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Climate Change and Protection of the Habitat: Empirical Evidence for the Greenhouse Effect and Global Warming

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Summary

Our understanding of the greenhouse effect and global warming is based on fundamental laws of physics, chemistry and thermodynamics. The greenhouse effect has been measured directly by high precision radiometers on satellites and the feedback processes through which the greenhouse effect warms the planet have also been measured. In addition, there is unambiguous empirical evidence for the link between the greenhouse effect and global warming. In this paper I will document these compelling observational evidence for the link between chemical pollution, increase in greenhouse gases and global surface warming. These empirical data lead us to conclude that the observed increase in the greenhouse gases is sufficient to ultimately warm the planet by more than 2°C during this century.

I. Background

i) Human Activities and Climate Change

Burning of fossil fuels leads to emission of carbon dioxide and several pollutant gases and particles into the atmosphere. Some of these gases and particles interfere with the flow of energy into and out of the planet thus altering the climate.

ii) Fundamental Drivers of Climate

The temperature of the surface and that of the atmosphere is largely determined by the flow of incoming solar radiation energy and the outgoing infrared radiation energy. About 30% of the solar radiation is reflected back to space by clouds, atmosphere and the surface. The remaining 70% heats the surface and the atmosphere, which in turn gives the energy back to space by emitting it as infrared radiation. So this process of net (incoming

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minus the reflected solar) incoming sunlight warming the planet and the warmer surface-atmosphere system emitting more outgoing infrared energy goes on until the two (net incoming solar and outgoing infrared) balance each other. On a long time average basis, the absorbed solar radiation (incoming minus the reflected solar) is balanced by the outgoing infrared radiation. So that's what determines the climate of the Earth. Gases and particles in the air regulate the outgoing infrared while particles regulate the reflected solar radiation and thus regulate the climate.

iii) The Natural Greenhouse Blanket

Certain polyatomic gases such as water vapour and carbon dioxide absorb the infrared energy from the surface and thus inhibit its escape to space. As a result not as much infrared energy escapes to space to balance the net incoming solar. I think the way the greenhouse effect works is similar to that of a blanket. On a cold winter night the blanket keeps us warm, not because the blanket gives us heat, but it traps body heat. That's exactly how the gases behave. They trap the infrared energy coming from the Earth. Nature has provided us with a thick blanket in the form of water vapour and carbon dioxide, without which our planet would be frozen like Mars. The greenhouse effect, which is a well-understood phenomenon, is based on fundamental laws of quantum mechanics and Planck's black body radiation. While oxygen and nitrogen are the most abundant gases in the atmosphere, these two gases do not exert a greenhouse effect. Earth's dominant greenhouse effect is primarily due to water vapour and carbon dioxide. Both are naturally occurring greenhouse gases. Human activities have increased the concentration of carbon dioxide by about 40%. They have also increased the concentration of numerous other greenhouse gases such as methane, nitrous oxide, and halocarbons among others.

iv) The Albedo Effect

The percentage of incoming solar radiation that is reflected to space is referred as the planetary albedo, or simply the albedo. The particles in the air intercept the solar radiation and thus reduce the solar radiation that reaches the surface and the albedo. The reduction of solar radiation reaching the surface is called dimming. Some of these particles, like sulphates from coal combustion, reflect solar radiation like mirrors, increase the albedo and cool the surface while other particles, like soot, trap solar radiation, decrease the albedo and warm the atmosphere.

I will start with the most spectacular example of the warming effect of carbon dioxide.

II. Empirical Evidence of the Greenhouse Effect

i) Greenhouse Effect of Venus, Earth and Mars [Fig. 1]

For my PhD work I looked at the energy budget of Venus and Mars (Ramanathan, 1974). After graduation, I could not get a job in that field. By sheer luck, I found a post-doctoral fellowship at NASA to study the impact of ozone destruction on Earth's climate. This is how I started working on Earth's climate and was able to use my graduate studies to compare the greenhouse effect of the three planets.

Let us compare Venus with Earth. Earth receives 340 Wm^{-2} of solar energy compared with 650 Wm^{-2} for Venus, since it is much closer to the sun. The unit of Wm^{-2} is Watts of energy per square meter of surface. The average temperature of the Earth's surface is 15°C whereas Venus is superhot at 430°C. It is tempting to conclude that the hot temperature of Venus is due to the fact that it receives nearly twice (650 Wm^{-2} compared with 340 Wm^{-2}) as much solar energy as Earth. However, if we compare the albedo (percentage of solar radiation reflected by the planet) of the two planets, we

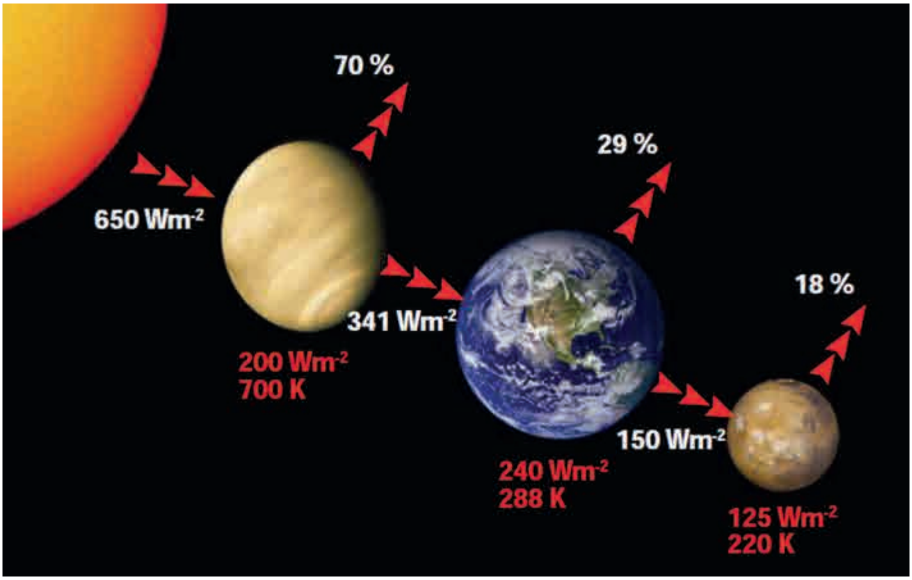

Figure 1. Why is Earth's albedo 29% and Was it always 29%? V. Ramanathan, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA. iLEAPS Newsletter Issue No. 5, April 2008. Space Images http://solarviews.com/ Photo copyrights: NASA/MODIS/USGS and Calvin J. Hamilton.

find that incoming solar radiation cannot explain the hotter Venus. Earth's albedo is only 0.29 whereas Venus' albedo is 70%. Earth is only partially cloud covered, whereas Venus is overcast all the time and that too by massively thick clouds (more than 40 km thick). As a result the solar radiation that is absorbed by Venus is only $200W^{-2}$ which is slightly even less than the $240Wm^{-2}$ absorbed by the Earth.

So solar energy is not the explanation for why Venus is hot. Venus is hot because of the greenhouse effect. It has about three hundred thousand times more carbon dioxide, and it is the greenhouse effect of carbon dioxide which maintains the superhot temperature of Venus at 425°C.

ii) Measuring the thickness of the greenhouse blanket from space [Fig. 2]

When I joined NASA in 1974 to model the climate impact of stratospheric ozone destruction I teamed up with engineers at NASA to design a satellite experiment, the Earth Radiation Budget Experiment [ERBE], to study the flow of solar energy and infrared energy in and out of Earth. ERBE had calibrated radiometers to measure both the incoming and the

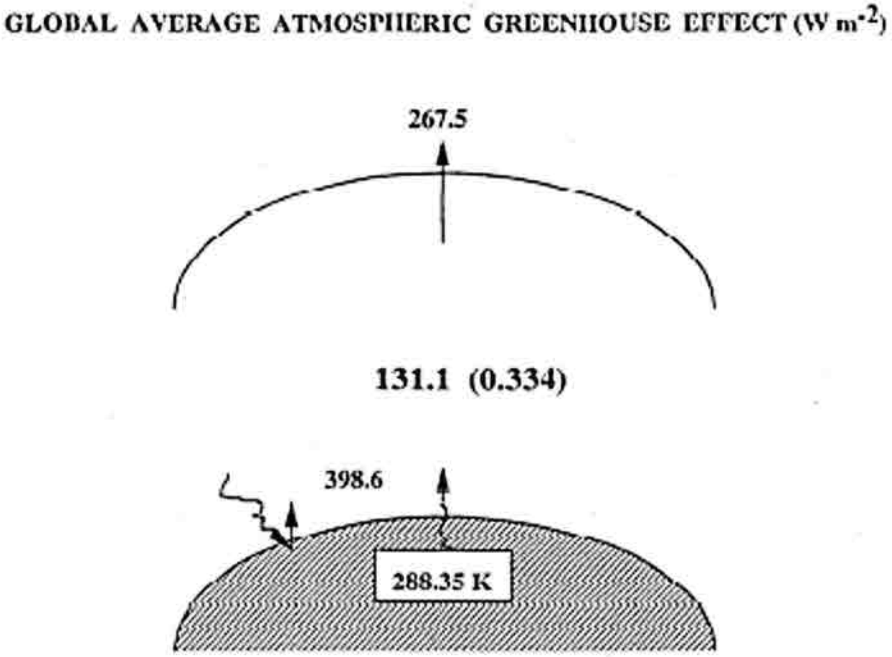

Figure 2.

reflected solar radiation and the outgoing infrared radiation. I proposed to use the infrared radiometer to determine the atmospheric greenhouse effect for the first time (Ramanathan, 1987; Raval and Ramanathan, 2000; Inamdar and Ramanathan, 1998). The method was very simple. We took the scanning radiometer to determine the outgoing infrared [OIR] from cloudless skies, i.e., the OIR escaping to space in-between overcast skies. The next step was to determine the infrared radiation from the surface. This was estimated from the surface temperature using black body radiation laws. The difference between the infrared energy emitted by the surface and that escaping to space is the energy trapped by the atmosphere and is a measure of the greenhouse effect in energy units [Wm^{-2}]. For the 1988 to 1990 period used in the study, the infrared energy from the surface was 398.6 Wm^{-2} [95% uncertainty of 1%] while the energy escaping to space (under clear skies) was only 267.5 Wm^{-2} [95% uncertainty 2%]. The trapping of the IR energy by the intervening atmosphere led to the reduction of IR by 131 Wm^{-2} (398.6-267.5) Thus the greenhouse effect was determined to be 131 Wm^{-2} [95% uncertainty of 4%]. This greenhouse effect of 131 Wm^{-2} is the sum of natural and anthropogenic effect and could be considered as the thickness of the blanket in energy units. Roughly 80% of the 131 Wm^{-2} greenhouse effect is due to naturally occurring water vapour.

III. Empirical Evidence for the Role of Human Activities on the Greenhouse Effect

i) How much have we added to the thickness of the greenhouse blanket?

Several international reports (Ramanathan *et al.*, 1985; IPCC-WGI 2013 report) have adopted the observed increase in the concentrations of greenhouse gases (CO_2; CH_4; N_2O; Halocarbons; Ozone; etc.) since the 1850s and integrated them with the quantum mechanical parameters for absorption of infrared radiation and estimated the infrared energy trapped in the atmosphere. The increase in the IR energy trapped by the greenhouse gases emitted by human activities is estimated to be 3 Wm^{-2} (with an uncertainty of 25%). Comparing this number with the 131 Wm^{-2} inferred from the satellite data for natural and anthropogenic greenhouse effect, we infer that: The Natural Greenhouse Effect by the atmospheric gases (water vapour; CO_2; and others) is 128 Wm^{-2} and the anthropogenic effect is 3 Wm^{-2}. Thus, human activities have thickened the greenhouse blanket by 2.3%. The build-up of carbon dioxide since the 1850s has contributed 1.7 Wm^{-2} – or about 57% – of the total anthropogenic effect of 3 Wm^{-2}.

ii) How long have we known about the anthropogenic greenhouse effect?

The first authoritative study on the greenhouse effects of carbon dioxide was published in 1896 by the Nobel Chemist Svante Arrhenius. For nearly 78 years we thought CO_2 was the only manmade climate pollutant of concern (see SMIC Report, 1972). That changed overnight when the greenhouse effect of a class of compounds called halocarbons was discovered in a study I published in 1975 (Ramanathan 1975). CFCs, one of the most popular refrigerants used then, was one such Halocarbon. I showed that the addition of one molecule of CFCs had the same warming effect on the planet as the addition of over 10,000 molecules of CO_2. CFCs were banned because of their effects on destroying the ozone layer (Molina and Rowland, 1974) under the Montreal Protocol. But now my work on the greenhouse effect of halocarbons has finally been recognized and last year, *The Economist* journal called the Montreal Protocol the most successful climate mitigation policy. CFCs were replaced by another halocarbon, called HFCs, also a potent greenhouse gas... There is now a global move to ban HFCs because of their global warming effect under the Montreal Protocol. What that means is that about 6% of the total anthropogenic greenhouse effect can be mitigated by the end of this century.

IV. Quantitative Link Between the Greenhouse Effect and Global Warming

Now that we have quantified the increase in the thickness of the blanket [since the time the British Engineer James Watt invented the improved steam engine], we have to address two important questions: *How large is the warming? & How soon will it descend on us?*

The thickening of the blanket has added 3 Wm^{-2} to the IR energy to the planet. In response, the planet will warm and radiate this energy to restore the energy balance between the net solar energy flowing in and the infrared energy flowing out. We will begin this discussion by making the simplest assumption possible, which is that the surface and the atmosphere behave like Max Planck's black body, in which case it will radiate energy to space as a black body, which is given by σT^4, where σ is a fundamental constant derived by Max Planck and T^4 denotes the fourth power of temperature T. Based on this law, the surface and the atmosphere will radiate 3.3 Wm^2 per 1°C of warming. In other words, the planet can get rid of 3.3 Wm^{-2} for every degree warming. So to get rid of the 3 Wm^{-2} energy trapped by manmade greenhouse gases, the planet will warm by (3/3.3=) 0.9°C. This analysis ignores some major feedbacks between warming and atmospheric greenhouse effect and planetary albedo.

i) Empirical evidence for the thermodynamic feedbacks between warming and the greenhouse effect of H_2O [Figs 3 & 4]

The water vapour (H_2O) in the atmosphere is to zeroth degree determined by the temperature of the air. It is an exponentially increasing function of temperature. For each degree (°C) rise in temperature, H_2O will increase by about 6% to 10% (depending on the value of temperature). With the increase in H_2O, the H_2O greenhouse blanket will increase (logarithmically). This increase is substantial since H_2O is the most powerful greenhouse gas in the planet. So, following the line of thought-experiment so far, increase in the concentration of greenhouse gases since the 1850s has increased the greenhouse effect by 3 Wm^{-2}. In response to this increase, the system begins to warm. The warmer surface and the atmosphere begin to

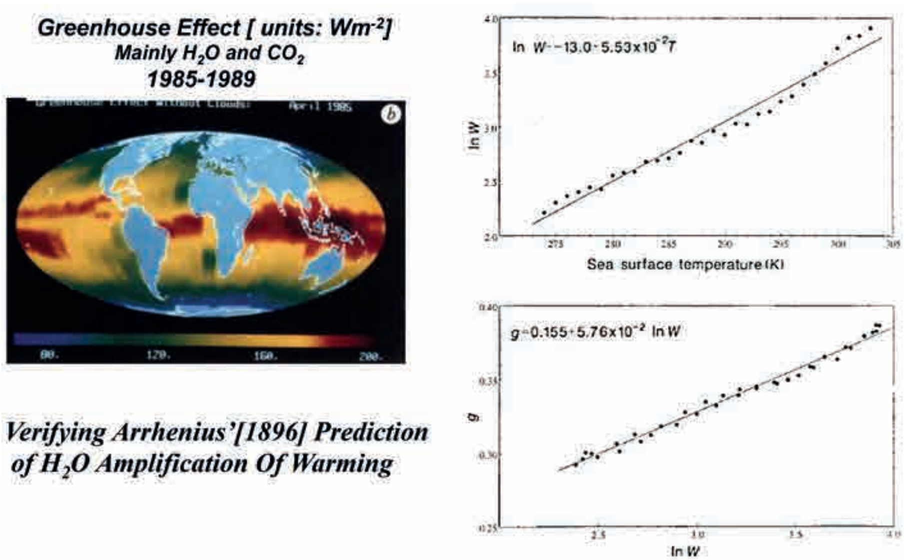

Figure 3. Atmospheric Greenhouse effect derived form satellite observation. Raval and Ramanathan, 1989. A: Natural logarithm of the atmospheric water content (W, kg m^{-2}) as a function of surface temperature, April 1982, monthly averages for 3° X 5° regions. The water content was derived from microwave satellite soundings available for 1979-1983. The error in W is ~ 10% (ref. 13). The strong positive correlation indicates that the behaviour of W follows simple thermodynamic laws; the slight upward and then downward deviations are consistent with the latitudinal variations in relative humidity and lapse rate which are governed by the dynamics of the atmosphere. B: Normalized clear-sky greenhouse effect (g) for April 1985 plotted against in W for April 1982. ERBE data is not available before 1985 whereas W is not available after 1983. To minimize the effect of year to year variations in W, we have used zonally averaged values.

radiate more IR energy, and with just this black body radiation and no feedbacks, the climate system should have warmed by about 0.9°C. However, as the atmosphere begins to warm, the water vapour content begins to increase and with it the water-vapour greenhouse effect begins to increase as well. In other words, the thickness of the greenhouse blanket, which increased due to human activities, is increasing further due to the Temperature-H_2O greenhouse effect feedback, and additional energy is being trapped and the temperature will increase further.

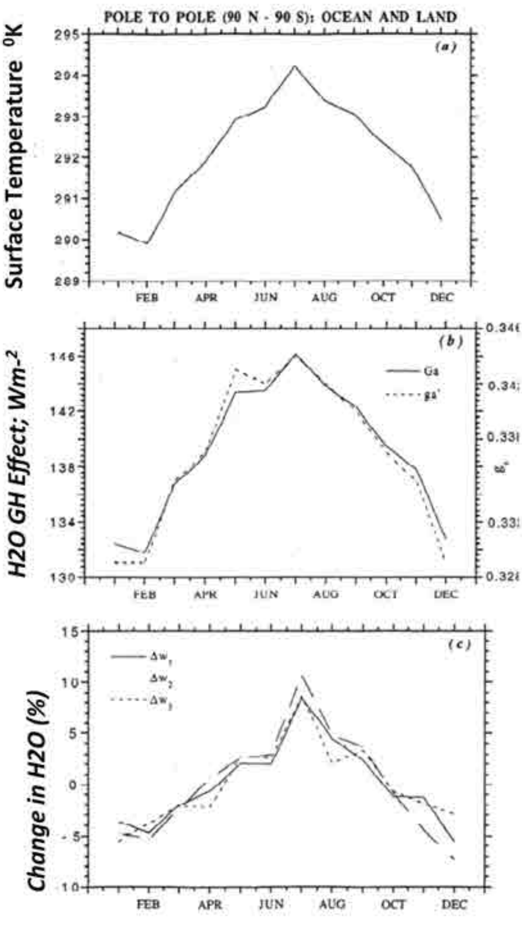

Figure 4. Observed data for climatological monthly variations in surface temperature (top), atmospheric greenhouse effect (middle) and water vapor amount (bottom) in lower (DW1), middle and upper troposphere (DW3). Ref: Inamdar and Ramanathan, 1998.

The link between atmospheric temperature, atmospheric water vapour content and its greenhouse effect was first proposed by Arrhenius in 1897. It has now been verified with satellite data (Raval and Ramanathan, 1988; Ramanathan and Inamdar, 1997) for the first time. Global distribution of the thickness of the blanket as obtained by the Earth Radiation Budget Experiment (see earlier discussion) reveals (Fig. 3, left hand panel) that the IR energy trapped in the humid tropics is twice as much as that in the drier extra-tropical regions. To look at it more quantitatively, the right hand panels plot the observed water vapour amount as a function of observed sea surface temperature (top panel) and the observed thickness of the blanket as measured in terms of the energy trapped in Wm^{-2} (vertical Y-axis) as a function of the observed water vapour amount (horizontal X-axis). The increase in water vapour amount with temperature is within 10% of the slope predicted by thermo-dynamical laws (top right hand panel). On the bottom panel the thickness of the blanket has been normalized by the surface emission. If the value of this normalized thickness is 0.3, it means 30% of the IR energy emitted by the surface has been trapped by the atmosphere. The bottom panel shows the normalized thickness increases with water vapour amount and furthermore it increases as the logarithm of the water vapour amount as predicted by quantum mechanics of the water vapour molecule. Thus far, our analyses use the observed spatial variation of water vapour and surface temperature to show the link between surface temperature, the water vapour amount and the thickness of the greenhouse blanket. It demonstrates that this link is governed by the thermodynamics of water vapour combined with the quantum mechanics of water vapour absorption of IR radiation. We will now look at a more critical test of the water vapour feedback.

Fortunately, the planet does a spectacular experiment every year. Each year, when we integrate temperature, water vapour amount and its greenhouse effect over the whole pole, from North Pole to South Pole, July is warmer by about 4° than January (Fig. 4 right hand top panel). We have millions of observations from satellites on this. As the planet warms from January to July, the humidity (measured by a microwave instrument on a NASA satellite) increases almost exactly by the amount (middle panel) predicted by the thermodynamics of water vapour (Fig. 4 middle panel). The humidity increases at all levels of the lower part of the atmosphere called the Troposphere. In conjunction with increase in surface temperature (top panel) and water vapour amount (middle panel), the atmospheric greenhouse effect increases proportionately (logarithm of the water vapour amount). The data in Fig. 4 shows that the greenhouse effect of water vapour increases by about 1.4 Wm^{-2} for each degree in warming. In the earlier analyses, we ignored all feedbacks, and estimated that the forcing of 3 Wm^{-2} due to the stock of greenhouse gases in the atmosphere as of 2010 should have warmed the planet by 0.9°C. The inclusion of the water vapour feedback would increase the projected warming from 0.9°C to 1.7°C.

ii) Empirical evidence for the ice-albedo feedback [Fig. 5]

In 1969 two studies, one by a Russian climatologist (Budyko, 1969) and another by an American meteorologist (Sellers, 1969) suggested that surface warming by CO_2 (or any other warming agent) would lead to an increase in the melting of snow and ice and the exposure of the underlying darker surface would lead to more absorption of solar radiation. The albedo (percent reflection of solar radiation) of fresh snow is about 0.8 or more, whereas land surface albedo is typically about 10% to 40%, while that of the underlying ocean is about 5% to 20%. Budyko and Sellers hypothesized that this link between warming, retreat of sea-ice and snow would lead to amplification of global warming. This hypothesis was verified recently by Pistone, Eisenman and Ramanathan (2014) using microwave data for sea ice and radiation budget data for albedo. They showed that from 1980 to 2010, the arctic warmed by about 2.5°C, annual mean sea ice retreated from 63% to 53% and the arctic averaged albedo decreased from 52% to 48%. The increased solar energy absorbed by the Arctic Ocean was about the same as the added energy trapped by thickening the CO_2 greenhouse blanket by 25%. This positive feedback between increase in the greenhouse gases, arctic warming and darkening of the arctic confirmed the Budyko-Sellers' hypotheses. Inclusion of this positive feedback to our estimates thus far, would amplify the projected warming from 1.7°C (with water vapour feedback) to about 2°C.

iii) Comparison of the empirically estimated warming with observed warming

Using observations from the ground and from satellites, we have concluded that the observed build up of greenhouse gases and the resulting thickness of the greenhouse blanket (by 3 Wm^{-2}) should have warmed the planet already by 2°C. In contrast, the planet has thus far warmed by about 0.85°C (as of 2010) since about the late 1880s.

So, where is the missing heat? Our estimate of 2°C is for so-called equilibrium warming, which is the warming of the system after it has had sufficient time to respond to the added heat. This inertia of the system is governed by the ocean, which has a huge heat capacity. Ocean observations suggest that the heat added by the blanket has penetrated to about 1000 meters in the ocean and, as a result, about 0.6°C is stored in the ocean and within several decades the system will warm by another 0.6°C, even if we stop adding greenhouse gases as of today. If we add this to the 0.6°C observed warming, the warming will increase from 0.85°C to 1.4°C compared with our predicted value of 2°C. We still have to account for another 0.6°C of the missing heat. It turns out that human activities, particularly coal combustion, diesel combustion and biomass burning, have also resulted in addition of particles to the air (aerosols) and these particles (with the exception of black carbon in soot) reflect the incoming sunlight and enhance the albedo, thus adding mirrors to the greenhouse blanket.

This cooling effect of these particles is an area of intense research by several hundred researchers around the world and suffers from a large uncertainty range, but the best value for the cooling effect of manmade particles is about -0.6°C (-0.2 to -1.8°C). This cooling effect is not a permanent effect and it should at best be considered as a mask behind which resides the greenhouse blanket.

So why should the aerosol cooling effect be treated as a mask? These particles are part of air pollution which kills about 7 million each year. Worldwide there are efforts to clean the air of these particles, as has already happened in many industrial nations. The lifetime of these particles is only of a few days. So mitigation efforts to clean the air (e.g. putting sulphur scrubbers in coal plants) will get rid of the particles and their cooling effects in a few weeks, which will then expose the planet to the full effect of the manmade greenhouse blanket and the planet will warm by additional 0.6°C of warming, which will increase the total warming from 1.4°C to 2°C in agreement with the predictions based on empirical data.

V. What Were The Predictions and How Do They Compare With Observations?

Every theory must be judged by the predictions it makes. We must judge the greenhouse theory of climate change accordingly. So what were the predictions? This is not an exhaustive list but includes the most important ones:

- *Warming will be amplified due to water vapour feedback (Arrhenius, 1896)*
- *Warming will rise above background noise by 2000 (Madden and Ramanathan, 1980)*
- *Warming will be amplified in polar regions due to snow/ice albedo feedback (Budyko, 1950s)*
- *Both land and oceans will warm (Manabe and Wetherald, 1975)*
- *Stratosphere will cool (Manabe and Wetherald, 1967 & others)*
- *Global average precipitation will increase (Manabe and Wetherald, 1975)*

The first five predictions have been confirmed by observations (see earlier descriptions for the feedbacks due to water vapour and snow/ice albedo feedback). The last one dealing with global average precipitation is yet to be verified. One issue is that the particles' effect is to decrease precipitation and this offsetting effect, coupled with the noisiness of the precipitation data, has obscured the greenhouse gas signal.