PCIC SCIENCE BRIEF: SPREAD IN MODEL CLIMATE SENSITIVITY TRACED TO ATMOSPHERIC CONVECTIVE MIXING

Recent findings published in the journal *Nature*, by Sherwood, Bony and Dufresne (2014), indicate that a part of the variance in climate sensitivity among climate models can be traced to vertical mixing in the atmosphere. Using this result, combined with mixing values derived from observations, the authors suggest a lower bound of 3 °C on the warming that would result from a doubling of the atmospheric CO_2 concentration.

The magnitude of the impacts that are projected to occur as a result of anthropogenic climate change depend, in part, on the magnitude and rate of the changes to the climate system. These, in turn, depend largely on how sensitive the climate system is to changes in the concentration of atmospheric greenhouse gases. The equilibrium climate sensitivity of the Earth's climate system, often just referred to as "climate sensitivity," is defined as the amount of warming that would eventually be seen in the Earth's average surface temperature if the atmospheric concentration of carbon dioxide were to be doubled and then held constant. The Intergovernmental Panel on Climate Change (IPCC) states that the likely[1] range[2] of climate sensitivity, from observations, studies of climate feedback mechanisms, paleoclimate data (such as ice cores and tree rings) and Global Climate Models (GCMs) is between 1.5 °C to 4.5 °C. The mean value for modern GCMs is 3.2 °C and the models that most closely simulate the modern climate have values in the range of 3 °C to 4 °C.

Using satellite observations, reanalysis data and GCM output from models that participated in the third and fifth phases of the Coupled Model Intercomparison Project[3] (CMIP3 and CMIP5), Sherwood, Bony and Dufresne (2014) examine how much of the variation in GCM climate sensitivity between GCMs can be explained by the differing ability of the models to represent vertical mixing of the atmosphere. The vertical mixing that they analyze in is made up of two shallow (~ 5 km), vertical, overturning air circulation patterns that dry the marine boundary layer[4], which reduces the formation of low clouds that cool the Earth by reflecting sunlight and increases the formation of higher clouds which absorb infrared radiation that is trying to escape the planet and thus have a net warming effect. If this mixing is strengthened by a warming climate, then low

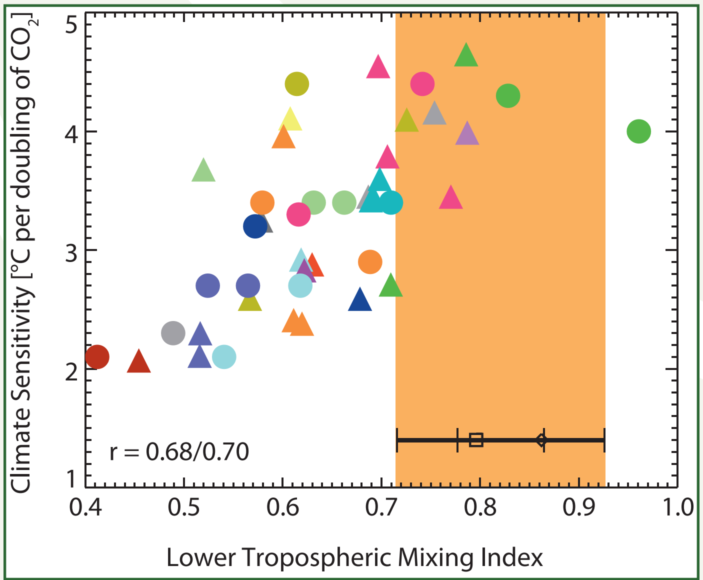

Figure: Climate Sensitivity versus Lower Tropospheric Mixing Index, modified from Sherwood, Bony and Dufresne (2014).

The above figure shows the Equilibrium Climate Sensitivity versus the Lower Tropospheric Mixing Index (LTMI). The coloured shapes represent the 43 Global Climate Models that the authors examined. Triangles indicate CMIP5 models, circles indicate CMIP3 models and the colours indicate the modelling centre. Light orange shading indicates the combined range (2σ see reference[5]) of observed LTMI values derived from satellite data and two reanalysis products. Models within the shaded region are consistent with observations of LTMI.

1. Here 'likely' is defined as having an assessed likelihood of 66-100%.
2. These figures are from the Technical Summary of Working Group One's contribution to the Fifth Assessment Report of the IPCC. This Summary is available—along with the full report and a high-level overview document, the Summary for Policymakers—from the IPCC's website: http://www.climatechange2013.org
3. For more on the Coupled Model Intercomparison Project, see: http://cmip-pcmdi.llnl.gov/
4. That part of the Earth's atmosphere that is closest to and directly affected by the ocean's surface, generally about 1 km to 2 km thick.
5. Here, σ is a standard deviation, a measure of the spread from the average of the measurements. For the 2σ range, about 95.4% of observations will lie within the shading if observations have a bell-shaped "normal" probability distribution.

cloud formation may be reduced, contributing further to the warming of the climate.

In order to determine how much of the variance in climate sensitivity can be explained by the mixing, the authors develop indices for the two components of the shallow circulation that mix the lower troposphere. The first index represents the small-scale mixing that occurs in processes such as transport by low-lying clouds and downdrafts. The second index represents the large-scale mixing that occurs when some of the air over sections of the ocean that generally would ascend to the upper troposphere does not ascend to this height, owing to ocean temperatures, and instead diverges and travels horizontally. They then compare the individual indices and the sum of the indices (which the authors term the Lower Tropospheric Mixing Index, LTMI) to the range of model climate sensitivities. The authors also calculate the sources of water vapour in the lower troposphere associated with the smaller- and larger-scale mixing to determine if drying occurs when oceans are warmed by 4 °C in GCM simulations.

Sherwood, Bony and Dufresne find that each index individually explains about a quarter of the variance in climate sensitivity and that the LTMI explains about one-half of the variance. When oceans are warmed by 4 °C in GCM simulations, the sources of water associated with the small- and large-scale mixing both indicate that drying occurs in the lower troposphere. The authors also note that the subsidence regions should be most affected by the boundary layer drying.

The authors then compare the climate sensitivity and LTMI from model output with the observed values from satellites and two types of reanalyses that incorporte satellite data. Their results suggest that the most likely value for climate sensitivity is about 4 °C and that models with climate sensitivities lower than about 3 °C produce values of the LTMI that are too low (i.e. do not exhibit enough shallow mixing) to be consistent with observations (see Figure). Sherwood, Bony and Dufresne suggest that this implies a lower limit of about 3 °C for climate sensitivity. As the authors note, their findings push "the likely long-term global warming towards the upper end of model ranges." This result may aid in climate model development, allowing for more robust climate change projections.

Methodology

The authors use the output of 18 CMIP3 models and 30 CMIP5 models to calculate the indices for the small-scale component of shallow mixing, S, and large-scale component of shallow mixing, D. S is calculated from the relative humidity and temperature at 700 hPa and 850 hPa heights[6], while D is calculated from vertical velocities at different heights. Reported values for climate sensitivity are used for all but one CMIP3 model and calculated from abrupt 4×CO_2 experiments for the 26 available CMIP5 models. In order to calculate the sources of moisture from small- and large-scale mixing, the authors use ten years of data from specified ocean temperature runs (called AMIP simulations) and runs in which the specified ocean temperature is raised by + 4 °C (AMIP+4K), from ten CMIP5 models. They also use the first and last ten years of runs from eight CMIP3 models in which atmospheric CO_2 is increased by 1% per year until quadrupling. The source of moisture from small-scale mixing is a variable provided as part of model output and the source of moisture from large-scale mixing is calculated from pressure, specific humidity and vertical velocities. The authors use satellite observations from the Integrated Global Radiosonde Archive and the ERA-Interim and MERRA reanalysis[7] products.

Once the above variables are gathered and calculated, the authors compare S with the differences in temperature and humidity between the 700 hPa and 850 hPa heights to determine if the temperature and relative humidity differences are affected by S. They also test how the source of moisture from small-scale mixing responds to a warming ocean and test for correlation between the source of moisture from small-scale mixing and S, to see if the drying is correlated with S. Next, the authors test D and S for correlation, in order to determine if they are controlled by different aspects of the models, and test for correlation between D and the source of moisture from large-scale mixing, to see if the source of moisture from large-scale mixing increases as D increases. The authors then perform linear regressions between each of S, D, LTMI and equilibrium climate sensitivity, to determine how much of the variance in climate sensitivity can be explained by the three indices. Following this, the authors examine the spread in climate sensitivity versus S, D and LTMI in models and compare these with observations of LTMI, in order to determine which models are consistent with observations.

Sherwood, S.C., S. Bony and J.L Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, **505**, 37-42, doi:10.1038/nature12829.

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[6] A hPa level refers to the altitude at which the air pressure is the specified number of hectopascals (a unit of pressure). Pressure is often used as a vertical coordinate in the study of the atmosphere because it is easy to measure from weather balloons and satellites, certain fluid dynamic equations take on a more convenient form when pressure is used as a vertical coordinate and the vertical distance between surfaces of different pressure is proportional to the average temperature between these surfaces, which is useful for weather forecasting and analysis.

[7] A reanalysis is a representation of the historical climate that is created from historical observations that are "assimilated" into a global weather forecast model that is run in a hindcast mode.