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Air pollution, greenhouse gases and climate change: Global and regional perspectives

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A B S T R A C T

Greenhouse gases (GHGs) warm the surface and the atmosphere with significant implications for rainfall, retreat of glaciers and sea ice, sea level, among other factors. About 30 years ago, it was recognized that the increase in tropospheric ozone from air pollution (NO_x, CO and others) is an important greenhouse forcing term. In addition, the recognition of chlorofluorocarbons (CFCs) on stratospheric ozone and its climate effects linked chemistry and climate strongly. 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 have revealed that air pollution is transported across continents and ocean basins due to fast long-range transport, resulting in trans-oceanic and trans-continental plumes of atmospheric brown clouds (ABCs) containing sub micron size particles, i.e., aerosols. ABCs intercept sunlight by absorbing as well as reflecting it, both of which lead to a large surface dimming. The dimming effect is enhanced further because aerosols may nucleate more cloud droplets, which makes the clouds reflect more solar radiation. The dimming has a surface cooling effect and decreases evaporation of moisture from the surface, thus slows down the hydrological cycle. On the other hand, absorption of solar radiation by black carbon and some organics increase atmospheric heating and tend to amplify greenhouse warming of the atmosphere.

ABCs are concentrated in regional and mega-city hot spots. Long-range transport from these hot spots causes widespread plumes over the adjacent oceans. Such a pattern of regionally concentrated surface dimming and atmospheric solar heating, accompanied by widespread dimming over the oceans, gives rise to large regional effects. Only during the last decade, we have begun to comprehend the surprisingly large regional impacts. In S. Asia and N. Africa, the large north-south gradient in the ABC dimming has altered both the north-south gradients in sea surface temperatures and land–ocean contrast in surface temperatures, which in turn slow down the monsoon circulation and decrease rainfall over the continents. On the other hand, heating by black carbon warms the atmosphere at elevated levels from 2 to 6 km, where most tropical glaciers are located, thus strengthening the effect of GHGs on retreat of snow packs and glaciers in the Hindu Kush-Himalaya-Tibetan glaciers.

Globally, the surface cooling effect of ABCs may have masked as much 47% of the global warming by greenhouse gases, with an uncertainty range of 20–80%. This presents a dilemma since efforts to curb air pollution may unmask the ABC cooling effect and enhance the surface warming. Thus efforts to reduce GHGs and air pollution should be done under one common framework. The uncertainties in our understanding of the ABC effects are large, but we are discovering new ways in which human activities are changing the climate and the environment.

1. Introduction

This article is largely a perspective on the role of air pollution in climate change. It summarizes the developments since the mid 1970s. Before that time, the climate change problem was largely perceived as a CO_2-restricted global warming issue. Furthermore, this paper also provides new insights into emerging issues such as global dimming, the role of air pollution in masking global warming, and its potentially major role in regional climate changes, such as the slowing down of the S. Asian monsoon system, and the retreat of arctic sea ice and the tropical glaciers. It concludes with a discussion on how air pollution mitigation laws will likely be a major factor determining the climate warming trends of the coming decades.

2. The role of climate–chemistry interactions in global warming

The first scholarly and quantitative work on the greenhouse effect of carbon dioxide was done nearly one hundred years ago by

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Svante Arrhenius, the Swedish Nobel chemist. Arrhenius (1896) developed a simple mathematical model for the transfer of radiant energy through the atmosphere–surface system, and solved it analytically to show that a doubling of the atmospheric CO_2 concentration would lead to a warming of the surface by as much as 4–5 K. Since then, there has been a tremendous amount of work on the science of global warming, culminating in the now famous Intergovernmental Panel on Climate Change (IPCC) reports. In this paper, we would like to focus on the scientific underpinnings of the link between greenhouse gases and global warming, and then place the role of air pollution in that context.

2.1. Inadvertent modification of the atmosphere

The atmosphere is a thin shell of gases, particles and clouds surrounding the planet. It is in this thin shell that we are dumping several billion tons of pollutants each year. The major sources of this pollution include fossil fuel combustion for power generation and transportation; cooking with solid fuels; and burning of forests and savannah. The ultimate by-product of all forms of burning is the emission of the colorless gas, carbon dioxide (CO_2). But there are also products of incomplete combustion, such as CO and NO_x, which can react with other gaseous species in the atmosphere. The net effect of these reactions is to produce ozone, another greenhouse gas. Energy consumption also leads to aerosol precursor gases (e.g., SO_2) and primary aerosols in the atmosphere, which have direct negative impacts on human health and ecosystems.

2.2. From local to regional and global pollution

Every part of the world is connected with every other part through fast atmospheric transport. For example, Fig. 1 shows a snap shot of how air can travel from one region to another in about a week. The trajectories clearly show that air parcels can travel thousands of kilometers across from East Asia into N America; from N America across the Atlantic into Europe; from S Asia into E Asia; from Australia into the Antarctic, and so on. Aircraft and satellite data clearly reveal that within a week, emissions can be transported half way around the world into trans-oceanic and trans-continental plumes, no matter whether they are from Asia, or N America, or Africa.

The lifetime of a CO_2 molecule in the atmosphere is of the order of a century or more. This is more than sufficient time for the billions of tons of man-made CO_2 to uniformly cover the planet like a blanket. The steady increase of atmospheric CO_2 has been documented extensively. The question is, why should we worry about this colorless gaseous blanket?

2.3. The climate system: basic drivers

The incident solar radiation drives the climate system, atmospheric chemistry as well as life on the Earth. About 30% of the incoming solar energy is reflected back to space. The balance of 70% is absorbed by the surface–atmosphere system. This energy heats the planet and the atmosphere. As the surface and the atmosphere become warm, they give off the energy as infrared radiation, also referred to as 'long wave radiation'. So the process of the net incoming (downward solar energy minus the reflected) solar energy warming the system and the outgoing heat radiation from the warmer planet escaping to space goes on, until the two components of the energy are in balance. On an average sense, it is this radiation energy balance that provides a powerful constraint for the global average temperature of the planet. Greenhouse gases (GHGs) absorb and emit long wave radiation, while aerosols absorb and scatter solar radiation. Aerosols also absorb and emit long wave radiation (particularly large size aerosols such as dust), but this process is not significant for the smaller anthropogenic aerosols.

2.4. The greenhouse effect: the CO_2 blanket

On a cold winter night, a blanket keeps the body warm not because the blanket gives off any energy. Rather, the blanket traps the body heat, preventing it from escaping to the colder surroundings. Similarly, the CO_2 blanket, traps the long wave radiation given off by the planet. The trapping of the long wave radiation is dictated by quantum mechanics. The two oxygen atoms in CO_2 vibrate with the carbon atom in the center and the frequency of this vibration coincides with some of the infrared wavelengths of the long wave radiation. When the frequency of the radiation from the Earth's surface and the atmosphere coincides with the frequency of CO_2 vibration, the radiation is absorbed by CO_2, and converted to heat by collision with other air molecules, and then

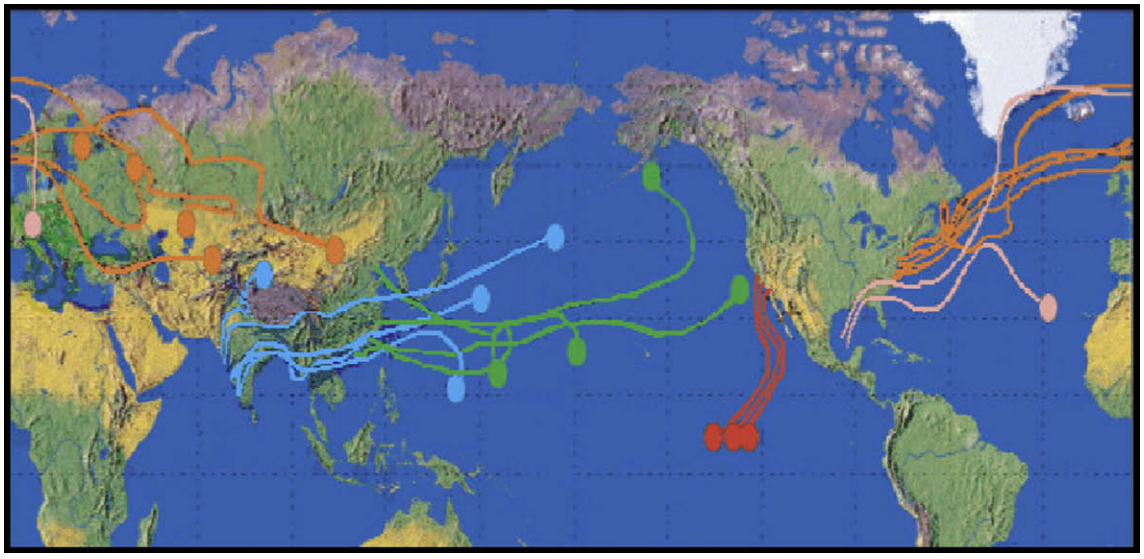

Fig. 1. Potential trans-continental nature of the "haze". Forward trajectories from London, Paris, Berlin, India, China, Mexico, and US East and west coasts, at 700 mb, on March 14–21, 1999 (Courtesy of T. N. Krishnamurti).

given back to the surface. As a result of this trapping, the outgoing long wave radiation is reduced by increasing CO_2. Not as much heat is escaping to balance the net incoming solar radiation. There is excess heat energy in the planet, i.e., the system is out of energy balance. As CO_2 is increasing with time, the infrared blanket is becoming thicker, and the planet is accumulating this excess energy.

2.5. Global warming: getting rid of the excess energy

How does the planet get rid of the excess energy? We know from basic infrared laws of physics, the so-called Planck's black body radiation law, that warmer bodies emit more radiation. So the planetary system will get rid of this excess energy by warming and thus emitting more infrared radiation, until the excess energy trapped is given off to space and the surface–atmosphere system is in balance. That, in a nutshell, is the theory of the greenhouse effect and global warming. A rigorous mathematical modeling of this energy balance paradigm was originated by Arrhenius (1896), but the proper accounting of the energy balance of the coupled surface–atmosphere system had to await the work of Manabe and Wetherald in 1967 (Manabe and Wetherald, 1967).

2.6. CFCs: the super greenhouse gas

For nearly eighty years since the Arrhenius paper, climate scientists assumed that CO_2 was the main anthropogenic or man-made greenhouse gas (e.g., SMIC Report, 1971). Since CO_2 does not react with other gases in the atmosphere, the greenhouse effect was largely a problem of solving the physics, thermodynamics and dynamics of climate. This picture changed drastically when it was discovered that there are other man-made gases, which on a per molecule basis could be up to ten thousand times stronger than the CO_2 greenhouse effect (Ramanathan, 1975). Chlorofluorocarbons, or CFCs, used as refrigerants and propellants in deodorizers, drug delivery pumps, etc are some of the strongest of such super greenhouse gases. These are purely synthetic gases. In 1974, Molina and Rowland published a famous paper in Nature (Molina and Rowland, 1974). They proposed that CFC11 and CFC12 (known then as Freon 11 and Freon 12) will build up in the atmosphere including the stratosphere, because of their century or longer life time. According to their theory, UV radiation from the sun will photodissociate the CFCs, and the released chlorine atoms will catalytically destroy ozone in the stratosphere.

Why do CFCs have such a disproportionately large greenhouse effect? There are three important reasons (Ramanathan, 1975): (1) CFCs absorb and emit radiation in the 8–12 μm region. The background atmosphere is quite transparent in this region; i.e., the natural greenhouse blanket is thinnest in the 8–12 μm region, and for this reason this region is called as the atmospheric window. The background water vapour has very little absorption. (2) Next, the quantum mechanical efficiency (also knows as transition probability) of CFCs is about 3–6 times stronger than that due to CO_2. In addition, CFCs have many absorption bands in this region. (3) Lastly, the CFC concentrations are so low (part per billion or less) that their effect increases linearly with their concentration, where as the CO_2 absorption is close to saturation since their concentration is about 300,000 times larger. So it's a lot harder for a CO_2 molecule to enhance the greenhouse effect than CFCs. These three factors combine to make CFCs a super greenhouse gas. Within a period of 10 years after the CFC paper by Ramanathan in 1975, several tens of anthropogenic greenhouse gases were added to the list (e.g., Wang et al., 1976; Ramanathan et al., 1985a). They have similar strong absorption features in the window region, making the window a dirty window (Fig. 2).

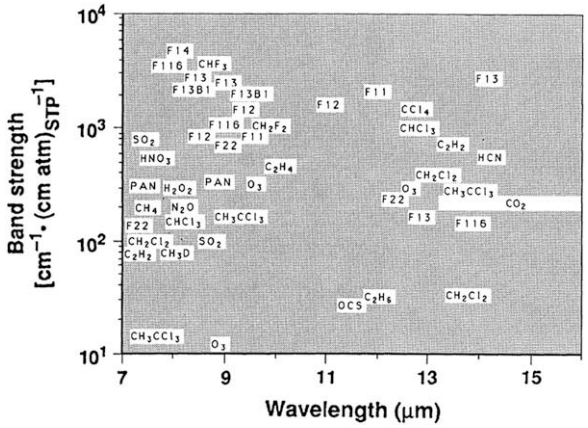

Fig. 2. Spectral absorption of trace gases in the atmospheric window (Ramanathan, 1988).

2.7. Climate–chemistry interactions

The independent discoveries of the CFC effect on stratospheric ozone chemistry and on the greenhouse effect, coupled atmospheric chemistry strongly with climate. Another major development that contributed to the chemistry–climate interactions is (Crutzen, 1972) Crutzen's paper on the effect of nitrogen oxides (another pollutant) on the stratospheric ozone layer. Stratospheric ozone regulates the UV and visible solar radiation reaching the surface–troposphere system (the first 10–16 km from the surface where the weather is generated); in addition, ozone is a strong greenhouse gas, absorbing and emitting radiation in the 9.6 μm region. It was shown that reducing ozone in the stratosphere would cool not only the stratosphere (anticipated earlier) but will also cool the surface (Ramanathan et al., 1976). This was surprising, because the additional solar radiation to the surface (from ozone reduction aloft) was expected to warm the surface. While this indeed happened as shown by Ramanathan et al. (1976), the reduced long wave radiation from the cooler stratosphere and the reduction on ozone greenhouse effect dominated the solar effect. Thus climate and air chemistry became strongly linked (Fig. 3). There was another important development in 1976, when Wang et al. (1976) showed methane and nitrous oxide to be strong greenhouse gases as well. Both of these gases have natural sources, as well as, anthropogenic ones (agriculture; natural gas; increase in cattle

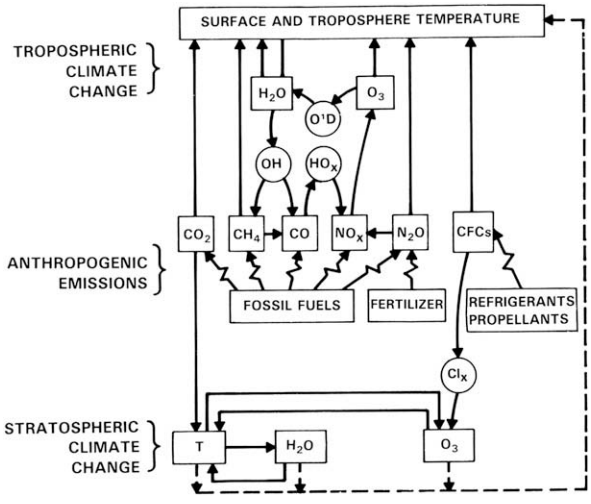

Fig. 3. A schematic of chemistry–climate interactions (Ramanathan, 1980).

population, etc.). These two gases also interfered with the ozone chemistry, and contributed to the increase in lower atmosphere ozone along with carbon monoxide and NO_x (major air pollutants). It was shown by Fishman et al. (1980) that increase in tropospheric ozone from air pollution (CO and NO_x) is an important contributor to global warming. Until the Fishman et al. (1980) study, lower atmosphere ozone was recognized only as a pollutant. Thus in a matter of five years after the discovery of the CFC greenhouse effect, chemistry emerged as a major climate forcing process (Fig. 3).

Thus through tropospheric ozone, air pollution became an important source for global warming. The global warming problem was not just a CO_2 problem, but became recognized as a trace gas – climate change problem.

2.8. WMO's recognition and lead into IPCC

But it took five more years for the climate community to accept this view, when WMO commissioned a committee to look into the greenhouse effect issue of trace gases. The committee published as a WMO report in 1985, and concluded that trace gases other than CO_2 contributed as much as CO_2 to the anthropogenic climate forcing from pre-industrial times (Ramanathan et al., 1985b). This report also gave a definition for the now widely used term: Radiative Forcing, which is still used by the community. Shortly thereafter, WMO and UNEP formed the Intergovernmental Panel on Climate Change (IPCC) in 1988. The IPCC (2001) report confirmed that the CO_2 contributed about half of the total forcing and the balance is due to the increases in methane, nitrous oxide, halocarbons and ozone. The anthropogenic radiative forcing from pre-industrial to now (year 2005) is about 3 Wm^{-2}, out of which about 1.6 Wm^{-2} is due to the CO_2 increase and the rest is due to CFCs and other halocarbons, methane, nitrous oxide, ozone and others. The unit Wm^{-2} represents the number of watts added energy per square meter of the Earth's surface.

3. Prediction and detection: the missing warming

3.1. When will the warming be detected?

As the importance of the greenhouse effect of trace gases began to emerge, it became clear that the climate problem was more imminent than assumed earlier. In fact, it was predicted by Madden and Ramanathan in 1980 that we should see the warming by 2000 (Madden and Ramanathan, 1980). The IPCC report published in 2001 confirmed this prediction, but the observed warming trend of about 0.8 °C from 1900 to 2005, was a factor of two to three smaller than the magnitude predicted by most models, as shown below.

3.2. Magnitude of the predicted warming

IPCC (2007) concludes that the climate system will warm by 3 °C (2 °C–4.5 °C) for a doubling of CO_2. The radiative forcing for a doubling of CO_2 is 3.8 Wm^{-2} (±15%) (Ramanathan et al., 1979; IPCC, 2001). Thus, we infer that the climate sensitivity term (also referred to as climate feedback) is 1.25 $Wm^{-2}\,°C^{-1}$ (= 3.8 Wm^{-2}/3 °C), i.e., it takes 1.25 Wm^{-2} to warm the surface and the atmosphere by 1 °C. If the planet, including the atmosphere, were to warm uniformly with no change in its composition including clouds, water vapour and snow/ice cover, it will take 3.3 Wm^{-2} to warm the planet by 1 °C. The reduction in the feedback term from 3.3 $Wm^{-2}\,°C^{-1}$ to 1.25 $Wm^{-2}\,°C^{-1}$ is due to positive climate feedback between atmospheric temperature (T) and water vapour, snow and sea ice. Basically as the atmosphere warms, the saturation vapour pressure increases exponentially (by about 7% per °C increase in T); and as a result, humidity increases proportionately. Since water vapour is the strongest greenhouse gas in the atmosphere, the increase in water vapour greenhouse effect amplifies the initial warming. Similarly, snow cover and sea ice shrinks with warming, which enhances solar absorption by the underlying darker surface, thus amplifying the warming (IPCC, 2007).

Using the IPCC (2007) estimated radiative forcing of 3 Wm^{-2} due to anthropogenic GHGs and the climate feedback term of 1.25 $Wm^{-2}\,°C^{-1}$, we obtain the expected warming due to the pre-industrial build up of GHGs as 2.4 °C (1.6 °C to 3.6 °C). This should be compared with the observed warming of 0.8 °C from 1850 to now. IPCC (2007) infers that about 30% (about 0.2 °C) of the observed warming is due to natural factors, such as trends in forcing due to volcanic activity and solar insolation. While the observed warming is consistent with the GHGs forcing, its magnitude is smaller by a factor of about 3 ~ 4. One point to note is that the predicted warming of 2.4 °C is the equilibrium warming, which is basically the warming we will observe decades to century from now, if we held the GHG levels constant at today's levels. Some of the heat is stored in the ocean because of its huge thermal inertia. It mixes the heat by turbulence quickly (within weeks to months) to the first 50–100 m depth. From there in about a few years to decades, the large-scale ocean circulation mixes the heat to about 500–1000 m depth. Some of the excess energy trapped is still circulating in the ocean. Oceanographers have estimated that about 0.6 (±0.2) Wm^{-2} of the 3 Wm^{-2} is still stored in the ocean (Barnett et al., 2001). So about 0.5 °C (= 0.6 Wm^{-2}/1.25 $Wm^{-2}\,°C^{-1}$) of the warming will show up in the next few decades to a century. We still have to account for the missing warming of about 1.3 °C {= 2.4 °C–(0.8 °C − 0.2 °C + 0.5 °C)}.

Let us summarize our deductions thus far. Based on the build up of greenhouse gases since the dawn of the industrial era, we have *committed* (using the terminology in Ramanathan, 1988) the planet to a warming of 2.4 °C (1.6–3.6 °C). About 0.6 °C of the observed warming can be attributed to the GHGs forcing; and about 0.5 °C is stored in the oceans; and the balance of 1.3 °C is unaccounted for. The stage is set now to consider the masking effect of aerosols, a topic which was pursued actively since the 1970s (e.g., see Mitchell, 1970, and Rasool and Schneider, 1971).

Aerosols start off as urban haze or rural smoke, and ultimately become trans-continental and trans-oceanic plumes consisting of sulfate, nitrate, hundreds of organics, black carbon and other aerosols. To underline their air pollution origin, we refer to the aerosols as atmospheric brown clouds (ABCs) (Ramanathan and Crutzen, 2003).

4. Atmospheric brown clouds: global and regional radiative forcing

In addition to adding greenhouse gases, human activities also contributed to the addition of aerosols (condensed particles in sub micron size) to the atmosphere. Since 1970 (Mitchell, 1970), scientists have speculated that these aerosols are reflecting sunlight back to space before it reaches the surface, and thus contribute to a cooling of the surface. This was further refined by Charlson et al. (1990) with a chemical transport model. They made an estimate of the cooling effect of sulfate aerosols (resulting from SO_2 emission), and concluded that the sulfate cooling may be substantial. Essentially, aerosol concentrations increased in time along with greenhouse gases, and the cooling effect of the aerosols have masked some of the greenhouse warming. We are choosing the word "mask" deliberately, for when we get rid of the air pollution, the masking would disappear and the full extent of the committed warming of 2.4 °C would show up. Several tens of groups around the world are working on this masking effect using models and satellite data. Thus, the emergence of ABCs as a major agent of climate change links all three of the major environmental

problems related to the atmosphere under one common framework (Fig. 4).

Our understanding of the impact of these aerosols has undergone a major revision, due to new experimental findings from field observations, such as the Indian Ocean Experiment (Ramanathan et al., 2001a) and ACE–Asia (Huebert et al., 2003) among others, and global modeling studies (e.g., Boucher et al., 1998; Penner et al., 1998; Lohmann and Feichter, 2001; Menon et al., 2002; Penner et al., 2003; Lohmann et al., 2004; Liao and Seinfeld, 2005; Takemura et al., 2005; Penner et al., 2006). Aerosols enhance scattering and absorption of solar radiation, and also produce brighter clouds that are less efficient at releasing precipitation. These in turn lead to large reductions in the amount of solar radiation reaching Earth's surface, a corresponding increase in atmospheric solar heating, changes in atmospheric thermal structure, surface cooling, disruption of regional circulation systems such as the monsoons, suppression of rainfall, and less efficient removal of pollutants. Black carbon, sulfate, and organics play a major role in the dimming of the surface (e.g., IPCC, 2007; Figure. 2.21; Ramanathan and Carmichael, 2008, Figure 2). Man-made aerosols have dimmed the surface of the planet, while making it brighter at the top of the atmosphere.

Together the aerosol radiation and microphysical effects can lead to a weaker hydrological cycle and drying of the planet, which connects aerosols directly to the 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 models to aerosols (Williams et al., 2001; Rotstayn and Lohmann, 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 during the last 50 years (Ramanathan et al., 2005; Held et al., 2005; Lambert et al., 2005; Chung and Ramanathan, 2006). On a regional scale, aerosol induced radiative changes (forcing) are an order of magnitude larger than that of the greenhouse gases; but the global climate effects of the greenhouse forcing are still more important because of its global nature. 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.

4.1. Regional plumes of widespread brown clouds

Brown clouds are usually associated with the brownish urban haze such seen over the horizon in most urban skies. The brownish color is due to strong solar absorption by black carbon in the soot and NO_2. Due to fast atmospheric transport, the urban and rural haze becomes widespread trans-oceanic and trans-continental plumes of ABCs in a few days to a week. Until 2000 we had to rely largely on global models to characterize their large-scale structure. The launch of TERRA satellite with the MODIS instrument provided a whole new perspective of the ABC issue, because MODIS was able to retrieve aerosol optical depths (AODs) and effective particle size over the land as well as the oceans (Kaufman et al., 2002). Furthermore, NASA's ground based AERONET (Aerosol Robotic Network) sites with solar-disc scanning spectroradiometers provided not only ground truth over 100 locations around the world but also aerosol absorption optical depth and single scattering albedo (Holben et al., 2001).

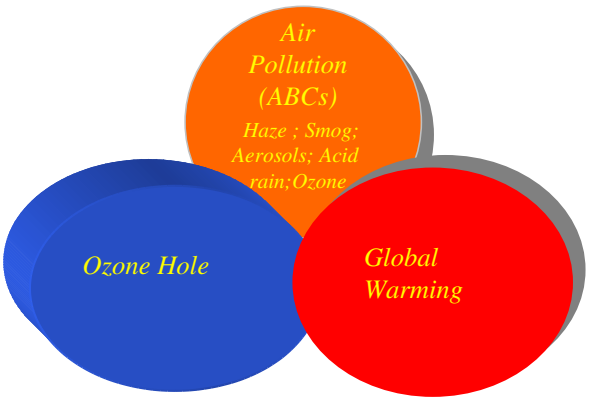

Fig. 4. ABCs, which have emerged as a major agent of climate change, link to three environmental problems: ozone hole, air pollution, and global warming.

Field observations such as the Indian Ocean Experiment (Ramanathan et al., 2001a) and ACE–Asia (Huebert et al., 2003) provided *in situ* data for the chemical composition of ABCs as well as their vertical distribution. Another important development is the advent of atmospheric observations with light-weight and autonomous UAVs (unmanned aerial vehicles), which could be flown in stacked formation to measure directly solar heating rates due to ABCs (Ramanathan et al., 2007a; Ramana et al., 2007). By integrating these data and assimilating them in a global framework, Chung et al. (2005) and Ramanathan et al. (2007b) were able to provide a global distribution of aerosol optical properties dimming and atmospheric solar heating for the 2000–2003 time period. Using these integrated data sets, we characterize the various ABC plumes around the world (Fig. 5). The figure shows anthropogenic AODs for all four seasons of the year. The following major plumes are identified in Fig. 5:

1) Dec to March: Indo-Asian-Pacific Plume; N Atlantic-African-S Indian Ocean Plume;
2) April to June: N Atlantic-African-S Indian Ocean Plume; E Asian-Pacific-N American Plume; Latin American Plume;
3) July to August: N American Plume; European Plume; SE Asian-Australian Plume; N Atlantic-African-S Indian Ocean Plume; Amazonian Plume;
4) September to November: E Asian-Pacific-N American Plume; Latin American Plume.

It should be noted that ABCs occur through out the year in most continental and adjacent oceanic regions, but their concentrations peak in some seasons: dry season in the tropics and summer seasons in the extra tropics. Simulated AODs for year 2001 using a chemical transport model (the LLNL/IMPACT model at Univ. of Michigan) documented elsewhere (Liu and Penner, 2002; Rotman et al., 2004; Liu et al., 2005; Feng and Penner, 2007) is shown in Fig. 6 (Feng and Ramanathan, in preparation). There is overall correspondence between regional plumes derived from observationally retrieved AODs and simulated AODs. The simulations also reveal the seasonally dependent plumes identified from the assimilated values; since the color scales and seasons are identical in the two figures, it can be seen that the simulate values are also quantitatively consistent.

4.2. Global distribution of dimming

The major source of dimming is ABC absorption of direct solar radiation. This is further enhanced by the reflection of solar radiation back to space by ABCs. This should be contrasted with the TOA forcing that is solely due to the reflection of solar radiation back to space. This distinction has been ignored frequently; as a result, the dimming has been mistakenly linked with surface cooling trends (e.g., Wild et al., 2004; Streets et al., 2006). The problems with this approach are the following: for black carbon, the dimming at the surface is accompanied by positive forcing at the top of the atmosphere (Ramanathan and Carmichael, 2008), thus it is erroneous to

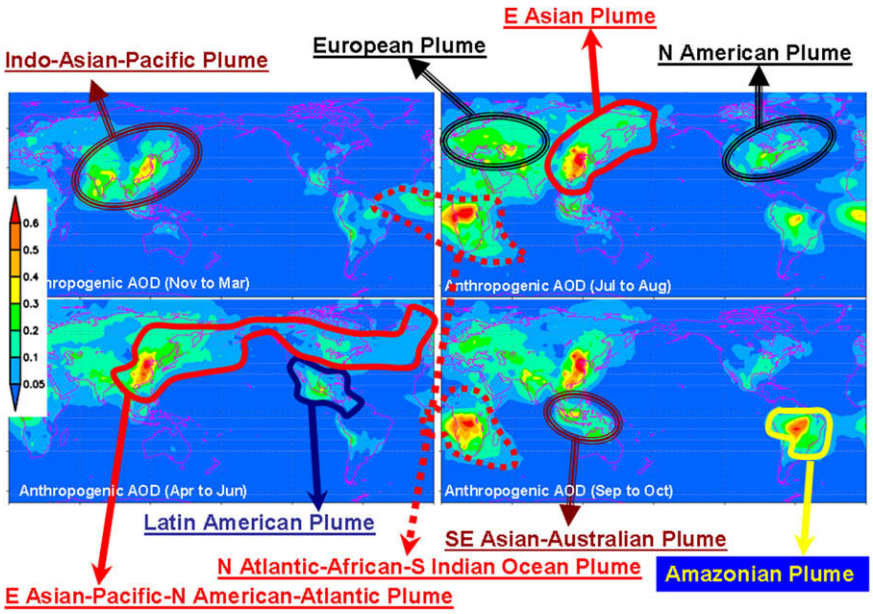

Fig. 5. Trans-oceanic, and trans-continental ABC plumes, represented by assimilated anthropogenic aerosol optical depth in all four seasons of the year (Chung et al., 2005; Ramanathan et al., 2007b).

assume dimming will result in cooling. Furthermore, as we will show later, the surface dimming due to ABCs with absorbing aerosols is a factor of 2–5 larger than the aerosol TOA forcing, and for many regions they can be even of opposite sign. Most of the solar absorption is due to elemental carbon and some organics, and these aerosol species are referred to as black carbon. The reflection of solar radiation is due to sulfate, nitrate, organic matter, fly ash and dust. Additional dimming is caused by soluble aerosols (e.g. sulfate) nucleating more cloud droplets, which in turn enhance reflection of solar radiation back to space. But the major source of dimming is due to the direct absorption and reflection of solar radiation by aerosols as shown in Fig. 7, along with emissions of black carbon and sulfur (gaseous precursor of sulfate). Over most regions of the ABC plumes, the dimming is large in the range of 6–25 Wm^{-2}. In remote oceanic regions, the dimming is much smaller and is in the range of 1–3 Wm^{-2}. The large dimming values over oceanic regions downwind of polluted continents are consistent with the results from the Indian Ocean Experiment (Ramanathan et al., 2001a).

Global average ABC forcings at the surface, in the atmosphere, and at the top of the atmosphere are compared with the greenhouse forcing in Fig. 8. At the TOA, the ABC (that is, BC + non-BC) forcing of -1.4 W m^{-2}, which includes a -1 W m^{-2} indirect forcing, may have masked as much as 50% (±25%) of the global forcing due to GHGs. The estimated aerosol forcing of -1.4 W m^{-2} due to ABCs is within 15% of the aerosol forcing derived in the recent IPCC report

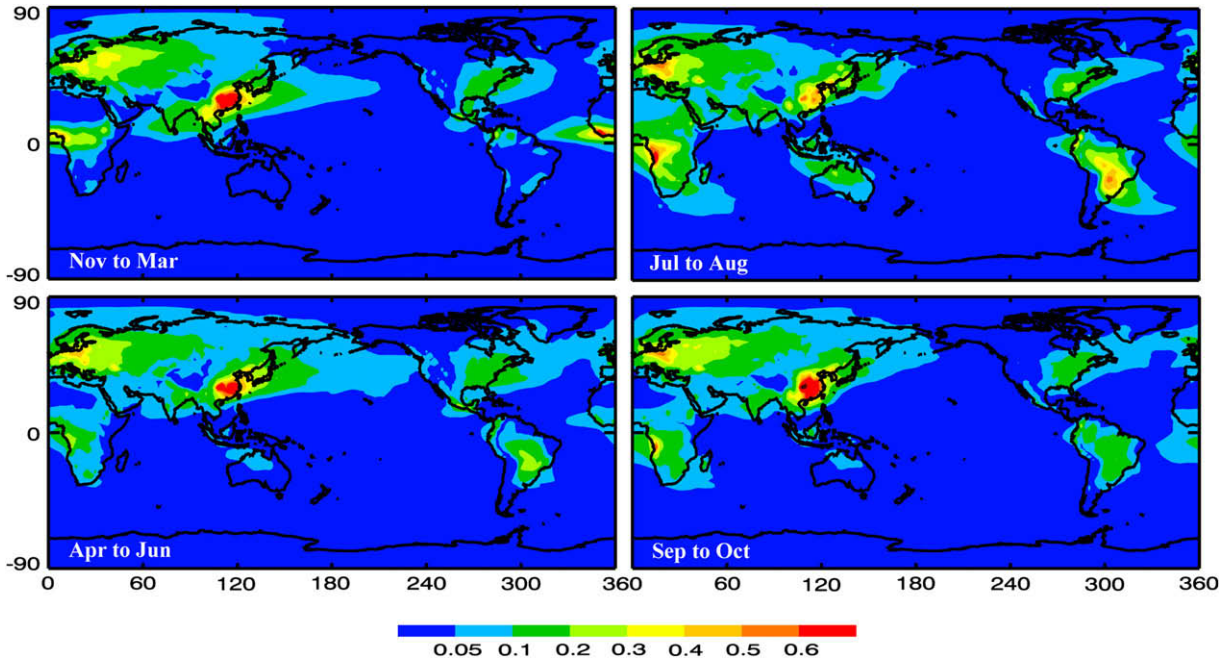

Fig. 6. Simulated anthropogenic aerosol optical depth for year 2001, using a chemical transport model.

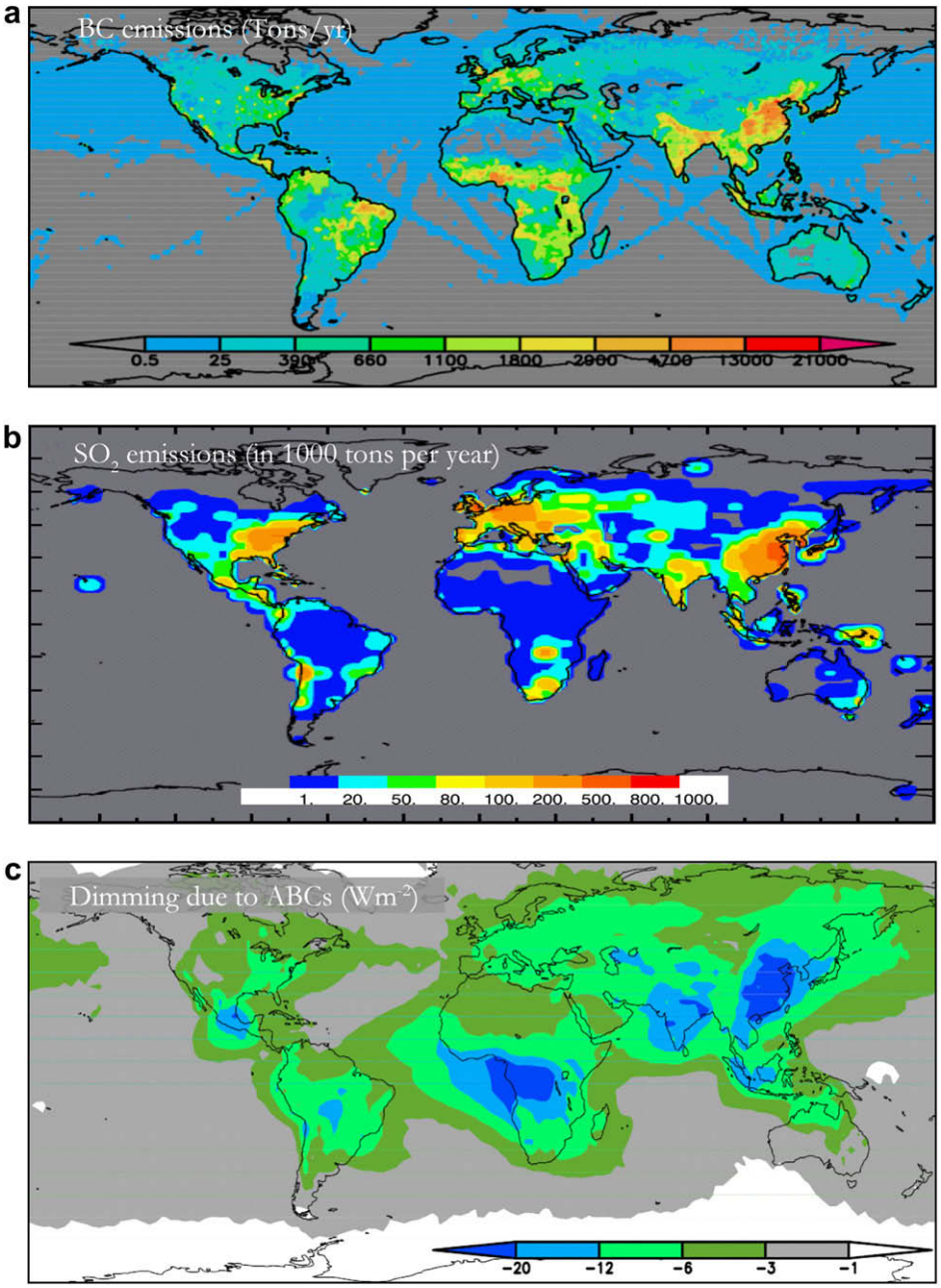

Fig. 7. Emissions of (a) black carbon (Bond et al., 2004), and (b) sulfur (Nakicenovic et al., 2000). And the simulated global dimming at the surface due to ABCs (Chung et al., 2005).

(IPCC, 2007). The main point to note is that, because of the solar absorption within the atmosphere ($3\ Wm^{-2}$), the ABC surface forcing ($-4.4\ Wm^{-2}$) is a factor of 3 larger than the TOA forcing ($-1.4\ Wm^{-2}$). The dimming at the surface is approximately estimated as surface forcing/$(1-A_s)$, where A_s is surface albedo. Assuming an average A_s of 0.15, we obtain for the dimming $-5.2\ Wm^{-2}$ ($=-4.4\ Wm^{-2}/0.85$). This is the dimming that occurred during 2000–2002 due to anthropogenic aerosols, or, ABCs. Since emissions of some aerosol precursors such as SO_2 peaked in the 1970s followed by a decline of about 30% from the 1970s to date, the dimming during the 1970s could have been larger.

There is an important distinction between the dimming by scattering aerosols like sulfate, and that due to absorbing aerosols like soot. For sulfate, 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; therefore, 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 a factor of 3 larger than the dimming due to reflection of solar (a cooling effect).

4.3. How long has the dimming been going on?

IPCC (2007) estimates that the net global average aerosol forcing from pre-industrial to year 2005 is negative. This negative forcing is due to enhanced reflection of solar radiation. The deduction from

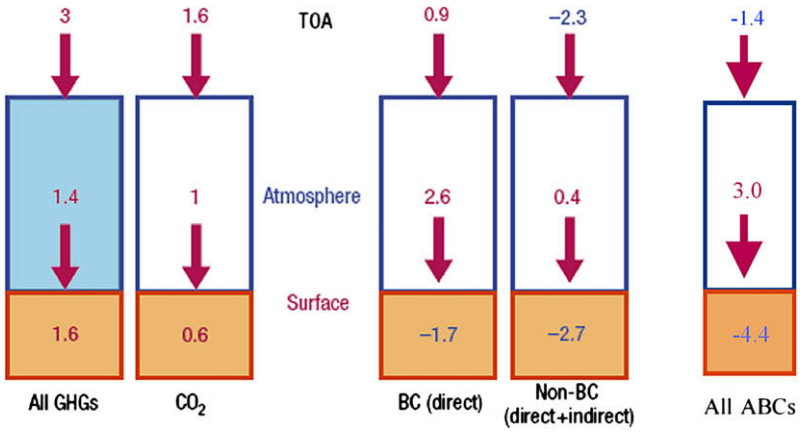

Fig. 8. Global average radiative forcing of ABCs at the surface (brown box), in the atmosphere (blue box), and at the top of the atmosphere (on the top), compared with the forcing of greenhouse gases (GHGs). Positive and negative forcings are shown in magenta and blue colors, respectively (Source: Ramanathan and Carmichael, 2008.).

this finding is that global scale dimming has been going on since the pre-industrial to now. The magnitude of the aerosol forcing from IPCC (2007) is $-1.2\ Wm^{-2}$. In terms of trend, assuming that most of the aerosol forcing is from 1900 onwards, the trend is of the order of -0.1 (with an uncertainty of factor of 2) Wm^{-2} per decade. However, the forcing at the surface ($-4.4\ Wm^{-2}$) is much larger in magnitude than the TOA forcing as shown in Fig. 8. The global dimming trend due to ABCs is most likely of the order of $-0.5\ Wm^{-2}$ per decade (with an uncertainty of factor of two). It should also be noted that the dimming would have been larger in the 1970s when the SO_2 emission peaked (Streets et al., 2006).

There have been numerous studies that claimed widespread reduction of solar radiation at the surface (Gilgen et al., 1998; Ohmura et al., 1989; Stanhill and Cohen, 2001; Liepert, 2002), using surface network of radiometers (mainly broad band pyranometers). We begin with the first study that used the term "global dimming" (Stanhill and Cohen, 2001). They reviewed earlier studies and sub-selected the data to include only thermopile radiometers, and their data set included more than 150 stations from both the northern and southern hemisphere. The data covered the period from 1958 to 1992. Based on analysis of this data set, they reported a globally averaged dimming of $-20\ Wm^{-2}$ for a 34-year period from 1958 to 1992. This was followed by Liepert (2002), who conducted a trend analysis of the so-called GEBA network of pyranometers (over 150 stations) maintained by Ohmura et al. (1989) for the 1961–1990 period. Liepert differenced the decadal-average surface solar radiation between 1981–1990 and 1961–1970 and obtained a "globally averaged" dimming of $-7\ Wm^{-2}$. Although Liepert refers to the inferred trend as a thirty year trend form 1961 to 1990, it is really a twenty year trend since the difference is between two ten year periods (1961–1970 and 1981–1990) separated by 20 years. These trends are for downward solar radiation whereas we need the trend in absorbed solar radiation, which is obtained by multiplying the downward solar radiation trend by 0.85 (following Wild et al., 2004). Thus the 20-year trend (1965–1985) in absorbed solar radiation is $-6\ Wm^{-2}$ for Liepert (2002), while the 34-year trend (1958–1992) in absorbed solar radiation at the surface is $-17\ Wm^{-2}$ for Stanhill and Cohen (2001). The underlying message is that the dimming trend has been going on at least from the 1950s onwards.

By analyzing later GEBA data sets, Wild et al. (2005) conclude that the dimming trend is reversing in most locations of the globe, except over S Asia. They suggest that this reversal to brightening commenced around 1990. Most of the GEBA stations analyzed in their data sets did reveal brightening. However, the length of the period analyzed in their study is only of 6 years to about 10 years, thus not of sufficient duration to infer a long term trend. Another major problem with this study is that, a companion paper that is published in the same issue of Science by Pinker et al. (2005) seems to contradict Wild et al. (2005) data. Pinker et al. (2005) analyzed satellite data from 1983 to 2001 and finds an overall positive trend of surface solar radiation of about $1.6\ Wm^{-2}$ per decade, with a net increase of $2.8\ Wm^{-2}$ for the 18-year period. The data also shows a negative trend from 1983 to 1990, followed by the positive trend from 1990 to 2001. But when Pinker et al. (2005) separated their data into oceans and land, the positive trend is observed only for world ocean averages and the average land values show slight negative trend, thus contradicting inference of Wild et al. (2005).

In summary, our estimates for the global mean dimming trend (i.e., trend in absorbed solar radiation at the surface) due to ABCs is of the order of $-0.5\ Wm^{-2}$ per decade (±factor of 2), and the trend in absorbed solar radiation at TOA, i.e., TOA forcing as per IPCC, is about -0.1 (±factor of 2) Wm^{-2} per decade. Dimming trends from surface radiometers (from 1960 to 1990) range from $-3\ Wm^{-2}$ per decade (Liepert, 2002) to $-5\ Wm^{-2}$ per decade (Stanhill and Cohen, 2001). In summary, there is about a factor of 6 to 10 difference in the global average dimming trend inferred from surface data and the global analysis of ABCs. Part, if not a major, source of the difference can be accounted for by the Alpert and Kishcha (2008) analysis. They show that the magnitude of the dimming is strongly dependent on the population density and that the dimming trend (for 1964–1989) varies from $-0.5\ Wm^{-2}$ per decade for sites with population density of $10\ km^{-2}$ to $-3.2\ Wm^{-2}$ per decade for sites with population density of $200\ km^{-2}$. This result is consistent with the ABC dimming estimates shown in Fig. 7, which reveals a large decrease in surface forcing away from the source regions.

This does not mean however there is no dimming outside the urban regions. As we described earlier, the dimming decreases by a factor of 5–10 away from the source regions. For example, the global mean trend of $-0.5\ Wm^{-2}$ per decade we infer from Figs. 7 and 8, varies from $-2\ Wm^{-2}$ per decade close to the source regions to $-0.2\ Wm^{-2}$ per decade far away (few thousand kilometers) from the source region. Trends of the order of $-0.2\ Wm^{-2}$ per decade are below the detectable threshold values in the pyranometers. But such seemingly low trends are still climatologically significant. However, Alpert and Kishcha (2008) use their result to deduce that the dimming is largely an urban phenomenon, which is inconsistent with either IPCC's findings of global negative forcing or the global ABC dimming values shown in Fig. 8. This is largely a semantic issue, for the term "global dimming" has become linked exclusively with the large dimming trends in the original paper in Stanhill and Cohen (2001).

In summary, we conclude the following:

1) There is global scale dimming during the last century due to ABCs (i.e., aerosols) and this deduction is consistent with the negative aerosol forcing reported by IPCC (2007).
2) Because ABCs absorb solar radiation, the dimming at the surface is a factor of 3 larger than the negative aerosol forcing at TOA.
3) A global mean dimming trend of the order of $-0.5\ Wm^{-2}$ per decade is consistent with our current understanding of global distribution of anthropogenic aerosols (factor of 2).
4) We cannot infer global mean trends from surface stations alone. Since the dimming decreases strongly from the source regions, inferring global mean dimming from solely surface stations will bias towards a significant overestimate of the dimming;

In order to examine dimming trend question further, we modeled the historical variations in ABCs and their dimming influence, by including historical variations in emissions of soot and SO_2 in the NCAR climate model (Ramanathan et al., 2005). Fortunately, we had well calibrated solar radiation data over India (12 stations), which was collected by a well-known Indian meteorologist, Dr Annamani, and incorporated into the GEBA data sets. The observations revealed that India has steadily been getting dimmer at least from the 1960s (data record began in the 1960s), and that India now is about 7% dimmer than the 1960s. Next, the simulations were able to estimate observations reasonably well, and the simulations suggested that the cause of the dimming is largely due to the 4 to 5 fold increase in emissions of soot and SO_2 from the 1960s to now.

4.4. Spectral nature of the dimming

During INDOEX, grating spectrometers were deployed on a ship to measure high-resolution solar spectrum, as the ship traveled in and out of the plume (Meywerk and Ramanathan, 1999). A spectrum of the direct sunlight and the reflected (downwards) solar radiation were obtained (Fig. 9). The data revealed that the brown clouds led to a large reduction of sunlight, with the largest reduction of 40% in UV and visible wavelengths (another indication of soot absorption).

4.5. Atmospheric solar heating

In addition to absorbing the reflected solar radiation, black carbon in ABCs absorbs the direct solar radiation and together the two processes contribute to a significant enhancement of lower atmosphere solar heating. The atmospheric solar absorption increase due to ABCs is shown in Fig. 10 (adapted from Chung et al., 2005). The increase in solar absorption is the vertical integral of the ABC induced solar absorption from the surface to the TOA; but more than 95% of this increase is confined to the first 3 km above the surface where the ABCs are located. Within the regional plumes, the heating ranges from 10 to 20 Wm^{-2}, which is about 25% to 50% of the background solar heating in the first 3 km. Until recently there was no direct observational confirmation for such large ABC heating rates, since it requires multiple aircraft flying in stacked formation with identical radiometers on the aircraft. This challenge was recently overcome by deploying 3 light-weight unmanned aerial vehicles (UAVs) with well calibrated and miniaturized instruments to measure simultaneously aerosols, black carbon and spectral as well as broad band radiation fluxes (Ramanathan et al., 2007a; Ramana et al., 2007; Corrigan et al., 2008). This study (Ramanathan et al., 2007a) demonstrated that ABCs with a visible absorption optical depth as low as 0.02, is sufficient to enhance solar heating of the lower atmosphere (surface to about 3 km) by as much as 50%. Absorption in the UV, visible and IR wavelengths contributed to the observed heating rates. If it is solely due to BC, such large heating rates require BC to be mixed or coated with other aerosols. Global average ABC solar heating, as per the present estimate, is 3 Wm^{-2} (Fig. 8) with a factor of 5–10 larger heating over the regional hot spots (Fig. 10).

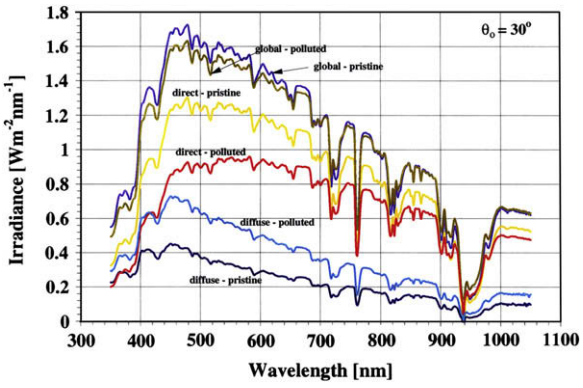

Fig. 9. Global, direct, and diffuse portion of the spectral irradiance for the most pristine day, day 78 (March 19, 1998) at −12°S, and the most polluted day, day 85 (March 28, 1998) at 8°N. Solar zenith angle for both samples was 30°(Meywerk and Ramanathan, 1999).

5. Atmospheric brown clouds: global and regional climate changes

5.1. Magnitude of the missing global warming

The ABC TOA forcing is $-1.4\ Wm^{-2}$ (-0.5 to $-2.5\ Wm^{-2}$). Using the IPCC climate sensitivity of $1.25\ Wm^{-2}\,°C^{-1}$, we infer that surface cooling due to ABCs is about −1.2 °C (−0.4 °C to −2 °C). Therefore, the inferred ABC surface cooling effect can account for the missing surface warming of 1.3 °C (discussed in Section 3). The deduction from this result is that the buildup of GHGs since the pre-industrial to present has already committed the planet to a surface warming of 2.4 °C, out of which about 0.6 °C has already been realized, and the 0.5 °C stored in the oceans will manifest in the next few decades, and the balance of 1.3 °C will be realized if we eliminate ABCs.

5.2. Global hydrological cycle

As pointed out earlier (Ramanathan et al., 2001b; Wild et al., 2004, and others), the large reduction of solar radiation at the surface (−4.4 Wm−2) will result in reduced evaporation and in turn reduced precipitation. Of course this will be countered by increased precipitation from the GHGs warming. It is likely that the reduction in precipitation will occur in the tropics where the dimming is the largest and the increase in precipitation will occur in the extra tropics where the GHGs warming is larger than the tropical warming.

5.3. Regional hydrological cycle

Of major concern is rainfall over sub-Saharan Africa and the Indian summer monsoon (ISM). The major emerging theme is that rainfall in these regions is strongly, if not dominantly, influenced by latitudinal sea surface temperature (SST) gradient, while ABCs play a major role in influencing the SST gradient. This is because the ABC dimming is concentrated more in the northern oceans than in the southern oceans. In the Atlantic, during the 1960s to 1990s, ABCs from N America and Europe caused major dimming in the northern

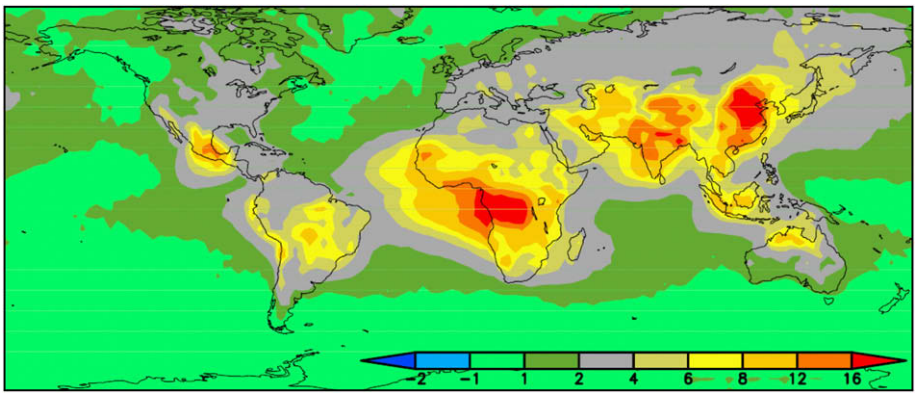

Fig. 10. The absorption of solar radiation by the atmosphere due to ABCs (Chung et al., 2005).

part of the Atlantic Ocean, thus potentially reducing the north-south SST gradient and shifting the rain belt southwards (Rotstayn and Lohmann, 2002). This has been suggested as the major influence in causing the Sahelian rainfall (also see Held et al., 2005). For the ISM, Ramanathan et al. (2005); Meehl et al. (2008) and Lau et al. (2008) have suggested similar reasons. As noted by Ramanathan et al. (2005) and Chung and Ramanathan (2006), the summer time SST gradient has weakened since the 1950s and they attribute this weakening to the observed reduction in ISM rainfall. According to Ramanathan et al. (2005) and Meehl et al. (2008), the ABC cooling is masking the GHGs warming in the northern Indian Ocean (NIO), such that the NIO is not warming as much as the southern Indian Ocean in response to the GHGs warming. Additional factors that contribute to the weakening of the ISM include: reduced evaporation from the NIO due to the dimming; increased atmospheric stability caused by simultaneous dimming at the surface and atmospheric solar heating of the lower atmosphere; and reduced land–sea contrast in surface temperatures due to the fact the ABC dimming is much larger over the land surface (Fig. 7).

As a caveat to the regional climate change discussions above, it should be pointed out that natural variability due to interactions between the coupled ocean–atmosphere–land surface system is a major source of regional changes on annual and decadal scales. The ABC induced regional changes described above are inferred from simulations that include ABC forcing in coupled ocean–atmosphere models. However, these models do not reproduce many important characteristics of regional climate variability. Hence, we should treat the ABC effects on monsoon described here as merely illustrative of the potential effects. The simulations however suggest that the ABC regional forcing is large enough to perturb ISM sufficiently that the effects are comparable or larger than the natural variability of the system.

5.4. Retreat of Hindu Kush-Himalayan-Tibetan (HKHT) glaciers

There is increasing evidence that over two thirds of glaciers in the HKHT region are retreating more rapidly since the 1950s (e.g. IPCC, 2007 and references listed therein). This retreat is attributed to the large warming of the order of 0.25 °C per decade that has been observed since the 1950s over the elevated regions of the HKHT. It has been generally believed that the warming at elevated levels is largely due to GHGs warming. However, recent studies have pointed out that atmospheric solar heating by BC in ABCs is a major source of warming at the elevated levels (Chung and Seinfeld, 2002; Ramanathan et al., 2007b; Meehl et al., 2008). Furthermore, as shown by Ramanathan et al. (2007a) with CALIPSO Lidar data, about 2–5 km thick ABCs surround the HKHT region most of the year and the solar heating by ABCs in this layer is as much as 25% to 50% of the background solar heating. Model simulations that employ ABC solar heating demonstrate that the warming due to ABCs is as large as that due to GHGs forcing (Chung and Seinfeld, 2002; Ramanathan et al., 2007b; Meehl et al., 2008).

5.5. Retreat of Arctic sea ice

Deposition of black carbon over snow and ice reduces albedo of these bright surfaces because of enhancement of solar absorption. Numerous studies have used climate model simulations to suggest that as much as 50% of the observed retreat in arctic sea ice may be due to BC forcing (Hansen and Nazarenko, 2004; Flanner et al., 2007).

6. Conclusion and future directions

6.1. General conclusions

(1) The primary conclusion is that without a proper treatment of the regional and global effects of ABCs in climate models, it is nearly impossible to reliably interpret or understand the causal factors for regional as well as global climate changes during the last century; (2) until 1950s, the extra-tropical regions played a dominant role in emissions of aerosols, but since the 1970s the tropical regions have become major contributors to aerosol emissions, particularly black carbon. The chemistry and hence the radiative effects of aerosols emitted in the extra tropics are very different (even possibly in the sign) from that of the aerosols emitted in the tropics; and as a result, treatment of ABCs as just sulfate aerosols is inappropriate for simulating fundamental processes such as dimming and atmospheric solar heating; (3) the TOA aerosol forcing is an inadequate and even an inappropriate metric for understanding the regional climate changes due to ABCs; (4) Global average dimming is not an appropriate metric for understanding global average impacts of ABCs on surface temperature. This is because the TOA forcing is a factor of 2–4 smaller than the surface forcing and for black carbon they are of opposite signs.

6.2. Specific conclusions

1) The missing warming: global average TOA forcing of ABCs is about $-1.4\,\mathrm{Wm}^{-2}$. The implication is that, when ABCs are eliminated, the surface can warm by about 1.3 °C.
2) The committed warming: effectively the greenhouse gas increase from pre-industrial to now has committed the planet to a surface warming of 2.4 °C (using IPCCs central value for climate sensitivity), and only about 0.6 °C of this has been realized thus far.
3) Global dimming: aerosol observations from satellites, surface stations and aircraft (for the 2000–2002 period) suggest that

there is a global wide dimming of about $-5\ Wm^{-2}$ due to ABCs. Assuming negligible dimming before 1900s, this result translates into a global dimming trend of $-0.5\ Wm^{-2}$ per decade, with factors of 2 or larger dimming trend over land areas. The ABC induced global mean dimming trend is much smaller than the 3–6 Wm^{-2} per decade inferred from radiometers over land stations.

4) ABC impact over Asia: regionally, ABCs may have played a very large role in the widespread decrease in precipitation in Africa and in S. Asia (the Indian summer monsoon) and the widespread retreat of glaciers in the Hindu Kush-Himalaya-Tibetan region. The former is due to dimming and the latter is due to solar heating of elevated layers by ABCs.

6.3. Future scope for reduction of ABCs

Fig. 11a, b, c and d, show respectively total emissions and per capita emissions of SO_2 and BC for selected nations that include developed and developing countries. With respect to SO_2, China and USA are the major emitters. Furthermore, we note that in developed nations (USA, Germany and UK) SO_2 emissions have been reduced significantly, particularly in Germany and UK. However, the largest per capita SO_2 emissions happen in USA, which suggests the difficulty in eliminating SO_2 even in developed countries. With respect to BC emissions, there is a major shift in emissions from developed to developing nations in 1990s. In 1980s, BC emissions in China and Germany were large, but in circa 2000, China and India emerged as large emitters. However, when we view the same data in terms of per capita emissions, Germany and UK were the highest before 1990s, while in circa 2000 USA is the top of the list, because of large reductions in per capita emissions in Germany and UK. The Germany emission data is largely influenced by the merger of East with West Germany. The large reductions in per capita as well as in total emissions of SO_2 in Germany, UK, USA and other developed nations is the major reason why Organization for Economic Co-operation and Development (OECD) countries have emerged as the major contributors to global warming, as shown by Andronova and Schlesinger (2004).

We are not pointing this out to suggest that reduction of sulfur emissions is undesirable, but simply note the strong coupling and feedback effects of air pollution mitigation efforts and global warming commitment. The second point we wish to note is the large per capita emissions of BC even in developed nations. This of course offers options for mitigating global warming, since black carbon is the second largest contributor to global warming and to the retreat of arctic sea ice, next to CO_2 (e.g., Jacobson, 2002; Ramanathan and Carmichael, 2008). Another point we wish to convey with the black carbon emission data is the importance of absorbing aerosols even in developed nations. A rapid reduction of SO_2 emissions without corresponding reductions in black carbon and greenhouse gases will accelerate the global warming.

We also have to consider the problem in terms of fuel type. Fig. 12 shows contribution of various fuel types to emissions of SO_2 and BC. It is clear that coal is the major source (about 78%) of SO_2 emissions. With respect to emissions of CO_2, coal contributed 41% to the total CO_2 emissions in 2005 (International Energy Agency, 2007). Thus it is likely that the warming effect of coal combustion was either balanced or exceeded by the cooling effects of its SO_2 emissions. The implication is that burning of fuel oil and natural gas, which emit less CO_2 than coal (per unit of energy released), may be the largest contributors to global warming, because their SO_2 emissions are much smaller than that of coal. With respect to diesel fuel, it contributes as much as 20% to global BC emissions and thus diesel contributes to global warming both by emitting CO_2 and by emitting BC. We are pointing out the above intersection between air pollution related climate change effects and greenhouse gas emissions of each fuel type, to alert to the fact that we need to develop socio-economic-climate change and impact models on regional to global scales to assess the real impact of each fuel on global warming.

Since 1979 the Convention on Long-Range Transboundary Air Pollution (CLRTAP) has addressed some of the major environmental problems of the UNECE region through scientific collaboration and policy negotiation. The CLRTAP has been extended by eight protocols that identify specific measures to be taken by its 51 parties (as of 2008) to cut their emissions of multiple air pollutants. If the recent protocol is fully implemented by 2010, the SO_2 emissions in Europe would be cut by at least 63%, together with its NO_x emissions by 41%, VOC emissions by 40% and ammonia emissions by 17%, compared to 1990. The CLRTAP also sets tight limit values for specific emission sources (e.g. combustion plant, electricity production, dry cleaning, cars and lorries) and requires best

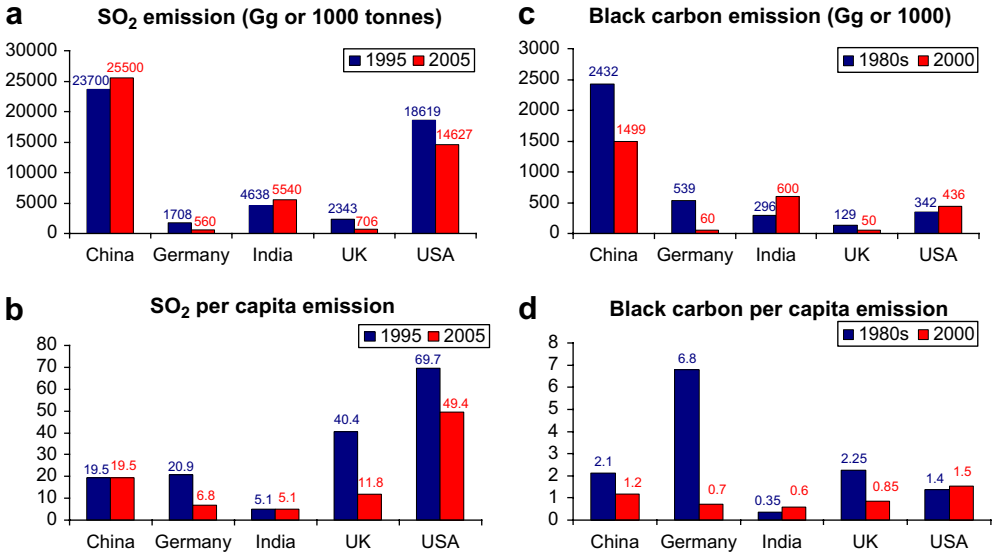

Fig. 11. Total and per capita emissions by nations (China, Germany, India, UK, and USA), for SO_2: (a) and (b); and black carbon: (c) and (d). Reference: SO_2 emissions in China (State Environmental Protection Administration, 2005); Germany and UK (Vestreng et al., 2007); India (Garg et al., 2001 and 2003); USA (EPA, 2005). For circa 2000 BC emissions, China (Cao et al., 2007); Germany and UK (Novakov et al., 2003); India (Streets et al., 2003); USA (EPA, 2005); and BC emissions in the 1980s (Liousse et al., 1996).

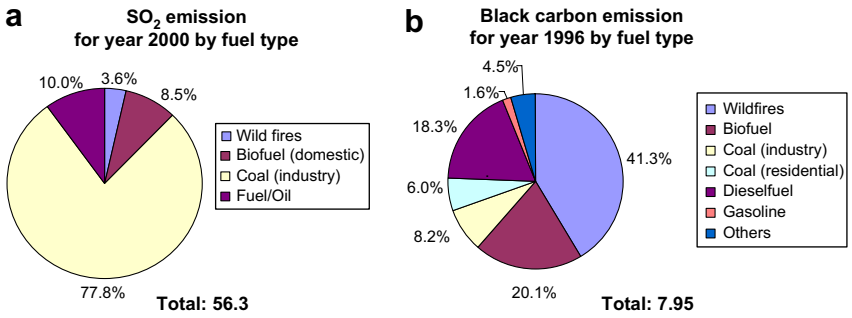

Fig. 12. SO_2 and black carbon emissions divided by fuel type, for years 2000 and 1996, respectively. Reference: Dentener et al., 2006; Bond et al., 2004.

available techniques to be used to keep emissions down. Guidance documents adopted by the CLRTAP (see reference for further information) provide a wide range of abatement techniques and economic instruments for the reduction of emissions in the relevant sectors, which can be shared with the other regions.

The ABC research also offers hope for mitigating ABC effects on global to regional climate changes and HKHT glacier retreat. It has identified soot as the major contributor to the negative effects of ABCs. Fortunately, we have the technology and the financial resources to significantly reduce soot emissions. Cooking with wood, coal, and cow dung fires is the major source for soot emissions in many parts of S Asia and East Asia. Replacing such solid fuel cooking with solar and biogas plants is an attractive alternative. The lifetime of soot is less than few weeks and as a result the effect of deployment of the cleaner cookers on the environment will be felt immediately. To understand the socio-economic-technology challenges in changing the cooking habits of a vast population (700 million in India alone), we have started Project Surya with engineers, social scientists and NGOs in India. For its pilot phase, Surya will adopt two rural areas: one in the HHK and the other in the Indo-Gangetic plains with a population of about 15,000 each and deploy locally made solar cookers and biogas plants. The unique feature is that Surya will accurately document the positive impacts of soot elimination on human health, deposition of soot on the glaciers, atmospheric heating and surface dimming. Additional details of Surya can be found in (Ramanathan and Balakrishnan, 2006; http://www-ramanathan.ucsd.edu/ProjectSurya.html).

By improving the living conditions of the rural poor (average earning is less than 2 $ a day) and by minimizing the negative health impacts of indoor smoke, Surya is a win–win proposition. Surya is but one example, of how each one of us must think of practical and innovative ways for solving the air pollution and global warming problem. Replacing solid fuel cooking with other alternative clean energy sources such as solar and biogas plants may seem promising, but there are sociological and cultural implications to be considered, particularly since solid fuel has been used for cooking for centuries. Science has provided us with immense knowledge of the impact of humans on the climate system, and we have to use this knowledge to develop practical solutions that combine behavioral changes with adaptation and mitigation steps.

Acknowledgement

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References

Alpert, P., Kishcha, P., 2008. Quantification of the effect of urbanization on solar dimming. L08801. Geophys. Res. Lett. 35, doi:10.1029/2007GL033012.

Andronova, N.G., Schlesinger, M.E., 2004. Importance of sulfate aerosol in evaluating the relative contributions of regional emissions to the historical global temperature change. Mitigat. Adapt. Strateg. Global Change 9 (4), 383–390. doi:10.1023/B:MITI.0000038845.44341.bb.

Arrhenius, S., 1896. On the influence of carbonic acid in the air upon the temperature of the ground, the London. Edinb. Dublin Philos. Mag. J. Sci. 41, 237–276.

Barnett, T.P., Pierce, D.W., Schnur, R., 2001. Detection of anthropogenic climate change in the world's oceans. Science 292, 270–274.

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.-H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. D14203. J. Geophys. Res. 109. doi:10.1029/2003JD003697.

Boucher, O., et al., 1998. Intercomparison of models representing direct shortwave radiative forcing by sulphate aerosols. J. Geophys. Res. 103, 16,979–16,998.

Cao, G., Zhang, X., Wang, Y., Che, H., Chen, D., 2007. Inventory of black carbon emission from China. Adv. Clim. Change Res. 3 (Suppl.), 75–81.

Charlson, R.J., Langner, J., Rodhe, H., 1990. Sulphate aerosol and climate. Nature 348, 22.

Chung, C.E., Ramanathan, V., Kim, D., Podgorny, I.A., 2005. Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations. D24207. J. Geophys. Res. 110. doi:10.1029/2005JD006356.

Chung, C.E., Ramanathan, V., 2006. Weakening of North Indian SST Gradients and the monsoon rainfall in India and the Sahel. J. Climate 19, 2036–2045.

Chung, S.H., Seinfeld, J.H., 2002. Global distribution and climate forcing of carbonaceous aerosols. J. Geophys. Res. 107. doi:10.1029/2001JD001397.

Corrigan, C.E., Roberts, G., Ramana, M.V., Kim, D., Ramanathan, V., 2008. Vertical profiles of aerosol physical and optical properties over the Northern Indian Ocean. Atmos. Chem. Phys. 8, 737–747.

Crutzen, P.J., 1972. SSTs: a threat to the earth's ozone shield. Ambio 1, 41–51.

Dentener, F., et al., 2006. Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom. Atmos. Chem. Phys. 6, 4321–4344.

Vestreng, V., et al., 2007. EMEP (Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe) expert emissions, Inventory Report 2007.

EPA (Environmental Protection Agency), Air emissions summary through 2005.

Feng, Y., Penner, J.E., 2007. Global modeling of nitrate and ammonium: interaction of aerosols and tropospheric chemistry. D01304. J. Geophys. Res. 112. doi:10.1029/2005JD006404.

Feng, Y., Ramanathan, V., Investigation of aerosol-cloud interactions using a chemical transport model constrained by satellite observations, in preparation.

Fishman, J., Ramanathan, V., Crutzen, P.J., Liu, S.C., 1980. Tropospheric ozone and climate. Nature 282, 818–820.

Flanner, M.G., Zender, C.S., Randerson, J.T., Rasch, P.J., 2007. Present-day climate forcing and response from black carbon in snow. D11202. J. Geophys. Res. 112. doi:10.1029/2006JD008003.

Garg, A., Shukla, P.R., Bhattacharya, S., Dadhwal, V.K., 2001. Sub-region (District) and sector level SO_2 and NO_x emissions for India: assessment of inventories and mitigation flexibility. Atmos. Environ. 35, 703–713.

Garg, A., Shukla, P.R., Ghosh, D., Kapshe, M., Rajesh, N., 2003. Future greenhouse gas and local pollutant emissions for India: policy links and disjoints. Mitigat. Adapt. Strateg. Global Change 8, 71–92.

Gilgen, H., Wild, M., Ohmura, A., 1998. Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data. J. Climate 11, 2042–2061.

Hansen, J., Nazarenko, L., 2004. Soot climate forcing via snow and ice albedos. Proc. Natl. Acad. Sci., U.S.A. 101, 423–428.

Held, I.M., et al., 2005. Simulation of Sahel drought in the 20th and 21st centuries. Proc. Natl. Acad. Sci., U.S.A. 102 (50), 17891–17896.

Holben, B.N., et al., 2001. An emerging ground-based aerosol climatology: aerosol optical depth from AERONET. J. Geophys. Res. 106 (D11), 12067–12097.

Huebert, B.J., Bates, T., Russell, P.B., Shi, G., Kim, Y.J., Kawamura, K., Carmichael, G., Nakajima, T., 2003. An overview of ACE-Asia: strategies for quantifying the relationships between Asian aerosols and their climatic impacts. J. Geophys. Res. 108 (D23), 8633. doi:10.1029/2003JD003550.

Intergovernmental Panel on Climate Change (IPCC), 2001. Climate change 2001: the scientific basis. In: Houghton, J.T. (Ed.), Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, New York, p. 881.

Intergovernmental Panel on Climate Change (IPCC), 2007. Climate change 2007: the scientific basis. In: Solomon, S. (Ed.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, New York.
International Energy Agency, 2007. World Energy Outlook 2007: China and India Insights Paris, France.
Jacobson, M.Z., 2002. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. J. Geophys. Res. 107 (D19), 4410. doi:10.1029/2001JD001376.
Kaufman, Y.J., Tanré, D., Boucher, O., 2002. A satellite view of aerosols in the climate system. Nature 419, 215–223.
Lambert, F.H., Gillett, N.P., Stone, D.A., Huntingford, C., 2005. Attribution studies of observed land precipitation changes with nine coupled models. L18704. Geophys. Res. Lett. 32. doi:10.1029/2005GL023654.
Lau, K.-M., Ramanathan, V., Wu, G.-X., Li, Z., Tsay, S.S., Hsu, C., Sikka, R., Holben, B., Lu, D., Tartari, G., Chin, M., Koudelova, P., Chen, H., Ma, Y., Huang, J., Taniguchi, K., Zhang, R., 2008. The joint aerosol-monsoon experiment. Bull. Amer. Meteor. Soc. 89, 1–15.
Liepert, B.G., 2002. Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. Geophys. Res. Lett. 29 (10), 1421. doi:10.1029/2002GL014910.
Liao, H., Seinfeld, J.H., 2005. Global impacts of gas-phase chemistry-aerosol interactions on direct radiative forcing by anthropogenic aerosols and ozone. D18208. J. Geophys. Res. 110. doi:10.1029/2005JD005907.
Liu, X.H., Penner, J.E., 2002. Effect of Mount Pinatubo H_2SO_4/H_2O aerosol on ice nucleation in the upper troposphere using a global chemistry and transport model. J. Geophys. Res. 107 (D12). doi:10.1029/2001JD000455.
Liu, X., Penner, J.E., Herzog, M., 2005. Global modeling of aerosol dynamics: model description, evaluation and interactions between sulfate and non-sulfate aerosols. D18206. J. Geophys. Res. 110, doi:10.1029/2004JD005674.
Lohmann, U., Feichter, J., 2001. Can the direct and semi-direct aerosol effect compete with the indirect effect on a global scale? Geophys. Res. Lett. 28 (1), 159–161.
Lohmann, U., Kärcher, B., Hendrichs, J., 2004. Sensitivity studies of cirrus clouds formed by heterogeneous freezing in ECHAM GCM. D16204. J. Geophys. Res. 109. doi:10.1029/2003JD004443.
Liousse, C., Penner, J.E., Chuang, C., Walton, J.J., Eddleman, H., Cachier, H., 1996. A global three-dimensional model study of carbonaceous aerosols. J. Geophys. Res. Atmos. 101, 19411–19432.
Madden, R.A., Ramanathan, V., 1980. Detecting climate change due to increasing carbon dioxide. Science 209, 763–768.
Manabe, S., Wetherald, R.T., 1967. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J. Atmos. Sci. 24, 241–259.
Meehl, G.A., Arblaster, J.M., Collins, W.D., 2008. Effects of black carbon aerosols on the Indian monsoon. J. Climate 21, 2869–2882. doi:10.1175/2007JCLI1777.1.
Menon, S., Hansen, J.E., Nazarenko, L., Luo, Y., 2002. Climate effects of black carbon aerosols in China and India. Science 297, 2250–2253.
Meywerk, J., Ramanathan, V., 1999. Observations of the spectral clear-sky aerosol forcing over the tropical Indian Ocean. J. Geophys. Res. 104 (D20), 24359–24370.
Mitchell Jr., J.M., 1970. A preliminary evaluation of atmospheric pollution as a cause of the global temperature fluctuation of the past century. In: Fred Singer, S. (Ed.), Global Effects of Environmental Pollution. Springer-Verlag, New York, pp. 139–155.
Molina, M.J., Rowland, F.S., 1974. Stratospheric sink for chlorofluorocarbons: chlorine atom catalysed destruction of ozone. Nature 249, 810.
Nakicenovic, N., et al., 2000. Emissions scenarios. In: Nakicenovic, N., et al. (Eds.), Special Report on Emission Scenarios. Cambridge University Press, New York, p. 599.
Novakov, T., Ramanathan, V., Hansen, J.E., Kirchstetter, T.W., Sato, M., Sinton, J.E., Sathaye, J.A., 2003. Large historical changes of fossil-fuel black carbon aerosols. Geophys. Res. Lett. 30 (6), 1324. doi:10.1029/2002GL016345. 57–1 to 57–4.
Ohmura, A., Gilgen, H., Wild, M., 1989. Global energy balance archive GEBA, World Climate Pmgram – Water Project A7. Report 1: Introduction. Zurrcher GeogrqLdte Schripcn, 34. Vedag der Fachvercine, Zucrich. 62pp.
Penner, J.E., Chuang, C.C., Grant, K., 1998. Climate forcing by carbonaceous and sulphate aerosols. Clim. Dyn. 14, 839–851.
Penner, J.E., Zhang, S.Y., Chuang, C.C., 2003. Soot and smoke aerosol may not warm climate. J. Geophys. Res. 108 (D21), 4657. doi:10.1029/2003JD003409.
Penner, J.E., et al., 2006. Model intercomparison of indirect aerosol effects. Atmos. Chem. Phys. Discuss. 6, 1579–1617.
Pinker, R.T., Zhang, B., Dutton, E.G., 2005. Do satellites detect trends in surface solar radiation? Science 308, 850–854.
Ramana, M.V., Ramanathan, V., Kim, D., Roberts, G., Corrigan, C.E., 2007. Albedo, atmospheric solar absorption, and atmospheric heating rate measurements with light weight autonomous stacked UAVs. Q.J.R. Meteorol. Soc. 133, 1913–1931.
Ramanathan, V., 1975. Greenhouse effect due to chlorofluorocarbons: climatic implications. Science 190, 50–52.
Ramanathan, V., Callis, L.B., Boughner, R.E., 1976. Sensitivity of surface temperature and atmospheric temperature to perturbations in stratospheric concentration of ozone and nitrogen dioxide. J. Atmos. Sci. 33, 1092–1112.
Ramanathan, V., Lian, M.S., Cess, R.D., 1979. Increased atmospheric co_2: zonal and seasonal estimates of the effect on the radiation energy balance and surface temperature. J. Geophys. Res. 84, 4949–4958.
Ramanathan, V., 1980. Climatic effects of anthropogenic trace gases. In: Bach, W., Pankrath, T., Williams, J. (Eds.), Interactions of Energy and Climate. D. Reidel Publishing Co, pp. 269–280.
Ramanathan, V., Cicerone, R.J., Singh, H.B., Kiehl, J.T., 1985a. Trace gas trends and their potential role in climate change. J. Geophys. Res. 90, 5547–5566.
Ramanathan, V., et al., 1985b. Trace gas effects on climate, in atmospheric ozone 1985: assessment of our understanding of the processes controlling its present distribution and change, WMO Report, No. 16., pp. 821–893.
Ramanathan, V., 1988. The greenhouse theory of climate change: a test by an inadvertent global experiment. Science 240, 293–299.
Ramanathan, V., et al., 2001a. The Indian ocean experiment: an integrated assessment of the climate forcing and effects of the great Indo-Asian Haze. J. Geophys. Res. 106 (D22), 28371–28399.
Ramanathan, V., Crutzen, P.J., Kiehl, J.T., Rosenfeld, D., 2001b. Aerosols, Climate, and the hydrological cycle. Science 294, 2119–2124.
Ramanathan, V., Crutzen, P.J., 2003. New directions: atmospheric brown "Clouds". Atmos. Environ. 37, 4033–4035.
Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J.T., Washington, W.M., Fu, Q., Sikka, D.R., Wild, M., 2005. Atmospheric brown clouds: impacts on south Asian climate and hydrological cycle. Proc. Natl. Acad. Sci., U.S.A. 102 (15), 5326–5333.
Ramanathan, V., Balakrishnan, K., 2006. Project Surya: Reduction of air pollution and global warming by cooking with renewable sources: a controlled and practical experiment in rural India, a white paper, 14pp.
Ramanathan, V., Ramana, M.V., Roberts, G., Kim, D., Corrigan, C.E., Chung, C.E., Winker, D., 2007a. Warming trends in Asia amplified by brown cloud solar absorption. Nature 448, 575–578. doi:10.1038/nature06019.
Ramanathan, V., Li, F., Ramana, M.V., Praveen, P.S., Kim, D., Corrigan, C.E., Nguyen, H., 2007b. Atmospheric brown clouds: hemispherical and regional variations in long range transport, absorption, and radiative forcing. D22S21. J. Geophys. Res. 112. doi:10.1029/2006JD008124.
Ramanathan, V., Carmichael, G., 2008. Global and regional climate changes due to black carbon. Nat. Geosci. 1, 221–227.
Rasool, S.I., Schneider, S.H., 1971. Atmospheric carbon dioxide and aerosols: effects of large increases on global climate. Science 173, 138–141.
Rotman, D.A., et al., 2004. IMPACT, the LLNL 3-D global atmospheric chemical transport model for the combined troposphere and stratosphere: model description and analysis of ozone and other trace gases. D04303. J. Geophys. Res. 109. doi:10.1029/2002JD003155.
Rotstayn, L.D., Lohmann, U., 2002. Tropical rainfall trends and the indirect aerosol effect. J. Climate 15, 2103–2116.
State Environment Protection Administration (SEPA), Department of International Cooperation, China, 2005. Report on the State of the Environment in China 2005 (Beijing:China).
Report, S.M.I.C., 1971. In: Wilson, C.M., Matthews, W.H. (Eds.), Report of the Study of Man's Impact on Climate (SMIC). M.I.T. Press, Cambridge, Mass, London, England.
Stanhill, G., Cohen, S., 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. Forest Meteorol. 107, 255–278.
Streets, D.G., et al., 2003. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. J. Geophys. Res. 108 (D21), 8809. doi:10.1029/2002JD003093.
Streets, D.G., Wu, Y., Chin, M., 2006. Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition. L15806. Geophys. Res. Lett. 33. doi:10.1029/2006GL026471.
Takemura, T., et al., 2005. Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model. D02202. J. Geophys. Res. 110. doi:10.1029/2004JD005029.
Wang, W.-C., Yung, Y.L., Lacis, A.A., Mo, T., Hansen, J.E., 1976. Greenhouse effects due to man-made perturbation of trace gases. Science 194, 685–690. doi:10.1126/science.194.4266.685.
Wild, M., Ohmura, A., Gilgen, H., Rosenfeld, D., 2004. On the consistency of trends in radiation and temperature records and implications for the global hydrological cycle. Geophys. Res. Lett. 31 2003GL091188.
Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C., Dutton, E., Forgan, B., Kallis, A., Russak, V., Tsvetkov, A., 2005. From dimming to brightening: decadal changes in solar radiation at the Earth's surface. Science 308, 847–850.
Williams, K.D., et al., 2001. The response of the climate system to the indirect effects of anthropogenic aerosol. Clim. Dyn. 17, 845–856.

References for further information

Chatterton, T.J., Longhurst, J.W.S., Leksmono, N.S., Hayes, E.T., Symons, J.K., 2007. Ten years of local air quality management experience in the UK: an analysis of the process. Clean Air and Environmental Quality 41 (4), 26–31.
Longhurst, J.W.S., Beattie, C.I., Chatterton, T., Hayes, E.T., Leksmono, N.S., Woodfield, N.K., 2006. Local air quality management as a risk management process: assessing, managing and remediating the risk of exceeding an air quality objective in Great Britain. Environ. Int. 32 (8), 934–947.
Longhurst, J.W.S., Irwin, J.G., Chatterton, T.J., Hayes, E.T., Leksmono, N.S., Symons, J.K., 2008. The development of effects based air quality management regimes. Atmos. Environ. 43 (1), 64–78.
United Nations Economic Commission for Europe. Convention on the Long-Range Transboundary Air Pollution.
United Nations Reports on the Asian Brown Cloud, 2002. The Atmospheric Brown Cloud: Climate and Other Environmental Impacts.

United Nations Reports on the Long Range Transport of Air Pollutants, 2007. Task Force On Hemispheric Transport of Air Pollution.

List of Acronyms

ABC	Atmospheric Brown Cloud
ACE	Asia Asian Pacific Regional Aerosol Characterization Experiment
AERONET	Aerosol Robotic Network
AOD	Aerosol optical depth
BC	Black carbon
CALIPSO	The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CFC	Chlorofluorocarbon
CLRTAP	Convention on Long-Range Transboundary Air Pollution
EMEP	Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe
EPA	Environmental Protection Agency (US)
GEBA	Global Energy Balance Archive
GHG	Greenhouse gas
HHK	Himalayan-Hindu Kush
HKHT	Hindu Kush Himalayan Tibetan
IMPACT	Integrated Massively Parallel Atmospheric Chemistry Transport
INDOEX	Indian Ocean Experiment
IPCC	Intergovernmental Panel on Climate Change
ISM	Indian summer monsoon
LLNL	Lawrence Livermore National Laboratory
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NGO	Non-governmental organization
NIO	Northern Indian Ocean
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Fundation
OECD	Organization for Economic Co-operation and Development
SEPA	State Environment Protection Administration (China)
SMIC	Study of Man's Impact on Climate
SST	Sea surface temperature
TOA	Top of the atmosphere
UAV	Unmanned aerial vehicle
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UV	Ultra-violet
VOC	Volatile organic compound
WMO	World Meteorological Organization