CIRRUS CANOPIES IN TROPICAL STORMS

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ABSTRACT

An analysis is made of the generation, advection, and dissipation processes of the cirrus canopy in tropical storms with particular emphasis on the formation of sharp edges. Although subsidence and accompanying evaporation may be factors, this formation is closely tied with the wind flow pattern near the edges. The stronger the radial wind velocity in the vicinity of the edges, the greater is the rate of subsidence required to evaporate the cloud over a distance sufficiently short so that the edge may be considered sharp.

Analyses of the wind fields in typical hurricanes indicate that cirrus generated at the eye wall and advected outward could produce in 12 to 18 hr. a canopy similar to those observed by meteorological satellites. If, in addition, generation occurs in the spiral arms, these times are shortened somewhat. Sharp edges would occur in regions where the radial outflow becomes small, probably less than 1 m. sec.$^{-1}$, and where the tangential velocity is at a relative maximum.

1. INTRODUCTION

Satellite photographs of hurricanes frequently show a cirriform canopy enveloping the mature storm. The size of the canopy has been found to be correlated to the storm intensity; Fritz et al. [3] developed a technique for estimating maximum winds from the degree of organization of the overall cloud pattern associated with the storms and the size of the cirrus canopy. The canopy is frequently missing or relatively small during the growing stages of the storm, and may vanish or become thin and tenuous during the dissipation stages.

Well defined sharp edges have been observed, either in some sectors of the cirriform canopy or extending almost completely around the mature storm. Hubert [4] interpreted the cloudless ring around mature tropical storms to be "an area of subsidence that has evaporated the cloud to form an almost cloudless moat around the storm." Sadler [10] deduced from a TIROS view of hurricane Madeleine, 1961, that the storm was of hurricane intensity because of the large cirrus shield and, in particular, the surrounding clear zone which indicated "extreme subsidence being established by the storm." Fett [2] refers to "an annular zone of subsidence," lying between the cirrus shield and the outer convective band, as typical of the mature storm. Merritt [8] observed an apparent sharpening of the western canopy edge during the transition from a tropical depression to a tropical storm.

These observations, their variability, and the empirical relationships proposed (as summarized above) make it desirable to study the physical processes of the cirrus canopy as an aid to proper inference of cyclone size and stage of development from satellite observations of tropical storms.

It is the purpose of this study to analyze the generation, advection, and dissipation processes of the cirrus canopy, and to assess the role of evaporation in subsiding air in the formation of sharp edges. In order to achieve these objectives, an approximate physical model has been devised. This model relates the cirrus canopy to (1) the field of motion in the outflow layer, (2) the quantity of ice in the cirrus, and (3) the distribution and mean vertical velocities of penetrative cumulus in the storm. The following sections will present discussions of each element of the model.

2. CIRRUS CANOPY GENERATION AND THE OUTFLOW-LAYER FIELD OF MOTION

Observations by Malkus et al. [7] indicate that the cirrus canopy largely results from cumulus towers penetrating into the outflow layer of the storm. This occurs most frequently in the eye wall and major spiral bands. There is, however, a marked decrease in these penetrations with increasing radial distance from the eye.

For the purpose of evaluating the influence of advection of cirrus particles on canopy generation, we shall assume that all cirrus is produced in the eye wall within 25 km. of the geometric center of the storm. We shall further assume that the cirrus production is continuous, infinite in amount, and unaffected by any subsidence other than that imposed by the descent velocities of the ice crystal sizes involved. Particle lifetimes of up to 18 hr. are assumed. (Section 3 of this study will show the range of lifetimes of cirrus particles in a hurricane environment as a function of initial temperature, pressure, and humidity.)

From data in existing literature, we have prepared

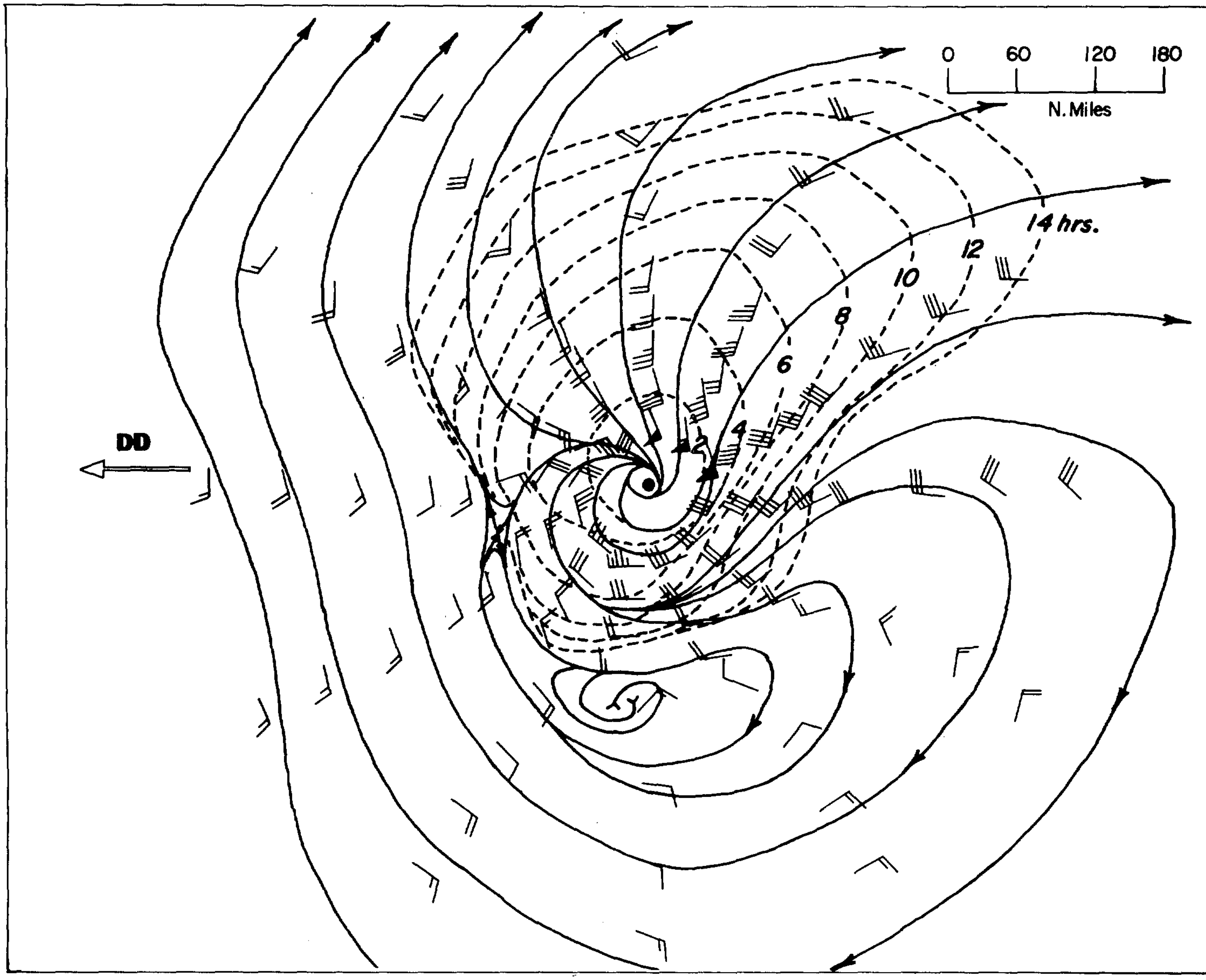

FIGURE 1.—Wind field at 45,000 ft. in hurricane Donna 1960 and time change of the canopy when cirrus production at 25-km. radius is assumed.

analyses of the field of motion at a single level (45,000 ft.) assumed to be representative of the outflow layer. Cirrus particles, generated within the eye wall are assumed to enter the outflow layer at 25 km. from the storm center. The wind field is assumed to be steady, thereby allowing construction of time displacement of the cirrus particles along the assumed outflow trajectories. Isochrones of the translation of all particles have been prepared from the individual particle's time displacements.

"DONNA" WIND FIELD—SEPTEMBER 1960

Riehl [9] presented a composited 45,000-ft. wind field for hurricane Donna of 1960. Donna was a rather intense storm with winds up to 150 m.p.h. at maximum intensity. Numerous radar photographs were taken while Donna passed over Florida and the United States east coast. These photographs indicated heavy spiral banding in the northeast quadrant, and a well defined eye wall. The southwest quadrant had a weak banded structure. This pattern appears in many intense hurricanes and typhoons.

Figure 1 shows the composite wind field and isochrones of the canopy edge assuming cirrus production at 25-km. radius and a steady state wind field. Note that in the west and southwest through southeast, where the radial component of the wind is small, the edges of the cirrus approach their limiting radial distances in approximately 5 hr., whereas in the north through northeast where the

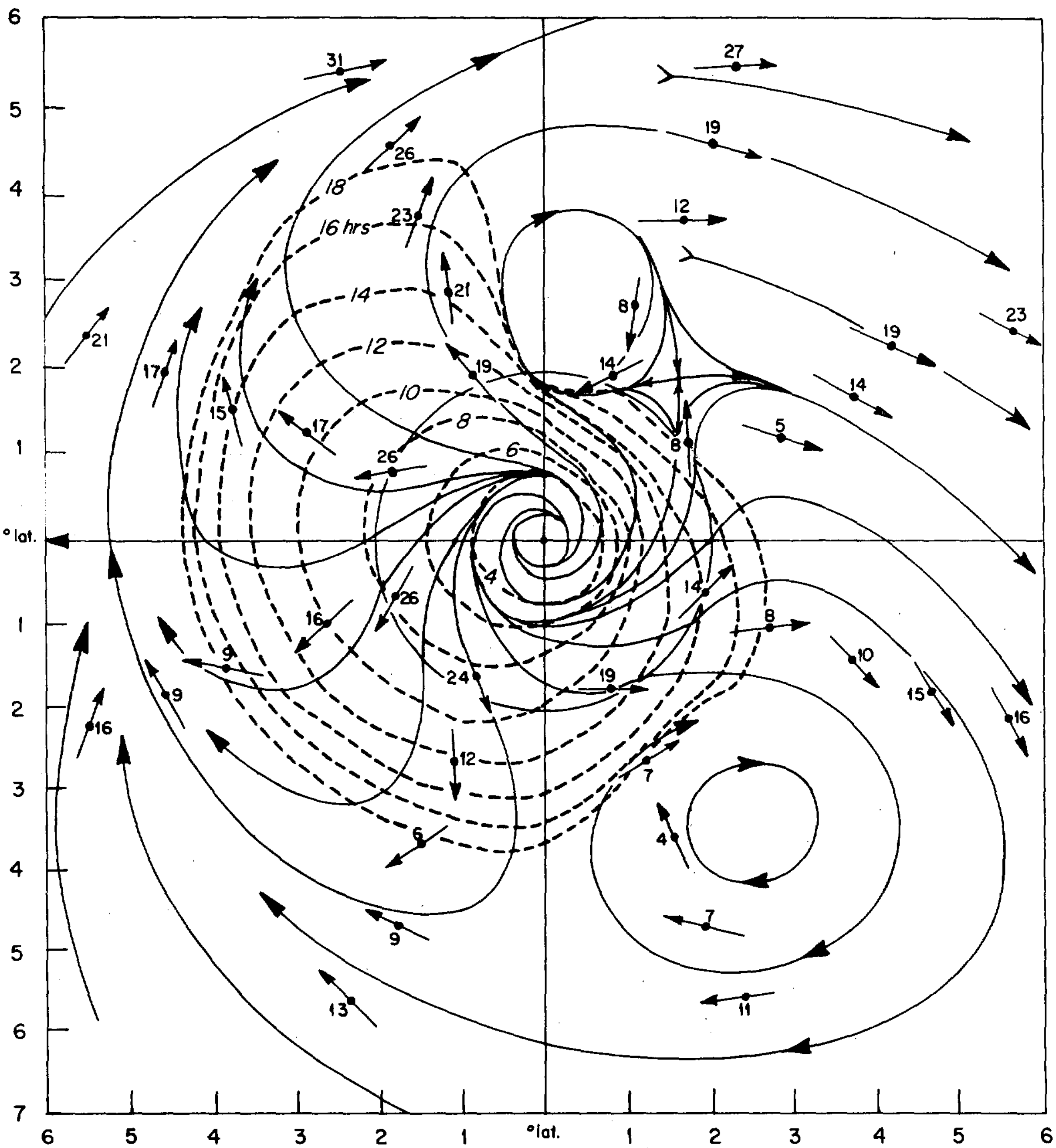

FIGURE 2.—Composite 45,000-ft. wind field surrounding tropical cyclones (Jordan [5]) and time change of the canopy when production at 25-km. radius is assumed.

radial component is at a relative maximum, the cirrus edges are still expanding at 12 hr. On the assumption that cirrus particles have visible lifetimes of at least 12 hr., the overall edge pattern shown at the end of 12 hr. should be representative of a satellite-observed canopy. Sharp edges would appear along the southwestern through southeastern sides. The northern and northeastern sides should appear diffuse.

JORDAN'S COMPOSITE WIND FIELD

The 45,000-ft. wind field prepared by Jordan [5] from composited upper wind observations surrounding tropical cyclones provided a second opportunity to examine the effects of translation on canopy development.

We again assumed production at ~25-km. radius and a steady state wind. Figure 2 presents the bi-hourly isochrones out to 18 hr. Note that a translational limit

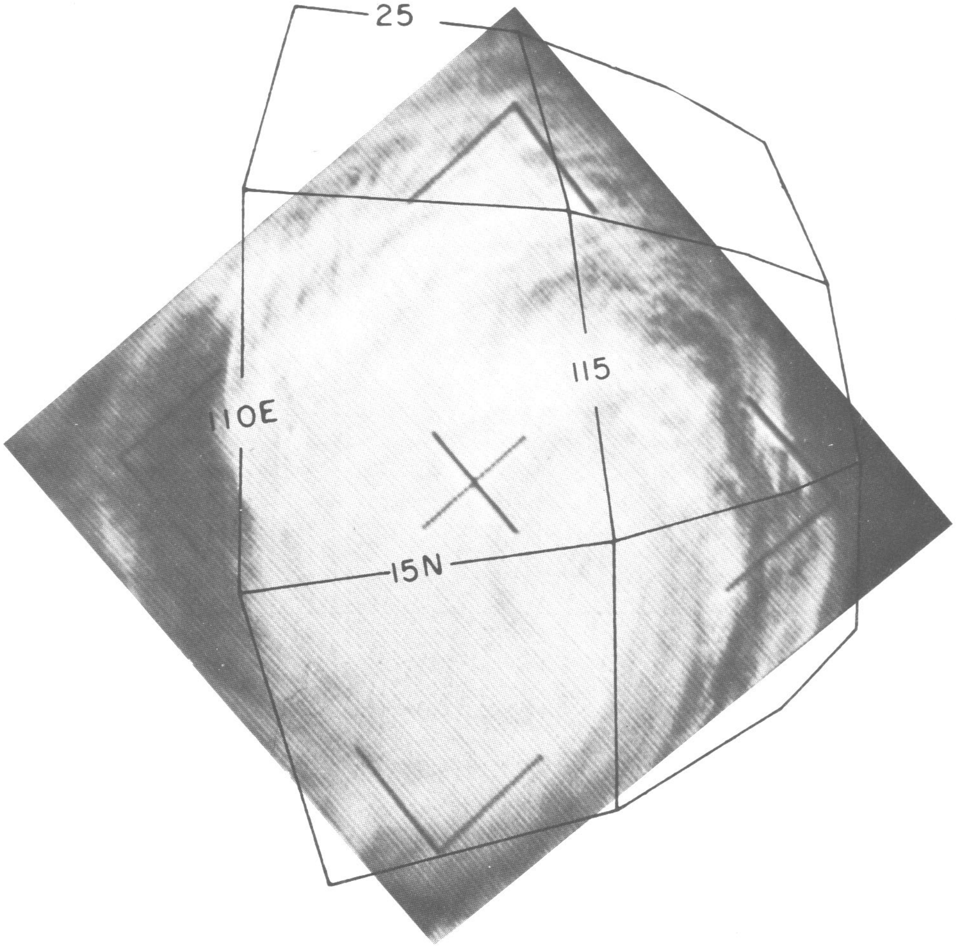

FIGURE 3.—Typhoon Jean, TIROS VI, 1403 GMT, November 8, 1962.

is reached in the northeastern side in about 12 hr. and on the southeastern side in about 15 hr. The western side appears to be reaching its limit in about 18 hr. The 18-hr. advection isochrone pattern thus represents the canopy which might have been satellite-observed in this case. Sharp edges should be apparent on the northeastern and southeastern sides, again where tangential winds are at a relative maximum. The northwestern and southwestern sides should appear most diffused. Figure 3 is a TIROS photograph of typhoon Jean on November 8, 1962, which is assumed to approximate the canopy to be expected for this type of wind field.

"DAISY" (1962) WIND FIELD

Observations were taken in 1962 at approximately 45,000 ft. by a B–47 in the southwest quadrant of hurricane Daisy. Observations from Bermuda and islands in the Bahamas permit an extension of these observations and the construction of an approximate 45,000-ft. wind field for Daisy on October 5, 1962. In this example, we have made two calculations of the time displacement of the cirrus edge: (1) assuming production in the eye wall at ~25-km. radius, and (2) assuming a realistic spiral band structure taken from the Malkus et al. [7] study of Daisy of 1958. Figure 4 shows the pattern for cirrus production in the eye wall only. Notice that a relative advection limit is reached in about 5 to 6 hr. on the western and southwestern sides. The northwestern side approaches a limit in about 8 hr. while the northeastern through southeastern sides are still expanding at 12 hr. Accordingly, the satellite should observe a sharply defined edge on the western and southwestern sides, and a diffuse edge on the northeastern through southeastern sides.

In the second calculation, presented in figure 5, the composited radar patterns for Daisy of 1958, from Malkus et al. [7], have been superimposed. On the assumption of continuous production of cirrus in the eye wall at ~25-km. radius and in the spiral bands, isochrones of particle displacement from the eye wall and spiral bands were prepared from the field of motion shown in figure 4. As figure 5 shows, the only change from the time displacements for the eye wall alone, shown in figure 4, is an expansion of the canopy at 12 hr. on the eastern and southeastern sides. Thus, it might be expected that a satellite photograph of Daisy would have shown a sharply

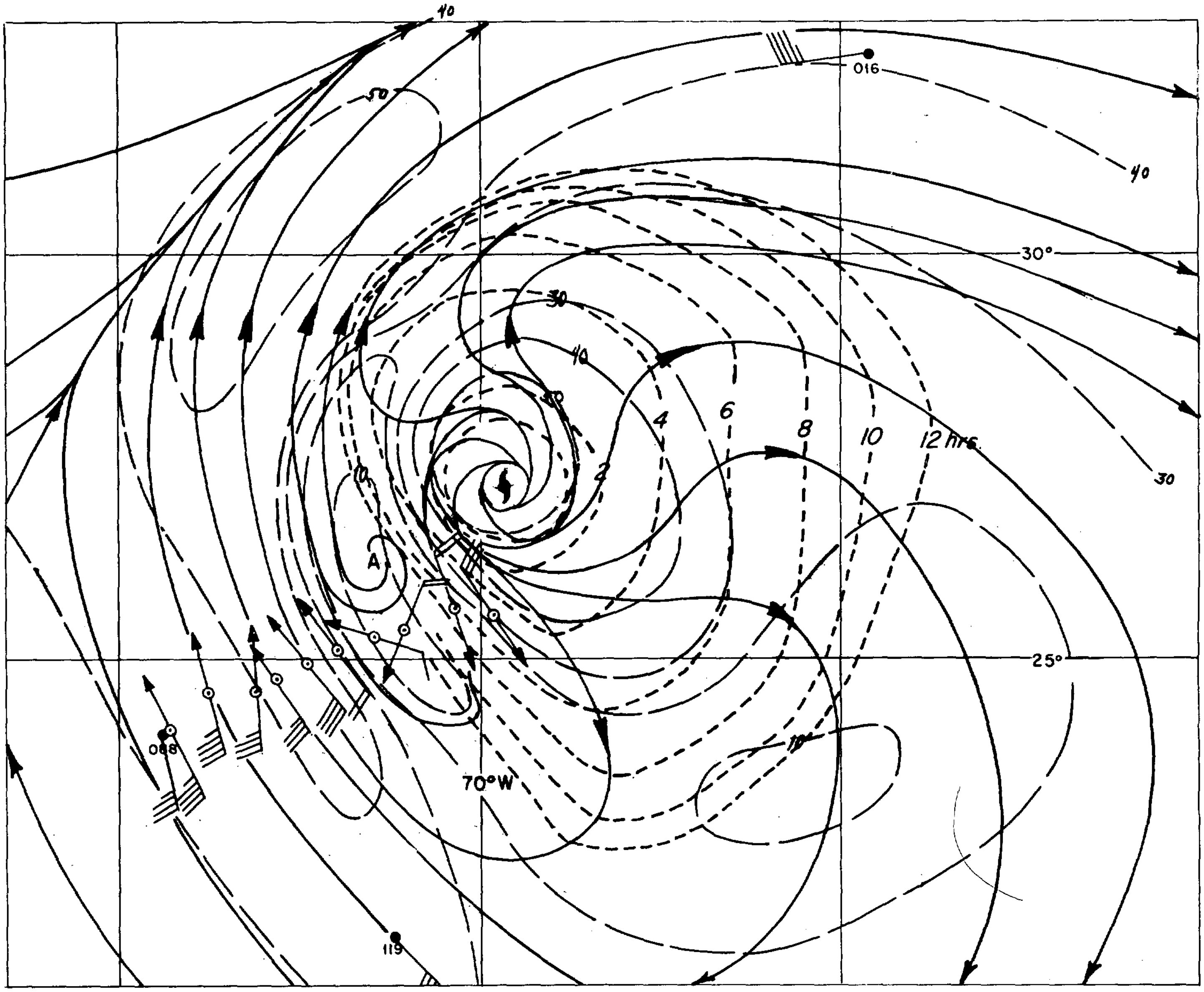

FIGURE 4.—45,000-ft. wind field of hurricane Daisy, October 5, 1962 and time displacement of cirrus canopy when production at 25-km. radius is assumed.

defined edge along the western and southwestern sides with a diffuse edge on the eastern and southeastern sides regardless of whether the significant cirrus generation occurs only in the eye wall or in both the wall and the spiral bands.

An opportunity to test this speculation is available, in this case, using the TIROS photograph of hurricane Daisy on October 5, 1962 presented in figure 6. Note the overall pattern similarity to that achieved by simple translation of particles in the upper wind field (figs. 4 and 5). Details of the satellite-observed pattern such as the clear zone on the southeastern side and the zone of decreased brightness surrounding the eye "disk" or "donut" cannot be explained by simple translations.

The time changes of the canopy depicted in figures 4 and 5 show, as mentioned previously, a particle displacement limit at about 5–6 hr., beyond which no further translation occurs on the western and southwestern sides, whereas the eastern and southeastern sides have no limit except that imposed by the cirrus particle lifetimes assumed to be at least 12 hr.

3. CIRRUS PARTICLE LIFETIMES AND EVAPORATION

LIFETIMES

Evaporation of water clouds in subsiding air has been analyzed in detail by Shulepov and Buikov [11]. It was

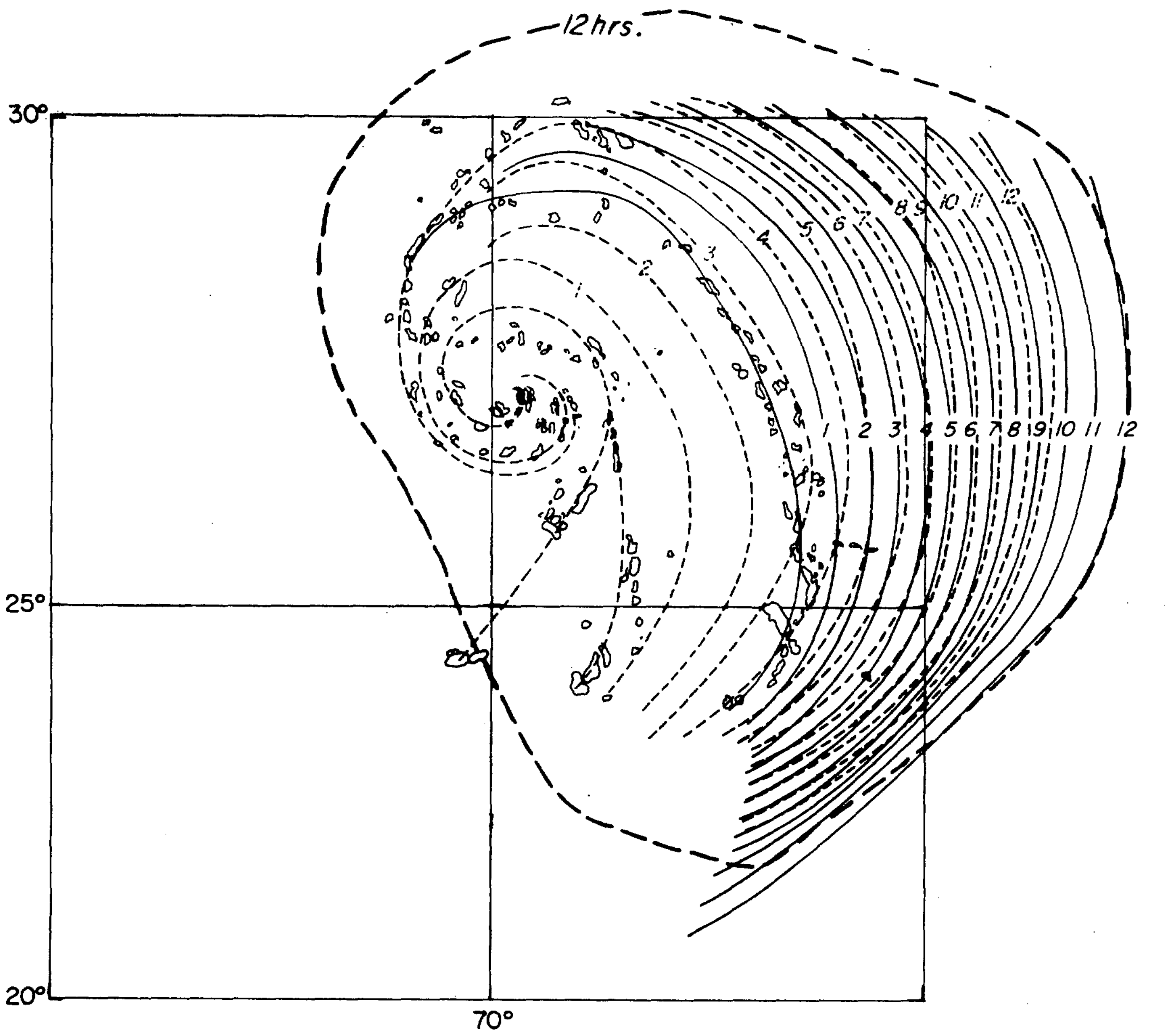

FIGURE 5.—Composite radar pattern of hurricane Daisy 1958, and time displacement of cirrus canopy, when production is assumed at eye wall, 25-km. radius, and in the spiral bands, from the 45,000-ft. wind field of figure 4.

shown that the evaporating of a cloud is a relatively slow process, and occurs over a period of several hours under typical conditions. This conclusion is supported by Ludlam and Miller [6], who suggest from experience in temperate zones that "the edge of an evaporating ice cloud may be anticipated to lie several hundreds of kilometers beyond the region in which the cloudy air begins its descent." Evaporation over tropical cyclones must, however, be considered in terms of the outflow characteristics of these storms at cirrus levels.

Although ice crystals form at or near water saturation, no evaporation will occur until the vapor density of the air is below ice saturation. If, for example, the cirrus cloud is at a temperature of $-60°$ C. (approximately 200 mb. in a mean hurricane rain area sounding), descent to about $-55°$ C. is required before any evaporation will occur. With a lapse rate of 9° C. km.$^{-1}$, this corresponds to a distance of about 0.55 km. In the absence of active subsidence, 20μ particles (fall speed 1.3 cm. sec.$^{-1}$) would take approximately 12 hr. before any evaporation occurred. Many more hours would be required for the evaporation of an appreciable amount of ice. Therefore, ice crystal lifetimes do not seem a limiting factor to canopy evolution.

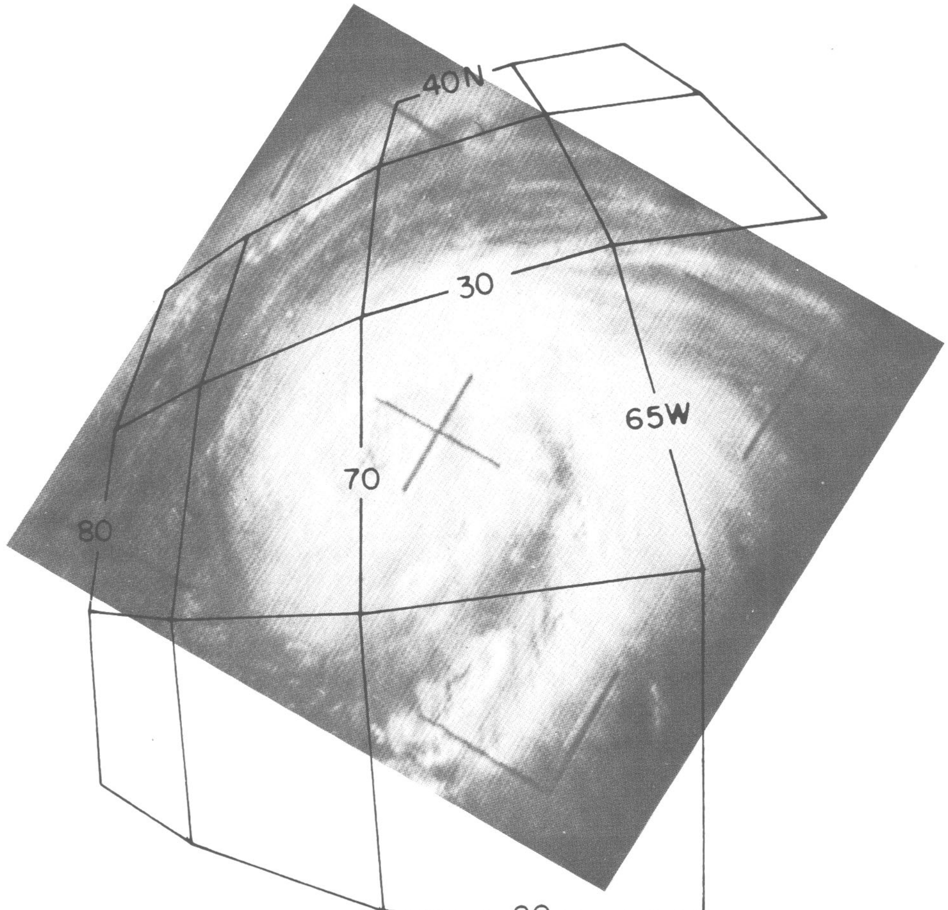

FIGURE 6.—Hurricane Daisy, TIROS V, 1241 GMT, October 5, 1962.

EDGE EVAPORATION

Some sectors of the cirrus canopy show a gradual fading away of the cloud over a considerable distance, while in other sectors, it disappears rather abruptly. There is some difficulty in defining the distance over which a cloud edge may disappear and still be considered sharp. This distance is probably considerably greater than the resolution of the TIROS (3 km.) or Nimbus (less than 1 km.) pictures, in both of which sharp edges have been observed. We shall assume somewhat conservatively that in order for the edge to be considered sharp, the cloud must change from a dense white to the black ocean appearance within a distance of: (1) 15 km. and (2) 30 km. Certainly, there are some pictures in which the transition occurs over a smaller distance than 15 km. Distances where the cirrus appears to fade off gradually are considerably greater than 30 km.

The maximum amount of ice which can be evaporated in air descending from a level with air temperature T_0 to a level with air temperature T is then $(q-q_0)\ \rho$, where q_0 and q are the respective saturation specific humidities and ρ is the air density at temperature T. The minimum time for evaporating this amount is equal to $\Delta z/w$ where Δz is the depth of the layer between T_0 and T and w is the rate of subsidence. For reasonable values of w and Δz, it is probable that the actual time for evaporation is relatively close to the minimum time. For the purposes of assessing evaporation as a factor near the cloud edge, the minimum time will be used as a conservative estimate. Figure 7 shows the maximum amount of water which can be evaporated in air initially at ice saturation at $-55°$ C. and descending along the 26° C. saturation adiabat. The ordinate represents the depth of descent from the $-55°$ C. level (temperature on right). This adiabat at high levels is representative of hurricane rain areas.

The time it takes for a radial outflow of speed v to traverse a horizontal distance d is $t=d/v$. During this time it is assumed that air is descending with constant speed w and on descending to a depth wt, evaporates an amount of ice given by wt. Figure 8 shows the combination of radial outflow and downdraft required to evaporate a given amount of ice over a distance of 15 km. for cloudy air initially at ice saturation at $-46°$ C. Thus, for a

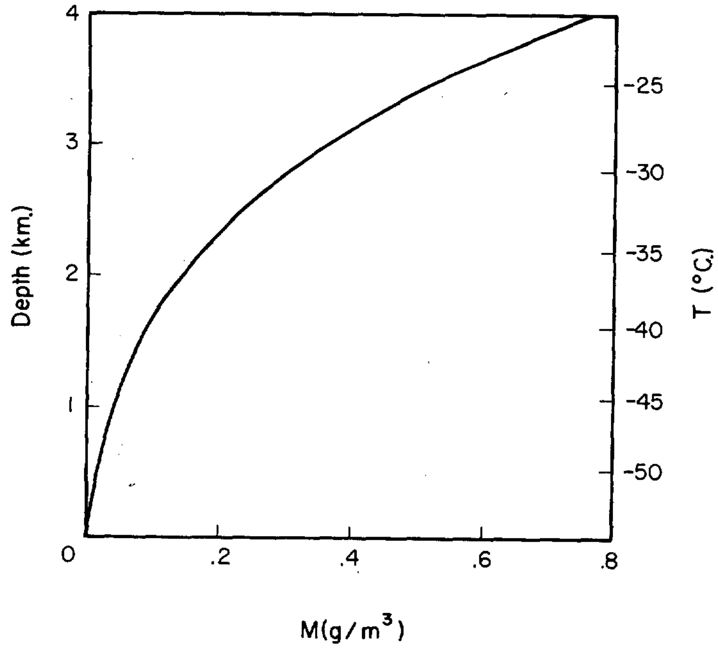

FIGURE 7.—Maximum amount of ice which can be evaporated during descent from $-55°$ C. along 26° C. saturation adiabat.

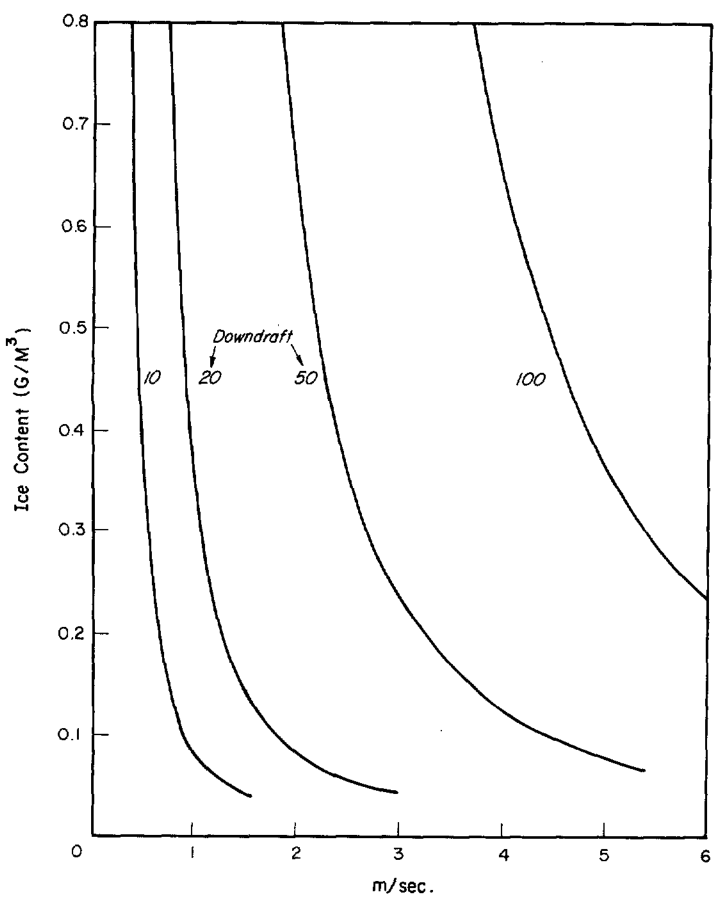

FIGURE 8.—Radial outflows and downdrafts required to evaporate different ice contents over a distance of 15 km. For a "sharpness" distance of 30 km., the curves would be relabeled, 5, 10, 25, and 50 cm./sec.

1-m. sec.$^{-1}$ outflow, a 10-cm. sec.$^{-1}$ downdraft would evaporate 0.08 gm. m.$^{-3}$ ice within 15 km., while a 20 cm. sec.$^{-1}$ downdraft would evaporate 0.35 gm. m.$^{-3}$. If the sharpness distance were taken to be 30 km., then the various downdraft curves would be labeled 5, 10, 25, and 50 cm. sec.$^{-1}$.

Ackerman [1] reports liquid water contents in the vicinity of 4 gm. m.$^{-3}$ at 18,000 ft. in the wall cloud of hurricane Daisy (1958) and it appears probable that ice contents of about that amount can be transported to cirrus levels. Ludlam and Miller [6] also estimate ice contents of several gm. m.$^{-3}$ in cirrus anvils above thunderstorms. At the edges of the cirrus canopy we would expect less than maximum amounts, but probably not less than 1 gm. m.$^{-3}$.

Downdraft speeds over a distance of 15 km. near the edge of a cirrus canopy are difficult to estimate. This region is generally far removed from the area of cumulonimbus towers where strong up and downdrafts are encountered. There is no known dynamic reason for strong downdrafts in the region, although some authors have reasoned that the presence of a sharp edge to the cirrus is evidence of strong subsidence. However, figure 8 shows that for a relatively high subsidence rate of 50 cm. sec.$^{-1}$ and a 2 m. sec.$^{-1}$ radial outflow only about 0.65 gm. m.$^{-3}$ ice can be evaporated. Since ice contents are probably in the vicinity of at least 1 gm. m.$^{-3}$, figure 8 shows that the radial outflow must be less than 2 m. sec.$^{-1}$. This lends further support to the analyses (figs. 1, 2, and 4) of wind flow patterns which indicated that sharp edges may be the result of adjacent flows of cloudy and clear air in a region where the radial outflow is relatively small.

4. CIRRUS GENERATION BY CUMULONIMBUS CLOUDS

For hurricane Daisy 1958, Malkus et al. [7] estimated that the total area of cumulonimbi was about 1 percent of the "rain area" to 200 n. mi.* on the day of formation, rising to 2 percent on the second day, and to 4 percent on the first day of maturity. These estimates were based on observations of only a small portion of the storm. About 22 percent of the area had radar echoes. The 4 percent estimate would signify that roughly one-fifth of the radar echoes should contain penetrative cumulonimbi, which, from experience with radar observations, seems a little high.

If we assume that the cirrus originates from the cumulonimbi, then the rate of production of cirrus volume is wA_c, where A_c is the area of cumulonimbi and w is a mean updraft at the base of the cirrus layer. If we assume a steady state, an incompressible fluid, and a cirrus layer of constant depth, the rate of cirrus production by the cumulonimbi must be equal to the rate of increase of the cirrus volume:

*Evidently, the total area within a radius of 200 n. mi. was meant.

$$A_c w = H \frac{dA}{dt} \tag{1}$$

where H is the thickness of the cirrus layer and A is the horizontal area of the cirrus.

The rate of increase of the area dA/dt may be estimated from the time changes of the canopy edge (figs. 1, 2, 4, and 5) as computed from the outflow patterns. For figure 4 which assumes cirrus generation only in the eye wall of hurricane Daisy, dA/dt was found to be almost constant with time and equal to 5×10^4 km.^{2} hr.$^{-1}$. In figure 5, which assumes cirrus generation in both the eye wall and the spiral arms dA/dt was not appreciably different during the later stages. For the Jordan composite (fig. 2) dA/dt was 4×10^4 km.^{2} hr.$^{-1}$. The thickness of the cirrus layer in tropical storms fed by the cumulonimbi (exclusive of fallout) is not known but is estimated to be 2 km. If we insert the above values in equation (1) with $A_c = 1 \times 7 \times 10^4$ km.^{2} (4 percent of area to 200-n. mi. radius), values of w between 1.2 and 1.6 m. sec.$^{-1}$ are found.

Up drafts within the central portions of cumuliform towers may exceed 1.6 m. sec.$^{-1}$ by an order of magnitude. However, the mean updraft entering the outflow layer in areas of penetrative cumulonimbi may be 1–2 m. sec.$^{-1}$. If these estimates are valid then it appears that the 4 percent area of convection estimated by Malkus during the mature stage of Daisy 1958 is capable of supplying a continuous cirrus layer. If A_c were only 2 percent of the area to 200 n. mi., and the other values were the same, the required w would be about 3 m. sec.$^{-1}$.‡ It is probable, however, that with reduced values of A_c the rate of increase of the cirrus volume would also be reduced.

5. CONCLUSION

The principal features of the cirrus canopy, as observed by satellites, such as overall size, organization, and the appearance of sharp or diffuse edges, are closely related to the wind field at cirrus levels. The sharp edges occur in regions with a relative maximum in tangential velocity. In the region where the cirrus appears to fade off gradually, the direction of decreasing cirrus coincides with the wind direction. In fact, the cirrus streamers often reveal graphically the streamline pattern at cirrus levels. Thus, the horizontal wind field can frequently be inferred, at least qualitatively, from satellite observations of the canopy.

Cirrus clouds are evidently produced when cumulonimbus clouds penetrate into stable layers, such as at the tropopause, and spread out with the wind flow. The main convective activity producing cirrus is concentrated at the eye wall with some additional activity in the spiral arms. By postulating cirrus production at the eye wall and assuming advection by the wind field at cirrus levels in typical hurricanes it is found that a cirrus canopy similar to those observed by satellites can be evolved in a period of 12 to 18 hr. If additional generation is assumed in the spiral bands, this time interval is shortened somewhat.

The cirrus is advected with the anticyclonic flow pattern outside the eye wall. In some sectors where the radial outflow is strongest—typically 10–15 m. sec.$^{-1}$—the cirrus spreads out in diffuse streamers to relatively long distances. In other sectors, however, the lines of flow converge and cirrus, advected from near the eye wall, flows side by side with cloud-free air. A relative tangential wind maximum exists at the cloud edge and the radial outflow is near zero so that cirrus transport by advection is at a minimum. It is in this region that the sharp edge will appear. This edge appears to remain almost stationary with time relative to the center. Thus, in hurricane Daisy 1962 (fig. 4) the lines for 6 and 12 hr. on the western side of the storm are practically at the same location with respect to the eye, while on the eastern side the cirrus veil would drift out along the lines of flow during this period at a rate of about 15 m. sec.$^{-1}$.

While subsidence around hurricane canopies has been inferred from aircraft and satellite cloud observations and time sections of temperature dew points read at island stations, the model used in this study indicates that subsidence is not a necessary requirement to produce or maintain a sharp canopy edge. The juxtaposition of cloudy air originating from the eye region with clear air outside the storm region in a region of minimum radial velocity flow appears to be sufficient to produce and maintain the observed sharp edges. Advection across the boundary may be relatively small particularly when there is a relative tangential velocity maximum in the flow pattern at the cloud boundary. The main requirement is that the component of the wind from cloudy to clear air be relatively small. However some subsidence could also be present and help maintain the sharp edge. The greater the rate of subsidence, the greater is the wind component from cloudy to clear air which could be tolerated and still maintain a sharp edge.

The penetration of cumulonimbus towers into a stable layer, e.g., the tropopause, apparently is sufficient to produce the cirrus canopy of a tropical storm without additional large-scale vertical motions being required. However, this conclusion is based on very inadequate observations of "hot" towers in one storm, hurricane Daisy 1958. Many more observations of the numbers, distribution, and areas of those towers entering cirrus levels are desirable for a conclusive analysis of the problem. Measurements of the field of vertical velocity within and around these towers would also be helpful.

‡Discussions with Dr. J. Simpson suggest that the updrafts into the outflow layer may be 3–5 m. sec.$^{-1}$ in the penetrative cumulus.

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