2 in the last 150 y. Plants tend to respond to high CO_2 environments by increasing their stomatal resistance, thus reducing their transpiration losses by increasing their water use efficiency. Studies have used this concept of a direct CO_2 effect to infer that river runoff should increase with increasing CO_2 (32–34), yet others suggest that leaf adaptations balance the reduced conductance to keep canopy level evapotranspiration relatively unchanged (35–37).

The stomatal resistance parameters used in the present study come from measurements made in the 1970s and 1980s (38, 39). Therefore, if the direct CO_2 effect indeed impacts ET across the landscape, the flux of water vapor from vegetation in the current study is appropriate for the latter half of the study period and should underestimate the flux that would have occurred in the former half.

This investigation of the response of runoff in the UCRB to radiative forcing by dust in snow has implications for the calibration of dendrochronological reconstructions of runoff in the UCRB (14, 40). The calibration period for the dendrochronological reconstructions of runoff from the UCRB are 1906–1995 (14) and 1906–2004 (40). The present study suggests that runoff during both periods may have been reduced by dust-accelerated melt. Given the bias in runoff affected by dust during the historical record, runoff inferred for the paleorecord (BDL) may require recalibration.

Industrial black carbon (BC) in the atmosphere and surface layers has been suggested as a forcing of accelerated snowmelt and ice melt with implications for global climate (41–44), regional hydrology (45), and glacier hydrology (28, 45). A recent modeling study of BC impact on hydrology in the western United States suggests that the regions impacted by BC lie proximal to urban areas and they conclude that BC's impact in the UCRB is much smaller than that of dust loading (45). Likewise, the global inventory of BC emissions shows nearly negligible BC in the UCRB (46). The UCRB does lie downwind of several coal-fired power plants in the Four Corners region of the Colorado Plateau, but measurements of BC are sparse and more frequent measurements are needed.

Validation of these results by comparison with stream records is not presently possible because we lack annual dust accumulation data across 1916–2003. Our knowledge of interannual variability of dust deposition in the SBBSA is limited to the period 2004–2010. The Interagency Monitoring of Protected Visual Environments monitoring network has sites in the UCRB that date back to 1989 with sampling every 3–4 d. Although useful for general visibility monitoring, this sampling frequency may not adequately resolve the episodic dust deposition events to the UCRB.

Multiple lines of evidence demonstrate that disturbance of most dryland soil surfaces increases dust production both locally and regionally (7). A decline in the cover of natural soil stabilizers (including physical and biological soil crusts, rocks, and plants), caused by grazing, drought, fire, plowing, or vehicles, can increase sediment movement by up to several orders of magnitude (8, 47). Such surface disturbance also enhances the invasion of exotic annual plants that do not generally germinate in drought years and leave soils exposed to wind erosion (48).

Cessation of disturbance generally results in stabilization of soil surfaces within days to years, depending on the type of stabilizers available. Physical soil crusts can reform with intense rains, and thus can stabilize surfaces quickly. Cyanobacterial crusts can reform within a few years after disturbance (49, 50). As mentioned above, dust input into high-elevation lakes increased more than 6 times coincident with the arrival of large livestock herds and intensive agriculture in low-elevation lands of the western United States in the mid- to late-1800s (6). When livestock numbers were decreased in the region as a result of the Taylor Grazing Act in the 1930s, dust deposition into these lakes declined as well (6). Importantly, though paleoclimate records show multiple examples of regional droughts and megadroughts during A.D. 900–1300, consistent with the Medieval Warm Period (51), lake sediment analysis does not indicate increased dust accumulation during these periods, emphasizing the importance of soil disturbance to dust emission (6).

Although the present study is historical in focus, it lays the foundation for studies of impacts of future climate change on dust emission and radiative forcing in snow. Predicted future increases in temperature (52) will likely result in a decline of soil moisture and overall plant cover in the dust source regions (53), whereas expected increases in energy and mineral exploration/development and recreation would further disturb soils. Drier conditions are also expected to substantially increase fire potential, which would leave soils exposed to wind erosion. Therefore, the frequency and magnitude of wind erosion events could increase, absent a shift in storm tracks or active management for dust.

Restoration of the river flow to near BDL conditions of timing and total runoff through reduced dust radiative forcing would have substantial policy and operational ramifications. Currently, earlier and faster runoff due to dust impacts presents a substantial forecasting challenge to operational runoff models, and reduces the margin for error for water managers when balancing flood control, storage, and deliveries. We reiterate that these results are a first estimate and that further work is needed before management decisions are based on the Δ runoff results. However, the change in timing is unambiguous and has deep implications for management and climate-change mitigation.

To the Upper Basin states, a greater future impact of dust on runoff timing would likely be as disruptive as runoff losses. The snowpack represents a critical storage reservoir in the Upper Basin, which does not enjoy substantial main-stem storage capacity like the Lower Basin. At present, as allowed by the *Colorado River Compact*, the Lower Basin uses some of the Upper Basin's allocated but unused water to meet their demands. During normal periods, this surplus water has been reliably, although irregularly, released from Lake Powell and delivered to Lake Mead for use by the Lower Basin. In the future, under full Upper Basin use of the river, the potential additional runoff provided by dust mitigation represents water that would be used by the Upper Basin states under their compact entitlements.

In the Lower Basin states, the change in timing is largely mitigated by Lake Powell and Lake Mead, but the possibility of recovery of additional runoff has long-term implications. During the recent drought (2000–2009), only normal deliveries to the Lower Basin were made from Lake Powell, resulting in decreases in Lake Mead storage from nearly full (30.8 bcm) in 2000 to about 42% full (12.8 bcm) in mid-2010, an annual overdraft of almost 1.9 bcm/y (54). Our estimated loss of inflow to Lake Powell because of dust represents over half of this overdraft. Hence, restoration to BDL conditions could significantly lessen the overdraft and reduce the probability of future Lower Basin delivery shortages under the 2007 agreement (55).

Climate-change studies suggest that earlier runoff and a reduction in flow will cause management challenges including uncertainty in timing of reservoir release, large reservoir fluctuations, and regular shortages (1, 55). Even partial restoration of BDL runoff conditions would help counter potential climate-change-induced change in timing and reductions in flow with concomitant reductions in reservoir oscillations and future delivery shortages (1, 55). Unlike the challenging, international efforts to reduce global carbon emissions, mitigation of soil disturbance and stabilization of soils in dust source regions is achievable through local, regional, and national efforts, and could have a near-term impact on dust emission and thereby the runoff response of the UCRB.

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Supporting Information

Painter et al. 10.1073/pnas.0913139107

SI Text

Basin Description. The headwaters of the Colorado River Basin lie in the Rocky Mountains of Colorado, Wyoming, and Utah (Fig. S1). The Upper Colorado River Basin (UCRB) lies downwind of the Colorado Plateau and the Great Basin physiographic provinces, optimally positioned to receive dust emitted from these regions given the southwesterly flow of deposition events observed in the mountains of the UCRB (1). The eastern half of the basin lies downwind of the yellow and red soils of the Colorado Plateau. The western half generally lies downwind of the predominantly yellow soils of the Great Basin. Ultimately, quantification of the spectral absorptivity (color) of these soils will be an important component of an integrated desert-mountain model.

The land cover for the UCRB from the National Land Cover Database (2) is mapped in Fig. S2, overlain with the Variable Infiltration Capacity (VIC) one-eighth degree resolution model grid. In general, the regions of greater snow accumulation lie in the forest (subalpine) or barren (alpine) classes at elevations above 1,800 m. Due to the resolution of the model grid, the majority of grid cells, even at high elevations, contain some fraction of forest canopy cover. The UCRB receives an area-averaged 405 mm/y of precipitation and drains 29 million hectare of largely semiarid landscape above Lees Ferry, AZ. Although the average annual runoff over 1916–2003 was 18.3 bcm, reconstructions of flow indicate that the long-term flow lies in the range 17.7–18.1 bcm (3, 4).

Unlike the Upper Basin states, the Lower Basin states fully use their allocations. Recent concerns over Lower Basin long-term use of unused Upper Basin water and a major drought led to two recent landmark agreements that address surpluses (in 2001) and shortages (in 2007). The 5% of flow lost due to radiative forcing by dust is a large proportion of Lower Basin municipal use, representing twice the annual allocation of Las Vegas (0.37 bcm, 0.30 maf), and 50% more than the basic annual allocation for the Los Angeles metropolitan area (0.68 bcm, 0.55 maf).

VIC Hydrological Model. The same meteorological inputs of precipitation, maximum and minimum temperature, and wind speed were used as in ref. 5, as were the physical characteristics of the basin (i.e., terrain, soil depth, vegetation type, and coverage). Snow processes are configured in a two-layer snow system within five snow elevation bands, to improve representations of snow accumulation in areas with rough topography. Land cover is represented with a subgrid mosaic, allowing multiple, fractional cover types per cell. Canopy interception and throughfall of precipitation vary with vegetation type. Energy and moisture fluxes in each grid cell are calculated for a three-layer soil system, with baseflow calculated empirically from the moisture content in the lowest soil layer. Infiltration and runoff are determined using the variable infiltration curve, which describes the subgrid variability in soil moisture. Each grid cell is treated as a level surface and is evaluated for the full time period independently, and streamflow is simulated via a postprocessing step that routes runoff and baseflow from individual cells through a stream network.

Albedo Parameterizations. Dust and soot are more absorptive of solar radiation in the visible and near-infrared wavelengths than ice and snow (1, 6, 7). When these impurities lie in near surface layers, they absorb incident solar radiation and transfer this energy to the surrounding snow grains largely through conduction. In a snow cover that is below 0 °C, this absorbed radiation warms the snow column and, once the snow temperature reaches 0 °C, the additional absorbed radiation contributes to melt. As mentioned in the main text, the increase in snow surface temperature and more frequent melting of the surface increase the saturation vapor pressure at the snow surface, increasing sublimation and evaporation.

In Fig. S3*A*, we show the range of albedos under accumulation (solid) and melt (dashed) conditions for the after disturbance dust loading (ADL) parameterization across 30 d (red; used in the historical base run of VIC), the before disturbance dust loading (BDL) parameterization across 30 d (blue), and that for clean snow under accumulation and melt conditions (black). The clean snow parameterizations shown here (Fig. S3 *A*) are based on results in ref. 8.

The following describes how the parameterizations are handled. No instantaneous dust events occur in the model. Rather, a snowfall event returns snow age to 0 and the snow albedo ages according to elapsed days since this snowfall. The aging is more aggressive in the ADL scenarios than in the BDL scenarios. Likewise, the aging is more aggressive in the ablation period than the accumulation period because of the greater dust loading during that period and more rapid snow metamorphism and grain growth.

The BDL scenario does not include changes in atmospheric scattering and absorption associated with a lesser atmospheric dust loading because there is great uncertainty and spatial heterogeneity in the net forcing from scattering and absorption of aerosols (9, 10). Moreover, the dust storms that produce the loading to the UCRB are markedly episodic, whereas dust's presence and radiative forcing in snow surface layers is sustained and increases with snowpack ablation as buried dust layers emerge on the surface (1).

Discussion. Though the peak discharge is lower under the current ADL conditions than under BDL, the rising limb of the ADL hydrograph is steeper (Fig. 2*A*). Therefore, accelerated melt from dust and this steeper rising limb induces stress in current water management in the Colorado River Basin (CRB) at a range of scales. Recall that water management has always been subject to this stress because water management began in the CRB in the 20th century, after dust forcing reached its modern levels. A reduction in dust loading would reduce present system stress and recover lost runoff.

In spring 2009, dust emission into the UCRB reached the highest levels in our period of observation of dust deposition (2003–2009) and by far the greatest in memory according to anecdotal reports from water managers and mountain residents. Its impact was widely felt by reservoir managers who saw dramatic melt rates and far earlier than normal peak runoff, necessitating unprecedented early releases and rapid responses. Many of the management decisions were informed by qualitative dust in snow advisories produced collaboratively by the Center for Snow and Avalanche Studies, the Snow Optics Laboratory at the Jet Propulsion Laboratory, and the National Snow and Ice Data Center under the Colorado Dust-On-Snow program. Estimates of dust impacts on runoff thus have immediate water management implications in addition to longer-term planning ramifications, and management interests would stand to benefit from a quantitative dust impact forecasting capability.

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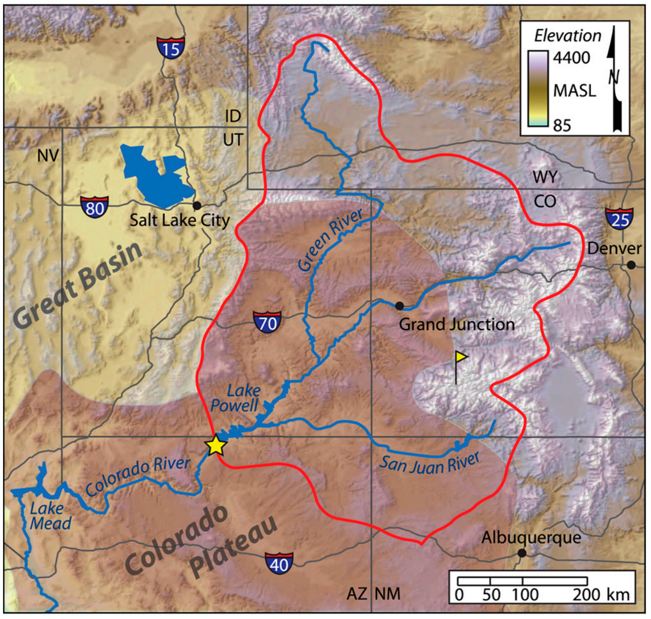

Fig. S1. Elevation map of the Upper Colorado River Basin, outlined in red. Star marks Lee's Ferry, AZ, the dividing point between the Upper and Lower Basins. Flag marks Senator Beck Basin Study Area, in the San Juan Mountains of Colorado, where energy balance modeling and albedo measurements were used to constrain this sensitivity study.

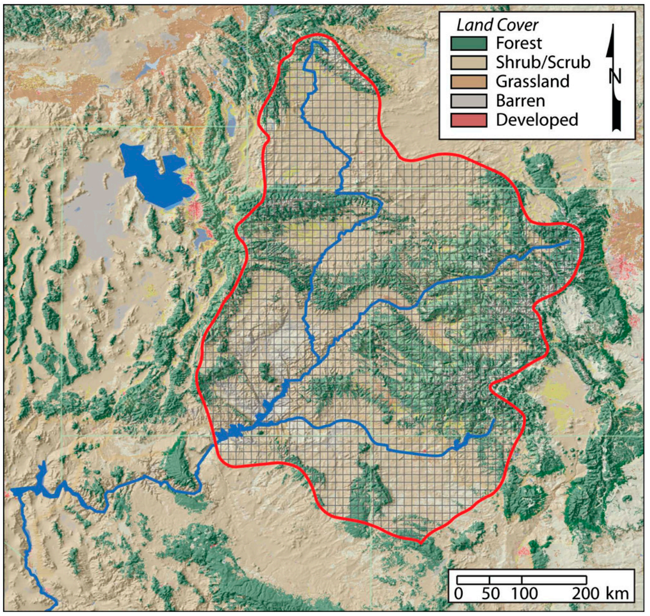

Fig. S2. Land cover of the Upper Colorado River Basin and surrounding region, based on the National Land Cover Dataset (2). The VIC modeling grid is draped on the land cover map to show the spatial distribution of forest, tundra, and bare ground in the UCRB.

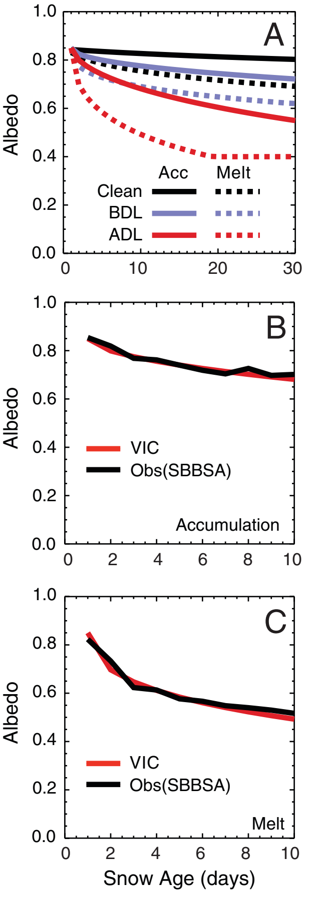

Fig. S3. (*A*) Clean snow, BDL, and ADL albedo age curves for accumulation (T < 0 °C) and melt (T > 0 °C) periods. Clean snow curves are for optical grain sizes ranging from 40 to 200 μm radius (accumulation) and 40 to 800 μm radius (melt) (11–13). (*B*) Comparison of VIC parameterization for accumulation period with measurements from the Senator Beck Basin Study Area (SBBSA) (1). (*C*) Comparison of VIC parameterization for melt period with measurements from the SBBSA (1). The albedo age curves from SBBSA were from the means of three age curves for each period from 2005 and 2006 (1).

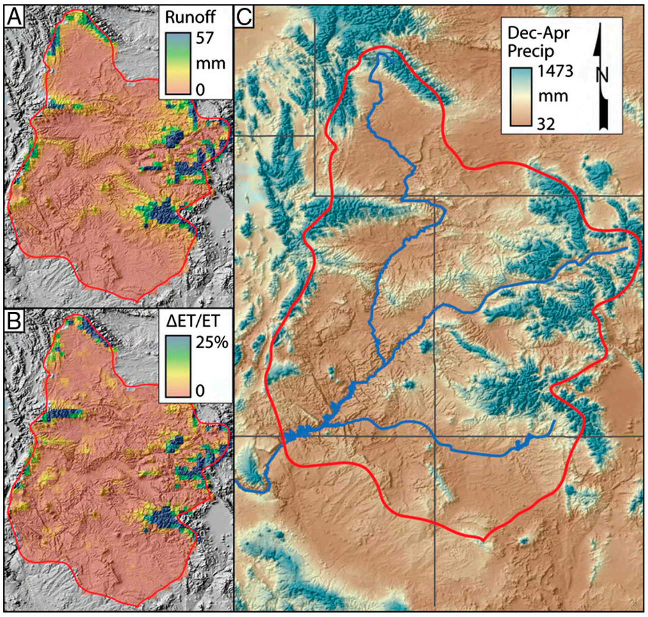

Fig. S4. (*A*) Time-averaged total annual runoff for ADL scenario across Upper Colorado River Basin, averaged across 1916–2002. (*B*) Annual change in evapotranspiration (ET) between BDL and ADL relative to total ET for ADL across the UCRB, averaged across 1916–2002. (*C*) Annual average precipitation across the UCRB. These data show that the greatest impact on ET occurs in those regions of the greatest contribution of runoff to the river: the mountains.

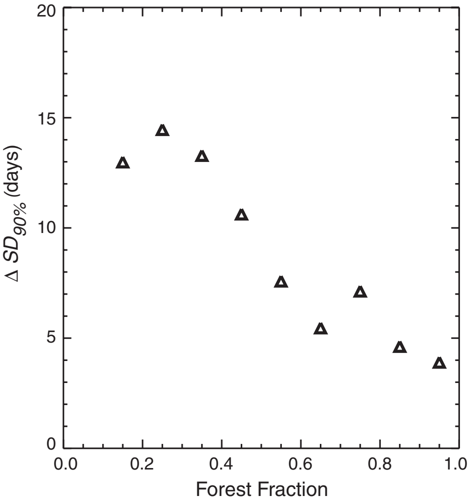

Fig. S5. Change in date of 90% snow water equivalent ablation, $\Delta SD_{90\%}$, versus forest fraction. This result shows that VIC appropriately reduces solar irradiance with greater forest fraction and thus reduces the capacity of dust to impact snow melt.

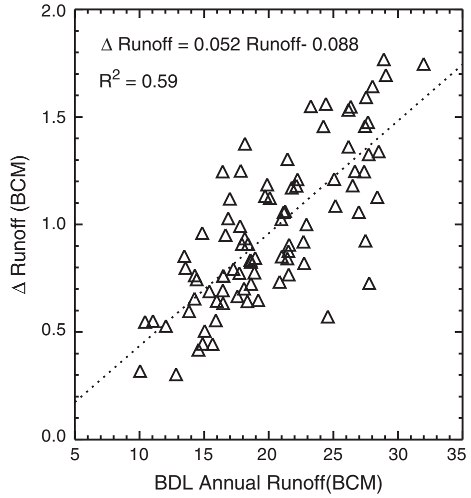

Fig. S6. ∆ runoff versus BDL annual runoff (billion cubic meters) for the period of simulation 1916–2003. Each symbol represents an individual year.