Progress in Physical Geography 27,3 (2003) pp. 448–455

Global warming

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The role of General Circulation Models (GCMs) has become predominantly important as the practical interest in regional impacts from anthropogenic greenhouse gases such as carbon dioxide (CO_2) grows. This first report documents the quality of GCMs as a tool for describing and predicting 'global warming' and the related geographical pattern of climate change from the CO_2 added to Earth's atmosphere.

I Validation problems in climate modelling and General Circulation Models (GCMs)

Quantification of the impact of anthropogenic CO_2 forcing, as well as its connection to global warming and other natural or man-made climatic forcings, requires validation of GCMs and reduction of their common deficiencies in simulating important climatic variables. Recent reviews (Palmer, 2001; Pielke, 2001; Soon *et al.*, 2001; Munk, 2002; Pittock, 2002; van der Veen, 2002) call for a more comprehensive consideration of nonlinear processes to describe the interactions among the atmosphere, oceans, land and ice-covered surfaces. Those media, the reviewers argue, must be treated as interactive, rather than mere unchanging surfaces or reservoirs, in order to progress in the study of year-to-year and century-long climate change on both regional and global scales (i.e., as distinct from the problem of weather prediction). The enormity and urgency of the scientific task, with modern societal needs for coping with climate change regardless of the added concerns about anthropogenic CO_2 forcing, has led Pielke (2001: 313), among others, to remind us that 'there have been no model experiments to assess climate prediction in which all important atmosphere–ocean–land surface processes were included'. Observational capability must also advance significantly before climate model validation can reach the next level of maturity (Goody *et al.*, 2002). Robust long-term monitoring of key climate quantities such as thermal and dynamical outputs of the Sun (Parker, 2000), spectrally resolved infrared radiance (Keith and Anderson, 2001), cloud properties (Wang *et al.*, 2000; Rossow *et al.*, 2002),

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 10.1191/0309133303pp391pr

surface radiative energy fluxes (Wild *et al.*, 2001), mass balance of glaciers (Dyurgerov, 2002; van der Veen, 2002), sea ice thickness (Holloway and Sou, 2002; Preller *et al.*, 2002) and even a global mass-distribution constraint such as Earth's mean dynamic oblateness parameter J_2 (Cox and Chao, 2002) would be important improvements.

II Simulations of climate variables

The current generation of GCMs have shown serious gaps and systematic deficiencies in calculating both regional and global changes for many variables such as temperature, precipitation, cloud properties and important oceanic variables, including oceanic circulation, pattern of sea surface temperature, as well as sea surface elevation (sea-level) and bottom pressure (Palmer, 2001; Pielke, 2001; Soon *et al.*, 2001; Munk, 2002; Schneider, E.K., 2002; van der Veen, 2002; Huang and Jin, 2002; Davey *et al.*, 2002).

1 Temperature

As noted by Johnson (1997), the appearance of the 1990 Intergovernmental Panel on Climate Change (IPCC) report (Houghton *et al.*, 1990) marked the recognition that all GCMs suffer from 'the general coldness problem', which is particularly acute in the lower tropical troposphere (below 500 mb) and upper polar troposphere (above 500 mb). The general coldness problem is seen in 104 out of the 105 outcomes, covering the entire troposphere, from 35 different simulations by 14 climate models. The ubiquitous cold-bias problem persists to date, as shown in the collection of GCM simulations compared with observed stratospheric and tropospheric temperatures in Pawson *et al.* (2000).

Johnson (1997) suggested that the origin of the cold bias arises from an extreme sensitivity of GCMs to systematic, aphysical entropy sources introduced by spurious numerical diffusion, Gibbs oscillations or inadequate sub-grid-scale parameterizations. Johnson estimated that a temperature bias of 10°C may be expected from only a 4% error in modelling net heat flux that is linked to any number of aphysical entropy sources, including those owing to numerical problems with the transport and phase changes of water in vapor, liquid or ice, and the spurious mixing of moist, static energy. A follow-on study by Johnson *et al.* (2000) shed further light on how the cold bias associated with spurious, positive-definite entropy contaminates the computation of hydrologic and chemical processes by virtue of their strong inherent dependence on temperature. Johnson *et al.*, estimated that the error in saturation-specific humidity doubles for every 10°C increase in temperature. Johnson (1997: 2842) further stressed that 'erroneous sources of entropy in atmosphere and ocean models differ in both origin and intensity. Efforts in coupled climate modeling to simulate accurately energy exchange across the mutual atmosphere–ocean interface will be extremely difficult . . . The implication is that atmospheric and oceanic energy balances within coupled climate models that do not require flux adjustment are suspect'.

2 Precipitation

Soden (2000) documented the inability of some 30 different atmospheric GCMs in the Atmospheric Modeling Intercomparison Project (AMIP) to reproduce faithfully interannual changes in precipitation over the Tropics (30°N to 30°S). Good agreement was found between observations and the GCMs' simulations of atmospheric water vapour content, tropospheric temperature at 200 mb and outgoing longwave radiation. However, observations and model simulations of precipitation and net downward longwave radiation at the surface disagreed. Considering the direct association of latent heat release by precipitation from moist air to the warming and cooling of the atmosphere, Soden (2000) noted that the good agreement between the observed and modelled temperature at 200 mb is surprising, given simultaneously the large difference between the observed and modelled precipitation fields. One explanation for the good temperature agreement at 200 mb is that it could be fortuitous because the atmospheric GCMs were forced with observed sea surface temperatures. Meanwhile, the modeled interannual variabilities of the hydrologic cycle, seriously underestimated by a factor of three to four (Soden, 2000), correctly diagnose miscalculation of the precipitation fields. Based on the models' relatively constant values of downward longwave radiation reaching the surface (see Wild *et al*., 2001 for further quantitative comparisons around the globe), Soden (2000) points to possible systematic errors in current GCM representations of low-lying boundary-layer clouds. However, the study cannot exclude the possibility of errors in algorithms that retrieve precipitation data from satellite observations, which would emphasize the need for improved precipitation data products.

3 Clouds

Wielicki *et al*. (2002) offered observational evidence for large decadal variability of the tropical mean radiative energy budget of the past two decades, which may be explained by independently observed changes in tropical mean cloudiness. More significantly, those results highlighted 'the critical need to improve cloud modeling' because several GCMs failed to simulate that large observed variability in the tropical energy budget. Grabowski (2000) emphasized the importance of proper evaluation of the effects of cloud microphysics on tropical climate by using models that directly resolve mesoscale dynamics. Grabowski pointed out that the main effect of cloud microphysics is on the ocean surface rather than directly on atmospheric processes. Because of the great mismatch between the timescales of oceanic and atmospheric dynamics, Grabowski was pessimistic about quantifying the relation between cloud microphysics and tropical climate. The parameterizations of cloud microphysics and cloud formation processes, as well as their interactions with other variables of the ocean and atmosphere, remain major challenges.

4 Ocean thermodynamics and dynamics: tropical ocean climatology and the stability of the North Atlantic Thermohaline Circulation (THC)

In a systematic comparison of the performance of 23 dynamical ocean–atmosphere models, Davey *et al*. (2002: 418) found that 'no single model is consistent with observed behaviour in the tropical ocean regions . . . as the model biases are large and gross errors are readily apparent'. Without flux adjustment, most models produced annual mean equatorial sea surface temperature (SST) in the central Pacific that are too cold by 2–3°C. All GCMs except one simulated the wrong sign of the east–west SST gradient in the equatorial Atlantic. The GCMs also incorrectly simulate the seasonal climatology in all ocean sectors and its interannual variability in the Pacific ocean; surface wind stress is diagnosed as the key parameter leading to those poor outcomes. The shortfall in interannual variability is more pronounced for zonal wind stress than for SST. Schneider, E.K. (2002) made the first progress in isolating and understanding specific intramodel and intermodel disagreements in the simulations of the equatorial Pacific ocean climatology and variability by using various flux-corrected experiments.

Russell and Rind (1999) noted that despite a global warming of 1.4°C around the time of CO_2 doubling, large regional coolings of up to 4°C were forecasted in both the North Atlantic Ocean (56–80°N, 35°W–45°E) and South Pacific (near the Ross Sea, 60–72°S, 165°E–115°W) because meridional poleward heat transfer was reduced over the North Atlantic and local convection was suppressed over the South Pacific. However, Russell *et al*. (2000) subsequently demonstrated that their GCM predicted unreliable regional changes over the Southern Ocean because of the model's excessive sea ice variability. Another GCM's high-latitude Southern Ocean suffers from a large, unphysical drift (Cai and Gordon, 1999). For example, within 100 years of coupling the atmosphere to the ocean, the modeled Antarctic Circumpolar Current artificially intensified by 30 Sv (from 157 to 187 Sv) despite the use of flux adjustments. Cai and Gordon identified the instability of convection patterns in the Southern Ocean of the GCM to be the primary cause of that large drift.

The reasons for the projected weakening of the North Atlantic THC in various models remain unclear because, as Mikolajewicz and Voss (2000) caution, the GCMs give contrasting roles to individual atmospheric and oceanic fluxes of heat, moisture, salinity and momentum. Thus, although a complete breakdown of the North Atlantic THC is predicted for sufficiently strong CO_2 forcing in some simulations (Schmittner and Stocker, 1999, Rahmstorf, 2000), Wood *et al*. (1999) and Mikolajewicz and Voss (2000) cautioned that the predicted changes of the THC are very sensitive to parameterizations of various components of the hydrologic cycle, including precipitation, evapouration and river runoff. For example, without a perpetually enhanced influx of freshwater (from any source) or extreme CO_2 forcing, the transient decrease in THC overturning eventually recovers as time progresses in the model (Mikolajewicz and Voss, 2000; Holland *et al*., 2000). In addition, when a dynamic sea ice module is included in a coupled atmosphere–ocean model, Holland *et al*. (2000) report a reduction (rather than an enlargement) in the variance of the THC overturning flowrate under the doubled CO_2 condition, down to 0.25 Sv^2 (or only 7% of value simulated for present-day forcing) from the high value of 3.6 Sv^2 simulated under the present-day forcing level.

Furthermore, Latif *et al*. (2000) reported a new stabilization mechanism that counters previous expectations of a CO_2-induced THC weakening. Latif *et al*.,'s state-of-the-art coupled ocean–atmosphere GCM of the Max Planck Institut für Meteorologie at Hamburg (MPI) resolves the tropical oceans at a meridional scale of 0.5°, rather than the more typical scale of 2–6°, and produces no weakening of the THC when forced by increasing CO_2. Latif *et al.* showed that anomalously high salinities in the tropical Atlantic, produced by excess freshening through the remote forcing at the equatorial Pacific, were advected poleward to the sinking region of the THC. The effect was sufficient to compensate for the local increase in freshwater influx at North Atlantic. Updated experiments for a similar CO_2 forcing scenario by Gent (2001) and Sun and Bleck (2001) also confirm the relative stability of the THC because of compensating effects among thermal perturbation, changes in surface hydrology and salinity.

Therefore, sophisticated GCMs results are consistent with both a stable and unstable North Atlantic THC under a future high CO_2 radiative forcing scenario. Latif *et al.* (2000) concluded that the response of THC to enhanced greenhouse warming is still an open question, and Gent (2001) reiterated that estimating the response of the THC in the twenty-first century, important as the question may be, is 'a very demanding question to ask of current state-of-the-art coupled climate models'.

III The incorrect fingerprint of CO_2 forcing in GCMs

No GCM has successfully simulated the observed relative warming trend of the surface layer compared with the low troposphere. All GCMs consistently predict that the troposphere should warm faster than surface air when radiative forcing is enhanced by CO_2 (Bengtsson *et al.*, 1999). Santer *et al.* (2001) confirmed that the wrong fingerprint is observed compared with that expected from CO_2 forcing on the atmosphere. GCMs simulate trend differences of surface-minus-lower troposphere temperature significantly smaller than the observed results for 51 out of 54 simulations examined, even for best-effort attempts to account for trend biases introduced by effects of volcanoes and El-Niño–Southern Oscillation (ENSO).

Some theoretical proposals expect a warming of the surface relative to the lower troposphere because of nonlinear climate dynamics (Corti *et al.*, 1999). That expectation is because of the differential surface response with the pattern of Cold Ocean and Warm Land (COWL) that becomes increasingly unimportant with distance from the surface (see Soon *et al.*, 2001, for additional explanation). Nevertheless, no GCM has incorporated such an idea into an operationally robust simulation of the climate system response to greenhouse effects from added CO_2. This incorrect forecast of the fingerprint of carbon dioxide forcing on the surface and atmosphere temperature needs resolution.

IV Summary

Climate models are now being used extensively to diagnose the causative, especially anthropogenic, factors of observed climatic changes of the past few decades (Palmer, 2001; Stott *et al.*, 2001; Thorne *et al.*, 2002). These models are also used to make long-term climate projections and climate risk assessments based on future anthropogenic forcing scenarios (Saunders, 1999; Palmer, 2001; Houghton *et al.*, 2001; Pittock, 2002; Schneider, S.H., 2002). Many such exercises help to shape public policy recommendations concerning future energy use and various 'climate protection' measures in order to prevent 'dangerous climate impacts' (e.g., Schneider, S.H., 2002; O'Neill and

Oppenheimer, 2002). But meaningful and credible scientific confidence, resting either on the traditional deterministic method of quantification or the probabilistic mode of measuring change (as favoured by, for example, Washington, 2000; Räisänen and Palmer, 2001; Schneider, S.H., 2002) cannot yet be made to such computer experiments because climate models do not yield sufficiently reliable, quantitative results in reproducing well-documented climatic changes around the world.

Govindan *et al*. (2002) highlighted, by performing the detrended fluctuation analysis on daily maximum temperature records for six sites spread across the globe, that seven leading coupled GCMs systematically underestimated the observed long-range persistence of the atmosphere (roughly after timescales longer than 2 years or so) and overestimated the daily maximum temperature trend. From that failure of computer models to emulate the observed behaviour in the real atmosphere, Govindan *et al*., deduced that 'the anticipated global warming is also [likely] overestimated' by those leading GCMs.

Another key uncertainty in climate modelling concerns the true sensitivity of the Earth's climate system to a given radiative forcing. Andronova and Schlesinger (2001) deduced a large range of values for the climate sensitivity parameter, ΔT_{2x} (i.e., the equlibrium global-mean surface temperature warming in response to a doubling of atmospheric CO_2 concentration) owing to limited understanding of natural variability and uncertainty in climate radiative forcing. That sensitivity parameter, so necessary for an accurate prediction of CO_2 radiative forcing, has a 90% confidence interval of 1.0ºC to 9.3ºC. Using a different model and tuning scenarios, Forest *et al*. (2002) similarly obtained 1.4°C to 7.7ºC as the 5% to 95% confidence interval for ΔT_{2x}.

Acknowledgements

This work was supported by the Air Force Office of Scientific Research grant AF 49620-02-1-0194 and by the National Aeronautics and Space Administration grant NAG5-7635.

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