Critical Issues in the Domain of Climate Dynamics

Part 1: Climate Sensitivity

Cover Sheet

This is the revised text of a paper currently being prepared for publication. The first draft has been revised in the light of feedback received from the global community, for which I am profoundly grateful. It is being re-circulated in this form as part of our commitment to a stringent and open process of peer learning and review, prior to the more formal and anonymous procedure of peer-review espoused by the leading journals. Your help and collaboration in this process would be immensely appreciated.

- **Please circulate the file by all means at your disposal to all to whom its content might be of interest.**
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- **The energy-radiation image in section 2.2 was copied from the web but its source is unknown. Do you recognise it? Can you help us to identify its source so that permission for its use can be sought and due acknowledgement can be made?**
- **For your assistance, every section, paragraph and sub-paragraph is numbered. If applicable, please quote the number to which your comments apply.**
- **Please send all your comments by e-mail to info@meridian.org.uk . Please identify the subject as “Climate Sensitivity” and set the priority as “high”.**
- **We would also be very interested to receive any comments you can give concerning the significance, implications, applications, or consequences of the analysis.**
- **Several people have experienced quite strong emotional reaction to the material, so please do not feel inhibited from sharing your response at this level.**

Thank you in advance for engaging as a learning partner. I look forward to hearing from you.

With best wishes,

David Wasdell (Director of the Apollo-Gaia Project)

Critical Issues in the Domain of Climate Dynamics

By

David Wasdell

Director of the Apollo-Gaia Project *

Abstract

Part 1: Climate Sensitivity

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.

Part 2: Beyond the Stable State

The most significant boundary in climate dynamics is the strength of the feedback factor 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.

Part 3: Developing a Strategic Response

Boundary conditions of the macro-system set the constraints which determine the envelope of sustainability of all dependent sub-systems. Regaining long-term viability, stability and sustainability of the interdependent set of climate, population, energy, consumption, entropy, politics and economics, and will require a phase-change in global dynamics, the initiation of which is the fundamental challenge facing human civilisation in the 21st Century.

This three-part paper was delivered in outline form at a public seminar conducted on 3rd November 2010 in the

Department of Land Economy

of the University of Cambridge

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Part 1: Climate Sensitivity

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Critical Issues in the Domain of Climate Dynamics

Part 1

Climate Sensitivity

Amplification of the Anthropogenic Disturbance of the Climate System

1. Preface

1.1 **Human activity during and before the final doubling period of the population explosion has had a significant effect on the energy balance between the planet and its environment. The pre-industrial dynamic thermal equilibrium between energy received from the solar source and energy radiated to the cold spatial sink has been disturbed. Three main factors are involved. The dominant intervention has been an increase in the atmospheric concentration of carbon-dioxide, methane and other trace greenhouse gases. The second factor stems from the presence of particulates and contrails in the atmosphere. The third and minor impact derives from a small shift in the planetary albedo caused by change in land-use. The resultant decrease in the total amount of energy radiated to space by the planet (the anthropogenic forcing) requires an increase in average surface temperature to compensate for the disturbance and re-balance the dynamic thermal equilibrium of the system.**

1.2 **In addition to initiating a process of global warming, the anthropogenic disturbance 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 required increase in average surface temperature if thermal equilibrium is eventually to be restored.**

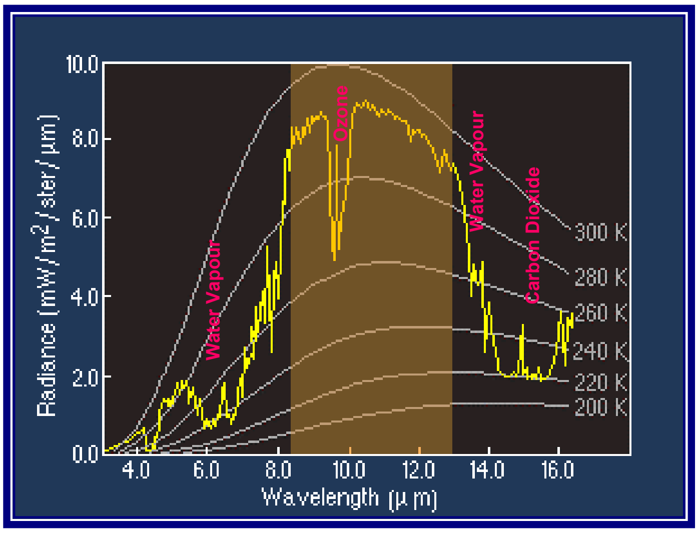
1.3 **By checking modelled values of the amplification factor against the historical sensitivity of the whole earth system, the first part of this paper offers a radical re-evaluation of climate sensitivity with serious consequences for our current strategic attempts at mitigation of climate change.**

2. By Way of Introduction

2.1 The set of smooth white curves in the diagram represents the distribution of energy radiated in the infra-red spectrum by ‘black bodies’ of varying surface temperature, set in a cold spatial environment at 0ºK.

2.2 If the earth had no atmosphere (or its atmosphere were completely transparent to all electro-magnetic radiation) then assuming a planetary albedo of 30%, the average surface temperature required to balance the heating effect of energy received from the sun, would be 255ºK. Its infra-red spectrum would be represented by a smooth white trace just below the 260ºK line.

Enlarge Image



2.3 The presence of greenhouse gases in the atmosphere prevents a proportion of infra-red radiation from leaving the troposphere. The average surface temperature is therefore increased to 288ºK (15ºC). At this temperature the energy budget is balanced. The decrease in infra-red radiation in the wavelengths affected by the greenhouse gases is compensated by increase in infra-red radiation in those areas of the spectrum unconstrained by the greenhouse effect. The yellow trace in the diagram displays the current distribution of radiant energy across the infra-red spectrum of planet earth.

2.4 If the **reflectivity of the planet** is modified by, for example, change in land use, temperature driven decrease in the area, duration or reflectivity of snow and ice cover, increase in scattering particulates in the atmosphere, or change in cloud behaviour, then the average surface temperature will adjust to compensate.

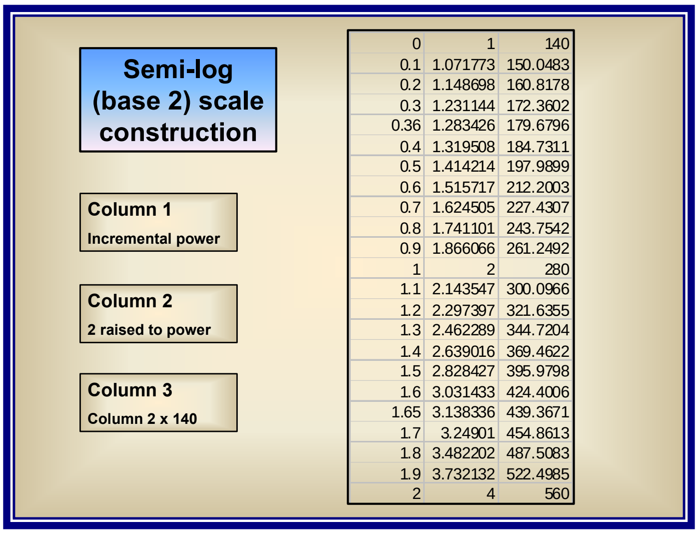
2.5 If there is any **increase in the concentration of existing greenhouse gases**, or the introduction of new greenhouse gases generated by processes of the global chemical industry, then the average surface temperature increases to a new dynamic equilibrium in order to re-balance the energy budget of the planet. Change in atmospheric composition is initially driven by anthropogenic emissions. As the average surface temperature begins to rise to compensate, a 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.

2.6 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 reduce its efficiency as a greenhouse gas. The forcing associated with each doubling is a constant 4 watts per square metre (wm^{-2}) at the earth surface. That requires a change of 1.2ºC 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.

3. Constructing the Graphic Simulator

3.1 While the graphical display of logarithmic functions communicates fairly well within the mathematical community, non-mathematicians often struggle to understand their significance. This paper has therefore 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.

Enlarge Image



Semi-log (base 2) scale construction

Column 1
Incremental power

Column 2
2 raised to power

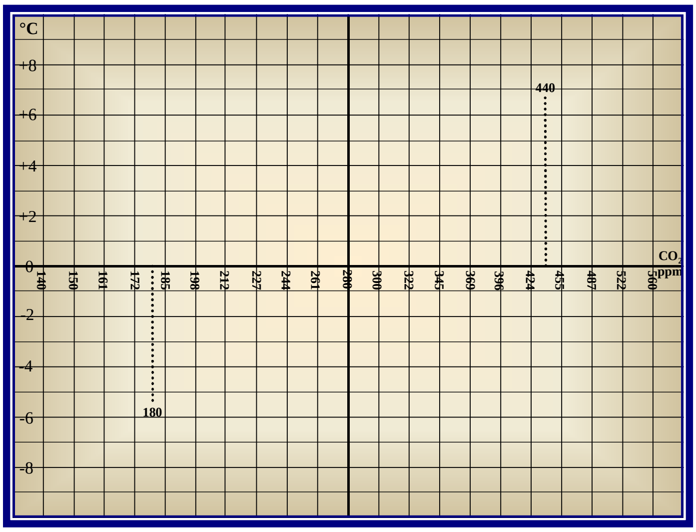
Column 3
Column 2 x 140

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

3.2 The tables present the **basis on which the semi-log display is constructed**. 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. 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 in 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 c.e. 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.

3.3 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:

Enlarge Image



3.4 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.

3.5 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.

4. CO_2 Forcing and the Effects of the Feedback System

4.1 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 dynamic feedback system.

4.2 **The effect of doubling CO_2 concentration on its own is extremely accurately known from observation, theoretical calculation and laboratory testing.**

4.3 It stands at 1.2°C and is represented by the black line on the semi-log scale below. The forcing generated by such an intervention is also accurately known to be 4.0 wm^{-2}.

4.4 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. The ‘black body’ value is adjusted to take account of the emissivity of the planet. The change in radiation from the earth generated by a change of 1ºC in surface temperature is 3.3wm^{-2}.

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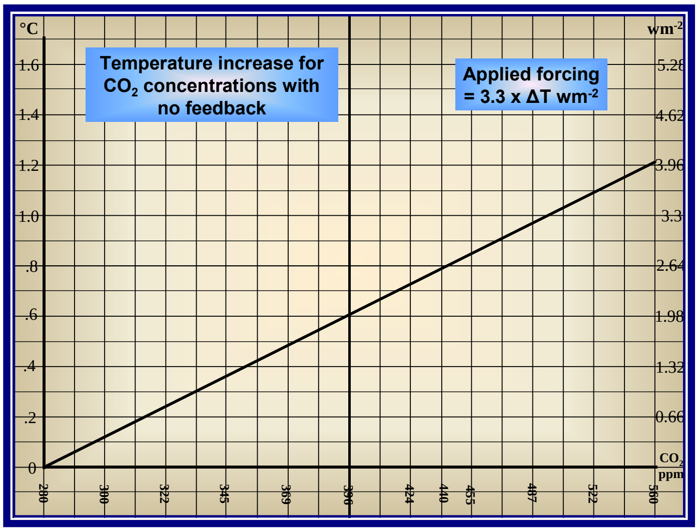
Image



4.5 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.

4.6 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.

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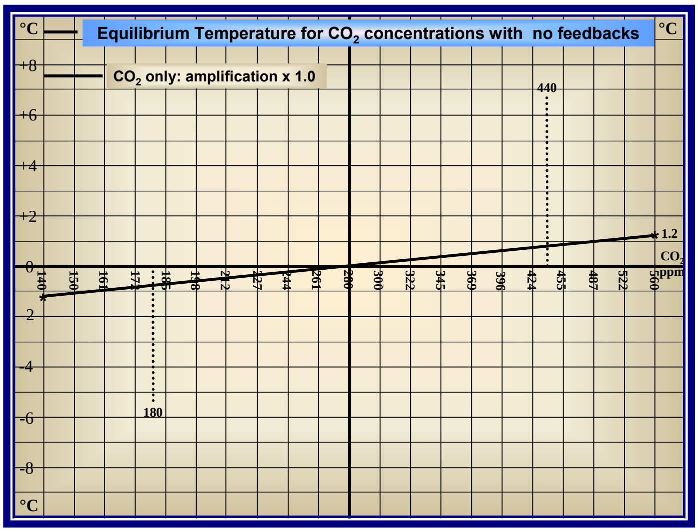

4.7 Conversely the effect of doubling the concentration from 140 ppm to 280 ppm (the pre-industrial value) is the same as halving it from 560 ppm to 280 ppm. In all cases the change is 1.2ºC.

5. For Clarification: Four Complementary Definitions

5.1 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.

5.2 **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.

5.3 **The amplification factor (AF)** differentiates between the role of the change in concentration of atmospheric CO_2, and that of the feedback system. It 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 representing the contribution of the interdependent set of feedbacks in the earth system dynamic. The relationship is represented by the equation:

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

5.4 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.

5.5 **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.

5.6 **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.

5.7 With this set of definitions in mind we can now 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.

6. The Charney Sensitivity

6.1 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?”**

6.2 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 ignores the 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.”**

6.3 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”.**

6.4 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”**. (p17) This is the “Charney Sensitivity” graph presented as the blue line in the semi-log format below.

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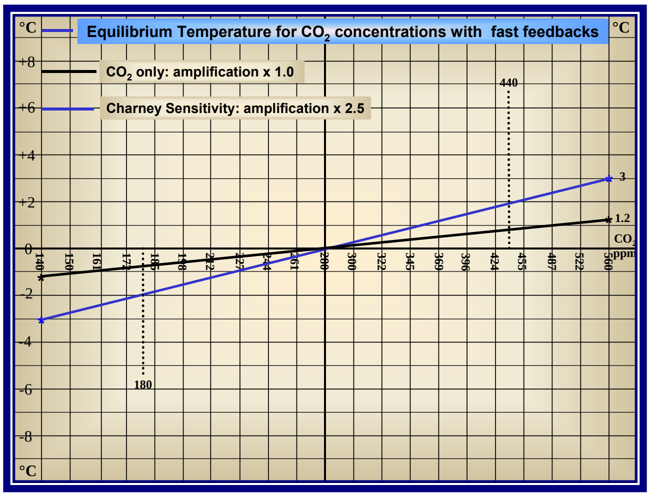

6.5 The body of the Report notes **“a probable error of +/- 1.5ºC”** but for the sake of clear communication, the uncertainty shading around the central line is omitted in this presentation. The 3ºC increase for a doubling of concentration of atmospheric CO_2 is constant whether the starting point is 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 c.e., 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 $0.75^{\circ}Cw^{-1}m^{-2}$.

7. Adding the Carbon-cycle Feedbacks: the Hadley Sensitivity

7.1 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.

7.2 **Ocean-based feedbacks of the carbon-cycle 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:

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

7.2.2 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.

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

7.2.4 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].

7.2.5 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%)

7.3 **Two further feedbacks of the ocean carbon-cycle actively increase the flow of CO_2 to the atmosphere:**

7.3.1 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.

7.3.2 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 (a slow endothermic process). 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.

7.4 **The set of land-based feedbacks of the carbon-cycle includes the following:**

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

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

7.4.3 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].

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

7.4.5 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.

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

7.5 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.

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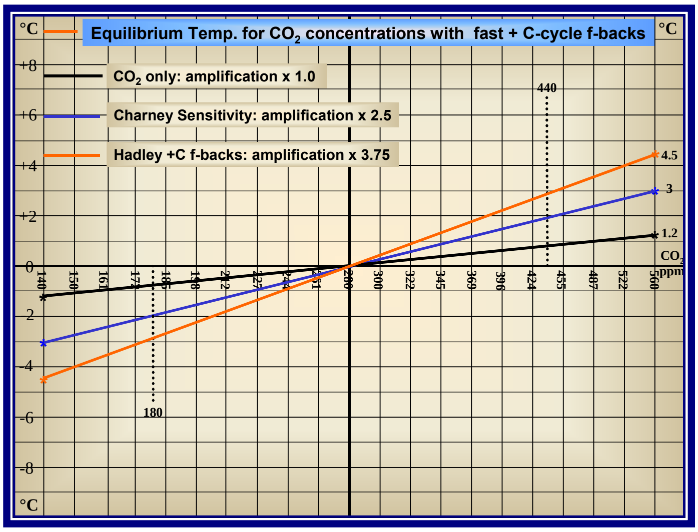

7.6 The value of the Hadley Sensitivity is therefore approximately 4.5ºC for a doubling of atmospheric concentration of CO_2. That in turn correlates with an Amplification Factor of 3.75 times the effect of CO_2 on its own, and a Temperature-Forcing ratio of 1.125ºCw^{-1}m^{-2}.

8. Incorporating other Slow Feedbacks: the Hansen Upgrade

8.1 In his most recent writing ("Paleoclimate Implications for Human-Made Climate change", draft text, released 18th January 2011), James Hansen concentrates exclusively on working with the fast feedbacks and a climate sensitivity of 3ºC for a doubling of CO_2, the criteria that underlie the Charney Sensitivity. His methodology, however depends on paleo data and calculations of total fast-feedback forcing, giving a quasi-empirical value with much higher certainty than is provide by the modelling ensemble. He notes:

> 8.1.1 "This empirical climate sensitivity incorporates all fast response feedbacks in the real-world climate system, including changes of water vapour, clouds, aerosols, aerosol effects on clouds, and sea ice. In contrast to climate models, which can only approximate the physical process and may exclude important processes, the empirical result includes all processes that exist in the real world – and the physics is exact" [op. cit. p5]

8.2 And again:

> 8.2.1 "The empirical result is more precise, and it includes all real-world processes. Moreover, by examining observed climate change over several Milankovic oscillations it is now possible to further reduce the uncertainty in this fast-feedback sensitivity." [op. cit. p6]

8.3 Unfortunately his analysis does not support these claims. He uses the figure of 5ºC for the change in global temperature between the last ice-age and the Holocene (a value which does indeed incorporate all effects of all processes in the earth system in conditions of dynamic equilibrium). He calculates the forcing from changes in CO_2, CH_4, and N_2O over the same period, summing the values to 3 wm^{-2}. To this he then adds his calculated value of 3.5 wm^{-2} for forcing from albedo change in ice-sheets and vegetation, making a total forcing of 6.5 wm^{-2} which most certainly does not take account of all effects of all processes in the earth system. Dividing the temperature change by the total forcing provides a figure of 0.75ºC per wm^{-2}. This corresponds to 3ºC for a doubling of CO_2 concentration (a forcing of 4.0 wm^{-2}) and it is this "empirical sensitivity" that he notes as being in agreement with the Charney sensitivity and the outputs of modern climate models. The correlation is purely accidental. The total forcing he uses takes no account of water vapour feedback, lapse rate, or cloud feedbacks, all of which are categorised as fast feedbacks and taken into account by the Charney sensitivity and modern climate models.

8.4 The extra heat radiated to the cold spatial sink by the planet amounts to 3.3 wm^{-2} for every degree rise in temperature. An increase of 5ºC therefore requires a total forcing from all sources of 16.5 wm^{-2} if dynamic equilibrium is to be maintained. It is clear that Hansen has lost a net forcing of 10 wm^{-2}. His resulting calculation of "empirical sensitivity", while accidentally agreeing with the Charney value, is a gross underestimate of the sensitivity of the whole earth system.

8.5 That raises the fundamental "Emperor's Clothes" question of climate science:

> 8.5.1 **"If the Charney sensitivity, supported by our modern computer models, projects that a doubling of the concentration of atmospheric carbon-dioxide leads to a temperature rise of 3ºC at equilibrium, then why, in the empirically measured behaviour of the planetary system, does an increase of only 56% in CO_2 concentration (from 180 ppm to 280 ppm) lead to a 5ºC change in temperature?"**

8.6 If we take into account the non-linear relationship between the variables as expressed in the semi-log (base 2) presentation, the 56% increase in absolute value of the CO_2 concentration across this particular range, equates to only 63.4% of the effect of doubling, i.e. a forcing of 2.54 wm^{-2}. Applying the Charney Sensitivity to this proportion yields an increase of only 2ºC for the change from coldest point of the ice-age to the pre-industrial benchmark. Historical data tells us that the shift should be 5ºC. It just does not compute. The inescapable conclusion is that the computer modelling ensemble, together with the Charney sensitivity and supported by Hansen's "empirical sensitivity" are all omitting something fundamental. They are grossly under-representing the contribution of the complex feedback system to the amplification of the effects of change in CO_2 concentration.

8.7 **The implications are profound. The whole international strategic response to climate change is based on the output of the computer ensemble. The basis is recognised to be "conservative", but to be under-representing the threat by a factor of two-and-a-half is a culpable collusion with a process of collective denial.**

8.8 In an attempt to close the gap between computer modelling and empirical measurement, Hansen et al offered a hybrid solution in their earlier paper "Target Atmospheric CO_2: Where Should Humanity Aim?", published March 2008 [7]. They started with the assertion:

8.8.1 "Paleoclimate data show that climate sensitivity is ~3ºC for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6ºC for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica." [op. cit. p1]

8.9 The methodological approach is summarised in the paragraph:

8.9.1 "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." [op. cit. p2]

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

8.10.1 "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." [op. cit. p4]

8.11 This "Hansen Upgrade" is represented by the green line on the semi-log (base 2) scale. The sensitivity of 6ºC for a doubling of CO_2 yields an Amplification Factor of 5.0. However, it still falls short (by some 4 wm^{-2}) of the forcing required to balance a 5ºC rise in temperature.

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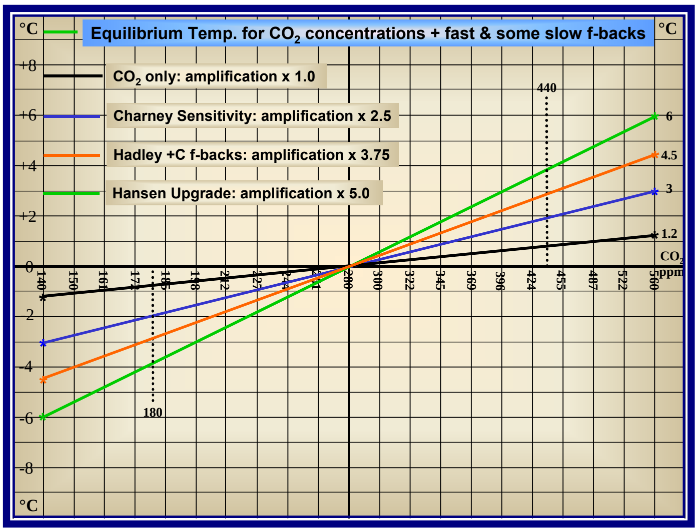

9. Earth System Sensitivity

9.1 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.

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9.2 In empirical terms 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**. It is the holistic, reality-based, figure towards which the modelled values are partial approximations.

9.3 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.

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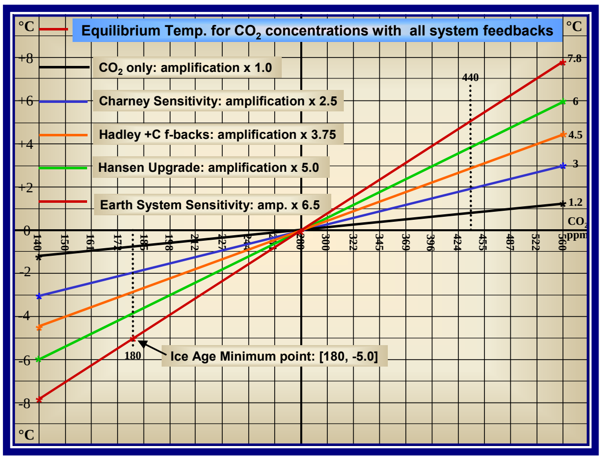

9.4 **Ice-Age Anchor Point.** The concentration of atmospheric CO$_2$ in the depth of each of the last four ice ages stood at 180 ppm. Utilising the correlate symmetry of halving and doubling effects in the semi-log (base 2) presentation scale, we note that at this concentration value of 180 ppm:

9.4.1 Taking account of the contribution of the CO_2 with no feedback amplification we arrive at a correlate temperature 0.8ºC below the pre-industrial benchmark.

9.4.2 Using the Charney amplification factor of 2.5 the figure decreases to -2.0ºC.

9.4.3 Incorporating the carbon cycle feedbacks of the Hadley model yields -3.8ºC.

9.4.4 Adding other slow feedbacks for the Hansen amplification factor yields -4ºC.

9.5 **However, 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.**

9.6 This provides us with an 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 line is of course the pre-industrial benchmark of 280 ppm and 0.0ºC. Projecting that forward into the next doubling of CO_2 concentration yields an **AF** of 6.5, a climate sensitivity of 7.8ºC, and a Temperature-Forcing ratio of $2^{\circ}\mathrm{C}\,\mathrm{W}^{-1}\mathrm{m}^{-2}$. **Those figures are just over 2½ times the values derived from the Charney Sensitivity.**

10. Testing the Earth-System Sensitivity (a): Engelbeen

10.1 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.

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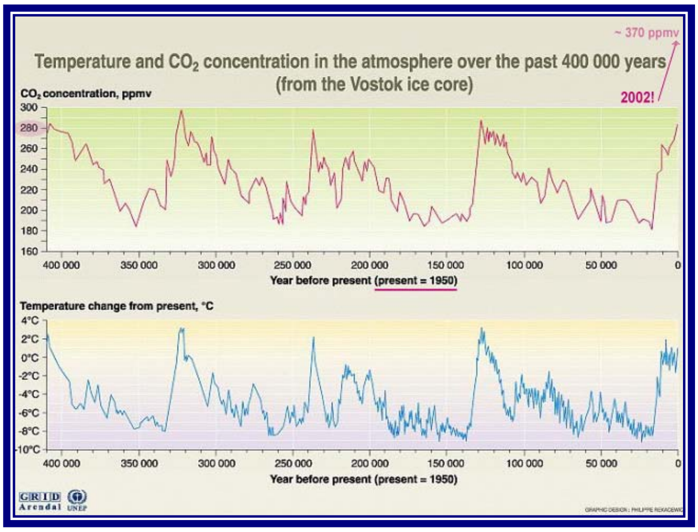

10.2 In 2005, Ferdinand Engelbeen, a Belgian scientist, conducted a regression analysis of the correlated values of temperature and CO_2 concentration based on the Vostok records. It was posted on the Real-Climate web site and little further attention was paid to it [9].

10.3 He 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 1ºC 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 $^{\circ}\mathrm{C}^{-1}$ 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.

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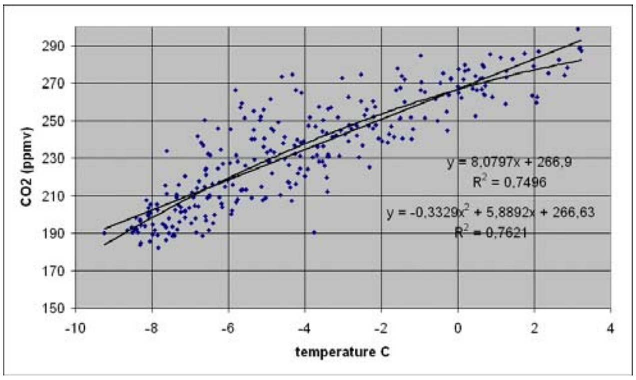

See: **http://www.ferdinand-engelbeen.be/klimaat/correlation.html**

10.4 Temperature change at Vostok is a just over twice that for the average surface temperature of the whole earth. So an 11ºC shift at Vostok translates to a 5ºC change for the global value (a ratio of 0.45). Applying this ratio to Engelbeen's figure we arrive at 17.8 ppm ºC^{-1} for the sensitivity of the earth system as a whole across the range of CO_2 concentration from the depth of the ice-ages to the maximum of the warm interglacial periods.

10.5 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 halved. The logarithmic relationship between concentration and forcing therefore requires a halving of his sensitivity value from 17.8 ppm ºC^{-1} to 35.6 ppm ºC^{-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 7.1ºC at a concentration of 534 ppm.

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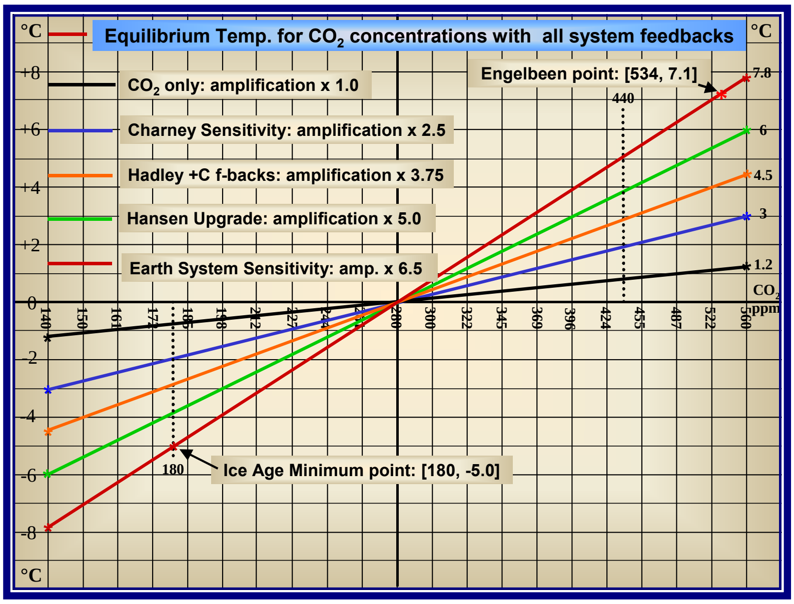

10.6 The Engelbeen point is on the same straight line as the other two anchor points, and would appear to provide significant corroboration of the amplification factor for the whole earth system.

10.7 ***Note:** The Engelbeen sensitivity, of ppm per 1ºC change in temperature, varies logarithmically with the concentration of atmospheric CO_2. His regression analysis smoothes out this variability over a range of about 100 ppm. If we therefore apply his sensitivity value of 17.8 ppm per 1ºC at concentration of 267 ppm, to a hypothetical halving of CO_2 concentration from 280 ppm to 140 ppm, we arrive at a figure of 7.86ºC below the pre-industrial benchmark. The figure is of course mirrored to an increase of 7.86ºC above the pre-industrial benchmark for a doubling of CO_2 concentration to 560 ppm. That gives confidence that applying the sensitivity of 35.6 ppm per 1ºC at 534 ppm should provide a good approximation for the equilibrium temperature increase due to the change in concentration of 254 ppm over the range from 280 to 534 ppm.

11. Testing the Earth-System Sensitivity (b): Pagani

11.1 Towards the end of 2009, Mark Pagani et al published a paper on “High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations” [Nature Geoscience Letters 20 December 2009] [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”.

11.2 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].

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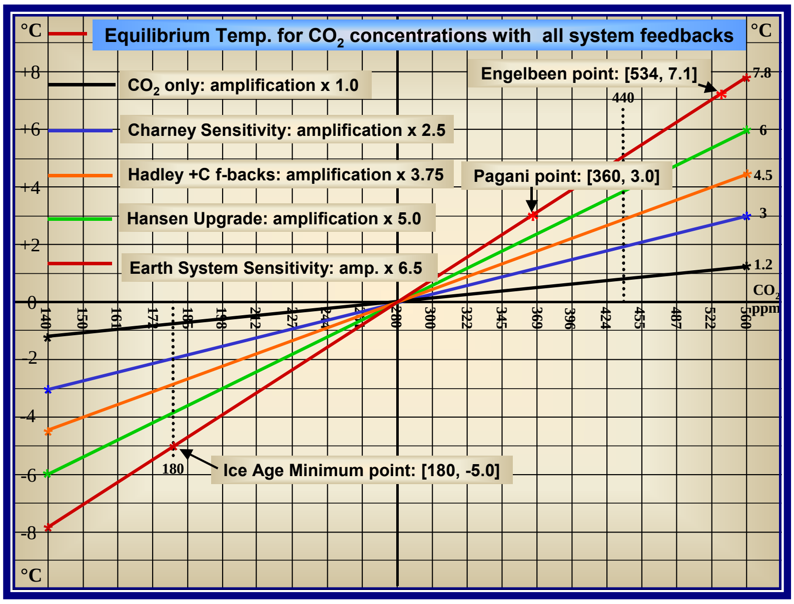

11.3 It is worth noting that values for both the Engelbeen and Pagani points had to be constrained towards the lower range of their probabilities, indicating that the value of 6.5 for the amplification factor of the Earth-system sensitivity may still be somewhat conservative and should be regarded as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

12. An Overview of Paleo Evidence for the ESS: Kiehl Perspective

12.1 Writing in the "Perspectives" section of the Jan. 2011 edition of Science, 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 feedback factor is ~2ºC$w^{-1}m^{-2}$. 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.

12.2 Re-working Kiehl's figures using the graphic simulator leads to a marginally higher outcome. Earth surface temperature decreased by 16ºC 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 dynamic feedback system. That yields an amplification factor of 7.0, a sensitivity value of 8.47ºC for a doubling of CO_2, and a climate feedback factor of 2.1ºC$w^{-1}m^{-2}$.

13. A Concluding Mathematical Check-out

13.1 As has been noted before, the Radiative Damping coefficient for planet earth stands at 3.3 $wm^{-2\circ}C^{-1}$ (Derived from an application of the Stephan-Boltzman law of black-body radiation adjusted for the emissivity factor for the planet). In other words, for each degree rise in average surface temperature of the earth surface an extra 3.3 wm^{-2} is radiated to space. Maintaining the dynamic thermal equilibrium therefore requires a forcing from all sources of 3.3 $wm^{-2o}C^{-1}$. The change in temperature between the last glacial minimum and the pre-industrial benchmark is known to be ~5ºC. That requires a total forcing of 16.5 wm^{-2}.

13.2 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 dynamic 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 AF by a factor of 1.2 (temperature increase from a doubling of CO_2 with no feedbacks) yields a climate sensitivity value of 7.79ºC. (Compare with sensitivity value of 7.8ºC derived from the graphic simulator.) Dividing the sensitivity by 4.0 (the forcing from a doubling of CO_2) gives a temperature-forcing ratio (feedback factor) of 1.95.

13.3 We are also now in a position to account for the 16.5 wm^{-2} change in forcing for the period since the last glacial minimum. CO_2 forcing stands at 2.5 wm^{-2}. Water vapour feedback including the lapse-rate feedback stands at 1.5 $wm^{-2o}C^{-1}$, so for an increase of 5ºC this provides a feedback forcing of 7.5 wm^{-2}. Hansen's forcing for CH_4 and N_2O is 0.8 wm^{-2}. His calculation for ice and vegetation albedo feedback stands at 3.5 wm^{-2}. Finally best current estimate of cloud feedback stands at 0.5 $wm^{-2o}C^{-1}$, yielding 2.5wm^{-2} for the 5ºC change. The total of 16.8 wm^{-2} correlates well with the required value of 16.5 wm^{-2}.

14. Of Probabilities and Uncertainties

14.1 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 temperature scale.

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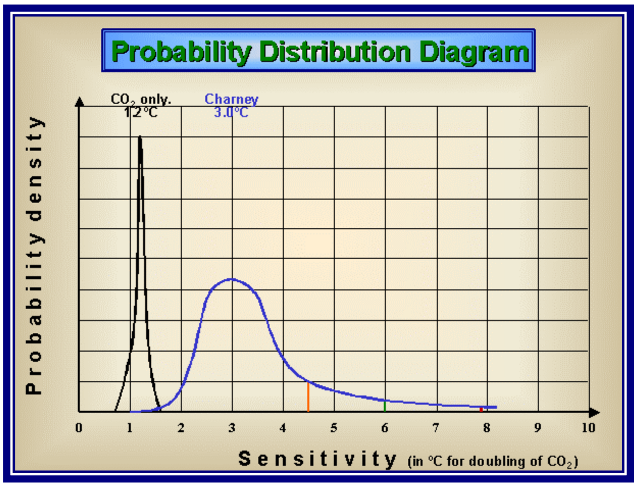

14.2 The ensemble of climate models on which the IPCC Fourth Assessment Report [12] was based, was used by Meinshausen et al to generate the probability density function (PDF) of climate sensitivity [13]. It reaffirmed the 3ºC value of the Charney Sensitivity, shown as the blue distribution. It has a 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.

14.3 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.

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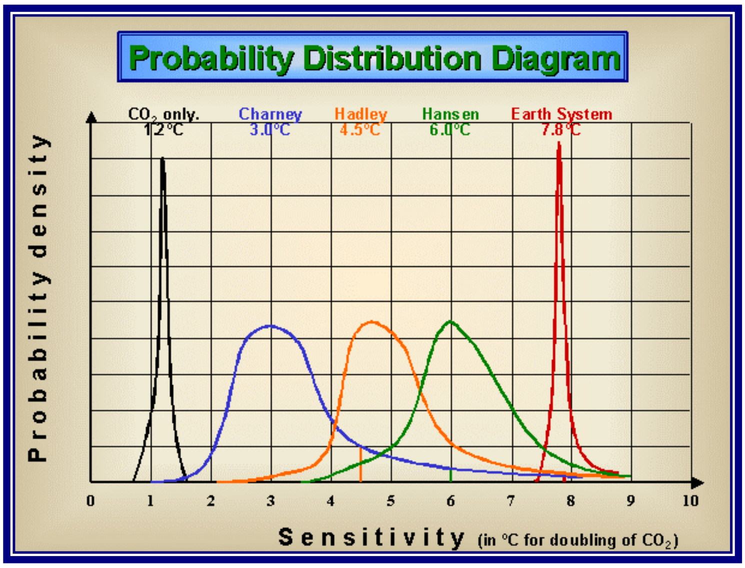

14.4 For the Charney, Hadley and Hansen values, large uncertainties are associated with difficulties in quantifying and modelling the complex set of feedback processes and their dynamic interrelationships. That leads to comparatively wide spread in the probability ranges.

14.5 **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.

14.6 **The high level of certainty associated with the Earth System Sensitivity of at least 7.8ºC for a doubling of CO_2, requires that the Charney Sensitivity (of 3ºC) should now be abandoned and replaced by that figure for all future strategic negotiations.**

15. Adding the 350 ppm marker

15.1 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. It provides a basic visual context in which to explore and evaluate the range of policy proposals currently being considered by the world community.

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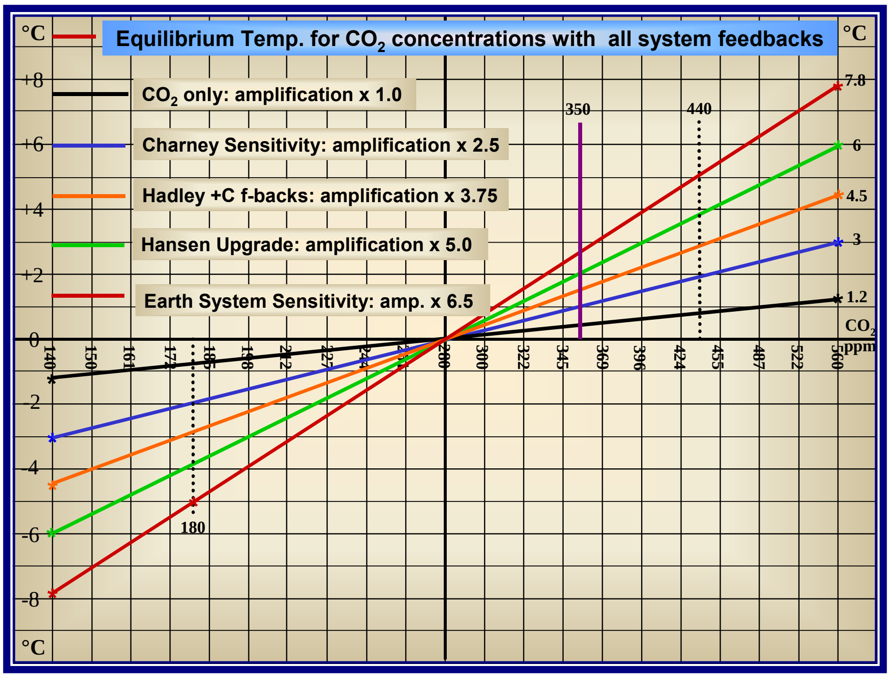

16. A Survey of Correlations and Consequences

16.1 1. The Charney Sensitivity line intersects the 2ºC 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 2ºC 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 2ºC 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 2ºC 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 5ºC above the pre-industrial benchmark In this case the 2ºC guardrail has already been overwhelmed by some 60 ppm. The 2ºC threshold was passed when the concentration reached 330 ppm.

16.2 2. 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 3ºC [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 commons 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 2ºC beyond the pre-industrial benchmark.

16.3 3. If we explore the Hansen amplification factor of 5.0 (a sensitivity of 6ºC for a doubling of atmospheric CO_2) then we see he predicts an equilibrium of rise of 4ºC with a stabilised CO_2 concentration of 440 ppm. The “safe” ceiling of 2ºC 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].

16.4 4. The “One Degree War Plan” of Randers and Gilding [20] is grounded in the Charney sensitivity which cuts the 1ºC 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 1ºC level at a value of some 310 ppm of atmospheric CO_2, requiring a draw-down of around 536 GT below the current level.

16.5 5. 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 2ºC threshold when we apply the Earth System sensitivity.

17. Exploring the C-ROADS Simulator

17.1 Using the best available expertise in system dynamics simulation, field leaders from the MIT Sloane School of Management and Ventana Systems created 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. The simulator is now hosted independently at www.ClimateInteractive.org.

Enlarge Image

CLIMATEINTERACTIVE

C-ROADS

(Climate Rapid Overview and Decision Support)

The Climate Scoreboard

www.climateinteractive.org

17.2 Its underlying model architecture has been stringently reviewed by an august panel of leading scientists. They 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 Nov. 2010 prior to the COP 16 gathering in Cancun.

17.3 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. (UNEP p.38) 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.

Enlarge Image

17.4 The set of proposals was updated over time and by 31st August the scoreboard was showing a probable rise in global temperature of 4.0ºC above the pre-industrial benchmark by the year 2100. In preparation for the Cancun gathering the figures were further updated as of the 27th November at which point the temperature rise was reduced to 3.8ºC. The range of uncertainty was indicated by the shading around the simulated value.

17.5 It is difficult to overemphasize the significance of the climate sensitivity value that is embedded in the C-ROADS simulator. It is fundamental to the prediction of the outcome rise in temperature as well as the calculation of the budget of available capacity of the global commons to assimilate further emissions before passing the "safe guardrail" of 440 ppm.

17.6 The ClimateInteractive.org website clarifies their assumptions as follows:

Important assumptions

- Climate sensitivity set at 3.0
- Simulation doesn't include several positive feedbacks found in the climate system, results are therefore provide a **conservative** picture of future climate impacts

17.7 The C-ROADS simulator uses the Charney Sensitivity and limits the effects of positive feedback to the fast mechanisms associated with that value.

17.8 Co-incidentally, the UNEP "Emissions Gap Report" prepared for the COP16 gathering in Cancun is based on the same set of assumptions. The authors note that:

17.8.1 "A joint probability distribution of the most important climate response uncertainties has been used, with climate sensitivity uncertainties closely reflecting the estimate provided by the IPCC (4th Assessment Report 2007). The climate sensitivity distribution used for the analysis throughout this report is the "illustrative default" case as described in Meinshausen et al. (2009). This distribution gives the probability of a particular response of temperature to emissions." (p 32)

17.9 Or again:

17.9.1 "Important uncertainties exist in our understanding of the climate system…. Future shifts in the underlying probability distributions, as a result of improved understanding of parameters and/or feedbacks in the climate system, could change the expected probability with which a certain pathway would meet a specified temperature limit." (p 36)

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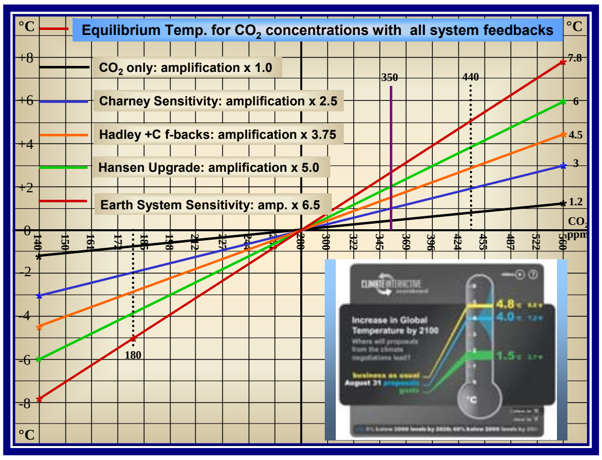

17.10 Returning to examine the "Scoreboard" thermometer of the C-ROADS simulator against the background of the climate sensitivity grid. We note that the intersection of the 4ºC horizontal line with the slope of the Charney Sensitivity (blue line) is off the scale to the right. In order to accommodate 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 set out below:

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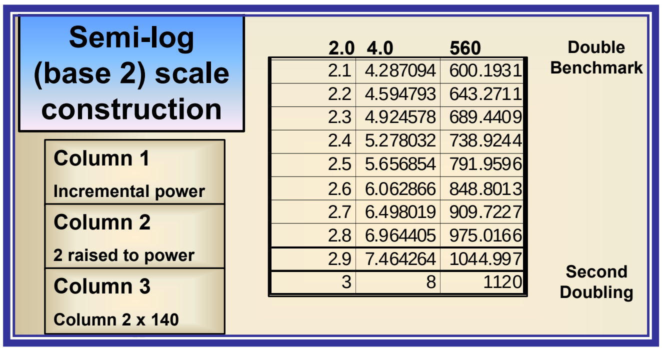

Semi-log (base 2) scale construction

Column 1
Incremental power

Column 2
2 raised to power

Column 3
Column 2 x 140

2.0	4.0	560
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

Double Benchmark

Second Doubling

17.11 In the next illustration the upper right quadrant of the Sensitivity Grid has been moved to the lower left position and we have expanded the scale to encompass the second doubling of CO_2 concentration to 1120 ppm.

17.12 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.

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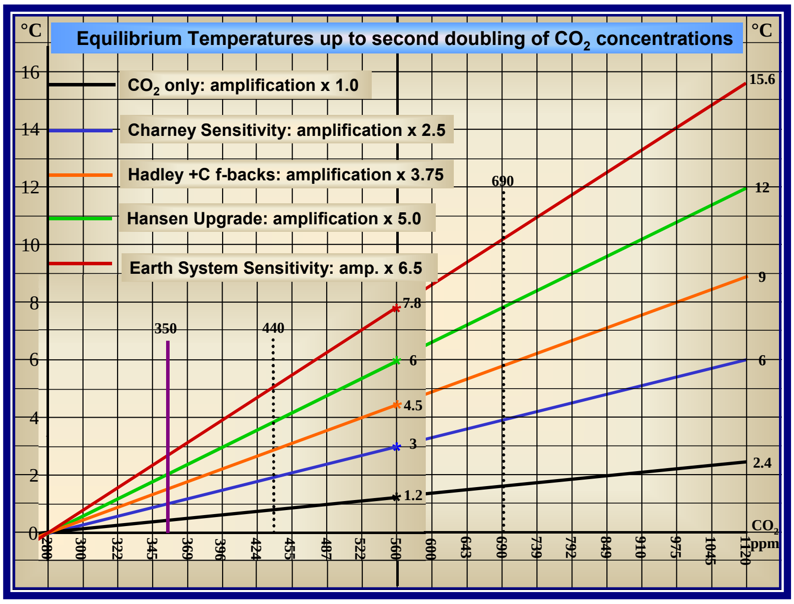


17.13 It can now be seen that the Charney Sensitivity line intersects the 4ºC level at a concentration just in excess of 690 ppm. However, the C-ROADS simulator calculates outcome temperature rise at the year 2100, and not at eventual equilibrium. A 4ºC rise by 2100 is equivalent to an equilibrium rise of some 4.5ºC. 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.

18. Outlining Implications

18.1 1. Temperature implications of the Copenhagen Accord pledges:

18.1.1 Using the **Charney** Sensitivity (as in C-ROADS) at the year 2100 we would expect a rise of 4.0ºC, increasing to 4.5ºC at equilibrium.

18.1.2 Using the **Hadley** amplification factor, we would expect 5.9ºC at 2100, rising to 6.7ºC at equilibrium.

18.1.3 With the **Hansen** amplification we would expect 8.0ºC at 2100, rising to 9.0ºC at equilibrium.

18.1.4 Applying the **Earth System Sensitivity** we would now predict 10.4ºC at 2100, rising to 11.8ºC at equilibrium.

18.2. 2. Caveats associated with the Copenhagen Accord pledges:

18.2.1 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 figures might be too high. However, the eventual equilibrium values would not be affected.

18.2.2 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.

18.2.3 Promises are not actions. There are considerable doubts concerning the ability of the various nations to deliver the pledged reductions in emissions.

18.2.4 No account is taken of non-CO_2 greenhouse gases, the effect of which could increase the whole range of temperature outcomes by over 15%

18.3. 3. Collapse of the budget approach:

18.3.1 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 to the Copenhagen Accord would imply a further release of some 5,800 GT of CO_2.

18.3.2 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 2ºC were to be respected.

18.3.3 For sensitivity values above the Charney figure the commitment to limiting the increase in equilibrium temperature to 2ºC collapses the budget into a debt requiring net negative emissions.

18.3.4 Reduction of 1 ppm requires draw-down of 7.25 GT. This is half the figure of the emissions needed to increase concentration by 1 ppm, since the global commons absorb approximately 50% of emitted CO_2.

18.3.5 For example using the Hadley amplification factor, then at the current concentration of 390 ppm we have already overshot the budget threshold and require a draw-down of 32.6 GT CO_2. That increases to 261 GT with the Hansen upgrade, and rises to net negative emissions of 392 GT in the light of the Earth System Sensitivity.

18.3.6 If the contribution to climate change from non-CO_2 greenhouse gases is included then we already have a concentration of some 450 ppm CO_{2e}. Even the Charney Sensitivity would require net negative emissions of 72.5 GT if the 2ºC threshold were to be protected. Hadley would increase the figure to 467.6 GT, Hansen to 696 GT, while the Earth System Sensitivity would require a massive draw down of some 827 GT of CO_{2e}.

18.4. 4. Limiting the temperature increase to 1ºC above the pre-industrial benchmark:

18.4.1 If the proposals from the World People's Congress on Climate Change held in Bolivia in April 2010 [23] were to be implemented then the Earth System Sensitivity indicates that concentrations of atmospheric CO_2 should stabilise at not more than 310 ppm.

18.4.2 That 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}.

18.4.3 For the Charney Sensitivity the figures would be 350 ppm, 290 GT CO_2, and 725 GT CO_{2e}.

18.4.4 Hadley value would imply 330 ppm, 435 GT CO_2, and 870 GT CO_{2e}.

18.4.5 The Hansen sensitivity would require 318 ppm, 522 GT CO_2, and 957 GT CO_{2e}.

18.4.6 Note: 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.

18.5. 5. Temperature increases already in the pipe-line:

18.5.1 If CO_2 concentration were to be stabilised at the current value of 390 ppm then predictions based on the Charney Sensitivity show an equilibrium rise of 1.6ºC (0.8ºC still in the pipe-line) for CO_2 only, rising to 2.0ºC (1.2ºC still in pipe-line) for CO_{2e}.

18.5.2 Figures for Hadley are 2.2ºC (1.4ºC) for CO_2 and 3.0ºC (2.2ºC) for CO_{2e}.

18.5.3 The Hansen amplification yields 3.0ºC (2.2ºC) for CO_2 only, and 4.1ºC (3.3ºC) for CO_{2e}.

18.5.4 The Earth System Sensitivity would indicate an expected rise in temperature at equilibrium of 3.8ºC. There is therefore an expected rise of 3.0ºC still in the pipe-line, to which we are already committed. If non-CO_2 GHGs are included then the expected increase would rise to 5.4ºC (4.6ºC still in the pipe-line).

18.6 Towards a Time-Frame for Strategic Intervention

18.6.1 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.

18.6.2 Over the last three decades of the twentieth century, the average surface temperature of the planet increased at a rate of 0.13ºC per decade. During the same period, the net radiative imbalance (NRI) of the earth varied between 1.0 and 1.6 watts per square metre. That now allows us to calculate a first order approximation for the thermal inertia coefficient of the whole earth system, giving a value of 0.1ºC per decade per watt per square metre of NRI.

18.6.3 Given the current understanding of the threshold of dangerous climate change as a rise of 1.5ºC above the pre-industrial benchmark, we have a buffer of only 0.7ºC of further increase beyond that already activated. Using the Earth System Sensitivity, the maximum CO_{2e} concentration that would lead to such an equilibrium outcome is at most 320ppm. If the net radiative imbalance peaks at $2wm^{-2}$, it would have to decay to zero in the time taken for the average surface temperature of the planet to increase by a further 0.7ºC. If we approximate the decay pattern to a linear path, the temperature increase would average 0.1ºC per decade. That gives us seven decades to complete the strategic intervention required to stabilise the planetary climate.

18.7 Essential Elements of the Strategic Intervention:

18.7.1 Termination of all activity that increases Net Radiative Imbalance.

18.7.2 Implementation of an aggressive programme of net negative emissions (i.e. draw-down economy) at a global level.

18.7.3 The achievement of a reduction in atmospheric concentration of CO_{2e} of some 130 ppm or 942 GT of CO_2 from the 2010 figure, to be completed by the year 2080.

18.7.4 Additional draw-down of an amount equivalent to 50% of all further emissions beyond the 2010 total, to be completed by the same date.

18.7.5 Notes:

18.7.6 a) If further research showed that even a ceiling of 1.5ºC increase is too high to avoid dangerous climate impacts, then the time frame would have to be shortened and the ceiling lowered.

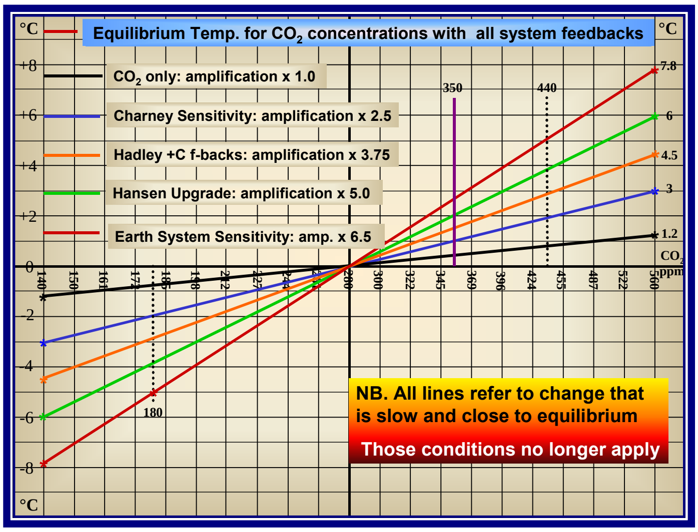
18.7.7 b) If the amplification factor were to increase during the period of far-from-equilibrium dynamics, the draw-down of atmospheric CO_2 would have to be more severe.

18.7.8 c) If the strategic intervention failed to constrain the temperature ceiling, then a period of negative NRI would have to be initiated to reduce the temperature increase to the required figure.

19. Rapid Climate Change in Far-from-Equilibrium Conditions

19.1 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.

19.2 **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.**



Enlarge Image

19.3 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).

19.4 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.

19.5 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:

19.5.1 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.

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

19.5.3 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.

19.5.4 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.

19.5.5 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.

19.5.6 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.

19.5.7 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.

19.6 **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 ºC for a doubling of the concentration of atmospheric CO_2 should therefore be taken as a conservative minimum figure in our current situation.**

19.7 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.

19.8 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. **The subject of the boundary conditions of runaway behaviour in the earth climate system as a whole is addressed in the second section of this paper under the title of “Beyond the Stable State”.**

* * * * * * * *

20. Conclusion: An Executive Summary

20.1 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.

20.2 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 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 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.

20.3 It is recognised that even the best climate model has 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?"**

20.4 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.**

20.5 Some implications of the revised understanding of Climate Sensitivity are spelled out in the text. For instance:

- 20.5.1 **Increase in Equilibrium temperature** following stabilisation of CO_2 concentration at 440 ppm is revised upwards from 2ºC (Charney) to 5ºC (ESS).
- 20.5.2 **CO_2 concentration consistent with limiting temperature rise to 2ºC** drops from 440 ppm (Charney) to 330 ppm (ESS).
- 20.5.3 **Available budget for further emissions consistent with the 2ºC guardrail** stands at 750 GT CO_2 (Charney). ESS collapses the budget into a massive debt. We are already in overshoot of the capacity of the global commons to absorb our industrial effluent. Maintaining the 2ºC Guardrail requires "negative emissions" (i.e. draw-down from CO_2 already in the atmosphere) of over 390 GT CO_2 to be achieved by 2080.
- 20.5.4 If CO_2 concentration could be stabilised at its current value of 390 ppm, then Charney estimates **temperature increase already in the pipe-line** as 0.8ºC. ESS predicts a further 3.0ºC.
- 20.5.5 The Charney Sensitivity estimates the **outcome of emission control pledges embedded in the Cancun Agreement** at 4.5ºC at equilibrium. ESS predicts an outcome rise of 11.8ºC.

20.6 **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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Appendix 1: Implicit Assumptions Embedded in the Paper

I am indebted to Prof. Chris Rapley for suggesting that the key assumptions implicit in the text of the paper should be made explicit in this way. I am confident that, within the terms of the first-order approximations engaged in the paper, the assumptions do not constitute a significant challenge to the fundamental argument, nor do they require significant qualification of the derived value of climate sensitivity. It will be interesting to note what changes to the analysis would be required if and when future research were to enable detailed quantitative assessment of the assumptive material.

Assumption 1: That the logarithmic relationship between CO_2 concentration and consequent forcing is constant across the range under consideration.

The forcing of 4.0 wm^{-2} attributed to doubling the concentration of atmospheric CO_2 on its own, without taking into account any feedback effects, is deemed to be invariate between concentrations of 180 ppm and 1120 ppm.

Assumption 2: That the value of climate sensitivity is constant between the glacial minimum and the second doubling beyond the pre-industrial benchmark (a range of some 21ºC, spanningCO_2 concentration from 180 ppm to 1120 ppm).

Variation in the detailed effects of the dynamic feedback system is to be expected in relation to increments in CO_2 forcing at different concentrations, temperatures, and levels of glaciation. The coincidence of the sensitivity value operating from glacial minimum to pre-industrial benchmark, with that derived from the transition from the ice-free Antarctic conditions of the Pliocene to the more recent inter-glacial warm periods, gives confidence to this assumption.

Assumption 3: That the value of the Radiative Damping Coefficient is constant for the temperature range under examination.

At the current average surface temperature of 288ºK, the planet radiates an extra 3.3 wm^{-2} for a change of 1ºK. In the equations of the Stefan-Boltzmann law, the value is modified by the fourth power of the absolute temperature. For the purposes of this paper, changes of 2 or 3ºK (i.e. not more than 1%) are deemed non-significant and the value is treated as a constant. Theoretically, when considering larger changes in temperature, (of the order of 10 – 20ºK) we should take account of the appropriate increase in the value of the RDC. However, as John Schellnhüber pointed out in his address to the Oxford 4ºC Conference: “Recent studies with Atmospheric-Oceanic GCMs suggest that radiative damping might not increase with temperature, due to elevated effective radiation height. (*Colman, 2009*)”.

Assumption 4: That the non-CO_2 greenhouse gasses, subsumed in the definition of CO_{2e}, can be treated as having the same logarithmic relationship between concentration and forcing as CO_2 itself.

While this assumption has no bearing on the derivation of the value of Climate Sensitivity, it could modify the projection of equilibrium temperature outcomes when those include the effects of non-CO_2 greenhouse gases. The absorption-efficiency of any greenhouse gas decays with rising concentration, following the logarithmic relationship of a constant effect for a doubling or halving of the concentration value. The calculation of CO_2 equivalence should take this into account, but there would still appear to be some inconsistencies in the methodology.

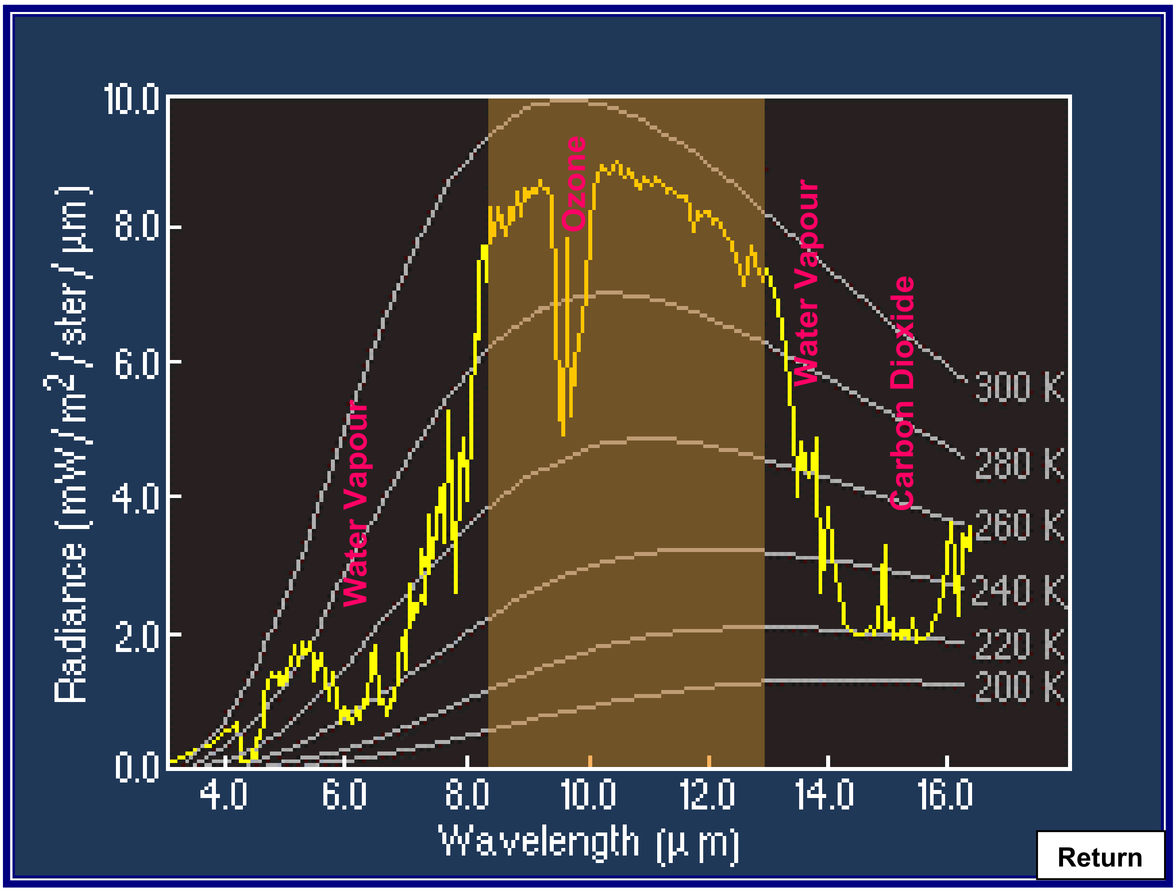
Assumption 5: That the relationship between CO_2 forcing and the associated dynamic feedback system which governs the value of Climate Sensitivity in the Paleo record, remains unchanged in the context of the Anthropocene.

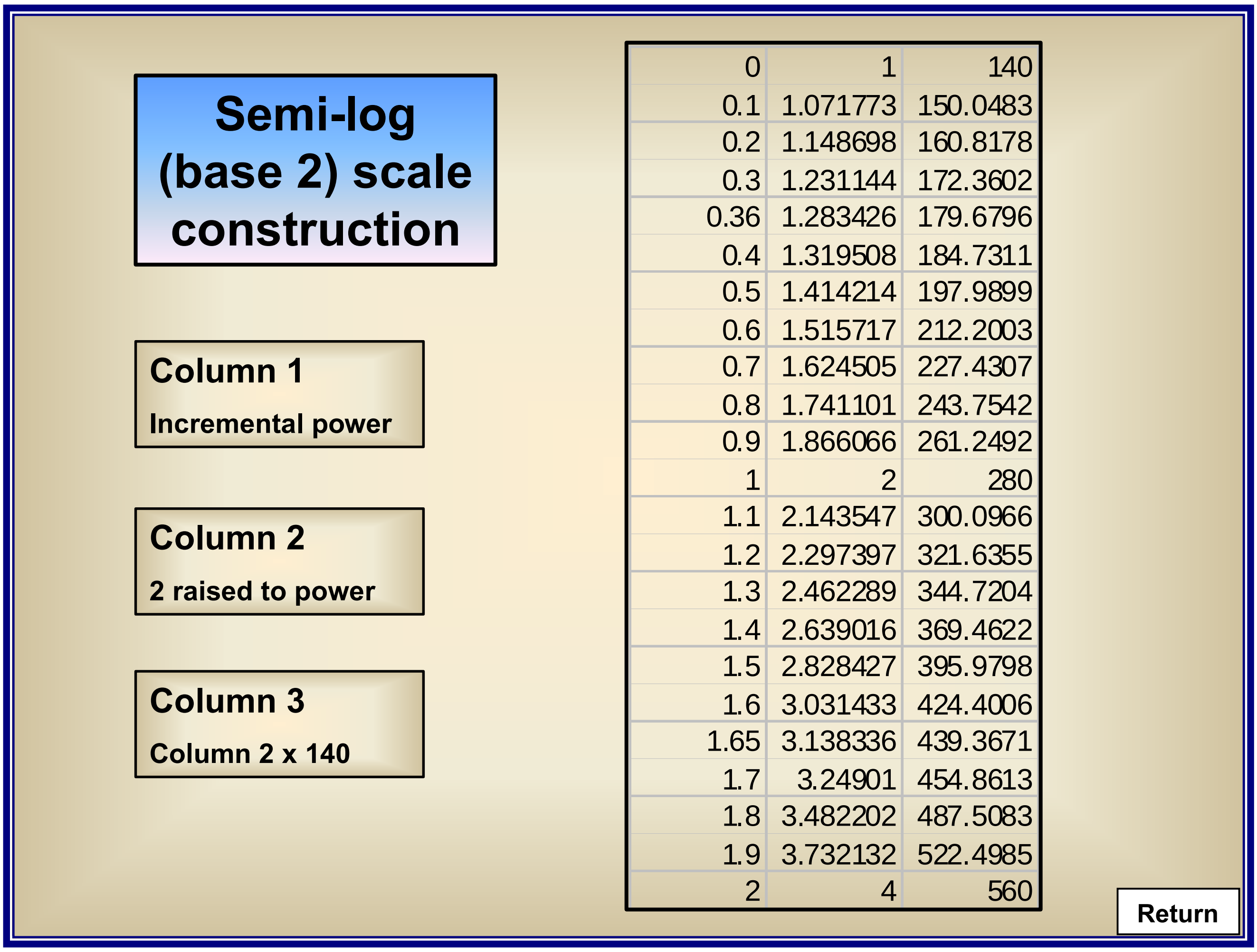
In the current situation, anthropogenic increase in the concentration of atmospheric CO_2 is causal. It generates imbalance in the dynamic thermal equilibrium of the planet, initiates the process of global warming and so triggers the complex interactive set of dynamic feedback mechanisms. These include the non-anthropogenic carbon-cycle feedbacks that further modify the CO_2 concentration.

In contrast, during the period of glacial/inter-glacial oscillation, changes in the concentration of atmospheric CO_2 have been consequential. They are feedback responses to the slight shifts in insolation and its distribution precipitated by the Milankovic cycles (periodic shifts in the shape of the earth orbit and of the tilt and wobble of the earth's axis relative to the orbital plane). The closely coupled correlation between CO_2 concentration and changes in equilibrium temperature enable the calculation of a value of Climate Sensitivity that reflects the amplification of the CO_2 forcing by the associated complex dynamic feedback system.

Justification of the assumption that we can apply this value of Climate Sensitivity to the projected climate response in the Anthropocene, is derived from the studies of the Pliocene correlation between temperature and CO_2 concentration. Here the change in CO_2 concentration is driven by mechanical and geo-chemical responses to tectonic activity. In parallel to the Anthropocene, the forcing is causal of the climate change. The fact that, under these conditions, the value of Climate Sensitivity would appear to be identical to that derived from the period of glacial/inter-glacial oscillation indicates that the direction of causality is non-significant. We can therefore apply the derived sensitivity value to the conditions of the Anthropocene with confidence.

Appendix 3: Library of Enlarged Visuals





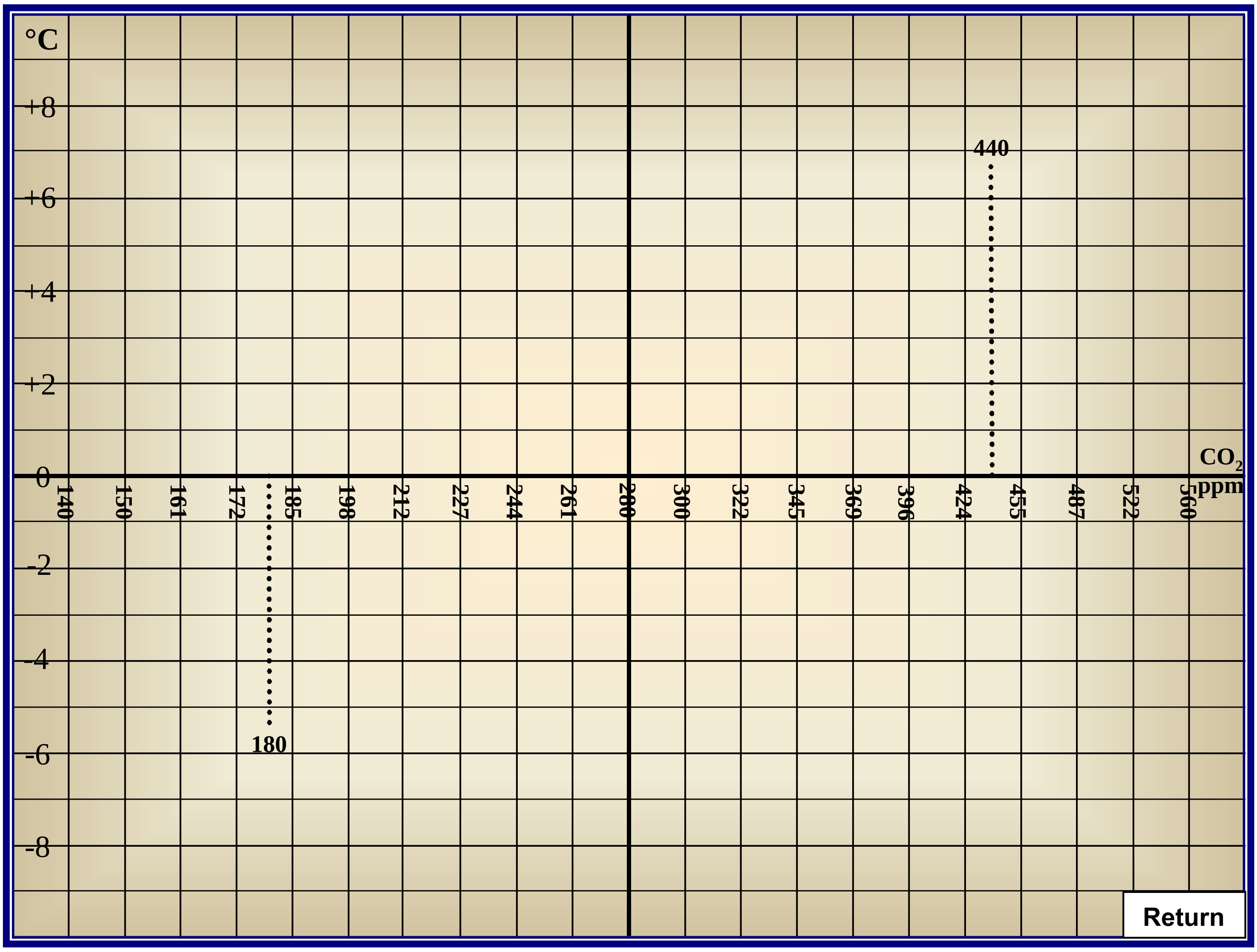
Semi-log (base 2) scale construction

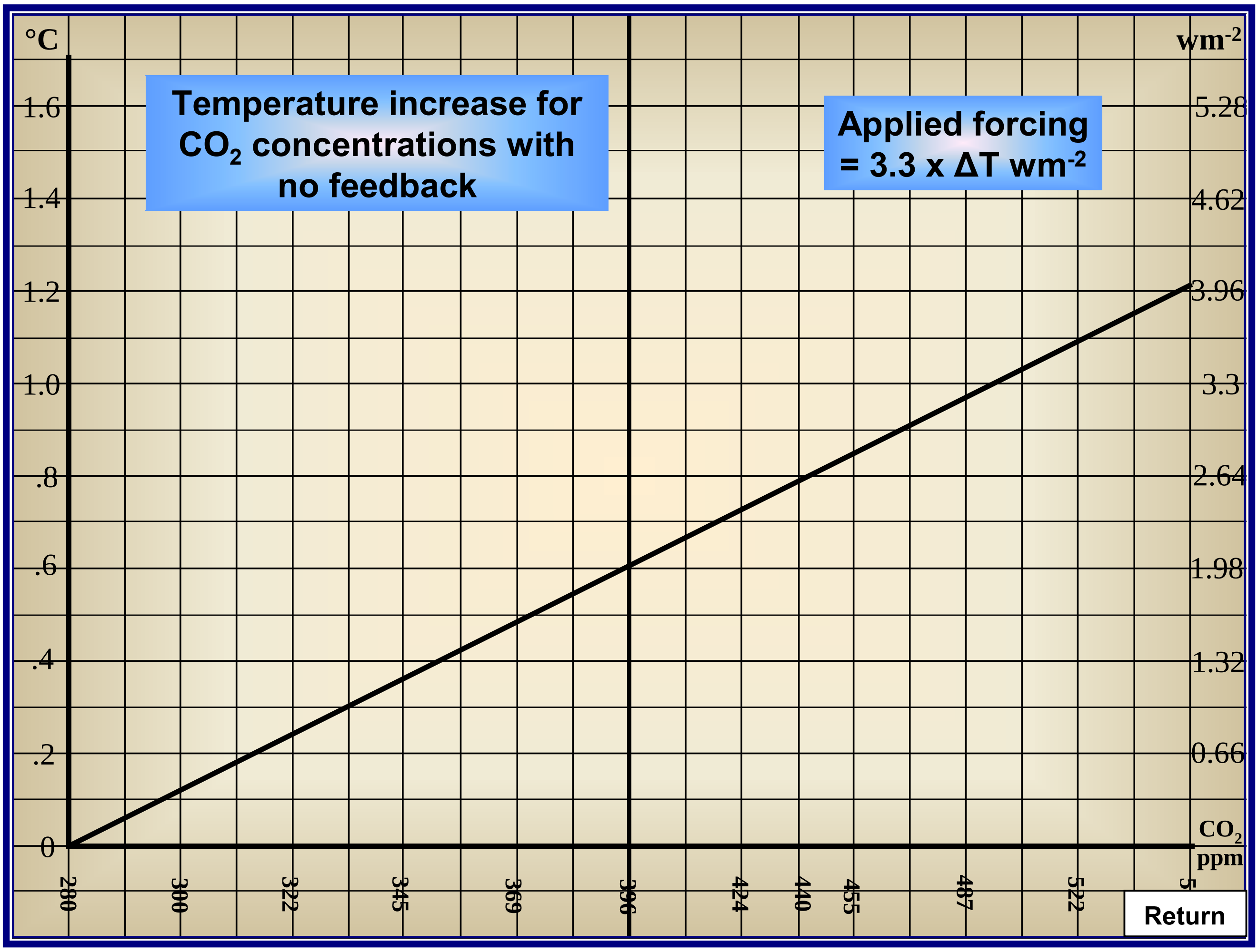
Column 1
Incremental power

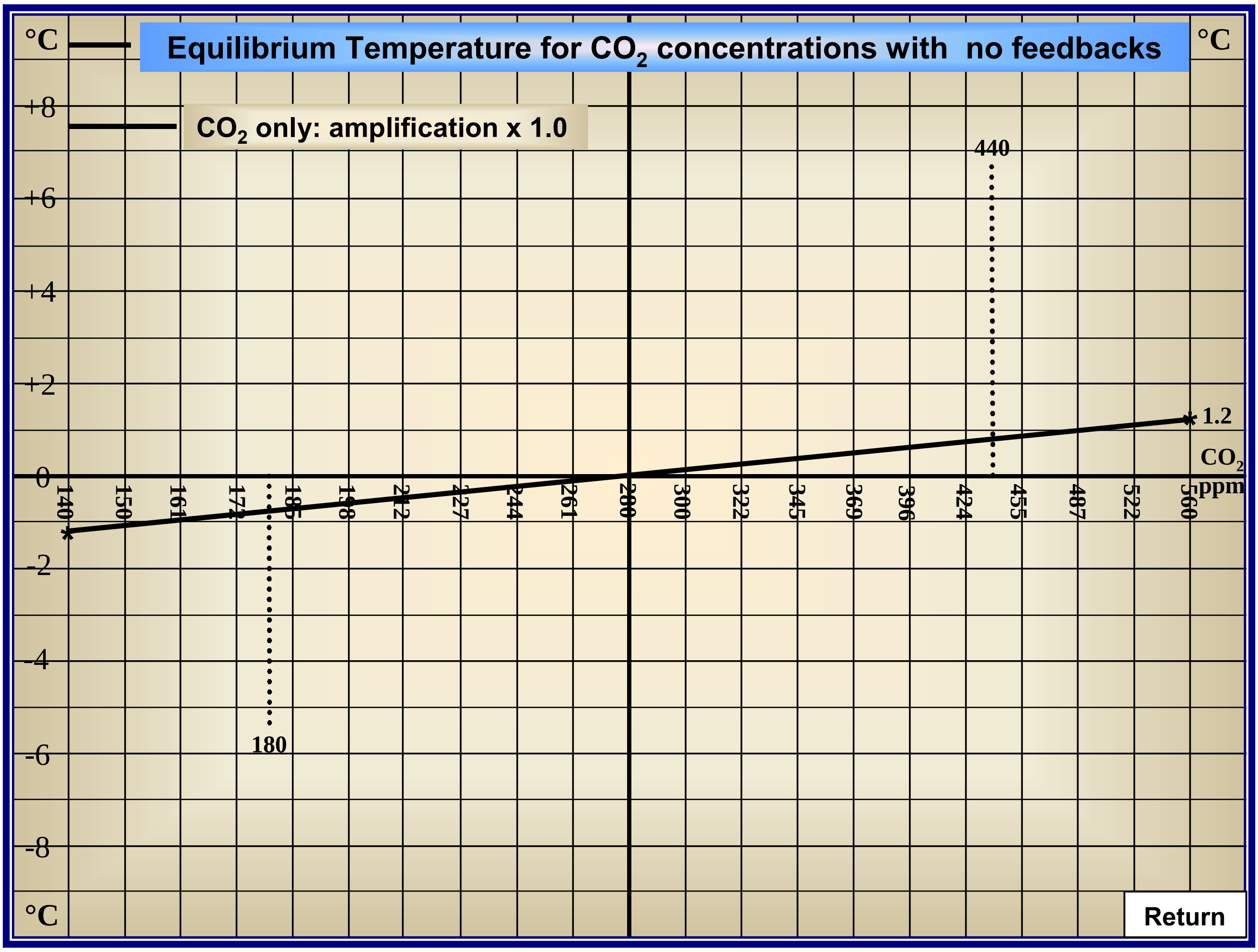
Column 2
2 raised to power

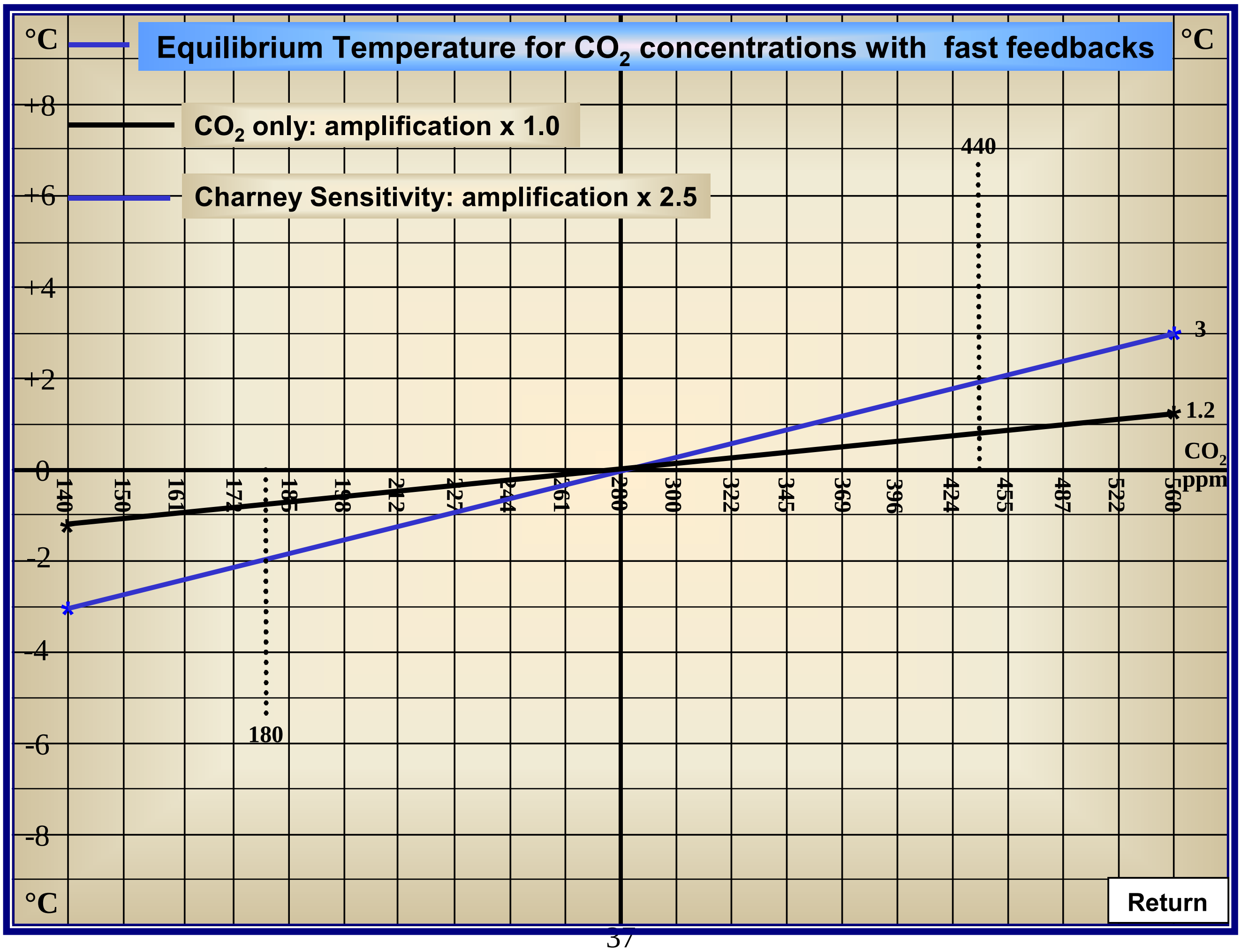
Column 3
Column 2 x 140

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


°C
+8
+6
+4
+2
0
-2
-4
-6
-8
440
180
CO$_2$ ppm
140
150
161
172
185
198
212
227
244
261
280
300
322
345
369
396
424
455
487
522
560
Return


°C
wm^{-2}
Temperature increase for CO$_2$ concentrations with no feedback
Applied forcing = 3.3 x ΔT wm^{-2}
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
5.28
4.62
3.96
3.3
2.64
1.98
1.32
0.66
CO$_2$ ppm
280
300
322
345
369
396
424
440
455
487
522
5
Return


°C
Equilibrium Temperature for CO2 concentrations with no feedbacks
°C
+8
CO2 only: amplification x 1.0
440
+6
+4
+2
1.2
0
CO2
ppm
140
150
161
172
185
198
212
227
244
261
280
300
322
345
369
396
424
455
487
522
560
-2
-4
-6
180
-8
°C
Return


°C
Equilibrium Temperature for CO2 concentrations with fast feedbacks
°C
+8
CO2 only: amplification x 1.0
440
+6
Charney Sensitivity: amplification x 2.5
+4
3
+2
1.2
0
CO2
ppm
140
150
161
172
185
198
212
227
244
261
280
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369
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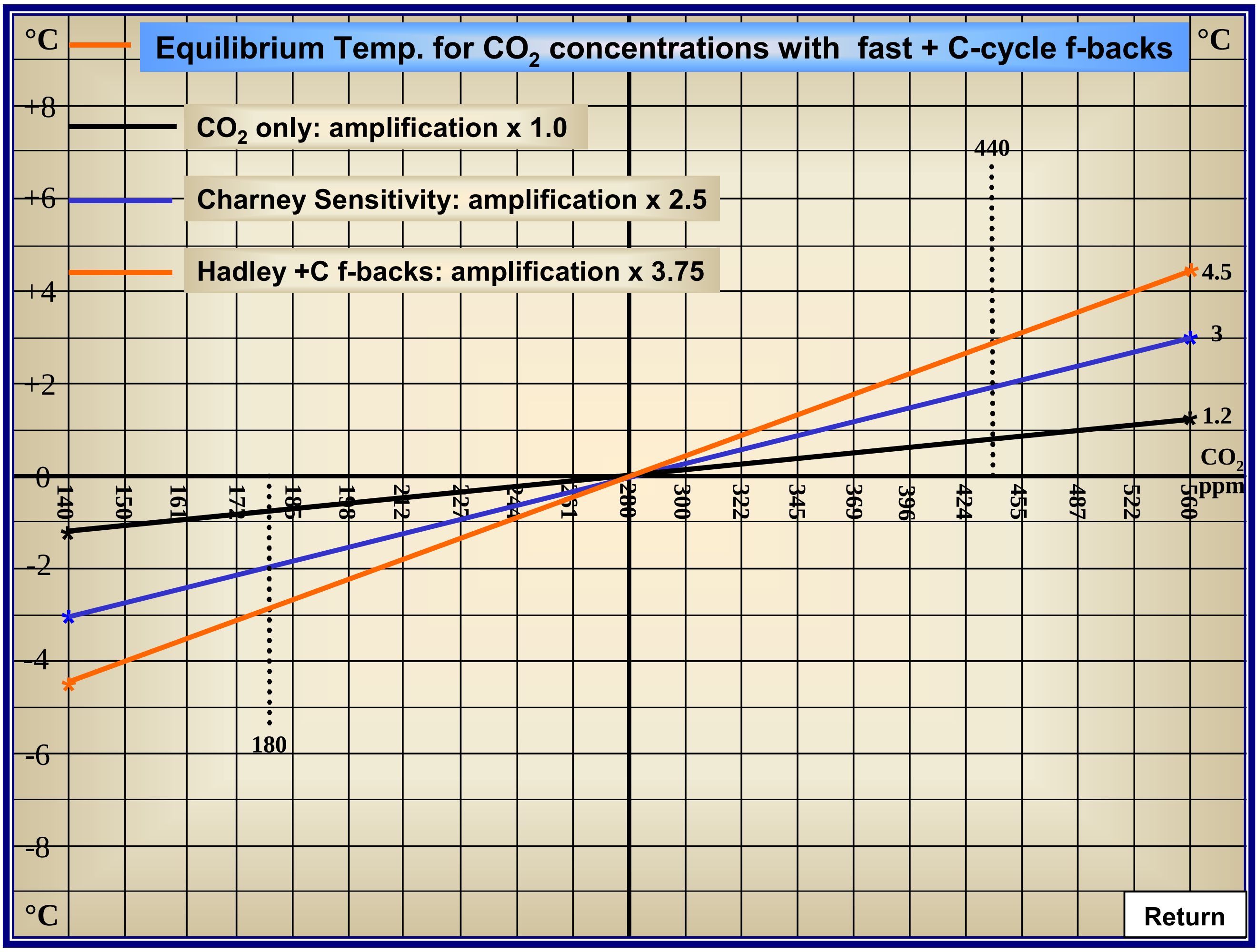
455
487
522
560
-2
-4
-6
180
-8
°C
Return


°C
Equilibrium Temp. for CO_2 concentrations with fast + C-cycle f-backs
°C
CO_2 only: amplification x 1.0
Charney Sensitivity: amplification x 2.5
Hadley +C f-backs: amplification x 3.75
+8
+6
+4
+2
0
-2
-4
-6
-8
°C
440
180
4.5
3
1.2
CO_2 ppm
140
150
161
172
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198
212
227
244
261
280
300
322
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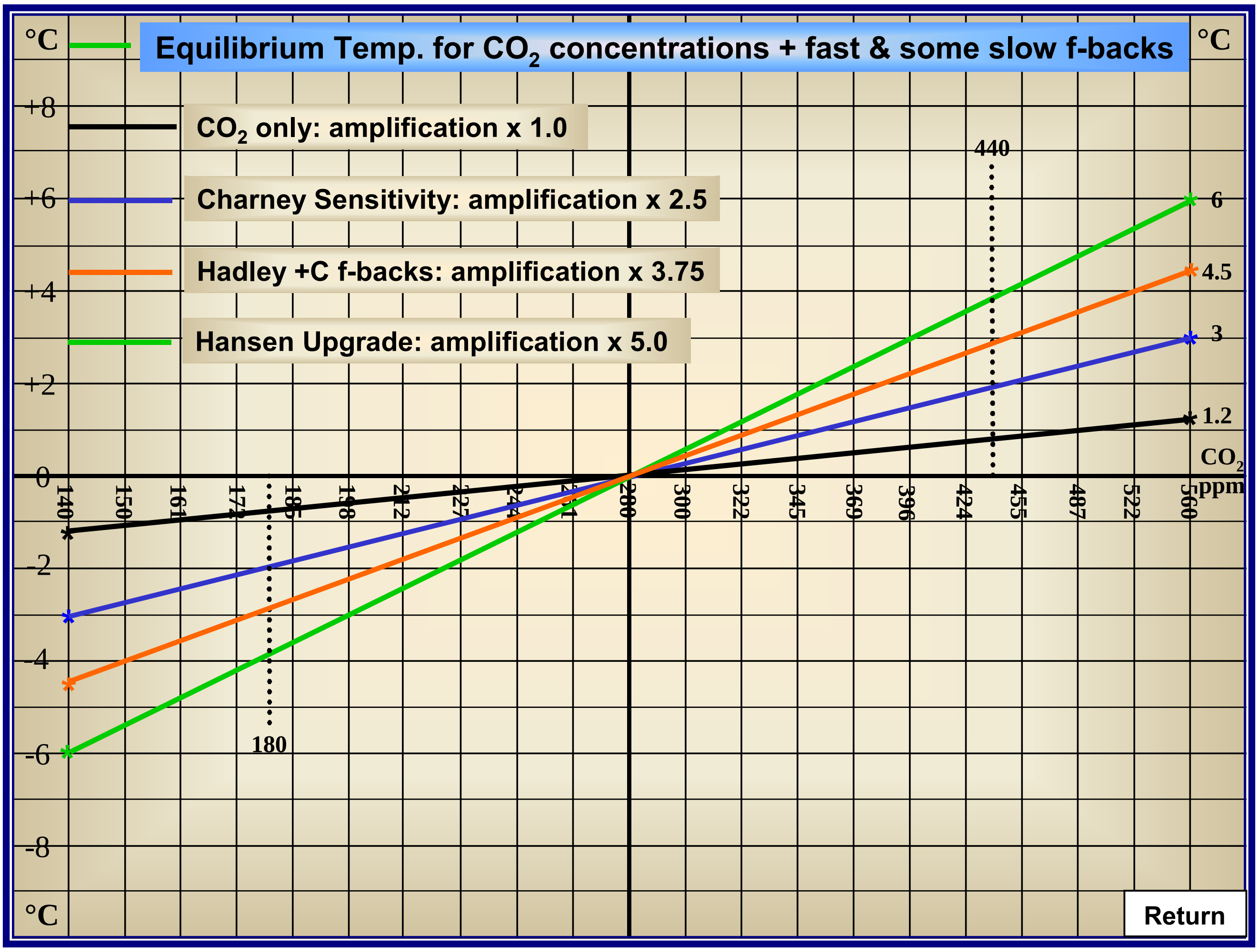
369
396
424
455
487
522
560
Return


°C
Equilibrium Temp. for CO_2 concentrations + fast & some slow f-backs
°C
CO_2 only: amplification x 1.0
Charney Sensitivity: amplification x 2.5
Hadley +C f-backs: amplification x 3.75
Hansen Upgrade: amplification x 5.0
+8
+6
+4
+2
0
-2
-4
-6
-8
°C
440
180
6
4.5
3
1.2
CO_2 ppm
140
150
161
172
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487
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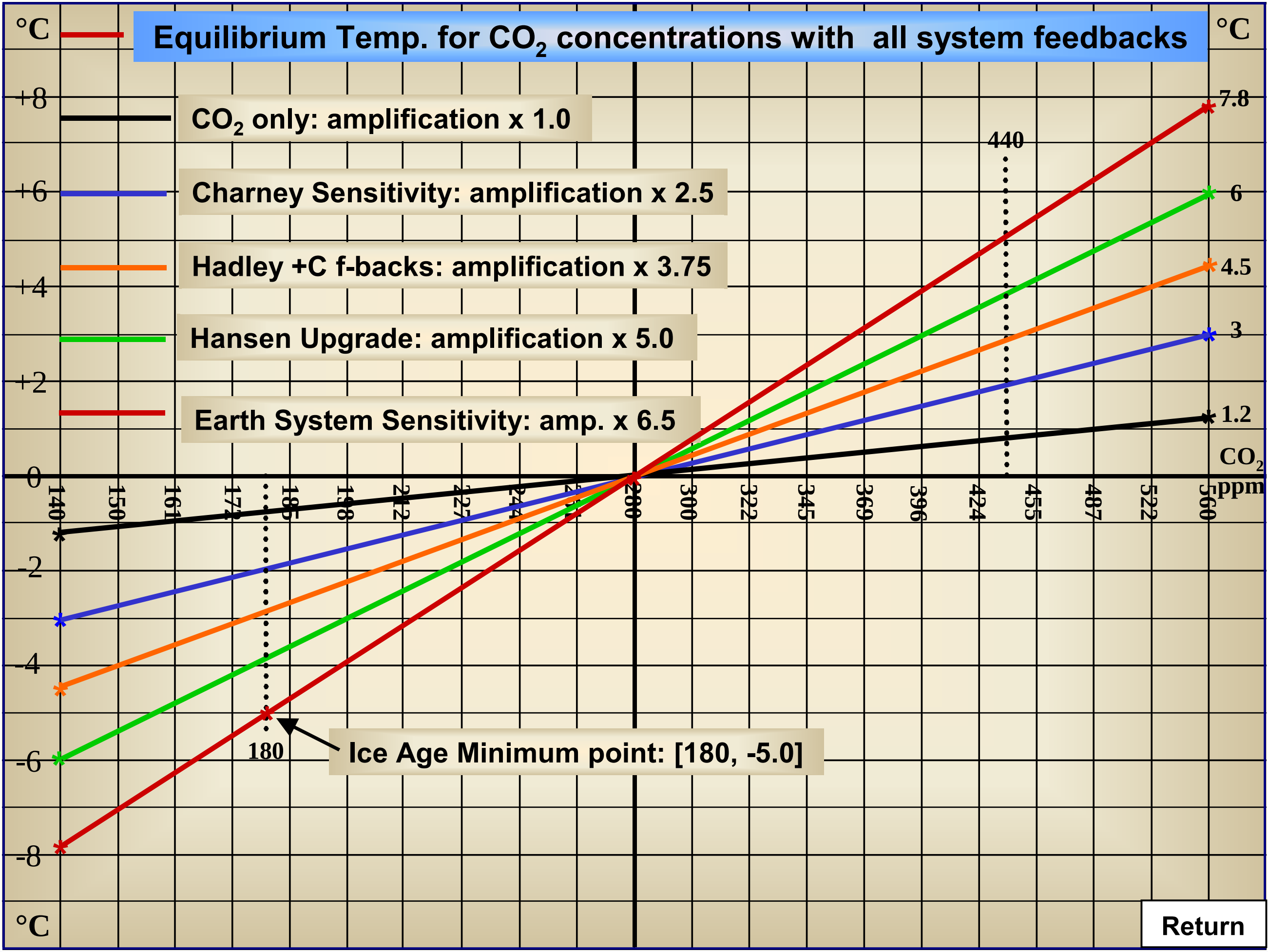
560
Return

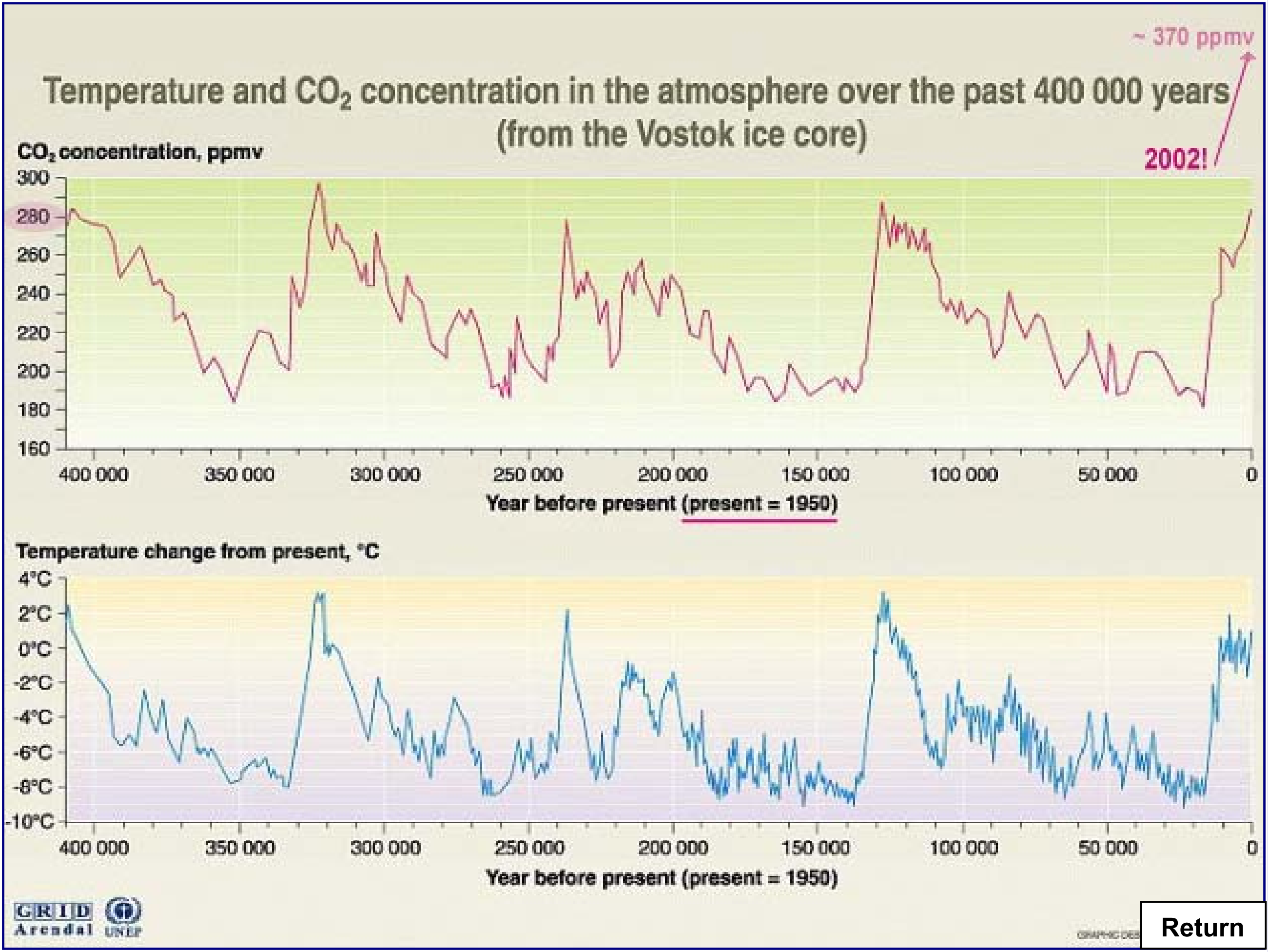
Earth System Sensitivity?

Return



Equilibrium Temp. for CO_2 concentrations with all system feedbacks

Return



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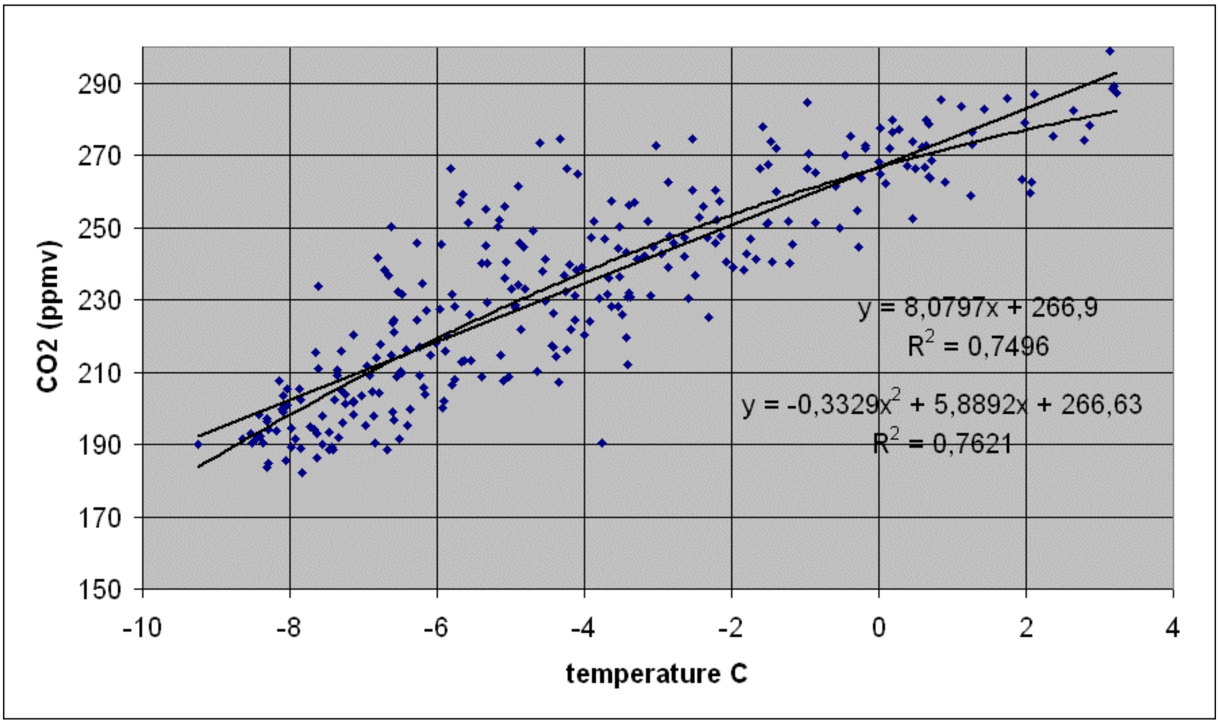
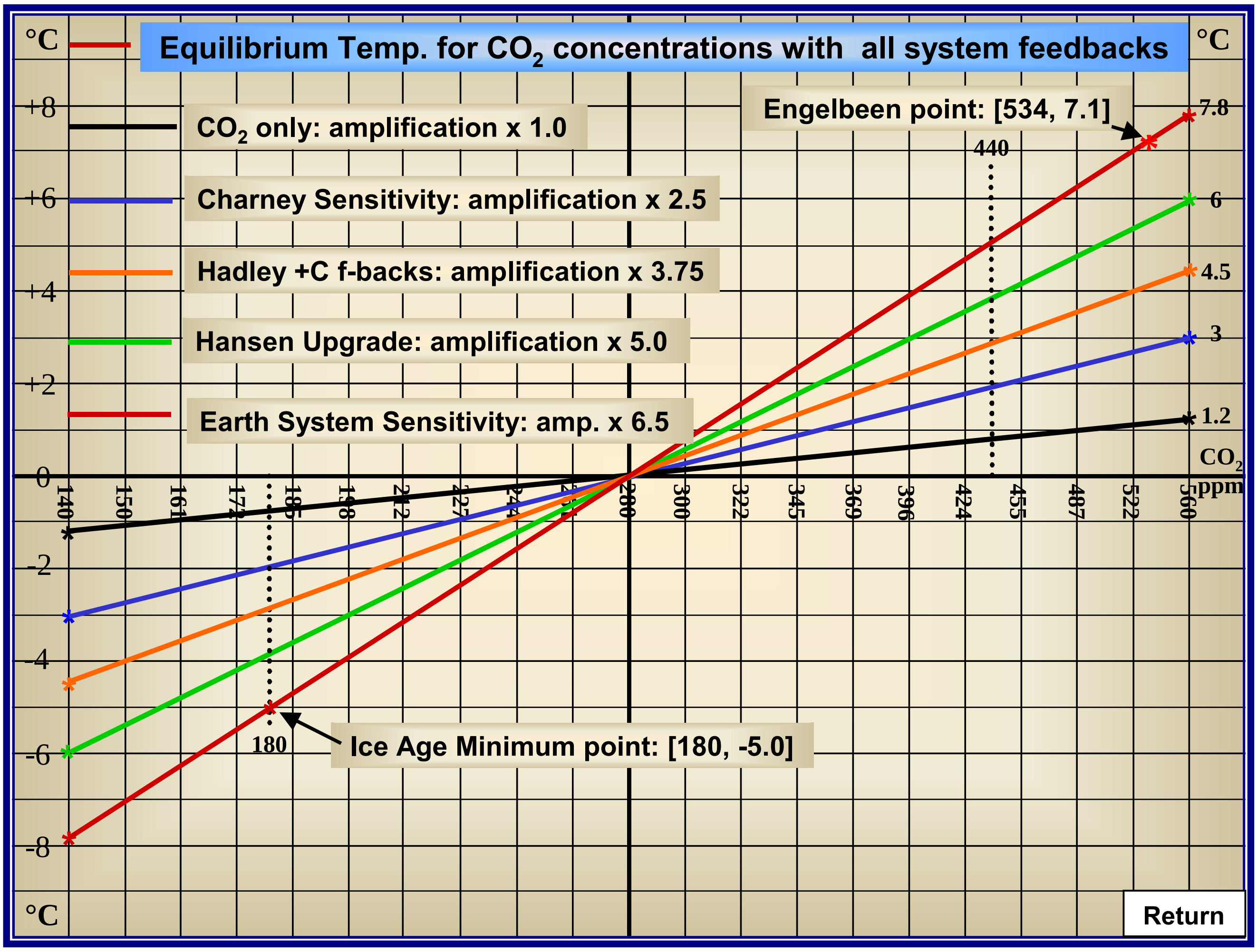
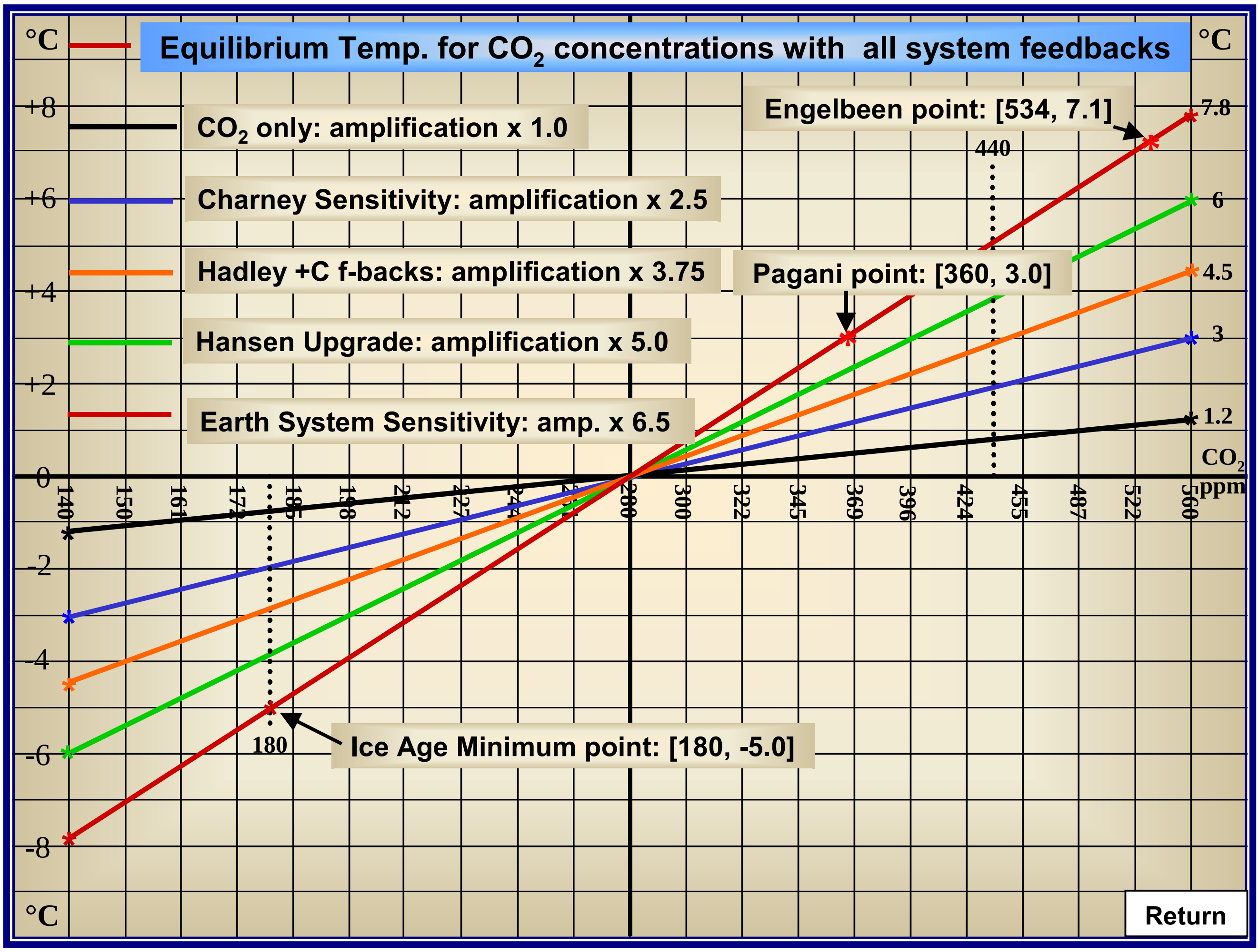
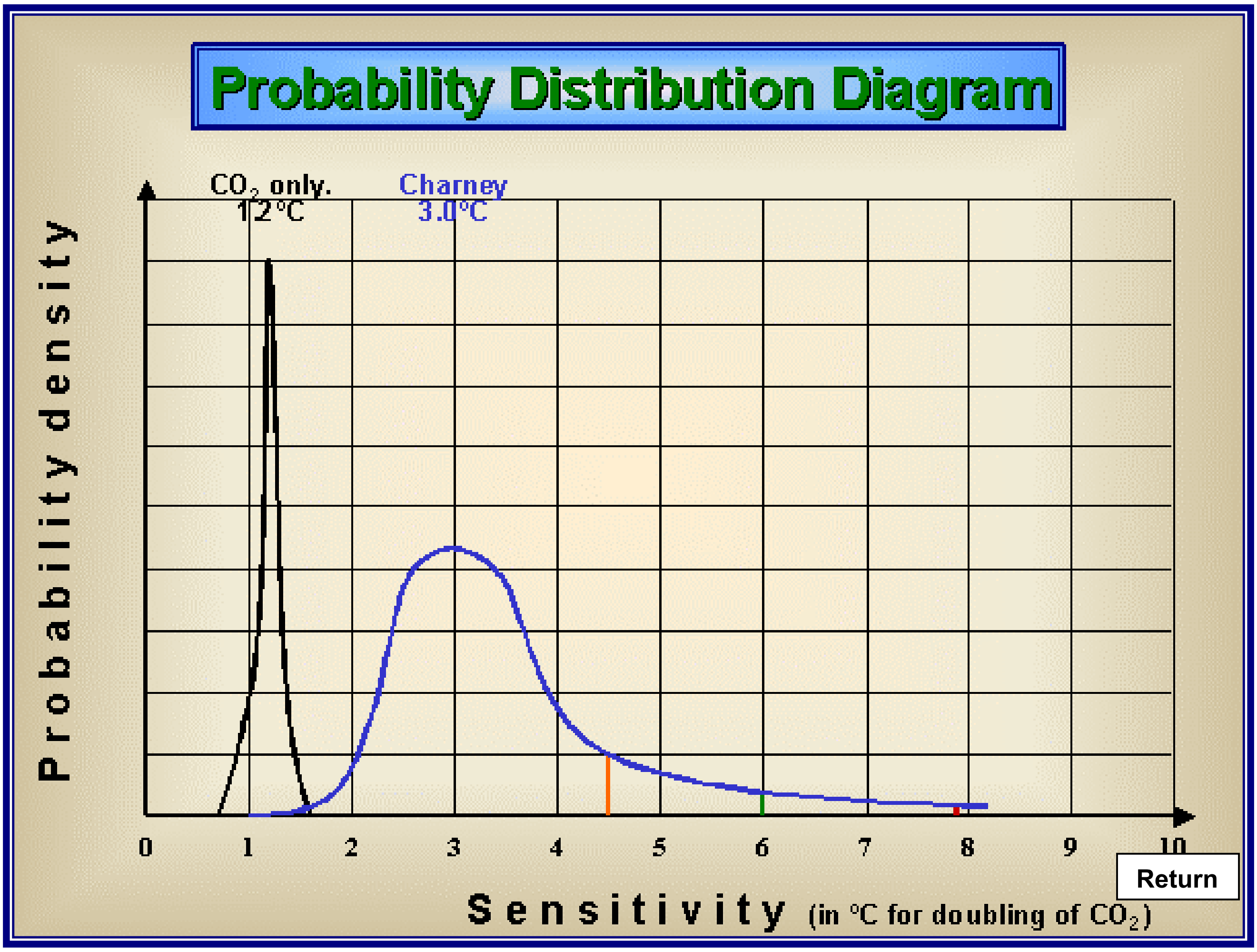


See: **http://www.ferdinand-engelbeen.be/klimaat/correlation.html**

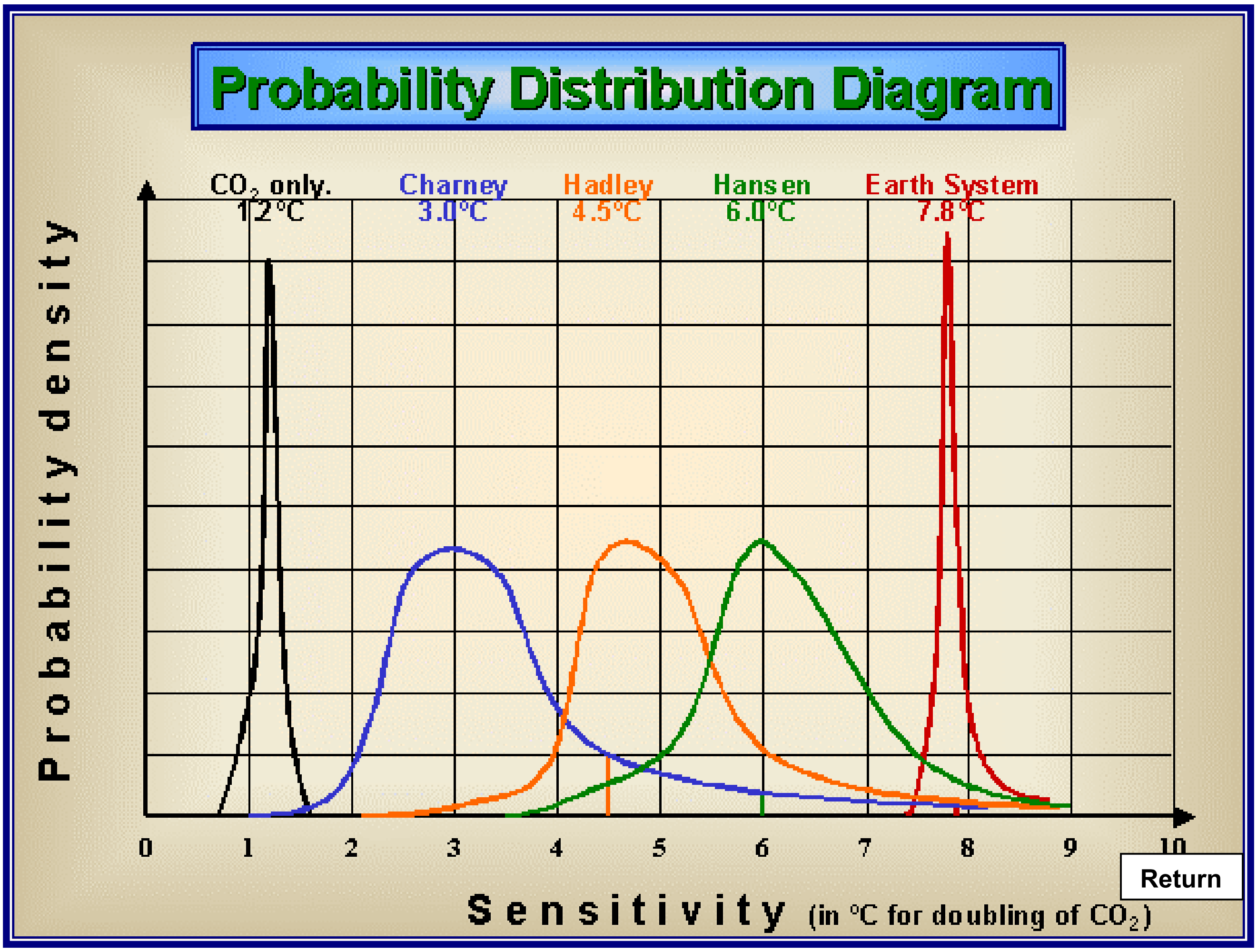
Return


Equilibrium Temp. for CO₂ concentrations with all system feedbacks
°C
°C
°C
CO₂ only: amplification x 1.0
Charney Sensitivity: amplification x 2.5
Hadley +C f-backs: amplification x 3.75
Hansen Upgrade: amplification x 5.0
Earth System Sensitivity: amp. x 6.5
Engelbeen point: [534, 7.1]
440
Ice Age Minimum point: [180, -5.0]
180
+8
+6
+4
+2
0
-2
-4
-6
-8
7.8
6
4.5
3
1.2
CO₂ ppm
140
150
161
172
185
198
212
227
244
261
280
300
322
345
369
396
424
455
487
522
560
Return

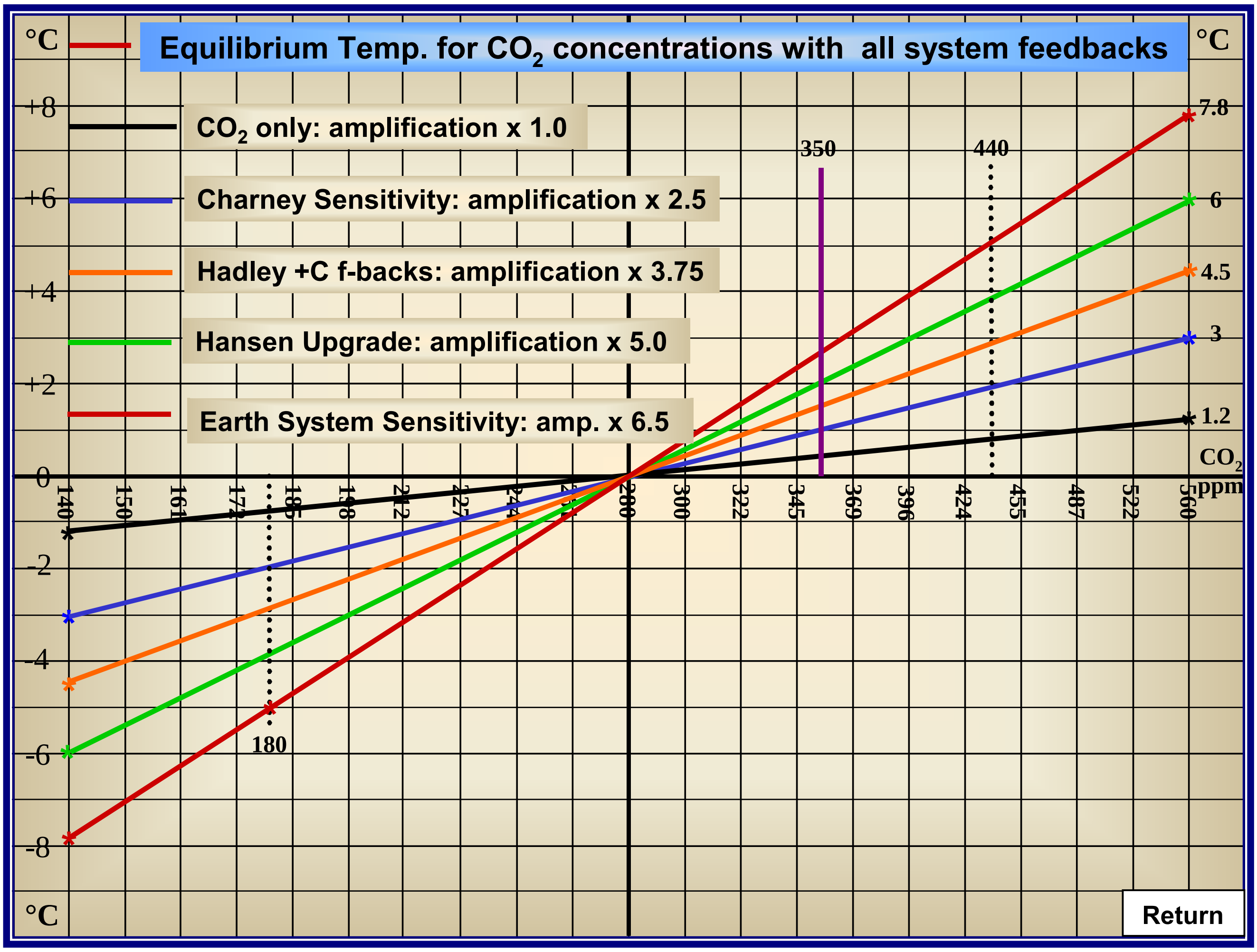

Equilibrium Temp. for CO₂ concentrations with all system feedbacks
°C
°C
°C
CO₂ only: amplification x 1.0
Charney Sensitivity: amplification x 2.5
Hadley +C f-backs: amplification x 3.75
Hansen Upgrade: amplification x 5.0
Earth System Sensitivity: amp. x 6.5
Engelbeen point: [534, 7.1]
440
Pagani point: [360, 3.0]
Ice Age Minimum point: [180, -5.0]
180
+8
+6
+4
+2
0
-2
-4
-6
-8
7.8
6
4.5
3
1.2
CO₂ ppm
140
150
161
172
185
198
212
227
244
261
280
300
322
345
369
396
424
455
487
522
560
Return



Probability Distribution Diagram



Probability Distribution Diagram



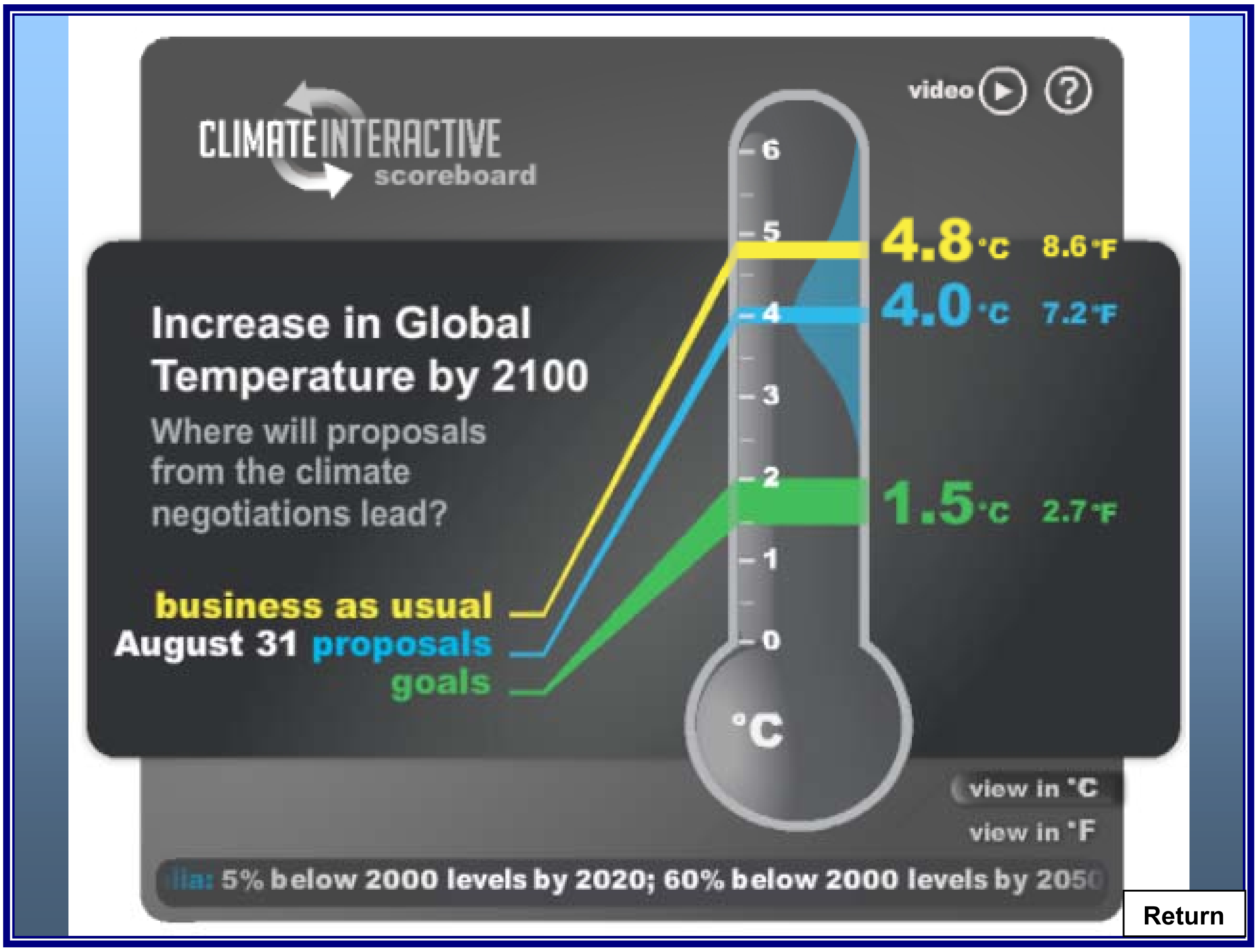
C-ROADS

(Climate Rapid Overview and Decision Support)

The Climate Scoreboard

www.climateinteractive.org

Return



CLIMATE INTERACTIVE scoreboard

Increase in Global Temperature by 2100

Where will proposals from the climate negotiations lead?

business as usual

August 31 proposals

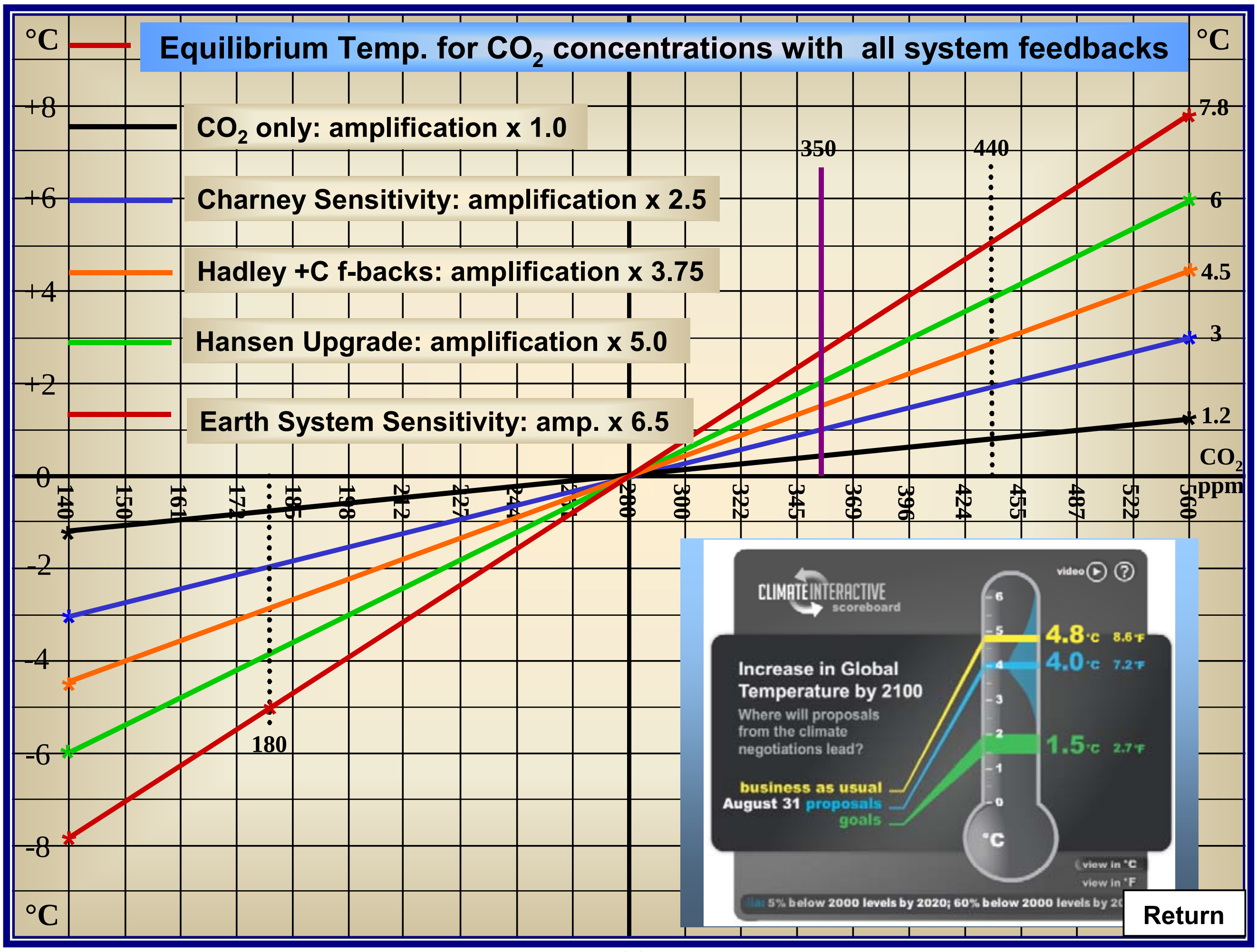
goals

4.8 °C 8.6 °F

4.0 °C 7.2 °F

1.5 °C 2.7 °F

lia: 5% below 2000 levels by 2020; 60% below 2000 levels by 205



Equilibrium Temp. for CO_2 concentrations with all system feedbacks

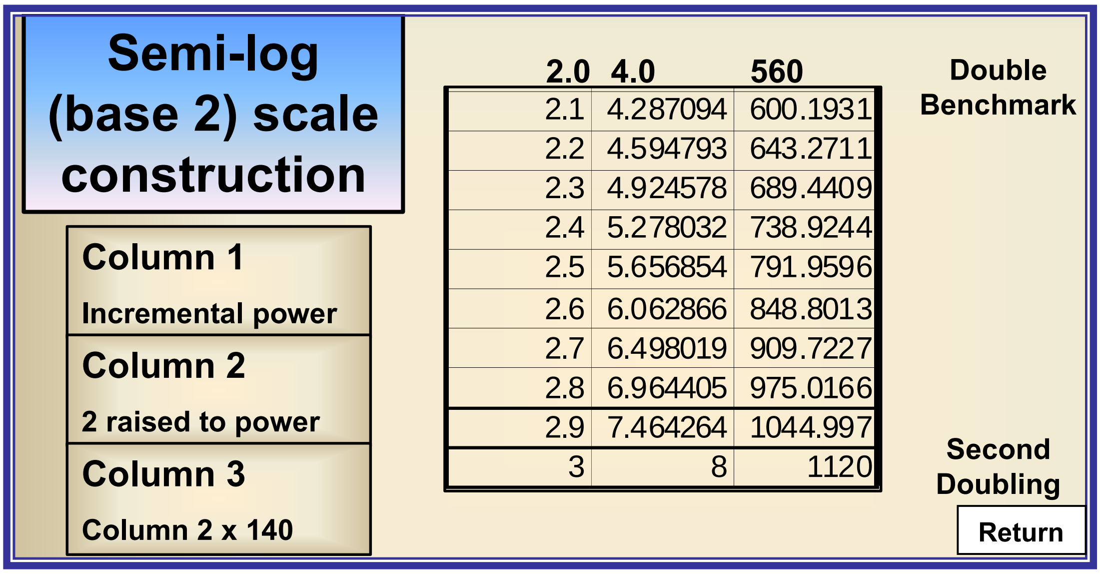
CO_2 only: amplification x 1.0

Charney Sensitivity: amplification x 2.5

Hadley +C f-backs: amplification x 3.75

Hansen Upgrade: amplification x 5.0

Earth System Sensitivity: amp. x 6.5



Semi-log (base 2) scale construction

Column 1

Incremental power

Column 2

2 raised to power

Column 3

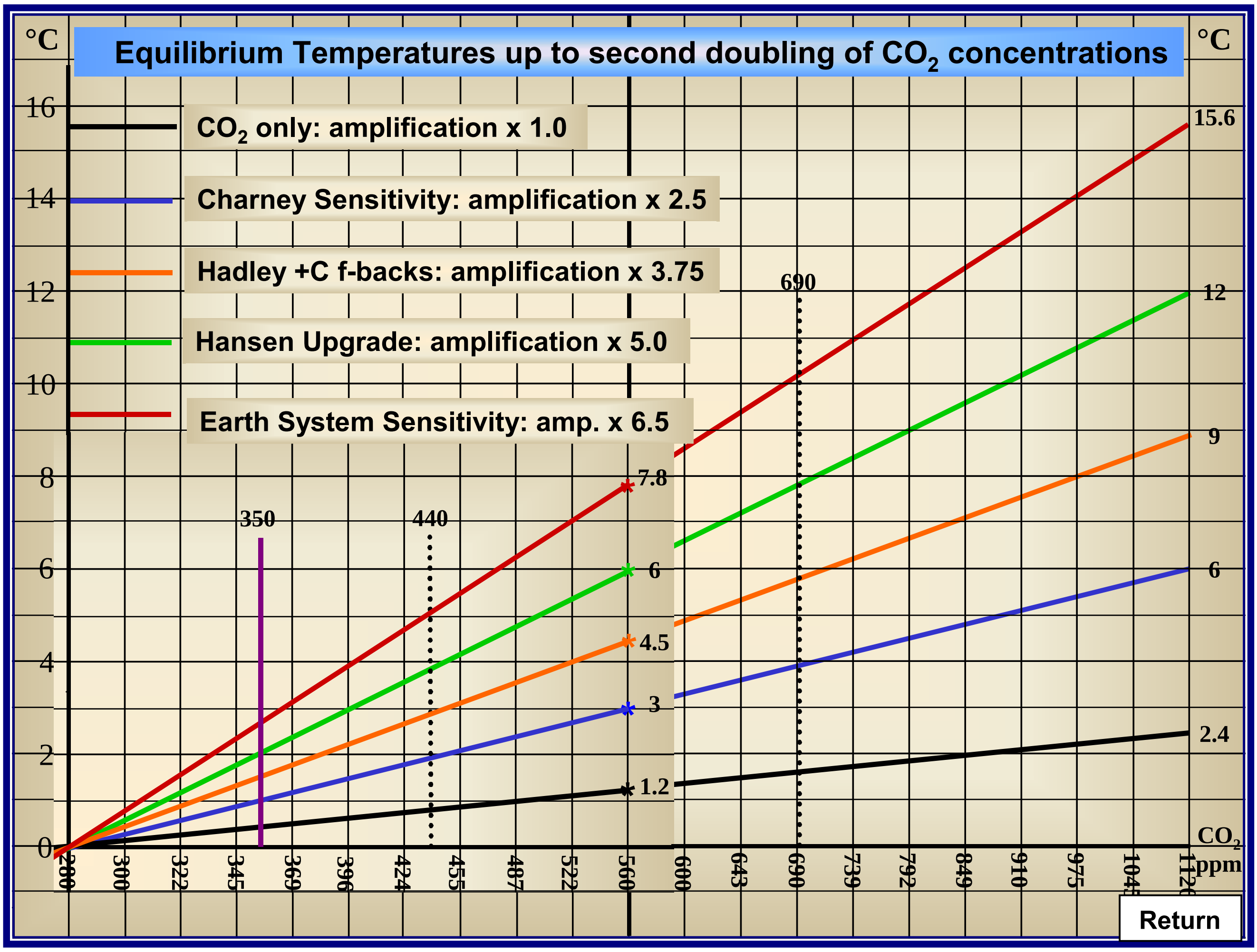
Column 2 x 140

2.0	4.0	560
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

Double Benchmark

Second Doubling

Return



Equilibrium Temperatures up to second doubling of CO_2 concentrations

CO_2 only: amplification x 1.0

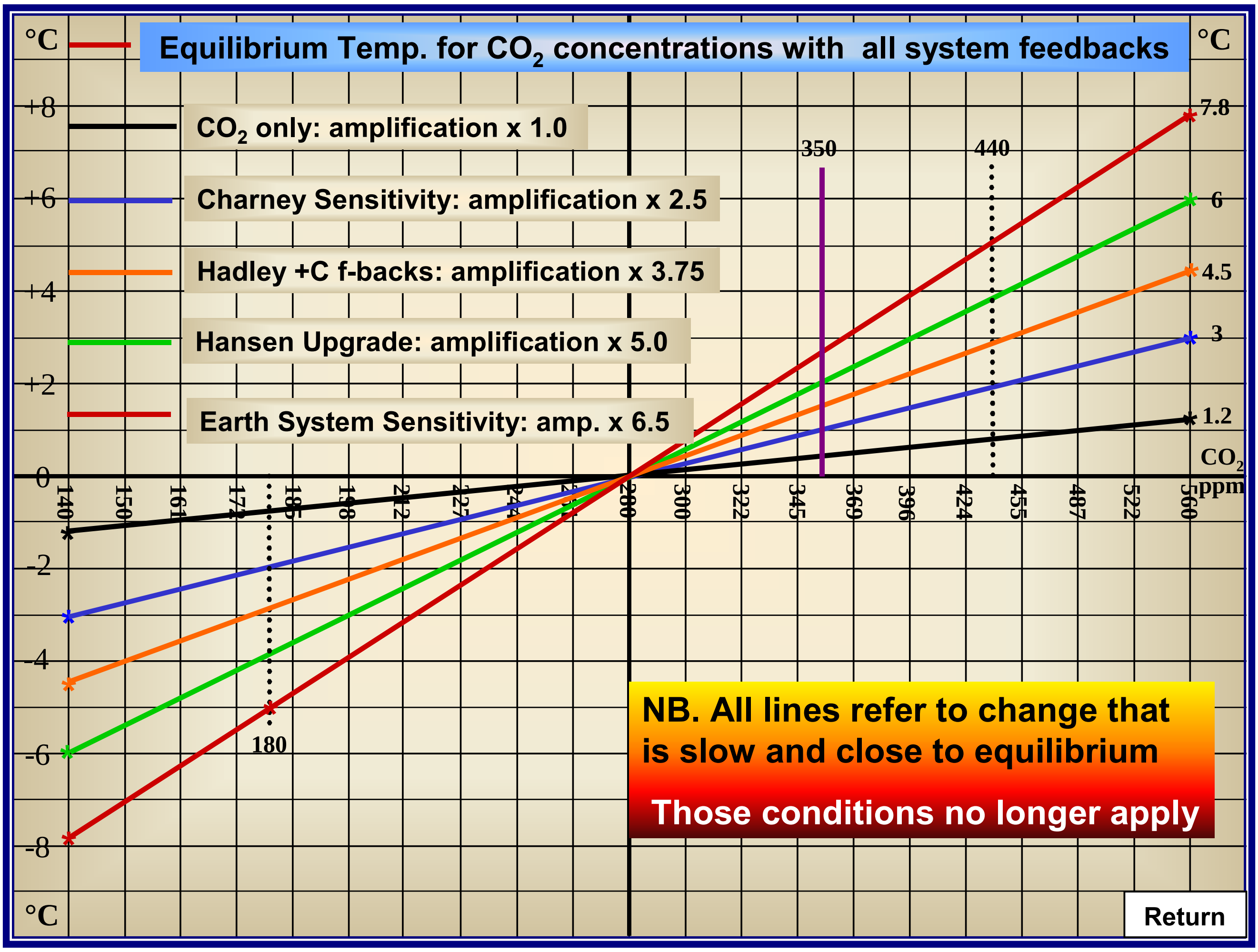
Charney Sensitivity: amplification x 2.5

Hadley +C f-backs: amplification x 3.75

Hansen Upgrade: amplification x 5.0

Earth System Sensitivity: amp. x 6.5

Return



NB. All lines refer to change that is slow and close to equilibrium

Those conditions no longer apply