Reply

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The criticisms which Bin Wang directs to Emanuel (1987) apply equally to the same mechanism proposed simultaneously by Neelin et al. (1987, NHC hereafter). It therefore seems appropriate to add a brief extension to Kerry Emanuel's response, with which I concur.

NHC show that this mechanism, which they refer to as the "evaporation-wind feedback," is extremely important to the Madden–Julian wave in the GFDL climate group GCM when zonally symmetric fixed sea surface temperature (SST) boundary conditions are used. It is also shown that a secondary mechanism exists in the GCM for producing such variability and that this mechanism can be brought into evidence by use of a zero heat capacity, moist lower boundary ("swamp"). Lau et al. (1988, LHN hereafter) find the Kelvin-wave CISK hypothesis to be consistent with this second mechanism, using basic state temperature and moisture profiles and perturbation heating structure derived from the GCM. As pointed out by Emanuel, Wang's calculation based on the LHN composites (his Fig. 3) provides no further evidence for or against either the CISK or the evaporation–wind feedback hypothesis.

To respond to Wang's concern with respect to the possible effect of regions of low-level westerlies on the evaporation–wind feedback, Fig. 1 shows composites of the Madden–Julian wave from an integration of the same GCM but with standard continental geography and observed SST lower boundary conditions. These composites were kindly provided by Thomas Knutson (personal communication, 1988) and were prepared following the procedure of Knutson and Weickman (1987) using empirical orthogonal function analysis of the 200 mb velocity potential to define the phase of the oscillations. The climatology of the low-level wind field may be found in Lau (1985). The Indian Ocean region does not have as strong a signature of westerlies along the equator during the summer monsoon as in Wang's Fig. 1, but certainly the linearization of the wind speed on which the evaporation–wind feedback is based is invalid in this region during all seasons, as Wang suggests.

The composites show the oscillation in four phases of the cycle. The large-scale low-level convergence is centered at about 100°E, 160°E, 120°W and 0°, respectively, in the four phases. Associated with this predominantly wavenumber 1 convergence pattern are the low-level, primarily zonal winds shown in the figure, consistent with the $v = 0$ solution of a mixed Kelvin wave CISK–evaporation-wind feedback mode. The point to be noted is that, indeed, over the Indian Ocean the wind anomalies do not produce significant evaporation anomalies via the evaporation-wind feedback. However the wind anomalies over the Pacific do produce the predicted evaporation anomalies and these are in the correct phase to stoke the disturbance as it passes over Indonesia. Because of the large-scale nature of the wave, the lack of evaporation-wind feedback over the Indian Ocean does not appear to be of crucial importance. Note that on smaller scales, the correlation between zonal wind and evaporation anomalies is imperfect even in regions of mean easterlies.

Although the nature of the oscillation in the GCM with realistic boundary conditions appears similar to that in the zonally symmetric case (Lau and Lau 1986, compared to LHN), little can be deduced about the dynamics of the wave by its structure alone. Comparison of the LHN composites of the wave for the zonally symmetric fixed SST case, in which the evaporation-wind feedback has been shown to be important, to unpublished composites from the "swamp" case, in which it is hypothesized that CISK is responsible for the wave, shows little difference in structure. The differences between the two mechanisms occur in very subtle dynamic quantities which are difficult to observe, even in a GCM. For instance, the difference between the latent heating and adiabatic cooling can be calculated from the composite perturbation, in an attempt to evaluate the CISK hypothesis. This small difference between large quantities proves to be noisy and sensitive to details of the method of calculation, making it difficult to draw reliable conclusions from it. The evaporation-wind feedback mechanism can be reliably

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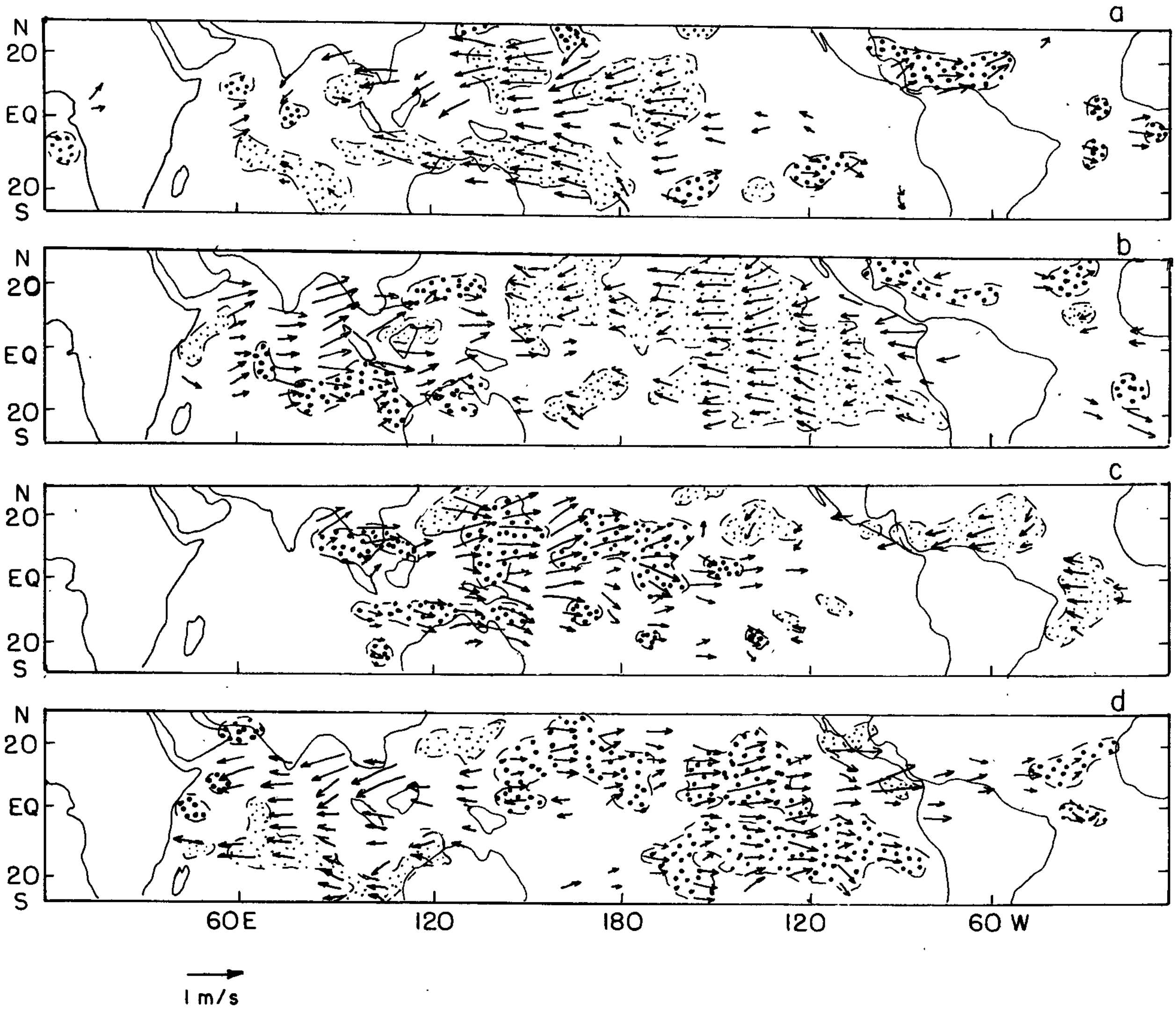

FIG. 1. Evaporation and 950 mb wind anomalies from a composite of the Madden–Julian wave in the GFDL GCM. Four roughly equally spaced phases of the cycle are shown. Light stippling indicates evaporation anomalies greater than 0.1 mm day^{-1} and dark stippling those less than −0.1 mm day^{-1}. After figures provided by Thomas Knutson (personal communication, 1988).

tested in a GCM because it can be directly suppressed without influencing the climatology, as in NHC. This test could be repeated in a GCM with realistic climatology if it were deemed worthwhile. Devising an equally rigorous test for CISK seems, unfortunately, to present insurmountable difficulties, even in the GCM, because of the strong dependency of the climatology on convective processes.

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