Some Implications of the Mesoscale Circulations in Tropical Cloud Clusters for Large-Scale Dynamics and Climate[1]

DENNIS L. HARTMANN, HARRY H. HENDON AND ROBERT A. HOUZE, JR.

Department of Atmospheric Sciences, AK-40, University of Washington, Seattle, WA 98195

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ABSTRACT

Recent calculations suggest that mature cloud clusters produce a vertical distribution of diabatic heating with a sharp maximum near 400 mb and very weak heating below 600 mb. It is demonstrated that when such a vertical distribution of heating is applied to a linear steady-state model it results in simulated tropical east-west circulations which are in much better agreement with observations than those which are produced with a more conventional heating profile. In particular, the mature cloud cluster heating profile produces a Walker Circulation with its centers at the observed altitudes and with the observed westward tilt with height. It is suggested that the mature cloud cluster heating profile may provide the appropriate vertical distribution of tropical diabatic heating in many cases, since the presence or absence of mature cloud clusters is often the proximate cause of heating variations in the tropical atmosphere. Some further implications of this suggestion for large-scale dynamics and climate are discussed.

1. Introduction

One of the most central and difficult problems in the theory of climate is the proper treatment of the interactions among moist convection, radiative transfer and large-scale dynamics in the atmosphere. Because of the complexity of the processes taking place in each of these areas and the large difference in the spatial scales of moist convection and large-scale dynamics, even a numerical approach to the complete interaction problem has not been attempted. In large-scale climate modeling it is necessary to simplify the treatment of radiative transfer and to parameterize the moist convection in terms of the large-scale variables in order to obtain a practical model. Even the most sophisticated schemes for the parameterization of convection, which attempt to take into account the effect of the small-scale circulations associated with moist convection, begin with conceptualizations of moist convection which are rather simple compared to the complex structures observed in the atmosphere.

Recently Houze (1982) has provided an assessment of the net heating of the atmosphere produced by a mature tropical cloud cluster. Cloud clusters produce a large fraction of the precipitation in the tropics. Typically, a cloud cluster consists of cumulonimbus towers organized into mesoscale lines or groups, and an extensive mid-to-upper-tropospheric stratiform cloud deck connecting the mesoscale groups of cumulo-

nimbus. The top of this extensive cloud deck covers the whole cluster and appears in satellite imagery as a broad continuous cloud shield. A broad, gentle mesoscale updraft driven by condensational heating exists within the cloud deck. Precipitation falls from the stratiform cloud and a lower-tropospheric mesoscale downdraft is driven by melting and evaporation of the stratiform precipitation below the base of the cloud deck. Houze showed that the latent and radiative heating associated with the stratiform cloud deck are comparable in magnitude to the heating associated with the cumulus towers. Moreover, the vertical distribution of the heating associated with the upper level stratiform cloud is such that it augments the tower heating at upper levels (due to condensational and radiative heating) and counteracts the tower heating in the lower troposphere (a result of cooling by melting and evaporation).

Fig. 1 presents a schematic representation of the shapes of the heating profiles assuming that the heating is produced by convective towers alone (the conventional profile, CP) and assuming that the total heating is produced by the combination of convective tower heating and stratiform cloud heating typical of a mature tropical cloud cluster (the mature cluster profile, MC). These profiles are idealized adaptations from Fig. 12 of Houze (1982). Note that for the mature cluster profile there is almost no heating below 4 km and the heating in the upper troposphere is greatly enhanced over that produced by the convective towers alone. The contrast between the conventional heating profile and the profile obtained by Houze for mature cloud clusters is significant, since the implications of the two
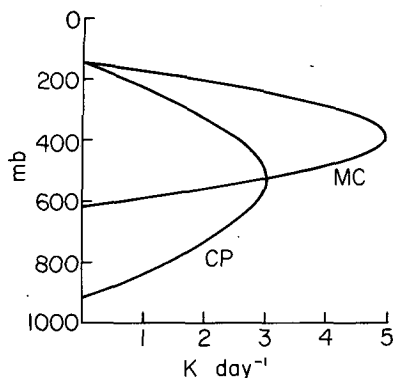

FIG. 1. Vertical profiles of the idealized heating distributions for the convective plume or conventional profile (CP) and the mature cloud cluster profile (MC).

profiles for large-scale dynamics and climate are quite different. As Houze (1982) pointed out, since heating in the tropics is balanced to first order by large-scale vertical motion, the heating profile for a mature cluster requires strong large-scale convergence in the mid-troposphere and stronger vertical velocities in the upper troposphere than the conventional profile, which requires significant convergence in the lower troposphere and a vertical velocity profile which is centered more in the mid-troposphere.

In this paper we will examine more quantitatively the differences in the large-scale response to the two heating profiles shown in Fig. 1. This will allow an assessment of the potential importance of heating associated with mesoscale cloud decks for large-scale dynamics. As the vehicle for this comparison, we will employ a linear, steady-state model of a phenomenon for which diabatic heating associated with moist convection in the tropics is known to be important. This is the Walker Circulation of the tropical Pacific. The Walker Circulation and associated east–west circulations in the equatorial atmosphere are discussed in Section 2. The model to be used is described briefly in Section 3. The effect of the two heating profiles in forcing stationary equatorially trapped waves is described in Section 4 for isolated heat sources and in Section 5 for a more realistic horizontal distribution of heat sources. A summary and further discussion are provided in Section 6.

2. Stationary equatorial planetary waves: The Walker Circulation

The convective heating in the tropics is not zonally uniform, but tends to occur preferentially in three regions of active convection. These are over the Indonesian maritime continent, over equatorial Africa, and over tropical South America. Local concentrations of convective heating give rise to east–west circulations in the equatorial plane (e.g., Krishnamurti et al., 1973).

The best developed and best known of these is the Walker Circulation, which has a rising branch over the most intense of the convection zones in the tropics, that centered near the Indonesian maritime continent (near 135°E). Subsidence occurs both to the east and west of Indonesia, but the circulation over the Pacific Ocean with a broad region of subsidence, low-level easterlies, and upper level westerlies is most closely associated with the name Walker Circulation. The east–west circulations are illustrated in Fig. 2 which was adapted from Newell et al. (1974). Fig. 2 displays contours of the so-called zonal mass flux

$$M_z(p) \equiv \frac{a\Delta\phi}{g} \int_{p_0}^{p} \bar{u}^* dp,$$

where $\bar{u}^*$ is the deviation of the time-mean zonal velocity from its zonal average, a the radius of the earth, g the gravitational acceleration, and $\Delta\phi$ an increment of latitude (corresponding to 10° in the case of Fig. 2). The zonal mass flux is not a true streamfunction, and the zonal gradients of it cannot be taken to accurately represent the vertical velocity. Newell et al. (1974) suggest, however, that there is a qualitative correspondence between vertical velocity and zonal gradients of M_z. The zonal mass flux contours become increasingly representative of a true streamfunction as $\Delta\phi$ is increased and the influence of the divergence of the meridional wind on the zonal mass flux becomes small.

The example from Newell et al. (1974) shown in Fig. 2 is for the December 1962–February 1963 period during which the Walker Circulation was particularly well developed. In Fig. 3 we show the zonal mass flux along the equator derived from the 15-year (May 1958–April 1973) climatological zonal winds for the December–February season. The data set and analysis are described in Oort and Rasmusson (1971) and Oort (1983). The long-term average in Fig. 3 and the example for 1962–63 shown in Fig. 2 are qualitatively similar, although the 1962–63 winter had stronger overturning cells than the long-term mean. The 1963–
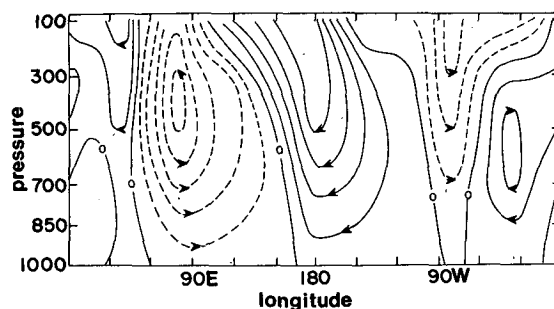

FIG. 2. Contours of the observed zonal mass flux along a 10° wide strip centered on the equator for the December 1962–February 1963 period adapted from Newell et al. (1974). The contour interval is 5 × 10⁹ kg s⁻¹; negative contours are dashed.
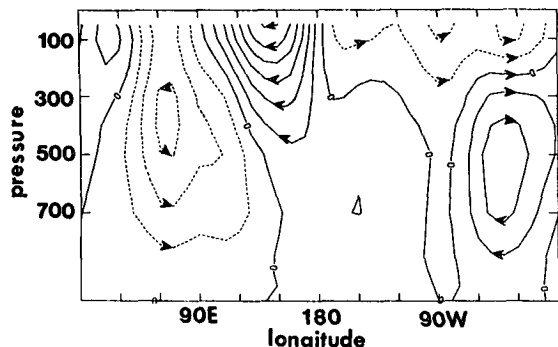
FIG. 3. Contours of the observed zonal mass flux along a 10° wide strip centered on the equator for the December–February season average over the 15 winters between 1958 and 1973. The contour interval is the same as in Fig. 2. Data provided by A. H. Oort.

64 example shown in Newell et al. (1974) (not reproduced here) is much closer to the long-term mean shown in Fig. 3.

The east–west circulations along the equator are coupled with the equatorial ocean currents and sea-surface temperatures. They exhibit a rather large interannual variability (e.g., Pan and Oort, 1983), which has important implications for tropical fisheries in addition to its implications for the climate of the land areas in the tropics. The interannual variability of the east–west circulations in the tropics appears to be associated with equally important interannual variability in the extratropics (e.g., Bjerknes, 1969: Horel and Wallace, 1981: Pan and Oort, 1983). A complete understanding of the nature of these circulations and their variability would be of great value.

A number of theoretical and modeling studies of tropical east–west circulations have been reported. Webster (1972) studied the tropical response to heating in a two-layer model. Gill (1980) used an analytical treatment to show how the horizontal structure of the Walker Circulation could be understood in terms of forced, stationary, equatorially trapped waves. Geisler (1981) confirmed this interpretation and used a linear three-dimensional steady-state model to simulate successfully many of the observed properties of the Walker Circulation. One problem Geisler experienced was that he was unable to obtain an east–west circulation whose center was as high as that observed. Figs. 2 and 3 suggest a center (level of zero zonal wind) for the circulation at ~400 mb. With the heating functions he was using, which resembled the conventional profile in Fig. 1, Geisler was unable to get the center of the circulation to rise above 500 mb, and the zonal winds in the lowest 3 km of the atmosphere were larger than observed, even in the presence of a substantial surface drag. In this paper we will show that an elevated heating profile such as that associated with mature tropical cloud clusters can alleviate these problems with linear simulations.

Since it is obvious at this point that the mature cluster heating profile is going to help move the center of the simulated Walker Circulation upward in the atmosphere and reduce the low-level zonal winds, it is worth considering briefly why the mature cluster profile might be more appropriate for the problem at hand. The rising motion in the Walker cell is driven by enhanced diabatic heating in the Indonesian region, where the diabatic heating substantially exceeds the zonal average diabatic heating, and the sinking takes place where the diabatic heating is less than the zonal average. Thus the forcing function to be applied in this linear calculation is the deviation of the diabatic heating from its zonal average. An assumption often made is that the deviation from the zonal average has the same vertical distribution as the zonal mean heating itself. This is the assumption being made when the conventional profile, which resembles the vertical distribution of the zonal-mean diabatic heating (Hantel and Baader, 1978), is employed in a linear model of the Walker Circulation. One could argue, perhaps equally well, that the mature cloud cluster profile is the appropriate one to use, since what produces the enhanced heating over Indonesia is in fact a greater occurrence of well-developed cloud clusters than in the zonal mean. Certainly the observed structure of the Walker Circulation suggests that the latter is a workable hypothesis, insofar as the observed circulation seems to require a heating profile like that of a mature cluster, as we shall soon confirm.

3. The model

The model to be used in this study is a steady-state primitive equation model linearized about a zonal-mean basic state. A detailed description of the model and its use is given in Hendon and Hartmann (1982). In the experiments described here the model domain is centered on the equator and a meridional grid spacing of 4° of latitude is used. The linear responses of zonal wavenumbers 1–5 are calculated and combined. The boundary conditions are vanishing perturbation geopotential at the northern and southern boundaries and vanishing vertical velocity at the top and bottom of the model. The 12 pressure levels used, together with the assumed temperature profile are given in Table 1. Rayleigh friction and Newtonian cooling with equal coefficients provide damping. A motionless basic state is assumed in all of the calculations presented here.

The two idealized heating profiles shown in Fig. 1 are used to prescribe the vertical distribution of heating. The analytic forms of these profiles are given by

$$Q_{CP} = \sin[(920 - p)\pi/770], \quad 150 < p < 920$$
$$Q_{MC} = \sin[(625 - p)\pi/475], \quad 150 < p < 625 \Big\},$$

where the pressure p is given in millibars and Q_{CP} and Q_{MC} are dimensionless shape functions for the con-

TABLE 1. Pressures and basic state temperatures
for the 12 model levels.

Level	Pressure	Temperature
12	0.	223
11	70.	223
10	152.	223
9	239.	243
8	329.	258
7	421.	260
6	516.	268
5	613.	275
4	711.	282
3	810.	288
2	911.	293
1	1013.	298

ventional profile and the mature cluster profile, respectively. In both cases the total heating in the atmospheric column is set equivalent to 3.6 m per year of precipitation at the location of the maximum heating. This yields the maximum heating rates of 3K day^{-1} at 535 mb for the conventional profile and 5K day^{-1} at 387 mb for the mature cluster profile indicated in Fig. 1. The two profiles presented in Fig. 1 represent extreme cases. It is possible that neither of these is an accurate representation of the true heating profile. Indeed, a unique tropical heating profile, applicable to all cases, probably does not exist. It is our intention merely to examine the responses to these different profiles and compare the responses with the available observations.

4. Single-source experiments

In order to illustrate certain features of the forced equatorial response we will first consider cases where the horizontal distribution of the heating is particularly simple. The model is forced by prescribing a localized source of heat with a horizontal structure which varies as cosine-squared in an ellipse of major axis 60° of longitude and minor axis 30° of latitude. When centered on the equator the heating extends from 15°S to 15°N with half-amplitude points at 7.5°N and 7.5°S. In the figures which follow, this localized source is centered on the equator at 180° longitude. The apparent structure of the response is sensitive to the amount of dissipation present. Gill (1980) showed that the response of the gravest vertical mode was an east-west asymmetry of the horizontal structure with a weak circulation of broad longitudinal extent to the east and a narrower but more intense circulation to the west. The asymmetry is related to the greater propagation speed of the eastward moving Kelvin wave than the westward propagating Rossby–gravity wave. In Gill's infinite β-plane this asymmetry appears for any value of the dissipation. In the atmosphere, however, this asymmetry only appears clearly when the dissipation is strong enough to prevent the Kelvin wave from propagating all the way around the equator and interfering with itself and the Rossby-gravity wave. Figs. 4 and 5 show the responses in the upper and lower troposphere for damping times of 15 and 2.5 days, respectively. The conventional heating profile (CP) was used to force these responses. The upper (329 mb) and
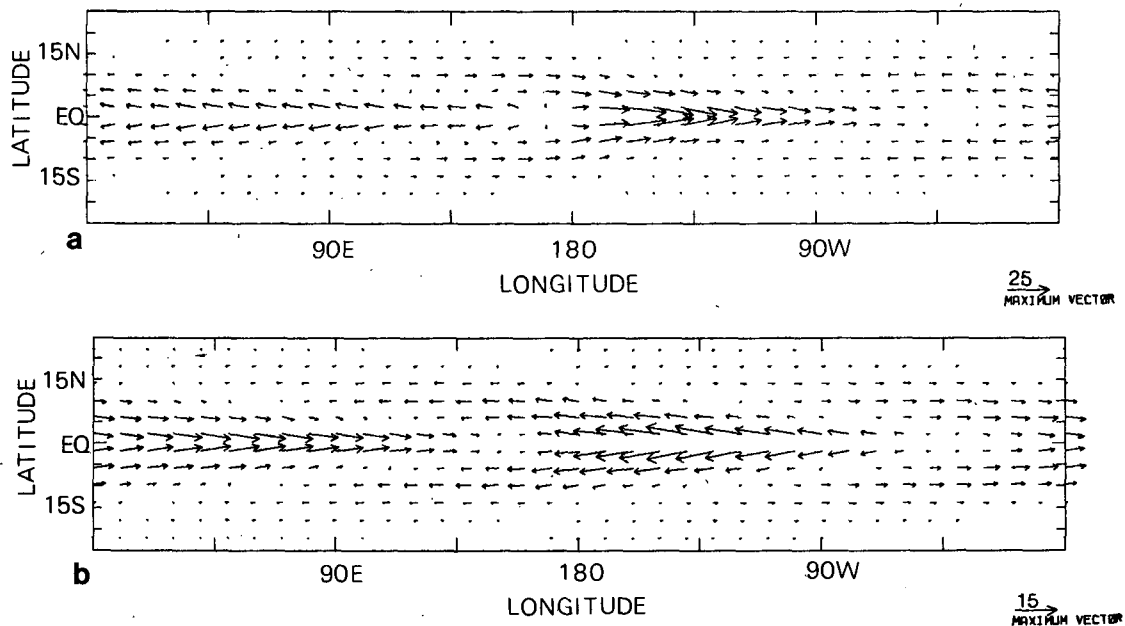

FIG. 4. Wind vectors at the (a) 329 mb and (b) 911 mb levels for an isolated heat source centered in the equator at the dateline (180°). The conventional profile (CP) and a damping time of 15 days for both temperature and wind has been used. The vectors are scaled in m s^{-1} according to the scaling vector to the lower right of the figure.
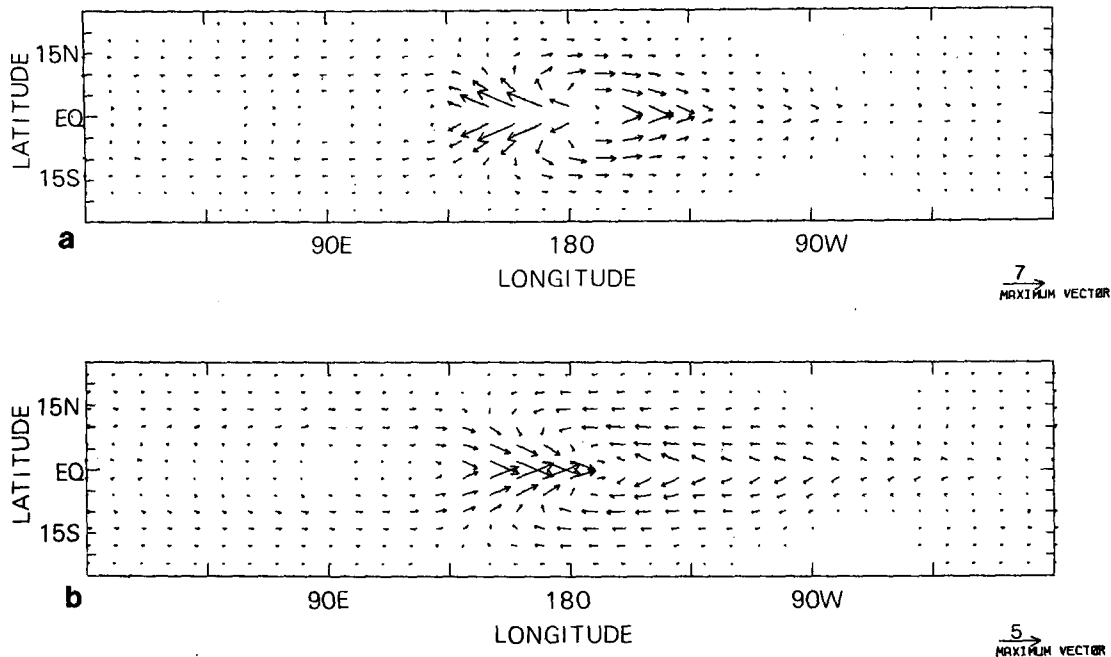
FIG. 5. As in Fig. 4 except for a damping time of 2.5 days.

lower (911 mb) wind vectors are nearly opposites of each other except for a modest growth of the velocities with altitude.

When the damping is weak (Fig. 4) the eastward and westward propagating waves can extend around the circumference of the equator and interfere with each other. Under such conditions the asymmetry inherent in the wave dynamics may not be apparent in the response. In fact, a reversal of the asymmetry may result, as it does, weakly, in Fig. 4. When the damping is sufficiently strong (Fig. 5) the waves die out before propagating very far and the asymmetry appears essentially as it does in a zonally infinite domain. For the extreme damping of Fig. 5 the equatorial response of the westward propagating wave does not extend much beyond the region of forcing. How great the effective damping in the real atmosphere is remains a matter of question. In the atmosphere transience and nonlinearity may produce the effects which in this linear, steady-state model are represented by simple linear damping.

The sensitivity of the response to the vertical structure of the heating is illustrated for the case of a single isolated heat source in Fig. 6. Fig. 6a shows the zonal mass flux for the response to an isolated heat source with a damping time of 2.5 days. This is the same case as that shown in Fig. 4. The response for the mature cluster profile under the same conditions is shown in Fig. 6b. The mature cluster heating profile produces a zonal overturning cell with its center at ~400 mb, compared to about 500 mb for the conventional profile. The zonal winds are stronger in the upper troposphere
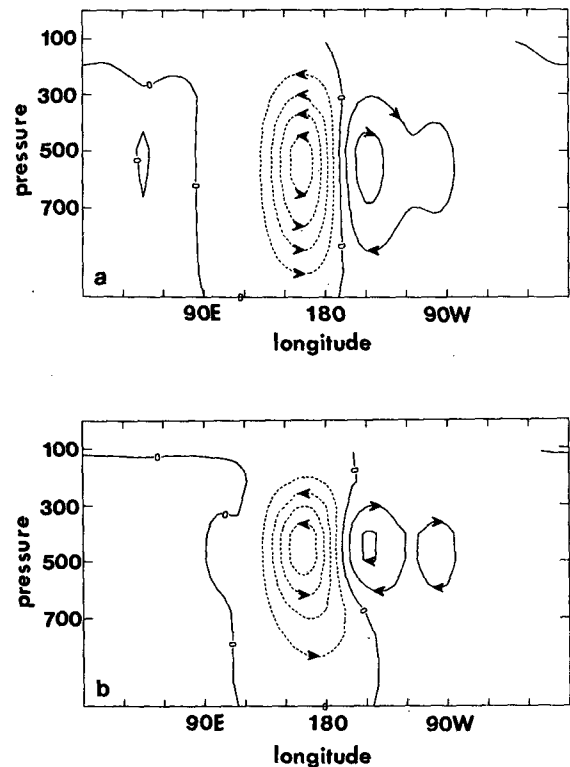

FIG. 6. Zonal mass flux of the linear response to an isolated heat source on the equator at the dateline with a damping time of 2.5 days and (a) the CP heating profile (same case as Fig. 5) and (b) the MC heating profile. The mass flux is calculated for a 12° wide latitude strip centered on the equator. The contour interval is the same as in Fig. 2.

and weaker in the lower troposphere when the mature cluster profile is substituted for the conventional profile. The raised center of the zonal overturning circulation forced by the MC profile is closer to the observed level of about 400 mb shown in Figs. 2 and 3. The CP profile produces an overturning cell whose center is too low.

5. Realistic horizontal distribution of heating

In this section the response to multiple heat sources will be investigated. In order to synthesize a horizontal distribution of heat sources which is similar to reality, we have used the fact that outgoing longwave radiation at the top of the atmosphere is negatively correlated with precipitation, particularly when averaged over space and time (e.g., Griffith *et al.*, 1978: Richards and Arkin, 1981). We have taken the outgoing long-wave radiation for the December–February season from Liebmann and Hartmann (1982) and removed the zonal average. The resulting field was then multiplied by the fourth power of the cosine of latitude in order to deemphasize features away from the equator. This cosine to the fourth weighting has little effect on the equatorial response. The resulting field was then multiplied by −1 and scaled so that the maximum heating corresponded to the maximum heating in the isolated source experiments described previously. The maximum heating was adjusted so that the CP and MC profiles gave the same mass-integrated heating rate. The shape of the resulting heating distribution is illustrated in Fig. 7, which shows the heating rate in Kelvins per day at the level of maximum heating for the MC profile.

The horizontal distribution of heating shown in Fig. 7 was applied with the two vertical distribution functions shown in Fig. 1. The resulting zonal mass flux
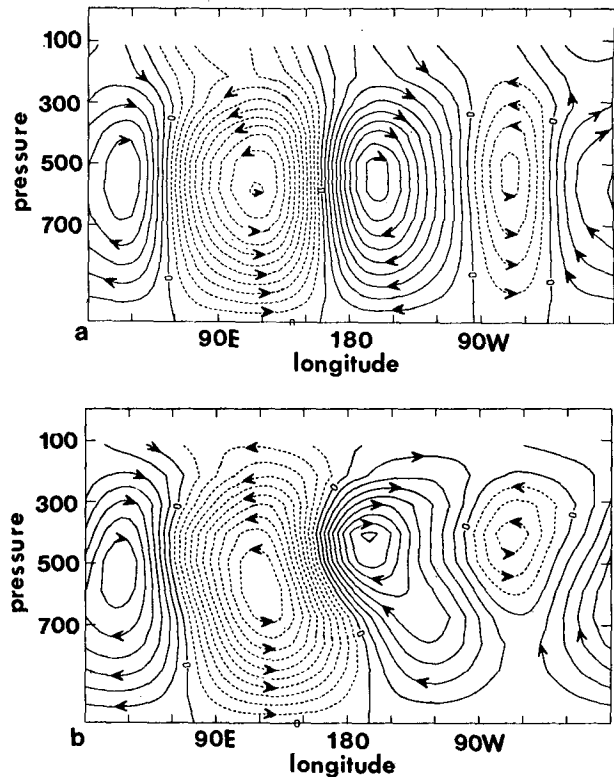

FIG. 8. Zonal mass flux associated with the linear response to the horizontal heating distribution in Fig. 7 with a 5-day damping time for (a) the CP heating profile and (b) the MC heating profile. The contour interval is the same as in Fig. 2.

cross sections for the 12° wide latitude belt centered on the equator are shown in Fig. 8. Rayleigh friction and Newtonian cooling with damping time scales of
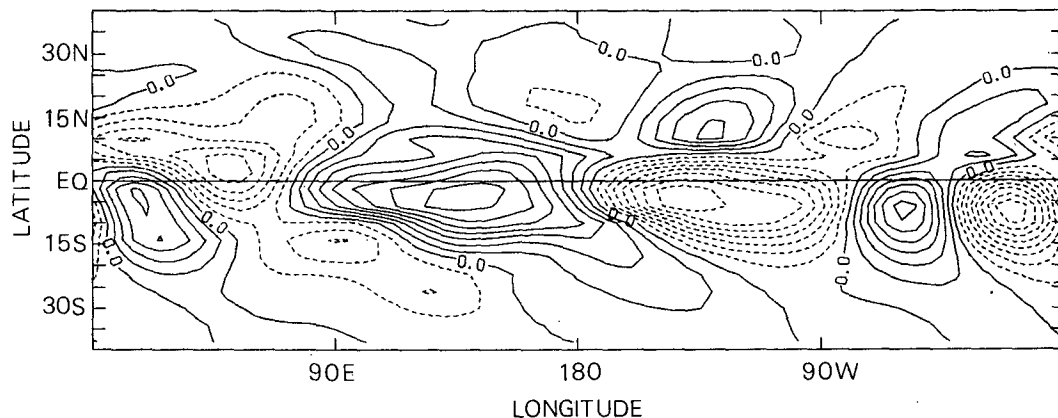

FIG. 7. Contours of the synthetic horizontal heating distribution of heating based upon climatological December–February values of the outgoing flux at the top of the atmosphere. See text for explanation. The quantity contoured here is the heating rate (K day⁻¹) for the MC profile at the level of maximum heating. The contour interval is 0.5 K day⁻¹ and negative contours are dashed.

5 days were used in these experiments. The centers of the zonal overturning cells are too far west and too intense compared to the observations in Figs. 2 and 3. A quantitatively accurate simulation of the observed equatorial east–west circulations is not the goal of this investigation. Nonetheless, if we concentrate on the differences between Figs. 8a and 8b, we can see that the elevated mature cluster heating profile improves the simulation of the observed circulation in at least two important respects. First, the averge altitude of the centers of the overturning cells is raised from below 500 mb to above 500 mb. Second, the MC profile produces the observed westward tilt with height of the major pair of cells centered near the dateline and the observed asymmetry in the heights of the centers of the cells to the east and west of the major convection zone over Indonesia. Some minor features such as the weakness near the surface of the negative cell west of South America (near 80°W) are also improved when an elevated heating profile is employed.

The westward tilt with height in the lower troposphere of the simulated Walker Cell is a reflection of a downward flux of wave activity. The vertical component of the Eliassen-Palm flux for a pure Kelvin wave is proportional to the upward flux of zonal momentum, i.e.,

$$F_z \simeq \overline{u'w'}.$$

The westward tilt with height of the simulated zonal mass flux contours results directly from the fact that the perturbations are forced in the upper troposphere and propagate downward toward the surface. That the

observed Walker Cell also exhibits this tilt may be an indication that the primary drive for the Walker Circulation is at upper levels. If this is the case, then tropical cloud clusters and associated upper level cloud can provide the physical mechanism for elevating the diabatic heating distribution.

The velocity vectors at 329 mb for the same two cases as in Fig. 8 are shown in Fig. 9. These are similar to each other and, near the equator, are in broad agreement with observations. Zonal flow away from the major heating zone west of the dateline is evident.

6. Summary and discussion

Recent calculations by Houze (1982) have shown that there is a fundamental difference between the vertical distribution of the diabatic heating provided by isolated convective towers and that provided by a mature cloud cluster. The difference is due to the extended cloud deck connecting the active cumulonimbus of a cloud cluster. This deck is thermodynamically and dynamically active, and the heating associated with it reinforces the heating of the convective towers at upper levels and offsets the heating at lower levels. The net result is a heating profile for the mature cluster which has very little heating below 600 mb and greater than average heating above. According to the estimates of Houze (1982), radiative heating at upper levels is smaller than the latent heating in convectively active upper-level cloud decks. Nonetheless, absorption of longwave radiation by cloud particles and droplets may
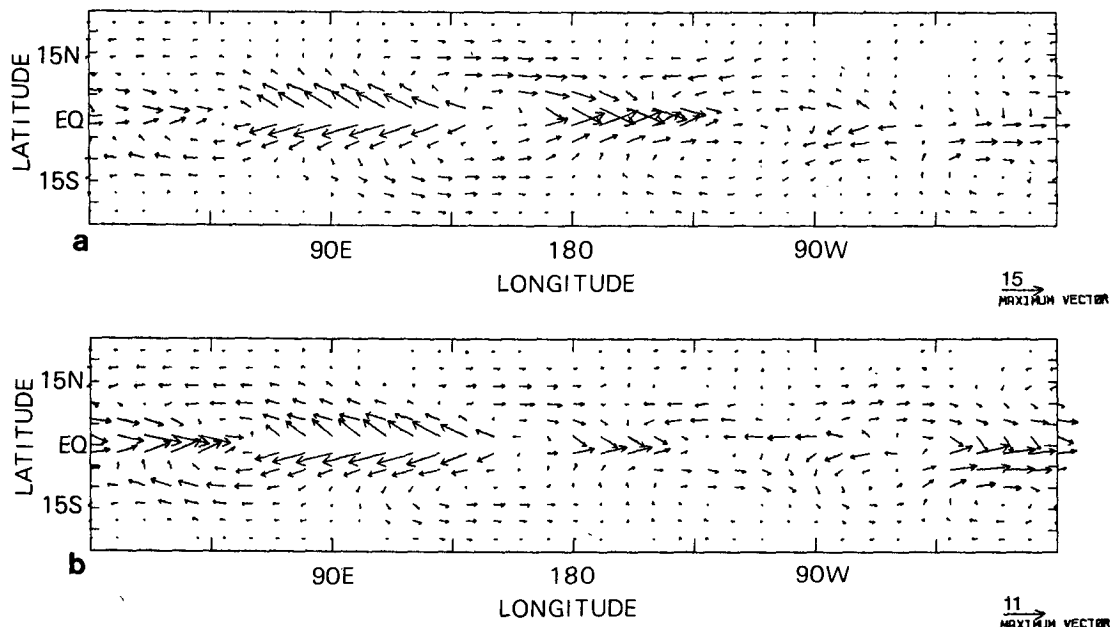

FIG. 9. Velocity vectors at the 329 mb level for the conditions of Fig. 8: (a) CP profile, (b) MC profile.

become the dominant upper-level heat source when active convection ceases. Organized deep convection in the tropics serves as a source of upper-level cloud which may continue to heat the upper troposphere by absorption of longwave radiation long after active deep convection has ceased.

In this paper, we have illustrated the implications of this altered heating profile for large-scale dynamics by contrasting the dynamical response produced by the mature cluster heating profile to that produced by a profile more like those conventionally assumed. It has been argued that perhaps the mature cluster profile is the appropriate one to use for perturbation studies, because it is usually the presence or absence of mature cloud clusters which is the proximate cause of large-scale thermal forcing changes in the tropics.

The assertion that the mature cloud cluster profile may be the applicable one for perturbation studies is supported by the result that it produces more realistic results than does a conventional heating profile when applied to a linear model of the Walker Circulation. In contrast to the conventional heating profile, the mature-cluster profile produces a circulation which is centered at the observed altitude and produces sufficiently weak low-level winds, even in the absence of surface drag. In addition, the observed westward tilt with height of the Walker Circulation is only reproduced by a linear, locally forced model of the tropical atmosphere when it is forced with an elevated heat source. This westward tilt in the lower troposphere is consistent with downward flux of wave activity.

Results of experiments not described here show further that the two heating profiles in Fig. 1 also produce rather different responses when tropical heating anomalies are used to force mid-latitude circulation anomalies. Such mid-latitude/tropical connections require westerly winds for the meridional propagation of planetary Rossby waves (e.g., Opsteegh and van den Dool, 1980: Webster, 1981: Hoskins and Karoly, 1981). The contrast between the MC and CP heating profiles in the upper troposphere, where the climatological zonal mean winds are westerly, is much larger than that of the heating profiles considered by Simmons (1982). For this reason we find a much larger mid-latitude response to tropical heating with the elevated MC profile than we do to the CP profile. The production of elevated heating profiles by cloud clusters and associated upper-level cloud decks may thus be important for tropical-extratropical interaction as well as for trapped equatorial waves.

Having established the dynamical significance of the difference between the mature cluster heating profile and the conventional heating profile, and having put forward the hypothesis that the mature cluster profile may be the more appropriate one to use in the perturbation studies, we may consider how the remaining doubts might be reduced. One obvious suggestion is

to compare heating profiles estimated from synoptic or radar data for regions with different but well-known properties. Another approach would be to attempt to calculate the vertical distribution of the heating function in the tropics as a function of longitude. A first approximation to this latter problem would be simply to multiply the observed time-mean vertical velocity along the equator (a rather poorly known quanity) by the static stability. Since we already know that the vertical velocity and the Walker Circulation along the equator are elevated and centered around the 400 mb level, this procedure would likely return an elevated heating profile, much like the mature cluster profile.

If the mature cluster profile is the operative one in many cases, then its implications for the coupling between large-scale dynamics and latent heat release, and for climate sensitivity via radiative-convective equilibrium should be carefully studied. Because of their role in producing strong heating in the upper troposphere and hence elevating the level of maximum diabatic heating in the atmosphere, cloud clusters may be an essential element in determining the climatic response to changes in atmospheric composition and the coupling between atmospheric and oceanic temperatures.

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