The Occurrence of Vertical Tilt in Tropical Cyclones

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(Manuscript received 22 January 1981, in final form 4 May 1981)

ABSTRACT

Developing tropical cyclones are often observed with significant displacements between their surface and upper level circulation centers. The slope is in the direction of the convective cloud mass which also is displaced from the surface center during the early stage of development. As the cyclone intensifies, the surface and upper level centers become vertically aligned. Three representative tropical cyclones in the western North Pacific with extensive aircraft reconnaissance are discussed to illustrate this phenomenon.

1. Introduction

The literature contains little observational data on the vertical relationship of surface and middle-level circulation centers during the development stage of tropical cyclones. With the exception of Sadler (1967), Hovermale and Livezey (1977), and the *Annual Typhoon Reports* published by the Joint Typhoon Warning Center (JTWC) for tropical cyclones in the western North Pacific, the authors were unable to locate references that document the existence of a tilted vertical axis in tropical cyclones during their development stage. Sadler (1967) originally postulated that some tropical cyclones are initiated by the Tropical Upper Tropospheric Trough (TUTT) sloping downward to the surface, placing the surface circulation center under divergent flow aloft. Sadler (1976) later modified his earlier model and showed that a direct vertical linkage does not exist between the upper and lower level circulation centers. In Sadler's later model, the tropical cyclone develops vertically upward from the surface. Also, to the authors' knowledge, numerical simulations of tropical cyclones reported in the literature all spin up from an axisymmetric vortex (Kurihara and Tuleya, 1974; Hovermale and Livezey, 1977; Rosenthal, 1978). Hovermale and Livezey (1977) reported the results of using the NMC operational hurricane model to forecast the track of Hurricane Eloise (1975), which had a strongly tilted vertical axis during the development stage. They attributed large errors by the model to specification of an overly intense vortex in the initial state and to the fact that a tilted cyclone cannot be achieved with an axisymmetric initial state.

During the 1979 tropical cyclone season, 11 of 23 named tropical cyclones in the western North Pacific exhibited a vertical tilt between their surface and 700 mb centers (Table 1). The 1979 *Annual Typhoon Report* contains the reconnaissance data and a brief description of each cyclone. These tilts were observed by Aerial Reconnaissance Weather Officers (ARWO) of Detachment 4, Headquarters Air Weather Service, onboard aircraft from the 54th Weather Reconnaissance Squadron (54WRS) stationed at Andersen Air Force Base, Guam. The location of the surface center, the location of the 500 m or 700 mb center, the minimum sea level pressure, the minimum 700 mb standard pressure level height in the vicinity of the 700 mb center, and the meteorological and navigational accuracy are part of the Detailed Vortex Message passed via high frequency radio from the ARWO to JTWC immediately after penetration of the cyclone and location of the surface center. Tropical cyclones were listed in Table 1 if the displacement between their surface center and upper level center (either 500 m or 700 mb) exceeded twice the meteorological accuracy estimated by the ARWO on at least two reconnaissance missions during the life cycle of the cyclone.

Table 1. List of 1979 western North Pacific tropical cyclones that exhibited a vertical tilt between their surface and 700 mb centers.

Tropical Storm Dot	Typhoon Owen
Typhoon Ellis	Typhoon Sarah
Tropical Storm Faye	Super Typhoon Tip
Tropical Storm Gordon	Tropical Storm Wayne
Typhoon Irving	Typhoon Abby
Tropical Storm Ken	

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Observational evidence presented in this paper indicates that the occurrence of tilt of the tropical cyclone's vertical axis and the displacement of the convective cloud mass from the surface circulation center are highly correlated with the intensity and direction of vertical wind shear. The reader should not infer that vertical tilt is only a low-level phenomenon due to the absence of observations above 700 mb. Data at 500 m and 700 mb are presented here because aircraft reconnaissance missions are flown at these levels into western North Pacific tropical cyclones. In fact, high-level cirrus outflow centers observed in satellite imagery indicate that the vertical axis continues to slope well above the 700 mb level in the developing and dissipating stages of tropical cyclones.

In the development stage, the center of the convective cloud mass is frequently displaced by more than 100 km from the surface circulation center. This separation is verified by Defense Meteorological Satellite Program (DMSP) imagery at direct readout sites in the western North Pacific as well as by aircraft reconnaissance. The satellite imagery frequently displays both the convective cloud mass and an exposed low-level circulation, i.e., in the clear region outside or along the periphery of the convective cloud mass. Arnold (1977) observed that 25% of low-level circulation centers were exposed during the development stage. Examples of such an occurrence are shown later in the paper. During the development stage, aircraft reconnaissance generally observes the vertical axis of the tropical cyclone to slope toward the convective cloud mass. With reduced vertical wind shear, intensification occurs and the axis becomes more vertical as the surface center moves under the convective cloud mass. This process culminates with eye formation.

A vertical tilt is often observed during the dissipating stage of a tropical cyclone. Vertical tilt in this stage of the life cycle also is related to strong vertical wind shear which develops as the cyclone moves to more northern latitudes and upper level westerly flow increases. The convection is sheared away from the surface center which, again, leads to an exposed low-level circulation on satellite imagery during the dissipating stage.

Aircraft and satellite observations for three tropical cyclones are presented to illustrate the existence of significant vertical tilts during the development stage. Data are presented for Super Typhoon[3] Tip (October 1979), Typhoon[4] Abby (December 1979) and Tropical Depression[5] (TD) 80-01 (March 1980). The first two cyclones were selected because of extensive aircraft reconnaissance during their development stage. These cyclones progressed through a complete life cycle, maturing to maximum intensities of >50 m s^{-1} before extratropical transition. TD 01 was selected to illustrate a cyclone that failed to intensify to tropical storm strength.[6]

2. Super Typhoon Tip (5–19 October 1979)

Super Typhoon Tip was the most significant tropical cyclone during the 1979 season in the western North Pacific region. Forty aircraft reconnaissance missions were flown on Tip by the 54WRS. Many of these missions, which produced 60 cyclone fixes, were during Tip's development stage in the vicinity of Truk in the Caroline Islands. Aircraft and synoptic data showed that Tip achieved the lowest sea level pressure ever observed in a tropical cyclone (870 mb) and also the largest circulation pattern on record (nearly 2220 km in diameter).[7] The complete surface best track for Super Typhoon Tip is illustrated in Fig. 1. This paper will concentrate on the segment of the best track between 5 and 7 October 1979 when Tip was moving erratically and intensifying slowly. The complete life cycle of Super Typhoon Tip is discussed by Dunnavan and Diercks (1980).

During the period 5–7 October 1979, Tropical Storm Tip first executed a cyclonic loop southeast of Truk, then accelerated to the northwest, only to stall and meander to a position south of Truk. On 7 October 1979, Tip finally began a prolonged movement to the northwest toward Guam. An expanded segment of Tip's best track prior to 1200 GMT 8 October 1979 is shown in Fig. 2. This segment of the best track is based almost entirely on aircraft surface positions, because satellite fixes were based largely on an upper level outflow center which was displaced from the surface center.

Displacements between the surface and 700 mb circulation centers during Tip's development stage were observed by aircraft reconnaissance to exceed 80 km. The surface and 700 mb circulation centers are connected by arrows in Fig. 2. Table 2 lists the time and coordinates of the surface position, the heading and distance of the 700 mb center

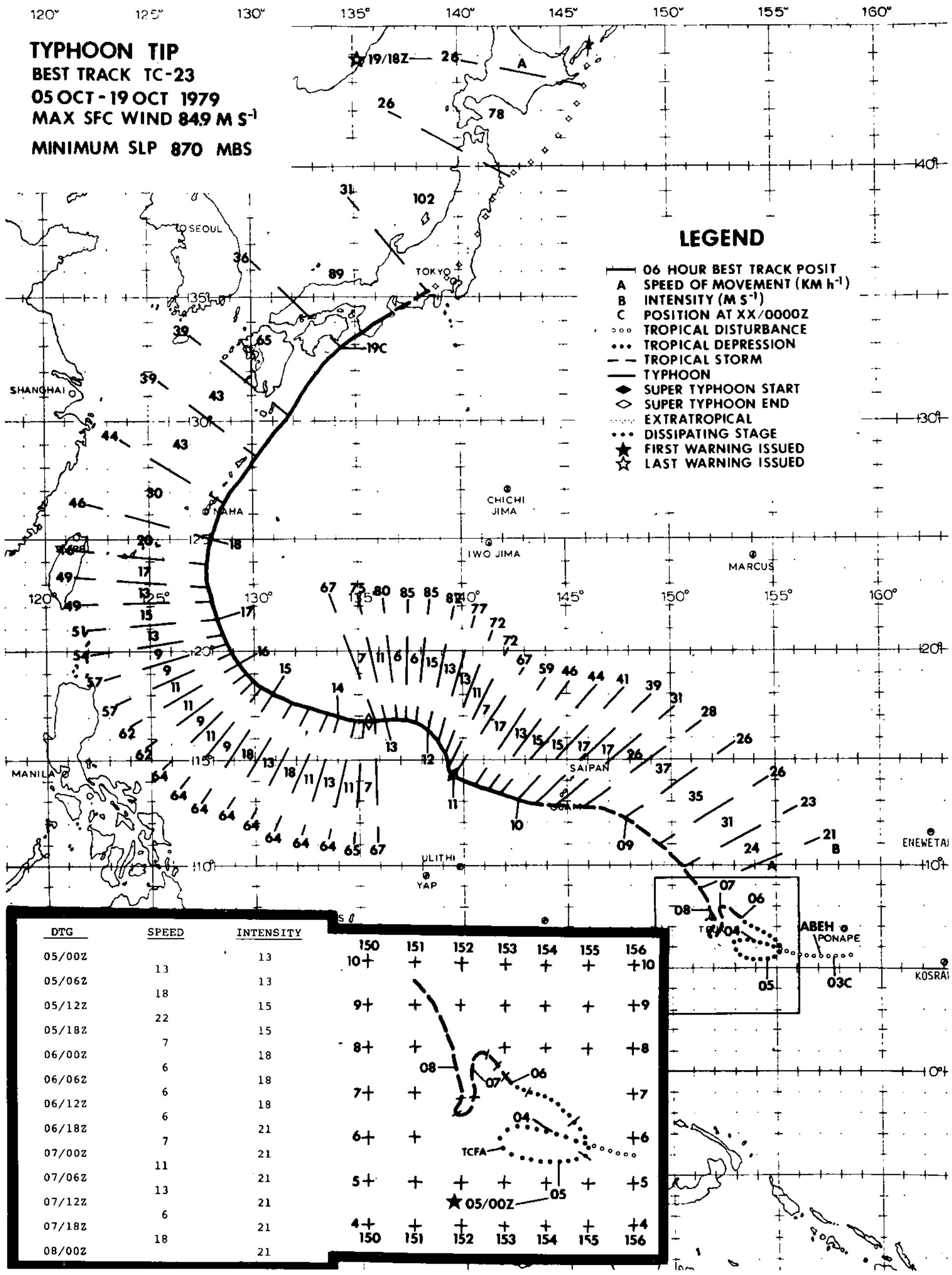
[3] A typhoon is designated a super typhoon when maximum surface winds reach a velocity of 67 m s^{-1}.

[4] A tropical cyclone is designated a typhoon in the western North Pacific when maximum surface winds reach a velocity of 33 m s^{-1}.

[5] A tropical depression is a tropical cyclone with maximum surface winds less than a velocity of 17.5 m s^{-1}.

[6] A tropical storm is a tropical cyclone with maximum surface winds > 17.5 m s^{-1} but <33 m s^{-1}.

[7] The size of the circulation pattern is determined by the diameter of the highest closed isobar associated with the tropical cyclone.



DTG	SPEED	INTENSITY
05/00Z		13
	13	
05/06Z		13
	18	
05/12Z		15
	22	
05/18Z		15
	7	
06/00Z		18
	6	
06/06Z		18
	6	
06/12Z		18
	6	
06/18Z		21
	7	
07/00Z		21
	11	
07/06Z		21
	13	
07/12Z		21
	6	
07/18Z		21
	18	
08/00Z		21

FIG. 1. Surface best track for Super Typhoon Tip.

from the surface center, the minimum surface sea level pressure, and the minimum 700 mb standard pressure-level height as observed by aircraft reconnaissance. Also shown in Table 2 are the diameters of the light and variable wind centers associated with the surface and 700 mb circulation centers. In developing cyclones, the diameter of light and variable winds is characteristically large. As the cyclone intensifies, the diameter slowly decreases until formation of the wall cloud and eye occurs. The light and variable wind center observed in Tip was smaller than observed in many of the cyclones during the 1979 season. Finally, the accuracy of the surface center fix is listed in Table 2. This accuracy is subdivided into errors introduced by navigation equipment and subjective observation of surface wind speed and direction. Although not provided in the Detailed Vortex Message, the meteorological accuracy of the 700 mb center position should be somewhat better than the

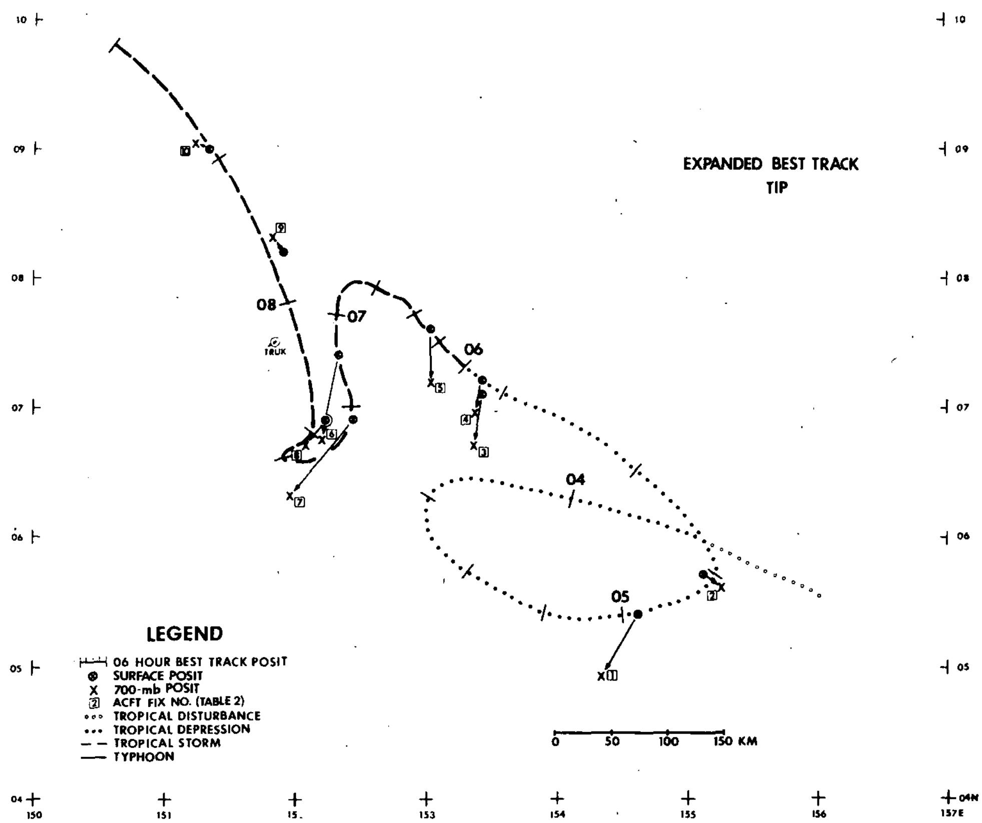


FIG. 2. Expanded segment of Super Typhoon Tip's best track prior to 1200 GMT 8 October 1979. Arrows indicate the position of the 700 mb circulation centers relative to the surface circulation centers. Boxed numbers correspond to numbered aircraft observations of Table 2.

surface center accuracy because flight level winds are directly measured by the Doppler Radar System and standard pressure heights are measured using the APN-42 Absolute Altimeter and the Airesearch Pressure Altimeter. The ARWO estimates surface winds by observing the sea state. The navigational accuracy of 700 mb and surface centers should not vary on a given fix at a given time.[8]

At 0030 GMT 5 October 1979, aircraft reconnaissance observed the first of two large displacements between Tip's 700 mb and surface centers. The displacement, which measured 61 km during the cyclonic loop, decreased somewhat after exiting the loop. The displacement again increased, reaching the maximum distance of 83 km as Tip approached Truk and the track became more erratic. As Tip accelerated northwestward toward Guam and intensified, the displacement decreased to distances within the stated navigational and meteorological accuracy of the surface fix location. This trend is evident in Table 2 which includes aircraft observations through 0241 GMT 9 October 1979. At this time, Tip was approaching typhoon strength of 33 m s^{-1} and had become vertically aligned.

On one occasion, satellite imagery during Tip's development stage illustrated a displacement of the convective cloud mass from an exposed low-level circulation. Aircraft reconnaissance observations generally reported that the tilt from the surface center to the 700 mb center was toward the region of strong convection. Often the 700 mb center was, in fact, observed within the convection. Fig. 3 is Defense Meteorological Satellite Program (DMSP) imagery at 0017 GMT 6 October 1979. An exposed low-level circulation (noted by short arrow west of Ponape) exists north-northeast of the strong convection. Aircraft reconnaissance reported displacements of the 700 mb center from the surface center to be 190°T at 48 and 30 km at 1943 and 2222 GMT 5 October 1979, respectively (see Table 2).

3. Typhoon Abby (1–14 December 1979)

Abby, the last typhoon of the 1979 season, developed over the Marshall Islands from a mid-level

[8] A typical navigational accuracy is 9 km. Typical meteorological accuracies vary from 18 km for a weak tropical cyclone to 9 km for a tropical cyclone with an eye.

TABLE 2. Aircraft observations for Tip.

Fix time (GMT)	Surface position	Heading (°T) and distance (km) of 700 mb center relative to surface center	Minimum sea level pressure (mb)	Minimum 700 mb standard height (m)	Accuracy (km) NAV/MET	Diameter (km) of light and variable winds	
						Surface	700 mb
1. 050030	5°25′N 154°35′E	210/61	1004	3095	9/18	46	28
2. 050800	5°43′N 155°7′E	310/22	1003	3113	4/11	22	*
3. 051943	7°8′N 153°28′E	190/48	1002	3112	15/7	6	9
4. 052222	7°10′N 153°23′E	190/30	1004	3124	7/4	6	*
5. 060713	7°37′N 153°00′E	180/46	1000	3110	9/9	37	15
6. 070305	7°23′N 152°16′E	190/74	1002	3101	7/9	7	7
7. 070617	6°56′N 152°24′E	220/83	1001	3095	9/18	28	37
8. 072030	6°55′N 152°10′E	200/28	997	3054	9/9	*	18
9. 080248	8°10′N 151°55′E	329/17	995	3047	9/9	18	18
10. 080650	9°00′N 151°16′E	290/13	994	3038	7/7	*	18
11. 090241	12°33′N 146°48′E	320/9	985	2690	4/6	9	18

* Diameter of the light and variable winds was not reported by aircraft reconnaissance.

circulation in early December. The complete track for Typhoon Abby is illustrated in Fig. 4. This was an unusual tropical cyclone in several ways. Thus, throughout much of Abby's existence, the typhoon was not vertically aligned. Aircraft reconnaissance located the mid-level circulation center displaced as much as 102 km from the surface center. At one point, two centers were observed for a short period. In addition, Abby fluctuated between tropical depression and tropical storm strength several times before reaching typhoon strength 10 days after formation. The northward jogs in Abby's overall westward track were associated with mid-tropospheric troughs moving eastward in the mid-latitude flow north of Abby.

Fig. 5 is an expanded portion of Abby's track during the period 2–6 December 1979. The surface and 700 mb circulation centers are connected by arrows in Fig. 5. Table 3 lists aircraft observational data for Abby.

Abby's surface and 700 mb circulation centers were displaced for most of her existence. The largest displacement was observed after Abby first weakened to less than tropical storm strength on 6 December 1979. While tracking west-northwest from Truk, Abby's outflow was restricted to the southwest quadrant by a strong upper level anticyclone centered northeast of Guam (Fig. 6). At this time,

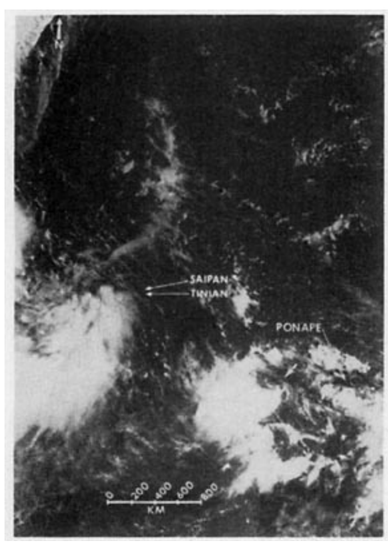


FIG. 3. DMSP imagery of Tip at 0017 GMT 6 October 1979. The location of an exposed low-level circulation is noted by the short arrow west of Ponape.

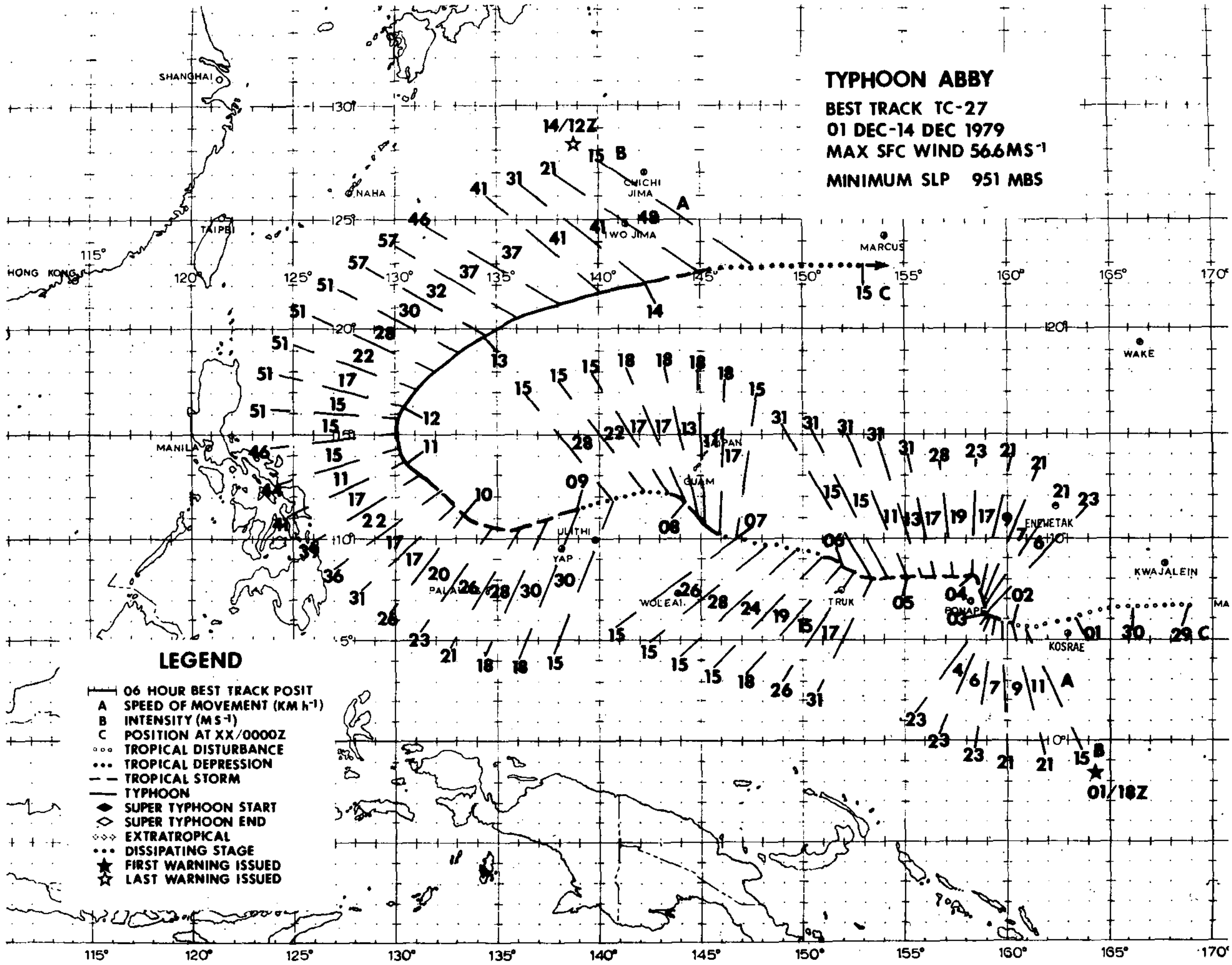


FIG. 4. Surface best track for Typhoon Abby.

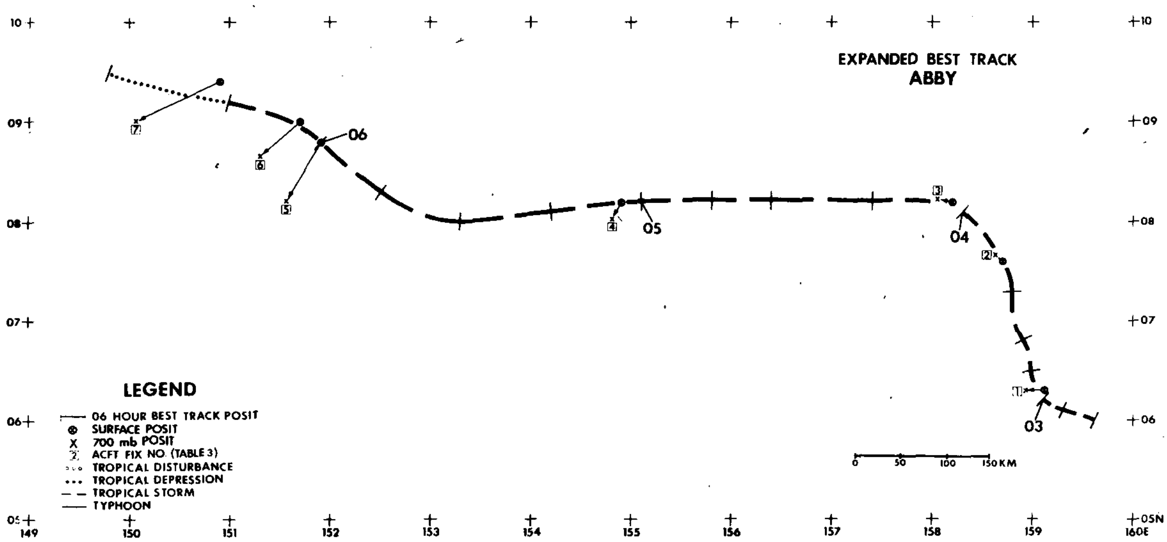


FIG. 5. Expanded segment of Typhoon Abby's best track between 2–6 December 1979. Arrows indicate the position of the 700 mb circulation centers relative to the surface circulation centers. Boxed numbers correspond to numbered aircraft observations of Table 3.

the displacement of the 700 mb center relative to the surface center was 245°T at a distance of 102 km. This displacement was in close agreement with the large-scale upper level flow in the vicinity of Abby. The small-scale anticyclone analyzed over Abby was based on weak cirrus outflow observed in satellite imagery. Fig. 7 illustrates a similar relationship between the convective cloud mass and Abby's exposed low-level circulation center at 0022 GMT 8 December 1979. As Abby tracked west of the anticyclone center, the surface and 700 mb centers became better aligned, although not completely vertical.

On 9 December 1979, an interesting and unusual occurrence of two mid-level centers was observed by aircraft reconnaissance making a center fix at 0617 GMT. By the time of entry into Abby for a 0830 GMT center fix, only one well-organized, intensifying center was found. The following is a cyclone mission summary by the ARWO who made the double penetration into Abby: "This mission started out as a normal fix but ended up being unusual. On our way inbound for the supplemental fix, there was no problem reading winds at flight level or on the surface. Winds were 20–25 kt the entire way. An area of thunderstorm activity became visible ahead of us. As we neared it, the Doppler indicated that the 700 mb center was in the middle of the thunderstorm. Not eager to go find this out, we went back to find the surface center. Enroute, we saw surface winds in

TABLE 3. Aircraft observations for Abby.

Fix time (GMT)	Surface position	Heading (°T) and distance (km) of 700 mb center relative to surface center	Minimum sea level pressure (mb)	Minimum 700 mb standard height (m)	Accuracy (km) NAV/MET	Diameter (km) of light and variable winds: Surface	Diameter (km) of light and variable winds: 700 mb
1. 022010	6°15′N 159°4′E	090/22	999	3075	4/9	4	*
2. 032130	7°45′N 158°45′E	310/13	992	3050	9/9	*	13
3. 040108	8°14′N 158°14′E	280/15	994	3050	9/9	15	18
4. 050159	8°12′N 154°54′E	210/22	986	3002	4/9	9	*
5. 060051	8°50′N 151°53′E	210/74	1006	3135	4/6	11	9
6. 060215	9°00′N 151°42′E	228/59	1002	3123	9/9	18	9
7. 060835	9°25′N 150°54′E	245/102	1000	3094	18/9	18	28
8. 072128	11°5′N 144°45′E	315/37	996	3062	7/9	18	28
9. 080553	12°12′N 143°38′E	255/37	1000	3084	9/9	9	9
10. 092207	11°3′N 134°12′E	270/22	983	2935	9/6	9	9
11. 102247	13°31′N 130°54′E	290/37	964	2797	7/9	9	13
12. 110827	14°25′N 130°7′E	270/11	963	2776	9/9	*	18
13. 112149	15°56′N 130°19′E	345/30	954	2682	9/9	9	18
14. 130806	20°41′N 136°50′E	050/32	962	2762	9/13	*	9
15. 132220	22°14′N 142°2′E	040/37	990	3002	9/18	*	18

* Diameter of the light and variable winds was not reported by aircraft reconnaissance.

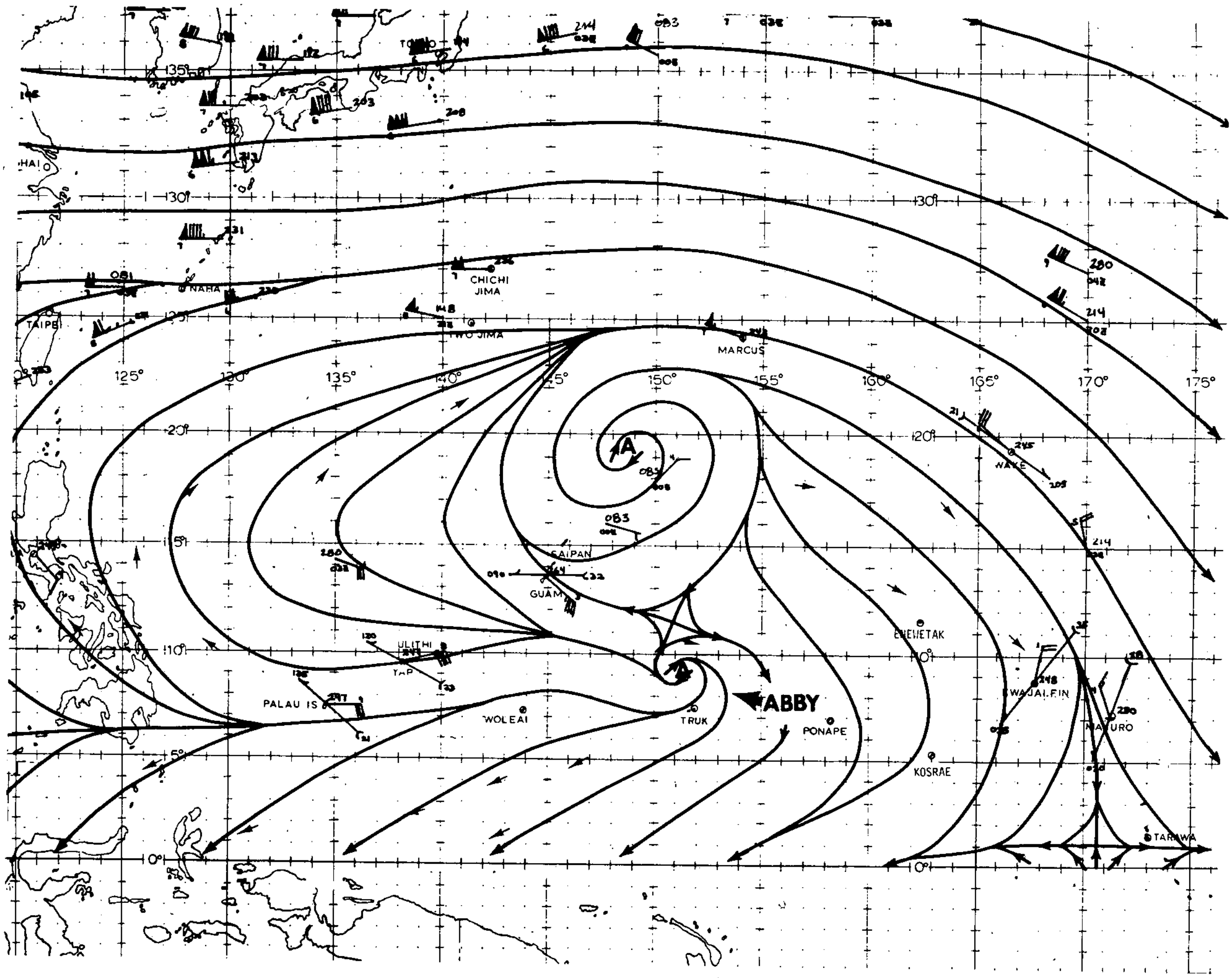


FIG. 6. The 0000 GMT 6 December 1979 200 mb streamline analysis. The analysis is based on a composite of rawinsonde reports (winds in knots and 200 mb heights in meters), aircraft reports (winds in knots, flight level in meters), and satellite blow-off wind vectors (direction only).

excess of 35 kt which led us to a fairly disorganized surface center just east of the main thunderstorm. Over it was a fairly small light and variable wind center. Radar showed little curvature in the shower pattern, but the surface winds did indicate a weak circulation existed at this position. No weather existed to the east of our first fix, and this position was right on the JTWC forecast track. On the second fix, things had changed. As we came in the second time, we encountered considerable precipitation. Doppler and search radar indicated a center with a possible wall cloud forming considerably west of our first fix. Winds were stronger at flight level and we penetrated a wall cloud of ~80% coverage. When we broke through, we encountered our strongest winds at flight level. The surface center was under the eastern wall cloud with a small light and variable wind center at 700 mb centered in the eye. Lightning started in the eastern wall cloud and spread around the eye. Our drop was made as close to the surface center as was possible and indicated a good 988 mb sea level pressure. The 700 mb height was down 72 m from the first fix. The positions were 85 mi apart causing me to believe that two centers existed for a short time with the latter becoming the predominate one. The pressure profile seems to indicate this theory."[9]

Satellite imagery at 0144 GMT 9 December 1979 also indicated the possible existence of multiple convective centers (Fig. 8). While reorganizing into a single center, Abby began to intensify, reaching typhoon strength on 10 December 1979.

[9] Charles B. Stanfield, Captain, 54th Weather Reconnaissance Squadron, U.S. Air Force.

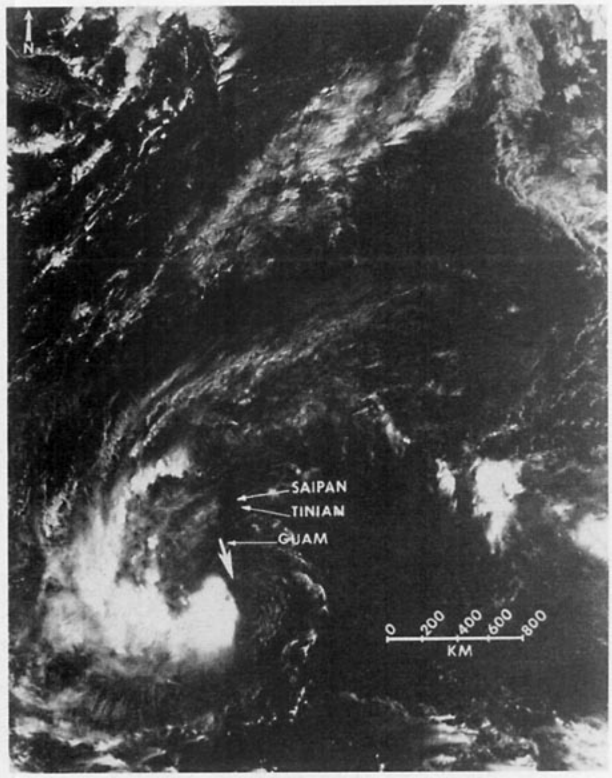


FIG. 7. DMSP imagery of Abby at 0022 GMT 8 December 1979. The location of an exposed low-level circulation is noted by the heavy arrow south of Guam.

Even after reaching typhoon strength, aircraft reconnaissance continued to observe a significant vertical tilt to the eye (Table 3). Normally, the 700 mb center is vertically aligned over the surface center after a tropical cyclone reaches typhoon strength.

4. Tropical depression 80-01 (18–26 March 1980)

On 16 March 1980, Tropical Depression (TD) 01, spawned along an extension of the equatorial trough south of Guam in the Caroline Islands. From TD 01's formation to landfall on Luzon, aircraft reconnaissance reported the 700 mb center (500 m center on 18 March 1980) displaced at various distances to the northwest of the surface circulation. The complete track for TD 01 is illustrated in Fig. 9. Fig. 10 is a segment of TD 01's track with aircraft reconnaissance surface and 700 mb center positions superimposed. Table 4 lists observational data received from aircraft reconnaissance.

As with Super Typhoon Tip and Typhoon Abby, the 700 mb center was displaced from the surface center toward the area of strong convection. However, in contrast to Tip and Abby, TD 01's displacement of the 700 mb center was always north of the surface center as suggested by satellite imagery in Fig. 11 for 0101 GMT 19 March 1980. The exposed low-level circulation is positioned southeast of the area of strong convection. A maximum displacement of 139 km was observed at 0635 GMT 21 March 1980. A portion of the 157 km displacement at 2315 GMT 22 March 1980 is attributed to the 3.5 h time lag between 700 mb and surface fixes.

Throughout most of TD 01's existence, strong upper level southeasterly winds adversely in-

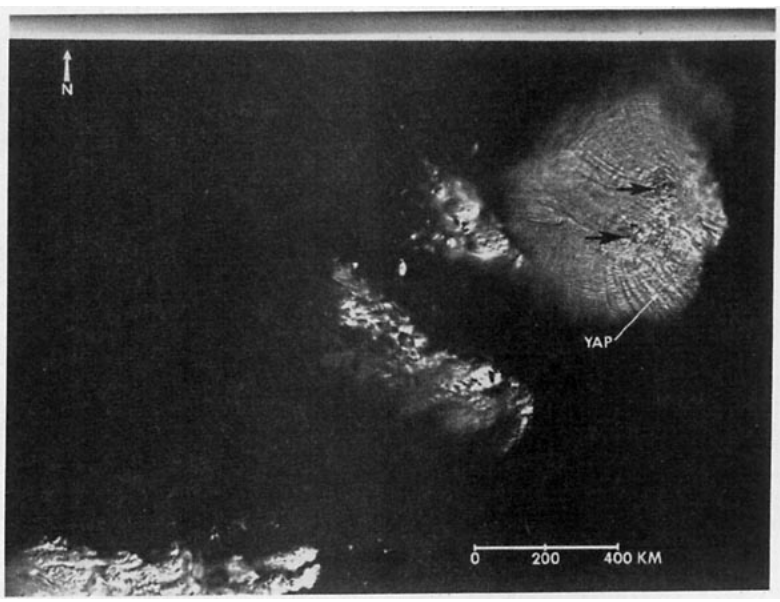


FIG. 8. DMSP imagery of Abby at 0144 GMT 9 December 1979. The locations of suspected dual convective centers are noted by the black arrows.

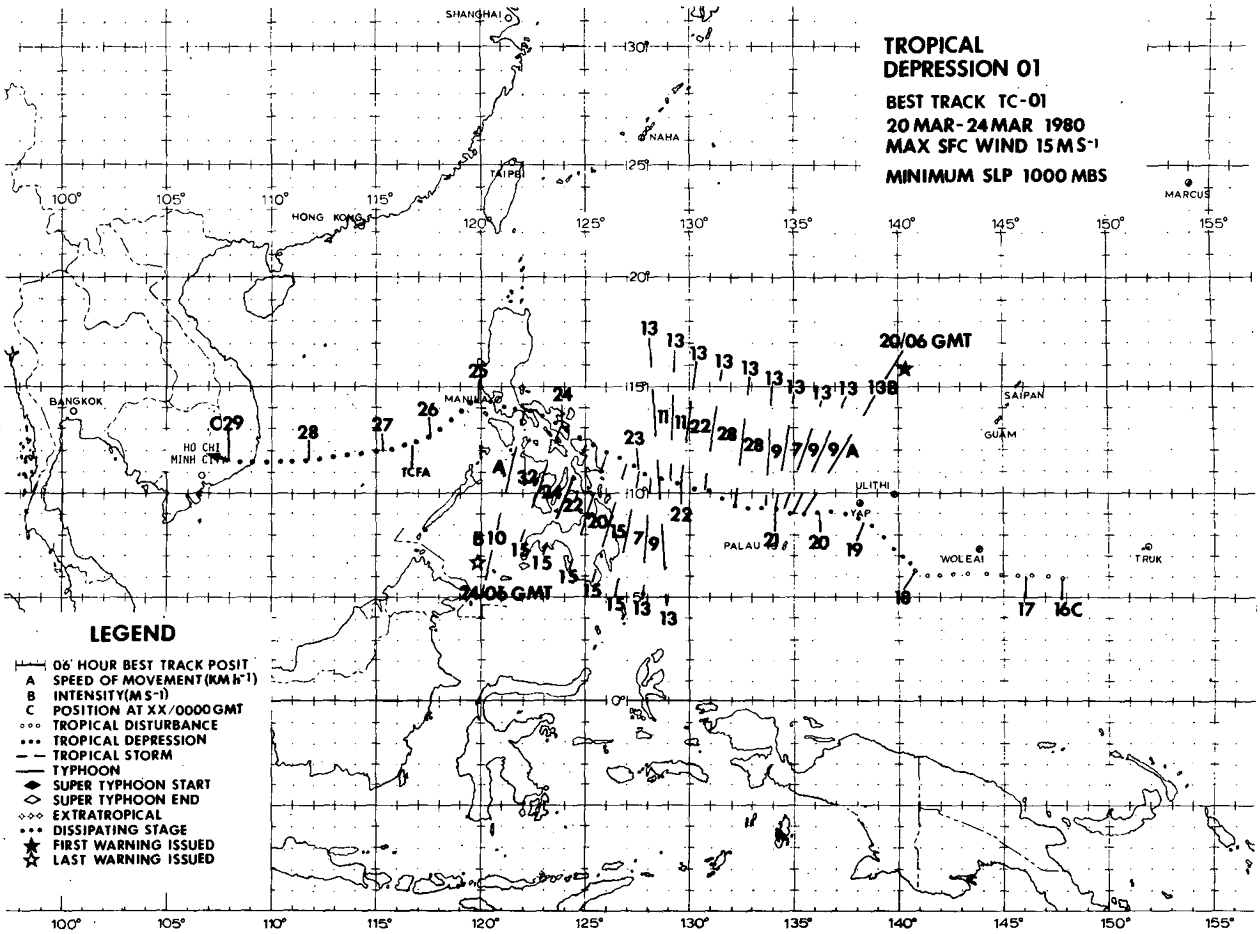


FIG. 9. Surface best track for TD 01.

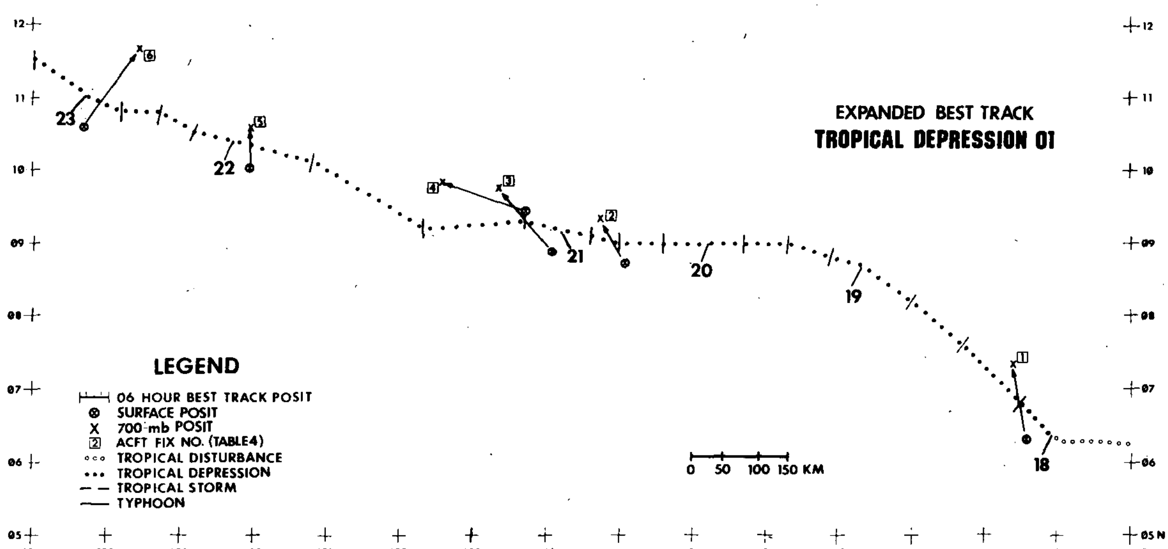


FIG. 10. Expanded segment of TD 01's best track between 18–23 March 1980. Arrows indicate the position of the 700 mb circulation centers relative to the surface circulation centers. Boxed numbers correspond to numbered aircraft observations of Table 4.

TABLE 4. Aircraft observations for TD 01.

Fix time (GMT)	Surface position	Heading (°T) and distance (km) of 700 mb center relative to surface center	Minimum sea level pressure (mb)	Minimum 700 mb standard height (m)	Accuracy (km) NAV/MET	Diameter (km) of light and variable winds	
						Surface	700 mb
1. 180205	6°16′N 140°34′E	350/111	1005	[a]	9/9	18	46
2. 200926	8°42′N 135°4′E	330/74	1004	3123	9/18	*	18
3. 210100	8°54′N 134°6′E	320/130	1001	3097	11/15	28	37
4. 210635	9°24′N 133°42′E	290/139	1000	3083	18/18	37	28
5. 212207	10°25′N 129°58′E	360/56	1003	3101	9/28	56	92
6. 222315	10°35′N 127°41′E	035/157[b]	1005	3104[b]	—	*	*

[a] 1500 ft flight level fix.
[b] Time of 700 mb fix at 221946 GMT.
* Diameter of the light and variable winds was not reported by aircraft reconnaissance.

fluenced the development of TD 01. Thus, due to strong vertical wind shear and the resulting displacement betwen the 700 mb and surface centers, TD 01 had little chance for further development as a tropical cyclone.

5. Concluding remarks

Aircraft reconnaissance data and satellite imagery were presented to show that tropical cyclones in the western North Pacific often possess significant horizontal displacements between their surface and

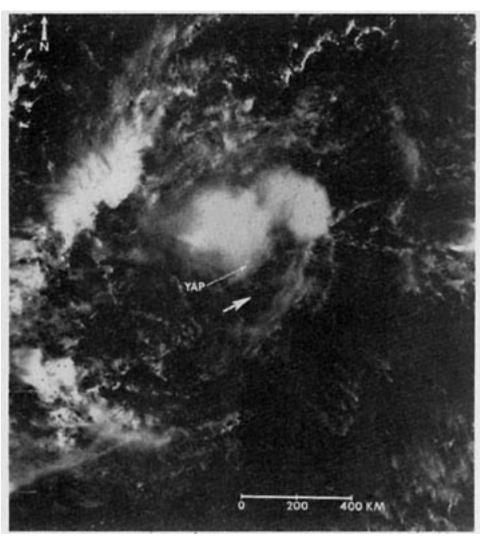


FIG. 11. DMSP imagery of TD 01 at 0101 GMT 19 March 1980. The location of an exposed low-level circulation is noted by the short arrow south of Yap.

700 mb circulation centers during the development stage. Super Typhoon Tip, Typhoon Abby and Tropical Depression 01 were selected to illustrate this phenomenon due to frequent aircraft reconnaissance and the range of peak intensities of these tropical cyclones.

The horizontal displacement decreased as Tip and Abby intensified to typhoon strength. Abby, however, still possessed a fairly large displacement even after reaching typhoon strength. Abby was also interesting from the viewpoint that she displayed two mid-level circulation centers for a short period before rapid intensification to typhoon strength. Strong vertical wind shear inhibited Tropical Depression 01 from reaching tropical storm strength. The displacement of the 700 mb center relative to the surface center appeared related to the direction of upper level flow over Typhoon Abby and Tropical Depression 01. The evidence is less conclusive for Super Typhoon Tip which developed a well-defined outflow center by 0000 GMT 8 October 1979. The displacement of the 700 mb center from the surface center was generally toward the convective cloud mass associated with each of the three tropical cyclones.

The observational evidence in this paper raises several interesting questions. First, is the displacement between surface and upper level centers related to the fields of convergence which are necessary to organize and intensify a tropical cyclone or simply a reaction to upper level shearing flow? Second, would a numerical model initialized with a weak sloping vortex spin up to typhoon strength? The intention of the authors in this paper was only to present observational evidence that tropical cyclones have a vertical slope during their development stage. The questions raised in this paper are left to other researchers to answer.

Acknowledgments. Satellite data used for this paper were processed by Operating Location-C, 27th Communications Squadron (USAF) and analyzed by Detachment 1, 1st Weather Wing (USAF), Nimitz Hill, Guam. The figures were prepared by the staff of the Joint Typhoon Warning Center and the manuscript was typed by Mrs. Anna Bamba. Aerographer's Mate Second Class Stephani Bubanich assisted with data compilation.

REFERENCES

Arnold, C. P., 1977: Tropical cyclone cloud and intensity relationships. Atmos. Sci., Pap. No. 277, Colorado State University, 155 pp.

Dunnavan, G. M., and J. W. Diercks, 1980: An analysis of Super Typhoon Tip (October 1979). *Mon. Wea. Rev.*, **108,** 1915–1923.

Hovermale, J., and R. E. Livezey, 1977: Three-year performance characteristics of the NMC hurricane model. *Preprints 11th Tech. Conf. Hurricanes and Tropical Meteorology*, Miami Beach, Amer. Meteor. Soc., 122–125 pp.

Joint Typhoon Warning Center, 1979: *Annual Typhoon Report*. Guam, 191 pp.

Kurihara, Y., and R. E. Tuleya, 1974: Structure of a tropical cyclone developed in a three-dimensional numerical simulation model. *J. Atmos. Sci.*, **31,** 893–919.

Rosenthal, S. L., 1978: Numerical simulation of tropical cyclone development with latent heat release by the resolvable scales I: Model description and preliminary results. *J. Atmos. Sci.*, **35,** 258–271.

Sadler, J. C., 1967: The tropical upper tropospheric trough as a secondary source of typhoons and a primary source of trade wind disturbances. Hawaii Institute of Geophysics, Rep. No. HIG 67-12, 44 pp.

——, 1976: Tropical cyclone initiation by the tropical upper tropospheric trough. Naval Environmental Prediction Research Facility, Tech. Pap. No. 2-76, 103 pp. [NTIS ADA 025456].