Climate Sensitivity:

A Whole-Earth Dynamic Approach

Introduction

Computer simulations of the whole-earth system dynamics are constantly improving their capacity to model the complex feedback mechanisms involved. Nevertheless there is still significant uncertainty in the prediction of climate sensitivity which is defined as:

> **The increase in average global temperature at equilibrium resulting from a doubling of concentration of atmospheric carbon dioxide from its pre-industrial base.** (That is from 282 parts per million to 564 ppm.)

The leading ensemble of computer models offers a range of outcomes from 1.4ºC to some 5.6ºC. Programmes take into account the thermodynamic equations of CO_2 absorption of infra-red radiation from the earth surface, together with an array of related dynamics, feedbacks and other contributing factors, integrated across a grid of earth-surface cells with interacting vertical layers. For a summary of the categories of feedbacks and the many specific mechanisms, see the treatment in "Positive Feedback and the Acceleration of Climate Change, Part 2". It is available in presentation and pdf versions at:
www.meridian.org.uk/Resources/Global%20Dynamics/TippingPoint/index.htm

This brief working paper, however, moves away from the world of computer modelling to examine the Vostok ice-core data for information that could throw new light on the issue of climate sensitivity. The rate of change in geological time was comparatively slow, and radiative forcing remained close to zero. As a result the earth system responded to insolation changes in a state of near equilibrium. The record therefore affords an indication of correlation of CO_2 concentration with equilibrium temperature.

It is important to note that in this paper, the CO_2 concentration data is seen not as causal of the temperature variation, but as an indicating marker of the equilibrium temperature reached by the whole earth system. The beauty of this approach is that the sensitivity reading includes by definition the equilibrium effects of all the feedbacks and complex dynamic responses currently approximated in the computer models.

A validity-test of the accuracy of any computer model requires that its predictions must match closely with the observed behaviour of the system under simulation. The significant mismatch between prediction and observation is an indication that further refinement of the model is now required.

If the sensitivity figures indicated in this study of the Vostok data can be trusted, we face an urgent and radical re-evaluation of the current strategic response to global warming.

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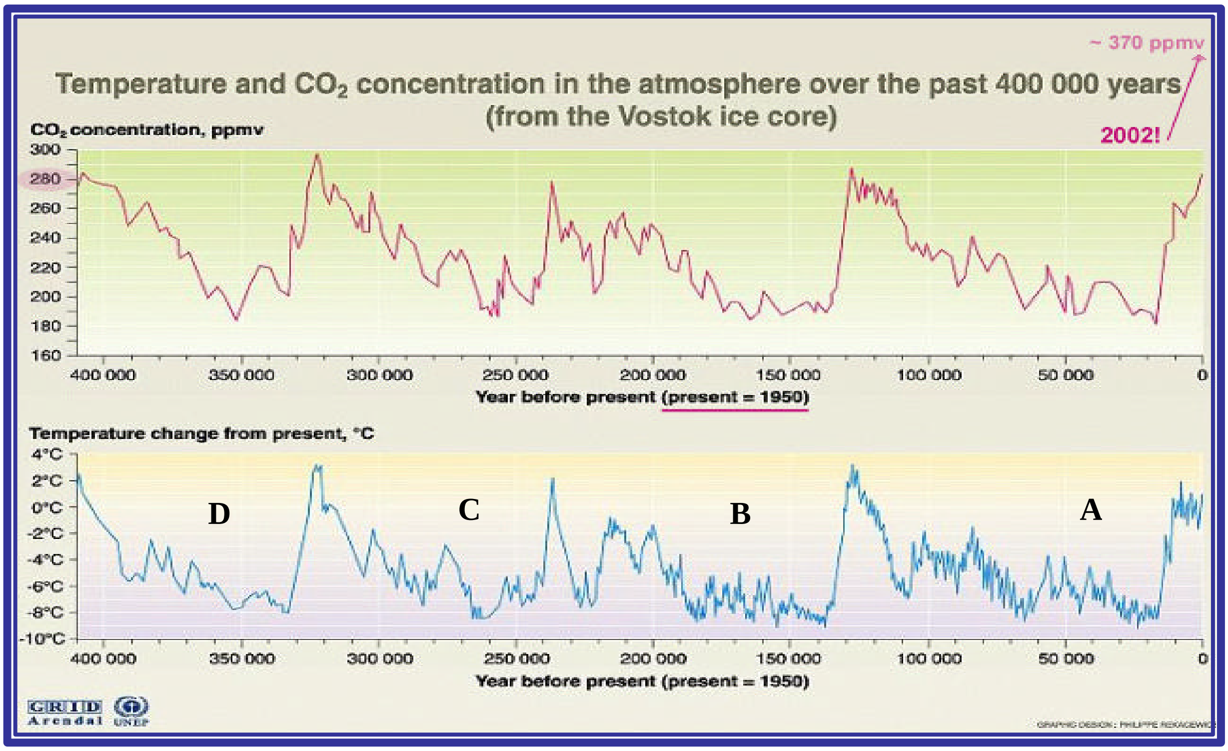
Observational Data



The Vostok ice core analysis now provides us with information correlating temperature with the concentration of atmospheric CO_2 reaching back over 650,000 years. However, in order to achieve the most accurate figures for climate sensitivity which are relevant to our current situation, this study limits its attention to the four most recent glacial and interglacial cycles covering the last 400,000 years. These records enable us to explore climate sensitivity based on observational data and so test the predictive accuracy of the computer models currently employed.

Temperature changes at Vostok are larger than the average temperature changes for the whole earth system. For instance the temperature difference between the coldest stage of the last ice age and the peak of the current warm inter-glacial period shows as some 11ºC at Vostok, while we understand the average global temperature shift to be about 5ºC. An adjustment ratio of 0.455 has therefore been applied to the Vostok figures in order to give the best approximation of the global average shift. The timescales involved are long and the changes in radiative forcing are therefore small. Temperatures can therefore confidently be taken as representing equilibrium outcome levels throughout the sequence.

Sensitivity Analysis

Cycle A (-100ky to present)

- CO_2 concentration increased from a floor of 182 ppm to a maximum (pre-industrialisation) of 282 ppm, a rise of 100ppm.
- Vostok records show a corresponding temperature rise of 11ºC representing a change in average temperature of 5ºC.
- Sensitivity in this cycle can be expressed as: a rise of 20.0 ppm in CO_2 concentration correlates with a rise of 1ºC.

Cycle B (-200ky to –100ky)

- CO_2 concentration increased from a floor of 185 ppm to a maximum of 290 ppm, a rise of 105 ppm.
- Vostok records show a corresponding temperature rise of 12ºC, representing a change in average temperature of 5.46ºC.
- Sensitivity in this cycle can be expressed as: a rise of 19.2 ppm in CO_2 concentration correlates with a rise of 1ºC.

Cycle C (-300ky to –200ky)

- CO_2 concentration increased from a floor of 187 ppm to a maximum of 280 ppm, a rise of 93 ppm.
- Vostok records show a corresponding temperature rise of 11ºC, representing a change in average temperature of 5.0ºC.
- Sensitivity in this cycle can be expressed as: a rise of 18.6 ppm in CO_2 concentration correlates with a rise of 1ºC.

Cycle D (-400ky to –300ky)

- CO_2 concentration increased from a floor of 183 ppm to a maximum of 300 ppm, a rise of 117 ppm.
- Vostok records show a corresponding temperature rise of 11ºC, representing a change in average temperature of 5.0ºC.
- Sensitivity in this cycle can be expressed as: a rise of 23.4 ppm in CO_2 concentration correlates with a rise of 1ºC.

If we take the average sensitivity across all four cycles we have an increase of 20.3 ppm in atmospheric concentration of CO_2 correlating with a 1ºC change in average global temperature in conditions of system equilibrium.

(Detailed regression analysis of the correlation between temperature and CO_2 concentration across the whole Vostok record performed by Ferdinand Engelbeen, [see Appendix 1 below] shows a sensitivity of 8 ppm per 1ºC at the Vostock site. If we apply the same adjustment ratio as that used in the paper above, this is equivalent to 17.6 ppm per 1ºC for the average global surface temperature.)

Implications of Observational Data

Doubling of concentration of atmospheric CO_2 from pre-industrial levels represents a rise of some 282 ppm. Applying the average sensitivity from the observed data from Vostok would lead us to expect an equilibrium temperature increase of 13.9ºC, in marked contrast to the prediction of about 3ºC of the current computer ensemble.

If we take Engelbeen's regression analysis across the whole Vostock time-frame then we arrive at a slightly more sensitive relationship yielding a possible equilibrium figure of 16ºC above the pre-industrial level.

There would appear to be a discrepancy between computer models and observational data of the order of a factor of 4.

Applying the above to the so-called "safe" ceiling of 440 ppm (the "policy goal" assumed to guard against dangerous climate change by keeping the rise in equilibrium temperature to a maximum of 2ºC) we find that such a concentration would result in a rise of approximately 8ºC (with a most sensitive outcome of 9ºC). We would expect the temperature rise in the polar regions to be at least double the average rise for the earth system as a whole.

If the implications of the observational data hold, then we have already initiated a level of catastrophic climate change. The situation would have to be declared a state of global emergency and action taken to reduce concentration of atmospheric CO_2 to a maximum of 300 ppm in the shortest possible time-span. Meanwhile other urgent initiatives would be required to prevent temperature-sensitive, feedback-driven overheating before the period of negative radiative forcing took effect.

An Outstanding Agenda

The fourfold mismatch between observational data and prediction from computer simulation in an area of such strategic significance is profoundly disturbing. It raises a set of critical questions:

1. Why should sensitivity below 300 ppm suddenly reduce to one quarter of its value in the range above 300 ppm?
2. Is there any evidence of strong non-linearity in overall climate sensitivity that could account for the observed discrepancy?
3. Is there any valid reason why observational data from the Vostok ice core should not be used in this way?
4. What factors are missing from the current computer simulation programmes that require adjustment in order to provide continuity with the observed system behaviour?

Causality, outcomes and the irreversibility of the arrow of time.

It is recognised that the glacial/interglacial cycles are initiated by change in the insolation of the northern hemisphere following the Milankovitch variation in the orbital precession, and the wobble and tilt of the earth's axis. These small shifts in radiative forcing are then amplified by the reinforcing feedback dynamics of the physical and biological elements of the system.

Historically, the increase in concentration of atmospheric CO_2 is an effected outcome of precipitating shifts in temperature. It also contributes, via the feedback dynamics of the greenhouse effect, to the subsequent amplification of the temperature change.

In the current situation, the initial shift in temperature is caused by the anthropogenic release of greenhouse gas. This replaces the initiating changes previously occasioned by the Milankovitch variations, so reversing the initial conditions of causality. Whatever the trigger, the inherent, positive-feedback-dominated, instability in the system dynamics then responds by amplifying the signal. To start with, the anthropogenic increase in concentration of atmospheric CO_2 precipitates the process of global heating, but then the positive feedback dynamics take over to drive the system to a new thermal equilibrium at a much higher level than that predicted from the effect of the precipitating signal on its own.

Amplifying contribution of the Hydrological Cycle

It may be that by focussing on the greenhouse effects of the anthropogenic increase in concentration of atmospheric CO_2, current climate science has somewhat overlooked the amplifying effect of the hydrological cycle. Once temperature starts to rise (however the initial change is caused), the density of water vapour in the atmosphere begins to increase. (See Appendix 2 for the working note on water-vapour feedback.) This factor then constitutes a self-sustaining positive feedback which amplifies the initial signal and could possibly account for the four-fold discrepancy between the observed data on climate sensitivity and the current computer simulation predictions.

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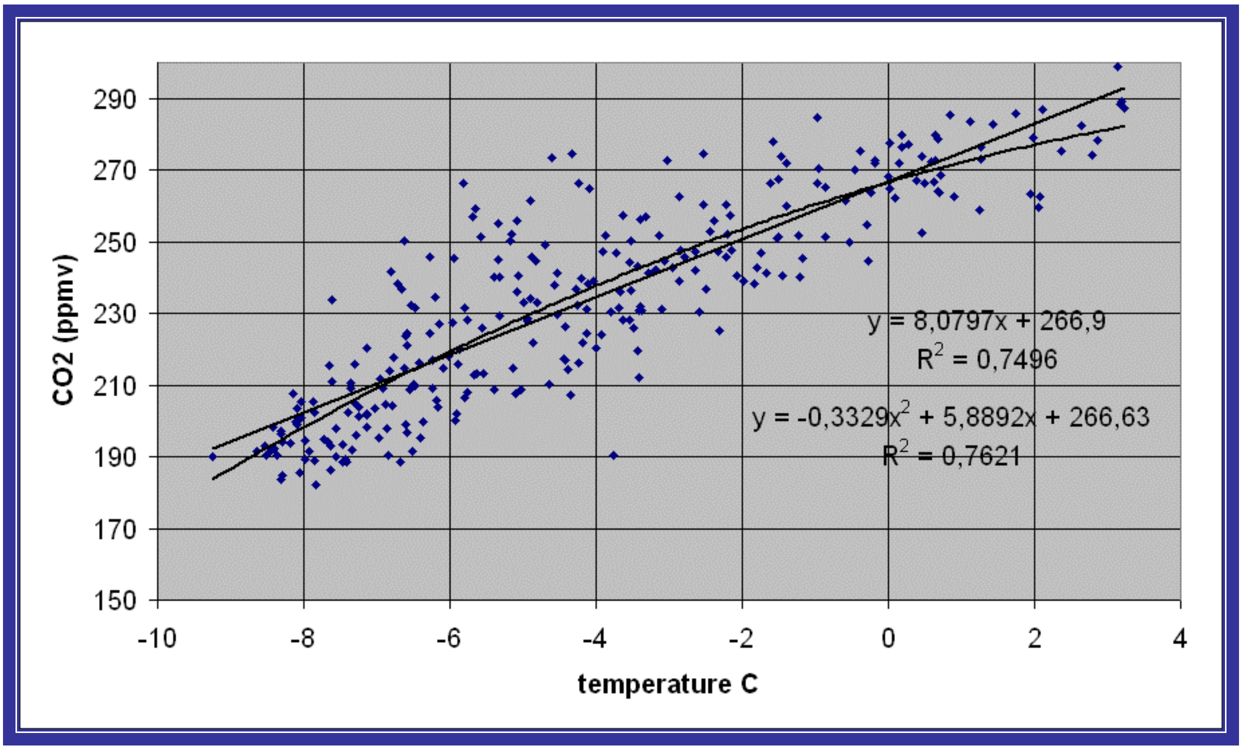
Appendix 1: Regression Analysis of CO_2/Temperature in Vostok Core

The analysis of the main text has used the maximum and minimum values of the glacial/inter-glacial records from the Vostok Ice Core. It is possible to generate a set of further correlation points from the record to check the minimalist approach adopted here. It is a task which has been undertaken by Ferdinand Engelbeen, who, on the 27th November 2005, posted the following to the Real Climate discussion group:

> "After carefully matching the CO_2 gas age to the nearest ice age, the change of CO_2 is some 8 ppmv for each change of 1 K in reconstructed temperature for the Vostok ice core over the full 420,000 years period. The Dome C record seems to confirm this correlation between CO_2 and temperature."

See: http://www.realclimate.org/index.php/archives/2005/11/650000-years-of-greenhouse-gas-concentrations/ (entry 39).

Engelbeen's regression analysis of the data is presented in visual form:



See: http://www.ferdinand-engelbeen.be/klimaat/correlation.html

The sensitivity of 8 ppm per 1ºC at Vostock correlates with a sensitivity of 17.6 ppm per 1ºC for the earth system as a whole. Engelbeen's analysis indicates that the overall sensitivity matches the lower end of the set of maximum/minimum sensitivities noted in the main paper. His values would yield a climate sensitivity at the Vostok site of 35ºC for a doubling of pre-industrial levels of atmospheric CO_2 concentration. This is equivalent to a climate sensitivity of 16ºC for the average global surface temperature.

Appendix 2: The Role of Water-Vapour in the Climate Feedback System

A Working Note

We know that uncondensed atmospheric water-vapour is far and away the most influential greenhouse gas. However, in macro-system terms, while average global temperature remains constant and close to equilibrium, change in the overall contribution of water-vapour can be ignored. Primary climate change is initiated by anthropogenic increase in the concentration of atmospheric CO_2. The carbon cycle (including feedbacks) is independent of water-vapour concentration.

It is only as global temperature begins to rise (as a long-time-delayed response to the greenhouse effect of increased concentration of CO_2), that we see the start of change in the water vapour concentration. As a temperature-dependent feedback process, water-vapour effects are therefore secondary processes in climate change.

Rising temperature at the water-air interface increases evaporation and raises water-vapour concentration. Warmer air holds more water-vapour in gaseous form before reaching dew-point and condensing to form clouds. The resultant increase in greenhouse effect further elevates temperature at the water-air interface. The process therefore constitutes a positive feedback loop in global heating.

The converse is equally true. Lower temperature at the water-air interface decreases evaporation and lowers atmospheric water-vapour concentration. Colder air holds less water-vapour in gaseous form before reaching dew-point and condensing to form clouds. The resultant decrease in greenhouse effect further lowers temperature at the water-air interface. The process therefore constitutes a positive feedback loop in global cooling.

Although omitted under pressure form Governmental agents from the final version of the Summary for Policy Makers of the IPCC FAR WG1, the polished scientific draft included the paragraph:

> **"Water vapour increases lead to a strong positive feedback that amplifies the global mean temperature response to increases in radiative forcing. New observational and modelling evidence confirms the importance of the expected feedbacks linked to water vapour, estimated to be approximately 1 W m^{-2} per ºC of global average temperature increase, or a 40-50% amplification of global mean warming."**

The final phrase should be read in the current context of a CO_2-driven radiative forcing of 1.5 W per m^{-2} and an average temperature increase of 0.7ºC. Water vapour driven increase in forcing of 0.7 W per m^{-2} represents an amplification of 40-50% of current global heating. However, if average global temperature increased by 3ºC, the contribution to radiative forcing from the effects of increased concentration of water vapour would reach 3 W per m^{-2}. This would overwhelm all other components of the radiative forcing and precipitate runaway climate change. It would also render impotent any anthropogenic reduction in CO_2 concentrations designed to prevent further global warming.

The processes are somewhat modified by the endothermic nature of the liquid-gas phase change (and conversely by the exothermic nature of the gas-liquid phase change). Energy absorbed in the phase change cools the water-air interface and damps the change in evaporation. Increased concentration in water-vapour therefore reduces the expected temperature rise of global warming (though not the overall increase in global energy due to change in radiative forcing!). Energy is stored in the atmosphere as latent heat, to be released later in time and elsewhere in location at the point of condensation and cloud formation. This is the process that drives increase in storm energy, and distributes heat from the hotter tropical areas towards the cooler polar regions.

For a given change in water-vapour concentration there is a one-off investment in latent heat of evaporation. Over time, this has to be set against the cumulative increase in energy flow due to the change in greenhouse effect driven by the increase in water-vapour concentration.

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In the geological time-scale, changes in average global temperature were initiated by small changes in received solar energy (caused by periodic shifts in procession of planetary orbit and variation in tilt and wobble of the earth axis). Positive feedback dynamics of the water-vapour cycle amplify the effects of small changes in received solar energy with consequent effects on the biological systems and their outputs of CO_2 and methane evident from the ocean sediment and ice-core records. In this way, the whole-earth climate system is held in a sensitive condition of unstable equilibrium in which small changes in received solar energy result in large changes in global climate. Changes in water-vapour concentration do not, of course, show up in the sediment and ice-core records. Attention has therefore been focussed on the more easily observed shifts in CO_2 and methane concentrations which follow the temperature change. Carbon cycle feedbacks also amplify the climate change, but do not account for the observed extent of the deviation.

In the contemporary dynamics of the Holocene period, changes in insolation are negligible (and are expected to remain so for the next 30-50k years). Primary change in average global temperature is now driven by anthropogenic increase in concentrations of atmospheric CO_2. As global warming begins to take effect, rising temperature triggers the positive feedback of the water-vapour cycle, so amplifying and accelerating the climate change and contributing to the mutually reinforcing effects of other elements in the temperature-driven positive feedback system (such as lowering albedo as ice-fields melt, the discharge of methane from thawing areas of permafrost, and cascade release of methane clathrates from shallow seas). Water-vapour feedback continues to remain operative while temperature goes on rising, even when CO_2 concentrations have been stabilised or reduced. It is possible that the water-vapour feedback cycle would be more powerful than the achievable damping effects of managed reduction in concentration of atmospheric CO_2. In this case the water-vapour feedback cycle would drive an accelerating and essentially uncontainable process of runaway climate change, eventually moderated only by denser and more general cloud-cover, increased cloud albedo and resultant reduction of air and surface temperatures.

Elements of Secondary Feedback. There are other factors which further enhance the role of water vapour positive feedback. One is that as polar ice retreats, the total area of open water (ocean surface area) increases. Total evaporation therefore increases on top of the increase due to the rise in average sea surface temperatures. When all the sea ice has gone, the total area of ocean surface would be increased by about 12%. (I am indebted to the contribution of Prof. Peter Wadhams for highlighting this particular point)

Another instance of secondary feedback stems from temperature-driven rise in sea level. As low-lying coastal areas become flooded the total area of ocean surface is again increased with effects on the water-vapour cycle as above. Main factors driving this are the thermal expansion as rising temperatures of ocean surface water lead to mixing and heat distribution to lower layers, and secondly to the temperature-driven melt of land-based glaciation and ice-cap formations.

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