# Cloud Patterns in Hurricane Daisy, 1958[1]

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*Abstract*

Maps of clouds in Hurricane Daisy, 1958, have been constructed from aerial ciné photographs made by the aircraft of the National Hurricane Research Project of the U.S. Weather Bureau. Films suitable for quantitative analysis were available for four flights on three separate days during the formation, deepening, and maturity of this small but intense Atlantic hurricane which moved slowly over the ocean in the vicinity of 30° N, 76° W. Clouds were located within 5—10 nautical miles relative to the known aircraft path (in coordinates with origin at hurricane center) by a modified method of aerial photogrammetry using the accurately known times for the image to cross a frame. Horizontal and vertical dimensions of important clouds and cloud forms have been measured to within about 10 %.

The photographic maps are compared to radar analyses made from the same and also different aircraft (U.S. Navy WV-4). The most significant results are first the remarkable persistence of recognizable cloud patterns throughout the three days studied, during which the storm deepened and moved about 200 nautical miles and second, the concentration of convective activity into a few lines of cumulonimbus towers which even on the mature day occupied only about 4 % of the rain area (radius within about 200 nautical miles).

**Intr duction**

Hurricane Daisy, 1958, afforded the first opportunity for a quantitative study of cloud structures during the formation and deepening of a tropical hurricane. The instrumented aircraft of the National Hurricane Research Project of the U.S. Weather Bureau (hereinafter referred to as NHRP) successfully obtained data from several flight levels on August 25, 26, 27, and 28, 1958, in the incipient, deepening, mature, and decay phases of the storm, respectively. The basic measurements were of winds, temperature, and humidity as functions of position as the aircraft executed their prescribed flight patterns. Time-lapse motion pictures (in kodachrome) were made from ciné cameras mounted in the nose of each aircraft; some of the footage was suitable for cloud measurements and mapping. We have undertaken this extensive labor for two main motives: first to provide a quantitative description of the cloud patterns; and second as a test and supplement to numerous calculations concerning individual clouds and their role in the processes of the storm (MALKUS, 1960).

Recent hurricane models (see, in particular, MALKUS and RIEHL, 1960) suggest the important function of convection. The furious winds are driven by latent heat released by giant clouds; their concentrated and highly buoyant character is also apparently essential in the heat and mass transports of the storm. The models envisage that the ascent in the core occurs in extremely restricted regions of undilute, rap-

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idly rising cumulonimbus towers, which only come to occupy a significant fraction of the rain area as the eye wall is approached (MALKUS, 1958). This latter concept has been informally christened the "hot tower hypothesis". Suggested originally by an equatorial trough study (RIEHL and MALKUS, 1958), it is currently being evolved and tested in the hurricane context (RIEHL and MALKUS, 1961). This paper lays a part of the background by presenting results of the cloud mapping.

The questions we hoped to answer were thus largely focussed on convective clouds. Are there orderly patterns or lines of cumulonimbus, and if so how are these oriented and how persistent are they? How many large cumulonimbus towers occur and are they clustered in particular quadrants or regions of the storm? Is penetrative convection occurring randomly throughout the rain area or is it highly concentrated in small regions separated by wide suppressed zones? What is the origin and distribution of the "cirrus shield" and stratus layers? And finally, how does a picture of the storm we see on a radarscope correspond with that which the eye or camera would behold?

## 2. The data and method of study

The basic data from which our measurements were made were the NHRP aircraft nose camera films. The most attention was concentrated on the flights of August 25 and 27, the formation and mature days of the storm. These are the days for which extensive budget, dynamic, and energetic calculations have been carried out (RIEHL and MALKUS, 1961) for the storm as a whole and can be used in comparison with the cloud study. On August 25th, three flight levels were flown, but only the upper, or C-level film, had time marks permitting detailed reduction. On August 27th, upper and middle-level flights were made and both have been analyzed herein. A somewhat rougher analysis of the high level flight on the 26th has been included for continuity.

The method of film reduction was adapted to the observational procedures of NHRP and designed to take advantage of the accurate Doppler navigation of their aircraft. Absolute geographic positions were known at all times to within 3—4 nautical miles. The position of the storm center was defined from radar photographs; it was found as a function of time using these, together with a preliminary temperature and wind analysis. All data were then repositioned in terms of coordinates relative to the moving center. The base maps for our cloud study consisted of "plot-outs" for each flight provided by NHRP showing the aircraft track in these coordinates with times entered thereon. Aircraft positions relative to defined storm center are accurate within 1—2 nautical miles.

The detailed procedures of cloud measurement and mapping from the films have been described elsewhere by RONNE (1959) and therefore will be summarized only briefly here. A simplified version of aerial photogrammetry was employed whereby clouds are located relative to the aircraft by measuring the time required to traverse the picture or fixed portions thereof, since the interval between frames was accurately determined. On the three upper-level flights, frames were exposed at an average rate of 50 per minute. A clock appeared continuously in the photographs, permitting the exact rate to be found at each measurement; synchronization with the plot-out was achievable within 30 seconds. Since the aircraft made a ground speed ranging between 6.8 and 7.5 nautical miles per minute, errors in cloud positions (in relative coordinates) did not exceed 4 nautical miles due to this cause. On the one mid-level flight analyzed, intermittent appearances of a watch were supplemented by frame counts from recognized turns in the flight pattern. The frame interval here was electrically fixed at 30 per minute throughout. Although synchronization of film to plot-out may have been off as much as 50 seconds, the slower ground speed of the aircraft (3.4—4.5 n.m. per min.) compensated, and again the resulting error in relative coordinates was never more than 4 nautical miles.

In general, a point on a selected cloud was located on the map by two or more separate fixes upon it from aircraft positions several minutes apart. A large-sized cloud usually required several points to locate it on the map. Horizontal dimensions of smaller ones were readily obtained from distance away, image size, and lens properties. These photogrammetric calculations can be shown to be accurate to about 5 %. Altogether, then, clouds within 50 n.m. of the flight path have been mapped to within about 5 n.m. of their actual (relative to storm center) positions, while those between 50—100 n.m. of the flight path are located within 10 n.m.

The vertical extent of a cloud presented a greater problem, as few were visible in their entirety from base to top. A horizon had therefore to be determined on the film. On August 25 this was not difficult; the actual horizon was visible during large portions of the flight and the aircraft attitude remained steady. Furthermore, an independent height-size relationship from dynamic computations (MALKUS, 1960) was available as a test. The top heights for the 25th are thus correct to within about 1000 ft. On the 27th, the horizon was visible less often and the aircraft wobbled more. The heights are thus only accurate to about 2000 ft for those clouds measured precisely. Many others have been indicated as approximately determined. Checks on the horizon were provided by the internal consistency of tower tops at varying distances, several cases of clouds visible from base to top, and one case of distance determination on a cloud whose base was exactly at the bottom of the frame, all with excellent results. A correction for the earth's curvature and atmospheric refraction was introduced for all clouds at distances greater than 10 nautical miles (see RIEHL, GRAY, MALKUS, and RONNE, 1959). Retrospectively, the greatest disadvantage in such a study is not the problem of accuracy, which proved adequate for the purposes desired, but the fantastic labor involved. The maps presented

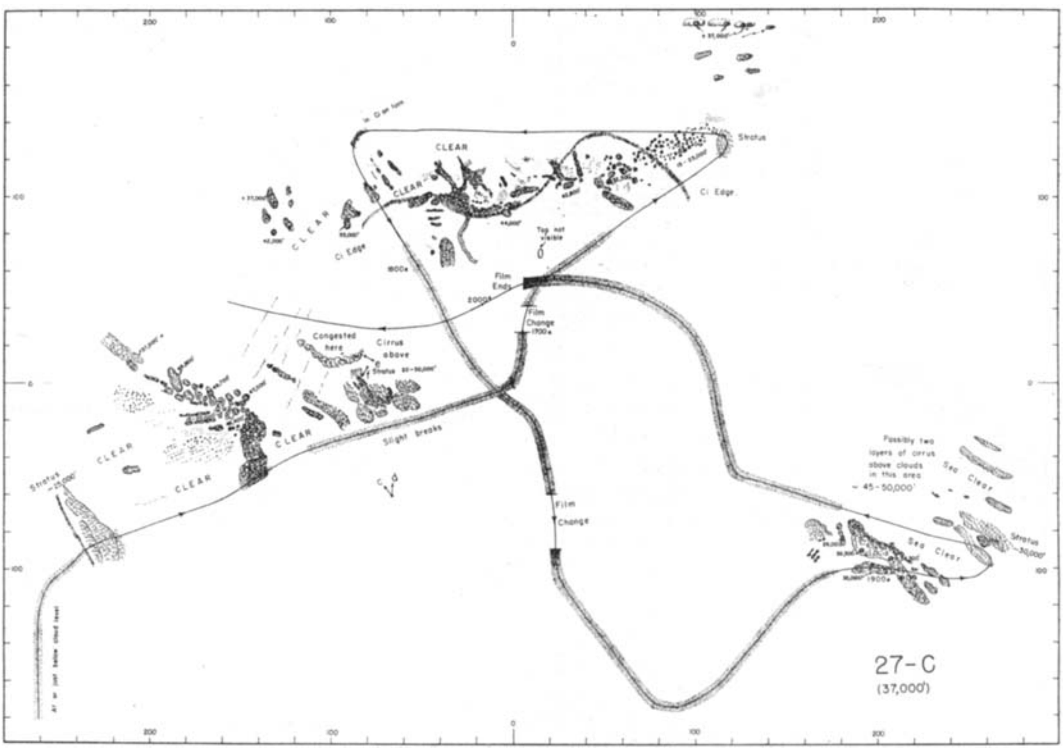


Fig. 1. Photographic cloud map for Daisy August 25, 1958, constructed from C-level (37,000 ft) NHRP nose camera film. Camera axis aimed 50° to left of flight path, horizontal view angle is about 53°. Coordinates are in nautical miles relative to origin at storm center. Solid line with arrows is flight path, with times (Greenwich or Z) noted every hour. Stippled portion of path denotes "in cloud" and relative darkness is indicated by dot density. Edge of cirrus shield (when above aircraft) denoted by dashed line with perpendicular hatching. Heights of tops of most penetrative cumulonimbi (tops > 37,000 ft) noted. Dotted regions to left of east flight leg are rows of suppressed small cumuli. Arrows marked "a" and "b" are locations and directions of corresponding still photographs shown in Fig. 5, made from mid-level (15,600 ft) flight during same period.

herein required six months full-time effort on the part of three experienced persons; in the future, the reduction time could conceivably be cut in half if the original photographs were taken with this use in mind.

### 3. Discussion of the cloud maps

The resulting cloud maps for the high-level flights (altitude about 37,000 ft) for August 25, 26, and 27 are shown in Figs. 1—3. The middle-level flight for the 27th (altitude 13,000 ft) is shown by itself in Fig. 4 and in red superposed on the corresponding upper flight in Fig. 6. Fig. 5 shows selected still photographs from the 25th and 27th; their locations and directions are indicated by arrows in Figs. 1, 3, and 4. Pertinent general information concerning hurricane Daisy on these days is summarized in Table I. A detailed presentation of analyses of the NHRP Daisy wind, temperature, and humidity data has been prepared by Colón et al. (1961).

*August 25—Formation Day*

The flights on August 25, 1958, explored hurricane Daisy between the hours of 1800—2300 Z or Greenwich Civil Time (1300—1800 EST). The storm was centered near 27° 30′ N, 76° W and was moving northwestward at 7 knots. The central pressure had achieved 997 mb and was thus at the transition point between "tropical storm" and "hurricane"; correspondingly the maximum wind strength had reached 60 knots, just short of hurricane force.

The cloud map is shown in Fig. 1. In studying it, the sampling problem should be brought to mind. On all the upper level flights, the

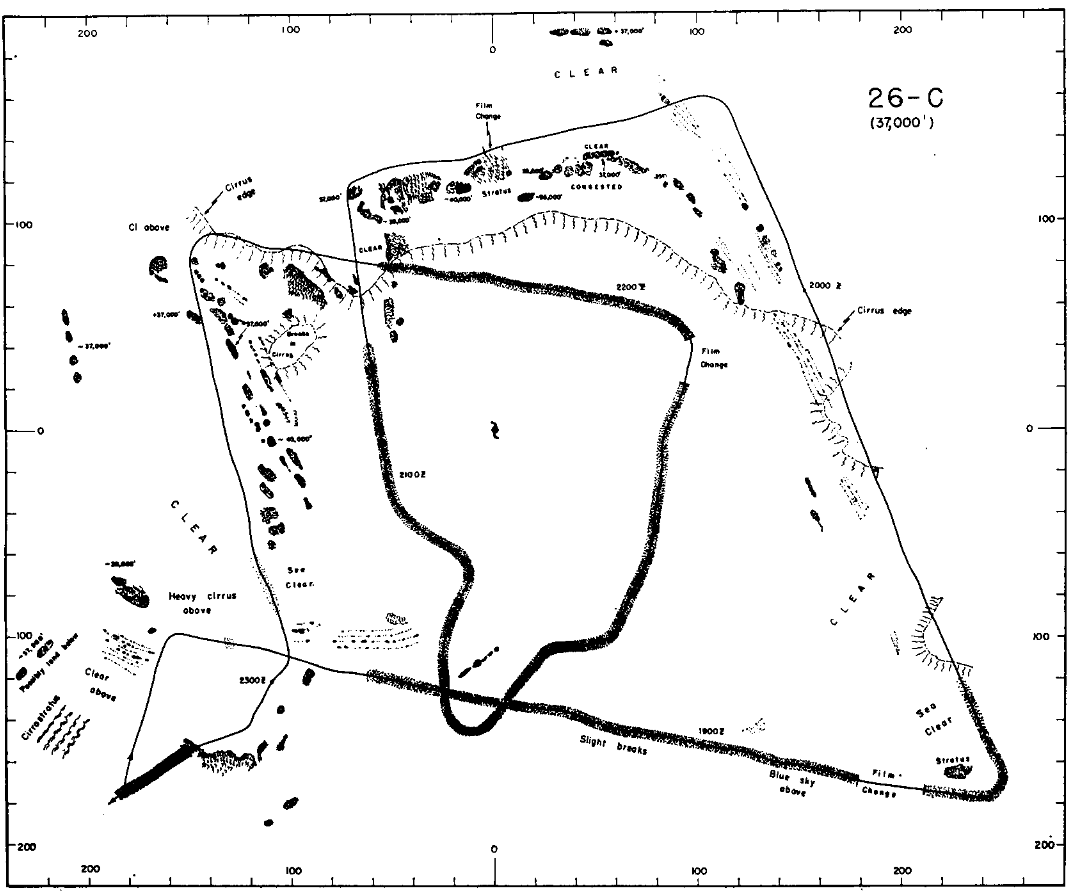


Fig. 2. Photographic cloud map for Daisy August 26, 1958, constructed from C-level (37,000 ft) NHRP nose camera film. Notation, coordinates, and procedure same as Fig. 1.

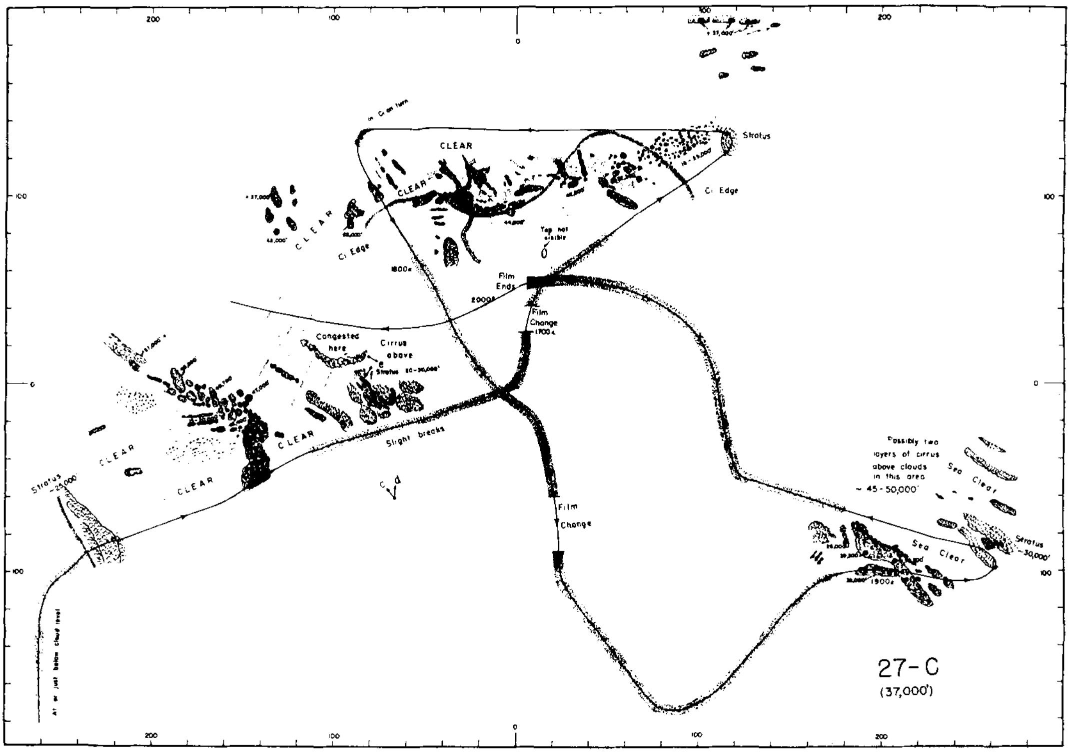


Fig. 3. Photographic cloud map for Daisy August 27, 1958, constructed from C-level (37,000 ft) NHRP nose camera film. Notation, coordinates and procedure same as Fig. 1. Arrows marked "c", "d", "e" and "f" are locations and directions of corresponding still photographs shown in Fig. 5, made from mid-level (c and d at 13,000 ft; e and f at 20,000 ft) flight during same period.

camera was pointed 50° to left of straight ahead so that very few clouds to the right of the aircraft's path could be seen. Secondly, the enormous labor of cloud plotting makes it inevitable that the coverage is less than complete, so that the actual cloudiness is always greater than the map suggests. Furthermore, the aircraft was "socked in" by cirrus during approximately 40 % of the time spent in the storm area; actually the lower flights and other evidence suggest that the region covered by cirrus (somewhat more than the southeast quadrant) was the most active portion of the storm, in terms of convective activity, precipitation, and wind speeds. These reservations must be kept in mind in drawing conclusions from our results. Our procedure in mapping was to concentrate on accurate locations of all visible well-delineated cumulonimbus towers reaching flight level and above, and upon accurate mapping of the cirrus shield. Samplings and height ranges of groups of middle level cumulus were taken wherever possible, and the organization of smaller suppressed cumuliform clouds was noted schematically in the proper locations. Stratus decks were entered schematically wherever these were prominent.

*Cumulonimbus structure*

The highest cumulonimbus tower seen was at 47,000 ft; it had an active, rounded top, 6 km across, located 80 n.m. due south of the center. About fourteen penetrative towers reaching above flight altitude (tops above 37,000 ft) were mapped. This sample permits us to estimate roughly the total number of towering cumulonimbi in the rain area. One-third of the rain area (radius 200 n.m.) was rendered invisible by cirrus. About one-half of the remaining two thirds was sampled by the camera. Therefore, if the unsampled portions were no more productive of cumulonimbi than the sampled portions, about forty towers in the active or just dying phase might be ex-

Fig. 5. Series of still photographs illustrating visual character of hurricane Daisy, a and b for August 25, remainder for August 27.

a. Still photograph, located and oriented as shown by arrow in Fig. 1. Time: 2143 Z, August 25, 1958. Made from mid-level aircraft at 15,600 ft.

b. Still photograph, located and oriented (approximately) as shown by arrow in Fig. 1. Time: About 2330 Z, August 25, 1958. Made from mid-level aircraft at 15,600 ft.

c. Still photograph, located and oriented as shown by arrows in Figs. 3 and 4. Time: 1544 Z, August 27, 1958. Made from mid-level aircraft at 13,000 ft.

d. Still photograph, located and oriented as shown by arrows in Figs. 3 and 4. Time: 1544 Z, August 27, 1958. Made from mid-level aircraft at 13,000 ft.

e. Still photograph, located and oriented as shown by arrows in Figs. 3 and 4. Time: 2048 Z, August 27, 1958. Made from continuation of mid-level flight at 20,000 ft.

f. Still photograph, located and oriented as shown by arrows in Figs. 3 and 4. Time: 2050 Z, August 27, 1958. Made from continuation of mid-level flight at 20,000 ft.

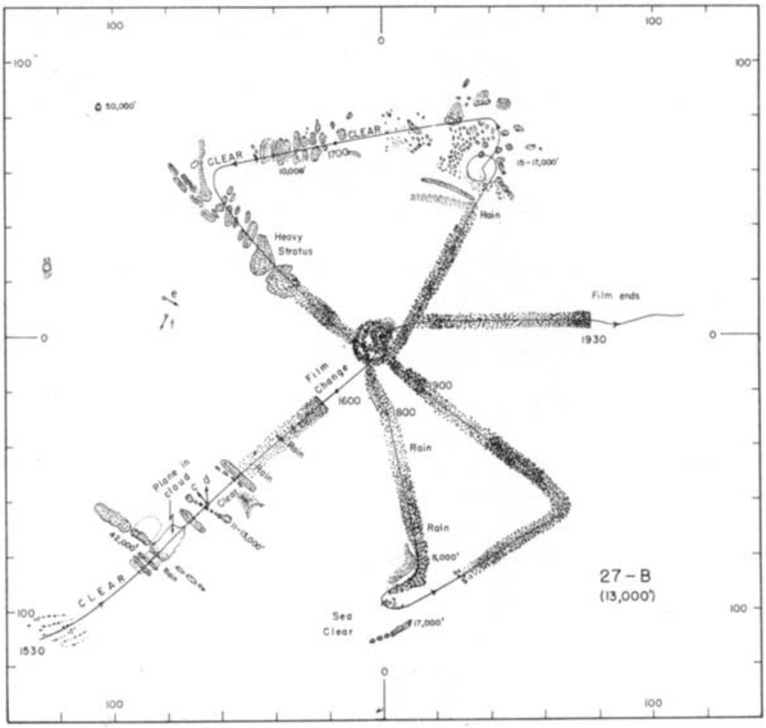


Fig. 4. Photographic cloud map for Daisy August 27, 1958, constructed from the B-level (13,000 ft) NHRP nose camera film. Notation, scale, coordinates and procedure same as Figs. 1—3, except for difference in aircraft, flight path, altitude, and camera orientation. The mid-level nose camera was aimed straight ahead. Arrows marked "c" and "d" denote corresponding still photographs in Fig. 5 taken on this flight, arrows marked "e" and "f" denote last two stills in Fig. 5 which were taken from a higher-level (20,000 ft) continuation of this flight not covered by the ciné film.

pected. Actually, since the eye wall and most active third of the rain area were those parts not sampled, we estimate the number as nearer sixty, since the lower level films suggest that the actively convecting regions were about twice as close together in the cirrus-covered region.

The cumulonimbus towers were clearly concentrated in widely separated rows, approximately parallel to the low-level flow, although the continuous "spiral band" character was both much less than ideal and less pronounced than that observed in hurricane Cleo a week previous (now being studied). The main row visible to the camera was found just south of the northern flight leg. Along this leg its distance from the center decreased from about 160 n.m. at the eastern end to 120 n.m. at the western. Later the radar comparison will suggest that this band spiralled into the eye wall on its west side, with a break to more suppressed cloud material occurring between 80 and 40 n.m. north-northwest of the center. The highly congested region 80 n.m. to the south of the center which contained the tallest (47,000 ft) tower was apparently a fragment of a second band which may have spiralled in to the eye wall on the east side. With the exception of an interrupted line of widely separated towers oriented northwest—southeast about 160 n.m. out in the southwest quadrant, and a faint suggestion of what could have been another distant partial band more than 200 n.m. to the north, these were all the "hot towers" which were visible on the film. We may therefore conclude that penetrative convection was extremely highly concentrated into very restricted regions, which in

**Table 1. Hurricane Daisy**

| Date | Time of C Flight | Location of Center | Central Pressure | Maximum Wind | Movement of Storm Center |
|---|---|---|---|---|---|
| Aug. 25 | 1800—2300 Z | 27°30'N; 76°W | 997 mb | 60 kt | 7 kt, to NW |
| Aug. 26 | 1800—2300 Z | 28°30'N; 76°50'W | 972 mb | 90 kt | 3 kt, to NNE |
| Aug. 27 | 1600—2100 Z | 29°30'N; 75°20'W | 950 mb | 115 kt | 8 kt, to NE |

turn were lined up with the low-level flow in widely separated rows; altogether not more than 1 % of the rain area within 200 n.m. can have been occupied with active towers at this level and at this time.

A remarkable and unexpected feature of the penetrative cloud structure on this flight was its persistence. For example, the group of cumulonimbi to the south of the center containing the 47,000 ft buildup and at least one more up to flight level was first observed on the entering leg at about 1830 Z although the aircraft went into cirrus too soon for a measurement on them at that time. The measurements were actually made on the southward leg (which terminated at 2100 Z) 2 ½ hours later, when remarkably enough, the cloud group had very nearly the same appearance, including a giant buildup! It will be recalled that the storm had moved some 12—13 n.m. in that time and thus this persistent cloud feature cannot be attributed to any fixed oceanic or geographic influence. Furthermore, the nearest Bahama Islands were 40—50 n.m. from this locality (see Fig. 7). From our knowledge of the life spans of non-hurricane cumulonimbi (MALKUS and RONNE, 1954), it is questionable whether the same cloud was seen on both legs; alternatively this spot, relative to storm center, may have been a preferred one for cumulonimbus production.

Another apparently persistent cumulonimbus was the 38,000 ft one passed through by the aircraft just northwest of the eye at 2155 Z, which was also located and measured on the southward leg at 2030 Z, or nearly 1 ½ hours earlier. This cloud apparently moved 10—15 n.m. toward the south in the interval and it is therefore not certain whether it was the same cumulonimbus, moving downwind at about one-third the low-level wind speed, or a new one regenerated in nearly the same spot, relative to storm coordinates. However, the appearance of the cloud in this location shown in the still photograph (Fig. 5a) from the mid-level flight at 2143 Z is recognizably similar to that on the nose camera film at 2030 Z, except for aging of the top and spreading out of the anvil.

If, in fact, it turns out upon further study that there are preferred spots for tower generation which remain relatively fixed in storm coordinates, this is a significant matter. It may be related to meso-scale wind and temperature streakiness and may further hold the key to interaction between the convective structure and the large-scale dynamics of the storm.

*Eye*

The high-level flight made no eye traverses on this day, although the lower flights and observers' reports record that throughout Daisy's history it was very small (about 10—15 n.m. diameter), and cloudy. The eye and wall cloud will be discussed later in connection with the radar.

*Cirrus*

Cirrus was first encountered by the aircraft on the entrance leg 160 n.m. from the storm center. It was in the form of streamers, oriented approximately north-south. Where the stippled region on the map begins, the plane entered cirrus at flight level and remained "socked in" almost to the northeast corner of the pattern. The edge of the cirrus (above flight level) is marked along that leg; it continued, in a banded and broken manner to the west of the storm center where it ended less than 100 n.m. from the eye wall, in contrast to its greater than 200 n.m. extent on the east side. In addition to its pronounced asymmetry on the 25th, the cirrus was not generally well organized into a uniform "shield" but was frequently in the form of streamers apparently emanating from the eye wall and congested regions of cumulonimbus such as the one 80

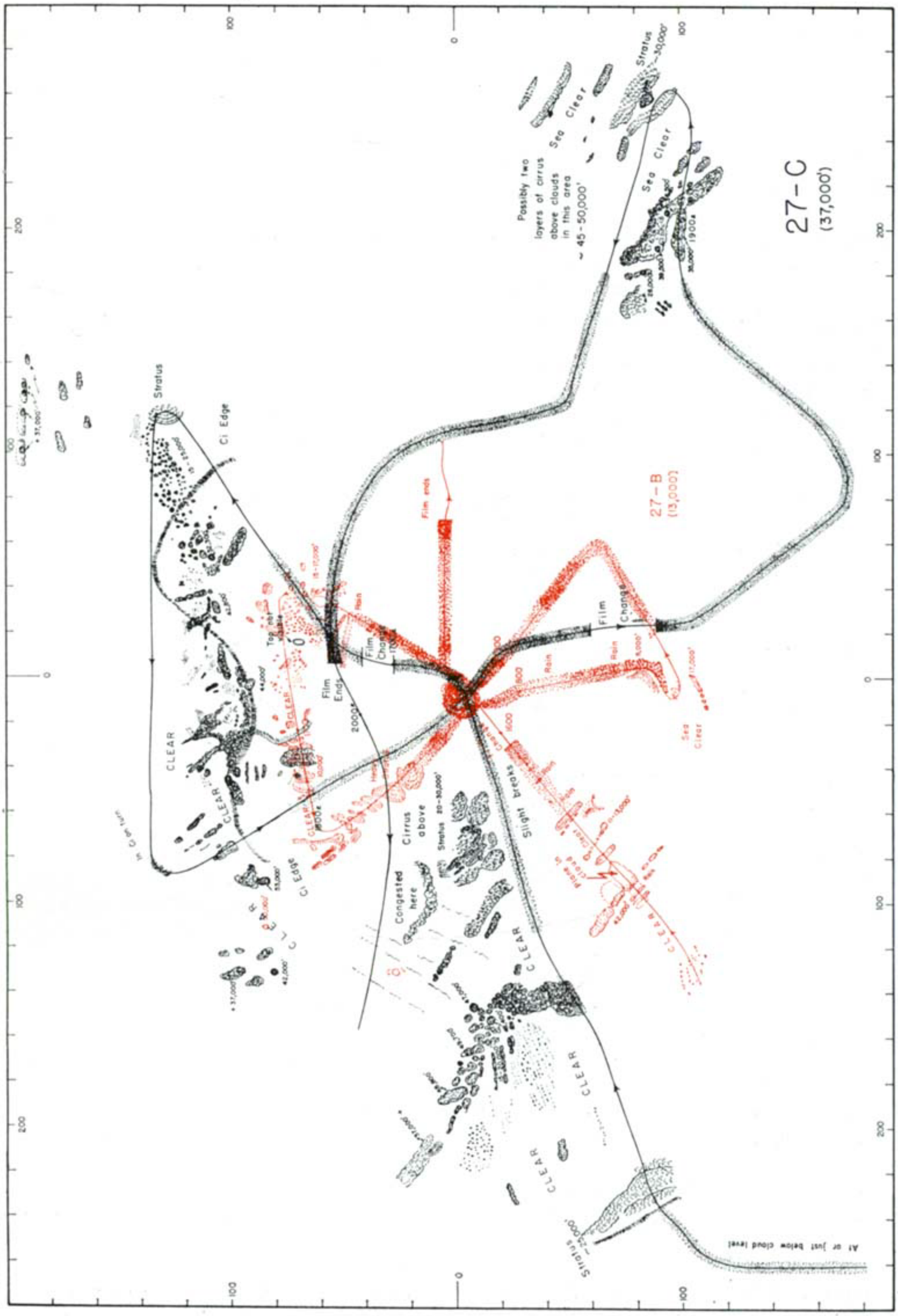


Fig. 6. Mid-level cloud map (red) for Daisy, August 27 (previous Fig. 4) superimposed on high-level cloud map for August 27 (previous Fig. 3).

n.m. to the south of the center (contrast Figs. 5a and b with 5f made two days later on August 27th).

*Summary of cloud features on August 25*

The cloud configuration on the 25th was apparently in a transitional stage from the deep easterly wave type (examples mapped elsewhere by this group, i.e. report by Riehl, Gray, Malkus, and Ronne, 1959) which is extremely asymmetrical, with the huge buildups and cirrus confined to a convection zone to the rear side (generally the east) and the full hurricane in which the distributions are generally more symmetrical about the center. It will be seen, however, that even on Daisy 25, the cloud patterns far more closely resembled those of Daisy 26th and 27th, than they did either the deep easterly wave or any other disturbance so far studied.

Visible cumulus congestus (tops 10—25,000 ft) were considerably rarer than in the easterly wave, although on Daisy 25 they were more common than later on in the storm. They were not seen inward of 100 n.m. except in the neighborhood of cumulonimbi. The visible parts of the inner rain area ($r < 100$ n.m.) were characterized by alternation between very restricted regions of huge buildups and much wider suppressed regions with two or more stratus layers (often very broken) showing scud and intermittent lines of suppressed cumuli below, as contrasted by the photographs in Figs. 5a and 5b. The stunted cumuli were particularly pronounced throughout the eastern flight leg; wherever one could see downward, the sea surface was obscured by small highly-organized rows of them lined up approximately from south-southeast to north-northwest, or parallel to the low-level flow.

The western portion of the "rain area" was very much freer of cloud than the eastern, with little or no precipitation beyond 40 n.m. from the center, except for a line of showering congestus nearly 260 n.m. out. This region contained mainly streaky cirrus aloft and rows of suppressed cumuli below, with wide patches of visible blue sea and sky.

*August 26—Deepening Day*

The high-level flight on August 26th took place just 24 hours after that of the 25th. The flight patterns flown were very similar. The storm had moved 95 n.m. to the northwest and was just at the re-curvature point, with a travel velocity of 3 knots to the north-northeast. It had deepened to show a central pressure of 972 mb; the flights on the 26th were made very close to the time of most rapid deepening. The maximum wind was now 90 knots, but speeds in excess of hurricane force covered only a very small region in the eye wall.

The cloud map constructed from the upper level flight is shown in Fig. 2. It was made with somewhat less detail and precision in height measurements than those of the 25th and 27th for the two reasons that a) nearly 60 % of the flight time was spent socked in by cirrus and b) this day has not been used (as yet) for overall storm computations and hence soundings, budgets, and plots of other important variables were less accessible for checks and comparisons.

*Cumulonimbus structure*

Despite the very small sampling by the camera (about 20 % of the area wherein $r < 200$ n.m., almost none of this in the inner rain area, where $r < 100$ n.m.) on the 26th, the resemblance of what can be seen of the cumulonimbus structure to that of the 25th is striking. In particular the line of cumulonimbus just south of the north flight leg is present twenty-four hours later at identical radius from the storm center. The changes in cumulonimbus structure are twofold: toward more and bigger buildups and toward a more symmetrical distribution about the storm center. There are now 16 towers visible above flight level. Taking into account the proportion of area sampled, we estimate a total of 80 buildups by pure extrapolation, or 144 if we assume that the unsampled inner area is twice as productive as that sampled. The main visible line of cumulonimbi contains at least twice as many penetrative ( > 37,000 ft) towers as on the 25th and has extended itself (in relative coordinates) westward, with a 37,000 ft tower just at the western turn which was definitely not present on the 25th. The final (westernmost, flying southward) flight leg revealed 8 towers above flight level, as indicated, in a region which had only suppressed lines of cumulus previously, indicating a symmetrizing of the storm's convection with time by developments in the western quadrants. Finally, a line of at

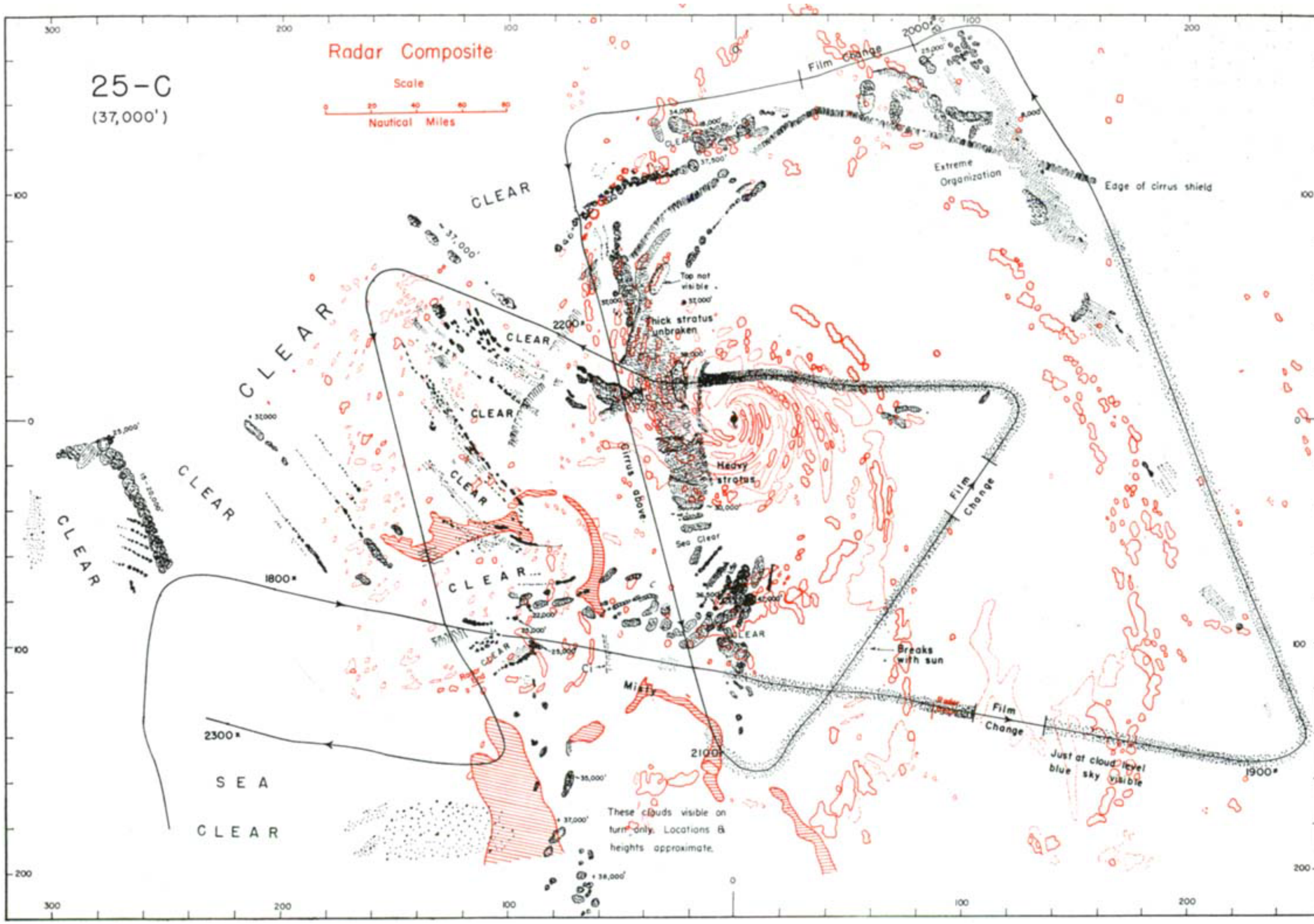


Fig. 7. Radar composite for Daisy August 25 in red superimposed on high-level cloud map (previous Fig. 1). The radar composite was prepared by W. S. Gray from the same NHRP C-level flight (using APS-64 3 cm radar) as was the cloud map; it was constructed by tracing a projected enlargement of successive frames of the radarscope movie film. Regions outlined by solid lines are "hard core" echoes, while those outlined by lighter dotted lines were more diffuse or fainter. The hatched regions are the Bahama Islands.

least four towers above flight level was now seen far ( $\geq$ 200 n.m. from center) to the north of the north leg, suggesting that expansion of the active convection zone was also occurring. Using the figure of 144 penetrative clouds within $r$ < 200 n.m. we compute that the area coverage by hot towers is now approximately 2 ½ % at this level.

*Cirrus*

On the whole, the cirrus distribution on the 26th was remarkably similar to that on the 25th; it dominated the flight in the southeastern portion and showed the same lowering or thinning just as the aircraft approached the southeastern turn. The main changes were toward greater symmetry about the storm center and consolidation into a more uniform "shield" in contrast to the somewhat streaky or banded structure frequently encountered on the formation day.

The shield had actually retreated somewhat on the east leg, which was no longer truly socked in, and on the north leg also, where its outer boundary was 20—30 n.m. nearer storm center. On the west side, on the other hand, it had markedly spread and consolidated. The inner western leg ($\sim$ 40 n.m. west of center) was now wholly socked in, and the outer western leg had banded and broken cirrus above the plane. The cirrostratus and cirrus in the extreme southwestern corner of the map was separated from the main hurricane cirrus by a band of blue sky above, at least 20 n.m. across. This "clear ring" to the southwest persisted throughout the three days at a radius of about 200 n.m. and may have marked the outer boundary of the storm convergence.

*Summary of cloud features on August 26*

Hurricane Daisy appeared to retain her individual cloud characteristics on the deepening day; these, however, showed further development from tropical wave to true hurricane by becoming a) more symmetrical, b) more productive of penetrative towers, both where found previously and in new places, particularly spreading into the previously inactive western quadrants and outward, at least to the north and c) more organized in both cirrus and convective structure. By the latter, we mean that fewer groups of cumulus congestus were seen scattered in the rain area; the upmotions appeared more concentrated in hot towers, separated by spreading layers of alto-stratus (now increasingly predominant on the north leg), below which were found either scud or organized rows of suppressed cumuli. This type of organization was also found on our previous Pacific study (RIEHL, GRAY, MALKUS, and RONNE, 1959, see cloud code types 13—16) characterizing severely disturbed or typhoon situations.

*August 27—Mature Day*

The middle and high-level flights on the 27th occurred between about 1600—2100 Z. The storm was located at 29° 30′ N, 75° 20′ W. In the 22 hour interval since the flights on the 26th, the center had moved 115 n.m. toward the northeast; it was now travelling in this direction at 8 knots, having accelerated somewhat after recurvature. The flights on the 27th encountered hurricane Daisy at her maximum development. The central pressure attained its minimal value of about 950 mb at this time, although the strongest winds did not appear to match this low pressure, since they exceed 100 knots only in a narrow region in the southeastern segment of the eye wall. On this day the upper flight performed a fairly similar pattern to the previous two, but unfortunately the exit leg was lost due to the film having ended just before 2000 Z. The aircraft was socked in by cirrus about 50 % of its time in the storm area. The results of the upper flight are shown in Fig. 3. Fortunately on this day the middle level flight had adequate time checks for reduction; its map is shown separately in Fig. 4 and superposed (in red) on the upper level flight map in Fig. 6.

*Cumulonimbus Structure*

Again the striking feature of the cumulonimbus structure is its pronounced resemblance, with gradual evolution, to that of the preceding two days. On the day of maximum intensity, hurricane Daisy showed a row of cumulonimbus towers just to the south of the northern flight leg, a highly congested active precipitation zone 80 n.m. due south of the center (see Fig. 4), and another row of active towers 150 miles west-southwest of the center. The first two of these features had persisted in nearly the same location relative to the storm center from the formation day on the 25th! The row of cumulonimbi in the western sector had only one member on the 25th, showed two or three on the 26th and now on the 27th had at least five towers with tops above 37,000 ft.

Development toward greater symmetry and more buildups was also apparent in the north line, which had extended further into the northwest quadrant and was slightly closer to storm center than previously. This line contained the tallest tower measured, which from the B flight (13,000 ft) came out to be 50,000 ft at 1700 Z, and from the C flight was topped at 53,000 ft about a half hour later. Whether the change was due to growth or errors in one or both measurements is not possible to say, although the tower appeared to be still rounded and rising at 1700 Z. The northernmost line was also still visible on the 27th, in about the same relative location and state of development as on the 26th. In addition, part of another cumulonimbus line was now visible about 200 n.m. out from center in the southeast quadrant; this was a region in which the aircraft had been socked in by cirrus on the previous two days.

Not more than 20 % of the rain area ($r <$ 200 n.m.) was seen by the camera on the mature day. We can furthermore be confident that on this day the "socked in" regions of the C flight were, in fact, the most convectively active portions of the rain area. The B flight (Figs. 4 and 6) shows clearly that the very black, rainiest, and bumpy portions of the storm were in the eye wall region and the southeast quadrant, and that therein these were spaced about twice as closely together as the visible cumulonimbus rows in the outer portions mapped. Since we counted 22 cumulonimbus towers above flight level on the C flight, we therefore estimate the total number of penetrative hot towers to be not less than 200. Hot towers may therefore cover about 4 % of the rain area at this level on the mature day of hurricane Daisy.

*Cirrus*

The cirrus shield also showed the same general character and distribution as previously, with gradual evolution toward consolidation and symmetrization, which were presumably at a maximum on the 27th. After that the storm began to accelerate northward and out of the tropics.

The cirrus shield at flight level had retreated on the east leg somewhat farther toward the center than on the 26th, but above the aircraft cirrus extended outward to at least a radius of 300 n.m. (where visible on the southeast turn). There was a real indication of a higher cirrus layer (55—60,000 ft) above the extension of the main shield which rose from flight level to about 45,000 ft on the corner.

To the north of storm center, the cirrus shield had shown little change in the three days and was on the 27th of about the same extent as on the 25th; however it had spread considerably to westward, now overlying the entire northwest quadrant in a continuous sheet reaching a radius of 100 n.m. (see Figs. 5e and f). Outward of that, banded cirrus extended about another 40 miles, with the bands aligned roughly north—south. Still, however, the entire western cirrus structure was less dense and less well developed than that in the southeast quadrant.

*Other cloud features on August 27*

The B-level map (13,000 ft. Fig. 4) provided a valuable supplementation; in particular it showed what was below the cirrus in the active southeast quadrant. The mid-level aircraft also performed numerous circles in the eye wall. The photographs showed there the blackest, most turbulent and rainy conditions encountered. That extraordinarily intense and penetrative convection, even for a hurricane, was occurring there was substantiated by the August 27th radar (see JORDAN, HURT and LOWREY, 1960) which shows that the eye wall contained cumulonimbus towers up to at least 60,000 ft. We may therefore use the pictures there as a rough calibration for the remaining B film. The next blackest, rainiest, and most convectively active region was found about 80 n.m. south of the center, in nearly the same relative location as the huge towers on the 25th. The photographic and radar evidence suggest this was a part of a well-developed line which in the southeast quadrant had a radius of 45 n.m. and spiralled gradually into the eye wall from the northwest.

More stratus layers were now present than previously; the northern flight leg on the B flight ($r \sim 65$ n.m.) passed between two of these in a convectively inactive region. Concentration of convection was a maximum on this day, with the eye wall and a few pronounced bands in the rain area accomplishing all of it; no congesti were found except in the close vicinity of these bands.

The photographs shown in Figs. 5c and d were made on the entrance leg of this flight (see Fig. 4 for location) and 5e and f were made on its continuation at 20,000 ft altitude after the movie film had ended. These stills were all made in the western sector of the storm, which was relatively cloud-free on the 25th, emphasizing the trend toward symmetrization. The generally blacker appearance, heavier stratus layers, and more suppressed low-level convection are obvious in contrast with Figs. 5a and b from the 25th. At the B-level on the 27th, individual hot towers were largely obscured by stratus and rain, and with one or two exceptions, could only be picked out clearly on the high-level flight.

### *Summary of Daisy's Visual Cloud Distributions on the Three Days*

By far the outstanding result of the photographic mapping of Daisy's visible cloud distribution was the persistence, in the same relative locations, of definite cloud patterns. This persistence was notable both between legs on the same flight, separated by hours, and, even more remarkably, over the entire three days. While these cloud patterns showed gradual evolution during the period studied from those resembling a deep easterly wave to those characteristic of a member of the species hurricane, persons who have looked at films from several hurricanes would never have confused Daisy with any of the others; her aspect remained as peculiarly her own as does a human's physical appearance.

Of significance in particular is the persistence of the lines or spiral bands of cumulonimbus in the same relative coordinate position over 48 hours, despite a travel of the storm some 200 n.m. If this feature proves characteristic of many hurricanes it may be one of the most potentially important revealed to date. The implication is that some kind of stable interaction between convective and hurricane scale motions is taking place such that clouds are continually regenerated in a few relative coordinate locations and suppressed elsewhere.

A puzzling outcome of this first endeavor of quantitative mapping of clouds in a hurricane over days is the quite different impression produced by our results from that discussed by most radar meteorologists concerning persistence versus fluctuations in patterns. The common impression among radar experts who have studied hurricanes seems to be the transience in both the life of individual echoes and their arrangement. We believe that an urgent need in future hurricane studies is a systematic comparison between radar and photographic maps, both at single instants and over periods of time. In the next section we have made a preliminary effort to make such a comparison for Daisy.

## 4. Comparison of the photographic maps with radar pictures

The radar data which will be compared with our maps herein have been taken primarily from a fine study by JORDAN, HURT, and LOWREY (1960) who participated in an operational reconnaissance flight into Daisy on August 27th in a radar Constellation of the U.S. Navy Airborne Early Warning Squadron Four (WV-4). Their paper shows selected photographs of its radarscope and also a few from the radar of the upper-level NHRP aircraft on the same day, for which our photographic map is Fig. 3. Fortunately, we also had one radar map available from August 25th, composited by W. S. Gray from the radar of the high-level NHRP aircraft, whose nose camera film was used to prepare Fig. 1. We should like to emphasize that our presentation in this section is only a fraction of what could and should be done with radar analysis on Daisy; many more thousands of feet of radar film are on file at NHRP and, in particular, August 26th has not yet been worked up.

### *Comparison for August 25th*

Fig. 7 shows Gray's radar composite (in red) superposed upon our cloud map shown previously in Fig. 1. Unfortunately there was a synchronization problem, since the clock in the radar frames was running 30 seconds behind the plot-out at the start and 60 seconds behind it at the end of the flight portion mapped. Resulting relative coordinate errors in the radar chart would thus grow from about 3 n.m. to 6 n.m. by the later flight legs. We have corrected some but not all of these errors in positions of large clouds after 2020 Z (final turn on north leg).

The radar in the C-level aircraft was a 3 cm set (APS-64) which operates at a fairly low power output. According to JORDAN ET AL., the energy from this installation "is sent out in a very broad beam below the aircraft but because of the location of the radome, none of the energy is sent out above the horizontal. Therefore the echoes shown can be considered as the integrated effect of the return from hydrometeors in the surface to 37,000 ft layer."

The comparison in Fig. 7 is extremely illuminating and valuably supplements the photographic map. We see that even on the 25th, the cumulonimbus-producing region 80 n.m. south of the center is the outer edge of a band spiralling into the eye wall on the northwest side. We also learn that the cumulonimbus line to the north, which the photography located on all three days, is part of a very long spiral arm extending roughly north-south slightly west of the eastern flight leg and crossing the south leg just inward of the southeast corner. Interestingly enough, this is exactly where the cumulonimbus towers were revealed by retreat of the cirrus on the 27th (Fig. 3), supporting our supposition that this, too, was a persistent feature. There is a relative scarcity of echoes on the western side, as already suggested by the pictures.

On the whole, the correspondence between hard core echoes and penetrative cumulus is good, but by no means perfect. There were a few visual penetrative buildups, even some reaching above 37,000 ft, which do not appear on the radar map. Conversely, in the well-sampled areas there were occasional hard cores with which cumulus towers were apparently not associated, although the later non-correspondence is less certain than the former due to obscuring of the field of view on the film by stratus, nearer clouds, etc. It appears likely, in close examination of the region just west of the eye (from about 100 n.m. north to 100 n.m. south) that some echoes coded as "hard core" may have had their origin from hydrometeors in heavy stratus. However, since this region was generously larded with penetrative towers, a conclusion that this type of echo came from "stratus precipitation" might be quite false.

The echoes delineated by lighter dotted red lines were dimmer and more diffuse than those called "hard core". The shape and distribution of these near the hard core echoes makes it likely that they were also convective in origin (shorter, older, less wet clouds, or smaller drop sizes, perhaps). Thus precipitation from stratus (without nearby convection) either was predominantly absent on the 25th, or so undeveloped that this radar set did not detect it. The nose camera film supports this; stratus sheets were rarer, less murky, and less extensive on the 25th than on the succeeding two days.

A calculation by Mr. R. H. Simpson[1] of the fraction of the rain area covered by all radar echoes on this day gave 22 %, over equal area radial intervals out to 55 n.m. The fraction so covered by hard core echoes was a uniform 6 %. It is interesting to note that the latter figure is six times greater than our maximum estimate from the photographic map of area covered by penetrative cumulonimbus (tops above 37,000) towers.

### *Comparison for August 27th*

The PPI presentations on the paper of JORDAN ET AL. were from two different radar sets and installations, one being that of the NHRP described above. The others were from an APS-20E set mounted in the U.S. Navy WV-4 (Lockheed Super-Constellation radar reconnaissance aircraft). The latter is, according to them, "a very high-powered set which operates at a wavelength near 10 cm with a maximum range of 250 miles" and is much less affected by attenuation than sets of shorter wavelengths. The vertical width of the beam is 6° and variable gain, antenna tilt and position of aircraft result in the fact that different layers, intensities of echoes, and portions of the storm are seen as these are varied. JORDAN ET AL. have presented an excellent critique of these in each scope photograph they reproduced, which will be accepted without modification here.

Perusal of the radar photographs of JORDAN ET AL. might lead the casual reader to conclude

[1] During a graduate class analysis of Daisy conducted at the University of Chicago in January 1959 by Professor Herbert Riehl.

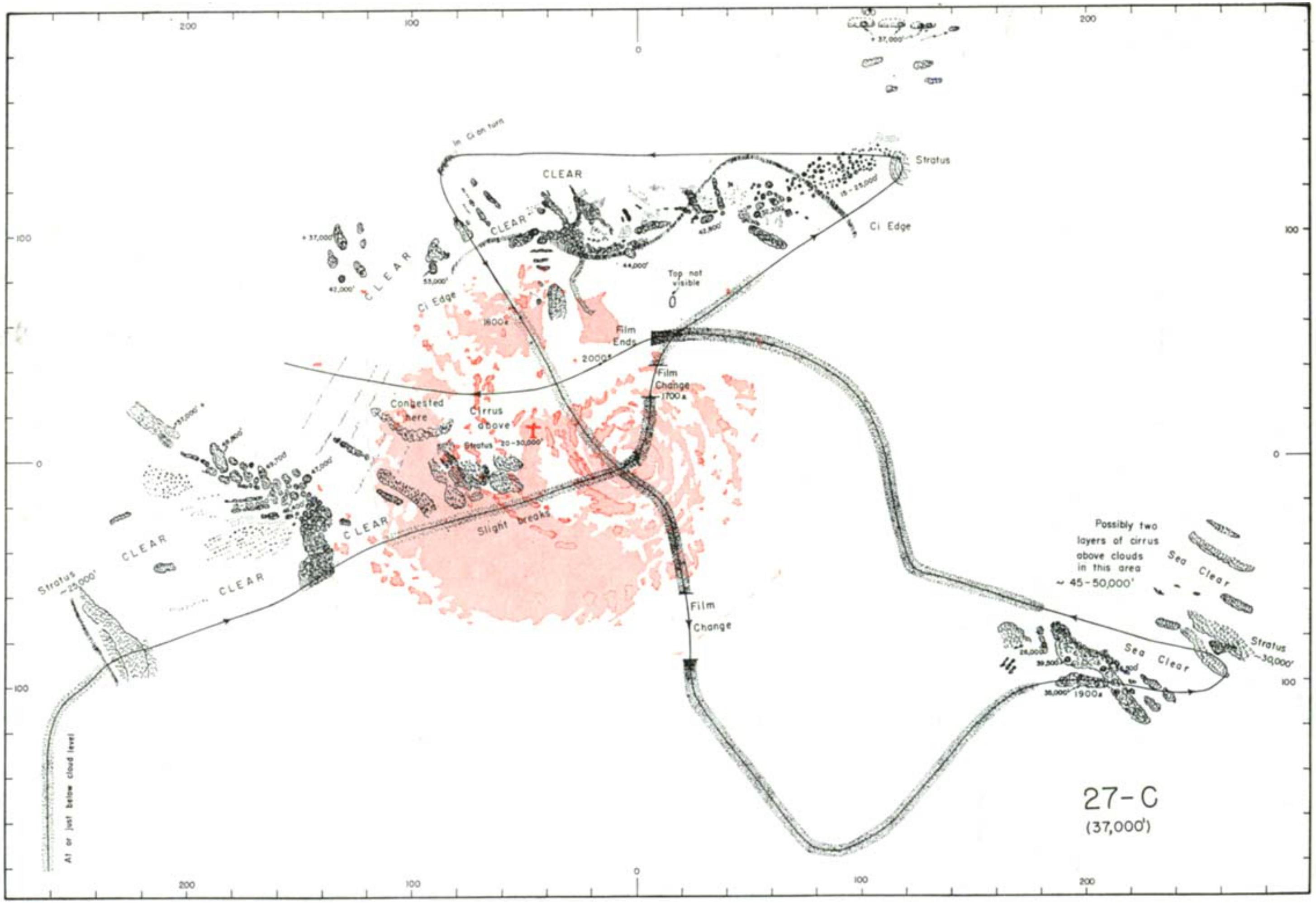


Fig. 8. Radar map (red) constructed from single-frame photograph of radar Constellation's (WV-4, U.S. Navy) APS-20E scope at 1511 Z August 27th (after Fig. 2 from Jordan et al., 1960) superimposed on C-flight cloud map (previous Fig. 3). The Constellation at the time of this frame was at 8500 ft altitude about 45 n.m. west-north-west of storm center. The coding into "hard core" echoes (hatched) and fainter or more diffuse echoes (shaded) was introduced subjectively by us from the photograph provided by Jordan et al.

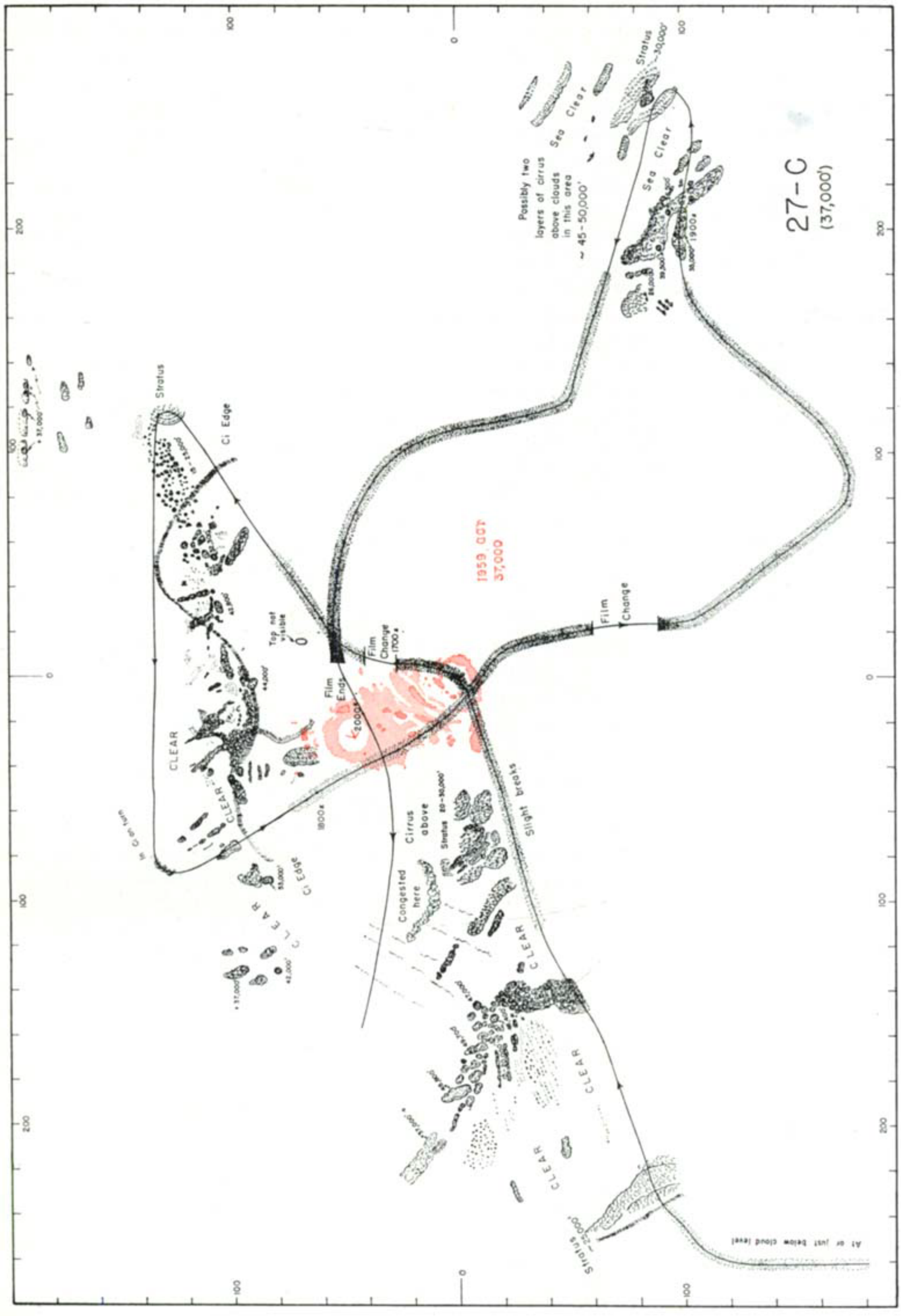


Fig. 9. Radar map from single frame of NHRP APS-64 set(after Jordan et al. Fig. 10) superimposed upon our August 27 C-level cloud map. Radar frame was take from same flight as photography but on exit leg at 1959 Z just after nose camera film had ended.

that Daisy's echo patterns were chaotic, confusing, and highly variable from one time, location of aircraft, and type of radar set to the next. On some of the pictures a spiral band wound around the north of the center and none to the south; on others, a band wound around on the south but not the north, and on still a third no spiral bands at all were detectable but only a concentric ring of echoes around the eye. With the possible exception of the last problem (largely resolved in the discussion by JORDAN ET AL.), most of the apparent inconsistencies are removed by reproducing all radar pictures on the same distance scale (we chose that of our photographic maps) and superimposing them on each other. The remaining problems in interpretation are then greatly illuminated by using the radar pictures as overlays for the cloud maps, aided by the analysis of JORDAN ET AL. concerning what layers were seen by the radar. It should be kept in mind that all the radar figures to be shown for August 27th are photographs of single frames and not composites.

Fig. 8 shows a map we made from an APS-20E radarscope photograph (after Fig. 2 in JORDAN ET AL.) superposed on our C-level cloud map, shown earlier by itself in Fig. 3. The scope photograph was made at 1511 Z when the radar Constellation was flying at 8500 ft and was located, as shown, about 45 n.m. west-northwest of the eye center. It is thus within 1 ½—2 hours synoptic with the corresponding patterns of the photographic map. According to Jordan et al., since the antenna tilt was kept at about 4 degrees above horizontal during

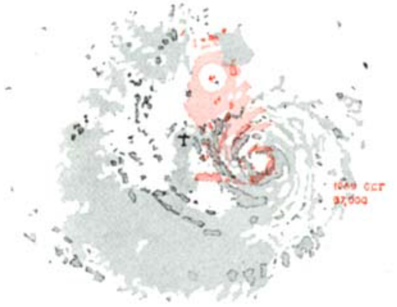

Fig. 10. NHRP APS-64 radar frame (red) from Fig. 9 superimposed on radar Constellation's APS-20E frame shown in Fig. 8. Note similarities despite nearly five hours time difference (APS-20E frame earlier), difference in equipment, and aircraft altitudes.

most of the Constellation flight on the 27th, the patterns shown result primarily from returns in a layer from about 12,000—35,000 ft.

Fig. 9 shows a superposition of an APS-64 radarscope frame (after JORDAN ET AL. Fig. 10) upon the same cloud map. This was taken from the C-level NHRP flight on the exit leg at 1959 Z just after the photographic film had ended. It shows echoes from hydrometeors extending from the surface to flight level in the vicinity of the aircraft's location at 1959 Z.

Fig. 10 consists of the NHRP APS-64 radar map (red) superimposed on the Constellation's APS-20E map of Fig. 8.

Fig. 11 shows a much later (2345 Z, 3 hours after the NHRP aircraft had left the storm) map made from the APS-20E (after JORDAN ET AL., Fig. 11) as overlay on the C-flight cloud map. The Constellation was now 200 n.m. to the west of the storm center and saw a bigger portion of the rain area, but presumably with more effect of attenuation.

Fig. 12 superposes the two APS-20E radar maps (1511 Z in red, 2345 Z in black), and finally Fig. 13 shows the 1511 Z APS-20E map in red upon the B-level photographic map.

The results of the superpositions in Figs. 8—13 are both gratifying and illuminating. Allowing for different radar sets, gains, times, aircraft locations, etc., we find the radar maps in good agreement with each other and a valuable supplementation of the photography (or vice versa). The main conclusion now becomes not chaos or transience, but a remarkable persistence in pattern throughout all observations. Figure 8 shows that the much-photographed cumulonimbus line to the north spiralled into the eye wall from west and southwest. It also shows that the line of near 50,000 ft buildups 160 n.m. west-southwest of center which crossed into the "blind" region of the nose camera, was part of the spiral band containing the big buildups 70—80 n.m. south of the eye. It continued (more weakly) spiralling toward the center, joining the eye wall from the north. As we have seen, these two main spiral bands were characteristic of Daisy throughout her observed lifetime. It is not clear whether the more diffuse echoes are from stratus or cirrus, although the marked increase and spreading of such echoes between the two NHRP radar maps of the 25th and 27th, together with the photographically recorded

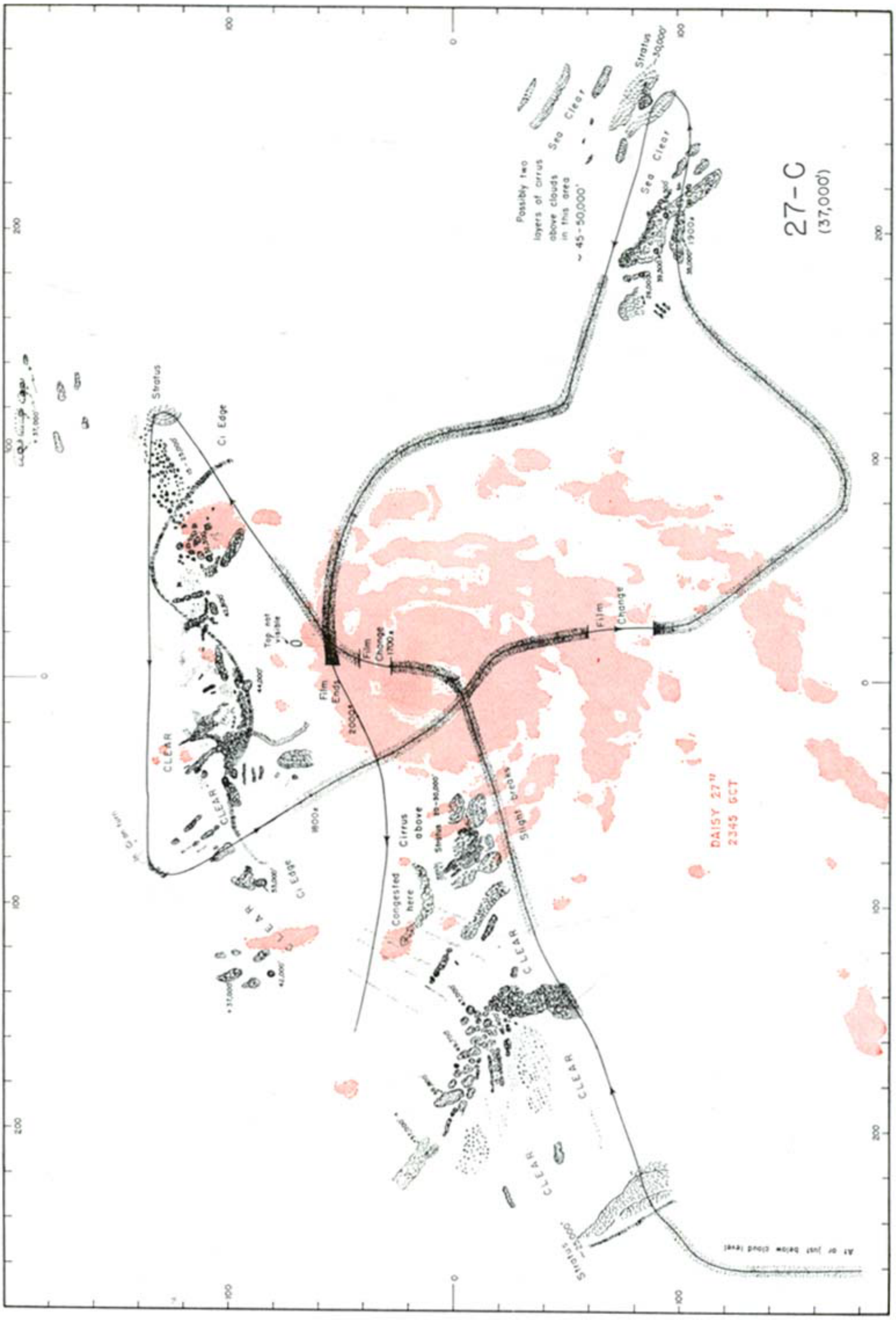


Fig. 11. Much later radar Constellation frame (2345 Z, after Fig. 11 Jordan et al.) in red, superimposed on Fig. 3 photographic cloud map. Constellation was now 200 n.m. to west of storm center at an altitude of 7000 ft. Shading has been designed (subjectively) to correspond to brightness on radar print.

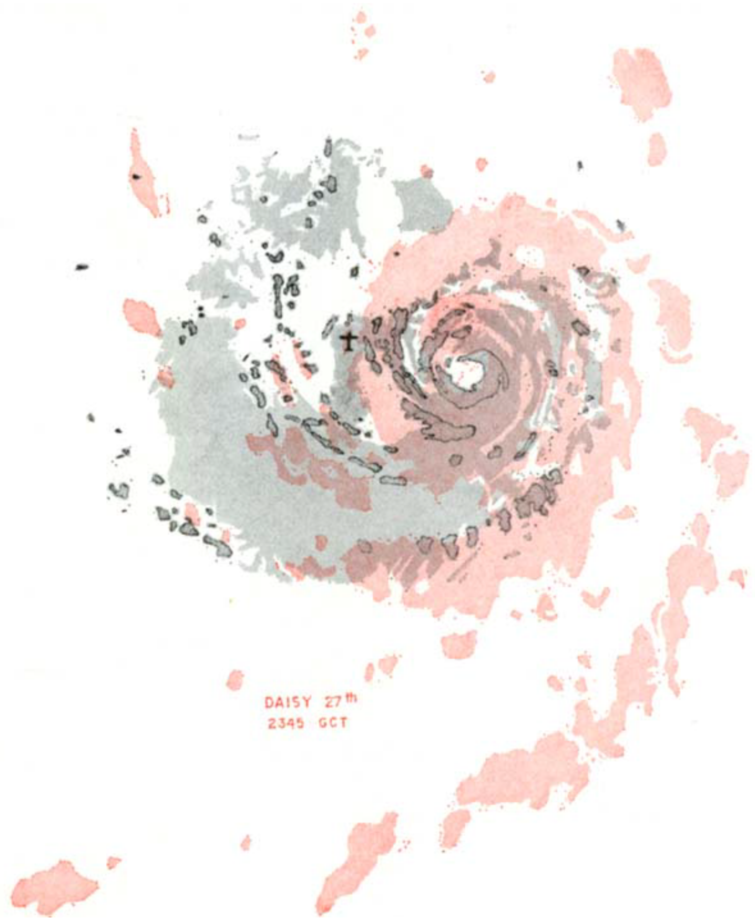


Fig. 12. Superposition of radar frame in Fig. 11 (red) upon that in Fig. 8. Both from Constellation's APS-20E set, comparable altitudes (7000 and 8500 ft, respectively) but at different times and aircraft locations. The red chart is from a frame nearly nine hours after the black with aircraft at a far greater distance from storm center.

increase and darkening of stratus decks, suggests the former. This is confirmed if, as stated by JORDAN ET AL., the radar saw little above flight level; much or most of the cirrus was at or above 37,000 ft.

Figure 11 shows little change in the main radar features from Fig. 8, despite a nearly nine-hour time difference. It also gives us a look, albeit probably attenuated, into the cirrus-covered southeastern quadrant. This further validates our photographically-deduced conclusion that this was the most convectively active portion of the rain area. Figure 11 shows another spiral band of echoes crossing the C-flight track about 120 n.m. south-southeast of the center. This may be identified with a fragmentary band only about 10 n.m. farther from storm center on the 25th NHRP radar (Fig. 7) and is almost surely also convective in origin, being so similar to others now positively shown to be such. Since the photographs showed still another cumulonimbus row about 220 n.m. out to the southeast, we have about three major bands (exclusive of eye wall) in the southeastern quadrant, compared to about one and a half in the same radial coverage to the north, west, and southwest.

Superposition of the APS-20E 1511 Z radar map on the B-flight cloud map (Fig. 13) gives equally agreeable and consistent results. It

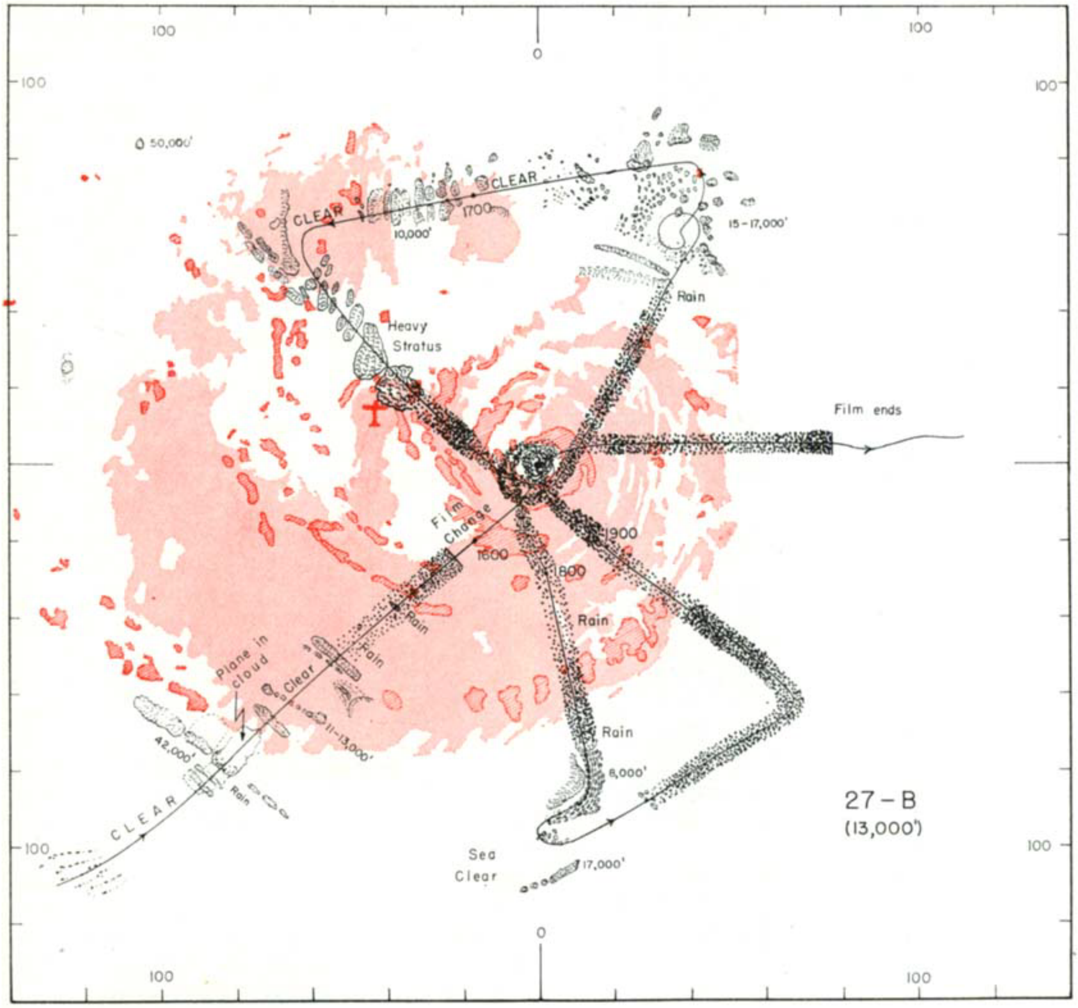


Fig. 13. Radar chart from Constellation's APS-20E 1511 Z frame (red, formerly in Fig. 8) superimposed on our B-level photographic cloud map (previously Fig. 4).

further confirms our operational conclusion that generally very black, rainy, heavily "socked in" portions of mid-level nose camera films would coincide with relatively strong radar echoes, and that maps constructed showing regions of "equal blackness" from film records would be in pretty good agreement with radar maps.[1] Outside the eye wall itself, the film's blackest, most rainy portion was that convective area, previously discussed, 70—80 n.m. to the south, which shows here also the hardest core radar echoes, despite being more than 100 miles away from the aircraft.

An important point brought out by this figure is the difference in convective activity between the northern cloverleaf and southern cloverleaf of the B-flight. Further consequences of this and its relevance to the averaging and sampling problems are brought out in Section 5.

Finally, we may compare the radar patterns on the 25th (Fig. 7) with those of the 27th (Figs. 8—13). Especially with allowances for different sets, gains, altitudes, etc., and for the fact that the 25th map is a composite while

[1] Our currently undertaken study of hurricane Cleo (August 18, 1958), mapping from films and radar, is showing this general agreement also.

those for the 27th are single frames, we are more impressed with the similarities between the pictures than the differences, which themselves may now largely be explained in a logical manner. The arrangement of echoes into essentially the same (in pattern and in relative storm coordinates) broken spiral bands is obvious, and even the breaks (along themselves) in the bands occur at roughly the same distance and direction from storm center. The main differences on the 27th radar from the 25th are: 1) greater symmetrization in echo distribution; in particular, more echoes in western quadrants, 2) the weaker and diffuse echoes are more spread out and extensive, suggesting stratus decks, rather than isolated, smaller convective towers, as on the 25th, and 3) the two main bands are 10—20 n.m. radially closer to the center. It is not likely that the latter change had anything to do with the presence of the Bahama Islands on the 25th, since the 26th map put them in the same relative locations as the 25th. All these differences were independently suggested by the photographic maps, and we believe they had little, if any, origin in differences in radar instrumentation or usage.

We conclude this section in strong support of the advocacy by JORDAN ET AL. of the usefulness of careful radar analysis in hurricane studies, with the further recommendation that the addition of synoptic photographic analyses would multiply the usefulness of radar many times.

## 5. Asymmetries of convective structure in hurricane Daisy

We have seen from all the cloud and radar maps studied herein that the southeast quadrant of Daisy was, throughout the three days, her most convectively active portion. Marked asymmetries in other variables, such as winds, temperatures, and humidities might be sought in consequence of this concentration of active convection. In this section, we present a preliminary attempt to relate the observed temperature field to the convective structure of the storm as depicted by our cloud maps.

In Daisy, the asymmetry should be particularly pronounced in the case of the 27th B flight (Figs. 4 and 13). Here the southern cloverleaf traversed an intensely active part of the storm, twice crossing the southeastern spiral cumulonimbus band, and the northern cloverleaf passed through a suppressed zone. The northernmost leg, in fact, passed largely between two stratus decks, with good visibility and little precipitation throughout.

In Fig. 14 we compare the small-scale temperature structure on the suppressed northern leg and the active southeastern cloverleaf of this flight, using the records of the NHRP vortex thermometer, adjusted for altitude fluctuations. The top graph gives temperature (plotted every two seconds) as a function of time in the vicinity of 1700 Z, when the aircraft was passing from a relatively clear region (cirrus shield above) into a zone of broken stratus undercast. The temperature fluctuates less than $\pm$ 0.5° C on each side of its average of about 3.5° C. The lower graph similarly gives temperature as a function of time on rounding the end turn (from northeast to northwest heading) of the southeastern cloverleaf, continuing into the heart of the main rainband (dark region at 1850 Z on cloud map in Fig. 13; hard core echoes on superposed red radar map).

In the first place, it is obvious that the convectively active southern leg averaged 2—2.5° C colder than the suppressed leg. This is in good agreement with Woods Hole aircraft observations (MALKUS, 1958a) in normal trade winds and weak-to-moderate tropical storms, where it was found that cloud areas are consistently cooler than the intervening clear or suppressed regions, by 0.2—0.5° C in the normal situations and by as much as 1—2° C under disturbed conditions. However, this by no means implies that active convection elements are virtually cooler than their *immediate* environment; that the very small fraction of visible cloud matter which is actively rising is usually also buoyant has been demonstrated by other Woods Hole observations (for example, BUNKER, 1959). Fig. 14 suggests that the hurricane rain area is qualitatively similar.

On the active leg shown in the lower graph, which was all within cloud, relative darkness of the film is indicated below the temperature trace. We see that blackest portion of the rainband (1849 Z to end) averaged 1.5° C warmer than the surroundings, with a peak value of 3° C warmer at the edge closest to storm center. The clearly buoyant region ap-

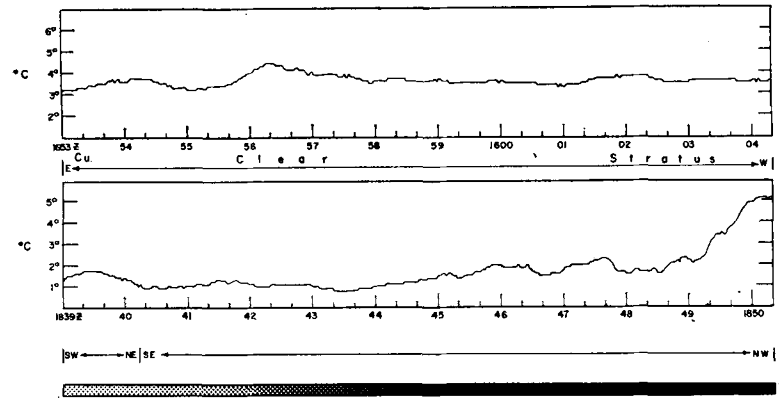


Fig. 14. Upper graph shows temperature as a function of time (altitude-adjusted vortex readings plotted at 2-minute intervals) on northern leg of northern cloverleaf of August 27th B-flight (Fig. 4, region around 1700 Z). Lower graph similarly shows temperature as a function of time for portion of southern cloverleaf on same flight near southeastern turn, where flight heading changes from northeast to northwest. The shaded region below denotes degree of blackness on film, which darkened markedly as heart of convective band was penetrated. Note pronounced difference in character, mean tempera ture, and fluctuations between upper (convectively inactive or suppressed region) and lower (convectively active region) temperature graphs.

peared about 8 n.m. across, although the lag of the vortex thermometer (about 10 seconds) precludes its accurate definition or recognition of individual convection elements.

These fragments in Fig. 14 are typical of the character of Daisy's temperature structure and its relation to the cloud patterns. Suppressed flight legs were warm and showed little or no spatial fluctuations, while convective legs were cool, with marked hot and cold spots of 1.5—3° C amplitude. We conclude that radial averages of temperature from limited and necessarily arbitrary flight paths must be interpreted with caution. The cloud maps provide a tool to investigate the sampling problem and to relate the convective structure to the thermal and dynamic features of the storm.

## 6. Conclusions

The primary conclusions to be drawn are four in number:

1) The patterns of clouds associated with hurricane Daisy were remarkably persistent over the three days studied, in that the major cumulonimbus rows and cirrus shield were found *in nearly the same coordinates relative to storm center* over more than 48 hours and 200 n.m. travel of the center.

2) While persistence was the major feature of Daisy's cloud patterns, they also showed a slow and gradual evolution toward a symmetrical distribution about the center, consistent with the maturing of the storm circulation. On the first day studied (August 25, 1958) Daisy's cloud patterns appeared transitional between those we have mapped in easterly-wave type, sub-hurricane disturbances (RIEHL, GRAY, MALKUS, and RONNE, 1959) and those characteristic of the full hurricane or typhoon, in that the forward quadrants were significantly less convectively active than the rear (particularly the southeast). Symmetrization was achieved by gradual extension of the cumulonimbus rows and cirrus shield into the forward quadrants, with amazingly small changes elsewhere, except toward more buildups per line and extension of the convective area by appearance of an additional row at a larger radius.

3) Penetrative convection was extremely restricted in area and occurred only in the major lines of cumulonimbus. On the formation day about 1 % of the rain area ($r < 200$ n.m.) was covered with "hot towers", defined here as photographically well-defined cumulonimbi with tops above 37,000 ft. This figure had increased to 2½ % on the

deepening day, and 4 % on the mature day, on which a total of about 200 hot towers was estimated from our sample.

4) On all three days, we can fairly safely infer that the southeast quadrant of the storm contained roughly twice as many cumulonimbi as did the remaining quadrants. This concentration is reflected in the temperature field. In addition to posing a sampling problem, such asymmetry in convective activity may be of importance in hurricane dynamics and movement.

These hurricane cloud maps, taken in context with our similar analyses of sub-hurricane perturbations (RIEHL, GRAY, MALKUS, and RONNE, 1959) begin to suggest that each type of tropical disturbance has a characteristic arrangement of cloud forms which identifies it as a member of a species. Our study of Daisy raises the further possibility that, within the species, each storm may show a relatively persistent or slowly evolving character of its own which distinguishes it from other members of the same species, in a similar manner as do the physical features of a human being. If it proves sound, "fingerprinting" of atmospheric disturbances by cloud patterns may be valuable in interpretation of satellite photographs, which can be used to develop and test our suggestion further, and to explore its dynamic implications.

**Acknowledgments**

The writers acknowledge with deep gratitude the assistance provided by the Director and Staff of the National Hurricane Project of the U.S. Weather Bureau, who have generously made available their data, facilities, and vast experience in hurricane research. In particular, we thank Mr. Harry Hawkins, the Acting Director, without whose constant help and encouragement this labor could not have been completed.

Much of the work on hurricane Daisy was carried out at the University of Chicago in a graduate class and program under the direction of Prof. Herbert Riehl, whose participation has been invaluable. In an effort as extensive as this, it is difficult to sort out the contributions of individuals and groups, of which there have been many. This phase of the study is intended as a part of an overall analysis of hurricane Daisy going on at several institutions. The radar maps herein have been reproduced with the kind permission of Mr. W. S. Gray and Prof. Charles L. Jordan. Mrs. Mary C. Thayer was responsible for preparations of the manuscript.

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