climate extremes
ARC centre of excellence

Earth Systems and Climate Change Hub
National Environmental Science Programme

Australian Government
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How sensitive is the Earth's temperature to the amount of carbon dioxide in the atmosphere?

A joint ARC Centre of Excellence for Climate Extremes and NESP Earth Systems and Climate Change Hub briefing note

- **Equilibrium Climate Sensitivity is a measure of the sensitivity of the Earth's temperature to a doubling of the amount of carbon dioxide in the atmosphere. It is crucial for understanding climate change but, until recently, our estimates of likely values of Equilibrium Climate Sensitivity varied by a factor of three.**
- **A landmark new international review of climate sensitivity led by ARC Centre of Excellence for Climate Extremes researcher Prof Steven Sherwood has reduced the uncertainty in Equilibrium Climate Sensitivity. Estimates of likely values now vary by less than a factor of two.**
- **The new assessment concludes that the climate is more sensitive to atmospheric carbon dioxide than some previous estimates. This means that significant reductions in global carbon dioxide emissions are needed over the coming decade to give a better-than-even chance of meeting the Paris Agreement's 2°C global warming limit.**

What is climate sensitivity?

The Earth's climate is warming, primarily due to carbon dioxide (CO_2) emitted into the atmosphere by the burning of fossil fuels and other human activities. Climate sensitivity describes how much the global average temperature increases in response to a doubling of the amount of CO_2 in the atmosphere from its pre-industrial level of 280 parts per million (ppm) to 560ppm, a level that could be reached this century. Estimating climate sensitivity is fundamental to assessing the scale of future climate change.

There are several definitions of climate sensitivity, including:

Equilibrium Climate Sensitivity (ECS) – As the oceans warm very slowly, it would take many centuries for the global average temperature to adjust, or reach "equilibrium", following a doubling of atmospheric CO_2 concentrations. ECS is the increase in the global average temperature between the pre-industrial era and a future doubled carbon dioxide climate once equilibrium has been reached. Estimates of ECS do not account for slow changes in the Earth's carbon cycle, the ice sheets on Greenland and the Antarctic continent, permafrost and vegetation. This means that they under-estimate long-term warming.

Transient Climate Response (TCR) –TCR is the increase in the global average temperature over a hypothetical ~70-year period during which atmospheric CO_2 concentrations increase gradually, by 1% per year, from 280ppm to 560ppm. TCR is smaller than ECS as it does not include warming during the period of equilibration following a doubling of CO_2 concentrations.

It has been argued that TCR is more relevant to climate change in the 21st century than ECS. However, research led by CSIRO and the Australian Bureau of Meteorology undertaken as part of the National Environmental Science Program's Earth Systems and Climate Change (NESP ESCC) Hub[1] has shown that ECS is a better guide to warming over the 21st century for both global average and Australian average temperatures in computer simulations of the climate.

Why is it difficult to estimate climate sensitivity?

A precise estimate of climate sensitivity has not yet been obtained. In 1979, a report by the US National Academy of Sciences[2] estimated ECS as being between 1.5 and 4.5°C. Our understanding of climate sensitivity has improved since 1979, and methods of estimating climate sensitivity have become more sophisticated. However, assessments of climate sensitivity by the Intergovernmental Panel on Climate Change (IPCC) made between 1990 and 2013, based on more than a hundred scientific papers, failed to come up with a more precise value for ECS. In 2013, the most recent IPCC assessment[3] estimated that ECS was likely (meaning with >66% chance) to be between 1.5 and 4.5°C.

Climate sensitivity depends on the strengths of a range of different "feedback" processes in the Earth's climate system. Positive feedbacks act to enhance the warming of the planet while negative feedbacks act to dampen it. An example of a positive feedback involves water vapour in the lower atmosphere. As the lower atmosphere warms in response to the enhanced greenhouse effect of CO_2, it retains more water vapour. Since water vapour is, itself, a powerful greenhouse gas, this greatly amplifies the greenhouse effect of CO_2. The size of many other feedback effects is uncertain, making it difficult to estimate climate sensitivity.

New estimates of climate sensitivity

A major new international report on climate sensitivity has provided new estimates of ECS[4]. The assessment took a team of 25 experts led by ARC Centre of Excellence for Climate Extremes Chief Investigator Prof Steven Sherwood, and including ANU's Prof Eelco Rohling, four years to complete.

The report considered three "lines of evidence", each of which provided useful, but incomplete, information about ECS:

Thermometer measurements since 1850 – Recorded thermometer measurements have enabled scientists to deduce how much the planet has warmed since 1850. This warming provides some information about climate sensitivity as atmospheric CO_2 concentrations have increased by almost 50% over this period.

Paleoclimate data – Large changes in the Earth's climate have occurred in the distant past (e.g. between the Ice Ages over 19,000 years ago). Scientists can estimate changes in global average temperature during these times from paleoclimate proxy data (e.g. from ice cores, marine sediment cores, tree rings and coral cores).

Research on relevant climate processes – This involves developing sufficient understanding of the climate system to establish the strengths of individual climate feedback processes. For example, it includes using satellite data and detailed computer simulations to understand clouds and paleoclimate data to understand feedbacks in the polar regions.

The new assessment took the novel approach of scrutinising extremely high and low values of ECS to check that they were consistent with these lines of evidence. It concluded that ECS is not likely to be less than 2.6°C and not likely to be more than 4.1°C. The report was therefore able to reduce the uncertainty in ECS from the 1.5 to 4.5°C likely range estimated by the IPCC in 2013 to a new range of 2.6 to 4.1°C (see Figure 1). The report also concluded that the chance of ECS being less than 2.2°C is 1-in-20 and that it is equally unlikely that ECS is more than 4.9°C.

ECS estimates

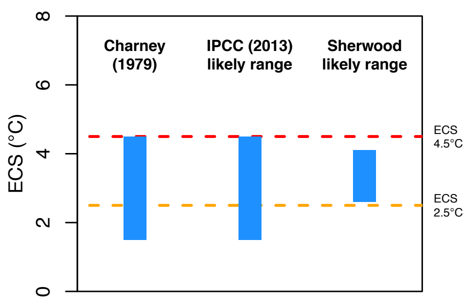

Figure 1 - ECS estimates: The new Sherwood et al. assessment has succeeded in reducing the uncertainty in ECS relative to previous assessments in 1979 and 2013. The new likely range for ECS is 2.6 to 4.1°C (third bar).

Implications for the Paris Agreement

Estimates of ECS are important for estimating CO_2 emissions The UN's 2015 Paris Agreement aims to limit global warming relative to pre-industrial times to "well below" 2°C. If we can precisely estimate ECS and understand how much of our CO_2 emissions will remain in the atmosphere (as opposed to being absorbed by the ocean, vegetation and soil), we can estimate the scale and urgency of emissions reductions required to stay under this limit. The uncertainty in ECS means that a range of scenarios with different scales and timing of future emissions reductions are consistent with the 2°C global warming limit. The new assessment of climate sensitivity has assigned a chance of less than 1-in-20 to ECS values of less than 2.2°C, which were previously considered more likely. Therefore, the less ambitious emissions reductions scenarios previously believed to be consistent with the Paris Agreement target have been all but ruled out by the new study.

The most recent IPCC assessment[3] provided climate projections for four different scenarios for the future energy imbalance of the climate system due to CO_2 emissions and other effects – Representative Concentration Pathways (RCPs) 2.6 (low emissions), 4.6 and 6.0 (medium emissions) and 8.5 (high emissions). According to the new assessment of climate sensitivity, RCP2.6, under which annual global CO_2 emissions reach a peak before 2030 and then decline to zero before 2090, gives a better than 80% chance of remaining within the 2°C global warming limit this century. RCP4.5, under which emissions peak in the 2040s and then decline to 1960s levels before 2090, gives only a ~20% chance of remaining within the 2°C limit this century. The chances are even less for RCP6.0 and RCP8.5, under which annual emissions continue to increase significantly until near the end of the century.

Implications for climate change impacts

Climate sensitivity has implications for the impacts of climate change across the globe, including in Australia. ECS should not be interpreted as an estimate of global warming that could occur this century. However, as a measure of the response of the climate system to CO_2, it is a key determinant of global warming that could occur this century under a given scenario for future atmospheric CO_2 concentrations. ECS is therefore an important factor for projections of the warming and associated impacts that we may experience.

Using information from computer models of the climate, the NESP ESCC Hub has estimated how much the average temperature of the planet may have increased by the end of the 21st century under the low emissions RCP2.6 and high emissions RCP8.5 scenarios for different values of ECS[5] (see Figure 2). Differences in estimates of global warming for different ECS values are significant in the context of the impacts of climate change for Australia. This highlights the need for even better estimates of ECS.

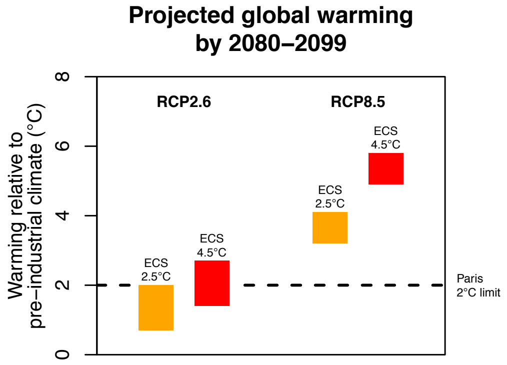

Figure 2 - Projected global warming between the pre-industrial era and the end of the 21st century: The NESP ESCC Hub has estimated warming for RCP2.6 and RCP8.5 between 1986-2005 and 2080-2099. The figure accounts for the ~0.6°C of warming between the pre-industrial era and 1986-2005. Projected warming for RCP2.6 is between 0.7 and 2.0°C or an ECS value of 2.5°C, near the low end of the likely range from the new Sherwood et al. ECS assessment (see Figure 1), and 1.4 to 2.7°C of warming for an ECS value of 4.5°C, considered unlikely but possible by the new assessment. The difference in warming between different ECS values is greater for RCP8.5. The corresponding ranges for warming under RCP8.5 are 3.2 to 4.1°C for an ECS value of 2.5°C and 4.9 to 5.8°C for an ECS value of 4.5°C

How is Australia contributing to the global understanding of climate sensitivity?

Extensive efforts to refine our understanding of climate sensitivity are underway at the CSIRO, the Australian Bureau of Meteorology and Australian universities. For example, the CSIRO is investigating ECS in computer models of the climate. Other research on climate processes relevant to climate sensitivity includes work by the ARC Centre of Excellence for Climate Extremes on clouds, the uptake of heat by the oceans and changes in the temperature of the surface of the sea. The Australian Research Council is also supporting work on climate feedbacks during the distant past. Further research on climate feedbacks has been identified as a priority by a recent report by Australia's National Climate Science Advisory Committee[6].

Computer modelling of the climate system is important for much of this research. For example, detailed modelling is critical to understanding the uptake of heat by the oceans. Planned investment by the Australian Government in research infrastructure to support Australia's climate modelling capabilities via the National Collaborative Research Infrastructure Strategy (NCRIS) will therefore contribute to greater understanding of climate sensitivity.

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