An

APOLLO-GAIA

Presentation

Feedback Dynamics, Sensitivity and Runaway Conditions in the Global Climate System

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The presentation was given in the Suleyman Demirel Cultural Center of the Istanbul Technical University, which prides itself on being the third oldest university in the world.

The timing was chosen to ensure that the new analysis could be taken into account in the Fifth Assessment Report of the Inter-Governmental Panel on Climate Change (IPCC 5AR). The aim was to contribute to a re-framing of the international agenda in the immediate aftermath of RIO+20, the global gathering exploring "The Future we Want".

The Global Conference on Global Warming was a truly scientific occasion, untrammelled by political or economic constraints. It concentrated on accurate diagnosis of the problem and effective identification of appropriate solutions, both technical and socio-economic.

Currently sandwiched between the escalating political conflict of Syria and the socio-economic turmoil of Greece, the symbolic city of Istanbul is set dynamically at a bifurcation point of human history and civilisation. It straddles East and West, Islam and Christianity, Orthodox and Catholic. It connects the Eurasian community in the North with the African continent to the South. It carries in its very heart the tension between the traditions of yesterday and the emergent complexity of tomorrow, the out-dated energy sources of fossil hydrocarbons and the future promise of solar power. It is hard to imagine a more creatively appropriate entry-point for this seminal contribution from the Apollo-Gaia Project.

An academic revision of the paper, with wider references to the peer-reviewed literature, is currently in preparation prior to submission for publication in the on-line journal Earth System Dynamics (Discussion).

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Contents

Abstract

Working with the dynamic thermal equilibrium of the whole earth system, a conceptual model of the **complex feedback system** is introduced. This allows a comprehensive overview of the inter-related factors which combine to amplify the effects of anthropogenic disturbance of the global climate. A semi-log scale graphic simulator is constructed and used to map a series of historical attempts to quantify the value of **climate sensitivity**. The limitations of the piecemeal modelling approach are noted.

An alternative, observation-based, analysis of the **Earth System Sensitivity** is presented using five independent disciplines grounded in the paleological data. The approaches converge to provide a value of 7.8ºC for the equilibrium response of the average surface temperature of the planet when the atmospheric concentration of carbon-dioxide is doubled. The figure has much lower uncertainty range than the outcome of the ensemble of climate models currently used as the basis for international negotiations. A paleo-mathematical critique of model-driven estimates of climate sensitivity is conducted. The set of implications and consequences of the new value is reviewed.

The **non-linear relationship** between system sensitivity and the strength of the feedback factor is delineated and quantified, allowing an examination of the extreme sensitivity of the planetary climate to small perturbation of the atmospheric composition. Increase in the feedback factor drives the system sensitivity towards (and potentially past) the **critical threshold** separating **equilibrating behaviour** from the onset of **self-amplification (runaway conditions)**. Boundary conditions of this tipping point are quantified and outcomes are mapped.

In the unprecedented current conditions of the Anthropocene, (rate of change and magnitude of dys-equilibrium) a set of factors is identified that increases the magnitude of the feedback factor beyond the paleological base-mark. The **risk** of initiating a period of self-amplifying behaviour is evaluated. A further set of factors which would eventually saturate and damp the runaway behaviour is noted, and potential outcomes are mapped. The paper concludes with an executive summary and an initial review of **strategic implications** for the world community.

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Keywords: complex feedback system, climate sensitivity, Earth System Sensitivity, non-linear relationship, critical threshold, equilibrating behaviour, self-amplification (runaway conditions), risk, strategic implications.

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Introduction

At its inception some seven years ago, the agenda of the Apollo-Gaia Project was focussed on two fundamental questions. Both were positioned right at the centre of concern of the climate science community. Both were subject to levels of uncertainty that jeopardised effective decision-making in the field of international negotiation, uncertainty that made the whole process vulnerable to the spread of paralysing levels of doubt and confusion, aided and abetted by powerful vested interests, whether commercial, economic, political or psychological.

The first question concerned the amount by which the feedback processes of the global climate system might amplify the effects of the anthropogenic contribution to climate change. It was well-known that values of climate sensitivity emanating from the world of climate modelling were on the conservative side. No one knew just how conservative they were.

The second question addressed the dilemma of the possible existence of a critical threshold ("tipping point") in the global climate system beyond which climate change might be precipitated into a period of self-amplification or "runaway" behaviour. The issue concerned the greatest possible threat to human civilisation. Leading scientists described it as "absolutely scary" while noting that no institution was prepared to commit research resources to its exploration.

The analysis evolved through four stages. An initial topological treatment of global dynamics was quickly followed by a conceptual model of the complex feedback system, presented in March 2009 in a workshop during the IARU Scientific Conference held in Copenhagen prior to COP 15. The difficulty in quantifying the myriad feedback mechanisms and their complex interrelationships led to a strategic change in methodology from the modelling of complex system dynamics to graphic simulation of historic behaviour of the earth system as a whole. The resulting breakthrough in the analysis of earth system sensitivity was presented in July 2011 at the third Global Conference on Global Warming in Lisbon. Then followed the delineation and quantification of the non-linear relationship between feedback dynamics and climate sensitivity, combined with an exploration of the critical threshold between equilibrating and runaway behaviour in the global climate system. The completed analysis in response to the two fundamental questions was presented on 9th July 2012, at the Fourth Global Conference on Global Warming, held in Istanbul. The presentation is profoundly bicameral and the visual and verbal elements are deeply interdependent.

Carbon-Dioxide, the Greenhouse Effect

Atmospheric molecules of CO$_2$ absorb infra-red radiation from the planetary surface at the wavelength of c. 15 μm. The energy emitted at this wavelength amounts to some 3.5 mwm^{-2}. As the concentration of atmospheric CO$_2$ is increased, the energy available within this waveband becomes increasingly saturated.

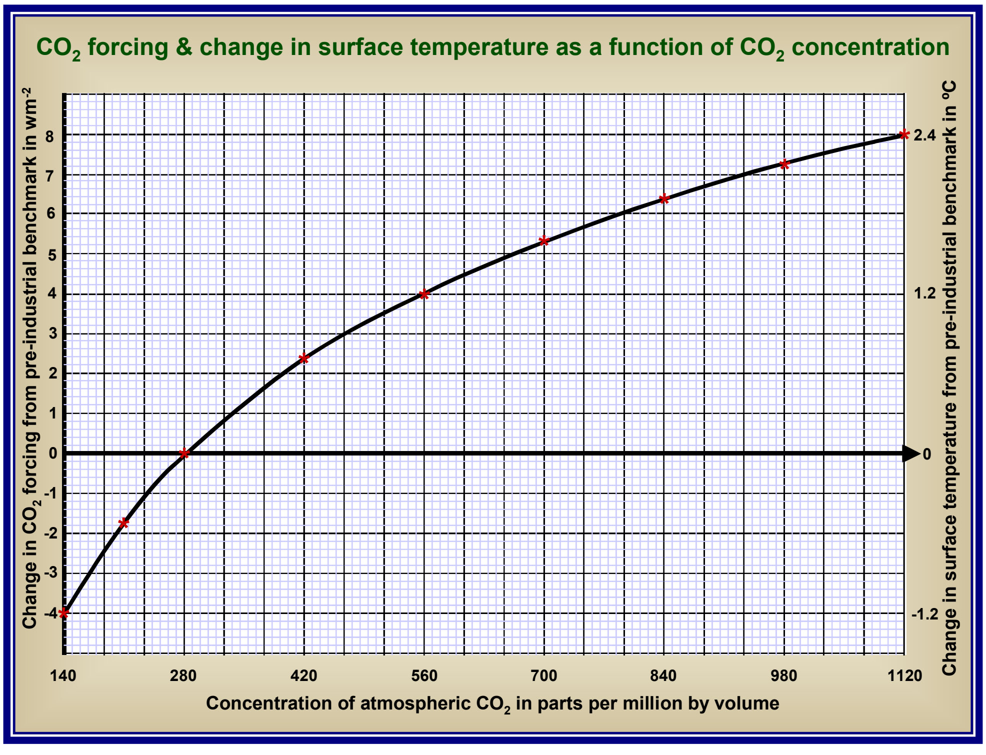

Figure 1: CO$_2$ forcing and change in surface temperature as a function of CO$_2$ concentration

The increase in greenhouse effect generated by increase in CO_2 concentration is therefore subject to a logarithmic decay. The relationship is accurately quantified at a constant value of 4 watts per square metre (wm^{-2}) for every doubling (or halving) of the atmospheric concentration of CO_2. The logarithmic function does not conform to this constant value for very small and very large concentrations, but may be taken as an accurate base-line for the range of doublings that include the minimum value of the coldest ice-ages (180 ppm), the pre-industrial benchmark concentration (280 ppm), and two further doublings (to 560 ppm and 1120 ppm) which cover likely outcomes of the Anthropocene as well as the peak value of the Eocene (c 1000 ppm). Change in the greenhouse effect for varying atmospheric concentrations of CO_2 across this range is plotted in *figure 1*. *(*For data see *Table 1)*

Change in the dynamic thermal equilibrium of the Planet

Planet earth exists in a state of dynamic thermal equilibrium with its environment. Energy received at its surface (from geo-thermal and solar sources) is dynamically balanced by energy transmitted through its atmosphere and radiated to space. If there is any modification of the energy output of the planet that disturbs the dynamic thermal equilibrium, then there will inevitably be an adjustment in the average surface temperature such that the condition of dynamic thermal equilibrium is restored. The magnitude of the adjustment is governed by the Radiative Damping Coefficient ($\boldsymbol{\lambda_0}$), the net amount of extra energy radiated per square metre of the planetary surface for a change in average surface temperature of 1ºC. In current conditions of temperature and emissivity, the value of $\boldsymbol{\lambda_0}$ is calculated to be 3.3 watts per square metre per degree change in temperature. The figure is derived from the Stefan-Boltzmann law of black-body radiation adjusted for the current planetary emissivity.

So, for example, if there is a net change in planetary albedo combined with change in the greenhouse effect that together reduce planetary radiation by 3.3 wm^{-2}, then, in order to rebalance the dynamic thermal equilibrium, there will be an increase of 1ºC in the average surface temperature of the planet. Conversely if we observe an increase in the average surface temperature of 1ºC then we can deduce that there has been a decrease in radiant energy of 3.3 wm^{-2} caused by changes in the surface albedo of the planet combined with change in the atmospheric concentrations of the greenhouse gases.

This provides us with a powerful tool for both historical assessment and for future prediction. For instance, the increase in temperature between the coldest point of the last glacial maximum and the pre-industrial benchmark is c. 5ºC, so there must have been a modification of 16.5 wm^{-2} in planetary radiation occasioned by shifts in surface albedo and greenhouse gas concentration during that period.

For present purposes we note that the change in planetary radiation of 4 wm^{-2}, generated by a doubling or halving of the concentration of atmospheric CO_2 as a single variable, requires an adjustment of 1.2ºC in the average surface temperature in order to re-balance the dynamic thermal equilibrium of the planet. The temperature change associated with change in CO_2 concentration is therefore added as the right-hand axis of *figure 1*.

Constructing the Graphic Simulator

The same data can be displayed using a semi-logarithmic presentation (see *figure 2*). The horizontal axis uses a logarithmic scale (to base 2) providing a constant graphical distance for each doubling or halving of the CO_2 concentration. The vertical axis displays change in equilibrium temperature from the pre-industrial benchmark. In this format, the log curve of *figure 1* transforms to a linear function. The device enables clarity of comparison between a variety of feedback-driven amplification factors applied to the relationship between CO_2 concentration and the change in equilibrium temperature.

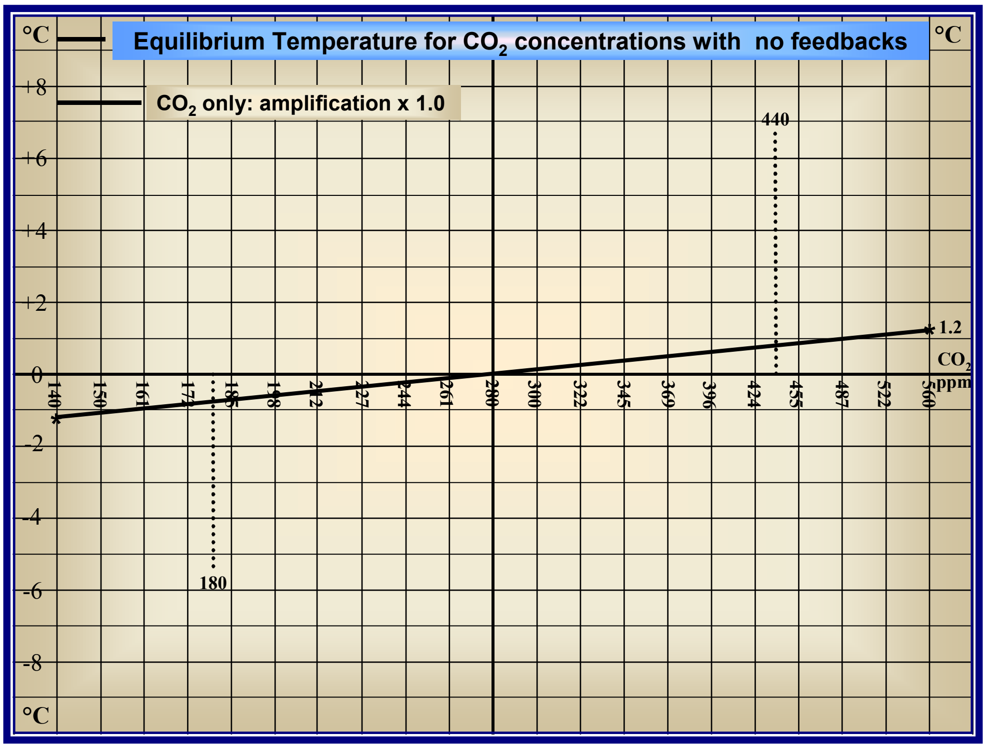

Figure 2: The Graphic Simulator

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. Scale-data used in the construction of the Graphic Simulator are provided in *Table 2*.

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 5ºC in the average surface temperature of the planet rather than the 2ºC currently predicted as the equilibrium response to a concentration of 440 ppm.

Feedback Dynamics and the Amplification of CO_2 Forcing

Although the climate of the earth changes in strong correlation with the concentration of atmospheric CO_2, the actual contribution to the greenhouse effect by CO_2 on its own goes nowhere near to accounting for the magnitude of the changes involved. The major driver of the change comes from a complex and highly connected system of feedback processes, including both negative (damping) and positive (amplifying) mechanisms. The net effect of the system is to provide a strong positive (amplifying) factor to the effects of change in CO_2 concentration. The fundamental question, at the very heart of climate science, concerns the magnitude of this amplification.

Mapping this complex feedback system is a major task. It involves identifying the many mechanisms involved and their differing drivers. Some are fast acting, others are slower. Some are strong while others make a smaller contribution. Some are global in distribution, others are more local in operation but contribute in various ways to the global dynamics. All are highly interconnected in that change in any one parameter drives modification in the behaviour of all other variables in the system. There are critical thresholds (“tipping points”) in the behaviour of many of the sub-systems, the activation of which can have unpredictable knock-on effects in other parts of the system dynamics. *Figure 3* presents a schematic diagram of a conceptual analysis of the climate feedback system of the planet.

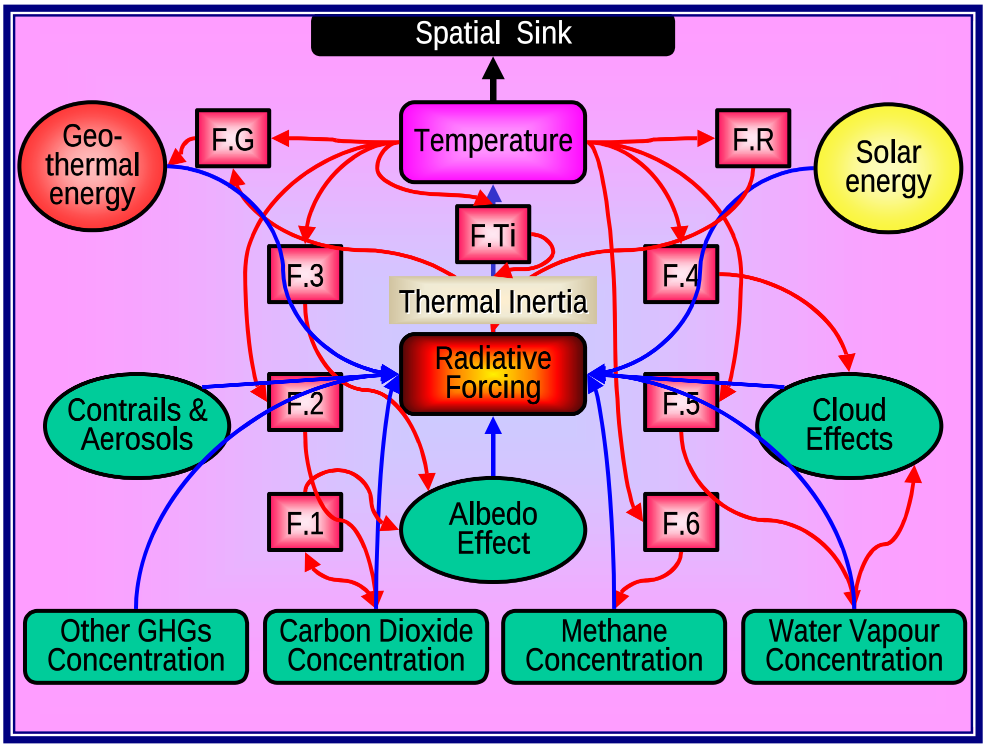

Figure 3: Schematic diagram of the climate feedback system of the planet

The numbered boxes represent sets of feedback mechanisms differentiated by their activating drivers and by the forcing elements on which they operate. No representation can ever be complete, as new mechanisms are continuously being identified by the research community, and many are still unknown. Exposition of the details of the conceptual analysis is available in video-lecture format at http://www.apollo-gaia.org/PlanetEarth/index.htm (see Part 2). It is also documented as a pdf at http://www.apollo-gaia.org/BaliandBeyond.htm (see Presentation 1).

Quantification of the strength of each mechanism, its response dynamics within the overall system performance, and the interactive paths and effects between the many variables, make this whole area subject to immense difficulty in the field of climate modelling. Uncertainties are large and compound as the model complexity progresses. That is why the ensemble of models currently employed to simulate climate change tends to include only the strongest, fast acting and best known mechanisms. The result is a conservative estimate of feedback contribution to climate dynamics, with high margins of uncertainty. It does not provide a very secure basis for executive decision-making in the negotiations of the international community.

Relationship between CO_2 Forcing and Climate Sensitivity

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 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 forcing by the dynamic feedback system. 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.

The amplification factor (AF) is defined as the ratio by which the feedback 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 (1.2ºC) by the amplification factor. 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.

In *figure 2* the black line presents the change in final equilibrium temperature correlated with a 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.

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. 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 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 3ºC will occur"**.

This is the "Charney" Sensitivity graph presented as the blue line in *figure 4*.

The body of the Report notes **"a probable error of +/- 1.5ºC"** but for the sake of clear communication, the uncertainty shading around the central line is omitted in this presentation. Issues of uncertainty and probability distribution are addressed in a later section of this paper. The value of Sensitivity is deemed to be constant throughout the range, though it is recognised that there will be small variations stemming from changes in the feedback system driven by shifts in the physical conditions of the planetary surface. In relation to the effect of CO_2 on its own, the Charney Sensitivity has an Amplification Factor of 2.5.

Adding the Carbon-Cycle Feedbacks: 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 [2] fall into two main groups, those involving the ocean, and those involving land. 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 [3]. 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 HadGen3 programmes [4], but even they are not yet including several of the specific processes. The second order factors are also difficult to quantify. Hadley currently estimate that inclusion of the carbon-cycle feedbacks [5] increases the Charney sensitivity by around 50% as illustrated by the orange line in *figure 4*.

The value of the Hadley Sensitivity is therefore approximately 4.5ºC 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.

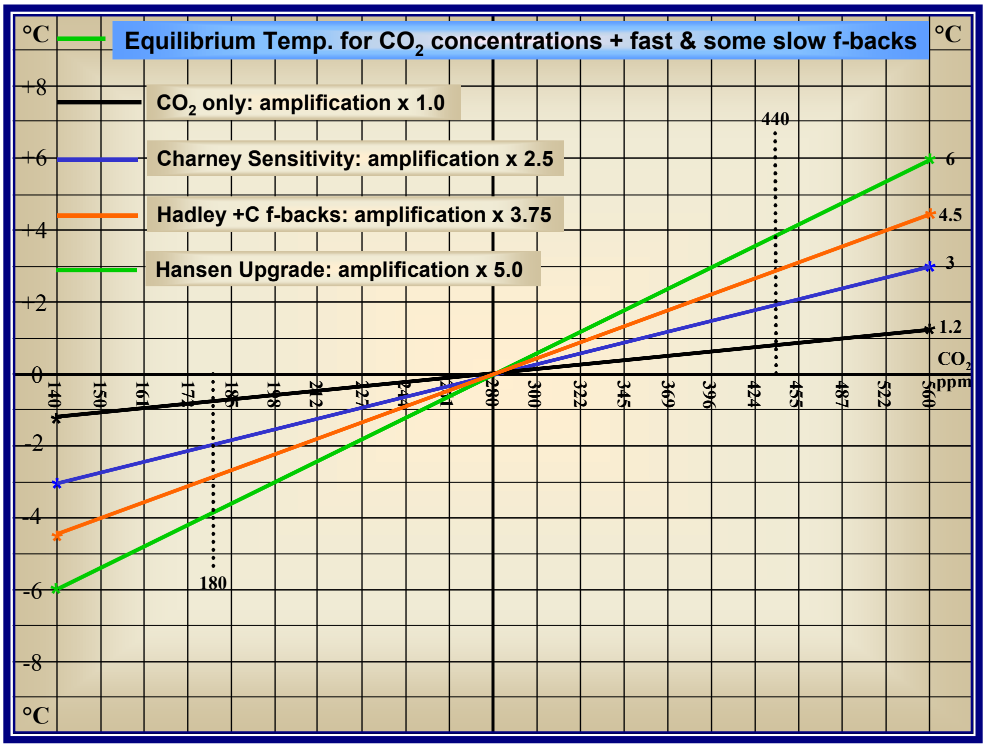

Figure 4: “Charney”, “Hadley” and “Hansen” values of Climate Sensitivity

Incorporating other Slow Feedbacks: the “Hansen” Sensitivity

In an attempt to close the gap between computer modelling and empirical measurement, Hansen et al offered a hybrid solution [6]. Their methodological approach is summarised in the paragraph:

> “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, for the range of climate states between glacial conditions and ice-free Antarctica:

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

This "Hansen" Sensitivity is represented by the green line on the Graphic Simulator (see *figure 4*). The sensitivity of 6ºC for a doubling of CO_2 yields an Amplification Factor of 5.0.

Paleo-Mathematical Assessment of Modelled Sensitivity Values

A fundamental criterion in the assessment of the outcome of any computer model is that it must generate values consistent with known observation of reality. Modelled predictions of Climate Sensitivity are no exception. The paleo-data, against which the current set of modelled values can be checked, is the change in average surface temperature of the planet between the last glacial maximum and the pre-industrial bench-mark. This change is taken as 5ºC. Using a value of 3.3 wm^{-2}ºC^{-1} for λ_o, we deduce that any value of sensitivity must account for a change of 16.5 wm^{-2} in the radiative budget of the planet.

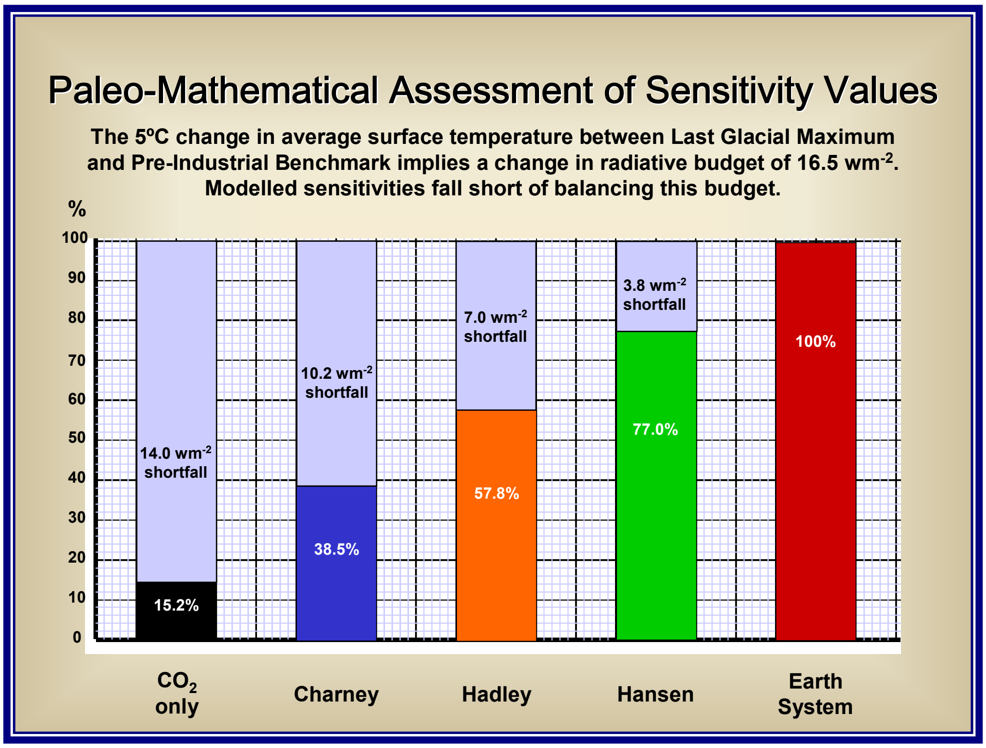

Figure 5: Paleo-Mathematical assessment of sensitivity values

By measurement from the graphic simulator we note that the forcing generated by the shift in concentration of atmospheric CO_2 from 180 ppm to 280 ppm is equivalent to 63.4% of a doubling, namely 2.54 wm^{-2}. Multiplication of this figure by the appropriate amplification factor provides the measure of compliance of any specific model with the paleo-data, (see *figure 5*):

- If the **increase in CO_2 concentration is treated in isolation** from any feedback mechanism, then the contribution to the required budget of 16.5 is 2.54 wm^{-2}, namely 15.2%, a shortfall of 14.0 wm^{-2}.

- For the **Charney sensitivity**, the amplification factor is 2.5, the contribution to the budget is therefore 6.35 wm^{-2}, or 38.5%. The shortfall is 10.2 wm^{-2}.

- For the **Hadley sensitivity**, the amplification factor is 3.75, the contribution to budget is 9.5 wm^{-2}, or 57.8%. The shortfall is 7.0 wm^{-2}.

- For the **Hansen sensitivity**, the amplification factor is 5.0, the contribution to budget is 12.7 wm^{-2}, or 77%. The shortfall is 3.8 wm^{-2}.
- By definition there is a value for the **sensitivity of the whole earth system**, including all known and unknown feedbacks and their complex interactions. This is the value which has a 100% match to the paleo-data, and to which the computer models provide more or less accurate approximations.

Climate Sensitivity of the Whole Earth System

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. However, modelling the complex dynamics involved becomes increasingly difficult (and costly). The uncertainties in the global contribution of specific feedback mechanisms (and particularly their complex inter-relationships) tend to compound, leading to widespread patterns in the probability distribution functions of the outcomes from the computer ensemble. 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 governing the response of the whole-earth system [7]. Five distinct approaches are employed, (see *figures 6 & 7)*:

1. Paleo-Mathematical Calculation. The 5ºC increase in average surface temperature of the planet, from the last glacial maximum to the pre-industrial benchmark, was required to maintain the dynamic thermal equilibrium in the face of a shift in the radiative budget of 16.5 wm^{-2}. The contribution from CO_2 on its own, ignoring all feedback dynamics, stood at 2.54 wm^{-2}. The **amplification factor is therefore 6.49**. Multiplying this by 1.2 gives a value of for the **whole earth climate sensitivity of 7.79ºC**.

2. Derivation from the Graphic Simulator. 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 5.0ºC below the pre-industrial benchmark. This provides us with the ice-age anchor-point of [180 ppm, -5.0ºC] through which the amplification line representing the sensitivity of the whole earth system must pass. The second point on the straight-line function is the pre-industrial benchmark itself, of 280 ppm and 0.0ºC. Connecting those two points and projecting the line forward into the next doubling of CO_2 concentration yields an **amplification factor of 6.5**, and a **climate sensitivity of 7.8ºC**.

3. Ice-core Correlation. In 2005, Ferdinand Engelbeen [8] published results of a regression analysis of the correlated values of CO_2 concentration and temperature based on the gas analysis of bubbles trapped deep in the Antarctic ice cap at Vostok. His study covered the last four glacial/inter-glacial cycles. Back-reading from his graphical presentation we find that the concentration for which his analysis is most accurate is c. 267 ppm at which we derive a value of 17.8 $ppm^{o}C^{-1}$ for the (non-log) gradient of the relationship.

Doubling the concentration value (of 267 ppm) at which Engelbeen's work is deemed to be most accurately applicable we explore behaviour at 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 the gradient of his derived correlation to 35.6 $ppm^{o}C^{-1}$. The concentration change from the pre-industrial benchmark is 254 ppm at this point. If we divide that increase by the calculated Engelbeen factor of 35.6 we obtain a projected temperature increase of 7.1 ºC at a concentration of 534 ppm. This "Engelbeen Point" is virtually on the same straight line as the other two anchor points, and would appear to provide significant corroboration of the amplification factor and sensitivity value for the whole earth system.

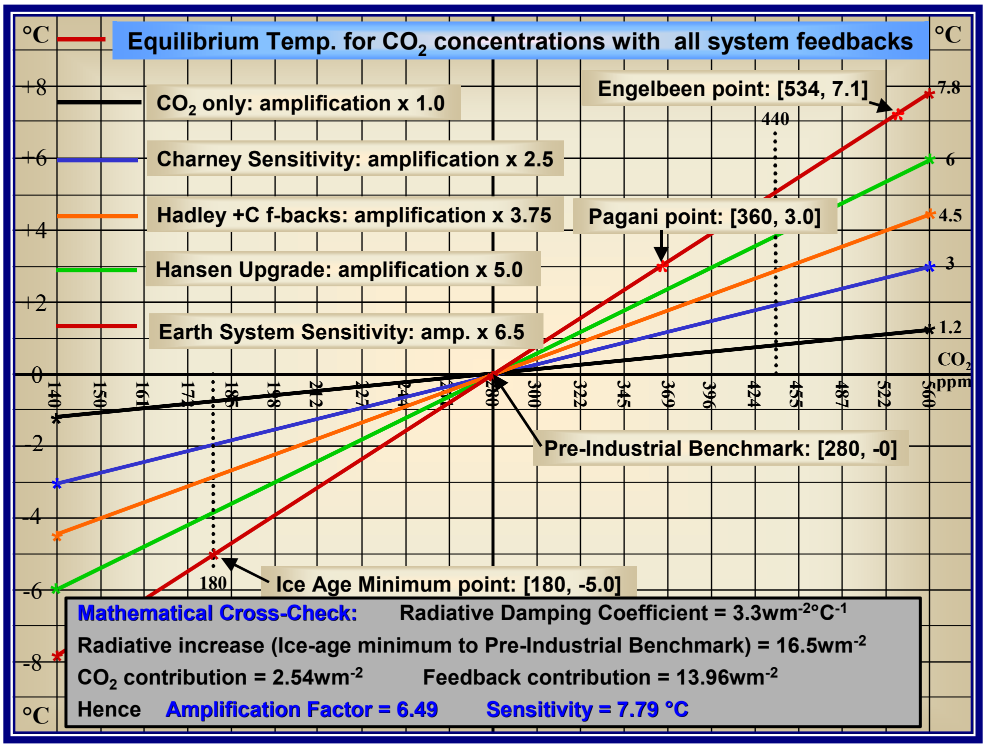

Figure 6: Whole Earth Sensitivity

4. Ocean Sediment Studies. Towards the end of 2009, Mark Pagani et al published a paper on "High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations" [9]. Their analysis was based on proxy derivation of temperature and CO_2 concentrations using ocean-floor sediment cores reaching back some 60 to 100 million years. Conservative application of their work yields a value for the Earth-system climate sensitivity of around 8ºC 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].

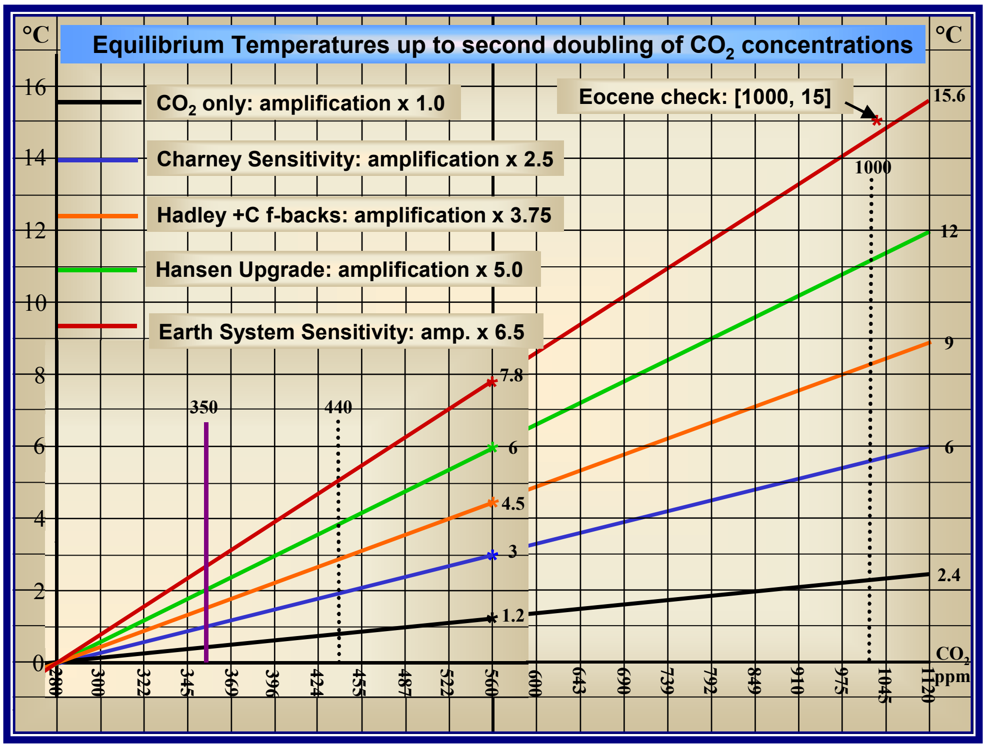

Figure 7: Equilibrium temperatures up to second doubling of CO_2 concentrations

5. Eocene Check-out. This final approach requires expanding the Graphic Simulator to encompass a second doubling of CO_2 concentration beyond the pre-industrial benchmark (see *figure 7*). Jeffrey Kiehl surveyed current peer-reviewed academic papers reporting on the reconstruction of values of atmospheric CO_2 concentration reaching back through ~100 million years [10]. 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 feedback factor is approximately $2^oCw^{-1}m^{-2}$. That is equivalent to a **climate sensitivity of 8ºC** for a doubling of atmospheric concentration of CO_2, with an **amplification factor of 6.7**.

Re-applying the Paleo-Mathematical Calculation to this early period, we note that initially the earth surface temperature was some 15ºC above the pre-industrial benchmark, with a CO_2 concentration of the order of 1000 ppm. Using a value of 3.3 $wm^{-2o}C^{-1}$ for $\boldsymbol{\lambda_o}$ we deduce a change in the radiative budget of 49.5 wm^{-2}. The contribution of CO_2 on its own accounts for 7.48 wm^{-2} (change in concentration from 1000 ppm to 280 ppm constitutes 1.87% of a doubling/halving of the CO_2 greenhouse effect). That yields an **amplification factor of 6.6** and a value for **whole earth climate sensitivity (ESS) of 7.9ºC**.

Note 1: During this period the change in CO_2 concentration was the causal driver of climate change, while during the glacial/inter-glacial sequence it was a highly correlated feedback responding to the causal stimulus of the effects of the Milankovic cycles. The high value of the **ESS** makes it abundantly clear why the planetary climate responds so strongly to comparatively small changes in system dynamics.

Note 2: The value of the whole earth sensitivity appears to stay almost constant at a value of 7.8ºC to 8.0ºC for a doubling or halving of CO_2 concentration across the range from 180 to 1000 ppm. The feedback system dynamics do, however, undergo significant modification. The ice-albedo processes contribute strongly during the glacial/inter-glacial series, but disappear during the warmer ice-free conditions during which they would appear to be replaced by net amplifying feedback from cloud dynamics.

In conclusion, the multi-disciplinary approach establishes an Amplification Factor of 6.5 and a value of 7.8ºC for the Whole Earth System Sensitivity.

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 1.2ºC on the sensitivity scale of *figure 8*.

The ensemble of climate models on which the IPCC Fourth Assessment Report (2007) [11] was based, was used by Meinshausen et al [12] to generate the probability density function (PDF) of climate sensitivity. It reaffirmed the 3ºC value of the Charney Sensitivity, shown as the blue distribution. It has a skewed pattern showing lower probability of sensitivity below 3ºC, 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. It is vital to differentiate between models and reality. The probability distribution represents the outcome of computer modelling. In reality the value of sensitivity is sharply defined. The PDF represents the spread of our current uncertainty. It is also important to note that the IPCC makes no attempt to evaluate the competence of the various climate models with respect to their relative ability to represent the effects of the complex dynamic feedback system. It is deemed politically inappropriate so to do. It is therefore hardly surprising that the PDF is dominated by the least competent models whose simulation is limited to the basic fast feedback mechanisms originally delineated in the Charney Report.

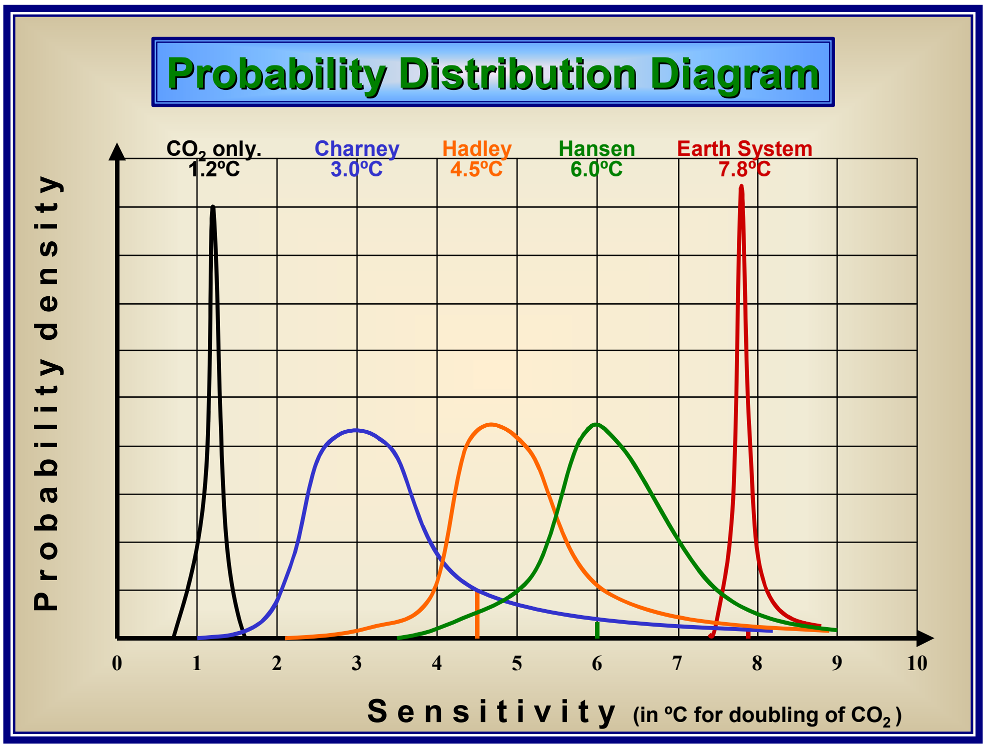

Figure 8: Probability distribution diagram

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 five 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 (ESS) of at least 7.8ºC for a doubling of CO_2, requires that the Charney Sensitivity (of 3ºC) should now be replaced by this new value for all further engagement in climate science, and as the basis for all strategic negotiations of the international community.

Some Consequences and Implications

Using the completed Graphic Simulator (see *figures 6 & 7*) it is now possible to draw out a set of implications consequent upon adopting the new figure of 7.8ºC as the value of Earth System Sensitivity:

The "safe guard-rail" beyond which it is postulated lies the onset of "dangerous climate change" was set at a concentration of 440 ppm of atmospheric CO_2, and an equilibrium temperature increase of not more than 2ºC.beyond the pre-industrial benchmark [13], [14], [15]. Applying the new **ESS** value indicates that anthropogenic disturbance of the climate equivalent to the effect of 440 ppm of CO_2 would lead to an increase in equilibrium temperature of 5ºC above the pre-industrial figure. The 2ºC guard-rail was already broken as the CO_{2e} concentration passed 330 ppm.

Temperature change in the pipe-line consequent upon the current concentration of 392 ppm of atmospheric CO_2 was deemed to be a further 0.8ºC beyond the present value. Applying the **ESS** we recognise that we are already committed to a further rise of 3.2ºC (or 4.3ºC if non-CO_2 greenhouse gases are taken into account).

Collapse of the Budget Approach. Based on the "Charney" sensitivity it was assumed that the global commons could still absorb some 750 GT of CO_2 emissions [16] before jeopardising the 2ºC ceiling, a "budget" whose allocation has bedevilled international negotiations. Applying the new **ESS** value it is clear that there is no such budget. Far from allocating spare capacity in the global commons, we face the imperative of draw-down of CO_{2e} concentrations from current values to some 330 ppm if the 2ºC ceiling is not to be exceeded.

The "Pledges" of the Copenhagen Accord, made by some 80 countries and renewed in Cancun and Durban, were assessed as leading to an increase of some 4ºC above pre-industrial values by 2100 [17]. Apart from the fact that no emission-descent pathways were embedded in the pledges, that non-CO_2 greenhouse gases were not included, and that many of the promises are unlikely to be honoured in the current political and economic context, the calculations were made using the Charney sensitivity with its associated uncertainty spread and elision of known amplifying feedback mechanisms. 4ºC by the end of the current century is equivalent to some 6ºC at eventual equilibrium reflecting an expected concentration of CO_{2e} of over 1000 ppm. The **ESS** indicates that under these conditions, temperature increase would top 10ºC by the end of the century and move to some 16ºC above the pre-industrial benchmark as eventual equilibrium is approached.

Boundary conditions of "safe" climate change are continuously being revised downwards in the light of current observation of the consequential effects of the present increase of 0.8ºC [18]. The "350.org" campaign [19] seeks to draw-down CO_2 concentrations to a value estimated to limit temperature increase to 2ºC using the Hansen sensitivity (2.6ºC applying the **ESS**). Figueres (UNFCCC Chief Negotiator) following the Bolivian "Peoples Congress" [20], and with the support of many of the small nation states is seeking to limit increase to not more than 1.5ºC, while Jorgen Randers [21] is proposing a ceiling of 1ºC above the pre-industrial value. Both of these are still dependent on the Charney sensitivity value. In private conversations, Hansen and Schellnhuber, both affirm that equilibrium temperature increase should not be allowed to rise significantly beyond that already achieved. In the light of the new value for **ESS** that would imply that total anthropogenic forcing from all sources would have to be reduced from its present value to the equivalent of a concentration of just under 300 ppm of atmospheric CO_2.

Non-Linear Dependence of Sensitivity on the Feedback Factor

For any particular value of sensitivity, any change in the radiative budget of the planet is derived from the change contributed by the shift in CO_2 concentration on its own, multiplied by the amplification factor appropriate to the given value of sensitivity. The contribution from the feedback system is therefore derived from the total change in radiative budget less the contribution from the shift in CO_2 concentration. If we divide this feedback contribution by the value of the temperature change required to re-balance the dynamic thermal equilibrium of the planet, then we arrive at a value of the feedback factor appropriate to the particular value of sensitivity. We can therefore offer a **definition of the feedback factor:**

The Feedback Factor (FF) is the forcing per square metre generated at equilibrium by the feedback system for a 1ºC change in average surface temperature of the planet. It is measured in $wm^{-2o}C^{-1}$

As an example we take the Earth System Sensitivity with an amplification factor of 6.5 and an equilibrium temperature change of 7.8ºC for a doubling of CO_2 concentration. The reduction in radiant energy caused by a doubling of CO_2 concentration is 4 wm^{-2}, so the total change in radiative budget (4 x 6.5) is 26 wm^{-2}. Of this the feedback system (excluding the contribution from the change in CO_2 forcing) accounts for 22 wm^{-2}. Dividing this by the temperature change gives a value for the Feedback Factor associated with the **ESS** of 2.82 wm^{-2}ºC^{-1}.

Repeating the set of calculations for other values of sensitivity provides these Feedback Factor values:

For CO_2 on its own	**Amplification Factor = 1.0**	**Feedback Factor = 0.00 wm^{-2}ºC^{-1}**
For Charney Sensitivity	**Amplification Factor = 2.5**	**Feedback Factor = 1.98 wm^{-2}ºC^{-1}**
For Hadley Sensitivity	**Amplification Factor = 3.75**	**Feedback Factor = 2.44 wm^{-2}ºC^{-1}**
For Hansen Sensitivity	**Amplification Factor = 5.0**	**Feedback Factor = 2.67 wm^{-2}ºC^{-1}**
For ESS	**Amplification Factor = 6.5**	**Feedback Factor = 2.82 wm^{-2}ºC^{-1}**

These values are specific solutions of the equation:

$$\boxed{AF = \frac{\lambda_o}{\lambda_o - FF}}$$

where (as before) λ_o is the radiative damping coefficient of the planet, value 3.3 wm^{-2}ºC^{-1}.

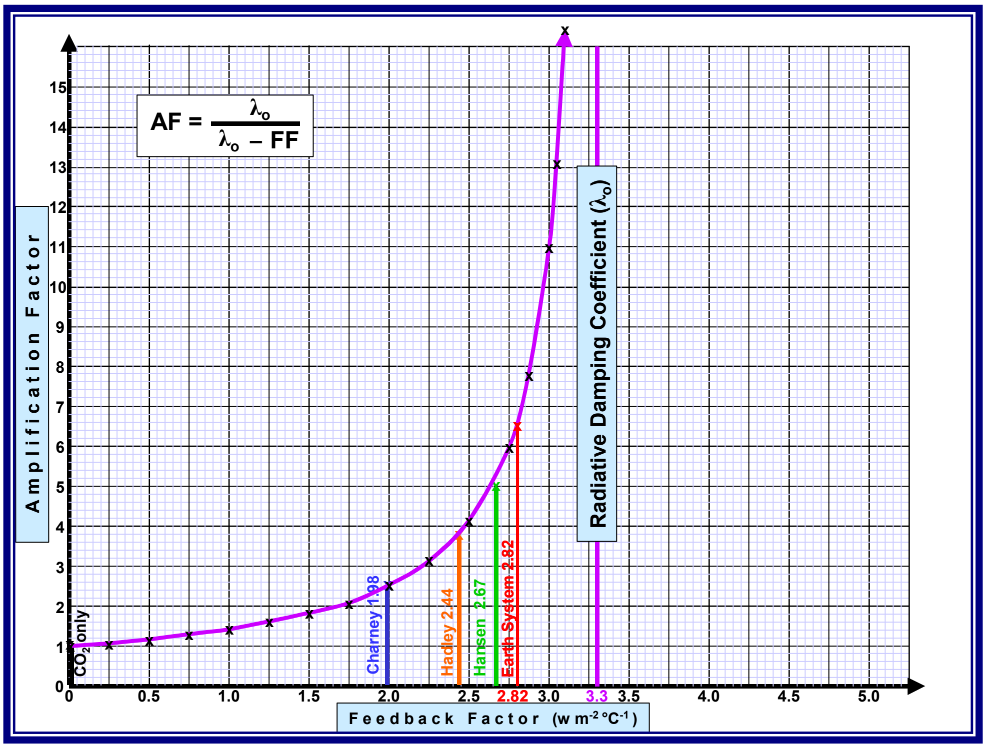

Figure 9: Non-linearity in the relationship between amplification factor and feedback factor

In effect, λ_o acts as the negative or damping system feedback, reducing the value of net radiative imbalance with changing temperature. Conversely, **FF** acts as the positive or amplifying system feedback, increasing the value of net radiative imbalance with changing temperature. The net radiative damping coefficient of the system (λ) can therefore be expressed by the equation:

$$\boxed{\lambda = \lambda_o - FF}$$

As the value of the Feedback Factor approaches that of the Radiative Damping Coefficient, so λ approaches zero and the values of the Amplification Factor (and so also of Sensitivity) tend to infinity. This non-linearity in the relationship between the Amplification Factor (with its associated Sensitivity value) and the Feedback Factor is presented in *figure 9*. Data is presented in *Table 3*.

Climate models incorporating only the basic fast-feedback mechanisms operate with values of the Feedback Factor of around 2 wm^{-2o}C^{-1}. In this area of the graph, changes in the feedback factor have comparatively small effects on the outcome of the sensitivity value and hence of the projected change in eventual equilibrium temperature. The presentation makes it clear why increasing the competence in modelling the complex feedback system has increasingly powerful impact on the value of the eventual equilibrium temperature.

Applying the value for the Whole Earth System Sensitivity, with its Feedback Factor of 2.82 wm^{-2o}C^{-1}, takes us into an area of the curve where small changes in Feedback factor have large effects on the eventual equilibrium temperature. At this point, λ, the net radiative damping coefficient, is reduced to a value of only 0.5 wm^{-2o}C^{-1}. Any further reduction in λ would have massive implications for the stability of the planetary climate. However, provided the value of λ remains positive, the rate of change in the system decelerates over time and moves towards an eventual state of equilibrium with zero net radiative imbalance.

Beyond the Stable State: Boundary Conditions of Runaway Change

The evaluation of the Earth System Sensitivity is grounded in historical conditions of dynamic thermal equilibrium in which the rate of change was slow and the net radiative imbalance remained close to zero.

Those conditions no longer apply.

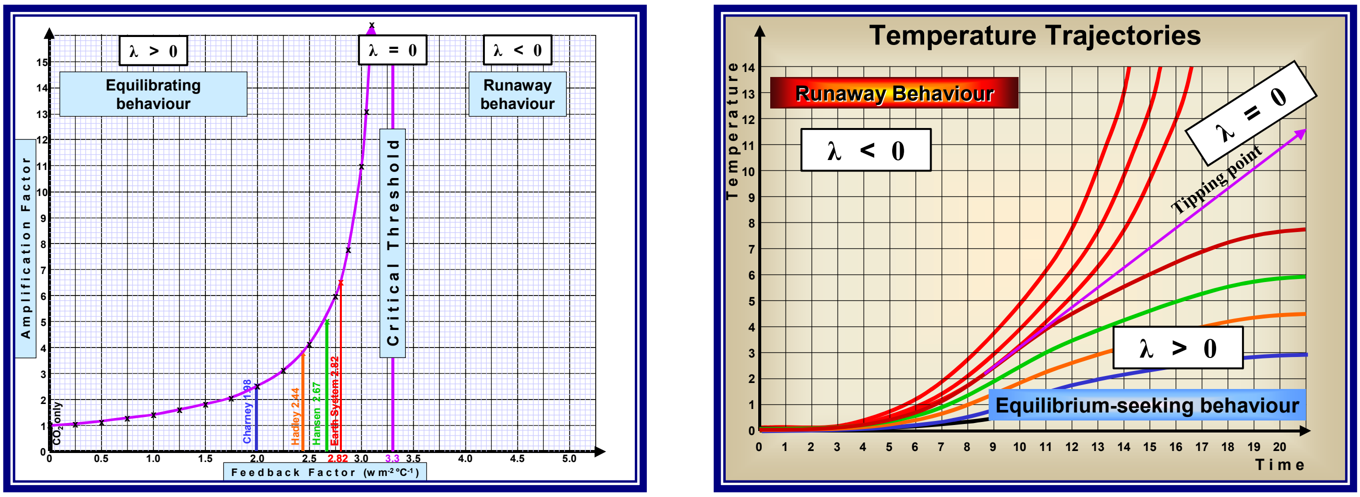

Figure 10: Temperature trajectories across non-linearity of AF to FF

Historically a change in CO$_2$ concentration of 100 ppm has taken place over a period of some 10,000 years. Humanity is currently generating the same change in the space of thirty years, three hundred times faster than at any point in the historical record. Net Radiative Imbalance during the past has not exceeded 0.01 wm^{-2}. Anthropogenic forcing at the end of the last century generated a net radiative imbalance of between 1.0 and 3.0 wm^{-2}. This rate of global heating is also 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. In this situation a set of feedback dynamics is enhanced or initiated that increases the value of the **ESS**.

That correlates with an increase in the Feedback Factor and a corresponding decrease in the value of **λ** with the potential to move the system behaviour towards or even beyond the critical threshold of **$\lambda = 0$**.

The value of the Feedback Factor at which **$FF = \lambda_o = 3.3\ wm^{-2o}C^{-1}$** marks the tipping point in the global climate system between conditions that lead to equilibrating outcomes and those that generate a period of self-amplification or "runaway" behaviour.

If the value of the Feedback Factor exceeds **λ_o** then **λ** itself becomes negative, the system moves into accelerating change, and the net radiative imbalance increases with rise in temperature (see *figure 10*).

Factors which can increase the ESS beyond its historical value

As was noted above, under current conditions of rapid change and far-from-equilibrium behaviour, a set of complex feedback processes is activated that enhance the Earth System Sensitivity beyond its historically stable value. It is extremely difficult to establish the time-frame and quantification of the parameters involved, but the conceptual modelling is fairly clear. Some examples are in order:

1. **Tropical and Boreal Forests.** In conditions of slow and close-to equilibrium change these have been able to adapt to climate change, evolve species modification and mobile their habitat boundaries. In the Anthropocene, the response to rapid change involves widespread forest fires and die-back releasing large amounts of carbon from the biomass and the underlying soil into the atmosphere. Forest destruction also diminishes the capacity for biological sequestration of CO_2, a "sink degrade" which acts as a further amplifying feedback in the carbon cycle.

2. **Rapid thaw of Tundra Permafrost.** Arctic response to global heating shows temperature changing more than three time faster than the global average. This energy transfer to areas of historic permafrost accelerates microbial activity and drives the release of CO_2 and methane. It also increases the run-off temperature of northward flowing rivers, so accelerating the reduction of sea-ice extent and thickness over the arctic continental shelf, and warming shallow seas covering clathrate-rich deposits. The process also enhances albedo-reduction feedbacks from reduced sea-ice cover as well as the area and duration of highly reflective snow-fields.

3. **Methane Clathrate Cascade Feedback**. In slow climate change, methane released from its frozen "clathrate" state in the sea-bed deposits is oxidised before reaching the ocean surface with resultant CO_2 being absorbed in the water column. In conditions of rapid change the gas reaches the ocean surface and is released into the atmosphere. The increased rate of methane emission from both tundra and sea-bed sources overwhelms the limited supply of OH radicals in the atmosphere, slowing the decay of the powerful greenhouse gas. That constitutes a second-order feedback process which adds to the rate of increase in methane concentration.

4. **Enhanced Seismic Activity.** Increase in the rate of mass-loss from the melting of the Greenland ice-cap accelerates tectonic up-lift in a seismically active area which also happens to be very rich in methane clathrate deposits.. Under these conditions there is potential for abrupt and massive earth-quake triggered release of methane.

5. **Stratification of Ocean Surface.** In geological time-scales heat is slowly mixed from ocean surface to deep ocean stores. In rapid climate change the inertia of this process leads to comparative increase in the rate of heating of the ocean surface, stronger stratification of the thermal layers of the ocean, more rapid evaporation, higher levels of water-vapour concentration in the atmosphere, more intense storm behaviour and enhanced energy transfer from hot equatorial to cold polar regions of the planet. The process also blocks up-welling of cold nutrient-rich deep ocean water which inhibits plankton population and degrades another sink in the carbon cycle.

6. Endothermic Phase-change Feedbacks. There are two change-of-state phenomena in the climate dynamic, both of them endothermic in conditions of rising temperature. The first is solid to liquid (ice to water). The second is liquid to gas (water to water-vapour). Both processes are connected to positive feedbacks, ice-melt leads to albedo reduction, and evaporation drives increase in water-vapour content of the atmosphere. When change is slow the energy-exchange processes are evened out in the system. Under conditions of rapid change both processes drive heat-retention feedbacks while slowing rise in surface temperature and its related negative feedback.

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. If together they reduce λ by less than 0.5 $wm^{-2o}C^{-1}$ they will raise the temperature of eventual equilibrium significantly higher than that predicted using the undisturbed value of ESS. If together they reduce λ by more than 0.5 $wm^{-2o}C^{-1}$ they will usher in a period of self-amplification (runaway change) in the global climate system.

Saturation and Damping of Self-amplifying Dynamics

In purely mathematical treatments, asymptotic parameters and self-amplifying processes are shown as progressing to infinity. This never occurs in any practical physical system. Runaway behaviour is always subject to saturation and damping of key variables. Self-amplification is therefore always limited in both extent and duration. The global climate system is no exception.

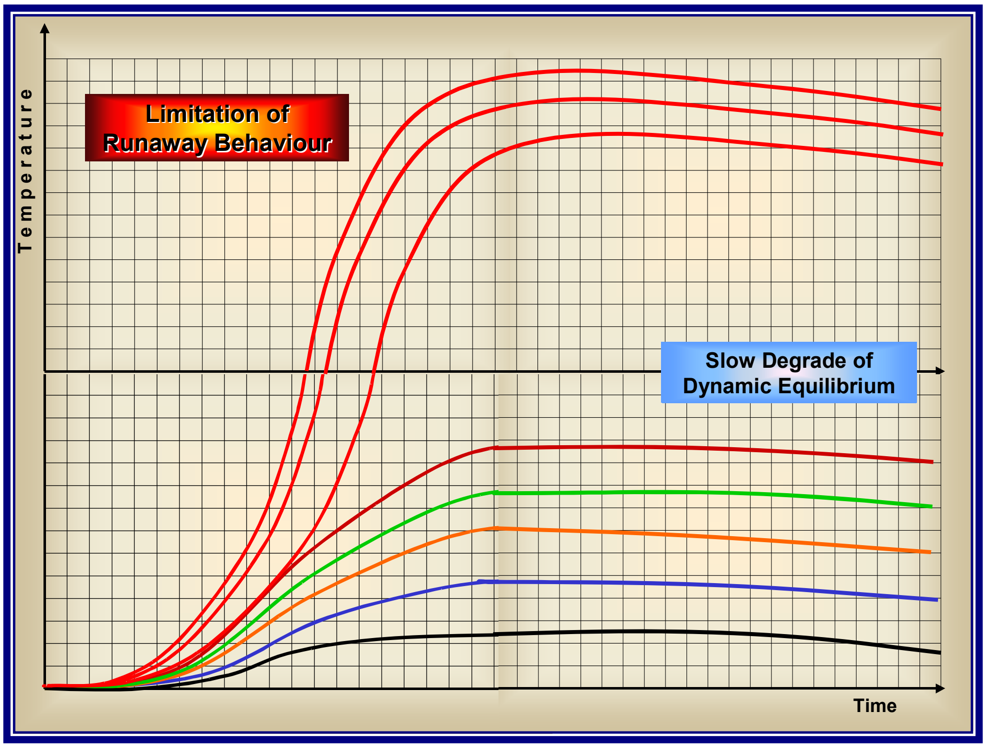

Figure 11: Multi-millennial diagram of temperature trajectories

The containment of the runaway condition is not governed purely by sensitivity dynamics, but by other factors which emerge during the process. Over time, these reduce the power of the feedback system and so return the behaviour to an equilibrating condition. Some of these dynamic processes are as follows:

- **Snow and ice albedo** and phase-change feedbacks degrade with rising temperature, disappearing altogether once ice-free conditions are established.

- There is a **finite limit to the mass of carbon** stored in bio-mass and available for release to the atmosphere. Once these stocks are depleted, the associated feedback process is reduced to zero.
- Similarly there is also a **finite limit to the amount of methane** (stored in frozen Tundra or sea-bed clathrate) that is available for release to the atmosphere.
- As the resonant **wave-band in the infra-red spectrum** becomes more and more saturated, the efficiency of the greenhouse effect of CO_2 continues to degrade with rising concentration.

As these dynamics are brought into play, the exponential rate of change slows and eventually re-stabilises at a new equilibrium. Beyond that point, slow geological processes of sequestration take over, which would, over many millennia, tend to return the global climate to pre-Anthropocene conditions. The behaviour is illustrated diagrammatically in *figure 11*, in which the time and temperature scales have been left without quantification.

Concluding Summary (with Strategic Implications for the World Community)

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. An overly 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 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 3ºC 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.

A multi-disciplinary approach, independent of any climate model, and supported by a specially designed Graphic Simulator, identifies a (minimum) value for the Earth System Sensitivity of 7.8ºC 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.**

An exploration of the non-linear relationship between the Amplification Factor and the Feedback Factor confirms the existence of a critical threshold (tipping point) in the global climate system beyond which climate change moves into a limited period of exponential or runaway behaviour. The high level of climate sensitivity, coupled with factors brought into play in current conditions of rapid and far-from-equilibrium change, risk pushing the global climate system into conditions of extreme global warming. They could even initiate an episode of runaway behaviour. That represents the ultimate threat to human civilisation and the life-support system of the planet. **It is a risk that must now be avoided whatever the cost.**

If the analysis of climate dynamics presented in this paper cannot be refuted, then it becomes imperative that we move collectively, as a global civilisation, towards the total cessation of any and all activity that increases the net radiative imbalance of the planetary climate system, or that profits from so doing. The strategic imperative applies equally to the reduction of the current concentration of atmospheric greenhouse gases to the equivalent of c. 300 ppm of CO_{2e} within a timeframe set by the thermal dynamics of the planetary climate system.

This has nothing to do with the availability or profitability of fossil energy, nor even political feasibility. It is now an issue of survival in conditions of global crisis.

Tables

Table 1: (Data for *Figure 1*)

CO_2 Forcing and change in surface temperature as a function of CO_2 concentration

Concentration ppm	Forcing wm^{-2}	Temperature Change °C
140	-4.0	-1.2
210	-1.7	-0.5
280	0.0	0.0
420	2.4	0.7
560	4.0	1.2
700	5.3	1.6
840	6.4	1.9
980	7.2	2.2
1120	8.0	2.4

Note

a) Values of forcing and temperature are given as variation from the pre-industrial Benchmark.

b) Temperature change implied by the forcing reflects the effect of change in the CO_2 concentration alone which ignores all other variables.

Table 3: (Data for *Figure 9*)

Non-Linear Dependence of Sensitivity on Feedback Factor

AF	FF	λ (Net Radiative Damping Coefficient)
1	0	3.3
1.08	0.25	3.05
1.18	0.5	2.8
1.29	0.75	2.55
1.43	1	2.3
1.61	1.25	2.05
1.83	1.5	1.8
2.12	1.75	1.55
2.5	1.98	1.66
2.54	2	1.3
3.14	2.25	1.05
3.75	2.44	0.88
4.13	2.5	0.8
5	2.67	0.66
6	2.75	0.55
6.5	2.82	0.507
7.76	2.875	0.425
11	3	0.3
13.2	3.05	0.25
16.5	3.1	0.2

Table 2: **(Data for *Figure 2*)**

Graphic Simulator Construction

Incremental Power	2 Raised to Power	Column 2 x 140
0	1	140
0.1	1.071773463	150.0482848
0.2	1.148698355	160.8177697
0.3	1.231144413	172.3602179
0.36	1.283425898	179.6796257
0.4	1.319507911	184.7311075
0.5	1.414213562	197.9898987
0.6	1.515716567	212.2003193
0.7	1.624504793	227.430671
0.8	1.741101127	243.7541577
0.9	1.866065983	261.2492376
1	2	280
1.1	2.143546925	300.0965695
1.2	2.29739671	321.6355394
1.25	2.37841423	332.9779922
1.3	2.462288827	344.7204357
1.4	2.639015822	369.462215
1.5	2.828427125	395.9797975
1.6	3.031433133	424.4006386
1.65	3.138336392	439.3670948
1.7	3.249009585	454.861342
1.8	3.482202253	487.5083154
1.9	3.732131966	522.4984753
2	4	560
2.1	4.28709385	600.193139
2.2	4.59479342	643.2710788
2.3	4.924577653	689.4408715
2.4	5.278031643	738.92443
2.5	5.656854249	791.9595949
2.6	6.062866266	848.8012772
2.7	6.498019171	909.7226839
2.8	6.964404506	975.0166309
2.9	7.464263932	1044.996951
3	8	1120

Nomenclature

S	Sensitivity. The increase in average surface temperature of the planet once dynamic thermal equilibrium has been regained following a doubling of the concentration of atmospheric CO_2. Measured in ºC.
ESS	Earth System Sensitivity. The sensitivity of the planet as a whole, taking into account the dynamic contribution of all feedback mechanisms, known and unknown.

AF	Amplification Factor. The ratio by which the earth climate, for a given understanding of the feedback system, is deemed to multiply the effect of increase in the concentration of atmospheric CO_2 on its own. Note that **S = 1.2AF**.
FF	Feedback Factor. The increase in energy radiated to space from the planet for each change of 1ºC in the average surface temperature, generated by the complex feedback system independently of the effect of change in the concentration of atmospheric CO_2. It is measured in wm^{-2o}C^{-1}.
$\boldsymbol{\lambda_o}$	The Radiative Damping Coefficient. The increase in energy radiated to space from the planet for each change of 1ºC in the average surface temperature. Measured in wm^{-2o}C^{-1}. In this paper the value used is 3.3 wm^{-2o}C^{-1}.
$\boldsymbol{\lambda}$	The Net Radiative Damping Coefficient. Derived from $\boldsymbol{\lambda_o}$ less the value of **FF**. It represents the change in energy radiated to space per 1ºC change in average surface temperature for any given understanding of the strength of the feedback system. It is measured in wm^{-2o}C^{-1}. It should be noted that $\boldsymbol{\lambda = \lambda_o -}$ **FF**.

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