Evidence of the Existence and Eastward Motion of Superclusters at the Equator

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ABSTRACT

A numerical experiment with an atmospheric general circulation model (GCM) indicates that moist convection in the equatorial region is spontaneously organized into a form of "supercluster" which is an area of precipitation with a spatial extent of about 2000 km and an eastward propagation speed of about 15 m s^{-1}.

In this article, the existence of superclusters in the real atmosphere is shown through a comparison between satellite observations and the GCM results. It is argued that eastward motion of convective activity occurs not only as the well-known property of the 30–60 day oscillation, but as a property of synoptic-scale disturbances at the equator.

1. Introduction

For the purpose of revealing general features of cumulus convective activity in an equatorial large-scale field, a numerical experiment was performed by Hayashi and Sumi (1986; hereafter referred to as HS) using an atmospheric general circulation model (GCM) with longitudinally uniform surface boundary conditions. The results show that the cumulus activity in the equatorial region appears in the form of eastward moving precipitation areas. Despite the zonally symmetric boundary conditions, the distribution of convective activity is not symmetric; convection is organized into a synoptic-scale structure and keeps moving eastward. The precipitation areas were named "superclusters".

In HS, the actual features of such synoptic-scale convective activity were not described in detail, although it was assumed that superclusters could be easily recognized in the equatorial atmosphere. The purpose of this study is to give further support to the results of the numerical experiment. Although the superclusters realized in the model are at the limit of numerical resolution, we can conclude that they are not numerical artifacts. We will show that synoptic-scale convective activity, which can be regarded as superclusters, actually exists in the real equatorial region, and demonstrate that eastward motion of convective activity, which has been considered to be one of the characteristics of the 30–60 day oscillation, appears also as synoptic scale disturbances.

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2. An idealistic form of tropical convection expected from the "aqua-planet" experiment

A GCM can be useful for considering the behavior of cumulus convection from the viewpoint of large-scale (planetary-scale) field. The present computer resources made it possible to simulate the evolution of the global atmosphere with a resolution of about 500 km. Such a resolution is not sufficient for resolving moist convection explicitly; it is parameterized in a rather heuristic manner. This resolution is not sufficient even for describing so-called cloud clusters. Deep cumulus clouds over the tropical oceans are often organized in the form of cloud clusters which have a horizontal extent of about 100 km × 400 km (Houze and Betts 1981). A global atmospheric model cannot exhibit such structures. Despite these difficulties, we will begin by assuming that cumulus parameterization can pick up some of the features of the behavior of cumulus convection in a large-scale field. Since the results depend on this assumption, they must be checked by some other means.

In this section, we will review the results of the GCM experiment of HS. The experiment was performed in order to see what the tropical convection and circulation would be if the geometry were very simple. The surface boundary utilized in HS is completely covered with the ocean (aqua-planet). The SST (sea surface temperature) distribution has its maximum at the equator and is symmetric about the equator and zonally uniform. The initial condition of the atmosphere is also symmetric around the equator and zonally uniform. The cumulus parameterization employed is a Kuo-type (Kuo 1974).

The results of 90-day integration show three basic characteristics of the cumulus convection and atmospheric circulation around the equator (Figs. 1 and 2). First, despite the zonally symmetric boundary conditions of the model, the precipitation along the equator is organized into areas with a horizontal extent of about 2000 km (Fig. 2). The interesting feature of these synoptic scale areas is that, regardless of the easterly (westward) wind over the tropical region, they move eastward fairly coherently at a speed of about 15 m s^{-1} (Fig. 1a). This coherent motion suggests that a structure different from ordinary cloud clusters exists at the equator, for cloud clusters do not move eastward against the dominant easterly wind. Additionally, the horizontal extent of cloud clusters is smaller than the areas resolved in the model. These eastward moving synoptic-scale precipitation areas were termed "superclusters" to distinguish them from cloud clusters.

The second property is that the existence and intensity of the superclusters suffer a planetary-scale (zonal wavenumber-1) modulation (Fig. 1a or upper part of Fig. 2). The wavenumber one structure can be seen more clearly in the zonal wind field (not shown here). This zonally asymmetric circulation propagates eastward at a speed of about 15 m s^{-1}, which is the same as that of superclusters. Therefore, by observing the signal at a fixed point at the equator, the period of successive westerlies is about 30 days. The asymmetric circulation realized in the model is found to have characteristics similar to those of the observed 30–60 day oscillation in the real atmosphere (e.g., Madden and Julian 1972; Murakami and Nakazawa 1985; Nakazawa 1986a,b) and hence was termed "30-day oscillation". The cumulus activity around the equator of the aqua-planet spontaneously forms the 30-day oscillation through the development and modulation of superclusters.

The third property is the double ITCZ (intertropical convergence zone) structure (right-hand side of Fig. 2). Although the maximum value of SST is located at the equator, the longitudinally averaged precipitation has its peaks slightly poleward from the equator. The noticeable point asssociated with the ITCZs is that the precipitation in the equatorial strip between the ITCZs occurs in the form of superclusters. In the regions poleward from the ITCZs, precipitation areas stand still or move westward occasionally (Fig. 1b).

In this way, the aqua-planet experiment shows that interesting precipitation patterns and circulation fields which are different from the symmetry of the boundary conditions appear spontaneously in the equatorial region. Around the ITCZ latitudes, however, the experimental results do not exhibit the dominant westward propagation of precipitation areas. Around these lati-

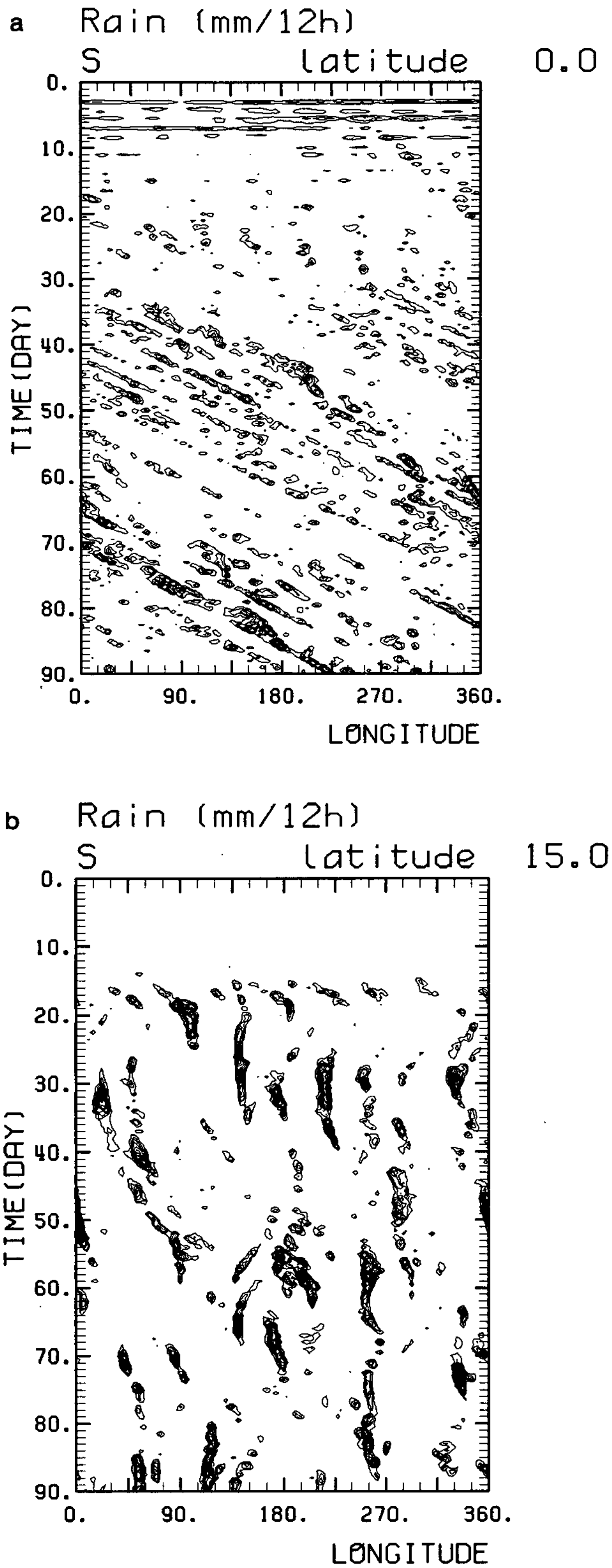

FIG. 1. Longitude–time sections of 12-h precipitation of the aqua-planet model at (a) the equator and (b) 15°N. The sampling rate is twice a day. No filtering procedure is employed. The contour interval is 2.5 mm (12 h)$^{-1}$.

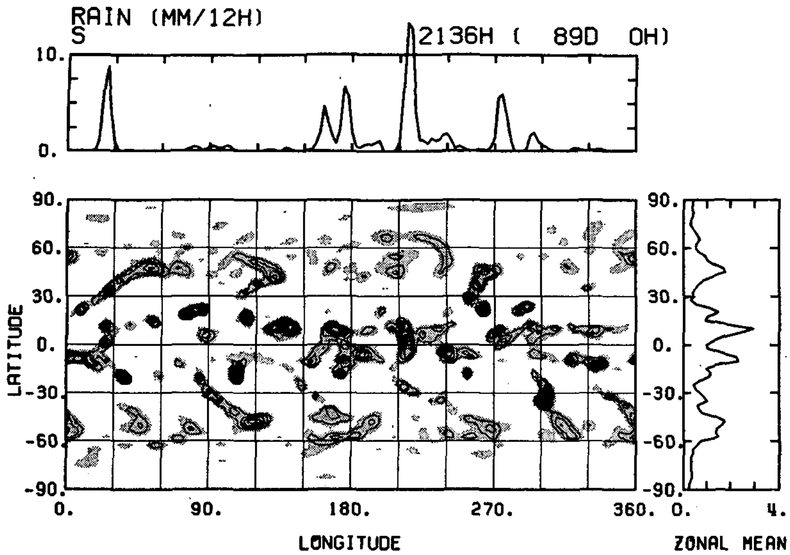

FIG. 2. A snapshot of global 12-h precipitation at t = 89 days of the aqua-planet experiment. The contour interval is 2.5 mm (12 h)$^{-1}$ and regions greater than 1 mm (12 h)$^{-1}$ are shaded. Zonal mean value and the equatorial value of precipitation are plotted at the right-hand side and the upper side of the figure, respectively.

tudes the easterly waves should appear as a synoptic-scale disturbance (WMO GATE monograph 1982). There are, in fact, westward moving signals in the vorticity and precipitation fields of the model ITCZ latitudes (10°N or 10°S), but even there the eastward motion is dominant in the precipitation field (not shown). Unfortunately, model analyses have not yet been completed to fully answer the question of what becomes of the easterly waves and to clarify the conditions for the generation of superclusters and their modulation by the wavenumber-1 (30-day) oscillation.

3. Observational evidence of the existence of superclusters

In this section, we reexamine the behavior of deep cumulus activity in the real atmosphere in the light of the aqua-planet experiment. The most interesting experimental result is the existence of an eastward propagating synoptic-scale structure (supercluster) along the equator, which has not yet been recognized in the modeling literature. On the other hand, this experimental result could simply be the artificial feature of the malfunction of the cumulus parameterization or the lack of dynamical resolution. The synoptic-scale precipitation areas in Figs. 1a and 2 might be a numerical noise.

There have been several reports which indicate that synoptic-scale convective activity exists at the equator and propagates eastward (Wallace and Chang 1972; Murakami 1972; Yasunari 1979). However, until Nakazawa (1986b), the existence and eastward motion of synoptic scale disturbances at the equator do not seem to have attracted enough attention. In the large-scale (planetary-scale) field, on the other hand, the variation of convective activity associated with the 30–60 day oscillation has been well documented (Lau and Chan 1985, 1986; Murakami et al. 1986). The temporally and/or spatially filtered variation of deep cumulus activity oscillates at intraseasonal time scales and propagates eastward. Madden and Julian (1972) suggested the existence of such a large-scale variation of convective activity and termed it the enhanced large-scale convection (their Fig. 16). Lau and Chan (1986) beautifully illustrated the behavior of the enhanced large-scale convection with 5-day mean OLR (outgoing longwave radiation) data.

In order to detect synoptic-scale activity along the equator, we need higher temporal resolution. Figure 3 is time–longitude sections of OLR at (a) the equator, and (b) 15°N, where the sampling rate is twice per day. The most interesting feature appears at the equator during the period from May–June (Fig. 3a). There we can easily recognize the several convectively active regions with a longitudinal width of 2000–3000 km which move eastward uniformly at a speed of 7–16 m s^{-1}. This characteristic is quite similar to that of the superclusters in the aqua-planet model. At 15°N, on the contrary, the convectively active regions propagate westward; the propagation speed is 5–10 m s^{-1}—the same as trade wind velocity in the lower troposphere. They are considered to be the same cloud activity as Chang (1970) produced in an illustration of the cumulus convection modulated by the easterly waves. At the equator it is noticeable that, although there is east-

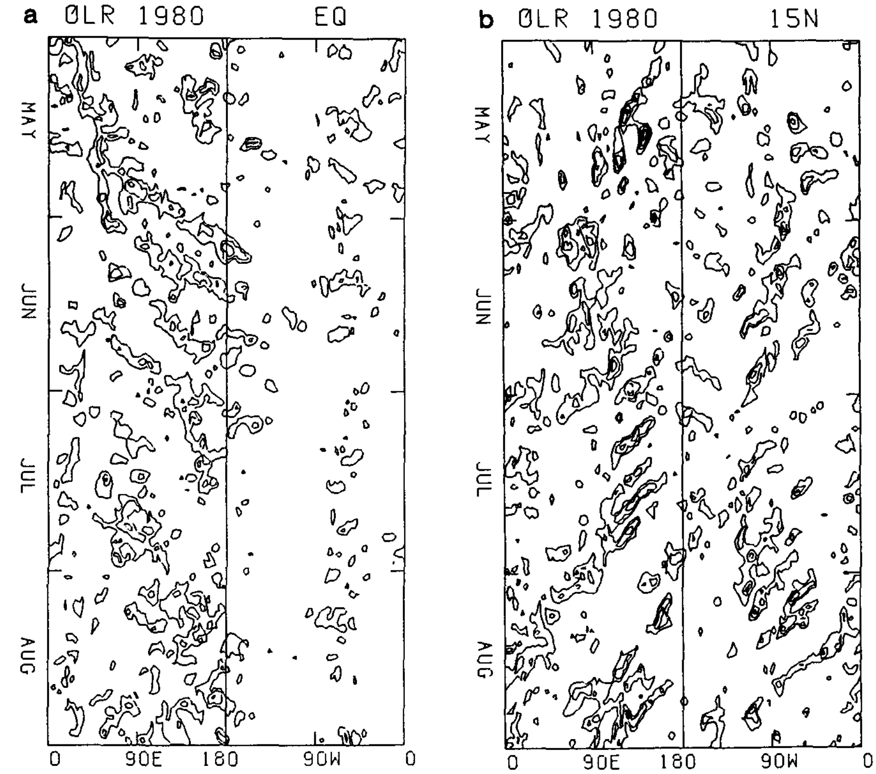

FIG. 3. Longitude–time sections of OLR during the period from May to August 1980 at (a) the equator, and (b) 15°N. The sampling rate is twice a day. The seasonal trend is subtracted. The contour interval is 40 W m^{-2} and only those regions less than -20 W m^{-2} are plotted.

erly (westerly) wind similar to that of 15°N, the convective activity of this time scale (recall twice a day sampling) moves eastward.

Figure 4 is an example of eastward moving convective activity. Three IR (infrared) snapshots were taken by the GMS (geostationally meteorological satellite) in 1985 at 140°E over the western Pacific. When we observe these snapshots separately, it appears that cumulus convection occurs rather randomly. However, with the knowledge obtained so far, an eastward propagating region of active convection with a spatial extent of about 2000 km can be identified as indicated by arrows. The region is difficult to recognize because the boundary of the convective region cannot be determined definitely because of the day-to-day evolution of clouds and cloud clusters. The situation is the same for the case of the aqua-planet, where the shape of the superclusters (Fig. 2) changes completely from day to day. However, in light of the temporal information (Fig. 1a) it becomes possible to recognize the existence of a dynamically meaningful structure at the equator. Similarly, in the real atmosphere, the eastward propagating convective region exemplified in Figs. 3 and 4 can be referred to as superclusters.

As for the real superclusters, we can observe their inner structure. As clearly seen in Fig. 4, they are composed of clouds and cloud clusters. These inner cloud activities behave differently than the enveloping supercluster. Infrared imageries with a higher resolution in time (for instance, every 3 h) show that clouds and cloud clusters move westward, while the enveloping supercluster moves eastward (not shown). The westward propagation speed is similar to that of 15°N; it is almost the same as the lower tropospheric wind. At the equator, however, we find a supercluster that acts as a synoptic-scale structure modulating the convective activity of those cloud and cloud clusters.

In the ITCZ latitudes, a synoptic-scale modulation of cumulus activity is well known as the easterly waves. Figures 3 and 4 indicate that, at the equator, there also exists a synoptic-scale modulation. It is different than that of the ITCZ latitudes however, because it propagates eastward rather than westward.

The examples of superclusters presented in Figs. 3 and 4 are not unique. In every year, we can identify several cases where the eastward propagation of OLR is quite coherent, as shown in Figs. 3 and 4. In the figures of Wallace (1970) for instance, it is possible to identify eastward propagation in the 5°S–5°N belt. Apart from the coherency which enables us to recognize

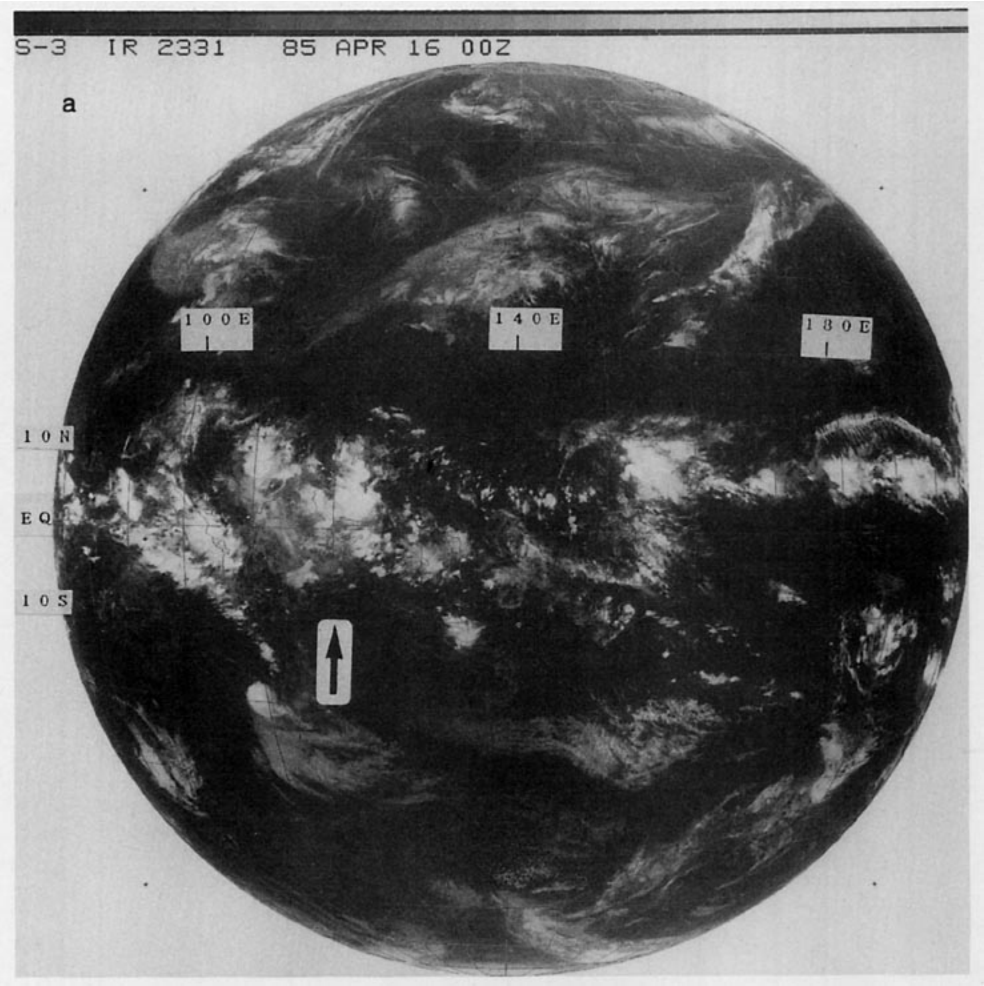

FIG. 4. The IR imageries photographed from the GMS at 140°E on (a) 16 April (b) 18 April and (c) 20 April 1985. Note that a convectively active area indicated by arrows is moving eastward over the maritime continent.

the possible existence of a dynamical structure, the convective activity at the equator, if seen in the scale of superclusters, always moves eastward (Nakazawa 1986b).

It is surprising that although the boundary conditions of the real atmosphere are complicated with the land–sea distribution and inhomogeneous SST distribution, the cumulus activity at the equator is modulated by the eastward propagating synoptic scale structures (as expected by the aqua-planet experiment) where the boundary conditions are quite simple. In the real atmosphere, the existence region of the superclusters is restricted to the ocean with high SST, i.e., from the Indian Ocean to the central Pacific. In the eastern Pacific, it is usually difficult to identify synoptic-scale activity. However, in the El Niño years, we can recognize superclusters propagating eastward (Fig. 1b of Nakazawa 1986b). We believe that in the Atlantic, it is sometimes possible to trace eastward motion of synoptic activity.

It is also surprising that although the cumulus parameterization in the GCM is probably not exactly correct, the aqua-planet experiment does predict the existence of structure in the real atmosphere. Contrary to the existence of such features, the westward propagating precipitation areas corresponding to easterly waves cannot be seen very clearly in the model (Fig. 1b vs Fig. 3b). In a separate numerical experiment performed by Hayashi and Golder (1986), the existence of superclusters is not very clear; both the eastward and westward motions of synoptic-scale convective activity seem to coexist in their Fig. 11. They considered synoptic-scale activity to be noise and only paid attention to the planetary-scale activity. However, after comparing the aqua-planet experiment and the OLR data, we believe that there is a synoptic-scale structure at the equator; it is not a numerical noise.

4. The eastward motions of the superclusters and the 30–60 day oscillation

We emphasize here that organization of convective activity and its eastward motion occurs not only in the

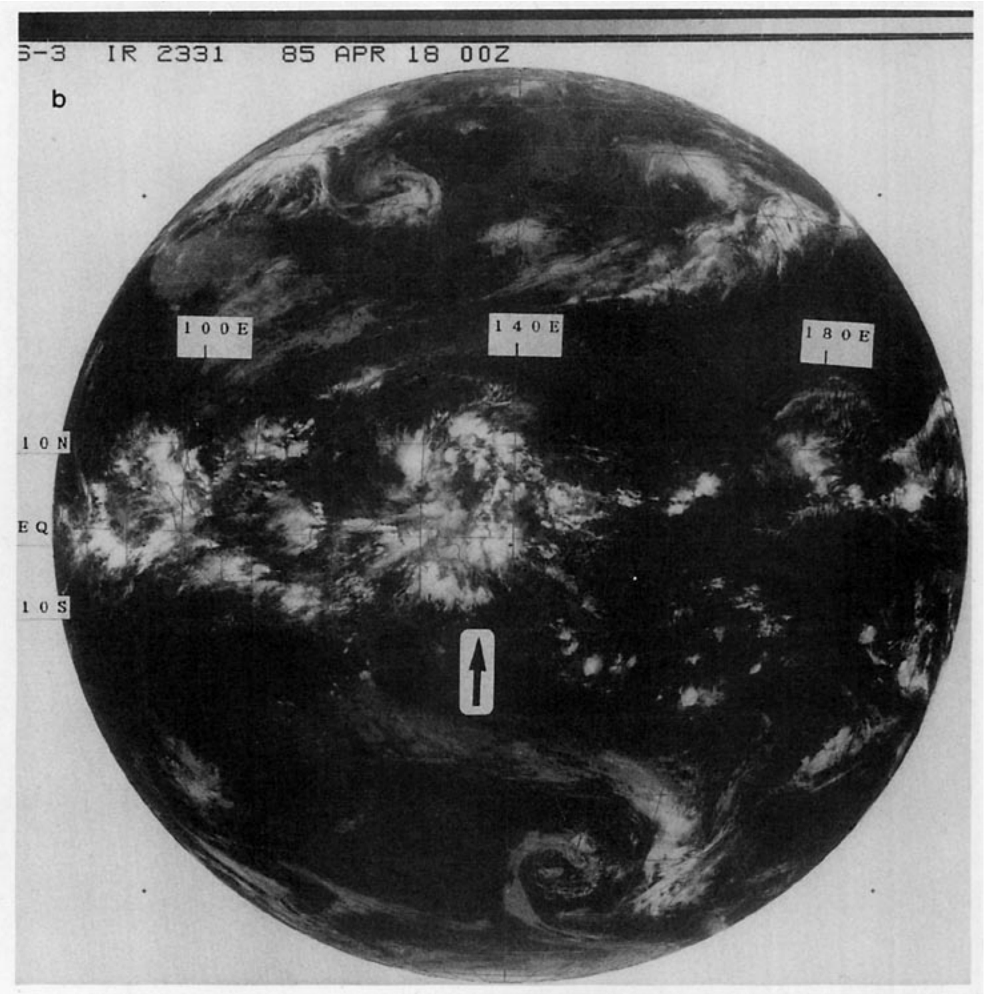

FIG. 4. (*Continued*)

temporal and spatial scales of the 30–60 day oscillation (the enhanced large-scale convection) but also in the scales of synoptic field superclusters. In order to show the eastward motion of a convective system, we need very little temporal or spatial filtering, which is often utilized in the illustrations of the 30–60 day oscillation.

There are even cases where the eastward motion of the 30–60 day oscillation is unclear, while that of superclusters is clearly defined. Figure 3a contains such a period. According to the definition of Murakami (1987), mid-May to mid-June is the period when the movement of the 30–60 day oscillation is irregular. This, on the other hand, is the duration where the eastward moving superclusters appear most typically, as shown in Fig. 3a. The situation can also be understood by comparing the period of Fig. 3a with the same period of the illustration of Lau and Chan (1986) in which 5-day mean OLR is used. This simple time filtering procedure completely obscures the synoptic-scale eastward motion of Fig. 3a.

The tendency of eastward motion of cumulus activity with the scale of supercluster can be seen at almost any time in the equatorial strip (Nakazawa 1986b). Although the coherency of cumulus activity in the real atmosphere may not be as good as that of the aquaplanet experiment, the tendency of eastward motion is quite clear. Since the work of Madden and Julian (1972), the 30–60 day oscillation has been one of the main features of the variation of convective activity in the equatorial regions. In the investigations of the 30–60 day oscillation, planetary-scale features have been of primary interest. They can be obtained by adequate time and/or space filtering (e.g., Lau and Chan 1986; Murakami and Nakazawa 1985). In their time averaging of 5 days, Lau and Chan (1986) do not necessarily mean to focus only on the planetary-scale features, but they still filter out the synoptic-scale features of equatorial convective activity. These methods are a good way to visualize the variation of convective activity of intraseasonal time scales. However, they obscure the existence of synoptic-scale cloud activities, whose long term, large-scale modulation forms the enhanced large-scale convection (the 30–60 day oscillation). The existence of synoptic-scale disturbances (superclusters)

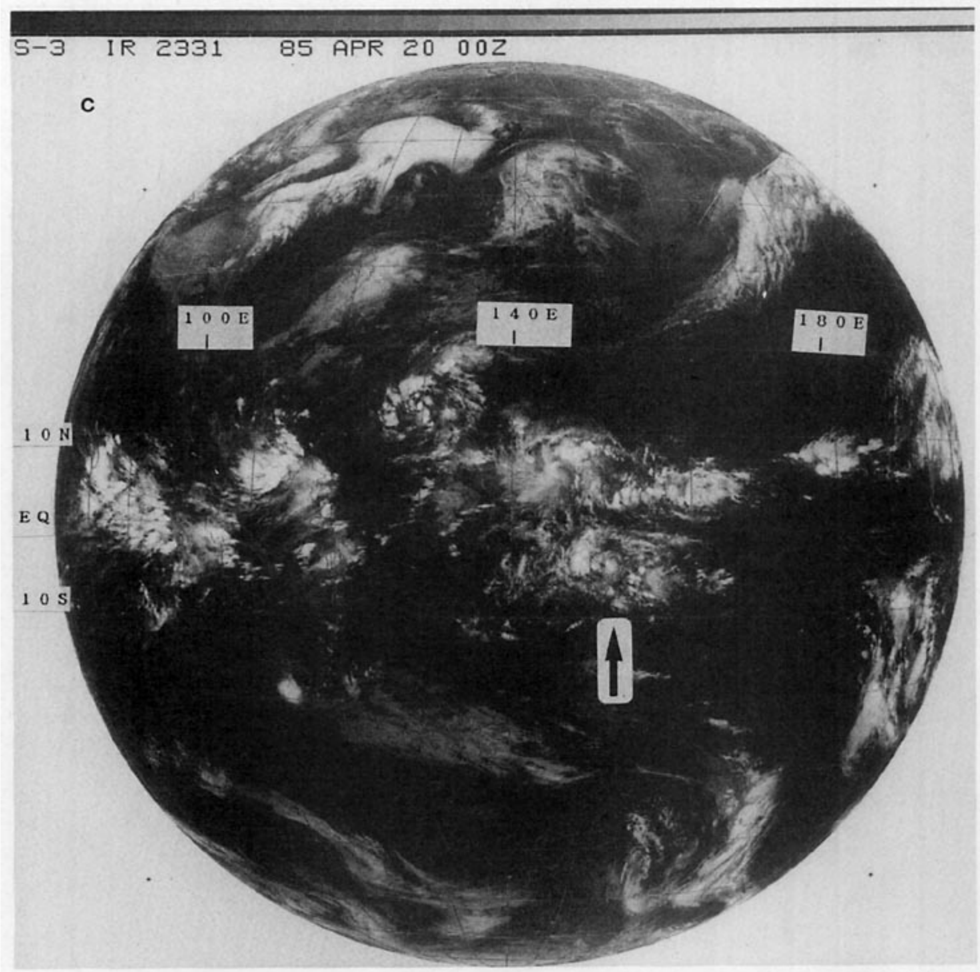

FIG. 4. (*Continued*)

and their modulation should be considered separately. Eastward motion, which has been considered to be one of the characteristics of the 30–60 day oscillation, occurs also in the equatorial synoptic scale field.

5. Concluding remarks

The activity of cumulus convection, which seems to occur in a random manner, is, in fact, organized by a hierarchy of modulating motion systems. The variability of convection has several levels. The hierarchical structure with regard to cumulus activity, squalls, easterly waves, and the ITCZ is well recognized for the ITCZ latitudes (WMO GATE monograph 1982). In the equatorial region the structure is different from that of the ITCZ latitudes. For the smallest scale of organization, deep cumulus clouds over the tropical ocean form cloud clusters. For larger scales, the hierarchical structure depends on latitude. At the equator the activity of cloud clusters is modulated by synoptic-scale superclusters, while in the ITCZ latitudes it is modulated by the easterly waves. The superclusters are further modulated by large-scale, long-period signals to form the enhanced large-scale convection (the 30–60 day oscillation). In the GCM experiment, the modulation of the activity of superclusters is quite evident. The resultant circulation is clearly recognized as the 30-day oscillation.

Similar structures also seem to exist in the real atmosphere. However, at the real equator, there is an interesting case where the eastward motion of superclusters is quite clear, while that of the 30–60 day oscillation cannot be well defined. The modulation of superclusters can behave independently from its components.

Unfortunately, the shapes of the components of each level, cloud clusters, superclusters and the enhanced large-scale convection (30–60 day oscillation) are less clear in the real atmosphere, and the distinction between them is sometimes very unclear. The whole argument presented here depends solely on pattern recognition. Without the GCM results, Figs. 3 and 4 alone would be weak evidence for the existence of synoptic-scale disturbances along the equator, as distinct from the existence of the enhanced large-scale convection illustrated by Lau and Chan (1986). For the case of easterly waves, the synoptic-scale variation of wind and pressure fields was recognized long before Chang (1970) visualized the disturbances by using satellite OLR imagery. On the other hand, for the superclusters, there have not been any reports of the variation of dynamical variables which indicate the existence of synoptic-scale coherent structure. However, as a result of the aquaplanet experiment, the possible existence of superclusters is suggested, and the observations presented here represent plausible examples of this phenomenon in nature.

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