Role of Black Carbon on Global and Regional Climate Change

V. Ramanathan
Scripps Institution of Oceanography
University of California at San Diego

Testimonial to the House Committee on Oversight and Government Reform
Chair: The Honorable Henry A Waxman

Hearing on the role of black carbon as a factor in climate change

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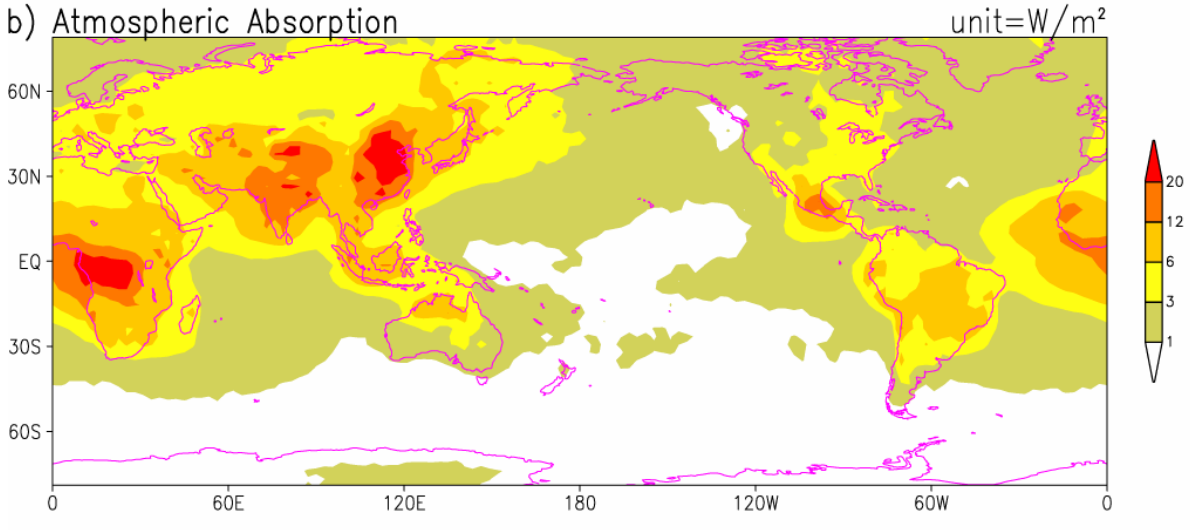
Some of the material in this paper is extracted from lectures given at the Pontifical Academy of Sciences, Vatican, (2006), the Bjerknes lecture given at the AGU fall symposium in San Francisco (2006) and the keynote talk at the *17th International Conference on Nucleation and Atmospheric Aerosols, Galway, Ireland (2007)*



Atmospheric Solar Heating (Wm^{-2}) by Black Carbon for the period 2000-2003.

Synopsis

Our understanding of the impact of black carbon (BC) aerosols has undergone major revisions, due to new experimental findings from field observations such as the Indian Ocean Experiment (Ramanathan *et al.* 2001b) and ACE-Asia (Huebert *et al*. 2003), new satellite observations (MODIS, MISR and CALIPSO), surface observatories such as AERONET (Holben *et al*. 2005) and Atmospheric Brown Cloud (ABC) Observatories (Ramanathan *et al*. 2007a), and aerosol chemical-transport models (Carmichael et al, 2003 and Chin et al, 2002 and Collins et al, 2001; Jacobson, 2002). Black carbon is a form of aerosol (suspended particle in the air) emitted as soot, both indoors (from cooking with wood, cow dung and crop residues) and outdoors through bio mass burning, coal and diesel combustion. The indoor smoke ultimately escapes outdoors and becomes part of air pollution. The outdoor pollution starts off as urban or rural haze. Fast atmospheric transport spreads the haze far and wide, in about 2 to 7 days, over an entire sub-continent or an ocean basin (see images in text).

Basically, black carbon solar absorption, gives rise to the blackish color in the vicinity of the smoke (e.g, tailpipe of a diesel truck) and contributes to the brownish color in the sky. In the atmosphere, BC is mixed with other aerosols such as sulfates, nitrates, numerous organic acids and dust (Guazotti et al, 2001), and together, the mix of manmade particles are sometimes referred to as Atmospheric Brown Clouds (ABCs). Globally, biomass and biofuel burning contributes about 65% and fossil fuel about 35% (Bond et al, 2004). There is a significant uncertainty (factors ranging from 2 to 5) in estimates of emission strengths. Until 1960s extra-tropical regions were the major sources of BC emissions, while now the major source regions have shifted to tropical regions (Bond et al 2007).

The greenhouse effect of CO_2 and gases arise from the trapping of heat radiation (also known as infrared radiation) given off by the earth's surface. On the other hand, the warming effect of BC arises because it absorbs (retains or traps) the solar radiation reflected by the earth's surface and clouds, which would have otherwise escaped to space. The CO_2 warming effect is known within $\pm$15%, whereas the estimated BC effect is subject to a threefold or larger uncertainty. Black carbon plays a major role in the dimming of the surface and a correspondingly large solar heating of the atmosphere. When globally averaged, BC is estimated to exert a net positive radiative forcing at the top-of-the atmosphere (i.e, a global warming effect). The estimates of BC heating by this author's group (Chung et al, 2005 and Ramanathan et , 2007a), using observationally constrained data from satellites, ground stations and field observations is that the current BC radiative forcing at the top-of-the atmosphere (the so-called radiative forcing as per IPCC) effect is as much as 60% of the current radiative forcing due to CO_2 greenhouse effect. Thus, next to Carbon Dioxide (CO_2), black carbon (BC) in soot particles is potentially the second major contributor to the observed twentieth century global warming (also see Jacobson 2002).

Reverting to the general effects of all aerosols (and not just BCs), ABCs enhance scattering and absorption of solar radiation and also produce brighter clouds (IPCC, 2007) that are less efficient at releasing precipitation (Rosenfeld et al, 2001). These in turn lead to large reductions in the amount of solar radiation reaching Earth's surface (also known as dimming), a corresponding increase in atmospheric solar heating, changes in atmospheric thermal structure, surface

cooling, atmospheric warming, alterations of north-south and land-ocean contrast in surface temperatures, disruption of regional circulation systems such as the monsoons, suppression of rainfall, and less efficient removal of pollutants (Ramanathan et al, 2001b, 2005, 2007b; Menon et al, 2001). Together the aerosol radiation and microphysical effects can lead to a weaker hydrological cycle and drying of the planet which connects aerosols directly to availability of fresh water, a major environmental issue of the 21st century (Ramanathan et al, 2001b). For example, the Sahelian drought during the last century is attributed by some models to aerosols (Rotstayn and Lohman, 2002). In addition, new coupled-ocean atmosphere model studies suggest that aerosols may be the major source for some of the observed drying of the land regions of the planet (e.g India and northern China) during the last 50 years (Ramanathan et al, 2005 and Meehl et al, 2007). Regionally aerosol induced radiative changes (forcing) are an order of magnitude larger than that of the greenhouse gases, but because of the global nature of the greenhouse forcing, its global climate effects are still more important. However there is one important distinction to be made. While the warming due to the greenhouse gases is projected to increase global average rainfall, the large reduction in surface solar radiation due to absorbing aerosols would decrease it.

The regional effects of BC are estimated to be particularly large over Asia, Africa and the Arctic. In these regions its effects, during the last century, may have been just as important as CO_2 in altering surface and atmospheric temperatures, monsoon circulation and rainfall patterns, and retreat of sea ice in the arctic and the retreat of glaciers in the Himalayas. However, this situation will change in a few decades, when CO_2 will become the dominant contributor to climate changes, both on global and regional scales. The interaction of the regional climate effects of greenhouse gases and ABCs deserve more attention. For example, a recent study (Ramanathan *et al*. 2007b) employing unmanned aerial vehicles suggest that BC enhances atmospheric solar heating by as much as 50%. When this data are combined with CALIPSO and other satellite data over S, SE Asia and the Indian Ocean and employed in a climate model, the simulations suggest the lower atmospheric warming over the S and SE Asian region, (including the elevated Himalayan regions) by ABCs is as much as that due to the greenhouse warming. Thus the atmospheric solar heating by BC may be intensifying the greenhouse gas effects on the Himalayan glacier retreat.

BC warming effect offers an opportunity to mitigate the projected warming trends in the *short term* (as also suggested by others, e.g, Jacobson, 2002; Bond and Sun, 2005). My thesis is that, BC reductions have the potential to delay the time of onset of the so-called dangerous climate change. For example, a reduction of BC emissions by a factor of 5, may reduce the radiative forcing (i.e. change in the net energy added to the planet) by about 0.3 Wm^{-2} to 0.8 Wm^{-2}. In comparison, if CO_2 continues to increase at the current rate of increase, it will add about 0.3 Wm^{-2} per decade. Thus a drastic reduction in BC has the potential of offsetting the CO_2 induced warming for a decade or two. Effectively, BC reduction may provide a possible mechanism for buying time to develop and implement effective steps for reducing CO_2 emissions. There are three issues that need to be factored in further consideration of this proposal:

i) The life time of BC is of the order of days to several weeks, depending on the location. Thus the BC concentration and its global heating will decrease almost immediately after reduction of its emission;

ii) Inhalation of soot is a major public health issue. For example, in India, alone it is estimated inhalation of indoor smoke is responsible for over 400,000 deaths annually (mostly among women and children; Pachauri and Sridharan, 1998). Air pollution related fatalities for Asia is estimated to be as high as 2 million (indoor smoke inhalation and outdoor brown clouds). Thus reduction of BC emissions may be warranted from public health considerations too.

iii) The developed nations have reduced their BC emissions from fossil fuel sources by a factor of 5 or more since the 1950s. Thus the technology exists for a drastic reduction of fossil fuel related BC. With respect to biofuel cooking, it can be reduced of not eliminated, by providing alternate cooking methods to rural areas in Asia and Africa. But we need to conduct a careful and well documented scientific study of the impact of BC reduction on radiative forcing and its cost effectiveness. Towards this goal, this author along with a team of NGOs, public health experts and alternate energy experts, has proposed Project Surya, that will adopt a large rural area of about 20,000 population, in India, and provide alternate cooking with biogas plants, smoke free cookers and solar cookers. The objective of the pilot phase of this experiment is to estimate from observations, the warming potential of BCs and the impact of BC reduction on human health (http://www-ramanathan.ucsd.edu/ProjectSurya.html) and the cost of reducing BC emissions from biofuels. Results from this pilot experiment will be used to scale up for the entire sub continent.

iv) The notion that we may reach the state of dangerous climate change during this century is increasingly perceived as a possibility. Given this development, options for mitigating such dangerous climate changes. The present BC reduction proposal should also be considered in this context, and by no means, BC reduction is being proposed by this author as an alternative to CO_2 reduction. At best, it is a short term measure, to buy a decade or two time for implementing CO_2 emission reduction.

I. Global Effects of Anthropogenic Aerosols

The global build up of greenhouse gases (GHGs), is the most vexing global environmental issue facing the planet. GHGs warm the surface and the atmosphere with significant implications for, rainfall, retreat of glaciers and sea ice, sea level, among other factors. What is less recognized, however, is a comparably major global problem dealing with air pollution. Until about ten years ago, air pollution was thought to be just an urban or a local problem. But new data (Ramanathan et al 2001a and 2007a) have revealed that, due to fast long range transport, air pollution is transported across continents and ocean basins, resulting in trans_oceanic and trans-continental plumes of atmospheric brown clouds (ABCs) containing sub micron size particles, i.e, aerosols, consisting of sulfates, nitrates, black carbon(a mix of elemental carbon and organic carbon compounds) among numerous other compounds. ABCs intercept sunlight by absorbing as well as reflecting it, both of which, lead to a large reduction of solar radiation at the surface (sometimes referred to as dimming). The dimming effect is enhanced further because aerosols nucleate more cloud drops which makes the clouds reflect more solar radiation. The other side of this dimming issue, is the absorption of solar radiation by ABCs (mainly by black carbon), which adds solar heating to the lower atmosphere. The sum of the surface dimming and atmospheric solar heating is the so-called top-of-atmosphere (TOA) radiative forcing (as per IPCC), which is estimated by us to be about -1.5 Wm^{-2} ($\pm$0.75 Wm^{-2}). When this is compared with the 3 Wm^{-2} (TOA) forcing due to greenhouse gases, it leads us to the conclusion that, globally, ABCs may have masked as much as 50% ($\pm$25%) of the warming due to greenhouse gases. Note that the uncertainty estimates given inside the parentheses should be interpreted as follows: The masking effect has a three-fold range of 25% to 75%. The logical deduction from this estimate is that, if and when air pollution regulation succeeds in eliminating the emission of these particles, the surface warming can intensify by about 0.7 to 1.5 K, where the range is due to a range in assumed climate sensitivity of 2 to 4 K due to doubling of CO_2. When this range is factored in with the threefold uncertainty in the aerosol masking effect, stopping the emission of anthropogenic aerosols, could result in a global mean warming of about 0.4 ºC to 2.4 ºC. Similar conclusions of the role of ABCs have been inferred by others (e.g, see Andreae *et al*. 2003). There are two key issues: First the life time of ABCs in the atmosphere are of the order of weeks and thus atmospheric concentrations of ABCs as well as their radiative forcing will respond (i.e. decrease) within several weeks after the emission reductions. However, the climate system may take a decade or more to respond completely to the reduction in aerosol forcing due to the inertia of the ocean-atmosphere system.

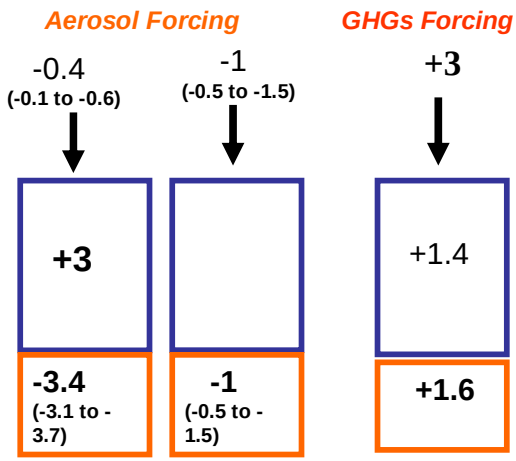


Figure 1. Global Mean anthropogenic forcing due to aerosols (the two panels on the right) and due to greenhouse gases. The blue boxes show the atmospheric forcing; the brown box at the bottom show the surface forcing; the sum of the two is the forcing at top-of-atmosphere (TOA). The aerosol values are estimayed for 2000 to 2003 and are taken from Ramanathan *et al*. (2001) and Chung *et al*. (2005) and Ramanathan (2007), while the GHGs at TOA is from IPCC (2007) for 2006. Also see Crutzen *and Ramanathan* (2003) on the *parasol* effect of aerosols.

The global mean estimates shown in Fig 1 underscores the relative contributions of aerosols and GHGs at the surface, the atmosphere and the surface. While at the surface, the aerosol dimming (negative forcing of -4.4 Wm^{-2}) is much larger than the GHGs forcing of 1.6, the positive atmospheric forcing of 3 Wm^{-2} within the atmosphere by aerosols (ABCs) enhances the GHGs forcing of +1.4 Wm^{-2}, such that the sum of the surface and the atmospheric forcing, i.e, forcing at TOA, is -1.4 Wm^{-2} for ABCs and +3 Wm^{-2} for GHGs. Thus the net anthropogenic forcing by anthropogenic modification of the radiative forcing is positive.

Because of the large reduction of solar radiation at the surface (see Fig 1, the bottom box in the left and middle panels) ABCs can lead to a weaker hydrological cycle and drying of the planet which connects aerosols directly to availability of fresh water, a major environmental issue of the 21st century. Thus, there is one important distinction to be made: *While the warming due to the greenhouse gases will make the planet wetter, i.e. more rainfall, the large reduction in surface solar radiation due to absorbing aerosols will make the planet drier (Ramanathan et al, 2001a).*

The Particular Role of Black Carbon

Some aerosols, like sulfates and nitrates, have a negative forcing (surface cooling effect) while black carbon has a net positive forcing (surface warming). Black carbon is a mix of elemental and organic carbon emitted by fossil fuel combustion, bio mass burning and bio-fuel cooking (wood fires and cow dung) as soot. In the atmosphere, black carbon aerosols are mixed with sulfates and organics and it is not straight forward to untangle the effect of black carbon from that of the mixed (black carbon and others) aerosol. Thus most if not all of the published estimates of black carbon are derived from models. Black

carbon affects the radiative forcing of the planet in many different ways (taken from Ramanathan *et al,* 2001):

i) Interception of direct sunlight: BC absorbs the direct solar radiation and this is the largest contributor to the surface dimming and atmospheric solar heating by ABCs. This effect, however, does not contribute too much to the top-of-the atmosphere forcing, and its main contribution is to reduce the surface solar heating and thus perturb the hydrological cycle. Globally, its effect is to reduce evaporation and rainfall.

ii) Interception of reflected sunlight: BC also absorbs the solar radiation reflected by the surface and clouds and thus reduces the solar radiation reflected to space by the earth-atmosphere system. It is this effect that is the main contributor to the positive radiative forcing by BC.

iii) Deposition in Sea Ice and snow: Deposition of BC over sea ice and snow, increases the absorption of solar radiation by ea ice and snow which is another source of positive radiative forcing.

iv) In addition to the above direct effects, BC solar heating is linked with evaporation of low clouds which is another source of positive radiative forcing.

Based on the observationally constrained regional effects of ABCs shown later (from Chung *et al*. 2005 and Ramanathan *et al*. 2007b), we estimate the net effect of BC (from items i and ii above) for the 2000 to 2003 period to be about **+0.9 Wm^{-2}**. This should be compared with the 1.6 due to CO_2 and 1.4 Wm^{-2} due to all other greenhouse gases (CH_4, N_2O, Tropospheric Ozone and Halons, IPCC, 2007). The published estimates for item iii varies from + 0.1 to 0.3 Wm^{-2}. Thus, with a combined forcing (from items i, ii, and iii) of **1 to 1.2 Wm^{-2}** ($\pm$ 0.4 Wm^{-2}) BC is likely to be the second most important contributor (next to CO_2) to global warming.

II. Regional Hotspots of ABCs

It is important to recognize that ABCs are a hemispherical to global scale problem. However, because of the short life times (days to weeks) ABCs are concentrated in regional and mega-city hot spots. Long range transport from these hot spots gives rise to wide spread plumes over the adjacent oceans (see Fig 2). Using satellite data such as those shown in Fig 2, Ramanathan *et al*. (2007b) recently identified *5 regional hot spots* around the world: *1) East Asia* (eastern China, Thailand, Vietnam and Cambodia); *2) Indo-Gangetic Plains in S Asia* (the north west to north east region extending from eastern Pakistan, across India to Bangladesh and Myanmar***);*** 3) Indonesia; 4) Southern Africa extending southwards from sub-Saharan Africa into Angola and Zambia and Zimbabwe; 5) The Amazon basin in S America. In addition, the following 13 *mega city hot spots* have been identified: *Bangkok, Beijing, Cairo, Dhaka, Karachi, Kolkata, Lagos, Mumbai (Bombay), New Delhi, Seoul, Shanghai, Shenzen and Tehran*. Over these hotspots, the annual mega AODs exceed 0.3 and the absorption optical depth is about 10% of the AOD, indicative of the presence of strongly absorbing soot accounting for about 10% of the anthropogenic aerosol amount.

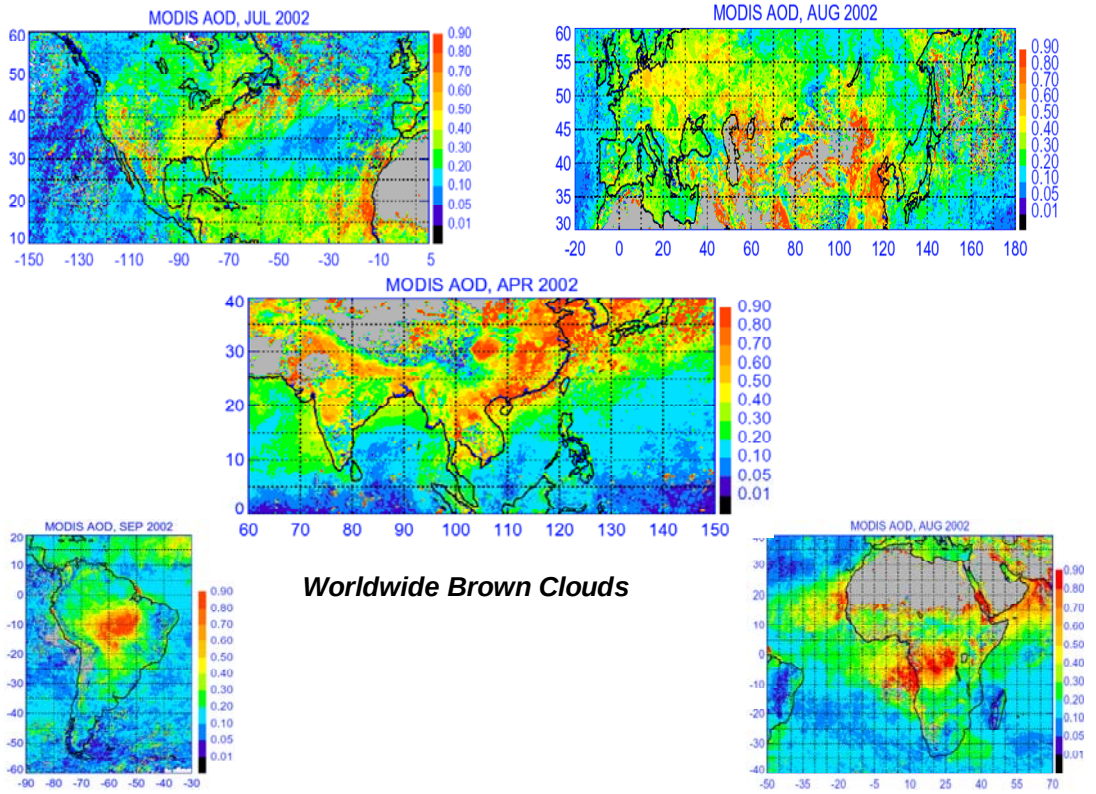


Figure 2. Monthly mean aerosol optical depths derived from MODIS aerosol instrument on NASA's TERRA satellite. The optical depth is a good index for the product of the aerosol number concentration and their surface area from the surface through the depth of the atmosphere. The color shading is dark blue for AODs smaller than 0.05 (clean marine background); green for 0.2 (visible brown clouds) , yellow for 0.4 to 0.5 (very hazy)and red for AODs>0.6 (heavily polluted). Source: Ramanathan et al (2007).

III. Surface Dimming by ABCs

Is the Planet dimmer now than it was during the early twentieth Century? Solar radiometers around the world are indicating that surface solar radiation in the extra tropics was less by as much as 5% to 10% during the mid twentieth century (e.g, see Stanhill, and Wild et al), while in the tropics such dimming trends have been reported to extend into the twenty first century. But many of these radiometers are close to urban areas and it is unclear if the published trends are representative of true regional averages. The Indian Ocean Experiment (Ramanathan et al 2001b) used a variety of chemical, physical and optical measurements to convincingly demonstrate (Satheesh and Ramanathan, 2000) that ABCs can lead to dimming as large as 5% to 10% (i.e, decrease in annual mean absorbed solar radiation of about 15 $W.m^{-2}$), over widespread regions in the N Indian Ocean and S Asia. In order to get a handle on the global average dimming,

recently we integrated such field observations with satellite data and aerosol transport models to retrieve an observationally constrained estimate.

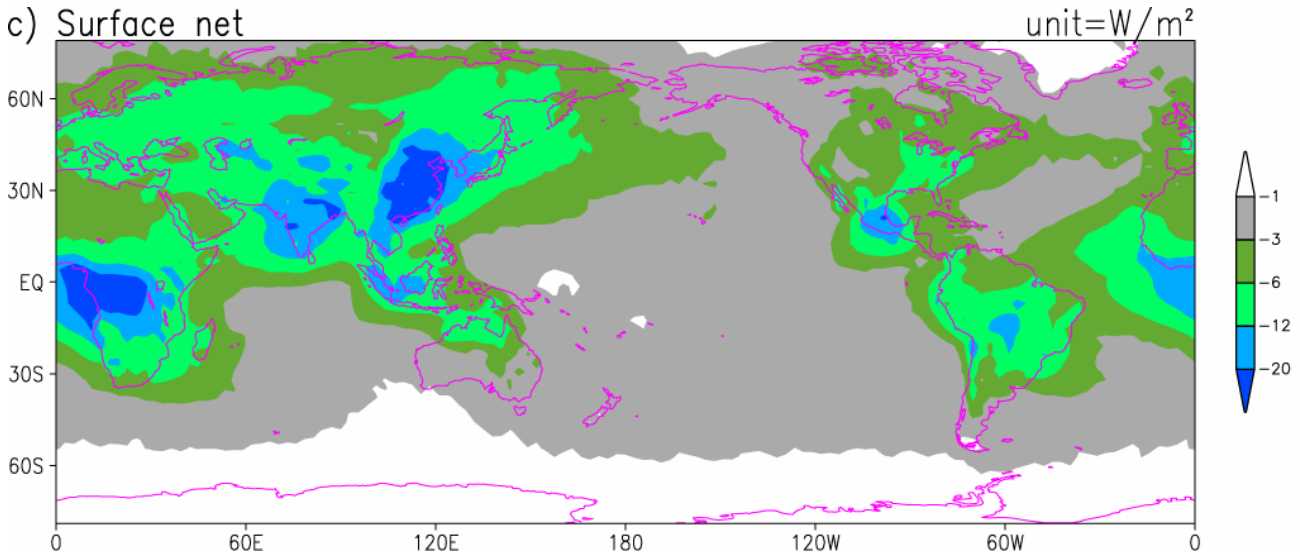


Figure 3. Integrated and Observationally constrained estimate of Annual mean Global Dimming by ABCs around the world for 2001-2003. Ref: Chung, Ramanathan, Podgorny and Kim, 2005.

As seen from Fig.3, over large regions the reduction of solar absorption at the surface exceeds 12 Wm^{-2} (>5%), which is consistent with the dimming reported from surface observations. The global-annual average dimming (for 2002), however, is -3.5 $W.m^{-2}$, as opposed to 10 to 20 Wm-2 global averaged dimming estimated by studies that used surface radiometers over land areas. *Thus great care should be exercised to extrapolate surface measurements over land areas to global averages*. The global dimming of -3.5 Wm^{-2} has been compared with the GHGs forcing of 3 Wm^{-2} from 1850 to present, i.e, 2005, (IPCC, 2007). Such comparisons, without a proper context could be misleading, since the dimming at the surface is not the complete forcing. It does not account for the atmospheric solar heating by ABCs, discussed next.

IV *Global Solar Heating of Atmosphere by BCs*

There is an important distinction in the forcing by scattering aerosols, like sulfates, and that due to absorbing aerosols like soot (see Ramanathan et al 2001 for a detailed elaboration of the points noted below). For sulfates, the dimming at the surface, is nearly the same as the net radiative forcing due to aerosol since there is no compensatory heating of atmosphere, and hence a direct comparison of the surface dimming with GHGs forcing is appropriate. For soot, however, the dimming at the surface is mostly by the increase in atmospheric solar absorption, and hence the dimming does not necessarily reflect a cooling effect. It should also be noted that the dimming at the surface due to soot solar absorption can be factor of 3 larger than the dimming due to reflection of solar (a

cooling effect). Figure 3 below shows our recent estimates of the global distribution of the atmospheric solar heating by manmade aerosols for the period 2001-2003.

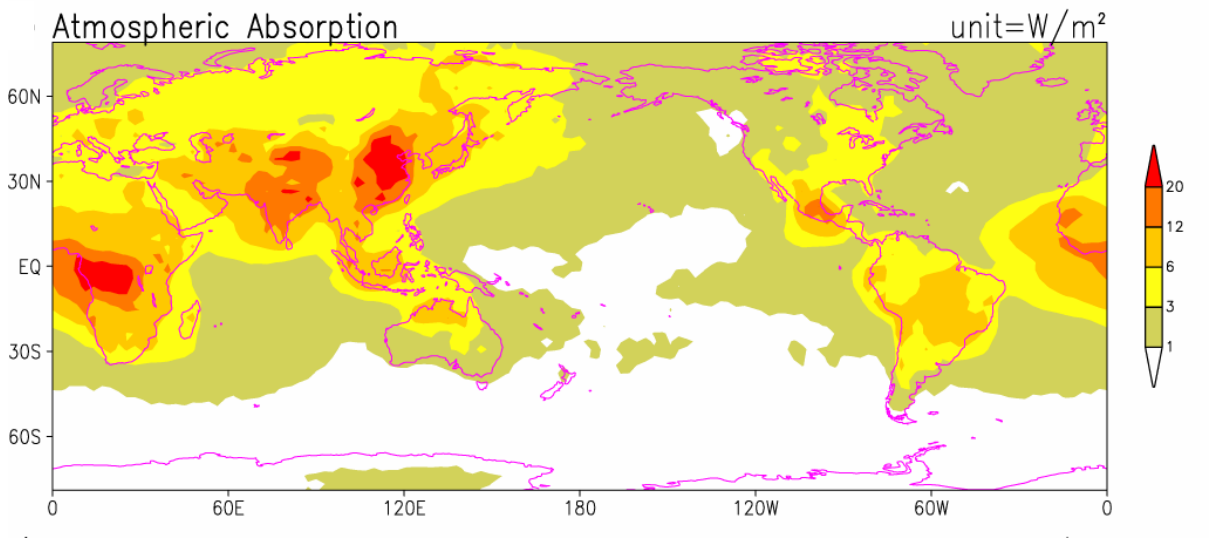


Figure 4. **Integrated and observationally constrained estimate of annual mean atmospheric Solar heating by ABCs for 2001-2003. Ref: Chung, Ramanathan, Podgorny and Kim (2005).**

V. Interactions between GHGS and ABCs on Regional Scales

The Asian Monsoon

The fundamental driver of evaporation of water vapor is absorbed solar radiation at the surface, particularly, over the sea surface. The precipitation over land is driven by two major source terms: evaporation from the land surface and long range transport of moisture from the oceans and its subsequent convergence over the land regions. It is then logical to posit that the large reduction of absorbed solar radiation by the land and sea surface due to interception of sunlight by ABCs (Fig 2) should lead to an overall reduction of rainfall. The observed precipitation trends over the last 50 years reveal major regions which experienced an overall reduction of rainfall (Sahel and the Indian monsoon) as well as a shift in the rainfall patterns (Fig 4). Numerous climate model studies have been published which suggest that inclusion of the aerosol dimming can help explain the Sahelian drought (Rotstayn and Lohmann, 2002); the decrease in Indian monsoon rainfall (Chung and Ramanathan, 2002; Ramanathan *et al*, 2005; Meehl *et al*. 2007; Lau *et al*. 2007); and the north-south shift in east Asian rainfall (Menon *et al*. 2002). Ramanathan *et al*. (2005) conducted a coupled ocean atmosphere model study with

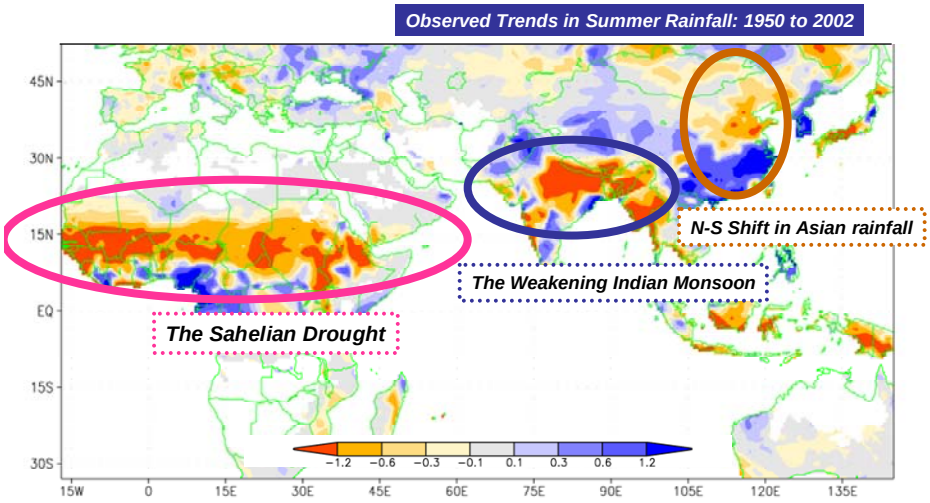


Figure 5. Trend in observed rainfall from 1950 to 2002. The figure shows the change in rainfall between 1950 and 2002; It was obtained by multiplying the year linear trend in mm/day/year by 52 years. The precipitation data is the Hadley center CRU data (Ref: Mitchell and Jones, 2005)

prescribed greenhouse forcing and ABC forcing (Figs 2 and 3) over S. Asia from 1930 to 2002. For the time dependent ABC forcing, they scaled the observationally constrained forcing (2001-2003) with history of SO_2 and soot emission for S. Asia from 1930 to 2002. Their model simulations, along with those reported in Meehl *et al*. (2007) and Lau *et al*. (2007), suggest the following effects of ABCs on the regional rainfall:

1. Dimming Trends: the simulated trend in dimming of about 7% over India was consistent with the observed trends obtained from radiometer stations (12 stations) in India, thus providing evidence for large dimming due to ABCs.
2. Atmosphere: heated by absorption and scattering of solar radiation
   - Warmer atmosphere is more stable: less precipitation
3. Surface: less solar radiation ('dimming'), thus more cooling (offset GHG warming)
   - Reduced solar radiation over Northern Indian Ocean (NIO): less evaporation, ***less precipitation***
   - Pollution is greater over NIO than SIO, which weakens the summertime sea surface temperature gradient: less circulation, weaker monsoon, ***less precipitation***
4. Monsoon Impact: the resulting deceleration of summer monsoonal circulation, the decrease in evaporation, and the increase in stability are the primary mechanisms for the reduction in the summer monsoon rainfall in the model simulations of Ramanathan *et al.* (2005) and Meehl *et al.* (2007).

These recent findings have catalyzed the creation of an international program for a better understanding of aerosol effects on the Asian monsoon (Lau *et al*. 2007).

Retreat of Himalayan Glaciers

UAVs document solar heating by BC (Stacked UAV montage from the Cover of Nature, Aug 2, 2007).

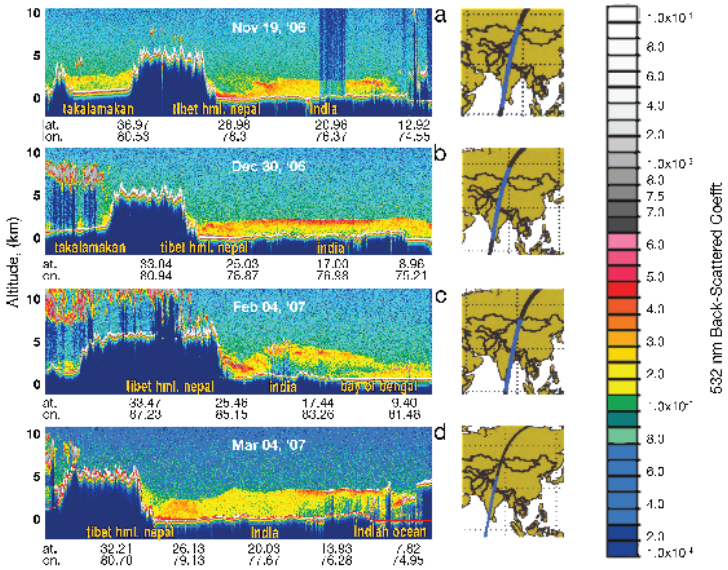


Figure 5. Color-coded profiles of 532nm backscatter return signal from the CALIPSO satellite lidar showing the vertical distribution of ABCs. The image shows ABCS surrounding the Himalyas from both the S and the SE Asian side (Source: Ramanathan et al, 2007b).

The retreat of the Himalayan-Hindu Kush (HHK) glaciers is one of the major environmental problems facing the Asian region. These glaciers feed several major Asian river systems including the Indus, Ganges, Brahmaputra, Mekong, Yangtze and Huang He. The livelihood of over 2 billion Asians are influenced by these rivers. The glacier retreat began in the mid nineteenth century in response to the termination of the mini ice age. The retreat has accelerated since the 1970s and includes major HHK glaciers such as Gangotri and over 90% of the Tibetan glaciers. Glaciologists (e.g. Thompson et al, 200x) link this acceleration to the large warming trend of about 0.25 C per decade that has been observed over the elevated HHK regions. The prevailing understanding is that the warming trend is part of the global warming due to greenhouse gases. But several American and European scientists have speculated that solar heating by soot in Atmospheric Brown Clouds and deposition of dark soot over bright snow surfaces may also be important contributing factors.

New research published in the Aug 2 issue of the journal Nature (Ramanathan et al, 2007a) offers direct observational evidence for the magnitude of the solar heating of the lower atmosphere by tiny soot particles resulting from fossil fuel combustion, bio mass burning and cooking with wood and other bio fuels. We launched light weight (30kg) unmanned aerial vehicles with miniaturized instruments to sample the brown clouds. Since the UAVs were flown simultaneously at different altitudes from surface to 3000 m, we were able to capture the ABCs between our aircraft and measure the sunlight absorbed at different altitudes as well as the dimming at the surface. We found that ABCs enhanced atmospheric solar heating by as much as 50% between 1 and 3 km. NASA's CALIPSO satellite carrying a laser instrument, tracked the thick Indian Ocean plume all the way across S Asia into the HHK region. It also showed ABCs stretching from the western Pacific Ocean across E Asia up to the Tibetan Plateau. Thus the HKK was surrounded by ABCs up to about 3 to 4 km.

The next obvious question was the impact of the large soot solar absorption on the atmospheric warming trends. For this we had to rely on an American climate model developed by over 20 scientists from around the US over a period of two decades. I was one of the early developers of this model in the 1980s. We adopted satellite and ground base observations for over 5 years and simulated the impact of the ABCs on the climate. In addition, we integrated into the model, the emission history of soot for the last 70 years and simulated the Asian climate from 1930 to 2005 with and without ABCs. These simulations showed that ABCs contributed as much as greenhouse gases to the warming trend of the atmosphere between 1 to 5 km, i.e, the elevations where the HKK glaciers are located. It is important to note that our simulations do not contradict the surface cooling effect of ABCs. In fact, in our simulations, ABCs cooled the surface over most of the plains in Asia, while warming the overlying free atmosphere. The surface cooling and the atmospheric warming are two sides of the same energy-balance coin: absorption by ABCs causes solar radiation that otherwise would have warmed the surface to instead warm the free atmosphere from1 to 5 km above the surface. In addition, the ABC induced warming was due to air pollution originating from all of Asia and not just S Asia, as can be seen most every day from satellite particle sensors. The latter two points were missed by the media covering the finding.

While our finding about the magnitude of the solar heating and its spatial extent are robust, the model simulations of the atmospheric warming require confirmation by independent studies. This process may take decade or two, for it took over a century to reach consensus on the global warming effects of greenhouse gases such as CO_2.

VI. Major Source of Uncertainty: Emission Sources for BC

Our ability to model the effects of BCs in climate models is severely limited. One of the main reason is the large uncertainty (factor of 2 or more) in the current estimates of the emission of the organic (OC) and elemental carbon (EC) (See Bond *et al*. 2004 and 2007).. Furthermore, biomass burning contribute significantly to the emissions of OC and EC and the historical trends (during the last 100 years) in these emissions are unknown and models currently resort to ad-hoc methods such as scaling the current day emissions with past trends in population.

Acknowledgements

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