THE EFFECTS OF CLOUD RADIATIVE FORCING ON AN OCEAN-COVERED PLANET

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1. Introduction Cloud radiative forcing (CRF) may be defined as the difference between the radiative flux (at the top of the atmosphere, say) which actually occurs in the presence of clouds, and that which would occur if the clouds were removed but the atmospheric state were otherwise unchanged. The term CRF can also be used to denote warming or cooling tendencies due to cloud-radiation interactions.

The Colorado State University general circulation model (GCM) is being used to simulate the CRF. Like most current climate models, the CSU GCM does not include an interactive ocean. As a result, the simulated surface CRF acts only on the land surface. The model results show, however, that the surface CRF and the atmospheric CRF (hereafter, ACRF) have very different effects on the large-scale circulation.

In order to isolate the effects of the ACRF, we have simulated the general circulation of an ocean-covered earth, which we call "Seaworld." The key simplifications in Seaworld are the fixed boundary temperature with no land points, the lack of mountains, and the zonal uniformity of the boundary conditions.

2. Computational procedure The CSU GCM is derived from the UCLA GCM developed by A. Arakawa and collaborators. The main differences in the CSU model are revised parameterizations of terrestrial and solar radiation, which have been introduced in order to allow more satisfactory simulations of cloud-radiation interactions.

Three types of clouds are generated by the model: convective "anvil" clouds, supersaturation clouds, and boundary layer stratocumulus clouds. Cumulus convection is parameterized following the theory of Arakawa and Schubert (1974). Convective clouds are assumed to have negligible cloud fraction below 400 mb. If convection penetrates above 400 mb, however, an optically thick "anvil" cloud is assumed to horizontally fill the grid column, from 400 mb to the highest level reached by the convection. Supersaturation clouds are assumed to occur when the relative humidity equals or exceeds 100%, are assigned a cloud fraction of 1, and are assumed to vertically fill the GCM layer where they occur. Boundary-layer clouds can be arbitrarily thin; their cloud fraction is 1 when they are more than 12.5 mb deep, and decreases to zero linearly as their pressure thickness decreases from 12.5 mb to zero. The optical properties of the supersaturation and boundary-layer clouds are assumed to vary with cloud pressure-thickness and also with temperature, such that cold clouds are optically thinner than warm clouds of the same pressure-thickness. This crudely represents the "optical depth feedback". The clear-sky radiative fluxes have been saved as diagnostic results before cloud effects are accounted for; they are thus defined for all grid points, not just those that happen to be cloud-free.

The prescribed zonally uniform sea-surface temperatures of Seaworld are based on the simulated zonally averaged (including both land and sea) boundary temperature obtained in a July "Earth" simulation. For simplicity, an albedo appropriate to the oceans has been used everywhere; we have not included any effects of seaice.

The Seaworld simulations were initialized from the June 1 conditions of the Earth simulation, and all boundary conditions were instantaneously changed to those of Seaworld, except that the mountains were gradually flattened out over a period of two simulated days, to avoid extreme sloshing of the model atmosphere. We performed two 90-day "perpetual July" simulations, and analyzed the last 60 days of each. The first run included all of the model's physical parameterizations, while the second omitted the effects of clouds in both the solar and terrestrial radiation parameterizations. Since the boundary temperatures are fixed and identical in the two runs, the clouds can affect the results *only* through the ACRF; the differences between the two runs, therefore, reveal the direct and indirect effects of the ACRF on the large-scale circulation and the parameterized hydrologic processes.

3. Results The ACRF in the cloudy run corresponds very well to the radiative heating perturbation relative to the cloud-free run. Fig 1 shows the integral of the ACRF across the atmosphere in the cloudy run. This represents a warming of up to 70 W m^{-2} in the Northern Hemisphere tropics. Also shown in the figure are the change in the net radiation into the atmosphere (including both the earth's surface and the top of the atmosphere), and the change in the total energy flux into the atmosphere, from both radiation and turbulent sensible and latent heat fluxes. The change in the net radiation between the two runs essentially reflects the existence of ACRF in the cloudy run. The change in the total energy flux is similar to the change in the change in the net radiation, but the tropical peak is higher. The tropical atmosphere adjusts to the ACRF in such a way that *the warming due to the ACRF is amplified, i.e., there is a positive feedback.*

Fig. 2 shows the zonally averaged precipitable water for both runs. Interestingly, the clouds act to drastically increase the moisture content of the atmosphere. The cloudy run has much more precipitable water than the cloud-free run--almost twice as much in the tropics. This increased moisture has qualitatively the same effect on the atmospheric radiation balance as the ACRF: both tend to warm the atmosphere. The atmospheric moisture content of the cloudy Seaworld is much more earth-like than that of the cloud-free Seaworld, although of course it is not clear to what extent we should expect "Seaworld" to look like the earth.

The net effect of the ACRF is to warm the middle troposphere by up to 8 K at the 6 km level. The increased precipitable water content of the cloudy model atmosphere cannot be explained by assuming fixed relative humidity and taking into account the warmer temperatures. The actual reason for the increased moisture content of the cloudy atmosphere involves the large-scale motions, as discussed further below.

Fig. 3 shows the zonally averaged precipitation for both the clear and cloudy runs. There is a double tropical rain band in the cloud-free run, and a single, more intense tropical rain band in the cloudy run. Generally, the precipitation is much more concentrated in the cloudy run, and much more diffuse in the cloud-free run. The cloud-free run produces relatively weak but frequent convection, while the cloudy run produces relatively intense but infrequent convection. The globally averaged precipitation is about 15% greater in the cloudy run, which is a remarkably small change considering the large difference in the moisture content of the atmosphere. Tropical evaporation increases significantly in the cloudy run. The increased evaporation is partly due to the fact that the tropical PBL air is about 2 g kg^{-1} drier in the cloudy run, and partly due to a 3 m s^{-1} increase of the PBL wind speed in the cloudy run. The reason for the stronger winds is discussed further below.

Not surprisingly, the mean meridional circulation differs quite substantially between the two runs. As shown in Fig. 4, both runs produce two Hadley Cells--a weak cell in the Northern Hemisphere, and a strong one in the Southern Hemisphere. With clouds, the main Hadley Cell transports slightly more than 200 x 10^9 kg sec^{-1}, and is centered on the equator, with its rising branch at about 10 ° N. Without clouds, it transports only about 120 x 10^9 kg sec^{-1}, and is centered at about 10 ° south. The mean meridional circulation in the cloudy run is considerably more realistic than that in the cloud-free run.

In association with the stronger Hadley circulation in the cloudy run, the PBL wind speed increases by about 3 m s^{-1} in the tropics. This is partly responsible for the stronger surface evaporation. The increased surface latent heat flux in the cloudy run explains the "amplification" of the atmospheric warming due to the ACRF.

The cloudy run has more deep convective activity, concentrated in a narrow band near 15 ° N, where the intense Hadley Cell has its rising branch. The cloud-free run has two relatively weak convective heating maxima, near 10° S and 25° N. When ACRF is included, radiative cooling at the tops of avils leads to intense penetrative convection from the PBL, and it also promotes moist adjustment in the upper tropical troposphere. This intense convective activity leads to increased tropical precipitation. This drives a stronger Hadley circulation, further increasing the precipitation. The Northern Hemisphere circulation is selectively amplified because the sea surface temperatures are warmer there. The subsidence associated with the Northern Hemisphere Hadley Cell tends to suppress the Southern Hemisphere Hadley Cell and its associated precipitation. When ACRF is present, the system selects a relatively narrow but intense zone of latent heating.

Naturally, the zonal wind is strongly influenced by the changes discussed above. The ACRF increases the intensity of the tropical easterlies, particularly near the surface and the tropopause; and it also enhances the midlatitude westerly jets, shifting the Northern Hemisphere jet equatorward.

The PBL is considerably deeper in the cloudy run particularly near 10 ° N, where the cloudy run has strong low-level rising motion. Increased large-scale convergence favors an increased PBL depth in this region. A deeper PBL is also favored by the warmer troposphere in the cloudy run, which implies a weaker inversion at the PBL top; and by radiative cooling at the tops cf PBL stratus clouds, which promotes rapid entrainment.

As a result of the increased PBL depth, the precipitable water content of the PBL is much larger in the cloudy run, even though, as noted above, the PBL specific humidity is actually slightly smaller. Most of the simulated increase in the precipitable water occurs in the troposphere above the PBL, however. Moisture is introduced there by a two-step process. First, it is carried out of the PBL and injected into the troposphere by cumulus detrainment; the cumulus clouds transport moisture upwards even as they rain it out. It is then redistributed vertically, through advection by the rising branch of the Hadley Cell, and also by large-scale precipitation/re-evaporation.

The cloudy run has a strong maximum of cumulus detrainment that coincides precisely with a radiative cooling maximum due to cumulus anvil tops. The intense deep convection in the ITCZ of the cloudy run is promoted by radiative destabilization of the column. It is also favored by the increased strength of the Hadley circulation. The Hadley Cell is invigorated by the greater warming at 10° N, due to both ACRF and cumulus convection.

Of course, in the "cloud-free" run the clouds were radiatively inactive, but we saved their distribution as a diagnostic. The upper tropical troposphere is almost twice as cloudy in the "cloud-free" run as in the cloudy run. This is partly due to an increase in the relative humidity there, associated with cooler temperatures, but it is also due to the increased frequency of cumlus activity, which leads to greater anvil cloudiness.

The ACRF is the only difference between the model formulations used in the two Seaworld runs. The effects of ACRF on Seaworld's climate are dramatic, to say the least. By destabilizing the tropical atmosphere, and at the same time providing a net warming of the column, it favors both an enhanced Hadley circulation and deeper, more intense, but less widespread convection. The intensified convection further invigorates the Hadley circulation, and vice versa. The stronger surface winds associated with the more intense Hadley circulation lead to greater surface evaporation in the tropics, while the rising branch of the Hadley circulation dramatically moistens the free atmosphere. At the same time, the greatly reduced frequency of convection and the increased temperature of the tropical middle troposphere tend to reduce the cloudiness, especially at the upper levels, and so feedback on the ACRF.

The net effects of ACRF on the radiative-convective-dynamical system of Seaworld are to locally intensify deep cumulus convection, to reduce the cumulus incidence, to amplify the mean meridional circulation, and to dramatically increase the moisture content of the atmosphere, at the same time reducing the upper level cloudiness that is primarily responsible for the ACRF. All of this occurs without any major changes in the *globally averaged* precipitation or evaporation rates. These results illustrate a three-way regional interaction among the ACRF, the convection, and the large-scale dynamics. The feedbacks among the three components are strongly positive. At the same time, however, each of the three components feeds back negatively on itself: the ACRF warms the column and so tends to reduce the relative humidity; the convection increases the moist static stability of the column and so tends to shut itself off; and the large-scale circulation depletes its own source of available potential energy. These negative feedbacks determine how the system equilibrates.

8. Summary and concluding remarks Cumulus anvil clouds, whose importance has been emphasized by observationalists in recent years, exert a very powerful influence on deep tropical convection by tending to radiatively destabilize the troposphere. In addition, they radiatively warm the column in which they reside. Their strong influence on the simulated climate argues for a much more refined parameterization in the GCM.

For Seaworld, the ACRF has a powerful influence on such basic climate parameters as the strength of the Hadley circulation, the existence of a single narrow ITCZ, and the precipitable water content of the atmosphere. It seems likely, however, that in the real world the surface CRF feeds back negatively to suppress moist convection and the associated cloudiness, and so tends to counteract the effects of the ACRF. Many current climate models have fixed sea surface temperatures but variable land-surface temperatures. The tropical circulations of such models may experience a positive feedback due to ACRF over the oceans, and a negative or weak feedback due to surface CRF over the land. The overall effects of the CRF on the climate system can only be firmly established through much further analysis, which can benefit greatly from the use of a coupled ocean-atmosphere model.

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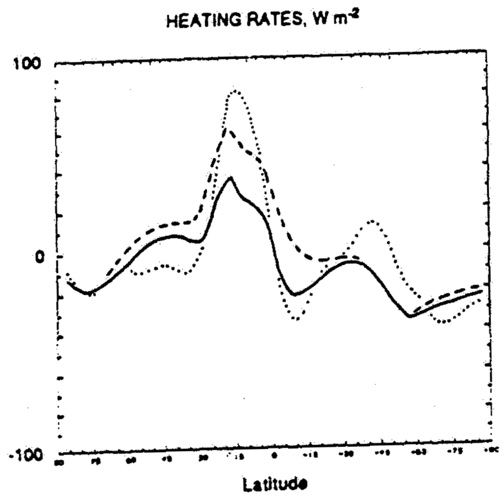

Figure 1 (left): *Differences* between the Seaworld runs with and without clouds. Solid line: The ACRF across the atmosphere. Dashed line: Net radiation into the atmosphere, including both the earth's surface and the top of the atmosphere. Dotted line: Total energy flux into the atmosphere, from both radiation and turbulent sensible and latent heat fluxes.

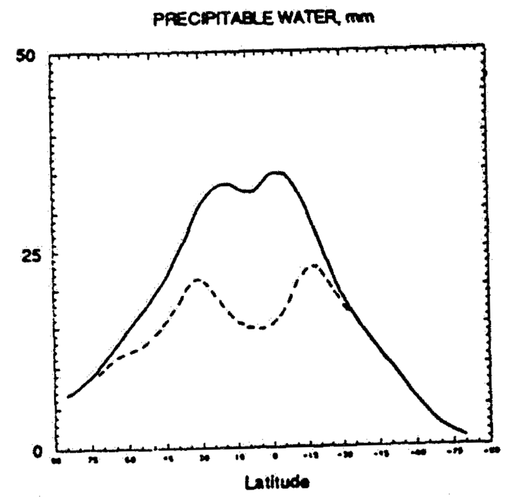

Figure 2 (right): Zonally averaged precipitable water for the cloudy run (solid line) and the cloud-free run (dashed line).

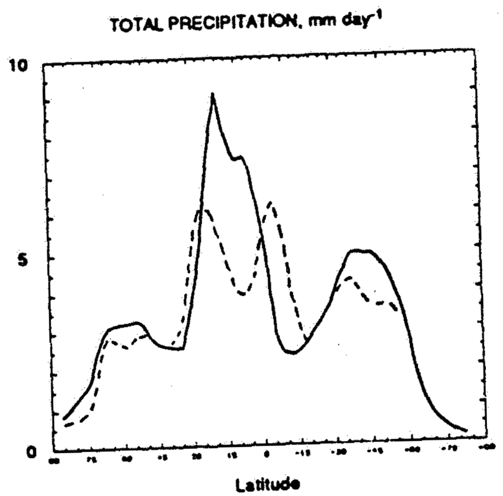

Figure 3: Zonally averaged precipitation for the cloudy run (solid line) and the cloud-free run (dashed line).

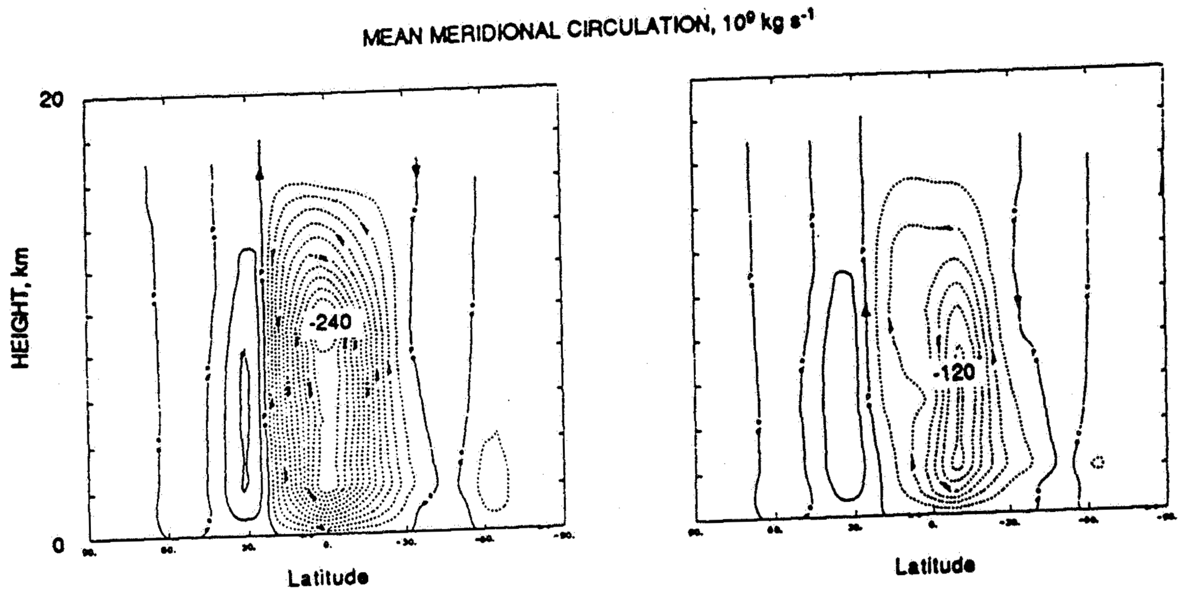

Figure 4: Mean meridional circulations for the cloudy run (left panel) and the cloud-free run (right panel).