# Global Dimming by Air Pollution and Global Warming by Greenhouse Gases: Global and Regional Perspectives

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*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 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. 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 nucleate more cloud drops which makes the clouds reflect more solar radiation. The surface cooling from this dimming effect has masked the warming due to GHGs.*

*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. Such a pattern of regionally concentrated surface dimming and atmospheric solar heating, accompanied by wide spread 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. The large north-south gradient in the ABC dimming has altered the north-south gradients in sea surface temperatures, which in turn has been shown by models to decrease rainfall over the continents. In addition to their climate effects, ABCs lead to acidification of rain and also result in over few million fatalities worldwide.*

*The surface cooling effect of ABCs may have masked as much 50% of the global warming. This presents a dilemma since efforts to curb air pollution may unmask the ABC cooling effect and enhance the surface warming. Thus efforts to curb GHGs and air pollution should be done under one 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.*

**Some of the material in this paper is taken from a lecture given at the Pontifical Academy of Sciences (2006) and the Bjerkenes lecture given at the AGU (2006).**

## 1. INTRODUCTION:

Human activities are releasing tiny particles, aerosols, into the atmosphere in large quantities. 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, 2001) and ACE-Asia (Huebert et al, 2003), among others and global modeling studies. 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 plays a major role in the dimming of the surface. Manmade 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 availability of fresh water, a major environmental issue of the 21$^{st}$ century. For example, the Sahelian drought during the last century is attributed by models to aerosols. 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. 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 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.

Without a proper treatment of the regional aerosol effects in climate models, it is nearly impossible to reliably interpret the causal factors for observed regional as well as global climate changes during the last century. 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. The paper presents the following recent results and findings:

- Identification of Regional and Mega City Aerosol Hotspots
- Global distribution of the surface dimming and atmospheric heating by ABCs
- The magnitude of the masking effect of global warming by ABCs
- Reconciliation of the large surface dimming with the observed global warming
- Effects of ABCs on the Asian monsoon
- The combined effects of ABCs and GHGs on regional climate

We conclude with the following outstanding issues that can influence the response of our climate to GHGs increases during the next several decades:

1) Why is the planetary albedo 29% and how is it regulated?
2) Will a warmer planet also become more cloudy?
3) What is the role of the biosphere in determining the aerosol chemistry and nuclei for cloud formation?
4) What is the role of ABCs in nucleating mixed phase and ice phase clouds in the mid and upper troposphere?

## 2. ABCs: REGIONAL AND MEGA CITY HOTSPOTS

It is important to first recognize that ABCs are a worldwide problem. Monthly mean aerosol optical depth (AOD) analyzed from the MODIS instrument (Kaufman et al, 2001) on NASA's TERRA satellite that monthly mean AODS exceeding 0.2(indicative of strong pollution) occur even over large areas of industrialized countries.  The figure also indicates how, due to long range transport, ABCs from east Asia spreads across the Pacific and like wise, pollution from N America spreads across the Atlantic.

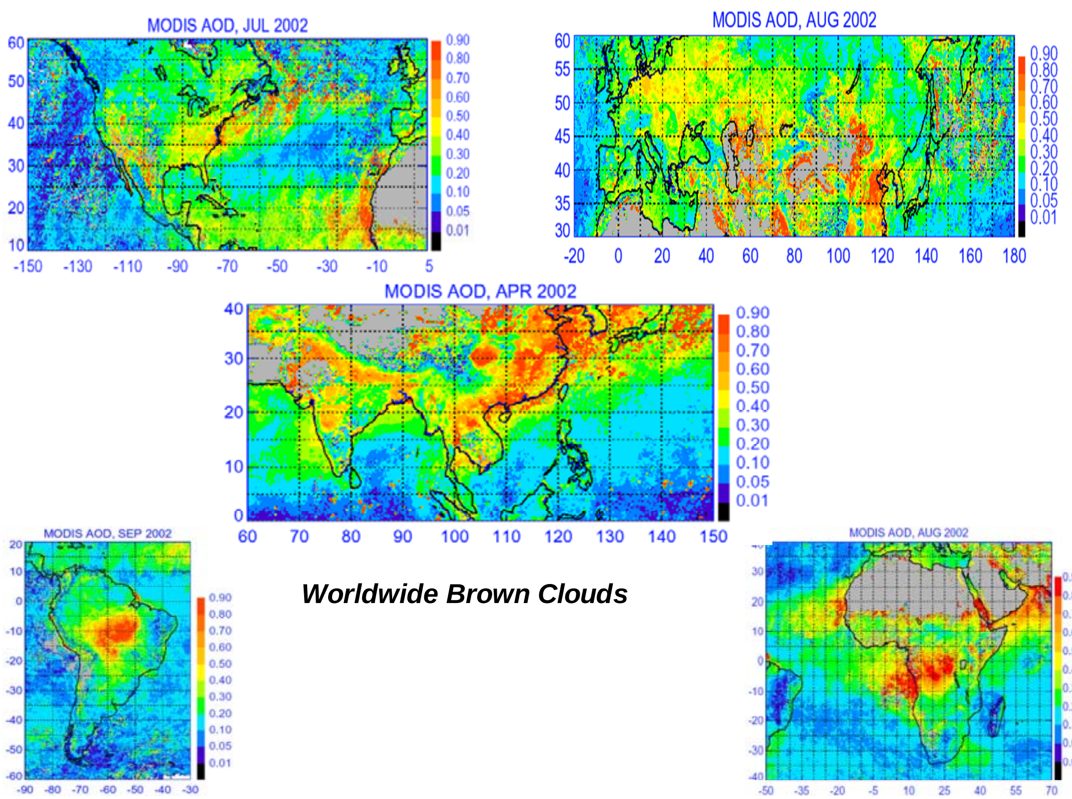


**Figure 1: Monthly mean aerosol optical depths derived from MODIS aerosol instrument on NASA's TERRA satellite. The color shading is dark blue for AODs  smaller than  0.05 (clean marine background); green for 0.2 (visible brown clouds) , yellow for 0.4 to 0.5 (very hazy)and red for AODs>0.6 (heavily polluted).**

Using a combination of satellite observations, aerosol transport models and field campaign data, Ramanathan et al (2007) 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 mea 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.

## *3 GLOBAL 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 2001) used a variety of chemical, physical and optical measurements to convincingly demonstrate (Satheesh and Ramanathan, 2000) that ABCs with AODs of about 0.2 and absorption of AODs of about 0.02, can lead to dimming as large as 5% to 10% (i.e, decrease in annual mean absorbed solar radiation of about 15 $W.m^{-2}$). 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.

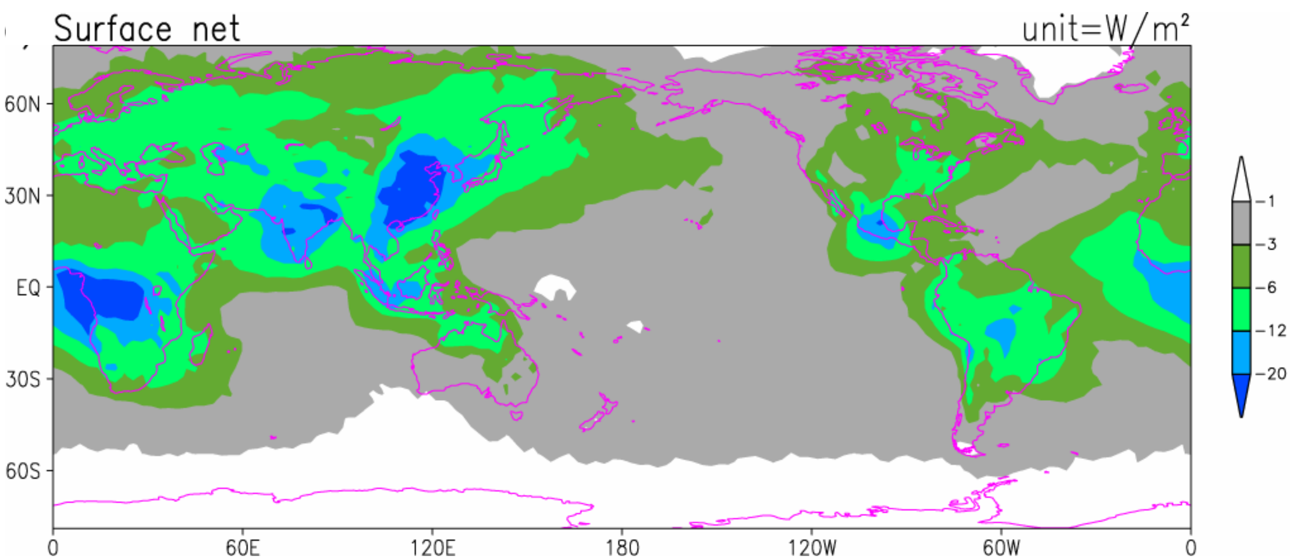


**Figure 2: Integrated and Observationally constrained estimate of Annual mean Global Dimming by ABCs around the world for 2001-2003. Ref: Chung, Ramanathan, Podgorny and Kim, 2005.**

As seen from Fig.2, 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 $W.m^{-2}$. *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.

**4. *GLOBAL SOLAR HEATING OF ATMOSPHERE BY ABCS***

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.

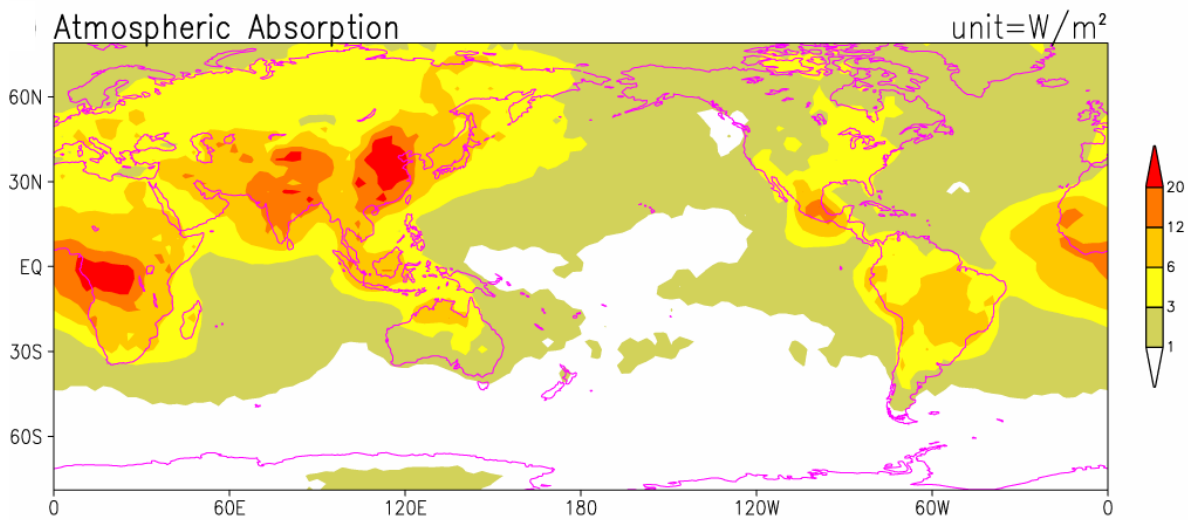


***Figure 3:*** **Integrated and observationally constrained estimate of annual mean atmospheric Solar heating by ABCs for 2001-2003. Ref: Chung, Ramanathan, Podgorny and Kim, 2005.**

**5. *MASKING OF GLOBAL WARMING***

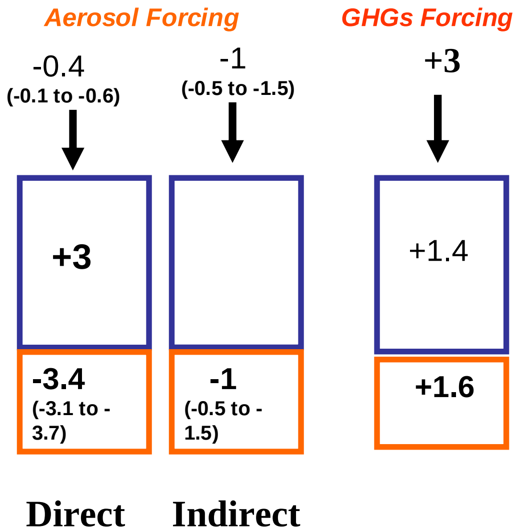


**Figure 4: Global Mean anthropogenic Forcing due to aerosols (the two panels on the right) and due to greenhouse gases. The blue boxes show the atmospheric Forcing; the brown box at the bottom show the surface forcing; the sum of the two is the forcing at top-of-atmosphere (TOA). The aerosol forcing is for 2001-2003 and is from the present study; while the GHGs at TOA is from IPCC (2007). Also see Crutzen and Ramanathan (2003) on the *parasol* effect of aerosols.**

The global mean estimates shown in Fig 4 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. We also note that, globally, the ABC forcing (-1.4 $Wm^{-2}$ ) has masked about 50% of the GHGs forcing (+3 $Wm^{-2}$ ). The implications of this masking to global warming and climate sensitivity is discussed in Andreae et al(2005).

## 6. INTERACTIONS BETWEEN GHGS AND ABCS ON REGIONAL SCALES: THE ASIAN MONSOON AS AN EXAMPLE

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 5). Numerous climate model studies have been published which suggest that inclusion of the aerosol dimming can help explain the Sahelian drought (Rotstayn and Lohmann, 2001); 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

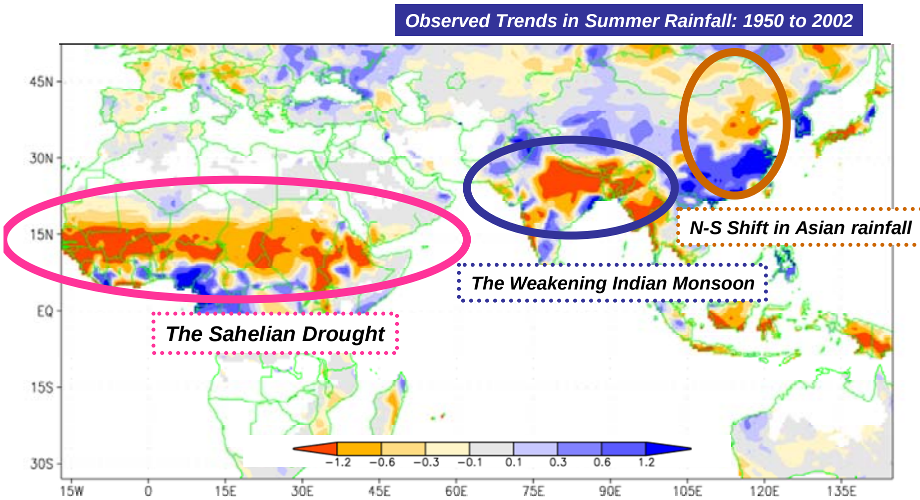


**Figure 5: Trend in observed rainfall from 1950 to 2002. The figure shows the change in rainfall between 2002 and 1950; It was obtained by multiplying the year linear trend in mm/day/year by 52 years.The precipitation data is the Hadley center CRU data (Ref: Mitchell and Jones, 2005)**

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 (for 2001 to 2003) with history of $SO_2$ and soot emission for S Asia from 1930 to 2002. . Their model simulations led to the following findings

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 the summer monsoonal circulation, the decrease in evaporation, and the increase in stability are the primary mechanisms for the reduction in the summer monsoon rainfall.*

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).

## 7. OUTSTANDING ISSUES:

### 7.1 How Will Clouds and their Radiative Forcing Respond to and Feedback on Global Warming?

Figure 6 shows the net radiative forcing (in $Wm^{-2}$) due to clouds obtained from cloud forcing observations (Ramanathan et al 1989) from the Earth Radiation Budget Experiment (Harrison et al 1991).

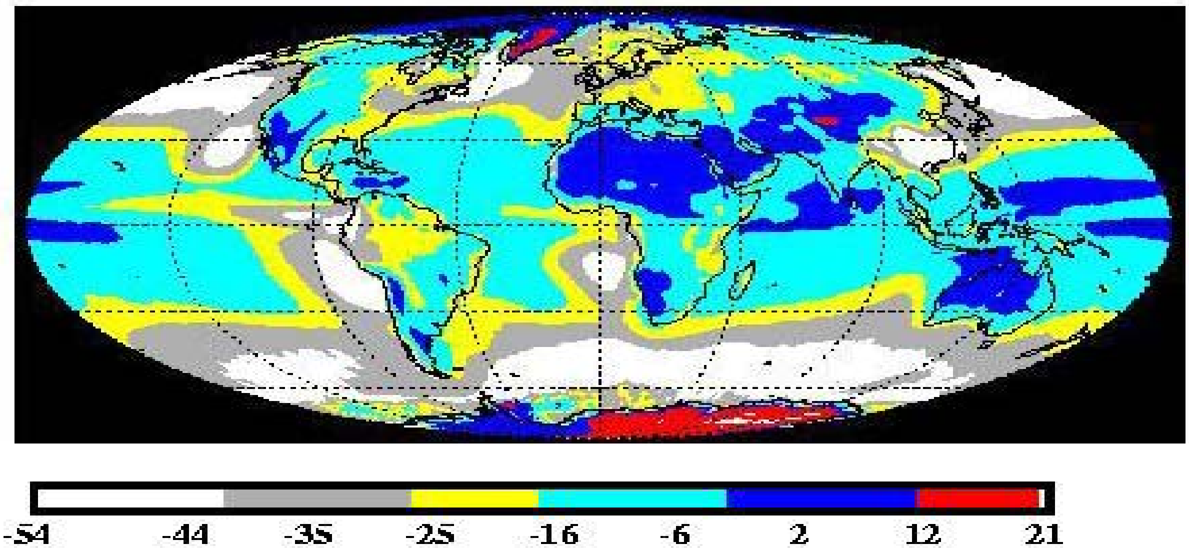


**Figure 6: Net (sum of the short wave forcing, i.e, reflection of solar, and greenhouse effect of clouds) radiative forcing due to clouds for the 1985 to1989 period. See Ramanathan et al, 1989 for how cloud forcing data were obtained.**

Globally, clouds enhance the albedo (percent reflection to space of incident solar radiation) of the planet from about 14% in clear skies to the observed albedo of about 29%. The resulting short wave radiative forcing is about -48 (uncertainty is about $\pm$5) $Wm^{-2}$. Clouds also enhance the greenhouse effect and this positive forcing is about +30 $Wm^{-2}$, such that the net effect of clouds is to exert a net negative forcing of about -18 $Wm^{-2}$. The global distribution of the net cloud forcing reveals the strong regional variations. Essentially the extra tropical storm track cloud systems (ET_STCS), are the dominant cooling agents of the whole planet (Weaver and Ramanathan, 1999), without which the entire planet would be warmer by more than 10 C. Thus a small change in the cloud forcing, say a 2% decrease or increase in cloud shortwave forcing, is enough to amplify or ameliorate the 0.8 K global warming of the last 100 years by about 70%. Currently we neither have any theoretical constraint nor observational constraint to rule out such a possibility. The other major source of concern is that the ET_STCS cloud systems are susceptible to anthropogenic effects because: 1) The fast retreat of sea ice is reducing the equator to pole temperature gradient which is one of the major factors that regulate the latitudinal extent of the extra tropical cloud systems; and 2) advection of ABCs from the surrounding continents (east Asia for the Pacific; and N America for the Atlantic) as shown in Figs 2 and 3, can significantly perturb the nucleation of water drops and ice crystals in these systems.

## 7.2 Biospheric Influences on Aerosols and Clouds and its Feedback Effects:

Biogenic emissions of aerosol precursor gases by terrestrial and marine microorganisms, DMS (Charlson et al, 1989), , Isoprenes (Meskidze and Nenes, 2006) and other organic vapours (O'Dowd et al 2002)are now well known to be important biogenic sources of aerosols and cloud condensation nuclei. There have been several suggestions that the biogenic emission sources respond to temperature changes and thus possibly feedback on climate changes (e.g, Charlson et al, 1989 and O'Dowd et al 2002). The climate models have not been able to incorporate these biogenic effects largely because the details of the aerosol formation nor the emission strengths are largely unknown. Yet the potential of these biogenic aerosols to influence climate can be appreciable and we need observational constraints for their effects.

## 7.3 Emission Sources for Elemental and Organic and Carbon:

These carbonaceous aerosols are the major source of dimming by ABCs (Ramanathan et al, 2001 and 2007) but our ability to model their effects in climate models are severely limited. One of the main reason is the factor of 2 or more uncertainty in the current estimates of the emission of the organic (OC) and elemental carbon (EC). Further more, that biomass and bio-fuel burning contribute over 50% of the OC and EC and the historical trends (during the last 100 years) in these emissions are unkonown and models currently resort to scaling the current day emissions with past trends in population.

## 7.4 Why Is The Planetary Albedo 29%:

One of the fundamental unanswered (and perhaps unasked) questions in climate is: Why is the planetary albedo 29% ( $\pm$1%). Let us consider first why this question is important. A global albedo of 32% would plunge the Earth into a climate similar to that of the last ice-age; while an albedo of 26% would be comparable to a six fold increase in the $CO_2$ concentration from about 300 ppm to 1800 ppm. Is it sheer chance that the planet just settled into the 29% albedo? I am not aware of any theory that has contemplated this issue seriously, except for the untestable Gaia theory (Lovelock and Margulis, 1974). It is remarkable that our general circulation climate models are able to explain the observed temperature trends during the last century solely through solely variations in greenhouse gases, aerosols and solar irradiance. This implies that the role of clouds in planetary albedo has not changed during the last 100 years by more than ±0.3% (out of 29 %). Clearly we need theoretical and observational verification for this remarkable model result. Most discussions of pale climate changes also implicitly assume clouds have not changed much over time scales ranging from $10^3$ to $10^8$ years( see http://www-c4.ucsd.edu/gap/ for additional discussions of this topic).

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