Some Examples of Rapidly Growing Oceanic Cumulonimbus Clouds

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ABSTRACT

Infrared satellite photographs of the tropical oceanic regions within and around the GATE A/B array point to the existence of large, rapidly growing, cumulonimbus clouds. The region along 10°N experiences the greatest frequency of these storms. Also a pronounced diurnal variation is found in the times of initial development with maximum frequencies near midnight. In most cases, this anvil cloud grows to an areal extent $\sim$7000 km^2 in about 4 h, then dissipates in another 3 h. The velocity divergence in the anvil is $1\text{–}3\times10^{-4}$ s^{-1} and the mass outflow is 100–200 kton s^{-1}. These storms account for some of the difference in diurnal variation of high cloudiness that is observed between tropical oceanic and continental regions. A large number of rapidly growing cumulonimbus clouds was observed on 10 August 1974 in connection with a disturbance in the tropical easterlies that ultimately developed into Tropical Storm Alma.

1. Introduction

Convection over the tropical ocean within and around the GARP Atlantic Tropical Experiment (GATE) A/B array takes several forms. Under suppressed conditions fields of cumulus mediocris and cumulus humilis predominate over large areas. More active conditions are characterized by scattered areas of stratocumulus and altocumulus often associated with cumulus and cumulus congestus reaching to altitudes of 4–6 km. As convection becomes more pronounced cumulonimbi appear, surrounded by cumulus of all sizes and layers of altocumulus and stratocumulus. In the most active stage of convection, cumulonimbi are clustered with altocumulus and stratocumulus and together cover areas of 10^4 to 10^5 km^2. The study of these cloud clusters and their life history was one of the major goals of GATE.

The average cumulonimbus may cover an area of a few hundred square kilometers, reach an altitude of 10 km and have a lifetime of 2–4 h. In addition to the many average cumulonimbi, a few clouds of this genus are observed that almost explosively grow to considerably larger sizes and have lifetimes perhaps twice as long. These clouds generally begin growing during the night, often after midnight, and decay by about noon. Because of their unusual vigor these clouds may be important in the hydrologic cycle in tropical oceanic regions. This paper describes an investigation of these storms. Additional information appears in Weickmann (1975).

2. Cloud photogrammetry

In the GATE A/B array most cloud clusters are composed primarily of stratiform clouds (Burpee and Dugdale, 1975). Regions of active convection comprise only a small fraction ($\lesssim 10\%$) of the cluster and have an average lifetime of only 3–4 h, considerably shorter than the 1–2 day lifetime of a typical cluster [see Marks (1975) and Martin (1975)]. This description of a typical cloud cluster comes from a combination of satellite and radar data. Infrared satellite data examined during the course of GATE also led to the discovery of the cumulonimbus clouds considered in this paper. Photogrammetry has yielded some of their characteristics.

Each photograph used in the present study originates from an SMS/GOES geosynchronous satellite located over the equator at about 45°W and covers approximately one-fourth of the earth's surface. Resolution of each photograph is 4 n mi at the satellite's subpoint, and it is possible to detect an individual cloud mass with area as small as 200 km^2. Thus, single, isolated large cumulonimbus clouds can be readily detected, although two adjacent cumulonimbus clouds may not be resolvable in all cases. The error in estimating cloud area is approximately $\pm 50\%$ at 400 km^2, decreasing to $\pm 15\%$ at 7000 km^2.

The rapidly growing, large cumulonimbus clouds observed in the photographs (see, e.g., Figs. 1 and 2) have the following characteristics:

1) Rapid growth of cold cloud in a region where little or no cold cloud previously existed. A typical growth period would be 3–5 h.

2) Bright circular or oval appearance in the growing stage. This is a signature for a developing cumulonimbus-cirrus anvil system.

3) Mature stage with horizontal dimensions of 50–200 km. This corresponds roughly to the meso-β scale defined by Orlanski (1975) and is somewhat smaller

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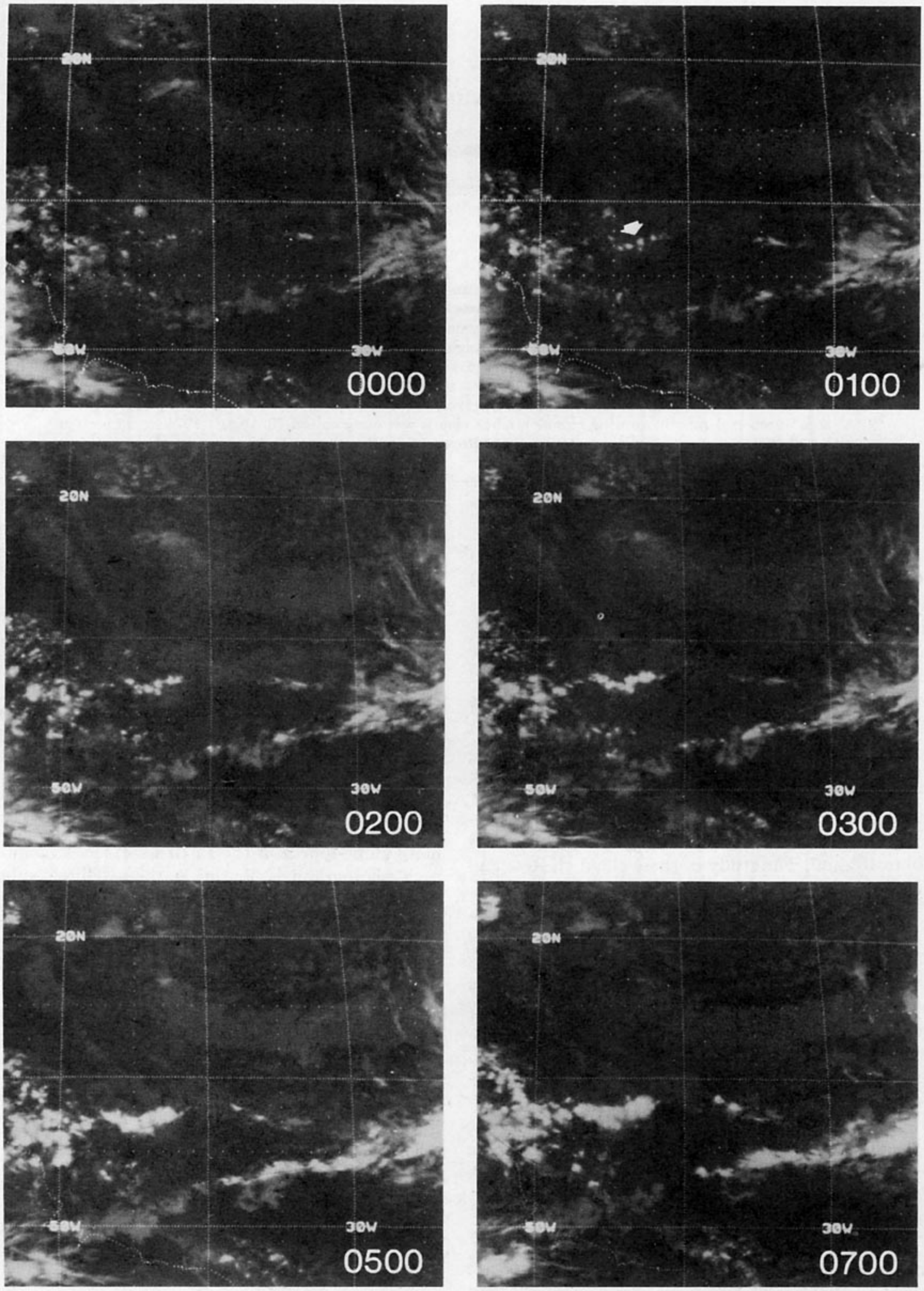

FIG. 1. SMS/GOES infrared photographs showing rapid growth of cumulonimbus on 28 July 1974. Arrows point to examples of strong convective storms in their early stages of growth. Time is Greenwich Mean (GMT).

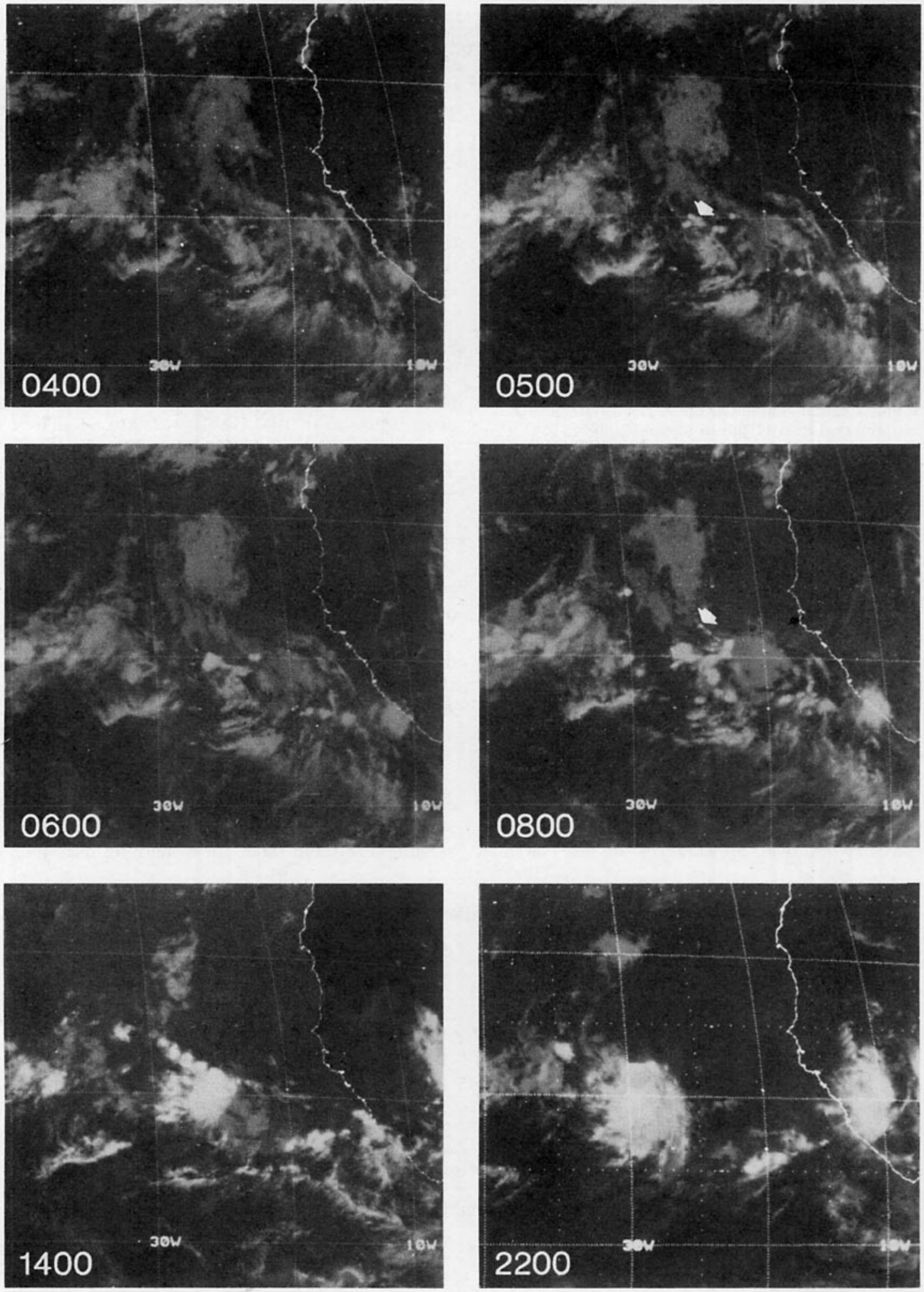

Fig. 2. As in Fig. 1 except on 10 August 1974. The initial development of tropical storm Alma is clearly depicted.

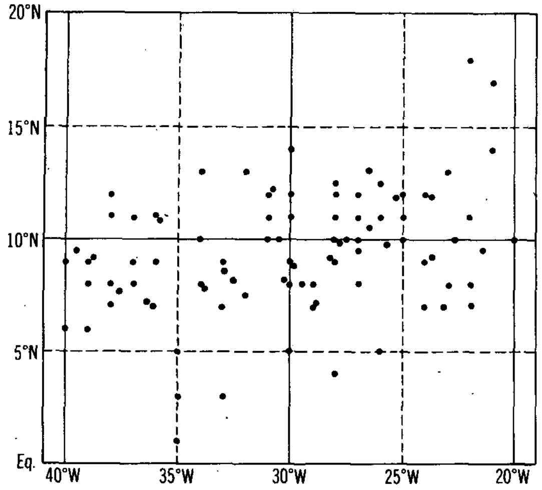

FIG. 3. Initial locations of the 92 cloud systems observed from 17 July–6 September, 1974.

than the average dimensions (100–500 km) of cloud clusters studied by Martin (1975). His clouds are truly clusters, whereas the features examined in the present paper are believed to be large, isolated, single convective elements, although some may have consisted of two or more cumulonimbi.

The cold moisture produced by these cumulonimbus clouds comprises only a small fraction of all that existing in the region studied and associated with cloud clusters and other features. It was possible to distinguish the cirrus anvils being studied from this larger fraction of cold moisture whenever the development occurred in a region with little existing cold cloud. Moreover, clouds that developed in an environment with little vertical wind shear best maintained their circular or oval appearances in the satellite imagery, while the cirrus anvil is advected and diffused downwind in cases with large shear and strong winds aloft. The selection procedure is therefore biased toward systems developing in clear areas without large vertical wind shears.

3. Results

The study of cloud systems was confined to the area from the equator to 20°N and from 20° to 40°W and to the period 17 July–6 September 1974. Fig. 3 shows the initial positions of the 92 observed rapidly growing cirrus anvils, excluding those of Fig. 1.

a. Diurnal variation

The diurnal variation in the time of initial development of these clouds is shown in Fig. 4. Growth most often begins near 0100 GMT or 2300 LST. There is a broad minimum from 0500–1400 LST with a secondary minimum near 2000 LST. Initial development occurs four times as frequently near midnight as near local noon. Fig. 4 is similar to one presented by Martin (1975) for cloud clusters larger than about 10^4 km^2 and reproduced here as Fig. 5. Initial development of these clusters also occurs most often near midnight and least often around noon. Approximately one-third of the 92 cloud systems in Fig. 4 grew larger than the 2° latitude diameter criterion or merged with other clouds to form the more typical cloud cluster. Therefore some of the storms examined in the present study grew to sizes large enough to have been included in Martin's study. Most, however, were of substantially smaller area.

The results in Fig. 4 are also consistent with the extensive analysis of Jacobson (1976). He presents considerable evidence, based on upper air, rainfall, satellite and radar data, for a morning maximum and

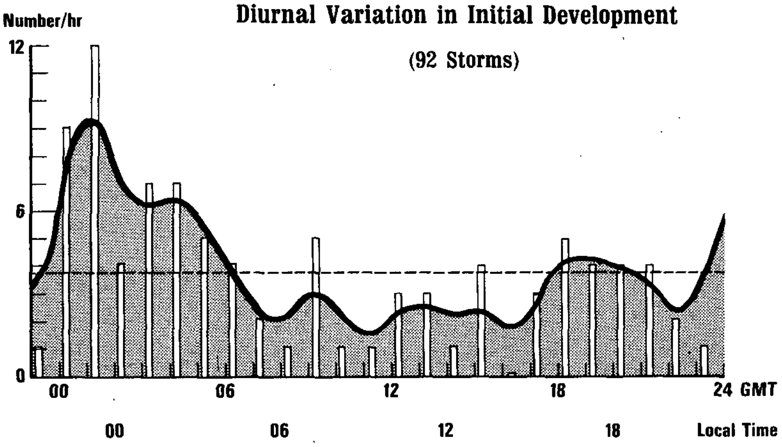

FIG. 4. Diurnal variation in the time of initial development of the rapidly growing cirrus anvils. Both GMT and local solar time (LST) at 30°W are shown. The number within each hourly period is given by the height of the bars. The curve results from applying a $\frac{1}{4}$, $\frac{1}{2}$, $\frac{1}{4}$ smoothing scheme to the hourly totals, while the horizontal dashed line represents the average over all hours.

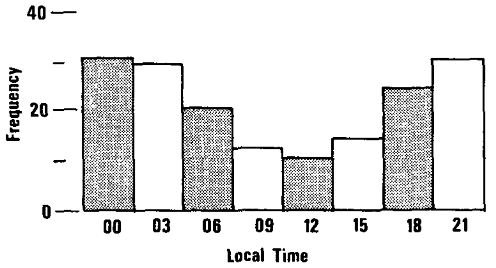

FIG. 5. Diurnal variation in the time of appearance of cloud clusters covering more than 1 deg^2 of the eastern Atlantic. Study area is 10°E–40°W, 10°E–25°N from 28 June–16 July, 1974, and 9°–25°N, 0°–30°W from 17 July–18 September, 1974, with all land and coastal water excluded. From Martin (1975).

afternoon minimum in oceanic deep cumulus convection. In particular, he finds a tropical oceanic rainfall maximum between 0300 and 0600 LST and minimum between 1800 and 2000 LST. Although Jacobson does not state what type of clouds are responsible for this diurnal variation, he does state that the fewer, heavier rains ($\gtrsim$0.3 inches h^{-1}) contributed most to it. Combining the results in Fig. 4 for the clouds treated here with a typical 3–5 h growth period would yield a similar morning maximum and afternoon minimum in the rainfall.

Marks (1975) examined radar data collected during GATE Phase I (28 June–16 July) and Phase II (28 July–17 August) by the Canadian research ship *Quadra* located at 9°15′W, 22°12′N. He found the highest echoes occurred most often between 0030 and 0630 LST. Furthermore, maximum echo heights greater than or equal to 9–11 km occurred most frequently between 0130 and 0430. This consistency with the diurnal variation in Fig. 4 is only somewhat diminished by the observation by Marks that the fraction of the area observed by the radar that was covered by echoes of *any* height, large or small, had a *semidiurnal* variation with maxima at 0530 and 1330 LST and minima at 0830 and 2130 LST. An explanation for this semidiurnal variation may be that the position of the *Quadra* was close enough to the African coast to be in a transition zone between the truly oceanic (morning) and continental (afternoon) convective regimes.

b. Growth of individual storms

The history of 12 rapidly growing cirrus anvils observed on 10 August 1974 appears in Fig. 6. Large amounts of cirrus were produced by several storms starting around 0200–0400 LST and within a few hours each had covered an area of several thousand square kilometers.

The average behavior of these clouds may be summarized by placing growth curves such as those in Fig. 6 at a common starting time and averaging them. The result in Fig. 7 is based on four clouds on 28 July 1974, three clouds on 29 July 1974 and five clouds on

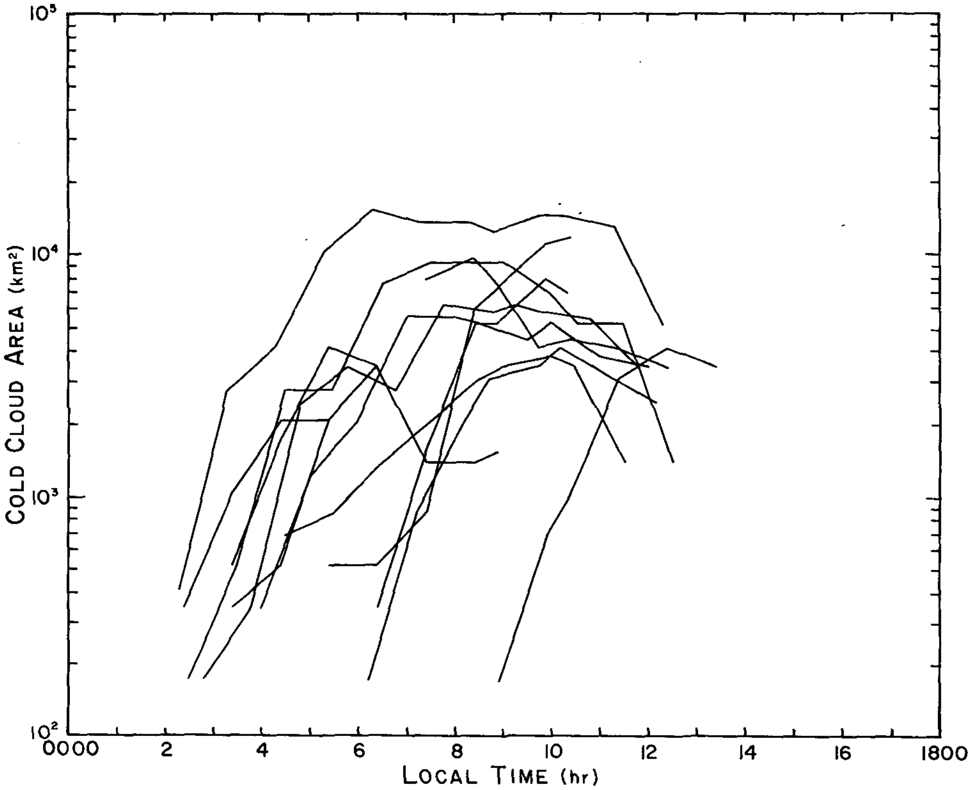

FIG. 6. Histories of 12 rapidly growing cirrus anvils observed on 10 August 1974.

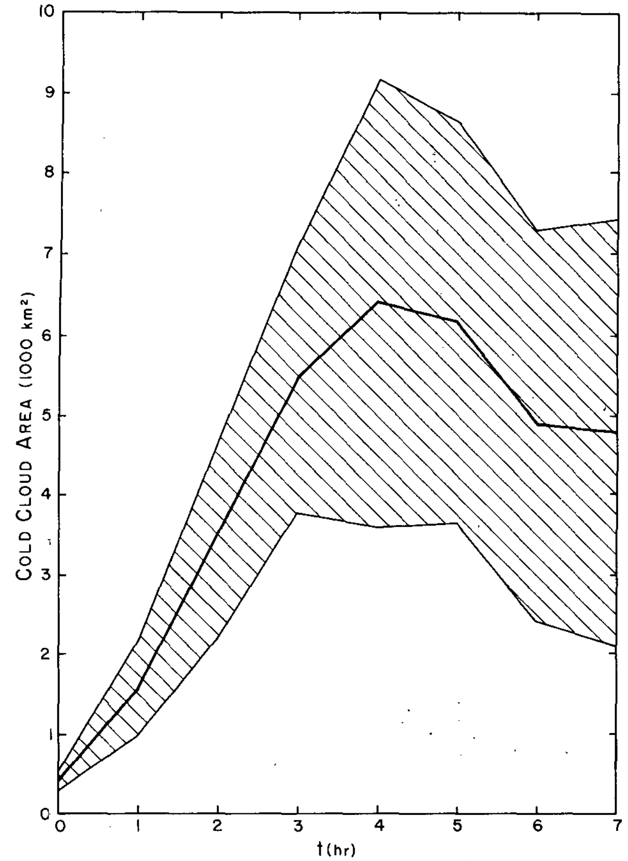

FIG. 7. Mean growth history of rapidly growing cumulonimbus-cirrus anvils. One-half of all storms' histories lie within the shaded region.

18 August 1974, in addition to the 12 on 10 August 1974, and shows that the growth stages of the clouds are fairly similar, at least when compared to the dissipating stages. Within 4±0.5 h each cirrus anvil covered an area of 7300±2300 km^2. The average lifetime of the cirrus anvil was 6.5±1.5 h. Individual differences in the lifetime are the cause of the large variation in anvil area after 4 h in Fig. 7.

If it is assumed that the thickness of a cirrus anvil is constant in space and time, the fractional increase in its area with time gives the velocity divergence at the top of the cumulonimbus cloud (see Sikdar and Suomi, 1971, 1972). Fig. 8 displays the velocity divergence based on mean results in Fig. 7. Inasmuch as the active area of convection beneath the anvil may be no more than 10% of the anvil area the convergence into the underlying cumulonimbus cloud or clouds must be appreciably greater in absolute magnitude. Fig. 8 also gives the mean mass outflow from the anvil, assuming it to be centered at 11 km altitude and to have a thickness of 1 km (Ludlam, 1966). The mass outflow increases by 10% if the anvil is at 10 km and decreases by 10% if the anvil is at 12 km. In any case, the mass outflow is substantial and is similar to that for severe convective storms in the Great Plains.

4. Comparison between oceanic and continental convection

The nocturnal rapidly growing cumulonimbus clouds examined here may contribute to the difference in diurnal variation of the high, cold cloudiness (cirrus anvils) that is observed between the oceanic region around the GATE A/B array and the Amazon region of South America. This latter region is here defined by 45° and 65°W meridians, the 5°S parallel, and the South American coastline to the north. Fig. 9 shows the average high cloudiness over this region during Phase II of GATE from 28 July to 17 August. The data can be divided naturally into 13 days of active convection, when the fraction of the region covered by cold cloud is 8% or more averaged over the day, and into eight days of relatively suppressed convection when the coverage is 5% or less. In both cases heating of the land after daylight induces convection. After a minimum at 1100 LST cloud cover begins to increase; it reaches a maximum at about 1700. This is followed by a marked decrease in cloudiness overnight. Fig. 10 is a similar graph of the high cloudiness over the region from 5° to 15°N and from 20° to 30°W enclosing the GATE A/B array. For this region there is also a maximum in high cloudiness during daytime hours, at

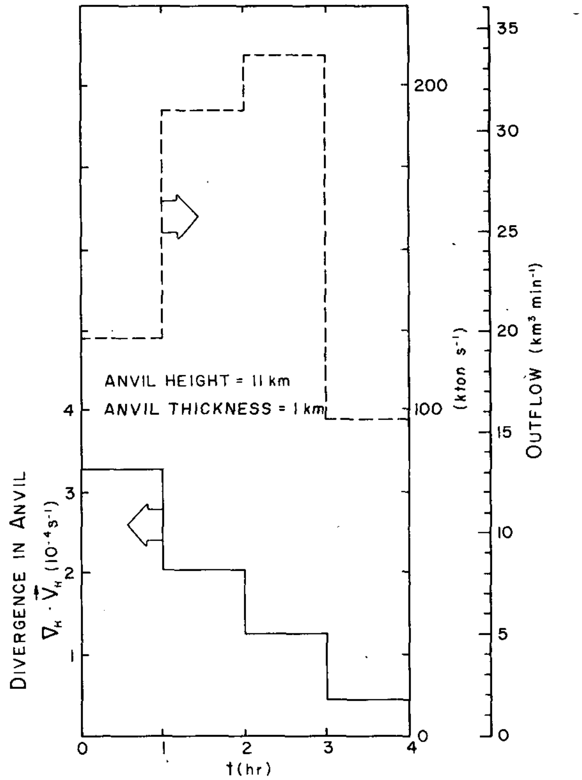

FIG. 8. Velocity divergence and mass and volume outflow in the anvil of a rapidly growing cumulonimbus. Based on mean growth data in Fig. 7. The arrows attached to the two graphs point to the appropriate ordinates.

about 1300. However, in contrast to the Amazon region there is no marked decrease in cloudiness during the late night hours.

The diurnal variation in Fig. 10 is similar to that recently presented by Gruber (1976). Gruber, however, found a much higher percentage (approximately 23% as compared with about 8% in Fig. 10). These differences are probably due to the selection criteria as well as differing sampling areas and time periods.

Both Gruber's data and Fig. 10 show an average daily variation of 5–8% with minimum values near midnight. Recalling the selection proceedings listed in Section 2, there is a slight bias toward selecting convective clouds during the period of less high cloudiness. This bias, however, cannot account for the large diurnal variation in the times of initial development as shown in Fig. 4. We believe that the slight increase in the amount of high cloudiness observed after local midnight over the GATE A/B scale area is due to an increase in the development of convective clouds as shown in Figs. 4 and 5.

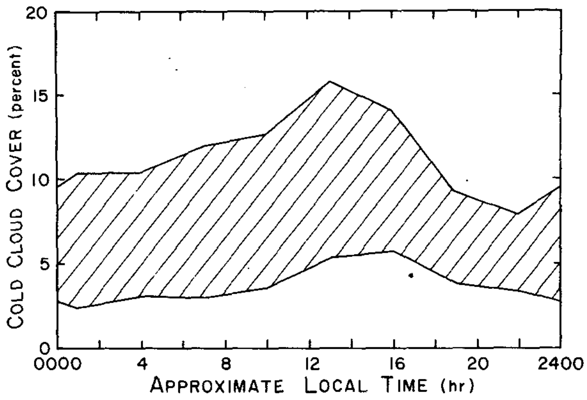

Fig. 10. As in Fig. 9 except for a region from 5°N to 15°N and from 20°W to 30°W enclosing the GATE A/B array.

5. Formation mechanism

Although there are little meteorological data to suggest detail mechanisms leading to the formation of the rapidly growing cumulonimbus clouds examined here, satellite data do suggest most are associated with disturbances in the tropical easterlies (see Fig. 1). During the time interval from 0400 to 0600 GMT on 10 August several rapidly growing cumulonimbus clouds began developing near 25°W, 9°N. Several others began developing about 0800 GMT along a NW–SE line centered at about 24°W, 12°N. These developments occurred as a strong disturbance in the tropical easterlies moved off the African coast into the GATE A/B scale network. By 1400 GMT the individual cloud systems had grown and merged into a well-defined cloud cluster, and by 2200 GMT this cloud cluster had assumed the shape of a weak cyclonic vortex. It moved slowly westward and ultimately became Tropical Storm Alma.

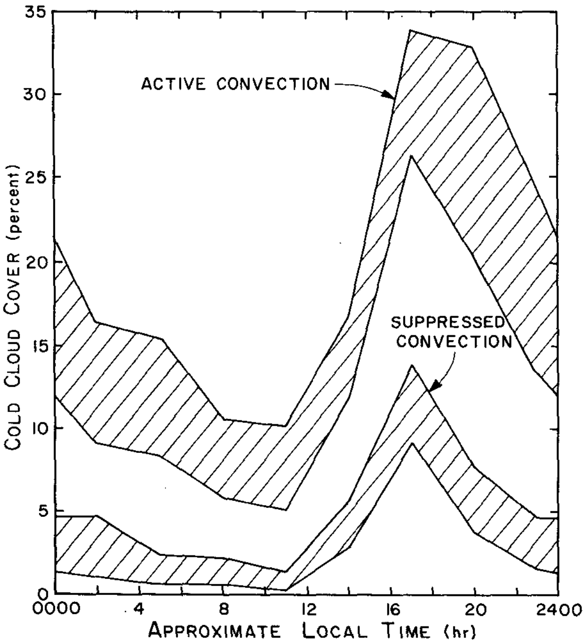

Fig. 9. Percent of the Amazon region of South America covered by high, cold clouds from 28 July to 17 August, 1974. Mean values and one-half of all values lie within the shaded regions. See text for definitions of active and suppressed convection.

6. Summary

Infrared satellite photographs of the tropical oceanic regions within and around the GATE A/B array point to the existence of larger-than-average rapidly growing cumulonimbus clouds. These clouds most often begin producing cirrus anvils at about 2200–0300 LST. On the average, these anvils grow to an areal extent of 700 km^2 in about 4 h. Most dissipate in another 3 h. The velocity divergence in the anvil is 1–3×10^{-4} s^{-1} and the mass outflow is 100–200 kton s^{-1}. These storms may be responsible for the difference in diurnal variation of high cloudiness that is observed between tropical oceanic and continental regions. A large number of rapidly growing cumulonimbus clouds was observed on 10 August 1974 in connection with a disturbance in the tropical easterlies that ultimately developed into Tropical Storm Alma.

REFERENCES

Burpee, R. W., and G. Dugdale, 1975: A summary of weather systems affecting western Africa and the eastern Atlantic during GATE. GATE Rep. No. 16, Report on the Field Phase of the GARP Atlantic Tropical Experiment—Scientific Programme, 2.1–2.42.

Gruber, A., 1976: An estimate of the daily variation of cloudiness over the GATE/AB area. *Mon. Wea. Rev.*, **104**, 1036–1039.

Jacobson, R. W., Jr., 1976: Diurnal variation of oceanic deep cumulus convection. Paper 1: Observational evidence. Dept. Atmos. Sci., Colorado State University, 48 pp.

Ludlam, F. H., 1966: Cumulus and cumulonimbus convection. *Tellus*, **18**, 687–698.

Marks, F., 1975: Study of diurnal variations in convection using Quadra radar. Phases I and II. GATE Rep. No. 14, Preliminary Scientific Results, Vol. 1, 191–204.

Martin, D. W., 1975: Characteristics of West Africa and Atlantic cloud clusters. GATE Rep. No. 14, Preliminary Scientific Results, Vol. 1, 182–190.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, **56**, 527–530.

Sikdar, D. N., and V. E. Suomi, 1971: Time variation of tropical energetics as viewed from a geostationary altitude. *J. Atmos. Sci.*, **28**, 170–180.

——, and ——, 1972: On the remote sensing of mesoscale tropical convection intensity from a geostationary satellite. *J. Appl. Meteor.*, **11**, 37–43.

Weickmann, H. K., 1975: Observations on convective clouds over the tropical Atlantic. GATE Rep. No. 14, Preliminary Scientific Results, Vol. 2, 145–155.