Basis for a Carbon Budget?

by David Wasdell

(Director of the Apollo-Gaia Project *)

A Critical Evaluation of the

"Summary for Policymakers" of the
The Inter-Governmental Panel on Climate Change
Fifth Assessment Report
Work-group 1: The Scientific Basis

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Background and Introduction

The Summary for Policymakers of the IPCC AR5 WG1, was published on 27th September 2013 in Stockholm after four days of intense scrutiny by agents representing the governments of all participating countries. Every word and line of the text previously submitted by the scientific community was examined and amended until it could be endorsed unanimously by the political representatives. The same process also applied to the diagrams and illustrations. Critical comparison between the scientific original and the published outcome of the political process casts light on the editorial interventions that ensured that the Summary for Policymakers was already acceptable to the policymakers prior to publication.

The most intense debate appears to have focussed around Figure 10. This diagram provides the basis from which to determine the available budget of carbon emissions still permitted to the international community before exceeding a given risk of temperature increase passing the policy target of 2°C. This central issue is of the most fundamental importance as the international community seeks to formulate a legally binding agreement on the mitigation of climate change. Greatest pressure to establish grounds for the highest possible budget came from those countries whose national economy, political power and social stability depend on sustaining the asset value and production revenue derived from exploitation of their resources of fossil energy. Additional pressure was applied to the political agents by those vested interests whose sustained profitability was based on the extraction, refining, marketing and use of fossil energy as the ground of the global economy.

Collusional pressure is not confined to the four days of political scrutiny. It is brought to bear throughout the complex writing, review and editorial process of the IPCC. It is also experienced acutely throughout the global discipline of climate science in the conduct and writing-up of academic research and its subsequent publication. The result is a marked tendency to take refuge in the safety of consensus-thinking, conservative formulation, and underestimation of critical risk. The outcome is a document of appeasement, that, while offering hope of "climate stabilisation in our time", is not fit for the purpose of strategic policy-making.

Four days after publication I had the privilege to attend a seminar at the Royal Society in London, at which Prof. Thomas Stocker introduced the Summary for Policymakers to a packed audience. As co-chair of Workgroup 1 of the IPCC AR5, Thomas had presided over the marathon session in Stockholm which ended at 5.30 am prior to the publication deadline of 10.00 am. As noted above, the most difficult sticking point was focussed around Figure 10 and its associated text. The material presented a near-linear relationship between cumulative anthropogenic emissions of carbon and the consequent change in average global surface temperature. It provided the scientific basis for determining the potential budget of permitted future emissions before risking transgression of the agreed policy ceiling of an increase of 2°C above the pre-industrial benchmark. As the country with arguably the most to lose from the future implementation of any restriction on the use of fossil hydrocarbons, the objections were led by Saudi Arabia, strongly supported by China, and associated with an emerging group of "like-minded nations". The impasse was broken following suggested modifications of both text and diagram provided by the representatives of the USA. The resulting compromise safeguards the vested interests of global dependency on fossil sources of energy, while constraining the capacity of the international community to take any effective action to deal with the threat of dangerous climate change.

Ten days before this seminar I had provided the keynote presentation to the annual conference of the Club of Rome. My subject was "Sensitivity, Non-Linearity and Self-Amplification in the Global Climate system". It was the culmination of eight years of intense systems-dynamics research as director of the Apollo-Gaia Project. We had established a robust value for the change in average global surface temperature to be expected at eventual equilibrium as a result of a doubling of the concentration of atmospheric carbon dioxide. This "Earth System Sensitivity" was derived from analysis of data covering the last 65 million years of planetary climate. It was some two-and-a-half times greater than the value of the "fast-feedback sensitivity" generated by the ensemble of climate models involved in the Climate Modelling Inter-comparison Project, Phase 5 (CMIP5) on which the IPCC Report was based. Sensitivity in the Anthropocene, under present conditions of rapid change and far-from equilibrium behaviour, is expected to be even greater.

The July 2013 edition of the Quarterly Journal of the Royal Meteorological Society had carried a Review Article entitled "Climate sensitivity in the Anthropocene". It was co-authored by an august group of twelve leading climate scientists, two of whom had also been involved in the drafting and review of the IPCC AR5 WG1 SPM. The following quotation from the introduction to the paper is most pertinent:

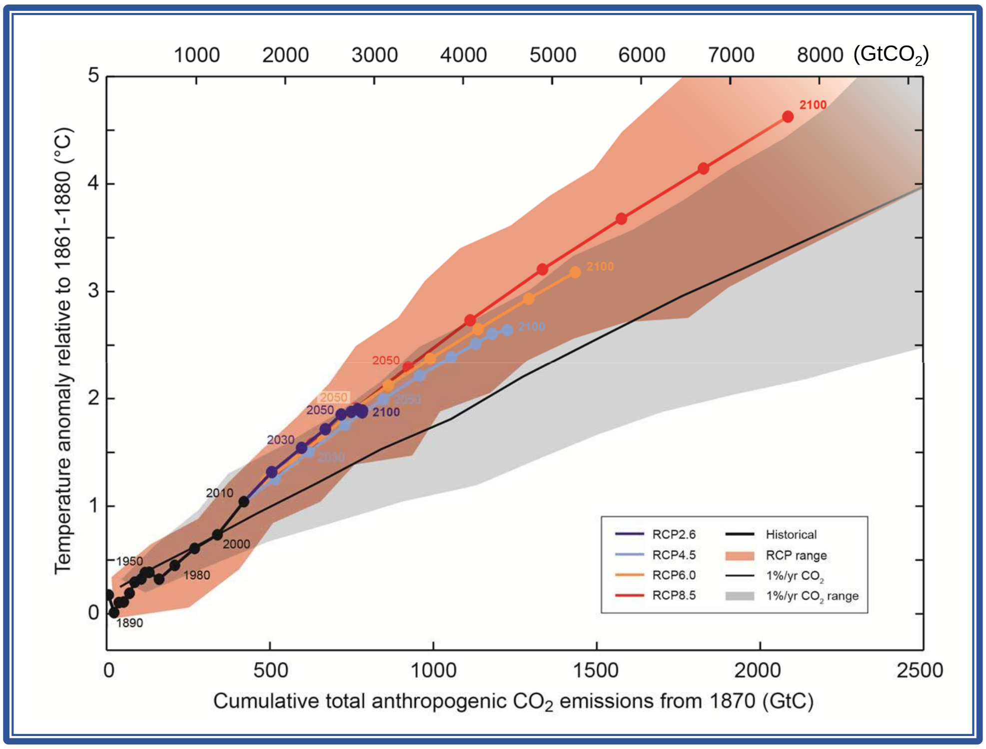
> "Based on evidence from Earth's history, we suggest here that the relevant form of climate sensitivity in the Anthropocene (e.g. from which to base future greenhouse (GHG) stabilization targets) is the Earth System sensitivity, including fast feedbacks from changes in water vapour, natural aerosols, clouds and sea ice, slower surface albedo feedbacks from changes in continental ice sheets and vegetation, and climate-GHG feedbacks from changes in natural (land and ocean) carbon sinks. Traditionally, only fast feedbacks have been considered (with the other feedbacks either ignored or treated as forcings), which has led to estimates of the climate sensitivity for doubled CO_2 concentrations of about 3°C. The $2xCO_2$ Earth System sensitivity is higher than this, being ~4-6°C if the ice sheet/vegetation albedo feedback is included in addition to the fast feedbacks, and higher still if climate-GHG feedbacks are also included. The inclusion of climate-GHG feedbacks due to changes in the natural carbon sinks has the advantage of directly linking anthropogenic GHG emissions with the ensuing global temperature increase, thus providing a truer indication of the climate sensitivity to human perturbations." *[Q.J.R. Meteorol. Soc. 139: 1121-1131, July 2013 A]*

The historically derived equilibrium value of 7.8°C for a doubling of the atmospheric concentration of CO_2, (from the Apollo-Gaia Project), includes, by very definition, all possible feedback dynamics, known and unknown, as well as their complex interactions. The remaining uncertainty in the value stems from uncertainty in the relationship between temperature and CO_2 concentration in the historical data. If the temperature sensitivity to changes in CO_2 concentration is lower, then, paradoxically, the global climate dynamics are even more sensitive to small changes in average surface temperature, so the implications for policy making are unchanged.

It was against this background that I raised the question of sensitivity at the end of Prof. Stocker's Royal Society presentation. Noting concern at the discrepancy between the conservative values of modelled sensitivity generated by the computer ensemble on which the IPCC Report was based, and the observation-based understanding of the way the earth's climate actually responds, I asked him to comment on the effect of higher values of sensitivity on the available carbon budget. In his reply he noted that: *"Equilibrium Sensitivity is no longer seen as the most relevant parameter. Climate scientists have identified a new metric with less uncertainty than Sensitivity."* It is to the construction of that "new metric" and its subsequent modification by the governmental agents in Stockholm, that we now turn our attention.

Part 1:
The "New Metric" of Climatic response to Carbon Emissions

The final version of the "new metric" was published as Figure 10 in the Summary for Policymakers of the IPCC AR5 WG1. It is reproduced below:



On the grounds that "Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st Century and beyond", the cumulative total human emissions in gigatons of carbon is plotted along the horizontal axis, beginning at the start of the industrial revolution. With the same starting point, the modelled change in average global surface temperature, driven by the carbon accumulation, is plotted up the vertical axis. The top of the graph translates the weights of carbon into their equivalent amounts of carbon dioxide.

The graphic display is complex and is explained in the supporting text. The four coloured lines with date markers represent the modelled change in future temperature corresponding to the accumulation of carbon emissions for the four "representative concentration pathways" (RCPs) associated with differing rates of emissions to the year 2100. The thick black line portrays the modelled temperature change corresponding to total emissions over the historical period up to 2010. The thin black line demonstrates the temperature change driven by carbon accumulation at the rate of 1% per year (a "compound interest" or exponential rate of change that compensates for the exponential decay in efficiency of the greenhouse gas effect of CO_2 as the wavelength at which it absorbs infra-red radiation becomes more and more saturated). The grey shading represents the uncertainty spread around the thin black line, generated by the array of climate models involved. The coloured plume does the same for the coloured lines.

One immediate observation is that the temperature change is related to the total cumulative emissions and does not vary significantly in relation to the rate of emission. The temperature anomaly is independent of the RCP but is solely a function of the total anthropogenic accumulation of carbon.

Background to the development of the New Metric

Figure 10 of the Summary for Policymakers was constructed from composite technical sources which are presented and referenced in the main body of the Workgroup 1 Report.

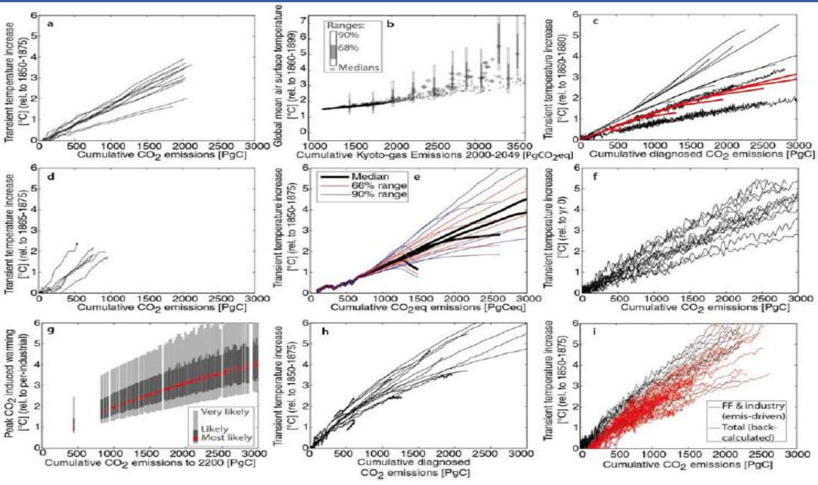
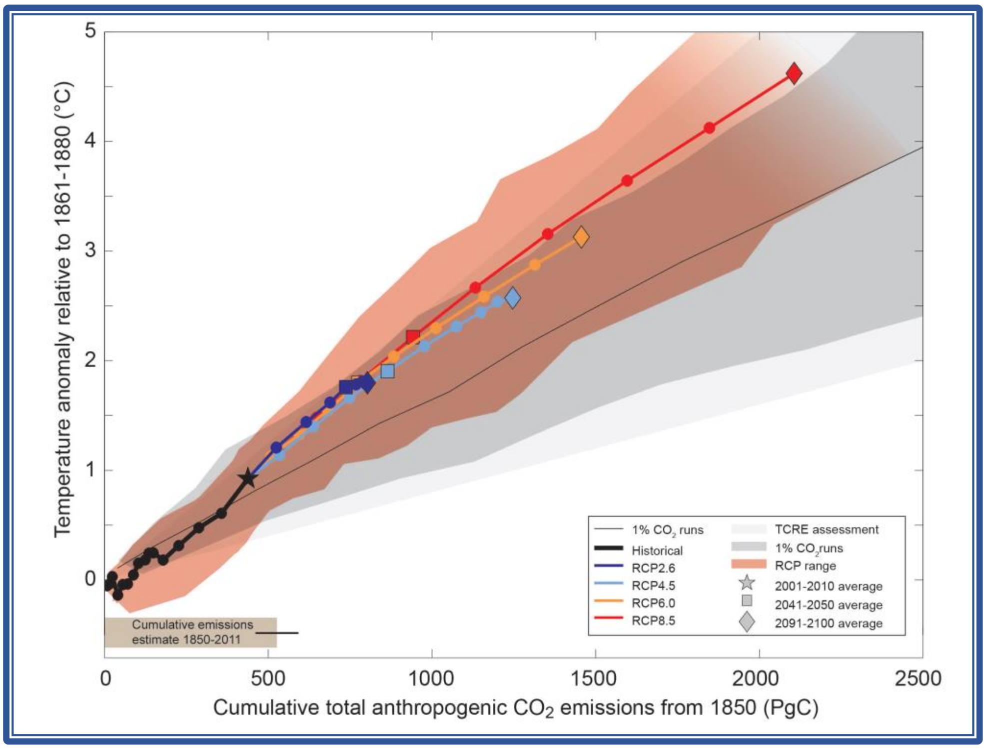


Figure 12.45: Global temperature change vs. cumulative carbon emissions for different scenarios and models. a) Transient global temperature increase vs. cumulative CO_2 emissions for C^4MIP (Matthews et al., 2009), b) maximum temperature increase until 2100 vs. cumulative Kyoto-gas emissions (CO_2 equivalent, note that all other panels are given in C equivalent) (Meinshausen et al., 2009), c) transient temperature increase vs. cumulative CO_2 emissions for IPCC TAR models (red, IPCC TAR Figure 13.3) and IPCC AR4 EMICs (black, IPCC AR4 Figure 10.35), d) as in panel (a) but for the ENSEMBLES E1 scenario (Johns et al., 2011), e) transient temperature increase for the RCP scenarios based on the MAGICC model constrained to C^4MIP, observed warming, and the IPCC AR4 climate sensitivity range (Rogelj et al., 2012), f) transient temperature change from the CMIP5 1% yr^{-1} concentration driven simulations, g) peak CO_2 induced warming vs. cumulative CO_2 emissions to 2200 (Allen et al., 2009; Bowerman et al., 2011), h) transient temperature increase from the new EMIC RCP simulations (Zickfeld et al., 2013) and i) transient temperature change from the CMIP5 historical and RCP8.5 emission driven simulations (black) and transient temperature change in all concentration-driven CMIP5 RCP simulations with back-calculated emissions (red). Note that black lines in panel (i) do not include land-use CO_2 and that warming in panel (i) is higher than in panel (f) due to additional non CO_2 forcings.

See Figure 12.45 on pp 1109-1113 of the [Workgroup 1 Technical Summary]

It was inserted into the draft of the SPM around January 2013, possibly by Prof. Stocker himself in his dual role as co-chair of Workgroup 1 and member of the team of Drafting Authors of the SPM. It went through a process of review before being presented (as part of the final scientific draft of the SPM) to the Stockholm conference of the governmental agents in September 2013. The final scientific version is reproduced here:



Several significant alterations were made to the scientific version by the governmental agents, and these are explored in the next section.

Changes to the Scientific Version of the New Metric

Several clarifying changes have been introduced during the final governmental review. The measure of carbon mass has been changed from the scientific "(PgC)" or Petagrams of Carbon, to the more easily understood "GtC)" or Gigatons of Carbon. Along the top axis the equivalent mass of carbon dioxide has been helpfully added. Instead of the set of icons marking current, 2050 and 2100 levels of cumulative carbon emissions for each of the RCPs, actual dates have been included on each RCP projection. The key to the graphic has been modified: the date icons have disappeared, the four RCP colour identifiers have been given pride of place in the first column, and finally the confusion between run and range for the 1% per annum model has been resolved.

Two further alterations are less cosmetic in function. The light grey shading and its key have been removed completely. They represented the uncertainty spread of the computer output for the "TCRE assessment", or "Transient Climate Response to Emissions", assessment around the 1% per annum run. Attention of policymakers is thus diverted from the wide uncertainty range emanating from the CMIP5 computer ensemble, (~ 1–4°C at a carbon output of 1500 Gt). More importantly this was the only remaining note that the temperature predictions are represented by "transient" outcomes rather than eventual equilibrium or peak temperature responses to the anthropogenic disturbance. Seven of the nine original computer resources, on which the new metric is based, label their temperature axes as "Transient Temperature Change", but the word "transient" does not appear at any point in the SPM. Tying the RCP projections to transient temperature outcomes in this way hides the fact that eventual temperature responses will be higher and include the effects of slower or more complex feedback processes. Policymakers are left with the false impression that the 2°C policy target can be identified with the 2°C level on the temperature axis of the new metric. The error allows a significantly higher volume of cumulative carbon emissions before exceeding a given risk of temperature increase passing the policy target of 2°C.

The modification with the most significance and greatest visual impact, is the complete removal of the shaded bar and error spread of the estimate of the total cumulative emissions between 2011 and the start of the industrial revolution (lower left corner of the scientific version). Although a brief note of the information is included at a later point in the text of the SPM, readers are left with no visual indication of the scale of the cumulative current carbon output of ~ 531 GtC (=1947 $GtCO_2$) by 2011. It is currently rising by about 10GtC per annum.

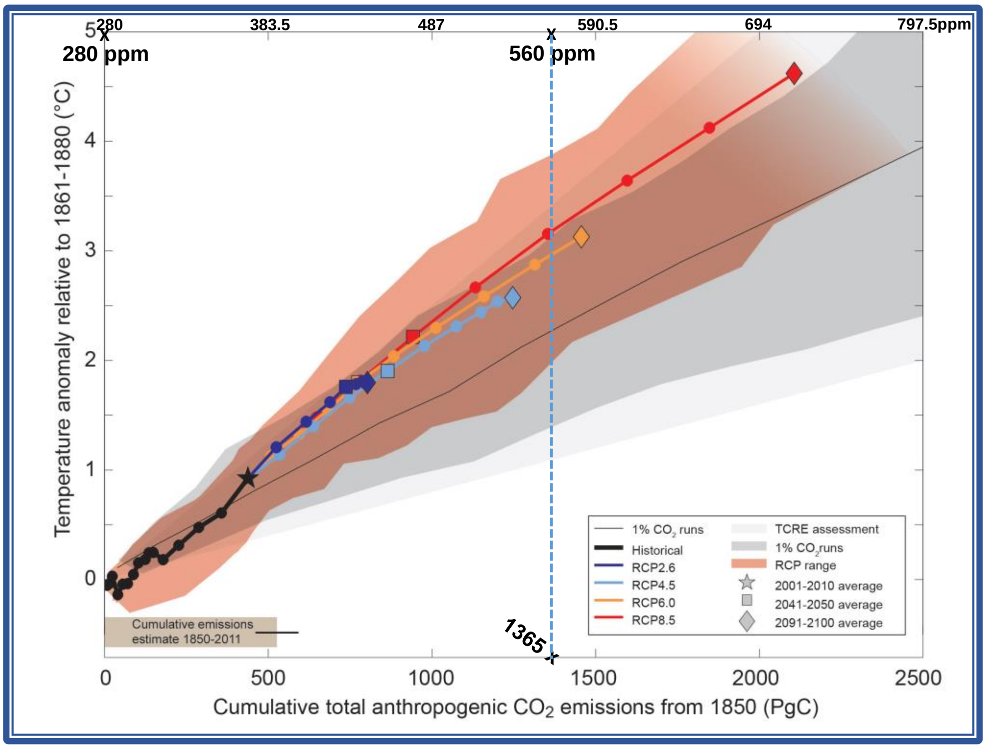
Exploring the Scientific Basis of the New Metric

In the main body of the Report, the global mean surface temperature response is described as "a function of cumulative total global CO_2 emissions". That wording is preserved in the small print below Figure 10 of the SPM. In the main body of the text, however, policymakers are informed that "Cumulative total emissions of CO_2 and global mean surface temperature response are approximately linearly related", a simplification that we explore in greater detail below. The main Report also notes that the function is dependent on the both the airborne fraction of the total cumulative emissions and also on the value of climate sensitivity. Both of these two important qualifications are omitted from the SPM.

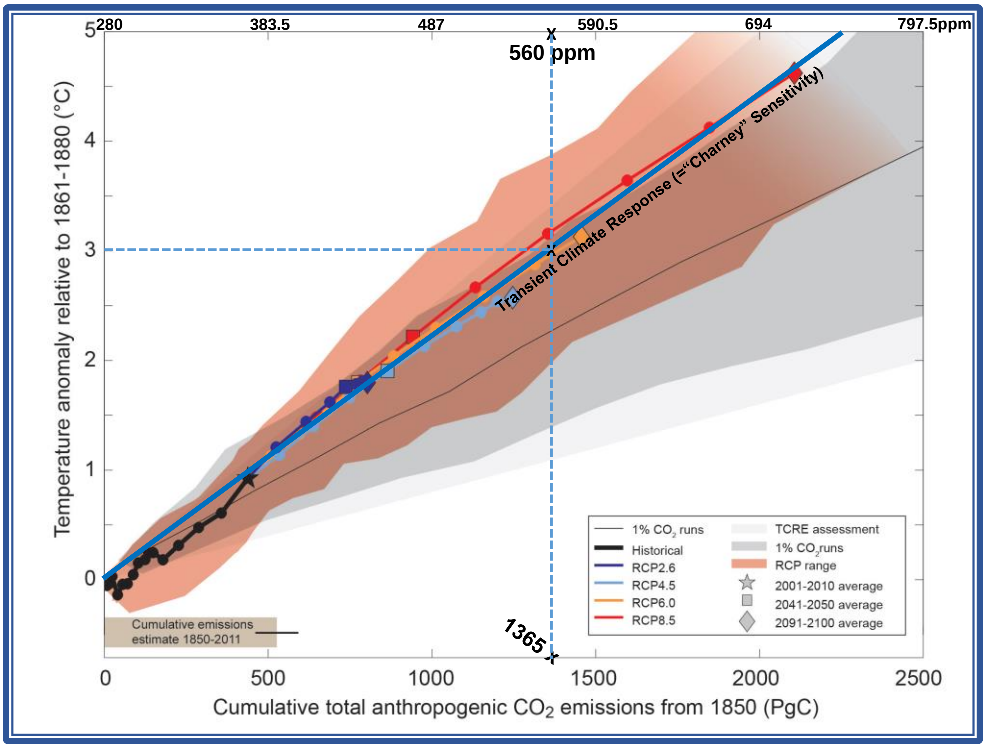
The Airborne Fraction: Only the airborne fraction of total carbon emissions contributes to the greenhouse effect of atmospheric concentration of CO_2 and so leads to temperature change. The rest is absorbed into the ocean surface (where it changes water acidity), or is taken up by other land-based carbon sinks in the mineral and vegetative domains. The actual proportion of emitted carbon retained in the atmosphere varies significantly from year to year, but averages out at about 48% over periods of decades and beyond. It is therefore reasonable to ignore this parameter in any advice to policymakers.

Taking the cumulative total of emitted carbon to be 531 GtC by 2011 and adding an extra 20 GtC to represent the emissions from 2012 and 2013, we have a 2013 cumulative total of 551 GtC. This corresponds to an atmospheric concentration of some 394 parts per million (by volume) of atmospheric carbon dioxide, an increase of 114 ppm since the start of the industrial revolution. We therefore have an average of 1 ppm added to the atmospheric concentration for every 4.8 GtC emitted.

Using that figure, and with a starting point of 280 ppm as the pre-industrial benchmark, it is now possible to calculate the values for atmospheric concentration of carbon dioxide that are equivalent to the cumulative total anthropogenic CO_2 emissions. These values have been added to the top horizontal axis, replacing the $GtCO_2$ equivalents of the SPM 10. Next we mark the 560 ppm point as the first doubling of atmospheric concentration, then drop a vertical line to show its cumulative carbon equivalent of some 1365 GtC.



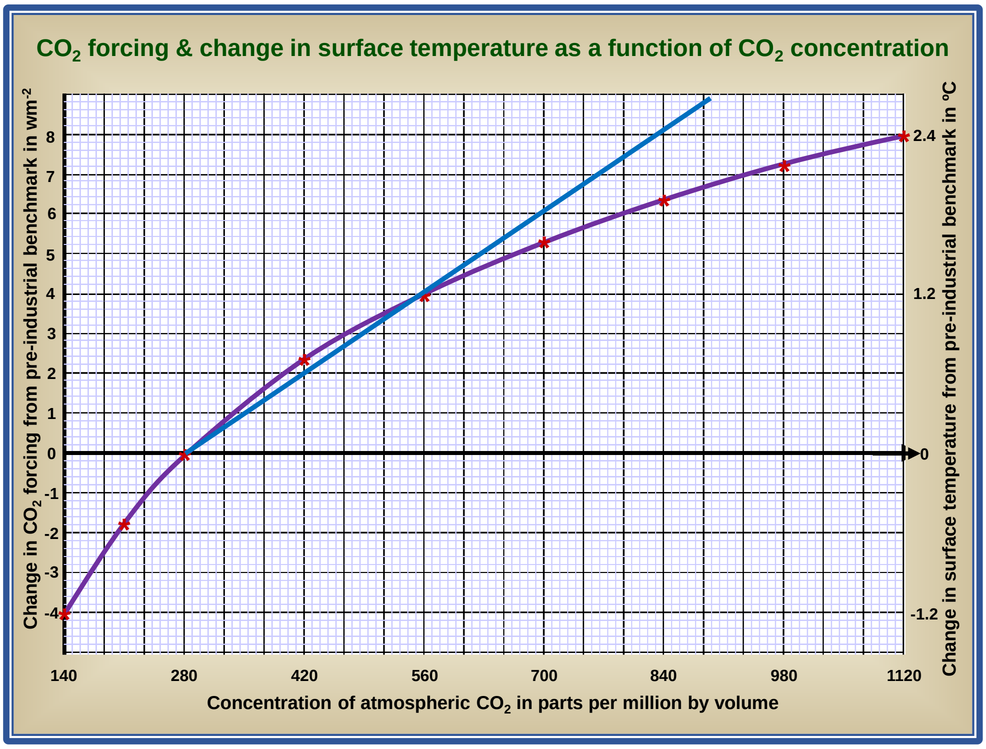
Embedded value of Sensitivity: If the function of temperature response to cumulative carbon emissions depends on climate sensitivity, then it is clearly vital to ascertain the value of climate sensitivity embedded or implicit in the new metric. The "Charney" or fast-feedback sensitivity yields a value of around 3°C for the equilibrium outcome of a doubling of atmospheric CO_2. We therefore draw the 3°C line across till it intercepts the 560 ppm value, then project the "Charney" sensitivity line from the origin through this point of intersection. It is immediately clear that the "Transient Climate Response" to cumulative CO_2 emissions is identical to the "Charney" or fast-feedback value of climate sensitivity



In selecting only the fast-feedback amplification of the CO_2 forcing to generate the transient response, the computer ensemble of CMIP5, on which this new metric is based, does not demonstrate "less uncertainty than Climate Sensitivity", (the transient response will be the same whatever the value of sensitivity). It simply removes Climate Sensitivity from all consideration. That is in clear contravention of the qualification of the function embedded in the main body of the Report. It also runs counter to the advice to policymakers generated over the last five years by the Apollo-Gaia Project, and flies in the face of the recommendations set out in the Royal Meteorological Society article quoted at the start of this paper.

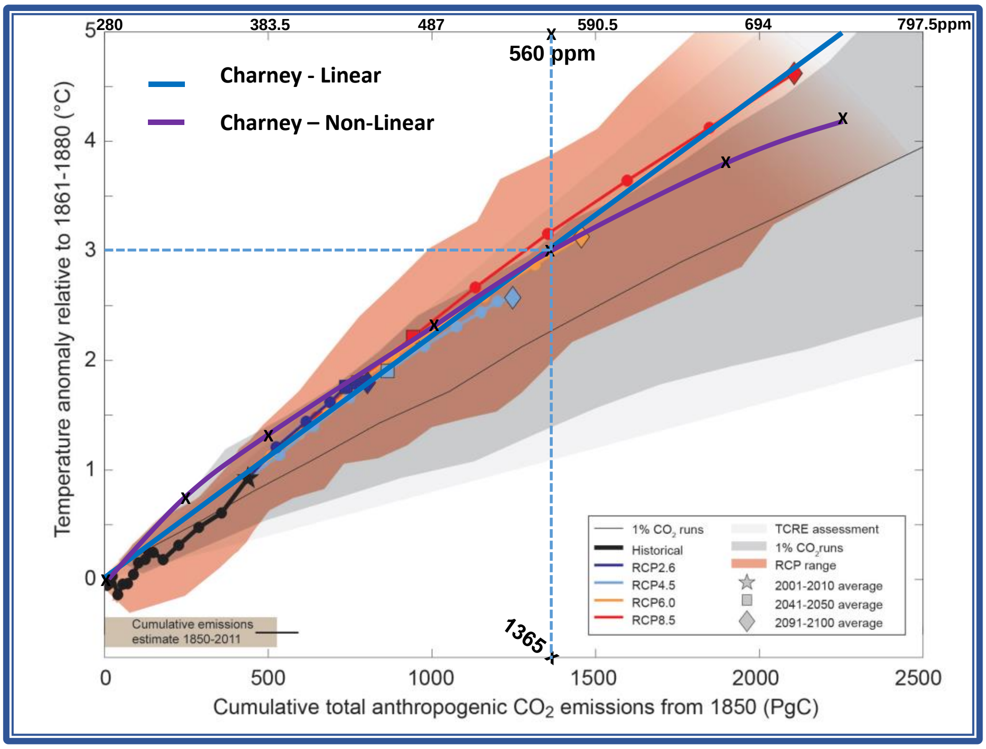
Non-Linearity: In reality, the forcing effect from rising concentrations of atmospheric CO_2 is not linear. There is a constant forcing (of approximately 4 watts per square metre) from each doubling of atmospheric concentration, requiring an equivalent temperature response. The logarithmic decay in effectiveness of forcing stems from the increasing saturation of the wavelength at which CO_2 molecules absorb the infra-red radiation (see the purple curve in the diagram below).

In treating the function as linear, the new metric effectively draws a straight line from the pre-industrial benchmark (280 ppm of atmospheric CO_2, and zero forcing anomaly), and extrapolates it through the first doubling point (560 ppm and 4 wm^{-2}).



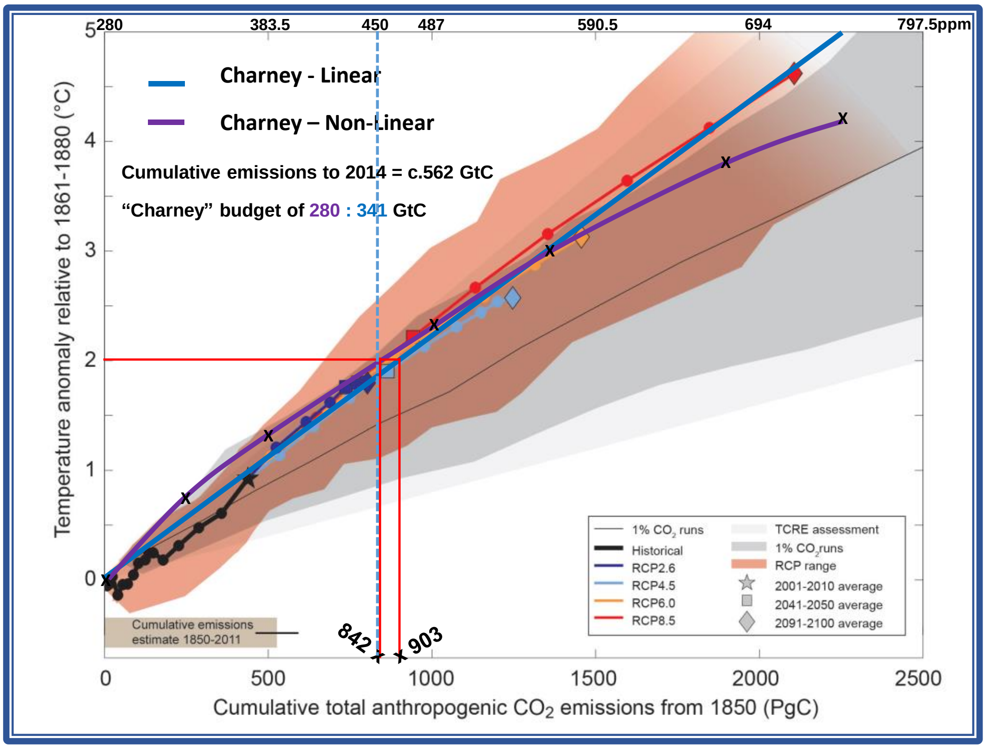
When the non-linear correction is transferred to SPM 10 it can be seen that the new metric underestimates the temperature outcome for cumulative carbon emissions below the 1365 marker, but progressively overestimates the temperature response beyond that point.

Just as using the transient temperature anomaly in place of the final equilibrium response inflates the available carbon budget, so also linearizing the temperature response to CO_2 forcing exaggerates the level of cumulative carbon emissions at which we risk passing the agreed policy target of a 2°C rise in average global surface temperature. That opens up the question of the derivation of a carbon budget based on the new metric.



Derivation of Available Carbon Budget

In order to derive a value for the amount of cumulative carbon emissions still available if the policy ceiling of a 2°C temperature anomaly is not to be exceeded, we draw a horizontal line from the 2°C point till it intersects the lines representing the linear function and its corrected curve. Dropping vertical lines from the intersection points we note that the 2°C anomaly would be exceeded when the cumulative carbon emissions passed c.903 GtC on the linear function.



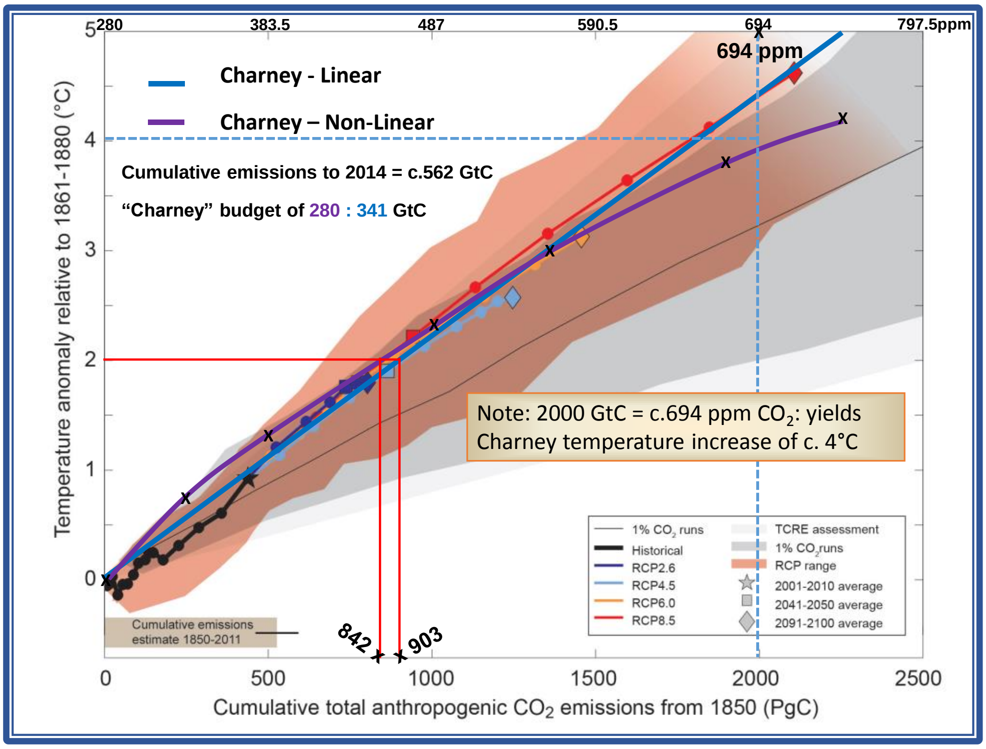
This reduces to c.842 GtC when the non-linear correction is applied. Taking the total cumulative emissions at 2011 as 531 GtC, and adding a further 31 GtC to represent emissions over the following three years, we derive a value of total cumulative emissions in 2014 as 562 GtC. Subtracting this figure from the values at which the 2°C ceiling is breached gives a value for the available budget of carbon emissions of 341 GtC using the linear function. The budget reduces to 280 GtC when the corrected non-linear function is applied. It is on this basis that the international community is attempting to negotiate the equitable sharing out of the available carbon budget, while recognising that the budget varies if the temperature target is changed, if the risk of passing the 2°C marker is altered, or if the forcing from other non-CO_2 greenhouse gasses is included.

By using the linear function, the "New Metric", as provided in the Summary for Policymakers, exaggerates the carbon budget by some 60 GtC. That is equivalent to an additional 6 years of emissions at the current rate. The use of the transient temperature response in place of the eventual equilibrium increase, also inflates the available carbon budget.

As a cross-check, the 842 GtC point is matched to the equivalent concentration of atmospheric CO_2. It is seen to be equivalent to c. 450 ppm. This correlates well with previous models (using only fast feedbacks but taking into account the non-linear nature of the CO_2 forcing) whose projections showed some 440 ppm as the concentration at which the 2°C equilibrium temperature ceiling would be passed.

Quantifying the "Carbon Gap"

Beginning with the "Copenhagen Accord" of 2009 and continuing through the subsequent "Conferences of the Parties" to the UNFCCC, some 80 participating countries have made promises, pledges, commitments, or, since Warsaw, "contributions" towards reducing their emissions of CO_2.



As was pointed out in the 2013 UNEP Report, even the full outcome of action on such pledges would still be an emission of carbon that would take the cumulative total to some 2000 GtC by the year 2100. Plotting that figure onto the new metric shows it to be equivalent to a concentration of some 694 ppm of atmospheric CO_2, which yields a transient increase in temperature of around 4°C. There is a massive gap between the pledged reduction in emissions and that required to keep within the available budget if the agreed policy target of a 2°C ceiling is not to be broken. Using the non-linear corrected target of 842 GtC, we can now quantify that gap as around 1158 GtC. The linear function embedded in the SPM reduces the gap somewhat to 1097 GtC. Those figures should be compared to the available budget of only 280 GtC, (341 GtC in linear version) while noting that present rates of emission are even greater than those consistent with the current set of pledges.

Those are the stark figures underlying the stalled impasse in international negotiations toward an agreed, legally binding treaty on emissions reduction, due to be drawn up in 2015 at the COP 21 in Paris and implemented by 2020. Ominously, the economic, energy-policy and political tides are moving strongly away from emission reduction in favour of sustained and increasing use of fossil fuel. As a consequence there are several gaps to close:

- **Gap 1:** First is the policy gap between increasing support for fossil energy and the commitment to effective problem-solving in the face of dangerous climate change.
- **Gap 2:** Second is the gap between current use of fossil energy and the set of emissions-reduction pledges already tabled.
- **Gap 3:** Third is the gap between promised reductions and the nominal "budget" that would apparently give a chance of limiting global temperature rise to the 2°C target.
- **Gap 4:** Fourth is the gap generated in the new metric of the SPM of IPCC AR5, by inappropriate use of linear approximations and by substituting a smaller transient temperature response to cumulative carbon emissions in place of the full equilibrium value.

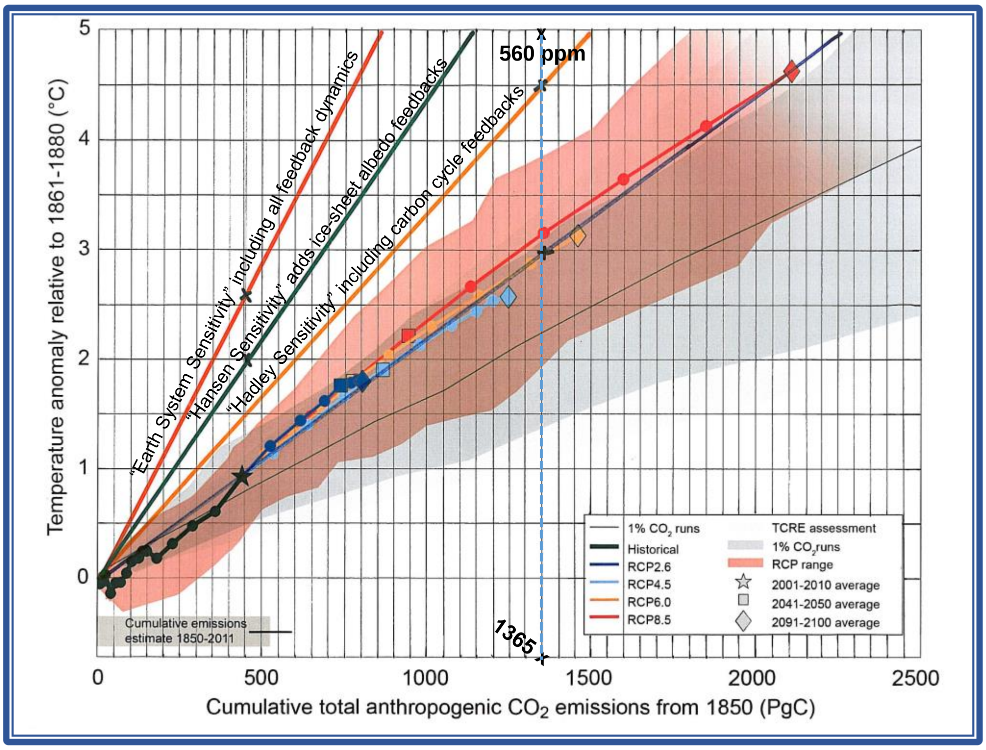
All four gaps fade in significance, however, when confronted by the implications of replacing the transient response with the full value of the Earth System Sensitivity. The adoption of the "transient temperature response" originated as an attempt to overcome difficulties in sensitivity modelling, and to avoid the high degree of uncertainty in sensitivity value, stemming historically from the model ensemble. The understandable simplification restricts modelled behaviour to certain fast feedback dynamics, but grossly misrepresents the response of the climate system to anthropogenic disturbance. The total elision from the Summary for Policymakers of all recognition that temperature response depends critically on climate sensitivity is an unacceptable methodology that deprives policymakers of vital information. It strikes at the very heart of our global capacity to take effective action in the face of dangerous climate change.

Part 2:
Introducing the "Earth System Sensitivity"

Because it is based solely on fast feedback amplification, the transient temperature response is essentially independent of the value of climate sensitivity. In contrast, as affirmed in the main body of the Report, the function of equilibrium temperature response to cumulative carbon emissions depends critically on the value of climate sensitivity. The time-scale may be longer than typical political horizons, but nevertheless, it is this response that must now be taken into account in strategic executive decision-making at all levels of our world community. It is the basis on which to calculate values of greenhouse gas concentration that lead to climate stabilisation at a temperature consistent with the commitment to avoid dangerous climate change.

The Earth System Sensitivity is introduced in three discrete stages, but first, a more finely divided grid is superimposed on the SPM 10 graphic to facilitate hand-plotting of each step. The vertical line denoting a doubling of CO_2 concentrations from the pre-industrial benchmark is also included

Step 1: First, remaining within the climate modelling methodology, we introduce the feedbacks of the natural vegetative carbon cycle and add these to the fast feedbacks of the "Charney" sensitivity. This sophistication is now being attempted by several of our most comprehensive climate models, perhaps the most advanced and best known being that of the Hadley Centre run by the UK Met Office. The **carbon cycle sensitivity** is represented by the yellow line in the figure below, and labelled "Hadley Sensitivity" in recognition of their work. The transient climate response (equivalent to the "Charney" fast feedback sensitivity) amplifies the effects of CO_2 forcing by a factor of 2.5, and gives a response to doubled CO_2 concentration of some 3°C. The carbon-cycle sensitivity amplifies the CO_2 forcing by about 3.75, leading to an equilibrium temperature increase of some 4.5°C.



Step 2: The next stage is to introduce the longer term slow feedbacks occasioned by the shift in albedo occasioned by the melting of the great land-based ice-sheets. The dynamics of ice-sheet disintegration are poorly understood, so this step uses a hybrid approach. Complex climate models are used to simulate the fast feedbacks and those of the vegetative carbon cycle, but paleo records are introduced to deal with the **ice-sheet albedo feedbacks**. The methodology has been a feature of the innovative approach of James Hansen of NASA, and the green line in the illustration is labelled the "Hansen Sensitivity" in recognition. The inclusion of these factors increases the amplification of the CO_2 forcing to a factor of about 5,

and leads to an equilibrium rise in average global surface temperature of some 6°C for a doubling of CO_2 concentration. Historically these mechanisms have taken place on millennial time-scales, following the slow, astronomical change in the shape of the earth orbit and the rate of tilt and wobble about its axis (the Milankovic cycles). Human perturbation of the climate is happening at around 300 times the speed of astronomical change, so albedo feedback from ice-sheet melt is expected to be much faster than is shown in the historical records. (Though how much faster, nobody really knows!). Ice sheet melt not only decreases planetary albedo and accelerates global warming, it also drives the acceleration of change in sea-level around the world.

Step 3: Each improvement in our understanding of the feedback dynamics takes us a step closer to the real behaviour of the planetary system and to the discovery of the actual value of the **Earth System Sensitivity**. By its very definition, this figure incorporates the effects of all feedback processes, known and unknown. It also includes all the complex interactions and inter-dependencies between the various mechanisms involved. Our lack of knowledge of all factors involved, incomplete data about even those mechanisms we do understand, coupled with uncertainty surrounding their complex interactions, all combine to render the task of computer simulation virtually impossible. Our methodology therefore depends totally on data-sets from the historical records (ice-cores, tree-rings, pollen, sediment cores, isotope ratios, and other proxy measures of the relationship between average global surface temperature and the concentration of atmospheric CO_2). It is on this basis that a robust value for the full Earth System Sensitivity has been derived under the aegis of the Apollo-Gaia Project.

Represented by the red line in the illustration, the **Earth System Sensitivity** amplifies the forcing effect of CO_2 on its own by a factor of 6.5, yielding a projected equilibrium temperature change of 7.8°C corresponding to a doubling of the concentration of atmospheric CO_2. The value is unique in that it alone satisfies the need to balance the change in radiative budget between the last glacial maximum and the pre-industrial benchmark. All previous estimates of sensitivity fall short of this mathematical criterion. The value appears to be stable across the two doublings of CO_2 concentration from 180 ppm at the LGM to over 1,120 ppm, even though the precise feedback dynamics vary in response to the changing physical conditions of the planet.

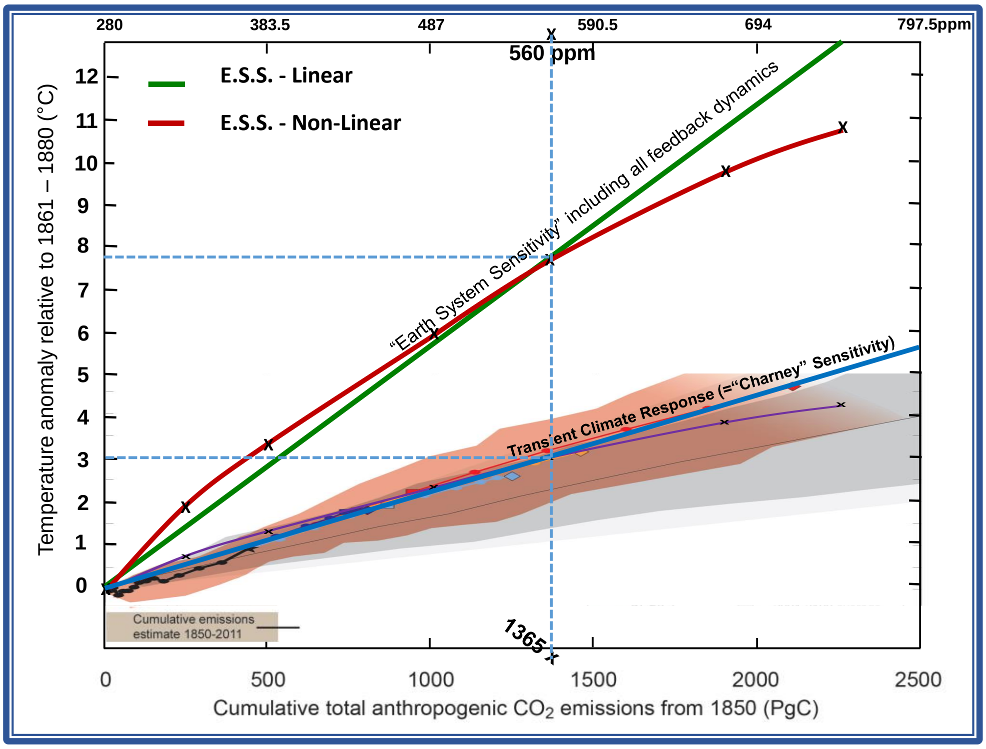
Those relying on the probability distribution generated by the CMIP5 have consistently rejected vales of sensitivity above about 4.5°C as low probability outliers. This should now be seen as a function of the computer modelling ensemble, rather than anything to do with the actual behaviour of the planetary climate system. In the light of the robust value for the Earth System Sensitivity, the "Charney Sensitivity" itself should now be seen as a low probability outlier reflecting the limited use of feedback dynamics incorporated in the conservative climate models.

Some terminological confusion has been introduced in the IPCC AR5 WG1, in that the phrase "Earth System models" is used to describe the growing cluster of computer models incorporating carbon cycle feedbacks. The innovation masks the distinction between the model simulations and the reality of the system itself. The map is confused with the territory. If the confusion is to be avoided, it will be necessary to retain the label of "Earth System Sensitivity" as referring to the actual, physical behaviour of the planetary climate. This would reinforce the contrast between the objectivity of the planetary system in distinction to the computer simulations that can never be other than more or less sophisticated approximations to that reality.

In the illustration, all three steps are presented in linear form. The non-linear correction required to take account of the decay of GHG efficiency with rising atmospheric concentration is reintroduced for the Earth System Sensitivity in the next figure. The linear presentation in the Apollo-Gaia analysis has been achieved by using a semi-log (base 2) scale for the horizontal axis. This mapping embeds a constant increment of axis for each doubling of the concentration of atmospheric CO_2, a modification which is absent from SPM 10.

Changing the Temperature Scale

The steep gradients of the lines representing the Hansen and Earth System sensitivities mean that the temperature anomalies associated with a doubling of the concentration of atmospheric CO_2 (let alone those representing the response to a total accumulation of emitted carbon of some 2000 GtC) are right off the top of the scale of SPM 10. In this next figure, the temperature axis has been compressed by a factor of 2.5 to accommodate the full range of temperature anomaly associated with the Earth System Sensitivity (ESS). The SPM 10 representation of the new metric has been compressed to fit the new scale. Both the linear and corrected non-linear versions of the ESS have been included, as has the vertical line showing the doubling of atmospheric concentration of CO_2 beyond the pre-industrial benchmark. The temperature anomaly of 3°C predicted by the transient climate response has been complemented by the inclusion of the predicted temperature anomaly of 7.8°C based on the application of the ESS.



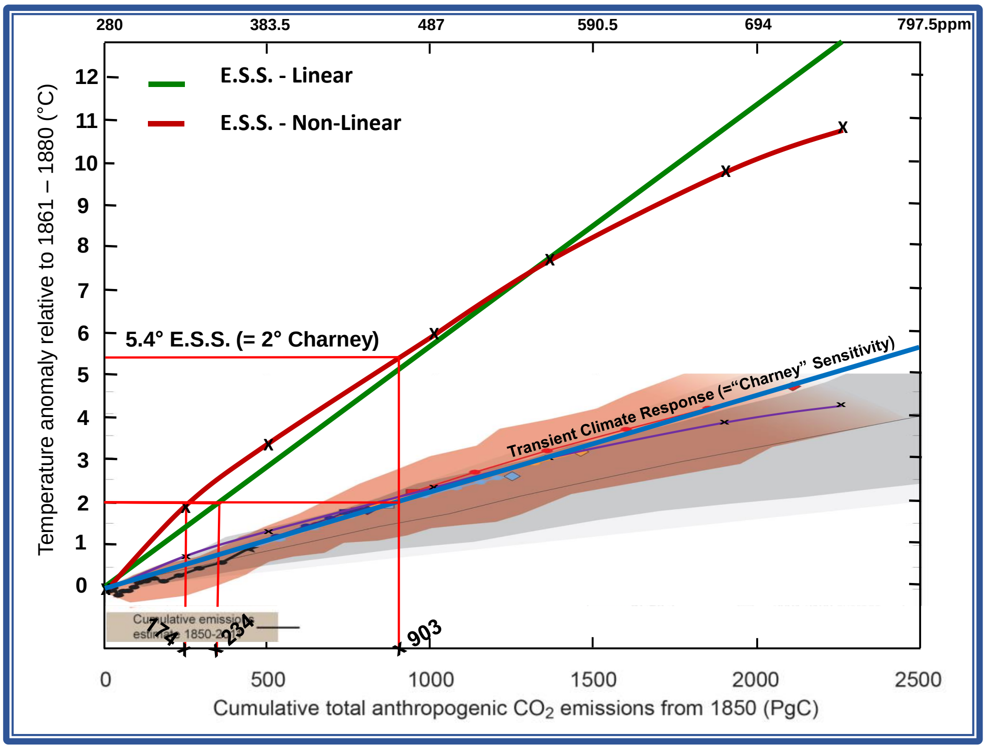
Enhanced Sensitivity in the Anthropocene

All data on which the value of the Earth System Sensitivity is based, come from conditions of dynamic equilibrium and slow change in the planetary climate system. In today's world, however, those conditions no longer apply. Human activity in both pace and scale has driven the system significantly out of equilibrium and into a rate of change some 300 times faster than at any time in the paleo records. In consequence, a number of amplifying feedback mechanisms have been brought into play that increase the value of the ESS. Vegetative systems no longer have the time for slow adaptation to change but are facing die-back and burn which releases carbon from both soil and bio-mass. Natural carbon sinks are decaying. The rate of methane release raises concentrations of atmospheric methane instead of allowing its slow degrade to CO_2. Phase-change related feedbacks (net ice melt and water evaporation) enhance global heating. In short, while the established value of the Earth System Sensitivity is valid for the Holocene as a whole, it is subject to significant increase in the current conditions of the Anthropocene.

While the Holocene value of the ESS is used throughout the rest of this paper, it should be treated as a conservative baseline. The actual response of the earth's climate system is expected to be even higher.

2°C Response using the Earth System Sensitivity

As before, the 2°C marker line is extended horizontally. It crosses the red line (non-linear corrected curve of the ESS) as the cumulative total of anthropogenic CO_2 emissions passes 174 GtC. Moving further to the intersection with the green line (uncorrected linear version of the ESS), even this point is passed as the cumulative emissions reaches the 234 GtC level. Once again, adopting the linear approximation allows some 60 GtC extra carbon emissions (or about six years' worth at current rates).

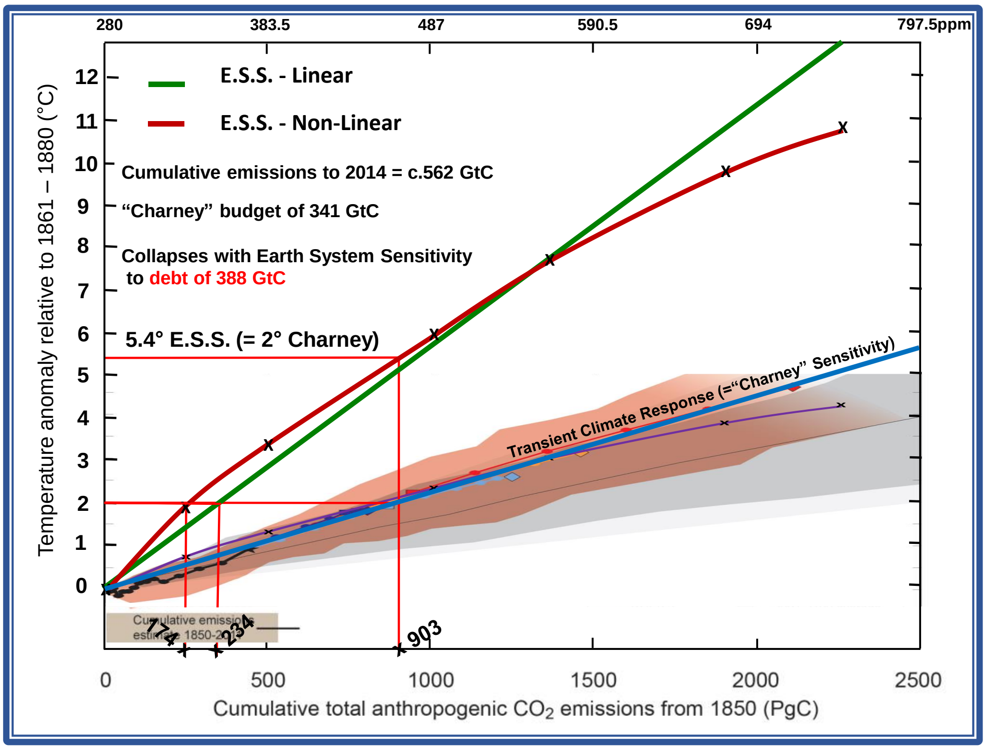


Extending the 2°C line even further till it crosses the linear un-corrected line of the transient temperature response (= "Charney" sensitivity) embedded in the Summary for Policymakers, we recall that the appropriate cumulative carbon emissions stood at 903 GtC, a discrepancy of 729 GtC.

The most profound implication of replacing the transient temperature response of the SPM with the full value of the Earth System Sensitivity, is the dramatic change in predicted temperature. Where the "Charney" sensitivity indicated that a 903 GtC level of total cumulative anthropogenic emissions would lead to a 2°C rise in temperature, that same total can now be seen to give rise to an equilibrium temperature response of 5.4°C. It is starting to become clear why the "New Metric" of the SPM is so politically and economically attractive, and why the pressure not to base GHG stabilization targets on the Earth System Sensitivity is so intense.

From Available Carbon Budget to Growing Carbon Debt

Given the "policy target" of restraining increase in global surface temperature to below 2°C, the Summary for Policymakers supports the impression that there is still slack in the system. With current (2014) cumulative total anthropogenic carbon emissions standing at c. 562 GtC, and a ceiling target of 903 GtC, there is an apparent available carbon budget of some 341 GtC, (or a budget of c. 1663 $GtCO_2$, translating into the carbon-dioxide equivalent using the ratio embedded in SPM 10).



However, when we apply the full Earth System Sensitivity, the equilibrium planetary response to anthropogenic emissions can be seen to have exceeded the policy target (of a maximum increase of 2°C) as the cumulative emissions passed 174 GtC.

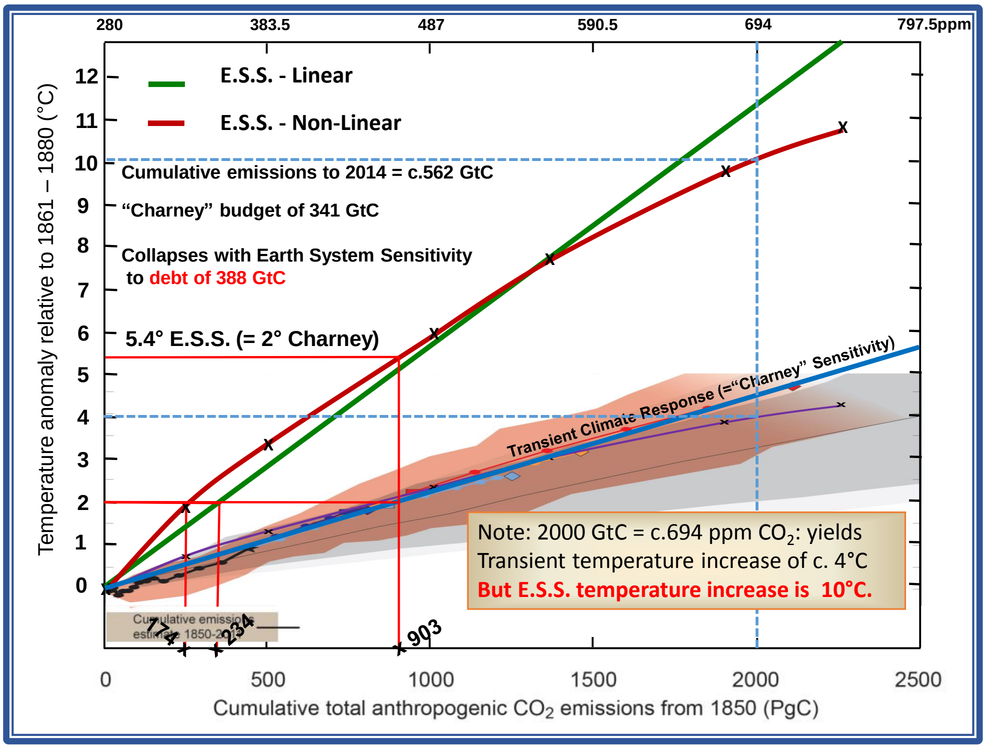
It is therefore clear that there is no available carbon budget.

In fact the account is massively overdrawn by a total of 388 GtC. In other words, there is no surplus in the account to be shared out (equitably or otherwise) across the international community. Civilization is deeply in debt to the planetary environment, and every extra tonne of emitted carbon simply adds to that debt. Sadly there are no bankruptcy arrangements in place between human civilisation and its planetary environment.

Re-evaluating the “Carbon Gap”

In a previous section we quantified the “Carbon Gap” on the basis of the transient temperature response embedded in SPM 10. We noted that present levels of international contribution towards the reduction of emissions still led to a cumulative total of 2000 GtC by the year 2100. That left an emissions reduction gap of some 1097 GtC between promised reductions and the 903 GtC required to prevent temperature increase exceeding the policy goal of 2°C.

Now we can apply the full Earth System Sensitivity, (replacing the SPM value of the transient or “Charney” sensitivity emanating from our conservative computer simulations of fast feedback responses). **The Carbon Gap has to be increased by a further 729 GtC to a total of 1826 GtC**. That represents the difference between the best available set of promises and the cumulative total at which there was an equivalent risk of exceeding the 2°C target. The increase comes from two parts. First is the 388 GtC “overshoot” difference between the 2°C generating figure of 174 GtC and our current accumulation of 562 GtC. The second element is the 341 GtC gap between current accumulation and the SPM target of 903 GtC.



The other outcome of applying the ESS is the recognition that the presently tabled set of international contributions to emissions reduction leads to a projected temperature rise of some 10°C beyond the pre-industrial benchmark, rather than the 4°C increase suggested by the SPM. With polar amplification that would spell an ice-free world and c. 120 m rise in sea-level.

Some of the strategic implications will need to be spelled out elsewhere. Here it is sufficient to note that climate stabilization at a level close to the 2°C policy target cannot be achieved simply by a programme of emissions reduction on its own. The 388 GtC gap between current and target concentration requires an urgent and aggressive reduction in the airborne concentration of CO_2, in concert with a termination of emissions from fossil hydrocarbon sources and a rejection of all other activity that increases the net radiative imbalance of the planet.

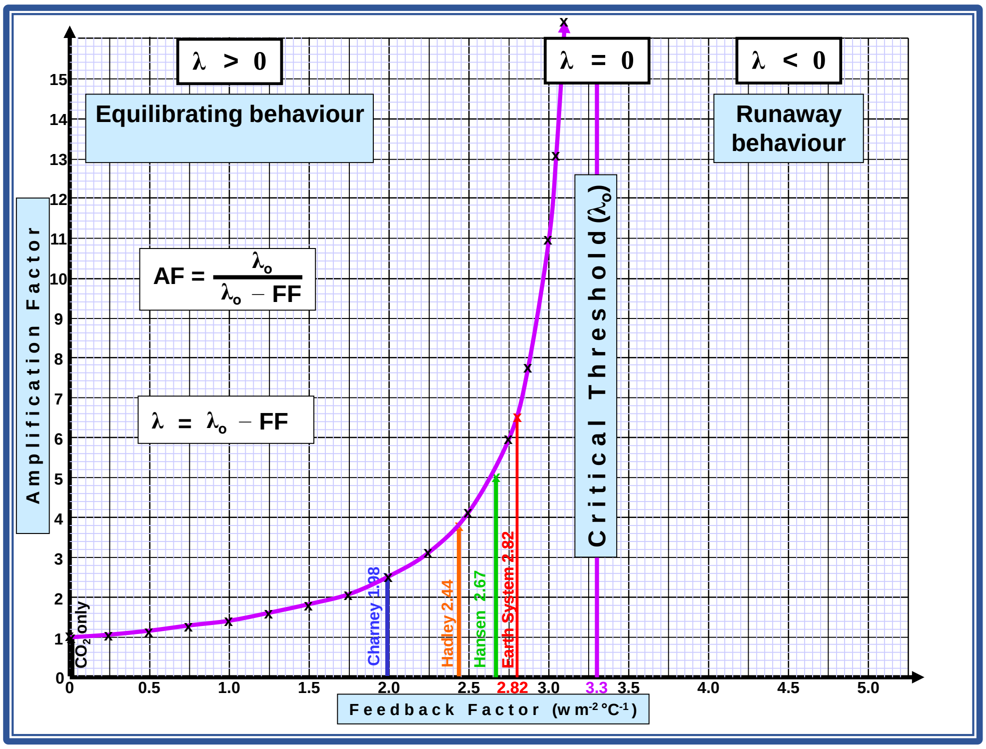
Beyond the Stable State

As was noted in a previous section ("Enhanced Sensitivity in the Anthropocene"), all data sets from which the value of the ESS is derived, were laid down in conditions of very slow change and dynamic thermal equilibrium. In the Anthropocene we have moved beyond the stable state and need to recognise that other factors have been brought into play that push the value of the Earth System Sensitivity beyond that which applies to the undisturbed conditions of the Holocene. Stabilizing planetary climate at or below the 2°C policy limit would therefore require draw-down to cumulative levels of carbon significantly below the 174 GtC figure. Conversely the temperature anomaly implicit in the current set of emissions reduction pledges would be significantly above 10°C.

An overview of the situation is provided by reference to the complex graphic below (produced by the Apollo-Gaia Project):

The ratio by which the earth system multiplies the greenhouse effect of carbon-dioxide on its own is known as the amplification factor (AF). It is plotted up the vertical axis. Sensitivity values (eventual temperature anomaly to be expected as a result of doubling the atmospheric concentration of CO_2) are derived by multiplying the Amplification Factor by the temperature change required to balance the earth's radiative budget taking into account the forcing from a doubling of CO_2 concentration on its own without any feedback effects (i.e. about 1.2°C).

Values for the Feedback Factor (FF) are plotted along the horizontal axis. The Feedback Factor represents the number of watts per square metre added by the climate feedback system for each 1°C change in average surface temperature. The Critical Threshold marker (**λ_o**) is placed at 3.3w m^{-2} °C^{-1} representing the value of the "radiative damping coefficient", the number of watts per square metre by which the radiative imbalance is reduced (by changes in the amount of energy radiated to space) for every 1°C change in average surface temperature. The various values of Feedback Factor associated with differing approaches to Climate Sensitivity are entered as specific points on the curve of the underlying equation.



The non-linear relationship between Amplification Factor and Feedback Factor is immediately obvious. AF depends on the difference between λ_o and the FF. AF approaches infinity as the gap approaches zero.

The ensemble of climate models (CMIP5) on which the IPCC AR5 is based, employs the transient set of fast feedback mechanisms with a Feedback Factor value of around 2. In this area of the curve, variations in the FF value have comparatively small effects on the Amplification Factor and its associated sensitivity. More sophisticated representations of the feedback system have higher values of the FF. So introducing the vegetative feedbacks of the carbon cycle (Hadley) has a FF value of 2.44. Expanding to include the slow albedo feedbacks from land-based ice sheet decay (Hansen) has a FF value of 2.67. The full Earth System Sensitivity with its AF of 6.5 has a FF value of 2.82. In this area of the curve small changes in behaviour of the feedback system have large effects on the value of the Amplification Factor and its associated sensitivity.

As we move **beyond the stable state of the Holocene** into the rapid change of the Anthropocene, the value of the FF is pushed to the right towards the critical threshold. Here, tiny increments in the FF have massive effects on the AF and its associated equilibrium temperature. Provided the value of the FF remains below 3.3 (the value of the radiative damping coefficient) the climate system does eventually reach a new equilibrium state. However, beyond that critical threshold or "tipping point", the system moves into a temporary condition of self-amplification (or "runaway") behaviour.

Not only should the Earth System Sensitivity replace the transient (fast-feedback) response used in the SPM Figure 10, but the value of the ESS based on the stable conditions of the Holocene should be taken as the minimal, conservative baseline. The reality of conditions in the Anthropocene increases the value of the ESS and so sharpens both the scale and urgency of the critical situation we now face.

The 2°C Delusion

The dynamics of planetary climate change depend on two inter-connected forms of sensitivity. The first is the sensitivity of temperature response to changes in the atmospheric concentration of carbon-dioxide. The second is the sensitivity of the climate system itself to changes in average surface temperature. It is to this second relationship that we now turn our attention.

The Holocene value of the ESS depends on the temperature difference between the pre-industrial benchmark and the coldest point of the last glacial maximum. For the sake of calculation that difference has been taken as 5°C. Slight uncertainty concerning the relationship between temperature and CO_2 concentration in the ice-core records means that the figure could be as low as 4°C, so reducing the Holocene value of the ESS from 7.8°C to about 6.3°C. While reducing the overall carbon debt, this modification would also imply that the dynamics of the planetary climate system were even more sensitive to small changes in average surface temperature. The implications for strategic avoidance of dangerous climate change would therefore not be affected.

The "policy goal" of restraining anthropogenic increase in average surface temperature to no more than 2°C was never based on a scientific safety-case analysis. It is now clear that such an increase represents about half the difference between the depth of an ice-age and the warm inter-glacial conditions in which human civilization has developed. Major changes in planetary climate dynamics are precipitated by very small changes in average surface temperature. Strong additional evidence for the critical dependency is now being provided by the experience of significant shifts in global climate dynamics in response to a mere 0.85°C increase in surface temperature. As it begins to dawn on us just how sensitive our planetary climate is to changes in average surface temperature, it becomes ever more clear that the threshold of dangerous climate change is already upon us. The assumption that no such threat would be encountered below some arbitrary ceiling of 2°C is, to put it bluntly, a delusion. Any international agreement to limit temperature change to the policy target of 2°C based on the ESS, (let alone one based on the transient temperature response to fast feedback dynamics embedded in the Summary for Policymakers of the IPCC AR5) would condemn our planetary system, and the human civilization on which it depends, to unthinkable levels of catastrophic climate change.

We can no longer honour the UNFCCC commitment to the avoidance of dangerous climate change. That threshold has already been passed. Limiting the extent of dangerous climate change requires a reduction in the policy target to a mere 1°C above the pre-industrial benchmark. Even at that level we would have to adapt to changes in the planetary dynamics significantly more intense than those already being experienced around the world.

The year of 2014 sees total accumulated carbon emissions reaching around 562 GtC, and an atmospheric concentration of CO_2 of 396 ppm. That puts us exactly half way towards the forcing effect of a doubling of CO_2 concentration. The associated, but grossly underestimated, projected temperature anomaly based on the transient, fast-feedback response of the model ensemble at the heart of the Summary for Policymakers, would be c. 1.5°C, of which 0.85°C has already occurred, leaving a further projected rise of only 0.65°C.

The situation is seen to be radically different when we apply the full value of the Earth System Sensitivity. We already face an equilibrium temperature change of at least 3.9°C above the pre-industrial benchmark, leaving over 3°C still to come as a result of today's anthropogenic disturbance of the planetary atmosphere. That figure rises still further to over 5.4°C (4.6°C still to come) if we include the forcing already in place from other anthropogenic non-CO_2 greenhouse gasses. The stark reality of now faces human civilization with a planetary increase in average surface temperature in excess of 4°C. That figure can only rise as further emissions are released and human activity continues to degrade the natural carbon sinks.

Executive Summary

1. Let us first summarise the analysis of the basis for a carbon budget embedded in the Summary for Policymakers of the IPCC AR5 WG1:

1.1. The adoption of a transient temperature response to cumulative carbon emissions, instead of the full equilibrium impact, allows a higher carbon output before the critical 2°C target is breached. No reference to the substitution is made in the text of the SPM.

1.2 Treating the relationship between temperature response and cumulative carbon emissions as a linear, straight-line function also inflates the available carbon budget by some 6 years' worth of emissions at the current rate.

1.3. Removal of all visual representation of the current value of the cumulative carbon emissions, reduces the clarity of the present situation.

1.4. Failure to link the total cumulative carbon emissions to the equivalent concentration of the airborne fraction of CO_2 adds to the obfuscation of the presentation.

1.5 Limiting the extent of climatic response to the fast feedback (transient or "Charney") dynamics eliminates dependency on the function of climate sensitivity. This hides uncertainty in the modelling ensemble at the expense of portraying a grossly underestimated temperature response and a massively inflated carbon budget.

2. Secondly we note the consequences of applying a robust value for the Earth System Sensitivity:

2.1. The temperature response to the proposed ceiling of allowed carbon emissions is 5.4°C, not the 2°C indicated in the SPM.

2.2. The temperature response to the current set of emission-reduction pledges is c. 10°C, not c. 4°C as indicated in the SPM.

2.3. The temperature response to which we are already committed at the present level of cumulative carbon emission is 3.9°C (+ effect of non-CO_2 GHG emissions) not 1.5°C implied in the SPM

2.4 The budget of c. 300GtC of available carbon emission before breaching the 2°C policy target is seen to be an illusion. In reality the carbon account is already overdrawn by c. 288GtC.

2.5. All the above figures should be treated as conservative underestimates as we move from the stable conditions of the Holocene into the far-from-equilibrium, rapid change and enhanced sensitivity of the Anthropocene.

2.6. Recognition of the sensitivity of global climate dynamics to small changes in average surface temperature implies that the degree of safety assumed in the policy target of limiting increase to no more than 2°C above the pre-industrial value, is a delusion.

2.7. Avoiding dangerous climate change is no longer possible. Limiting its intensity requires restriction of the target temperature increase to no more than 1°C.

2.8. Achieving that goal requires reduction in the atmospheric concentration of greenhouse gasses to around 310 ppm of CO_{2e} (from the current value of some 450 ppm CO_{2e}).

On these grounds the Summary for Policymakers of the IPCC AR5 WG1 should be rejected as not fit for the purpose of policy-making. It is a compromise between what is scientifically necessary and what is deemed to be politically and economically feasible. It is a document of appeasement, in active collusion with the global addiction to fossil sources of energy.

David Wasdell **April 2014**

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