The Mechanisms of Natural Variability and its Interaction With Anthropogenic Climate Change

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Jan30, 2015

1 Title and Grant Period

Title: The Mechanisms of Natural Variability and its Interaction With Anthropogenic Climate Change
Reporting Period: 9/1/10 – 8/30/14
Funding Period: 9/1/10 – 8/30/14

2 PI Information

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3 Project Synopsis

The project had two main components. The first concerns estimating the climate sensitivity in the presence of forcing uncertainty and natural variability. Climate sensitivity is the increase in the average surface temperature for a given increase in greenhouse gases, for example a doubling of carbon dioxide. We have provided new, probabilistic

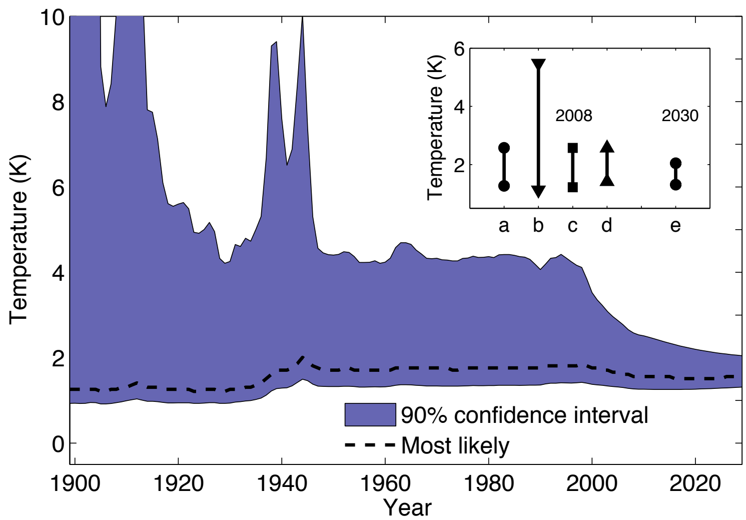

Figure 1: Evolution of TCS probability as more data from the past is used as a constraint. Most likely TCS indicated by the dashed line. Shaded region is 90% confidence interval. Inset: 90% confidence intervals for other uncertainty scenarios outlined in table **??**.

estimates of climate sensitivity using a simple climate model an the observed warming in the 20th century, in conjunction with ideas in data assimilation and parameter estimation developed in the engineering community. The estimates combine the uncertainty in the anthropogenic aerosols with the uncertainty arising because of natural variability.

The second component concerns how the atmospheric circulation itself might change with anthropogenic global warming. We have shown that GCMs robustly predict an increase in the length scale of eddies, and we have also explored the dynamical mechanisms whereby there might be a shift in the latitude of the jet stream associated with anthropogenic warming. Such shifts in the jet might cause large changes in regional climate, potentially larger than the globally-averaged signal itself. We have also shown that the tropopause robustly increases in height with global warming, and that the Hadley Cell expands, and that the expansion of the Hadley Cell is correlated with the polewards movement of the mid-latitude jet.

4 Research and Development Activities

4.1 Estimates of climate sensitivity

We provided new estimates of transient climate sensitivity (TCS) of the globally averaged surface temperature that include both uncertainty in past forcing and internal variability in the climate record. In particular we provided a range of probabilistic estimates of the TCS that combine these two sources of uncertainty for various underlying assumptions about the nature of the uncertainty. We also provided estimates of how quickly the uncertainty in the TCS may be expected to diminish in the future as additional observations become available. We made these estimates using a nonlinear Kalman filter coupled to a stochastic, global energy balance model, using the filter and observations to constrain the model parameters. We first verified that model and filter are able to emulate the evolution of a comprehensive, state-of-the-art atmosphere-ocean general circulation model and to accurately predict the TCS of the model, and then apply the methodology to observed temperature and forcing records of the 20th century.

For uncertainty assumptions best supported by global surface temperature data up to the present time, we found a most-likely present-day estimate of the transient climate sensitivity to a doubling in CO_2 to be 1.6 K with 90% confidence the response will fall between 1.3–2.6 K, and we estimated that this interval may be 45% smaller by the year 2030. We calculated that emissions levels equivalent to forcing of less than 475 ppmv CO_2 concentration are needed to ensure that the transient temperature response will not exceed 2 K with 95% confidence. The flat temperature trend of the last decade was found to have a detectable but small influence on transient climate sensitivity.

Two important results are graphically illustrated in fig. 1 and fig. 2. Figure 1 shows the evolution of the knowledge of transient climate sensitivity as more data are added. The most likely value is indicated by the dashed line and the 90% confidence interval is indicated by the gray shading. Figure 2 shows various range of PDFs and 90% confidence intervals for the transient climate sensitivity for the various sets of assumptions made. For the parameter values and natural variability thought to be most representative of the true system, we estimate that transient climate sensitivity falls between 1.3 K and 2.3 K, with a most likely value of 1.6 K. The timescales of global warming are greatly influenced by the rate at which heat uptake occurs in the ocean.

4.2 Mechanisms of Natural Variability

This part of the project examined if and how the atmospheric circulation, and its natural variability, might change with anthropogenic global warming. We first analyzed output from the Coupled Model Intercomparison Phase 3. It was shown that for the 'A2' business as usual scenario, every model exhibits an increase in the eddy length scale in the future compared with the simulation of 20th Century climate. The increase in length scale is on the order of 5% by the end of the 21st century, and the Southern Hemisphere exhibits a larger increase than the Northern Hemisphere. The inter-model variability in the increase in the eddy length scale was found to be correlated with the

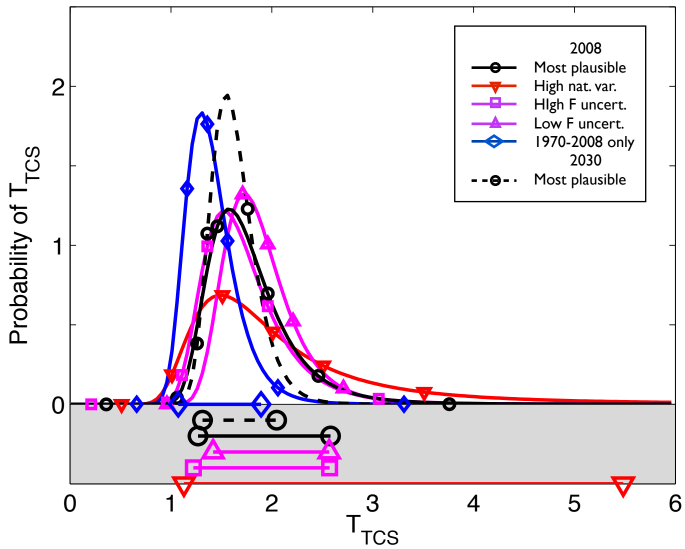

Figure 2: The range of PDFs and 90% confidence intervals for the transient climate sensitivity for various sets of assumptions made, with variious levels of natural variability and forcing uncertainty.

variability in the increase in dry static stability at 700 hPa. We next analyzed whether the increase in the length scale might cause the poleward shift of the jet stream under global warming. Numerical experiments indicate that an increase in the length scale of a mid-latitude perturbation can result in a poleward shift in the acceleration of the zonal flow. A simplified GCM was used to show that the latitude of the eddy-driven jet is well correlated with the eddy length scale. We argued that the increase in the eddy length scale *causes* the poleward shift of the jet in these experiments, rather than vice-versa.

Related work has explored the mechanisms that determine the tropopause height. Since the tropopause height has been found to change in some simulations of global warming with comprehensive climate models, so that understanding its dynamics is important if we are to understand how the atmosphere might change as the climate warms. The tropopause height is determined by a combination of diabatic effects (e.g., radiative transfer) and dynamical effects (in particular the vertical and horizontal transfer of heat by baroclinic eddies). One result is that we find little evidence that the tropopause height is determined by the so-called baroclinic adjustment hypothesis. We also examined mechanisms whereby the tropopause height may change as the planet warms, and obtained an analytic expression for the tropopause height, which agrees well with observation. The expression shows that the tropopause can be expected to robustly in-

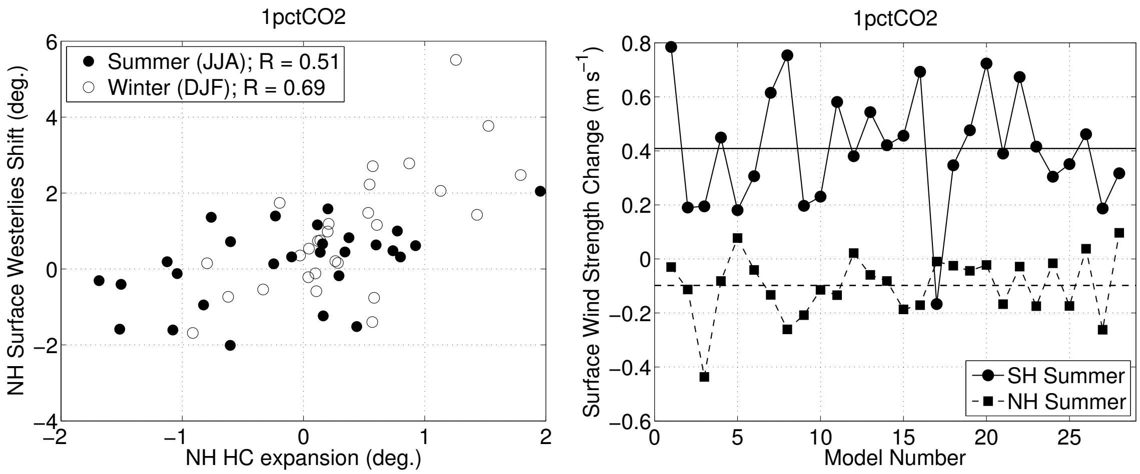

Figure 3: (a) Scatter plot of the HC expansion vs shift of the westerlies for the Northern Hemisphere. (b) Change in strength of the surface westerly winds in the Northern Hemisphere. Both panels are from CMIP5, for a doubling of carbon dioxide.

crease in height with global warming, in proportion to the amount of warming itself, and this is robustly found in CMIP5 results. In a comprehensive study of global warming (that is continuing) we examined how the structure of the atmosphere may change with global warming, we found that the Hadley Cell is likely to expand, and that this expansion is correlated with the polewards movement of the midlatitude jets (Fig. 3).

5 Project Participants

P.I.: Geoffrey K. Vallis
Graduate Students: Lauren Padilla, Peng Xie
Postdocs: Joe Kidston, Yu (Sophie) Zhang

Publications

Vallis, G.K., Zurita-Gotor, P., Cairns, C. and Kidston, J., 2014. The response of the large-scale structure of the atmosphere to global warming. *Quart. J. Roy. Meteor. Soc.* doi:10.1002/qj.2456.

Zurita-Gotor, P. and Vallis, G.K., 2013. The determination of extratropical tropopause height in an idealized gray-radiation model. *J. Atmos. Sci.* doi:http://dx.doi.org/10.1175/JAS-D-12-0209.1.

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Zhang, Y. and Vallis, G.K., 2013. Ocean heat uptake in eddying and non-eddying ocean circulation models in a warming climate. *J. Phys. Oceanogr.*, 43(10), 2211–2229.

Kidston, J. and Vallis, G.K., 2012. The relationship between the speed and latitude of the eddy-driven jet in a stirred barotropic model. *J. Atmos. Sci.*, 69, 3251–3263. doi:http://dx.doi.org/10.1175/JAS-D-11-0300.1.

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Padilla, L., Vallis, G.K. and Rowley, C., 2011. Probabilistic estimates of transient climate sensitivity subject to uncertainty in forcing and natural variability. *J. Climate*, 24, 5521–5537. doi:doi:10.1175/2011JCLI3989.1.

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Zurita-Gotor, P. and Vallis, G.K., 2011. Dynamics of tropopause height in a simple dynamical model. *J. Atmos. Sci.*, 68, 823–838. doi:http://dx.doi.org/10.1175/2010JAS3631.1.

Kidston, J., Dean, S.M., Renwick, J.A. and Vallis, G.K., 2010. A robust increase in the eddy length scale in the simulation of future climates. *Geophys. Res. Lett.*, 37, L03806. doi:10.1029/2009GL041615.

Kidston, J. and Vallis, G.K., 2010. The relationship between eddy-driven jet latitude and width. *Geophys. Res. Lett.*, 37, L21809. doi:10.1029/2010GL044849.

6 Presentations, Travel and Meetings Attended

2013 University of Washington, Departmental Seminar.
University of Washington, Public Lecture.
Climate Summer School, Greece (2 lectures).
NCAR, Boulder, One seminar, one general lecture.
Kyoto, Japan. Invited lecture.

2012 Los Alamos Nat'l Laboratory, three Ulam lectures.
Yale University, Departmental Seminar.
Leeds University, Departmental Seminar.
University of Cambridge, Departmental Seminar.
British Antarctic Survey, Seminar.
University of Exeter, Inspiring Science Lecture.
University of Oxford, Departmental Seminar.

2011 McGill University, Departmental Seminar.
University of Montreal, CRM meeting. Invited speaker.
U. K. Met. Office. Seminar.
MIT, EAPS seminar
AGU Fall Meeting American Meteorology Society, AOFD meeting

2010 University of Chicago. Departmental Seminar.
American Geophysical Union, Ocean Science Meeting.
Scripps Institution of Oceanography. Departmental seminar
University Madison, Wisconsin. Departmental Seminar.