SENATE MISLED ON CLIMATE SCIENCE

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Economics Legislation Committee, 20/10/2016
Estimates, INDUSTRY, INNOVATION AND SCIENCE PORTFOLIO
Office of the Chief Scientist, Estimates Committees, Page 51

Evidence of Chief Scientist, Dr Finkel

> "So, when it comes to carbon dioxide, it is clear what would be driving increases in carbon dioxide. Then you got out and measure it. And carbon dioxide goes up every year. Last year, carbon dioxide in the atmosphere went up 3.05 parts per million, which is more than any other time. So the carbon dioxide is going up. Does that create warming?
>
> The theory that carbon dioxide in the atmosphere does trap heat—ultraviolet light comes through the atmosphere without interruption or almost without interruption, hits the ground, warms the ground, and you get an infrared radiation back from the ground which is then to some extent trapped by the carbon dioxide—goes back to 1896. A Swiss physical chemist, Svante Arrhenius, did the initial work on that. He subsequently got a Nobel prize for other work. He identified, back in 1896, that carbon dioxide in the atmosphere, for basic physical reasons, will trap heat. "

Chief Scientist quotes erroneous physics

The claim by the Chief Scientist at Senate Estimates is that carbon dioxide traps heat emitted from the Earth as longwave radiation. This is a false representation because it only partially represents the physics of carbon dioxide's interaction with Earth's radiation. The Chief Scientist quoted the Swedish chemist Svante Arrhenius as his authority but Arrhenius' 1896 hypothesis (developed from the 1820s work of French mathematician Joseph Fourier) was formulated before there was a reasonable understanding of the structure of the atmosphere. It remains truly surprising that Arrhenius hypothesis is still quoted by many in authority to advance the proposition that increasing carbon dioxide in the atmosphere will lead to dangerous global warming.

The correct physics

During the first half of the 20th century direct observations from balloons and aircraft clarified many aspects of the atmosphere's physical structure and chemical composition. Research into the interaction between radiation and various component gases of the atmosphere led to new understandings about the climate system, particularly how certain gases both absorb and emit electromagnetic radiation in characteristic wavebands. This understanding was further advanced as

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data derived from satellite sensors were used to better quantify the magnitudes of solar radiation reaching Earth and longwave radiation being emitted to space.

By the 1960s it was well known that, in the atmosphere, greenhouse gases (water vapour and carbon dioxide) emit more radiation than they absorb, contrary to the hypothesis of Arrhenius. This is clear from the more recent depiction of the global energy budget by Kiel and Trenberth (1997)[i] and cited by the IPCC (Figure 1).

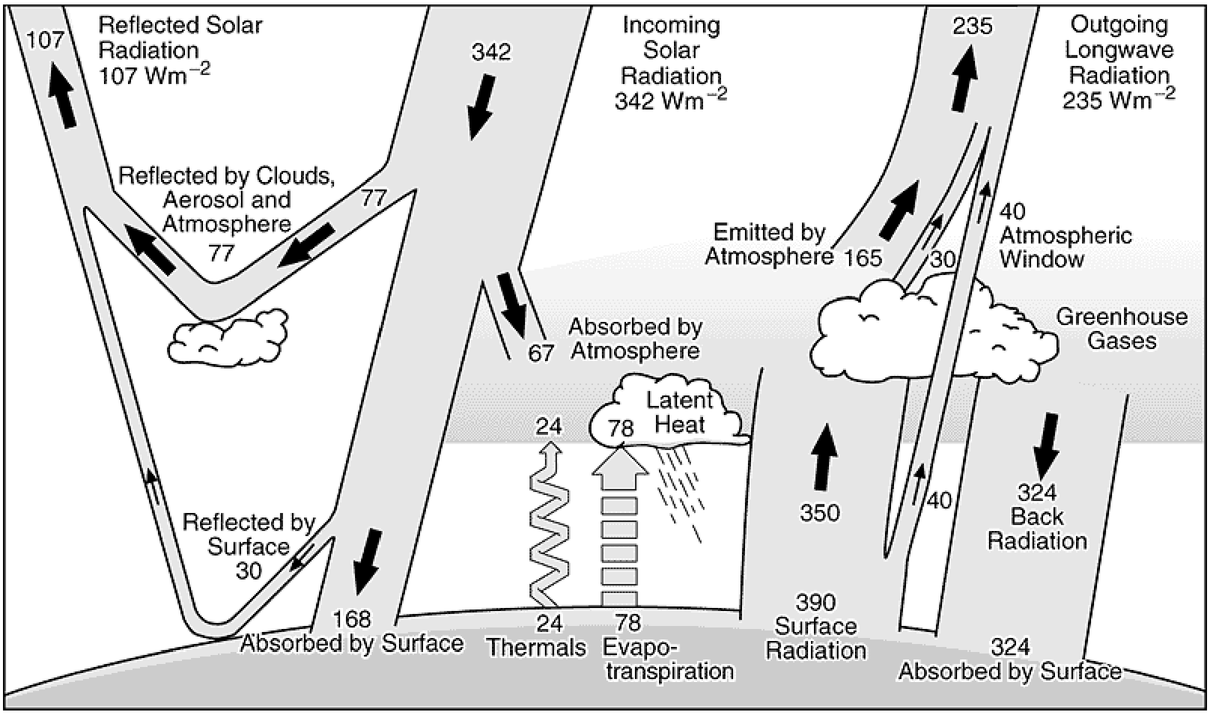


Figure 1: The global and annual averaged Earth energy budget (Kiehl and Trenberth (1997)

The energy budget shows that 390 W/m2 of longwave radiation are emitted from the surface and only 235 W/m2 reaches space. One might be tempted to suggest, as Arrhenius surmised, that 155 W/m2 of energy are absorbed by greenhouse gases to warm the atmosphere, acting much like a blanket. However, the budget also shows that 324 W/m2 are emitted by the greenhouse gases back to Earth. There is an ongoing net loss of 169 W/m2 of longwave radiation from the Earth's atmosphere layer demonstrating that the greenhouse gases do not trap radiation to warm the atmosphere, rather there is a net emission of longwave radiation that tends to cool it.

What Arrhenius and followers of his hypothesis fail to realise is the important contribution of emission of longwave radiation by the greenhouse gases. Because of the back radiation emitted by the greenhouse gases the net loss of longwave radiation energy from the Earth's surface is only 66 W/m2. The net upward transfer of longwave radiation increases with altitude and reaches a rate of 235 W/m2 being emitted to space. The ongoing interaction between the greenhouse gases and clouds of the atmosphere and the Earth's radiation is a tendency to cool the atmosphere – at a rate of about 2°C per day.

The claim that Earth is kept warm through the trapping of longwave radiation by greenhouse gases not only misrepresents the physics but, by induction, leads to erroneous conclusions. The statement that adding more carbon dioxide to the atmosphere will cause the Earth to warm cannot logically be drawn from the erroneous statement that greenhouse gases in the atmosphere trap longwave radiation. While it is true (as will be shown below) that adding more greenhouse gases to the atmosphere will lead to global warming the explanation is more complex than the simplistic and erroneous one given by the Chief Scientist.

The real question is, how sensitive is the Earth's surface temperature to changing atmospheric carbon dioxide?

The basis of climate sensitivity

Many of the energy exchanges involving the Earth's surface, as depicted diagrammatically in Figure 1, are temperature dependent:

- The sensible heat loss from the surface (24 W/m2) is a function of the surface temperature and the atmospheric boundary layer temperature gradient.
- The latent heat loss through evapotranspiration (78 W/m2) is a function of saturation vapour pressure at the surface (linked to surface temperature) and vapour pressure of the atmospheric boundary layer (linked through relative humidity to atmospheric boundary layer temperature).
- The surface longwave radiation emission varies with the fourth power of the absolute surface temperature (the Stefan Boltzmann Law).
- The back radiation at the surface (emission from the atmospheric greenhouse gases) is linked to emissivity and temperature near the Earth's surface.

The only component of the surface energy budget not directly affected by the temperature of the surface or the temperature near the surface is the absorbed solar radiation (168 W/m2).

The Earth's surface temperature is sustained at a near constant value because the solar radiation absorbed at the Earth's surface (168 W/m2) is offset by the sum of the losses by way of the different components: net longwave radiation emission (66 W/m2), sensible heat loss to the atmosphere (24 W/m2), and latent energy exchange with the atmosphere (78 W/m2). Solar radiation is the energy source to the surface and the Earth's temperature adjusts to ensure that the sum of the losses equates to the magnitude of the source.

The only component of the energy budget at the surface directly responsive to carbon dioxide concentration is the back radiation emitted from the greenhouse gases. Thus, if the carbon dioxide concentration of the atmosphere were to increase then the first impact is that the back radiation to the surface would increase (emission from closer to the surface and thus at a warmer temperature). That is, there is reduced net longwave radiation loss from the surface and the surface energy exchanges are no longer in balance – there is less energy leaving the surface than the solar radiation being absorbed.

The response to a reduction in net radiation loss is for the surface temperature to increase. As the surface temperature increases so too do the sensible and latent heat losses and the longwave radiation emission increase. There is a repartitioning of the energy exchanges such that the sensible and latent heat exchanges and radiation emission increase, each according to its temperature dependency, to match the increase in back radiation from the atmosphere.

For an incremental rise in carbon dioxide concentration there will be an incremental rise in surface temperature. The magnitude of the response is the sensitivity of the Earth's surface temperature to carbon dioxide variations.

Evaluating climate sensitivity

The IPCC has claimed, in each of its reports, that the only way to determine the sensitivity is by way of complex computer models that replicate the even more complex climate system; there is no simpler way. Yet each report has delivered an estimate of the sensitivity with a wide margin of uncertainty – a mean value of approximately 3°C for a doubling of concentration but with a lower bound of 2°C and an upper bound of 4.5°C.

The IPCC offers no alternative methodology to at least support the correctness of the order of magnitude of its sensitivity estimates.

There is an alternative methodology, written about since the 1960s, that suggests the model estimates of sensitivity are much too high. The methodology is based on evaluating the changes in the components of the surface energy budget; its deficiency has been the difficulty in quantifying how some of the components vary with temperature. Notwithstanding, there have been advances in understanding that should at least be considered.

The Earth's surface energy budget can be represented by the components depicted in Figure 1. The back radiation from the greenhouse gases is largely from two sources: that part from the changing concentration of carbon dioxide and that part from the increasing water vapour concentration as air temperature rises. These are the driver and feedback respectively.

From the surface energy budget we can derive the following relationship (see Appendix A):

$$\Delta T = [\Delta F_{dc}/(\partial SL/\partial T)].[1/(1 - r)]$$

Where ΔT is the incremental surface temperature change for an increase in back radiation ΔF_{dc} from an incremental increase in carbon dioxide concentration; $\partial SL/\partial T$ is the rate of surface energy loss with temperature (radiation emission and sensible and latent heat exchange); r is the ratio of the rate of increase of back radiation with temperature to the rate of increase of surface energy loss with temperature. The term in the first square bracket is the direct response to carbon dioxide forcing and the second is the amplification factor.

The sensitivity ΔT for a doubling of carbon dioxide varies markedly with the characteristics of the surface being considered. For example, if the surface is dry desert with no change in latent heat exchange as temperature increases then method returns a direct response of near 0.6°C and an amplification factor of near 8 and an overall sensitivity of 4.3°C. In contrast, if the surface is ocean and freely evaporating then the direct response is only about 0.3°C and the amplification about 1.8 times to give a sensitivity of 0.5°C.

The surface energy budget approach has returned a value for sensitivity ranging from a low of near 0.5°C to an upper value of 4.3°C. This range is greater than that of climate models (2.0°C to 4.5°C) although the upper values are similar. The characteristic of the surface energy budget estimates is that the range of this methodology reflects vastly different physical states: the high value is consistent with no change to surface evaporation with temperature (for example if the Earth's surface were all desert) while the low value represents maximum evaporation response to temperature (for example if the Earth's surface were completely ocean).

Recognising that the Earth's surface is about 70% ocean and much of the remainder is land with transpiring vegetation then a sensitivity nearer the lower value (at least less than 1°C) would seem to be a more reasonable estimate. This is less than one-third of the 'most likely' value returned by climate models.

Carbon dioxide variations do change surface temperature but the surface energy budget evaluation suggests that carbon dioxide increase will be a major cause of global temperature change. The only basis for alarm is the projections of computer models that have not been validated against real-world data.

The changing climate

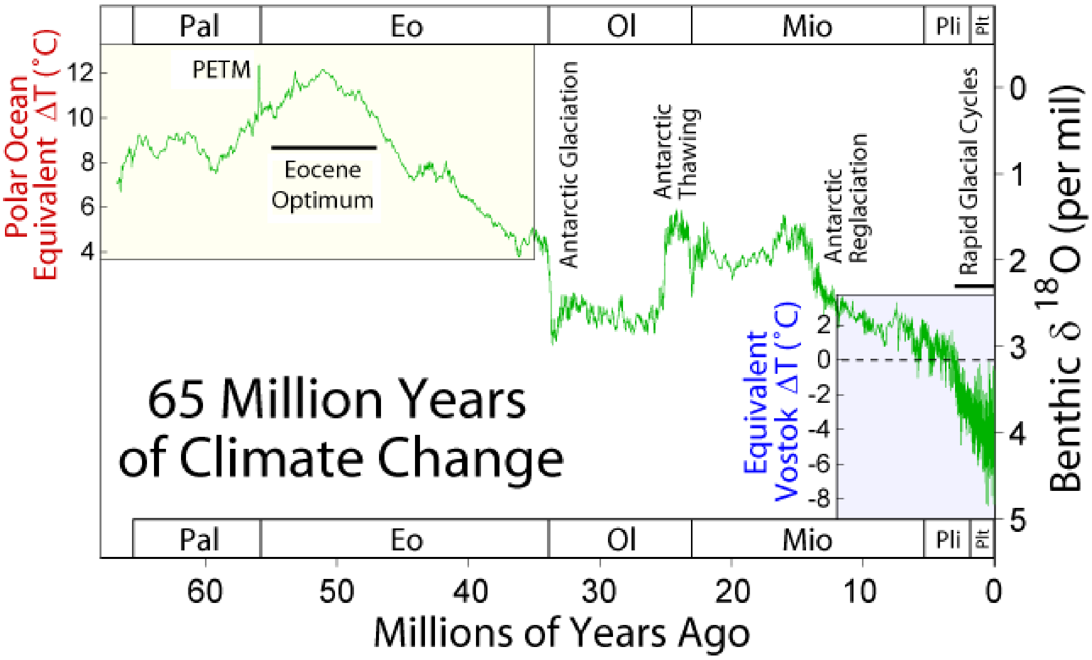


Figure 2: Climate change during the last 65 million years as expressed by the oxygen isotope composition of benthic foraminifera. From Zachos, Dickens and Zeebe (2008)

Knowledge of past climates is derived from several geological sources; the further back in time the less the temporal detail that can be gleaned about the record. A primary source of information about early climate is derived from analysis of material in cores obtained during ocean floor drilling. Analysis of changing oxygen isotope values in benthic foraminifera (representing ocean temperature and ice mass) by Zachos et al (2008)[ii] suggests that Earth has been cooling for the recent 50 million years (Figure 2). This was during a period of significant rearrangement of continental plates and ocean currents. For example, at the beginning of the period South America and Antarctica were connected but the Isthmus of Panama was still open.

The opening of Drake Passage meant that a continuous ocean formed around Antarctica in the latitude belt of the westerly winds; the westerly winds generated the Antarctic Circumpolar Current to thermally isolate Antarctica from warmer subtropical waters and allow the formation of wintertime coastal sea ice. As Broeker (2010)[iii] has explained, formation of sea ice expels salt and increases the density of the water below to drive the deep meridional circulations of the ocean – the deep oceans are filled, and continually replenished, with cold water, thus cooling the planet.

A more detailed structure of the recent 5 million years (Figure 3) is available from an analysis of more than 50 ocean globally distributed ocean drilling cores by Lisieki and Raymo (2005)[iv]. The analysis shows a cooling planet but with increasing amplitude of temperature variability over the recent 3 million years.

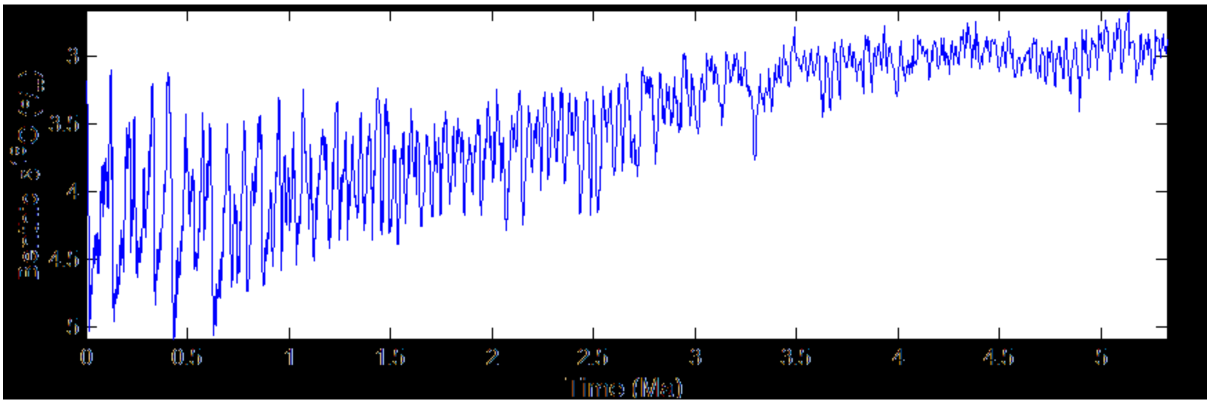
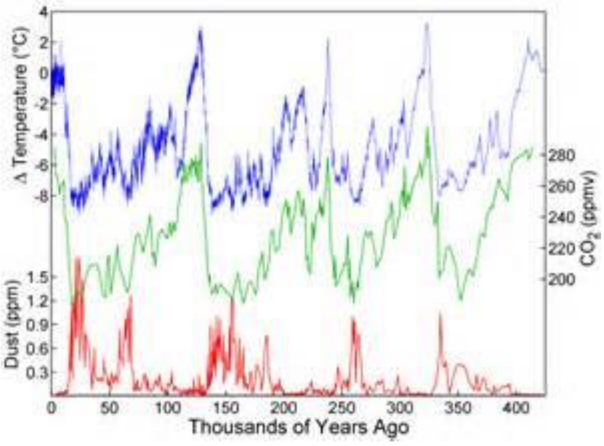


Figure 3: An average of 57 globally distributed benthic d18O records (which measure global ice volume and deep ocean temperature) collected from the scientific literature. Lisieko and Raymo (2005)

The analysis of ice cores from Vostok in Antarctica, with their annual layers of snow deposit, by Petit et al (1999)[v] has provided a history of temperature, carbon dioxide and rate of dust accumulation over the last half million years (Figure 4). The records show near synchronous fluctuations that conform to the period of the ellipticity of Earth's orbit around the Sun. While the temperature and carbon dioxide records are in phase that for dust is out of phase. During the warm intervals there is little dust; dust accumulation increases markedly during the cold periods. It is reasonable to conclude that during warmer intervals there is more rainfall and plant growth that bind the soil; during colder intervals there is less rain, lands are more arid, and there is more dust in the atmosphere.

Significant uncertainty surrounds the reasons why and how the recent fluctuations are linked to the Earth's orbital characteristics. Many have suggested that the glaciation responds to the varying amplitude of summer solar radiation over the polar regions. However the period of the major solar radiation amplitude corresponds to the precession cycle of a little more than 20,000 years. Fluctuations on about this period can be seen in the records but it is not the period of major temperature amplitude.



The changing declination of Earth's axis with a period of 40,000 years also varies the relative amounts of solar energy received over tropical and polar latitudes but neither is this period dominant. The dominant period in the temperature record is the near 100,000-year eccentricity cycle yet the Earth receives similar solar energy over each year regardless of the orbital eccentricity. How then does orbital eccentricity regulate climate on these timescales?

Figure 4: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Petit et al (1999)

Ice cores from the Greenland ice sheet provide higher resolution than those from Antarctica because of Greenland's higher precipitation. The record of GISP2 provided by Alley (2004)[vi] covers little more than the recent 50,000 years but shows much variability (Figure 5). Through the era generally referred to as the Last Glacial Maximum (to about 15,000 years ago) there are significant short-period warming events of up to 10°C (referred to as Dansgaard Oeschger events), each spanning a thousand years or more. These fluctuations only cease about 11,000 years ago with the warming to the current interglacial period.

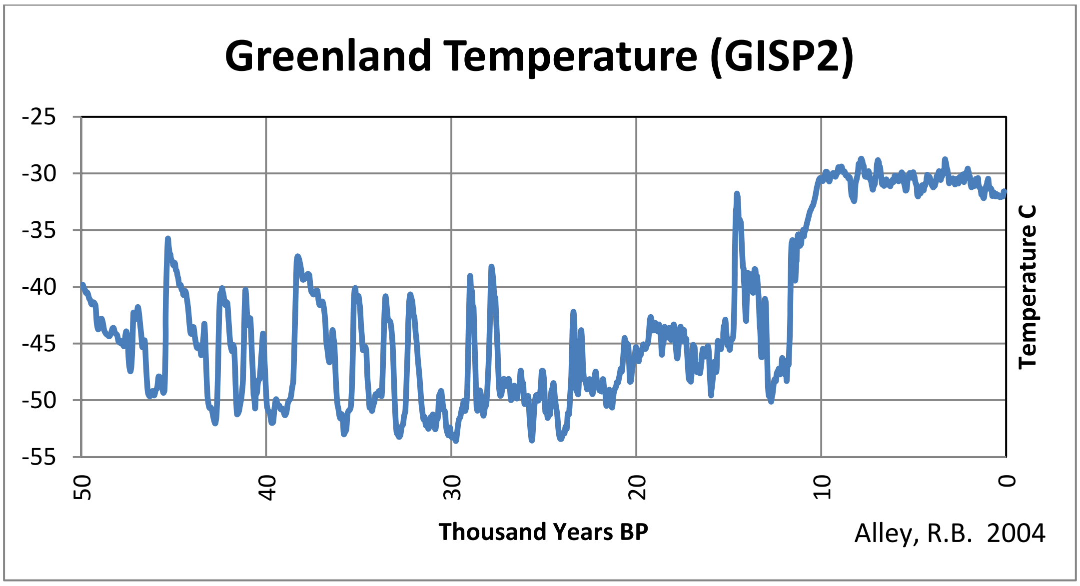


Figure 5: Temperature reconstruction over the last 50,000 years derived from a Greenland ice core. Alley (2004)

On the scale of the glacial-interglacial duration the temperature of the last 10,000 years (the Holocene Optimum) would seem to be relatively steady. However by expanding the scale (Figure 6), significant fluctuations in temperature continue.

The first thing to note is that the data suggest regional cooling has been taking place for the last 3,500 years. The last warm period before 3,000 years ago corresponds with recorded prosperity of civilisations from Egypt (Tutankhamen through Rameses III) to the Middle East. The next warm period is about 1,000 years later corresponding to the rise of the Greek and Roman empires; the last warm period is about 1,000 years later corresponding to the so-called Medieval Warm Period. The data suggest that the Little Ice Age, which had its nadir during the 16th century, was about as cold as any period for 8,000 years. One might reasonably ask whether the recent warming since the Little Ice Age is really a basis for alarm?

From the evidence it is apparent that Earth's climate is not static. Although the general cooling over the last 50 million years can be linked to changing plate tectonics the details of the latter's influence are yet to be quantified. The reasons for the increasing variability of climate over the recent 5 million years remain a mystery. So too is how the glacial cycle has come to be in harmony with the Earth's elliptical orbit. It would be heroic to suggest that science of climate change is settled; there remains too many unknowns.

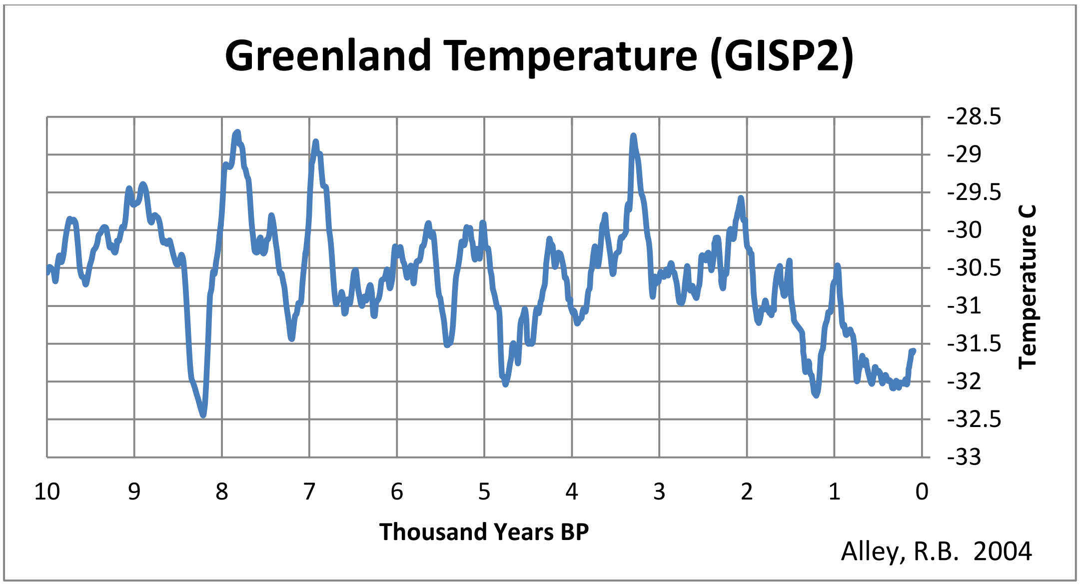


Figure 6: Temperature reconstruction for the Holocene Optimum of the recent 10,000 years from a Greenland ice core. Alley (2004)

When it comes to rationalising the variability revealed in the high resolution Greenland ice core data then there are few even remotely plausible explanations being offered. For those pushing the carbon dioxide climate forcing hypothesis these data are best ignored – the really inconvenient truths!

Limitations to climate models

Climate models are a simplistic representation of the climate system. In their earliest formulations they were relatively crude depictions of the atmospheric circulation linked to a static shallow ocean layer, often no more than 30 metres in depth. The premise was that climate variability was a response to radiation forcing and the shallow ocean provided sufficient thermal mass to ensure climate stability.

The early climate models were notorious for their inability to return a consistent global mean surface temperature. Not only was the actual global mean temperature not well specified from observations but the range of model estimates spanned several degrees C. In order to circumvent this problem the climate sensitivity was defined as the change in mean global temperature of the model when carbon dioxide concentration was doubled. It was such models that were the basis for the IPCC’s 1990 first assessment of sensitivity to carbon dioxide forcing.

By the 1995 second IPCC assessment the models had evolved to include a representation of the ocean circulation coupled to the atmosphere by way of heat, moisture and momentum exchanges. Unfortunately the thermal and inertial masses of the oceans are so large that they dominated the energetics of the atmosphere - to the extent that even during climate simulations without carbon dioxide forcing (the control) the model global average surface temperature would rise! The workaround was to define climate sensitivity as the difference between the rising control temperature and the even faster rising temperature of the model when forced by carbon dioxide.

Adjustments were made to the exchange of heat, moisture and momentum between the ocean and atmosphere (referred to as ‘flux adjustment’) in order to stabilise the temperature of the control. When the model was forced by additional carbon dioxide then similar flux adjustments were made as in the control. In these model formulations the sensitivity was again defined as the difference between the control and that forced by carbon dioxide. Given that the response to carbon dioxide forcing is manifest as changes in the surface exchange processes then the extent that the flux adjustment biased the sensitivity is not readily apparent. It was flux adjusted models that were the basis for the IPCC’s 2001 third assessment.

Recognising the potential impact of flux adjustment on the realism of the models, steps were made to develop alternative methodologies for stabilising the coupled models. The underlying problem is that the oceans transport a significant fraction of the heat from the tropics to polar regions necessary to achieve global energy balance. Trenberth and Caron (2001)[vii] estimated that ocean transport contributes about 8 percent of the total in the Southern Hemisphere and about 22 percent in the Northern Hemisphere. The actual ocean circulations and their heat transports are poorly monitored and the estimates were derived as residuals from top of the atmosphere radiation measurements and calculations of atmosphere transport of heat.

Current monitoring of ocean currents is inadequate because it does not provide the necessary information to calculate the poleward transport of heat with any fidelity. Furthermore, there is insufficient information to identify the magnitude of variability of ocean heat transport. It is known from El Nino events of the equatorial Pacific Ocean that regional ocean variability has significant impact on global weather and Earth’s temperature; slow changes in the large-scale ocean circulations not currently detected (but highly likely to be occurring given the properties of the ocean fluid) would similarly be expected to cause longer term trends in global temperature and climate.

The lack of knowledge of ocean heat transport and its variability are major impediments to current models of the climate system. Workarounds are used to compensate for this lack of knowledge. Thus there remains doubt as to the extent to which model projections under carbon dioxide forcing are realistic or a consequence of compounding error growth resulting from inadequate specification and artificial compensation. The fact that the model sensitivity has been maintained within relatively fixed bounds during model evolution is, in itself, not justification for the veracity of models as a tool to project carbon dioxide forcing.

The climate conundrum

For two and a half decades the UN, through its IPCC, has been warning of the dire consequences to the planet from continuing to burn fossil fuels and other activities that increase carbon dioxide concentration in the atmosphere. According to the IPCC’s model projections the expected rise in global temperature since 1980 should have been about 1.1°C but with a plausible range of between 0.7°C (low estimate) and 1.6°C (high estimate). Notwithstanding the annually increasing carbon dioxide concentration as measured at Mauna Loa[viii] the projected global temperature rise has not materialised. Apart from brief peaks during El Nino years (emphasising how ocean variability can influence global temperature) the satellite derived lower troposphere global temperature for recent years (Figure 7) as assessed by Spencer and Christy[ix] is barely 0.3°C warmer than 1980, or less than half the low value projected by the models.

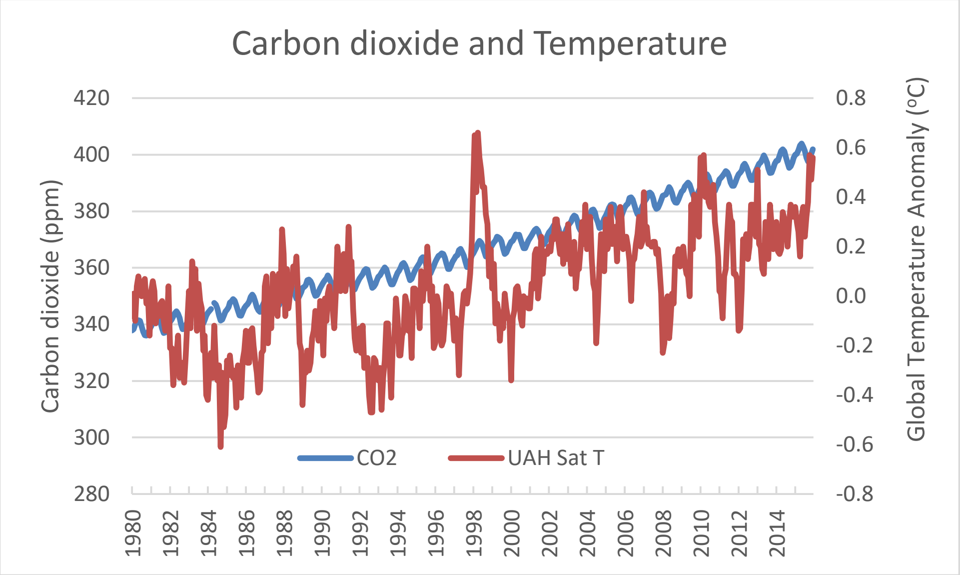


Figure 7: Carbon dioxide concentration at Mauna Loa and lower troposphere global temperature as measured by satellite

Normally in science, when hypothetical projections are so different from reality it is cause for the scientists to carry out a thorough assessment of the hypothesis and methodology. For reasons that remain obscure, climate science and its practitioners seem to be above these routine checks and balances; the adherents to the dangerous global warming alarmism prefer to defend their hypothesis and methodology against all criticism, valid or otherwise.

It is not too late for the Chief Scientist, using the authority of his position, to initiate an enquiry into the basis for Australia's continuing adherence to the exaggerated alarmism of the IPCC. After all, the public policy that has developed from the alarmism is pushing the nation towards more expensive energy, less reliable energy, increasing the cost of production across a range of industries and ultimately lowering employment opportunities in the community. All this when, in all likelihood, carbon dioxide has not been a significant factor regulating past climate and will not be the main driver of future climate change.

APPENDIX

The Earth's surface energy budget shown in Figure 1 can be depicted as:

$$S_o = H_o + L_o + F_u - F_d$$

Where

S_o	is the magnitude of solar radiation absorbed at the surface
H_o	is the magnitude of sensible heat loss to the atmosphere
L_o	is the magnitude of latent energy exchange with the atmosphere
F_u	is the magnitude of longwave radiation emitted from the surface
F_d	is the magnitude of back radiation at the surface

The back radiation F_d can be considered as two components: that due to carbon dioxide emissions (F_{dc}) and that due to water vapour emissions (F_{dw}). As noted previously, the terms on the right side of the equation are all temperature dependent and the temperature dependence of the components can be depicted as:

$$\partial S_o/\partial T = 0 = \partial H_o/\partial T + \partial L_o/\partial T + \partial F_u/\partial T - \partial(F_{dc} + F_{dw})/\partial T$$

Rearranging the terms for an incremental increase in downward radiation ΔF_{dc} from an increase in carbon dioxide concentration the surface temperature response is given by:

$$(\partial SH/\partial T).\ \Delta T - (F_{dw}/\partial T).\ \Delta T = \Delta F_{dc}$$

Where $\partial SH/\partial T$ is the rate of surface heat loss with temperature given by:

$$\partial SH/\partial T = \partial H_o/\partial T + \partial L_o/\partial T + \partial F_u/\partial T$$

That is (dividing through by $\partial SH/\partial T$ and rearranging:

$$\Delta T = [\Delta F_{dc}/(\partial SH/\partial T)].[1/(\ 1 - \{(\ \partial F_{dw}/\partial T)/(\ \partial SH/\partial T)\}]$$

the term in the first square bracket is simply the sensitivity of surface temperature to carbon dioxide forcing in the absence of any feedbacks (feedbacks being additional back radiation from water vapour, etc. as temperature rises). The second term, of form $1/(1 - r)$, is the amplification of sensitivity due to feedback $\partial F_{dw}/\partial T$. If the rate of increase of back radiation with temperature is much less than the rate of increase of surface energy loss then r is small and the amplification is small. If, however, the rate of increase of back radiation approaches the magnitude of the rate of increase of surface energy loss with temperature then r approaches unity and the amplification due to feedback is very large.

The above analysis is not novel. Indeed, during the early 1960s there were several attempts to evaluate the sensitivity of surface temperature to increasing carbon dioxide using simplifications of the essential equations. In a review Manabe (1983)[x] explained that, at the time, there were limitations in the ability to assess the values of the component terms. The calculations that were made suggested that the sensitivity was so small as to be inconsequential.

Our understanding of the surface energy exchange processes has advanced immeasurably over the succeeding half century, as has our ability to compute the magnitudes and rates of change. Advances in radiation physics has enabled a very good assessment of the two atmospheric radiation terms, ΔF_{dc} (the change in back radiation from a doubling of atmospheric carbon dioxide concentration) and $\partial F_{dw}/\partial T$ (the change in back radiation with temperature due to water vapour increase). Radiation codes like those used in computer modelling of the climate system are publicly accessible for such computations. The rate of increase of surface emission with temperature, $\partial F_u/\partial T$, comes from the well-established Stefan Boltzmann Law.

The major remaining uncertainties from using the surface energy budget method are the assessments of the rates of change of sensible and latent heat exchange with temperature. We note from the form of the equations that an underestimation of these rates will lead to an exaggerated sensitivity whereas an overestimation will give a false low sensitivity. To give an extreme example, if we ignore changing sensible heat and moisture flux and consider only the surface longwave radiation as comprising the changing surface energy loss with temperature then the amplification term is reduced to:

$$\text{Amplification} = 1/\{1 - (\partial F_{dw}/\partial T)/(\partial H_u/\partial T)\}$$

From the MODTRANS radiation code[xi] and using the U.S. Standard Atmosphere (an approximation of the global average temperature profile of the atmosphere) we find that $(\partial F_{dw}/\partial T)$ is about 4.8 W/m2 per ^{o}C change and $(\partial H_u/\partial T)$ is 5.5 W/m2 per ^{o}C. These values return an amplification factor of near 8.

Turning to the changing rate of latent heat exchange with surface temperature, the computer models of the climate system utilise the bulk aerodynamic formula for computing surface evaporation. This is of the form:

$$E = \rho.C_D.W.u(e_s - e)$$

Where E is the rate of evaporation, ρ is air density, CD is a stability and drag factor, W is a wetness factor (unity over the oceans), u is the wind speed at a standard height above the surface, e_s is the saturated water vapour pressure at the surface temperature and e is the water vapour pressure at a standard height above the surface. The components in the brackets can also be represented as $e_s(1 - RH)$, where RH is the relative humidity at a standard height near the surface.

As a first approximation, it is reasonable to postulate that air density, stability and drag, surface wetness and wind speed do not vary appreciably with surface temperature. The IPCC reports also suggest that relative humidity remains near constant as surface temperature increases under a global warming scenario. The dominant term is thus the changing saturated water vapour pressure with temperature, well known at about 7% per ^{o}C (the Clausius Clapeyron relationship).

The Kiehl and Trenberth evaluation of the global energy budget (Figure 1) estimates that global average latent heat exchange is about 78 W/m2 and if this were to increase at 7% per ^{o}C then an order of magnitude estimate of the rate of increase of latent heat exchange with temperature $(\partial L_o/\partial T)$ is about 5.5 W/m2. Using this value increases the estimate of rate of surface energy loss with temperature from 5.5 W/m2 (radiation only) to 11.0 W/m2 (radiation plus latent heat exchange). The additional consideration of latent heat exchange reduces the amplification component of the sensitivity equation from a value of 8 times to a factor of 1.8 times.

In a similar way, it is possible to calculate a possible range for the direct response of surface temperature to carbon dioxide change given the above extremes: whether the surface energy response to temperature is only due to longwave radiation emission or whether we also include changing latent heat exchange.

The MODTRANS radiation code returns a value of an increase in back radiation at the surface ΔF_{dc} of 3 W/m2 for a doubling of carbon dioxide concentration (from pre-industrial 280 ppm to 560 ppm). If changing latent heat is ignored then the direct response to the doubling of carbon dioxide is less than 0.6°C but atmospheric water vapour feedback amplifies the response to near 4.3°C. When the changing latent heat exchange is included in the calculation then the direct response is only about 0.3°C and the atmospheric water vapour amplification increases the overall response to near 0.5°C.

Inclusion of the rate of change of sensible heat exchange with temperature in the calculations would further damp the sensitivity, both the direct response and the amplification. However it is reasonable to argue that the contribution from the changing sensible heat exchange with temperature is small and can be ignored. This is because the temperature of air near the surface is largely regulated by the surface temperature and thus the temperature gradient would change little as surface temperature changes. Note that in the global energy budget the sensible heat exchange (24 W/m2) is the smallest component.

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