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CLOUD FORCING AND THE EARTH'S RADIATION BUDGET: NEW IDEAS AND NEW OBSERVATIONS

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1. NEW PERSPECTIVES ON CLOUD-RADIATIVE FORCING

When the Earth Radiation Budget Experiment (ERBE) produced the first measurements of cloud-radiative forcing (Ramanathan, et al., 1989), the climate community interpreted the results from a context in which the atmosphere was a single column, strongly coupled to the Earth's surface. In this context, all forcings are created equal. When a modeler runs a climate experiment, he creates a perturbation in the energy flow through the system, allows the atmosphere to couple to the surface, and then watches as the surface responds to the coupled disequilibrium. Indeed, the perturbation to the global radiation balance at the tropopause after the atmospheric energy flow equilibrates with the net flow from the surface is the climate forcing, even through the surface has still not completely adjusted to the perturbation.

Recently, the modeling community has begun the task of interpreting the way the climate system works by considering systems with more degrees of freedom (Hansen, et al., 1996). In this context, a perturbation can excite several response modes, only some of which tie to the long-term response of the surface temperature. Of course, the response modes are the natural organizations of the temperature, humidity, and pressure fields that underlie the radiation budget. Thus, it appears useful to begin to interpret both theoretical calculations and observations from the standpoint of internally organized objects whose life extends over a much longer time period than the typical GCM time step. Storm systems are the obvious example, although we can incorporate such long-lived phenomena as ocean currents and ecosystem in this Earth system science view.

2. NEW PERSPECTIVES ON CLOUD-RADIATION OBSERVATIONS

The climate community is also on the verge of adding a new dimension to its observational capability. In classic thinking about atmospheric circulation and climate, surface pressure was a readily available quantity. As meteorology developed, it was possible to develop quantitative predictions of future weather by bringing together a network of surface pressure observations and then of profiles of temperature and humidity obtained from balloons. However, from a deeper perspective, surface pressure is a variable that responds to perturbations in frictional wind stress at the Earth's surface and to the divergence of atmospheric circulation throughout the atmosphere. The divergence, in turn, depends upon the structure of atmospheric heating and cooling.

The difficulty this train of reasoning poses for predicting the atmospheric circulation over long time periods is that it couples the fields of condensed water in clouds to the atmospheric heating and cooling and thereby to the circulation. Because clouds require the presence of a minor atmospheric constituent, water vapor, as well as Cloud Condensation Nuclei, their formation and dissipation depends upon the structure of atmospheric turbulence at both large and small scales. In practice, this fact means that only a very small fraction of the water in an atmospheric column needs to respond to phenomena that are very difficult to predict in order to drastically change the flow of energy through the whole column. There is no good physical reason to believe that clouds are conservative atmospheric constituents in the same sense that nitrogen, oxygen, and other longer-lived constituents are. In a certain sense, we can almost regard clouds as "atmospheric free agents". We have needed an observational net that catches clouds just as the network of surface observations catches the surface pressure perturbations.

What is encouraging is that our observational capability has begun to catch up with our need to understand where clouds form, what they do to the atmospheric water balance, and how they change the radiation flow. One component of that observational network was the observation of the flow of reflected sunlight and emitted terrestrial radiation provided by the Earth Radiation Budget Experiment and its precursors (Barkstrom, et al., 1989). This experiment provided a rough categorization of the cloud cover to perform its data reduction. A second component of that network comes from the pioneering work of the International Satellite Cloud Climatology Project (ISCCP) (Rossow, et al., 1993). This project has produced a valuable collection of data using radiation in the relatively conservative portion of the solar spectral range and in the atmospheric window.

Where we are headed in the next few years is an observational capability that combines radiation measurements like those of ERBE with a much more extensive capability to determine cloud properties (Wielicki, et al., 1995). The fields of radiation and clouds are very difficult to sample completely —an eight dimen-

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sional sampling problem can have many different kinds of gaps. However, the combined observations of the instruments from the investigation of Clouds and the Earth's Radiant Energy System (CERES) and the high quality imager data from MODIS is likely to lead to an observational "network" for clouds and radiation that rivals the network for surface pressure and atmospheric profiles.

From this perspective, we can note that the "sky network" has some interesting properties that contrast with the surface network. Particularly notable is the much higher spatial resolution that the satellite observations provide within the satellite observational swath. This resolution increases our ability to understand the phenomena we are watching and should help to constrain model predictions about the nature of the phenomena that cause clouds. In addition, when the Earth Observing System (EOS) has both morning and afternoon satellites sending down data, we obtain this high spatial resolution data four times per day.

3. ON COMBINING OBSERVATIONS AND THEORY

With this new capability, it is natural to seek recognizable features in the observations we make of the Earth. There are techniques we can use to group the remotely sensed data in the individual footprints into objects that we can track. We will present one such image-processing application to radiation budget data, showing how we can interpret the radiation budget data in terms of cloud systems that are organized into systematic patterns of behavior —an ecosystem-like view of cloud behavior. This approach to interpreting our observations will become much more valuable during the approaching era of EOS, when we will be able to obtain the first consistent and validated observations of simultaneous radiation and cloud properties on a global basis.

This new context for interpreting observations also allows us to build new concepts into simple models of the climate system. These, in turn, will allow us to improve our perceptions of how to understand the much more complex physics in larger and more detailed models. This viewpoint of the way models provide a context for interpretation appears to lead to the idea that Earth System Science is an interesting interdisciplinary discipline, in which the objects of study are different than the ones of the classic disciplinary approaches.

4. REFERENCES

Barkstrom, B. R., E. F. Harrison, G. L. Smith, R. N. Green, J. F. Kibler, R. D. Cess, and the ERBE Science Team, 1989: Earth Radiation Budget Experiment (ERBE) archival and April 1985 results. *Bull. Amer. Meteor. Soc.*, **70**, 1254–1262.

Hansen, J., R. Ruedy, A. Lacis, G. Russell, M. Sato, J. Lerner, D. Rind, and P. Stone, 1996: Wonderland Climate Model, submitted to *J. Geophys. Res.*.

Ramanathan, V., R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, and D. Hartmann, 1989: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment *Science*, **243**, 57–63.

Rossow, W. B., A. W. Walker, and L. C. Gardner, 1993: Comparison of ISCCP and other cloud amounts. *J. Climate*, **6**, 2394–2418.

Wielicki, R. D. Cess, B. R., M. D. King, D. A. Randall, and E. F. Harrison, 1995: Mission to Planet Earth: Role of Clouds and Radiation in Climate. *Bull. Amer. Meteor. Soc.*, **76**, 2125–2153.