Aerosol, Monsoon Rainfall Variability and Climate Change

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Climate Change≠ Global Warming

Climate Change is a change in the statistical distribution of weather over a period of time that range from season, years, decades to millions of years. It can be a change in the average weather or a change in the distribution of weather events around an average (for example, greater or fewer extreme weather events). Climate change may be limited to a specific region, or an environment, or may occur across the whole Earth System

Global warming is a realization of the effects of well-mixed greenhouse gases associated with modern (approx. since the last 1.5 centuries) climate change

Global and TOA

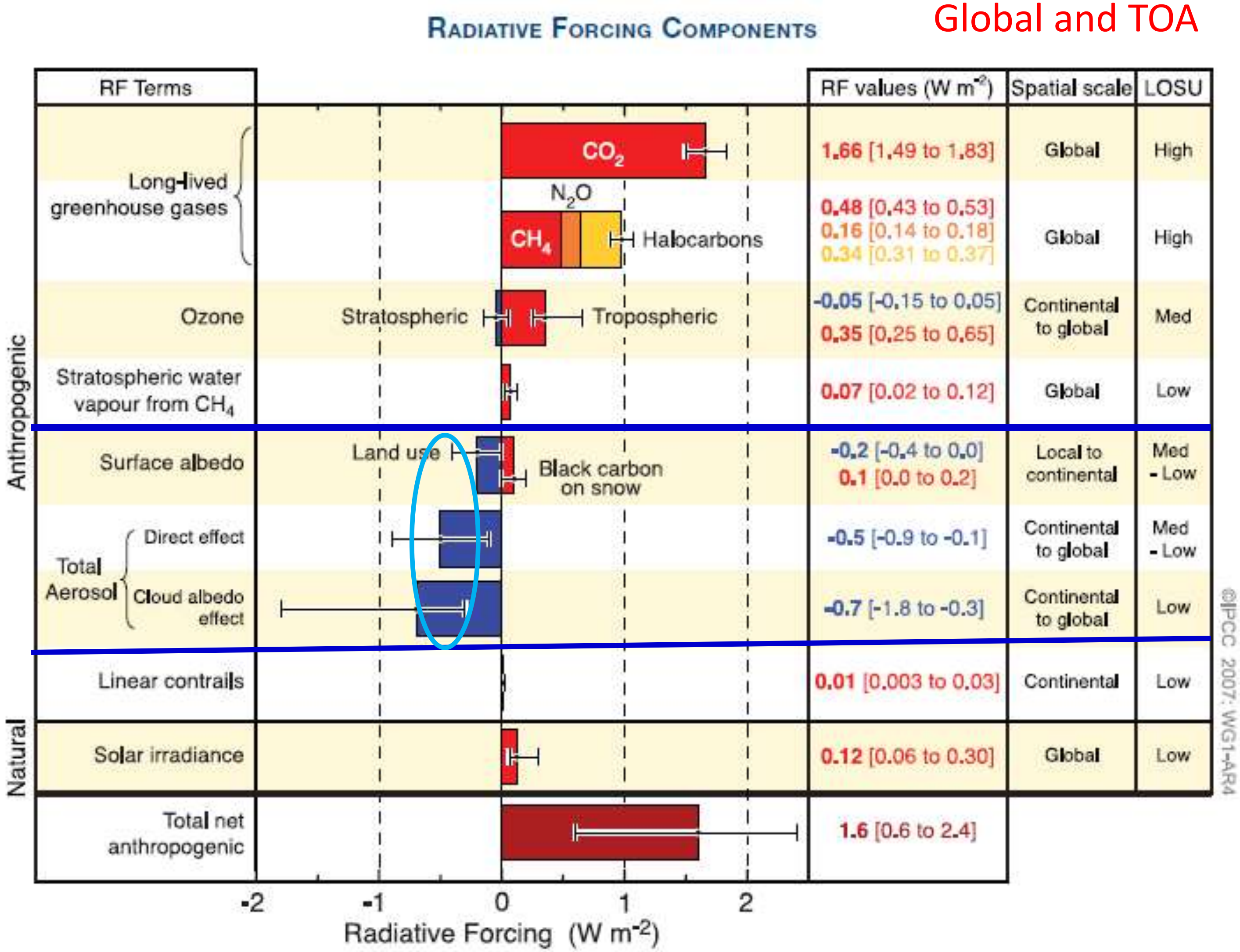


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

"……human influences are significant and involve a diverse range of first-order climate forcings, including , but not limited to the human input of well mixed greenhouse gases (CO_2, CH_4, N_2O etc.) The impacts of these other forcing (aerosols, LULC, urban heat island…..) are critically important in exciting climate feedbacks on regional and local scales, and in modulating the greenhouse warming effects."

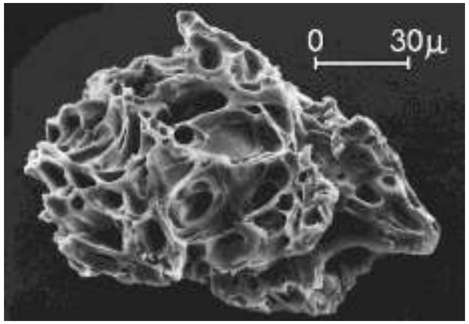
Climate Change: The Need to Consider Human Forcings Other than Greenhouse Gases, EOS, American Geophysical Union, 2009, Nov.

By Roger Pielke Sr[1]., Keith Beven[2], Guy Brasseur[3], Jack Calvert[3], Moustafa Chahine[4], Russ Dickerson[5], Dara Entekhabi[6], Efi Foufoula-Georgiou[7], Hoshin Gupta[8], Vijay Gupta[1], Witold Krajewski[9], E. Philip Krider[8], ***William K. M. Lau[10]****, Jeff McDonnell[11], William Rossow[12] , John Schaake[13], James Smith[14], Soroosh Sorooshian[15], Eric Wood[14]*

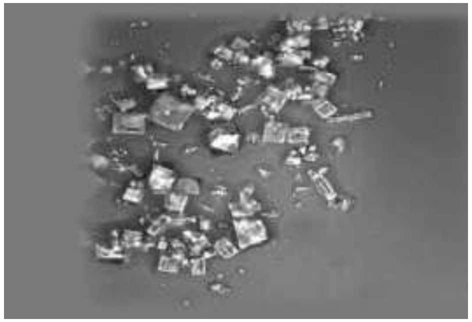
Definition of aerosol

An **aerosol** is a suspension of fine solid particles or liquid droplets in a gas. Aerosols come from both man-made (industry, motor vehicles), and natural sources (forest fires, oceanic haze, deserts). *Examples are: sulfate, soot (black carbon), organic carbon, dust, sea salt.*

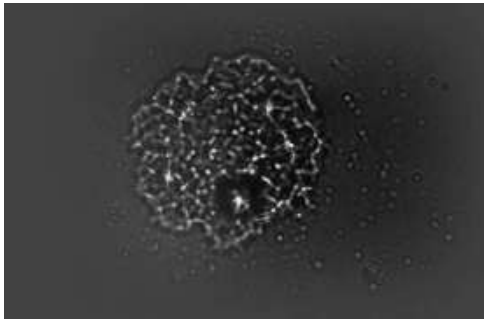
Soot is impure carbon particles resulting from incomplete combustion of a hydrocarbon *e.g.*, from internal combustion engines, power plants, heat boilers, waste incinerators, furnaces, fireplaces, slash and burn agriculture, forest fires.



Volcanic ash



Sea Salt



Tractor soot

Aerosols alter energy balance of the atmosphere-ocean-land system

Radiation (Direct) Effects

Back Scattering (Cooling)

Absorption (Atmospheric Column Warming by absorbing aerosols e.g. dust and soot)

Forward Scattering

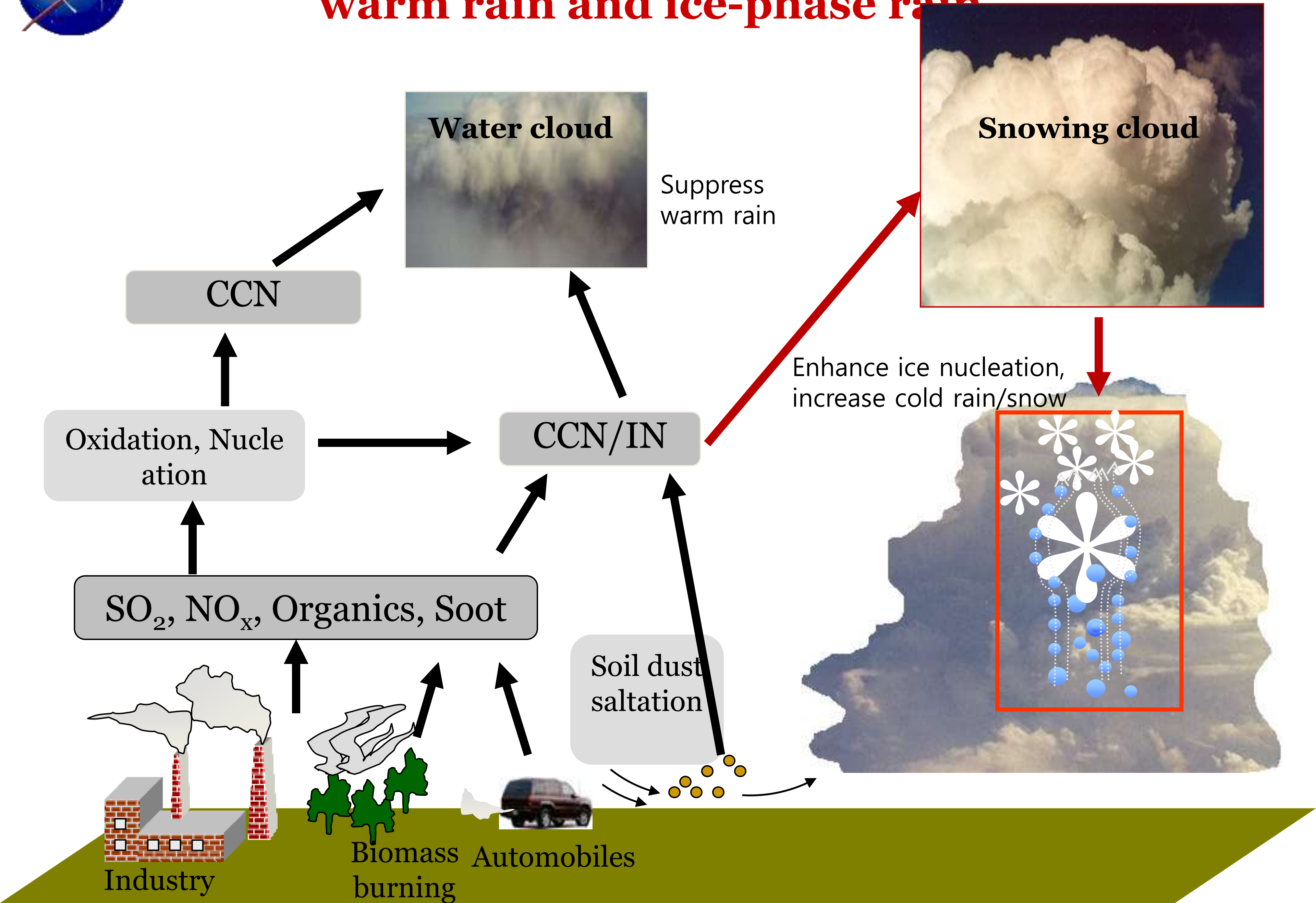
Dimming of Earth Surface (Cooling)

Microphysics (Indirect) Effects

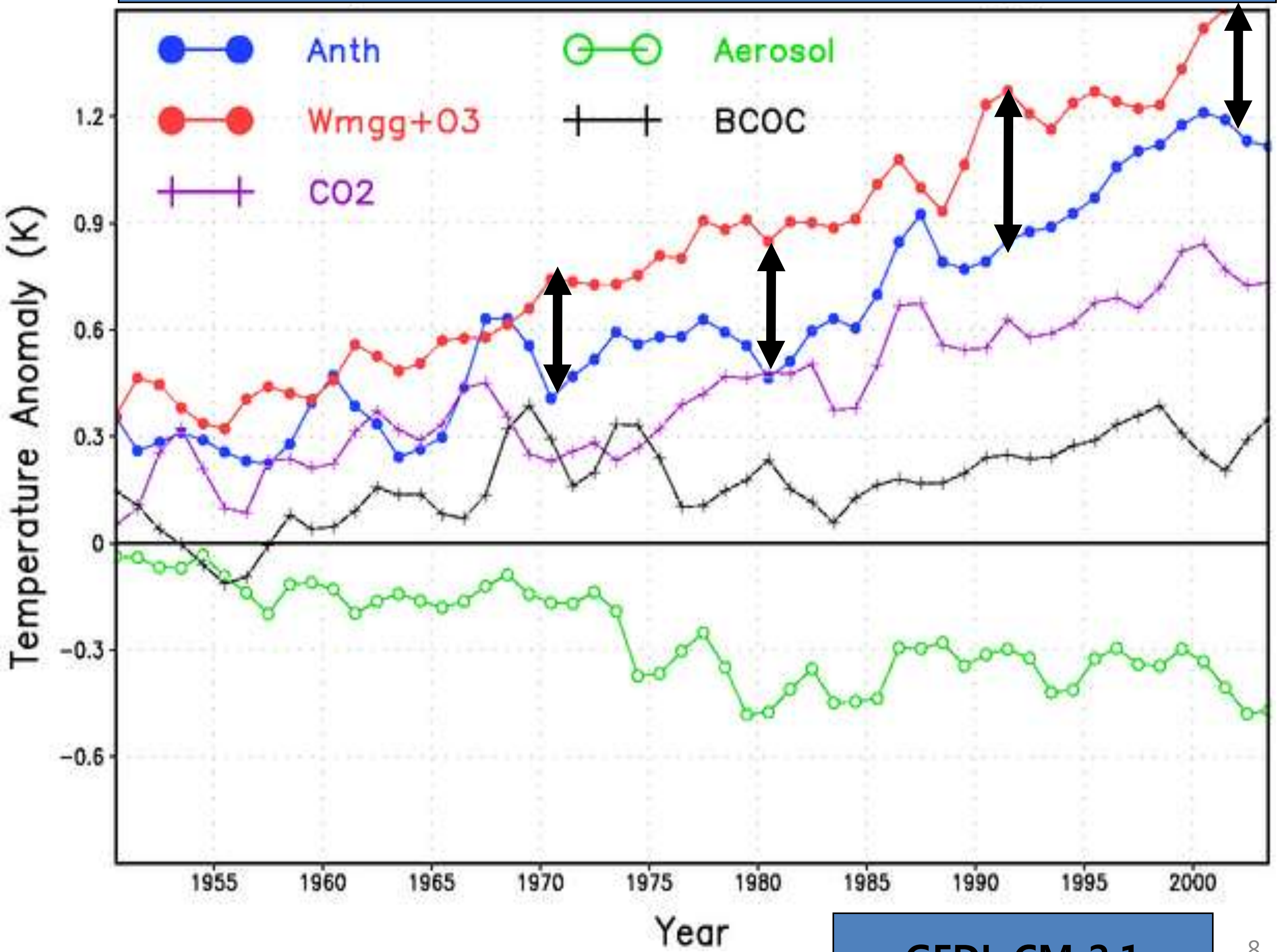
Warm Rain suppression, Increased cloud life time (cooling)
Increased ice nucleation, enhanced deep convection (warming)

Aerosol induced cloud-shielding → Surface cooling

Microphysics (indirect) effects of aerosols on warm rain and ice-phase rain



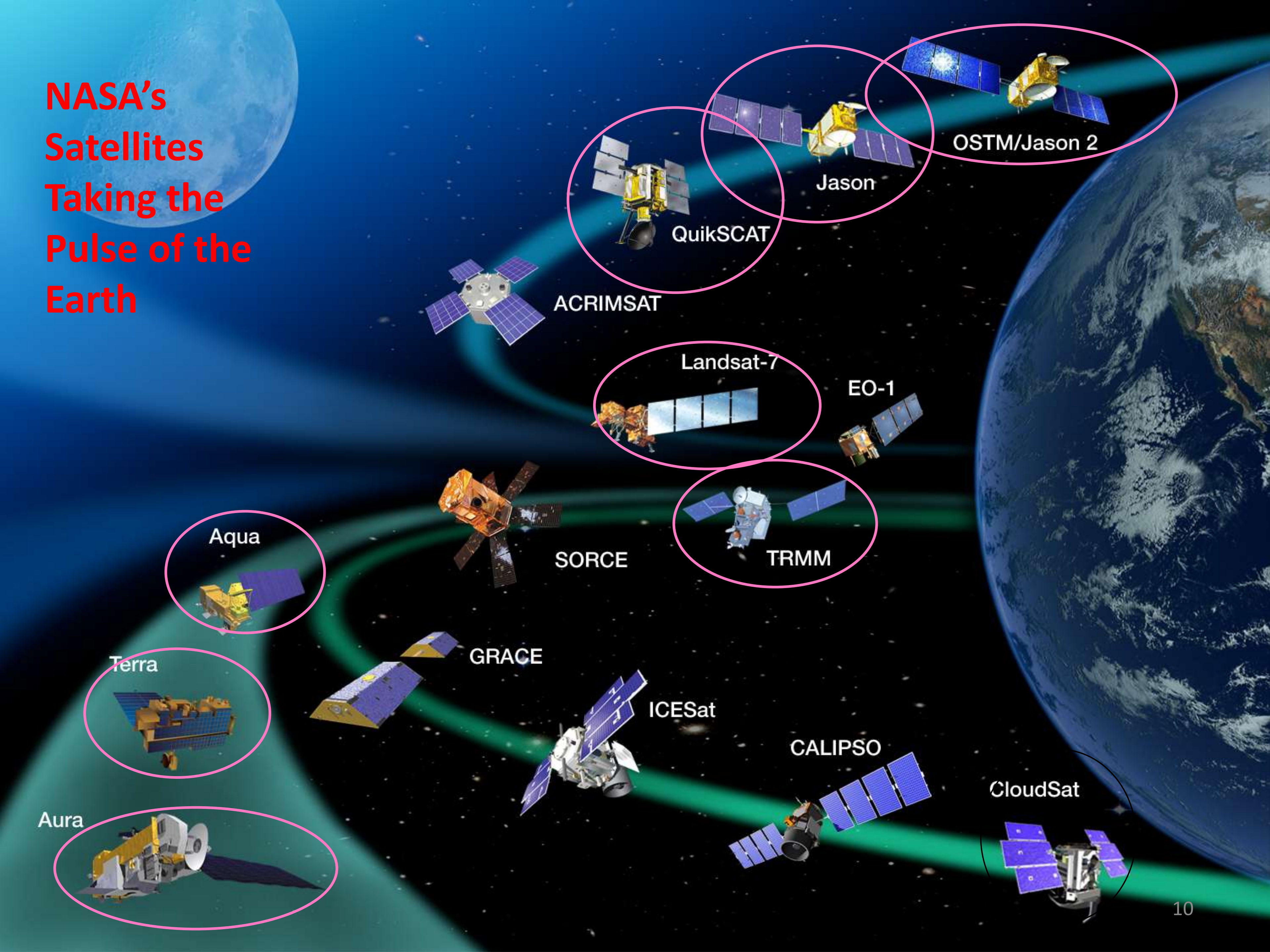
Aerosols mask global warming effects



GFDL CM 2.1

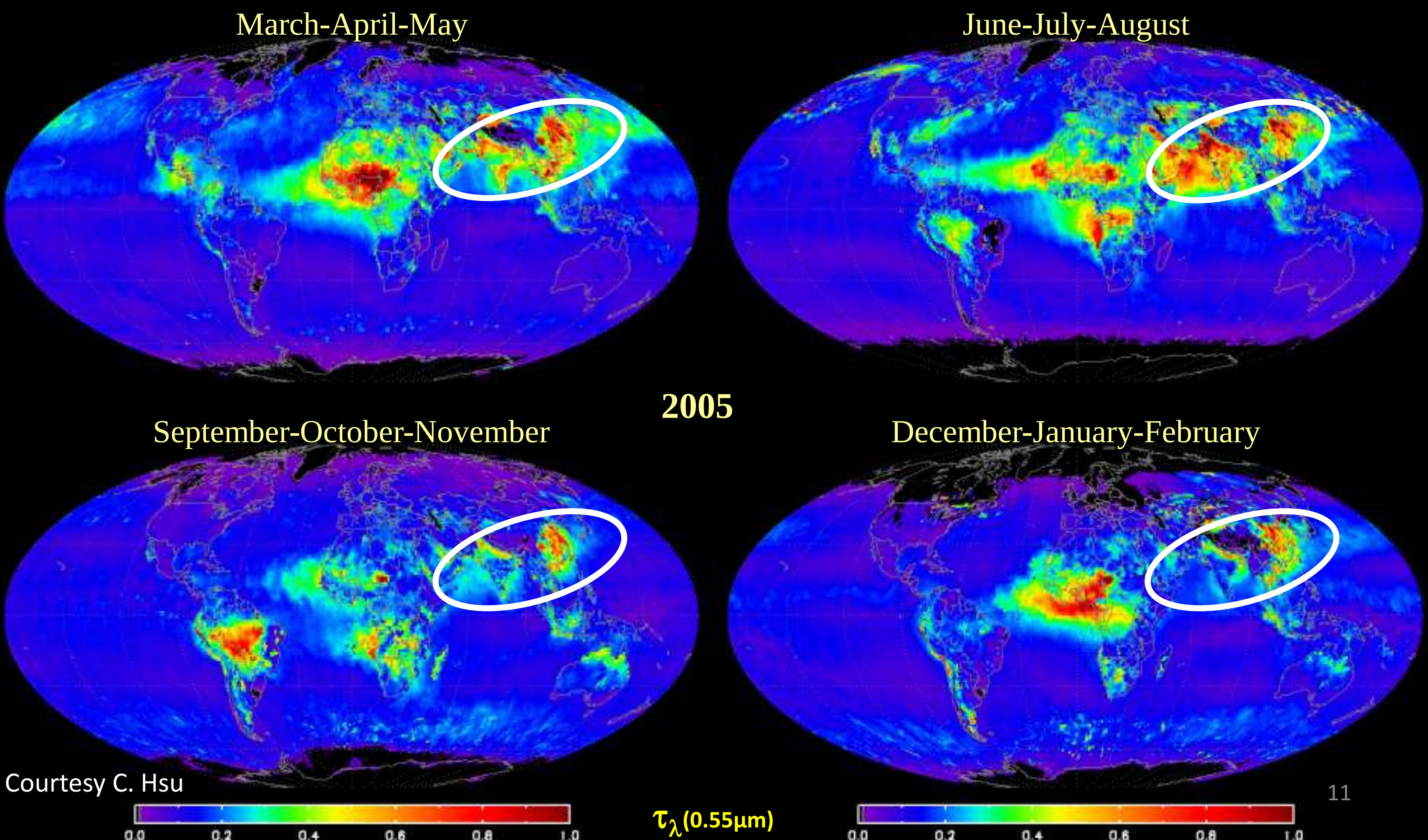
Aerosols have done a lot more than just "offset" the global-mean surface temperature due to long-Lived Greenhouse Gases, but also altered regional water cycle and climate in ways that are still not understood, or even known!!

NASA's Satellites Taking the Pulse of the Earth



Aerosol-Hotspots

Aqua Collection-05 Aerosol (Deep Blue & MODIS Composite)



Courtesy C. Hsu

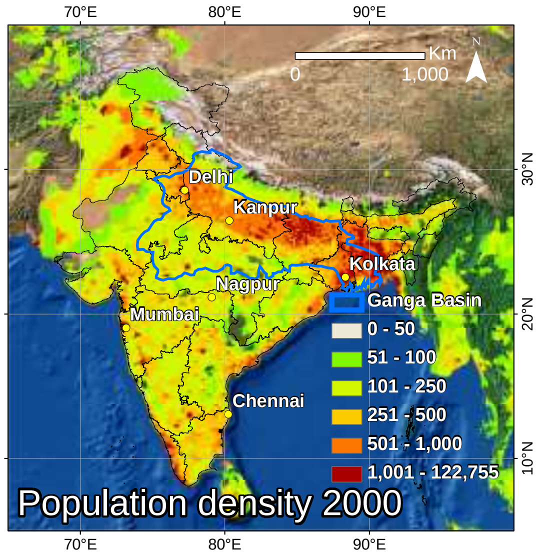
Climate Change hazards in Asia

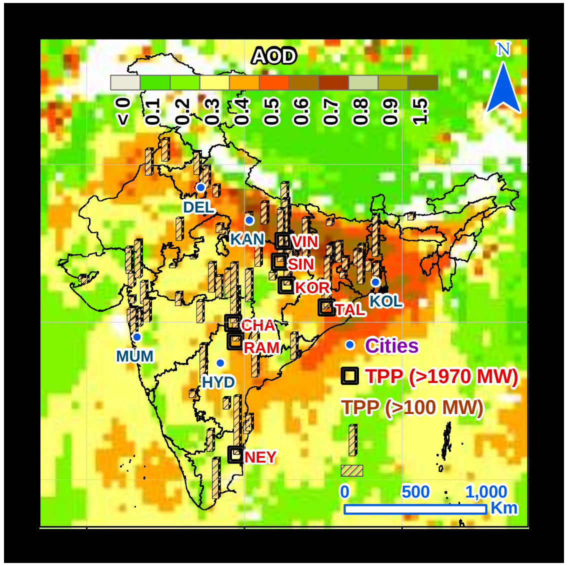
Aerosols and the Asian Monsoon

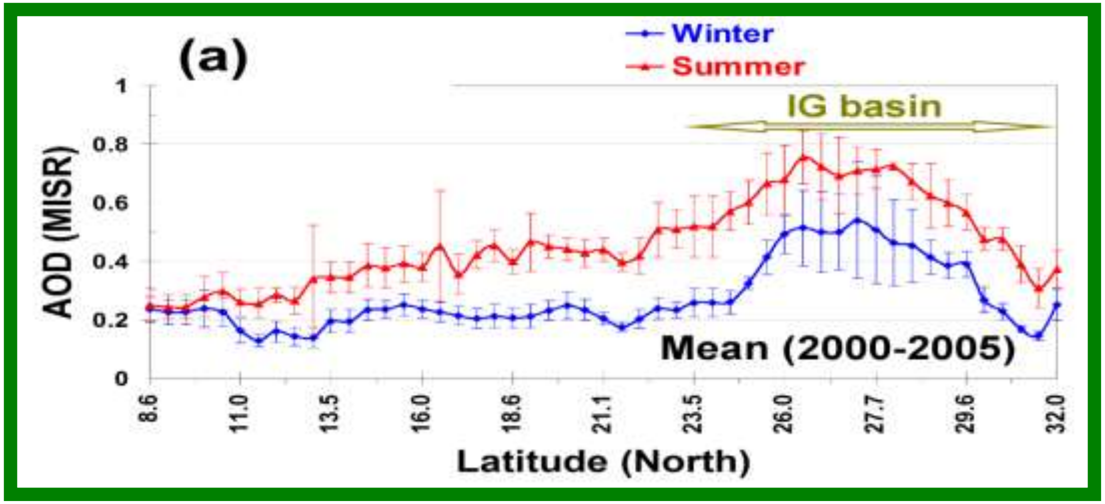
- Over 60% of world population live in the Asian monsoon regions
- Monsoon related droughts and floods, and aerosols are the two most serious environmental hazards in Asian monsoon regions,
- Sea surface temperature, and land surface processes drive the large-scale monsoon, through surface heating gradients and atmospheric heat sources and sinks.
- The monsoon water cycle is driven by atmospheric heating/cooling, through the dynamical interaction of wind, moisture, clouds and rainfall and surface processes.
- Suspended particles (aerosol, clouds, precipitation) in the atmosphere regulate with the land-sea thermal gradient, interact with heat sources and sinks, and alter the monsoon water cycle





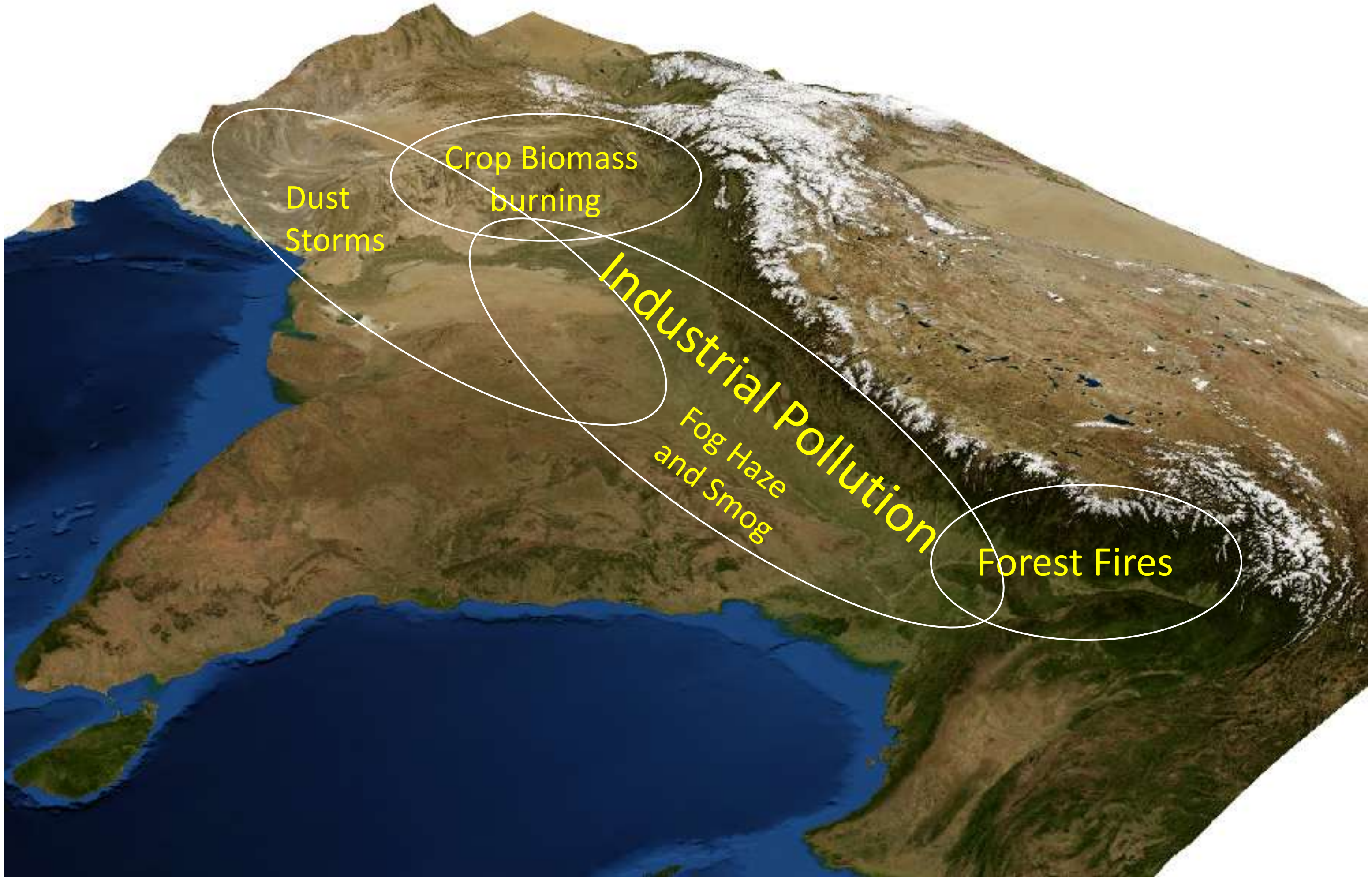



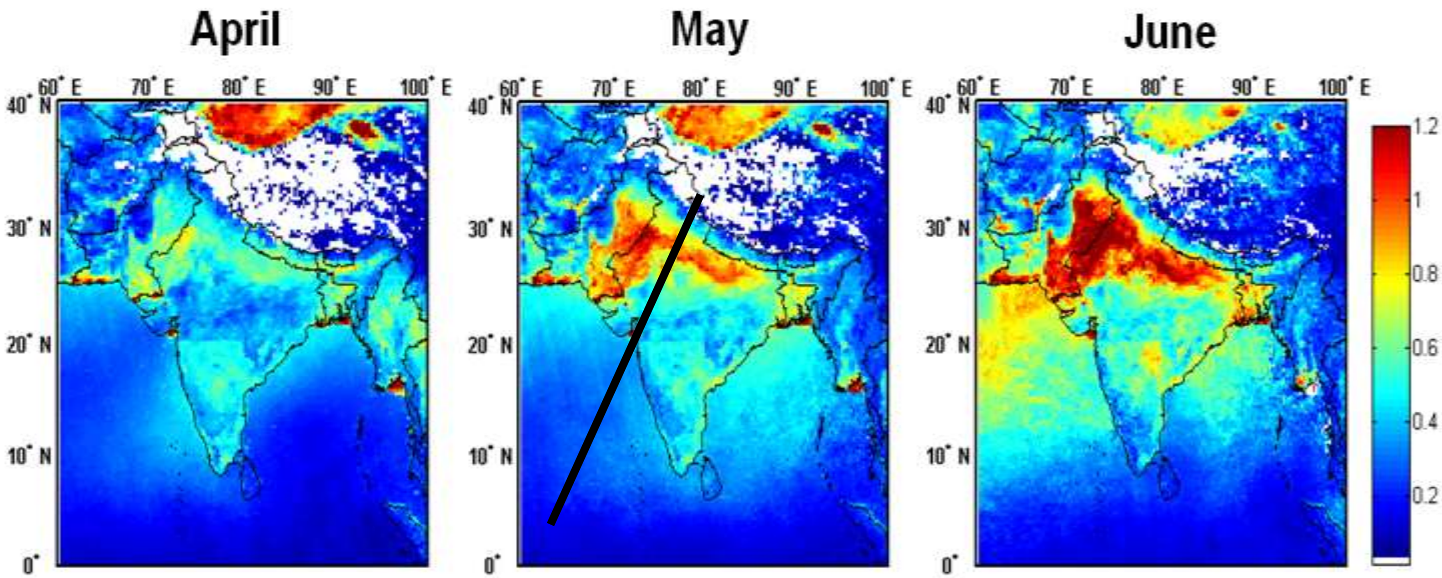




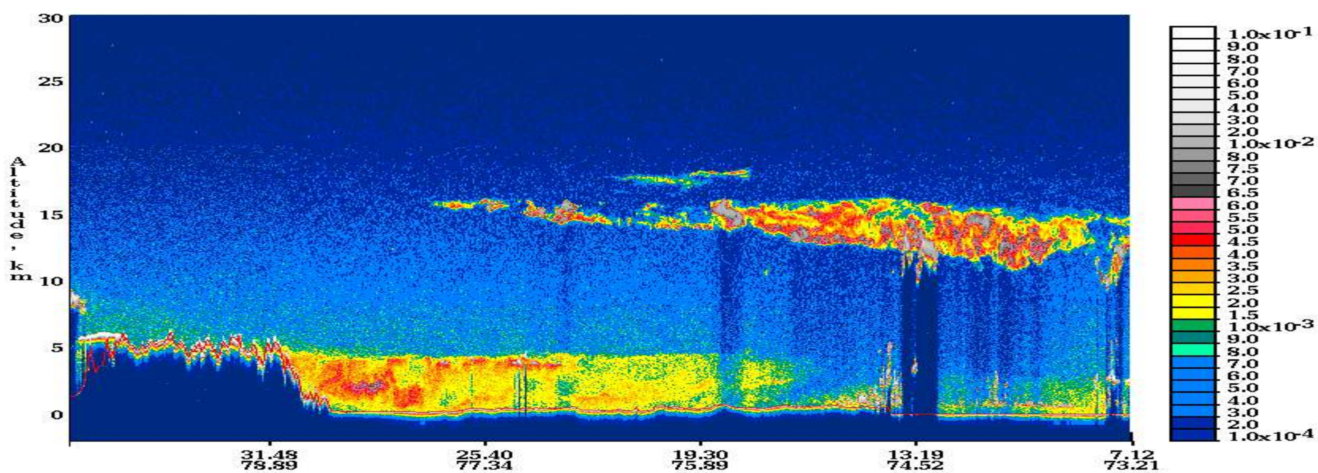
Courtesy
Ramesh and Prasad

Complex mixture of aerosols over the Indo-Gangetic Plain



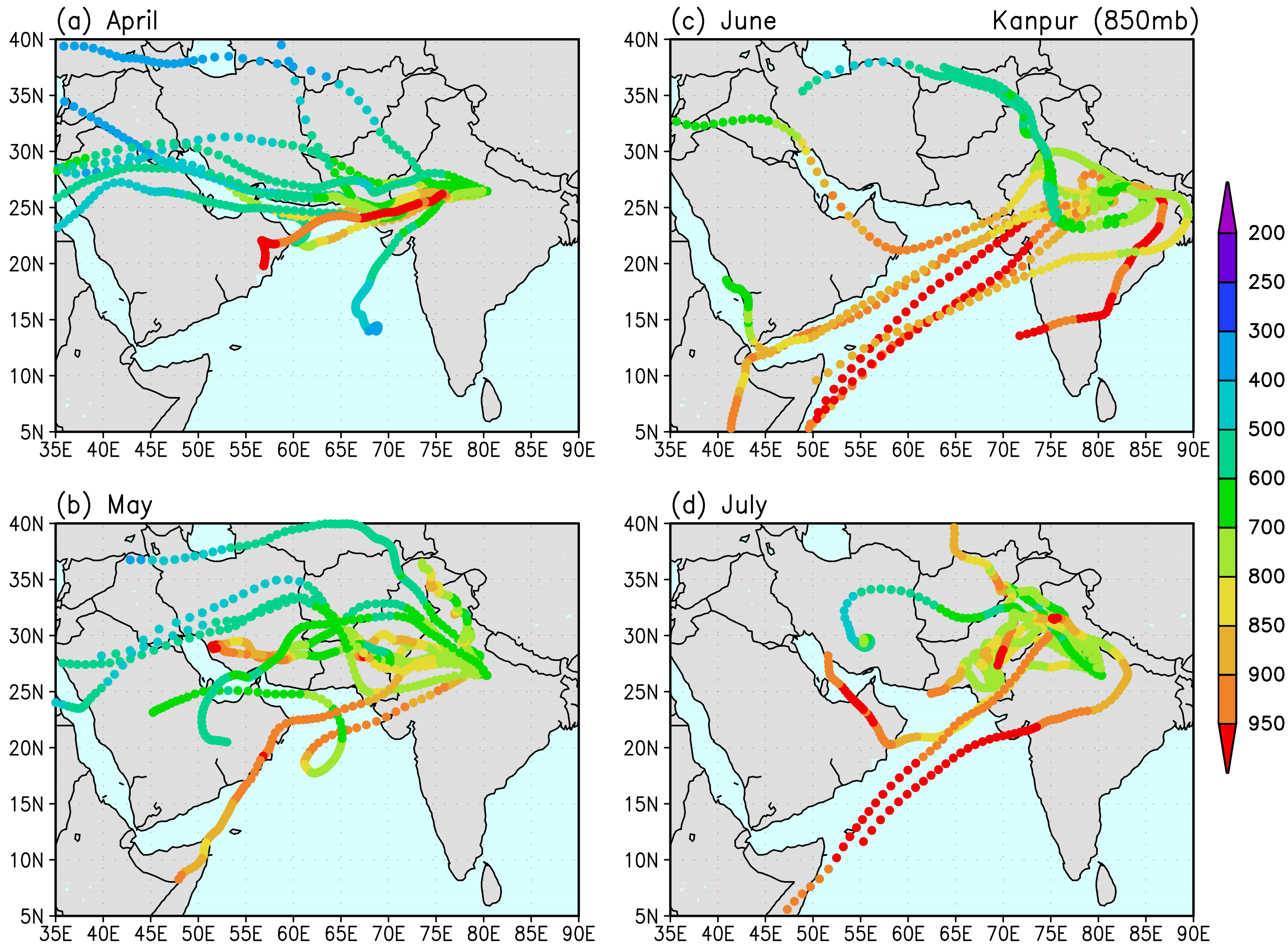


April
May
June
60° E
70° E
80° E
90° E
100° E
40° N
30° N
20° N
10° N
0°
1.2
1
0.8
0.6
0.4
0.2



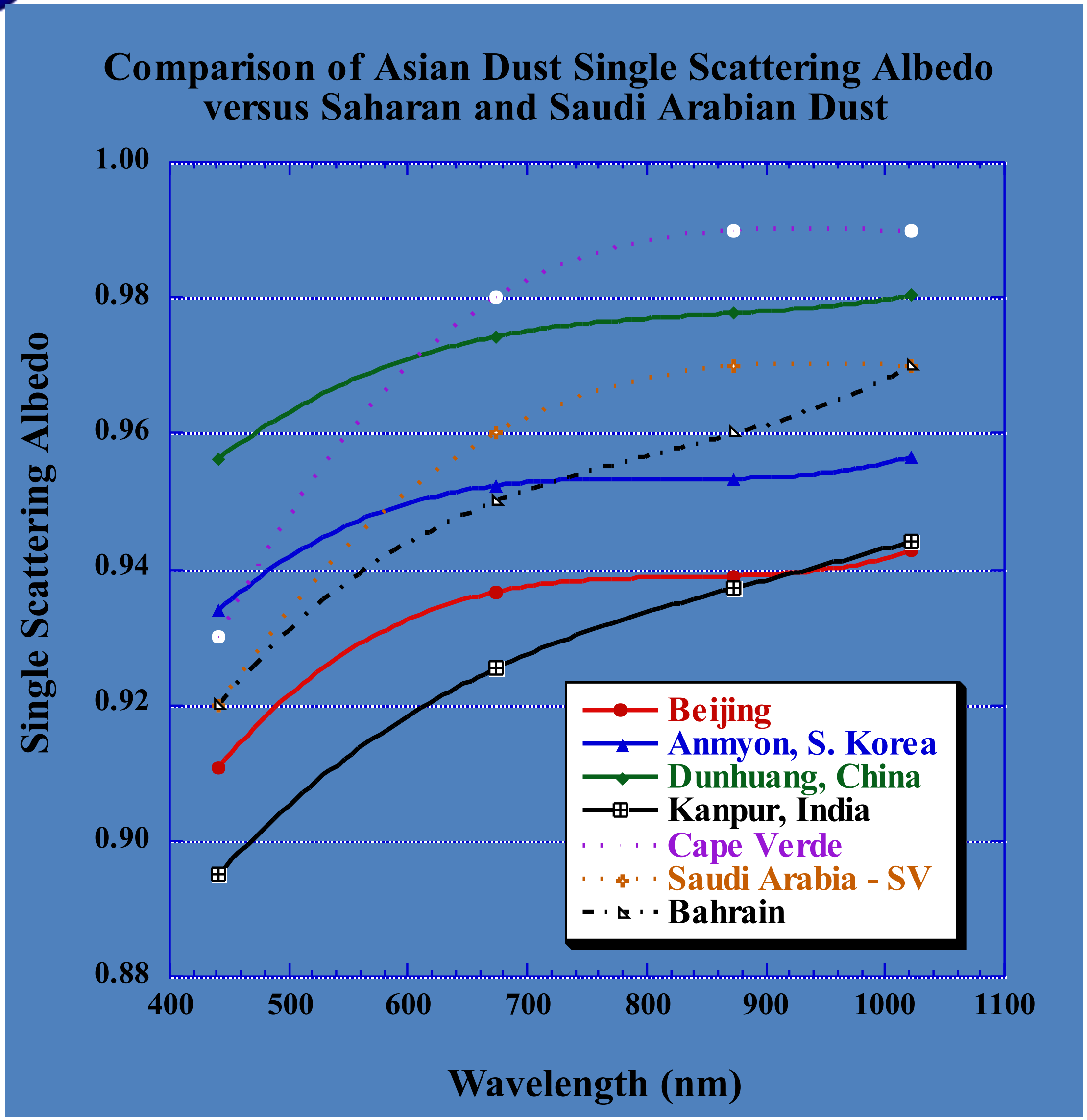
Altitude, km
30
25
20
15
10
5
0
31.48
78.89
25.40
77.34
19.30
75.89
13.19
74.52
7.12
73.21
1.0x10-1
1.0x10-2
1.0x10-3
1.0x10-4

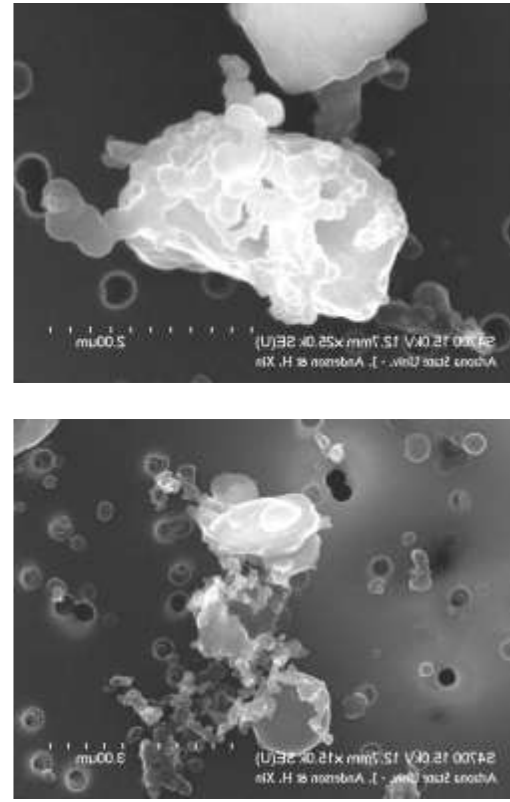
11-day Back Trajectories for 850hPa airmass at Kanpur, India , 2008



How absorbing are dust aerosols ?

More absorbing



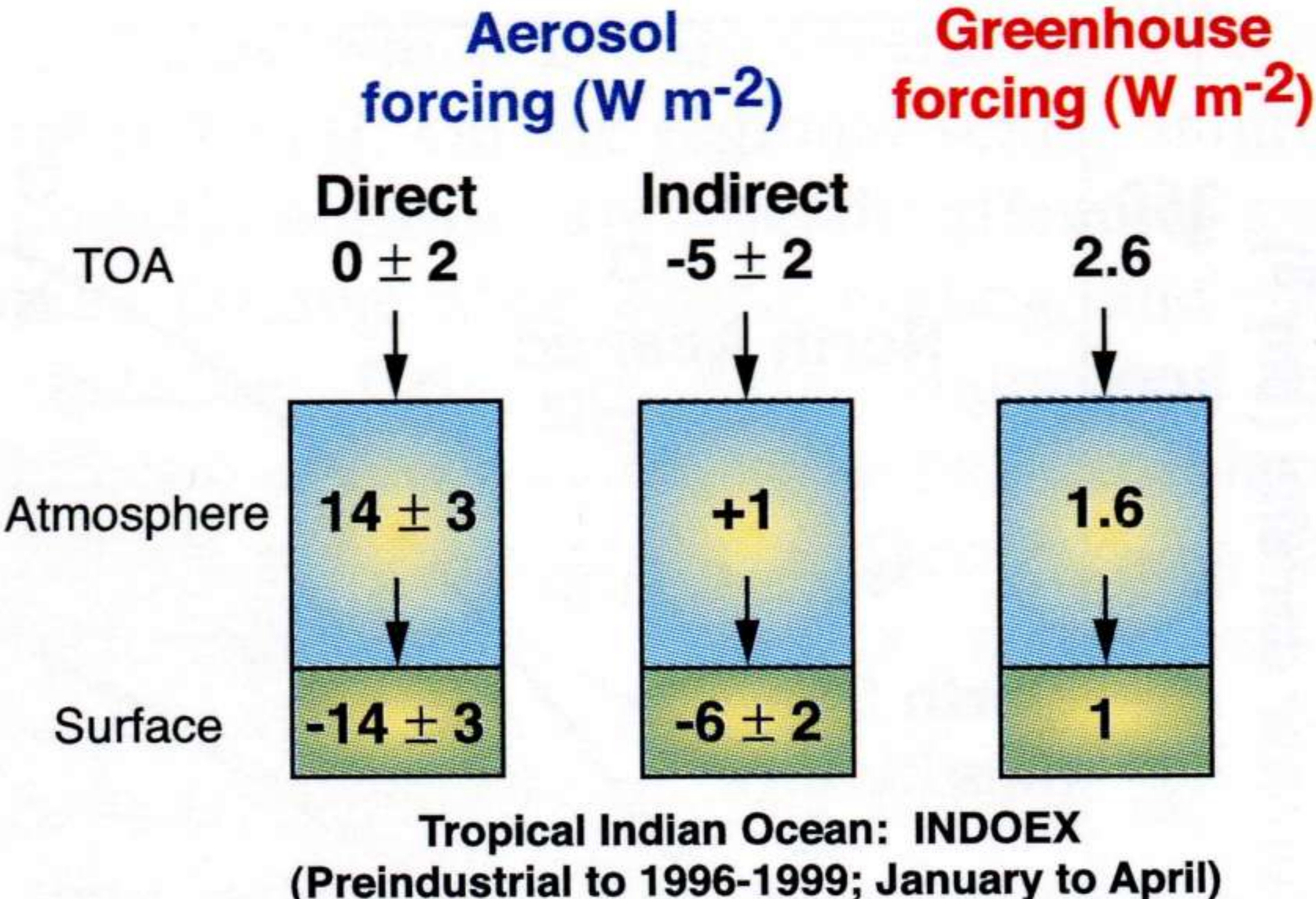


Micrographs of
soot coating and aggregate
on mineral dust from Asian d
ust (courtesy of J. Anderson)

Dusts over major industrial cities are more absorbing (solar radiation)

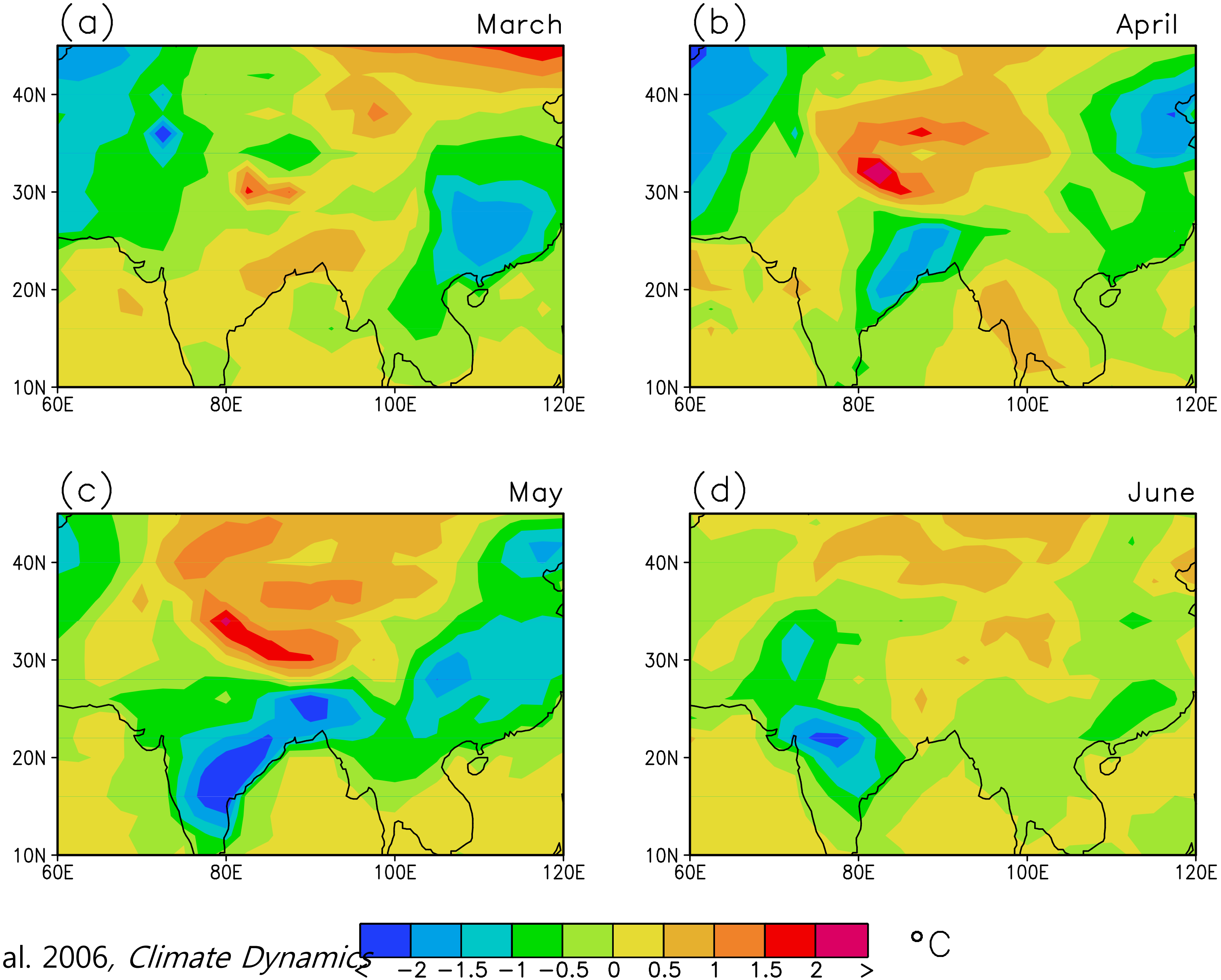
T. Eck et al 2004

ABCs and GHGs: Impact on Regional Radiation Budget



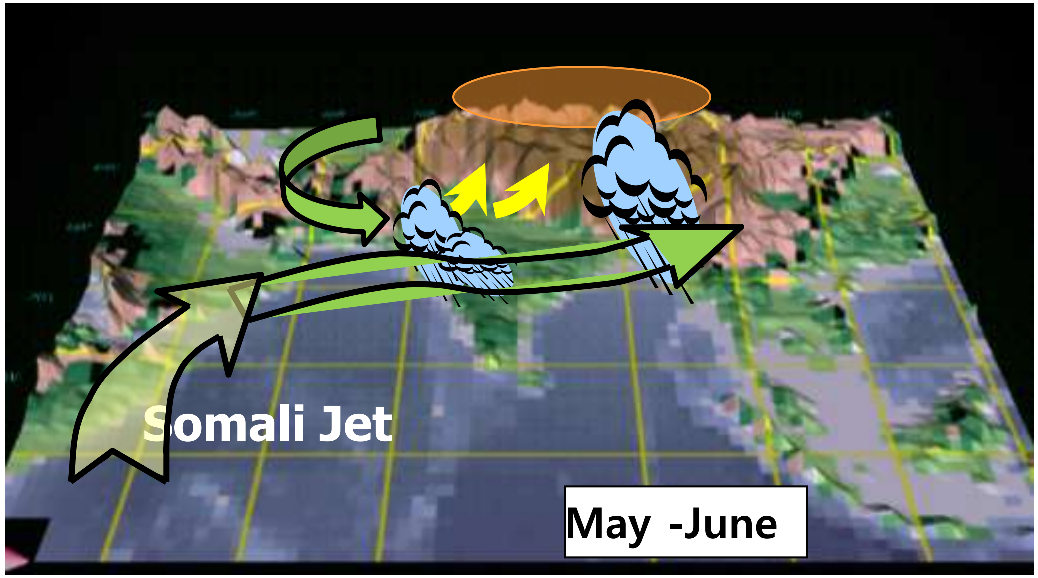
Ramanathan et al, Science 2001

Aerosol-induced anomalies of surface air temperature in NASA fvGCM

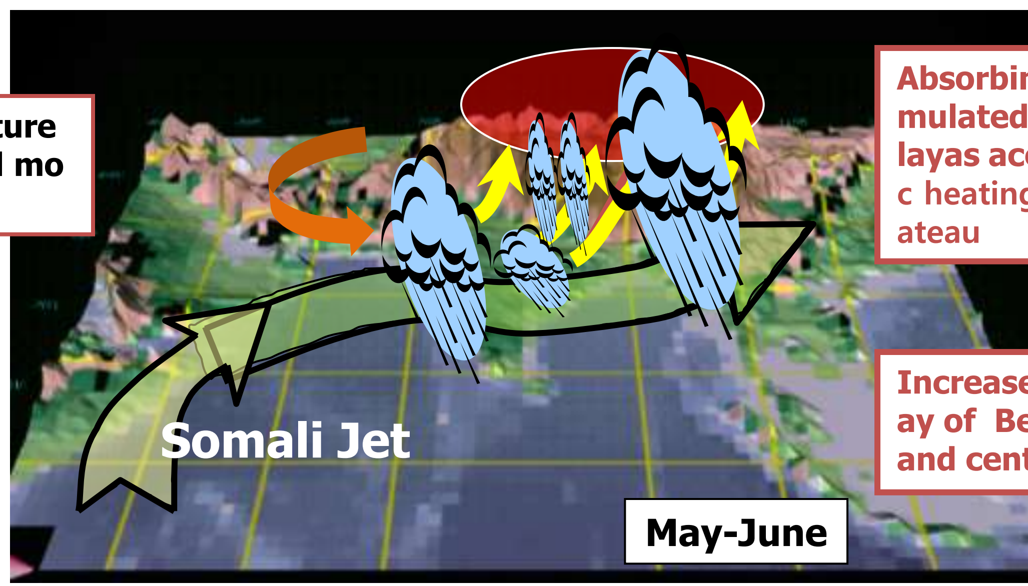


Lau et al. 2006, *Climate Dynamics*

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



Increase dust and moisture transport from low level mo nsoon westerlies

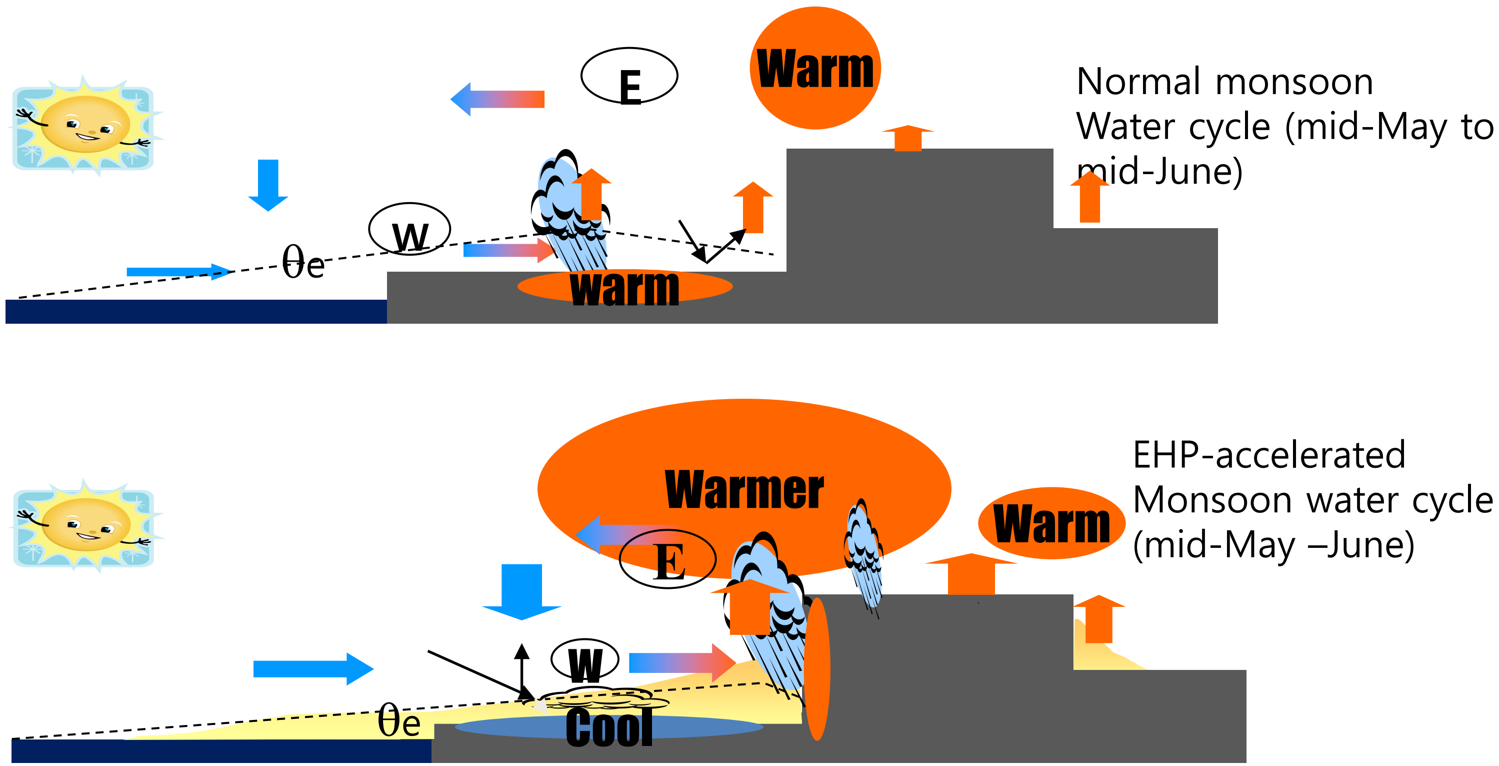


Absorbing dust and BC accu mulated on foothills of Hima layas accentuate atmospheri c heating over the Tibetan Pl ateau

Increased convection over B ay of Bengal, eastern TP,NE and central India

The Elevated Heat Pump (EHP) hypothesis

(Lau et al. 2006, Lau and Kim 2006, Lau et al 2008)



EHP postulates:

a) Warming and moistening of the upper troposphere over the Tibetan Plateau

b) An advance of the rainy season in northern India/Napal region in May-June

c) The increased convection spreads from the foothills of the Himalayas to central India, resulting in an intensification of the Indian monsoon. in June-July

d) Subsequent reduction of monsoon rain in central India in July-August

e) Enhanced snowmelt and rapid retreat of mountain glacier

Climate Change is a "clear and present" danger in high mountain regions:

Accelerated melting of Himalaya-Tibetan Plateau glacier will endanger the water supply of the entire Asia

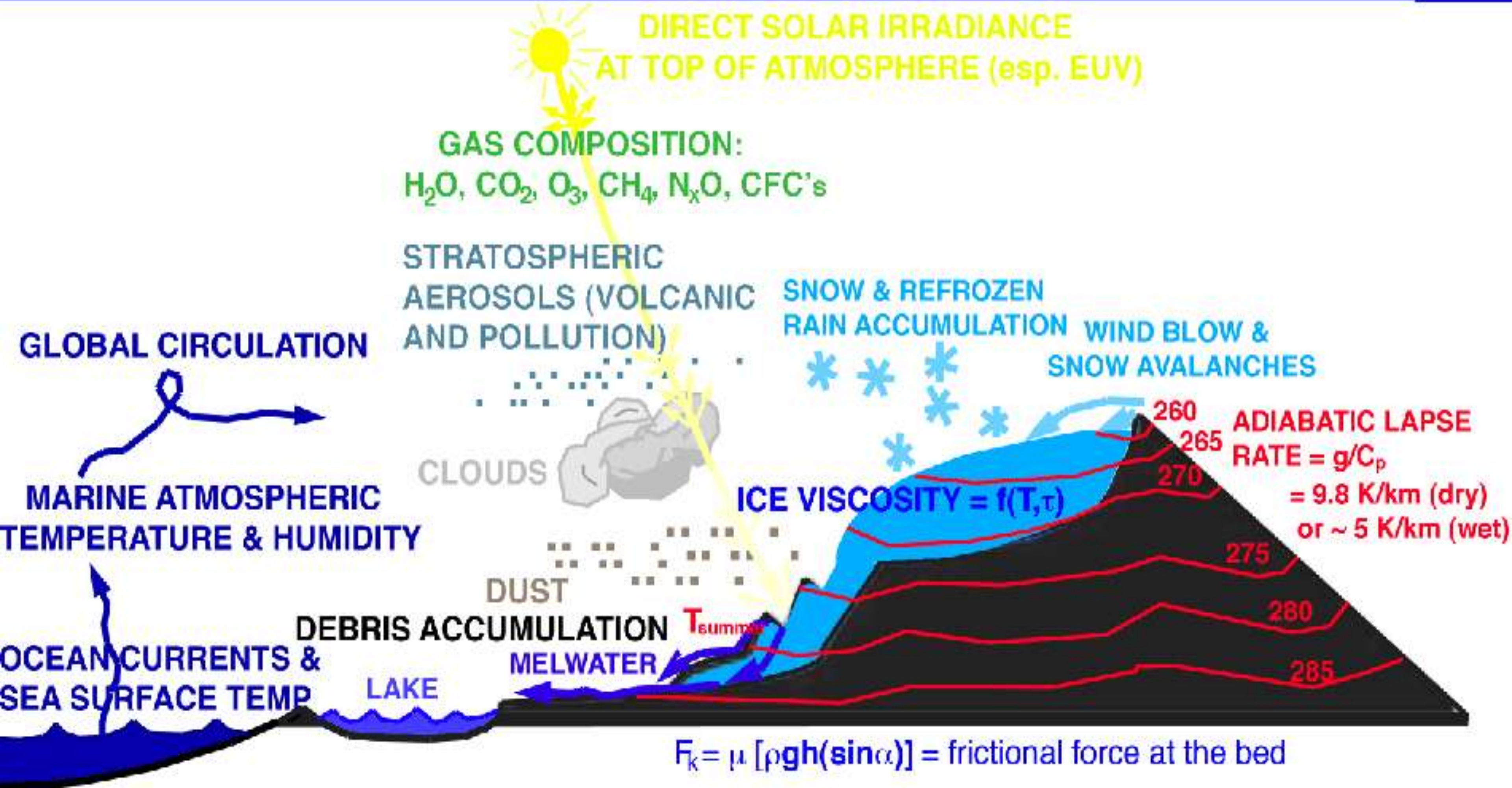
The Himalaya-Tibetan Plateau Glaciers feed seven of Asia's great rivers: the Ganga, Indus, Bramaputra, Salween, Mekong, Yangtze, and Yellow River that supply fresh water for over 60% of the world population

Accelerated melting of Himalaya-Tibetan Plateau glacier will endanger the water supply of the entire Asia!

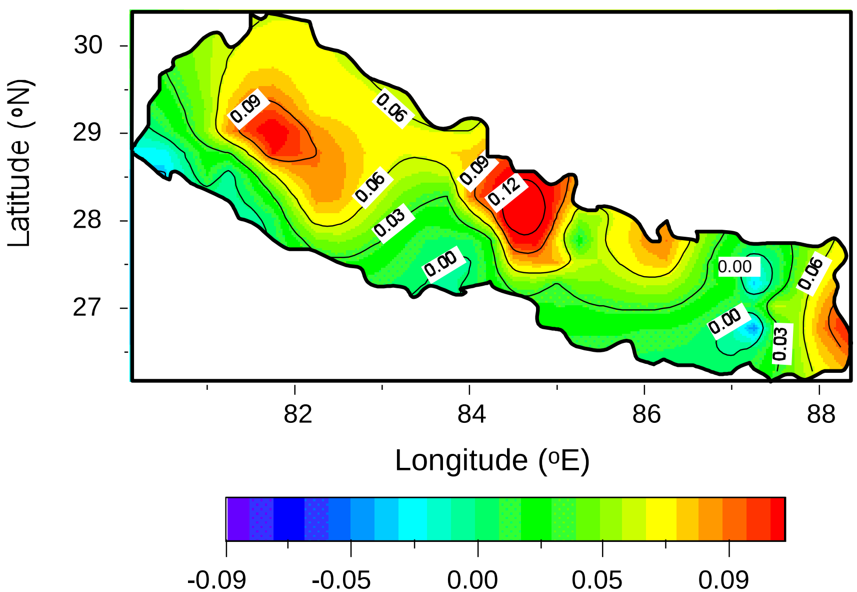
The Himalaya-Tibetan Plateau Glaciers feed seven of Asia's great rivers: the Ganga, Indus, Bramaputra, Salween, Mekong, Yangtze, and Yellow River that supply fresh water to many countries in Asia.

Courtesy: Jeff Kargel

Climate and environmental change related to glaciers is more than about rising temperatures



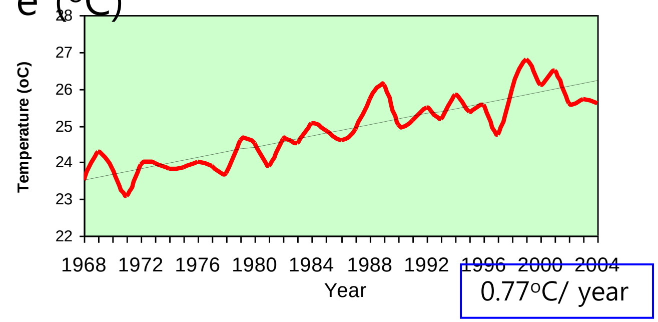
Spatial Distribution of maximum temperature trends in Nepal for the period 1977 to 1994.

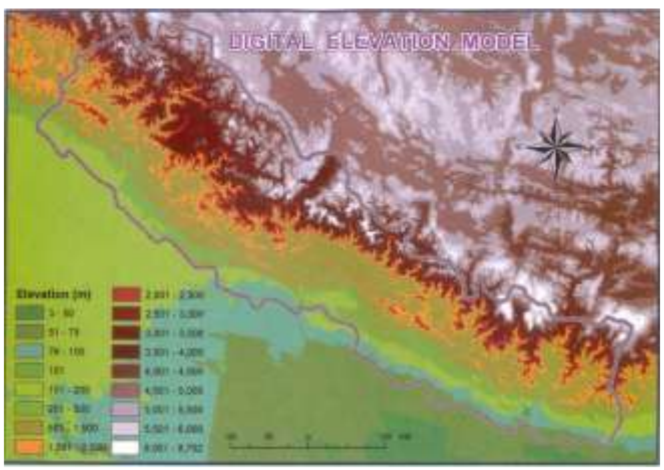


Color Coding of temperature trends

(oC year^{-1})

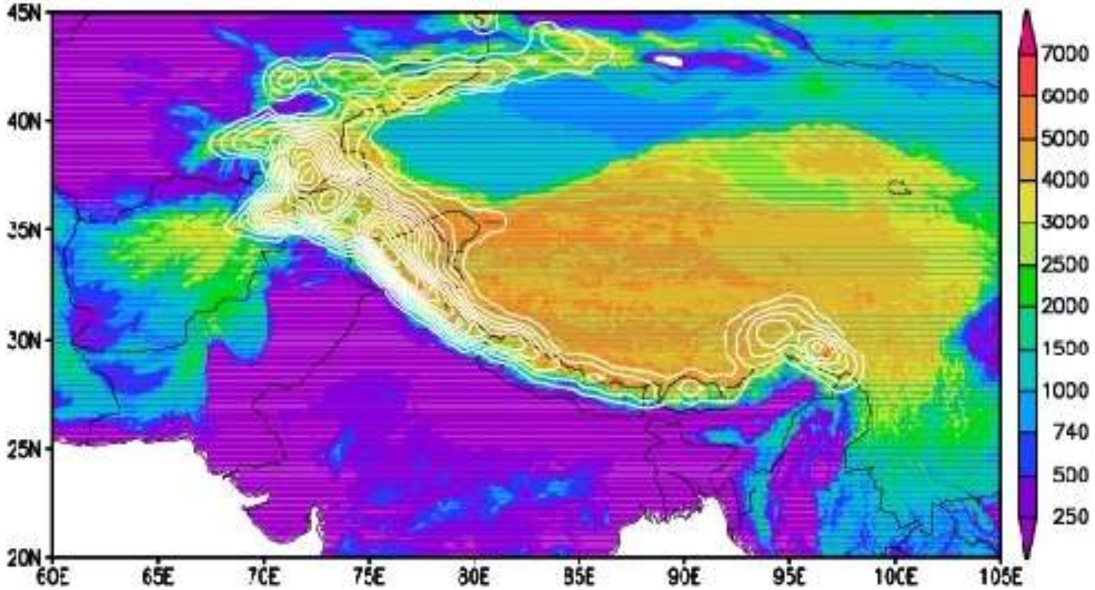
Kathmandu Maximum Temperature (oC)





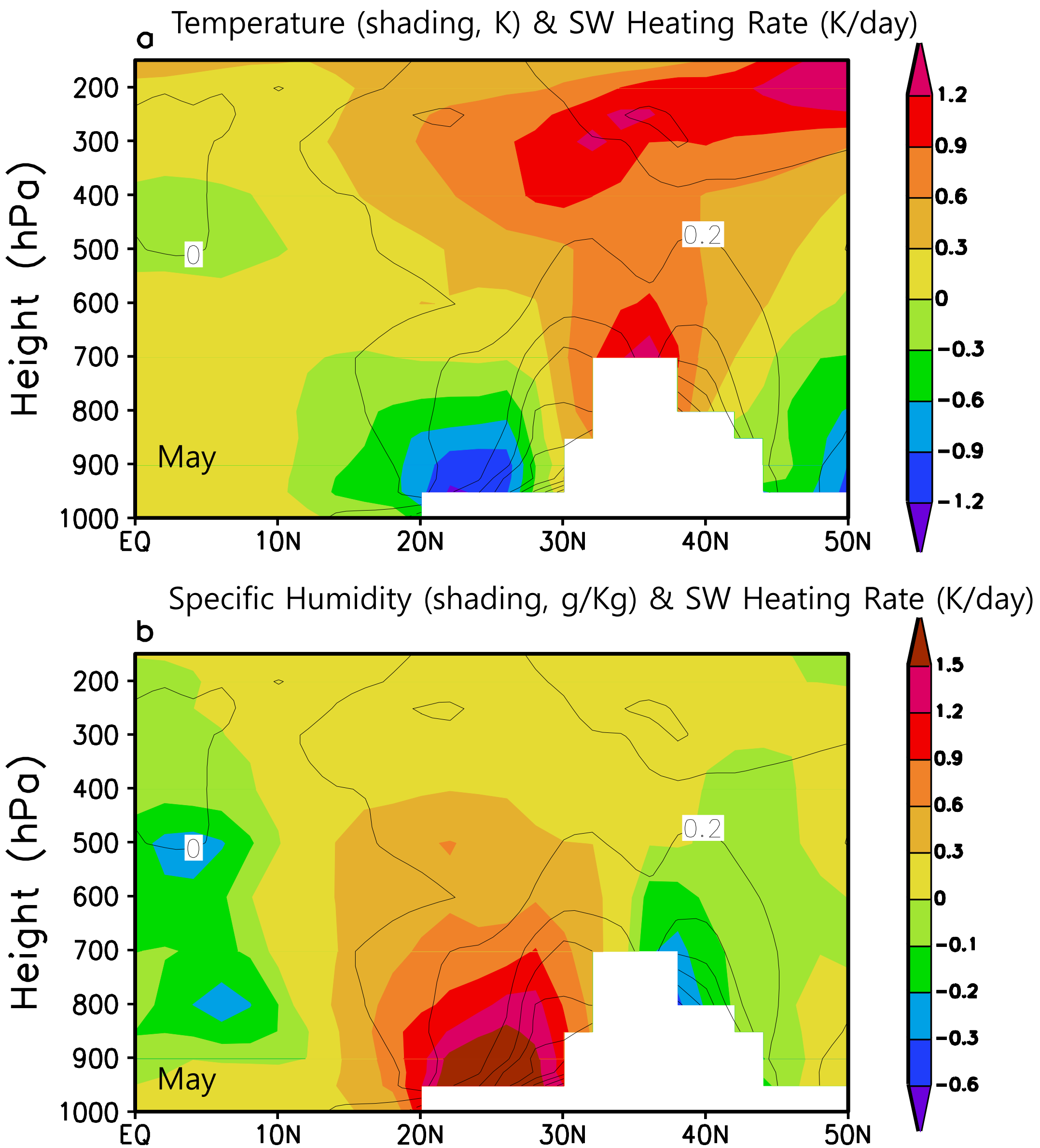
Courtesy of Dr. Madan Shrestha, DG, Met. Service, Nepal

Possible causes of accelerated melting of snowpack in the Himalayas and Tibetan Plateau

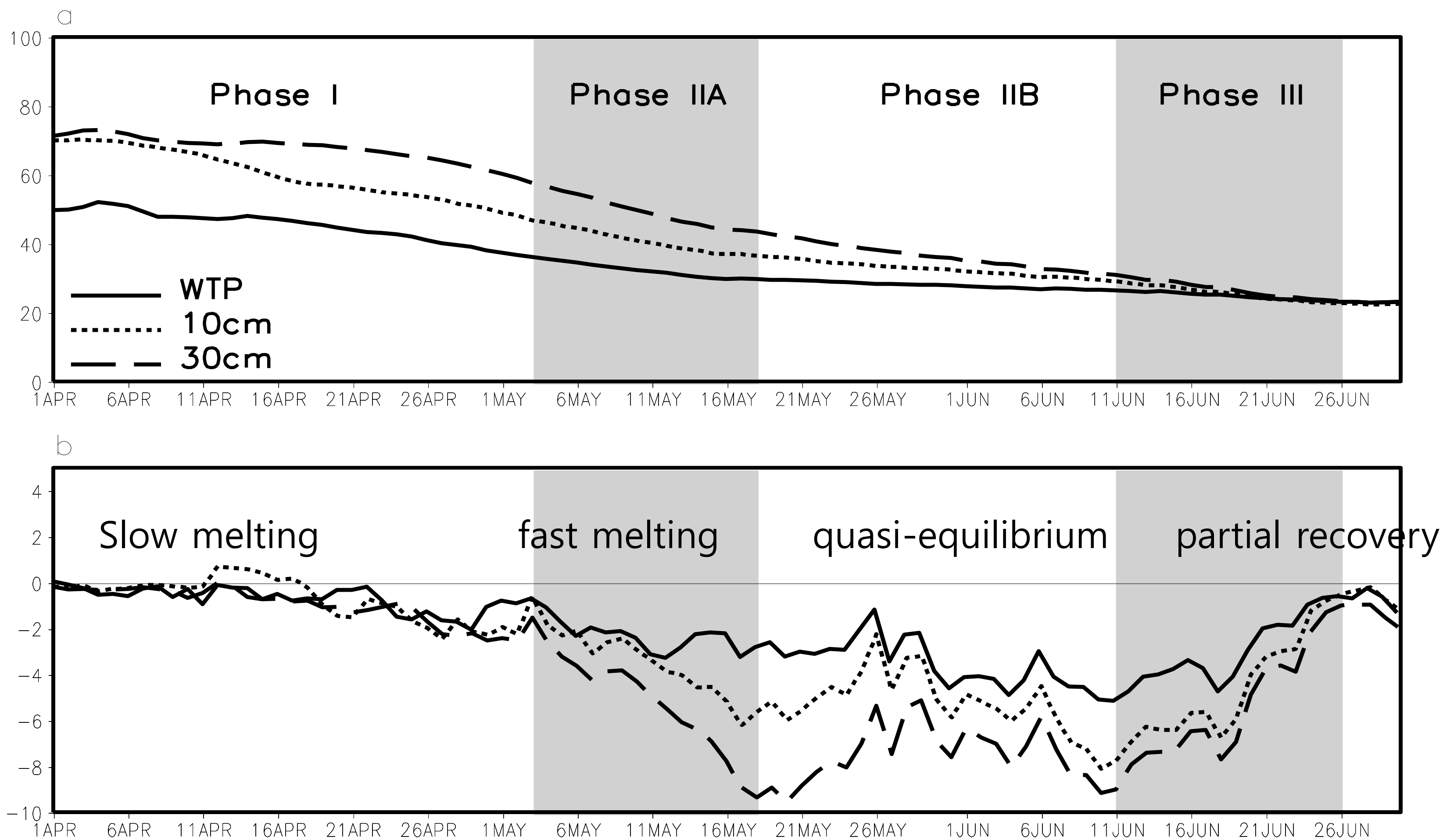


- Greenhouse Warming
- Atmospheric heating due to aerosols (EHP)
- Snow-darkening effect from soot and dust, and other impurities

EHP induced heating and moistening along 80°E



Relative percentage change of surface albedo (due to changes in snow-cover, and exposure of underlying land surface) from NASA climate model



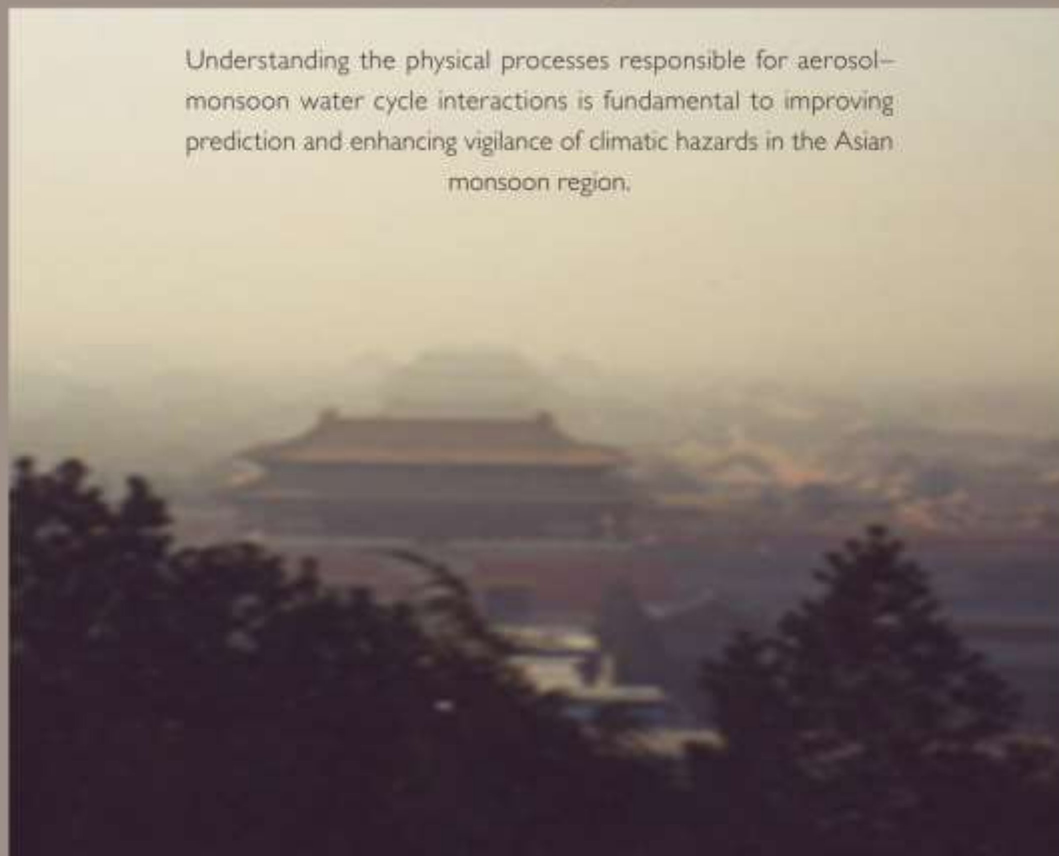
Bull. Am. Meteor. Soc., 2008

THE JOINT AEROSOL–MONSOON EXPERIMENT

A New Challenge for Monsoon Climate Research

BY K.-M. LAU, V. RAMANATHAN, G.-X. WU, Z. LI, S. C. TSAY, C. HSU, R. SIKKA, B. HOLBEN, D. LU, G. TARTARI, M. CHIN, P. KOUDELOVA, H. CHEN, Y. MA, J. HUANG, K. TANIGUCHI, AND R. ZHANG

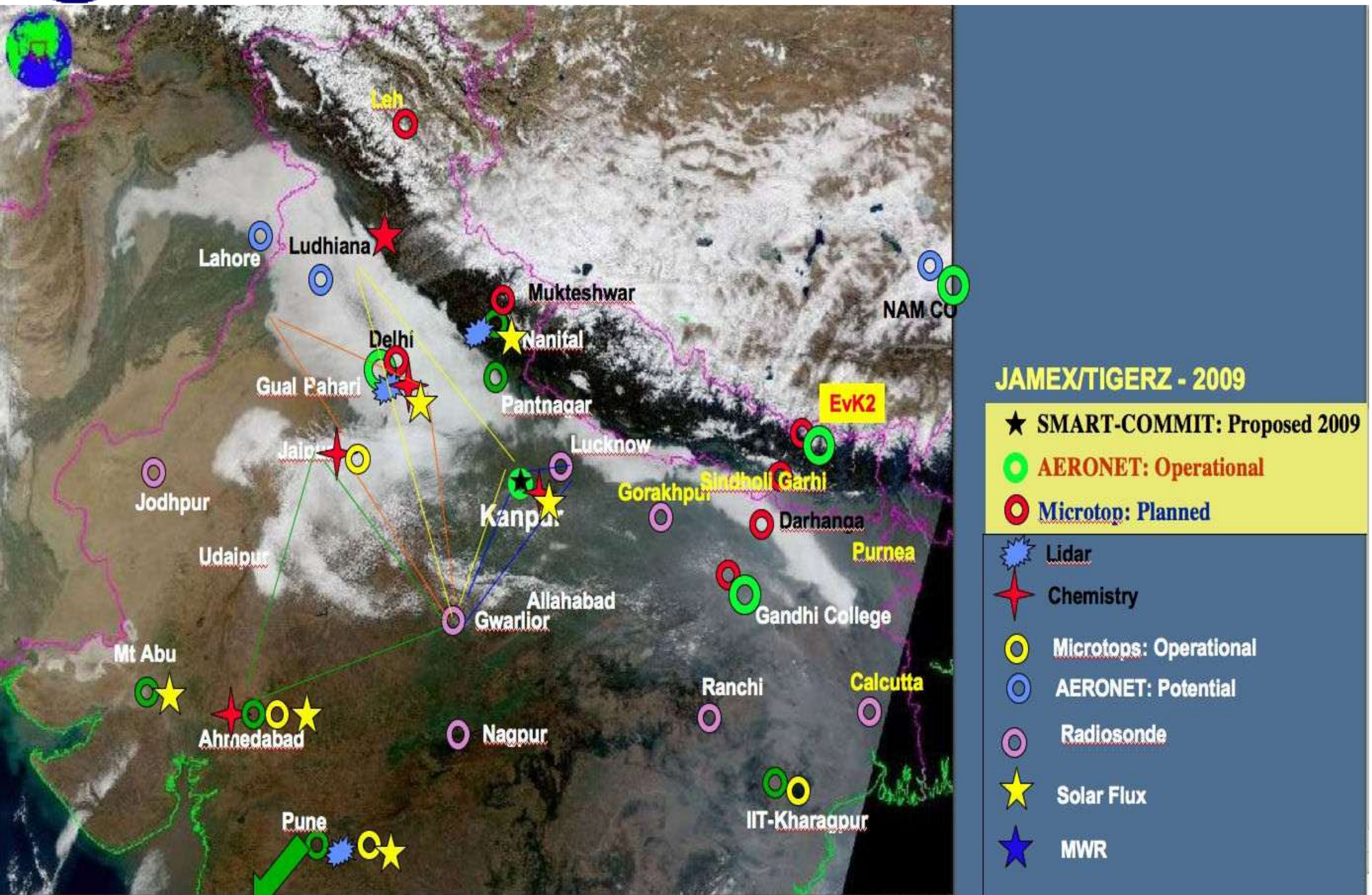
Understanding the physical processes responsible for aerosol–monsoon water cycle interactions is fundamental to improving prediction and enhancing vigilance of climatic hazards in the Asian monsoon region.



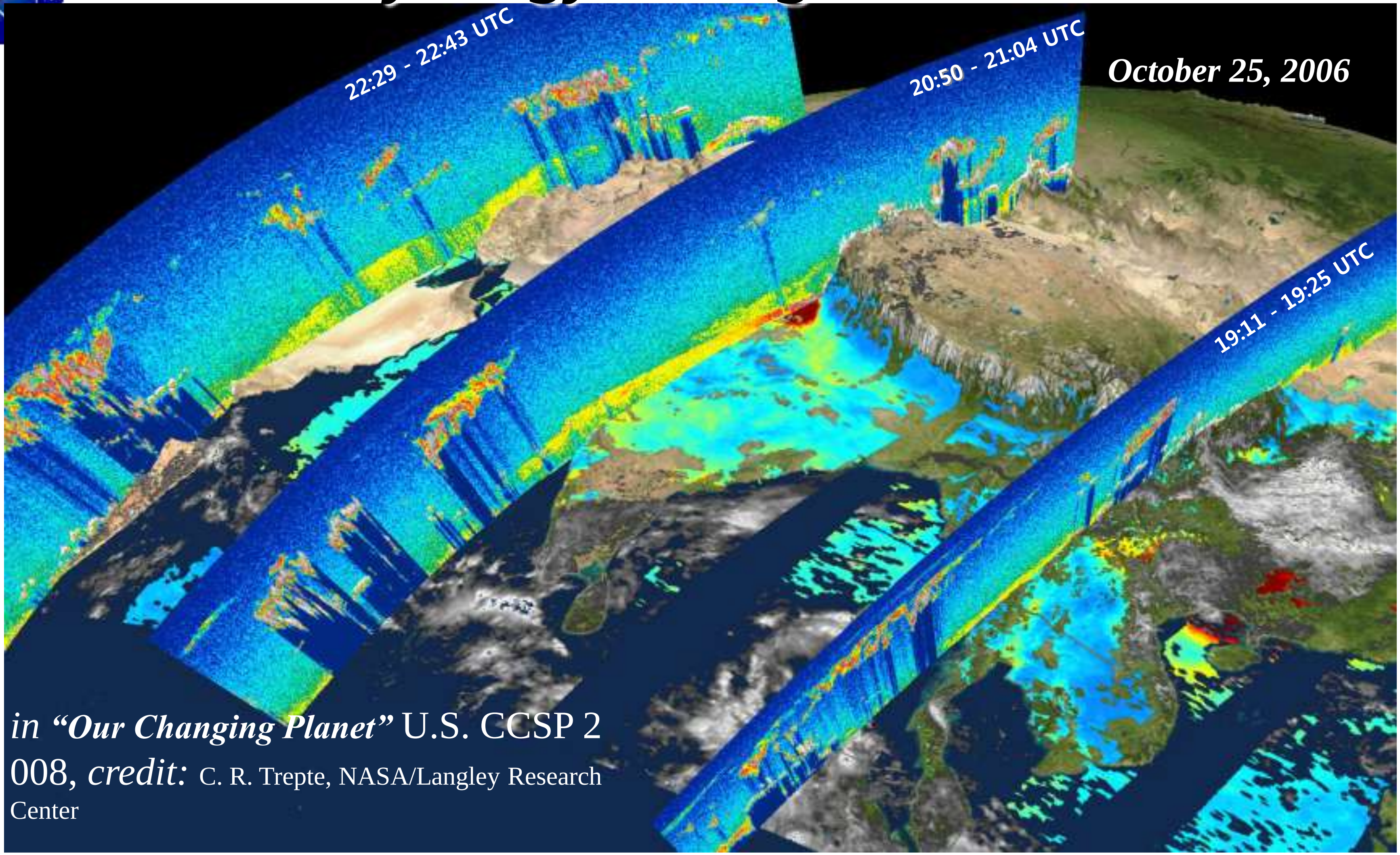
Smoke consisting of mixtures of dust and industrial pollution covering the Forbidden City, Beijing, China.

Air pollution and monsoon floods and droughts are

have found that anthropogenic aerosols may signifi-


Leh
Lahore
Ludhiana
Mukteshwar
Nanital
Delhi
Gual Pahari
Pantnagar
Jaipur
Lucknow
Jodhpur
Kanpur
Gorakhpur
Sindholi Garhi
Darhanga
Purnea
EvK2
NAM CO
Udaipur
Allahabad
Gwarlior
Gandhi College
Mt Abu
Ahmedabad
Nagpur
Ranchi
Calcutta
IIT-Kharagpur
Pune
JAMEX/TIGERZ - 2009
SMART-COMMIT: Proposed 2009
AERONET: Operational
Microtop: Planned
Lidar
Chemistry
Microtops: Operational
AERONET: Potential
Radiosonde
Solar Flux
MWR

Synergy: Imager + Lidar



- **Lau *et al*., 2008, *Bull. Amer. Meteor. Soc*., 8, 9, doi:10.1175/BAMS-89-3-369.**
- A ***three-dimensional*** perspective of aerosol/cloud distributions
- Enhance study of ***Elevated-Heat-Pump*** and ***aerosol-cloud-glacier*** interaction

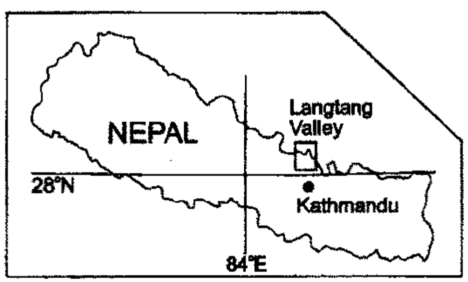
The highest aerosol observatory, NCO-P (ABC-Pyramid): the southern slope of the Himalayas (5079 m a.s.l.)

Meteorological parameters, Optical Particle Counter (OPC; 0.25-32 μm), Scanning Mobility Particle Sizer (SMPS; 10.31-669.8 nm), and equivalent Black Carbon concentration (MAAP) data in 2006 at NCO-P site were observed (Bonasoni et al., 2008) and used in this study.

Estimated "lower limit" of effect of BC deposition in darkening Himalayan glaciers

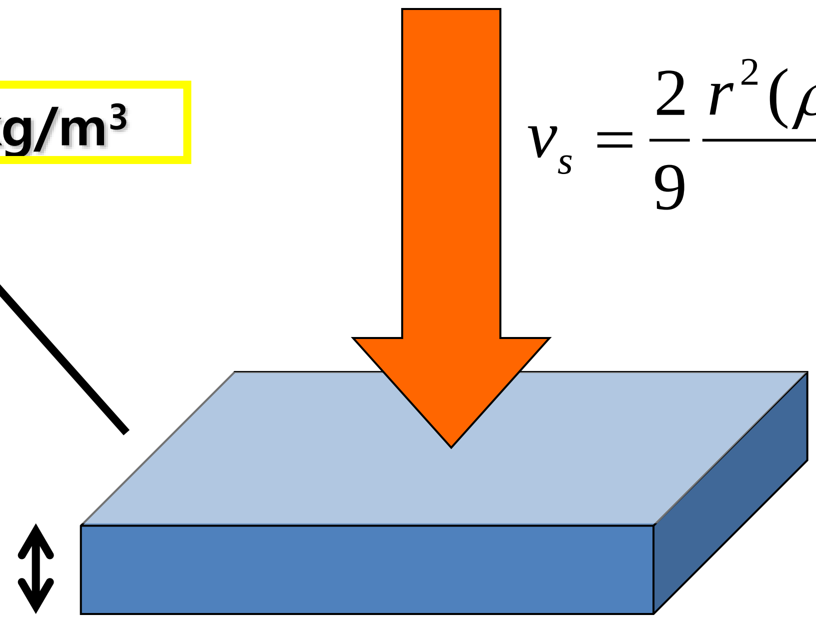
BC deposition of **209** μg/m^2 by dry fallout during March-May in 2006 (2.27 μg m^{-2} day^{-1})

Surface snow density at Yala glacier:195 to 512 kg/m^3 (Fujita et al., 1998)



$$v_s = \frac{2}{9}\frac{r^2(\rho_{BC} - \rho_{Air})g}{\eta}$$

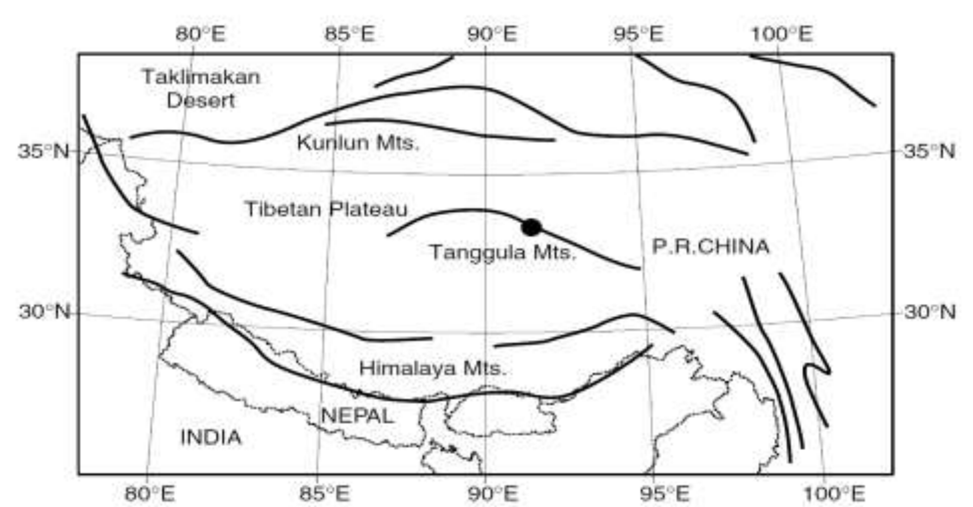
2cm surface snow



Now, imagine that we take snow samples from 2cm surface snow layer. At thi s time, we assume slight BC layer on the pure ice with no contamination.

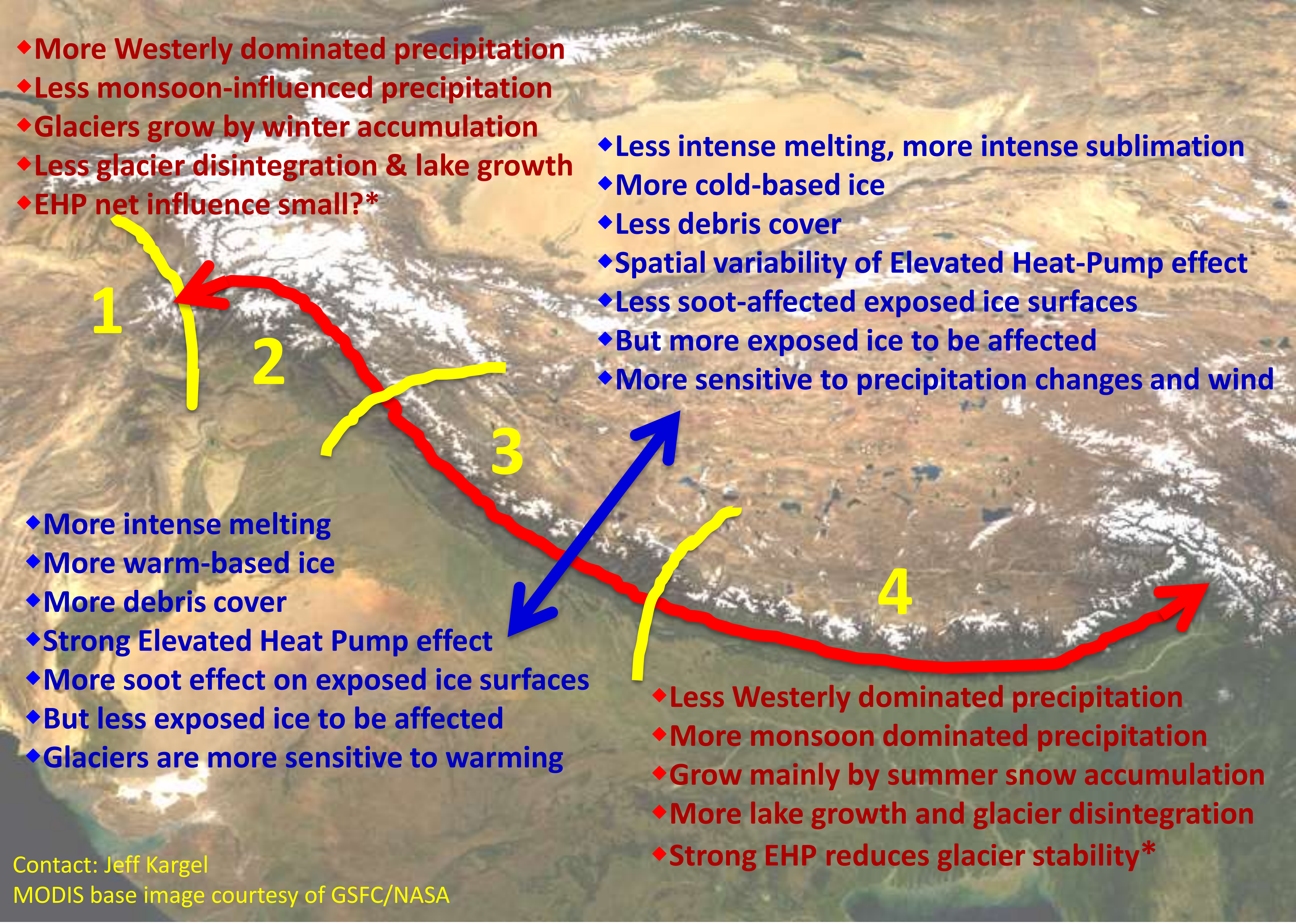
Estimation of additional annual runoff fro m snow-darkening effect

Figure 3. Photograph of the Da (left) and Xiao (right) Dongkemadi Glaciers



•Using a glacier mass balance model (Fujita, 2007, Fujita et al., 2007). with the same input data as used in previous studies

• Over a typical Tibetan glacier (Dongkemadi glacier), continuous albedo reductions of 1.6 & 4.1% may increase by 9.0-24.8% the annual run off from discharge of melted snow



•Glacier behavior varies across the region, with faster retreat in the east. Possibly glaciers in northwest pick up more snow precipitation due to Elevated Heat Pump (EHP) an d other climate mechanisms thus partly offsetting heating/melting. Glaciers in the eastern Himalaya may be more sensitive to EHP heating and are melting more quickly.

Thoughts on Mitigation/Adaptation Strategy

1) CO_2 has long-life time of centuries or longer; effects are long-term
Doing nothing now, will cost us more later.

2) The observed global rise in temperature is likely a delayed response to industrialization years past; even if we stablize CO_2, warming will continue for more than a century.

3) Regionally, climate change science is still unfolding. Asia is potentially the most vulnerable region: aerosol, monsoon floods/drought, high-mountain glaciers; fresh water supply ….

4) In Asia, availability of fresh water is a "clear and present danger" and is likely to get worse if nothing is done. Mitigation or adaptation strategy should be focused on alleviating hazards and potential conflicts arising from fresh water shortage

5) Politically, it would be wise to take actions that can produce benefits in the near term, i.e., reduce BC emission, and deal with short-lived GHG's first, e.g. CH_4, O_3, Nox.

6) Geo Engineering, e.g. injecting sulphate in lower strastosphere…..
Don't go there. *Beware of the "Law of Unintended Consequences" !*

NASA climate model simulation of accumulation of soot over the Indo-Gangetic Plain

Video Link

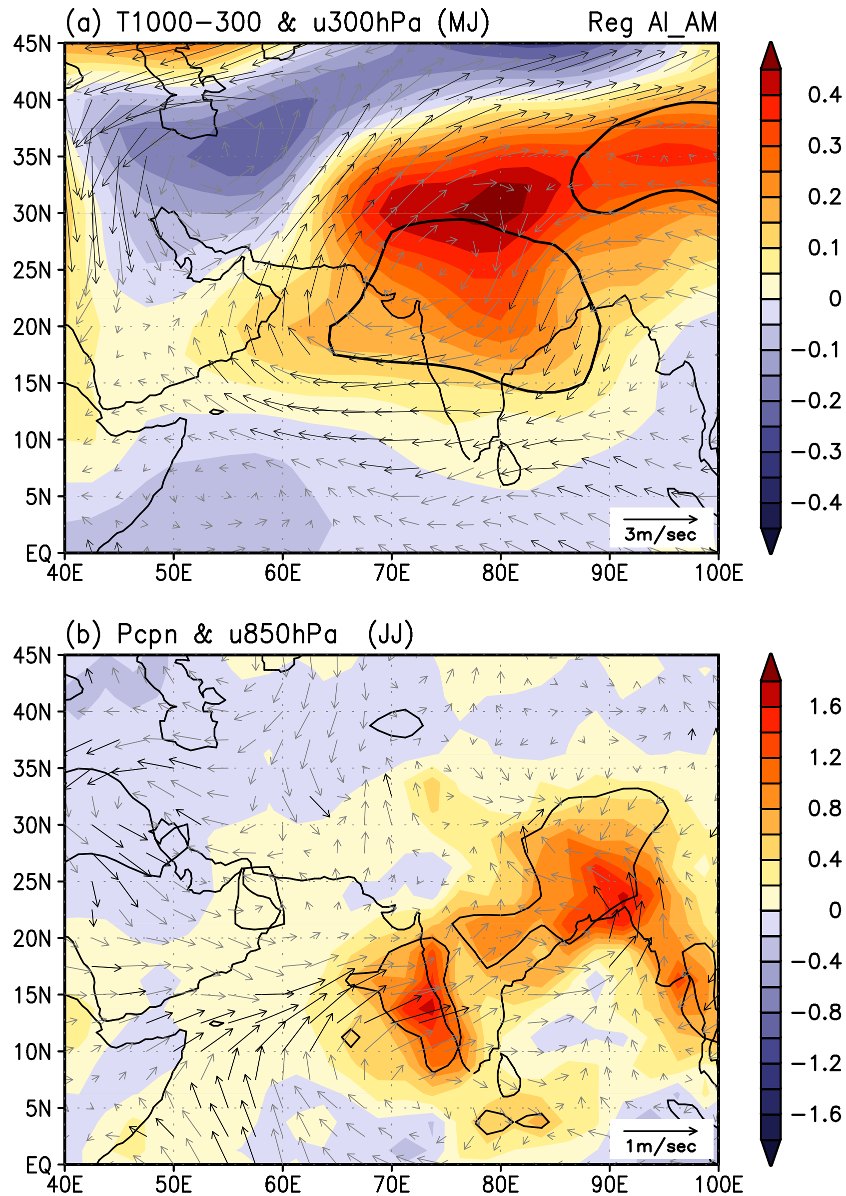
Back Up

Characteristic EHP large scale pattern from observations :

Enhanced tropospheric warming over the Tibetan Plateau and increased monsoon rainfall and winds in June-July, following major build-up of absorbing aerosol (dust and BC) over the Indo-Gangetic Plain in April-May

Data source: TOMS AI, GPCP, and NCEP re-analyses

Lau and Kim (2006, *GRL)*

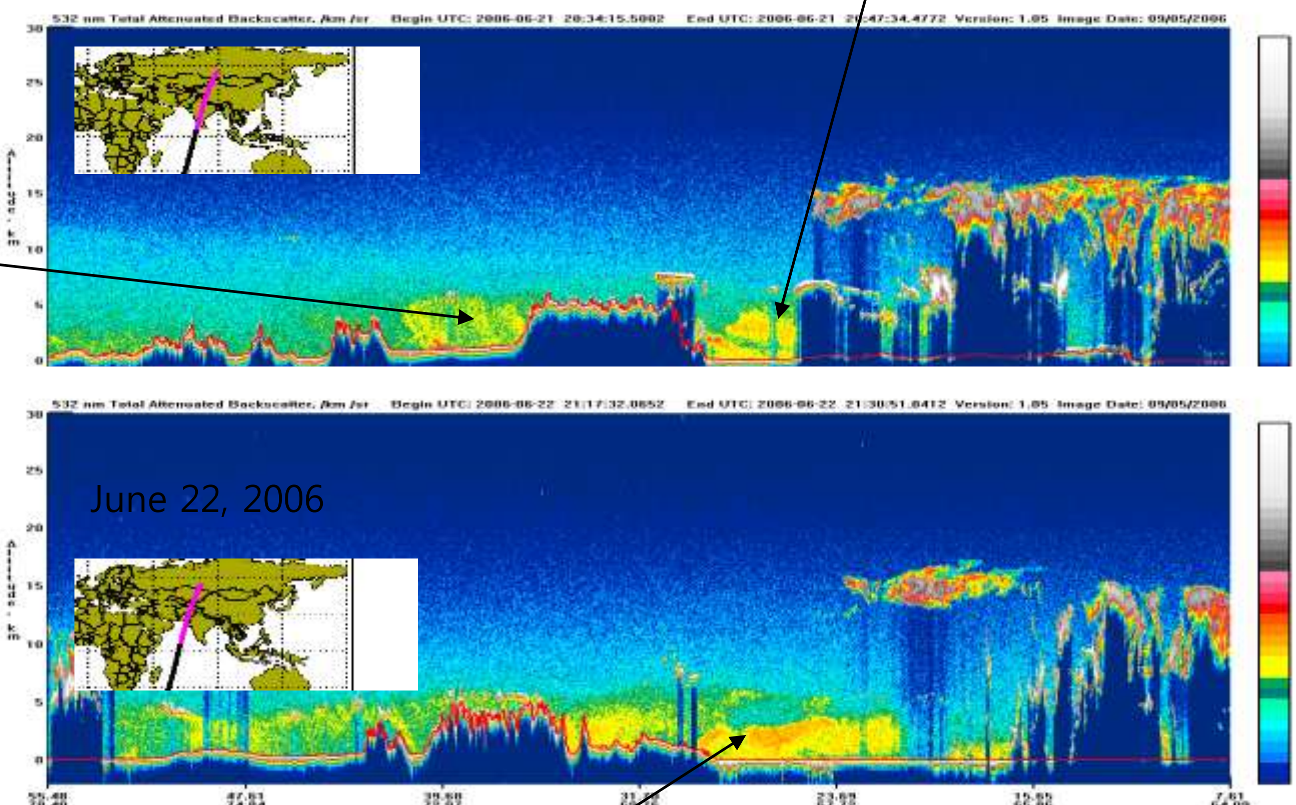


Merdional cross-section of aerosol concentration from Calipso

June 21,2006

Indo-Gangetic Basin

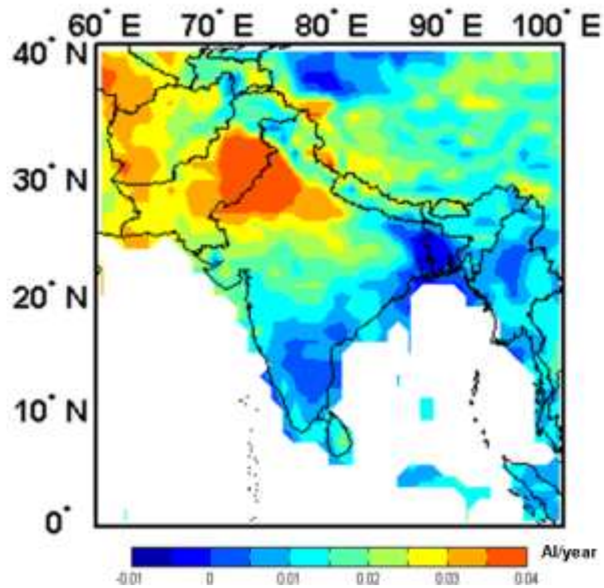
Taklamakan Desert



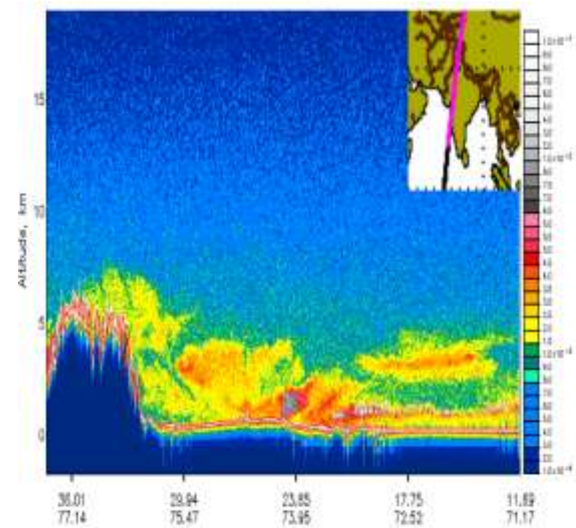
northeastern IGB

Reference"
Lau, K.-M., K.-M. Kim (2008), Absorbing aerosols enhance Indian summer monsoon rainfall. iLEAPS Newsletter, No. 5, 22-24.

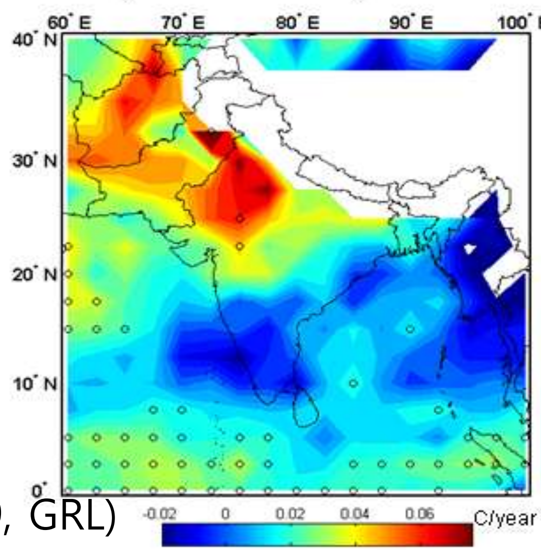
TOMS AI trend for May (1979-2001)



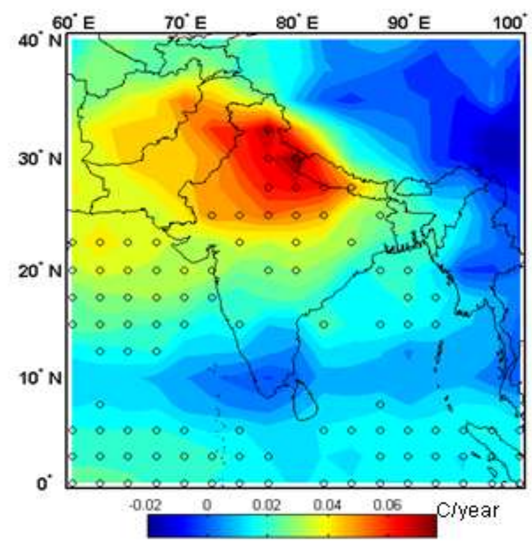
Aerosol profile from Calipso



Lower-Tropospheric Temperature (surface-4 km) Trend



Mid-Tropospheric Temperature (4-7 km) Trend



Gautam et al (2009, GRL)

Photo Gallery

Tibetan Plateau

National Geographic

Published: April 2010

Tibetan Plateau

Glaciers that feed great Asian rivers are shrinking. See photographs by Jonas Bendiksen.

Video

Behind the Photo

Sometimes called the Third Pole, the region is a lockbox of snow and glacial ice that supplies fresh water to nearly a third of the world's people.

Interactive

Freshwater 101

We live on a planet covered by water, but how much is freshwater?

The Big Melt

Glaciers in the high heart of Asia feed its greatest rivers, lifelines for two billion people. Now the ice and snow are diminishing.

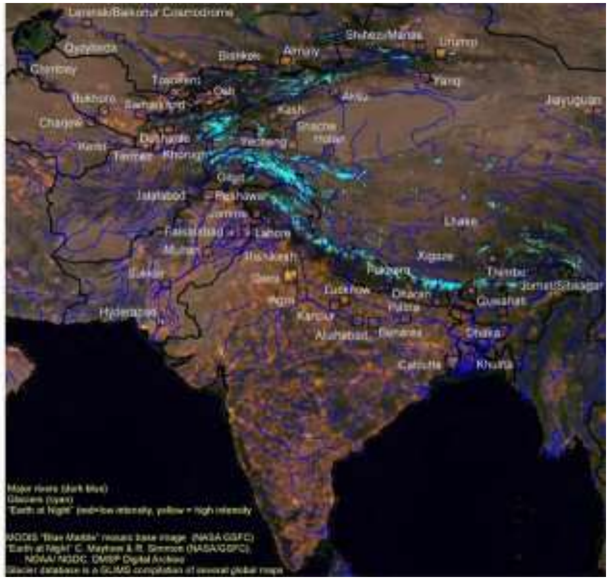
By Brook Larmer
Photograph by Jonas Bendiksen

The gods must be furious.

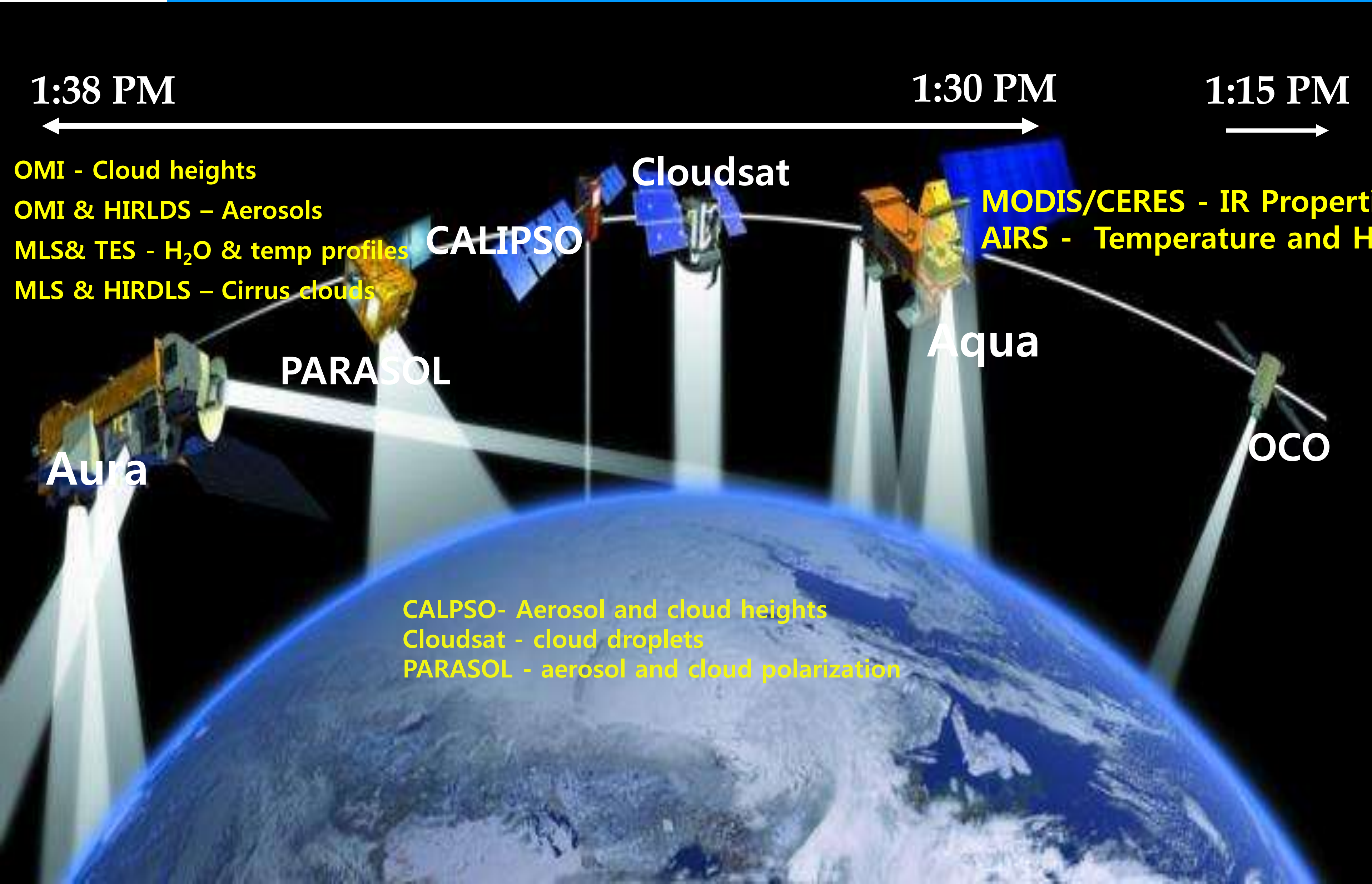
It's the only explanation that makes sense to Jia Son, a Tibetan farmer surveying the catastrophe unfolding above his village in China's mountainous Yunnan Province. "We've upset the natural order," the devout, 52-year-old Buddhist says. "And now the gods are punishing us."

Large-scale finger-prints of the "Elevated Heat Pump" effects on monsoon climate

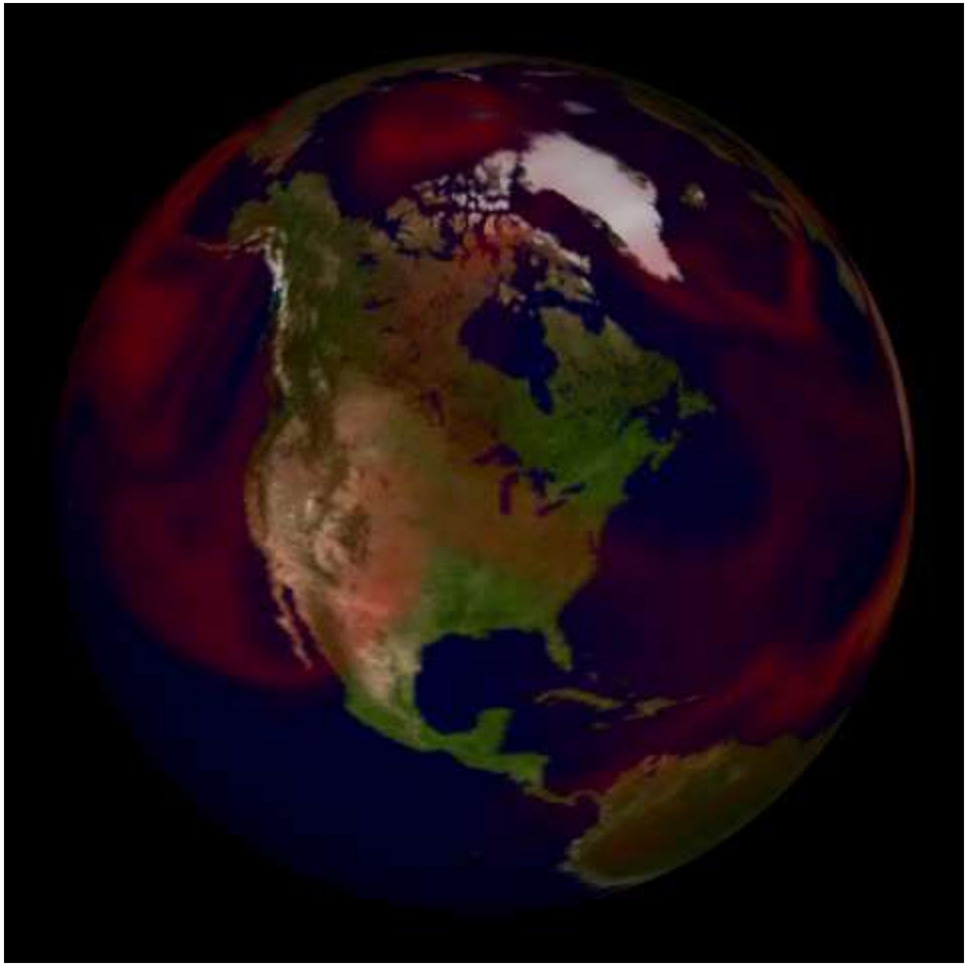
- Upper tropospheric anticyclone associated with warming over Himalayas foothills and Tibetan Plateau in late spring
- Advance of monsoon rainy season, more rain in Nepal and northeast India region in late spring and early summer; strengthening Indian monsoon in early monsoon season and weakening it in peak and late season.
- Weakening of the East Asian monsoon (Mei-yu rainfall), large scale dynamical adjustment to TP EHP heating, solar dimming and semi-direct effect-→ associated with a westward shift of the West Pacific subtropical high
- EHP →accelerated melting of mountain glacier→ expose land surface →surface warming → increased sensible heat flux → increased EHP;
- Deposition of dust and BC darken Himalayas accelerating glacier/snow melt



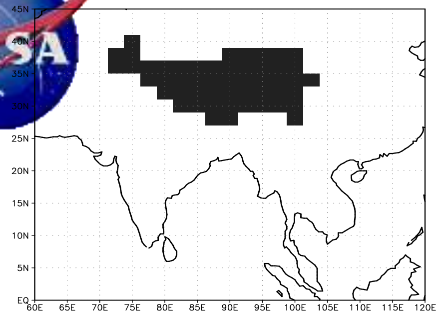
Afternoon Constellation of the "A-Train"



We need High-Resolution GCM or RCM with Interactive Aerosols with realistic aerosol microphysics to better understand Aerosol- Monsoon Water Cycle Interactions

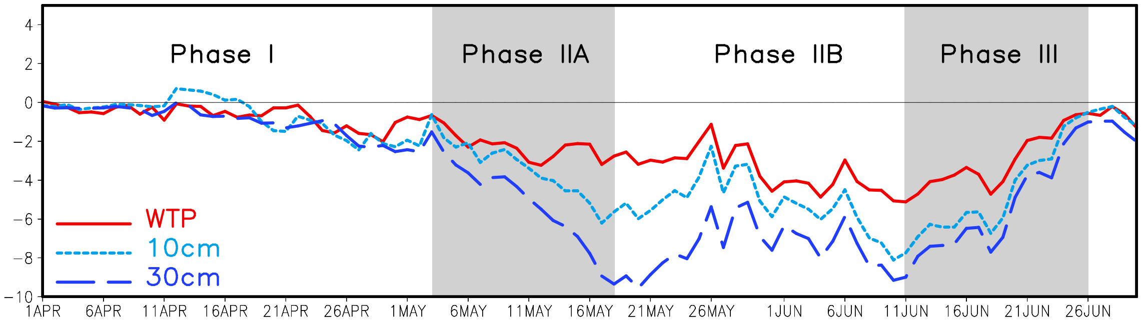


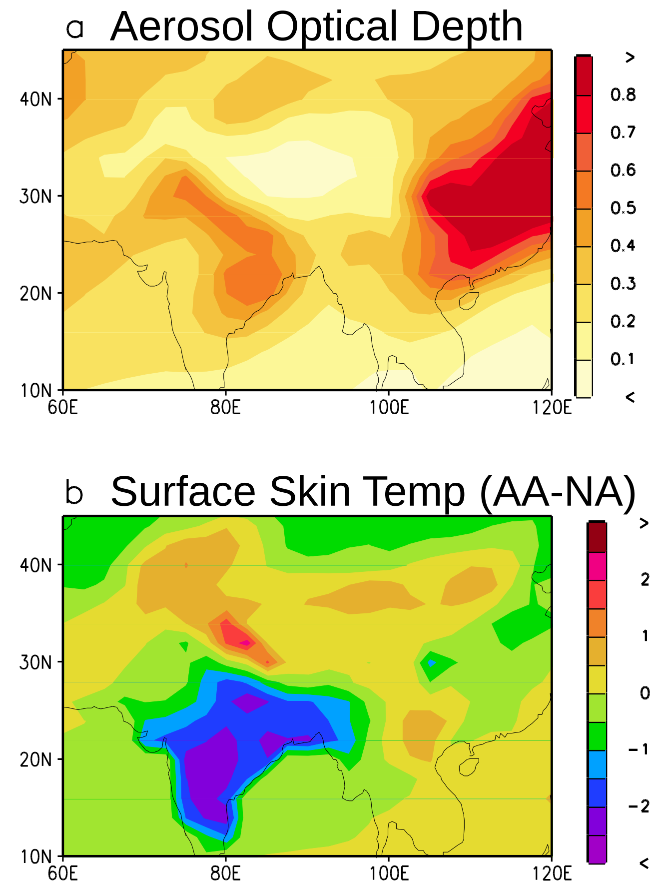
NASA GEOS5 model 5-day forecast of dust emission and transport (May 1-5, 2006)



Effect of absorbing aerosols on snow melt over the Tibetan Plateau (EHP Effect)

(GEOS4-fvGCM with Slab Ocean Model)

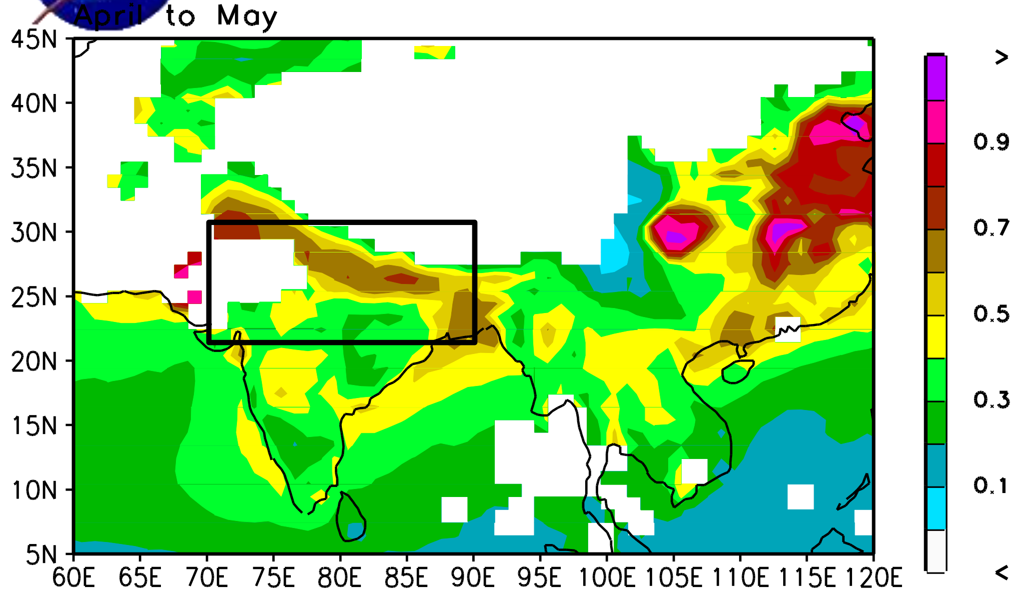




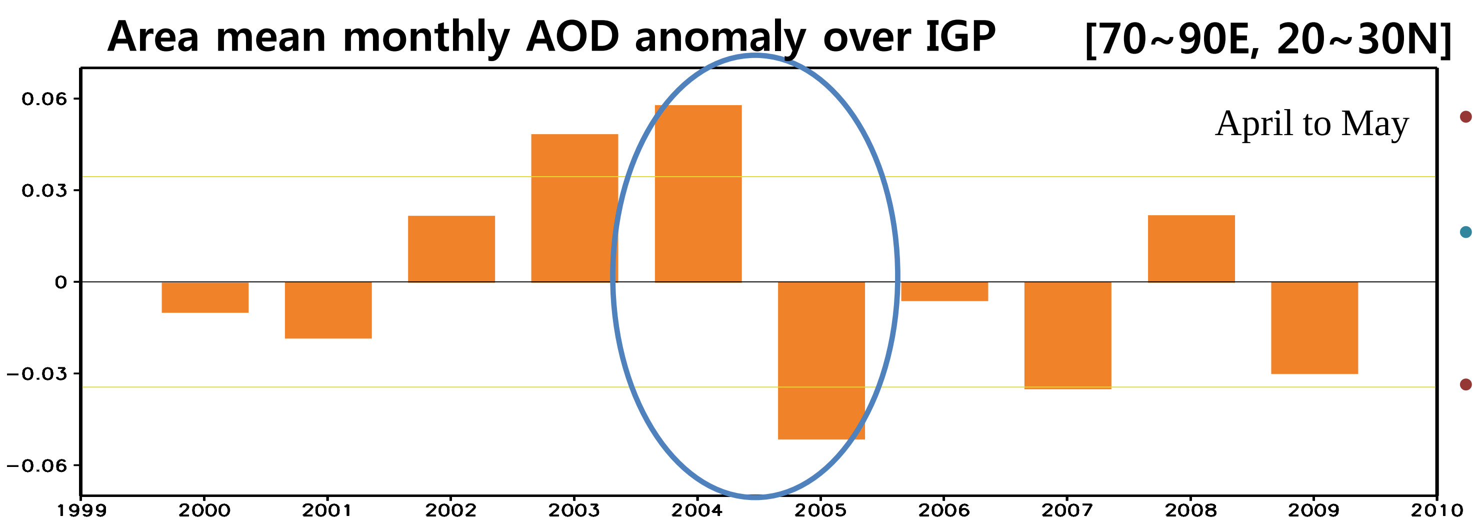
1. Slow melting phase (I) in April is initiated by sensible heat transfer from warmer atmosphere to land.
2. Rapid melting phase (IIA) is due to an evaporation-snow-land feedback coupled to an increase in moisture over TP
3. Melting is slowed down by increasing surface evaporation in Phase IIB.
4. Partial recovery (Phase III)

Lau, K. M., M. K. Kim, K. M. Kim, and W. S. Lee, 2010: Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. Environ. Res. Lett.

April-May mean aerosol optical depth(AOD) from 2000 to 2009



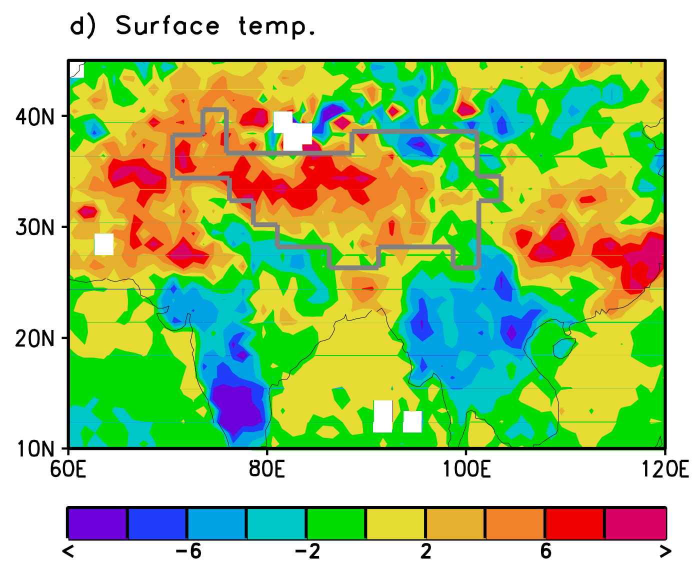
The dusts in IGP are coated with black carbon produced from local emissions and become a strong absorber of solar radiation and an efficient source of atmosphere heating(Lau and Kim, 2006).



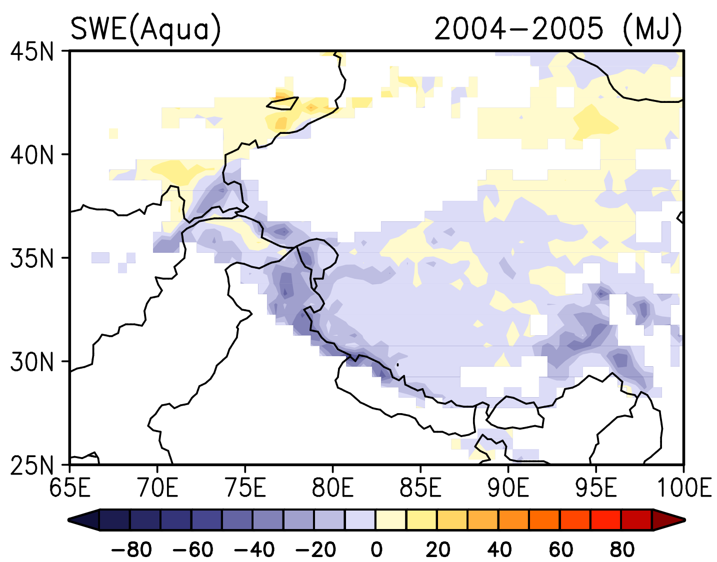
- **High AOD : 2004**
- **Low AOD : 2005**
- **Nino3 Index**

  DJF 2004: 0.29
  DJF 2005: 0.26
  DJF 2003: 0.83

May/June Difference between 2004 and 2005
Dirtier year minus cleaner year



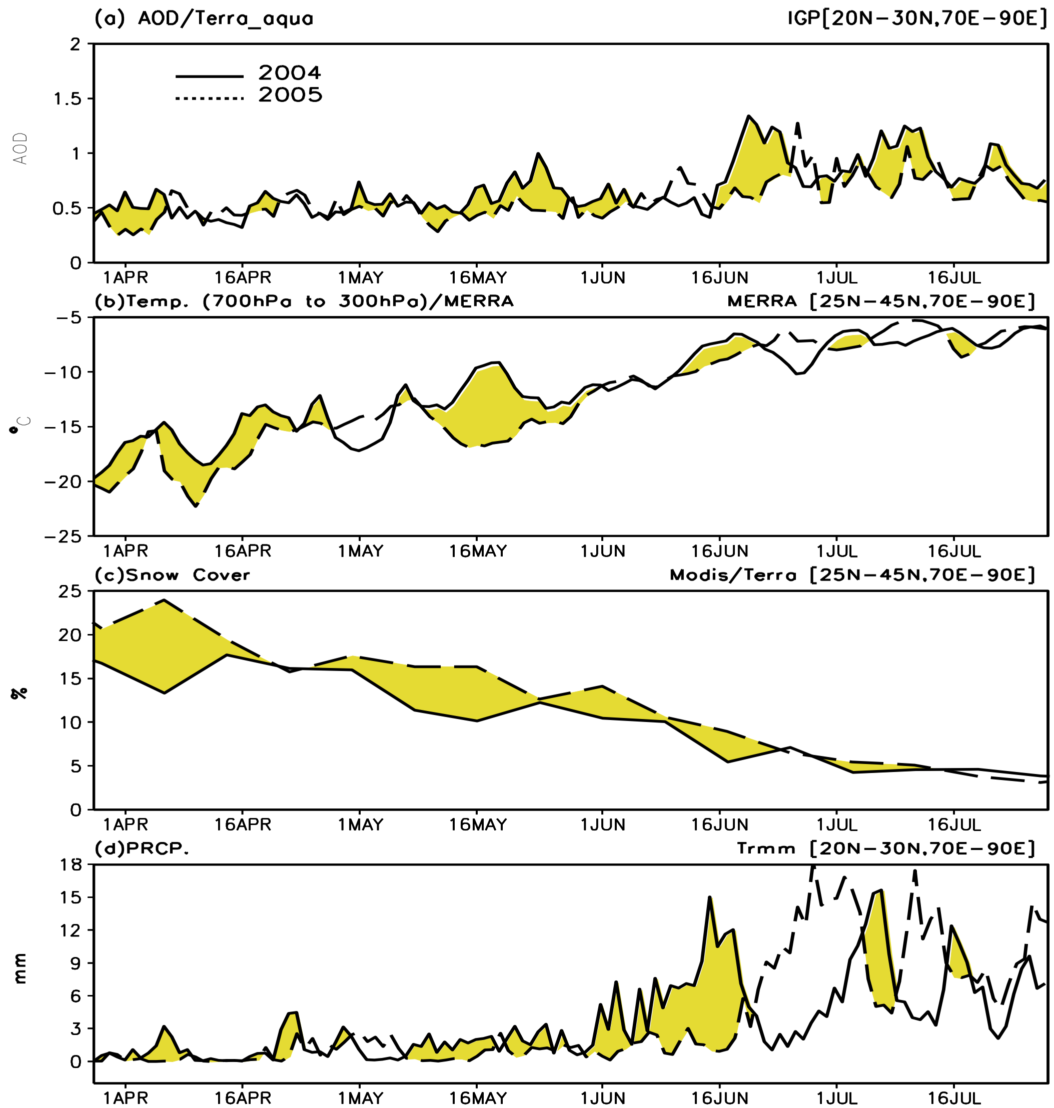
Increased surface temperature (AIRS) over NW India and HKHT



Reduced Snow Water Equivalent (Aqua) → more rapid snowmelt

Intra-seasonal variation

Dirtier year (MJ 2004) minus cleaner year (MJ 2005)



Increased AOD over N. India

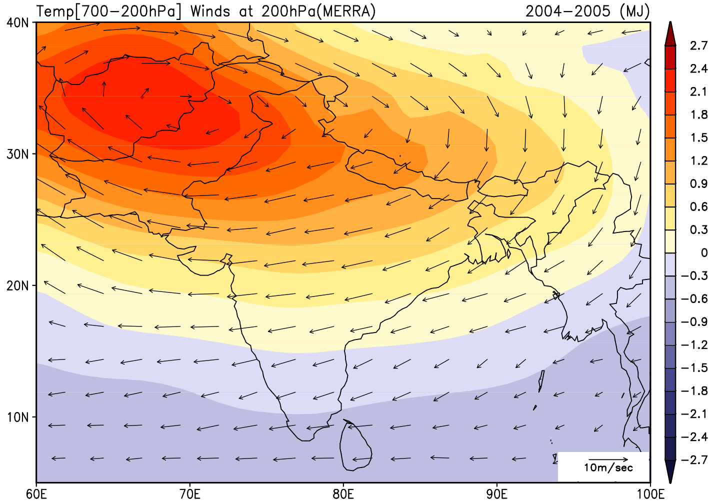
Increased Upper level Temperature Tibetan Plateau

Decreased Snow Cover over TP

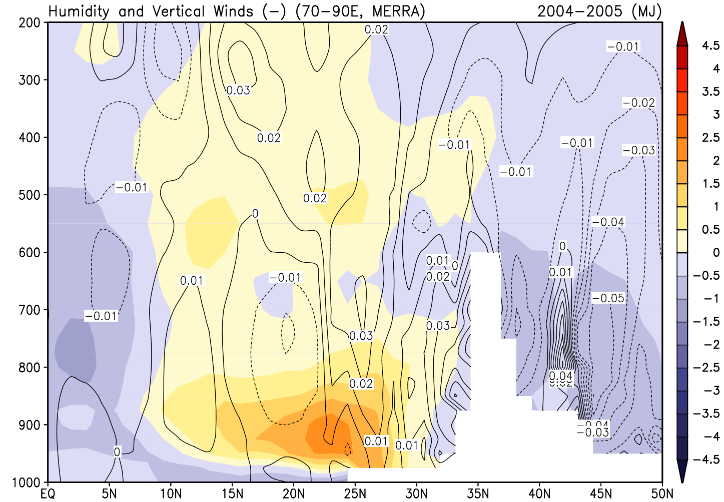
Increased Rainfall over N. India

May/June Difference between 2004 and 2005
Dirtier year minus cleaner year

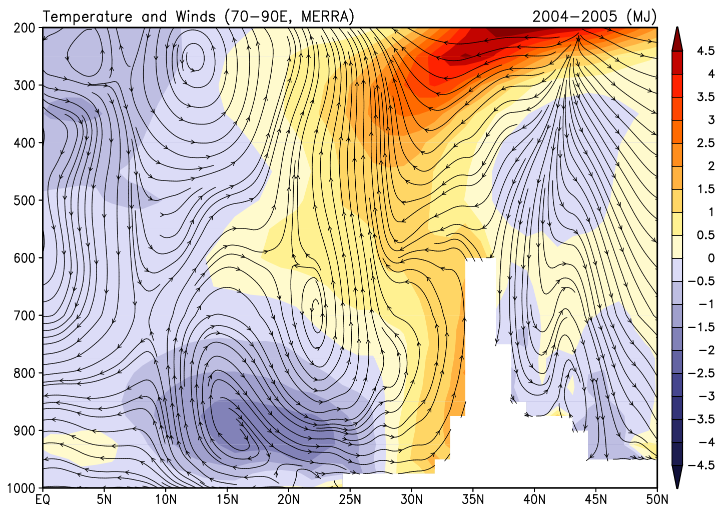
Upper level Temperature & Wind



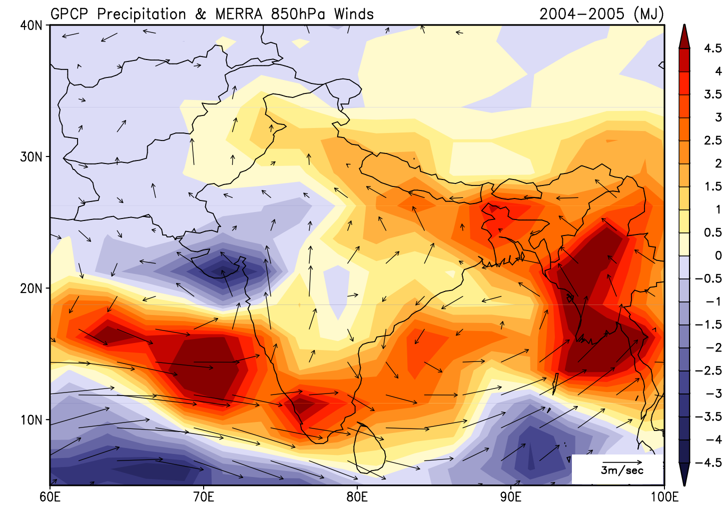
Moisture & Vertical Winds



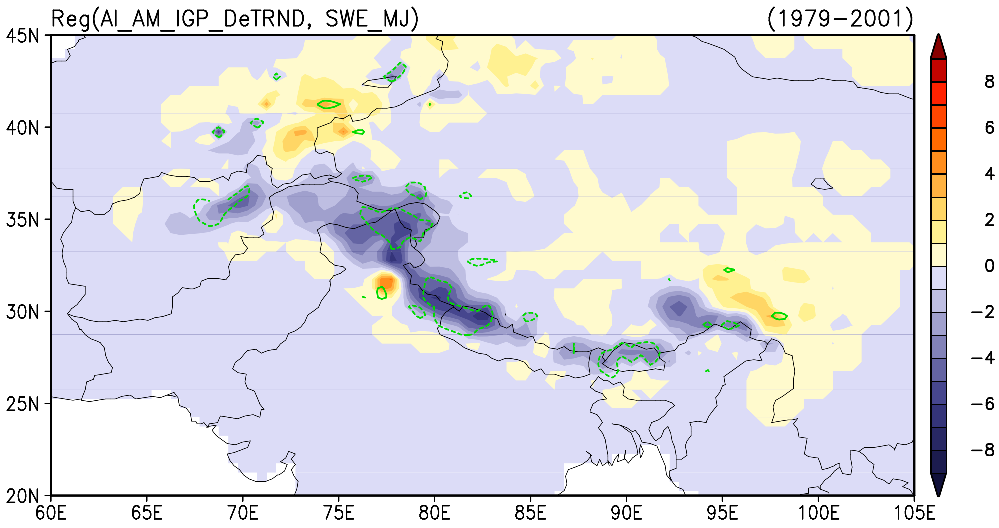
Temperature & winds (v-w)



Lower level Winds & Rainfall

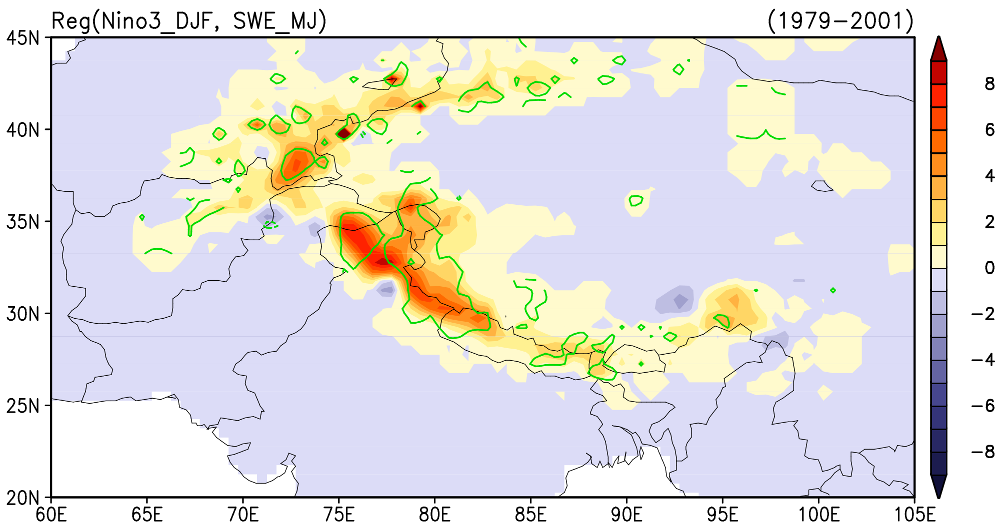


Interannual Variation of Snow Water Equivalent (Aerosol vs El Nino)



Aerosol Effect

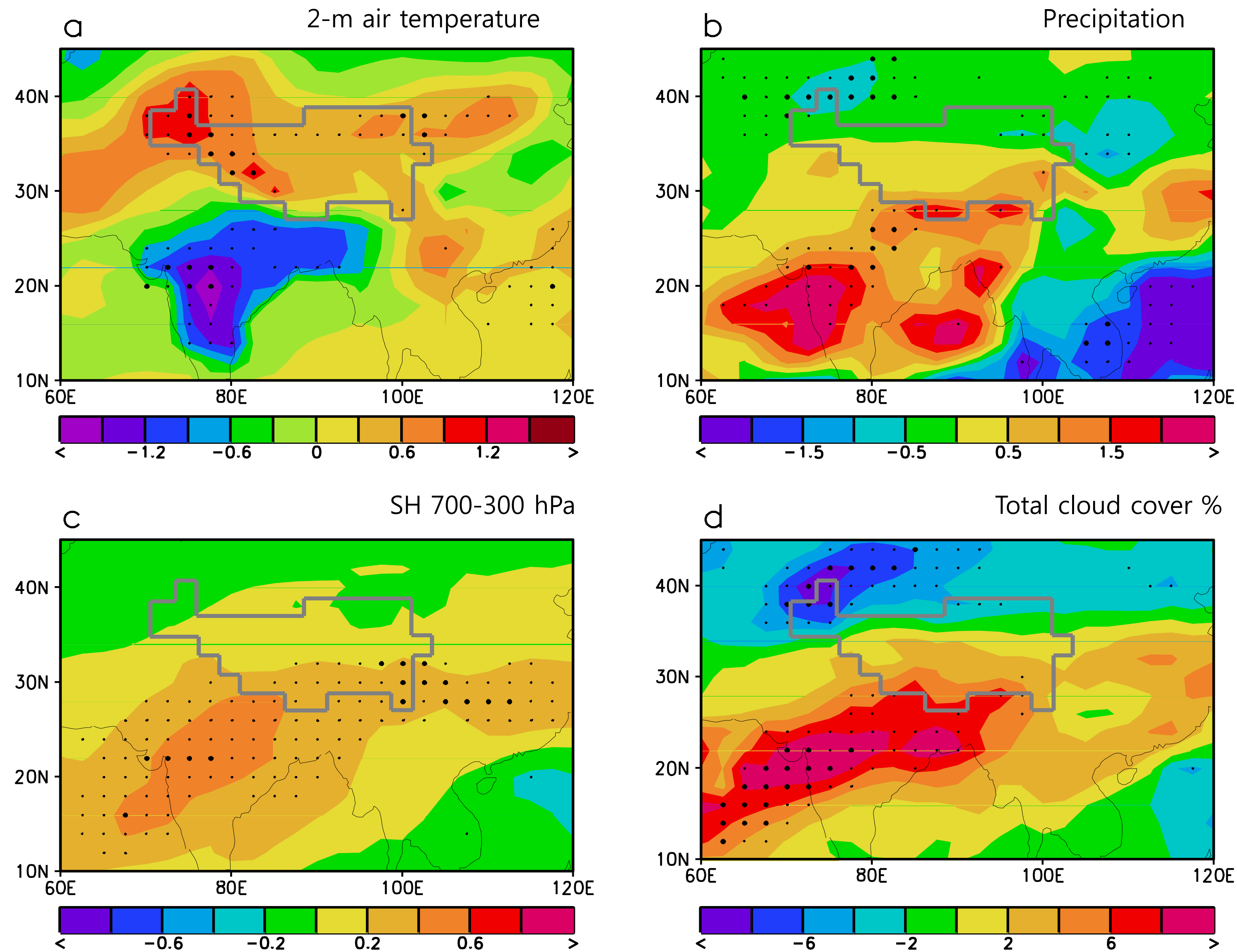
Heating of the atmosphere by dust and BC can lead to widespread enhanced warming over the TP and accelerated snow melt in the western TP and Himalayas. (Lau et al. 2010) Decreased snow albedo due to BC/dust deposition can further accelerate snow melt (Yasunari et al. 2010)

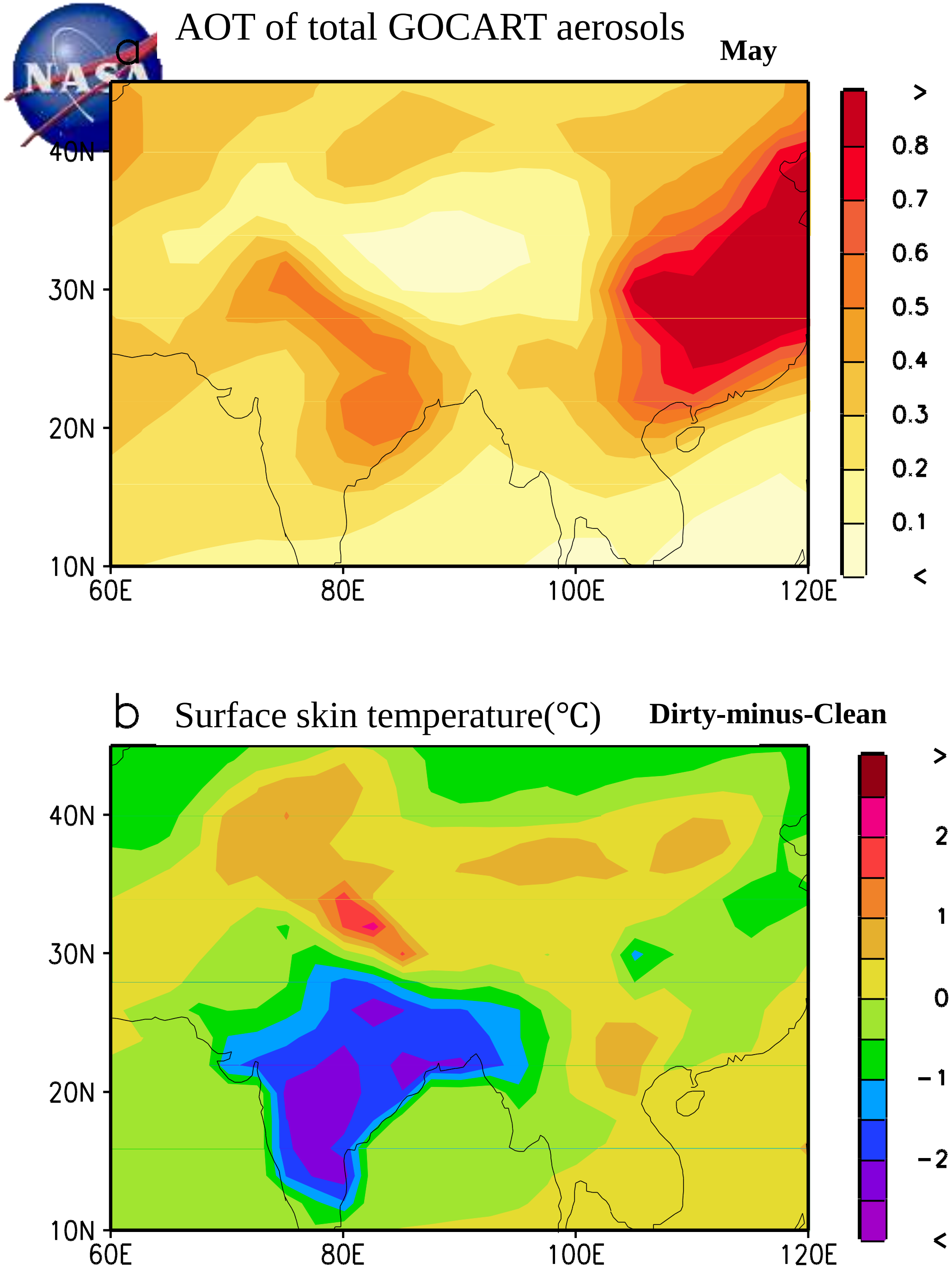


El Nino Effect

The atmospheric teleconnection pattern initiated by ENSO increase snowfall over TP during winter. The increased snowfall produces a larger snowpack which lasts through the spring and summer, and subsequently weaken the Indian monsoon (Shaman and Tziperman 2005).

GEOS GCM, Aerosol-minus-No Aerosol, for month of May





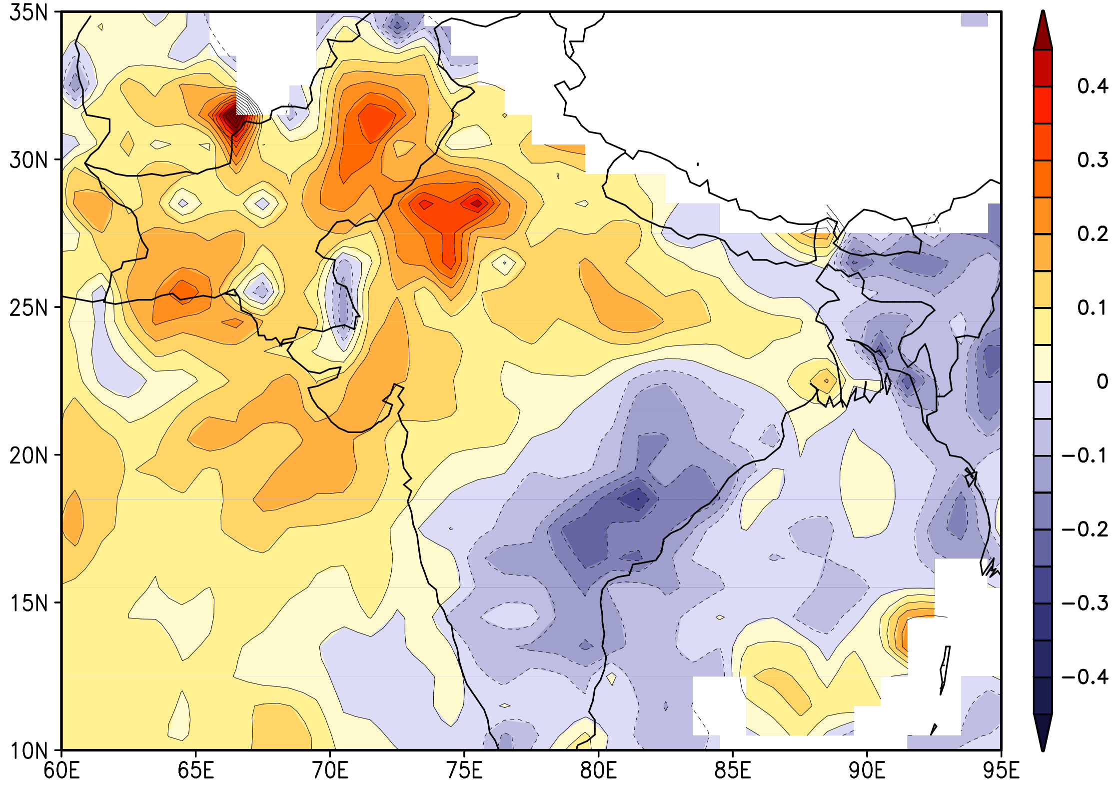
Area-averaged composition of aerosols in May

Region / Aerosol Type	IGP [75~90°E, 17.5~30°N]	TP [80~95°E, 30~35°N]	Central China [105~120°E, 25~35°N]
All aerosols	0.24	0.15	0.73
Black Carbon	(11.7%)	(10.7%)	(8.0%)
Dust	(41.9%)	(43.3%)	(15.8%)
Sulfate	(15.8%)	(22.3%)	(62.5%)
Organic Carbon	(26.5%)	(20.4%)	(12.4%)
Sea salt	(3.8%)	(3.0%)	(1.1%)

Lau et al. 2010 *ERL*

Observational Case Study
2004 vs 2005

Aqua AOD + DeepBlue
Apr-May (2004 minus 2005)



Data Used

MODIS AOD

Snow cover (MODIS/Terra)

Snow Water Equivalent (SSMR & SSM/I) & (AMSR-E)

MERRA Winds & Temperature

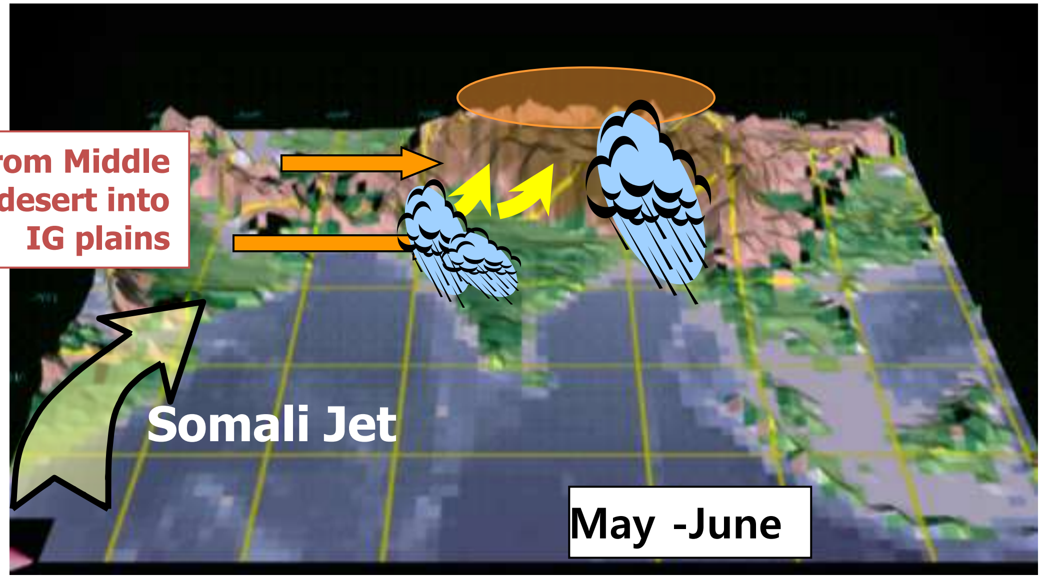
Surface Temperature (AIRS)

Nino3 SST Index

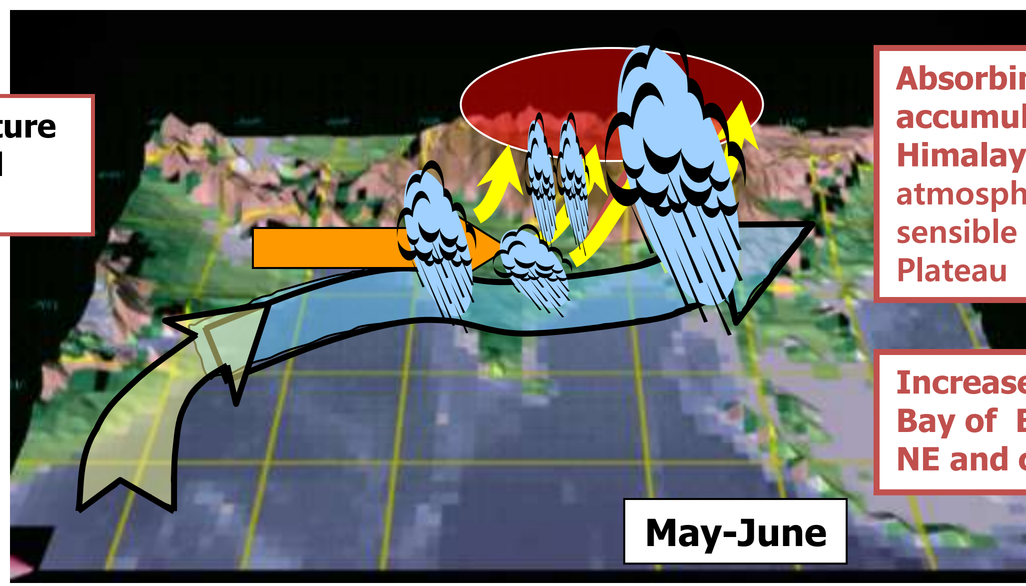
The Elevated Heat Pump Hypothesis

(Lau et al. 2006, Lau and Kim 2006)

Dust transport from Middle East and Thar desert into IG plains



Increase dust and moisture transport from low level monsoon westerlies



Absorbing dust and BC accumulated on foothills of Himalayas accentuate atmospheric heating by sensible heat flux over Tibetan Plateau

Increased convection over Bay of Bengal, eastern TP, NE and central India

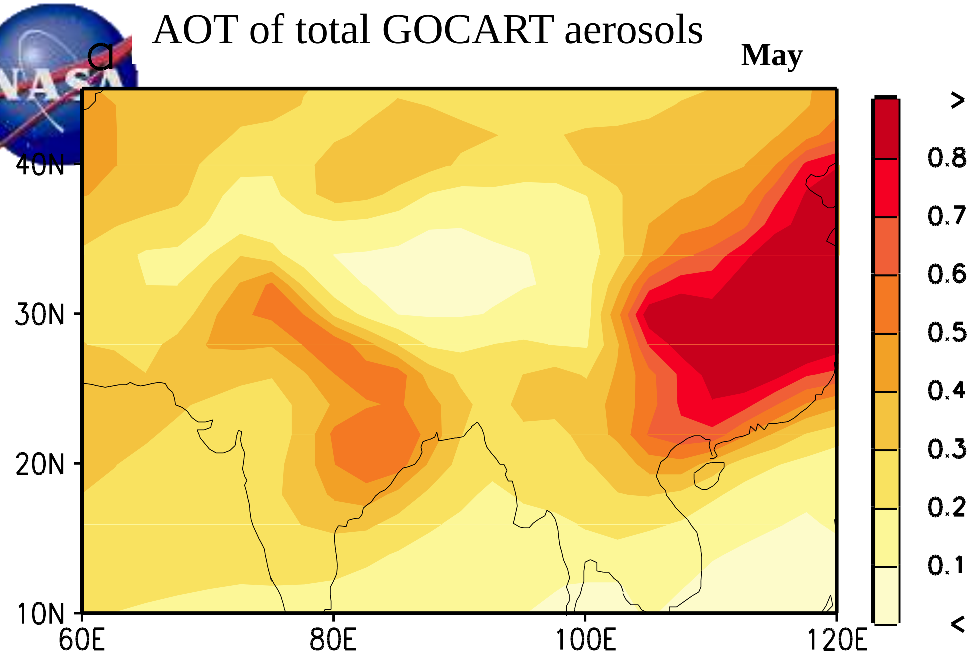
Possible effects by aerosols on the large-scale monsoon water cycle

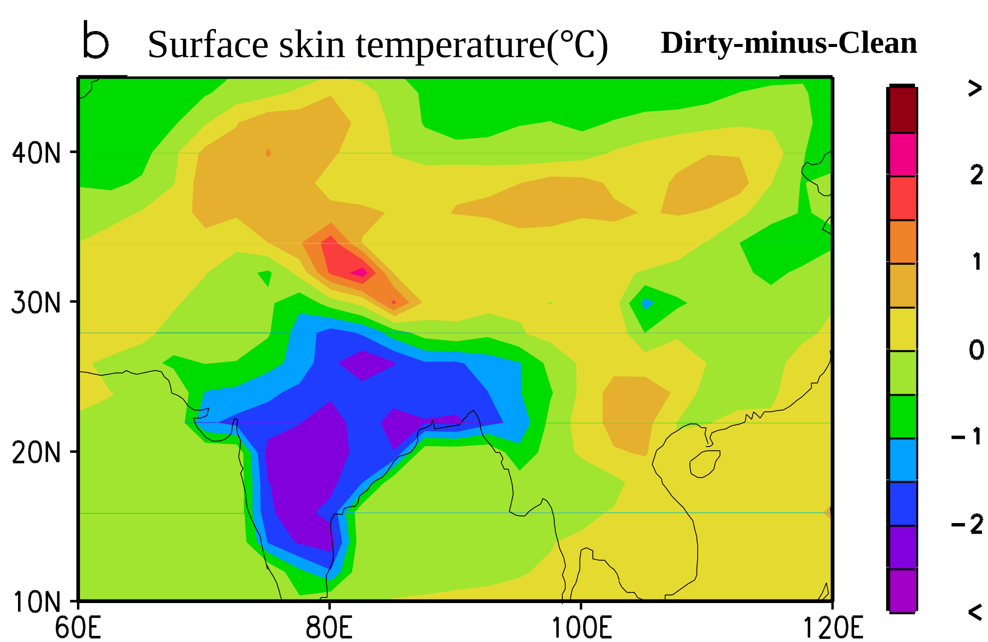
- The Solar Dimming Effect : More aerosol cooling over land and ocean to the north reduce meridional thermal contrast, causes a spin-down of the Hadley circulation, weakens the monsoon (Ramanathan et al 2005, Chung and Ramanathan, 2005..)

- Atmospheric heating feedback: Dust and black carbon piling up against the foothills of the Himalayas, heats up upper troposphere, producing a positive water cycle feedback, enhancing the monsoon (Lau et al. 2006, Lau and Kim, 2006, 2007, Meehl et al. 2007, Collier and Zhang 2009, Wang 2009…)

- Microphysics effects of aerosol – a wild card

- Coupled Atmosphere-land-ocean dynamics: All aerosols effects are likely to be confounded /modulated by large-scale remote forcing, e.g., El Nino, local SST, global warming…





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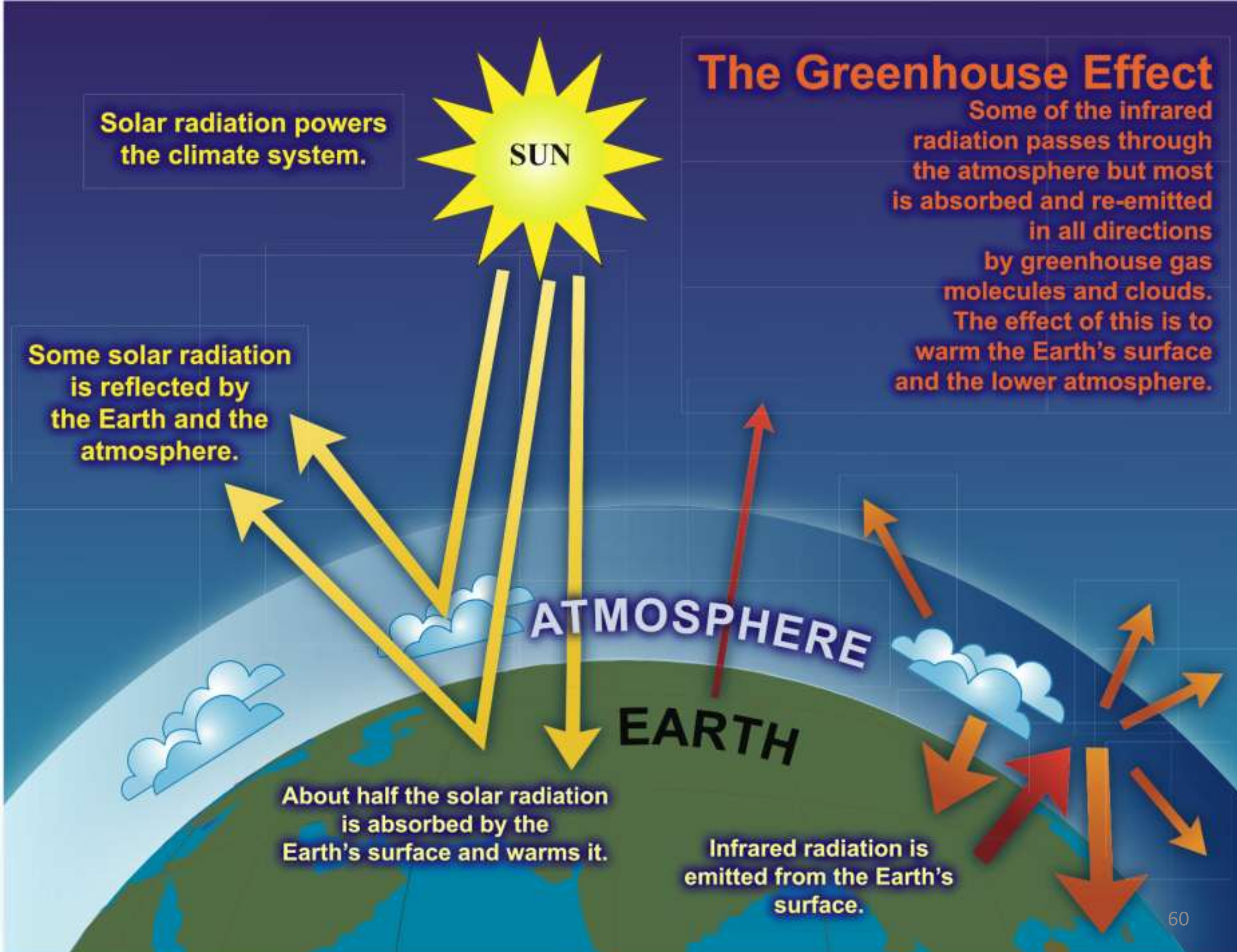
Lau et al. 2010 *ERL*

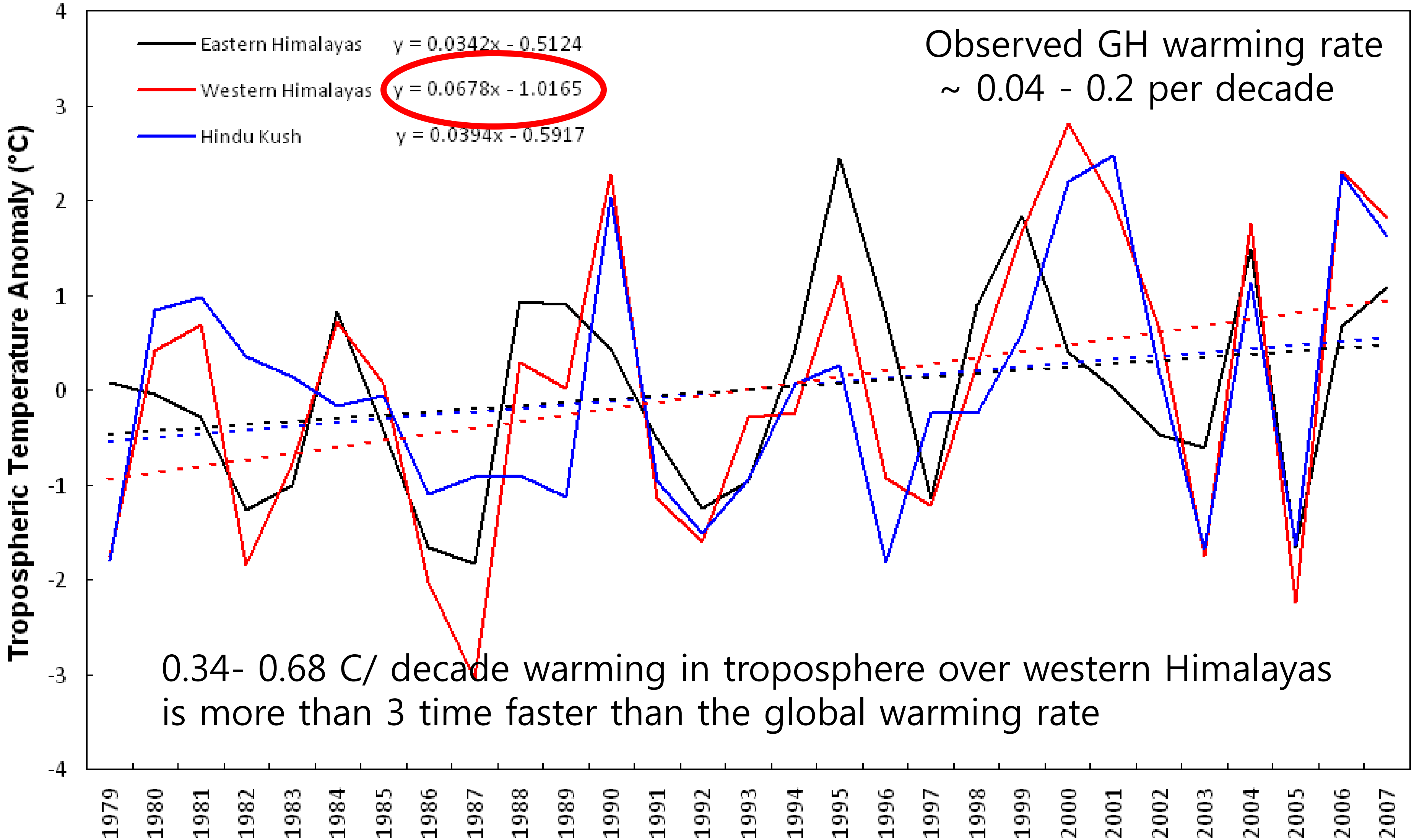
OUTLINE

- Asian Climate Change primer
- Possible impacts of aerosols on
  - Asian monsoon water cycle
  - Accelerated melting of snowpack in the Himalayas and Tibetan Plateau
- Some thoughts on adaptation and mitigation

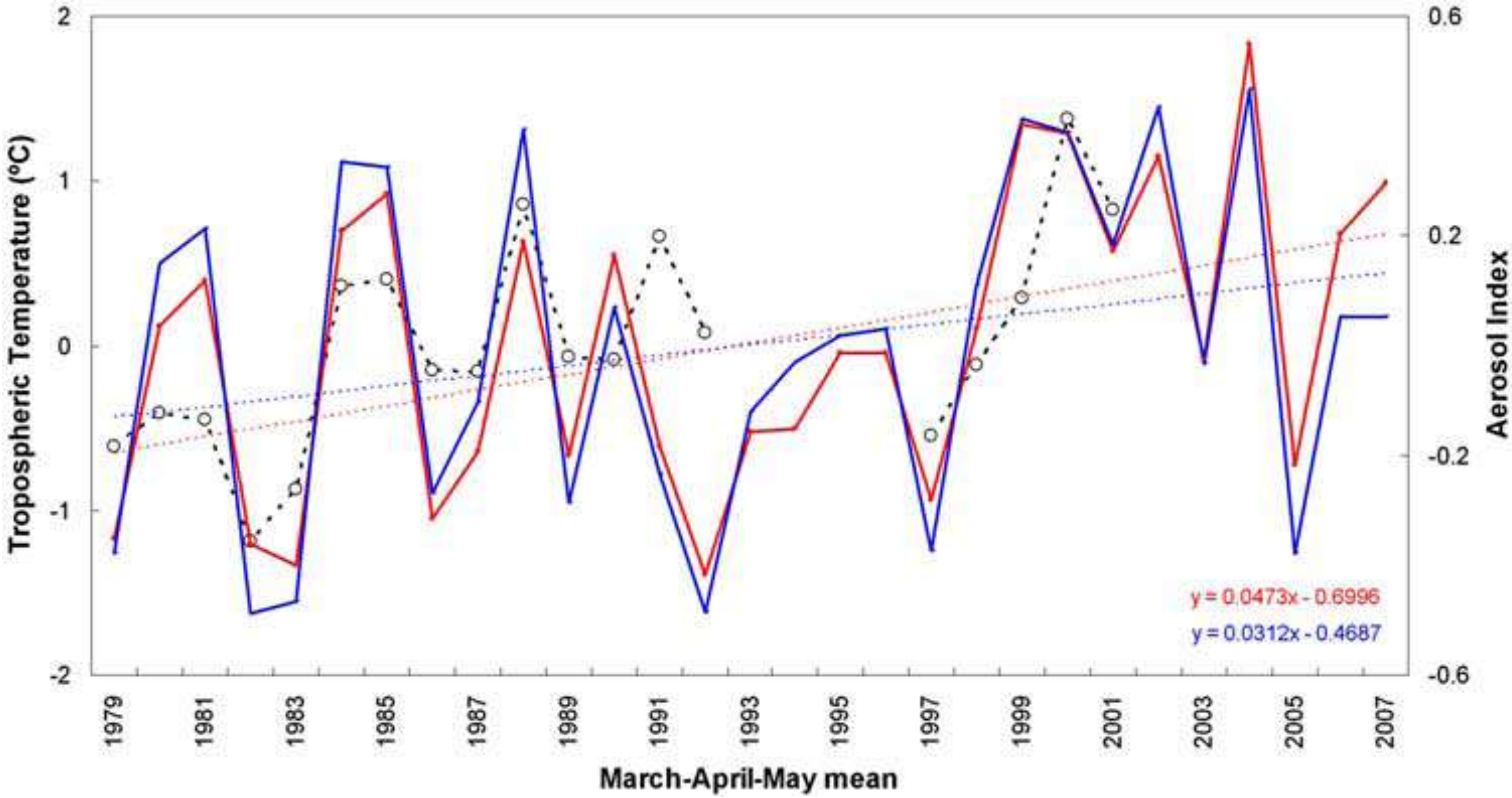


The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation powers the climate system.
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

May (1979-2007)



Inter-annual variability of pre-monsoon Tropospheric Temperatures and Aerosol loading



Mid-Tropospheric Temp

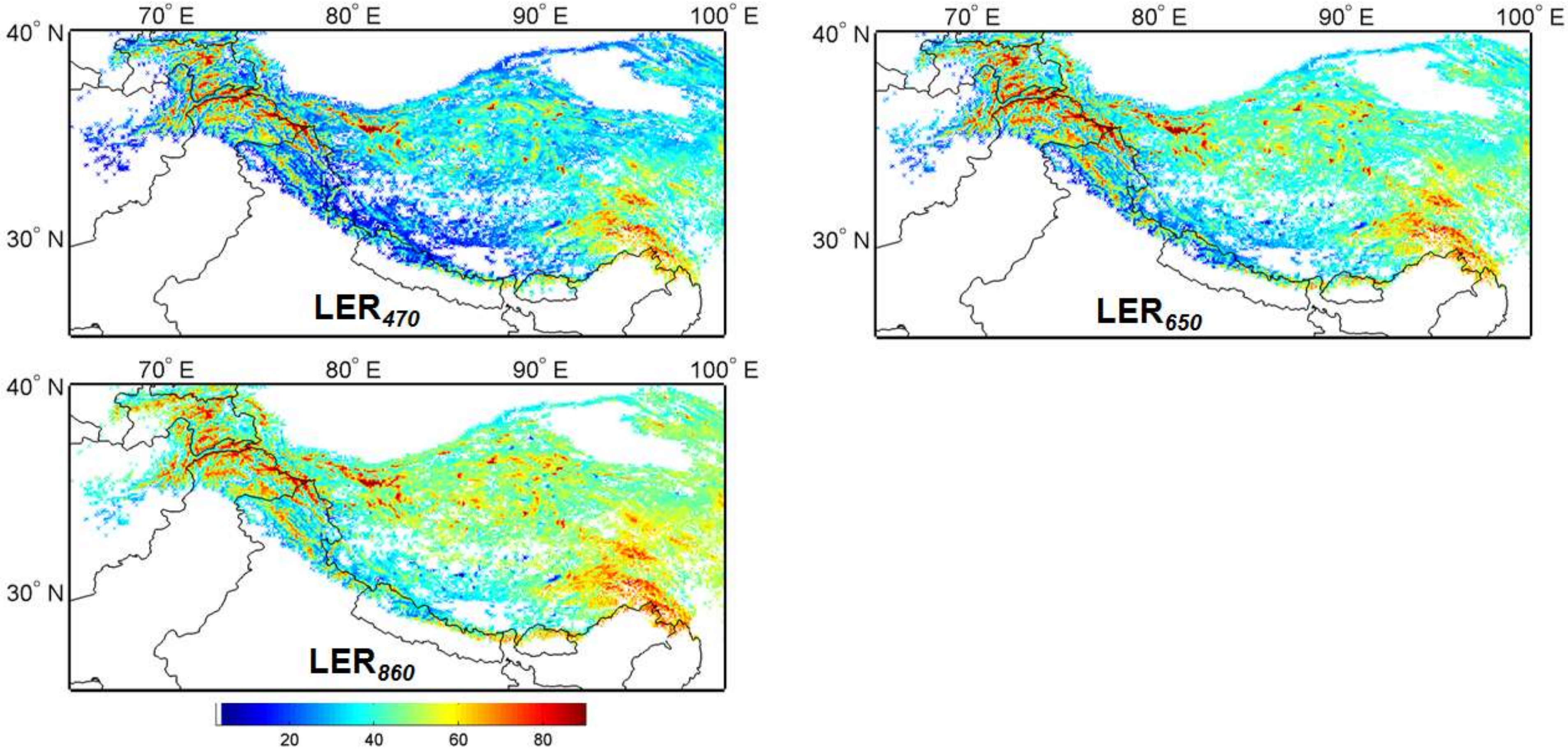
Lower Tropospheric Temp

TOMS Aerosol Index

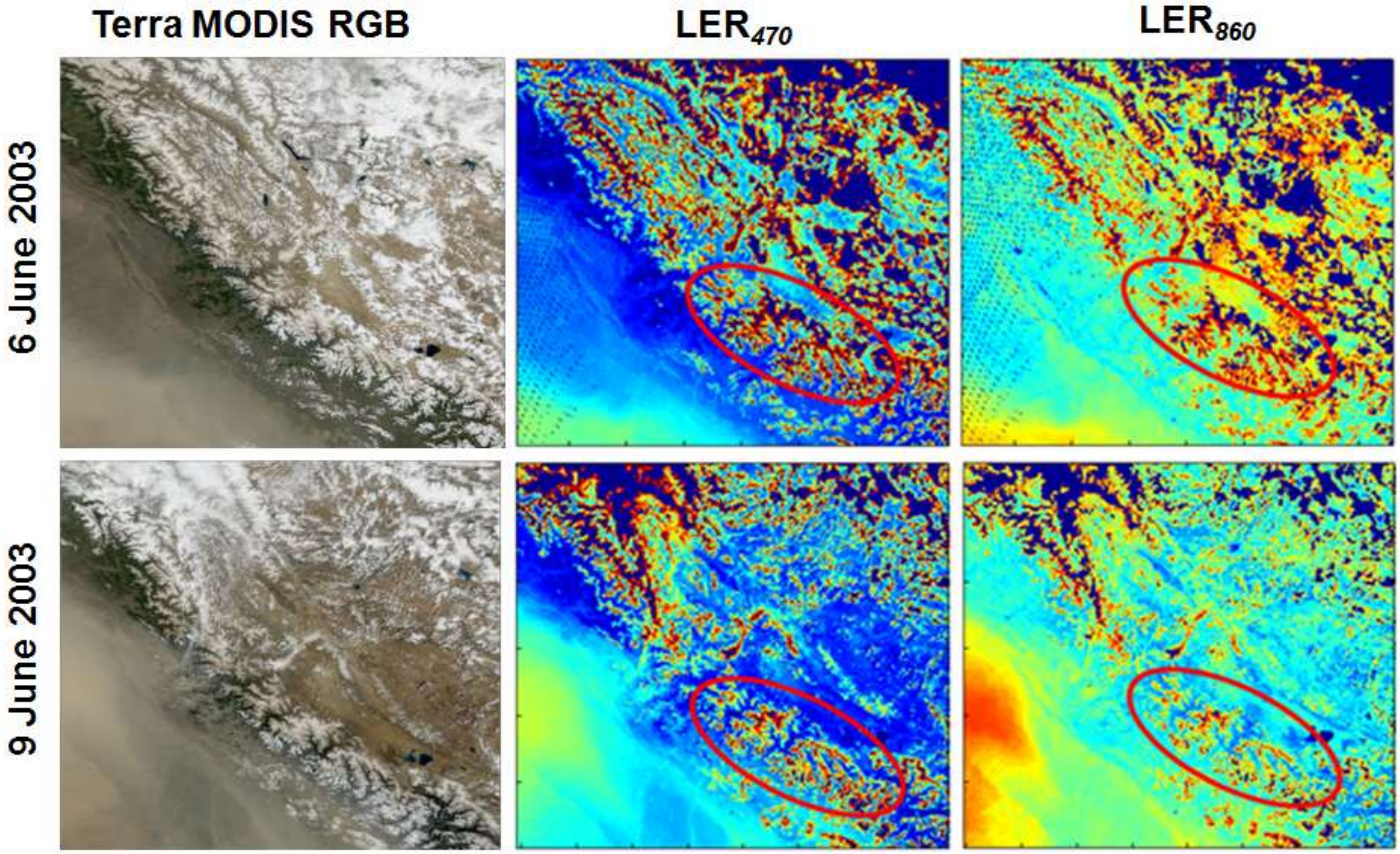
Correlation coef. Of 0.67 and 0.65 between T_{mid} and T_{low} with AI (exceeding 95% significance)

MODIS-derived Lambertian Equivalent Reflectance (LER) over the Himalayan-Tibetan Plateau Snow Surface at TOA

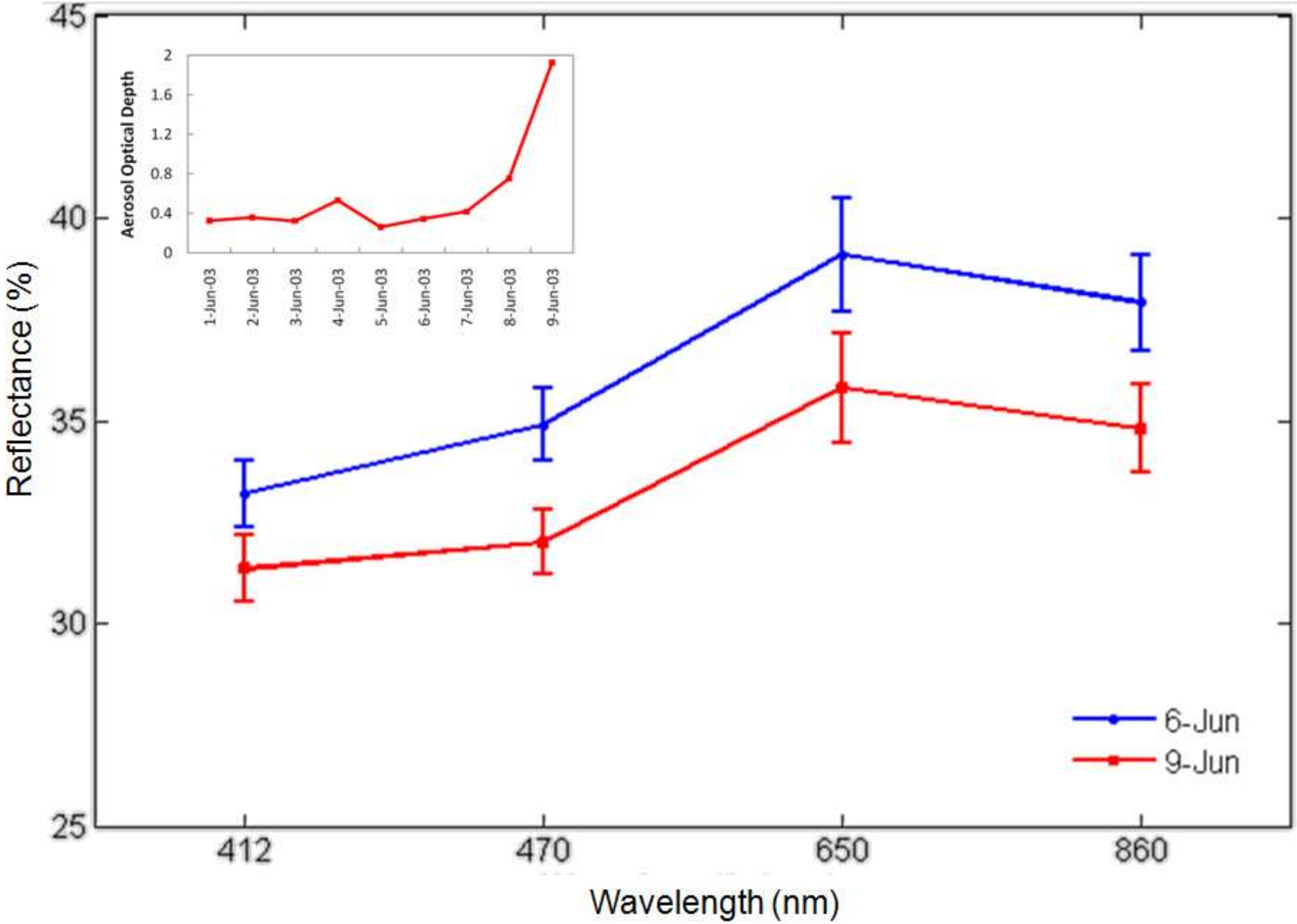
May 15 – June 15 LER



The spectral reflectance from MODIS suggests perturbation caused due to the dust layer over the snow surface as well as the reduced reflectance associated with dust deposition over snow covered pixels in the satellite scene.



Reduction of 5-8% in LER during dust transport. Inset plot shows anomalous high AOD on 9 June 2003 over foothills associated with the extensive dust plume.



Preliminary estimates, based on 14 days of Terra/Aqua MODIS observations during pre-monsoon season, of dust overlaying western Himalayan snow surface, indicate characteristic changes in spectral reflectance with 3 - 6% reduction at shorter wavelengths (412 and 470nm), while 5 - 7% decrease at 650 and 860nm channels.