

A Role of the Tropical Upper Tropospheric Trough in Early Season Typhoon Development¹

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ABSTRACT

A synoptic model is developed to describe a role of the tropical upper tropospheric trough (TUTT) in early season typhoon development in the western Pacific low-level near-equatorial monsoon trough. The role is threefold: 1) The accompanying sub-equatorial ridge on the south side of the TUTT lies over the low-level trough and decreases the vertical shear; 2) the divergent flow on the south and east side of a cyclonic cell in the TUTT increases the evacuation aloft to aid in depression development in a low-level trough; 3) a channel to large-scale westerlies is established for efficient outflow of the heat released by increased convection in the developing depression.

1. Introduction

The increasing quantity and quality of wind observations from jet aircraft platforms and excellent satellite data have focused attention in the past few years on the role of the upper troposphere in the problems of tropical storm development, movement and variations in intensity.

In previous papers (1967, 1975a) I discussed the role

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of the tropical upper tropospheric trough (TUTT) in initiating tropical cyclones in the trade-wind regions. This paper concerns the development of tropical cyclones in the near-equatorial monsoon trough.

In addition to the generally recognized favorable conditions for tropical cyclone genesis (Palmén and Newton, 1969) there is increasing evidence that an important factor in storm intensity changes is the facility with which the systems are furnished *multi-directional* outflow channels to the *large-scale* circulation of the upper troposphere for removing the excess heat.

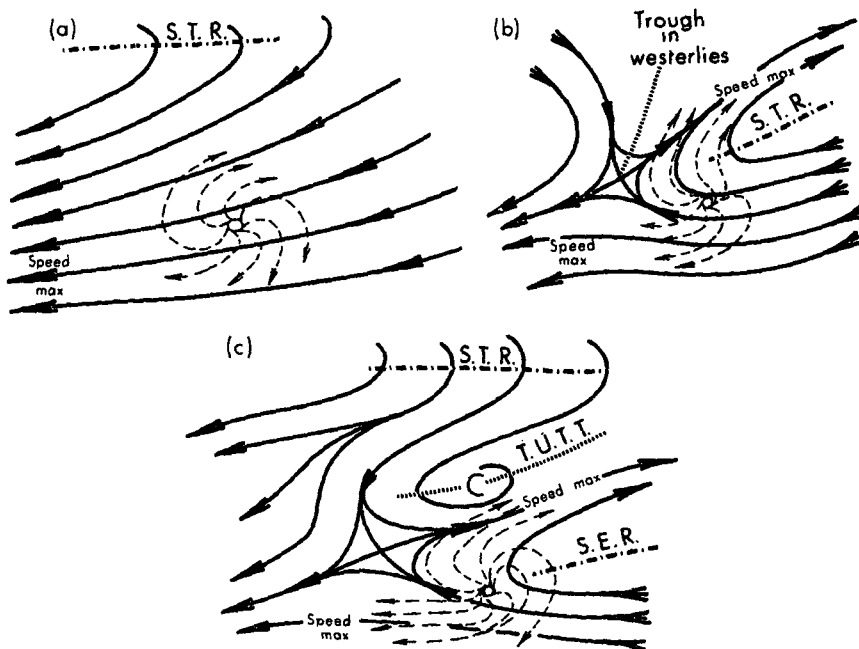


FIG. 1. Schematic of storm outflow interaction (dashed lines) with the larger scale upper tropospheric circulation (solid lines). STR is the subtropical ridge; SER, the sub-equatorial ridge; TUTT, the tropical upper tropospheric trough.

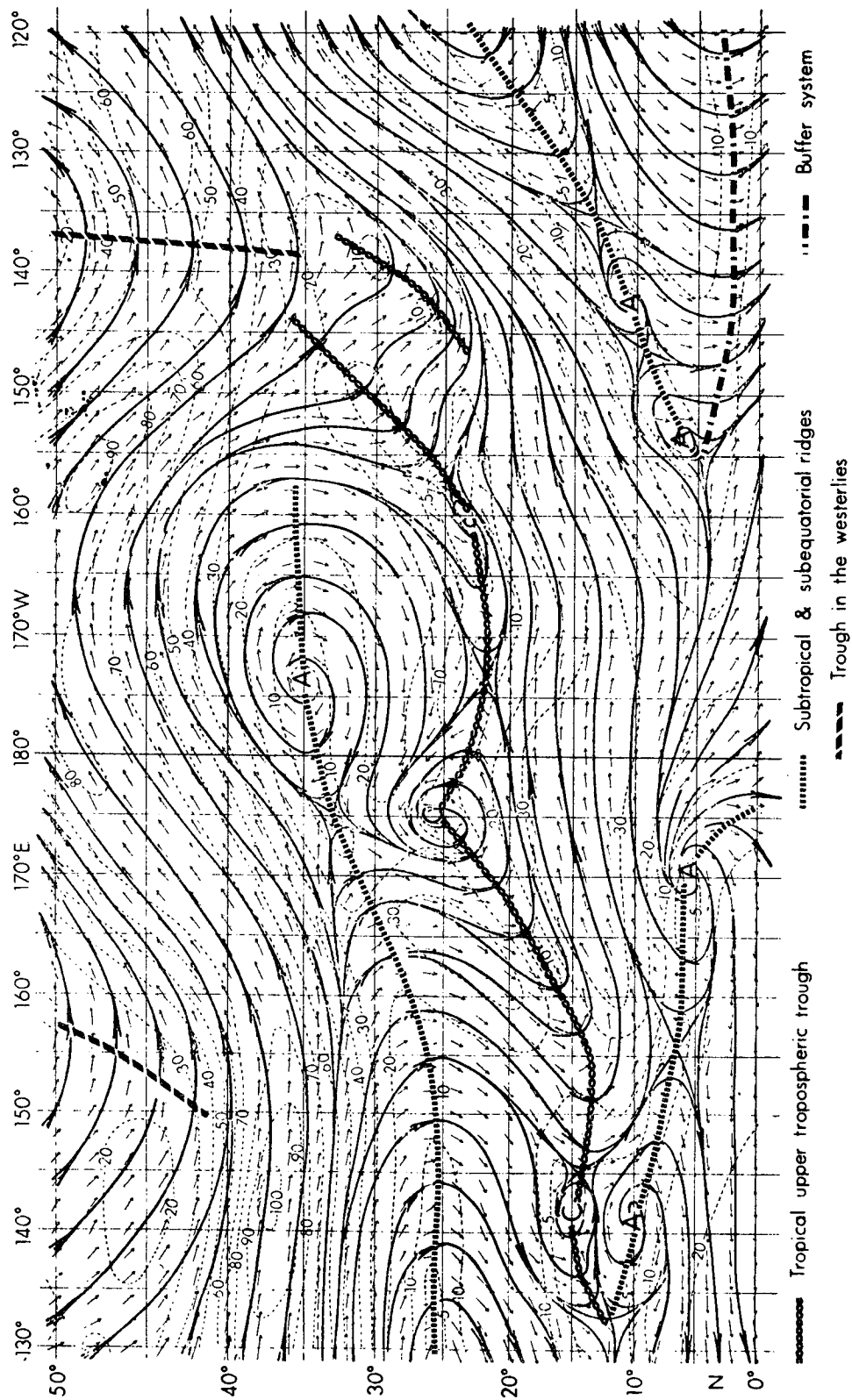


FIG. 2. The mean 250 mb circulation during the period of 13-24 June 1971. Wind speed (kt) shown by dashed lines.

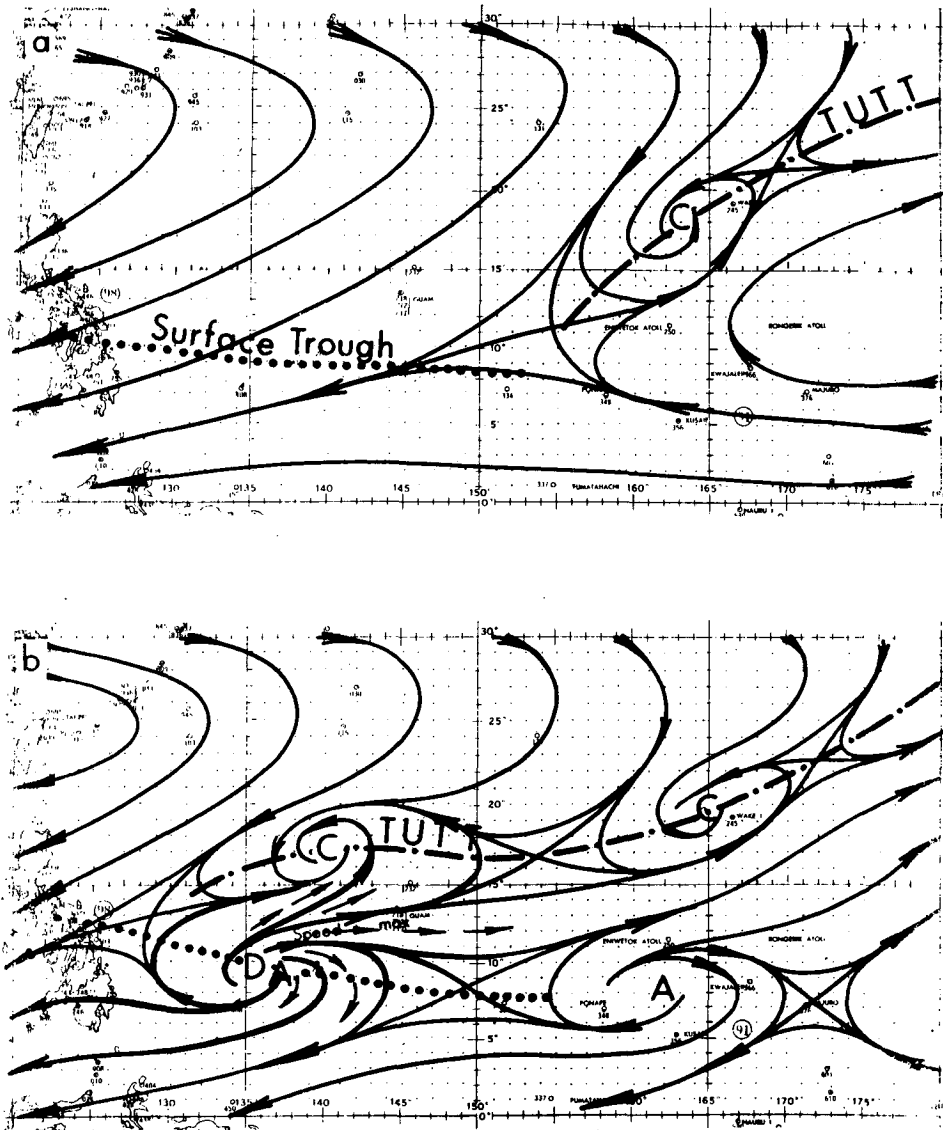


FIG. 3. A model of the upper tropospheric circulation changes as a mechanism for increased outflow for developing storms in the western North Pacific: (a) TUTT terminated near 160°E; (b) TUTT extending westward to 130°E. D denotes depression in the surface trough.

Fig. 1 is a schematic illustrating the interaction of storm outflows with some common large-scale circulation patterns.

In Fig. 1a the storm is located in a region of upper tropospheric northeasterlies. An anticyclonic outflow is impeded over much of the area and is directly opposed in the northern sector. Also, large values of vertical shear exist over portions of the storm. The upper tropospheric pattern is very similar to the mean during summer in the western North Pacific, being east-northeast with increasing speeds westward—or climatologically an ideal pattern for only the southern sector of the storm outflow. A facilitated outflow in the northern sector requires a channel to a westerly current. In late season (October and November) this channel

is often furnished by the deep troughs in the mid-latitude westerlies similar to the sketch in Fig. 1b. Ramage (1974) presented case studies to show the dominant influence of such troughs on the intensity of typhoons in the South China Sea during October. Erickson and Winston (1972) studied the role of the outflow from autumn tropical cyclones in increasing the circulation of the mid-latitude westerlies. The east side of deep troughs in the westerlies was a principal outflow channel for each cyclone. The satellite-observed cloud bands extending northeastward from intense tropical cyclones attest to the importance of an outflow channel to the mid-latitude westerlies in maintaining the intensity of these autumn storms in the Bay of Bengal [see for example, p. 129 of the 1972 Annual

Typhoon Report (U. S. FWC/JTWC, 1972)]. An outflow to the westerlies has long been recognized as a requirement for tropical storm development in the Australian region (Wilkie, 1964). Colón and Nightingale (1963) found that the majority of Atlantic hurricanes intensify under conditions of outflow to a westerly channel.

During summer, troughs in the mid-latitude westerlies seldom extend into the tropical western North Pacific; therefore, we must look to some other circulation feature for an outflow channel to westerlies. This circulation feature is the tropical upper tropospheric trough (TUTT) as illustrated in Fig. 1c. The influence of the TUTT in the rare development of storms in the South China Sea during summer was noted by Sadler *et al.* (1968).

The development period is the time of extreme intensity changes and this study concerns the role of the TUTT in the development of Typhoons Freda, Gilda and Harriet during June of 1971. These storms were chosen because of the repetitive similarity of relatively simple synoptic patterns during each development period, the relative abundance of aircraft wind observations, and good satellite observations from both daytime visual and nighttime infrared sensors.

2. General synoptic features—June 1971

Three storms in June are almost twice the normal for the western Pacific; yet, there was no obvious

abnormality in the low-level atmospheric features. The surface trough was near its normal June position between 5° and 10°N. Pressures in the trough were 1008 to 1010 mb. The low-level westerlies near 5°N seldom extended eastward of 140°E.

The abnormality, if any, appears to be in the upper troposphere. The uncertainty is due to the fact that only within the past few years of good aircraft wind observations has it been possible to depict in sufficient detail the upper tropospheric flow, so it may be premature to speak of anomalies. In any event, the TUTT was intense and a dominant feature during June 1971. It persisted in the eastern Pacific and westward to near 160°E. The trough extended periodically into the extreme western Pacific. East extension accompanied westward movement of an upper-level cyclonic cell between 15° and 20°N from the region of Wake Island.

The mean 250 mb circulation for the period 13–24 June 1971 (Fig. 2) was derived from the daily analyses by extracting the wind velocity at grid points spaced 2° latitude by 2° longitude. The TUTT is much more pronounced than in the long-term mean (Sadler, 1975b). However, as mentioned above, this June pattern may not be too uncommon.

3. Descriptive model

During each of the three occasions in June 1971 that the TUTT extended into the western Pacific, a tropical storm developed in the low-level trough between 5°

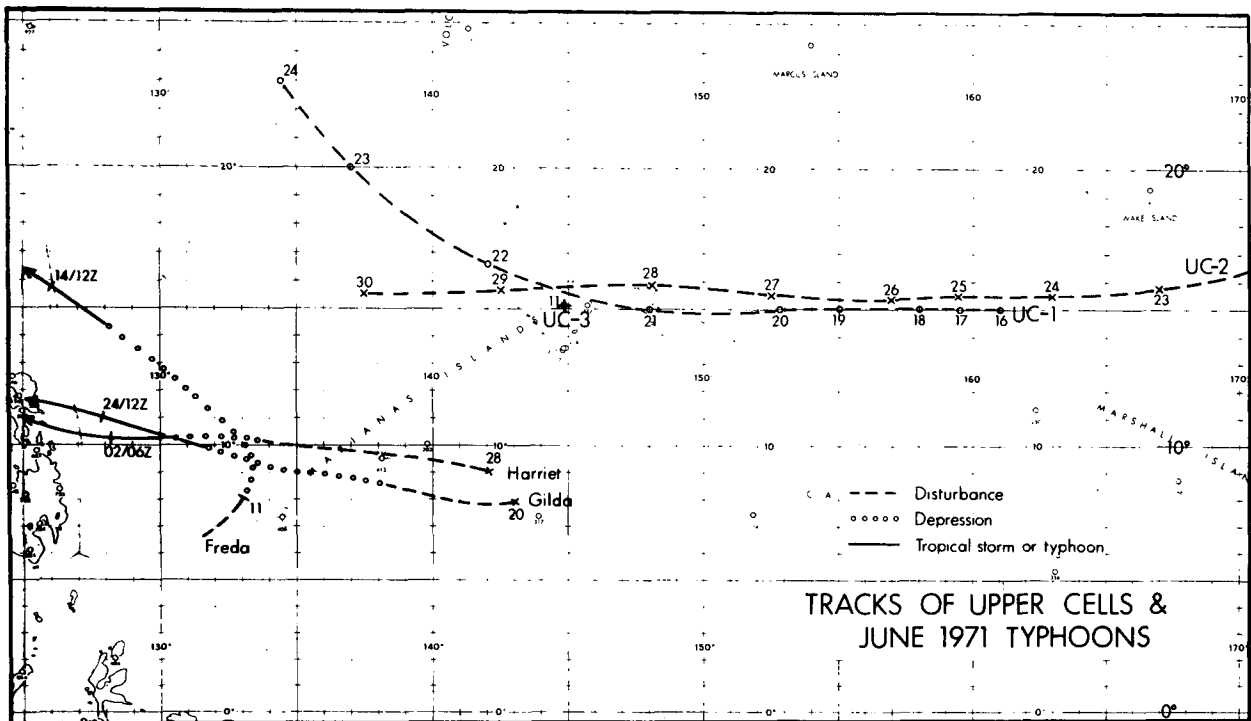


FIG. 4. The tracks of Gilda, Harriet and Freda and of the upper tropospheric cyclonic cells UC-1, UC-2 and the position of UC-3 on 11 June.

and 10°N near the islands of Koror (7.3°N, 134.5°E) and Yap (9.5°N, 138.1°E). The schematic of Fig. 3 illustrates the change in the upper flow pattern during these cycles. In Fig. 3a the TUTT terminates near 160°E and the upper tropospheric flow is northeasterly

over the tropical western Pacific. Fig. 3b, a few days subsequent to Fig. 3a, depicts the flow pattern as the TUTT extends westward to 130°E. A ribbon of westerly winds lies between the TUTT and the accompanying subequatorial ridge which lies over the low-level trough.

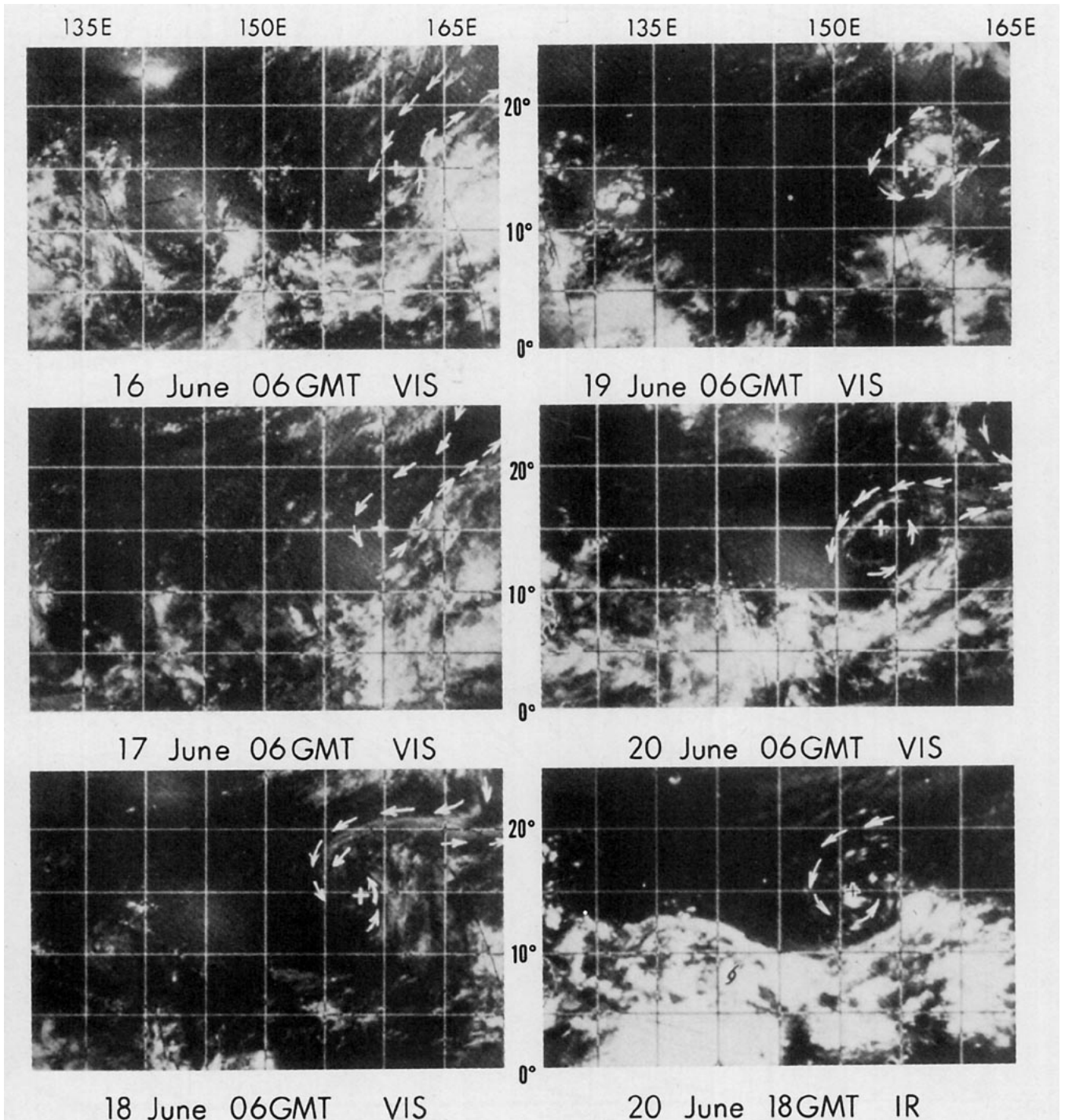


FIG. 6. NOAA-1 satellite mosaics of the visible and infrared channels. The positions of UC-1 are shown by the crosses and the upper tropospheric circulations near UC-1 are indicated by the arrows. The satellite coverage is shifted westward on 19 June and again on 21 June.

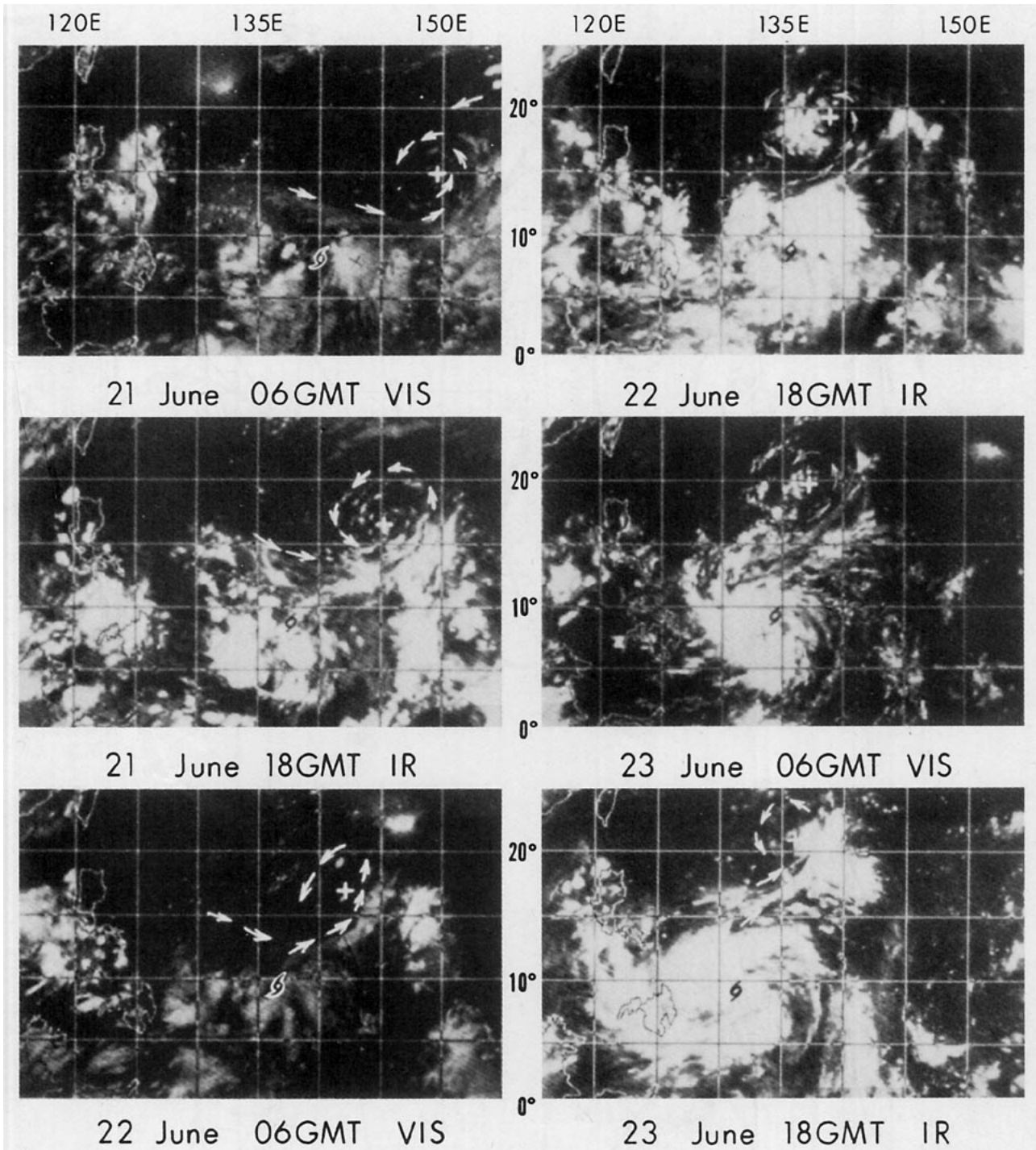


FIG. 6 (continued)

The effects of these changes aloft are threefold:

1) The sub-equatorial ridge over the low-level trough decreases the vertical shear and facilitates the development of an upper tropospheric anticyclone over the surface low.

2) The divergent flow indicated by the arrows in

Fig. 3b (also speed divergent due to stronger westerlies just south of cyclonic cell) increases the evacuation aloft to help initiate a low in the surface trough (indicated by a D in Fig. 3b).

3) A channel to the westerlies is established for efficient outflow of the heat released by increased convection in the developing depression.

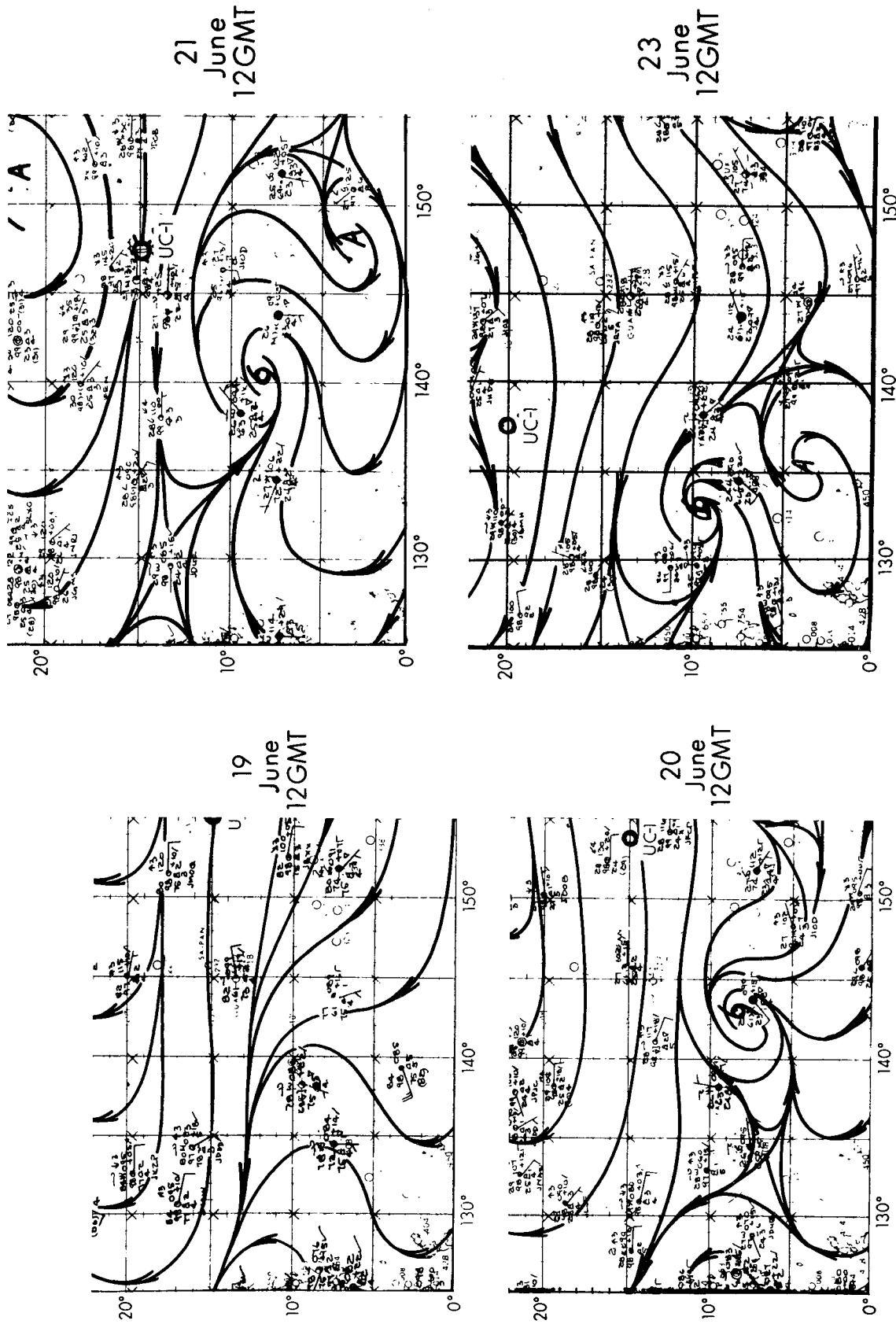


Fig. 7. Surface wind analyses for 19, 20, 21 and 23 June 1971. The positions of UC-1 are noted by the circles.

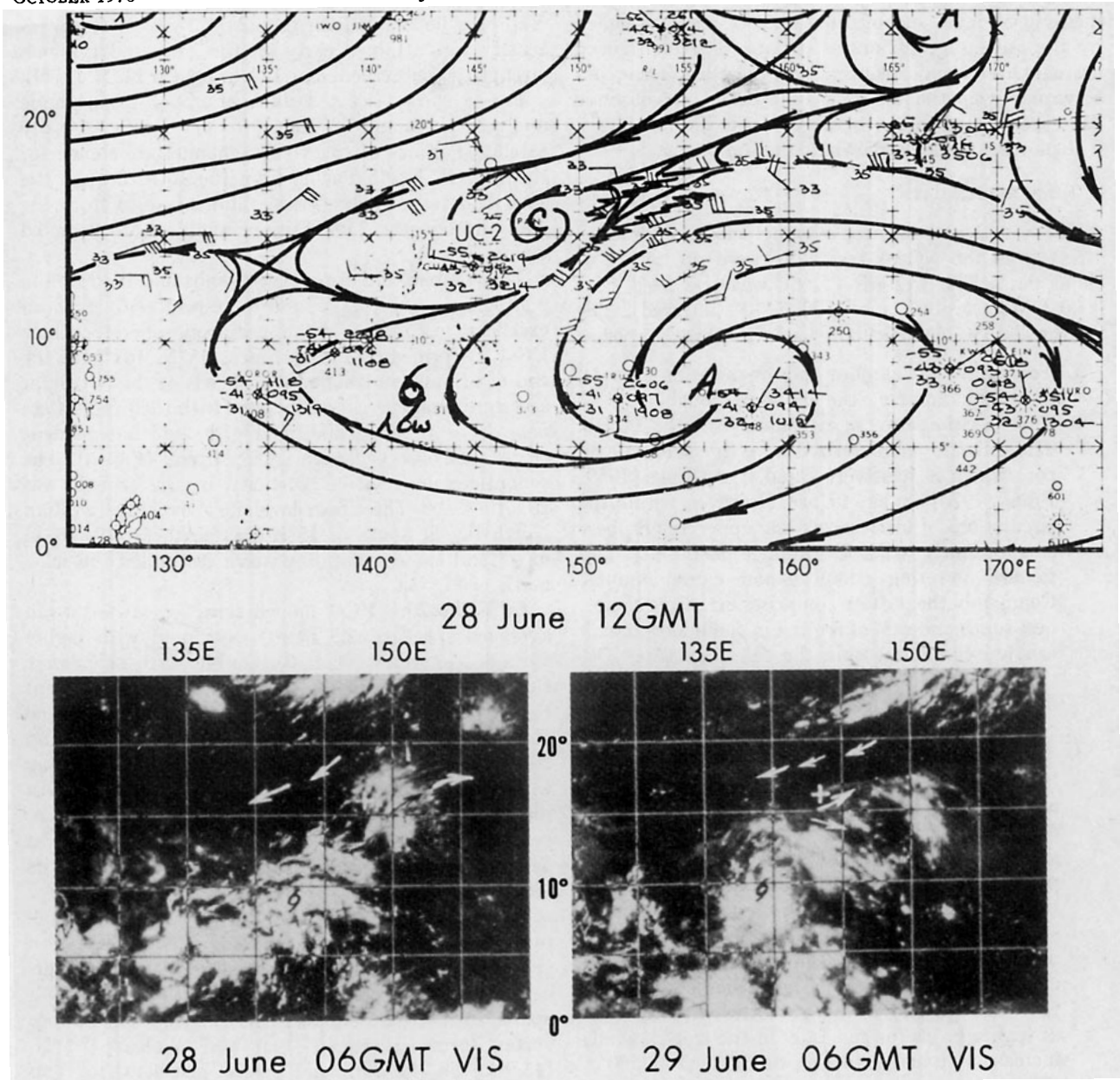


FIG. 8. Top: 250 mb wind analysis for 1200 GMT 28 June 1971; bottom: satellite photographs of visual channel for 28 and 29 June 1971. Harriet's low position is shown by storm symbol.

4. Case studies

The early histories of typhoons Freda, Gilda and Harriet obtained from the 1971 Annual Typhoon Report (U. S. FWC/JTWC) are shown in Fig. 4, together with the tracks of the upper tropospheric cyclones UC-1 and UC-2 and the position of UC-3 on 11 June 1971. Gilda was selected as the prime illustration of the model because the TUTT cell (UC-1) was intense and well defined by wind observations and satellite-observed cloudiness in the visual and infrared. For brevity, only a selection of analyses and satellite photographs are shown. Daily detail is available in Sadler (1974).

a. Data source and analyses

1) UPPER TROPOSPHERE

The 250 mb level was selected for the upper tropospheric analysis because aircraft wind observations are more numerous near this level. The aircraft data came from the operational "plotrep" charts of the Fleet Weather Central at Pearl Harbor. To minimize observational voids, the 250 mb chart was augmented by data from the 200 and 300 mb charts and by off-time data from the 0600 and 1800 GMT charts. The off-time data were plotted in different colors to avoid confusion; any confusion which might have arisen from

meshing off-level and off-time data is far outweighed by the advantage of increased data. The high speed currents are of major concern and these are fairly conservative over the analysis time scale. Rawinsonde data are plotted for both the 250 and 200 mb levels. The plotting model is shown at the top of Fig. 5.

2) SATELLITE DATA

The visual and infrared channel mosaics (tropical strip) from the NOAA-1 satellite were the source of cloud data. The western Pacific was traversed near 0600 GMT (visible) and 1800 GMT (infrared). The satellite data were particularly useful for three purposes:

1. To monitor the amount and organization of cloud systems in and near the low-level trough.
2. To locate the center of cyclonic cells in the TUTT. The cells are characterized by a dry sinking cold core which is relatively cloud free (Ricks, 1959; Frank, 1970; Sadler, 1975a). However, within the circulations of intense cells the upper troposphere is sufficiently cold to produce instability and *isolated* towering cumulus and cumulonimbus. Commonly the pattern comprises extensive cloudiness south and east of the cell in combination with isolated cumulus within the cell circulation. Occasionally, independent cirrus bands will partially or totally encircle the low. Diameters of intense cell circulations typically range from 800–1200 km.
3. To locate the narrow ribbons of high wind speed. Strong winds on either side of the TUTT and around the cyclonic cells will at times be associated with narrow bands of "independent" cirrus, sufficiently thick to show clearly on the satellite picture. Aircraft and balloon soundings in or near the edge of the cirrus band generally report wind speeds $> 25 \text{ m s}^{-1}$ at 10 600 m (35 000 ft). The wind direction at 10 600 m roughly parallels the cirrus bands; however, it should be kept in mind that the agreement may be better with the flow at higher levels for generally in the tropics winds increase with height to a maximum near 13 500 m (Kakagawa and Adams, 1966).

To aid in comparing the satellite-observed clouds and the upper wind field, the strong wind currents from the streamline analyses are shown on the satellite pictures by lines of short arrows and the bands of independent cirrus from the satellite photographs are shown on the streamline analyses by serrated lines. The observations are not synoptic but cover a period of plus or minus some six hours; no data positions have been adjusted.

b. Individual cases

1) TYPHOON GILDA

The Gilda low formed near 8°N , 143°E on 20 June. It moved west-northwestward and passed south of

Yap near 0600 GMT on the 22nd. Tropical storm intensity was attained early on the 24th and typhoon strength was observed some 12 h later near 11°N , 127°E .

Fig. 5 shows selected days of upper tropospheric analyses beginning on the 16th and in Fig. 6 daily satellite mosaics of the visible channel are shown for the western North Pacific from the 16th through the 19th and twice daily (visible and infrared) from the 20th through the 23rd. Surface analyses are depicted in Fig. 7.

The combination of observed winds and the satellite photographs (in Figs. 5 and 6, respectively) gave an excellent history of the upper tropospheric cyclone UC-1. It formed on the 16th near 15°N , 161°E in the end of an intense trough. The speeds of the northeast and southwest currents associated with the trough were near 35 m s^{-1} at 10 600 m (Fig. 5) and independent cirrus was observed with each current (Fig. 6). The synoptic-scale relative vorticity in the trough was $20 \times 10^{-5} \text{ s}^{-1}$. The upper-level flow over the western North Pacific south of 15°N was northeasterly $10\text{--}15 \text{ m s}^{-1}$ and the circulation pattern resembled the schematic of Fig. 3a.

Until the 20th UC-1 moved slowly westward at an averaged speed of 2.5 m s^{-1} associated with highly variable cloudiness (Fig. 6). On the 17th skies were clear in the vicinity of UC-1; as on the 16th independent cirrus bands were associated with the high speed currents on either side of the trough. On the 18th and 20th the upper low was surrounded by a cirrus ring with a few cumulonimbi inside the ring; on the 19th the cirrus ring was absent but the scattered convective cells were more prominent and arranged with a vortical pattern. Similar variations persisted throughout its lifetime.

The almost clear skies in the western Pacific, between 135°E and 150°E north of 5°N on the 19th (Fig. 6), establishes that the pre-Gilda surface disturbance did not migrate from the east but formed *in situ*. Sparse surface data support this (Fig. 7). The surface vortex formed between Yap and Woleai (7.5°N , 143.9°E) on the 20th and passed just south of Yap near 0600 GMT on the 22nd as an intensifying depression, as indicated by the Yap rawin observations at 0000 and 1200 GMT. The forward speed of UC-1 increased to 6 m s^{-1} on the 21st and its direction changed to northwest. From late on the 20th through the 21st a strong west-northwest current on the south side of the TUTT and some 500 km north of the surface vortex was indicated by the satellite-observed cirrus (Fig. 6). In the visual data for the 21st the independent cirrus band was particularly striking, extending from 135° to 150°E and circling the south and east side of UC-1. Widespread convection began in the vicinity of the low-level vortex on the 20th but there was no obvious organization to the pattern until the 22nd when UC-1 moved into position to change the upper flow to southwesterly north of the Gilda vortex for a more efficient

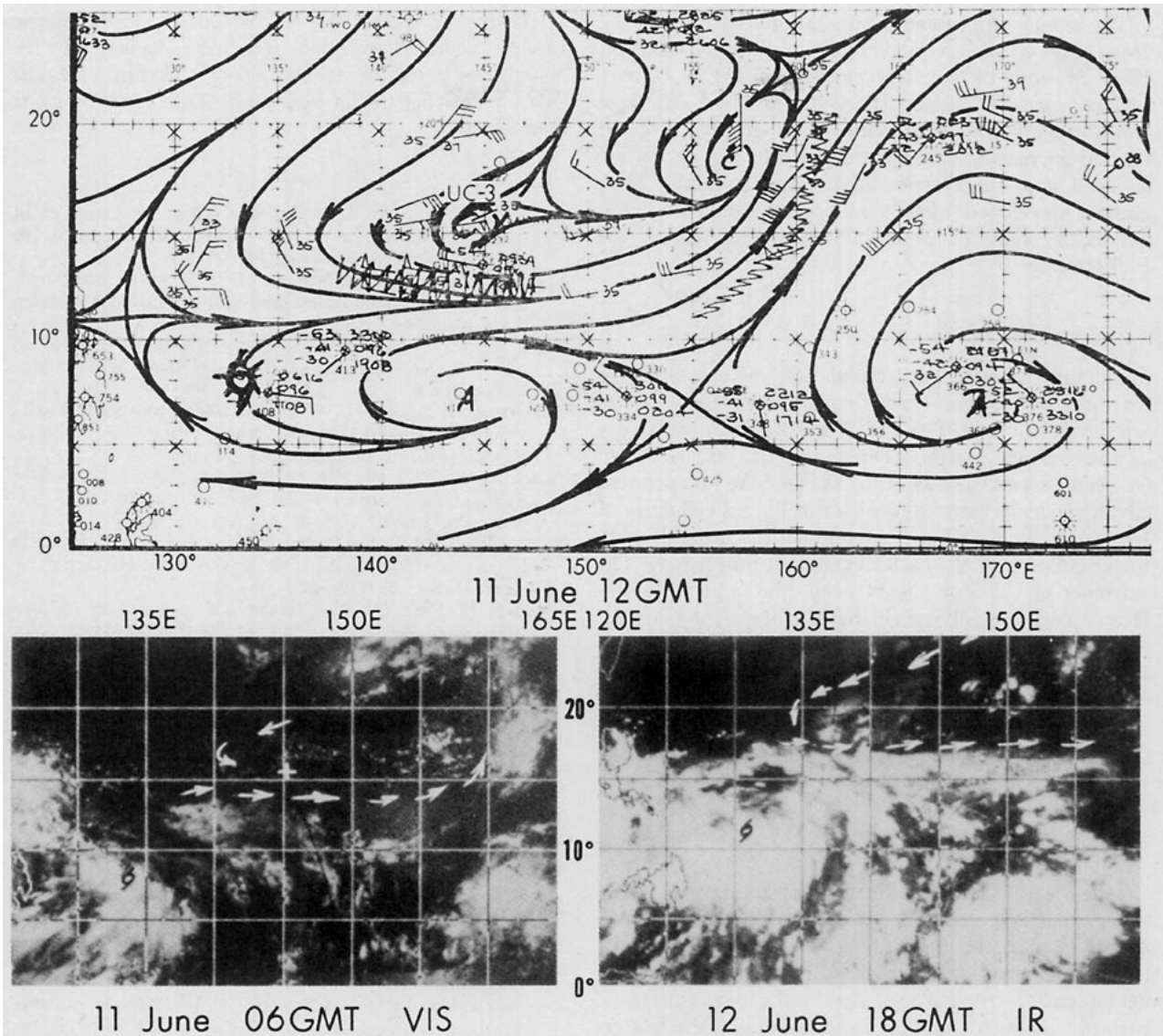


FIG. 9. Top: 250 mb wind analysis for 1200 GMT 11 June 1971; bottom: satellite photographs of visual channel for 11 June and infrared channel for 12 June 1971. Freda's low positions is shown by storm symbols. The satellite coverage is shifted westward on 12 June.

outflow. This direction change is shown by the cirrus band orientation in the visual and IR picture for the 22nd (Fig. 6). The band extends northeastward from the surface vortex and circles the upper low. This "bridging" cirrus band from the surface system to UC-1 was even more apparent on the 23rd when the clouds associated with the strong Gilda depression were more vortically organized than on the 22nd. The cloud organization also indicated an increased outflow south of the depression into the near-equatorial easterlies. The wind observations at Yap and Koror (Fig. 5) indicate that this outflow was confined to levels above 200 mb.

On the 24th UC-1 continued in a favorable position for effective outflow from Gilda which intensified to typhoon strength before landfall in the Philippines late on the 24th.

2) TYPHOON HARRIET

Harriet's history was very similar to Gilda's (Fig. 4). The track of the associated UC-2 and the TUTT extension westward were also similar to the events preceding Gilda. The upper tropospheric circulation pattern on the 23rd resembled that of the 16th (Fig. 5) and the subsequent track of UC-2 was almost identical to that of UC-1 (Fig. 4) except for the forward speed in the early stages. The major difference was in the size and intensity. UC-2 was smaller than UC-1 and the observed winds were near 15 m s^{-1} compared to 25 m s^{-1} . Probably because of its weakness the UC-2 circulation was seldom obvious in the satellite-observed cloudiness. The major cloudiness was confined to the south and east periphery and very few isolated cumulus were observed within the circulation.

The upper tropospheric circulation pattern on the 28th (Fig. 8) was very similar to that of the 21st (Fig. 5) and the relative positions of the Harriet surface low to UC-2 and the Gilda low to UC-1 were almost identical. The satellite photographs (Fig. 8) showed increasing organization of the cloudiness associated with the Harriet disturbance from the 28th. Harriet developed more slowly than Gilda and had maximum winds of 25 m s^{-1} at first landfall in the Philippines.

3) TYPHOON FREDA

The upper tropospheric circulation and satellite photographs during the early depression stage of Freda are shown in Fig. 9. The TUTT was narrow and intense in the western Pacific. Three aircraft just south of Guam observed west winds of 25 m s^{-1} . An independent cirrus band was associated with this high speed current. Isolated cumulonimbus existed along the trough and in the circulation of the eastern cell (not numbered). The existence of UC-3 on the 11th may be in some doubt. It was placed mainly on the basis of the strong current to its south and the backing of the wind at Guam to southwesterly 12 h later. Cloudiness associated with the Freda depression increased and became organized from the 11th (Fig. 9); she became a tropical storm on the 13th and a minimal typhoon just before landfall in the Philippines on the 15th.

5. Discussion

These case studies indicate that an upper tropospheric outflow channel to a large-scale westerly flow, in addition to the normally available channel to the large-scale tropical easterlies, is important in the development of tropical cyclones in the near-equatorial surface trough. In June 1971 the channel to the westerlies was supplied by an extension of the TUTT into the western Pacific during the developments of Typhoons Freda, Gilda, and Harriet.

The TUTT is a dominant climatological feature of the upper troposphere throughout the summer in the Pacific; therefore, similar studies are planned for mid-summer when the TUTT is more persistent and farther north and the upper tropospheric circulation is much more complex than in June.

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