Influences of dust and black carbon on melt of snow and ice: mitigation and geoengineering

Thomas H. Painter, JPL/Caltech
Last week
Lori Garver, NASA Dep Admin
Digging snow and scoping dust
Framework
1. Fundamentals
2. Observations from the globe
3. What limited information we have
4. Where we know the impact well
5. What then are the implications for where we do not know the impact well
6. Geoengineering efforts thus far
7. Mitigation of dust and BC
8. How do we make the proper observations?
Summit of Mt Sneffels, San Juan Mountains, Colorado May 2009.
Dust concentration ($\mu g/g$)

Albedo reduction caused by BC

- 10 ng/g BC
- 20 ng/g BC
- 100 ng/g BC
\[
\frac{dU}{dt} + Q_m = (1 - \alpha)S + L^* + Q_s + Q_v + Q_g + Q_r
\]
The *How and How Important* of Radiative Forcing by Dust

Rabbit Ears Pass, Colorado

- Dust decreases snow albedo
- Dust deposition comes generally in the spring (*Neff et al.*, 2005)
  - solar irradiance is increasing
  - snowpack is warming
- Dust generally accumulates in surface layers and is not entrained in melt - therefore, the surface continues to darken

April, 2009  May, 2009

*Elk Range*, Colorado River Basin, April 2009
Spectral Albedo
Effect of Increasing Concentration
Radiative Effects of Dust in Snow

As per Hansen and Nazarenko (2004, PNAS)

- Direct effect
  
  *Absorption in visible and near-infrared (for large concentrations)*

- First indirect effect
  
  *Enhanced grain growth that further decreases albedo*

- Second indirect effect
  
  *Earlier exposure of darker substrate (snow-albedo feedback)*
Here, we define *surface shortwave radiative forcing* as:

*The perturbation of net shortwave radiation due to the deposition of dust to snow cover (W m\(^{-2}\)).*

\[
F_{dust} = \int_{\lambda=0.28 \mu m}^{\lambda=3.0 \mu m} E_{\lambda,tot} \left( \alpha_{\lambda,dust,free} - \alpha_{\lambda,dust} \right) d\lambda + F_{dust,ind2}
\]
Second Indirect Effect

Mean $F_{dust}$ during period:

144 W m$^{-2}$

Based on snowmelt modeling
SNOBAL model
(Marks et al., 1998; Painter et al. 2007)
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Indian Himalaya + Tibet
Dust Radiative Forcing, Hindu Kush, Afghanistan

MOD-DRFS model (Painter and Bryant, 2011)
Tien Shan, Kazakhstan
Mera Glacier looking south toward Mera summits, May 2009

Source: Susan Kaspari (CWU)
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Dasuopu Core

Kiang Co (lake sediments)

Conway and Overpeck, 2010

Dasuopu Core

Thompson et al. 2000
Caucasus Mountains

ATMOSPHERIC DUST CONTENT AS A FACTOR AFFECTING GLACIATION AND CLIMATIC CHANGE

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[Graph showing atmospheric dust content over time]
Antarctic Peninsula

20th-Century doubling in dust archived in an Antarctic Peninsula ice core parallels climate change and desertification in South America


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Fig. 2. Monthly averaged aluminum and aluminosilicate dust concentration (A) and flux (B) from 1832 to 1991 measured in James Ross Island ice cores. The heavy red line shows annual averages. Aluminosilicate dust was computed from the aluminum measurements by using the mean crustal abundance by mass of 8.04%.
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Upper Colorado River Basin

Increasing eolian dust deposition in the western United States linked to human activity


Dust accumulation rate (cm yr⁻¹)

0.00 0.01 0.02 0.03 0.04 0.05

Years Before Present

Post-disturbance

Pre-disturbance

1850AD

Albedo reduction caused by BC

10 ng/g BC

20 ng/g BC

100 ng/g BC

Dust concentration (µg/g)
Crust disturbance is the key

- Desert surfaces are commonly armored by crusts
- Most surfaces have very low dust emissions until crusts are disturbed
- When disturbed, sediment production increases by up to 550 times
  (courtesy Jayne Belnap, USGS)
Dust Sources Are Regional

Colorado Plateau
Dust Sources Are Regional

Dust Plumes

Great Basin

Great Salt Lake

Images courtesy Steve Miller, CIRA
What do we face in the future?

Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau

Seth M. Munson*, Jayne Belnap*, and Gregory S. Okin†

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Projected increases in aridity throughout the southwestern United States due to anthropogenic climate change will likely cause reductions in perennial vegetation cover, which leaves soil surfaces exposed to erosion. Accelerated rates of dust emission from wind erosion have large implications for ecosystems and human well-being, whereas biological soil crust (BSC; composed of bacteria, mosses, and lichens) contributes to soil stability and vegetated surfaces by binding soil particles together at surface roughness (6). Here we couple 20 y of vegetation monitoring across four well-protected national park areas to model dust emission rates under different climate conditions. The results show that increased dust emission caused by reduced BSC is expected to lead to exponential increases in dust emission.

Increased aridity from climate change in American Southwest should then lead to exponential increases in dust emission.
\[
\frac{dU}{dt} + Q_m = \left(1 - \alpha\right)S + L^* + Q_s + Q_v + Q_g + Q_r
\]

where \(\alpha\) = albedo

\(S\) = solar irradiance

\(L^*\) = net longwave flux

\(Q_s\) = sensible heating flux

\(Q_v\) = latent heating flux

\(Q_g\) = ground heating flux

\(Q_m\) = melting energy flux

d\(U/dt\) = change in internal energy

Radiative Forcing by dust in snow

\[
F_{\text{dust}} = F_{\text{dust, direct}} + F_{\text{dust, indirect}_1} + F_{\text{dust, indirect}_2}
\]

\[
\begin{align*}
\text{minimum} & \quad F_{\text{dust, direct min}} = E_{\text{VIS, total}} (0.92 - \alpha_{\text{VIS}}) \\
\text{maximum} & \quad F_{\text{dust, direct max + indirect}} = E_{\text{VIS, total}} (0.92 - \alpha_{\text{VIS}}) + E_{\text{NIR, total}} \alpha_{\text{NIR}} \left( \frac{1}{AR} - 1 \right)
\end{align*}
\]

where

\[
AR = 1.0 - 1.689 (\Delta \alpha_{\text{VIS}}) \quad \{\Delta \alpha_{\text{VIS}} \in [0, 0.17]\}
\]

\[
AR = 0.67; \quad \{\Delta \alpha_{\text{VIS}} > 0.17\}
\]
Snow Melt
2005 - 2009

Springtime dust radiative forcing
25-110 W/m²

Dust Forcing
26-50 Days

Dust Plus 2°
28-50 Days

Clean Plus 2°
5-8 Days

Dust Plus 4°
32-50 Days

Clean Plus 4°
11-15 Days

from Painter et al 2007; Skiles et al, in preparation
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 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

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**Naturalized Runoff (BCM/day)**

- **Post-Distur**
- **Pre-Distur**

**3 week earlier peak**

**Steeper rising limb**

**~ 5% less total runoff**

*Daily averages, 1915-2003*
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Implications for Mountain Glaciers

- Warming of snow surface increases sublimation rates
- Accelerated snowmelt and retreat of snow cover markedly can increase energy fluxes to glacier ice
- Dust loading in most systems appears to be greatest in lower elevations, most heavily impacting and expanding ablation zones
- Dust’s impact is absolutely sensitive to temporal dynamics of snow cover, hypsometry, cloud cover
- The N-fold increases in dust loading that we are discovering since the mid-1800s poses a complication
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Niwot Ridge, Colorado

10 days, 35 cm differential melt
30 days, 1.05 m differential melt
Geoengineering

Gurschen Glacier
Andermatt

Chalon Sombrero, Peru
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Greenland BC

20th-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing
Joseph R. McConnell, et al.
Science 317, 1381 (2007);
DOI: 10.1126/science.1144856

20th-Century Industrial Black Carbon Emissions Altered Arctic Climate Forcing
Mitigation

• Dept of Interior, BLM, BOR now pushing for dust mitigation in the Upper Colorado River Basin
• Efforts underway with Navajo Nation to reduce dust emissions
• Inoculation of disturbed soils for reestablishment of cryptobiotic crusts
• Ramanathan and others pushing for the mitigation of black carbon emissions
Glacier Measurements Need to Be Expanded and Improved

The remoteness and dangerous nature of work above 6000 m is one reason why we have few detailed measurements, other than of glacier length and size, in high mountain systems like the Himalayas and Andes. **Current remote sensing technologies can detect changes in glacier and snow extent, but do not quantify relative forcings or provide important snow and ice properties, such as grain size, local impurities, and surface liquid water content.** However, airborne and space-borne imaging spectrometers will soon allow us to make spatially comprehensive measurements of these surface properties. Put in context by more extensive observations from large-scale field campaigns, and in situ energy balance and mass balance measurements, imaging spectrometers will be used to construct and validate the next generation of high resolution glacier mass balance models. Quantitative observations are the key.
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Recent Debate

Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate

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But they both are missing the most important dataset – the observations of radiative forcing and associated measurements of energy and mass balance
What does MODIS give us?
NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

- Spectral range: 350 to 2500 nm
- Spectral resolution: 10 nm
- Spatial resolution: 20 m (from 20km)
AVIRIS Light Absorbing Impurities in Snow and Ice (AVI-LAISI)

\[ RF = \sum_{0.35 \mu m}^{1.15 \mu m} E_\lambda (R_{\lambda,\text{clean}} - R_{\lambda,dust}) d\lambda \]

- Grain size from integral of ice absorption feature (Clark and Roush 1984; Nolin and Dozier 2000)
  - Gives clean snow spectrum against which radiative forcing is determined.

Local Spectral Irradiance
3.4 km elevation
SBDART RT model
21 May 2010 19:27 GMT

Plot of Spectral Albedo vs Wavelength (\(\mu m\))
Colorado River Basin

AVI-LAISI Painter 2010 in preparation
21 May 2010, Senator Beck Basin, Colorado
HyspIIRI Science Measurements

HyspIIRI is a global mission, measuring land and shallow aquatic habitats at 60 meters and deep oceans at 1km every 5 days (TIR) and every 19 days (VSWIR).

HyspIIRI’s VSWIR imaging spectrometer directly measures the full solar reflected spectrum of the Earth from 380 – 2500nm at 10 nm.

HyspIIRI’s TIR directly samples the Earth’s emitted thermal energy in 7 bands between 7.5-12 µm, & 1 band between 3-5 µm.

Both the VSWIR and TIR instrument concepts are high heritage with no new technology.
Conclusions

• In the Colorado Rocky Mountains, springtime dust radiative forcing ranges from 25-110 W/m².
• Shortening of snow duration ranges from 25-50 days.
• Dust loading in CRB has increased 5-7 times since the mid 1800s.
• There are clear indications of increasing dust loads in many of the glacier covered mountain systems of the globe. With increased aridity, we likely face increased dust emission unless surfaces can be restabilized.
Conclusions

• We lack the measurements in other systems and in particular in the HKH, in situ instrumentation is difficult to situate.

• Remote sensing must be used to address these needs, MODIS helpful in qualitative measures

• Imaging spectroscopy in particular is necessary to quantify the radiative forcings
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