Fate of Mountain Glaciers in the Anthropocene
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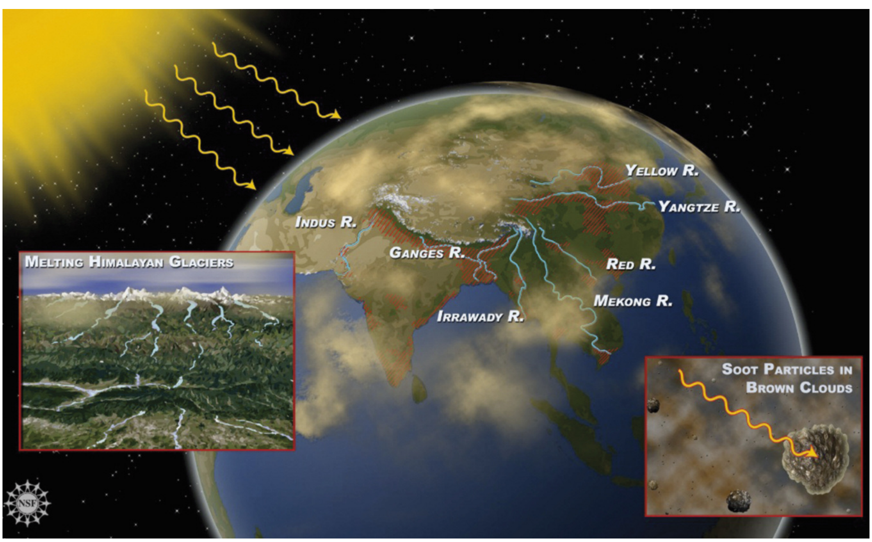
Himalayan-Tibetan Glaciers and Snowpack System: Multiple Destabilizing Influences

Veerabhadran Ramanathan

Synopsis

"We underline that climate change is one of the greatest challenges of our time"
Quote from the Copenhagen Accord signed by Heads of State, 2009

The Himalayan-Tibetan glaciers/snowpack system, along with millions of Asians, may suffer the most if we don't rise up to this challenge. These elevated regions are subject to numerous natural and manmade stresses that have a destabilizing influence on the glacier/snowpack mass balance. Natural factors for glacier melting include the recovery from the mini ice age of the 16th century and dust storms. Manmade factors include: land surface modification and destruction; build-up of CO_2 and other greenhouse gases; increase in air pollution such as black carbon aerosols which absorb sunlight and warm the air and the surface directly; drying by sunlight-intercepting aerosols in wide-spread atmospheric brown clouds over South and East



Kindu Kush-Himalayan-Tibetan Glaciers: Water Foundation of Asia.

Asia; warming amplified over elevated regions due to deep convective clouds; more frequent forest fires due to drying and warming; and precipitation falling more as rain rather than snow due to the warming. All of these factors act in the same direction to decrease the volume and extent of the glaciers and the snowpacks.

The overarching threat is that we have dumped enough greenhouse gases since the pre-industrial era, to warm the planet by about 2.5°C and likely a factor of 2 more warming in the Himalayas and Tibet region because of their high elevations. A sustained warming of such magnitudes, combined with the in-situ warming by black carbon and dust, shifting precipitation from snow to rain, overall drying, and increased habitat destruction, raises serious concerns about the stability of the Himalayan-Tibetan glacier/snow-pack ecosystem. Fortunately, as outlined here, there is still time to forestall or at least delay unmanageable changes. This approach requires a climate mitigation plan that combines global actions on CO_2 reductions with local, national and regional actions on reducing emissions of black carbon, ozone, methane and other air pollution which have local and regional sources. Such actions also have immense local co-benefits for poverty, health, and agriculture and water security.

I. Preamble

The Fifteenth Conference of the Parties (COP-15) of the United Nations Framework Convention on Climate Change (UNFCCC) met from December 6 to 18, 2009 in Copenhagen to arrive at the so-called "Copenhagen Accord". It states: "We agree that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective consistent with science and on the basis of equity".

The 2°C Copenhagen barrier is based, in part, on scientific studies (1-6) which suggest that global scale warming in excess of 2°C can trigger several climate tipping elements and lead to unmanageable changes (Figure 1). The 2°C barrier poses a major dilemma because the blanket of manmade GHGs as of 2005 has already trapped 3 (2.6 to 3.5) Wm^{-2} (7). A synthesis of available three-dimensional climate model studies (8) lead to the conclusion that the climate system should warm by 0.8°C (1-sigma range of 0.5 to 1.2°C) per one Wm^{-2} (watts per square meter of the earth's surface) increase in the radiant (infrared and solar) energy input. Thus, the 3 Wm^{-2} energy trapped by the GHGs blanket should have already committed the planet to a warming of 2.4°C (9).

So why has the 2°C barrier not been exceeded, as predicted? Ocean heat content observations suggest that about 20% (0.5°C warming) is still stored in the oceans and will be released in the coming decades (8,9). The other candidate is aerosols added by air pollution which reflect solar energy back to space. It is the same air pollution that is linked with millions of fatalities, crop destruction and acidity of rain. The resulting dimming effect at the surface has been observed in land stations around the world (10,11). IPCC (7,8) and other studies (12) lead to the conclusion that the manmade aerosols have masked about 50% (1.2°C) of the 2.4°C greenhouse warming. Once we clean the air, this 50% masking effect will disappear. Europe and N. America have already significantly reduced emissions of aerosols due to health and eco-system concerns. The main problem with these laws, with respect to Climate change, is that these laws target sulfates and nitrates which act like mirrors and hence are dominant cooling agents. They do not specifically target dark aerosols such as black carbon which are major contributors to warming on local to regional to global scales. The rest of the world is adopting European/North American air pollution laws.

Challenges for policymakers

The planet is likely to experience warming in excess of 2°C by mid-century if we continue to remove air-pollution aerosols without concomitant actions for thinning the GHGs blanket (12). Reducing emission of long-lived GHGs such as CO_2, while they are urgently needed and essential to prevent further thickening of the blanket, will not thin the blanket this century, because of the century-to-thousand-years lifetime of CO_2 molecules in the air. It is tempting to keep polluting the air with reflecting particles. But the particles consist of sulfates, organics and nitrates (referred to as SON_mixtures) which reduce air quality, lead to millions of fatalities each year, destroy crops and increase acidity of rain (13). The particles, by intercepting sunlight reaching the surface, can also suppress rainfall and lead to droughts, especially in the tropics (14,15).

II. Factors threatening the Himalayan-Tibetan glaciers

Basic constraints of physics and thermodynamics on glaciers and snowpacks

The glacier energy balance is governed by: incoming and reflected Solar radiation, downward IR radiation from the atmosphere primarily by water vapor and clouds, emitted upward IR radiation, evaporation (or sublimation) and turbulent heat flux through air-sea heat exchange which, in turn is governed by the surface wind and the temperature difference between the atmosphere and the surface. In very simple terms, at temperatures below freezing, addition of energy goes to warm the surface. Once it reaches freezing temperatures, addition of energy goes to melt the glaciers. The mass balance is governed by evaporation (or sublimation), precipitation and dynamics of glaciers and sub-surface water transport. For the central and the eastern Himalayas (the main focus here) the S. Asian monsoon is the main source for precipitation. During winter, however, southward migration of the jet stream brings precipitation to the Himalayas, particularly to its western flank. One important thermodynamic constraint is that the saturation water vapor pressure will increase by about 7% per degree (˚C) warming. Major outcome of this thermodynamic constraint is the water vapor feedback: in the absence of compensating influences from atmospheric dynamics, warming of the atmosphere will increase atmospheric humidity (by 7% per 1°C warming), which will increase downward IR radiation from the atmosphere and contribute to additional surface warming or melting. This effect can be important since water vapor is the dominant greenhouse gas in the atmosphere; but its effect on mass loss will be offset somewhat because the increase in atmospheric moisture can suppress loss of moisture through evaporation from the ice and snow surfaces. A warming of the atmosphere over the elevated regions contributes to glacier/snowpack melting in following ways: increased downward IR radiation from the warmer atmosphere; additional increase in IR due to water vapor feedback, and increased turbulent heat flux from the atmosphere to the surface. Another important constraint (also thermodynamic) is the link between surface warming and atmospheric warming over elevated altitudes (>5 km). The rate at which temperature decreases with altitude depends strongly on the absolute value of the temperature, because of the aforementioned increase in water vapor pressure by about 7% per degree of warming. In simple terms, as the lower atmosphere warms, by say 1˚C, it contains 7% more moisture. This excess moisture is transported upwards by convection and is released as precipitation at elevated levels. The additional latent heat released by precipitation contributes to a warming of the elevated regions. Empirical studies and climate models suggest that a 1˚C warming at the surface is amplified to about 2˚C warming at levels above 5 km. Thus a greenhouse warming of 1˚C over the plains regions of South and East Asia will manifest as 2°C warming over the elevated regions of Himalayas and Tibet. As shown later this region is experiencing such large warming trends.

Natural

During the sixteenth to the nineteenth centuries, many regions of the northern hemisphere experienced a cold period, popularly referred at as the

Little Ice Age (LIA). This period also witnessed expansion of many mountain glaciers, particularly in the northern hemisphere. The recovery from the LIA began around 1850s and initiated large-scale retreat of the mountain glaciers over many regions of the planet and this retreat due to ice-age recovery is documented well for the Alps. Its role in the Himalayan glacier retreat is likely to have been important at least until early twentieth century.

Anthropogenic forcing terms

There are a number of forcing factors as shown in Fig. 2 and we will start at the top and move in a clockwise direction. Land use modification and degradation due to the rapid increase in population and industrialization of the mountain regions in South and East Asia, contribute an increase in surface albedo and an increase in dust loading. Dust significantly increases absorption of solar radiation in the atmosphere (see paper by Painter in this volume) and when it deposits on the snow and ice, darkens the snow and ice and increases absorption of solar radiation by these bright surfaces.

GHGs warming of the atmosphere

Next is the atmospheric warming. Increased atmospheric CO_2 and other greenhouse gases (GHGs) is one major source for the warming. The evidence for this warming is documented in surface temperature records (Fig. 3) for Tibet. The warming trend increases significantly with altitude such that the trend above 3 km is a factor of two to three greater than the surface-warming trend. The increase of warming with altitude is consistent with the thermodynamic constraint due to moist convection, but the magnitude of the trend (> 0.2°C per decade) is much larger than that estimated for GHGs forcing.

Black and brown carbon warming of the atmosphere

Another major source is air pollution, which is typically a dense 3-km hazy layer of aerosols and pollutant gases such as ozone, NOx etc. This hazy layer is referred to as Atmospheric Brown Clouds (ABCs) because: 1) of the brownish color of the haze (Figure 4, left panel photos of ABC). The hazy appearance of the sky is primarily due to aerosols (particles) consisting of: black carbon; organic carbon; sulfates; nitrates; dust among others; and 2) it becomes widespread over vast regions (Figure 4, right panel satellite image of ABCs). Emissions of the air pollutants by fossil fuel combustion and biomass burning from South, Southeast, and East Asia enable these ABCs to persist most of the year and surround the Himalayan region from both the southern and north-eastern side (Fig. 5). ABCs absorb significant amount of sunlight (as much as 25%), a fact which was directly measured with instrumented unmanned aircraft (left 4 panels of Fig. 6 from (16)). When this data for atmospheric heating by black carbon aerosols was introduced in a climate model (same model as used in IPCC studies), the warming over the region surrounding the Himalayas was as large as the simulated warming due to CO_2 increase (rightmost panel of Fig. 6). The evidence for such anomalous warming was detected by microwave satellite data (Fig. 7). Such a large warming of the air over the elevated regions will contribute to glacier retreat in two different ways: 1) It will increase melting of the glaciers during the spring and summer season; 2) More of the precipitation will fall as rain instead of snow.

Surface dimming by ABCs and weakening of the monsoon

By intercepting sunlight, black carbon and other manmade aerosols in ABCs lead to large-scale dimming over South and East Asia. This dimming predicted by field studies (11) was detected by a network of surface radiometers in India and China (Fig. 8), which showed that solar radiation at the ground decreased by about 10% during the 1970s to 2000, when both regions witnessed 3- to 4-fold increase in aerosol emissions. This dimming weakens the monsoon circulation and reduces monsoon precipitation in two ways: first, since surface evaporation of moisture is determined by net radiation at the surface over the sea, dimming by aerosols over the ocean (Arabian Sea and Bay of Bengal) decreases evaporation, the fundamental source of moisture for the monsoon; and second, since the pollution aerosols (from South Asia) are concentrated mainly in the northern Indian Ocean, the surface cooling due to the dimming is mainly concentrated over the northern Indian Ocean. Indeed, observed sea surface temperature trends (Fig. 9) show that while the southern Indian Ocean has warmed over the last 50 years, the warming is a lot less pronounced in the northern Indian Ocean. The resulting weakening of the sea surface temperatures north to south has weakened the monsoon circulation (17). Observed monsoon rainfall trends support this inference (Fig. 10). Moderate rainfall has decreased over most of India, including the Himalayas. The data, however, reveal that intense rainfall (the sort that leads to flooding) has increased. This strengthening, a characteristic of precipitation trends in other regions of the world, is attributed to global warming. The weakening of monsoonal circulation and the reduction in moderate rainfall has two negative consequences for the Himalayan glaciers and snowpacks. Precipitation reduction would, by itself, reduce the supply of snow and ice to the glaciers and snowpacks. Second, the weakening of the monsoonal circulation in conjunction with the reduction in rainfall is likely to reduce the relative humidity of the air thus enhancing the sublimation of snow and ice.

Surface melting by black carbon deposition

Snow and ice reflects as much as 50% to 90% depending on the size of the crystals, the age, and the thickness of the ice and snow. Black carbon, on the other hand, absorbs as much as 60% to 80% of the solar radiation. Thus, when black carbon is transported by the atmosphere over the Himalayas and is deposited over the snow and ice, it increases the absorption of solar radiation and increases melting. Two recent global modeling studies (18,19) have looked into this issue and have conclude that enough black carbon is transported over the Himalayas to contribute as much as 30% of the melting of the glaciers, by this one mechanism alone.

III. An effective mitigation action plan for the Himalayas

As described above, several natural and manmade factors are contributing to the melting of the glaciers and the snowpacks. The contribution by the warming due to greenhouse gases has been studied the most to-date. Recent studies based on field observations and modeling studies have unearthed several other ways in which manmade pollutants are enhancing the CO_2 effect. Air pollution in the form of black carbon and atmospheric brown clouds is contributing as much, if not more than, the greenhouse gases to the melting of the glaciers and the snowpacks.

Mitigating global warming

The long-term problem

Most policy actions for limiting global warming focus on reducing emissions of CO_2 released by combustion of fossil fuels and biomass (e.g. deforestation). Typically such actions call for about 50% reductions of CO_2 emissions by 2050 and 80% by 2075 (2,12). The annual CO_2 emission was about 35 Gt CO_2 in 2005 and has been growing slightly (1% to 3%) since then. As shown in Fig. 12, even with 50% reductions by 2050, the greenhouse blanket will continue to get thicker. CO_2 concentrations will increase to 440 ppm (from its 2005 value of 385 ppm) and add another 1 Wm^{-2} to the heat trapped. This will lead to an additional warming of 0.8°C, most of which will be realized by end of this century. The cumulative warming, from pre-industrial times, will likely exceed 2°C by mid-century (see the blue curve in Fig. 12). This result leads to two important deductions:

> First, to limit large future warming, we have to start reducing CO_2 emissions now. For example, had we kept the emissions at the 2005 value of 35 GT/Yr until 2100, the CO_2 concentrations would have exceeded 550 ppm by 2100 and the warming would have exceeded 4°C.
>
> Second, CO_2 reductions by itself, is not sufficient to limit the warm-

ing to 2°C during this century. In fact, in our model the warming is likely to exceed 2°C by mid-century. This is because of several factors: 1) The GHG blanket is already thick enough to warm the planet by more than 2°C; 2) About 50% of this has been masked by air pollution aerosols (Sulfates-Organics-Nitrates: 'SON Mask') (Fig. 13) and we are unmasking this warming by air pollution laws; 3) The lifetime of CO_2 is long (century to more than 1000 years) and we have delayed mitigation actions too long to stave off the short-term problem.

The short-term problem

The solution for avoiding exceeding the 2°C warming in the short term (this century) has to lie elsewhere (12,20,21). Fortunately there is another avenue. Not all of the present day greenhouse warming is due to CO_2 (Fig. 13). In addition to CO_2, other manmade GHGs, methane, halocarbons, tropospheric ozone and nitrous oxide, N_2O, have added as much as 80% of the heat added due to CO_2 (12). In addition, black carbon aerosols (also known as soot), have added about 25% to 50% of the heat added due to CO_2. Of these non-CO_2 climate warmers, methane, some halocarbons (HFCs), tropospheric ozone and black carbon have very short lifetimes ranging from several days (black carbon) to a decade (methane) or two (HFCs). As a result, their concentrations and hence the heat trapped will decrease within weeks (in the case of black carbon) to a few decades (for methane and HFCs) of reductions in emissions. The next big advantage is the technologies which exist to reduce their emissions drastically by 30% to 50%. The real major benefits are the co-benefits to health, agriculture and water. A scenario estimate, in which these 4 short-lived climate forcers are reduced by 30% to 50% by 2050, shows that we can delay the 2°C warming by several decades (Fig. 12).

IV. Project Surya: knowledge to action for protecting Himalayan glaciers

As discussed earlier, direct heating of the atmosphere and the ice/snow surfaces by black carbon and organic carbon is one of the major forcing factors contributing to the melting of the ice and snow in the Himalayas. In South Asia about 60% of the black and organic carbon emissions from biomass burning and cooking and heating with biomass fuels is a dominant source for such emissions. It starts off as indoor smoke and spreads outdoors into widespread brown clouds, with impacts as far downstream as the Indian Ocean (22). Inhalation of the indoor smoke by women and children, as well as exposure outdoors in the form of ABCs, are responsible for 500,000 to 1 million deaths annually. The ozone produced by CO from the smoke and its subsequent impacts on agriculture and the impacts of the ABCs on rainfall and dimming leads to millions tons of crop damages (ABC-Asia Report). Over 800 million S. Asians are too poor to afford fossil fuels and hence are forced to burn solid biomass (fire wood; crop residues; dung).

The world has an unprecedented opportunity to mitigate some of the disastrous effects of black carbon and ozone on climate, agriculture, water and health with a simple act: replacing traditional cook stoves with energy efficient and pollution-free cooking technologies. While this work has already begun with international initiatives like the Global Alliance for Cook Stoves, challenges remain. The numerous cook stove initiatives that have taken place all over the world have demonstrated time and again that catalyzing widespread adoption of such clean cooking technologies will require innovative and affordable solutions. This is where Project Surya comes in.

Project Surya (www.projectsurya.org) is an internationally recognized cook stove project sponsored by the United Nations Environment Programme. The goal of Project Surya is to scientifically demonstrate the environmental and health benefits of the introduction of clean cooking technologies, with the ultimate goal of providing a rigorous evidence base for large-scale action in this area. Project Surya aims to deploy improved cooking technologies in a contiguous region with a population of approximately 50,000. The resulting "black carbon hole" that will be created in the otherwise omnipresent pollution cloud will be measured across space and time to quantify the multi-sector impacts of better cooking technologies. Project Surya will use cell phones, instrument towers, and satellites, and will empower village youth to work with world-class experts in documenting the impacts. A pilot phase was successfully completed in 2010 in a village in North India, one of the poorest and most polluted regions in the Indo-Gangetic plains. This pilot phase has already achieved a number of ambitious and measurable outcomes including documenting the connection between indoor air pollution from cooking and ambient outdoor pollution levels; identifying improved cooking technologies that reduce pollution significantly; deploying improved cook stoves in all households in the pilot village (about 500); and verifying that we will be able to measure the impacts of a larger-scale intervention. In addition, a parallel pilot test has been started in Nairobi, Kenya. Our recent data has additionally shown that the *measured* black carbon emissions are three to five times higher than the climate models predicted, making it all the more urgent to take action now to target black carbon and other short lived climate forcers.

V. Summary: following a success story

Fortunately, there is a great success story to draw upon in the case of non-CO_2 climate warmers. The enormous greenhouse effect of CFC-11 and CFC-12 was discovered only in 1975 (23). CFC was regulated by the Montreal Protocol (21) in 1987 due to its negative effects on stratospheric ozone without which CFCs would have added enough heat energy to warm the planet by about 1°C or more (24,25). Likewise, China and India have a common interest in cutting black carbon and ozone that are melting their shared glaciers, killing millions and destroying millions of tons of crops, while the US and Europe share common interest in the arctic where black carbon along with other short-lived pollutants are responsible for almost 50% of the melting ice. Modest steps that attack the short-lived climate forcers, with fast and measurable responses, is a better way to jump-start the stalled climate mitigation actions.

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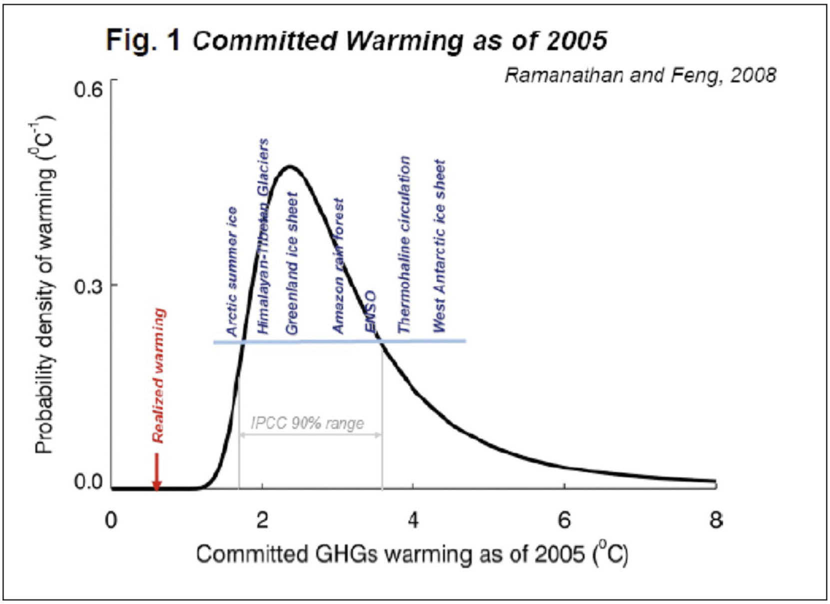


Fig. 1 Committed Warming as of 2005
Ramanathan and Feng, 2008
Probability density of warming (°C⁻¹)
0.6
0.3
0.0
Realized warming
Arctic summer ice
Himalayan-Tibetan Glaciers
Greenland ice sheet
Amazon rain forest
ENSO
Thermohaline circulation
West Antarctic ice sheet
IPCC 90% range
0
2
4
6
8
Committed GHGs warming as of 2005 (°C)

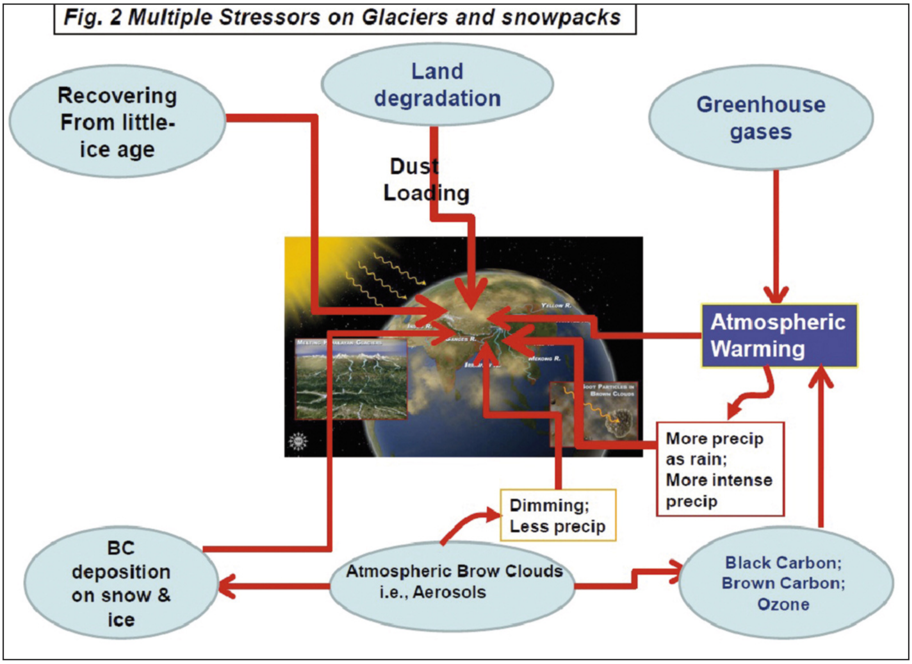


Fig. 2 Multiple Stressors on Glaciers and snowpacks
Recovering From little-ice age
Land degradation
Greenhouse gases
Dust Loading
Atmospheric Warming
More precip as rain; More intense precip
Dimming; Less precip
BC deposition on snow & ice
Atmospheric Brow Clouds i.e., Aerosols
Black Carbon; Brown Carbon; Ozone

Fig. 3: Altitude dependence of Temperature Trends over the Tibetan Plateau
Source: Liu et al, 2009

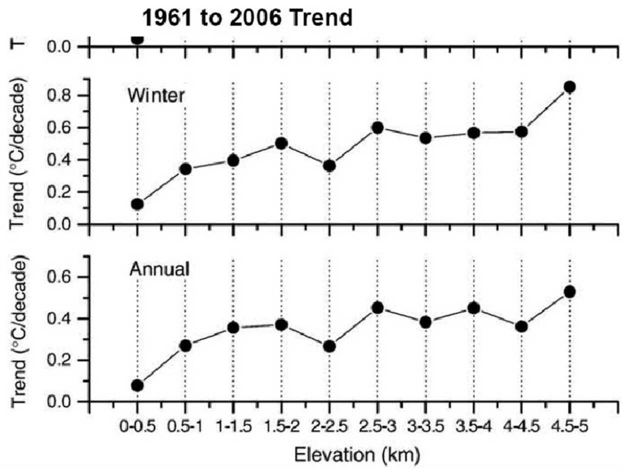


Fig. 4: Brown Cloud Photos

Fig. 5 CALIPSO Aerosol Depth: Ramanathan et al, Nature, 2007

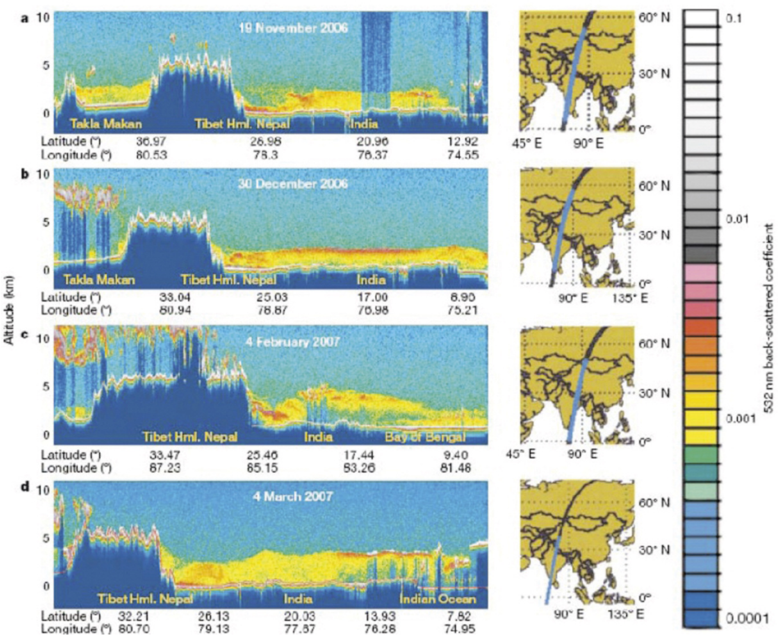


Fig. 6 Warming trends in Asia amplified by brown cloud solar absorption

Veerabhadran Ramanathan[1], Muvva V. Ramana[1], Gregory Roberts[1], Dohyeong Kim[1], Craig Corrigan[1], Chul Chung[1] & David Winker[2]
Nature 2007

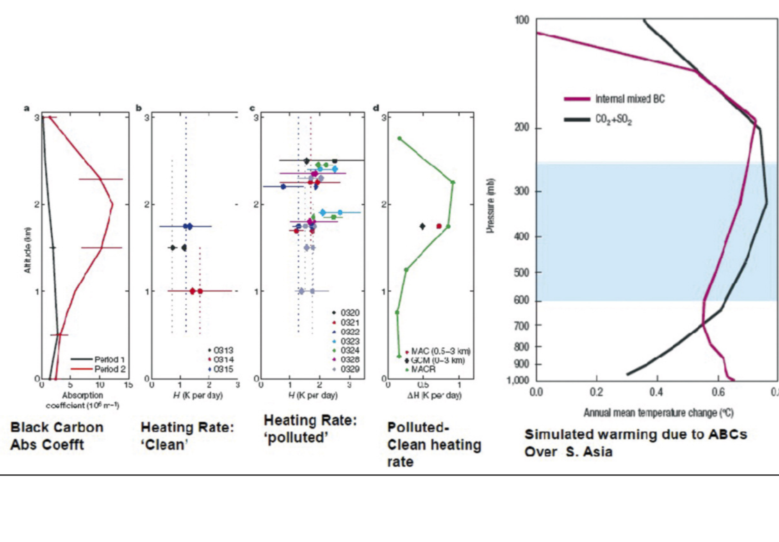


Fig. 7: Differential Temp Trend: Troposphere - Surface

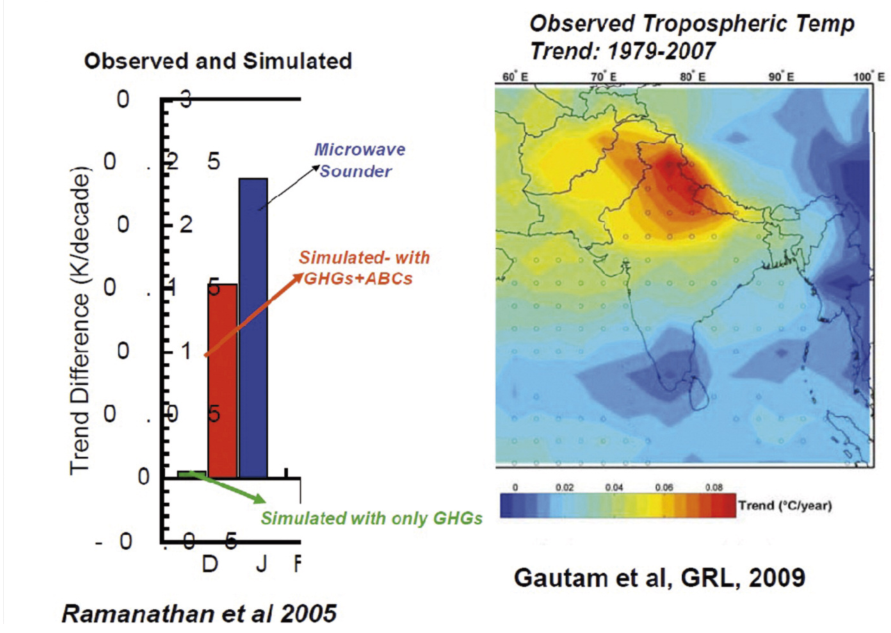
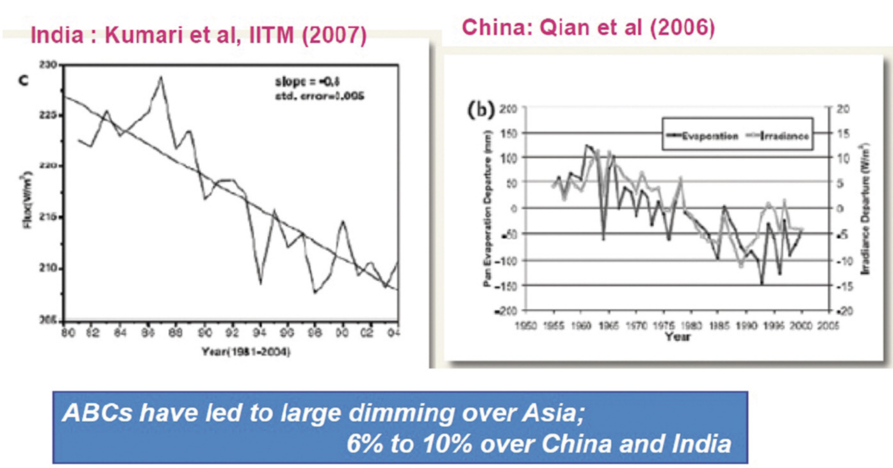


Fig. 8 OBSERVED DIMMING TRENDS OVER INDIA AND CHINA



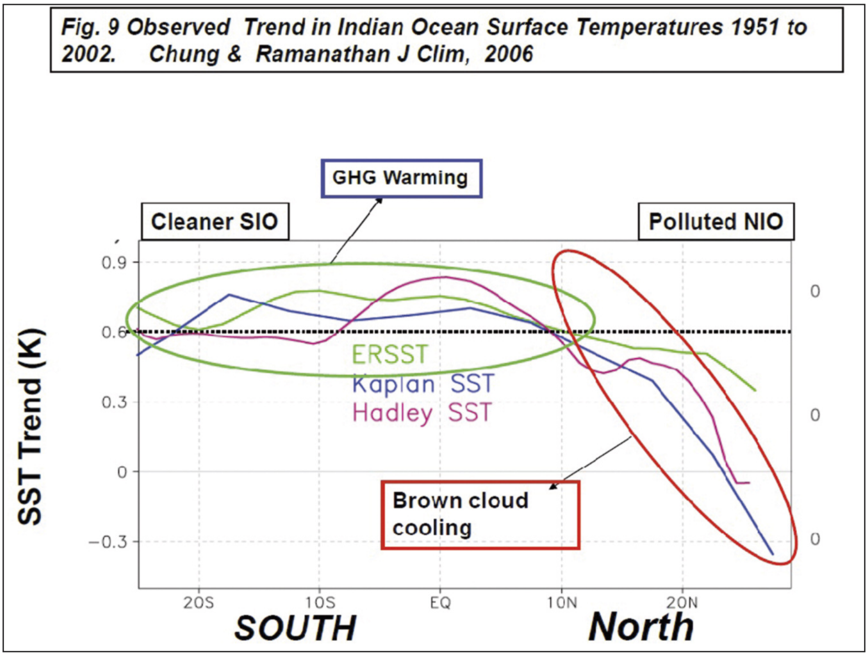


Fig. 9 Observed Trend in Indian Ocean Surface Temperatures 1951 to 2002. Chung & Ramanathan J Clim, 2006
GHG Warming
Cleaner SIO
Polluted NIO
SST Trend (K)
0.9
0.6
0.3
0
−0.3
ERSST
Kaplan SST
Hadley SST
Brown cloud cooling
20S
10S
EQ
10N
20N
SOUTH
North

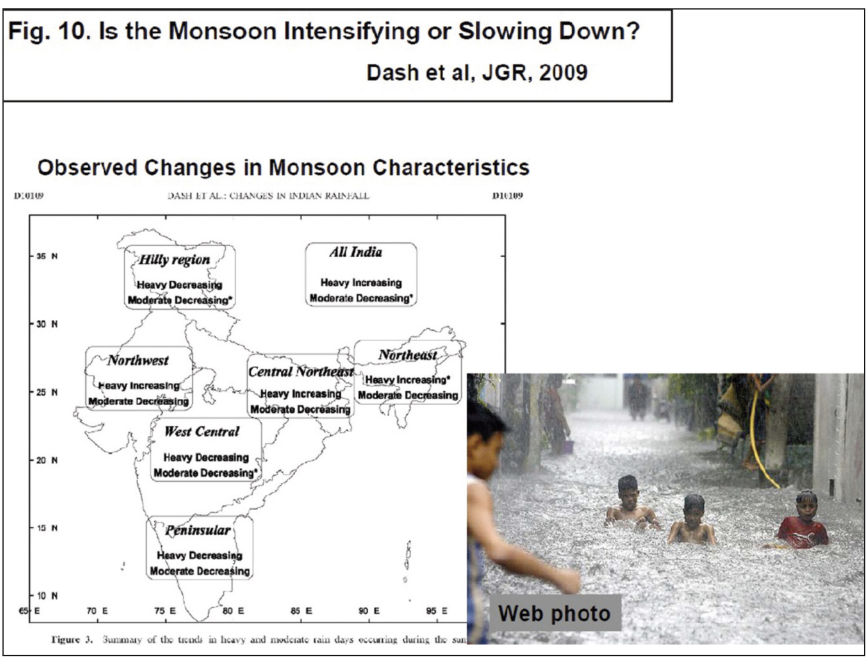
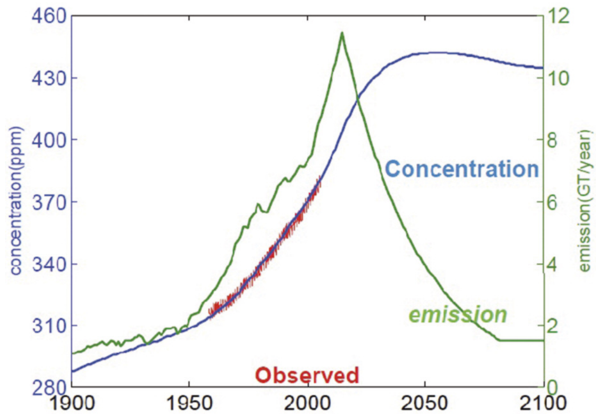


Fig. 10. Is the Monsoon Intensifying or Slowing Down?
Dash et al, JGR, 2009
Observed Changes in Monsoon Characteristics
D10109
DASH ET AL.: CHANGES IN INDIAN RAINFALL
D10109
Hilly region
Heavy Decreasing
Moderate Decreasing*
All India
Heavy Increasing
Moderate Decreasing*
Northwest
Heavy Increasing
Moderate Decreasing
Central Northeast
Heavy Increasing
Moderate Decreasing
Northeast
Heavy Increasing*
Moderate Decreasing
West Central
Heavy Decreasing
Moderate Decreasing*
Peninsular
Heavy Decreasing
Moderate Decreasing
35 N
30 N
25 N
20 N
15 N
10 N
65 E
70 E
75 E
80 E
85 E
90 E
95 E
Web photo

Fig. 11. Can we rely on drastic CO_2 reductions alone?
Scenario: 50% by 2030 and 80% by 2075. Source: Ramanathan and Xu, 2010



<u>By 2050</u>
CO_2 still increases: to 440 ppm
1 Wm^{-2} Heating added
0.8 C additional warming committed

Fig. 12. A Prudent, Practical and Effective Mitigation Solution:

I. Prevent 2^0C warming this century: Reduce Short-Lived Climate Forcers (Black Carbon, Methane, Ozone and Halocarbons)
II. Maintain it below 2C warming beyond 2100: Start Reducing CO_2 Now

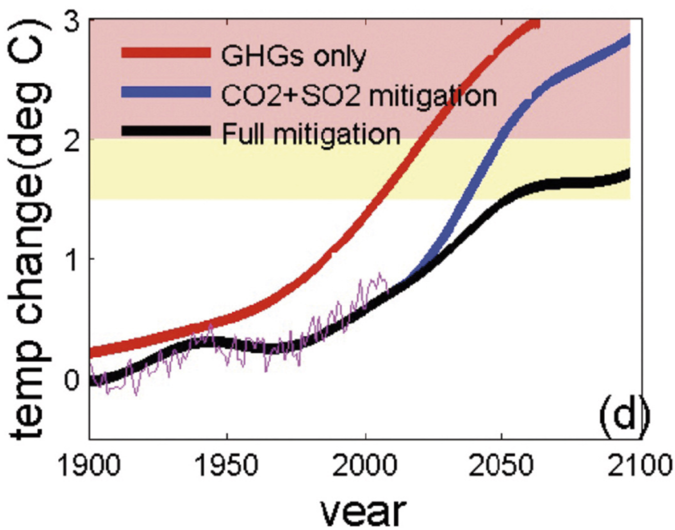
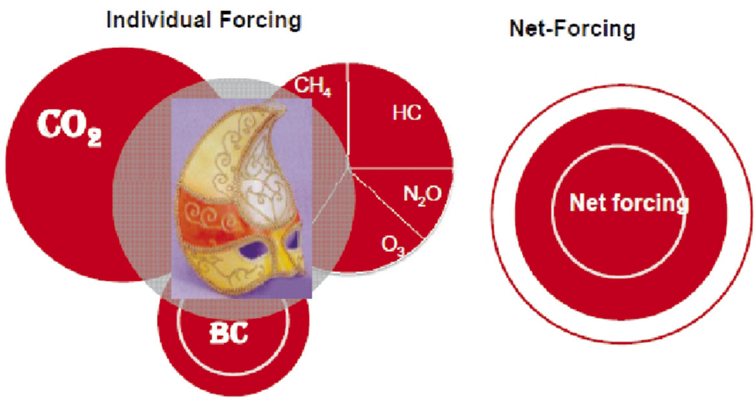


Fig. 13. Radiative Forcing (Wm^{-2}) as of 2005: Heat Trapped by CO_2, Non-CO_2 gases, Black Carbon Aerosol and Masking (heat reflected) by Sulfates-Organics-Nitrates Aerosols:



The area of each circle scales with its forcing. The CO_2 forcing is 1.65 W/m^2. CH_4 is methane, HC is halocarbons, N_2O is nitrous oxide, O_3 is tropospheric ozone, and BC is black carbon. The translucent area with mask represents the cooling effect of sulfate, organic, and nitrate aerosols. (Source: Ramanathan and Xu, 2010)