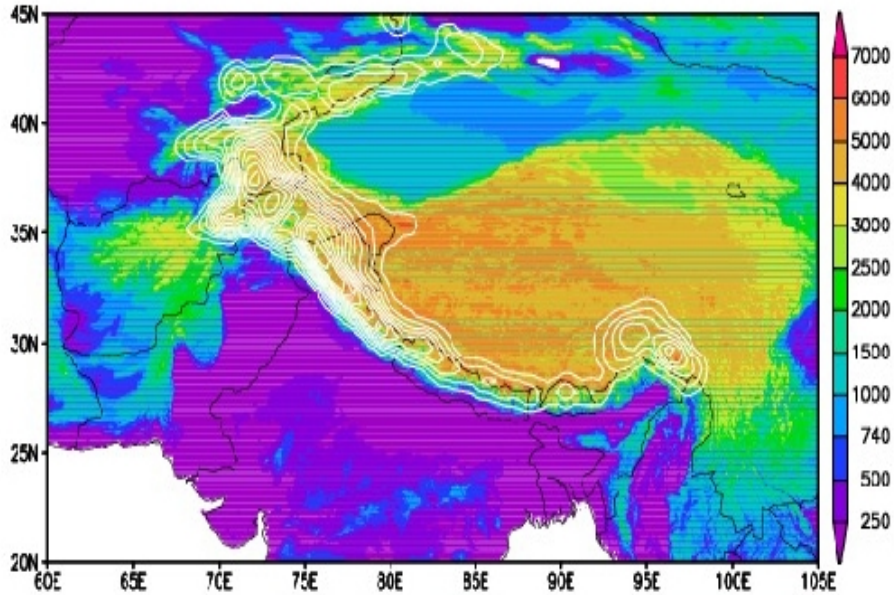
Impacts of absorbing aerosols on snowpack in the Himalayas/ Tibetan Plateau and regional hydroclimate

William K-M. Lau,
Co-authors: K-M. Kim, M-K. Kim, R.Gautam, T.J.Yasunari, C.Hsu, P. Colarco, A. da Silva



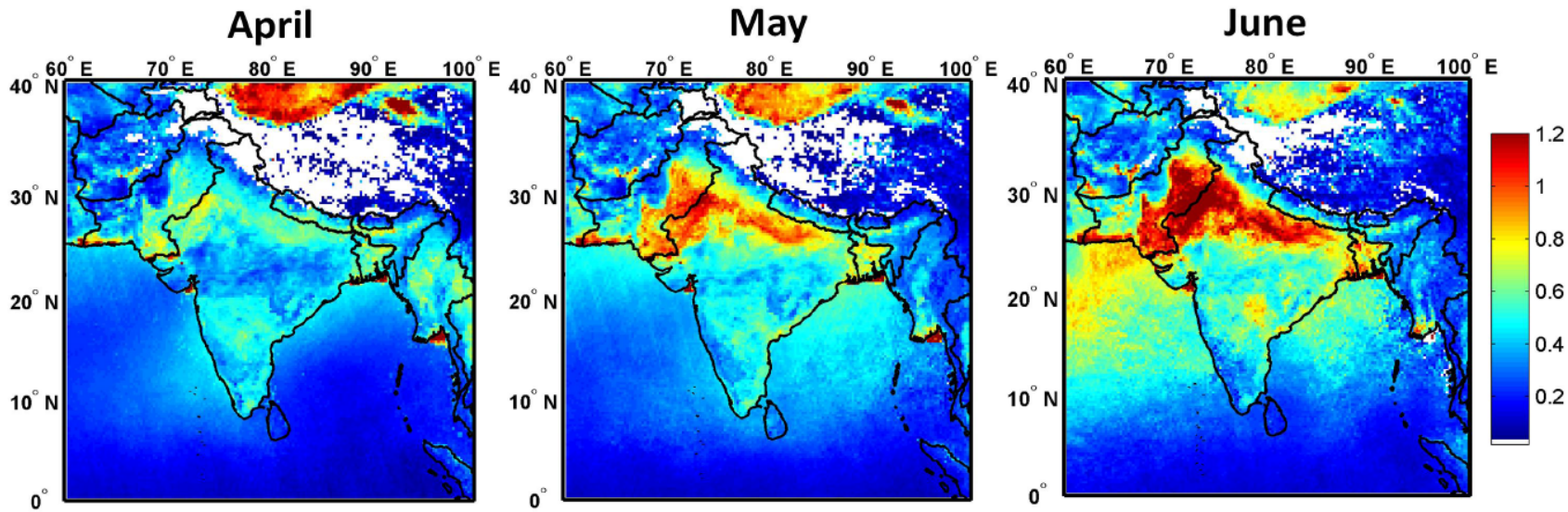
MODIS Science Tem Meeting, Silver Spring MD April 15-17, 2013

Possible causes for accelerated melting of glacier and snowpack in the Himalayas/ Tibetan Plateau region

- Greenhouse gases warming
- Snow-darkening
  - Satellite signal detection
  - Impacts on hydrology
- Atmospheric heating and feedback
  - hypothesis testing/validation

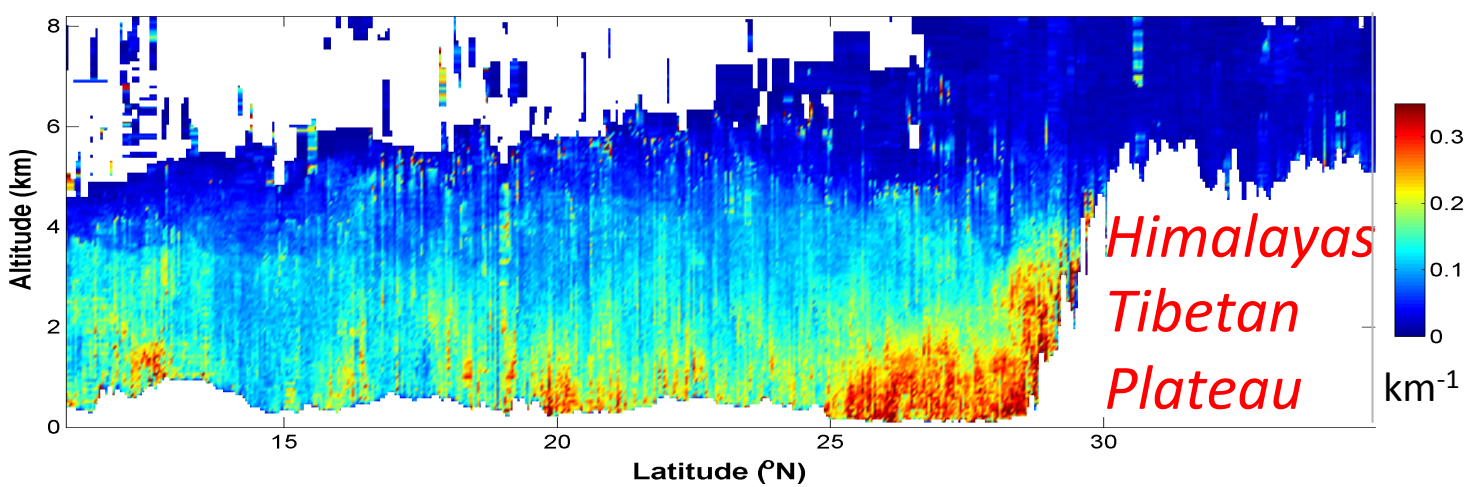
Lau et al 2010, ERL; Yasunari et al. 2011, ACP, Ritesh et al. 2013, Atm. Environ
Kim et al 2013 (in preparation), Yasunari et al 213 (in preparation)

Aerosol Optical Depth from Aqua MODIS (2003-09)



Gautam, Hsu, Lau (2010)

CALIOP Extinction Coefficient indicate aerosols piling up against the southern slopes of the Himalayas.

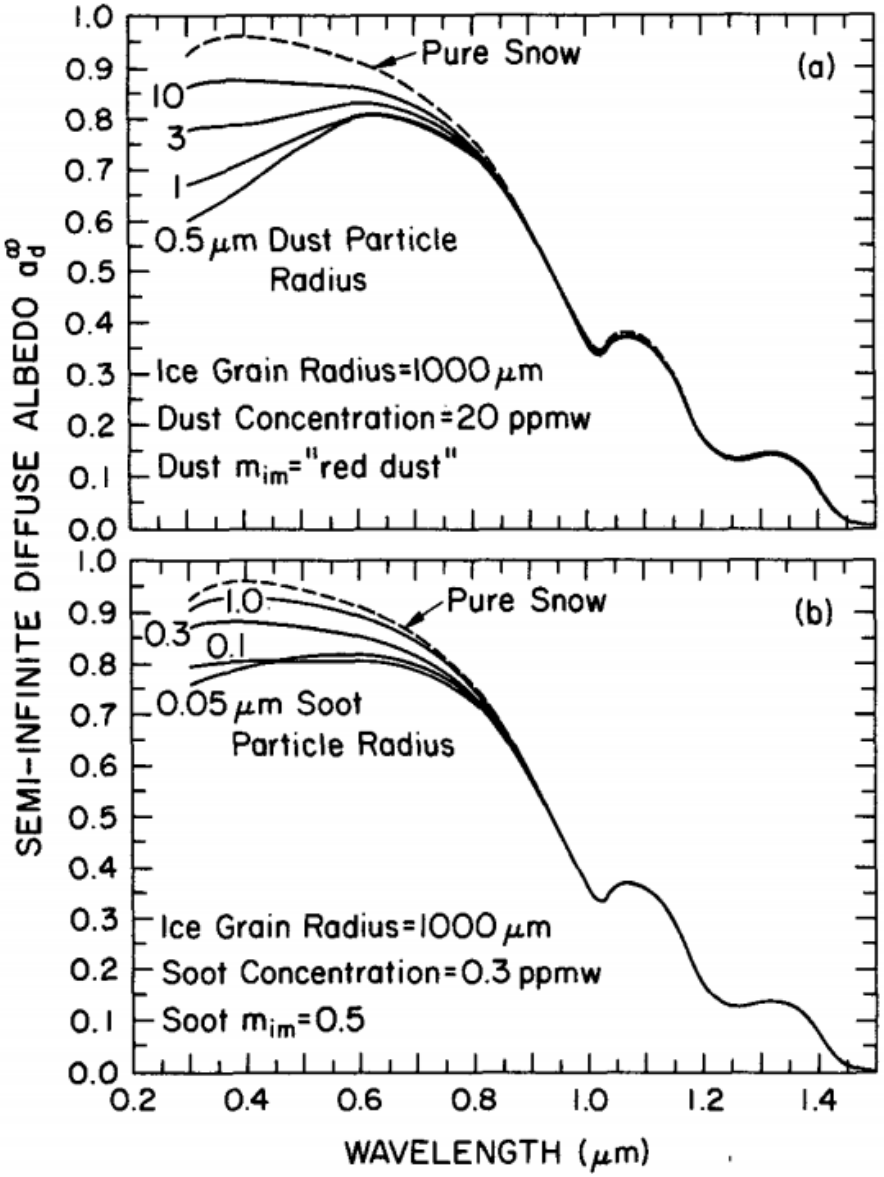


CALIOP data
March 15-June 15
2007-10

EHP hypothesis
Lau et al 2006, 2008, Lau and Kim 2010

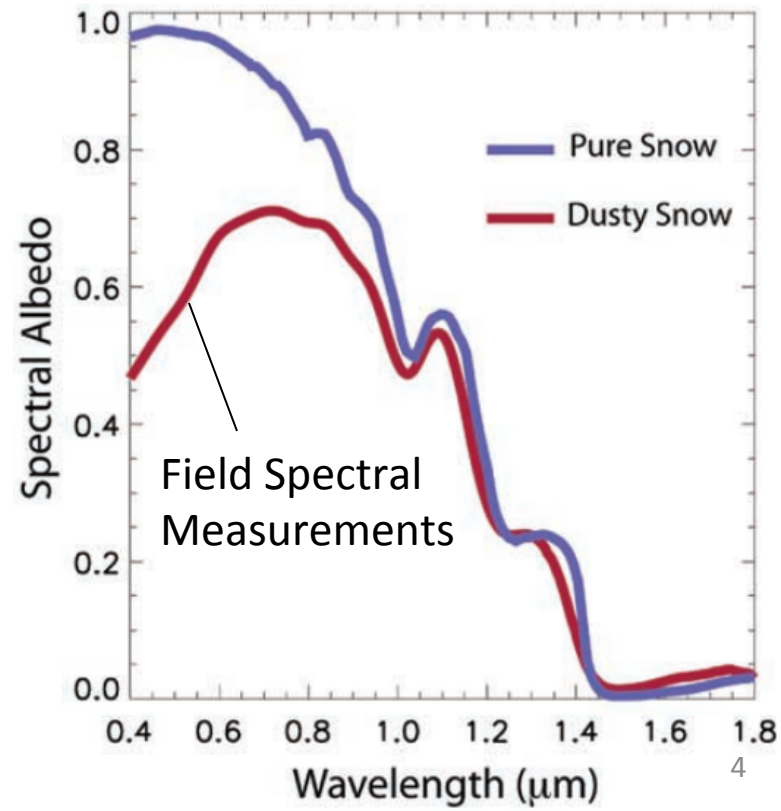
Satellite Detection of Snow Darkening effect

Warren and Wiscombe, 1980

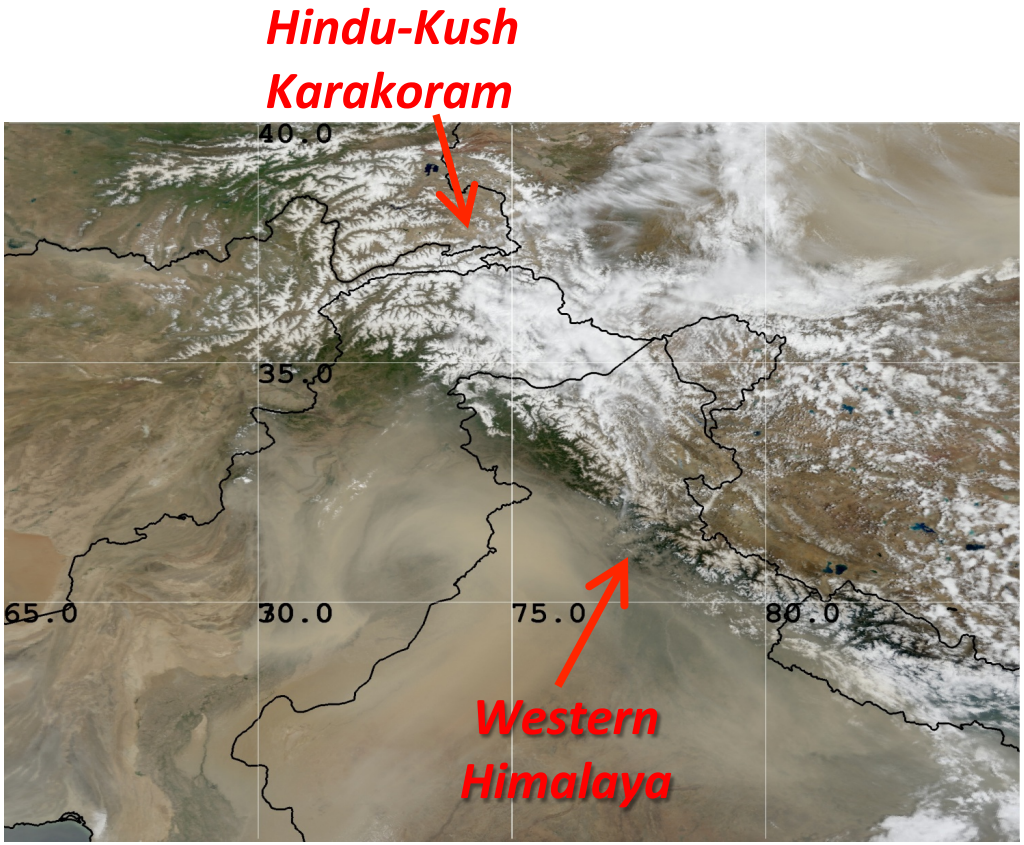


Dust and black carbon effectively reduce snow albedo in the visible wavelengths

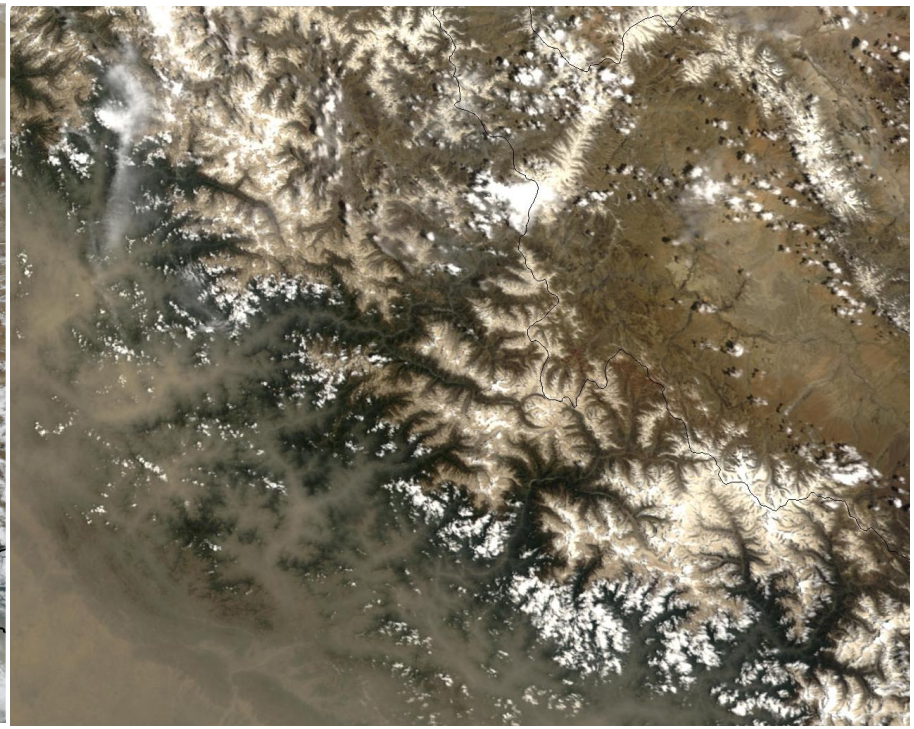
Painter et al., 2009



Dust Storm over southern Asia, 9 June 2003, Terra/MODIS



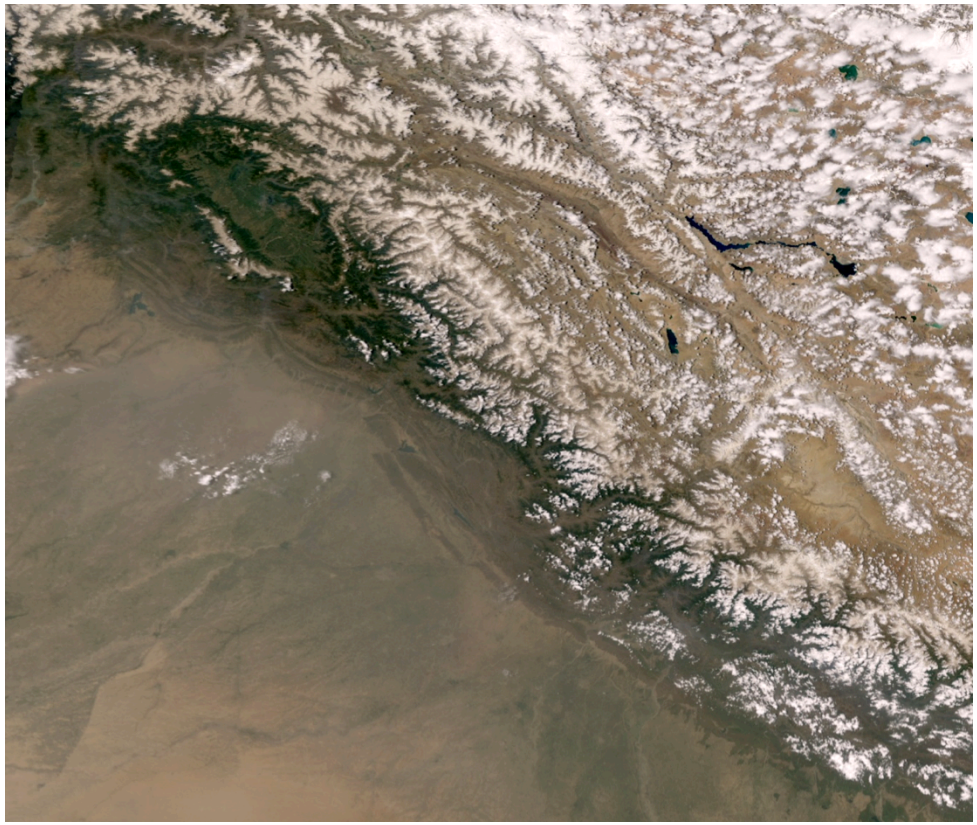
Zoom-in over western Himalaya

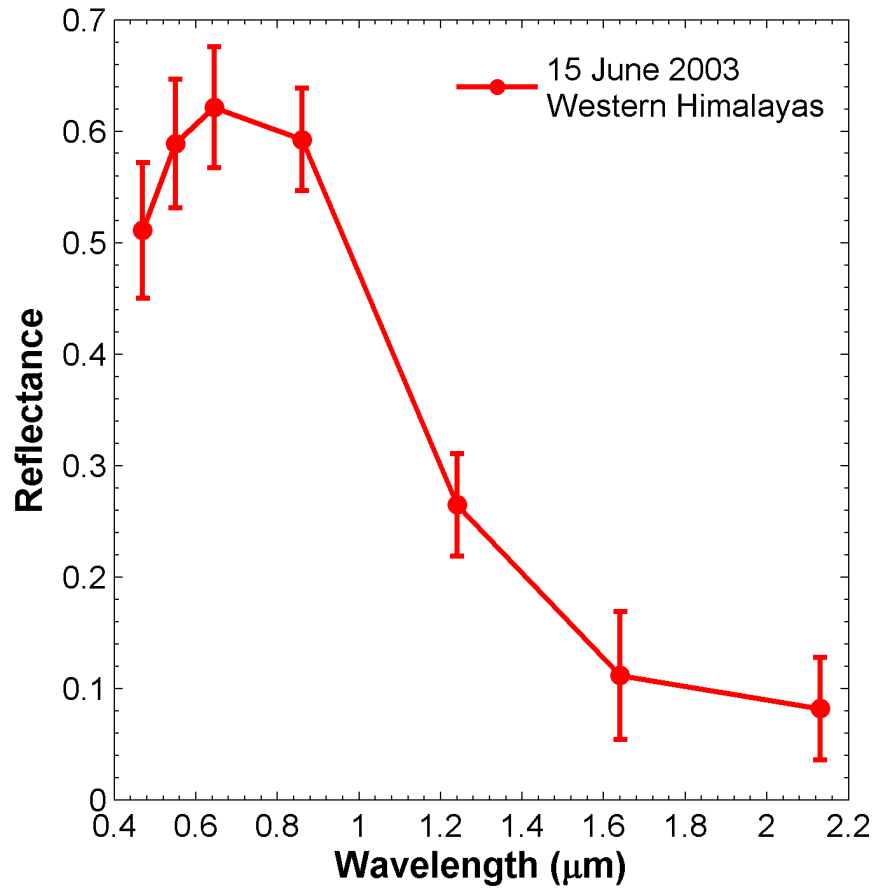


Enhanced absorption in visible wavelengths

VIS-NIR gradient

15 June (few days after dust event)

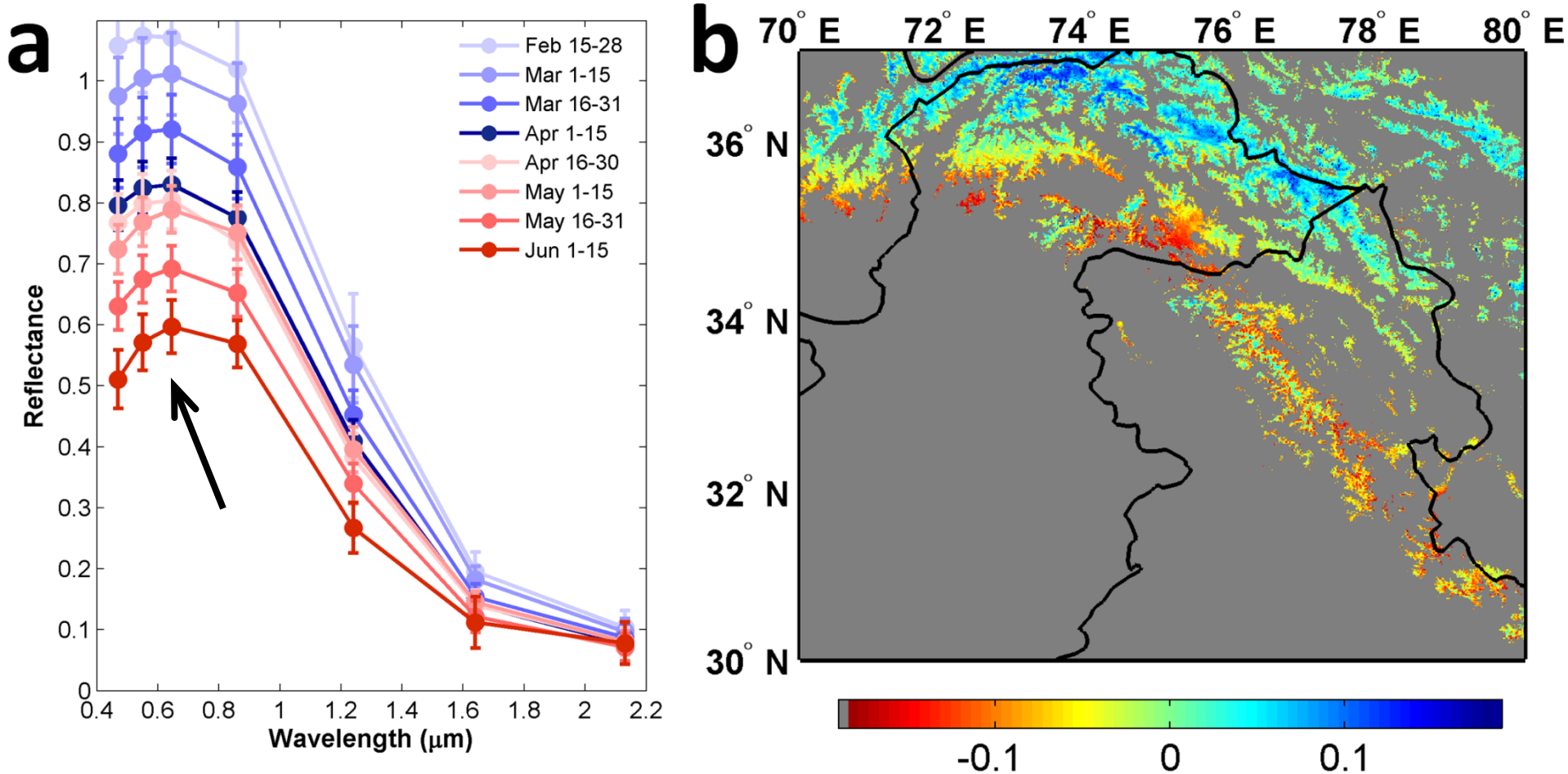




MODIS spectral surface reflectance (MOD09) over snow-covered region in the western Himalayas, collocated with MODIS Snow Cover Fraction swath data.

Seasonal variation of spectral Reflectance over western Himalaya

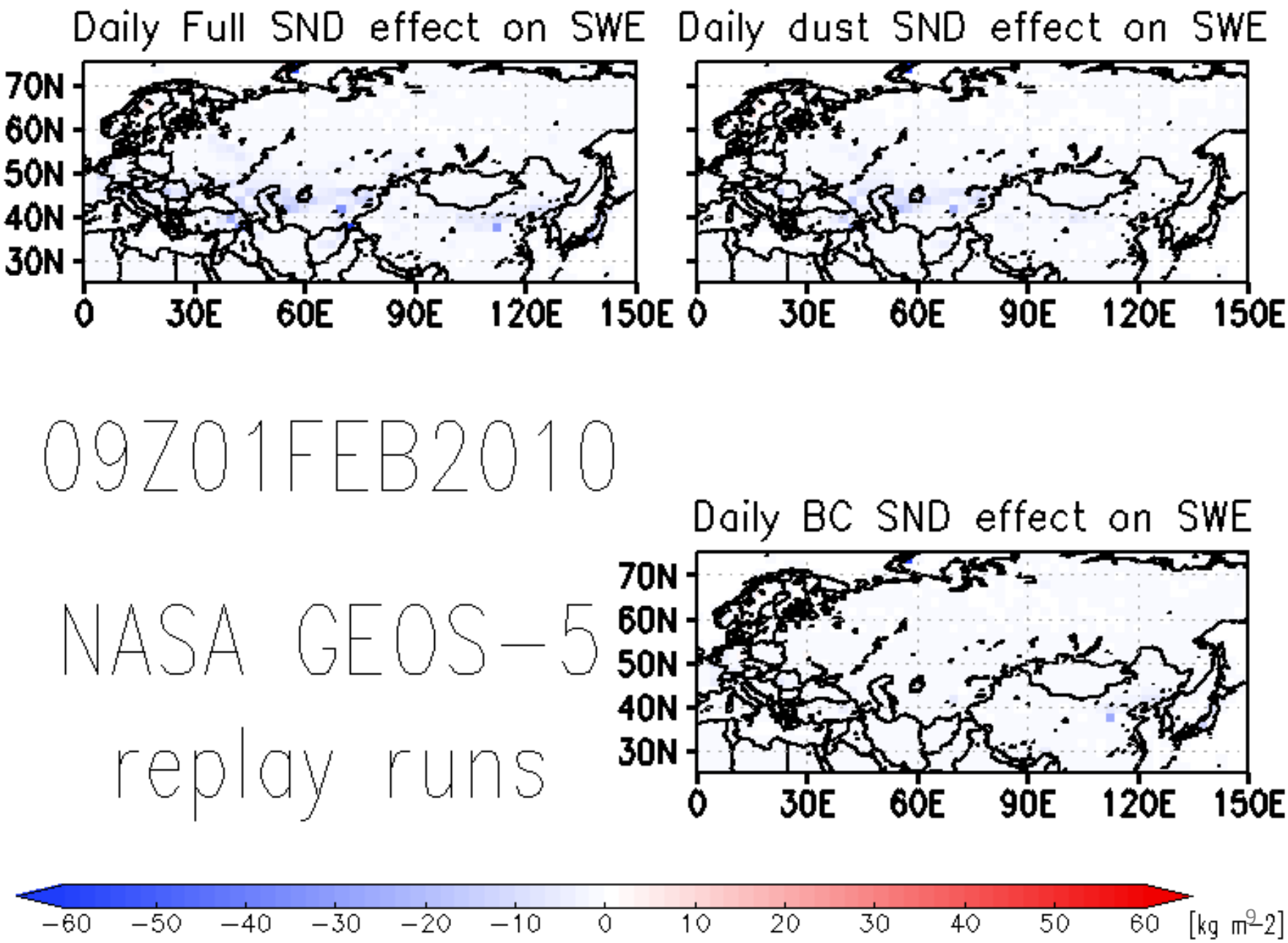
$R_{0.47\mu m} - R_{0.86\mu m}$



(a) Seasonal variations of surface reflectance (February-June, MOD09), shown as 15 day averages, (b) Absolute difference of surface reflectance between 0.47 and 0.86 μm, averaged for 6–15 June 2003. Positive difference is generally found over the Karakoram, while dust-laden western Himalaya and southern Hindu-Kush region are characterized by negative differences.

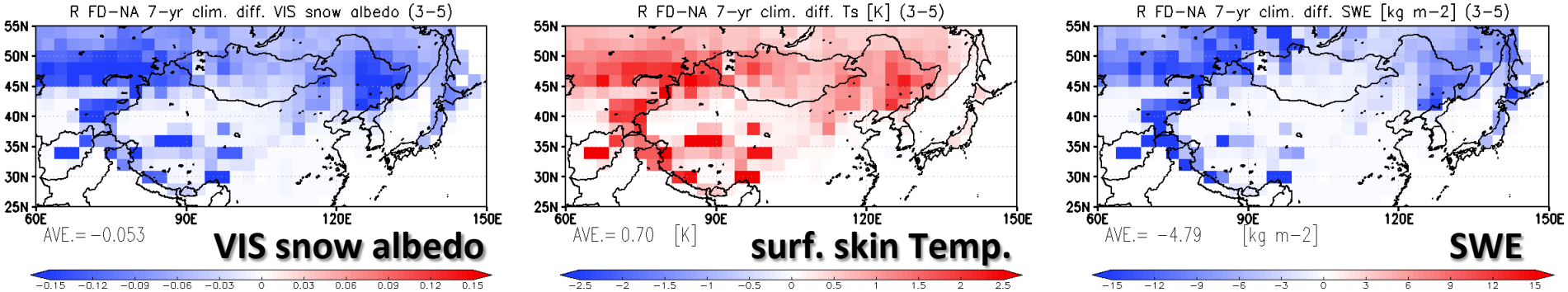
Impacts of the snow darkening effect on regional hydrology

- Snow-darkening physics package implemented in the NASA GEOS-5 earth system model
- 7- years of model integration from reply run GEOS-5 replay run experiment
- Control: with snow darkening (SND) physics module (dust and BC)
- Anomaly experiment: without SND

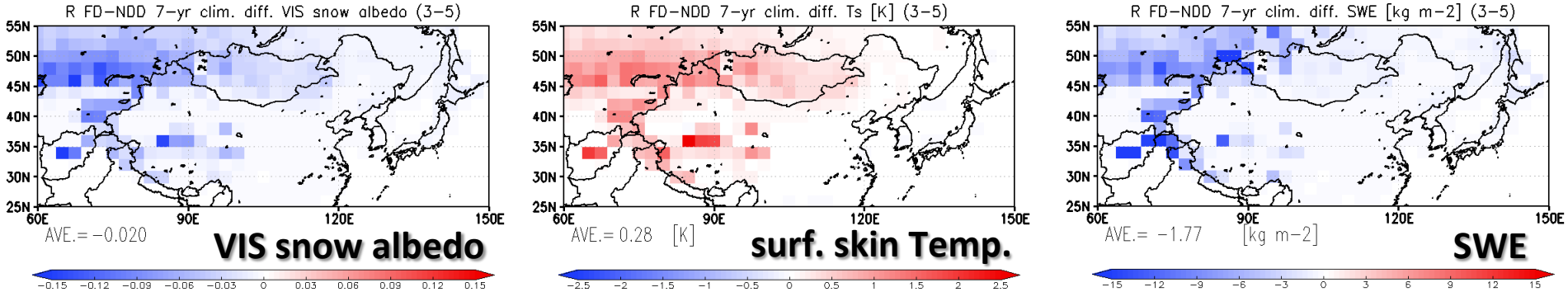

Daily Full SND effect on SWE
Daily dust SND effect on SWE
Daily BC SND effect on SWE
70N
60N
50N
40N
30N
0
30E
60E
90E
120E
150E
09Z01FEB2010
NASA GEOS-5
replay runs
−60
−50
−40
−30
−20
−10
0
10
20
30
40
50
60
[kg m−2]

7-year replay run climatology in MAM on snow darkening (SD) effect over HTP

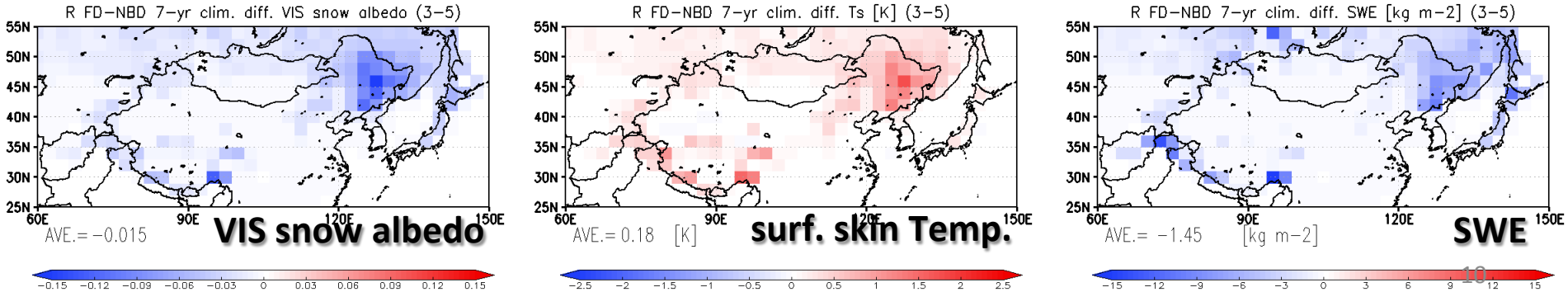
Full SD (dust, BC, and OC) – Non SD



Full SD (dust, BC, and OC) – Non dust SD (Dust only influence)

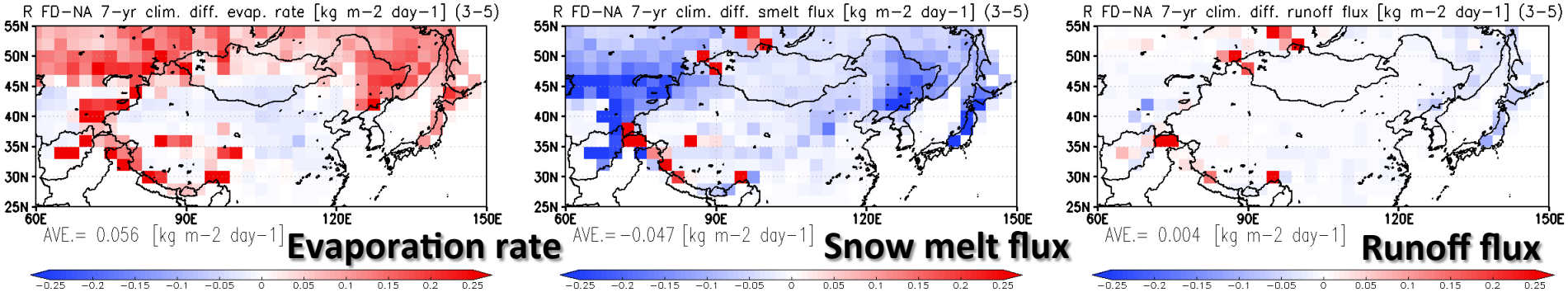


Full SD (dust, BC, and OC) – Non BC SD (BC only influence)

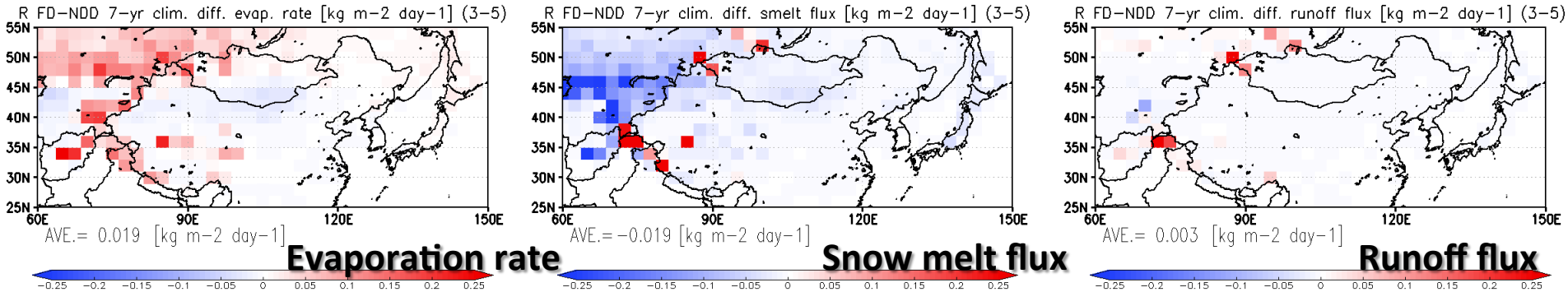


7-year replay run climatology in MAM on snow darkening (SD) effect over HTP

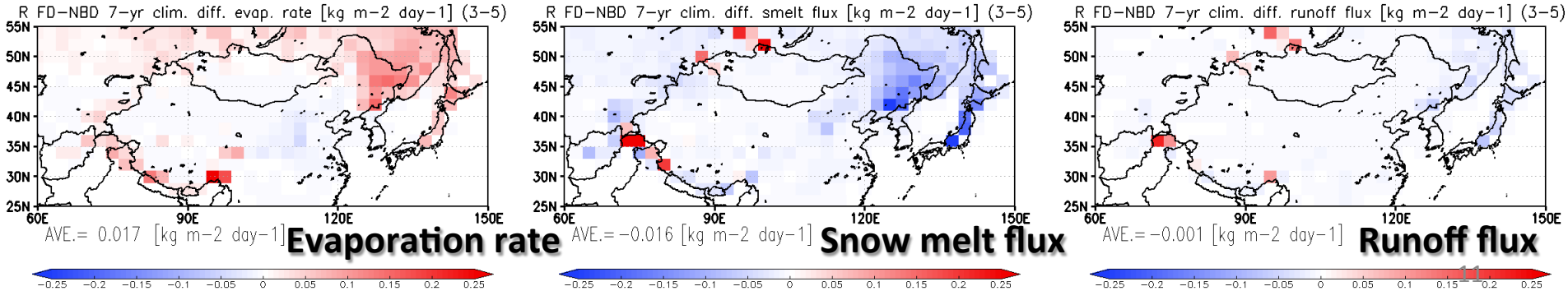
Full SD (dust, BC, and OC) – Non SD



Full SD (dust, BC, and OC) – Non dust SD (Dust only influence)



Full SD (dust, BC, and OC) – Non BC SD (BC only influence)



Summary of SND effect on runoff (no atmospheric feedback)

Snow melt flux (SMF) = ∂ SWE/ ∂ t

SMF = P - E- R

$\Delta P = 0$, for no atmospheric feedback

$\Delta SMF < 0$ due to SND effect

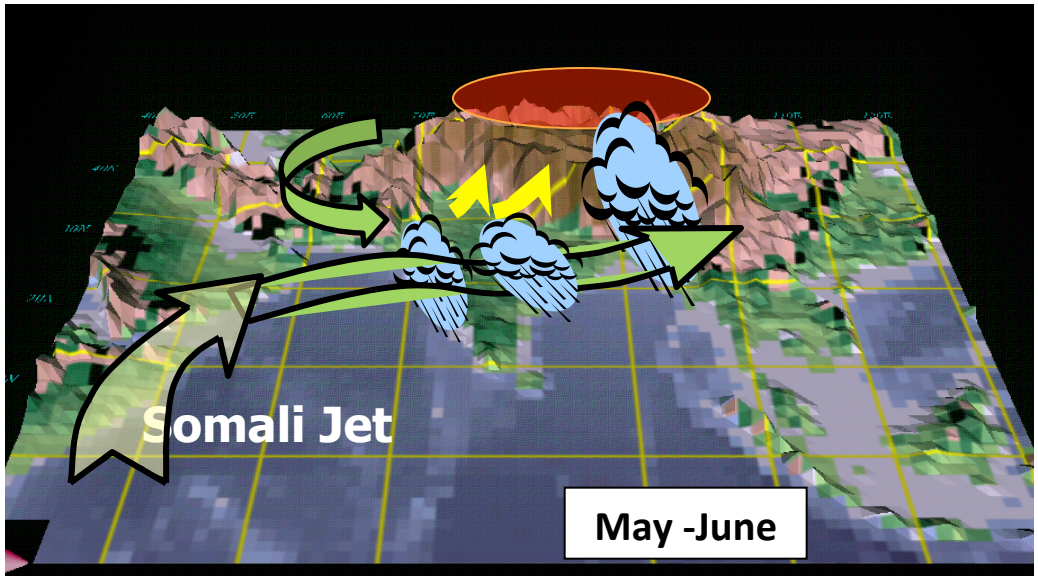
$\Delta E > 0$, more SW absorption → warmer surface increases evaporation

$\Delta R = - (\Delta E + \Delta SMF)$

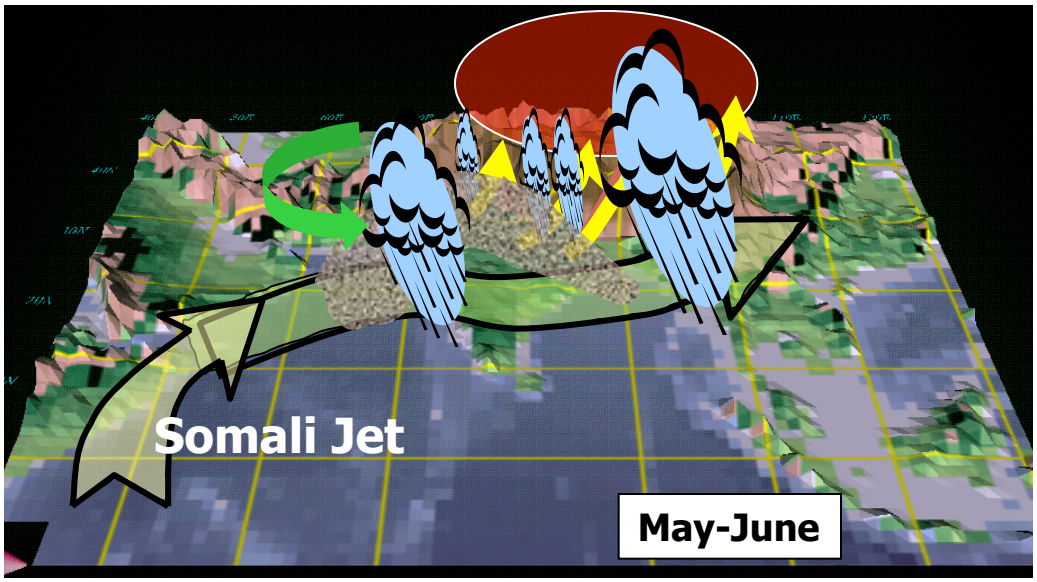
< 0 drying up of season snow cover over Eurasia land

> 0 melting of permanent snowpack on slopes of Tibetan Plateau

The Elevated Heat Pump Hypothesis
(Lau et al. 2006, Lau and Kim 2006, Lau et al. 2008)



"Clean" Monsoon

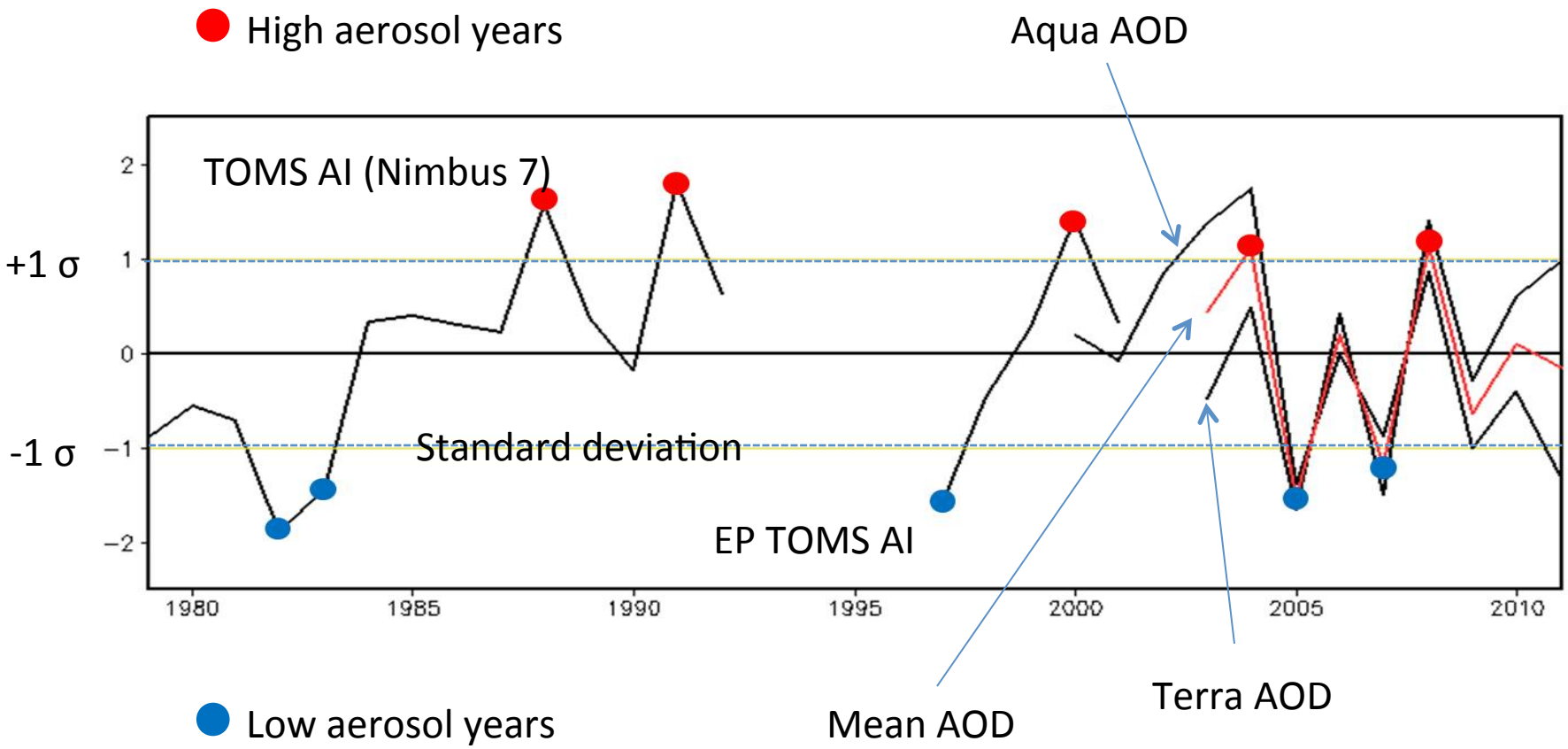


Polluted (dust and BC) monsoon

Datasets

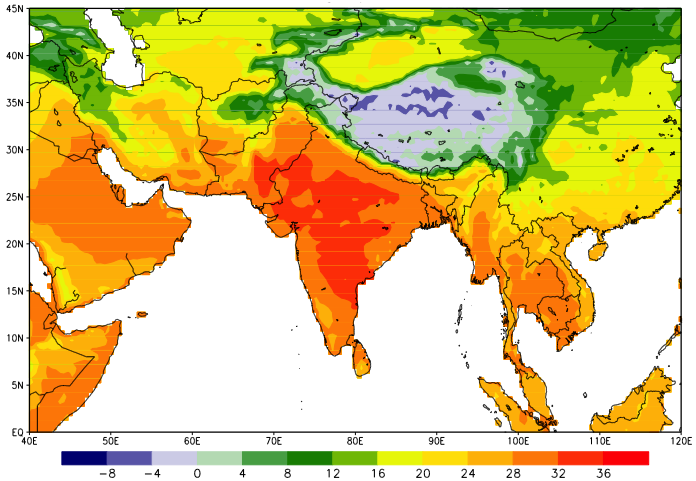
Variables	Period	Source
Aerosol Index	1979-2000	TOMS (Nimbus-7, Earth pr obe)
Aerosol optical dept h	2001-2011	MODIS(Aqua, Terra)
Snow water equival ent (SWE)	1979-2011	SSMR&SSM/I, AMSR-E
TS PRCP SLP, U, V, T, Q, ω		CRU GPCP MERRA

Normalized Aerosol Index (NAI)

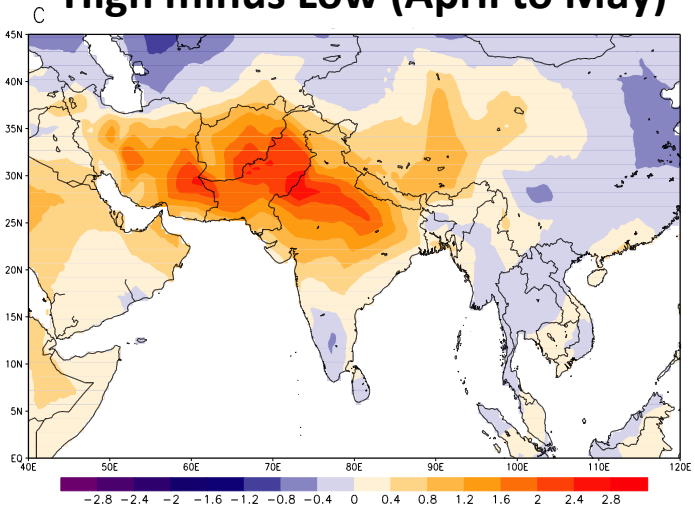


Composite Analysis (Tsfc)

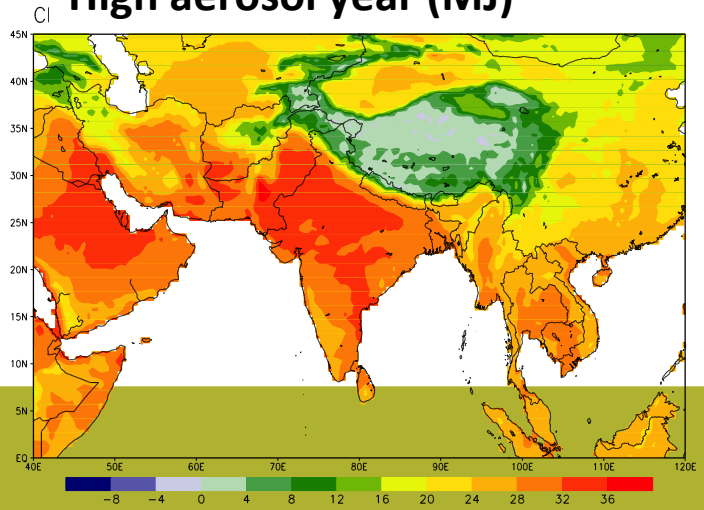
High aerosol year (AM)



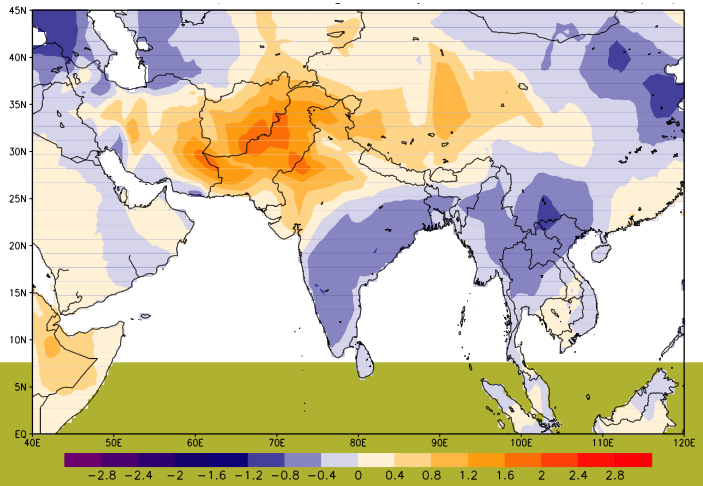
High minus Low (April to May)



High aerosol year (MJ)

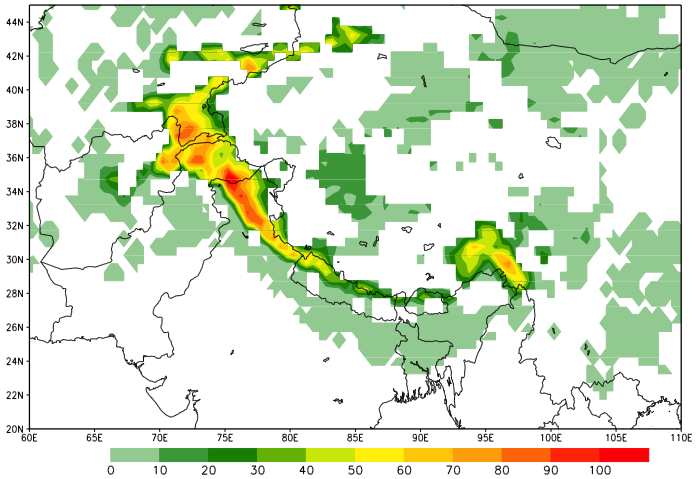


High minus Low (May to June)

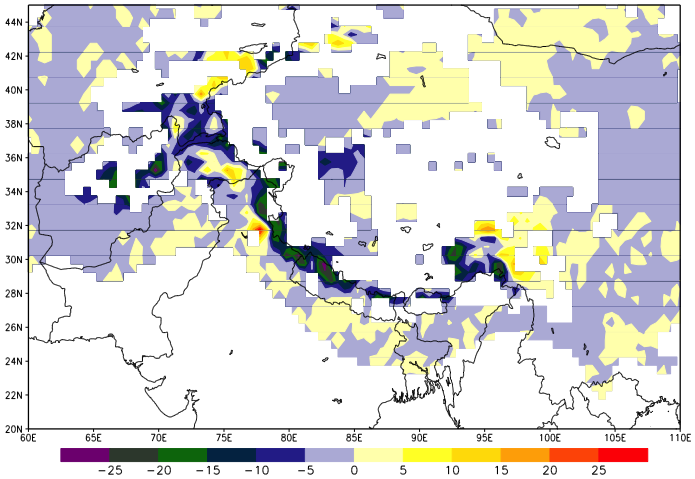


Composite Analysis (SWE)

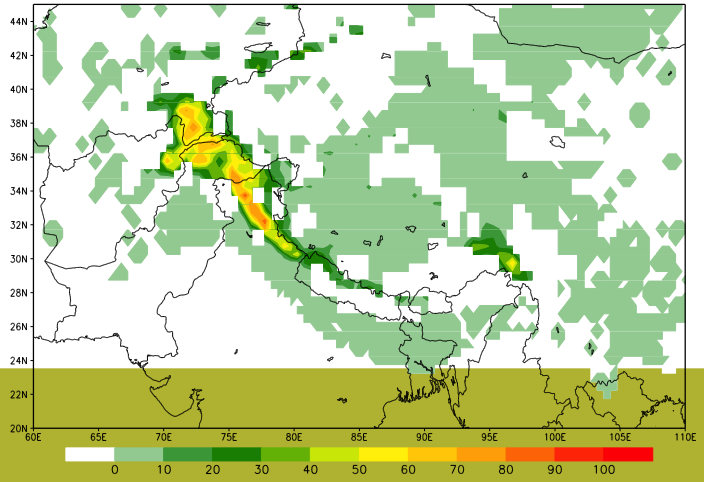
High aerosol year (AM)



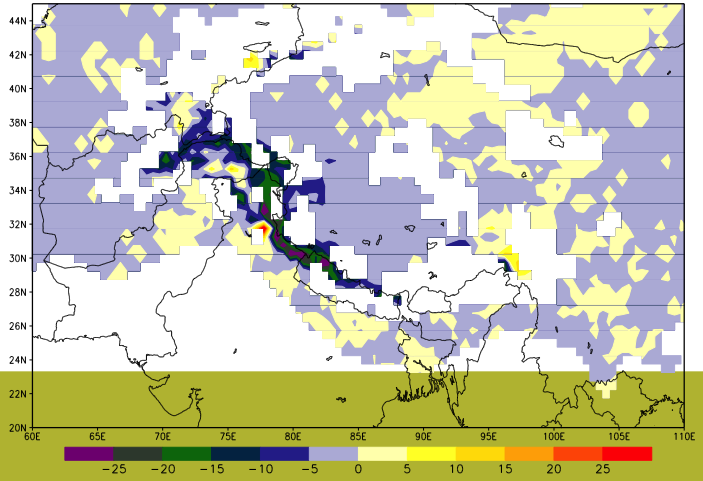
High minus Low (AM)



High aerosol year (MJ)

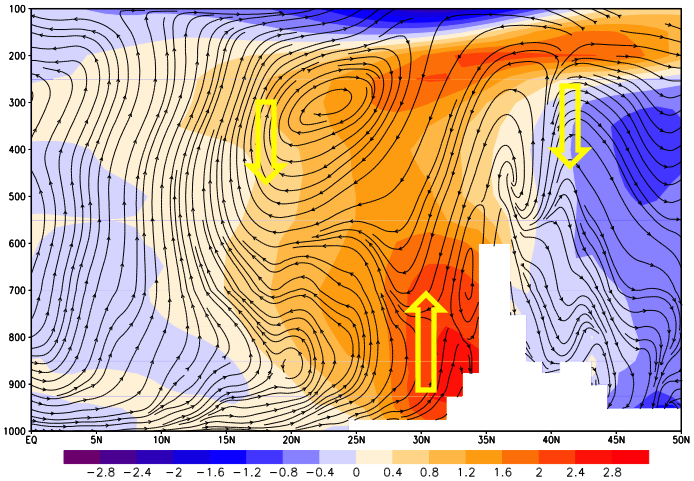


High minus Low (MJ)

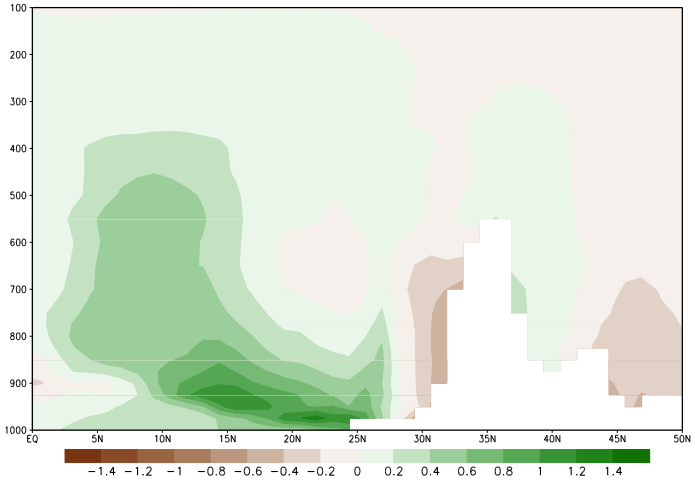


Atmospheric Heating and Moisture Increase

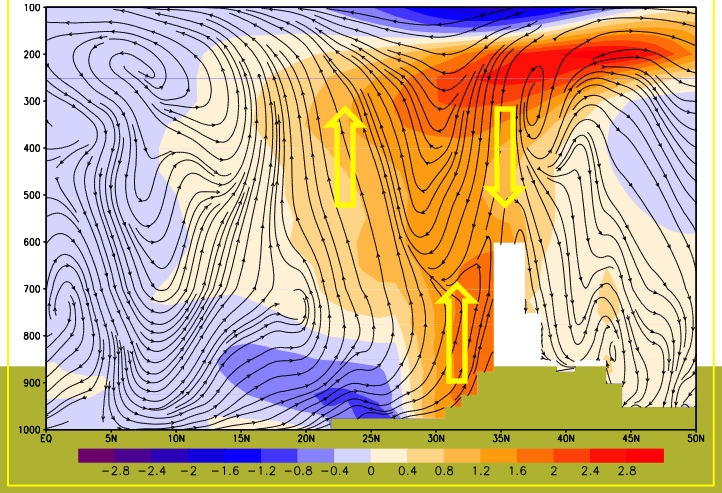
High minus Low (AM)



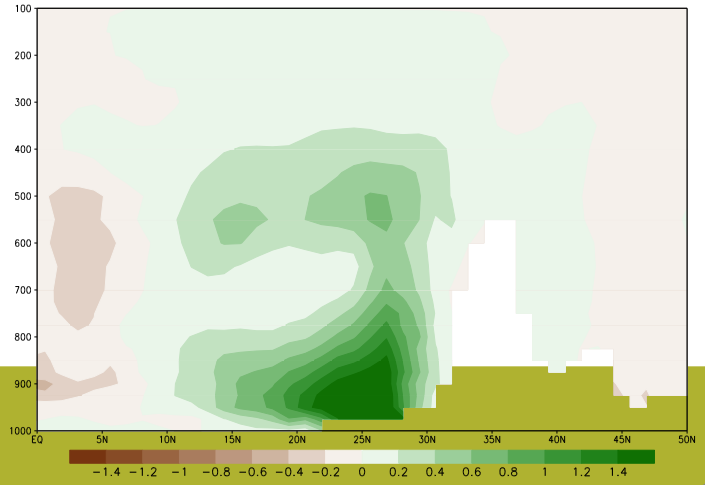
High minus Low (AM)



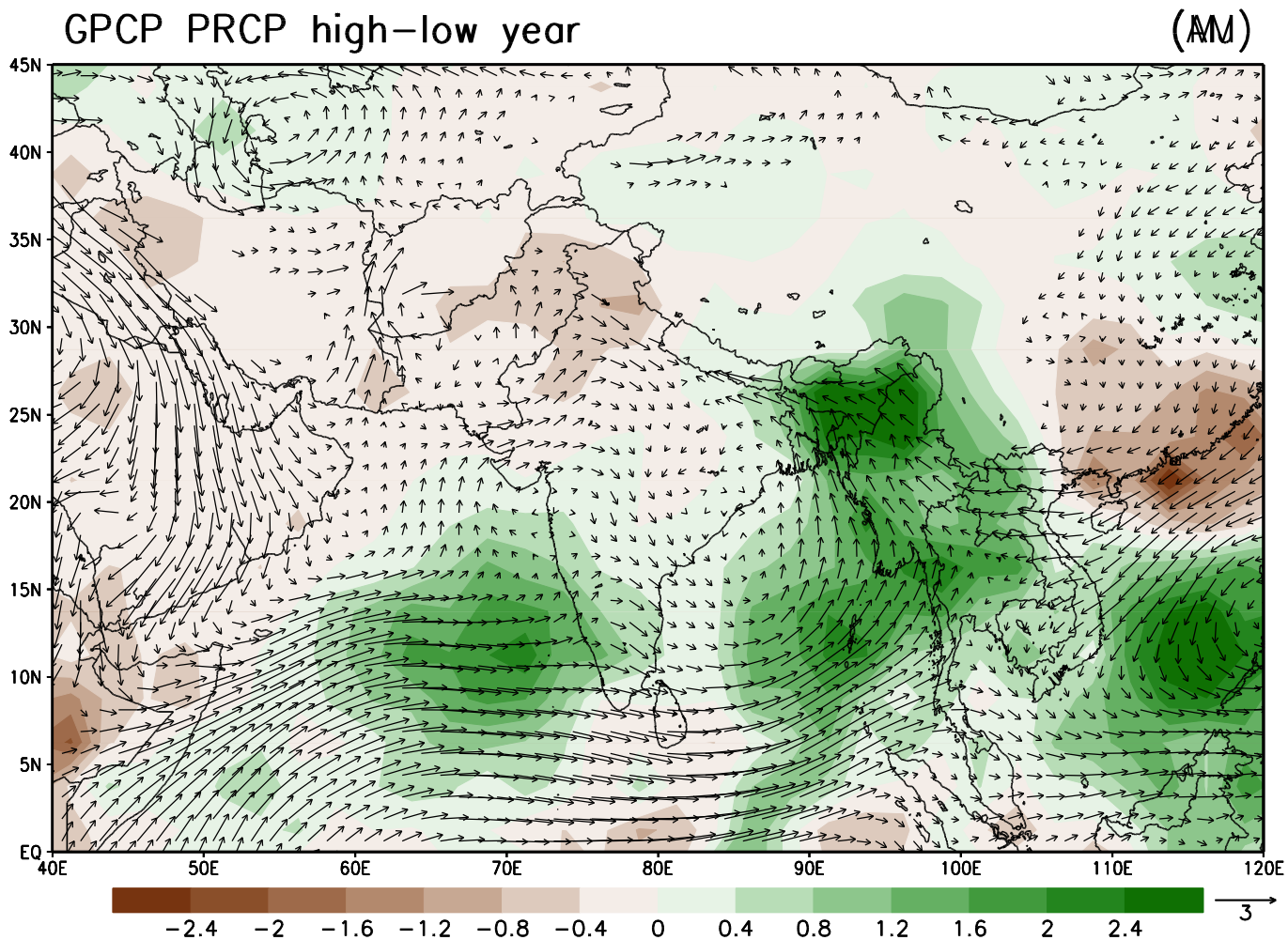
High minus Low (MJ)



High minus Low (MJ)



Anomalous Low and enhanced Precipitation



Conclusions

- Significant snow surface albedo reduction (~ 10-15%) due to darkening by desert dust over Himalayas can be detected from MODIS products.

- Over Eurasia, under conditions of no atmospheric feedback, darkening by deposition of dust and BC over snow cover regions can lead to a surface temperature warming (up to 2° C) during the melting season;
- SND reduces run-off over seasonal snow region but increased run off over permanent snowpack regions around slopes of the TP

- Increased aerosols over IGP in April-May is associated with early melting and reduced snow cover over the Himalaya foothills and TP; increased rainfall over N. India foothills, B. of Bengal, and western Ghats; enhanced the Indian monsoon in May-June, due to both atmosphere heating and SND by absorbing aerosols, consistent with the EHP hypothesis (Lau et al 2006, 2010).

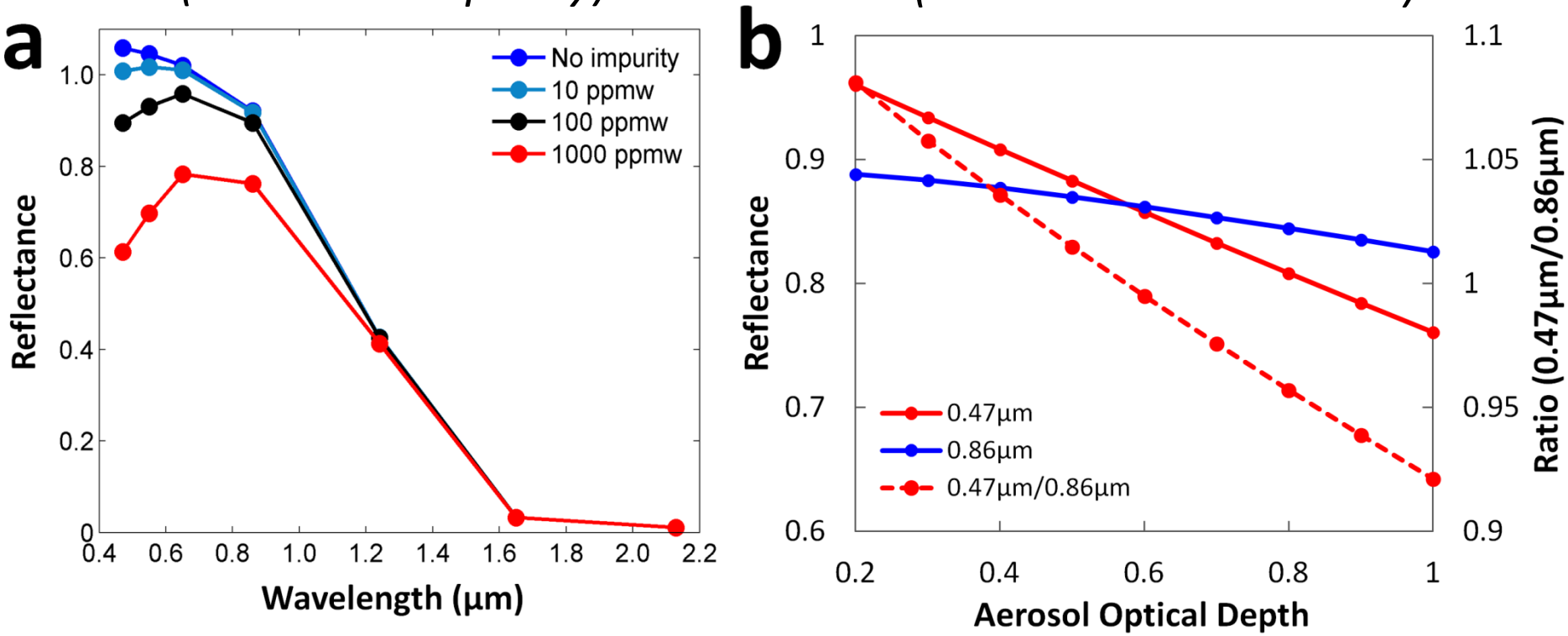
- Results implies an under-estimate of land surface warming in extratropics if SND effect is not included (most IPCC models in AR5 do not include snow darkening effect). Ongoing MAP modeling investigation (PI: W. Lau) to explore enhanced heat wave/drought over Eurasia by SND effect.

Back-UP

Model sensitivity study of Snow Reflectance

Snow surface reflectance (with dust impurity)

TOA reflectance (with dust above snow)



Model sensitivity calculations of reflectance of (a) pure snow mixed with varying levels of dust impurity at solar zenith, viewing zenith, and relative azimuth angles of 30°, 20°, and 140°, respectively, and (b) reduction of TOA reflectance due to dust above clean snow, with VIS-NIR gradient shown as ratio of reflectance between 0.47 and 0.86 µm (secondary *y* axis).

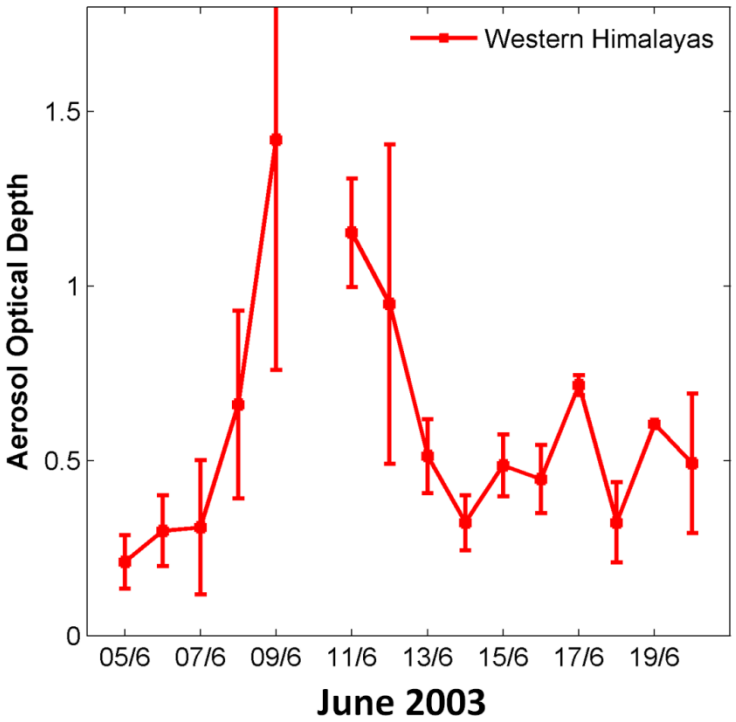
Conclusions

- From an observational viewpoint, this study underscores the ***possible effects of mineral dust deposition towards snow darkening in the western Himalayas***, with potential implications to ***accelerated seasonal snowmelt and regional snow-albedo feedbacks***. Characteristic ***VIS-NIR gradient*** is consistent with theoretical simulations of dust impurity-based reduction of snow reflectance. While the role of black carbon in snow cannot be ruled out, our satellite-based analysis suggests the observed spectral reflectance gradient dominated by dust-induced solar absorption during pre-monsoon season.

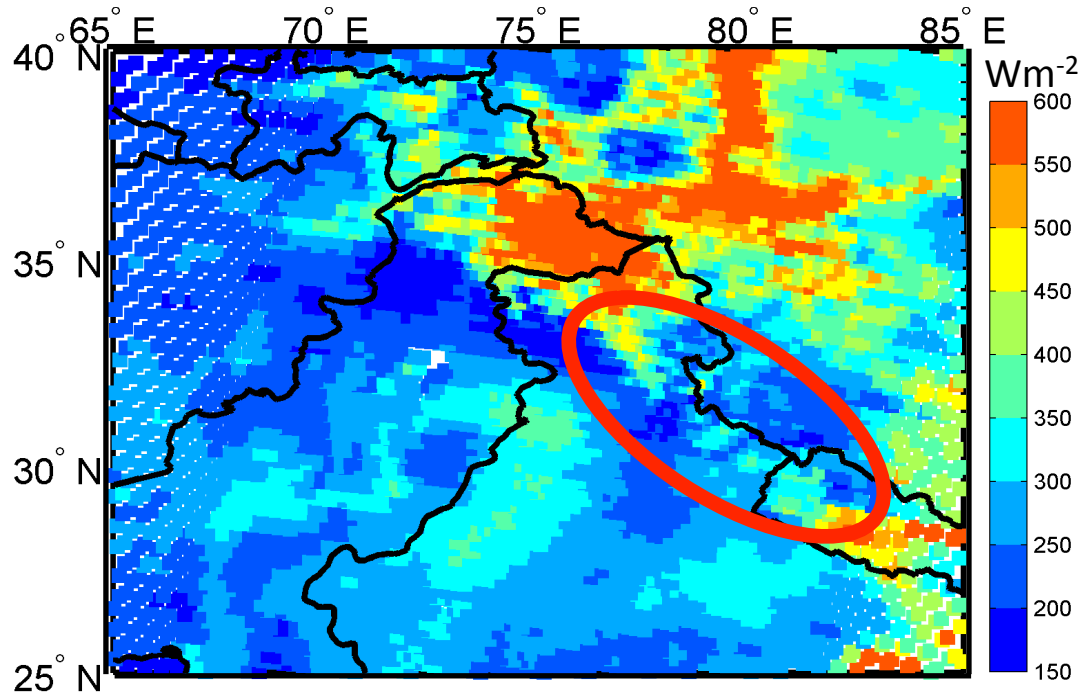
- ***Satellite data*** are useful in inferring dust deposition in snow; but ***uncertainties*** remain and need to be further minimized (e.g. sub-pixel contamination, atmospheric aerosol correction).

- ***Ground-based measurements*** of aerosol properties, particularly dust and BC, as well as coincident snow albedo (and impurity) characterization in the Himalayas are required to ***quantify the aerosol-snow radiative coupling in order to further understand effects of snow darkening***.

MODIS/Aerosol Optical Depth



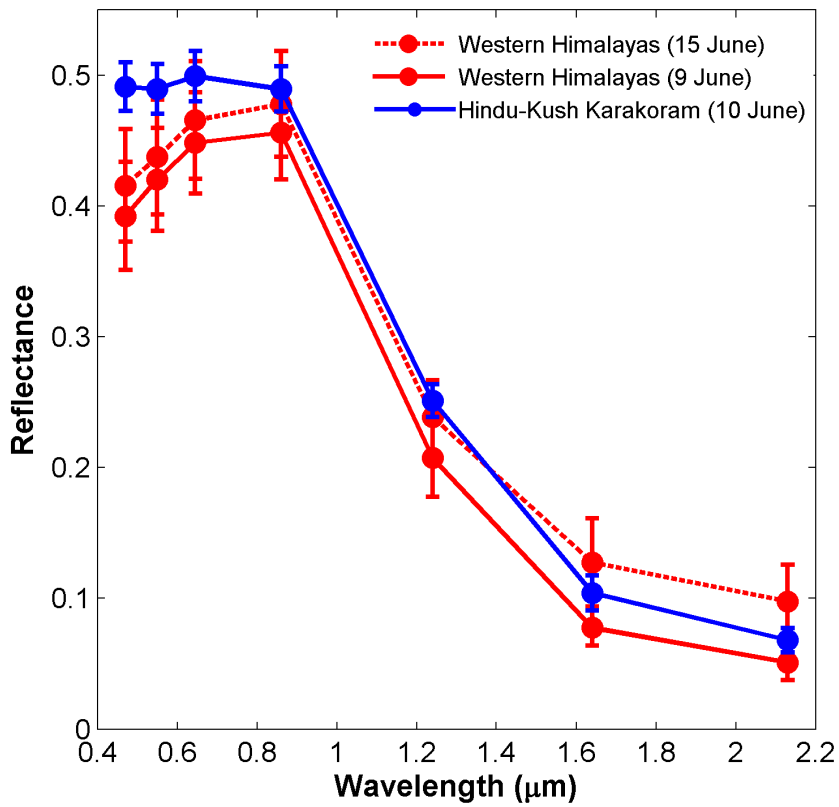
CERES Top-of-Atmosphere Shortwave Flux

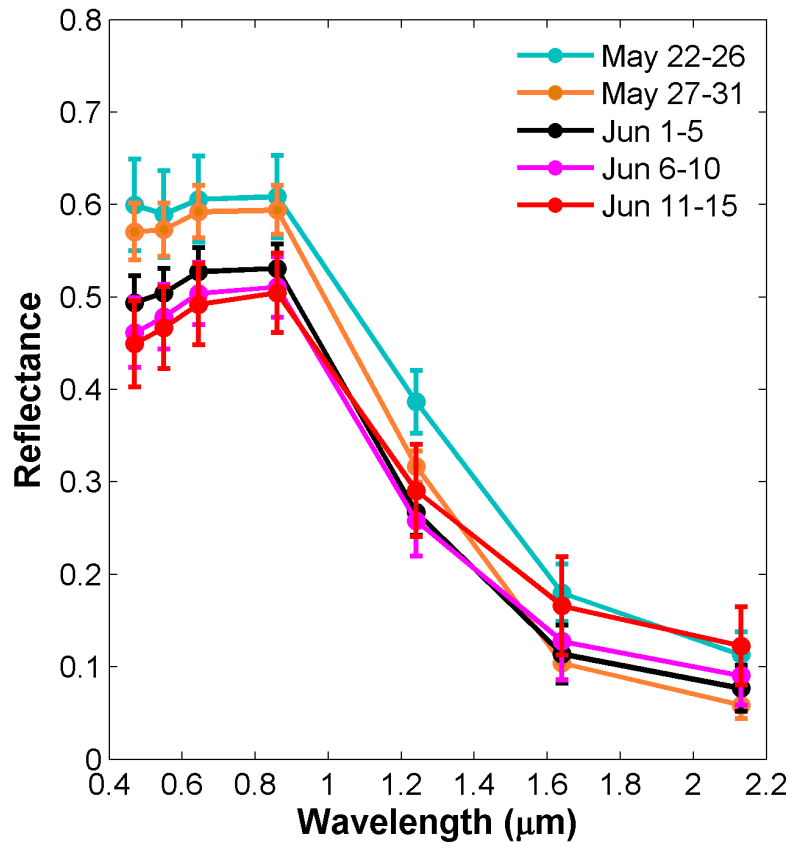


9 June 2003

Darkening observed over dust-laden western Himalaya with reduced TOA reflected shortwave flux (250-400Wm^{-2}), compared to northern Hindu-Kush-Karakoram (400-500Wm^{-2}), outside of dust front.

VIS-NIR gradient is also observed at TOA



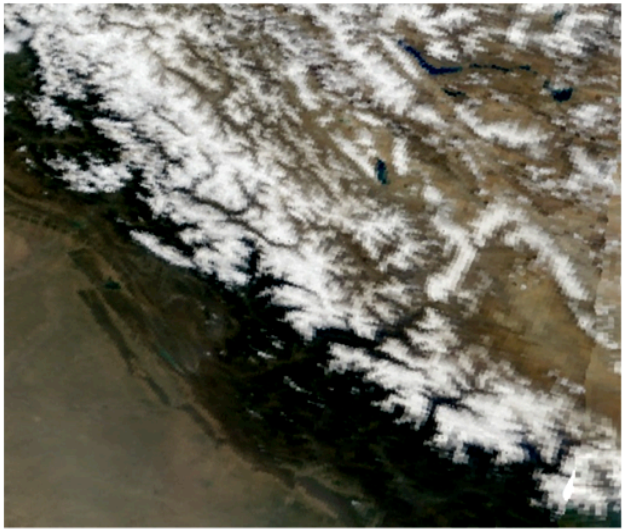


MODIS Top-Of-Atmosphere (TOA) reflectance over the western Himalayan snow cover , associated with the gradient between wavelengths 0.47μm and 0.86μm (VIS-NIR) is observed for TOA reflectance.

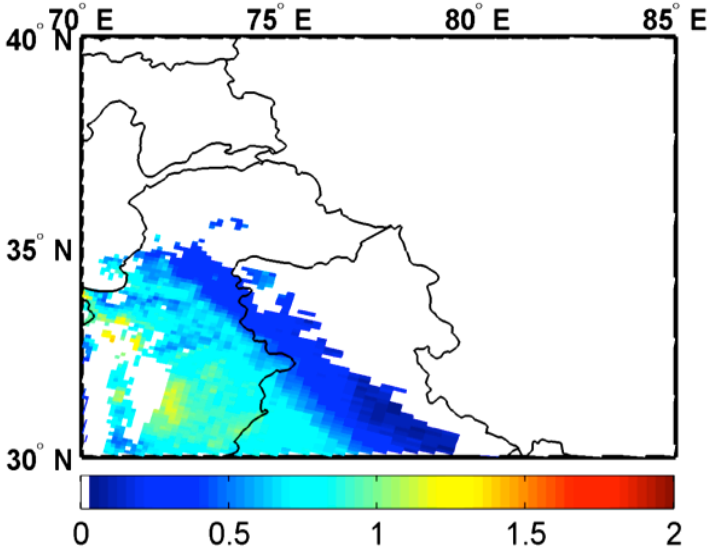
In addition to aerosol extinction, the TOA reflectance is affected by other atmospheric effects such as Rayleigh scattering (particularly at the shorter wavelength, i.e. 0.47μm) and gaseous absorption.

Comparison of Snow Surface Reflectance (MOD09) before and after dust event

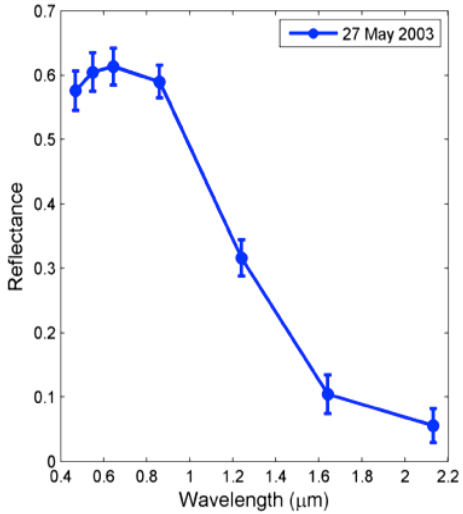
27 May 2003



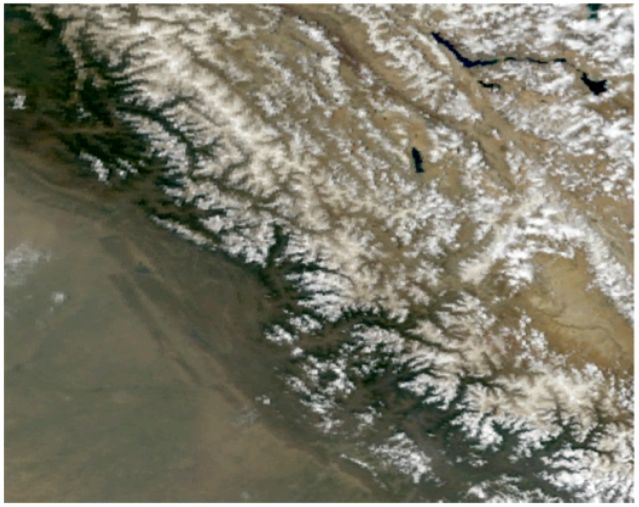
Aerosol Optical Depth



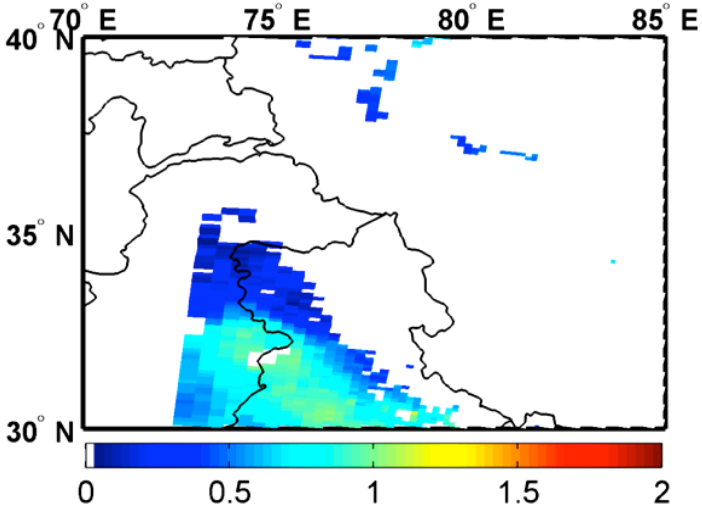
Reflectance



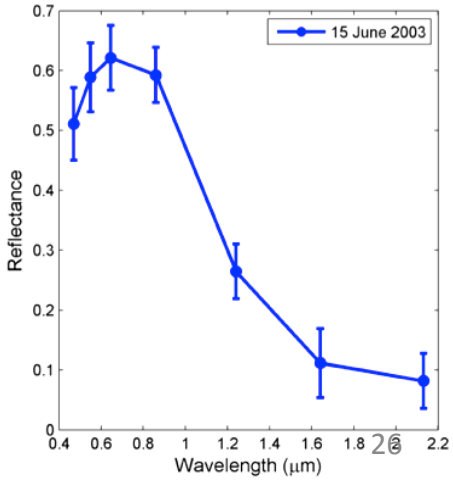
15 June 2003



Aerosol Optical Depth

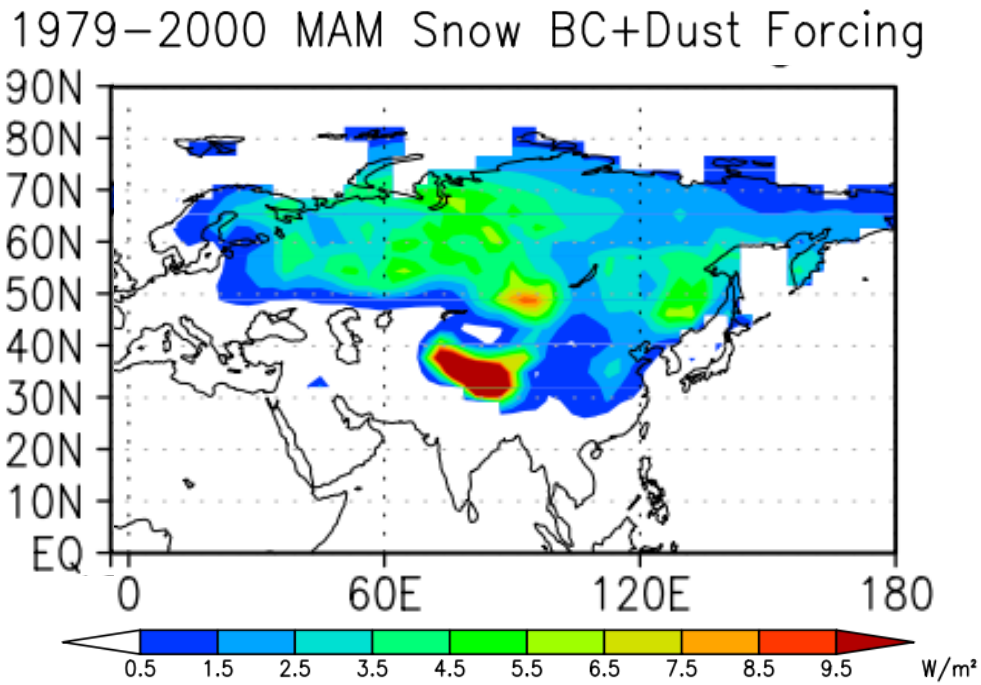


Reflectance



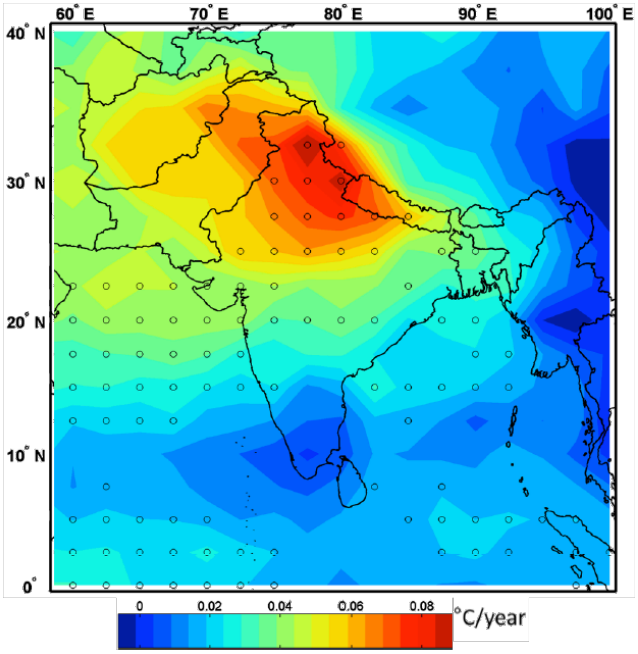
Accelerated Snowmelt due to Snow Darkening

- Himalayas-Tibetan Plateau (HTP) are among the largest ice-covered regions on Earth, major freshwater resource in Asia.
- GCM simulations suggest climate warming and accelerated snowmelt in the Himalayas*, due to dust and black carbon deposition, via snow-albedo feedbacks (Lau et al 2006, 2008, 2010).*



Flanner et al. 2009

Tropospheric Temp. Trend May 1979-2007



Gautam et al. 2009

TP & Himalayas