Time Variation of Tropical Energetics as Viewed from a Geostationary Altitude

D. N. SIKDAR AND V. E. SUOMI

Space Science and Engineering Center, The University of Wisconsin, Madison

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ABSTRACT

In this paper we have used time-lapse ATS-I satellite cloud photographs as our data source for the evaluation of the convective transport of latent heat from the lower troposphere to the tropical upper troposphere.

The analysis reveals that the meso- to subsynoptic-scale convection systems over the tropical mid-Pacific are well organized on a time scale of a few days and are controlled by the large-scale motion field. The time variation of this heat transport, in the sector 120W–180W, 15N–15S, indicates an approximate periodicity of five days. Furthermore, this pulsating feature seems to be tied to a wave-like disturbance field of wavelength nearly 75° of longitude and moving westward with an approximate speed of 15° of longitude per day.

1. Introduction

The dynamics of large-scale tropical disturbances and their interactions with mid-latitude circulations has been limited by lack of observations on an appropriate space scale. Riehl (1945, 1948) first pointed out the existence of "easterly waves" in the lower tropical troposphere based on synoptic data in the Caribbean Sea region. Over the tropical Pacific, Palmer (1952) found similar types of disturbances and classified them as "equatorial waves." The wavelength of these disturbances is stated to be of the order of 2–3000 km. Yanai and Nitta (1967) pointed out that these wave systems exhibit systematic upward motions to the east of the wave axis.

Tropical upper tropospheric circulations were first reported by Riehl (1948). He found large eddies in the upper troposphere at ~200 mb over the western Pacific. These eddies are seen to move westward with a phase velocity close to the speed of lower easterlies. Recently, Yanai and Maruyama (1966) studied these tropical upper tropospheric disturbances in detail and detected westward-moving waves over the equatorial Pacific despite the general flow field being eastward at those levels. The wavelength of these disturbances is estimated to be around 10,000 km. Based on power spectral analyses of upper tropospheric wind data over the tropical Pacific (150W to 150E) for the period April to July 1962, Yanai et al. (1968) reported a significant peak of power spectral density of the meridional wind component at 4–5 day periods. These high-level spectral density peaks are related to the traveling large-scale disturbances.

Based on these findings one might ask if there is a relationship between these westward-moving tropospheric perturbation fields and the intensity of tropical convection. In the tropics, a major part of the heat is transported from the boundary layer to the tropical upper troposphere by deep "wet" convection and then in the form of sensible heat and potential energy to the higher latitudes. The purpose of this paper is to show that tropical convective activity as revealed by geosynchronous satellite cloud photographs also has a strong periodic fluctuation.

This analysis covers the period 1–30 April 1969 during the Line Island Experiment. Frequent satellite pictures and additional surface and upper air observations were available.

2. On the scales of convection in the tropics

In tropical circulations, three broad scales of motion are mainly involved: 1) planetary scale (the equatorial trough and trade-wind regime, subtropical highs and

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Fig. 1. The scales of tropospheric motions in the tropics.

1 The research reported in this paper constitutes a part of the Ph.D. dissertation of the senior author at the University of Wisconsin, Madison.
jets, the tropical monsoon, etc.); 2) synoptic- or large-wave scale (easterly waves, tropical cyclones, waves in the upper troposphere, etc.); 3) meso-convective scale (cumulus clouds which can form cloud clusters).

Fig. 1, taken from the February 1970 GARP technical report, clearly explains these scales. On the meso-convective scale (10-100 km) one identifies individual cumulonimbus towers (1-10 km) surrounded by clear space on the satellite photographs. On the cloud-cluster scale (100-1000 km) there may exist a number of meso-convective-scale convective areas in proximity so that the high-level cirrus outflow in their mature and decaying stages merge to form a common cirrus shield. These scales are found embedded in a large-wave scale.

The half-globe cloud picture (Fig. 2) taken from ATS-III shows the cloud population on a day in July 1969 over the Atlantic. Various scales of convection can be easily identified on this photograph. Bright clouds marked A, B and C can be categorized as the cloud-cluster scale.

Fig. 3 is an enlargement of cloud cluster A in which one would anticipate the presence of a number of active deep meso-convective-scale elements. ATS satellites easily observe the composite cirrus canopies resulting from these deep convection cells. If one enhances the brightest portion of the photos, zones of deep convection can also be identified. Fig. 4 is an example of such a photograph which emphasizes the bright parts of cloud cluster A (Fig. 2), i.e., the deep portion of the cloud cluster. This picture suggests that the deep convection cells occupy a small area and they exist more or less around the geometric center of a cloud cluster.

Fig. 2. ATS-3 (half-globe) cloud picture over the Atlantic on a day in July 1969.

Cirrus canopies observed at the top of these deep convection cells have a lifetime much greater than the lifetime of a cloud cluster, so that the time variations in their areas can be excellent markers for the convective energy transport to the tropical upper troposphere (Sikdar and Suomi, 1969). In order to evaluate these transports we have used the 3-layer convection model (1) shown in Fig. 5. This model is similar to what Green et al. (1966) had presented for a large-scale convective circulation.

3. A brief physical description of the model used

As already pointed out, a cloud cluster may be regarded as an envelope of deep convection occurring in regions of organized rising motion associated with the large-wave scale. Deep tropical convection is essentially made up of three layers (Model I, Fig. 5). First, the layer of inflow (LIF) which includes the planetary boundary layer that extends from the sea surface to the lifting condensation level (LCL). In this layer, warm moisture-laden air is drawn into the cloud region because of the local convergence which might be produced by large-scale motion. The second layer, the layer of vertical motion (LVM), has a depth from the LCL to the throat of a convective tower in which the vertical motion is maximum at the core decreasing to a negligible value at the cloud periphery. It is assumed that the buoyant air starts condensing at the LCL and the heat of condensation thus released is conserved in the rising volume. The third layer is the layer of outflow (LOF), that between the throat and the tropopause in which
Fig. 3. Enlargement of cloud cluster A in Fig. 2 (not to scale).

Fig. 4. High-level enhancement of cloud cluster A in Fig. 2 (not to scale).
clouds diverge in the form of cirrus plumes. The cloud divergence in this layer is analogous to the horizontal spread of smoke particles in the atmosphere when a rising plume strikes a stable layer. The mean thickness of a cirrus shield atop a cloud cluster has been assumed as 1.0 km following Ludlum (1966), Borovikov et al. (1963) and Anderson. In this model the amount of rain ought to be related to the amount of cirrus present. We know this is true qualitatively and are now trying to quantify this relationship.

While it is possible to derive information on the convective mass and heat transport to the tropical upper troposphere, the proposed convection model does not treat the compensation current in the cloud environment explicitly. Nevertheless, an observed aperiodic or periodic fluctuation in the cirrus canopy and a lifetime much longer than a few hours suggests an unsteady convective circulation associated with cloud-cluster-scale convection, and the air evicted aloft of a deep convection zone does not descend in the immediate vicinity but is removed at considerable distances. Mass continuity is provided by convergence essentially in the planetary boundary layer and "all the air originating in the updraft remains in the upper troposphere, spreading out mainly in the anvil plume downshear but appreciably also in the upshear side" (Newton, 1966).

In a small-scale convective circulation (cumulus congestus), as shown in Model II of Fig. 5, there is hardly any outflow seen on the satellite photographs because rapid mixing with the dry environment inhibits their growth and a clear space is usually evident around them. In the case of an isolated deep convective circulation (Model III) the solenoid field is maintained as long as the colder air with lower moisture content, originating at some levels in the mid-troposphere (Newton, 1966), does not enter the center of the storm. As soon as this cold air current develops in the descending branch both inside and outside of these cells, clear spaces appear around these cells on satellite time-lapse photographs. Such a cloud circulation is often seen in isolated severe thunderstorms in mid-latitudes (Sikdar et al., 1970) and also in tropical regions. Model I may be a better representation for the deep convection cells apparently embedded in a cloud-cluster-scale convection that will be discussed in this paper.

Ludlum (1963) has also shown that the model for large-scale motion systems is similar to that for well-organized cumulonimbus clouds as observed in a cloud cluster, except that the horizontal scale is very much greater. In large-scale convection, the strongest acceleration appears along the trajectory that passes through the condensation region. From the isentropic relative-flow charts the circulations of large-scale mid-latitude convection can be traced back near the surface into much lower latitudes (Green et al., 1966). The magnitude of this far-region descending branch is mainly determined by the radiative heat loss at higher latitudes. The descent period may be up to 20 days before the current returns to the surface layer in the same latitude. The arms of the descending circulation have been left open to show, in the large-scale flow field in the meridional plane, that the descent continues in other systems and that there is no boundary on that side.

If we use Model I the volume \( V_0 \) of a buoyant parcel at the layer of outflow near the cloud top can be related to its volume \( V_L \) at the LCL, using the equation of state, in the form

\[
V_0 = \left( \frac{P_L T_0}{P_0 T_L} \right) V_L, \tag{1}
\]

where the subscript 0 represents the base of the outflow layer and \( L \) the top of the inflow layer, and \( P_0, T_0, T_L \) are corresponding pressure and temperatures.

With mean values of \( P_0, P_L, T_0, T_L \) obtained from upper air soundings in the environment, one gets an
It should be pointed out here that our exclusion of an in-cloud cold downdraft from the proposed flow model will simply reduce our estimates of mass and heat fluxes. The cold air detrained out of the storm bottom was probably entrained from mid-tropospheric levels. Cold air brought down has the same effect on the storm's heat transfer process as does warm air carried aloft.

4. Analysis of ATS pictures

A pronounced cirrus outflow resulting from a number of active penetrative convection cells embedded in a cloud cluster can be easily identified on the brightness-standardized ATS time-lapse pictures against isolated low and middle cloud backgrounds. A cloud cluster is not a Lambertian reflector, especially at large solar zenith angles (Bartman, 1967); at small angles (+30° to −30°), however, a thick cirrus canopy may closely behave as such a reflector. A systematic analysis of high- and low-level brightness-enhanced pictures shows that while the brightness gradient change of a cloud core is sensitive to solar zenith angle change within about 30° of local noon, the mean brightness of a cirrus shield hardly exhibits any such difference. In order to avoid

**Table 1. Number of cloud photographs used in the analysis.**

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<th>Date (April 1967)</th>
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In a deep convective circulation in the tropics, the major source of energy is the water vapor content (the average mixing ratio $W$ is $\sim 20$ gm kg$^{-1}$ in the planetary boundary layer) flowing into the storm which is almost completely converted to liquid or frozen water through expansion cooling of the air in the updraft. Of this liquid or frozen water, only a fraction falls out as rain (Braham, 1952), with as much as 90% remaining behind as cloud. Cirrus shield air carrying these hydrometeors penetrates deeply into the upper troposphere ($\sim 200$ mb) where the mixing ratio hardly exceeds 0.1–0.2 gm kg$^{-1}$.

In this model we have assumed that the equivalent temperature at the LCL is constant, and that all the water vapor passes to the condensed phase as it ascends through the cloud core. The latent heat flux (cal sec$^{-1}$) can be estimated from

$$E_c = L \Delta W \frac{dM_L}{dt},$$

where $L$ is 597 cal gm$^{-1}$ at 0C and $\Delta W = (W_{LOL} - W_0)$. 
any correction for brightness change due to change in solar zenith angle, we have selected satellite pictures over a period of 2 hr on either side of local noon at the sub-satellite point \((0^\circ, 150^\circ W)\), in which period at least 10 pictures are obtained provided the satellite maintains a continuous watch. Moreover, since the proposed technique is employed on two successive satellite photographs 23 min apart, the brightness change due to the change in solar zenith angle of \(\sim 5^\circ\) in each period may be regarded as insignificant (Sikdar, 1969).

5. Data source and coverage

For reasons mentioned in Section 4, we have selected the region 120W–180W, 15N–15S as our study area, and throughout this paper the sections 120W–180W, \(0^\circ\) 15N and 120W–180W, \(0^\circ–15^\circ S\) will be referred to as the Northern Hemispheric Sector (NHS) and the Southern Hemispheric Sector (SHS), respectively. Locations of the conventional surface and upper air stations used in this study are shown in Fig. 6.

The number of daily available ATS I pictures analysed are presented in Table 1. Although one can compute convective heat fluxes from two successive satellite photographs, \(\sim 23\) min apart, a longer sequence of pictures and greater observation frequency render higher accuracy in the evaluated magnitudes. Table 1 clearly shows that the number of photographs analyzed were less than satisfactory except for the period 13–26 April 1967. Nevertheless, we will present whatever information we could derive from this small data sample.

6. Results

a. Time variation of large-scale convective heat fluxes in the tropics

Fig. 7 shows the daily average percent cloud cover in the NHS as well as in the SHS for the investigation period. Each data point in this diagram represents the average of many growing and decaying cloud clusters in each grid sector. In addition to a significant day-to-day variation in percent cloud cover, a periodicity of 7–8 days is clearly evident in this diagram.

Fig. 8 presents the daily mean of the average convective heat transport to the upper troposphere over the mid-Pacific for April 1967 as computed from the model. These magnitudes are directly proportional to the rate of expansion of cirrus shields at the top of cloud clusters as determined from successive ATS pictures. Contrary to the 7–8 day periodicity in the cloudiness cycle which involves cloud motion (Fig. 7), Fig. 8 shows an approximate periodicity of 4–5 days in the convective heat release in the NHS, while in the SHS it ranges from 4 to 6 days. The absence of sharp peaks in the SHS might be attributed to the weak convective activity there during the study period. Nevertheless, these observations clearly suggest an association between the large-scale convective heat release and large-scale wave disturb-
Fig. 9. Latent heat fluxes in zones I and II in the Northern Hemispheric sector for April 1967.

Fig. 10. Latent heat fluxes in zones III and IV in the Southern Hemispheric sector for April 1967.

ances propagating in the tropical troposphere. From the 5-day periodic fluctuations one would be inclined to relate the convective activities over the tropical mid-Pacific to the equatorial wave-type disturbances (Palmer, 1951, 1952). Equatorial waves are known to have wavelengths of the order of 2000–3000 km (about 30° of longitude) and have a period of ~5 days.

b. Phase and speed of the upper tropospheric disturbance

Whether the large-scale heat release referred to in the previous section is initiated by upper or lower tropospheric disturbance fields, by a boundary layer phenomenon, or by some combination of all cannot be determined using present conventional data. However, one may be able to determine from satellite photographs whether the wave pattern indicated in Fig. 8 moves eastward or westward.

In order to determine the pattern motion the convective fluxes were computed in longitudinally separated grid zones, 120W–150W, 150W–180W, in the two hemispheric sectors. The new grids are shown in Fig. 6 by broken lines. The computed energy release (weighted over the respective grid sector) were plotted for each zone as a function of time in Figs. 9 and 10, respectively. The most spectacular change from Fig. 8 is the appearance of sharper peaks at a 4–5 day interval in all zones. A smaller longitudinal grid box is a sharper phase filter for longitudinal wave motions.

Starting with $t=0$ on 4 April 1967 in Figs. 9 and 10, one finds that the first maximum of energy flux density appears in zone II in the NHS. After two days the
FIG. 11. Time cross sections of cloud field in $S^\circ$ latitude belts in the Northern Hemispheric sector ($0^\circ - 15^\circ N$) for April 1967, prepared from ESRA III mosaics. Brighter cloud regions are darker.
maximum appears in zone I. The same feature is observed in the SHS as well. Apparently, a wave disturbance travels westward in both hemispheric sectors. There is a phase difference of 2 days in the appearance of a maximum between the eastern and western portions of the Northern Hemisphere zone and a similar but less distinct phase difference between the eastern and western portions of the Southern Hemisphere zone. When we assign the phase difference to the center-to-center distances between the zones we obtain a wave disturbance speed of 15° of longitude per day. The 5-day period yields a wavelength of 75° of longitude.

Figs. 11 and 12 present the time cross sections for cloud cover in each 5° latitude belt in the grid zone under investigation for April 1967, prepared from the ESSA III computer mosaics. Westward propagation of clouds is clearly evident on these photographs. Also, from the slope of the cloud lines one computes the speed of the cloud field as 6°–7° of longitude per day. Thus, the phase speed of the release of convection is more than twice the speed of the cloud field motion observed in Figs. 11 and 12. Yanai et al. (1968) also found a similar phenomenon involving the upper tropospheric meridional component in the same region and season but for a different year.

Furthermore, by superimposing the upper wave pattern in Fig. 9 on the upper wave pattern in Fig. 10 (western region), one finds a phase difference of 2 days in the maxima, with the one in the SHS leading during the period 4–18 April 1967. This phase difference decreased to 1 day in the case of the fourth maximum and disappeared thereafter. In the eastern sector, on the other hand, a 2-day phase difference is discernible for the period 4–16 April after which no significant difference can be found. The cloud population in the eastern region of the SHS was probably inadequate to reflect the persistence of this feature. The phase relationship between the cited tropospheric disturbance fields across the equator in this short-period study is also suggestive of a mixed Rossby-gravity wave (Matsuno, 1966). These findings therefore suggest that the convective heat release to the tropical upper troposphere over the central Pacific is associated with the mixed Rossby-gravity wave modea rather than the equatorial wave type disturbance of Palmer (1951). The existence of westward-moving waves of planetary scale over the Pacific has been further substantiated by a spectrum analysis of a long series of cloud data (Sikdar et al., 1970).

7. Summary and conclusions

In this paper we have shown, subject to some reasonable assumptions, that one can extract quantitative information on the cloud dynamics of the tropical atmosphere from geosynchronous satellite time-lapse cloud photographs. This short-period analysis suggests the following tentative conclusions:

1) In the tropics large-scale convective activity pulsates with an approximate periodicity of 5 days.

2) The cloud-cluster scale convection systems are well-organized on a time scale of a few days and are probably coupled to the large-scale meridional circulations.

3) The periodic excitation of the large-scale convergence field in both hemispheric sectors seems to be associated with a wave-like disturbance having a wavelength of 75° of longitude, moving westward with an approximate speed of 15° of longitude per day in the troposphere.

4) The westward cloud motion, as evident on the time cross sections, seems to have no relation to the westward propagating large-scale tropospheric disturbance field presented in this paper.

5) A phase difference of nearly 2 days is indicated (for a part of the study period) between moving disturbances north and south of the equator; for the remainder of the period no significant difference can be found.

One of the key problems in models of the tropical atmosphere is to account for the heat release by convection, a phenomenon whose scale is much smaller than the grid mesh used in the model. The statistics from this study have clearly shown that the release of convection in the tropics, at least in the region under investigation, is not random and is controlled by the large-scale motion. In view of the findings for this limited time sample, one is tempted to believe that the determination of heat release in the sub-mesh convective scale may be possible from a knowledge of the large-scale motion field in the tropics. Further investigation in this area is underway.

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