HEARTLAND INSTITUTE

International Conference on Climate Change: 8-10 March 2009

A Natural Limit to Anthropogenic Global Warming

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The burning of fossil fuels and other activities of modern industrial economies emit carbon dioxide (CO_2) and other so-called greenhouse gases into the atmosphere. CO_2 in particular is claimed to be enhancing the greenhouse effect and causing dangerous global warming. Further, it is claimed that the consequence will have catastrophic impact for life on Earth, including inundation of low lying coastal margins from rising sea levels, more frequent heatwaves and droughts reducing food and water availability, and the spread of disease to higher latitudes.

The concept of dangerous climate change, although central to the UN's Framework Convention on Climate Change and its Kyoto Protocol to restrict CO_2 emissions, has never been formally defined. A general understanding has evolved within scientific and political discussions on the issue that global warming exceeding 2°C would indeed be dangerous. Some scientists go so far as to suggest that 2°C represents a 'tipping point' beyond which 'runaway global warming' is likely. The evidence, however, is speculative and linked to the projections of computer models.

The scientific bases for the claims that human emissions of CO_2 will cause dangerous climate change largely have their foundation on three premises:

1. Prior to industrialisation the Earth was in radiation balance, emitting to space as infrared radiation as much energy as is intercepted as solar radiation. As a consequence, the Earth's climate was then stable.
2. The apparent stability is now being disrupted as accumulation of human-caused CO_2 emissions in the atmosphere is reducing infrared radiation to space in wavelengths characteristic of CO_2. In order to return to radiation balance it is necessary for the Earth to warm so that more infrared is emitted in other wavelengths at a higher temperature.
3. There is a direct and linear relationship between the reduction of infrared radiation to space[1] (the so-called radiation forcing, ΔF_{sp}) and the increase in surface temperature, ΔT_s

$$\Delta F_{sp} = \lambda \, \Delta T_s$$

There is little disagreement that additional CO_2 in the atmosphere will enhance the greenhouse effect. However, these seemingly plausible statements are either demonstrably false or not verified by rigorous theory or observation. The relationship between radiative forcing and surface temperature response does not have theoretical underpinning and the sensitivity factor, λ can only be estimated from computer models. The value of λ given by different computer models varies over a relatively broad range; there is no way of assessing whether λ should have a low value or a high

[1] The intergovernmental Panel on Climate Change (IPCC) refers to the 'radiation forcing' as the reduction in upward directed infrared at the tropopause due to the increase in CO_2 concentration.

value. The IPCC, without rigorous scientific analysis, suggests that the average of all models is the most realistic estimate that should be used.

Faced with such uncertainty it is reasonable to re-examine the scientific premises. It comes as little surprise that our understanding of the climate system has advanced since the premises were first formulated more than two decades ago. It is surprising that the IPCC has not incorporated new knowledge into its description of the climate system and its evaluation of computer model performance outlined in the most recent 2007 assessment report.

CARBON DIOXIDE AND RADIATION TO SPACE

CO_2 absorbs and emits radiation within selected bands of the infrared spectrum. That is, within these bands the CO_2 molecules absorb radiation that has been emitted from the earth's surface with intensity characteristic of the local surface temperature. Also, within these bands the CO_2 molecules emit radiation in all directions but with intensity that is dependent on the prevailing gas temperature.

Treating the atmosphere as a layer we find the emission to space is of much less intensity than the radiation emitted from the surface. This is because the earth's surface is much warmer than the cold high layer of the atmosphere from whence the radiation to space originates. However, the lowest warm layer of the atmosphere is also emitting radiation back to earth. What is of importance in this discussion is the change in radiation intensity as the concentration of CO_2 varies.

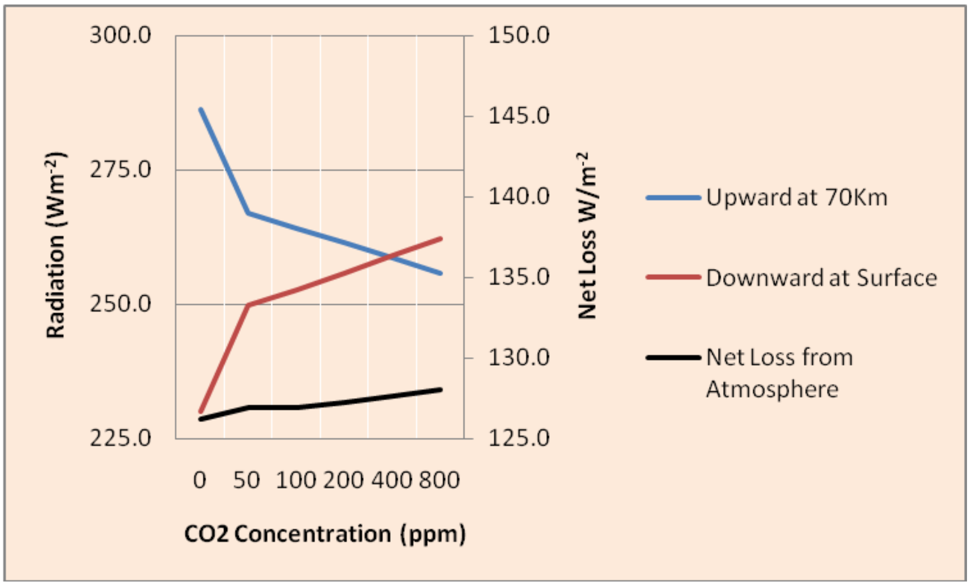

Figure 1: Changes in upward infrared emission to space, downward emission at the surface (both LH scale), and net radiation loss from the atmosphere (RH scale) for changing concentrations of CO_2. (Computed from MODTRANS for the US Standard Atmosphere and clear sky)

Figure 1 illustrates how the changing concentration of CO_2 affects the radiation intensity, both the emission from the atmosphere to space and the downward emission from the atmosphere to earth.

These calculations have been performed using the MODTRANS[2] radiation transfer model based on the US Standard Atmosphere under clear sky conditions. As the CO_2 concentration of the atmosphere increases the infrared radiation in the CO_2 wavelengths emanates from a higher, colder altitude and the intensity decreases. At the surface, the downward infrared radiation emanates from a lower, warmer altitude as the CO_2 concentration increases.

Two points of Figure 1 are of interest:

1. As the concentration of CO_2 increases the reduction in intensity of the emission to space is similar in magnitude to the corresponding increase in intensity of downward radiation at the surface. As a consequence, as CO_2 concentration increases there is only a small increase in net radiation loss from the atmospheric layer.
2. Figure 1 does not give support to the notion that, as the atmospheric CO_2 concentration increases, there is more absorption of infrared radiation by the atmospheric layer, leading to warming of the atmosphere. There is an equal or greater loss of energy to the surface as downward emission increases with increasing CO_2 concentration.

The notion of radiation forcing is further weakened when the variation with latitude of net radiation at the top of the atmosphere (solar absorption less infrared emission) is considered. Figure 2 clearly shows a surplus of solar radiation over tropical latitudes and excess emission to space over polar latitudes. Nowhere are surface temperatures determined by local radiation balance. In order to achieve overall global radiation balance large quantities of energy are transported from the tropics to polar regions by the ocean and (principally) the atmospheric circulations.

As a consequence of the poleward transport of energy the polar temperatures are warmer than they would be under local radiation equilibrium. Moreover, the polar temperatures (and ice mass magnitude) will vary as the poleward temperature transport varies. The ocean and atmospheric circulations are two interacting fluids and there is no reason to believe that the partitioning of the poleward energy transport will not vary over a range of timescales. Indeed, there is every reason to believe that the partitioning will fluctuate with time such that polar temperatures fluctuate on similar timescales.

The message of Figure 2 is that the ocean and atmospheric circulations are continually acting to bring about overall global radiation balance at the top of the atmosphere. At times the climate system is accumulating energy and at other times there is a net loss of radiant energy, depending on the changing energy storage of the respective fluids and the thermodynamics of the fluid flows. This is evident because the earth's annual climate cycle is not exactly repeated. In addition, known oceanic-atmosphere phenomena such as El Niño cause major variations to the climate cycle.

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[2] MODTRANS is a medium resolution radiation transfer model and is accessible through the University of Chicago at http://geosci.uchicago.edu/~archer/cgimodels/radiation.html

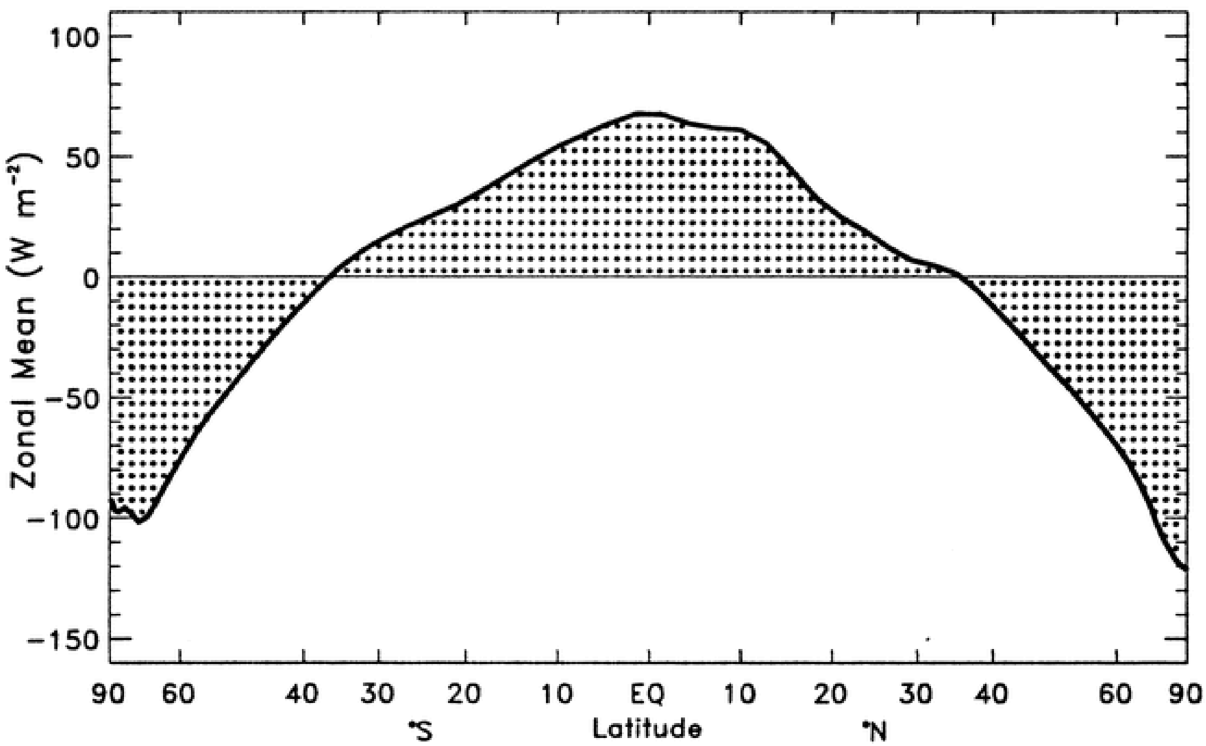

Figure 2: Average variation with latitude of net radiation (solar absorption minus infrared emission to space) at the top of the atmosphere (TOA). (Trenberth and Caron)[3]

An assumption of the anthropogenic global warming hypothesis is that a reduction of infrared radiation to space in the CO_2 wavelength bands will cause the earth to warm and increase the intensity of emissions across the radiation spectrum. This assumption does not take cognisance of the fact that, at least for tropical and subtropical latitudes, the main variation in infrared radiation emission to space is brought about through variations in cloud and water vapour distribution.

The dominant control of cloud and water vapour distribution can be readily seen in Figure 3. In regions of recurring deep convective clouds with tops in the high cold troposphere, such as over the Congo and Amazon Basins and the warm equatorial oceans extending from the Indian Ocean to the western Pacific Ocean, the radiation to space is reduced. In contrast, over much of the subtropics and other regions of dry subsiding air the radiation to space emanates from much lower in the atmosphere where temperatures are warmer.

Variations in infrared radiation emission to space can be more than 80 Wm^{-2} from cloud to cloud-free regions. In addition, these spatial patterns are not fixed in time. Not only do they vary according to the annual cycle but they also vary from year to year. There are major disruptions to the cloud and outgoing infrared radiation patterns during El Niño events when the deep convective clouds form over the central and eastern equatorial Pacific Ocean. The changing cloud and moisture patterns during El Niño events significantly change the magnitude and pattern of infrared radiation emission to space.

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[3] Trenberth, K.E. and J.M. Caron, 2001. Estimates of meridional ocean and atmospheric heat transports. J of Clim. 14:3433-3443

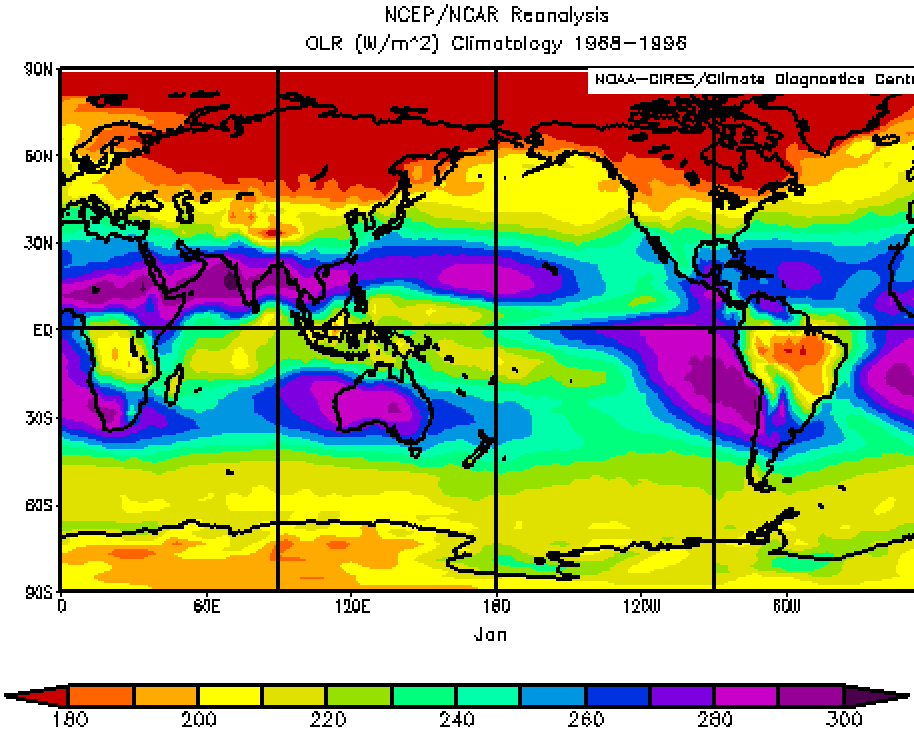

Figure 3: Spatial variations of climatological infrared radiation to space (OLR) for January. Radiation to space is reduced in the regions of deep tropical convection because the emission largely emanates from the high cold cloud tops. Radiation is much higher in the regions of dry descending air where the emission emanates from warm layers near the surface. Radiation is also reduced over the cold polar regions of the winter hemisphere.

It is clear that interactions between the ocean and atmosphere fluids regulate internal variability of the climate system, especially the changing poleward transport of energy and the changing cloud and moisture patterns. It is these latter that are the dominant control over the magnitudes and pattern of infrared radiation to space. It is not plausible that the only response from a change to CO_2 concentration, and its small reduction of infrared radiation to space, will be an increase of surface temperature. The small decrease in infrared radiation to space resulting from CO_2 increase will be overwhelmed by the magnitude of the ever-changing patterns resulting from the atmospheric circulation and associated cloud and moisture distribution. There is no sound theoretical basis to expect a reduction in infrared radiation to space in the relatively narrow CO_2 wavelength bands to cause an increase in surface temperature.

CARBON DIOXIDE AND SURFACE ENERGY EXCHANGE

In contrast to the upper atmosphere and the ever-changing infrared radiation to space, any change in CO_2 concentration and downward infrared radiation will directly affect the surface energy balance and surface temperature. An increase in the concentration of atmospheric CO_2 will increase the downward infrared radiation and tend to warm the surface. The magnitude of the actual surface temperature rise will be regulated by the response of other surface energy exchange processes to the CO_2 radiation forcing.

At the surface, the energy inputs are solar radiation and the emission of infrared radiation from the greenhouse gases (principally water vapour and CO_2) and clouds of the atmosphere back to the surface (often called back radiation). The surface energy losses are primarily by way of direct heat exchange between the surface and the atmosphere, Latent energy exchange between the surface and the atmosphere due to evaporation of water, and the emission of infrared radiation from the surface. There is also a loss or gain of energy to surface storage (in the land surface or ocean surface layer) if the surface temperature is warming or cooling.

The increase in downward radiation, ΔF_{CO2} due to increased CO_2 concentration will cause an increase in surface temperature, ΔT_s given by:

$$\Delta F_{CO2} = [dF_u/dT + dLH/dT + dH/dT - dS_o/dT - dF_d/dT] * \Delta Ts \qquad (1)$$

Here:
dS_o/dT is the rate of change of solar radiation absorbed at the surface with temperature;
dF_d/dT is the rate of change of downward radiation from water vapour emissions with temperature;
dF_u/dT is the rate of change of surface emission with temperature;
dH/dT is the rate of change of direct surface heat exchange with temperature; and
dLH/dT is the rate of change of latent energy exchange with temperature.

Absorption of solar radiation will vary with cloudiness changes but not directly with variation of CO_2 concentration. Cloudiness may change with surface temperature of the earth but *a priori* we do not know the direction or magnitude of any potential change. In the first instance solar radiation is treated as a constant that does not change with temperature.

The downward infrared radiation at the surface varies directly with greenhouse gas concentration and temperature of the air near the ground. The main greenhouse gases are water vapour and CO_2; water vapour concentration varies with temperature and CO_2 concentration varies with fossil fuel usage. In the context of anthropogenic global warming, CO_2 is the forcing process; atmospheric temperature and water vapour concentration are response processes. Increasing the concentrations of CO_2 and water vapour, each act to increase the downward radiation at the surface.

The direct exchange of heat between the surface and atmosphere varies with the vertical gradient of air temperature at the surface. The temperature of the air near the ground increases as the surface temperature increases. Consequently the rate of heat transfer does not vary appreciably as the surface temperature changes and is ignored in this discussion.

The infrared emission from the surface varies with temperature according to the Stefan Boltzman Law. The emissivity also has a small variation depending on the nature of the surface (land, vegetation or ocean) but this a second order effect and can be ignored.

The evaporation of water that exchanges latent energy between the surface and the atmosphere varies with the vapour pressure gradient near the surface. Empirical evidence suggests that the relative humidity near the surface does not vary with temperature. As a consequence the rate of evaporation and latent energy exchange vary according to the Clausius Clapeyron relationship, the same rate as the saturation vapour pressure varies with temperature.

Recognising that solar absorption and direct heat exchange vary little with temperature then equation 1 can be reduced to:

$$\Delta F_{CO2} = [dF_u/dT + dLH/dT - dF_d/dT] * \Delta T_s \qquad (2)$$

and rearranged to:

$$\Delta T_s = \Delta T_{CO2} / (1 - r) \qquad (3)$$

where

$$\Delta T_{CO2} = \Delta F_{CO2} / [dF_u/dT + dLH/dT] \qquad (4)$$

and

$$r = dF_d/dT / [dF_u/dT + dLH/dT] \qquad (5)$$

Here ΔT_{CO2} is the direct surface temperature response resulting from CO_2 forcing and $1/(1 - r)$ is the feedback amplification due to atmospheric temperature and water vapour increase.

It is important to note that the rate of change of surface energy loss with temperature, given by $[dF_u/dT + dLH/dT]$ constrains both the direct surface temperature response to radiation forcing and the magnitude of the feedback amplification.

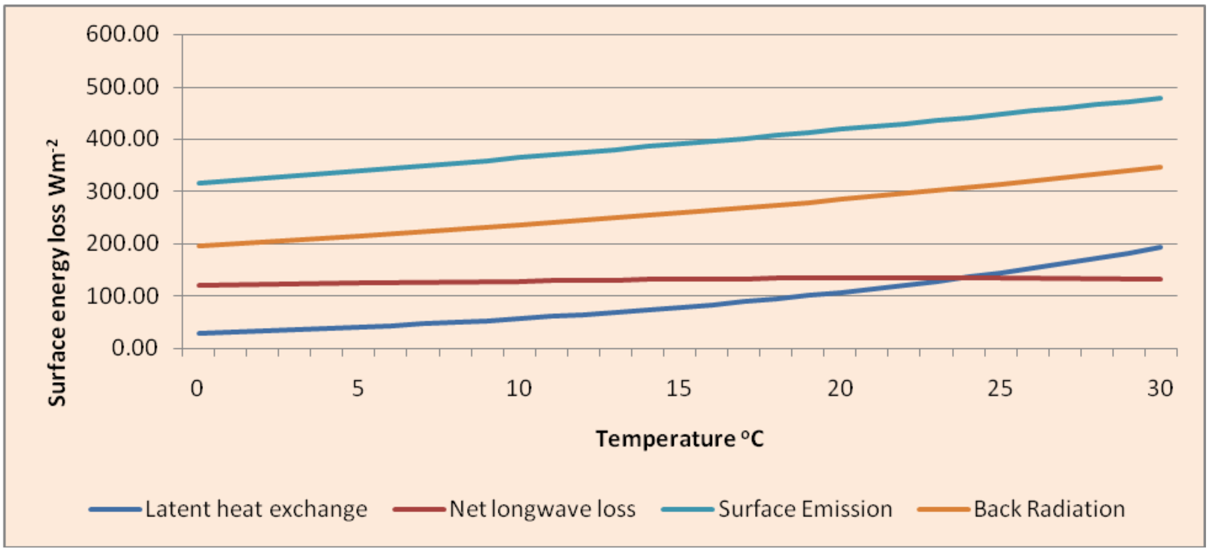

Figure 4: Changing magnitudes of the major surface energy exchange processes over the range of typical temperatures of the Earth's surface. (The Back Radiation is computed for the US Standard Atmosphere under clear sky conditions using the MODTRANS model)

At Figure 4 are plotted the magnitudes of the major surface energy exchange processes across the range of temperatures typical of the Earth's surface. The surface emission is according to the Stefan

Boltzman Law (emissivity = 1) while the back radiation is computed using the MODTRANS model for the US Standard Atmosphere (approximately average global temperature and moisture) under clear sky conditions and constant relative humidity. Latent energy exchange is according to the Clausius Clapeyron relationship (7 percent change with each degree Celsius variation – 7% C^{-1}) scaled to the global average exchange of 78 Wm^{-2} at 15°C.

What is clear from Figure 4 is that the magnitudes of surface emission and the back radiation increase in near parallel, as is to be expected because the temperatures of the surface and near surface atmosphere also increase in near parallel. As a consequence, there is little change in the magnitude of net infrared radiation loss from the surface across the temperature range. It is the latent energy exchange, approximately doubling in magnitude with every 10°C temperature rise, which dominates the changing surface energy loss with temperature. The importance of evaporation for limiting surface temperature has previously been discussed by Priestley (1966)[4].

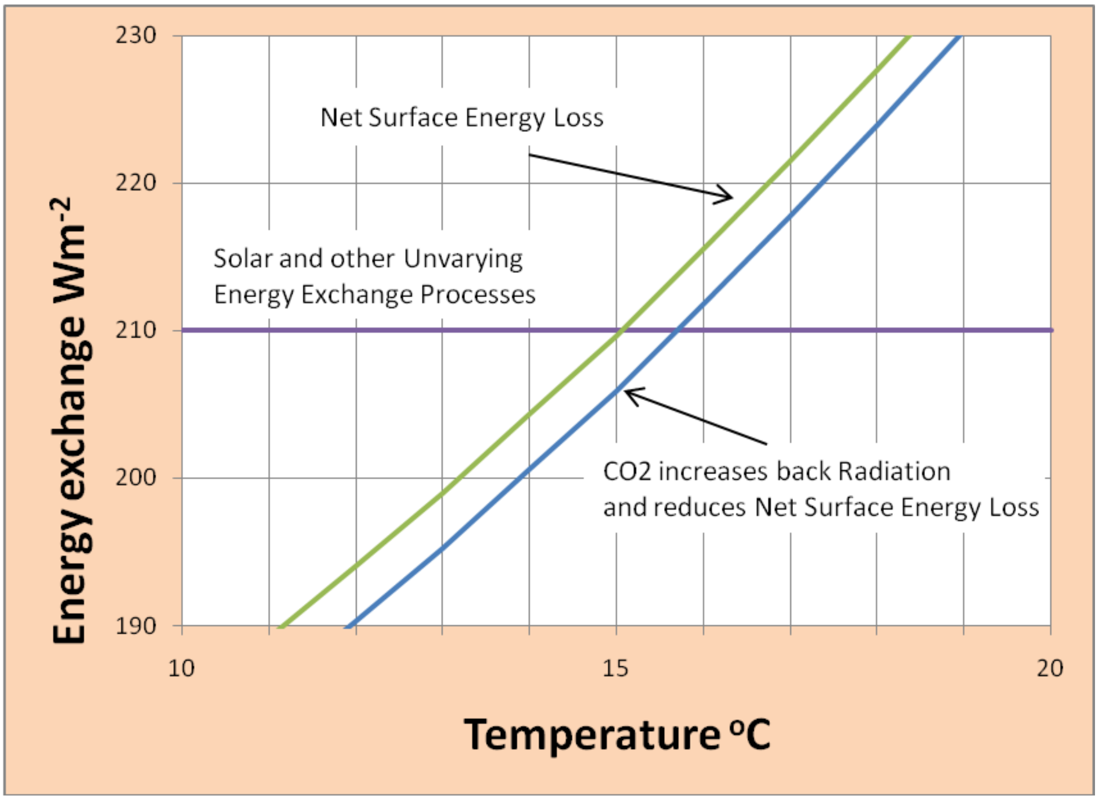

Figure 5: The magnitude of the net surface energy loss with the solar absorption and other unvarying processes scaled to be in steady state at the Earth's mean temperature of 15°C. As CO_2 concentration increases the back radiation also increases, thus reducing the net surface energy loss. The surface temperature rises to a new steady state for energy balance with the near constant energy input processes.

[4] Priestley, C.H.B., 1966. The limitation of temperature by evaporation in hot climates. Agr. Meteorol., 3: 241-246

When the magnitude of the net surface energy loss (net infrared radiation plus latent energy) is plotted against temperature and scaled for steady state at the average temperature of the Earth, as in Figure 5, it is found that the surface temperature is relatively stable. A small change in surface temperature, either to a lower or a higher value, causes the surface energy loss to be out of balance with the steady energy input and there is a strong tendency to return to the steady state temperature.

We can also readily ascertain the impact on the surface temperature from an increase in CO_2 concentration. For example, a doubling of the CO_2 concentration from prevailing values will increase the back radiation by about 4 Wm^{-2}. As a consequence, the net surface loss will be reduced by an equal magnitude and the surface energy processes are out of balance. A new steady state is achieved by an increase in surface temperature of about 0.6^{o}C.

It should be noted that this adjustment to surface temperature is independent of changes that might be wrought by changing atmospheric circulation and distributions of cloud and moisture patterns. The changing CO_2 concentration will directly affect the surface temperature because of the impact that CO_2 concentration has on back radiation and the ensuing surface energy balance. Unlike the CO_2 forced change to the infrared radiation to space that has only a tenuous connection to surface temperature the change in back radiation has a direct impact and the effect is mathematically tractable. Moreover, because of the rapid increase of latent energy exchange with temperature, the surface temperature rise is constrained to a relatively small response.

THE EXAGGERATED RESPONSE OF COMPUTER MODELS

There is nearly an order of magnitude difference between the relatively small surface temperature response of 0.6^{o}C to a doubling of CO_2 concentration calculated above and the projected responses quoted by the IPCC. The latter are based on computer models and range from about 2^{o}C to about 6^{o}C. The key to the difference is in the formulation of the changing rate of latent energy exchange with temperature used in the computer models.

As explained above, here the rate of increase in evaporation (and latent energy exchange) with temperature is equated to the Clausius Clapeyron relationship of 7% per degree C. As noted by Held and Soden (2006)[5], the rate of increase of evaporation with temperature rise for the computer models used in the fourth assessment of the IPCC was, on average, only about one-third this value. This low value in computer models was confirmed by Wentz et al (2007)[6], who also identified a range of 1-3% K^{-1} for the global average evaporation increase across the models.

A reduction in the rate of evaporation increase with temperature has significant consequences for temperature projections under CO_2 forcing. The reduced rate of change of latent energy exchange with surface temperature means that the rate of increase of surface energy loss with temperature is also reduced and the slope of the curve of Figure 5 is flattened. As a consequence, the surface temperature can vary over a wider range for the same imbalances between the fixed energy input

[5] Held, I.M. and B.J. Soden, 2006. Robust responses of the hydrological cycle to global warming. J of Clim 19: 5686-5699

[6] Wentz, F.J., L. Riccaiardulli, K. Hilburn and C. Mears, 2007. How much more rain will global warming bring. ScienceExpress, 31 May 2007.

and the surface energy loss variation. That is, the tendency to return to the steady state temperature is weakened.

Of more importance, if the rate of increase of latent energy exchange with temperature is significantly less than the Clausius Clapeyron relationship then the radiation forcing from a doubling of CO_2 concentration produces a larger increase in surface temperature to a new steady state.

The changing sensitivity of surface temperature to radiative forcing can be readily assessed by way of equation 3 above. At the average temperature of the Earth (15^oC) the rate of increase of surface infrared emission with temperature change is given by the Stefan Boltzman Law as 5.4 $Wm^{-2}C^{-1}$. The equivalent rate of increase with temperature of downward infrared radiation at the surface can be assessed, for example using the MODTRANS radiation transfer model. With the assumptions that the US Standard Atmosphere approximates the mean profile of the atmosphere, that relative humidity is constant (that is, the atmospheric water vapour increases with temperature in accordance with the Clausius Clapeyron relationship) and ignoring clouds, it is found that the increase in downward infrared radiation at the surface is 4.8 $Wm^{-2}C^{-1}$.

Table 1 sets out indicative values for the sensitivity of surface temperature to radiative forcing for a range of rates of latent energy exchange with temperature. The value of 6% C^{-1} is the global average estimate by Wentz et al (2007) based on satellite estimates of changing precipitation during global warming of recent decades. It is less than the Clausius Clapeyron relationship but this is not unexpected given the magnitude of arid and semi-arid land areas. The other values are typical for computer models (GCM) used in the IPCC fourth assessment of 2007.

dLH/dT	$\Delta T_s/\Delta F_{CO2}$	ΔT_s (2 x CO_2)
6% C^{-1} (satellites)	0.16$^oC/Wm^{-2}$	0.6^oC
2% C^{-1} (Average GCM)	0.45$^oC/Wm^{-2}$	1.7^oC
1% C^{-1} (Low-end GCM)	0.83$^oC/Wm^{-2}$	3.1^oC

Table 1: Indicative values of surface temperature response to radiative forcing and of surface temperature increase from a doubling of CO_2 concentration. The rates of surface latent energy exchange, dLH/dT correspond to global values assessed from satellite analysis, and values corresponding to computer models (GCM) used in the 2007 IPCC fourth assessment .

It is very clear from Table 1 that any assessment of the surface temperature response to CO_2 forcing is very sensitive to the specification of the rate of increase of evaporation, and hence latent energy exchange, with temperature increase. The analysis at Table 1 clearly points to a high likelihood that the computer models used as the basis for the IPCC estimates of anthropogenic global warming are significantly exaggerating the projected global temperature response. A doubling of CO_2 concentration even from current level to near 800 ppm by the end of the 21st century is not likely to cause global temperature rise exceeding 1^{o}C. Such a rise is well within the range of natural variability and should not be construed as dangerous.

CONCLUSION

Carbon dioxide is a greenhouse gas and interacts with the Earth's infrared radiation, both the emission to space and the downward radiation at the surface. Contrary to popular explanations, it is not the reduction in radiation to space across the CO_2 bands that are important for enhancing the greenhouse effect; it is the increase in downward radiation at the surface that is important. An increase to the concentration of CO_2 will enhance the greenhouse effect but only cause a modest increase in global surface temperatures.

Water vapour is important in regulating the magnitude of the enhanced greenhouse effect in two ways: increased water vapour in the atmosphere has an amplifying effect on the CO_2 forcing; and, more importantly, increased evaporation constrains the surface temperature rise. It is the evaporation that is dominant because the Earth's surface is more than 70 percent ocean and much of the remainder is covered by transpiring vegetation. A doubling of CO_2 concentration by the end of the century from current levels will cause a modest global temperature rise not exceeding 1^{o}C.

The computer models on which the IPCC based its fourth assessment projections have been shown to significantly underestimate the rate of increase of evaporation with temperature. As a consequence, surface temperature rise from CO_2 forcing is grossly exaggerated. Suggestions that global temperature might pass a 'tipping point' and even go into a phase of 'runaway global warming' are an outcome of the flawed computer models and are not a realistic future scenario. The extensive oceans and the hydrological cycle are a natural constraint on global temperature and dangerous anthropogenic global warming is not a feasible outcome.

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