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This study examines 16 recurving tropical storms and typhoons that occurred in the western North Pacific Ocean in 1971, to determine the characteristics of the storms after they became extratropical. Many of the extratropical storms that evolved from tropical cyclones maintained destructive seas and winds as long as 5 days after the point of recurvature. Six of the 16 extratropical storms crossed the North Pacific and affected

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EXTRATROPICAL STORM EVOLUTION FROM TROPICAL CYCLONES IN THE WESTERN NORTH PACIFIC OCEAN

SAMSON BRAND AND CHARLES P. GUARD

JULY 1978

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1. Enclosure (1) examines 16 recurving tropical storms and typhoons that occurred in the western North Pacific Ocean in 1971 to determine the characteristics of these storms after they became extratropical. These analyses of storm behavior should prove helpful to weather forecasters responsible for ship routing and issuing warnings of storm-related strong winds and high seas.

C R Ward

C. R. WARD

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CONTENTS

1. INTRODUCTION

The purpose of this study is to provide to the operational forecaster an analysis of the characteristics and behavior of extratropical storms that have evolved from tropical cyclones. Used in conjunction with conventional prediction techniques, this information should be useful to ship routers as well as to weather centrals responsible for issuing warnings of storm-related strong winds and high seas.

A tropical cyclone is identified as becoming "extratropical" when it loses its tropical characteristics. The term implies both northward displacement from the tropics and the conversion of the cyclone's primary energy source from latent-heat release to baroclinic processes; it does not carry any implication regarding the storm's strength or size.

As part of the U.S. Fleet Weather Central (FWC) Guam, the Joint Typhoon Warning Center (JTWC) is responsible for issuing tropical cyclone warnings in the western North Pacific. When a storm becomes extratropical, this responsibility passes to FWC Guam, which issues all gale and storm warnings for systems of nontropical character.

The reclassification from tropical to extratropical status is based on a number of factors including thermal and convective structure, inflow/outflow patterns at both the gradient and upper tropospheric levels, and the general synoptic situation. The warnings of JTWC and FWC Guam typically are coordinated 12-24 hours prior to the storm's reclassification to ensure uninterrupted forecasting service to operational users.

Recurved tropical cyclones are very difficult to forecast. Burroughs and Brand (1973) found that the average 24-hour movement forecast errors for the JTWC 1961-69 typhoon forecasts, verifying after the point of recurvature, were nearly 30% larger than the average annual forecast errors. These errors were associated with the increases in forward speed of movement after the point of recurvature. Although the recurved tropical cyclone generally weakens in intensity (maximum wind), it still remains a significant meteorological phenomenon in its extratropical stage. For example, for the typhoons to the east of the China mainland from 1971-75, the average maximum wind at the point at which the storms became extratropical was 54 kt (27.8 ms^{-1}). Typhoon Agnes (September, 1974) had a maximum wind of 100 kt (51.5 ms^{-1}) when it became extratropical at 34°N.

2. DISCUSSION OF RESULTS

2.1 TROPICAL CYCLONE TRANSFORMATION

The transformation of a tropical cyclone into an extratropical cyclone can occur in various ways. For example, Sekioka (1970, 1972a and b) and Matano and Sekioka (1971a and b) describe two observed transformational processes for western North Pacific tropical cyclones that do not dissipate over land or water:

(1) "Complex" transformation -- a pre-existing front meets a tropical cyclone; a new extratropical cyclone is induced on the front and becomes the dominant system. The process makes it appear that the tropical cyclone has been transformed into an extratropical cyclone (see Figure 1a).

(2) "Compound" transformation -- a pre-existing extratropical cyclone approaches and merges with a tropical cyclone and usurps the tropical vortex. The tropical system appears to have been transformed into an extratropical cyclone (Figure 1b).

Tropical cyclones can also decay and dissipate over water without first becoming extratropical (Figure 1c). (This study does not address tropical cyclones that dissipate over a land mass.)

2.2 STATISTICAL ANALYSIS

Of the 16 tropical storms and typhoons in the western North Pacific in 1971 that fit the categories cited above, 11 were "complex," 3 were "compound" and 2 were "dissipators." Table 1 lists these tropical storms and typhoons by individual categories and Figure 2 shows their tracks. Several of the tropical cyclones could be followed completely across the Pacific and three of the storms affected the ocean regions north of 55N.

Table 2 shows the average times that the 16 tropical storms and typhoons existed in the extratropical stage as well as their times in the recurvature-to-extratropical and the before-recurvature periods. The storms existed longer in the extratropical

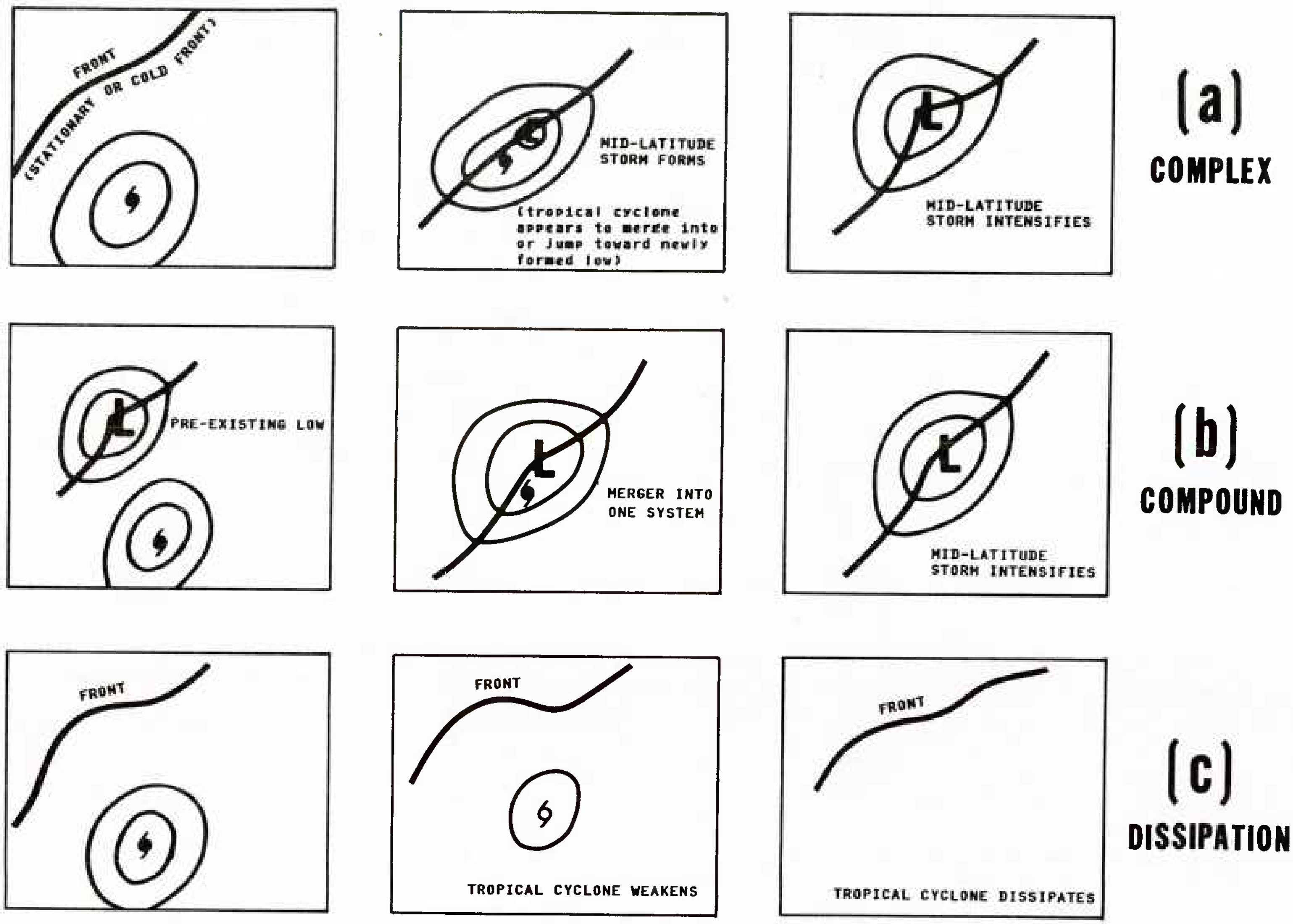

Figure 1. The transformation of a tropical cyclone into an extratropical cyclone by (a) the "complex" process; (b) "compound" process; and (c) decay over water without an extratropical cyclone being induced.

Table 1. Sixteen tropical storms and typhoons of the 1971 season that recurved east of the China mainland and either became extratropical or dissipated over water.

Name	Began	Extratropical	Dissipated	Recurvature Position	Extratropical Position	Dissipation Position
(Complex)						
TS SARAH	09 Jan	11 Jan	17 Jan	12N 137E	16N 142E	52N 121W
TS THELMA	18 Mar	19 Mar	23 Mar	10N 130E	14N 133E	25N 148E
T VERA	08 Apr	18 Apr	25 Apr	19N 125E	26N 133E	48N 162W
TS BABE	03 May	04 May	16 May	17N 118E	22N 135E	50N 121W
T OLIVE	29 Jul	06 Aug	12 Aug	32N 130E	40N 132E	45N 175E
TS POLLY	04 Aug	10 Aug	13 Aug	33N 123E	35N 125E	41N 141E
T SHIRLEY	13 Aug	17 Aug	19 Aug	31N 145E	42N 153E	55N 160W
T TRIX	20 Aug	30 Aug	05 Sep	30N 130E	34N 135E	48N 179W
T VIRGINIA	02 Sep	07 Sep	13 Sep	26N 136E	36N 142E	58N 138W
T WENDY	05 Sep	13 Sep	20 Sep	35N 147E	42N 149E	54N 172W
T IRMA	08 Nov	15 Nov	17 Nov	23N 127E	30N 137E	34N 178E
(Compound)						
T AMY	29 Apr	04 May	09 May	20N 142E	33N 156E	42N 176E
TS IVY	05 Jul	07 Jul	10 Jul	30N 133E	36N 141E	40N 172E
TS CARMEN	24 Sep	26 Sep	02 Oct	26N 132E	36N 142E	54N 130W
(Dissipators)						
TS CARLA	19 May	22 May	23 May	23N 126E	29N 132E	36N 130E
T MARY	17 Jul	20 Jul	22 Jul	35N 161E	40N 162E	45N 176W

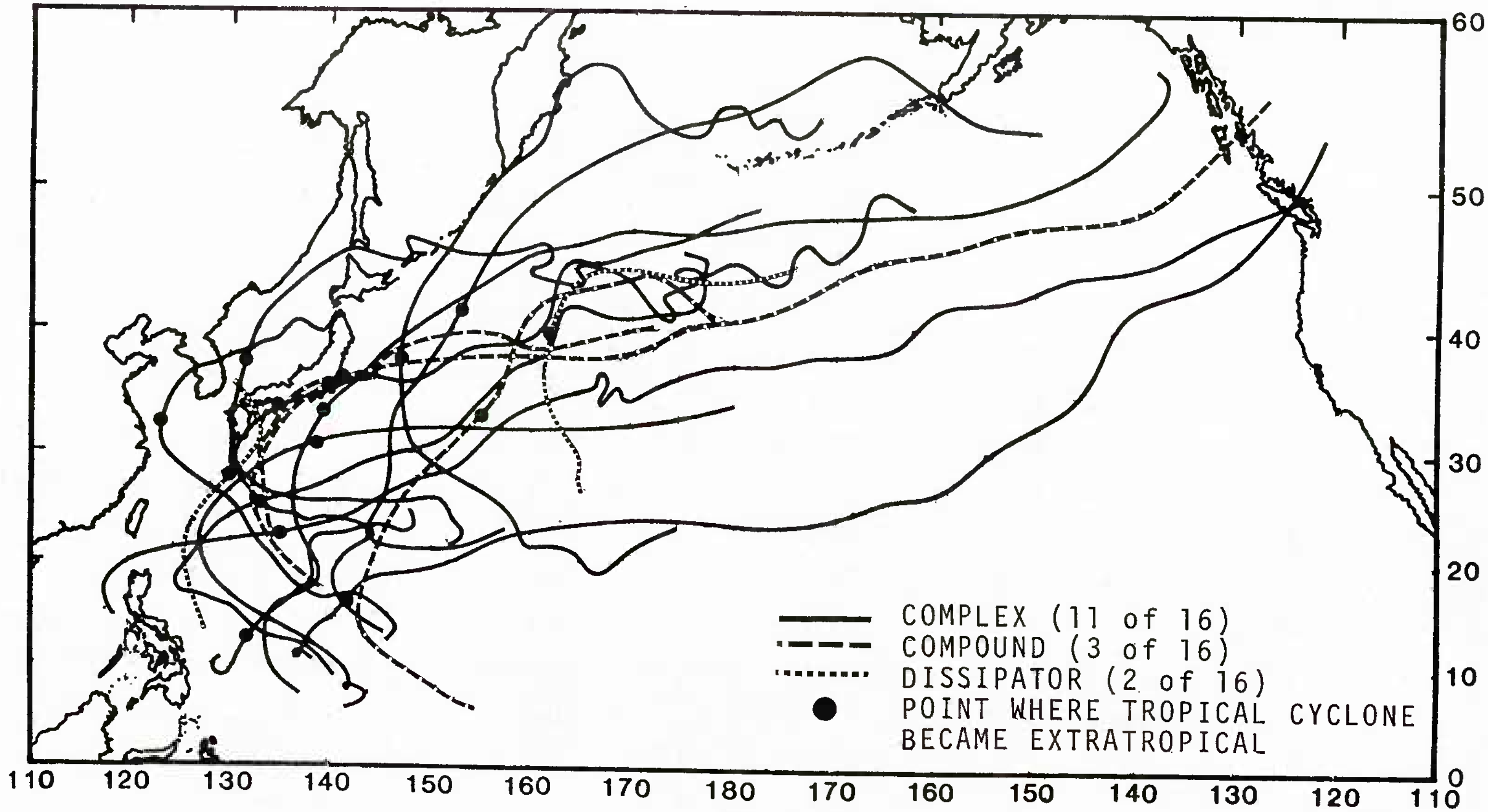

Figure 2. Tracks of the 16 tropical storms and typhoons of 1971 which recurved to the east of the China mainland and became extratropical or dissipated over water.

stage (4.4 days) than in the period before recurvature (3.9 days). One extratropical storm that evolved from a tropical cyclone existed longer than 9 days.

Table 2. Average duration by stages of the 16 tropical storms and typhoons examined for the 1971 season. Standard deviations and extremes are also given.

		Number of Days in Stage		
		Before Recurvature	Recurvature to Extratropical	Extratropical
Mean		3.9	1.5	4.4
Standard Deviation		2.8	0.9	2.7
Extremes	(Min)	1.0	0.3	0.7
	(Max)	8.9	5.5	9.3

The average distances traveled by the storms during the indicated stages are shown in Table 3. The average distance in the extratropical stage was 2644 n mi (4900 km) with a maximum value of 5640 n mi (10452 km).[1]

Table 3. Average distances traversed by stages of the 16 tropical storms and typhoons examined for the 1971 season. Standard deviations and extremes are also given.

		Distances Traversed (n mi/km)		
		Before Recurvature	Recurvature to Extratropical	Extratropical
Mean		836/1549	574/1064	2644/4900
Standard Deviation		549/1017	300/556	1540/2654
Extremes	(Min)	145/269	160/297	585/1084
	(Max)	2025/3753	1200/2224	5640/10452

[1]Track information and other meteorological/oceanographic data were reduced from the analyses of Fleet Weather Central, Pearl Harbor; the National Meteorological Center; Fleet Weather Central, Guam; Optimum Track Ship Routing, Fleet Numerical Weather Central; and the 1971 Annual Typhoon Report (U.S. FWC/JTWC, 1971).

The 16 recurving tropical storms and typhoons of 1971 were closely examined to determine the day-to-day variations, after the point of recurvature, of four parameters:

(1) Intensity (maximum wind)

(2) Speed of movement

(3) Average radius to 30 kt (15 ms^{-1}) wind

(4) Average radius to 12 ft (4 m) seas

Three days after the point of recurvature, 14 of the 16 storms were still discernable from synoptic information. By the fourth day, 11 were still noticeable and by the fifth day, 9 of the 16 still appeared. Figure 3 shows the mean day-to-day changes of the four parameters for the 9 storms existing out to 5 days after the point of recurvature.

It is interesting that such a large sample of the recurved storms extended out to 4 or 5 days after recurvature, thus presenting the severe maritime operational hazards indicated by the parameters shown in Figure 3. The intensity (maximum wind) decreases in the mean quite rapidly after the point of recurvature, with the intensity of most typhoons decreasing more rapidly than that of tropical storms. The speed of movement increases throughout the period. The average radius to 30 kt (15 ms^{-1}) wind apparently does not decrease throughout the period, but appears to oscillate near the mean. The average radius to 12 ft (4 m) seas decreases, but the decrease is not significant.[2]

Notice that while the average maximum wind value decreases sharply throughout the period, the extent of the area of 30 kt (15 ms^{-1}) winds and 12 ft (4 m) seas remain as significant features. A schematic depiction of the day-to-day variations of the azimuthally averaged wind profiles for the storms existing to 5 days is shown in Figure 4.

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[2]The intensity and speed changes were significant at the 1% level of a "t" test.

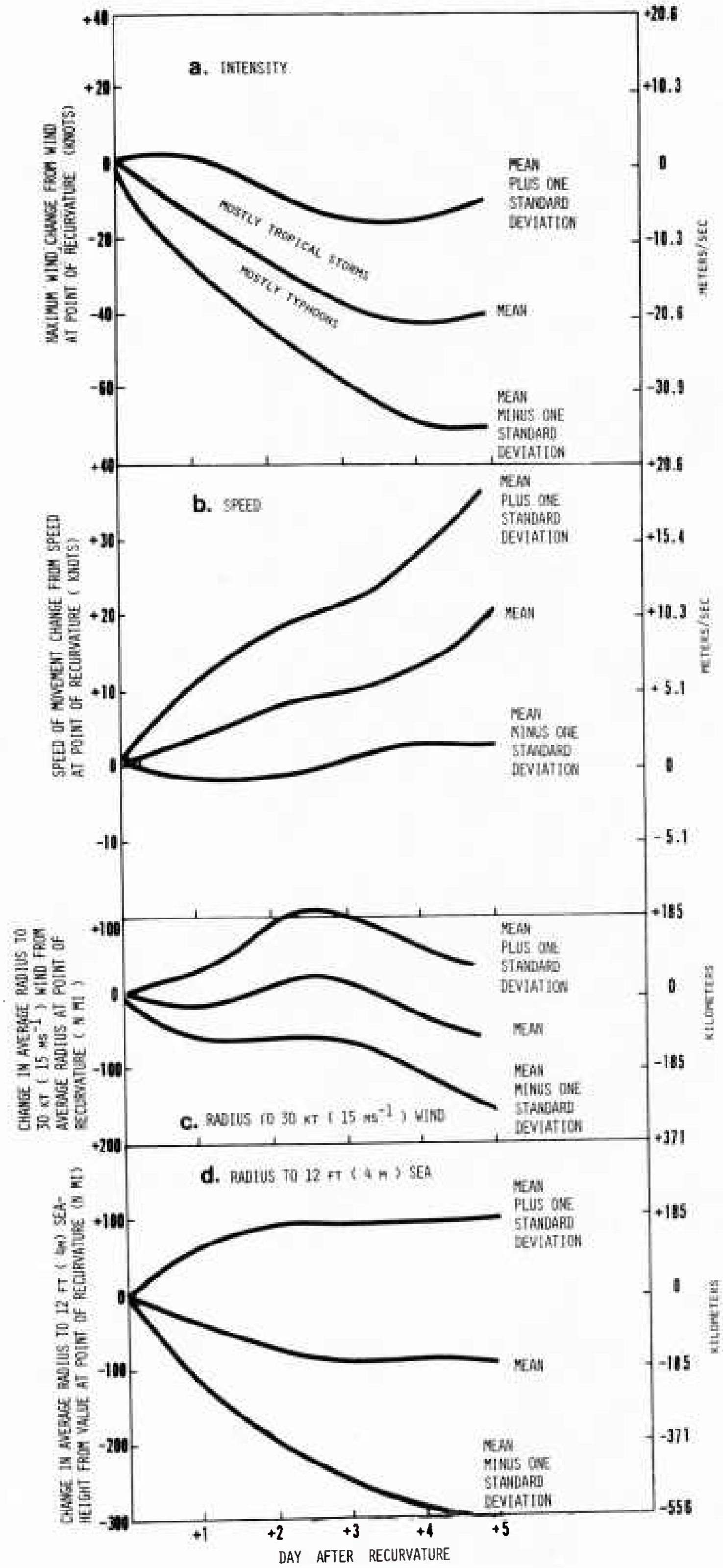

Figure 3. The mean day-to-day change in (a) intensity, (b) speed of movement, (c) radius to 30 kt (15 ms^{-1}) wind, and (d) radius to 12 ft (4 m) seas for the 1971 tropical storms and typhoons examined that existed out to 5 days. The mean values of the parameters at the point of recurvature were: maximum wind, 78 kt (40.2 ms^{-1}); speed, 10.6 kt (5.5 ms^{-1}); radius to 30 kt (15 ms^{-1}) wind, 171 n mi (317 km); and radius to 12 ft (4 m) seas, 307 n mi (569 km).

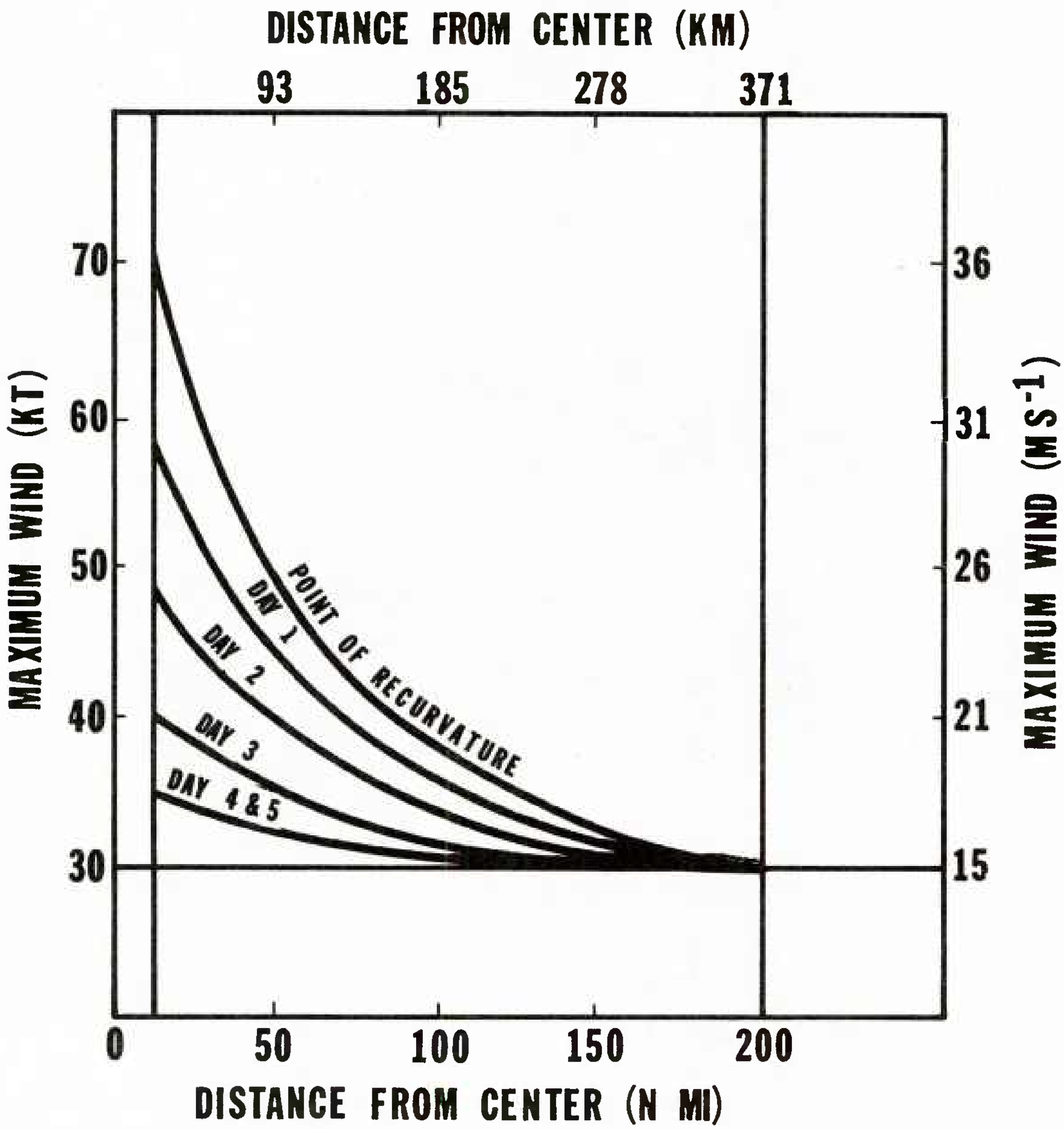

Figure 4. Schematic presentation of day-to-day variation in the azimuthally averaged wind profiles for the recurved tropical storms and typhoons existing for 5 days after the point of recurvature. Profiles are shown based on a radius to maximum wind of 15 n mi (27.8 km).

2.3 RECURVED TROPICAL CYCLONES

A tropical cyclone's maximum wind will typically weaken soon after the storm's recurvature (Riehl, 1972). The primary physical processes associated with a tropical cyclone's weakening or decay are those which degrade the release of latent heat, its main energy-producing mechanism.

There are a number of environmental factors that can be associated with a tropical cyclone's weakening: an increase in vertical shear; decreased outflow aloft; the incursion of cool, dry air; and the influence of cooler sea surface temperatures, for example. The infrared images[3] in Figure 5 show two periods 24 hours apart in the life of Typhoon June which demonstrate its weakening. Figure 5a shows the storm just after recurvature when it was entering a region of strong vertical shear and accelerating rapidly to the northeast. Figure 5b shows the deep convection reduced quite dramatically 24 hours later as the storm was approaching the extratropical stage.

Perhaps the most noticeable weakening of a tropical cyclone occurs with the incursion of cold, dry air at low levels or its passage over cooler sea surfaces. In weaker tropical cyclones the cold, dry air is normally observed to first penetrate the center in the cold sector of front quadrants. In intense systems, however, the first penetration of cold, dry air into the eye region is often observed to occur in the warm sector.

The effect of cold, dry air in degrading the tropical system is dependent on how cold and dry it is. Storms passing near land areas where cold outbreaks retain their character, fill much more rapidly than do storms at great distances from these land masses, where the cold, dry air has been significantly modified by the ocean waters. The cooler ocean waters also have a dramatic influence on the intensity of tropical cyclones. In the peak typhoon season (July-October) for example, the south-north sea surface temperature gradient near 40°N, is approximately 1°C per degree latitude (Robinson and Bauer, 1971).

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[3]All satellite data are taken from the Defense Meteorological Satellite Program (DMSP).

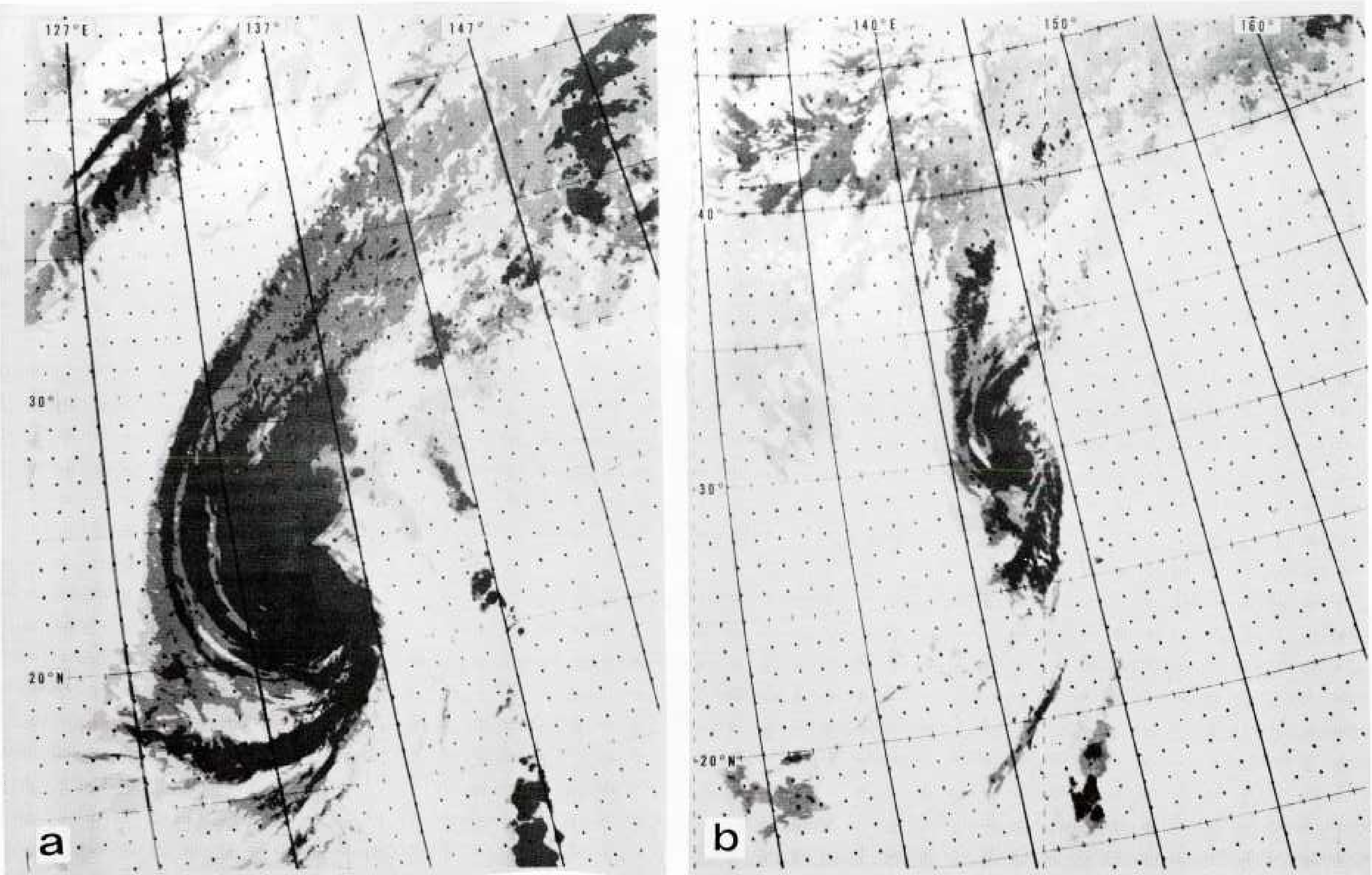

Figure 5. An infrared "sliced" depiction of Typhoon June (a) just after recurvature, 22 Nov 75, 1153 GMT, with maximum sustained winds approximately 110 kt (57 ms^{-1}), and (b) 23 Nov 75, 1134 GMT, with maximum sustained winds approximately 80 kt (41 ms^{-1}). The darkest shade of gray indicates high clouds with temperatures colder than 238°K. The white areas represent the lowest level of clouds (or no clouds) with temperatures warmer than 263°K. The other gray shades indicate intermediate level cloudiness (light gray: 253°-263°K; dark gray: 238°-253°K).

2.4 EXTRATROPICAL STAGE TRANSITION

The physical processes associated with a tropical cyclone's transition to the extratropical stage are those which produce a baroclinic environment whose tropospheric thermal and pressure patterns are favorable for extratropical cyclogenesis.

Tropical cyclones that undergo "compound" transitions generally have favorable tropospheric support for extratropical cyclogenesis. The resulting extratropical cyclone often undergoes further deepening, which is probably a response to the increased baroclinicity afforded by the convective latent heat associated with the tropical cyclone. The tropical cyclone linking with a frontal zone ("complex" transition) may or may not have favorable tropospheric support for extratropical cyclogenesis. If support is not present, the decay process will probably be slow and the tropical cyclone will ultimately dissipate. If support is present, the transition will result in extratropical cyclogenesis.

Figure 6a illustrates both the result of a "compound" and an impending "complex" transition. The northernmost storm is an intense extratropical cyclone which formed through a "compound" transition with Typhoon Tess (September 1975), merging with a nearly stationary mid-latitude low pressure center to the east of Hokkaido, Japan, approximately one day before this image was recorded. The resulting extratropical cyclone was considerably deeper than either of the merging cyclones. The southernmost storm is Typhoon Winnie, which is undergoing a "complex" transformation and is just about to merge with an approaching front. Figure 6b shows the two storms 24 hours later. Typhoon Winnie is becoming extratropical as it merges with the frontal system.

It should be noted that a tropical cyclone transition from a tropical to extratropical storm is not an instantaneous event. The periods of change can vary from hours to days, during which time the systems are hybrids that exhibit certain characteristics of both stages.

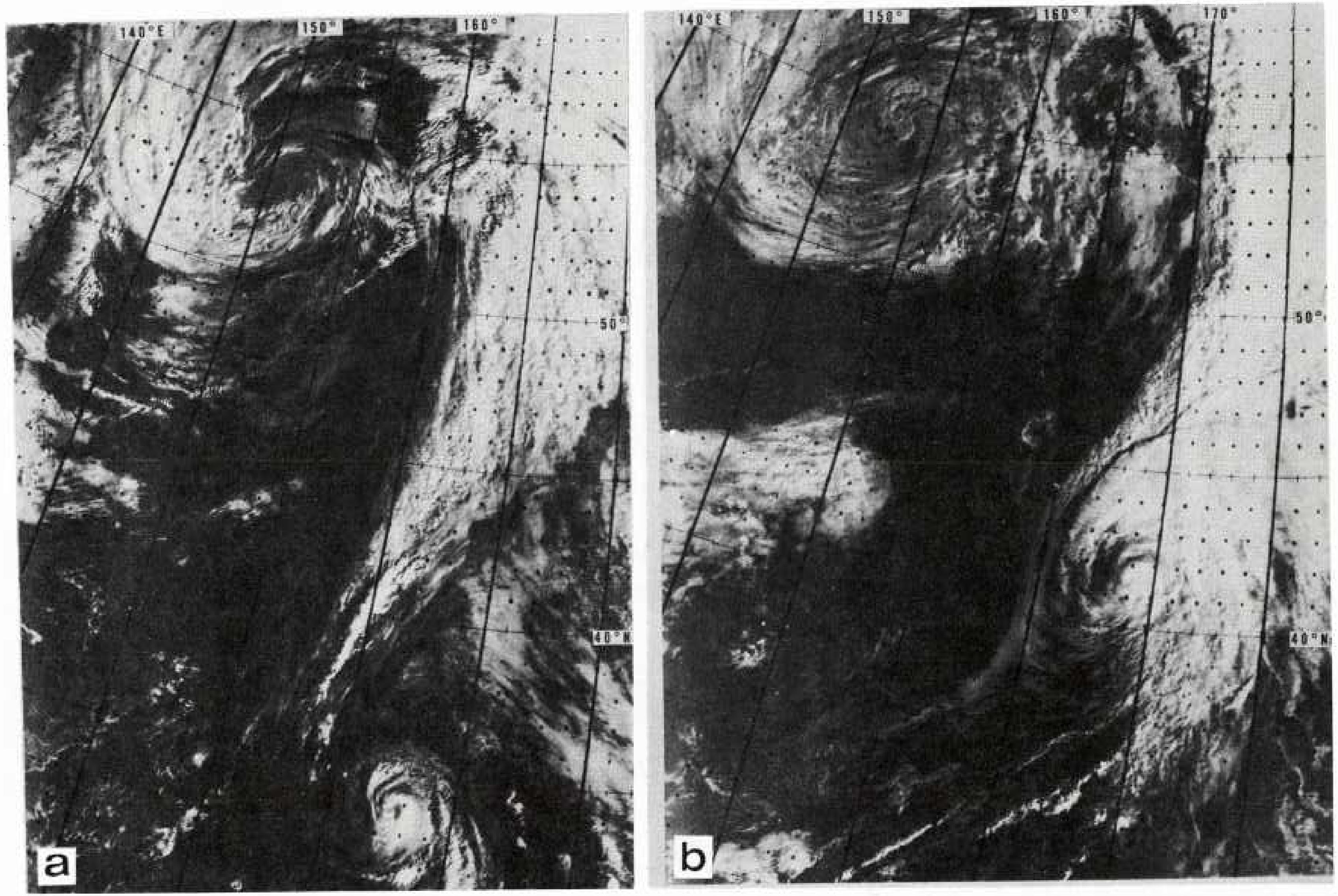

Figure 6. Visual images of the result of a "compound" and impending "complex" transformation. The northern cyclone was formed by the "compound" transformation of Typhoon Tess, while the southern cyclone is Typhoon Winnie about to undergo a "complex" transformation, 10 Sep 75, 2132 GMT, (a). The visual image of the storms 24 hours later, 11 Sep 75, 2114 GMT, is shown in (b).

A system in transition has very complex wind and temperature structures and occasionally produces dramatic increases in maximum winds. These increases occur because the storm's own mechanism for producing kinetic energy from available potential energy (derived primarily from latent heat release) is suddenly enhanced by the baroclinic conversion, in the surrounding environment, of potential energy to kinetic energy as cold air encounters, moves under, and lifts the warm moist air within the tropical cyclone circulation.

Ocean areas in which the transition process occurs are generally distant from reconnaissance bases, so detailed observations of transition are somewhat sparse. The transition of Typhoon Hope (October 1964) in the western North Pacific, however, was extensively observed by WB-50 aircraft of the 56th Weather Reconnaissance Squadron as it became extratropical while accelerating to the northeast following recurvature. Aircraft were in the storm area for approximately eight hours of each observing day.

Figure 7 shows analyses of Typhoon Hope by the Joint Typhoon Warning Center (FWC/JTWC, 1964) as cold air was entering the storm system. The sizeable increases in surface wind speeds, which appeared to last for about 12 hours, emphasize the operational hazards that could exist for vessels in such sectors during a storm's transition stage. No reconnaissance was flown the following day to observe duration or extent of strong winds, but available surface data indicate maximum surface winds of 45 kt (23 ms^{-1}).

Based on other observations of this type of phenomenon by reconnaissance aircraft in the western North Pacific, it appears that this sudden increase in wind over a short duration and over a small area is common during the transition stage, especially for early and late season tropical cyclones when cold air intrusions into low latitudes are more common.

Reconnaissance observations have also indicated that the following are characteristics of tropical cyclones as they are evolving into extratropical cyclones:

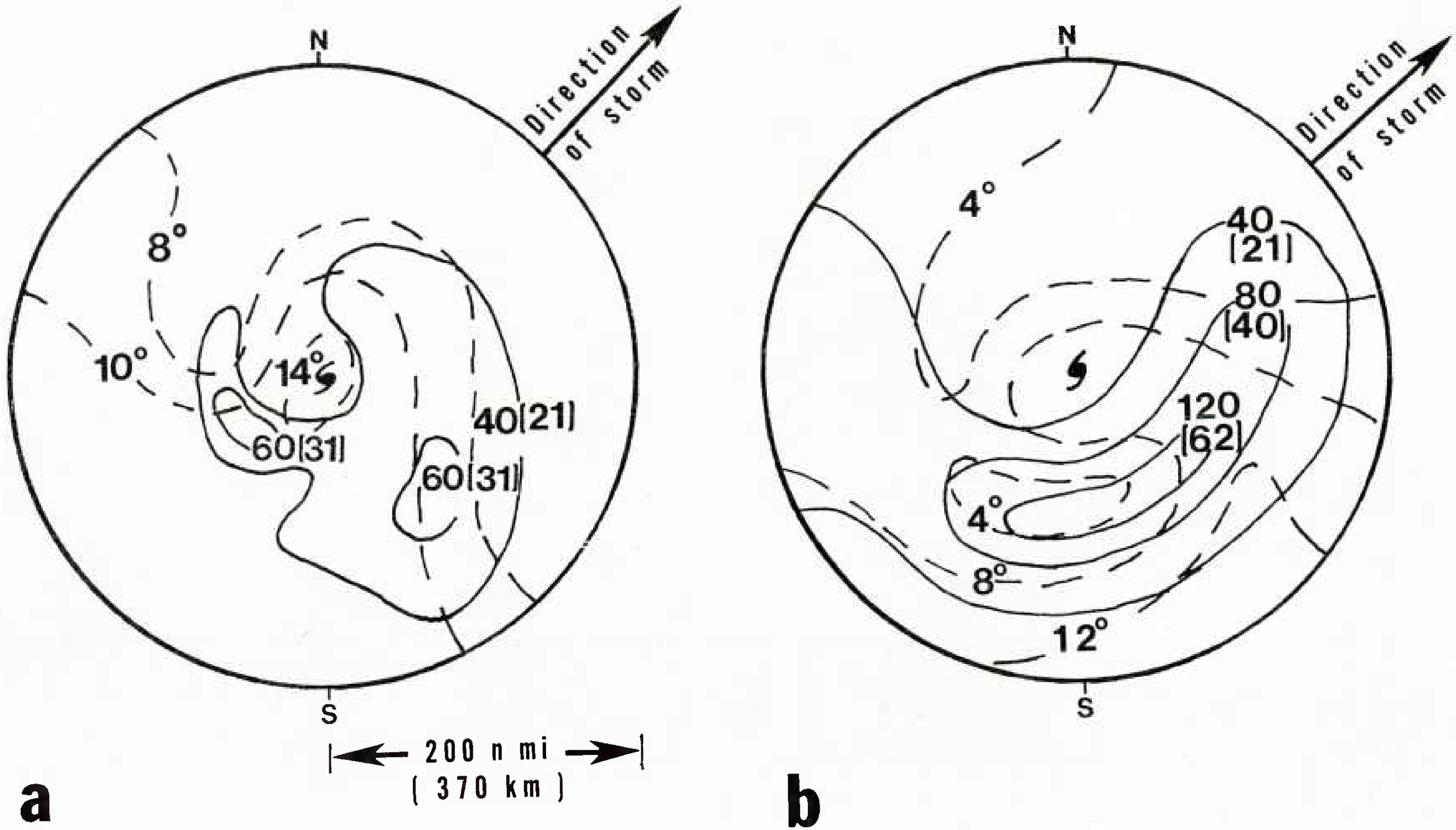

Figure 7. The estimated surface wind (solid line in kt [ms^{-1}]) and 700 mb temperature (dashed line in ^{o}C) of Typhoon Hope as the storm becomes extratropical on (a) 28 Oct 64 and (b) 29 Oct 64. Each analysis is based on approximately 8 hours of continuous reconnaissance observations in the areas outlined.

(1) Winds observed are in excess of the values that central pressures would indicate. The maximum wind area does not always relate to direction of storm movement (i.e., in right quadrant).

(2) There is a loss of cloud organization. The central area of the storm fills with clouds with tops 6000-12,000 ft (1800-3700 m). Clouds below 700 mb become stratiform. Remnants of the wall cloud as observed by radar appear to rotate rapidly, and at times the wall cloud completely disappears.

(3) There is a lack of torrential precipitation and many times there is no precipitation.

(4) Light to moderate clear air turbulence (CAT) occurs over a broad area surrounding the storm.[4]

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[4] In a recent encounter with Typhoon Mary (December 1977) as it was becoming extratropical, a reconnaissance aircraft experienced a free fall of 2500 ft (760 m) in 4 sec near the storm center with an updraft immediately preceding it. In addition, a gust front (estimated surface winds of 80 kt/41 ms^{-1}) was observed to pass near the storm center and hail was observed at the flight level of 700 mb.

3. FUTURE RESEARCH

This study has examined the characteristics and behavior of extratropical storms that evolve from tropical cyclones. As is true of many meteorological phenomenon at this scale, this evolutionary process is a complex situation that is further complicated by the lack of data for detailed studies. The fact that the storm environment poses an operational hazard during the transition period and many days afterward should encourage further synoptic and dynamic examination of all the processes involved. Numerical models capable of handling this scale could be used for diagnostic examination of the rapid, short-duration intensification that occurs. The results of such studies could give commanding officers and ship routing officials a better understanding of the nature and characteristics of storms at this stage in their life cycle, as well as be of value to the weather centrals that issue warnings of strong winds and high seas in the North Pacific Ocean.

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