Predictability in Science: Accuracy and Limitations
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GLOBAL WARMING SCIENCE: PREDICTIONS, SURPRISES AND UNCERTAINTIES

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Preface

Much too much has been written about climate change. Yet, very few of these articles elaborate on how the field has rapidly evolved over the last few decades; how discoveries are made to understand and keep up with the rapid warming of the planet; and above all, how climate science is conducted. These are the issues that I am going to dwell on in this lecture, since the title of this meeting at the Pontifical Academy of Sciences encourages me to do so.

The first scholarly and quantitative work on the greenhouse effect of carbon dioxide was done nearly one hundred years ago by 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 concentration would lead to a warming of the surface by as much as 4 to 5K. 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. The next major development was the idea of Lorenz proposed in the 1970s, in which he used simple but elegant mathematical models of the dynamics of the atmosphere to reveal the fundamental unpredictability of weather and thus laid a solid foundation for the science of Chaos. Arrhenius' greenhouse effect model of climate change and Lorenz's Chaos model of weather and climate prediction provides two strong book-ends to the book on climate change, parts of which have been written during the last century.

In this lecture I would like to focus on the scientific underpinnings of the link between greenhouse gases and global warming. I will describe a personal journey in trying to understand how human activities are modifying the earth's climate and environment. The journey took some major twists and turns through adventurous paths and I have made an attempt to describe how one question led to another and connect the various findings over a period of 35 years. Over time I also had to acquire and develop new tools including climate models, satellite observations, field experiments and lightweight unmanned aircraft. Ultimately these made me realize the seriousness of the climate change situation, threatening the water and food security of the planet. This realization has inadvertently taken me down the path of proposing practical solutions for mitigating unprecedented climate changes.

Since this is a lecture, I have not attempted to refer to many valuable references by groups other than mine. I refer the audience to many insightful surveys, including the historical background by Le Truet and Somerville (2007) in the IPCC-AR4 (2007) report, as well as to the entire IPCC report.

I. Predictions of the Anthropogenic Forcing of Climate

Inadvertent Modification of the Atmosphere

When we look up to the sky, the atmosphere seems enormous and limitless. But it is really a thin shell of gases, particles and clouds surrounding the planet (Figure 1, see p. 241). 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 (Figs 2a and 2b, see p. 241); cooking with solid fuels (Fig 2c, see p. 241); and burning of forests and savannah (Figure 2d, see p. 241). The ultimate by-product of all forms of burning is the emission of the colourless gas, carbon dioxide (CO_2). Now let us consider the following question: *Why should a person in my ancestral village in S India (Fig 2, bottom left panel) worry about the pollutant emitted by someone travelling in a car in the US (top right hand panel)? Likewise, why should we in the US worry about the cooking habits of people in my ancestral village?*

The answer is simple. Every part of the world is connected with every other part through fast atmospheric transport. For example Figure 3 (see p. 241) shows a one-day snapshot of the synoptic distribution of water vapour in the atmosphere as simulated by a climate model. This climate model is called the community climate model (CCM) developed by the National Center for Atmospheric Research in Boulder, Colorado. I was part of a team of 5 scientists who developed the first version of this model in the early 1980s (Pitcher *et al.*, 2003; Ramanathan *et al.*, 2003). It was then referred to as CCM0. The simulation shown in Fig. 3 is from CCM3, the fourth version of the model published recently (Kiehl *et al.*, 2004). The result shown for water vapour is basically a solution for a highly non-linear system of dynamical-thermodynamical equations. Most three-dimensional climate models solve for the climate by simulating individual weather systems like the ones shown in Fig. 3, every one hour for hundreds of years. The synoptic pattern clearly shows how air parcels can extend thousands of kilometres 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, be it from Asia, N America or Africa are transported half way around the world into trans-oceanic and trans-continental plumes.

The lifetime of a CO_2 molecule is of the order of decades to century. This is more than sufficient time for the billions of tons of manmade CO_2 to uniformly cover the planet like a blanket. Do we have evidence for this colourless blanket? Figure 4 (see p. 242) shows a time series of CO_2 in the air collected by Keeling of the Scripps Institution of Oceanography, from the now famous Mauna Loa observatory. The steady increase is basically the icon for most discussions about climate change. Clearly CO_2 concentration in the air is increasing and this increase is due to human activities. This CO_2 increase is observed no matter where we make these observations, attesting to the fact that, basically, carbon dioxide has surrounded the planet like a blanket, all the way from the surface up to 100 km.

The question is, why should we worry about this colourless gaseous blanket?

The Climate System: Basic Drivers

First, I have to provide a brief background of how the climate system works.

Fundamentally, the incident solar radiation drives the climate system as well as life (Figure 5, see p. 242). 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 warms, it gives off the energy as infrared radiation, also referred to as 'heat radiation'. So this process of the net incoming (downward solar energy-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. In an average sense, it is this radiation energy balance that provides a powerful constraint for the global average temperature of the planet.

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 heat radiation given off by the planet. The trapping of the heat 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 heat radiation.

When the frequency of the heat 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 is converted to heat and is given back to the surface. As a result of this trapping, the outgoing heat 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 (Figure 4), the infrared blanket is becoming thicker, and the planet is accumulating this excess energy.

Global Warming: Getting Rid of the Excess Energy

How does the planet get rid of the excess energy? We know from the basic infrared laws of physics, the so-called Planck's black body radiation law, that warmer bodies emit more heat radiation. So, the system will get rid of this excess energy by warming and 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. The rigorous mathematical modelling of this energy balance paradigm was originated by Arrhenius, but the proper accounting of the energy balance of the climate system containing the surface and the atmosphere had to await the work of Manabe and Wetherald in 1967.

CFCs: The Super-Greenhouse Gas

For nearly eighty years since Arrhenius' paper, climate scientists assumed that CO_2 was the main anthropogenic or manmade greenhouse gas (e.g., SMIC Report, 1971). For an entirely accidental reason, I stumbled onto the fact (Ramanathan, 1974) that there are other manmade gases, which on a per molecule basis are a thousand to more than ten thousand times stronger than the CO_2 greenhouse effect. Let me take the case of chlorofluorocarbons, or CFCs, used as refrigerants and propellants in deodorizers, drug delivery pumps, etc. These are purely synthetic gases. In 1974, Molina and Rowland published a famous paper in *Nature* (1974). In that paper, Molina and Rowland (1974) proposed that CFC11 and CFC12 (known then as Freon 11 and Freon 12), because of their century or longer lifetime, will build up in the atmosphere including the stratosphere. According to their theory, in the stratosphere, UV radiation from the sun will photo dissociate the CFCs and the chlorine atoms that are released will catalytically destroy ozone.

During 1974 to 1976, I was a National Research Council post doctoral fellow at the NASA Langley research center. The paper caught my attention. I was drawn to it, in part, because I had spent 2 years during 1965 to 1967 as an engineer in a refrigerator manufacturing company in Hyderabad, India. My job was to understand why CFCs leaked so quickly into the air from the sealed units, after delivery to the user! The other connecting event was my Ph D work during 1970 to 1973 in the US, where my thesis research dealt with the greenhouse effect of CO_2 in Mars and Venus. The CFC greenhouse effect finding was a question of connecting the dots.

One year after the Molina and Rowland paper, I published my findings in *Science* (Figure 6). What this work suggested, and it was met with disbelief, was that adding one molecule of CFC11 or CFC12 had the same effect as adding 10,000 molecules of CO_2! So suddenly human beings have synthesized and released this enormously powerful greenhouse gas. Why do CFCs have such a disproportionately large greenhouse effect? Before I can answer that, I need to explain the natural greenhouse effect.

Evidence for the Greenhouse Effect

Recall that, as I mentioned, adding a greenhouse gas would reduce the heat radiation escaping to space? How do we know this? Of course, in theory, basically all you need is quantum mechanics and radiation transfer equation to deduce the greenhouse effect rigorously, but I want to

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Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications

V. Ramanathan

Abstract. *The infrared bands of chlorofluorocarbons and chlorocarbons enhance the atmospheric greenhouse effect. This enhancement may lead to an appreciable increase in the global surface temperature if the atmospheric concentrations of these compounds reach values of the order of 2 parts per billion.*

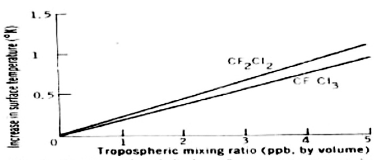

Fig. 1. Increase in global surface temperature is a function of the tropospheric concentrations of CF_2Cl_2 and $CFCl_3$. Results are for globally averaged conditions with 50 percent cloud cover.

Figure 6. CFC Warming.

demonstrate it through satellite observations. The satellite I used for this purpose is called the NIMBUS 4 which carried an infrared spectrometer looking down on earth with a scanning telescope; it was observing the emitted infrared radiation coming from the planet. I am showing (Figure 7) the emitted radiation data over the tropical ocean as a function of wavelength in the infrared region. I have superposed the black body radiation for two temperatures at 300 K and 200 K (the dashed lines). The 300 K (27 °C) is close to the surface temperature of the tropical oceans. The 300 K dashed curve is basically the IR radiation emitted by the ocean. Without an atmosphere, the radiation that would reach satellite altitudes would be exactly equal to the 300 K black body curve. What NIMBUS 4 measured was substantially smaller; and the difference shown by the shaded region is the greenhouse effect; or metaphorically, the thickness of the blanket. Gases in the atmosphere reduce the outgoing heat radiation, because the atmosphere is colder than the ground. The emitted radiation (or alternately number of photons) increases strongly with temperature. Thus the warmer surface is emitting a lot more radiation. The colder atmosphere absorbs it and reemits it at the lower temperature, so the net effect is to reduce the radiation energy leaving the planet, just like the

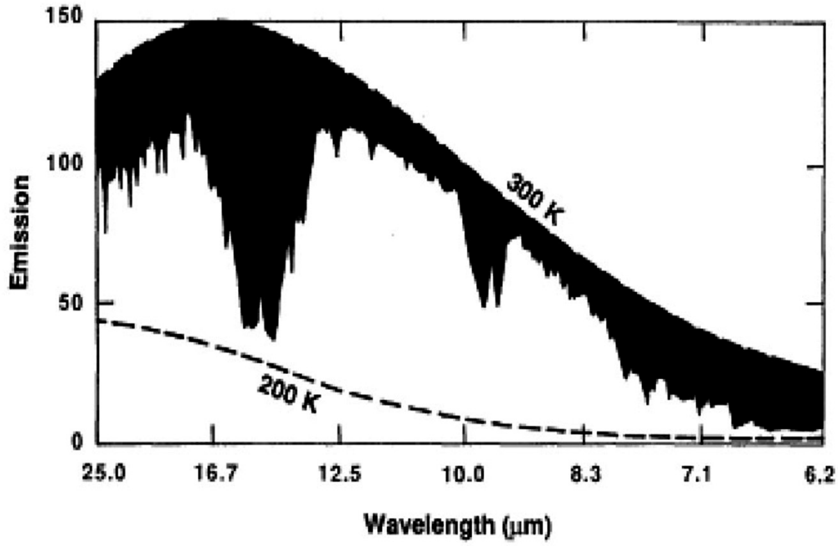

Figure 7. IRIS Spectra (adapted from Hanel *et al.*, 1972).

blanket inhibiting the flow of energy from your warm body to the colder environment.

We also see that the thickness is non-uniform and some (spectral) regions are much thicker than the others. This is because, there are many different greenhouse gases in the atmosphere and the greenhouse effect of each of these gases is different and in different spectral regions, as described next.

The Natural Greenhouse Effect: Nature's Blanket

The dip centered on the 15 μm (micrometer or micron) region is the greenhouse effect of CO_2; and that centered on 9.6 μm is due to ozone and most of the rest of the IR reduction is due to water vapor. Thus water vapour exerts the dominant greenhouse effect; CO_2 is next, followed by ozone and numerous other gases. The water vapour effect is completely natural. The CO_2 and ozone effects are also mostly natural. Later we will quantify the magnitude of the natural greenhouse effect and compare it with the manmade greenhouse effect. Figure 7 enables us to address the potency of the CFCs in reducing the outgoing IR.

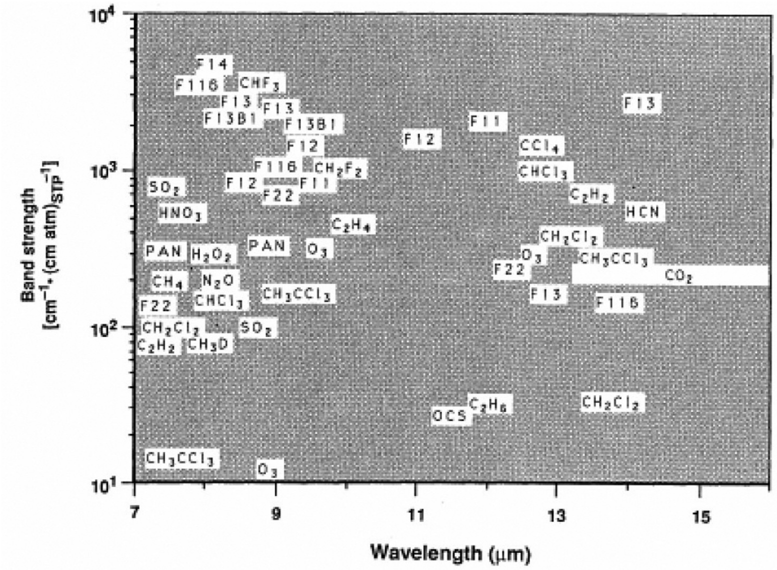

Figure 8. Ramanathan, 1988.

The Dirty Atmospheric Window

The blanket is thinnest in the 8 to 12 μm region, because the background atmosphere is mostly transparent in this spectral region and for this reason this region is called the atmospheric window. The background water vapour has very little absorption. What little you see is from the dimer, two water molecules dissociating to give this absorption. It is in this region that CFCs (and numerous other trace gases; Figure 8) absorb and emit radiation. In addition, the quantum mechanical efficiency (also knows as transition probability) of CFCs is about 3 to 6 times stronger than that due to CO_2. Lastly, the CFC concentrations are so low (part per billion or less) that their effect increases linearly with their concentration, whereas 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. Numerous other manmade greenhouse gases (Figure 8) have similar strong absorption features in the window region, making the window a less transparent dirty window.

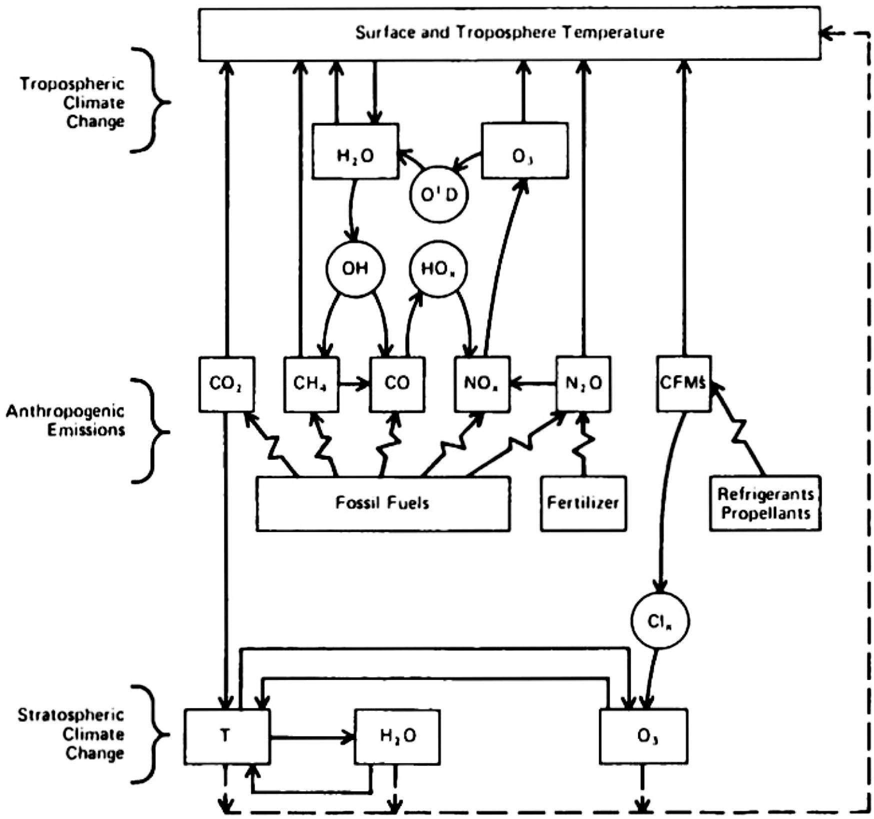

Figure 9. Ramanathan, 1980.

Climate-Chemistry Interaction

The independent discoveries of the CFC effect on the ozone chemistry and on the greenhouse effect coupled air-chemistry strongly with climate. Molina and Rowland's 1974 paper as well as Crutzen's (1972) earlier paper on the effect of nitrogen oxides (another pollutant) on the ozone layer, motivated me to look into the effect of stratospheric ozone on climate, because stratospheric ozone regulates the UV and visible solar radiation reaching the surface-troposphere (the first 10 to 16 km from the surface where the weather is generated) system; in addition, ozone, as discussed earlier, is a strong greenhouse gas. In 1976, I showed (Ramanathan *et al.*, 1976) that reducing ozone would cool not only the stratosphere (anticipated by others) but also the surface. 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 population etc). These two gases also interfered with the ozone chemistry and along with carbon monoxide (a pollutant) contributed to the increase in lower atmosphere ozone, which contributed to the surface warming (Fishman *et al.*, 1979). Until this 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 (Figure 9). The global warming problem was not just a CO_2 problem but became recognized as a trace gas- climate change problem.

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 trace gas greenhouse effect issue. The report of this committee published as a WMO report in 1986 (Ramanathan *et al.*, 1986) concluded that trace gases other than CO_2 contributed as much as CO_2 to the anthropogenic climate forcing from pre-industrial times. This report also gave a definition for the now widely used term: Radiative Forcing, which is still used by the community. Shortly thereafter, in 1988, WMO and UNEP formed the Intergovernmental Committee Panel on Climate Change (IPCC), which in its 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 (Figure 10, see p. 243, from the 2001 report of IPCC). The anthropogenic radiative forcing from pre-industrial to now (year 2005) is about 3 Wm^{-2}, out of which 1.6 Wm^{-2} is due to the CO_2 increase and the balance 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.

II. Predictions & Verifications of the Warming

When Will the Warming be Detected?

I now turn my attention to predictions of how the climate response would respond to the anthropogenic greenhouse forcing. As the trace gas importance began to emerge, I realized that the climate problem was a lot more serious than what we had thought; so I teamed up with the famous meteorologist Roland Madden and we started an analysis to see when were we going to detect this climate change and how much time did we have. Based on our analysis we made the prediction that if our greenhouse-global warming theory was reasonably accurate we should see the warming by the year 2000 (Madden and Ramanathan, 1980). This paper addressed some of the fundamental issues about natural climate variability. What we did was look at the temperature records of the North Atlantic and North Pacific, that's where we had a nearly homogeneous record of temperatures, and we quantified the climate noise, alternately the climate chaos, or natural variability. We quantified how that noise comes down with average in time (Figure 12, see page 243); i.e., the longer and the longer you average the noise comes down so that the signal (which should increase with time) can be detected. This is shown in Figure 11, which gives you an idea of the stochastic nature of detecting the climate change. Then we solved a couple of differential equations to look at what the expected temperature change was, and we also had to model how much of the emitted carbon dioxide would be airborne. Basically we concluded (quote from Madden and Ramanathan, 1980) *'Further consideration of the uncertainties in model predictions and of the likely delays introduced by ocean thermal inertia extends the range of time for the detection of warming, if it occurs to the year 2000'.* The IPCC report published in 2001 confirmed our predictions, when it concluded that the balance of evidence suggests a discernible human influence on climate. The observed surface temperature record (Figure 12) shows clearly how the temperature of the late twentieth century revealed the warming, although in 1980 (when we made our prediction), the warming was barely discernible.

I would also like to point out that the importance as well as the potential dangers of the global warming issue was well recognized more than 25 years ago by many scientists working in the field (e.g., Revelle; Manabe; Schneider; Hansen; Cicerone; Crutzen; Dickinson among others). For example, the Madden and Ramanathan (1980) paper began with the statement *'The possible climate effects of large increases in atmospheric* CO_2

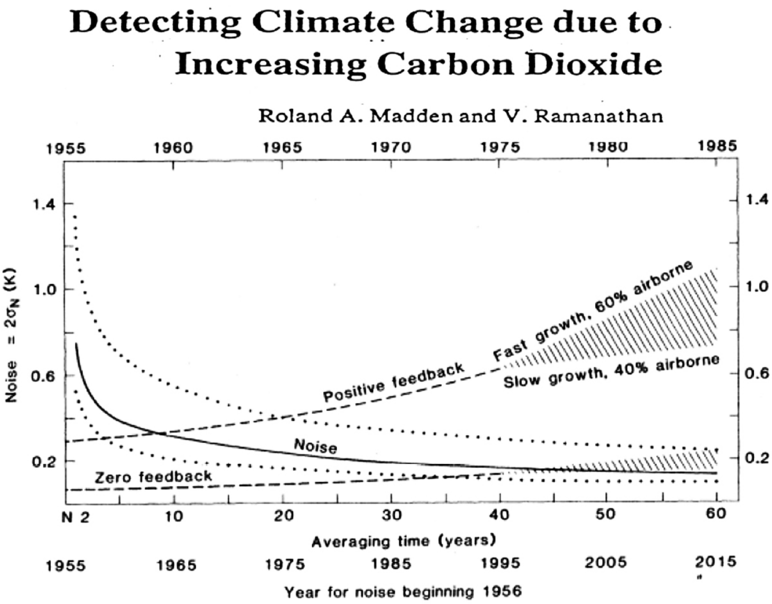

Figure 11. Madden and Ramanathan, 1980.

due to burning of fossil fuels may constitute one of the important environmental problems of the coming decades'. In a follow on paper written 8 years later (Ramanathan, 1988), I concluded that *'surface warming as large as that predicted by models would be unprecedented during an interglacial period such as the present'*.

A Tool for Verifying the Physics of the Warming

Thus far I deduced the greenhouse effect and the global warming using deductions from well understood physical laws. Now I would like to take up the issue of examining the magnitude of the forcing and the warming. This takes me back to the mid 1970s, when I was a post-doc at NASA Langley. My office happened to be in the same building where a group (headed by Dr G. Sweet, now deceased) was designing the Earth Radiation Budget Experiment (ERBE). I joined the ERBE science team and proposed to them that we should determine the atmospheric greenhouse effect quantitatively from the data. This was a satellite experiment that measured the incoming solar radiation, reflected solar radiation and the outgoing IR radiation (Figure 13 from Barkstrom, 1984, see page 244). Basically, what the satellite had was two scanning telescopes, which scanned the planet at 25-km footprint.

It took the team nearly 15 years from the concept stage to launch the satellite and publish the data! Using these data, we first quantified (Ramanathan *et al.*, 1989) that the incoming sunlight was 342 Wm^{-2}, out of which 102 Wm^{-2} was reflected to space; and the IR energy (heat radiation) leaving the planet was 237 Wm^{-2} (Figure 14, see page 244). The uncertainty in these estimates was about 5 Wm^{-2}. Let me explain the units. The W stands for the unit of energy flow per second which is Watts. The 'm^{-2}' denotes the energy flow per square meter of the Earth's surface. ERBE offered a powerful tool for verifying some of the scientific underpinnings of the theory of greenhouse effect and global warming.

Natural Greenhouse Effect: How Large is it?

We are now ready to put a number to the thickness of Nature's blanket. To determine the greenhouse effect of the planet, we estimated the IR energy given off by the surface. All this requires is data on the surface temperature (Ts) of the planet and the so-called emissivity of the surface, which is close to 1 for sea surface and varies by about 0.85 to 1 for land surfaces depending on the soil moisture. The IR energy emitted by the surface is about 399 Wm^{-2} (Figure 15, see page 245). The next quantity we need to know is the IR energy emitted by the atmosphere. To estimate this, we scanned the telescope in between clouds to extract the emission from clear skies (Ramanathan *et al.*, 1989) and the annual and global average of the emission was 268 Wm^{-2}. So the planetary surface emits 399 Wm^{-2} out of which only 268 Wm^{-2} escapes to space and the difference of 131 Wm^{-2} is trapped in the atmosphere, which is the greenhouse effect of the planet during 1985 to 1989. We have to subtract the anthropogenic greenhouse effect of a few Wm^{-2} to get the natural value. By comparing with the absorbed solar radiation (341-102=239 Wm^{-2}), it is clear the natural greenhouse effect is very large, without which the planet would be cold and frozen.

A Metric for Judging the Anthropogenic Greenhouse Effect

We now have a metric for assessing the manmade greenhouse effect. We have added 3 Wm^{-2} to the greenhouse effect by adding CO_2 and other greenhouse gases to the atmosphere. Comparing this with the observed greenhouse effect of 131 Wm^{-2}, we note that human activities have basically thickened the blanket by about 2.5%.

Magnitude of the Warming: Amplification by Water Vapour Feedback

The next issue is, how large is the warming going to be, given the forcing of 3 Wm^{-2}. Of course, we can run climate models to estimate this, but I was interested in obtaining an independent estimate solely from observations. I started working on this problem from the early 1990s and obtained the estimate by the late 1990s (Inamdar and Ramanathan, 1998).

Recall that I said, the planet will warm until it radiates the excess IR energy (3 Wm^{-2} in our case) to space. All we need to know is the rate at which the surface and the atmosphere radiate energy per degree warming… a fundamental number for the planet. Before we address this, we need to deal with one important complication concerned with water vapour thermodynamics.

Thermodynamics of water vapour, as given by the Clausius-Clapeyron equation (Figure 16) dictates that the saturation vapour pressure, es, of water vapor increases exponentially with temperature. If you take the differential of that equation with temperature, you find that at a temperature of 300 K (close to surface temperature of the tropical oceans) the vapour pressure increases by about 6% for each 1 degree rise in temperature. The percent increase is more at the colder atmospheric temperatures (7% to 10%). In essence, as the atmosphere warms, its moisture holding capacity increases. This is why, for example, in the extra tropics the summer is humid and the winter is dry. When it gets cold it gets dry because the vapour pressure drops precipitously. But the issue for us is that the water vapour is the strongest greenhouse gas in the planet.

Let's do a simple thought experiment. Before the industrial era, the planet is in energy balance with incoming sunlight. With the dawn of industrialization, we are adding CO_2 and other greenhouse gases and as a result the outgoing heat (IR) radiation decreases.

There is excess energy and the surface and the atmosphere begins to warm. But, as the atmosphere warms, the water vapour concentration begins to increase at the rate of 6% to 10% per degree warming; since water vapour is a strong greenhouse gas, this increase will amplify the greenhouse warming. Arrhenius was well aware of this feedback effect and included it. So when we attempt to estimate the rate of emission per degree warming, we have to account for this feedback.

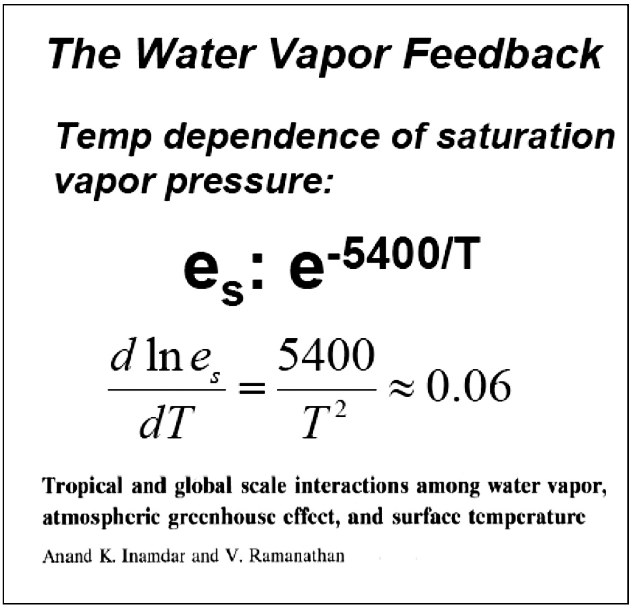

Figure 16.

Fortunately the planet does a major geophysical experiment every year. When you take the entire planet, its mean surface temperature in June-July-August is about 4 degrees Celsius warmer than during Dec-Jan-Feb. We had the ERBE and other observations at 200 km spatial scale for 1985 to 1989, and so we used it to estimate the greenhouse effect, Ga, the water vapour amount in three layers using a microwave instrument on another satellite and surface temperature data. These are shown in Figure 17 as a function of month. What we see is that, as surface temperature increases from Jan to July, water vapour amount in the three layers (between surface to 12 km) increases by about 7% per degree Celsius increase; and the atmospheric greenhouse effect increases at the rate of 3.5 Wm^{-2} per degree increase in surface temperature. Now we are ready to get the fundamental number we want. As shown in the bottom right panel, the outgoing heat radiation given off by the planet increases by 2.1 Wm^{-2} C^{-1}, i.e., the surface-atmosphere system gives off 2.1 Wm^{-2} of energy per Celsius increase in its temperature. I will subtract about 0.2 for solar absorption by the increase in water vapour (a minor detail) to get the final number of 1.9 Wm^{-2} C^{-1}

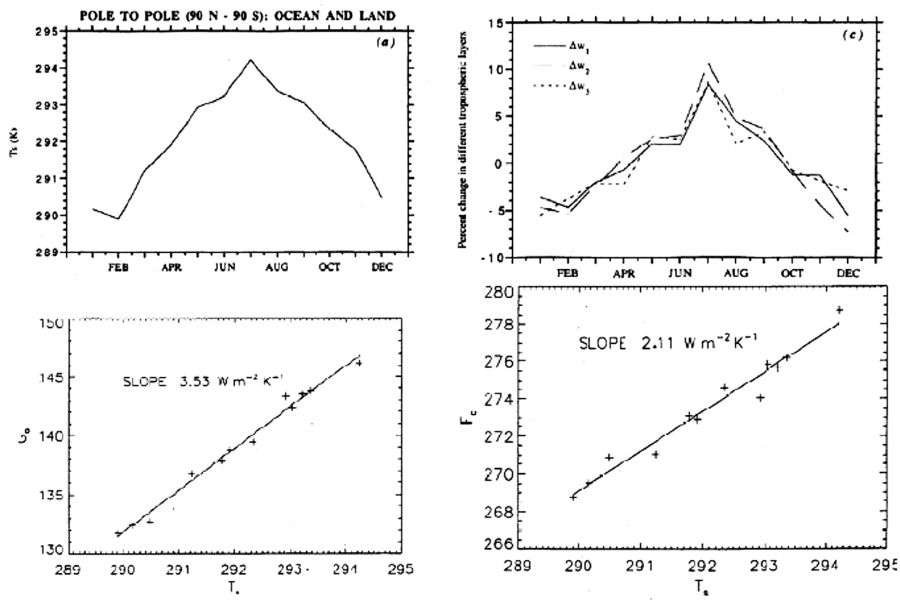

Figure 17.

(Figure 18, see page 245). These are all remarkably close to what we would expect from thermodynamics and basic radiation physics. Without the water vapour feedback, this number would have been about 3.4 Wm^{-2} C^{-1} instead of 1.9 Wm^{-2} C^{-1}, i.e. the planet would have gotten rid of more energy with warming without the thermodynamic coupling of water vapour with surface temperature. Alternately, the climate system is less stable with the positive water vapour feedback.

Warming Commitment: 2°C

Now we have all of the basic elements to put the pieces together. Since the dawn of the industrial era (say 1850) to now, the added greenhouse gases have trapped 3 Wm^{-2} of energy to the planet. It begins to warm. The planet can get rid of only 1.9 Wm^{-2} per degree Celsius increase in temperature. So it needs to warm by (3/1.9=) 1.5 °C (Figure 18) to restore the energy balance. A warming of this large magnitude, will melt and retreat sea ice and snow packs in mountain glaciers. Such melting will expose the underlying darker surfaces (ocean and rocks) which will absorb even more sunlight and thus amplify the warming. As the planet is warming and giving off 1.9 Wm^{-2} per degree warming, it begins to absorb about 0.4 Wm^{-2} more sunlight (this number is from models and hence is a bit soft) and thus it can get rid of only 1.5 Wm^{-2} $°C^{-1}$. Thus the required warming to balance the 3 Wm^{-2} greenhouse forcing, is (3/1.5) 2 °C. In effect, we have committed the planet to a 2 °C warming. I had used this term 'commitment' in a paper written in 1988 (Ramanathan, 1988) and it is nice to see its prevalent use now.

The Missing Warming of About 1 °C

A closer scrutiny of the temperature record (Fig. 12, see page 243) reveals that the observed warming is only about 0.7 °C, compared with our prediction of 2 °C. What happened to the rest? One obvious explanation is our model of climate sensitivity (the 1.5 Wm^{-2} $°C^{-1}$ number) is wrong. But let us look closer at the details… after all the devil is in the details. First, the ocean has a huge thermal inertia. It mixes the heat by turbulence quickly (within weeks to months) to the first 50 to 100 m depth. From there, the large scale ocean circulation mixes the heat in about few years to few decades to about 500m to 1000m 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. So about 0.4 °C of the warming will show up in the next few decades. Thus we have accounted for 1.1 °C (0.7+0.4) of the 2 °C committed warming. What happened to the remaining 0.9 °C? Although my prediction with Dr Madden (that the warming would be detected by 2000) was verified, I could take little comfort in that because the magnitude of the warming was almost a factor of two less than what we had predicted.

So the search was on for the missing 0.9 °C warming which led me to the masking effect of Atmospheric Brown Clouds (ABCs). But the path to ABCs was not a straight forward one, and I did not realize at that time it would take me more than 15 years to track the 0.9 °C down, but it was en exciting detour.

The Super Greenhouse Effect and a Thermostat in the Pacific Warm Pool

By the late 1980s it became clear to me that we have to look for analogues for a warmer planet. This quest took me to the western Pacific warm pool, the largest body of the warmest ocean in the planet (Figure 19, see page 246), somewhat accidentally. An undergraduate student, A. Raval, joined my lab to do research. I normally do not take undergraduate students for research, but Raval was recommended by a Nobel laureate in Physics at Univ of Chicago. We (Raval and Ramanathan, 1990) started using ERBE data for the greenhouse effect (Ga) to see how it increased with temperature due to the water vapour feedback (Figure 20, see page 246). We focused only over the oceans, because the ERBE data for land was not as accurate. Up to about a temperature of 20 °C (293 K in the figure) the Ga increased with sea temperature as expected from water vapour thermodynamics; but it started increasing more rapidly beyond 20 °C and for sea surface temperatures warmer than 27 °C, it increased at an unstable rate, referred to as super greenhouse effect. While the ERBE curve was published in 1990 (Raval and Ramanathan, 1989), the NCAR CCM3 with coupled ocean model simulated very warm climates similar to that experienced in the Cretaceous and the model was able to simulate the super greenhouse effect (see the red dots in Fig. 20). In the observations, the super greenhouse effect originated in the warm pool since this is the region where surface temperatures exceeded 27 °C. The question raised by this behaviour was: What process is preventing the western Pacific Warm pool temperatures to increase unstably? If any, it is a remarkable fact that the seasonally average warm pool surface temperatures rarely exceed 31 °C! As I was wondering about this remarkable situation, Raval's friend, W.D. Collins, an astrophysics grad student from Chicago, heard about this super greenhouse effect and expressed interest in joining my lab after his Ph D. He was recommended strongly to me by another Nobel laureate, Prof. S. Chandrasekhar (my neighbour and friend at U of Chicago), and Bill Collins joined my lab in early 1990, as I was getting ready to move to the Scripps Institution of Oceanography.

Bill and I started working on the problem and, after a year of intense study extending well into the night many days, came up with the thermostat hypothesis (Ramanathan and Collins, 1991). We proposed that, as the sea surface warms in response to the intense tropical solar radiation and the super greenhouse effects, it begins to form deep convective and thick cirrus anvil clouds. The widespread convective anvils reflect solar radiation and shield the sea surface from the intense solar radiation. In support of this hypothesis, we pointed out that the warm pool was very humid but mostly cloudy. In addition, we pointed out that even during an El Niño, when the normally cold central Pacific warms intensely, its temperature do not exceed 31 °C and the region which in normal years is mostly free of anvil clouds is filled with convective anvils during an El Niño. This hypothesis was strongly contested and we mounted a field experiment in 1993 to test it, thanks to the keen support of Dr Jay Fein (director of climate research at NSF) and the mentoring by Dr J. Kuettner, a legendary scientist, glider pilot and a pioneer in conducting complex field campaigns.

The Central Equatorial Pacific Experiment (CEPEX; Fig 21, see page 247), was my first entry into the world of field experiments, which became a life long passion. Teaming up with Dr Kuettner (who was 82 years old then), we deployed aircraft, ships and satellites (in search of the thermostat) to study the heat budget of the warm pool. There was another major surprise waiting for us in the warm pool. While the surface and the aircraft data confirmed our satellite findings of the warm pool to be very humid, very cloudy and subject to the super greenhouse effect, the sunlight reaching the warm pool surface was substantially (by about 8%) less than the value predicted by the best models we had (Ramanathan *et al.*, 1995). We had constrained the model at the top of the atmosphere by satellite data and thus the discrepancy could not be because the model clouds were not reflecting to space the correct amount. The discrepancy had to be due to the fact that our model atmosphere was not absorbing enough solar energy, i.e., it was missing an important process that was absorbing solar radiation in the atmosphere. I had to postpone my search for the thermostat and solve this puzzle first. This quest took me to the issue of aerosols, i.e., particles in the atmosphere. I had totally ignored this topic, although it had been pursued actively by several scientists since the early 1970s (e.g., see Rasool and Schneider, 1973). I knew I had to account for atmospheric aerosols in the model, particularly black carbon in soot, which was a major absorbing species. This enquiry, ultimately, led to new insights into the missing surface warming of 0.9 °C. But many more dots had to be connected first.

III. Masking of Warming by Atmospheric Brown Clouds

Synopsis

In addition to adding greenhouse gases, human activities also contributed to the addition of aerosols (sub micron size condensed particles) to the atmosphere. Since 1970 (Mitchell, 1970) scientists have speculated that these aerosols are reflecting sunlight 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, aerosols concentrations increased in time along with greenhouse gases, and the cooling effect of the aerosols has masked some the greenhouse warming. I am choosing the word 'mask' deliberately (Figure 22, see page 247), for when we get rid of the air pollution, the masking will disappear and the full extent of the committed warming of 2 °C will show up. Several tens of groups around the world are working on this masking effect using models and satellite data, but my route was a bit more tortuous and adventurous.

Indian Ocean Experiment: In Search of the Missing Absorption

In search of the missing solar absorption identified by CEPEX, I decided the Arabian Sea would be the ideal place for it, in part, because it was also a very warm ocean and very humid, not unlike the warm pool. Furthermore, during the 6 month long dry season, air from S Asia laden with pollution was blowing over the Arabian Sea on its way towards the inter tropical convergence zone south of equator. My colleague, Dr Paul Crutzen, became interested in this idea, because of his longstanding interest in air pollution in the tropics. Over a brief lunch at Scripps in 1994, Paul and I decided to look at how transport of air pollution from S Asia would impact the Indian Ocean. However it was difficult to get the funding based solely on this. We decided to broaden the scope to quantify the cooling effect of the aerosols… basically quantify the missing warming, i.e., the thickness of the mask. What started out as a simple experiment with one ship, emerged into a major international field experiment that would ultimately cost $25 M, the Indian Ocean Experiment (INDOEX) with participants from India, Maldives, Europe and USA (Figure 23 from Ramanathan *et al.*, 1996 in http://www-ramanathan.ucsd.edu/field_exp.html, see page 248). Again Dr Jay Fein of NSF played a major role in making this happen, my colleague Mr Hung Nguyen was a critical player in the execution, and Dr A.P. Mitra of India successfully mounted a major effort by Indian scientists to play a major role in INDOEX. We started ship observations in 1997, set up an observatory in the Maldives in 1997 and conducted a major field campaign in 1999 from the Maldives with 6 aircraft, 2 ships and surface observatories with over 200 scientists from Europe, India and USA, with Paul and me as the Co-Chief scientists. I was responsible for the field campaign in Maldives and it was a remarkable experience to lead this once in a lifetime campaign with impressive scientists from around the world speaking over 12 languages.

Widespread Brown Clouds

Brown clouds are usually associated with the brownish urban haze such as the one shown in the photograph (Figure 24, see page 248) taken by me flying over Los Angeles (Dec. 27, 2002). What we discovered instead during INDOEX was widespread brownish haze over most of S Asia flowing into the Indian Ocean (Figure 25, see page 249). This was due to fast long range transport by winds. Flying on a C-130 loaded with instruments, it became quickly evident that we were dealing with a huge problem. After the completion of the field campaign, NASA released a new aerosol instrument (MODIS) on the TERRA satellite and we analyzed the data which revealed that the brown clouds were not just an S Asian problem, but a worldwide issue (Figure 26, see page 249). As described next, the brownish color was due to strong solar absorption by black carbon in the soot.

Fingerprinting the Source of Missing Solar Absorption

Filters collected from the aircraft were analyzed by transmission electron microscope (by Dr J. Anderson) which revealed how the soot particles were attached to other aerosols and traveled as far south as 6S into the southern Indian Ocean (Figure 27, see page 250). It was only after we crossed the inter tropical convergence zone, south of 8S (close to Diego Garcia), that we were rid of the brown clouds. As mission scientist on one of the flights, I distinctly recall requesting the pilot to go as far south as possible until we see beautiful clear skies. The pilot informed me that he could not fly no further south, for we were about 1500 km from home and the aircraft was close to its endurance limit. Chemical analysis revealed that the brown cloud aerosols consisted of strongly absorbing black carbon and in addition, sulfates, nitrates and organics which were reflecting solar radiation and thus were the masking agents of global warming (Figure 28, see page 250). So, we had found both the source for both the missing absorption and the masking of global warming. What remained to be done was to quantify the energy absorbed and energy reflected. We had radiometers on the surface, ships, satellites and aircraft for this purpose.

Measuring the Solar Energy Absorbed and Reflected

We had deployed grating spectrometer to measure high resolution solar spectrum and as the ship traveled in and out of the plume, my post doctoral fellow, Dr Jens Meywerk, would take a spectrum of the direct sunlight and the reflected (downwards) solar radiation. The data revealed (Figure 29, see page 251) that the brown clouds led to a large reduction in sunlight, with the largest reduction of 40% in visible wavelengths (another indication of soot absorption); in addition, the data also quantified the reflected solar radiation, also shown in Figure 30 (see page 251). We needed one more piece of data before estimating the energy absorbed and reflected. This dealt with how the particles interacted with clouds. This issue arises because cloud drops are nucleated by aerosols and the manmade aerosols such as sulfates are very efficient in nucleating. Drs Heymsfield and McFarquhar, took measurements from C0130 and demonstrated that clouds embedded in pollution had an order of magnitude more cloud drops. Thus the polluted clouds with more drops will scatter more sunlight and lead to more cooling. This data plotted with other data worldwide (Figure 31, see page 252) shows how aerosols in brown clouds lead to increased cloud drops worldwide.

Finally, the energy absorbed and reflected to space by the ABCs (direct forcing in Figure 31) and by the ABC's influence on clouds (indirect forcing in Fig. 31) over the Indian Ocean is shown along with the radiative forcing due to greenhouse gases. Soot in the brown clouds increased solar absorption by about 14 Wm^{-2}, which is as much as 20% of the 70 Wm^{-2} absorbed by the background atmosphere. It also shows that at the top of the atmosphere, ABCs by reflecting solar radiation back to space, have reduced the net solar energy coming into the system by 5 Wm^{-2}. This is part of the masking effect of warming we were looking for, but we need a global average estimate. In short, INDOEX helped find the missing solar absorption; but the data in Fig. 31 raised another issue that caught me by surprise.

Dimming

Figure 31 (see page 252) also shows that ABCs reduce the solar radiation reaching the surface by as much as 20 Wm^{-2}, which is as much as 10% of the solar radiation absorbed by the Indian Ocean. In effect the surface is dimmer by about 10% during 1999, due to the shielding of surface by ABCs aloft. This raised two key questions: *How long has the dimming been going on? And what is its implication to regional climate.*

In order to examine the first question, 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 which I described in the beginning. Fortunately, we had well calibrated solar radiation data over India (12 stations) that was collected by a well-known Indian meteorologist, Dr Annamani. She was a dedicated scientist intent on the accuracy of the data. The results (Ramanathan *et al.*, 2005) are shown in Fig. 32 (see page 252) along with the simulated values. First the observations reveal 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 in the 1960s. Next, the simulations were able to track down observations reasonably well and they attributed the cause to the 4 to 5 fold increase in emissions of soot and SO_2. We will take up the next question next.

Impact on the Monsoon and Rice Harvest

Solar radiation at the surface is the fundamental source for evaporation of moisture. Hence if we reduce solar radiation, it is likely we will reduce evaporation and in turn the rainfall. As a result the most direct result of dimming is to reduce rainfall. But where? To answer this we turned to the NCAR climate model and the simulations suggested that the observed reduction in monsoon rainfall during the last 50 years is most likely due to the ABCs induced dimming (Figure 33, see page 253). The simulations revealed another way in which ABCs were slowing down the monsoon circulation. Since the ABCs were concentrated in the Northern Indian Ocean and S Asia, their cooling effects were concentrated there which reduced the north to south gradient in sea surface temperatures, which was also responsible for the rainfall decrease.

This result made me curious about the impact of this dimming and the long term rainfall decrease on food security of India. I teamed up with two agricultural economists from UC San Diego (Dr J. Vincent) and UC Berkeley (Dr M. Aufhammer) to model the impact on rain fed rice harvest. The integrated agro-climate model, a statistical model, suggested that ABCs have led to a 11% reduction in rice harvest, while the surface warming (due to greenhouse gases) has led to a 4% reduction in the harvest. Is there evidence for such a decrease in the actual harvest? It turns out, while rice harvest increased rapidly in the 60s due to green revolution, the harvest leveled off by the 1990s (Figure 34, see page 253).

Project ABC: The Next Step

In short, INDOEX data and the follow on modeling work helped identify ABCs as a major issue threatening the water and food security of India. This was just a beginning. The MODIS satellite data, that was analyzed after the INDOEX experiment (Figure 10, see page 243), revealed that we sought UNEP's help in organizing the project. All it took was one flight over the Nepal-Himalayas with Dr K. Toepfer, the head of UNEP in 2002 and Dr S. Shrestha, the head of UNEP's Asia office. They immediately formed the ABC project and brought in a team of scientists from Asia. We began setting ABC observatories (Figure 35, see page 254) and integrated the field data with satellite observations and aerosol-transport models to determine the dimming and solar absorption by ABCs over Asia and rest of the world (Chung *et al.*, 2005; Ramanathan *et al.*, 2007). Finally after nearly 15 years of detour through thermostat, CEPEX and INDOEX, I had a global view of the missing warming.

Magnitude of the Missing Warming

Global distribution of atmospheric solar heating and surface dimming by ABCs for the 2001-2003 period is shown in Figure 36 (see page 254). Both reveal peak values over polluted regions in S and E Asia, Eastern N America, Amazon, Southern Africa, Indonesia, etc. Focusing over Asia, the strong soot induced heating surrounding the Himalayan-Hindu-Kush region is contributing to the retreat of these glaciers and snow packs, a dominant source of many major river systems in the region. The dimming is spreading over the Indian Ocean, tropical Atlantic ocean and the western Pacific ocean, with implications to regional water budget over many tropical nations. The global average of the ABC forcing is compared with the greenhouse forcing in Fig. 37 (see page 255). Focusing just on the top of the atmosphere forcing, ABCs have led to a negative forcing of -1.4 Wm^{-2} (add the direct and the indirect panels), i.e., have reflected back to space 1.4 Wm^{-2} of the incoming solar energy. Comparing this with the 3 Wm^{-2} greenhouse forcing, we see that ABCs have masked about 50% of the warming.

IV. Uncertainties

Will Clouds Rescue us from Severe Warming or Make it Worse?

What's going to happen to the clouds in a warmer world? Will a warmer planet become cloudier? Why is this even an issue? The topic that addresses these questions is known as cloud feedback. It is a topic that worries me the most about the future. I started to work on it during the mid to 1980s but had to put it aside due to the detours I discussed earlier. We know clouds look white because they reflect a lot of sunlight back to space; and clouds also have an enormous infrared greenhouse effect because they are, after all, water molecules. Models (Manabe and Wetherald, 1967; Schneider, 1972) were suggesting that the cooling effect was larger than the warming effect and clouds had a net cooling effect. But observational determination of the effect became a passion for me.

I must now return to the ERBE satellite data to complete this story. I persuaded NASA to sort out the radiation budget over clear skies (i.e. pull the data for the gaps in between clouds). This is referred to as clear sky radiation budget. When we subtract the all-sky values (clear plus cloudy, which is what the satellite normally sees) from the clear sky values, we get an estimate of how clouds are regulating the radiative heating of the planet and this is referred to as cloud-radiative forcing (Charlock and Ramanathan, 1983).

This data analysis confirmed earlier model simulations that clouds have a major global cooling effect on the planet (Ramanathan *et al.*, 1989); i.e., they were significantly reflecting more sunlight (top panel in Figure 38, see page 255) than absorbing the IR. What was interesting about this experiment was the new questions it raised about the cloud feedback issue:

> In the tropics the greenhouse effect and the solar effect were large but they nearly cancelled each other. How will this delicate balance be perturbed by a large warming? Will the greenhouse effect become larger (e.g., due to clouds reaching higher in a warmer planet) and amplify the warming?

The global cooling effect was due to the extra tropical, storm track cloud systems. I know these systems are the source for huge weather problems for US and Europe but at least we can take comfort in the fact that these systems are keeping the planet cooler. Basically, what this experiment showed was that clouds were acting like two giant umbrellas centred over the Artic and the Antarctic and shielding the planet from solar radiation. The magnitude of this shielding effect is so large that, if these clouds were to expand just by 1.5%, that's enough to compensate all of the 3 Wm^{-2}; or if they shrink in response to global warming, they can amplify it by a factor of two or more. The shrinking scenario is not unlikely, because the arctic sea ice is retreating rapidly in response to global warming and this is amplifying the arctic warming. The resulting decrease in equator to polar temperature gradients, can lead to a pole ward retreat of the storm track cloud systems.

How will the Biosphere Respond?

The second major surprise in store for us in the coming decades may very well be the biosphere response. You can ask, why was this not an issue in the last 100 years; and why is it an issue for the future? If the planet warms at the rate it has been warming for the next 50 years, then the climate will have gone beyond any stage we can go back in the past and model. It is well-known that the greenhouse gases like CO_2, CH_4 and N_2O are regulated by the biosphere (Figure 39, see page 256). But cloud formation is also influenced by the biosphere. For example, dimethyl-sulphide emitted by planktons in the ocean is the precursor for sulphates, efficient cloud condensation nuclei in the marine atmosphere. How will climate change perturb the regulation of greenhouse gases and clouds by biota (e.g. see Charlson *et al.*, 1987)?

V. Mitigating Unprecedented Climate Changes

I want to end on a positive note. At the rate of current increase in energy combustion and atmospheric CO_2 increase, it is likely that we are on a path to a future climate that is about 2 to 4 °C warmer in this century. For example, just by cleaning up the atmosphere of all aerosols in ABCs, we will remove the masking effect and contribute to additional warming of 1 to 1.5 °C. I am not implying that we should keep the pollutants in the air, for they cause serious health impacts and ecosystem impacts in the form of acid rain etc. But, the need to clean up the air increases the urgency for decreasing the growth of CO_2 in the air. We have to urgently seek and implement solutions for mitigating the climate change, and there are many that we can implement immediately.

The ABC research also offers hope for mitigating ABC effects on global warming and HHK glacier retreat. It has identified soot as the major villain in 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 a few weeks and as a result the effect of the 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 (Figure 40, see page 256). 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 15000 each and deploy locally-made solar cookers and biogas plants. The unique feature is the 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 global warming problem. 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.

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Figure 1.

Figure 2.

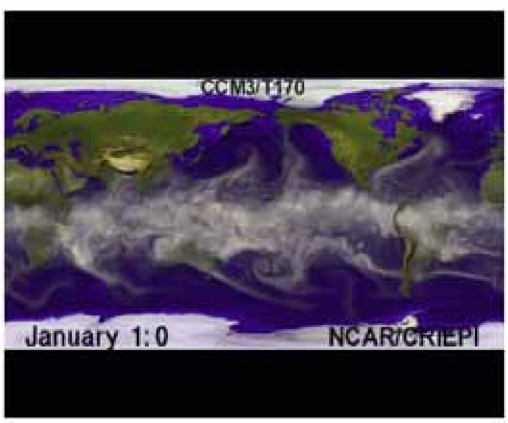

Figure 3. Ref. W.M. Washington.

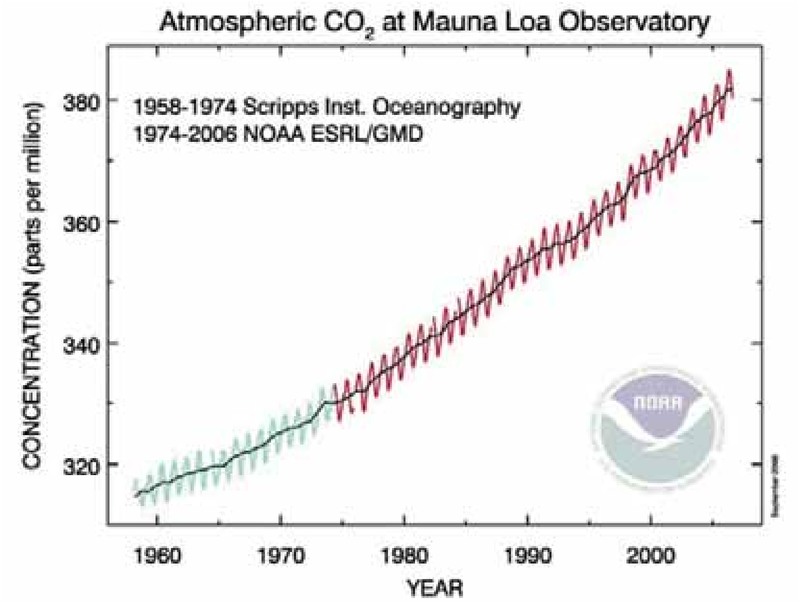

Figure 4. The Keeling Curve.

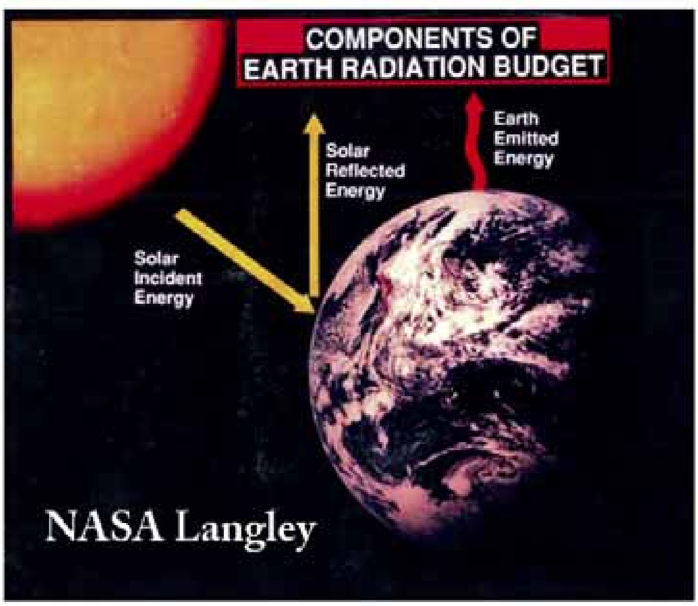

Figure 5. Earth Radiation Budget.

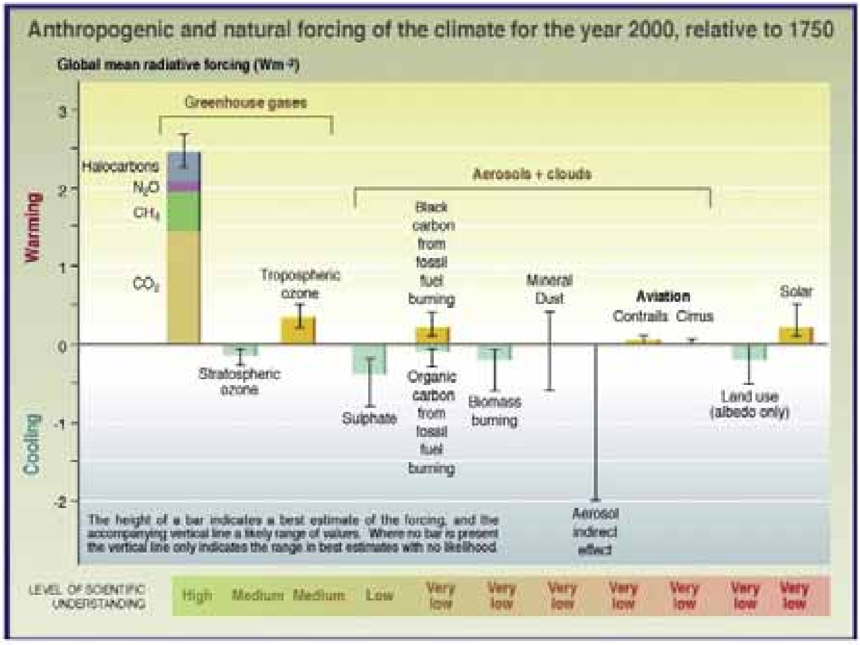

Figure 10. IPCC-AR3, 2001.

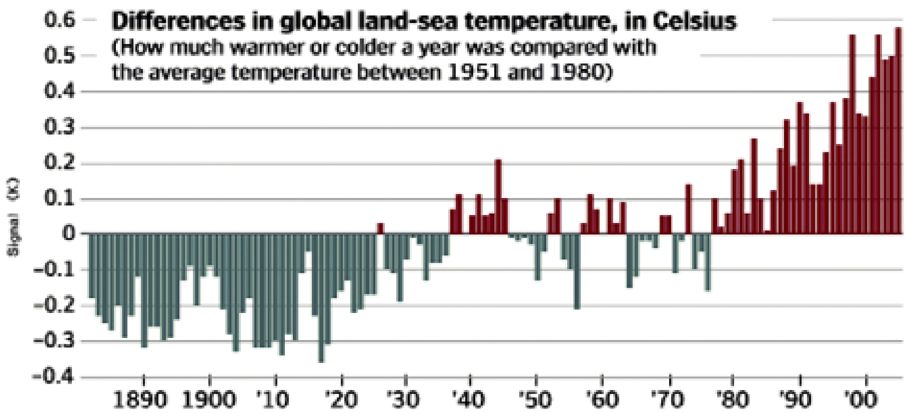

Figure 12. GISS Temperature Record. NASA_GISS.

Figure 13. ERBE Satellite.

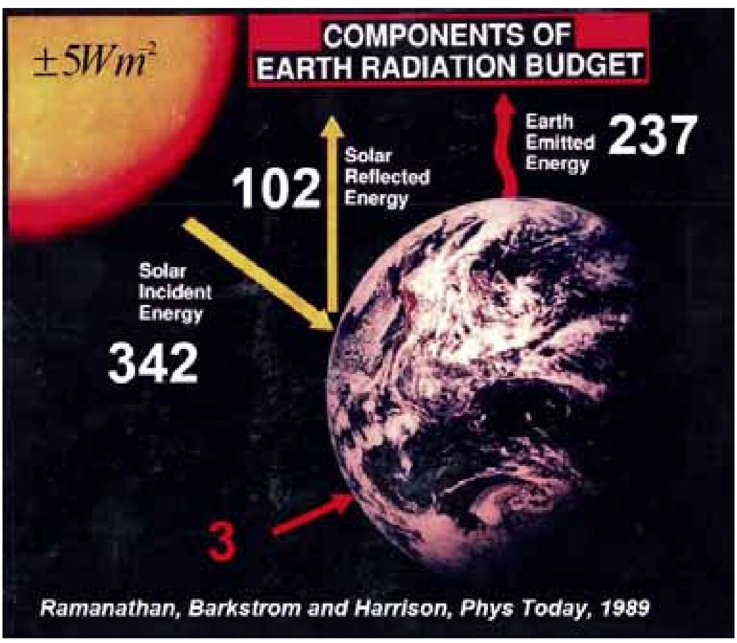

Figure 14. ERBE Data.

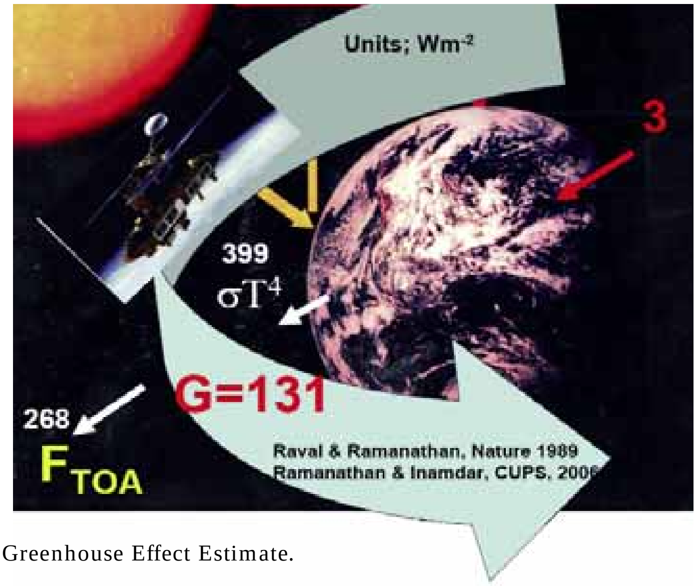

Figure 15. Greenhouse Effect Estimate.

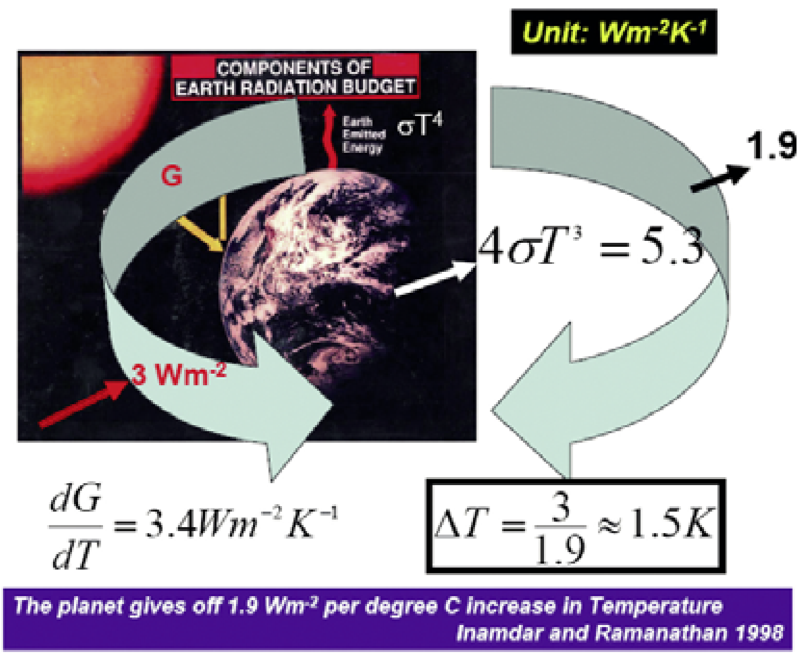

Figure 18. Climate Sensitivity.

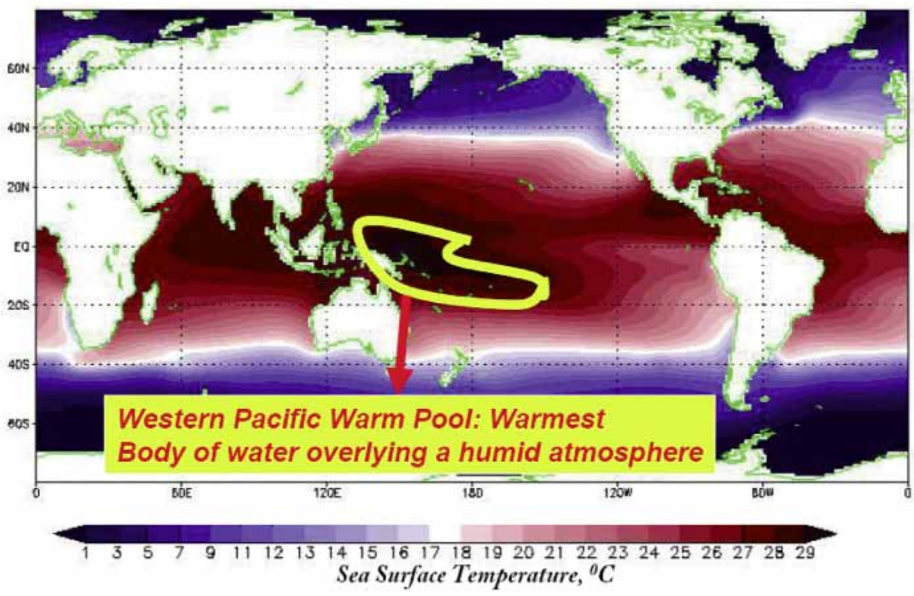

Figure 19. Observed Sea Surface Temp.

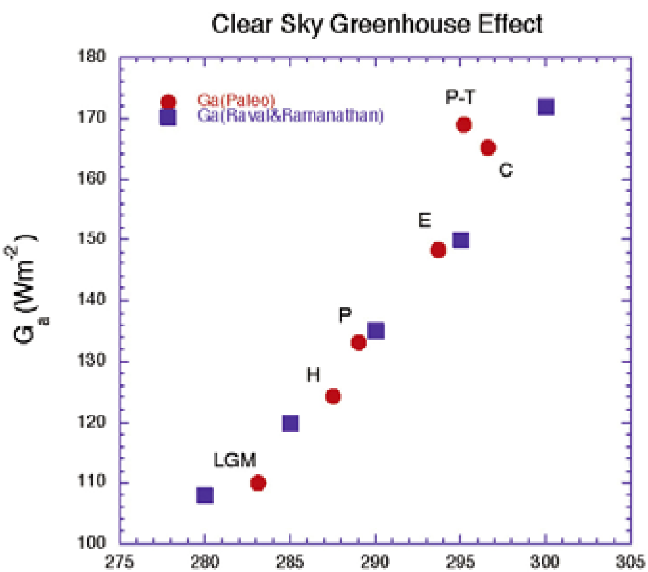

Figure 20. Kiehl, 2004. Private Comm.

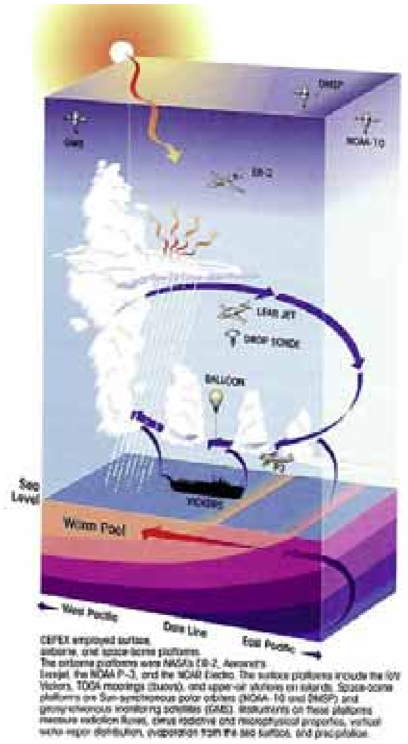

Figure 21. CEPEX Configuration.

Figure 22. ABC Mask.

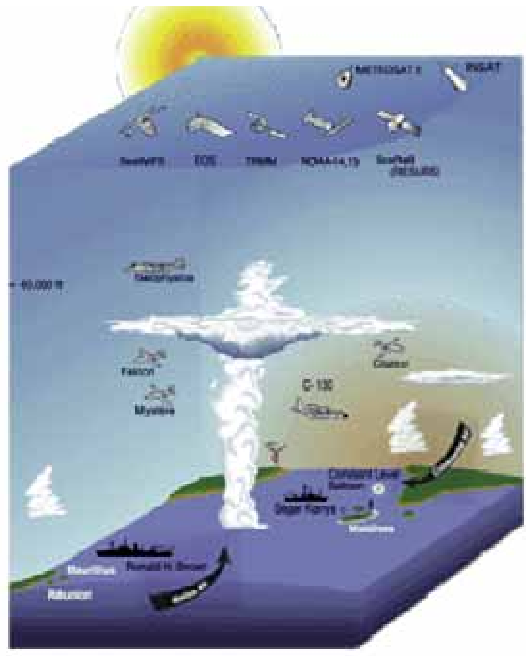

Figure 23. INDOEX Configuration.

Figure 24. Los Angeles, Dec. 27 2002.

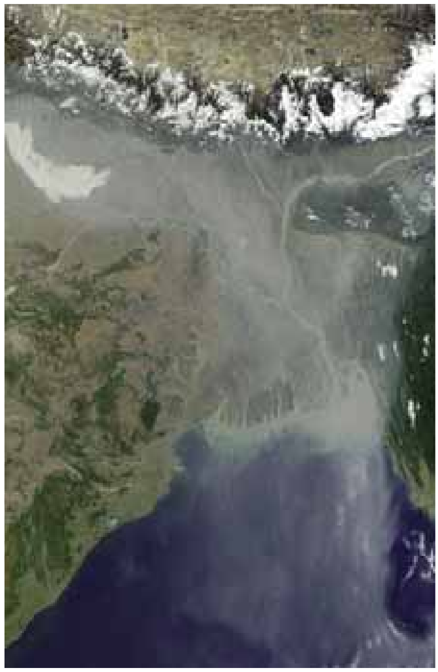

Figure 25. ABCs over India.

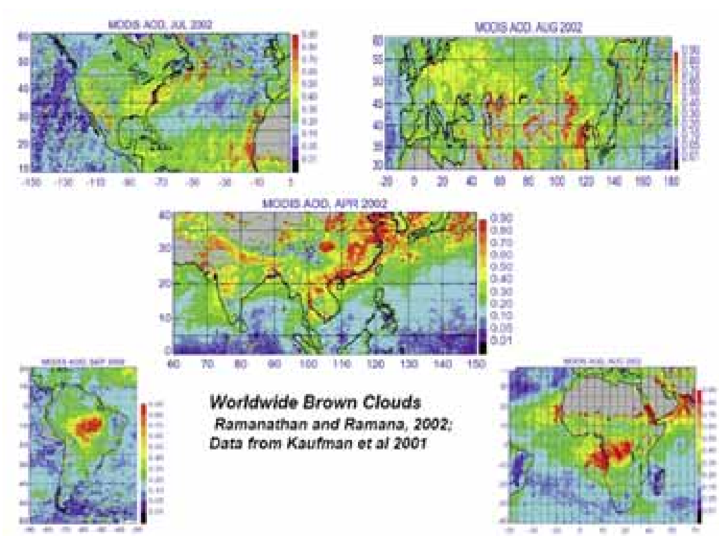

Figure 26. Satellite Aerosol Optical Depth.

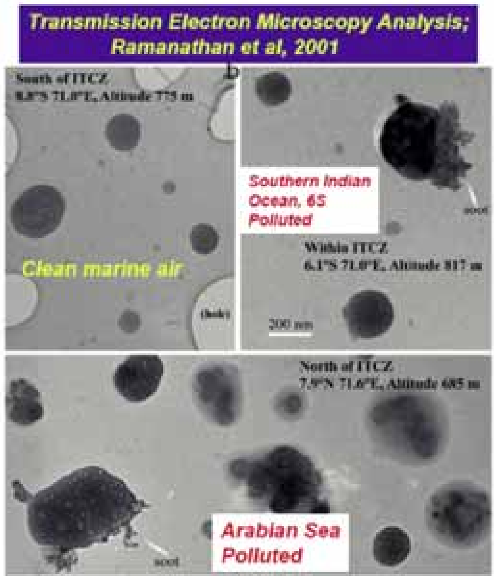

Figure 27. Filters from Indian Ocean.

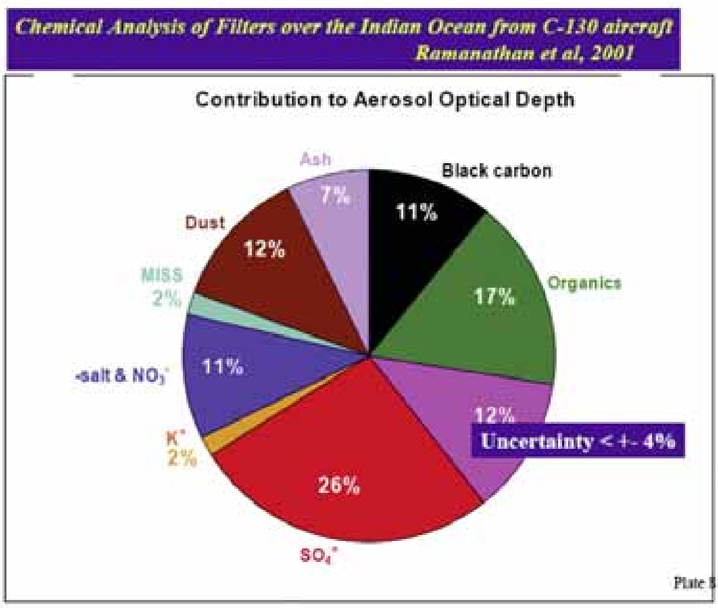

Figure 28. Chemical Speciation.

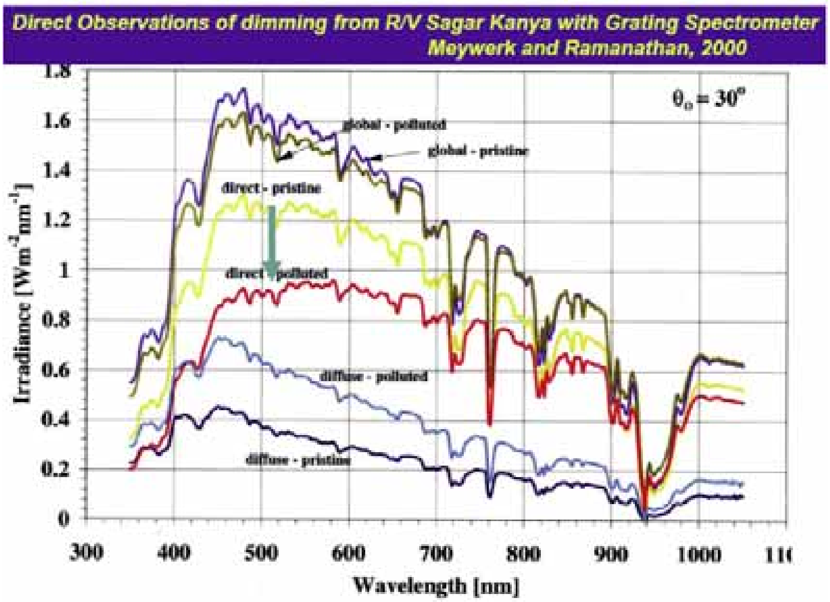

Figure 29.

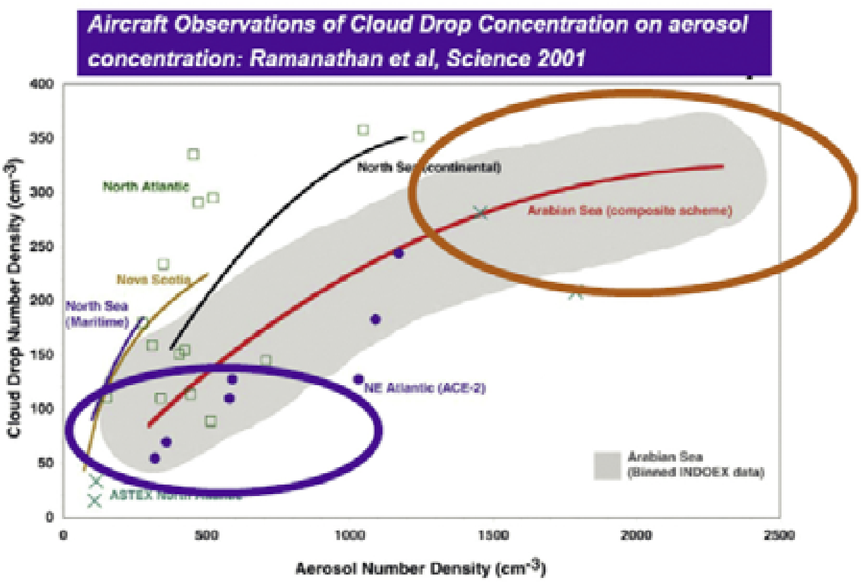

Figure 30.

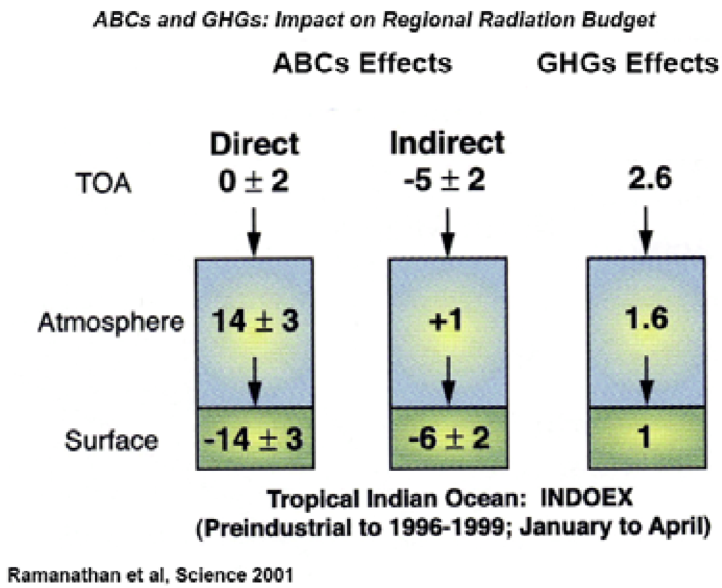

Figure 31.

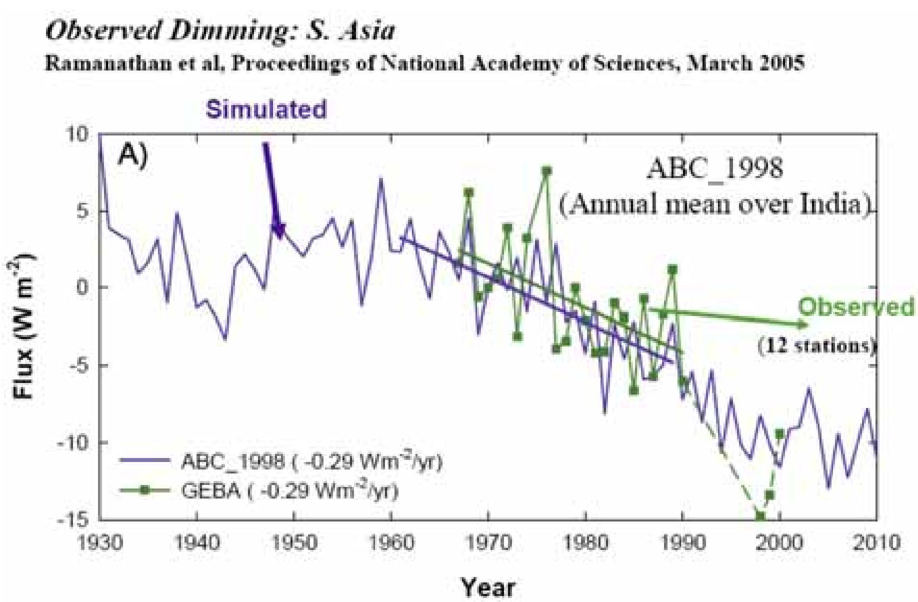

Figure 32.

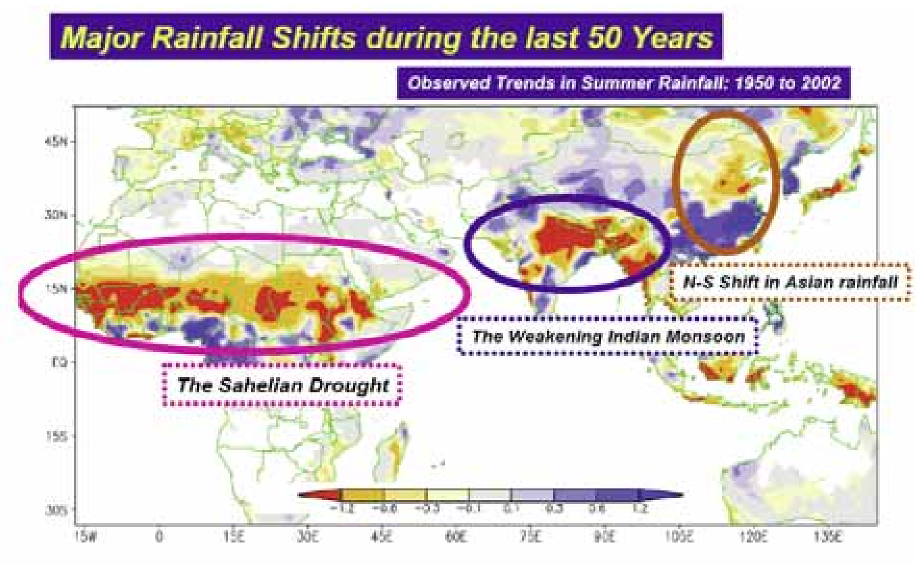

Figure 33.

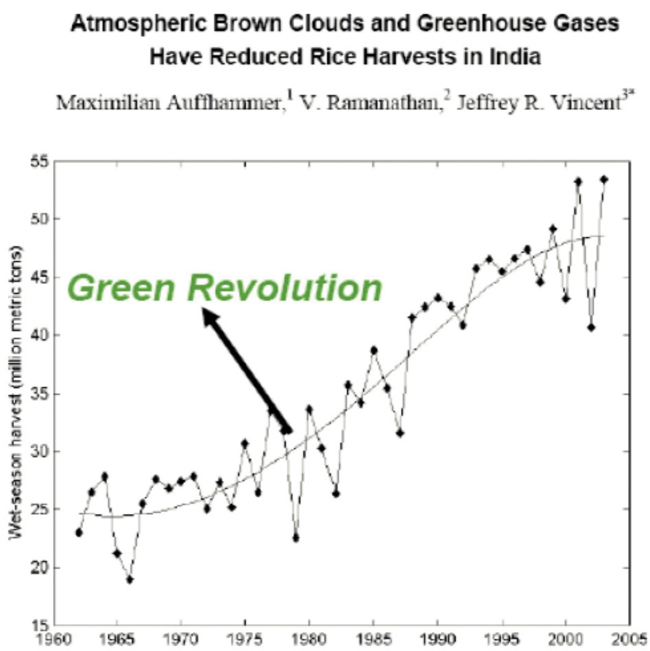

Figure 34.

Figure 35.

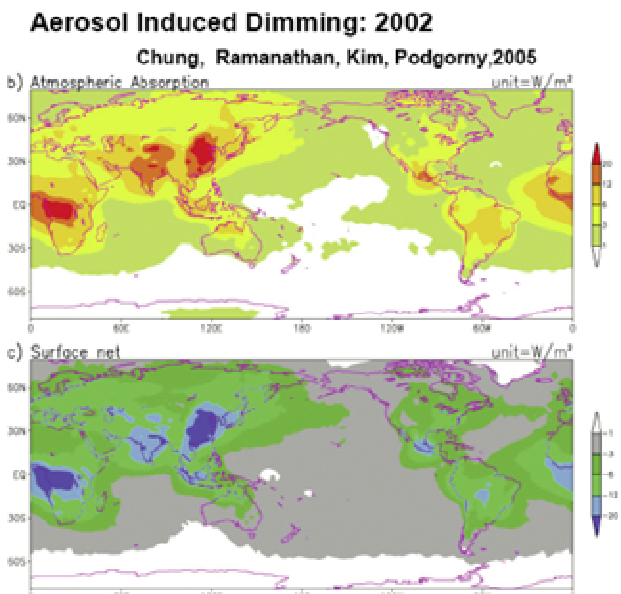

Figure 36. ABC forcing; solar heating of the atmosphere (Top panel); Dimming (bottom panel).

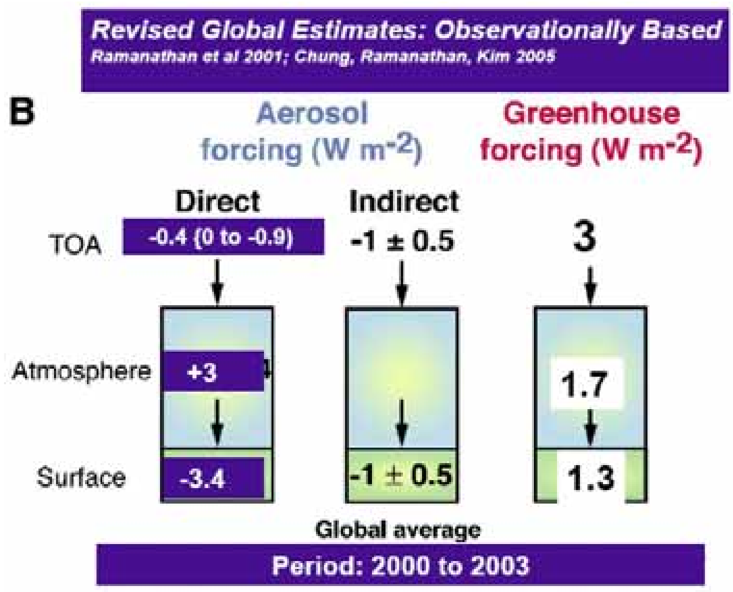

Figure 37.

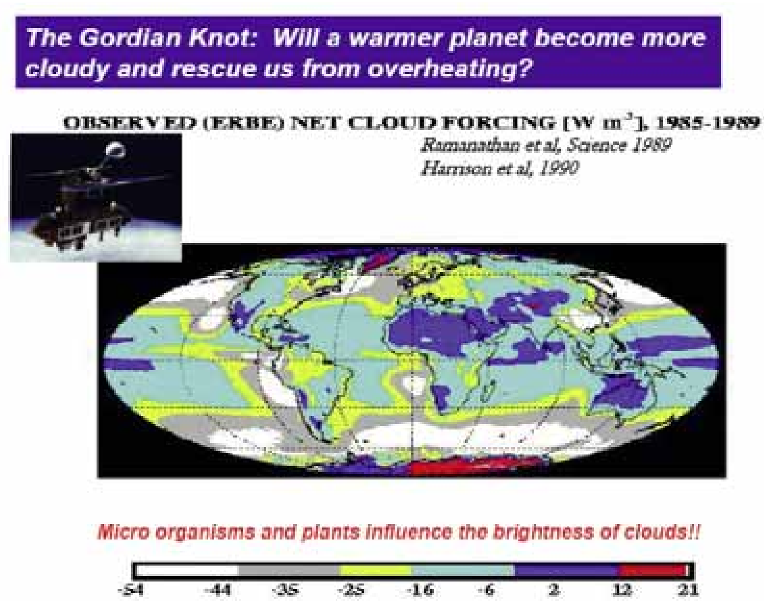

Figure 38.

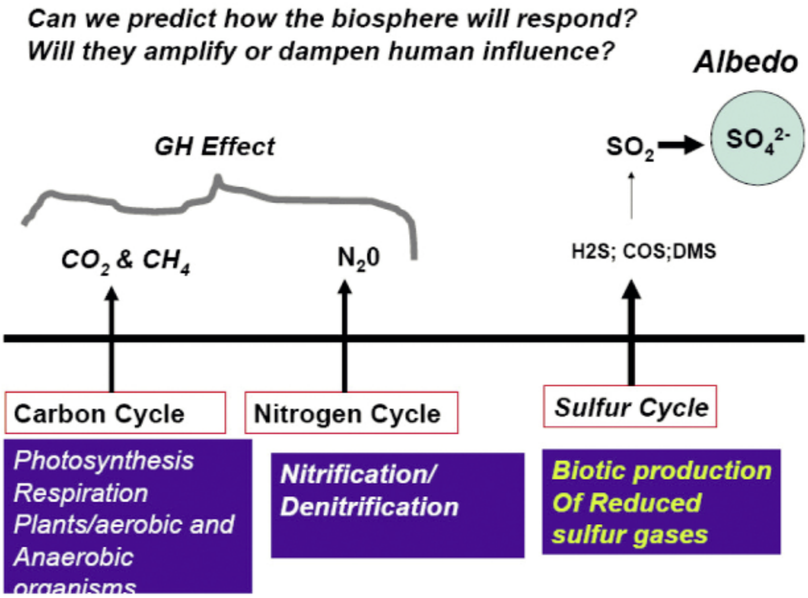

Figure 39.

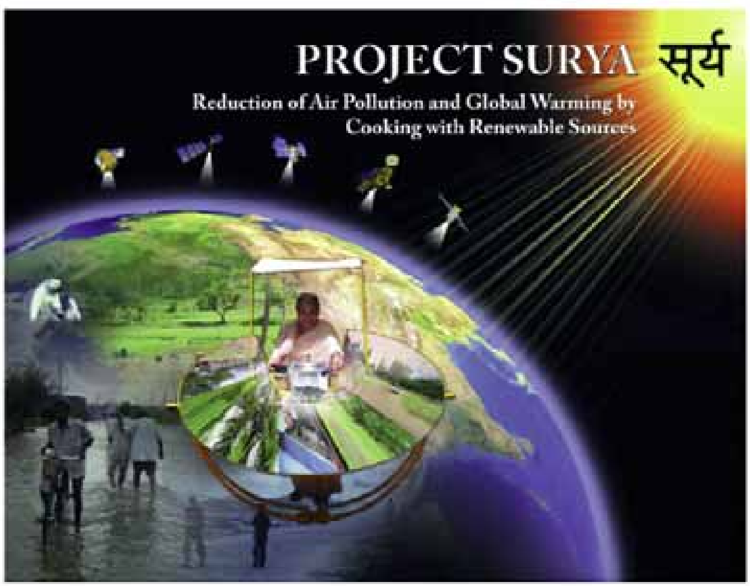

Figure 40.