Reply

D. L. HARTMANN, L. A. MOY, AND Q. FU

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

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In their critique of Hartmann et al. (2001, hereafter HMF), Chou and Lindzen (2002) begin by arguing that the top-of-atmosphere (TOA) net radiative effect of clouds in nonconvective regions of the Tropics is not small but is strongly negative. As evidence, they show the net radiation and cloud radiative forcing averaged from 10°S to 10°N and plotted as a function of longitude from 120°E to 100°W. They point out that the cloud radiative forcing near the equator becomes more negative than -10 W m^{-2} east of about 150°W and continues to get more negative as the coast of South America is approached. The equatorial tongue of cold SST associated with upwelling of the ocean extends from the coast of South America to about 150°W, and is associated with the occurrence of stratus cloud, which has a strongly negative cloud radiative forcing, as is well known (e.g., see chapter 3 of Hartmann 1994). These features can be clearly seen in Fig. 1 of HMF. When we say that the net radiative effect of the clouds in the ''nonconvective regions adjacent to convective regions'' is small, we are not referring to regions with boundary layer stratus over relatively cold SST. We are referring to the trade cumulus regions over the warmer waters of the Tropics and adjacent to the convective regions. In these regions, the net cloud forcing is small, as can be inferred from Fig. 1 in HMF, and as is discussed on the last paragraph of HMF (p. 4505).

Chou and Lindzen next assert that ''There is no evidence that albedo in the convective region increases with increasing vertical velocity. . . .'' At the outset we state the fact that the net radiative neutrality of tropical convective clouds is a property of the ensemble of clouds associated with convection. Our definition of the convective region includes not only the convective updraft, but also the region attached to it that includes the anvil cloud and cirrus. In the Tropics, precipitation is inversely correlated with OLR (Arkin and Meisner 1987), and OLR is inversely correlated with cloud albedo for spatial averages over areas of about 10^4 km^2 (Hartmann and Short 1980). If precipitation is correlated with mean vertical motion through latent heat release, then the evidence for a positive correlation between cloud albedo and mean vertical motion is clear. Within convective regions strong mesoscale updrafts and downdrafts exist, but since the net release of latent heat substantially exceeds the radiative cooling in this region, the mean motion is upward, and a circulation extending into the nonconvective region is implied. In nonconvective regions little latent heat release occurs above the boundary layer and radiative cooling is largely balanced by subsidence. This conceptualization is widespread in the literature and helps to explain the connection between tropical convection and associated circulations at scales larger than that of individual convective elements.

In the warm ocean regions of the Tropics, mean vertical motion, intense convection, and high albedos are well correlated in daily and monthly averages. We are not attempting to estimate the response to mean SST, but rather the response to SST gradients and associated circulations. Sea surface temperature, convection, and mean vertical motion are tightly coupled in the Tropics, both by thermodynamic and by large-scale dynamic processes. Because large-scale dynamics can suppress convection locally, some regions with high SST may be without convection. But latent heat release during convection usually supports mean upward motion in the Tropics, particularly since the radiative effect of convective clouds tends to reduce the vertically integrated radiative cooling above the boundary layer. So generally positive correlations exist among local maxima in SST, high convective cloud albedos, and mean upward motion in the midtroposphere, when appropriate averages are considered. We have applied the sense of these correlations to our heuristic model.

If we accept the above point of view, the relationship

Corresponding author address: Dr. Dennis L. Hartmann, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195-1640.
E-mail: dennis@atmos.washington.edu

among SST gradients, mean vertical motion, and the average albedo of clouds still may not be well approximated by a simple linear difference between seasonal mean climatologies for regions of mean upward motion and mean downward motion over the warm waters of the Tropics. Over the warm waters of the tropical ocean, where the atmosphere is always conditionally unstable, convection may be much more sensitive to small SST gradients and vertical velocity variations than is implied by large-scale climatological gradients. If such high sensitivities are relevant, then the feedback process we have proposed is much more efficient and could operate entirely within the region with the warmest SST. Under these conditions the assumption of uniform export from the convective and nonconvective regions also becomes increasingly robust.

The next significant question is whether it is acceptable to assume equality of the export terms in the energy balance equations for the convective and nonconvective regions. If we consider that both the convective and nonconvective regions are over the warm waters of the tropical west Pacific, then this assumption may be a good one. Zonal gradients in both TOA net radiation and ocean export are weak there. Meridional gradients of annual mean TOA net radiation are forced by the meridional gradient of insolation, but tend to be offset almost exactly by meridional gradients of ocean export in the west Pacific. So, in fact, the net atmospheric energy export is very nearly uniform in the warm pool region. In going from the equator to 20°N the net radiation goes from about 80 to about 40 W m^{-2}. The flux of energy into the ocean is more uncertain, but goes from about 40 W m^{-2} into the ocean near the equator to about 0 W m^{-2} at 20°N (Trenberth et al. 2001). Thus the meridional gradients in TOA net radiation and surface net flux tend to cancel each other. This gives an estimate of the atmospheric export term in the warm pool area that is nearly spatially invariant. In our model we neglect both the meridional gradient of net radiation and the meridional gradient of ocean heat export, since they approximately cancel, and seek a model for the local anomaly in net radiation caused by convection. This is equivalent to placing the convective and nonconvective regions of our model along a latitude circle in the warm Tropics, where the heat flux into the ocean and the atmospheric export would be the same in both regions. There is nothing inconsistent about these assumptions. If we make them the feedback we have hypothesized maintains the uniformity of net radiation in the presence of strong but compensating longwave and shortwave cloud forcing. The balance of longwave and shortwave cloud forcing is robust if the cloud albedo is sensitive to small spatial gradients of SST and associated mean vertical motion.

As we note in HMF, in the east Pacific ITCZ these conditions do not apply because the atmospheric export does vary spatially there. East of 130°W more than 100 W m^{-2} goes into the cool ocean in a narrow belt near the equator and the meridional gradient of TOA net radiation cannot compensate. Under these conditions, our heuristic model predicts that if the convective clouds along the east Pacific ITCZ are coupled to the equatorial region in the east Pacific, then their net radiative effect should be negative. This is indeed what is observed.

While our heuristic model is highly simplified, it is able to be so because the mechanism it employs is very simple and robust. It represents a viable explanation for why tropical convective clouds over the warmest waters of the Tropics tend to have a very small net effect on the local radiation balance at the top of the atmosphere. An explanation for this robust observation is needed, and may have significant implications for climate sensitivity.

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