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On the role of wind-induced surface heat exchange in a two-dimensional model of super cloud clusters

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Abstract. Experiments with a two-dimensional model of *Chao and Lin* [1994] are conducted to investigate the role of WISHE (wind-induced surface heat exchange) in the super cloud clusters. It is found that while WISHE as an instability mechanism is not responsible for the existence of the super cloud clusters, the process of surface fluxes being enhanced by surface wind has the important roles of prolonging the life span of the cloud clusters and making the super cloud clusters more robust. WISHE is also found not responsible for upstream propagation of the super cloud cluster. The latter is explained by the cloud cluster teleinduction mechanism proposed by *Chao and Lin* [1994].

Introduction

Since their discovery, the super cloud clusters [*Nakazawa,* 1988] have been considered as the essential component of the Madden-Julian oscillation (MJO). Understanding the super cloud clusters is not only intellectually interesting but also, through their link to the MJO, relevant for medium- and long-range forecasts [*Ferranti et al.*, 1990]. With some suitable choices of the cumulus convection scheme, *Chao and Lin* [1994] (hereinafter referred to as CL) successfully (at least qualitatively) simulated super cloud clusters in their highly simplified two-dimensional (2-D) (height-longitude) model. They attributed the origin of the super cloud clusters to what they call the cloud cluster teleinduction mechanism (CCTM). In CCTM, the rise of a cloud cluster excites gravity waves which trigger another cloud cluster on the upstream side (the east side, if the basic flow is easterly), giving rise to a chain reaction and an envelope of the cloud clusters, which is the super cloud cluster. To optimize their moisture supply, the cloud clusters move downstream relative to the boundary layer flow, thus giving rise to the internal (wave packet like) structure of the super cloud clusters. CL's model does not a priori exclude WISHE (wind-induced surface heat exchange, formerly known as the evaporation-surface wind feedback mechanism [*Emanuel,* 1987; *Neelin et al.*, 1987]. CL mentioned that WISHE may play some role in the growth of individual cloud clusters. However, its precise role in that model requires clarification. Several fundamental questions should be addressed, and these are (1) whether WISHE is an essential component of CCTM or it is entirely independent of CCTM and has merely modifying effects, if any, on CCTM; (2) whether the upstream propagation of the super cloud clusters has anything to do with WISHE; and (3) why the super cloud clusters propagate upstream rather than downstream. The purpose of this paper is to answer these questions through numerical experiments with the CL model.

To start out, we should state our definition of WISHE, lest we run into semantics problems. Since this term has been used to explain the origin of observed phenomenon, it must be considered as an instability. But first, we should give the more basic and related concept wave-CISK a definition. By wave-CISK we mean the instability that arises from the cooperation between convective heating and the circulation induced by it. The circulation can bring moisture into the convective region through both advection and evaporation. The moisture thus brought in can enhance the convective heating, i.e., a positive feedback between the two occurs. It is important to point out that the cooperation does not necessarily always lead to positive feedback. The cooperation must be strong enough to overcome the dissipation in order for the positive feedback (i.e., the instability) to occur. The circulation involved can have the help of surface friction. Also, we do not imply in the definition of wave-CISK a cumulus convection scheme. For most tropical phenomena that depend on convective heating for their energy source, the vertical motion in the convective heating region must be upward (to generate adiabatic cooling to compensate for the convective heating), thus leading to low-level moisture convergence into the convective region. Thus these tropical phenomena have the cooperation between convection and convection-induced circulation. However, whether such cooperation is strong enough to start a positive feedback (i.e., an instability) is not always very easy to determine and should be carefully investigated. It should be emphasized that the triggering of one convective entity by another is not included in the definition of wave-CISK.

The core of WISHE is the dependence of evaporation on surface wind speed. The surface fluxes calculation in model are usually formulated as

$$(\text{flux of } y)_{\text{surf}} = \rho C_d |v_s| (y - y_s) \qquad (1)$$

where ρ is the density; C_d is the flux coefficient; y denotes

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temperature, water mixing ratio, or wind velocity; y_S is y at the surface; and $|v_s|$ is the surface wind speed. The essence of WISHE is the $|v_s|$ factor in the above formula, i.e., that the surface fluxes can be enhanced when $|v_s|$ increases. Included in the definition of WISHE is the cooperation that is central to wave-CISK. However, such cooperation is not strong enough to lead to instability unless the surface heat fluxes are enhanced by the increased surface wind. Thus, in this sense, WISHE can be viewed as a conditional wave-CISK. It should further be emphasized that the enhancement in surface fluxes does not automatically imply WISHE instability.

Our definition of WISHE may deviate somewhat from what has been given in the literature. However, it does capture the essence of the conventional definition of the instability and it serves well the purpose of our discussion.

The model used is identical to that of CL. Briefly, this is a 2-D (longitude-height) model, a compression in the latitudinal direction of the three dimensional (3-D) Goddard Laboratory for Atmospheres general circulation model. The model covers 180° in longitude; cyclic boundary condition is used. The bottom surface is ocean. The Coriolis force is deleted. The radiation component of the model is replaced by zonally averaged observed cooling rate [from *Newell et al.,* 1972], which is a function of height only. This design feature sets the model apart from the real atmosphere in the sense that the externally preset extraction of energy through radiative cooling determines the amount of energy input into the model at the bottom through surface sensible and latent heat fluxes. Thus raising sea surface temperature (SST) would not lead to higher energy input at the bottom; it only raises surface air temperature and humidity. This feature, however, does not have any negative impact for our present limited purpose. The boundary layer parameterization is that of the European Centre for Medium-Range Weather Forecasts (ECMWF) model [*Louis*, 1979]. The basic zonal wind is maintained by a Rayleigh friction term acting on the zonally averaged zonal wind. The only differences in the experiment setups from those of CL are (1) SST is a uniform 30°C and (2) instead of the Rayleigh friction term, an instantaneous adjustment of the zonally averaged zonal wind to -5 m/s is done after every dynamics time step. These are only minor differences, creating only quantitative differences. Since the purpose of this paper is not to compare the behavior of different cumulus convection schemes, only one (the *Manabe* [1965] convective adjustment) scheme is used in the experiments reported in this paper. The reason for our continued use of the 2-D model is its ease in use and interpretation. For example, this model has clearly demonstrated that the cloud radiation interaction is not necessary for the existence of the super cloud clusters (CL).

Experiments

Figure 1 shows the precipitation plot for an integration with the two changes mentioned in the Introduction. Two closely spaced super cloud clusters emerged with clean separation between cloud clusters. The speed of the super cloud clusters is 10 m/s, which is greater than the 5 m/s shown in Figure 8 of CL, owing to the difference in the way the zonally averaged zonal wind speed is controlled. Figure 2 is a repeat of Figure 1 except that $|v_s|$ in the calculation of evaporation is replaced by a constant 5 m/s. This replacement cuts off the evaporation-surface wind feedback link (i.e., WISHE is effectively removed from the model). The structure and the propagation of the super cloud clusters remain intact. The speed of the super cloud clusters is hardly changed. However, the life span of individual cloud clusters is shortened by roughly a factor of 2. When the same replacement of surface wind is done to sensible heat flux only (Figure 3), the super cloud structure remains intact, its speed changes little, and the life span of individual cloud clusters is shortened. Figure 4 shows the result of a case where the $|v_s|$ replacement is done to both evaporation and sensible heat flux. Again, the super cloud clusters exist. However, there are some breaks in the super cloud cluster. The life span of the individual cloud clusters is likewise shortened. These experiments have clearly demonstrated that the existence of the super cloud clusters does not have anything to do with WISHE. Apparently, the evaporation-surface wind feedback has only the modifying effect of lengthening the life span of the individual cloud clusters and changes little the speed of the super cloud cluster. To investigate whether the upstream propagation of the super cloud clusters has anything to do with surface wind feedback on

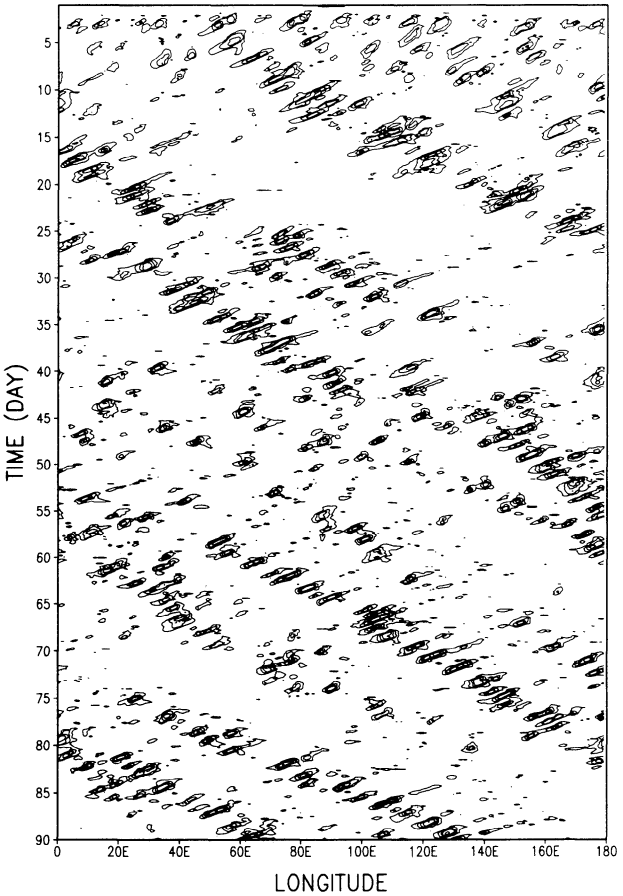

Figure 1. Time-longitude distribution of precipitation in an experiment repeating Figure 8 of *Chao and Lin* [1994], except with a uniform 30°C sea surface temperature and instantaneous restoration of zonal mean zonal wind to -5 m/s. The contour levels are 5, 20, 50, 100, 200, 300, and 400 mm/d.

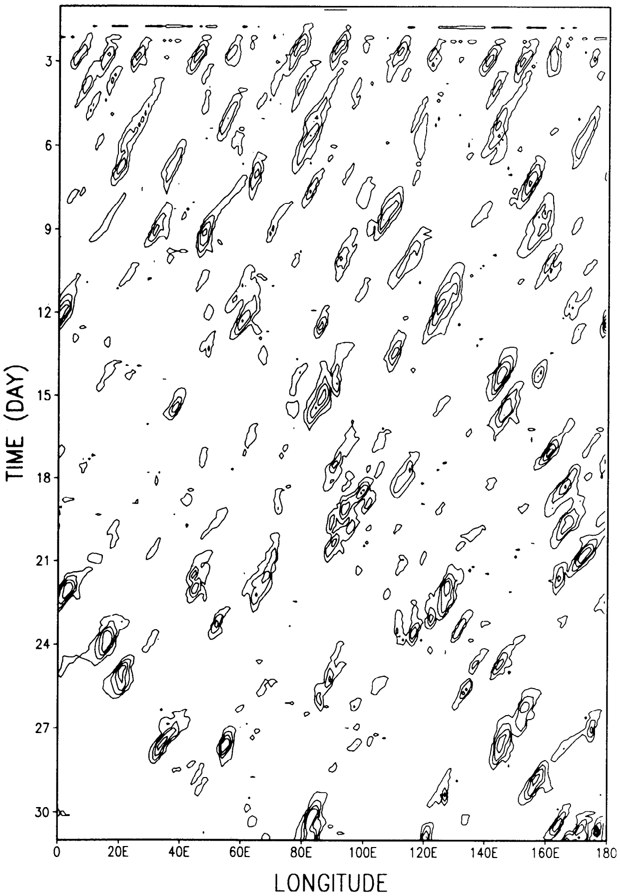

Figure 2. Same as Figure 1 except $|v_s|$ in the calculation of evaporation is replaced by a constant of 5 m/s.

the momentum flux, we conducted another experiment where the $|v_s|$ replacement is done to all surface flux calculations. The results (Figure 5) show that super cloud cluster structure is still discernible but is often interrupted. Our interpretation of these results is that without the help of surface fluxes feedback, the growth of individual cloud clusters is sometimes so weak that it does not have sufficient amplitude to trigger another cloud cluster. In order to verify this view, we repeated the same experiment (the one corresponding to Figure 5) with double radiative cooling rate. The idea behind this new experiment is that with higher radiative cooling rate, the growth of an individual cloud cluster can be intensified and the resulting stronger gravity waves can trigger a new cloud cluster more easily. The results (Figure 6) are consistent with our idea, and they show more organized super cloud clusters. However, after 18 days, the precipitation pattern turns into a more complicated regime. It appears that an additional mode has emerged. The new mode imposes an envelope of about 30^o-40^o wide on the super cloud clusters with a speed of about 5 m/s moving westward. The appearance of an envelope of about the same width encapsulating four super cloud clusters in Figures 1 and 2 of *Nakazawa* [1988] makes our finding very intriguing. However, the envelope in Nakazawa's two figures does not show much zonal movement. The transition into a more complicated flow pattern is consistent with the higher level of energy input and output of the model. Such bifurcation is rather common in geophysical fluid dynamics, and the search for the precise instability mechanism that gives rise to this bifurcation may lead to new insight. When the Figure 6 experiment is repeated without the fixed surface wind speed (i.e., repeating Figure 1 with double cooling rate), the flow pattern becomes more complicated (Figure 7). Such a flow pattern does not resemble anything observed (this may not imply the model is incorrect; it may just mean that the model is under external parameters outside the normal ranges) and appears to be the result of a number of instabilities and their nonlinear interaction.

From the experiments we have conducted thus far, we can conclude that suppression of the surface wind feedback on evaporation or sensible heat flux alone is not sufficient to hinder the CCTM. However, as the feedback on more fluxes is suppressed, the operation of CCTM can occasionally be disrupted. In other words, what we can say about WISHE is that it does help the CCTM through its help in the intensification of the growth of cloud clusters. While such help is not always crucial, it can sometimes make the difference of whether the results give uninterrupted super cloud clusters. However, to extrapolate these model results to the real atmosphere requires further careful study. It should be pointed out that the WISHE we are discussing here is the one operating on the cloud cluster scale and is entirely different from the WISHE operating at planetary scale mentioned in the literature concerning the origin of the MJO.

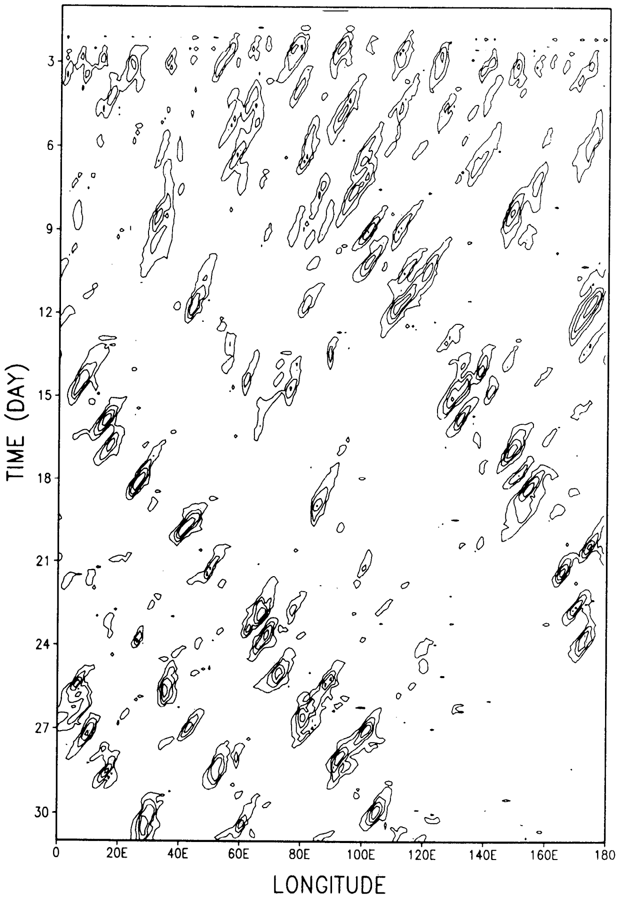

Figure 3. Same as Figure 1 except $|v_s|$ in the calculation of sensible heat flux is replaced by a constant of 5 m/s.

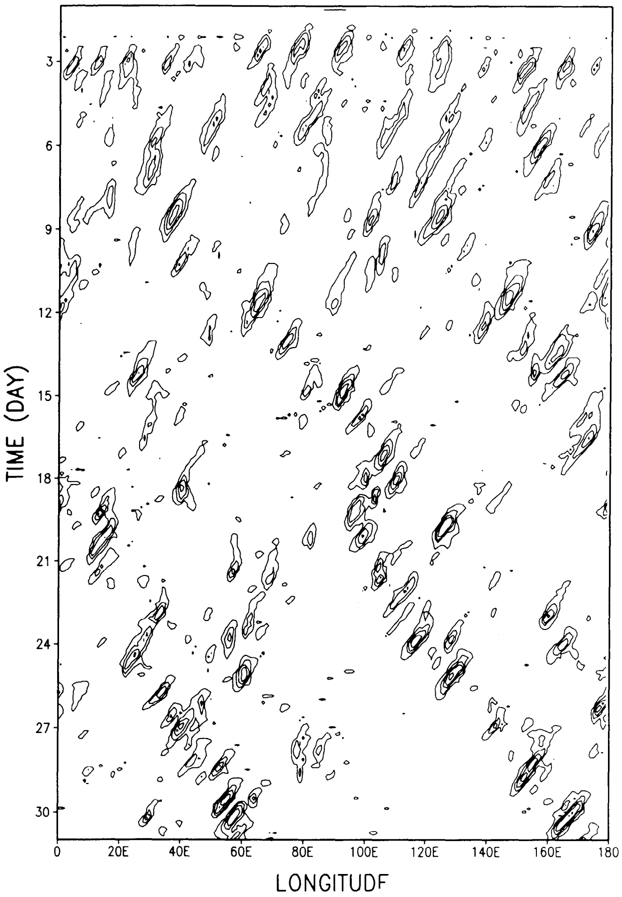

Figure 4. Same as Figure 1 except $|v_s|$ in the calculation of both evaporation and sensible heat flux is replaced by a constant of 5 m/s.

Our results indicate that the CCTM does not have to rely on surface wind feedback. According to CL, the reason for the upstream propagation is interpreted as the upstream side being the more favorable side for a new cloud cluster to be triggered. Could the fact that the upstream side is the favorable side then have anything to do with the asymmetry with respect to the cloud cluster in any of the surface fluxes? (Although the WISHE link has been cut off in the above experiments, the surface momentum fluxes can be asymmetric with respect to the individual cloud cluster. Note that the surface wind, denoted by y_S in (1), is asymmetric.) To answer this question, we conducted another experiment where all surface fluxes are replaced immediately after their calculation at each physics time step by their respective zonal mean values. The results (Figure 8) show that super cloud clusters and their upstream propagation can no longer occur. We therefore conclude that the upstream propagation does rely on the differential surface fluxes on the two sides of the cloud cluster. Thus we also have to conclude that the upstream propagation must have to do with the basic flow. To further confirm this idea, we repeated the first experiment and removed the zonal mean wind control term, thus keeping the basic zonal flow at rest. The results (Figure 9) show two super cloud clusters moving in opposite directions in the first two weeks triggered by the surface pressure hump in the initial conditions. After that the flow pattern became more incoherent (cf., Figure 1). This confirms our interpretation.

The question of what role, if any, wave-CISK plays in CL's model results can be answered by considering the last experiment which has resting zonally averaged zonal flow (Figure 9). This experiment does not exclude any cooperation between convective heating and heating-induced circulation, and yet it fails to produce super cloud clusters. Thus we can conclude that wave-CISK alone cannot explain the systematic propagation and the internal structure of the super cloud cluster. Obviously, the cooperation in wave-CISK exists in this experiment at the cloud cluster scale, and it must contribute to the growth of the cloud clusters in the model. Also, although the cooperation in wave-CISK does exist at the super cloud cluster scale, it does not give rise to any instability at this scale. The origin of the super cloud cluster has to be the CCTM. In the real atmosphere, cloud clusters do have the cooperation in wave-CISK. It is well known that wave-CISK prefers the smallest scale, which can be considered as the scale of the clouds [e.g., *Chao*, 1995] and that the existence of the cloud cluster depends on the nonlinear interaction between clouds (i.e., one cloud triggering another). The fact that wave-CISK prefers the cloud scale makes it almost indistinguishable from the conditional instability of the first kind (CIFK) (The word "conditional" is not a good choice of word. Any instability has a

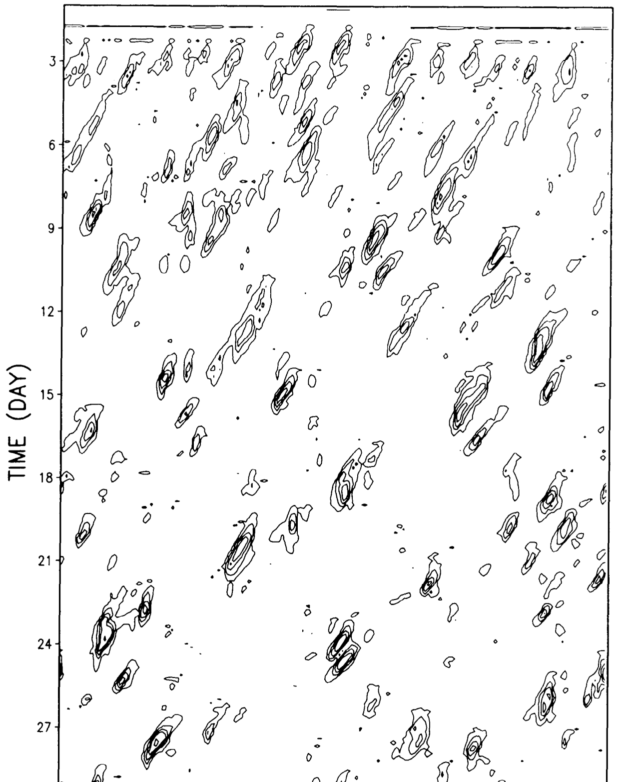

Figure 5. Same as Figure 1 except $|v_s|$ in the calculation of all surface fluxes is replaced by a constant of 5 m/s.

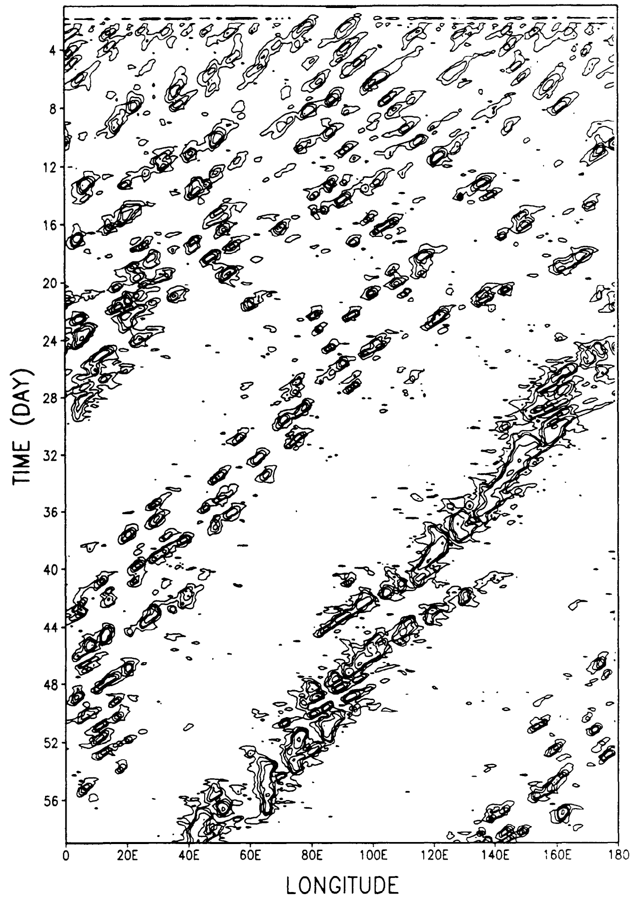

Figure 6. Same as Figure 5 except that the precribed radiative cooling rate is doubled.

condition to be met.) [*Ooyama*, 1982; *Chao*, 1995]. However, depending on one's definition of wave-CISK, it can have an important difference from CIFK. Many authors, when using the term wave-CISK, associate convective heating with low-level moisture convergence, whereas in CIFK, the onset of convective heating depends on unstable stratification (in the moist sense). Therefore wave-CISK as an instability mechanism is not suitable for explaining the onset of clouds. However, once a cloud starts, as a result of CIFK, the cooperation in wave-CISK does exist at the cloud scale.

Discussion and Summary

The answers to the questions raised in the Introduction can be summarized as follows. The cooperation in wave-CISK can be used to explain the growth (but not the onset) of individual cloud clusters in CL's model. However, such explanation is not valid for the cloud clusters in the real atmosphere, which depend on the nonlinear interaction between the clouds. At the super cloud cluster scale, although the cooperation between convective heating and heating-induced circulation exists, it cannot be used to explain the origin of the super cloud clusters nor can it be used to explain the upstream propagation of the super cloud clusters. Both have to be explained by the CCTM. WISHE is not a part of CCTM. The surface wind dependence of the surface fluxes (although not being able to give rise to any instability), however, does have the important modifying effects of lengthening the life span of individual cloud clusters and making the super cloud cluster more robust.

How do we then explain the upstream propagation of the super cloud clusters (as opposed to downstream propagation)? Our experiment with zonally uniform surface fluxes (Figure 8) clearly indicates that differential surface fluxes on the two sides of a cloud cluster, a result of the basic flow, are important in determining the propagation direction. Thus the propagation direction must be determined by the direction of the basic flow. We will assume that the basic wind is easterly. At a distance on the east side (i.e., the upstream side) of a growing cloud cluster, the boundary air has traveled for a long distance picking up moisture and is loaded with moisture. But on the western side and close to the cloud cluster on its eastern side (remember that relative to the boundary air, the cloud cluster moves westward), the air has just been "processed" by this growing cloud cluster and by the older generation of cloud cluster farther on the western side and is thus relatively dryer. The gravity waves that are excited by the growing cloud cluster have, by and large, an east-west symmetry with respect to the cloud cluster. Thus the eastern side's being the preferred side for the generation of a new cloud cluster has to do with the east-west asymmetry in the boundary layer thermodynamics fields as a result of basic flow advection and evaporation. Thus the

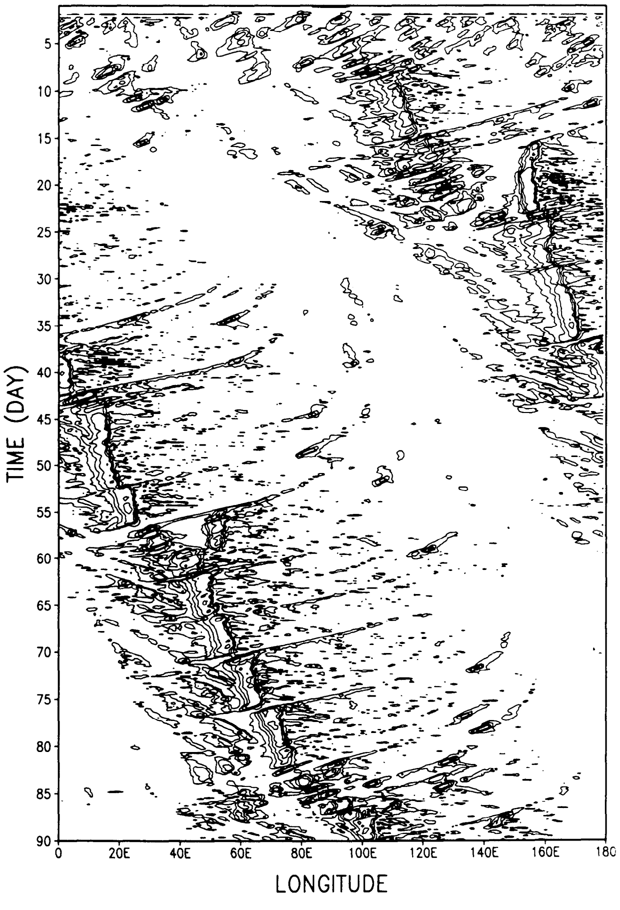

Figure 7. Same as Figure 1 except that the precribed radiative cooling rate is doubled.

reason that in CL's experiments the super cloud clusters move eastward is that the cloud cluster teleinduction mechanism is operating in an easterly basic wind of moderate speed. (In a basic easterly of high speed, although the location where the new cloud cluster arises is still on the upstream (east) side of the existing cloud cluster, it is on the west side of the location where the existing cloud cluster originated. Thus super cloud clusters move westward at a speed slower than that of the cloud clusters.)

Although our conclusions are drawn from experiments conducted using a 2-D model, they should remain qualitatively the same if a 3-D model had been used. *Chao and Deng* [1995] used a 3D model and have qualitatively reproduced CL's 2-D results. Therefore we expect that the 2-D results in this paper should not be qualitatively changed in a 3-D setting. There are, of course, some quantitative differences between 2-D and 3-D results. For example, as argued by *Chao and Deng* [1995] the 3-D model has a higher demand on the intensity of the cloud cluster for CCTM to operate. Also, the extra dimension allows the cloud clusters to move away from the equatorial region. The modifying effect of β is another difference.

Our discussions have been mainly on the super cloud clusters; however, similar conclusions can be drawn on the MJO. *Chao* [1995] has argued that wave-CISK cannot be used to explain the MJO. Although the wave-CISK type of cooperation exists in the MJO, as in any convective driven circulation, it does not lead to an instability that is responsible for the MJO. Similarly the WISHE type of enhancement in surface fluxes exists on the MJO scale, but it is not the reason that the MJO exists. As advocated by CL and *Chao* [1995], the MJO is driven by one or multiple super cloud clusters, and (as argued in the preceding section) the origin of the super cloud clusters is the CCTM.

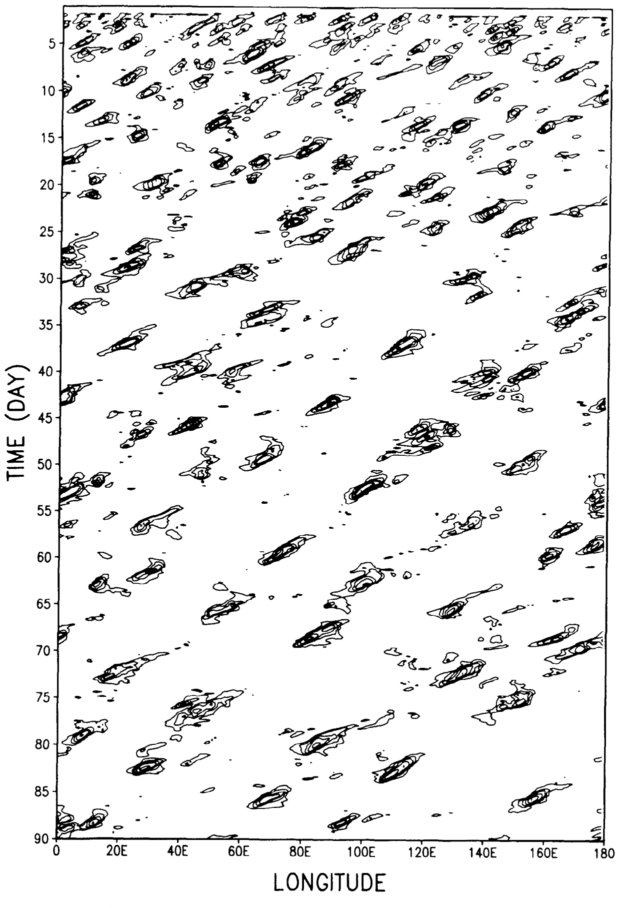

Figure 8. Same as Figure 1 except that all surface fluxes are replaced immediately after their calculation at each physics time step by their respective zonal mean values.

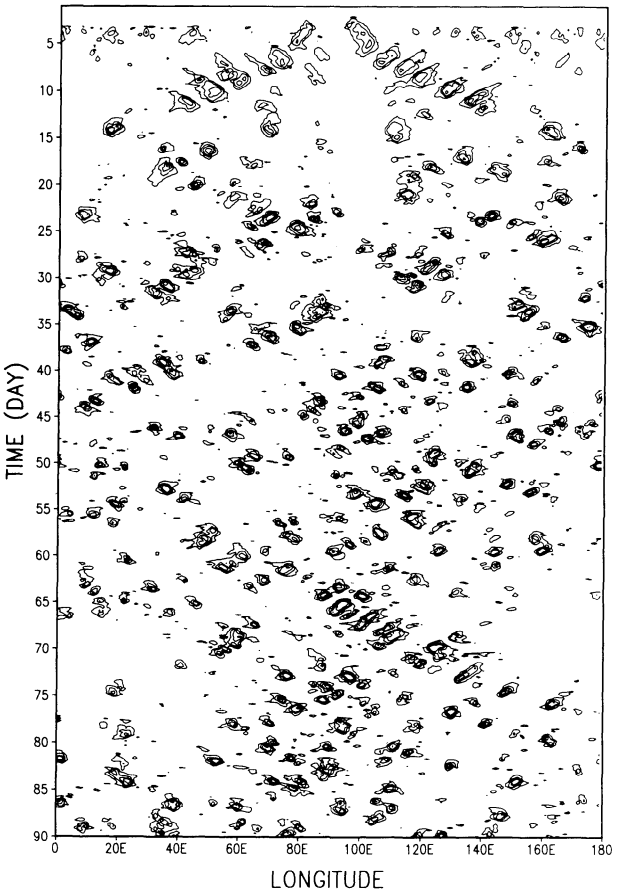

Figure 9. Same as Figure 1 except that the basic flow restoration is not done.

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