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RISK SHIFTS UNDER CHANGING CLIMATE SENSITIVITY ESTIMATES

- Briefing Note to the Global Challenges Foundation -

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Summary

This note discusses how assessments of how global-mean warming (measured in °C) can shift under changing estimates of equilibrium climate sensitivity. The focus is on relative low probability but high impact scenarios. It provides a short introduction to what climate sensitivity stands for and what it can be used for. Furthermore, it also provides an illustration of which CO_2-equivalent forcing levels would be consistent with limiting global-mean warming to specific levels, depending on various interpretations of possible distributions of climate sensitivity.

Contents

I. Introduction To Climate Sensitivity

The Earth's climate system has been studied by science since many centuries, with a notable intensification of interest in the past few decades. An important aspect of the study of the climate system is to understand and quantify the response of the climate system to increasing concentrations of greenhouse gases (GHG) in the atmosphere. Over the years, two quantities have been emerged in the climate science community to quantify the temperature response of the climate system to such an increase of GHG concentrations (often reported in terms of carbon-dioxide equivalence, CO_2e): the transient climate response (TCR) and the equilibrium climate sensitivity (ECS). Both the definition of ECS and TCR are rather academic*. However, these two quantities basically describe how the climate responds to an increasing forcing in transient and equilibrium conditions, respectively.

The TCR is defined as the global mean temperature increase the climate system would undergo at the time CO_2 concentrations are doubled following 70 years of linearly increasing forcing. The ECS is defined as the global mean temperature increase of the climate system in its equilibrium state after a sustained doubling of CO_2 concentrations. TCR thus provides an estimate of how the climate system's global mean temperature would respond, exactly at the time of stabilizing forcing after a period of increasing forcing. ECS, on the other hand, provides an estimate of how the global temperature would evolve a few decades to centuries after concentrations have been stabilized[1].

How much of the equilibrium response is already been realized at a certain point in time depends on the forcing path followed, Zickfeld and colleagues[2] find that about 75% of the equilibrium temperature increase (as defined by the ECS), is realized in 2100 in a scenario that stabilizes forcing in 2100. The remainder of the warming is then slowly expressed over the following centuries. Also changes in vegetation, ice sheets, permafrost thawing, and ocean circulation can further influence the final temperature increase. These aspects are mostly not included in ECS estimates[1]. ECS combined with all the aspects mentioned above is often referred to as Earth System Sensitivity (ESS). In this note we focus on estimates of ECS (see Figure 1), which represents a subset of the long-term response of the climate system. Estimating and quantifying the ESS, is still an active research question.

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* The IPCC Fourth Assessment Report provides definitions for both in its glossary as: Equilibrium climate sensitivity refers to the equilibrium change in the annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration.
The transient climate response is the change in the global surface temperature, averaged over a 20-year period, centred at the time of atmospheric carbon dioxide doubling, that is, at year 70 in a 1% yr^{-1} compound carbon dioxide increase experiment with a global coupled climate model. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing.

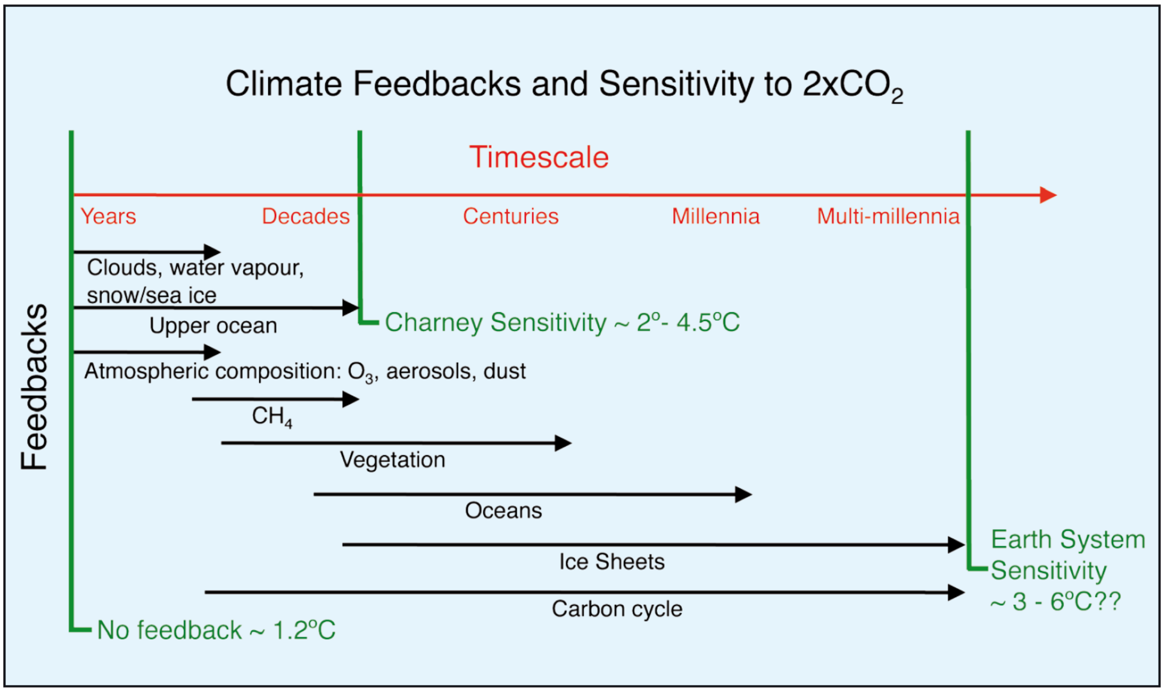

Figure 1: Overview of varying types of sensitivities to doubling CO_2 concentrations as a function of what feedbacks and time scales are considered. The actual sensitivity depends on which feedbacks are included. Equilibrium climate sensitivity (ECS) corresponds often to the "Charney Sensitivity" in the figure above (source: Reference 3).

II. Introduction To Recent Climate Sensitivity Estimates

At the time of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), the overall assessment of ECS, based on multiple lines of evidence, was that it was likely (greater than 66% probability) in the range between 2 and 4.5°C, very likely (greater than 90% probability) larger than 1.5°C, with a most likely value (mode) around 3°C, while values significantly higher than 4.5°C could not be excluded. With no strong constraints on its ranges, the IPCC AR4 ECS assessment illustrates the inherent uncertainty that estimates of ECS are subjected to.

Since the IPCC AR4, new studies have been published in the peer-reviewed literature which use various methodologies of different complexity. Some use very simple box models, but with new data or more sensitivity analyses (e.g. References 4 and 5). Others take different approaches, for example, by looking at the present climate in the most complex climate models (e.g. References 6 and 7), or by looking at the Paleoclimatic record (e.g. References 8 and 9).

New estimates that have appeared in the literature are not conclusive about whether and by how much the IPCC AR4 statement (based on literature before 2007) would need to change in order to reflect the new findings. Many studies which use a simple model approach combined with updated observations project lower climate sensitivity estimates (e.g. References 4, 5 and 10). However, a review of climate sensitivities from the Paleoclimatic record[8] generated estimates consistent with the IPCC AR4 ranges. Finally, also when looking at the results of the most complex climate models the IPCC AR4 range is confirmed[6] and in some cases a comparison of these models with key features of the present climate indicates that ECS estimates at the higher end of the spectrum (i.e., around 4°C) might be more plausible[7]. This range in quantifications of what the ECS could be illustrates the deep uncertainty[†] surrounding this issue. This uncertainty is not likely to disappear very soon[1], because of limited data availability required for constraining climate sensitivity and the chaotic processes ruling the internal variability of the climate system.

It is important to note that each of the approaches mentioned above uses both observations and some kind of model, ranging from very simple to very complex. Simple models have the advantage of being computationally inexpensive and can thus allow for probabilistic methods using a Bayesian approach to explicitly attempt to span the entire range of uncertainty. However, at the same time they run the risk of not being able to reflect the internal variability of the historical record (in particular in the last couple of years) or run the risk of not incorporating possibly important changing climate feedbacks over time. More complex models often incorporate such possibilities better. Nevertheless, many so-called tipping points in the climate system (like methane clathrate releases or massive tropical, or other, forest dieback) are not included in any of the models underlying these climate sensitivity estimates from the literature. In the past, these processes were often not included in models in an attempt to manage the complexity and therewith the computational cost of the modeled system. Some processes that are only now being incorporated in models could both result in an increase or decrease of ECS. For example, methane feedbacks and an interactive carbon-cycle are likely to increase the equilibrium temperature increase, while better resolved cloud processes could still shift ECS to both higher and lower values.

III. Differences In Uncertainties Between Single Studies And Large Assessments

All ECS estimates published in the peer-reviewed literature come with their associated uncertainty ranges. However, a fundamental difference exists between the uncertainty assessments of single studies and large assessments like the IPCC. While single studies in their uncertainty assessment can (and often do) account for uncertainties in historical observations of global-mean temperature and ocean heat uptake, or uncertainties in the historical forcing and biases due to different statistical methods (amongst many other aspects), they cannot account for structural model uncertainty. This means, the probability that the model used is inappropriate or fundamentally wrong. Large assessments, like the assessment carried out by the IPCC, do attempt to take into account such considerations as well as multiple lines of evidence. Furthermore, in their assessment the IPCC also tries to account for climate system properties that are not included in the underlying studies. In most cases, large assessments like the IPCC therefore arrive at significantly more conservative estimates than single model studies because they focus on the state of the current knowledge of the entire climate science community rather than on the results of one particular methodology and model.

[†] „Deep uncertainty“ is a term used to denote that there is not only uncertainty about the actual value of a quantity, but also about the shape of the distribution.

IV. Risk implications of the IPCC uncertainty language

When providing its assessment of ECS, the IPCC uses a calibrated language[11] to indicate varying levels of uncertainty and confidence. Table 1 provides an overview of the calibrated terms used for the IPCC likelihood scale. Besides these likelihoods, the IPCC can also attribute a level of confidence to a statement, ranging from low over medium to high confidence. Many of the terms included in the IPCC likelihood scale refer to probability intervals that are closed on one side but open on the other. For example, the use of the word *likely* denotes a "probability from 66 to 100 percent. The fact that the IPCC's ECS assessment is given in these terms and not in terms of an actual probability distribution again reflects the deep uncertainty surrounding the precise quantification of ECS.

Following the general statement of the IPCC, researchers have attempted to translate these ranges into one single workable probability density function[12] (PDF; probability distribution). It is important to note that constructing such PDF requires assumptions beyond the assessment of the IPCC. Such translations of the IPCC statement, if they are transparent, can thus be considered consistent with the IPCC statements, but always represent some kind of interpretation of the IPCC's assessment. Such interpretations can represent, for example, an average, pessimistic or optimistic view of the IPCC assessment of ECS. From a risk perspective, and particularly an extreme risk perspective, it is important to include and explore values that cannot be formally excluded. For example, in its 2007 assessment the IPCC stated that values significantly higher than 4.5°C cannot be excluded, but no probability was accorded to these.

Table 1: Overview of IPCC likelihood scale from the "Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties"[11].

Table 1. Likelihood Scale

Term*	Likelihood of the Outcome
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33 to 66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

* Additional terms that were used in limited circumstances in the AR4 (*extremely likely* – 95-100% probability, *more likely than not* – >50-100% probability, and *extremely unlikely* – 0-5% probability) may also be used in the AR5 when appropriate.

V. Risk shift under changing ECS estimates

As mentioned earlier, the IPCC AR4 assessed ECS to be likely (greater than 66% probability) in the range between 2 and 4.5°C, very likely (greater than 90% probability) larger than 1.5°C, with a most likely value (mode) around 3°C, while values significantly higher than 4.5°C could not be excluded. The recent IPCC Fifth Assessment Report[‡] (AR5) updated the assessment of ECS slightly. It now assesses that ECS is with greater than 66% probability between 1.5 and 4.5°C, with more than 95% probability larger than 1°C, and with less than 10% probability greater than 6°C. See Figure 2 for a graphical comparison between these two assessments.

A recent study[12] used these statements to construct 10'000 possible ECS distributions that each lie within the range of possibilities left open by the IPCC AR4 statement. The same methodology was applied in this briefing note for the AR5 assessment. From these 10'000 distributions, average, pessimistic or optimistic members can be selected. Table 2 (and Table 3 in Appendix) shows the characteristics of a selection of possible ECS distributions, all in line with the IPCC AR4 or AR5 statements. The illustrative ECS distributions in Table 2 and Table 3 show that even within the constraints provided by the IPCC AR4 ECS statement, there can be a large variation in the tails of the distribution (e.g. see the probability higher than 6°C). Moreover, the heaviness of the high-impact tail is independent of the most likely (peak) value of the distribution and of what happens at the lower end of the distribution. For extreme risks, it is this high-end tail of the distribution that determines the probability of extreme outcomes. Currently, however, from a risk perspective, high impact outcomes cannot go unaccounted for except if one can formally exclude them by taking into account all combined lines of evidence, like Paleoclimatic records, the most advanced climate models, and the recent observations.

Based on applying the same sampling methodology to both the IPCC AR4 and AR5 statements, the heaviness of the tail has been constrained in the time period between the AR4 and AR5. However, the current assessment still leaves a maximum probability of 10% open that ECS is higher than 6°C.

[‡] The Summary for Policymakers (SPM) of the AR5 was presented on 27 September 2013.

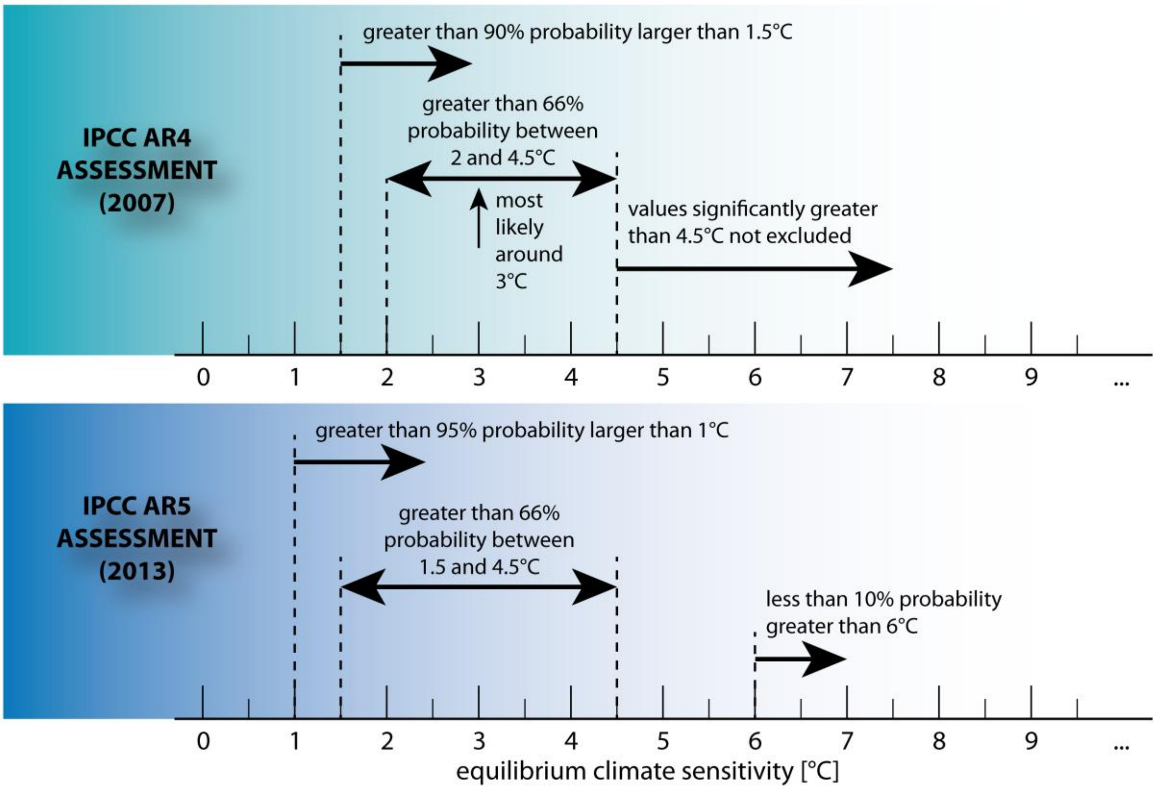

Figure 2: Graphical representation of the equilibrium climate sensitivity assessment statements of the Fourth (AR4) and Fifth (AR5) assessment reports of the Intergovernmental Panel on Climate Change (IPCC). The AR4 assessed ECS to be likely (greater than 66% probability) in the range between 2 and 4.5°C, very likely (greater than 90% probability) larger than 1.5°C, with a most likely value (mode) around 3°C, while values significantly higher than 4.5°C could not be excluded. AR5 assessed the ECS to be with greater than 66% probability between 1.5 and 4.5°C, with more than 95% probability larger than 1°C, and with less than 10% probability greater than 6°C. Background colors are visual guides only, without any scientific meaning.

Table 2: Overview of illustrative ECS distributions, all consistent with the IPCC AR4 or AR5 statements. The columns show an average interpretation of the AR4 (AR5) statements (AR4 average/AR5 average), while the other columns show illustrative interpretations that are either optimistic or pessimistic with regard to the high end of the distribution. These variations are drawn from a 10'000-member ensemble of possible interpretations (see Reference [12]). More examples of variations can be found in Appendix.

PROBABILITY	***IPCC Assessment***		***Cases***					
Case number	***AR4***	***AR5***	***AR4 average****	***AR4 pessim. high***	***AR4 optim. high***	***AR5 average****	***AR5 pessim. High***	***AR5 optim. High***
Lower than 1°C		<5%	1%	0%	0%	3%	1%	5%
Lower than 1.5°C	<10%		5%	0%	4%	9%	2%	13%
Lower than 2°C			12%	1%	15%	20%	8%	25%
Between 1.5 and 4.5°C		>66%	82%	67%	96%	74%	72%	79%
Between 2 and 4.5°C	>66%		76%	67%	88%	66%	67%	70%
Higher than 4.5°C	Not excl.		14%	33%	0%	16%	26%	8%
Higher than 6°C		<10%	6%	21%	0%	6%	10%	0%
50^{th} percentile			3.0°C	3.6°C	2.6°C	3.1°C	3.6°C	2.8°C
66^{th} percentile			3.4°C	4.4°C	2.8°C	3.7°C	4.2°C	3.4°C
90^{th} percentile			5.1°C	7.7°C	3.3°C	5.1°C	6.0°C	4.4°C
95^{th} percentile			6.4°C	8.8°C	3.6°C	6.4°C	7.1°C	4.7°C
Most likely (mode)	3.0°C		3.0°C	3.3°C	2.6°C	3.0°C	3.4°C	2.9°C

* Note that the average interpretation of the IPCC statements reflects the arithmetic average over 10'000 distributions that were randomly selected from a set of possible distributions. This, however, does not imply that for every range the probability level of the "average" distributions is situated exactly in the middle of the range indicated by the IPCC, as probability distributions were assumed to obey some additional criteria (like not being bimodal, for example, see Reference [12]).

VI. Illustrative distributions and their implications

In this section we compare a few illustrative distributions and their implications for limiting equilibrium warming to particular temperature levels. In particular, we look at the average interpretation of the AR4 and AR5 statements, described in

Table 2, as well as the ECS distribution found by Aldrin and colleagues (Reference 4; most likely value 1.6°C, 5-95% range 1.1-3.4°C). The latter distribution is representative of a series of recent studies[4,5,10], that find the lowest estimates for ECS among peer reviewed papers. Most of these studies all use an energy balance approach. Here we highlight a few interesting aspects for higher temperature outcomes.

Under the average AR4 distribution from Rogelj and colleagues[12], limiting equilibrium warming to below 4°C with a 95% probability would require stabilizing global net radiative forcing at levels equivalent to CO_2 concentrations of about 425ppm CO_2e. Also under an average ECS distribution based on the AR5 assessment, this would not change significantly, for instance to 430ppm CO_2e. Also when assuming recent single studies' estimates (from Reference 4), limiting long-term warming to below 4°C with 95% chance would be consistent with CO_2e levels of below 620ppm CO_2e, relatively close the IPCC's second lowest "representative concentration pathway"[§].

A same comparison can be made for alternative temperature levels, like a 99% chance to limit global-mean warming to below 6°C. For these warming levels, the average AR4 and AR5 distributions, together with Reference 4, would result in CO_2e forcing stabilization levels of 420, 425, and 570 ppm CO_2e, respectively.

These results indicate that even when assuming that the "most likely" (mode) of a possible ECS distribution is low, it is the heaviness of the high-end tail which defines the probability of high-impact outcomes. As long as such high-impact outcomes cannot formally be excluded by multiple lines of evidence, they continue to pose significant risks with regard to the long-term temperature outcome of a particular emission scenario.

[§] Also known as "RCPs". RCP4.5 stabilizes CO_2e concentrations at the end of the century between 580 and 590 ppm CO_2e.

VII. References

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VIII. Appendix

Table 3: Overview of illustrative ECS distributions, all consistent with the IPCC AR4 or AR5 statements. The column with number 1 (12) in the header shows an average interpretation of the AR4 (AR5) statements, while the other columns show illustrative interpretations, drawn from a 10'000-member ensemble of possible interpretations, that are in one or the other way deviating from the average. Each illustrative distribution is a valid interpretation of the report.

PROBABILITY	***Assessment***		***Cases***															
Case number	***AR4***	***AR5***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Lower than 1°C		<5%	1%	0%	4%	3%	0%	0%	0%	0%	1%	0%	0%	3%	0%	4%	1%	5%
Lower than 1.5°C	<10%		5%	0%	10%	8%	1%	0%	4%	5%	3%	1%	1%	9%	1%	31%	2%	13%
Lower than 2°C			12%	1%	18%	18%	3%	1%	15%	15%	7%	4%	3%	20%	6%	57%	8%	25%
Between 1.5 and 4.5°C		>66%	82%	77%	74%	76%	98%	67%	96%	80%	86%	71%	98%	74%	66%	67%	72%	79%
Between 2 and 4.5°C	>66%		76%	77%	69%	69%	97%	67%	88%	73%	84%	69%	97%	66%	63%	45%	67%	70%
Higher than 4.5°C	Not excl.		14%	23%	16%	16%	1%	33%	0%	15%	10%	28%	1%	16%	33%	2%	26%	8%
Higher than 6°C		<10%	6%	0%	9%	3%	1%	21%	0%	12%	3%	23%	1%	6%	8%	1%	10%	0%
50th percentile			3.0°C	3.6°C	3.0°C	2.9°C	3.1°C	3.6°C	2.6°C	2.7°C	3.3°C	3.3°C	3.1°C	3.1°C	3.9°C	1.8°C	3.6°C	2.8°C
66th percentile			3.4°C	4.1°C	3.3°C	3.5°C	3.2°C	4.4°C	2.8°C	3.1°C	3.6°C	3.8°C	3.2°C	3.7°C	3.7°C	2.2°C	4.2°C	3.4°C
90th percentile			5.1°C	5.1°C	5.8°C	5.0°C	3.7°C	7.7°C	3.3°C	6.9°C	4.6°C	10.8°C	3.7°C	5.1°C	5.8°C	3.2°C	6.0°C	4.4°C
95th percentile			6.4°C	5.4°C	7.5°C	5.6°C	3.9°C	8.8°C	3.6°C	10.0°C	5.6°C	13.3°C	3.9°C	6.4°C	6.3°C	3.7°C	7.1°C	4.7°C
Most likely (mode)	3.0°C		3.0°C	2.8°C	3.1°C	2.6°C	3.1°C	3.3°C	2.6°C	2.6°C	3.6°C	3.2°C	3.1°C	3.0°C	3.7°C	1.5°C	3.4°C	2.9°C

Case descriptions:
1: Average interpretation of the IPCC AR4 statement, computed as the arithmetic mean over 10'000 possible PDFs all in line with the IPCC AR4
2: Single member from 10'000-member ensemble in line with IPCC AR4, with lowest probability below 1.5°C
3: Single member from 10'000-member ensemble in line with IPCC AR4, with highest probability below 1.5°C
4: Single member from 10'000-member ensemble in line with IPCC AR4, with relatively low probability between 2 and 4.5°C
5: Single member from 10'000-member ensemble in line with IPCC AR4, with relatively high probability between 2 and 4.5°C
6: Single member from 10'000-member ensemble in line with IPCC AR4, with highest probability above 4.5°C
7: Single member from 10'000-member ensemble in line with IPCC AR4, with lowest probability above 4.5°C
8: Single member from 10'000-member ensemble in line with IPCC AR4, with lowest most likely value
9: Single member from 10'000-member ensemble in line with IPCC AR4, with highest most likely value
10: Single member from 10'000-member ensemble in line with IPCC AR4, with lowest temperature difference between the 17th and 83rd percentile
11: Single member from 10'000-member ensemble in line with IPCC AR4, with highest temperature difference between the 17th and 83rd percentile
12: Average interpretation of the IPCC AR5 statement, computed as the arithmetic mean over 10'000 possible PDFs all in line with the IPCC AR5
13: Single member from 10'000-member ensemble in line with IPCC AR5, with highest probability above 4.5°C
14: Single member from 10'000-member ensemble in line with IPCC AR5, with lowest probability above 4.5°C
15: Single member from 10'000-member ensemble in line with IPCC AR5, with highest probability above 6°C
16: Single member from 10'000-member ensemble in line with IPCC AR5, with lowest probability above 6°C