Proceedings of the Global Conference on Global Warming 2011
11-14 July, 2011, Lisbon, Portugal

Climate Sensitivity: Amplification of the Anthropogenic Disturbance of the Climate System

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Abstract —The threat to biodiversity and the intensity of the Anthropocene Extinction Event depend on the **value of climate sensitivity**. In addition to initiating the process of global warming, the anthropogenic disturbance of the climate system has also triggered the action of a complex web of interconnected feedback mechanisms which amplify the effect of the original disturbance. The value of the amplification factor determines the eventual increase in average surface temperature required to re-balance the dynamic thermal equilibrium of the planet. Using new visualisation techniques, this presentation offers a trans-disciplinary re-evaluation of climate sensitivity with profound implications for our current strategic approach to the mitigation of climate change. The most significant boundary in climate dynamics is the strength of feedback at which the system behaviour crosses the critical threshold between equilibrium-seeking and self-amplifying outcomes. This is the **tipping point at the boundary of runaway climate change**. The second part of this paper will explore current state of knowledge about this boundary, and indicate policy implications .

Keywords — Climate sensitivity of Whole-Earth System, Sensitivity graphic simulator, Tipping Point between equilibrium-seeking and self-amplifying dynamics.

1 INTRODUCTION

Change in atmospheric concentration of greenhouse gases is initially driven by anthropogenic emissions. As the average surface temperature begins to rise to compensate, the complex set of interactive feedback mechanisms is activated. Additional change in greenhouse gas concentrations is caused by non-anthropogenic feedbacks which are sensitive to climate change. Additional carbon dioxide, water-vapour and eventually methane, combined with the temperature-driven change in ice and snow albedo, together with complex oceanic, vegetative and cloud-system feedbacks, all contribute to amplify the original disturbance. The value of the eventual equilibrium rise in average surface temperature depends on the amplification factor applied to the original anthropogenic disturbance by the feedback system.

By checking modelled values of the amplification factor against the historical sensitivity of the whole earth system, this paper offers a radical re-evaluation of climate sensitivity with serious consequences for the boundary conditions of the onset of a period of runaway global warming.

2 CONSTRUCTING THE GRAPHIC SIMULATOR

2.1 A Logarithmic Relationship

The higher the concentration of any particular greenhouse gas, the less efficient it becomes at inhibiting infra-red radiation in the particular wavelength zone associated with its specific molecular structure. A long history of experimental verification has shown the relationship between concentration and absorption efficiency to be logarithmic. In particular, the change associated with a doubling of the concentration of carbon-dioxide is known to decrease its efficiency as a greenhouse gas. The forcing associated with each doubling is therefore a constant 4 watts per square metre (wm^{-2}) at the earth surface. That requires a change of 1.2°C in surface temperature to re-balance the energy budget. Logarithmic functions of this kind produce a constant output for any halving or doubling of the parameter across a given range.

This paper has adopted a graphical presentation using a semi-logarithmic scale in which the curves of normal log functions display as straight lines. The device enables clarity of comparison between a variety of amplification factors applied to the logarithmic relationship between carbon-dioxide concentration and the compensatory change in equilibrium temperature as enhanced by correlative feedback dynamics. Because we are addressing a phenomenon in which there is a constant output from a doubling or halving of the variable, it is necessary to use the values of a log to base 2.

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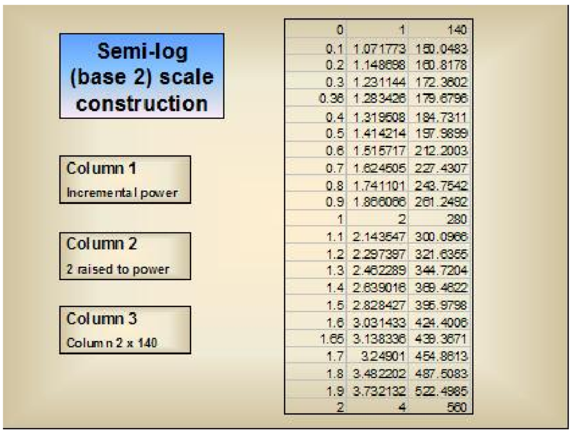
An expanded version of the paper with enlarged visuals is available at: www.apollo-gaia.org/Climate%20Sensitivity.pdf

2.2 Scale Values

The tables present the basis on which the semi-log display is constructed. Decimal increments in the power of 2 are listed in the first column. The values range from 0 to 2. The second column gives the value of 2 raised to the appropriate power from column 1. The figures in the third and final column are derived from the values from column 2 multiplied by140 (which is half the value of the concentration of atmospheric CO_2 at the 1750 CE pre-industrial benchmark of 280 parts-per-million by volume). Column 3 therefore provides the value of carbon-dioxide concentration appropriate for each point on the log (base 2) scale.



Semi-log (base 2) scale construction

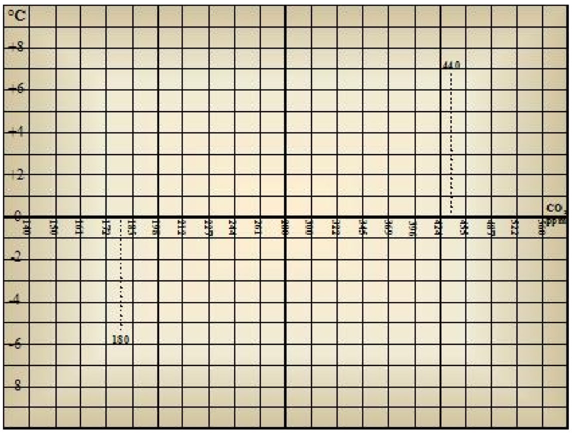
Column 1
Incremental power

Column 2
2 raised to power

Column 3
Column 2 x 140

0	1	140
0.1	1.071773	150.0483
0.2	1.148698	160.8178
0.3	1.231144	172.3602
0.36	1.283426	179.6796
0.4	1.319508	184.7311
0.5	1.414214	197.9899
0.6	1.515717	212.2003
0.7	1.624505	227.4307
0.8	1.741101	243.7542
0.9	1.866066	261.2492
1	2	280
1.1	2.143547	300.0966
1.2	2.297397	321.6355
1.3	2.462289	344.7204
1.4	2.639016	369.4622
1.5	2.828427	395.9798
1.6	3.031433	424.4006
1.65	3.138336	439.3671
1.7	3.24901	454.8613
1.8	3.482202	487.5083
1.9	3.732132	522.4985
2	4	560

The range of values thus provides for a halving and doubling of the benchmark concentration, (i.e. the range from 140 ppm to 560 ppm). Two additional points have been added to the scale. The first corresponds to the value of CO_2 concentration at the temperature minimum of the ice ages, namely 180 ppm. The second represents the concentration of 440 ppm commonly put forward as the threshold beyond which there is a heightened risk of precipitating dangerous climate change. The resulting graphical scale is shown below:



The central zero-point on the vertical axis represents the average surface temperature of the planet at the pre-industrial benchmark, and a range of plus or minus 8°C is available above and below the central horizontal axis.

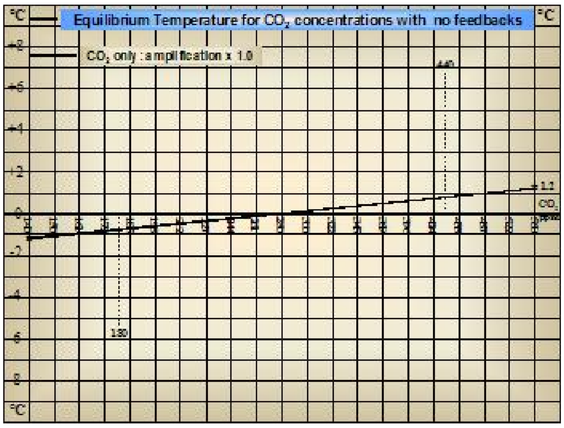
2.3 Implications of Symmetry

One completely unanticipated outcome of using the semi-log display is the almost perfect symmetry between the 180 ppm and the 440 ppm values with respect to the pre-industrial benchmark. Implications of this symmetry are drawn out later in the paper, for now we simply note that the change in CO_2 concentration from 180 ppm to 280 ppm may be expected to have the same effect as the increase in CO_2 concentration from 280 ppm to 440 ppm, namely a shift of 5°C in the average surface temperature of the planet rather than the 2°C currently predicted as the equilibrium response to a concentration of 440 ppm.

3 CO_2 FORCING WITHOUT FEEDBACK EFFECTS

Climate Sensitivity is made up of two fundamental parts. The first is the effect of doubling the concentration of atmospheric carbon dioxide on its own, holding all other system parameters constant. The second is the amplification of the primary change by a range of other system variables, namely the feedback system.

The effect of doubling CO_2 concentration on its own is extremely accurately known from observation, theoretical calculation and laboratory testing. It stands at 1.2°C. The forcing generated by such an intervention is also accurately known to be 4.0 wm^{-2}. The relationship between the two figures is governed by the Stefan-Boltzmann law concerning the energy radiated to the cold spatial sink by a "black body" at a given temperature, adjusted to take account of the emissivity of the planet. The change in radiation from the earth generated by a change of 1°C in average surface temperature is 3.3wm^{-2}. We can now map that information onto the original semi-log scale grid (*see below*).



Here the black line presents the change in final equilibrium temperature caused by change in concentration of atmospheric CO_2 without any amplification by feedback mechanisms. The amplification factor under these conditions is, of course, exactly 1.0.

Compared to the bench-mark temperature before the start of the industrial revolution, the effect of halving the concentration of atmospheric CO_2 to 140 ppm, mirrors the effect of doubling the concentration to 560 ppm. Conversely the effect of doubling the concentration from 140 ppm to 280 ppm (the pre-industrial value) is the same as halving it from 560 ppm to 280 ppm. In all cases the change is 1.2°C.

4 FOUR COMPLEMENTARY DEFINITIONS

Change in the atmospheric concentration of carbon dioxide may be the co-ordinating driver of climate change, but it is the amplifying effect of the complex system of feedback mechanisms that determines the eventual temperature change at equilibrium. Four different definitions are used to describe this relationship. Each has its own particular frame of reference and strengths of application. With this set of definitions in mind we can proceed to explore the four main approaches to determining the increase in equilibrium temperature consequent upon any given increase in the atmospheric concentration of carbon dioxide.

4.1 Climate Sensitivity (S)

Climate sensitivity (S) is defined as the increase in average surface temperature of the earth when it has reached dynamic thermal equilibrium after a doubling of the concentration of atmospheric CO_2. It includes the effect of the CO_2 forcing together with the contribution from a more-or-less comprehensive complex system of feedback processes. It represents a value of temperature increase at some indeterminate future time towards which the actual measured temperature of the earth's surface approaches asymptotically as the value of net radiative imbalance approaches zero. In the semi-log (base 2) presentation adopted in this paper, the value of climate sensitivity determines the gradient of the relationship between temperature change and concentration of atmospheric CO_2.

4.2 Amplification Factor (AF)

The amplification factor (AF) differentiates between the role of the change in concentration of atmospheric CO_2, and that of the feedback system itself. It is defined as the ratio by which the feed-back system multiplies the contribution of the forcing from any given change in atmospheric concentration of CO_2. Like climate sensitivity, its value is also constrained by the condition of dynamic thermal equilibrium. The value of climate sensitivity is obtained by multiplying the effect of doubling CO_2 concentration (1.2°C) by the amplification factor representing the contribution of the interdependent set of feedbacks in the earth system dynamic. The relationship is represented by the equation:

$$\mathbf{S = 1.2\,AF\,{}^{o}C}$$

In climate models, the value of the amplification factor depends on which feedback mechanisms are taken into account, and on the competence of the modelling of the various feedback mechanisms and their complex interactions.

4.3 Temperature-Forcing Ratio

This definition answers the question about the equilibrium temperature change required to balance the effect of any given CO_2 forcing. It is presented in degrees per watt per square metre, $\mathbf{{}^{o}Cw^{-1}m^{-2}}$. Since a doubling of atmospheric concentration of carbon dioxide delivers a forcing of $4wm^{-2}$, the temperature-forcing ratio is one quarter of the climate sensitivity.

4.4 Concentration-Temperature Ratio

This final definition relates the number of parts per million (by volume) of the atmospheric concentration of CO_2 required to generate a shift of one degree in equilibrium temperature. Measured in $\mathbf{ppm{}^{o}C^{-1}}$, it is specific to a given level of concentration and changes in step with the logarithmic decay in efficiency of CO_2 to act as a greenhouse gas as its concentration increases. For instance if the concentration-temperature ratio is 20 $ppm{}^{o}C^{-1}$ when the concentration is 280 ppm, then it will increase to 40 $ppm{}^{o}C^{-1}$ when the concentration is 560 ppm, and 80 $ppm{}^{o}C^{-1}$ for a concentration of 1120 ppm.

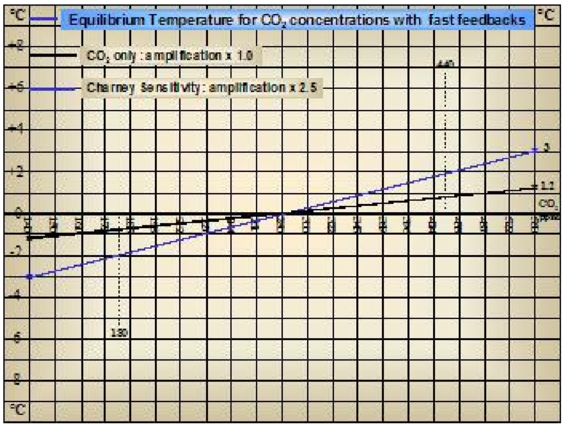
5 THE CHARNEY SENSITIVITY

In July 1979, Prof. Jule G Charney of MIT chaired an ad hoc study group on "Carbon Dioxide and Climate" [1]. It was held in Woods Hole, Massachusetts, and reported directly to the Climate Research Board of the US National Research Council. It was convened by the National Academy of Sciences at the request of the Office of Science and Technology Policy which had become concerned at the "Implications of this issue for national and international policy planning". The thirty-year-old report makes salutary reading. It started from the affirmation that "We now have incontrovertible evidence that the atmosphere is indeed changing and that we ourselves contribute to that change." The outstanding group of distinguished scientists focussed on a single basic question: **"If we were indeed certain that atmospheric carbon dioxide would increase on a known schedule, how well could we project the climatic consequences?".**

The report explicitly excludes the role of the biosphere in the carbon cycle (and so takes no note of the carbon-cycle and vegetation feedbacks). It also assumes very slow transfer of heat to the deep oceans, a position that leads to a fast approach to dynamic thermal equilibrium. Our current observation and understanding of this factor leads to slower predictions of the rate of temperature rise. The authors note prophetically: **"One consequence may be that perceptible temperature changes may not become apparent nearly so soon as has been anticipated. We may not be given a warning until the CO_2 loading is such that an appreciable climate change is inevitable. The equilibrium warming will eventually occur; it will merely have been postponed."**

Having identified some of the major positive feedbacks in terms of water-vapour concentration, some albedo change from reduced sea-ice coverage, together with estimates of change in cloud effects, the report turns to the possible existence of powerful damping (negative) feedback processes in the words: **"We have tried but have been unable to find any overlooked or underestimated physical effects that could reduce the currently estimated global warmings due to a doubling of atmospheric CO_2".**

The report concludes: **"*If* the CO_2 concentration of the atmosphere is indeed doubled and remains so long enough for the atmosphere and the intermediate layers of the ocean to attain approximate thermal equilibrium, our best estimate is that changes in global temperature of the order of 3°C will occur".** This is the "Charney Sensitivity" graph presented as the blue line in the semi-log format below.



The body of the Report notes **"a probable error of +/- 1.5°C"** but for the sake of clear communication, the uncertainty shading around the central line is omitted in this presentation. The 3°C increase for a doubling of concentration of atmospheric CO_2 is constant whether the starting point is taken as a hypothetical 140 ppm, or as 180 ppm at the lowest figure of the ice-ages, or as 280 ppm at the pre-industrial benchmark in 1750 CE, or (not shown) as a further doubling from 560 ppm to 1120 ppm. In relation to the effect of CO_2 on its own, the Charney Sensitivity has an **AF** of 2.5, and a Temperature-Forcing ratio of 0.75°$Cw^{-1}m^{-2}$.

6 THE HADLEY SENSITIVITY

The omission of the carbon-cycle feedbacks from the Charney sensitivity is a major weakness, reflected to a greater or lesser extent in the current ensemble of climate models. The carbon-cycle feedbacks fall into two main groups, those involving the ocean, and those involving land.

6.1 Ocean-based feedbacks of the carbon cycle

These include a number of processes that degrade the capacity of the ocean carbon-sink. As a result more CO_2 remains in the atmosphere, accelerating the process of climate change. Two further feedbacks of the ocean carbon-cycle actively increase the flow of CO_2 to the atmosphere.

6.1.1 As ocean surface temperature increases, the warmer water allows less absorption of CO_2 from the atmosphere.

6.1.2 As ocean surface temperature increases, there is greater stratification of the layering of the upper ocean and so less mixing of the CO_2-rich water to the ocean depths.

6.1.3 As the acidification of ocean surface water increases, less CO_2 can be taken up from the atmosphere.

6.1.4 As the acidification of ocean surface water increases, so the shell-forming plankton find it harder to generate the calcium-carbonate required to make their shells. As acidification increases still further shells already formed can start to dissolve. Both of these processes slow the sequestration of carbon to the sediment of the deep ocean floor [2].

6.1.5 The combination of rising temperature and acidification creates conditions that degrade both the population of phytoplankton and its capacity to fix carbon via photosynthesis, so decreasing the flow of carbon to the ocean food chain. (We have already reduced the global ocean population of phytoplankton by some 40%).

6.1.6 In those areas where deep cold water with high concentration of dissolved CO_2 is subject to up-welling (as in the Southern Ocean) warmer surface conditions lead to active out-gassing to the atmosphere.

6.1.7 Finally, the ocean floor contains vast deposits of frozen methane in the form of clathrates contained by virtue of both temperature and pressure. Further stores are trapped below layers of fossil ice left over from previous ice-ages. Rising water temperatures together with mixing of the warmer water to the ocean floor starts to release the clathrate deposits and the fossil ice also begins to melt, so releasing trapped methane from the underlying layers. The out-gassing of this methane to the atmosphere constitutes an endothermic phase-change feedback which accelerates the forcing while damping the increase in temperature.

6.2 Land-based feedbacks of the carbon cycle

6.2.1 Increased temperature drives rise in CO_2 and methane output from tropical and sub-tropical wetlands.

6.2.2 Increased temperature leads to rise in activity of soil-based bacteria with consequent increase in CO_2 output.

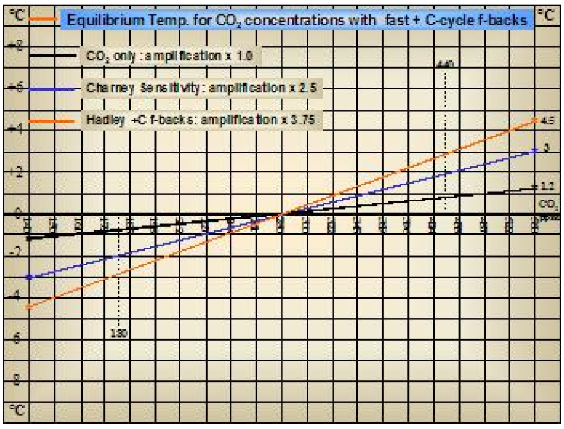
6.2.3 Increased CO_2 concentration together with rising temperature initially increase vegetation growth, but then set off adaptive responses that diminish CO_2 take-up [3], [4].

6.2.4 Local variations in rain-fall precipitate complex responses in local vegetation.

6.2.5 Die-back and burn of tropical and boreal forests release CO_2 to the atmosphere from the established bio-mass. They also degrade forest carbon sinks.

6.2.6 Increased heating and melt of Tundra permafrost releases CO_2 and methane to the atmosphere from previously inert store.

All the carbon-cycle feedbacks also reinforce each other via their mutual dependence on increase in temperature, CO_2 concentration, or both, so setting up second-order change in the feedback system. It is an extremely demanding task to incorporate all these processes into globally coupled climate models. The Hadley Centre of the UK Met. Office would appear to be leading the field with their currently evolving HadGEM3 programmes [5], but even they are not yet including several of the specific processes (particularly Ocean feedbacks 5 and 7, and Land feedbacks 5 and 6). The second order factors are also difficult to quantify. Hadley currently estimate that inclusion of the carbon-cycle feedbacks [6], increases the Charney sensitivity by around 50% as illustrated by the orange line in the semi-log presentation.



The value of the Hadley Sensitivity is therefore approximately 4.5°C for a doubling of atmospheric concentration of CO_2. That in turn correlates with an Amplification Factor of 3.75 times the effect of CO_2 on its own, and a Temperature-Forcing ratio of $1.125^{\circ}Cw^{-1}m^{-2}$.

7 THE HANSEN SENSITIVITY

In an attempt to close the gap between computer modelling and empirical measurement, Hansen et al [7], offered a hybrid solution. They started with the assertion:

"Paleoclimate data show that climate sensitivity is ~3°C for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6°C for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica."

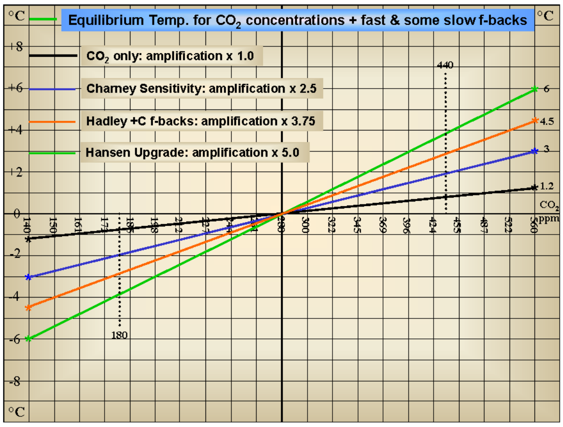
Their methodological approach was summarised in the words:

"Climate models alone are unable to define climate sensitivity more precisely, because it is difficult to prove that models realistically incorporate all feedback processes. The Earth's history, however, allows empirical inference of both fast feedback climate sensitivity and long-term sensitivity to specified GHG change including the slow ice sheet feedback."

After careful and technical evaluation of the long-term slow feedback mechanisms, they conclude that:

"Global climate sensitivity including the slow surface albedo feedback is 1.5°C per wm^{-2} or 6°C for doubled CO_2, twice as large as the Charney fast-feedback sensitivity."

This "Hansen Upgrade" is represented by the green line on the semi-log (base 2) scale.



The sensitivity of 6°C for a doubling of CO_2 yields an Amplification Factor of 5.0 and a Temperature-Forcing ratio of $1.5^{\circ}Cw^{-1}m^{-2}$. However, it still falls short of accounting for the radiative change required to balance the 5°C rise in temperature between the glacial maximum and the pre-industrial benchmark.

7.1 Mathematical check of Hansen Sensitivity

Change in CO_2 concentration from 180 ppm to 280 ppm represents 63.4% of a CO_2 doubling which contributes a forcing of 2.5 wm^{-2}. Non-CO_2 contribution from the feedback system must therefore be 14 wm^{-2}. Applying the Hansen Amplification Factor of 5.0 to the CO_2 forcing yields a radiative change of only 12.5 wm^{-2}, a shortfall of 4 wm^{-2}. (For fuller application of this methodology, see section 8.6 below).

8 CLIMATE SENSITIVITY OF THE WHOLE EARTH SYSTEM

The better our models become at incorporating the effects of feedback dynamics, the higher the value of the Amplification Factor, and the greater the climate sensitivity. We are now encountering the limits of current modelling capacity as we seek to incorporate more and more feedback processes and delineate the complex dynamics of their interaction and reinforcement [8]. With increasing sophistication the modelled value of the Amplification Factor should approach asymptotically to the actual value provided by the virtually infinite complexity of the dynamics of the whole earth system.

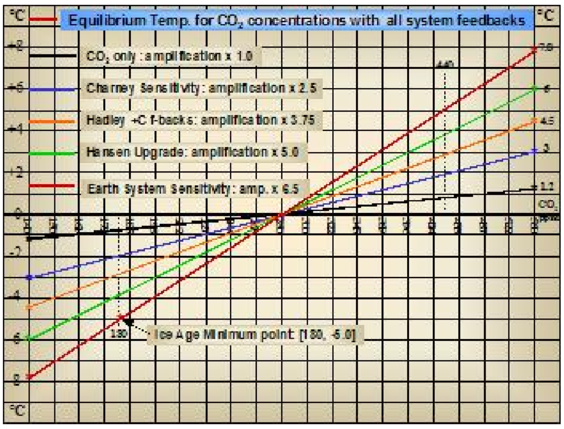
There is a potentially observable value of the Amplification Factor (and hence of climate sensitivity) for the whole earth system. This is known as the **earth-system sensitivity (ESS)**. At this point, therefore, we make a methodological shift and develop an empirical, observation-based, (i.e. independent of the ensemble of climate models) approach to determining the value of the Amplification Factor.

8.1 Ice-Age Anchor Point

The concentration of atmospheric CO_2 in the depth of each of the last four ice ages stood at 180 ppm. The empirically derived value for the average surface temperature during the depth of the ice ages stands at 5.0°C below the pre-industrial benchmark. This provides us with a point of [180 ppm, -5.0°C] through which the amplification line representing the sensitivity of the whole earth system must pass.

8.2 Bench-Mark Point

The second point on the line is of course the pre-industrial benchmark of 280 ppm and 0.0°C.

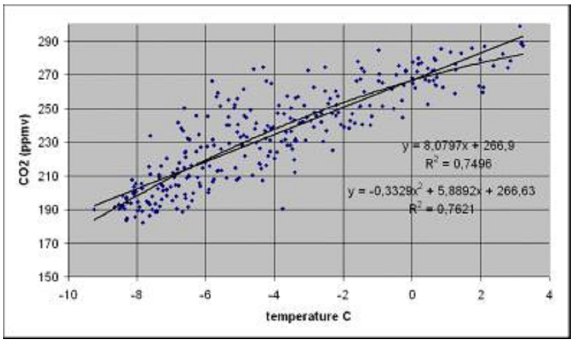


Projecting that forward into the next doubling of CO_2 concentration yields an Amplification Factor of 6.5, a climate sensitivity of 7.8°C, and a Temperature-Forcing ratio of 2°Cw^{-1}m^{-2}. **Those figures are just over 2½ times the values derived from the Charney Sensitivity.**

8.3 Engelbeen Point

Two points are both necessary and sufficient to define the characteristics of a straight line. However it would be an additional confirmation if we could find further empirically derived points to test the accuracy of the whole earth Amplification Factor. For this we turn first to the derived correlation of temperature and CO_2 concentration based on the gas analysis of bubbles trapped deep in the Antarctic ice-cap at Vostok.

In 2005, Ferdinand Engelbeen, a Belgian scientist, conducted a regression analysis of the correlated values of temperature and CO_2 concentration based on the Vostok records. It was posted on the Real-Climate web site and little further attention was paid to it [9].



Engelbeen was looking for a way of describing the sensitivity of the whole earth system in terms of the number of parts per million of CO_2 that correlate with a change of 1°C at the Vostok site. The straight line represents a first order approximation. The curve is a little more accurate, reflecting the non-linear relationship between CO_2 concentration and consequent forcing. He concluded that a figure of 8.0 ppm °C^{-1} was the best available value to be derived from this approach. The concentration for which his figure is likely to be most accurate (and which also corresponds most closely with the pre-industrial benchmark) is that at which the two lines intersect in conditions of least scattering of the correlate values. Back-reading from his graphical presentation this concentration is close to 267 ppm.

Temperature change at Vostok is a just over twice that for the average surface temperature of the whole earth. So an 11°C shift at Vostok translates to a 5°C change for the global value (a ratio of 0.45). Applying this ratio to Engelbeen's figure we arrive at 17.8 ppm °C^{-1} for the sensitivity of the earth system as a whole.

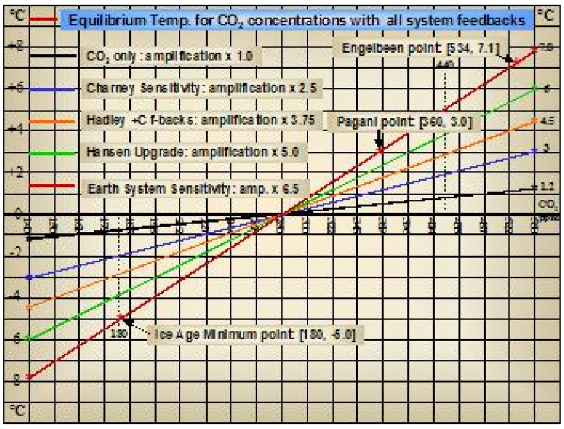
If we now double the concentration value of 267 ppm at which Engelbeen's work is deemed to be most accurately applicable, then we can explore a projection of his analysis at a concentration value of 534 ppm. Here the efficiency of CO_2 as a greenhouse gas is decreased. The logarithmic relationship between change in concentration and forcing therefore requires a halving of his sensitivity value from 17.8 ppm $^{\circ}C^{-1}$ to 35.6 ppm $^{\circ}C^{-1}$. The concentration change from the pre-industrial benchmark (of 280 ppm) is 254 ppm at this point. If we divide that increase by the calculated Engelbeen sensitivity value of 35.6 we obtain a projected temperature increase of 7.1°C at a concentration of 534 ppm.

This Engelbeen point is on the same straight line as the other two anchor points, and would appear to provide significant corroboration of the Amplification Factor for the whole earth system.

8.4 Pagani Point

Towards the end of 2009, Mark Pagani and colleagues published a paper on "High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations" [10]. They concluded that **"the Earth-system climate sensitivity has been significantly higher over the past five million years than estimated from fast feedbacks alone"**.

Conservative application of their work yields a value for the Earth-system climate sensitivity of around 8°C for a doubling of atmospheric concentration of CO_2 across a range that is commensurate with the pre-industrial benchmark. If we apply this to a doubling from the Ice Age Minimum point [180, -5.0] we establish a fourth point on the straight line at [360, 3.0].



It is worth noting that values for both the Engelbeen and Pagani points had to be constrained towards the lower range of their probabilities, indicating that the value of 6.5 for the Amplification Factor of the Earth-system sensitivity may still be somewhat conservative and should be regarded as a minimum value.

8.5 The Kiehl Perspective

Early in 2011 Jeffrey Kiehl [11], reviewed current peer-review academic papers reporting on the reconstruction of values of atmospheric CO_2 concentration reaching back through ~100 million years. The authors also derived values for earth system climate sensitivity across this period. Kiehl's summary conclusion was that the data for 30 to 40 million years before the pre-industrial benchmark indicate that Earth's climate Temperature-Forcing ratio is ~2°$Cw^{-1}m^{-2}$. That is equivalent to a climate sensitivity of 8°C for a doubling of atmospheric concentration of CO_2, with an Amplification Factor of 6.7.

Re-working Kiehl's figures using the graphic simulator leads to a marginally higher outcome. Earth surface temperature decreased by 16°C during the period requiring a shift of 52.8 wm^{-2} of forcing to balance the dynamic thermal equilibrium. During the same period, CO_2 concentration declined from1000 ppm to 280 ppm, equivalent to 1.87 of the doubling/halving forcing from CO_2 alone. CO_2 change therefore contributed some 7.48 wm^{-2} towards the overall forcing, leaving a balance of 45.32 wm^{-2} as the contribution from the feedback system. That yields an Amplification Factor of 7.0, a sensitivity value of 8.47°C for a doubling of CO_2, and a Temperature-Forcing ratio of 2.1°$Cw^{-1}m^{-2}$.

8.6 A Mathematical Cross-Check

The Radiative Damping coefficient for planet earth stands at 3.3 $wm^{-2\circ}C^{-1}$ Maintaining the dynamic thermal equilibrium therefore requires a forcing from all sources of 3.3 $wm^{-2\circ}C^{-1}$. The change in temperature between the last glacial minimum and the pre-industrial benchmark is known to be ~5°C. That requires a total forcing of 16.5 wm^{-2}.

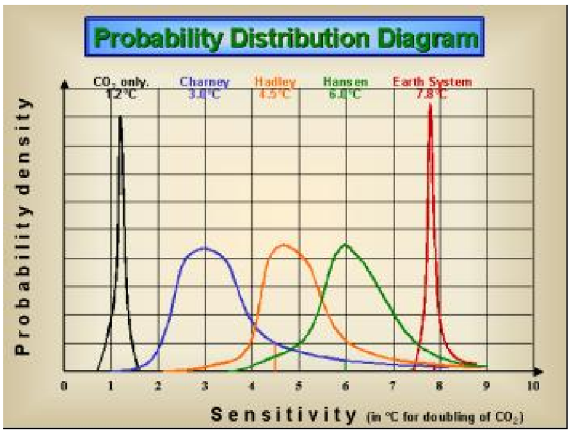
During the same period, the concentration of atmospheric CO_2 increased from 180 ppm to 280 ppm. From the graphic simulator we calculate that this represents some 63.4% of a CO_2 doubling. Since the forcing per doubling stands at 4 wm^{-2}, the CO_2 forcing since the last glacial minimum has a value of 2.54 wm^{-2}. The remaining amount of 14 wm^{-2} is contributed by the feedback system. The Amplification Factor of the earth system sensitivity is represented by the ratio of 16.5 to 2.54, namely 6.49. (Compare with Amplification Factor of 6.5 derived from the graphic simulator itself). Multiplying the Amplification Factor by 1.2 (temperature increase from a doubling of CO_2 with no feedbacks) yields a climate sensitivity value of 7.79°C. (Compare with sensitivity value of 7.8°C derived from the graphic simulator.) Dividing the sensitivity by 4.0 (the forcing from a doubling of CO_2) gives a Temperature-Forcing ratio of 1.95.

9 OF PROBABILITIES AND UNCERTAINTIES

There is a high level of certainty associated with the change in temperature caused by a doubling of the atmospheric concentration of CO_2 on its own. The probability distribution is therefore represented by the sharp black spike centred around 1.2°C on the temperature scale.

The ensemble of climate models on which the IPCC Fourth Assessment Report [12], was based, was used by Meinshausen and colleagues to generate the probability density function (PDF) of climate sensitivity [13]. It reaffirmed the 3°C value of the Charney Sensitivity, shown as the blue distribution. It has a skewed pattern showing lower probability of sensitivity below 3°C, and an extended "flat tail" of probabilities that the sensitivity value could exceed the Charney value. In this case, the higher sensitivity values were seen as being possible but with decreasing probability.

The Hadley, Hansen and Earth System sensitivity values must not be treated as low probability cases within the Meinshausen PDF. Each improvement in the treatment of the complex feedback system generates its own probability distribution with its peak at the newly stated sensitivity value, and decreasing probability ranges on each side of this figure. As the peak probability value is revised upwards, the Charney value is reduced to a lower and lower probability.



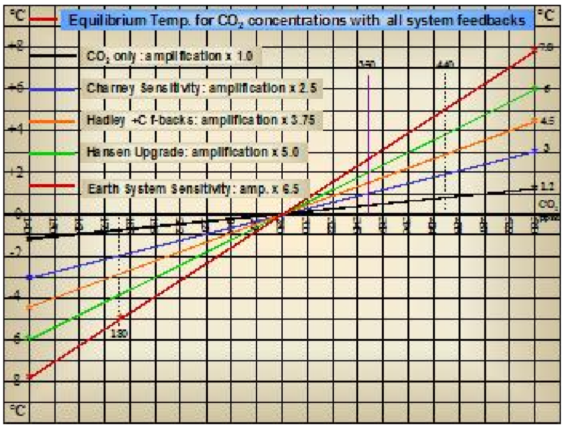
For the Charney, Hadley and Hansen values, large uncertainties are associated with difficulties in quantifying and modelling the complex set of feedback processes and their dynamic interrelationships. That leads to comparatively wide spread in the probability ranges.

The uncertainties associated with the Earth System Sensitivity are of a different order. Because the value is empirically constrained by observation and direct calculation, the certainty concerning the gradient of the straight line passing through a set of four points is very high. What uncertainties remain have to do with the correlation of temperature and CO_2 concentration at various points within the paleo record. Therefore the probability distribution around the Earth System Sensitivity can also be represented as a sharply defined spike. This relegates other values of sensitivity to positions of extremely low probability.

The high level of certainty associated with the Earth System Sensitivity of at least 7.8°C for a doubling of CO_2, requires that this value should now replace the Charney Sensitivity (of 3°C) for all future strategic negotiations.

10 ADDING THE 350 PPM MARKER

In view of the attention currently being given to the concentration value of 350 ppm [14],[7], we now add a marker line to correspond with that value. That completes our working grid from which values can be read off to an accuracy of two significant figures.



11 CORRELATIONS AND CONSEQUENCES

The completed graphic simulator provides a basic visual context in which to explore and evaluate the range of policy proposals currently being considered by the world community, and to conduct a survey of correlations and consequences.

11.1 The "Safe Guardrail" of 2°C

The Charney Sensitivity line intersects the 2°C level at a concentration of 440 ppm. The European Union commitment to an equilibrium concentration level of 440 ppm and a maximum rise in temperature of 2°C above the pre-industrial benchmark is deemed to constrain climate change within a "safe guardrail" [15].

The outcome of the COP 15 deliberations affirmed the need to limit temperature rise to the 2°C ceiling, and this element of the Copenhagen Accord [16], was subsequently embedded in the Cancun Agreement of COP16 [17]. These positions are totally dependent on the Charney Sensitivity.

Leaving aside for the moment the challenge that even a 2°C rise in temperature would take us well beyond dangerous climate change and into the domain of "extremely dangerous climate change" [18], we note that the Earth System Sensitivity indicates that a sustained CO_2 concentration of 440 ppm would result in an equilibrium increase of 5°C above the pre-industrial benchmark. In this case the 2°C guardrail has already been overwhelmed by some 60 ppm. The 2°C threshold was passed when the concentration reached 330 ppm.

11.2 Meinshausen Probability Density Function

As mentioned above, utilising the ensemble of climate models that underpin the IPCC Fourth Assessment Report, Malte Meinshausen produced a probability density function (PDF) showing the clustering of the model outputs around a climate sensitivity of 3°C [13], (co-incident with the Charney Sensitivity). With very few exceptions, that ensemble limits its treatment of feedback mechanisms to the same set of fast feedbacks utilised in the original Charney analysis.

Meinshausen's approach does not differentiate sensitivity values according to model competence in dealing with the feedback system. It is inevitable, therefore, that the Meinshausen PDF reaffirms the Charney value for climate sensitivity. His work was then used extensively to delineate the available budget of CO_2 emissions which could still be absorbed by the global system before the threshold of 440 ppm was exceeded [19]. At the time of his publication the CO_2 concentration stood at 388 ppm. Meinshausen's "safety margin" therefore allowed further emissions of 750 GT of CO_2 to take up the available balance of some 52 ppm.

If, however, we apply the Earth System Sensitivity then it is clear we are already in significant "overshoot". There is no available margin and therefore no allowed budget. We have already exceeded the 330 ppm threshold by 60 ppm and are in debt to the global commons. Draw-down of some 392 GT of atmospheric CO_2 would be required to provide the same guardrail probability of not exceeding a rise of 2°C beyond the pre-industrial benchmark.

11.3 The Hansen Approach

If we explore the Hansen Amplification Factor of 5.0 (a sensitivity of 6°C for a doubling of atmospheric CO_2) then we see he predicts an equilibrium of rise of 4°C with a stabilised CO_2 concentration of 440 ppm. The "safe" ceiling of 2°C is reached with a concentration of 350 ppm. That is why he consistently asserts that we need to reduce CO_2 concentration to below 350 ppm while warning that even then, the temperature rise would expose the system to further amplification from slow feedbacks as well as initiate a dangerous increase in sea level [7].

11.4 The "One Degree War Plan"

The "One Degree War Plan" of Randers and Gilding [20], is grounded in the Charney sensitivity which cuts the 1°C level at 350 ppm. Coincidentally Randers and Hansen both endorse the 350 ppm target but from totally differing values of climate sensitivity. The Earth System Sensitivity line intersects the 1°C level at a value of some 310 ppm of atmospheric CO_2, requiring a draw-down of around 536 GT below the current level.

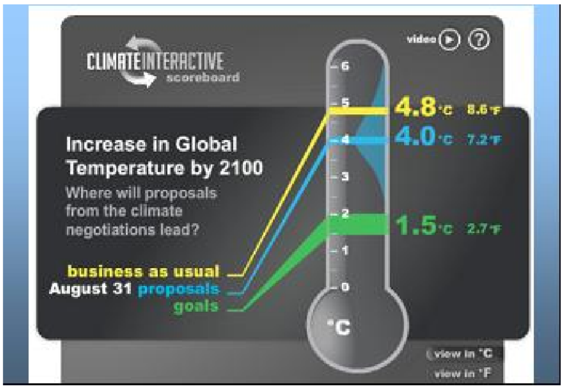
11.5 Including Other Greenhouse Gases

It should be noted that in none of the above set of correlations and consequences are the effects of non-CO_2 greenhouse gases taken into consideration. If current concentrations of these gases are taken into account then we already stand at a CO_{2e} level of 450ppm. That is 10 ppm beyond the "safe" ceiling using the Charney sensitivity, and 120 ppm beyond the 2°C threshold when we apply the Earth System sensitivity. .

11.6 The C-ROADS Simulator

System dynamics analysts from MIT combined with Ventana Systems to create the C-ROADS simulator in preparation for the COP 15 gathering in Copenhagen [21]. The acronym stands for "Climate Rapid Overview and Decision Support". The simulator provides a visual interface that responds in real time to inputs of proposed reductions in CO_2 emissions, relating outcomes to atmospheric concentration trajectories and implications for increase in global temperature.

Its underlying model architecture has been stringently reviewed by a scientific panel which validated its accuracy in representing the "state-of-the-art" climate models used in the preparation of the IPCC Fourth Assessment Report, (the same set utilised by Meinshausen to derive his PDF of Climate Sensitivity). They went on to recommend it for use as the official simulator for the UNFCCC negotiations. ClimateInteractive staff and simulation platform were extensively involved in the preparation of "The Emissions Gap Report" of the UNEP [22], released in November 2010 prior to the COP 16 gathering in Cancun.

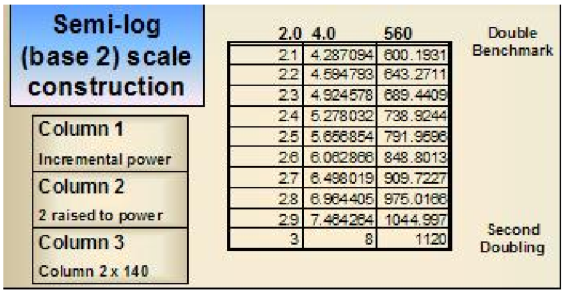


Following the promulgation of the Copenhagen Accord, nearly 140 countries associated themselves with the document and over 80 countries, representing about 80 per cent of global emissions, have appended targets and/or mitigation actions. These promises and commitments were entered into the C-ROADS platform and the resulting increase in average global temperature by the year 2100 was presented in the form of a Climate Scoreboard thermometer.

The set of proposals was updated over time and by 31st August the scoreboard was showing a probable rise in global temperature of 4.0°C above the pre-industrial benchmark by the year 2100. In preparation for the Cancun gathering the figures were further updated and the temperature rise was reduced to 3.8°C. The range of uncertainty was indicated by the shading around the simulated value.

The ClimateInteractive.org web-site clarifies the assumptions underlying the simulator. The value of climate sensitivity is set at 3.0. The simulator does not include several positive feedbacks found in the climate system, and its results therefore provide a **conservative** picture of future climate impacts.

Examining the "Scoreboard" thermometer of the C-ROADS simulator against the background of the climate sensitivity grid. We note that the intersection of the 4°C horizontal line with the slope of the Charney Sensitivity (blue line) is off the scale to the right. In order to accommodate the values needed to display the results of the C-ROADS simulation of the Cancun agreement we have to expand the scope of the semi-log (base 2) presentation to include a second doubling of the concentration of atmospheric carbon dioxide. The figures on which the new display is based are:

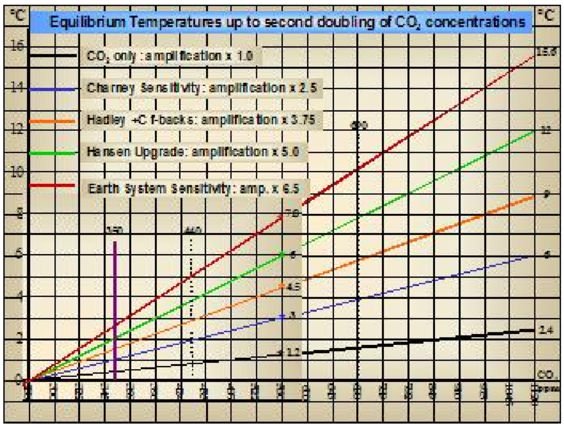


Semi-log (base 2) scale construction

Column 1
Incremental power
Column 2
2 raised to power
Column 3
Column 2 x 140

2.0	4.0	560	Double Benchmark
2.1	4.287094	600.1931	
2.2	4.594793	643.2711	
2.3	4.924578	689.4409	
2.4	5.278032	738.9244	
2.5	5.656854	791.9596	
2.6	6.062866	848.8013	
2.7	6.498019	909.7227	
2.8	6.964405	975.0166	
2.9	7.464264	1044.997	
3	8	1120	Second Doubling

In the next illustration the upper right quadrant of the Sensitivity Grid has been moved to the lower left position.



We have expanded the scale to encompass the second doubling of CO_2 concentration to 1120 ppm. The set of sensitivity gradients has then been extended into the new area and the predicted equilibrium temperatures following a second doubling of CO_2 concentration and associated with each Amplification Factor, are noted in the right-hand margin.

It can now be seen that the Charney Sensitivity line intersects the 4°C level at a concentration just in excess of 690 ppm. However, the C-ROADS simulator calculates outcome temperature rise at the year 2100, and not at eventual equilibrium. A 4°C rise by 2100 is equivalent to an equilibrium rise of some 4.5°C. This would result from a stabilisation of CO_2 concentration at c. 790 ppm, based on the effective implementation of the national pledges of the Copenhagen Accord and confirmed in the Cancun Agreement of December 2010.

11.7 Critical Implications

11.7.1 Temperature implications of the Cancun Agreement using the C-ROADS Simulator with Charney Sensitivity indicate an increase of 4°C at 2100, rising to 4.5°C. The Earth System Sensitivity requires a revision of these figures to 10.4°C at 2100, rising to 11.8°C at equilibrium. Note the thermal inertia of the earth system, with the mixing of heat to deep ocean strata, might slow the rate of increase in the average surface temperature, in which case the 2100 figure might be too high. However, the eventual equilibrium value would not be affected.

11.7.2 Promises are not actions. There are considerable doubts concerning the ability of the various nations to deliver the pledged reductions in emissions. Pledges concern constraints on emissions to be achieved by the year 2020. Descent pathways beyond that date are not defined, so there is no commitment to stabilise CO_2 concentrations at 790 ppm. Continuing emission at the rate of the pledges would continuously add to the atmospheric stock of CO_2, driving the equilibrium temperature even higher.

11.7.3 The C-ROADS Simulator does not take into account non-CO_2 greenhouse gases, the effect of which could increase the whole range of temperature outcomes by over 15%.

11.7.4 Turning to the question of emissions budget, we note that if the emissions descent pathways beyond 2020 did in fact lead to stabilisation of the atmospheric CO_2 at a concentration of 790 ppm, then using a figure of 14.5 GT of CO_2 per 1 ppm increase in concentration [22], the current set of pledges of the Cancun Agreement would imply a further release of some 5,800 GT of CO_2. Contrast that with the allowed budget of 750 GT CO_2 proposed (using the Charney Sensitivity value) as the limit if the "safe guardrail" of 440 ppm and 2°C were to be respected. Upgrading to the full value of the Earth System Sensitivity collapses the budget into a debt requiring net negative emissions of 392 GT, increasing to 827 GT if non-CO_2 greenhouse gases are taken into consideration. (Draw-down rate is approximately 50% of emission per 1 ppm of CO_2 since non-atmospheric elements of the global system absorb approximately 50% of emissions.)

11.7.5 If the "One Degree War Plan" [20], or the proposals from the World People's Congress on Climate Change held in Bolivia in April 2010 [23], to limit the temperature increase to no more than 1°C above the pre-industrial benchmark, were to be implemented then the Earth System Sensitivity indicates that concentrations of atmospheric CO_2 would need to stabilise at not more than 310 ppm. This would require a draw-down of 580 GT CO_2 from the 2010 figure. If non-CO_2 GHGs are included the figure would stand at 1,015 GT CO_{2e}. In practice there is no way that net emissions could be reduced to zero from 2010. For every 10 GT of CO_{2e} emitted beyond that date we would have to add a further 5GT to the above draw-down figures.

11.7.6 Temperature increases already in the pipeline if CO_2 concentration were to be stabilised at the current value of 390 ppm depend on the value of climate sensitivity. Predictions based on the Charney Sensitivity show an equilibrium rise of 1.6°C above the pre-industrial benchmark (0.8°C still in the pipe-line for CO_2 only, rising to 1.2°C still in pipe-line for CO_{2e}). The Earth System Sensitivity would indicate a rise in temperature at equilibrium of 3.8°C. There is therefore an expected rise of 3.0°C still in the pipe-line, to which we are already committed. If non-CO_2 GHGs are included then the expected increase at equilibrium would rise to 5.4°C (4.6°C still in the pipe-line).

11.7.7 The only way this increase could be avoided is by engaging an aggressive policy of net negative global emissions (i.e. a draw-down global economy) during the short window of opportunity afforded by the time-lag in global warming resulting from the thermal inertia of the earth system.

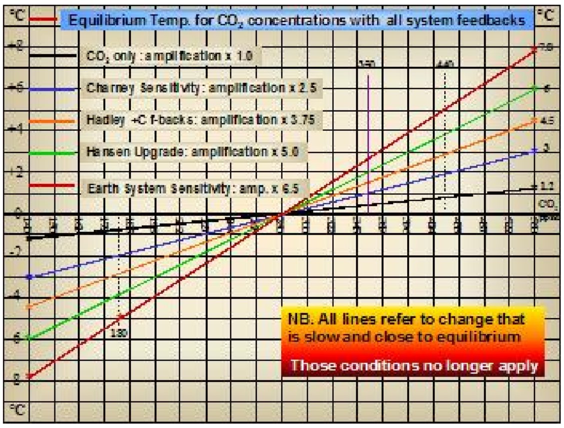
12 Rapid Climate Change in Far-From-Equilibrium Conditions

Historically climate change at a global level has been slow and in conditions of dynamic thermal equilibrium. Net radiative imbalance has remained close to zero and the earth system has responded to change at a pace that allowed continuous adaptation of the bio-geo-chemical systems. Within those conditions there have been examples of comparatively rapid change in limited sub-system behaviour where specific tipping points have been activated by the slow global change, and the sub-system has moved from one stable state to another.

All the work on climate sensitivity is based on paleo records of slow, close to equilibrium behaviour at a global level. Those conditions no longer apply.

Historically a change in CO_2 concentration of 100 ppm has taken place over a period of some 10,000 years. Humanity has now generated the same change in the space of a single century, one hundred times faster than at any point in the historical record (apart perhaps from the effects of the impact of a massive asteroid).

Net Radiative Imbalance during the past has not exceeded 0.01 wm^{-2}. Anthropogenic forcing over the last century has generated a net radiative imbalance of between 1.0 and 3.0 wm^{-2}. This rate of global heating is of the order of 300 times the historical maximum. It has pushed the earth system significantly away from equilibrium and activated increasing time-delay between forcing and the eventual achievement of a new state of dynamic thermal equilibrium.



12.1 Dis-Equilibrium Feedbacks

Under these conditions a range of feedback processes are brought into operation that can be considered negligible when the system is very close to equilibrium.

12.1.1 Time delay in mixing of ocean layers (thermal inertia of the deep ocean heating) leads to relative heating of the surface, increased stratification, less up-welling of cold nutrient-rich water, decay in plankton take-up of CO_2.

12.1.2 Increased acidification of the surface layer leads to lowered efficiency of the ocean sink of atmospheric CO_2.

12.1.3 Hotter ocean surface combines with hotter atmosphere to increase the water-vapour feedback and so enhance the endothermic phase-change feedback that increases forcing while bypassing the temperature-sensitive radiative damping negative feedback.

12.1.4 Heat transfer from equatorial to high latitude polar regions is partially taken up in the endothermic phase-change of net ice melt. The resultant decrease in albedo constitutes a positive feedback which is also partially independent of the temperature-sensitive radiative damping negative feedback.

12.1.5 The greater the net radiative imbalance the longer the time-lag to establish new dynamic thermal equilibrium. Non-temperature-sensitive feedbacks, driven by increased CO_2 concentration or by energy-flux in distinction from increased temperature, all contribute to amplification of the forcing, so increasing the time-lag and setting up second-order feedback reinforcement.

12.1.6 These non-temperature-sensitive feedbacks continue to accelerate global heating even during periods of increased heat-transfer to deep ocean with consequent slowing of the rate of change of average global surface temperature.

12.1.7 The pace of change overwhelms the capacity for smooth adaptation, evolution and mobility of the biological systems leading to patterns of die-back and burn that transfer carbon from biomass to atmosphere. That increases the carbon-cycle feedback dynamics.

Taken all together these phenomena enhance the system sensitivity and increase the amplification factor beyond the value of the Earth System Sensitivity previously developed from slow and close-to-equilibrium patterns of change. The value of the Amplification Factor of 6.5 representing a Sensitivity value of 7.8 °C for a doubling of the concentration of atmospheric CO_2 should therefore be taken as a conservative minimum figure in our current situation.

Rapid climate change, in conditions of dis-equilibrium, precipitates the activation of an interconnected series of sub-system tipping-elements [24]. That in turn drives turbulence and inherent unpredictability in the global climate system. There is also an increasing frequency of extreme events in local weather conditions.

At the overall global system level, the increasing power of amplifying feedback dynamics could push the system beyond the critical threshold which signals the onset of a period of self-amplifying or "runaway" climate change for which there is currently no modelling capacity.

13 CONCLUSION

Climate Sensitivity is a measure of the way the feedback dynamics of the natural world amplify the effects of the greenhouse gasses added to the atmosphere by human activity.

A conservative value for Climate Sensitivity underlies all current approaches to the mitigation of climate change, be they international negotiations, pledge-making, target setting, risk assessment, emissions control, energy scenarios, economic implications, etc. This conservative value is known as the Charney Sensitivity and dates back to 1979. It is still endorsed by the current ensemble of computer models on which the IPCC 4th Assessment Report is based. It stands at a figure of 3°C as the increase in average surface temperature of the earth resulting (at equilibrium) from a doubling of the concentration of atmospheric CO_2. That represents an Amplification Factor of 2.5 times the effect of the CO_2 on its own.

It is recognised that even the best climate models have great difficulty in simulating the complex interactive system of global feedback dynamics. This paper therefore addresses the question: **"How conservative is our current estimate of Climate Sensitivity?"**

The multi-disciplinary approach, introduced in this paper, is independent of any climate model, and supported by a specially designed Graphic Simulator. It identifies a (minimum) value for the Earth System Sensitivity of 7.8°C for the equilibrium outcome of doubling the concentration of atmospheric CO_2. That is an Amplification Factor of 6.5 times the effect of the CO_2 on its own. The new value has a much higher degree of certainty than the Charney Sensitivity and indicates that the current conservative estimate of climate sensitivity falls far short of reality and must be increased by a factor of just over 2½ times. **This new value of the Earth System Sensitivity (ESS) should now replace the Charney Sensitivity.**

Finally, the high level of climate sensitivity, combined with rapid change and far-from equilibrium dynamics, exposes us to a severe risk of triggering an episode of runaway climate change.

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