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Condensed Paper

Clouds, the Earth's radiation budget, and the hydrologic cycle

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ABSTRACT

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Water vapor plays a key role in climate change scenarios through the water vapor feedback loop. The distribution of water vapor obviously controls the distribution of clouds, but the opposite is also true because clouds carry out important vertical redistributions of the vapor. This paper presents comparisons of water vapor observations with general circulation model simulations of the distribution of water vapor and its effects on the Earth's radiation budget. The ability of the model to simulate the seasonally changing cloud radiative forcing is also discussed. Finally, the need for long-term monitoring of these fields is emphasized.

Introduction

The importance of moisture in determining our planet's climate has never been more fully appreciated than it is today. The heat capacity of the oceans, the albedos of ice and clouds, the greenhouse effects of water vapor and clouds, and the feedbacks that all of these exert on climate-perturbing "external" forcings such as increasing greenhouse gas concentrations are now recognized to be of fundamental importance for understanding and predicting the Earth's present and future capacity to sustain life.

It is, therefore, disturbing that we know so little about the distributions of vapor, liquid, and ice within the Earth's atmosphere. We lack adequate quantitative knowledge of what these distributions actually are, of what controls them, and of their effects on the Earth's radiation budget.

Water vapor

Passive microwave instruments such as SMMR and SSM/I are providing excellent data on the vertically integrated water vapor amount ("precipitable water", hereafter PW) over the oceans. TOVS is providing comparable data for both land and ocean. These PW observations are very useful for comparison with general circulation model (GCM) simulations. An example of such a comparison is given in Fig. 1, which shows the PW as observed over the oceans by SMM/I and as simulated by the Colorado State University (CSU) GCM. The CSU GCM is a modified version of the UCLA GCM, which has been developed by A. Arakawa and collaborators. A description of the CSU GCM has recently been given by Randall et al. (1989).

The observed PW pattern is fairly well captured

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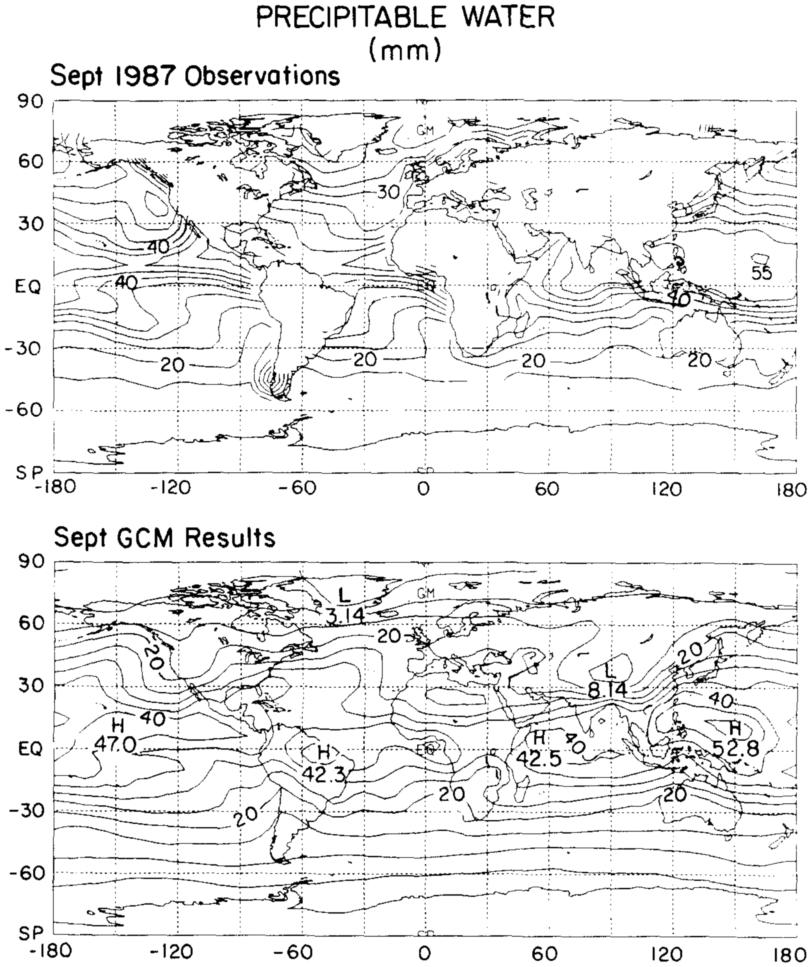

Fig. 1. The September distribution of precipitable water, as observed (for the oceans only) by SMM/I, and as simulated (for both land and ocean) by the CSU GCM.

by the simulation. Note, however, that in regions of intense tropical convection, such as the Western Equatorial Pacific Ocean, the model tends to underpredict the observed PW. This suggests that the model's convection scheme produces excessive drying of the atmospheric column. Cheng and Arakawa (1990) have drawn a similar conclusion, and have presented evidence that the drying is due to the parameterizations failure to include the effects of convective downdrafts.

Figure 2 shows the variation of the PW with surface temperature, as observed by both TOVS, and as simulated by the CSU GCM. The agreement is reasonably good, indicating that the model includes the essential physics that determines the

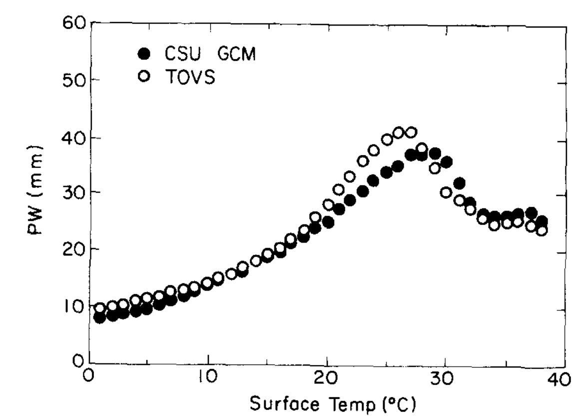

Fig. 2. The variation of the precipitable water with surface temperature, as observed by TOVS, and as simulated by the CSU GCM.

variation of PW with surface temperature in the real atmosphere. Although the agreement is reasonably good, the figure shows again the obvious underprediction of the PW over the warm (20–27°C) tropical oceans. The warmest surface temperatures (greater than about 30°C) occur exclusively over land, and are associated with drier columns, in both the model and the observations.

Of course, the vertically integrated water vapor amount is not the only aspect of the water vapor distribution that matters for climate. Lindzen (1990) has stressed the importance of the vertical distribution of water vapor in the middle and upper troposphere, particularly for determining the greenhouse effect due to water vapor. Unfortunately, current satellite observations of the vertical distribution of water vapor suffer from severe credibility problems. Instrument and/or algorithm improvements are drastically needed. In situ measurements will be crucial for evaluation of the quantitative accuracy of such retrievals.

Raval and Ramanathan (1989) and Stephens and Greenwald (1990) have discussed observations of the greenhouse effect of water vapor. In essence, the upward longwave radiation emitted by the Earth's surface is partially absorbed and re-emitted by water vapor, so that the outgoing longwave radiation at the top of the atmosphere is reduced. In the absence of clouds, this reduction is largely due to the effects of water vapor. The amount by which the clear-sky flux is reduced is, therefore, a measure of the water-vapor greenhouse effect. Stephens and Greenwald have defined a parameter G to represent this effect:

$$G = \frac{\sigma T_s^4}{\sigma T_e^4} \tag{1}$$

where σ is the Boltzman constant, T_s is the surface temperature, and T_e is the effective "black-body" temperature of the Earth. In the absence of an atmosphere, G would be equal to one; the greenhouse effect of the atmosphere leads to $G > 1$. Figure 3 shows G as a function of surface temperature, for both the CSU GCM and the Nimbus-7 earth radiation budget data (Ramanathan et al., 1989). For both the model and the observations, we have plotted the total greenhouse effect due to

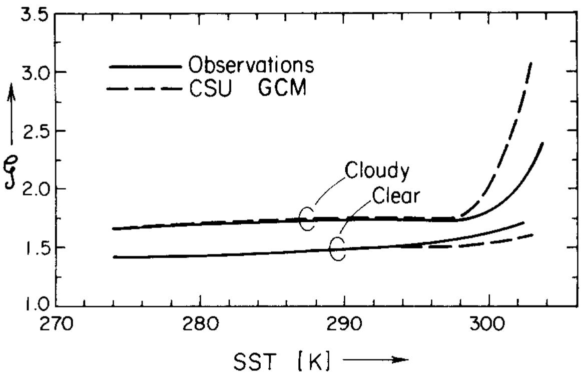

Fig. 3. The GCM-simulated water-vapor greenhouse effect, plotted as a function of sea surface temperature, (SST).

clouds and gases, as well as the "clear-sky" greenhouse effect due to clouds alone.

For clear skies, the model tracks the data reasonably well up to the warmest surface temperatures, beyond which the model underpredicts the clear-sky greenhouse effect. This underprediction is undoubtedly due in part to the excessive dryness noted earlier. It may also be partly accounted for by "cloud contamination" of the clear-sky observations, however.

When the effects of clouds are included, both the model and the observations show a dramatic increase in G for sea surface temperatures warmer than about 300 K. The model exaggerates this increase, but is qualitatively tracking the observations, perhaps to a surprising degree.

These results illustrate how satellite data can be used to evaluate the ability of GCMs to simulate the basic physics of the projected global warming.

The seasonally varying cloud forcing

As discussed by Schlesinger and Mitchell (1987), the existing coupled ocean–atmosphere GCMs give reasonably consistent predictions of the climate system's response to increasing CO_2, so long as attention is focused on such globally averaged quantities as the surface air temperature and precipitation rate. They also agree that the CO_2 induced warming of the surface air will be substantially stronger in high latitudes than near the equator, in part because of ice-albedo feedback, and in part because the relatively strong stratification at high latitudes prevents convective redistribution of surface warming to higher levels in the troposphere. Finally, they agree that the stratosphere will cool.

Here the agreement ends, however. When the results are examined in more detail, either by looking at regional distributions of climate change or by investigating the response of a wider variety of climate state variables, major disagreements among the models rapidly come to light. For this reason, current predictions of the magnitude, timing, and regional distribution of the climatic effects of increasing CO_2 concentrations are less than fully reliable. Certainly they are not suitable for use by policy makers planning for the future of energy consumption, agriculture, or other critical human activities.

Recently, the GCM Intercomparison Project sponsored by the U.S. Department of Energy has taken an important step towards resolving this troubling uncertainty. The participants have conducted identical controlled, idealized climate-change experiments with about twenty atmospheric GCMs. Each group has carried out three perpetual-July simulations. The first used observed climatological sea surface temperatures (SSTs), the second used SSTs increased to 2 K above climatology everywhere, and the third used SSTs reduced to 2 K below climatology everywhere. The group agreed upon a set of diagnostics to be saved in all simulations.

The results of these experiments have been reported by Cess et al. (1989, 1990). Briefly, they show that the gross climate sensitivities of the various models range over about a factor of three, but that virtually all of these differences can be accounted for by differences cloud feedbacks produced by the various models.

Even before the GCM Intercomparison Projects' results were analyzed, many researchers had concluded that uncertainties about the effects of clouds are a key obstacle to reliable quantitative climate change predictions (e.g. Hansen et al., 1984). The important contribution of the GCM Intercomparison Project has been to quantitatively demonstrate this fact through systematic model intercomparisons.

It is difficult to devise a practical way to observationally test simulations of the changes in the cloudiness and the CRF that accompany climate changes. We cannot observe the clouds of a future climate until that future arrives; moreover, it seems very difficult to obtain reliable evidence of the cloud distributions characteristic of paleoclimates that we may attempt to simulate with our models.

A strategy designed to partially avoid this difficulty is to study the seasonal changes in the CRF. If a model cannot realistically simulate the changes in cloudiness and CRF that accompany seasonal change, it certainly cannot be trusted to realistically simulate cloud feedbacks on climate change. Seasonal changes are eminently observable. For this reason, seasonal change has long been used, by climate modelers, as a proxy for climate change.

Cess et al. (1991) have recently investigated the seasonal changes in the planetary CRF, as revealed by the ERBE data. We have reproduced their computations, and generated corresponding results from the CSU GCM. Before presenting these results, it is necessary to introduce some definitions, following Cess et al. (1991). The forcing of the system due to the seasonal change of insolation, at any point on Earth, can be written as:

$$\text{net forcing} = (1 - \bar{\alpha})\Delta S \qquad (2)$$

where α is the planetary albedo, S is the solar irradiance, an overbar denotes the annual mean, and $\Delta(\square)$ denotes a departure from the annual mean. The system responds by producing a change in the planetary albedo and the outgoing longwave radiation, F. This response can be written as:

$$R = \bar{S}\Delta\alpha + \Delta F \qquad (3)$$

where the first term represents the "short-wave response," and the second term represents the longwave response." Let R_c denote the response of the clear-sky fluxes, as observed by ERBE and/or as simulated by a GCM. Then we can define the seasonal response of the cloud radiative forcing as:

$$R_c - R = S(\Delta\alpha_c - \Delta\alpha) + (\Delta F_c - \Delta F) \qquad (4)$$

Note that the seasonal change of S does not appear in eqn. (4), because it is considered to be part of the forcing, as expressed by eqn. (2). A more complete explanation of eqn. (4) is given by

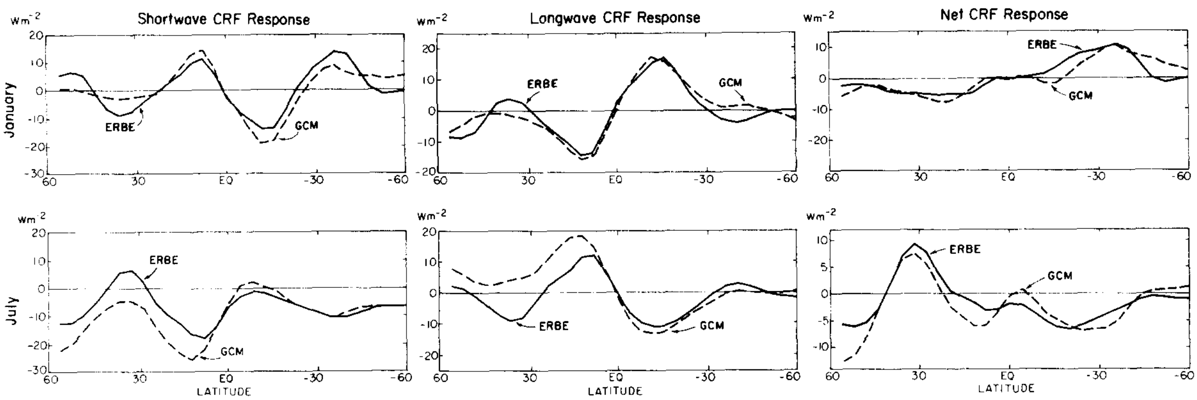

Fig. 4. The January and July seasonal response of the shortwave, longwave, and net cloud radiative forcing, as evaluated with ERBE data and as simulated by the CSU GCM.

Cess et al. (1991). The first term of eqn. (4) can be called the "response of the shortwave CRF," and the second the response of the longwave CRF."

We have evaluated the response of the shortwave CRF and the response of the longwave CRF using both ERBE data (Ramanathan et al., 1989) and simulations with the CSU GCM. Figure 4 shows the results, for both January and July, and for the shortwave, longwave, and net CRF. The shortwave CRF response is negative in the northern middle latitudes, because of the seasonal increase in the cloud amount and the corresponding increase in the albedo. In the middle latitudes of the Southern Hemisphere, the shortwave CRF response is positive because of the seasonal decrease in cloudiness there. In the tropics, the January shortwave CRF response is positive north of the equator and negative south of the equator, because of the seasonal shift of the ITCZ toward the south.

The longwave CRF response for January is positive in the northern middle latitudes because of the seasonal increase in cloudiness and the associated increased trapping of terrestrial radiation; conversely, it is negative in the middle latitudes of the southern hemisphere. In the tropics, the longwave CRF response is negative north of the equator and positive south of the equator because of the seasonal shift of the ITCZ.

The GCM results are in remarkably close agreement with the observations.

This exercise illustrates how satellite data can be used to test the ability of a climate model to simulate the response of the CRF to external perturbations – in this case, seasonal change. A demonstration that the model can reproduce the observed seasonal changes fairly well increases our confidence in its ability to simulate the response of the CRF to other types of external perturbations, such as those associated with increasing CO_2.

Trends

Figure 5 shows the December–January–February trend in low-cloud (stratus, stratocumu-

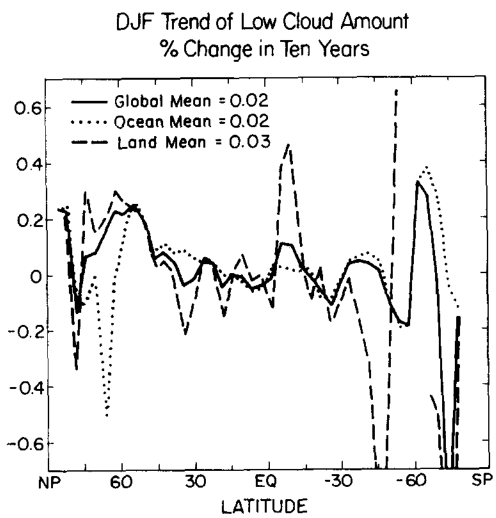

Fig. 5. The zonally averaged observed trend in low cloud amount, as reported by Warren et al. (1985, 1986, 1988), for December–January–February. Means for land, sea, and all longitudes are shown.

lus, and fog) amount, as reported by Warren et al. (1985, 1986, 1988), based on surface measurements. The figure shows an apparent tendency for low cloud amount to increase with time; if correct, this would have major potential implications for climate change, although of course the trends could be "short-term" (decadal) fluctuations due to natural variability.

We do not present this figure because we think that the results shown are unquestionably correct; obviously this type of analysis is subject to many uncertainties, as was well recognized by Warren et al. (1985), and the large values apparent at certain latitudes are almost certainly misleading or incorrect. We show the figure in order to call attention to the need for reliable, global data of this type, on time scales of many decades. We need to monitor clouds, water vapor, and the Earth's radiation budget continuously, not just for five years or ten years, but forever. Monitoring the Earth's radiation budget and the factors that control it should be viewed, therefore, as an *operational* rather than experimental task, at least as important as (arguably more important than) collecting data for short-range weather forecasts.

Conclusions

The climate of our planet is of more than purely scientific interest. It is regulated, to a large extent, by the exchange of radiation with space. There is an obvious need, therefore, to monitor the Earth's radiation budget and the key variables that affect it, such as clouds and water vapor. These observational programs must not be abandoned after a brief, experimental fling; they must continue *forever*. They must become part of the operational infrastructure, alongside the observations that are used for operational weather prediction.

Global measurement of clouds and water vapor from space is a difficult task. There are many uncertainties that arise from limitations of both data and algorithms. For this reason, ground truth will continue to be very important for the foreseeable future. Field programs such as FIRE (Cox et al., 1987) are essential.

It is often argued that observations are needed to evaluate models, but it is also true that modeling studies often suggest new and interesting ways to use the observations. The growing synergism between modeling and observations of the Earth's radiation budget is probably the only way to endow model results with sufficient credibility for use in policy decisions.

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References

Cess, R.D., Potter, G.L., Blanchet, J.P., Boer, G., Ghan, S.J., Kiehl, J.T., Liang, X.-Z., Mitchell, J.F.B., Morcrette, J.-J., Randall, D.A., Riches, M.R., Roeckner, E., Schlese, U., Slingo, A., Taylor, K.E., Washington, W.M., Wetherald, R.T. and Yagai, I., 1989. Intercomparison and interpretation of cloud-climate feedback as produced by fourteen atmospheric general circulation models. Science, 245: 513–516.

Cess, R.D., Potter, G.L., Boer, G., Blanchet, J.P., Ghan, S.J., Taylor, K.E., Mitchell, J.F.B., Randall, D.A., Roeckner, E., Schlese, U., Schlesinger, M.E., Washington, W.M., Wetherald, R.T. and Yagai, I., 1990. Intercomparison and interpretation of climate feedback processes in ten atmospheric general circulation models. Geophys. Res., 95: 16601–16615.

Cess, R.D., Harrison, E.F., Minnis, P., Barkstrom, B.R., Ramanathan, V. and Kwon, T.Y., 1991. An interpretation of seasonal cloud-radiative forcing using Earth Radiation Budget Experiment data, in prep.

Cheng, M.-D. and Arakawa, A., 1990. Inclusion of convective downdrafts in the Arakawa–Schubert cumulus parameterization. Proc. Indo-US Seminar on Parameterization of Sub-Grid Scale Processes in Dynamical Models of Medium Range Prediction and Global Climate, 6–10 August, 1990, Pune, India. Indian Inst. Trop Meteorol., Pune.

Cox, S.K., McDougal, D.S., Randall, D.A., and Schiffer, R.A., 1987. FIRE – The first ISCCP regional experiment. Bull. Am. Meteorol. Soc., 68: 114–118.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R. and Lerner, J., 1984. Climate sensitivity: analysis of feedback mechanisms. In: J.E. Hansen and T. Takahashi (Editors), Climate Process and Climate Sensitivity, Maurice Ewing Series, 5. Am. Geophys. Union, pp. 130–163.

Lindzen, R.S., 1990. Some coolness concerning global warming. Bull. Am. Meteorol. Soc., 71: 288–299.

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

Randall, D.A., Harshvardhan, Dazlich, D.A. and Corsetti, T.G., 1989. Interactions among radiation, convection, and large-scale dynamics in a general circulation Model. J. Atmos. Sci., 46: 1943–1970.

Raval, A. and Ramanathan, V., 1989. Observational determination of the greenhouse effect. Nature, 342: 758–761.

Schlesinger, M.E. and Mitchell, J.F.B., 1987. Climate model simulations of the equilibrium climatic response to increased carbon dioxide. Rev. Geophys., 25: 760–798.

Stephens, G.L. and Greenwald, T.J., 1990. Observations of the earth's radiation budget in relation to atmospheric hydrology. Part 1. Clear sky greenhouse effect and water vapor feedback. Geophys. Res., 1990, submitted.

Warren, S.G., Hahn, C.J. and London, J., 1985. Simultaneous occurrence of different cloud types. J. Cli. Appl. Meteor., 24: 658–667.

Warren, S.G., Hahn, C.J., London, J., Chervin, R.M. and Jenne, R.L., 1986. Global distribution of total cloud cover and cloud type amounts over land. NCAR/TN-273 + STR, 29 pp., 199 maps.

Warren, S.G., Hahn, C.J., London, J., Chervin, R.M. and Jenne, R.L., 1988. Global distribution of total cloud cover and cloud type amounts over the ocean. NCAR/TN-317 + STR, 40 pp., 170 maps.