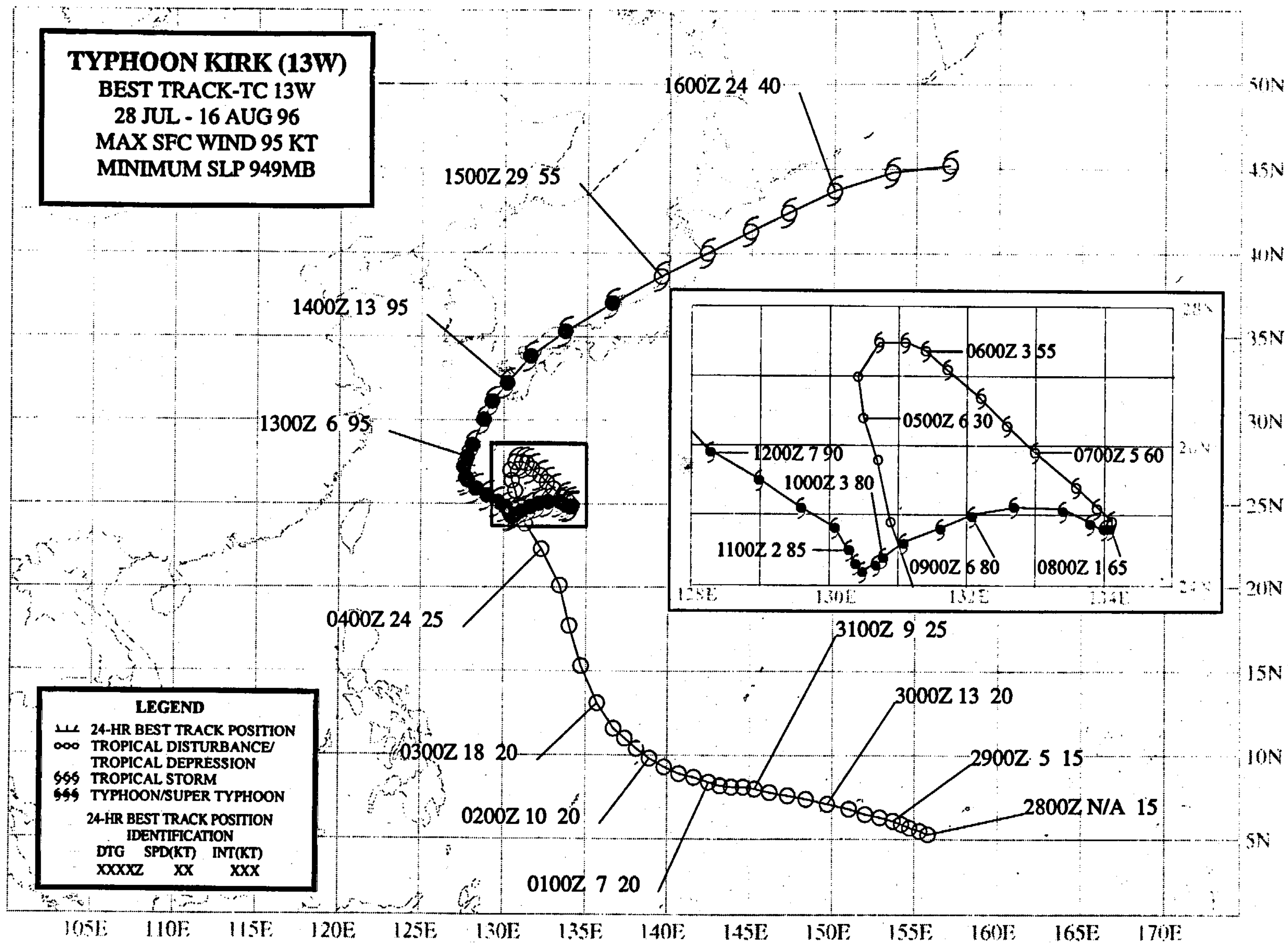

TYPHOON KIRK (13W)
BEST TRACK-TC 13W
28 JUL - 16 AUG 96
MAX SFC WIND 95 KT
MINIMUM SLP 949MB
1600Z 24 40
1500Z 29 55
1400Z 13 95
1300Z 6 95
0400Z 24 25
0300Z 18 20
0200Z 10 20
0100Z 7 20
3100Z 9 25
3000Z 13 20
2900Z 5 15
2800Z N/A 15
0600Z 3 55
0500Z 6 30
0700Z 5 60
1200Z 7 90
1000Z 3 80
1100Z 2 85
0900Z 6 80
0800Z 1 65
128E
130E
132E
134E
LEGEND
24-HR BEST TRACK POSITION
TROPICAL DISTURBANCE/ TROPICAL DEPRESSION
TROPICAL STORM
TYPHOON/SUPER TYPHOON
24-HR BEST TRACK POSITION IDENTIFICATION
DTG SPD(KT) INT(KT)
XXXXZ XX XXX
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
105E
110E
115E
120E
125E
130E
135E
140E
145E
150E
155E
160E
165E
170E

TYPHOON KIRK (13W)

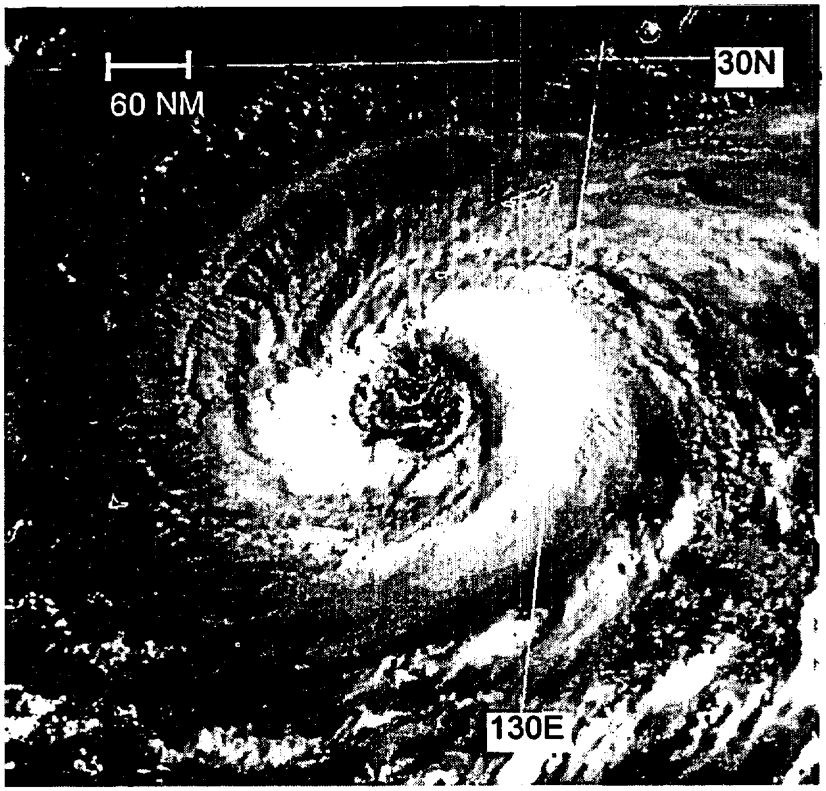

Figure 3-13-1 Kirk exhibits a very large eye as it approaches Okinawa (112331Z August visible GMS imagery).

I. HIGHLIGHTS

Forming from a monsoon depression in the Philippine Sea, Kirk moved on a complex north-oriented track which saw it undergo an unusual anticyclonic loop before passing directly over Okinawa. Kirk was the first of three TCs during 1996 to acquire a very large eye (Figure 3-13-1) — it took a full 12 hours for Kirk's 70-nm (130-km) diameter eye to pass over Okinawa. The NEXRAD Doppler radar at Kadena AB afforded a rare chance to investigate a typhoon with a ground-based radar from within the eye. After passing over Okinawa, Kirk moved north and passed over southern Japan where extensive property damage and loss of life were reported.

II. TRACK AND INTENSITY

During the final days of July, the tropical disturbance which became Kirk formed at the end of the monsoon trough to the southeast of Guam while both Herb (10W) and Joy (12W) were still active. During the first few days of August, Herb moved into China, Joy moved into the midlatitudes, and the pre-Kirk tropical disturbance was subsumed by a larger monsoon depression that formed in the Philippine Sea (Figure 3-13-2). Slow to consolidate (and undergoing a major structural change), the pre-Kirk disturbance received a total of five Tropical Cyclone Formation Alerts (TCFA) prior to the issuance of the first warning.

The tropical disturbance which became Kirk was first mentioned on the Significant Tropical Weather Advisory valid at 290600Z July, when synoptic data showed that a weak low-level circulation accompanied an area of convection near Chuuk. The first TCFA was issued valid at 292100Z when amounts of deep convection increased near the persistent low-level circulation center (LLCC). The second TCFA was issued valid at 300730Z to reposition the alert box for the continued west-northwestward motion of the pre-Kirk disturbance. This disturbance was undergoing large fluctuations in the amounts and organization of its deep convection which consisted of an ensemble of mesoscale convective systems (MCS), a hallmark characteristic of a monsoon depression. At 310300Z, the second TCFA was canceled when convection became more poorly organized. On 01 August, extensive amounts of deep convection formed in the Philippine Sea — disorganized bands and small clusters of MCSs occupied an area within a box bounded by 5°N to 25°N and 130°E to 150°E. On 02 August, this large area of deep convection became organized as a large monsoon depression (Figure 3-13-2) comprised of an enormous ensemble of MCSs associated with a large, but weak, cyclonic circulation and extensive cirrus outflow organized into an anticyclonic pattern. A third TCFA was issued valid at 020030Z August when scatterometer data indicated the presence of an LLCC with monsoon gales located to its southeast. Remarks on this TCFA include:

". . . A disturbance resembling a monsoon depression is located within the monsoon trough. Scatterometer data [from an earlier pass of the ERS-1 satellite] supports the presence of a closed low-level circulation center, with gale force winds located 180 nm to the southeast of the circulation. These winds are associated with a surge in the monsoon. . . ."

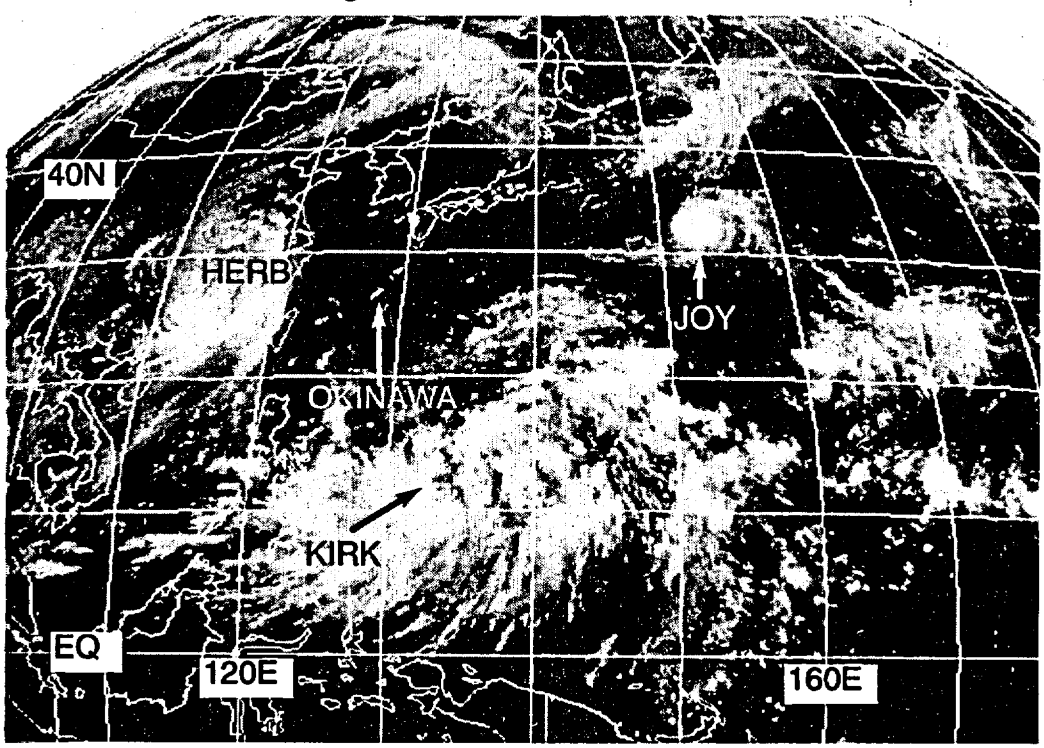

Figure 3-13-2 The monsoon depression in the Philippine Sea from which Kirk developed (020631Z August infrared GMS imagery).

As is often the case with TCs originating from a monsoon depression, the extensive ensemble of MCSs associated with the monsoon depression fluctuated greatly, and were slow to consolidate near a well-defined LLCC. Thus a fourth TCFA was issued valid at 030030Z when satellite imagery could not confirm the presence of a well-defined LLCC, and deep convection was still widely distributed and not showing signs of consolidation. The fifth, and last, TCFA was issued valid at 031100Z in order to reposition the alert box to encompass an area of deep convection that was becoming organized outside the alert box specified by the fourth TCFA. This area of deep convection increased in organization near the LLCC, and the first warning on Tropical Depression (TD) 13W was issued valid at 031800Z.

Moving on a north-oriented track within a monsoon trough which had become reverse oriented (see Appendix A), TD 13W gradually slowed its forward speed, and on 06 August, it turned toward the southeast as it began an anticyclonic loop in its track. On the warning valid at 060000Z, TD 13W was upgraded to Tropical Storm Kirk.

While executing its anticyclonic loop, Kirk intensified and became a typhoon at 080000Z. At this time, it began to move on a generally westward heading toward Okinawa. Before reaching Okinawa on 12 August, Kirk's eye became extremely large (see Discussion section). Radar and satellite measurements of its eye diameter exceeded 60 and 70 nm respectively during most of 12 August (Table 3-13-1).

After passing over Okinawa, Kirk turned toward the north, its eye diameter decreased, and the system reached its peak intensity of 95 kt (49 m/sec) (Figure 3-13-3) while accelerating along a recurving track that brought it across southern Japan and into the Sea-of-Japan. Kirk dropped below typhoon intensity as it skirted northeastward along the coast line on the Sea of Japan side of Honshu. On 15 August, Kirk crossed the northern end of Honshu from west to east and entered the Pacific. The system then accelerated within the midlatitude westerlies, became extratropical, and the final warning was issued valid at 160600Z August.

Table 3-13-1 EYE DIAMETER OF KIRK FROM NEXRAD AND SATELLITE DURING PASSAGE OVER OKINAWA.

DTG (Z)	NEXRAD eye diameter (nm)	Satellite eye diameter (nm)
120501	—	76
120530	—	70
120630	—	70
120640	70	—
120830	—	67
120930	61	71
120942	—	70
121030	63	74
121130	—	77
121151	63	—
121230	55	70
121240	—	65
121330	53	70
121430	51	68
121530	60	68
121630	66	67
121730	53	70
121815	58	—

III. DISCUSSION

a) *Unusual motion: a synoptic-scale anticyclonic loop*

It is well known that TCs tend to meander or oscillate about a mean path. These oscillations cover a wide range of scales and can take on several forms, including small-amplitude and short-period trochoidal oscillations around an otherwise smooth track, larger-scale and longer-period meanders, more erratic and nonperiodic meanders (occasionally including stalling, or small loops), or highly-erratic wandering with no well-defined track. A wide range of scales are involved as the meanders vary in period from a few days to less than an hour and have amplitudes up to a few hundred kilometers.

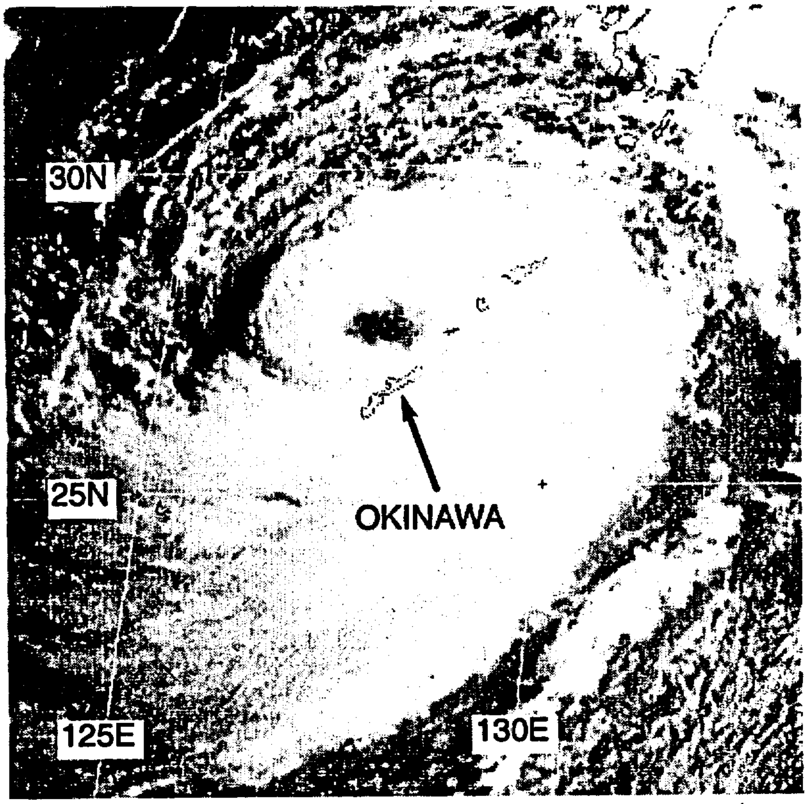

Figure 3-13-3 Kirk reaches its peak intensity of 95 kt (49 m/sec) (122131Z August visible GMS imagery).

During the two days prior to passing over the island of Okinawa, Kirk executed an anticyclonic loop with a diameter of approximately 300 nm (550 km). Well-defined looping of a TC, whereby the looping motion results in the TC recrossing its track, is unusual. According to Holland and Lander (1993), medium-scale meanders with period greater than one day and amplitude of several tens to hundreds of kilometers tend to have an equal distribution of cyclonic and anticyclonic rotation. There is a strong tendency toward exclusively cyclonic rotation at shorter periods as confirmed by an examination of 17 radar tracks of TCs provided by Meighen (1987): seven of these had no clearly discernible oscillation, and the remainder contained 23 small-scale meanders, all of which were cyclonic.

Potential mechanisms for the larger meanders include interactions with surrounding weather systems such as other TCs, TUTT cells, and synoptic-scale troughs and ridges in the subtropics or midlatitudes. During the period of its anticyclonic meander, Kirk probably interacted with other circulations in the monsoon trough and with a high-pressure system to its north. While Kirk was executing its anticyclonic loop, the monsoon trough had lifted to a very high latitude (Figure 3-13-4) and had become reverse-oriented along the portion of it that contained Kirk. Reverse orientation of the monsoon trough is often associated with north-oriented motion of its associated TCs (Lander, 1996). While this may be a satisfactory explanation for Kirk's overall northward drift, it does not offer much insight on the slow anticyclonic loop Kirk made during the period 050000Z through 120000Z. Possible explanations for this loop include an interaction of Kirk with other low-pressure systems along the reverse-oriented monsoon trough, and the affects of a midlevel anticyclone which passed slowly to Kirk's north during this time period. Once the midlevel high moved eastward into the Pacific, Kirk recurved and entered the midlatitude westerlies.

b) *Extremely large eye*

In Dvorak's analysis techniques (Dvorak 1975, 1984), the eye of a TC is considered to be small if its satellite-observed diameter is less than 30 nm (55 km), average if between 30 nm and 45 nm (55 km and 85 km), and large if greater than 45 nm (85 km). Kirk's satellite-observed eye diameter was in excess of 70 nm (150 km) during much of 12 August (the day it passed over Okinawa). This very large eye required 12 full hours to pass directly across Okinawa. Kirk was one of three TCs during 1996 — the others were Orson (19W) and Violet (26W) — which possessed, at some time during their evolution, an eye with an exceptionally large diameter (on the order of 75 nm).

Eye diameters on the order of 75 nm, or greater, are not common. None were observed during 1995. One of the TCM-90 TCs — Abe — possessed an eye with an exceptionally large diameter of about 80 nm. The unusual form of these TCs on satellite imagery led to their being called "truck tires" by JTWC satellite analysts and forecasters.

In a survey of past ATCRs, the largest eye diameter ever reported was that of Typhoon Carmen (1960). By strange coincidence, Carmen, like Kirk, passed directly over Okinawa. Carmen's eye diameter, as measured by the weather radar at Kadena was 200 statute miles (175 nm ; 325 km). Comments in the 1960 Annual Typhoon Report include:

" . . . Another feature quite unusual about this typhoon was the diameter of its eye. Reconnaissance aircraft frequently reported eye diameters of 100 mi, using as the basis of measurement, surface winds and pressure gradient. However, with respect to wall clouds surrounding the eye, radar photographs taken from the CPS-9 at Kadena AB show quite clearly that on 20 August, the eye had a diameter of approximately 200 mi . . . The eye diameter of Carmen was probably one of the largest ever reported . . ."

Kirk, like Carmen, was also viewed by a radar at Kadena: this time a new NEXRAD.

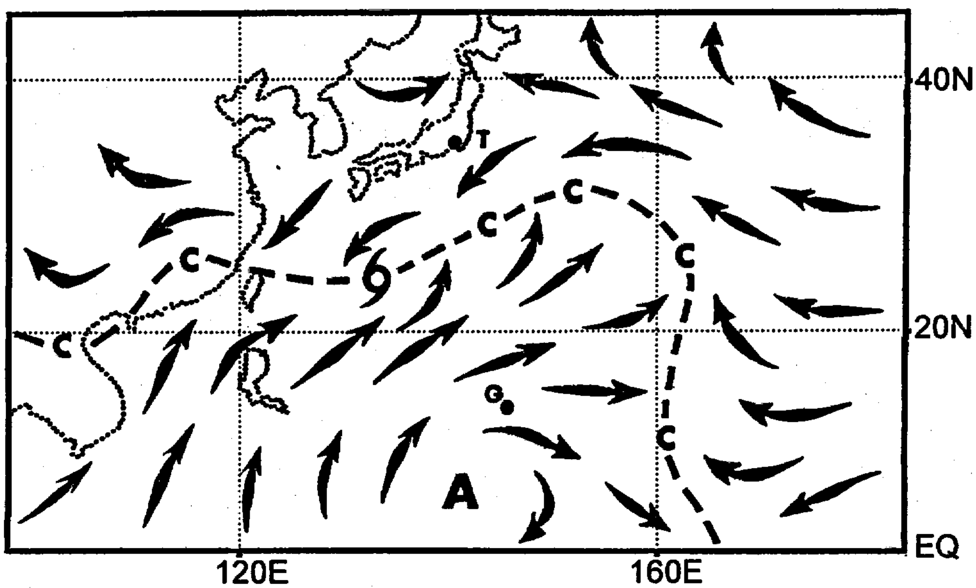

Figure 3-13-4 Schematic illustration of the monsoon circulation which became organized in an unusual pattern as Kirk underwent its anticyclonic loop along its north-oriented track (illustration based on 090000Z August JTWC surface analysis).

c) *Kirk's passage over Kadena's NEXRAD*

One of only four NEXRAD radar units to be installed in the WNP (the others are on Guam and in Korea), the NEXRAD installed on Okinawa affords an excellent opportunity to gather data on the TCs which frequently pass near or over this island. When Kirk passed directly over Okinawa, it was continuously under surveillance by NEXRAD. The NEXRAD support provided to the JTWC by Kadena base weather personnel was superb. They provided timely, thorough information on center positions, wind distribution and intensity. The most striking aspect of Kirk's radar signature was its large eye. During 12 August, as Kirk passed over the radar site from east to west the eye diameter was reported to have been consistently on the order of 60 nm (110 km) (Figure 3-13-5). This is about 10 to 15 nm less than the eye diameters as derived from satellite imagery during this time (Table 3-13-1). It is common for the eye diameter as observed from satellite to be larger than the radar-observed eye diameter due to the general outward sloping with height of the eyewall cloud.

Another fascinating aspect of the radar coverage occurred when the radar was exactly in the center of the eye: the Doppler velocity product indicated almost zero velocity along all radials. This is certainly what might be expected, but it may be the first time it has actually been observed. Another feature of the velocity product at this time was a slight asymmetry in the radial velocity which were mostly light inbound to the east-southeast and light outbound toward the west-northwest (i.e., indicative of the motion of the typhoon at that time).

d) *Fog in the eye, and other ground observations*

In recent years, there has been much debate concerning the possible effects of warmer sea-surface temperatures (SST) on the annual numbers and the potential peak intensities of TCs under conditions of a warmer climate. Emanuel (1988) set the theoretical ground work for this problem when he introduced his method for calculating the potential peak intensity of TCs. The potential peak intensity of a TC, in his framework, is largely a function of the difference between the warm SST and the colder temperatures of the upper-level outflow layer. Observationally, there is a relationship between the SST and the upper bound of TC intensity.

Granting for sake of argument that the climate will soon become warmer, and that the SST may become on the order of 1°C higher, a question arose as to the affects of this on TC distribution and intensity. This question was addressed in a special symposium at the third International Workshop on Tropical Cyclones (held in Huatulco, Mexico in 1993). The findings of this symposium (published in Lighthill, et al., 1994) were that any effects of a warmer world would likely be masked by the natural variability in TC distribution and intensity and the natural large-scale factors that govern TC formation and development.

A crucial part of this argument hinges on the physical processes which limit the intensity of a TC. As the intensity of a TC increases, frictional drag and evaporative cooling of sea spray have been suggested as brakes on the continued intensification of the TC. Other limiting factors on intensity may be the efficiency of the deep convection in the eye wall to evacuate the mass of the low-level inflow.

The thermodynamics of the TC are not fully understood. The relative contributions to the energy available to the TC by latent heat release and sensible heat fluxes from the ocean are not fully known. The cooling effects of sea spray which is produced at higher wind speeds has been introduced as an important factor in the energetics of the TC (Kepert and Fairall, 1993).

A tangential sidelight which may have important implications on the debate on the role of sea-surface fluxes on the energetics of TCs is the frequent observation of fog within the eye of TCs. During all TCs which have passed over Guam during recent years, ground fog has been reported in the eye. Observations from Kadena indicate fog was present in the eye of Kirk for the first three hours within the eye. Ramage (1974) discusses the occurrence of fog reported at sea by a ship in the eye of a typhoon (this was under the special condition of the SST having been significantly cooled by the recent passage over the same location by another typhoon). Simpson (personal communication, 1996) indicates ground fog was often reported in the eye of landfalling hurricanes in the United States. The suggested mechanism was sensible cooling of the air within the eye as it passes over land chilled by the rain and wind of the eye wall. Fog in the eye at ground or sea level could have relevance to the thermodynamic arguments concerning TC intensity (e.g., rates of sea-spray evaporation in the inflow layer, and extent of subsidence of warm dry air within the eye).

IV. IMPACT

Kirk's impact on Okinawa was largely superficial with many trees blown down, street signs broken, decorative wooden fences knocked over, and street light fixtures twisted or damaged. Some local flooding was reported. Some economic losses were incurred due to the cancellation of normal air service, the closing of shops, and a halting of an oil refinery.

Damage was more extensive, and loss of life was reported, as Kirk moved into southern Japan. There, at least two people were reported killed (a Japanese woman and a U.S. Navy serviceman were swept out to sea by high surf) and 15 injured. Over 100,000 homes were left without electricity.

At the Navy base at Sasebo, superficial damage was reported on some ships, while several other ships dragged anchor. Numerous trees were reported down on the main base, as well as a brief loss of power. At Misawa AB, some aircraft were evacuated and some others secured in hangars, but the effects of Kirk there were minimal, and no damage was reported.

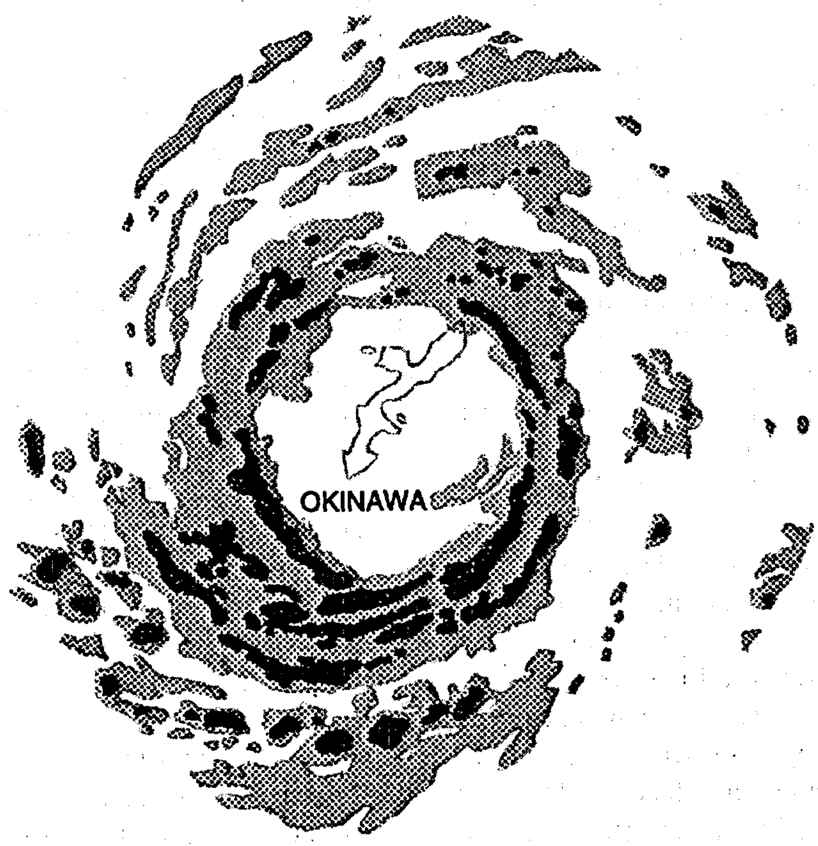

Figure 3-13-5 A radar depiction of Kirk while it was centered over Kadena. Shaded regions indicate reflectivity values of at least 30 dBZ, and the black regions indicate reflectivity values of at least 40 dBZ. (Depiction based upon the 120611Z NEXRAD composite reflectivity product).