Rainfall in the climate system: changes under global warming, and challenges for climate modelers[1]

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Anyone who has ever been drenched by a sudden downpour that failed to follow the weather forecast has a feeling for the problem that faces climate modelers. Small-scale features like thunderstorms, in which the core might be 5 km across, are much harder to predict in global models for weather and climate then are quantities like temperature that tend to vary on larger scales. Rain and snowfall, together known as precipitation, are one of the most important climate factors affecting human activities. So when planning for adaptation to global warming, one of the questions is always: how will the precipitation change? And because water resource management is done for relatively small regions like states, small countries or watersheds, this information is demanded at the regional scale. This turns out to be an enormous challenge for climate models. Here we give a quick tour of how rainfall is represented mathematically in climate models, what can currently be said, and what some of the challenges are.

How is rainfall represented mathematically in climate models?

Figure 1 shows a satellite photo in which a myriad of complex cloud systems may be seen. Tropical convective systems, with strong upward motion in thunderstorms, appear as tiny dots at the global scale, despite the fact that these contribute large amounts of rainfall in certain regions. At midlatitudes, the main regions of climatological precipitation are known as storm tracks, seen at about 30-50 degrees north in both Pacific and Atlantic oceans. On a particular day, what one sees is individual storms, and only by averaging over many of these does the shape of the storm tracks emerge.

To model the effects of clouds on climate change over a period of decades or centuries, we cannot currently afford to model millions of small clouds just to get to mean effects. The grid in Figure 1 illustrates how climate models represent the atmosphere, dividing up the continuous atmosphere into a series of discrete grid boxes. Rates of change of the average values of temperature, moisture, wind, etc. within each grid box are computed, including the effects of all the other boxes. A new value of each variable is computed a short time later, and the operation is repeated until a simulated year, decade or century has been reached. Now consider the area inside one grid box of Figure 1. In the computer representation, only an average across the grid box is included. In the observations, many fine variations occur inside. These include phenomena such as squall lines, mesoscale convective complexes, tower-anvil cumulonimbus clouds, and the average of these small scale effects has important impacts on large-scale climate. For instance, although each cloud is much smaller than the grid box, the latent heat released when water

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condenses in them will affect the average heating of the whole grid box. These average effects of the small scales on the grid scale change as a function of the large-scale fields, such as moisture and temperature. For instance, for a given grid-scale moisture and temperature, the buoyancy that would be experienced by a small plume of air rising in a cloud is computed. As moisture increases, the average heating and rainfall in the grid cell is then assumed to increase proportional to the resulting buoyancy increases. Analysis of data from ongoing satellite and field programs and mathematical techniques that introduce a random component due to the small-scale variations into this relationship (stochastic processes) may help to improve these representations in future.

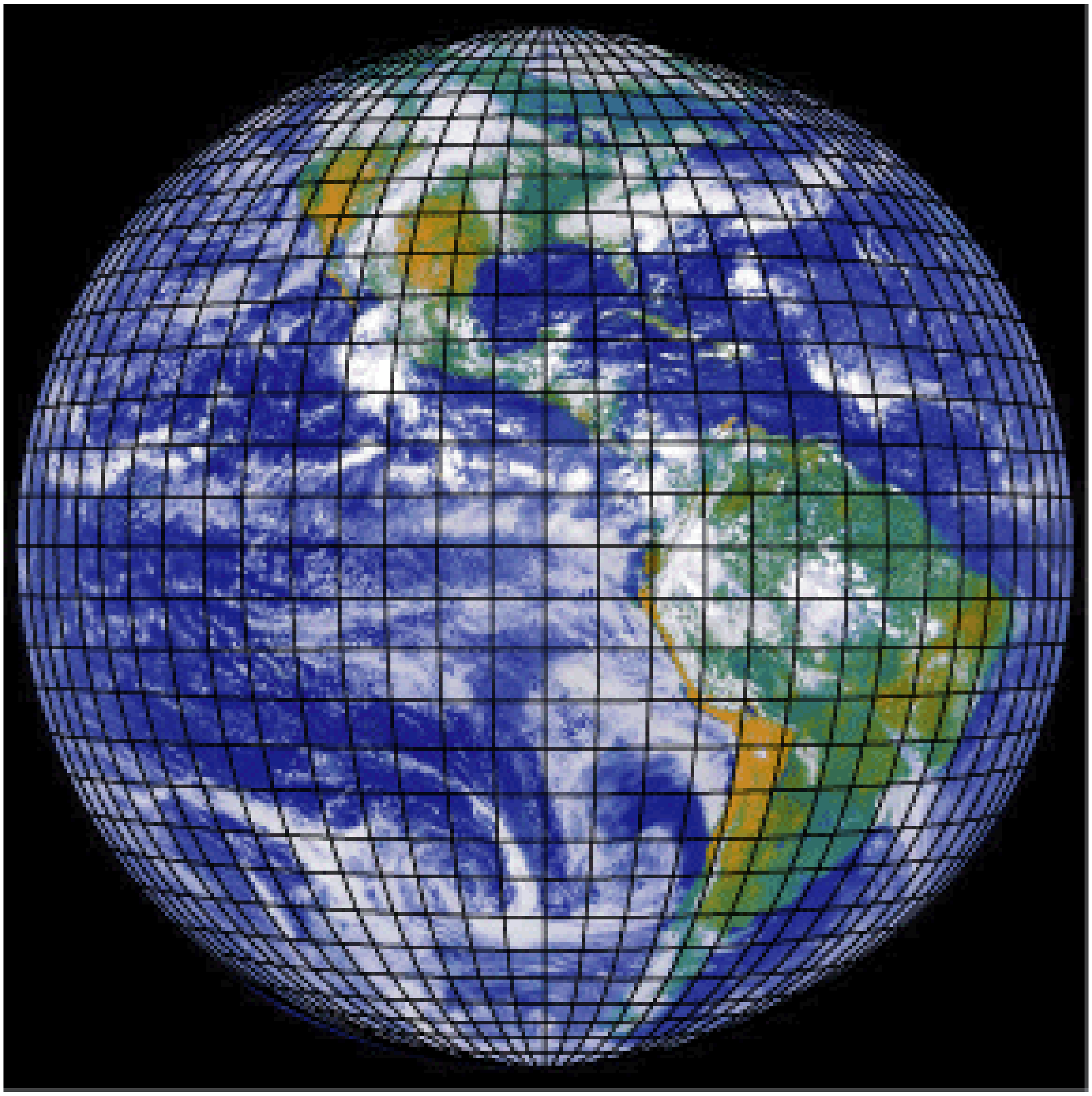

Figure 1. Instantaneous satellite image of Earth showing clouds (white) associated with weather and convective systems, overlaid with a latitude-longitude grid to illustrate grid cells used in climate models. For clarity, a coarse resolution grid is shown (5 degrees), but even with a finer grid, the cloud systems would have many features smaller than the grid size. Satellite image from GOES-8, courtesy NASA Remote Sensing Division.

The grid used in Figure 1to illustrate a climate model is not as fine as in some current models. It is roughly comparable to the coarsest resolution model used in the The Intergovernmental Panel on Climate Change (IPCC, 2007) Fourth Assessment Report, while some global models in this report ran with roughly 1 degree grid cells. A finer grid implies either greater computational costs or shorter simulation times, so there are strong barriers to making the grid extremely fine. As computers become faster, and mathematical methods for parallel computation are improved, modelers can afford finer grids. However, close examination of the small scales in the figure leads one to realize that climate models will never escape the need to deal with the effects of phenomena that are smaller than the grid. There is always some smaller scale, and there is a tendency for the scales to interact. This scale interaction is one of the main effects that makes climate modeling so challenging, and its mathematics to interesting. The successes and difficulties of representing the interaction of very small scales with a global scale are important factors in the accuracy of climate models.

What can be said about rainfall changes under global warming and what challenges remain?

The Intergovernmental Panel on Climate Change Assessment Reports present current best estimates of the changes under global warming, so far as they can currently be assessed by the majority of scientists in the field. These reports rely in part comparing simulations by different climate models produced by different governmental and university centers around the world. For changes in precipitation, common factors, many of which also meet the criterion of common sense, include the following. More precipitation falls as rain (less snow), and water storage in snowpack and glaciers will be reduced, effects that sound simple but have substantial implications for river runoff and water resources. Heavy precipitation events are estimated to be likely to become more common because of greater water vapor available in the atmosphere, although current climate models do not all accurately reproduce the statistics of heavy rainfall events. For a discussion of hurricane intensity changes, see the accompanying article by K. Emanuel.

Dry regions tend overall to get drier, and some wet regions get wetter in a warmer climate: Figure 2 shows the average of many current model simulations for the annual average precipitation change between the end of this century under a plausible scenario for greenhouse gas and other human emissions, relative to the climate of precipitation at the end of the 20th century (for details see Meehl et al 2007). Precipitation, and thus river runoff and water availability, tends to increase at high latitudes and in some wet tropical areas, and decrease in the already dry regions of the subtropics.

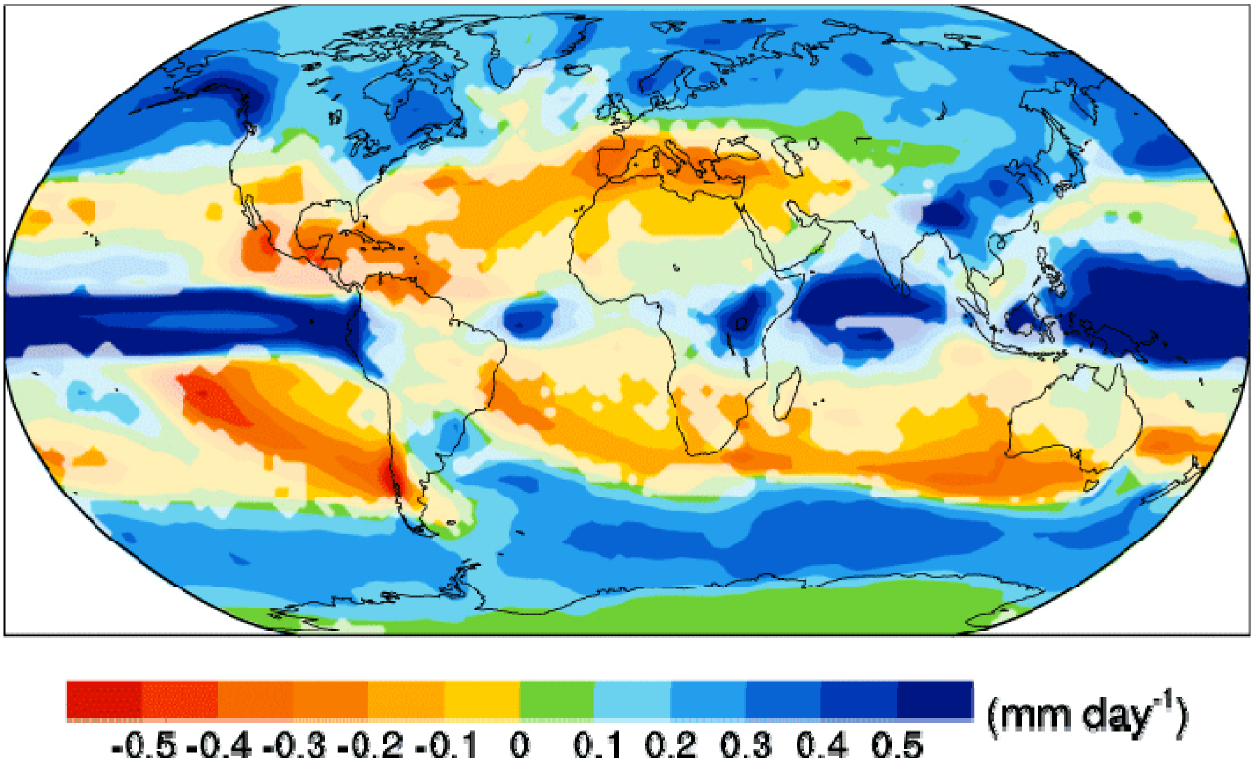

Figure 2. Changes in annual average precipitation (mm/ day), for the period 2080 to 2099 relative to 1980 to 1999, for the mean of an ensemble of climate models, each run with the same scenario for emissions of greenhouse gases. Orange colors show rainfall decreases, blue colors show increases. To indicate consistency in the sign of change, regions are only shaded where at least 80% of models agree on the sign of the mean change.. Modified from Fig. 10-12a of Meehl et al (2007).

As one asks more detailed information, such as the amplitude of the rainfall change at a particular location, the models exhibit considerable differences in their estimates, and tend to disagree on the locations of the strongest changes. For instance, Figure 3 shows the number of models (out of an ensemble of 10) that agree not only on the sign of the rainfall change, but are required to pass a statistical significance criterion for the trend evaluated at the model grid size shown, and furthermore to have an amplitude change that is large enough to possibly have significant impact (a trend over 1 century that exceeds 20% of the model ensemble mean precipitation in present-day climate). Figure 3 is zoomed in on one of the regions of highest model agreement, the projected drying in the Caribbean/Central American region. However, by these criteria most of the tropics would be blank on this figure; that is, fewer than five models have a significant trend of the same sign over large regions. Unfortunately, this lack of agreement is not because the change predicted by individual models is small, but because different models tend to put the large changes in slightly different places. The changes in rainfall under warming appear to be very sensitive to slight differences in the model formulation when one looks at regions of a few hundred kilometers. This suggests that we need to improve the accuracy with which the interaction of small-scale cloud processes with large-scale climate is represented. At every step in this endeavor, from analysis of satellite data, to computational methods for higher resolution climate models, to understanding the complexity of interactions across spatial scales, mathematics provides essential underpinnings to climate science.

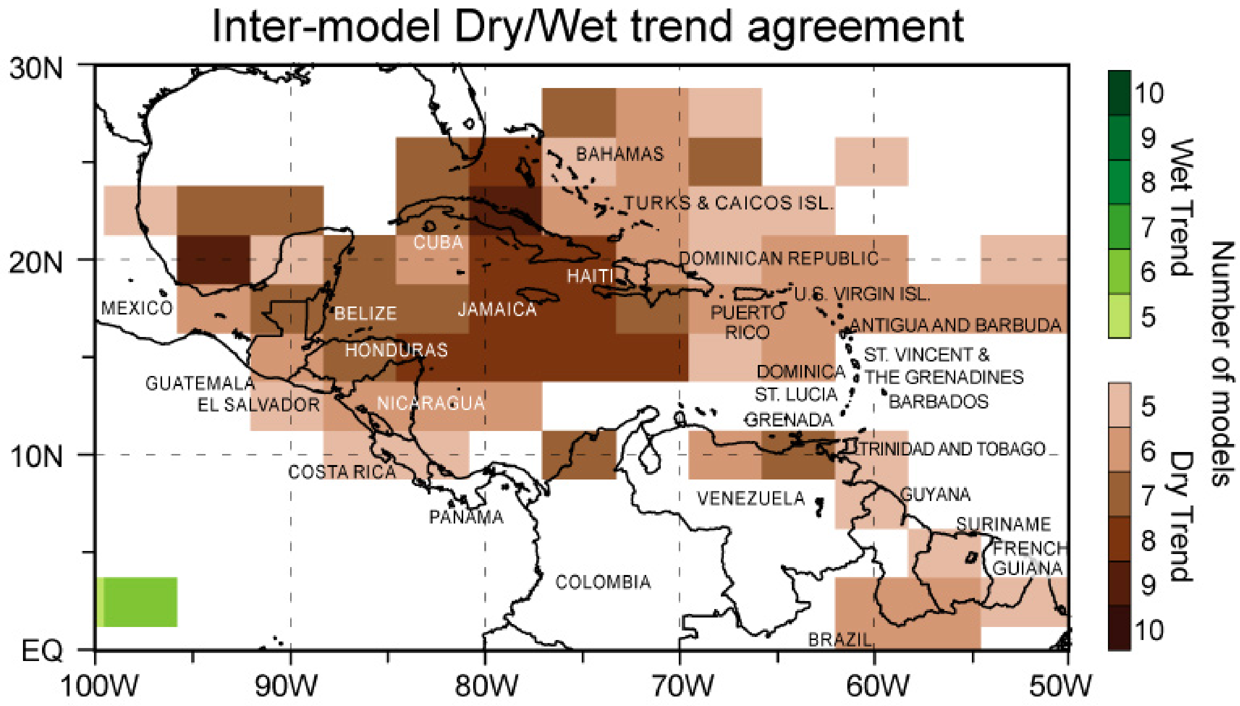

Figure 3. Model agreement on the predicted local precipitation trend from 1979 to 2099 for JJA. The number of models (out of 10) that agree on a dry trend or a wet trend at each location exceeding 99% significance and exceeding a minimum amplitude change (20% of the median climatology per century) is given by the brown or green color bars, respectively. Only regions with five or more of the 10 models agreeing are shaded. Modified from Fig. 5b of Neelin et al (2006, PNAS).

References:

Intergovernmental Panel on Climate Change Report of Working Group I. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Neelin, J. D., M. Munnich, H. Su, J. E. Meyerson, and C. E. Holloway, 2006: Tropical drying trends in global warming models and observations. *Proc. Nat. Acad. Sci.*, **103**, 6110-6115. (PDF 1.9 MB)

Further information:

Summary pages of the IPCC report:

http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

Related global warming material with further information on precipitation changes from US research labs:

http://www.ncdc.noaa.gov/oa/climate/globalwarming.html

http://www.cgd.ucar.edu/cas/Trenberth/GLOB_CHANGE/extremes.html

http://www.ncar.ucar.edu/research/climate/future.php

http://www.gfdl.noaa.gov/products/vis/gallery/climate_prediction/index.html