Climate sensitivity

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In Intergovernmental Panel on Climate Change (IPCC) reports, *equilibrium* **climate sensitivity** refers to the equilibrium change in global mean near-surface air temperature that would result from a sustained doubling of the atmospheric (equivalent) CO_2 concentration (ΔT_{x2}). This value is estimated, by the IPCC Fourth Assessment Report (*AR4*) as *likely to be in the range 2 to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C. Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values*. This is a slight change from the IPCC Third Assessment Report (*TAR*), which said it was "likely to be in the range of 1.5 to 4.5°C".[1]

The TAR defined climate sensitivity alternatively in systematic units, equilibrium climate sensitivity refers to the equilibrium change in surface air temperature (ΔT_s) following a unit change in radiative forcing (RF) and is expressed in units of °C/(W/m^2) or equivalently K/(W/m^2). In practice, the evaluation of the equilibrium climate sensitivity from models requires very long simulations with coupled global climate models, or it may be deduced from observations. Therefore the 2007 AR4 renamed the alternative climate sensitivity to *climate sensitivity parameter* (λ) adding a new definition of *effective climate sensitivity* which is "a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state".

$$\Delta T_s = \lambda \cdot RF$$ [2]

The terms represented in the equation relate radiative forcing of any cause to linear changes in global surface temperature change. This is more technically correct than the older measure of sensitivity relating doubling of CO2 to a particular temperature change.

Climate sensitivity is not the same as the expected climate change at, say 2100: the TAR reports this to be an increase of 1.4 to 5.8°C over 1990.

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Essentials

CO_2 climate sensitivity has a component directly due to radiative forcing by CO_2 (or any other change in Earth's radiative balance), and a further contribution arising from feedbacks, positive and negative. "Without any feedbacks, a doubling of CO_2 (which amounts to a forcing of 3.7 W/m^2) would result in 1° C global warming, which is easy to calculate and is undisputed. The remaining uncertainty is due entirely to feedbacks in the system, namely, the water vapor feedback, the ice-albedo feedback, the cloud feedback, and the lapse rate feedback."[3]

Radiative forcing due to doubled CO_2

In the 1979 NAS report[4] (p.7), the radiative forcing due to doubled CO_2 is estimated to be 4 W/m^2, as calculated (for example) in Ramanathan et al. (1979).[5] In 2001 the IPCC adopted the revised value of 3.7 W/m^2, the difference attributed to a "stratospheric temperature adjustment".[1] More recently an intercomparison of radiative transfer codes (Collins et al., 2006) showed substantial discrepancies among climate models and between climate models and more exact radiation codes in the forcing attributed to doubled CO_2 even in cloud-free sky; presumably the differences would be even greater if forcing were evaluated in the presence of clouds because of differences in the treatment of clouds in different models. Undoubtedly the difference in forcing attributed to doubled CO_2 in different climate models contributes to differences in apparent sensitivities of the models, although this effect is thought to be small relative to the intrinsic differences in senstivities of the models themselves (Webb et al., 2006).

Sample calculation using industrial-age data

Rahmstorf (2008)[3] provides an informal example of how climate sensitivity might be estimated empirically, from which the following is modified. Denote the sensitivity, i.e. the equilibrium increase in global mean temperature including the effects of feedbacks due to a sustained forcing by doubled CO_2 (taken as 3.7 W/m^2), as x °C. If Earth were to experience an equilibrium temperature change of ΔT (°C) due to a sustained forcing of ΔF (W/m^2), then one might say that $x/(\Delta T) = (3.7\ W/m^2)/(\Delta F)$, i.e. that $x = \Delta T * (3.7\ W/m^2)/\Delta F$. The global temperature increase since the beginning of the industrial period (taken as 1750) is about 0.8 °C, and the radiative forcing due to CO_2 and other long-lived greenhouse gases (mainly methane, nitrous oxide, and chlorofluorocarbons) emitted since that time is about 2.6 W/m^2. Neglecting other forcings and considering the temperature increase to be an equlibrium increase would lead to a sensitivity of about 1.1 °C. However, ΔF also contains contributions due to solar activity (+0.3 W/m^2), aerosols (-1 W/m^2), ozone (0.3 W/m^2) and other lesser influences, bringing the total forcing over the industrial period to 1.6 W/m^2 according to best estimate of the IPCC AR4, albeit with substantial uncertainty. Additionally the fact that the climate system is not at equilibrium must be accounted for; this is done by subtracting the planetary heat uptake rate H from the forcing; i.e., $x = \Delta T * (3.7\ W/m^2)/(\Delta F-H)$. Taking planetary heat uptake rate as the rate of ocean heat uptake, estimated by the IPCC AR4 as 0.2 W/m^2, yields a value for x of 2.1 °C. (All numbers are approximate and quite uncertain.)

Sample calculation using ice-age data

"... examine the change in temperature and solar forcing between glaciation (ice age) and interglacial (no ice age) periods. The change in temperature, revealed in ice core samples, is 5 °C, while the change in solar forcing is 7.1 W/m^2. The computed climate sensitivity is therefore 5/7.1 = 0.7 $K(W/m^2)^{-1}$. We can use this empirically derived climate sensitivity to predict the temperature rise from a forcing of 4 W/m^2, arising from a doubling of the atmospheric CO_2 from pre-industrial levels. The result is a predicted temperature increase of 3 °C."[6] Based on analysis of uncertainties in total forcing, in Antarctic cooling, and in the ratio of global to Antarctic cooling of the last glacial maximum relative to the present, Ganopolski and Schneider von Deimling (2008) infer a range of 1.3 to 6.8 °C for climate sensitivity determined by this approach.

History of the concept

Three degrees as the consensus estimate

The standard modern estimate of climate sensitivity - 3°C, plus or minus 1.5°C - originates with a committee on anthropogenic global warming convened in 1979 by the National Academy of Sciences and chaired by Jule Charney. Only two sets of models were available; one, due to Syukuro Manabe, exhibited a climate sensitivity of 2°C, the other, due to James E. Hansen, exhibited a climate sensitivity of 4°C. "According to Manabe, Charney chose 0.5°C as a not-unreasonable margin of error, subtracted it from Manabe's number, and added it to Hansen's. Thus was born the 1.5°C-to-4.5°C range of likely climate sensitivity that has appeared in every greenhouse assessment since..."[7]

Chapter 4 of the "Charney report" compares the predictions of the models: "We conclude that the predictions ... are basically consistent and mutually supporting. The differences in model results are relatively small and may be accounted for by differences in model characteristics and simplifying assumptions."[4]

Subsequent developments

In 2008 climatologist Stefan Rahmstorf wrote, regarding the Charney report's original range of uncertainty: "At that time, this range was on very shaky ground. Since then, many vastly improved models have been developed by a number of climate research centers around the world. Current state-of-the-art climate models span a range of 2.6–4.1°C, most clustering around 3°C."[3]

Other estimates

Andronova and Schlesinger (2001)[8] found that the climate sensitivity could lie between 1 and 10°C, with a 54 percent likelihood that it lies outside the IPCC range dead link. The exact range depends on which factors are most important during the instrumental period: "At present, the most likely scenario is one that includes anthropogenic sulfate aerosol forcing but not solar variation. Although the value of the climate sensitivity in that case is most uncertain, there is a 70 percent chance that it exceeds the maximum IPCC value. This is not good news." said Schlesinger.

Forest, *et al.* (2002)[9] using patterns of change and the MIT EMIC estimated a 95% confidence interval of 1.4–7.7°C for the climate sensitivity, and a 30% probability that sensitivity was outside the 1.5 to 4.5° C range.

Gregory, *et al.* (2002)[10] estimated a lower bound of 1.6°C by estimating the change in Earth's radiation budget and comparing it to the global warming observed over the 20th century.

Shaviv (2005)[11] carried out a similar analysis for 6 different time scales, ranging from the 11-yr solar cycle to the climate variations over geological time scales. He found a typical sensitivity of 0.54±0.12°K/(W m^{-2}) or 2.1°C (ranging between 1.6°C and 2.5°C at 99% confidence) if there is no cosmic-ray climate connection, or a typical sensitivity of 0.35±0.09°K/(W m^{-2}) or 1.3°C (between 0.99°C and 2.5°C at 99% confidence), if the cosmic-ray climate link is real. (Note Shaviv quotes a radiative forcing equivalent of 3.8Wm^{-2}. [ΔT_{x2}=3.8 Wm^{-2} λ].) More on climate sensitivity and this work can be found here.

Including geochemical evidence leads to similar results[12] in the lowest part of the IPCC range.

Frame, *et al.* (2005)[13]] and Allen et al. noted that the range of the confidence limits is dependent on the nature of the prior assumptions made.

Annan and Hargreaves (2006)[14] presented an estimate that resulted from combining prior estimates based on analyses of paleoclimate, responses to volcanic eruptions, and the temperature change in response to forcings over the twentieth century. They also introduced a triad notation (L, C, H) to convey the probability distribution function (pdf) of the sensitivity, where the central value C indicates the maximum likelihood estimate in degrees Celsius and the outer values L and H represent the limits of the 95% confidence interval for a pdf, or 95% of the area under the curve for a likelihood function. In this notation their estimate of sensitivity was (1.7, 2.9, 4.9)°C.

Forster and Gregory (2006)[15] presented a new independent estimate based on the slope of a plot of calculated greenhouse gas forcing minus top-of-atmosphere energy imbalance, as measured by satellite borne radiometers, versus global mean surface temperature. In the triad notation of Annan and Hargreaves their estimate of sensitivity was (1.0, 1.6, 4.1)°C.

Royer, *et al.* (2007)[16] determined climate sensitivity within a major part of the Phanerozoic. The range of values—1.5 °C minimum, 2.8 °C best estimate, and 6.2 °C maximum—is, given various uncertainties, consistent with sensitivities of current climate models and with other determinations. [17]

Related concepts

The **Transient climate response** (TCR) — a term first used in the TAR — is the temperature change at the time of CO_2 doubling in a run with CO_2 increasing at 1%/year.

The *effective* climate sensitivity is a related measure that circumvents this requirement. It is evaluated from model output for evolving non-equilibrium conditions. It is a measure of the strengths of the feedbacks at a particular time and may vary with forcing history and climate state. Details are discussed in Section 9.2.1 of Chapter 9 in the TAR [2].

A "long-term sensitivity" can be defined which includes the effects of slower feedbacks.[18]

See also

- Glossary of climate change
- Index of climate change articles
- Global warming controversy

Notes

1. ^ IPCC Third Assessment Report, Climate Change 2001, Working Group I, F3
2. ^ "IPCC Fourth Assessment Report (AR4)". p. 133. http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm. Retrieved 2009-12-19.
3. ^ ***a b c*** Rahmstorf, Stefan (2008). "Anthropogenic Climate Change: Revisiting the Facts". in Zedillo, E. (PDF). *Global Warming: Looking Beyond Kyoto*. Brookings Institution Press. pp. 34–53. http://www.pik-potsdam.de/~stefan/Publications/Book_chapters/Rahmstorf_Zedillo_2008.pdf.
4. ^ ***a b*** Ad Hoc Study Group on Carbon Dioxide and Climate (1979). "Carbon Dioxide and Climate: A Scientific Assessment" (PDF). National Academy of Sciences. http://www.atmos.ucla.edu/~brianpm/download/charney_report.pdf.
5. ^ V. Ramanathan, M.S. Lian, and R.D. Cess (1979) (PDF). *Increased Atmospheric CO_2: Zonal and Seasonal Estimates of the Effect on Radiative Energy Balance and Surface Temperature*. Journal of Geophysical Research. http://www-ramanathan.ucsd.edu/publications/Ram%20Lian%20and%20Cess%20JGR%201979.pdf.
6. ^ John Farley (2008). ""The Scientific Case for Modern Anthropogenic Global Warming"". Monthly Review. http://monthlyreview.org/080728farley.php.
7. ^ Richard A. Kerr (13 August 2004). "Three Degrees of Consensus". *Science* **305** (5686): 932–4. doi:10.1126/science.305.5686.932. PMID 15310873. http://www.sciencemag.org/cgi/content/summary/305/5686/932.
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11. ^ Shaviv, N.J. (2005). "On climate response to changes in the cosmic ray flux and radiative budget". *J. Geophys. Res.* **110**: A08105. doi:10.1029/2004JA010866. http://www.agu.org/pubs/crossref/2005/2004JA010866.shtml. (preprint)
12. ^ K. Scherer, H. Fichtner, T. Borrmann, J. Beer, L. Desorgher, E. Flükiger, H.-J. Fahr, S. E. S. Ferreira, U. W. Langner, M. S. Potgieter, B. Heber, J. Masarik, N. J. Shaviv and J. Veizer (2006). "Interstellar-Terrestrial relations: Variable cosmic environments, the dynamic heliosphere, and their imprints on terrestrial archives and climate". *Space Science Reviews* **127**: 327. doi:10.1007/s11214-006-9126-6.
13. ^ Frame, D.J.; Booth, B.B.B.; Kettleborough, J.A.; Stainforth, D.A.; Gregory, J.M.; Collins, M.; Allen, M.R. (2005). "Constraining climate forecasts: the role of prior assumptions". *Geophysical Research Letters* **32**: L09702. doi:10.1029/2004GL022241. http://www.agu.org/pubs/crossref/2005/2004GL022241.shtml.
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17. ^ Sceptics as Jan Veizer have pointed out that while data for the whole Phanerozoic are available Royer et al. left out the time span younger than 420 Ma with an ice age and extremely high carbon dioxide content during the Hirnantian.
18. ^ "Target CO_2". *RealClimate*. April 2008. http://www.realclimate.org/index.php/archives/2008/04/target-co2/.

External links

- Estimates of climate sensitivity, 1896-2006 (archived)
- Theoretical framework for modeling the climate sensitivity of a black body earth, a "gray body" earth, and a gray-body earth with feedbacks affecting albedo and emissivity

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- This page was last modified on 9 February 2010 at 08:46.
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