GLOBAL CIRCULATION OF THE ATMOSPHERE (2004)

BY TAPIO SCHNEIDER AND ADAM SOBEL

Despite the considerable advances in our ability to observe the global circulation of the atmosphere and to stimulate it numerically, basic features of Earth's climate, for example, storm-track position and many aspects of the tropical climate, remain poorly understood. For improvement and interpretation of climate simulations, and for an understanding of past and future climate changes, an understanding of the dynamical mechanisms responsible for the maintenance and variability of the global circulation of the atmosphere is indispensable. It is our perception that research whose direct goal is understanding—what might be called "theoretical" research, though that word is narrower than our intended meaning—commands a smaller share of the intellectual and financial resources in our field than it has in the past. If true, this may be due to the rapid technological advances in observation and simulation that have occurred, accompanied by a lack of similar advances in the capabilities of the human mind. We argue that the tremendous onslaught of new data and new simulation capabilities create a need for more theory, not less, to synthesize and interpret the new information.

GLOBAL CIRCULATION OF THE ATMOSPHERE

WHAT: Experts assembled to assess understanding of the global circulation with an eye toward identifying outstanding questions and improving the framework for synthesizing observations and simulations.
WHEN: 4–6 November 2004
WHERE: Pasadena, California

In November 2004, we held a three-day conference on the global circulation of the atmosphere at the California Institute of Technology, with the aim of assessing the current state of our understanding and defining important outstanding questions. About one-half of the conference was devoted to invited overview talks and the other half to contributed talks and posters.

Isaac Held (Geophysical Fluid Dynamics Laboratory, Princeton) opened the conference with a talk on outstanding questions in global circulation theory. Focusing on the large-scale dynamics of the extratropical atmosphere, Held pointed out that such basic questions as what sets the magnitude and structure of the eddy heat flux, the pole–equator temperature gradient, and the tropospheric static stability are still unresolved. He then discussed the role of moisture in baroclinic eddies, presenting simulations with idealized GCMs that suggest that these eddies may have to be viewed as fundamentally moist entities,

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rather than as dry entities modified by latent heat release. The conceptual foundations appropriate for viewing them as such are in need of further development. Some such development was presented at the conference, for instance, in a talk by Olivier Pauluis (New York University) on available potential energy budgets in a moist atmosphere.

The role of water vapor in baroclinic eddies and the role of baroclinic eddies in the atmospheric hydrological cycle were recurring themes in several other presentations, such as those by Richard Seager (Lamont, Columbia University) on dynamical challenges posed by the paleoclimate record, by Raymond Pierrehumbert (University of Chicago) and Joe Galewsky (Columbia University) on the mechanisms controlling the relative humidity of the atmosphere, by Darryn Waugh (Johns Hopkins University) on the influence of extratropical eddies intruding into the Tropics on deep convection, and by Dargan Frierson (Princeton University) on the dynamics of moist baroclinic eddies. There now is convincing evidence that quasi-isentropic transport by baroclinic eddies, in addition to the cross-isentropic large-scale subsidence associated with the Hadley circulation, influences the relative dryness of the subtropical atmosphere. It is still unclear how the balance of different large-scale processes, which is implicated in controlling the relative humidity, may shift as the climate changes. Because water vapor is the principal greenhouse gas, understanding the processes that control its abundance in the atmosphere is clearly fundamental for understanding climate changes.

Progress and challenges in understanding tropical circulations were the topic of several presentations. Kerry Emanuel [Massachusetts Institute of Technology (MIT)] reviewed the quasi-equilibrium hypothesis and its consequences for tropical dynamics. This hypothesis takes as a starting point the assumption that convection is in statistical equilibrium with large-scale flow perturbations, which tends to render the thermal stratification moist adiabatic. Quasi-equilibrium dynamics provides at least a qualitative (though not entirely uncontested) account of aspects of the tropical climate such as hurricanes, convectively coupled waves, and aspects of the time mean circulation. Taking the surface temperature and thermal stratification as given, Adam Sobel (Columbia University) discussed competing theories—thermodynamic versus dynamic control—for the tropical surface wind and precipitation fields. Though based on different principles, the different theories give predictions that are qualitatively similar (e.g., precipitation over warm SST). They differ in some details, for example, in their accounts of the narrowness and intensity of the intertropical convergence zones. Recent observational evidence from the East Pacific Investigation of Climate Processes (EPIC) field experiment, relevant to evaluating these theories, was presented by David Raymond (New Mexico Institute of Mining and Technology). Modeling work inspired by the same observations, focusing on the shallow circulation that occurs when dynamic forcing of the ITCZ is active but thermodynamic forcing is not sufficient to induce deep convection, was presented by David Nolan (University of Miami).

Determining what is right and wrong in these different theories for tropical dynamics would be helpful in the quest to understand and correct persistent precipitation biases in GCM simulations with fixed surface temperatures. These precipitation biases, biases in the phase of the diurnal cycle, and uncertainties in modeling cloud-radiative feedbacks were among the modeling challenges discussed by Chris Bretherton (University of Washington). Bretherton suggested idealized Walker circulations—circulations in the longitude–height plane, in the absence of rotation or latitudinal structure, forced by longitudinal gradients in SST or surface energy flux—as a paradigmatic problem in which important processes of tropical dynamics can be studied in isolation and in a way that is amenable to simulations with cloud-resolving models.

Alan Plumb (MIT) surveyed research on monsoon dynamics. Taking as a starting point the constraints that angular momentum conservation imposes on axisymmetric monsoon circulations, Plumb argued that an analogous circulation constraint also appears to be relevant for understanding more realistic three-dimensional circulations. In the case of a three-dimensional monsoon with a nonaxisymmetric pool of air with zero absolute vorticity in the upper troposphere, the constraint can be broken by the shedding of eddies. David Neelin (University of California, Los Angeles) used the framework of quasi-equilibrium dynamics, embodied in an intermediate climate model, along with moist static energy budget considerations to discuss a variety of mechanisms by which the low-latitude climate may respond to forcing variations on seasonal (monsoons), interannual (ENSO), or interdecadal (global warming) time scales. He offered an account, for example, of the drying that GCMs produce at the margins of many convective zones in response to increases in greenhouse gas concentrations.

Walter Robinson (University of Illinois at Urbana–Champaign) showed how midlatitude eddies can interact with tropical circulations to produce variations in the midlatitude climate, such as changes in surface temperature and storm-track position in response to ENSO. ENSO modifies the Hadley circulation, which alters the basic state upon which baroclinic eddies develop and propagate. The resulting changes in the eddy momentum fluxes shift the Ferrel cell, potentially producing quasi-axisymmetric droughts or pluvials in midlatitudes.

Compared to low-latitude circulations, midlatitude circulations are relatively well understood, perhaps due to the relatively smaller (though by no means negligible) role of moist processes in the extratropics. Nonetheless, there still are no satisfactory accounts of central features of the midlatitude climate, starting from the pole-to-equator temperature gradient and the static stability, and continuing to zonally asymmetric features such as storm-track strength and position. Richard Lindzen (MIT) reviewed baroclinic adjustment theories for the pole-to-equator temperature gradient. Tapio Schneider [California Institute of Technology (Caltech)] discussed recent ideas on the maintenance of the extratropical static stability and tropopause height. He showed idealized GCM simulations, suggesting that in a sufficiently baroclinic atmosphere, baroclinic eddies modify the static stability and tropopause height in such a way as to maintain a state of weak nonlinearity with weak eddy–eddy interactions. Kyle Swanson (University of Wisconsin—Milwaukee) discussed the low-frequency variability of storm tracks and pointed out the differences in their response to forcing on seasonal and interannual time scales. This produces apparent paradoxes, such as the minimum streamfunction variance in the Pacific storm track in midwinter. There is no satisfactory theory explaining this midwinter minimum, a feature only of the Pacific, and the response of storm tracks to longer-term climate changes, also discussed by Edmund Chang (State University of New York at Stony Brook) and Mankin Mak (University of Illinois at Urbana–Champaign), is likewise poorly understood. Swanson suggested that a route to an improved understanding may be to analyze stochastic models, in which the variability of storm tracks is excited by stochastic forcing representing nonlinear interactions, and is damped by linear relaxation toward a mean state.

Lively poster sessions at the end of the first and second days of the conference continued on themes raised by the talks, such as the Hadley circulation (Thomas Reichler, University of Utah, and Isaac Held; Christos Mitas and Amy Clement, University of Miami; Christopher Walker and Tapio Schneider, Caltech; Peng Xian and Ronald Miller, Columbia University), the ITCZs (John Chiang, University of California, Berkeley, and Cecilia Bitz, University of Washington; Chia-Chi Wang and Gudrun Magnusdottir, University of California, Irvine; Michela Biasutti, Columbia University), and wave mean flow interaction (Edwin Gerber and Geoffrey Vallis, Princeton University; Daniel Hodyss, University of Miami, and Terrence Nathan, University of California, Davis; Matthew Newman and Prashant Sardeshmukh, National Oceanic and Atmospheric Administration, Climate Prediction Center), as well as bringing up other topics, such as stratospheric dynamics.

More than 50 years after upper-air observations of the atmosphere and the first numerical models became available, there are numerous basic features of the atmospheric climate that still call for an explanation. What the conference has made clear is that the way to approach the challenges the atmosphere poses is by synthesizing theory, observations, and simulations with a hierarchy of models, from simple conceptual models encoding qualitative understanding to complex GCMs. We cannot rely on simulations with the most complex models alone; a road map to the climate system needs to be less complex than the system itself.

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