Summary of Typhoon Forecasts by the MM5 NWP System at HKUST for 1999

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1. INTRODUCTION

1999 was a busy year for tropical cyclone (TC) activities in the South China Sea (SCS). Tropical cyclone warnings were issued in Hong Kong (HK) for eight different TCs. Among them, LEO, MAGGIE, SAM and CAM brought gale to storm force winds to the territory. Typhoon YORK even brought winds up to hurricane force that has not occurred for more than 16 years. Figure 1 shows the tracks of all the TCs that affected HK as reported by the HK Observatory (HKO).

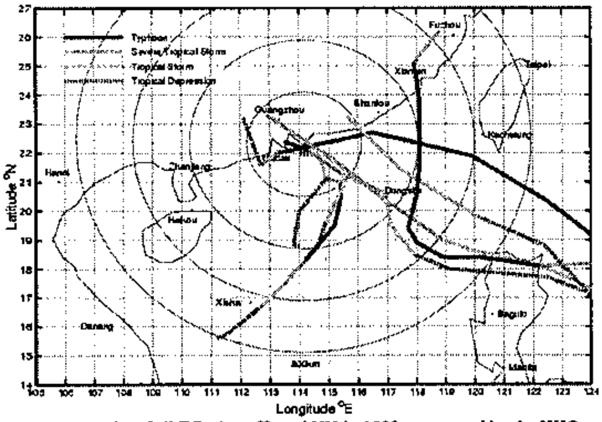

Figure 1: Tracks of all TCs that affected HK in 1999 as reported by the HKO.

HKUST has operated a real-time MM5 numerical weather prediction (NWP) system since October 1997. To assess the skill of the forecast system in predicting the TC tracks, summary and individual performances of our MM5 NWP system on the prediction of the 1999 TCs will be reported, and compared against similar statistics from other operational centers in the region. Satellite images from GMS-5 and U.S. National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) will be used to verify the simulated features of the TCs.

In the next section, an outline of the TCs affected HK in 1999 will be given, followed by a brief description of our MM5 NWP system in section 3. Performance statistics of the system will be provided in section 4, and a short summary in section 5.

2. SYNOPSIS

2.1 *Typhoon LEO*

A TC formation alert and the first warning were put out by the US Joint Typhoon Warning Center (JTWC) at 10Z April 26 and 00Z April 27, respectively. At the time, the disturbance was identified as broad circulation with multiple low-level circulation centers (LLCC). During the formation stage, it was difficult to pinpoint the center of LEO and the center was relocated a few times during the next two days. Thenafter, the TC underwent rapid development with maximum wind speed increased from 45 knots at 06Z on April 29 to 100 knots at 06Z on April 30 (Fig. 2a). LEO tracked northeastward up till 12Z April 30, and then turned northward under the influence of a subtropical ridge to the east. As the storm gained latitude, strong upper level westerlies sheared off much of its organized convection and the system weakened rapidly over water. By 07Z May 2, most of the deep convection had been sheared off to the east, leaving a much weaker system with an exposed circulation center. Finally LEO made landfall around 15Z on May 2 at about 50 km east of HK.

2.2 *Typhoon MAGGIE*

By the end of May, two regions of convections in the western North Pacific basin were identified and considered suspects for possible development into TC by JTWC. One was located in the SCS at around 11N 115E, and the other at around 10N 130E in the western Pacific (WP) east of the Philippines. The WP disturbance subsequently developed into MAGGIE, and tracked slowly northwestward between June 2 and June 4 towards southern tip of Taiwan. On June 5, MAGGIE sped up and entered the SCS through the northern Bashi Channel after interacting with the Taiwan mountainous terrain (Fig. 3a). MAGGIE then tracked westward and made landfall about 120 km east of HK around 12Z June 6. Contrary to most forecasts made at the time, MAGGIE then turned to move along the coast and passed over HK at around 20Z on the same night. Finally, MAGGIE made another turn northward at around 22N 113E between 12-16Z on June, during which it re-intensified briefly before dissipating inland the next day.

It is of interest to note that the other convective system in the SCS remained organized during most of the aforementioned period, and subject to a TC formation alert until 11Z June 6. Post-analyses of NCEP data and GMS-5 and NOAA satellite pictures suggested that the southwestward track of MAGGIE along the coast might partly be a result of its interaction with the SCS disturbance (which was moving northeastward at that time). Analyses also suggested that the brief re-intensification of MAGGIE on June 7 was possibly related to the Fujiwara effect between two circulations or merging of the remnants of the two disturbances.

2.3 *Tropical Storm (TS9906)*

During the last week of July, there were two disturbances located east and west of Taiwan and both intensified into tropical cyclones. The one east of Taiwan was named NEIL and headed towards South Korea. It caused severe damages to Cheju and Japan. The other disturbance in the SCS intensified briefly into a tropical depression (9906) and affected the coast of Guangdong.

TS9906 was not very organized when HKO first identified it as a tropical depression on July 25. No organized convection was found and no clearly defined circulation center can be identified from GMS-5 and NOAA images. The depression became more organized on July 26 as high convective clouds were seen from satellite pictures (Figs. 4a and 4b). TS9906 continued traveling northeastward and headed towards the eastern part of Guangdong and made landfall on July 27. The system got minimal attention from JTWC and Japanese Meteorological Agency (JMA) as TC warnings were issued by these agencies only on 00Z and 12Z July 27.

2.4 *Typhoon SAM*

SAM was the second storm to cross over HK in 1999. An area of organized convection developed into a tropical depression over the WP east of the Philippines on August 19 and subsequently intensified into a tropical storm the day after and named SAM. On August 21, SAM continued its west-northwest movement and swept across the northern most area of Luzon without losing much of the energy. Within 24 hours after entering the SCS, SAM intensified rapidly into a typhoon as it continued its northwesterly track towards HK. NOAA satellite picture and model forecast showed the main rain-band with intense convective activities was located to the south and east of SAM when it was southeast of the territory (Figs. 5a and 5b). However, when SAM approached land, the convection died rapidly and no hurricane force wind were recorded locally in HK. SAM was downgraded into a severe tropical storm right before it made landfall over HK.

2.5 *Tropical Storm WENDY*

Just at the beginning of September, JTWC issued a new warning for a TC over the WP at 00Z September 1. A tropical depression, formed east of the Philippines, was traveling west-northwest towards the northern tip of Luzon. The depression intensified into a tropical storm at the night of September 2 (Figs. 6a and 6b). After skirting the Philippines, WENDY took a more northerly track crossing the Bashi Channel towards the southwestern part of Taiwan. Afterwards, WENDY adopted a more northwesterly course and headed towards the eastern coast of Guangdong on September 3. It made landfall within 200 km east of HK and weakened into a low the day after. The system later brought heavy flood to the eastern China province of Zhejiang.

2.6 *Typhoon YORK*

SAM was the third storm to cross over HK in 1999 and was the first in 16 years to bring hurricane force wind to the SAR. A disturbance situated off the east coast of the Philippines intensified into a tropical cyclone about one week after WENDY dissipated. JTWC and JMA issued their first TC warning for this system at 00Z September 12 and 12Z September 13, respectively. Unlike SAM and WENDY that only skirted the northern tip of Luzon, this storm tracked westward over the mountainous part of Luzon. Due to terrain interaction, the center of the storm was torn apart and became very disorganized. Satellite pictures showed numerous LLCCs loosely packed near the northwest coast of Luzon (not shown). This made it difficult to identify the circulation center of the storm. However, warm sea surface temperature in SCS triggered the re-intensification of the storm and it became a tropical storm on September 13 and was named YORK. YORK gained strength very rapidly and became a typhoon on September 14. The convection wrapped around the center and the system became more organized (Figs. 7a and 7b). On September 16, the eye of YORK passed over HK from the southeast with hurricane force wind. The system moved inland and dissipated during the night.

2.7 *Severe Tropical Storm CAM*

An area of convection quickly organized off the east coast of Hainan Island and intensified into a tropical storm and was named CAM. TC warnings were first issued by JTWC and JMA at 12Z September 23 and 00Z September 24, respectively. The movement of CAM was rather erratic as it drifted to the east and northeast at the beginning and then almost stationary on September 25. CAM intensified into a severe tropical storm while standing still southeast of HK. Satellite picture and model forecast both showed a very small but intense convection southeast of the TC, right next to HK on 22Z September 25 (Figs. 8a and 8b). It then started to weaken due to the approach of cool northeast monsoon. CAM took a more northwesterly track and had a 'direct hit' over HK, which was the fourth time in the year. CAM was a minimal tropical storm when landed in HK and only brought very brief gale and heavy showers to the territory. CAM continued track northwestward and dissipated quickly inland.

2.8 *Typhoon DAN*

In early October, another disturbance gained organization and became a tropical depression about 1000 km east of the Philippine over the WP. The TC, named DAN, quickly reached typhoon strength on October 4, within 48 hours after its birth. DAN crossed over the northern part of Luzon of October 5 and maintained its broad circulation and convections entering the SCS. After reaching the 118E, DAN consolidated and started to slow down and drifted northward toward Fujian province. Satellite imagery showed that an eye with well-defined convection clouds in all quadrants (Fig. 9a). DAN posed no further threat to HK and landed near Xiamen on October 9.

3. REAL-TIME PREDICTIONS AT HKUST

Our research team at the Center for Coastal and Atmospheric Research (CCAR) at HKUST operates a near real-time NWP system based on the PSU/NCAR MM5 model (Lau et al. 1996, Gill et al. 1995). Our system makes 72-hour numerical forecasts for HK and the South China region. There are two forecast domains at 54 and 18 km resolution, and our system used the NCEP AVN forecasts as the model first-guess field and boundary conditions. Observations from the Global Telecommunication System (GTS) were used to enhance the first-guess fields from the AVN analyses. The forecasts are available on the Internet at http://ccar.ust.hk/~mm5v3op.

Substantial effort was spent during the first year to tune the modeling system for better prediction for the local HK / South China environment. In addition, a TC bogusing scheme based on TC warnings issued by the JTWC and the JMA was implemented. This TC bogusing scheme was necessary since the TCs cannot be very well resolved in the AVN first guess fields.

4. FORECASTS AND VERIFICATION AT HKUST

Forecasts of Tropical Storms TS9906, WENDY, and CAM were not verified in this study because of their weaker strength, their comparatively shorter life span, and the lesser forecasts issued by HKO (less than 6 warnings issued at 00Z and 12Z). On the other hand, forecasts and mean track error of the HKUST MM5 system for the five typhoons (LEO, MAGGIE, SAM, YORK and DAN) were evaluated based on features in satellite imageries and TC fixes by the HKO.

4.1 *Overall Performance*

The mean forecast errors of five typhoons (LEO, MAGGIE, SAM, YORK and DAN) affected HK in 1999 were shown in Table 1. In comparison with forecasts of other operational centers in the region, these results show that the HKUST MM5 system performed very well. The average error of our forecasts were about 150, 200 and 300 km at 24, 48 and 72 hours, respectively.

Mean Forecast Error (km)	*12 hr*	*24 hr*	*36 hr*	*48 hr*	*72 hr*
HKO	--	138	--	243	--
JMA (Japan)	--	147	--	262	425
JTWC (U.S.)	103	164	232	301	413
HKUST MM5	100	144	171	202	274

Table 1: Mean forecast error (km) of all the typhoons affected HK in 1999 as compared to other regional operational centers as a function of forecast time. [HKO issues tropical cyclone forecasts for 24 and 48 hours, JMA issues forecasts for 24, 48 and 72 hours, and JTWC issues forecasts for 12, 24, 36, 48 and 72 hours.]

4.2 *Typhoon LEO*

Most of the aforementioned features of LEO were successfully predicted by our MM5 system. The formation of the cyclone in the SCS was predicted as early as 12Z April 24. The subsequent development and the NE / N track of LEO were well predicted by our MM5 NWP system. It was also impressive to see that the cloud band structure at 0725Z April 30 shown in the AVHRR image (Fig. 2b) was very well forecasted in the 36-hour prediction initialized at 00Z April 29. The MM5 system was also successful in predicting the shearing off of the deep convection by upper-level westerlies and the rapid weakening of the storm (details not shown).

In term of track forecasts for LEO, the HKUST MM5 system compared very well with predictions issued by other forecast centers. Table 2 shows a comparison of the mean forecast error of LEO as a function of forecast hour for 10 predictions by different centers between 00Z April 28 and 12Z May 2. The error is defined as the distance between the forecasted location and the actual located reported by HKO. Table 2 shows that the MM5 system has the least error in its track forecasts of LEO, particularly for predictions beyond the first 24 hours. Analyses of the actual tracks show that the MM5 system was more successful in predicting the NE / N movement of LEO (not shown).

Mean Forecast Error (km)	*12 hr*	*24 hr*	*36 hr*	*48 hr*	*72 hr*
HKO	--	126	--	265	--
JMA (Japan)	--	127	--	181	210
JTWC (U.S.)	112	171	264	354	340
HKUST MM5	87	119	93	112	150

Table 2: Mean forecast error (km) of LEO for different centers as a function of forecast time.

4.3 *Typhoon MAGGIE*

The MM5 NWP system was also successful in predicting the NW / W / WSW track of MAGGIE over the WP and the SCS, its interaction with Taiwan (Fig. 3b), and its interaction with the SCS disturbance. However, we were less successful in predicting the rapid movement of the storm over the northern SCS on June 6. Apparently, this rapid movement was difficult to predict and similar errors were made by other forecast centers. The mean errors for 6 forecasts for MAGGIE between 00Z June 5 and 12Z June 7 are summarized in Table 3. It is apparent that the prediction of MAGGIE was more difficult than that of LEO. Nevertheless, the HKUST MM5 system still has the least error in its track prediction of MAGGIE beyond the first 24 hours. This may partly be related to our ability to better resolve the mesoscale interaction of MAGGIE with Taiwan and the SCS tropical disturbance.

Mean Forecast Error (km)	*12 hr*	*24 hr*	*36 hr*	*48 hr*	*72 hr*
HKO	--	191	--	302	--
JMA (Japan)	--	172	--	264	420
JTWC (U.S.)	108	173	235	288	452
HKUST MM5	130	185	196	194	244

Table 3: Mean forecast error (km) of MAGGIE for different centers as a function of forecast time.

4.4 *Typhoon SAM*

The MM5 NWP system was less successful in predicting the track of SAM compared to HKO and JTWC forecasts. Our system consistently predicted SAM would turn north to north-northwestward after crossing Luzon, and headed towards eastern part of Guangdong and Fujian due to the retreat of a weak ridge stretched from the WP. However, this weak ridge maintained its strength and SAM was directed northwestward HK instead. The reason of the unsatisfactory forecasts was likely to be related to the inability to resolve the weak ridge in the coarse resolution first-guess field, thus SAM was predicted to break through the ridge and moved north. Table 4 shows the mean errors 8 forecasts for SAM between 12Z August 19 and 00Z August 23. However, it is apparent that forecasts from JMA and JTWC also predicted the northward movement of SAM at the beginning and accumulated big forecast error.

Mean Forecast Error (km)	*12 hr*	*24 hr*	*36 hr*	*48 hr*	*72 hr*
HKO	--	111	---	249	--
JMA (Japan)	--	163	---	364	865
JTWC (U.S.)	77	128	212	317	627
HKUST MM5	109	172	252	308	339

Table 4: Mean forecast error (km) of SAM for different centers as a function of forecast time.

4.5 *Typhoon YORK*

Several features of YORK were predicted well by our MM5 system. After YORK skirted the northern tip of Luzon, YORK was disintegrated and only numerous LLCC can be seen. Hours before YORK made landfall near HK, the convections to the northern quadrant of the storm were less developed compare to those to the south. This can be seen from the NOAA satellite picture. Figure 7a and 7b show this feature correlated very well with the 24-hour MM5 forecast initialized at 12Z September 14.

In terms of track forecast, our system did very well in the prediction especially within 48 hours forecasts. This is related to the accurate prediction of disintegration and re-organization of YORK after crossing Luzon. Table 5 shows that MM5 system generally has a better error statistics within 48 hours forecasts. Mean forecast errors are calculated from 10 forecasts between 00Z September 12 and 12Z September 16.

Mean Forecast Error (km)	*12 hr*	*24 hr*	*36 hr*	*48 hr*	*72 hr*
HKO	--	140	---	192	--
JMA (Japan)	--	149	---	290	---
JTWC (U.S.)	141	218	260	279	325
HKUST MM5	96	118	167	201	367

Table 5: Mean forecast error (km) of YORK for different centers as a function of forecast time.

4.6 *Typhoon DAN*

The MM5 NWP system predicted the broad circulation of DAN throughout its life span. The model also captured the compactness of the storm and the formation of the eye (Fig. 9b). Regarding the track forecasts, the MM5 system successfully predicted the northward curvature of DAN after crossing Luzon due to the relaxation of the ridge over WP. Statistically, Table 6 shows mean errors for 12 forecasts for DAN between 12Z October 4 and October 10, and our system performed similar to other centers in the region.

Mean Forecast Error (km)	*12 hr*	*24 hr*	*36 hr*	*48 hr*	*72 hr*
HKO	--	123	---	206	--
JMA (Japan)	--	122	--	210	203
JTWC (U.S.)	76	131	187	265	321
HKUST MM5	77	127	147	196	271

Table 6: Mean forecast error (km) of DAN for different centers as a function of forecast time.

5. SUMMARY

Synopsis of the evolution of all the TCs affected HK in 1999, and an analysis of the track forecasts of the typhoons of the HKUST MM5 system were provided. It is found that the MM5 system had been performing quite well in predicting the evolution and the tracks of these TCs, showing that the MM5 system can be very useful for TC forecasts in HK and the South China Region.

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References

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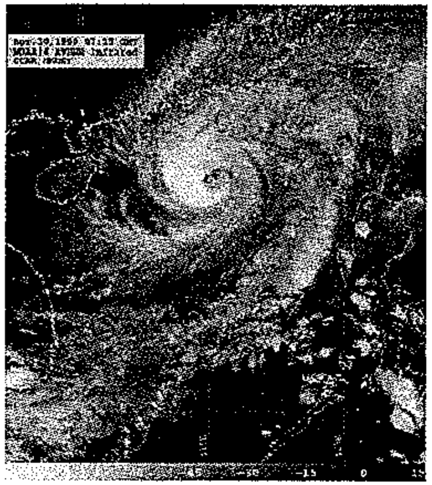

Figure 2a: IR image of LEO at 0725Z April 30. Maximum wind speed was estimated to be 100 knots.

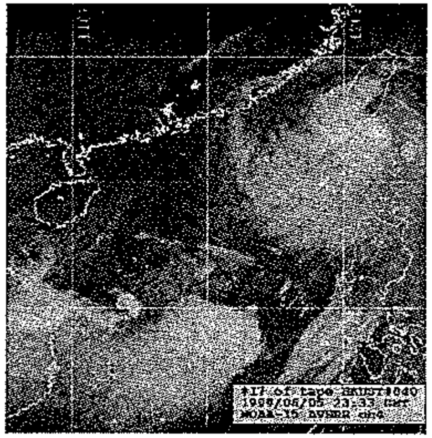

Figure 3a: IR image of MAGGIE at 2333Z June 5 showing the center of the typhoon near Taiwan. The image also shows a region of enhanced convection associated with another disturbance southwest of the TC.

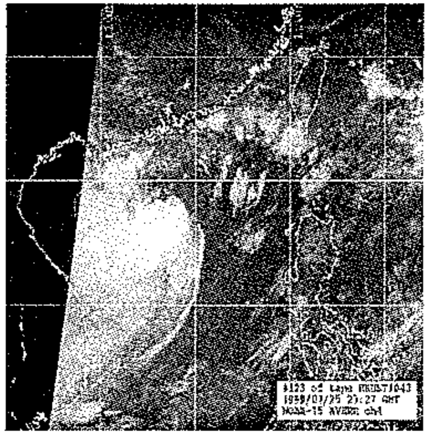

Figure 4a: IR image of TS9906 at 2327Z July 25 showing the convections flare up off the coast of Hainan Island where the tropical storm located.

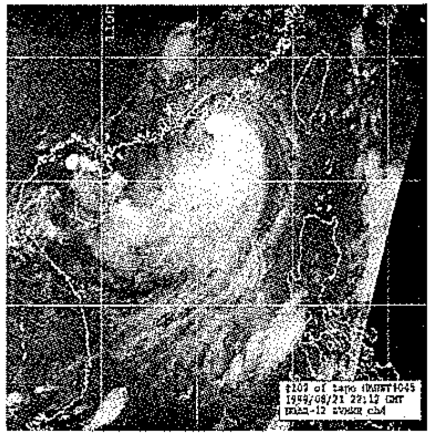

Figure 5a: IR image of SAM at 2212Z August 21 showing the main convection areas are located to the south and east quadrants of the storm center.

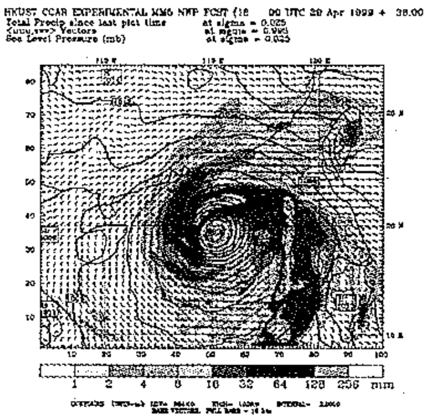

Figure 2b: 36-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 18km domain for the run initialized at 00Z April 29 (valid at 12Z April 30). The eye of LEO was very well defined with wrap around convections.

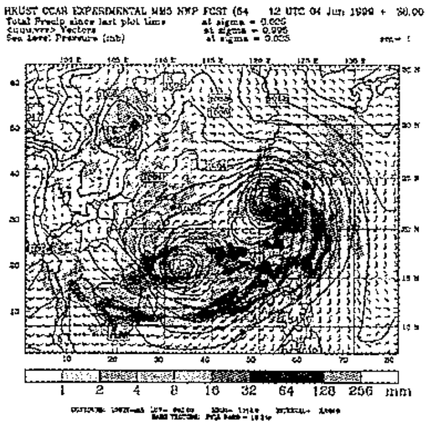

Figure 3b: 36-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 12Z June 4 (valid at 12Z June 5). The interaction of MAGGIE with the other disturbance over the SCS was evident.

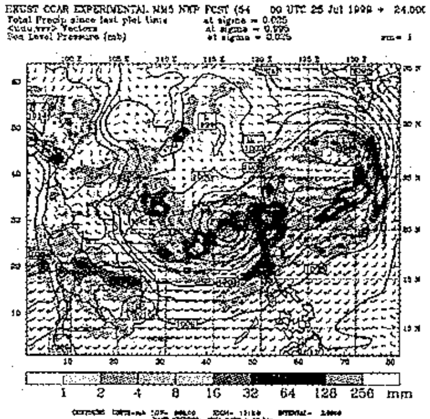

Figure 4b: 24-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 00Z July 25 (valid at 00Z July 26). TS9906 was south of HK and poorly organized.

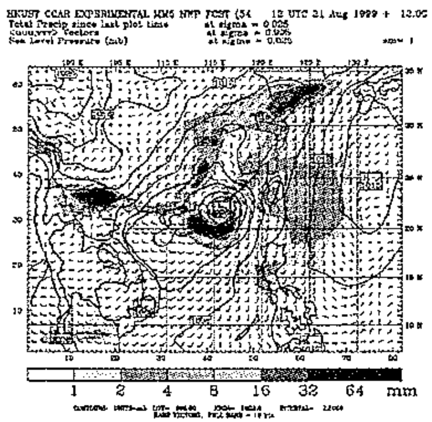

Figure 5b: 12-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 12Z August 21 (valid at 00Z August 22). SAM was just southeast of HK with convection to its south.

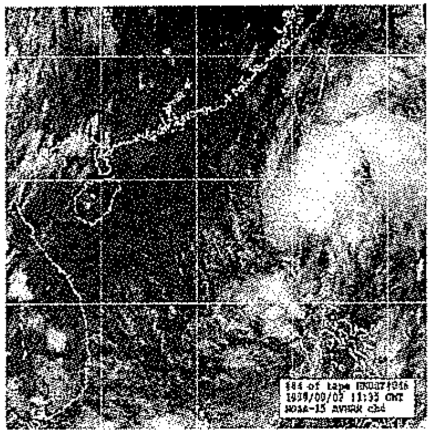

Figure 6a: IR image of WENDY at 1135Z September 2. Convections were mainly located to the north of the center which was disintegrated after crossing the northern part of the Philippines.

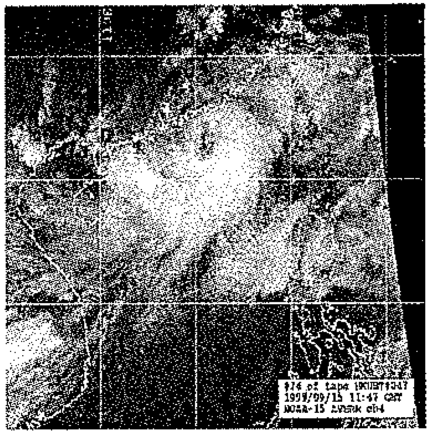

Figure 7a: IR image of YORK at 1147Z September 15 showing the center of the typhoon near Hong Kong. Convections are mostly concentrated to the southeast of the storm.

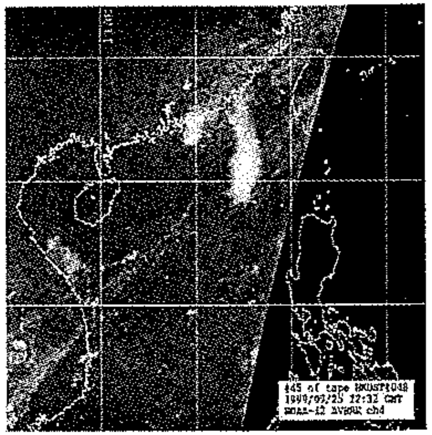

Figure 8a: IR image of CAM at 2232Z September 25 showing a small and intense convection cell just southeast of Hong Kong.

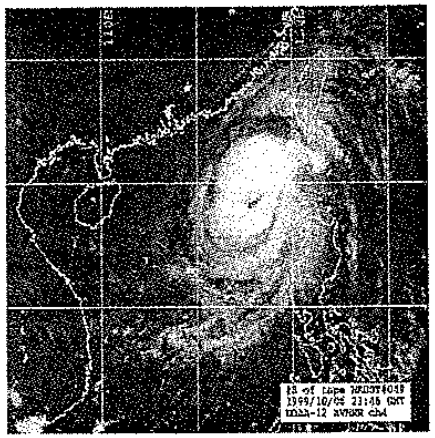

Figure 9a: IR image of DAN at 2146Z October 6 showing convections wrapping around a developing eye.

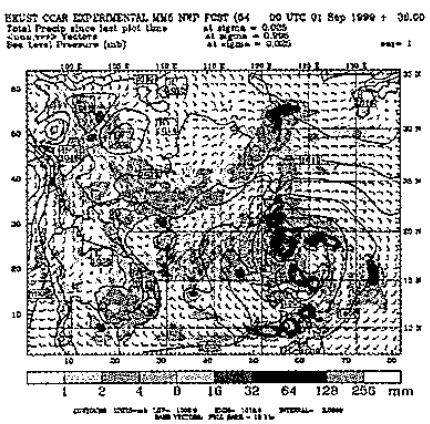

Figure 6b: 36-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 00Z September 1 (valid at 12Z September 2). Convections associated with WENDY were scattered around the low level circulations.

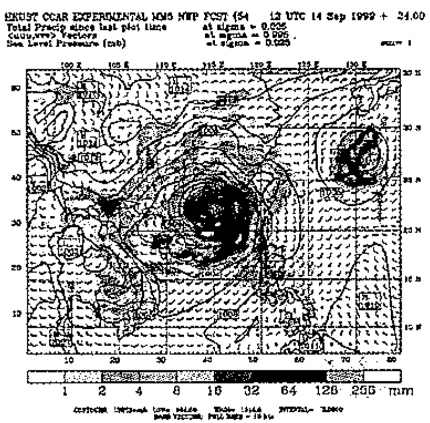

Figure 7b: 24-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 12Z September 14 (valid at 12Z September 15). Deep convections also located to the south of YORK.

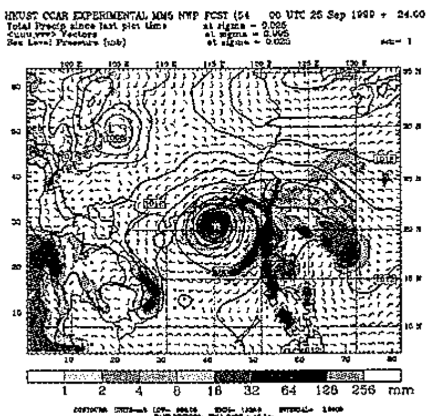

Figure 8b: 24-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 00Z September 25 (valid at 00Z September 26). CAM was a small system with convection only near its center

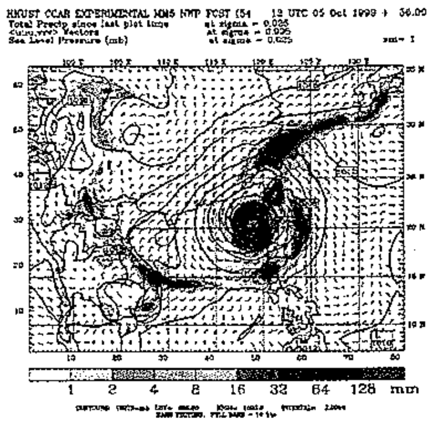

Figure 9b: 36-hour prediction of surface wind, 12-hr accumulated rainfall and sea-level-pressure of HKUST MM5 system in the 54km domain for the run initialized at 12Z October 5 (valid at 00Z October 7). DAN was southwest of Taiwan heading north.