

Recent Studies on Landfalling Tropical Cyclones near Hong Kong

C.C. Chan

Hong Kong Observatory, Hong Kong, China

Introduction

In the past few years, several tropical cyclones passed directly over the territory of Hong Kong. Typhoon Victor on 2 August 1997 was the first tropical cyclone that directly hit Hong Kong since 1983 (Figure 1a). In 1999, the eyes of four tropical cyclones traversed the territory, making it a record that will be very difficult to surpass. They included Severe Tropical Storm Maggie on 7 June, Severe Tropical Storm Sam on 22 August, Typhoon York on 16 September and Tropical Storm Cam on 26 September (Figure 1b). Finally, the most recent tropical cyclone to hit Hong Kong directly was the mid-level tropical depression on 18 June 2000 (Figure 1c). The mid-level tropical depression was the first of its kind to be detected and observed in some detail before hitting Hong Kong. It was about 100 km in diameter, formed over the sea about 35 km to the south of Hong Kong in the evening of 18 June and crossed Hong Kong later that night.

These tropical cyclones were closely monitored by a dense array of over 60 automatic weather stations (AWSs), 2 wind profilers and perhaps most importantly by Hong Kong Observatory's 2 S-band Doppler weather radars. In particular, the centre of Maggie actually passed between the two radar sites, spaced only 11 kilometres apart. The close encounter provided probably the first dual-Doppler observations of a tropical cyclone in the tropics by an operational radar array.

This network of observing equipment provides invaluable information in tracking the movement, estimating the intensity and depicting the structure of these tropical cyclones. Some of the work undertaken by staff of the Hong Kong Observatory will be described below.

Tracking

Studies show that the centres of tropical cyclones near the surface have a tendency to avoid hills as they move overland while the centres at higher

levels appears to be less affected. As a result, the centres are tilted with height (Li *et al.* 1998, Lam 2000, Leung *et al.* 2000 and Ginn *et al.* to be published).

The dual-Doppler winds of Maggie 1999 observed by the 2 Hong Kong Observatory (HKO) radars at 2000 UTC 6 June 1999 at different heights above MSL are given in Figure 2, together with the surface wind observations made by the HKO AWSs. Figure 3 shows the dual-Doppler winds of Maggie at 3-km height at 1930, 2000 and 2030 UTC as well as the AWS observations at corresponding times. The tracks of Maggie's centres at 1, 2 and 3 km heights as estimated from the dual-Doppler winds, as well as the surface track as determined from AWS observations from 1900 to 2100 UTC are given in Figure 4a.

Local terrain apparently had significant effects on the track of Maggie at lower levels. The surface track was one that avoided the hills (Figure 4b). The tracks at 1 and 2 km heights also showed this tendency. However, the initial half of the tracks between 1900 and 2000 UTC was south of the eastern range of hills in Hong Kong, that is, on the opposite side of the track on the surface. How this has come about is a subject to be studied further. Local terrain is at most 1 km high and the tracks above 3-km height showed steady west-southwestward movement with little fluctuation with respect to the terrain.

The relative positions of Maggie's centre at different heights from 1900 to 2030 UTC are presented in Figure 5. Bearing in mind that the general direction of movement was towards the west-southwest, it is apparent that the surface centre was lagging behind the centre around 3-5 km by a distance of about 10 kilometres. Noting further that the observed deviation of tracks at lower levels relative to hills, the terrain probably plays a significant role in causing this lag.

The tilting of centres with height was also observed in the midget Tropical Depression on 18 June 2000 (Figure 6). During its formation stage, the tilting was less from reflectivity analysis observed at various levels. Tilting increased as the tropical depression moved northward over Hong Kong. This is probably due to in part by land effect on landfall. The horizontal displacement was about 15 km northwest or north-northwest in the lower 3 km at 1330 UTC.

Similar tilting was also observed in Victor 1997 using zero-isodop analysis (Figure 7, only 1 Doppler radar was available at the time of Victor in 1997) and Sam 1999 using dual-Doppler winds (Figure 8).

To investigate the contribution of terrain to the tilting of the centre, a model experiment was carried out using the HKO Operational Regional Spectral Model (ORSM) by changing land grids to sea grids for the area 20-25 N, 110-120 E over southern China (Lam 2000). The ORSM was developed on the basis of the Japan Meteorological Agency RSM. It is a hydrostatic model with formulation in primitive equations of momentum, mass, specific humidity and virtual temperature using advection forms. Details of the model's formulation can be found in JMA (1997).

A model run was carried out for Sam 1999. The centres of circulation were tracked by the model forecast wind field at different levels, from surface up to 500 hPa. The model predicted track from the control run was slightly to the north of the actual. Significant vertical shift of the centres up to 500 hPa was observed in the model control run as shown in Figure 9, but not in the experiment with land grids changed to sea grids. It is apparent that the terrain contributed the tilting of centres of circulation with height in the low to mid levels.

Wind Field

Dual Doppler observations allowed the evaluation of asymmetry in the circulation of tropical cyclones. The circulation of Maggie 1999 was evidently asymmetric (Figure 2). The dual-Doppler winds of Maggie at all levels were significantly stronger in the northern semi-circle. This is consistent with the superposition of a symmetric vortex on a background easterly flow that steered the tropical cyclone to move generally westward.

Inspection of the dual-Doppler winds at an altitude of 1 km (Figure 10) of the midget tropical depression in June 2000 indicated that winds on the eastern side of the tropical depression were generally stronger. This is related to the northward movement of the tropical cyclone. The dual-Doppler wind average over the northeastern sector exhibits a linear relationship between wind strength and distance from the centre of the tropical depression (Figure 11).

The representation of the true signature of a tropical depression in numerical

models generally improves the accuracy of the forecast track of the tropical cyclone. In a model experiment for Leo 1999 (Lam *et al.* 2000), it was shown that a bogus asymmetric tropical cyclone was superior to a symmetric vortex in forecasting the track.

In the vertical, wind maxima at low levels were observed in these landfalling tropical cyclones. In Maggie's case, dual-Doppler winds showed that winds were in general stronger at the 2-km level and started to decrease gradually above this height. Wind profiler data for Victor showed a layer of winds of over 25 m/s below 2 km (Figure 12). In the case of the midlevel tropical depression, wind profiler data showed that a layer of winds of about 12 m/s in average could be observed below 2 km (Figure 13).

Wind profiler as a forecasting tool

Yeung (1998) showed that wind profiler data could also be used to forecast the onset of strong winds by making use of the observation that winds of a given speed would appear aloft first and gradually descending to the lower altitudes (Figure 14).

Wind profiler observations of Sam 1999 (Figure 15) showed that winds above 3000 m backed at an earlier time than those in the lower levels. As such wind profiler data may also be useful in forecasting the approach of tropical cyclones.

Intensity prior to landfall

Observations showed that as tropical cyclones were about to make landfall, intensification could take place when part of their circulation was over land (Lam 2000 and Leung *et al.* 2000).

One such example is the intensification of Sam into a typhoon prior to its landfall on the morning of 22 August 1999. Intense convection was initiated in the northern side near the concave side of the inner band where convection was previously inactive particularly in the northwestern quadrant (Figure 16). A relatively big eye with a diameter of 60-80 km appeared when it was around 150 km off the south China coast. The life span of typhoon strength was not more than 6 hours.

The intensification at this stage was studied by the model experiment replacing land grids with sea grids described above. In the experiment, the 24-hour accumulated rainfall for Hong Kong was around 85 mm. It was about 45% less than that obtained from the control run with no change in the land sea mask which yielded around 155 mm, which was in turn about half of the observed rainfall. Comparing the two runs, it appears likely that the presence of terrain contributed to more rain being dumped in the inner circulation, especially in the northern semi-circle of Sam. The increased release of latent heat would be consistent with the observed intensification of Sam just prior to landfall. The intensification at this stage might be attributed to the interaction of the circulation with coastal terrain, which enhanced low level convergence near the coastline.

Similar intensification just prior to landfall was also observed in York 1999 (Lee *et al.* 2000). The 3-km CAPPI maximum Doppler winds of York increased from 37.5 m/s at 16 UTC 15 September 2000 to the highest value of 50 m/s around 22 to 23 UTC (Figure 17). At the latter time, the eye of York was less than 40 kilometres from the coast.

The midget tropical depression in June 2000 formed just 35 km off the coast of Hong Kong was another example of intensification prior to landfall. Although the intensification in this case is thought to be due to horizontal vorticity advection as well as the enhancement of the conditional instability brought by the increase in the rate of change of equivalent potential temperature with height in the lower troposphere (Leung *et al.* to be published), the effect of land could also be part of the reason behind the intensification.

However, the intensity of tropical cyclones close to land might also be affected by other factors. The relative effect of each factor will determine whether a tropical cyclone will intensify prior to landfall. Prior to landfall, apart from interaction with coastal terrain, a tropical cyclone in late winter might also interact with the northeast monsoon which already exists in the coastal areas of south China. Typhoon Leo weakened rather rapidly on 1 and 2 May 1999 as it moved towards the coast of southern China then under the influence of the northeast monsoon (Lam *et al.* 2000). The satellite picture (Figure 18e) gives a good indication of dry air from the north being drawn into the western half of Leo. Convection was suppressed and the active convective area became more compact. At the same time, Leo experienced vertical shear as it moved into a region with strong westerlies in

the mid and upper levels and easterlies in the low levels. Figure 18f shows that the high cloud cover was sheared off by the upper westerly flow to the east of the TC centre. The low level centre was left exposed. In step with these changes, Leo weakened rapidly.

Intense Convection Over Land

In line with the intensification of tropical cyclones about to make landfall, convection could be enhanced over the northern part of the circulation where convection is inactive previously.

As mentioned above, intense convection was initiated in the northern side of Sam near the concave side of the inner band where convection was previously inactive particularly in the northwestern quadrant (Figure 16) due to enhanced low level convergence as a result of interaction with land.

In the case of the midget tropical depression, the modification of convection structure as revealed by radar reflectivity analysis (Figure 19) was quite revealing. Before landfall, the horizontal radar reflectivity in the vicinity of the tropical depression was distributed asymmetrically with heavier precipitation in its western sector. An organized spiral band was located in the vicinity of the centre at 1300 UTC before landfalling at Hong Kong. When the tropical depression moved closer to Hong Kong, the spiral band lost its banding signature and intense reflectivity developed over land in the northeastern sector of the tropical depression. The enhanced reflectivity or boundary layer convergence over land might have been related at least in part to topographic forcing.

Rainfall associated with enhanced southwesterlies after landfall

Sam 1999 is the wettest tropical cyclone ever to affect Hong Kong since records began in 1884. It brought more than 600 mm of rainfall to the territory during the period when Sam was first centred within 600 km of Hong Kong to 72 hours after its dissipation on 26 August.

Sam became slow-moving when it was close to the col region of the mid-level ridge later on 22 August after landfall. With its proximity to Hong Kong, the cyclonic flow to its south affected the territory and brought heavy rain on 23 August. A total of 235 mm of rain was recorded at HKO in 24 hours ending 12 UTC 23 August. During the period, Sam weakened over

land but remained a tropical cyclone. Hong Kong continued to experience heavy rain on 24 August. This conforms with the experience of forecasters in southern China, that is, enhanced southwesterlies in the wake of landfalling tropical cyclones often bring heavy rain.

The ORSM was basically successful in forecasting the heavy rain on 23 and 24 August (Lam 2000). In particular, the 24-hour rainfall forecast by ORSM for Hong Kong is around 190 mm and is close to the observed value. From the model 850 hPa relative vorticity field, a mesoscale positive vorticity maximum of around 60 km in size was tracked by the model run. It was initially located off the coast of western Guangdong about 170 km southwest of Hong Kong near the periphery of the low level jet at 03 hour forecast. This vorticity maximum area, which was thought to be associated with a mesoscale disturbance, then headed towards Hong Kong. Its position matched well with the rain echoes observed by radar. The time when this positive vorticity maximum passed Hong Kong coincided with the heaviest downpour in the early morning of 24 August. The exceptionally heavy rain over the region ceased when this positive vorticity maximum left the south China coast. Therefore, to forecast heavy rain in the southwesterlies in the wake of landfalling tropical cyclones requires the ability to detect and predict mesoscale features in the background flow.

Conclusions

Studies on tropical cyclones making landfall in the vicinity of Hong Kong were carried out using data from a network of AWSs, wind profilers and Doppler radars, more conventionally satellite data as well as by means of numerical modelling. With the benefit of the Operational Regional Spectral Model, the structure, intensity and track of these tropical cyclones were studied. Results obtained so far have added insight into the structure of tropical cyclones and their associated weather impacts. It is hoped that these observations would eventually translate into the better forecasting of tropical cyclones.

Acknowledgement

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Figure 1a. Track of Typhoon Victor over Hong Kong on 2 August 1997.



Figure 1b. Tracks of the four tropical cyclones, Maggie, Sam, York and Cam, when they crossed Hong Kong. Adapted from Ginn *et al.* (pers. comm.)



Figure 1c. Track of the midget tropical depression over Hong Kong on 18 June 2000.

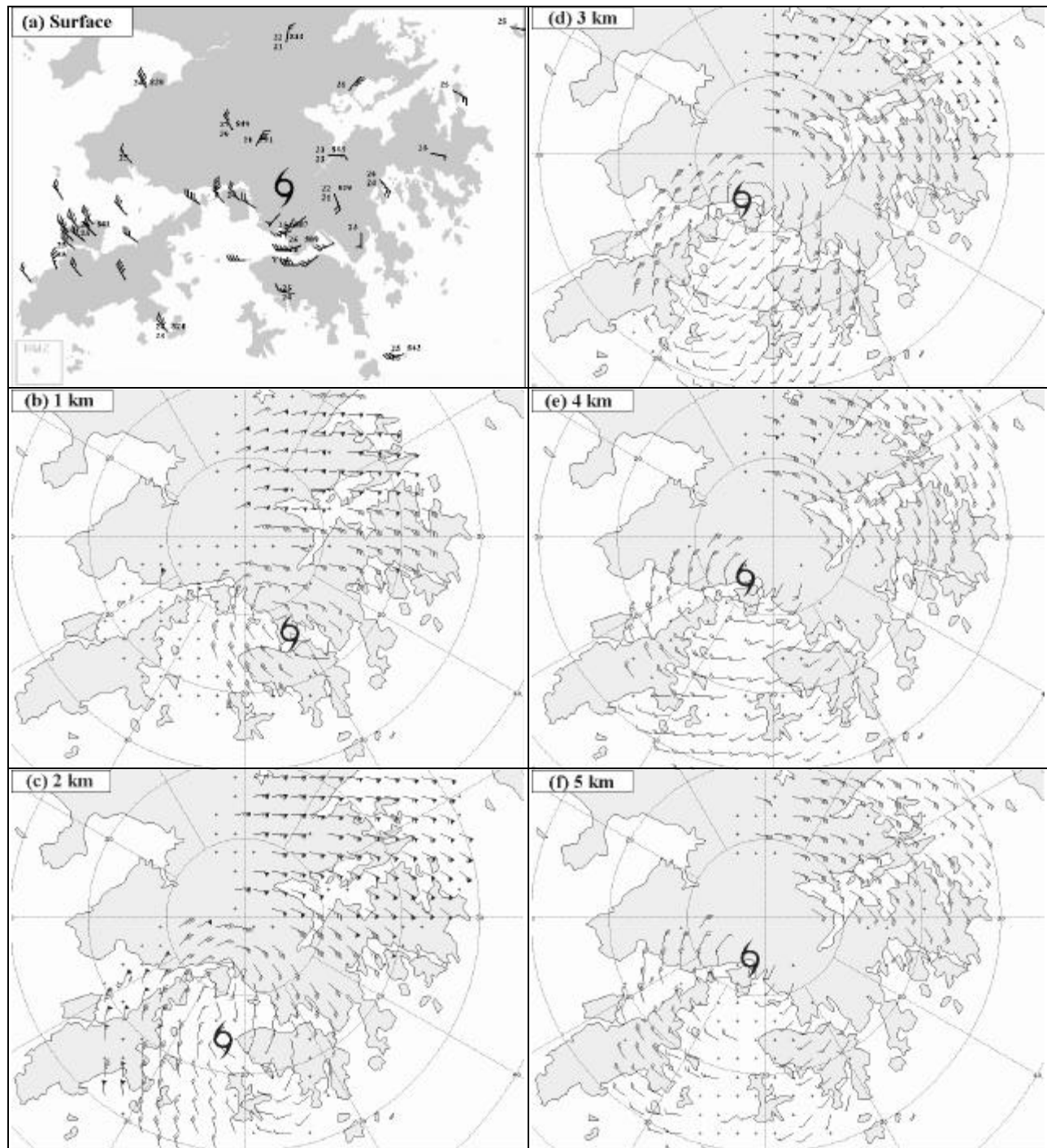


Figure. 2 (a) Surface observations; (b) to (f) Dual-Doppler winds at 1 to 5 km heights AMSL respectively at 2000 UTC 6 June 1999. The centre positions of Maggie are marked with the tropical cyclone symbol 6. Adapted from Ginn *et al.* (pers. comm.)

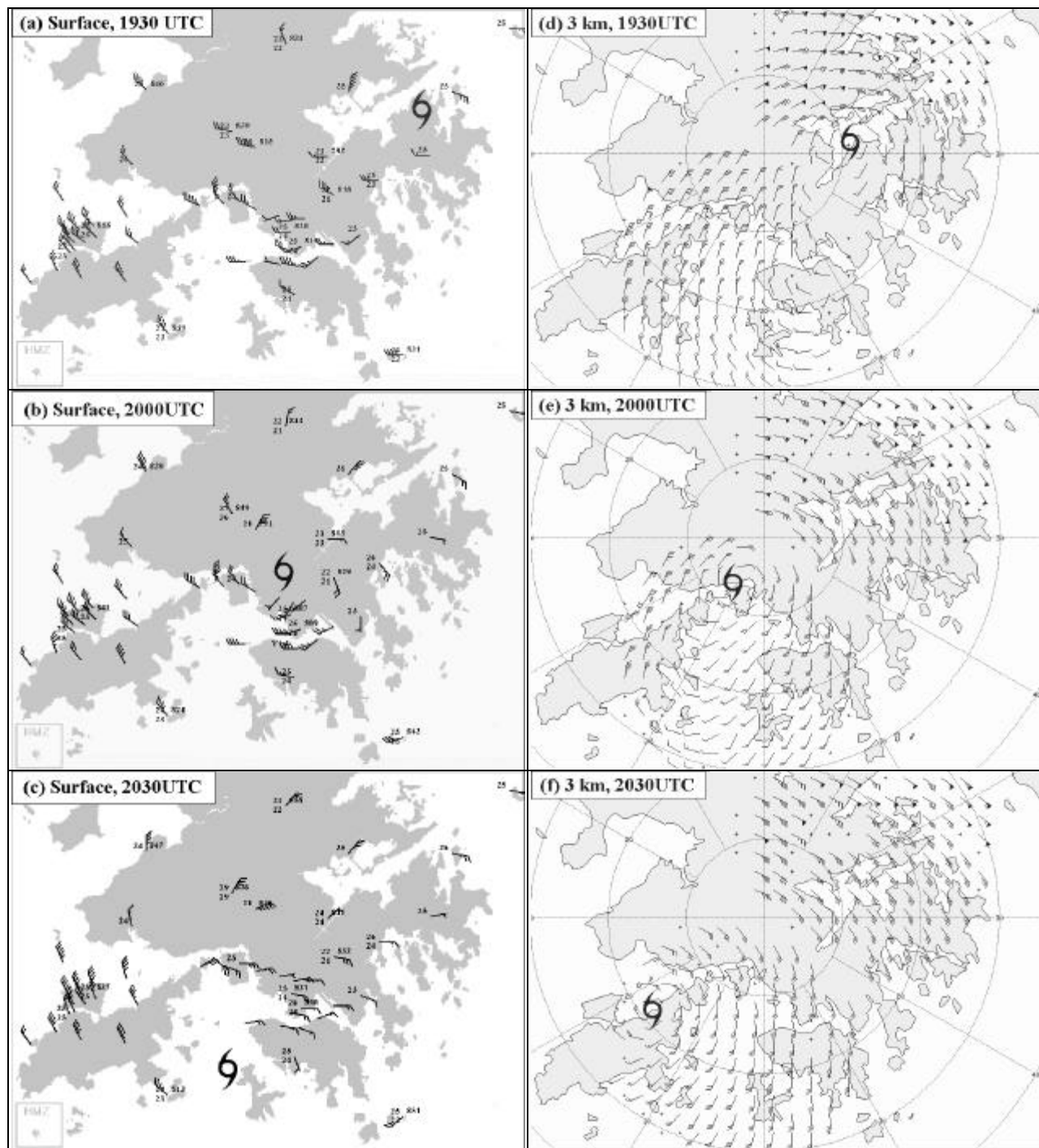


Figure. 3 (a) to (c) Surface observations; (d) to (f) Dual-Doppler winds at 3 km heights AMSL respectively from 1930 to 2030 UTC 6 June 1999. The centre positions of Maggie are marked with the tropical cyclone symbol 9. Adapted from Ginn *et al.* (pers. comm.)

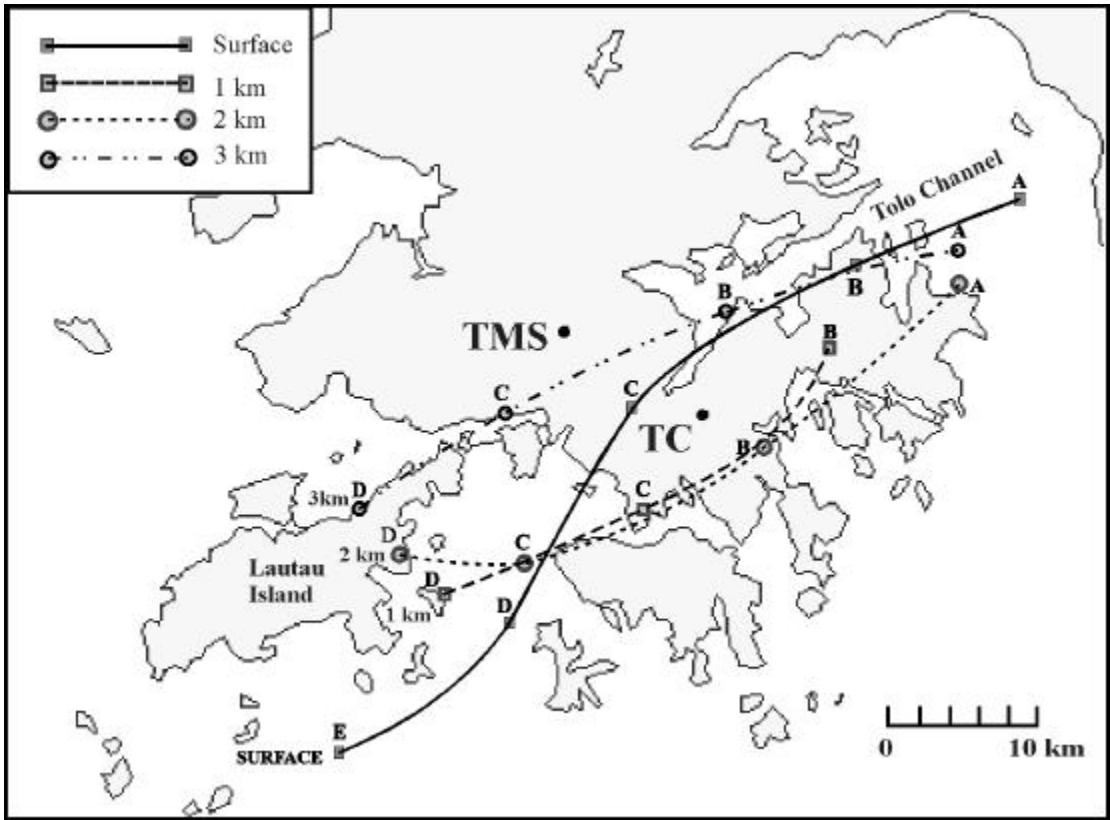


Figure. 4a Tracks of Maggie at 1, 2 and 3 km heights as estimated from the dual-Doppler winds, as well as the surface track as determined from AWS observations from 1900 to 2100 UTC, 6 June 1999. A to E marked on each track denote the time 1900, 1930, 2000, 2030 and 2100 UTC respectively. The 1-km 'A' position could not be determined. (TMS = Tai Mo Shan, TC = Tate's Cairn) Adapted from Ginn *et al.* (pers. comm.)

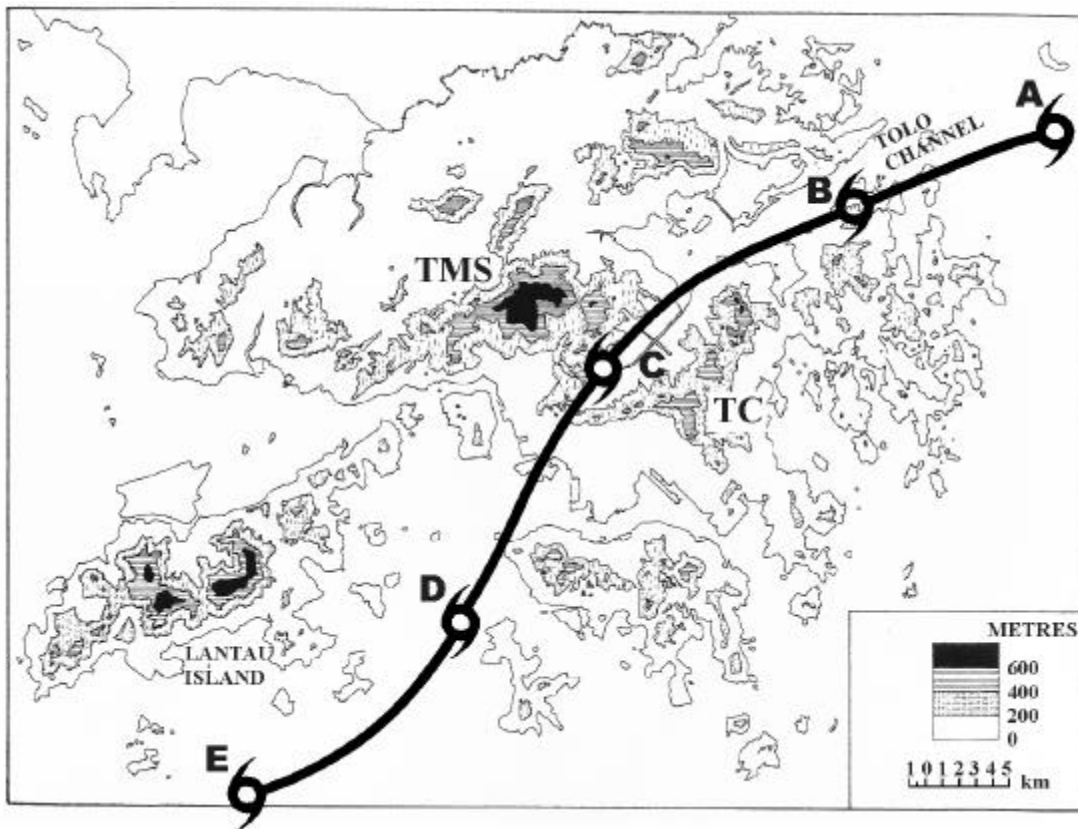


Figure. 4b Track of Maggie at the surface relative to the mountain ranges in Hong Kong. A to E marked on the track denote the time 1900, 1930, 2000, 2030 and 2100 UTC on 6 June 1999 respectively. (TMS = Tai Mo Shan, TC = Tate's Cairn) Adapted from Ginn *et al.* (pers. comm.)

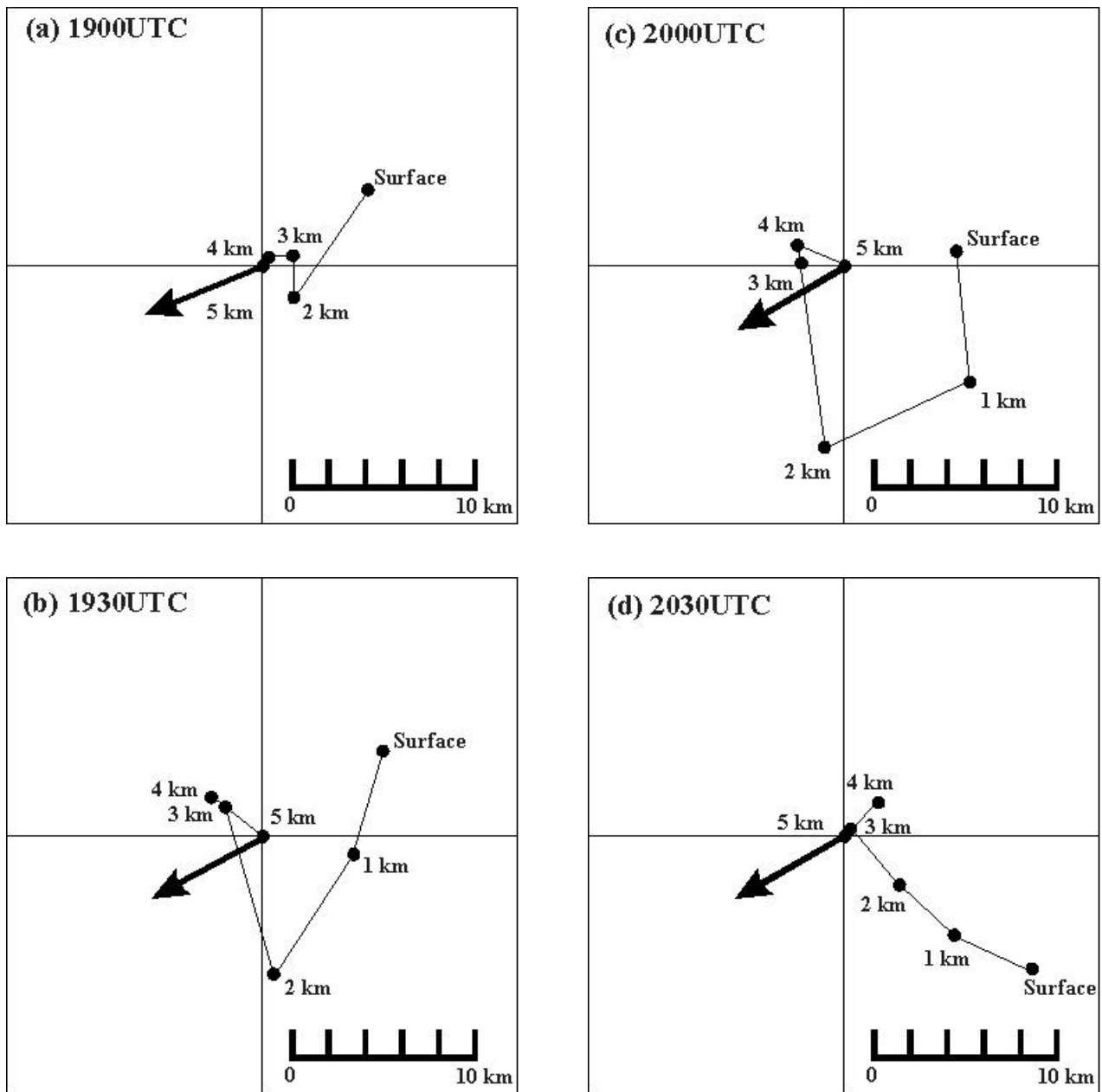


Figure 5 Positions of Maggie's centre at the surface and 1 to 4 km heights from 1900 to 2030 UTC relative to the centre position at 5 km. The centre at 1 km height at 1900 UTC could not be determined. The arrow shows the direction of movement of Maggie at 5 km level. Adapted from Ginn *et al.* (pers. comm.)

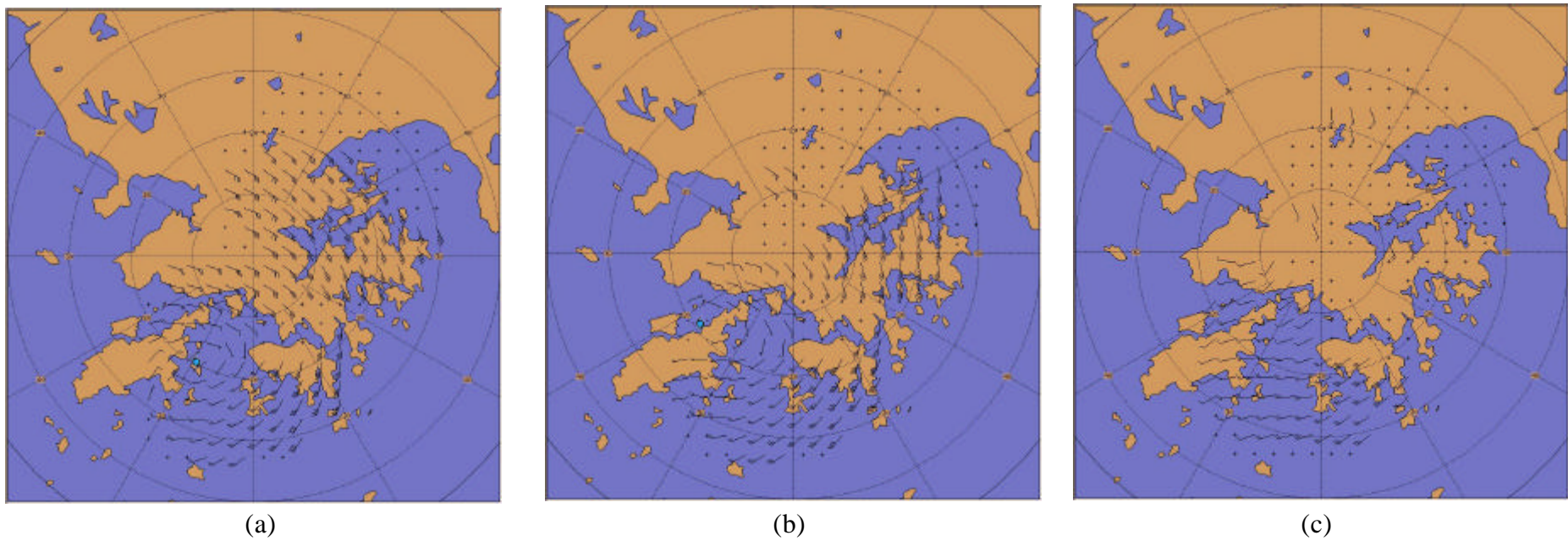
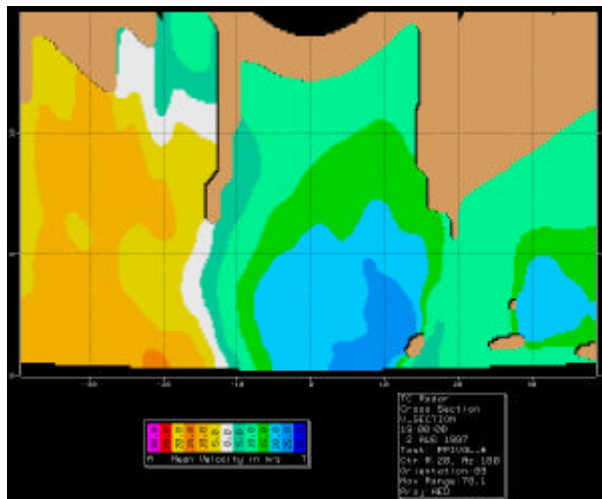
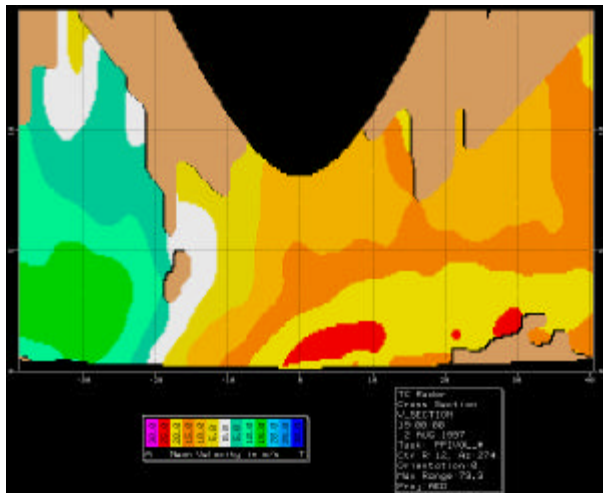


Figure 6 Dual-Doppler winds at (a) 1.5 km, (b) 2.5 km and (c) 5.0 km heights AMSL at 1330 UTC 18 June 2000. The centre of the tropical depression at 5.0 km is just off the left hand margin of Figure 6(c). Adapted from Leung *et al.* (pers. comm.)

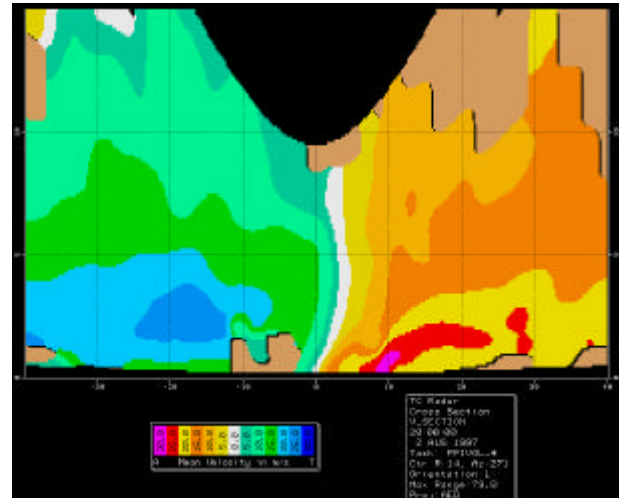


(a) 11:00 UTC

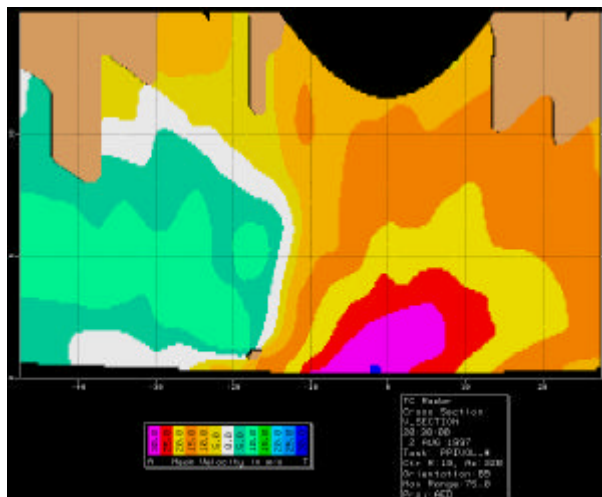


(c) 11:00 UTC

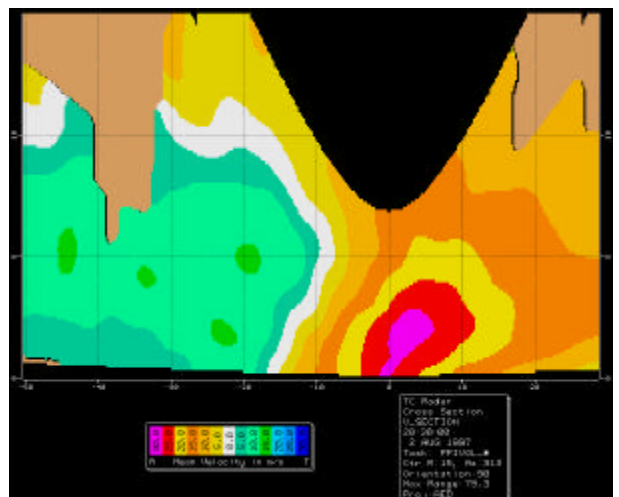
12:00UTC E-W X-section
not available



(d) 12:00 UTC

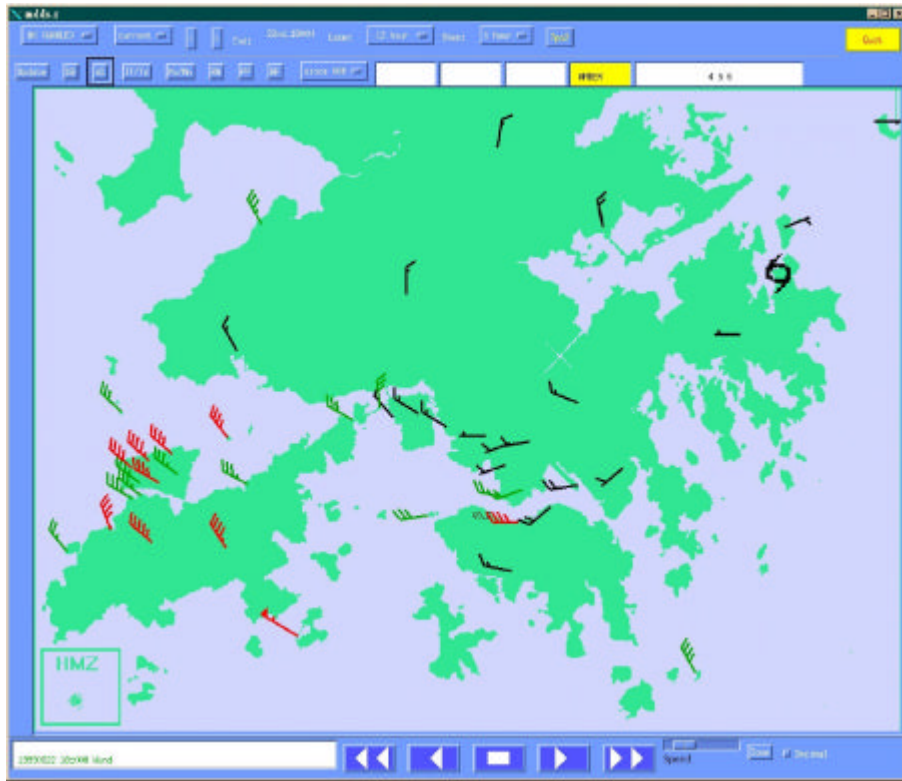


(b) 12:30 UTC

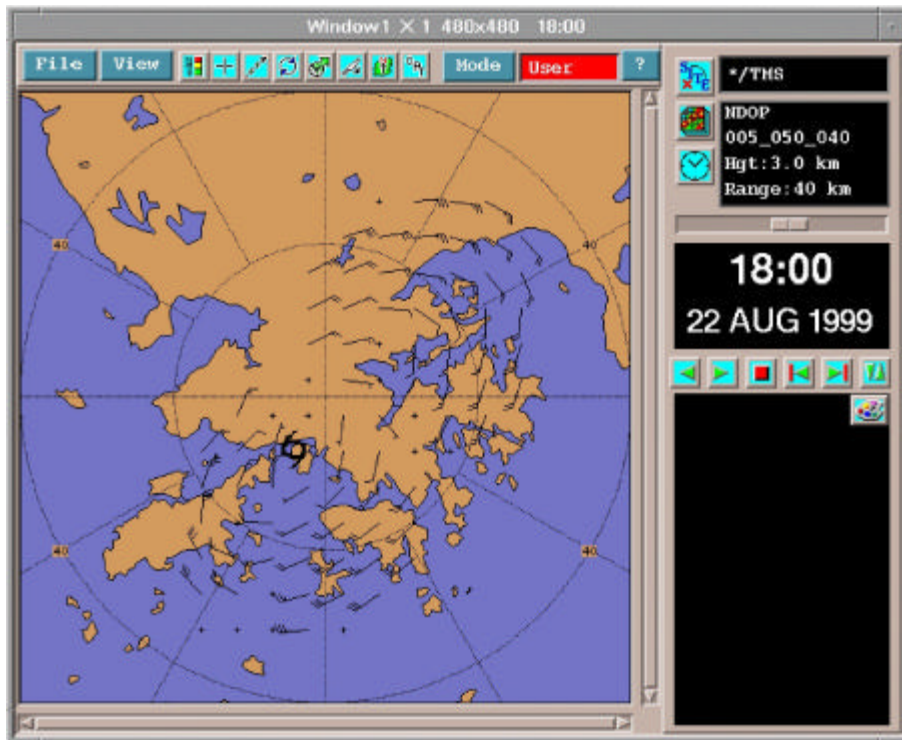


(e) 12:30 UTC

Figure 7 Vertical cross-sections of Doppler wind field at 11:00, 12:00 and 12:30 UTC 2 August 1997. (a) and (b) are cross-sections along the east(right)-west(left) direction. (c), (d) and (e) are cross-sections along the north(right)-south(left) direction. Adapted from Li *et al.* (1998).

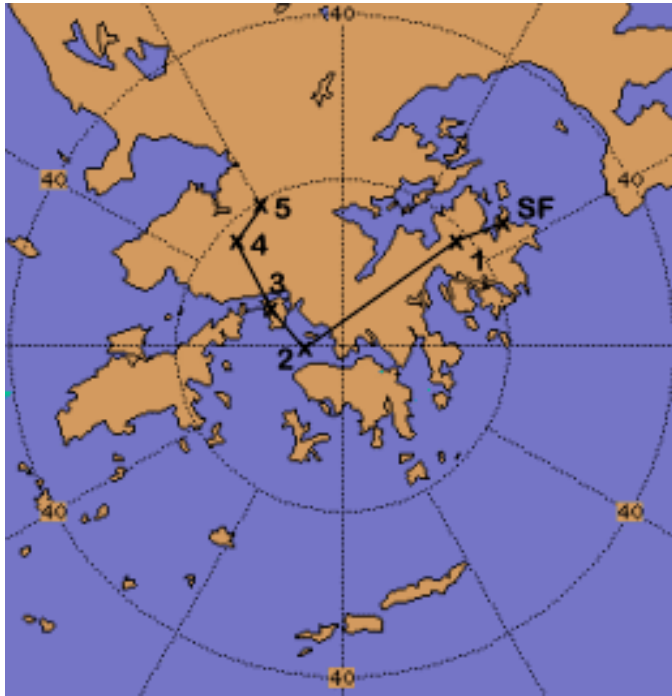


(a)

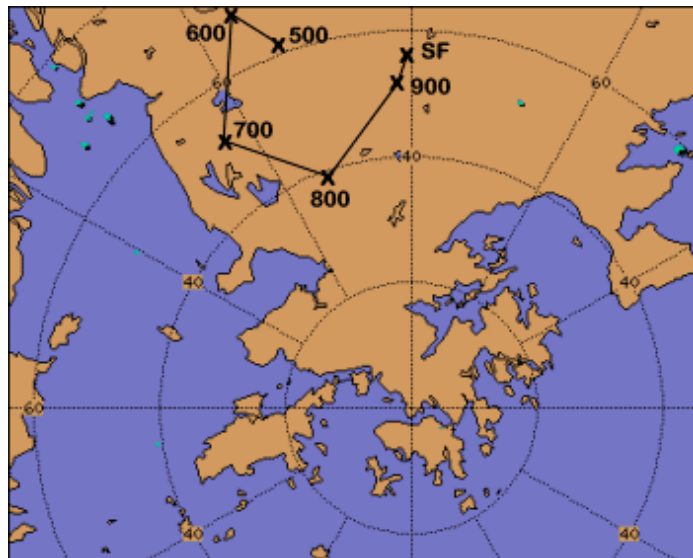


(b)

Figure.8 (a) Surface observations and (b) dual-Doppler winds at 3 km AMSL near 10 UTC 22 August 1999 when Sam made landfall over the eastern part of Hong Kong. Adapted from Lam (2000).



(a)



(b)

Figure 9 Positions of the center of Sam's circulation. (a) Based on radar data at different levels near 10 UTC 22 August 1999. (b) Predicted by the model at 09 hour forecast based on 00 UTC analysis of 22 August 1999. Symbol SF stands for surface and the numbers are in units of km and hPa for (a) and (b) respectively. Adapted from Lam (2000).

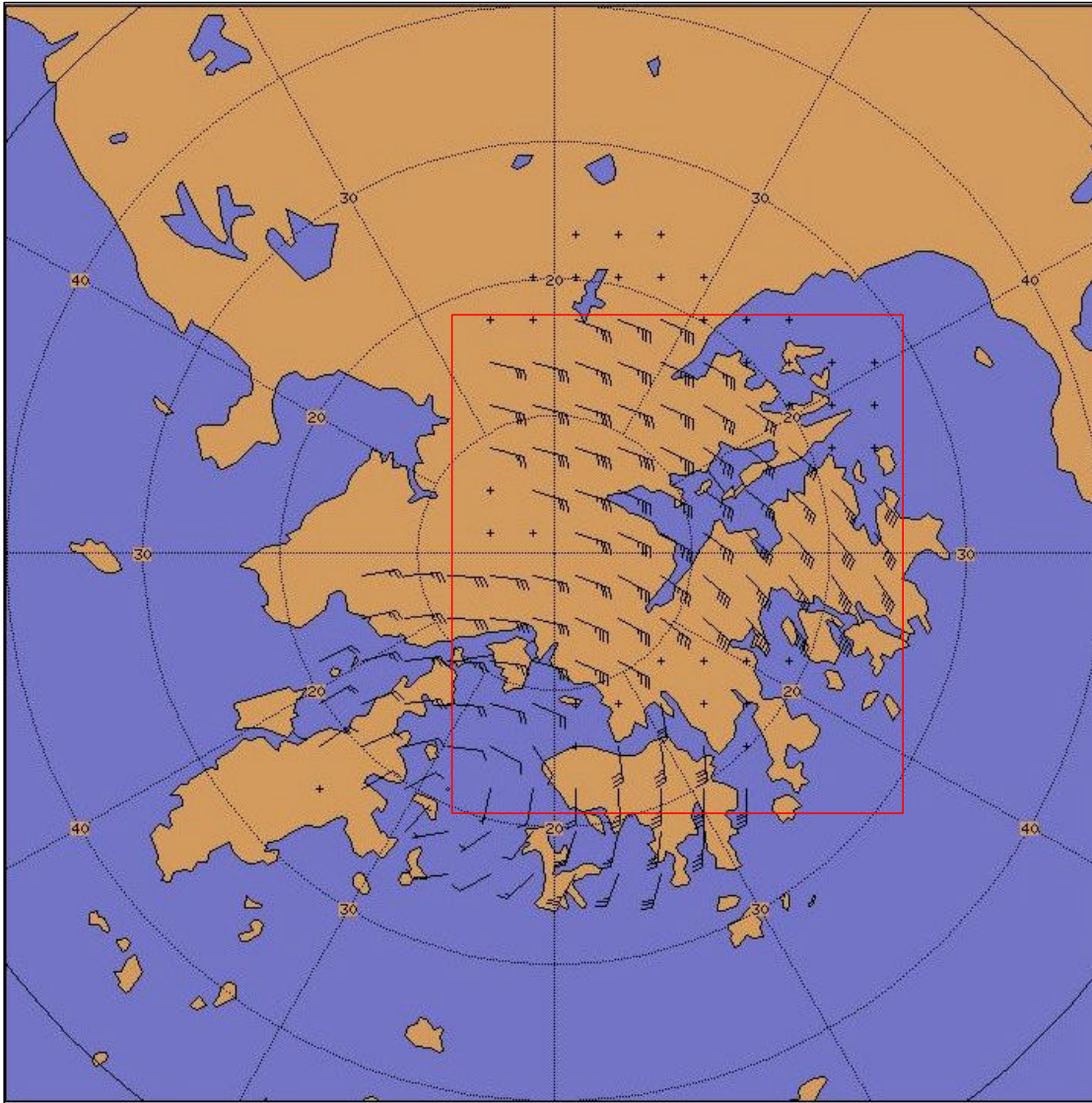


Figure 10. Dual-Doppler winds at 1 km AMSL at 1330 UTC 18 June 2000. The red box delineates the northeastern section where averaging is taken to consider the relationship between wind speed and radial distance from the centre of the tropical depression. Adapted from Leung *et al.* (pers. comm.)

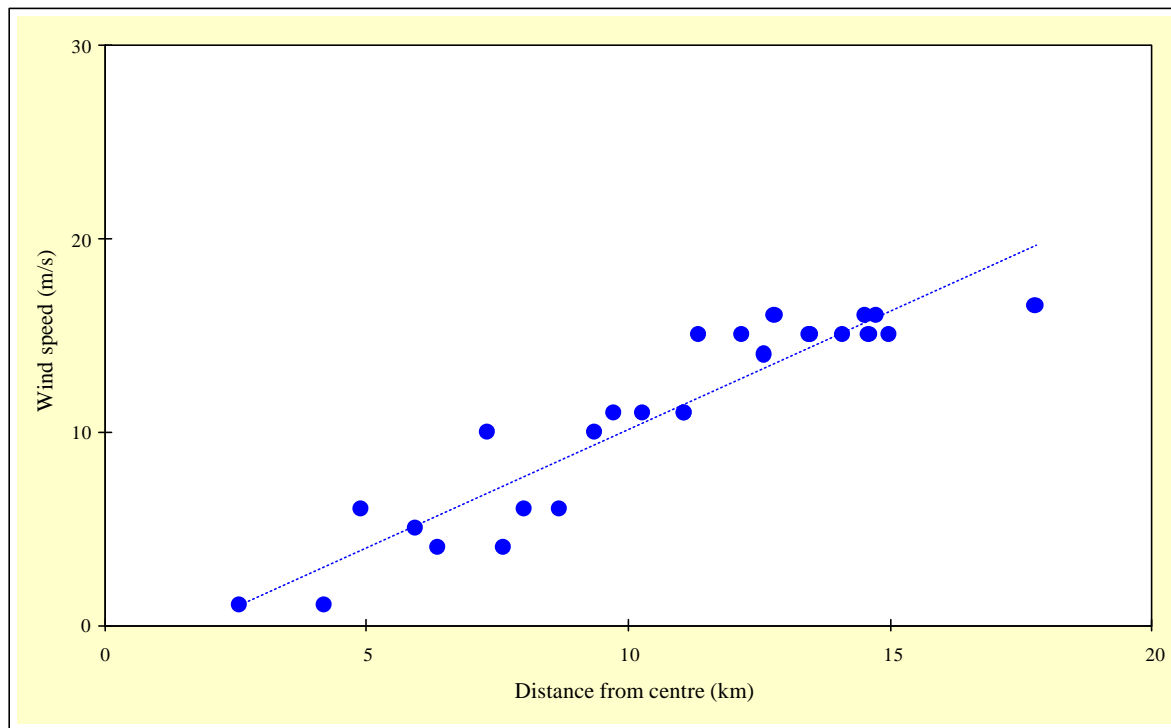


Figure 11. Dual-Doppler wind profile averaged over the northeastern sector (see Figure 16). Linear relationship between wind speed and distance from centre is suggested. Adapted from Leung *et al.* (pers. comm.)

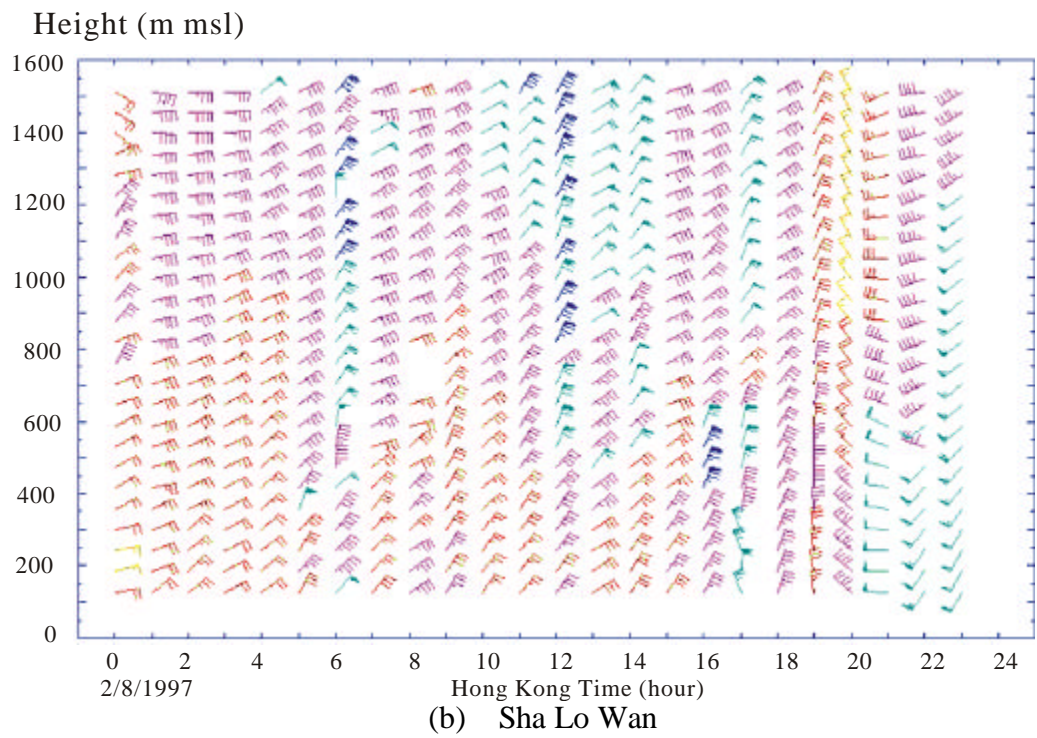
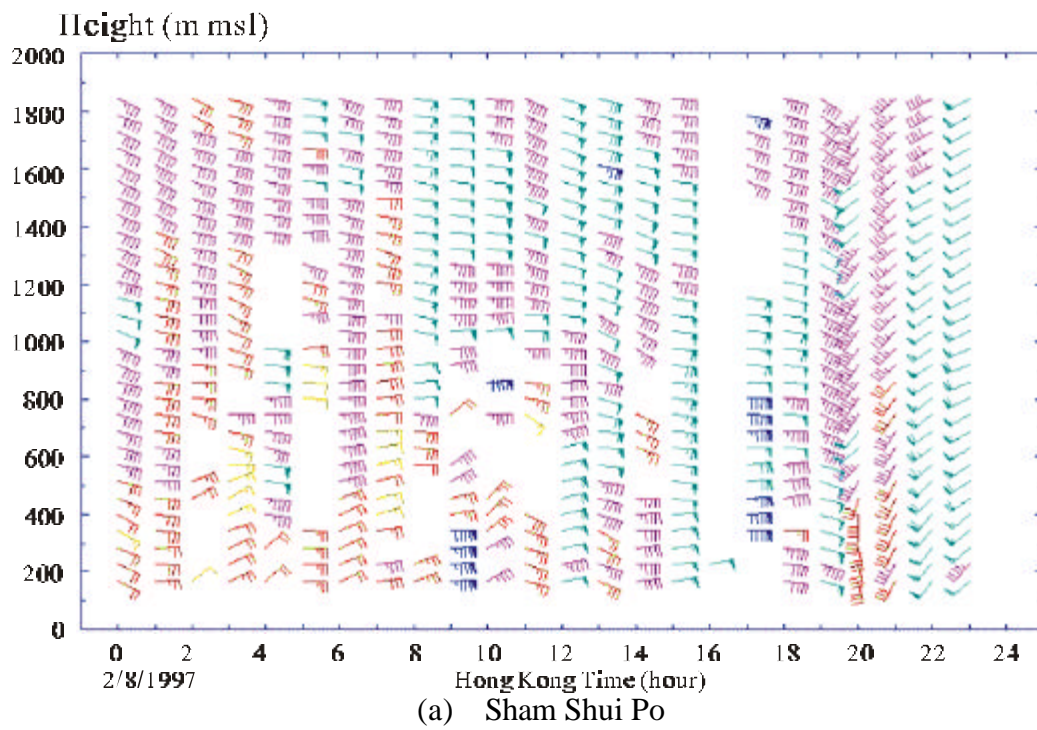


Figure 12 Wind profiler data for the period 16 UTC 2 August 1997 to 16 UTC 3 August 1997 during the passage of Victor. Adapted from Li *et al.* (1998).

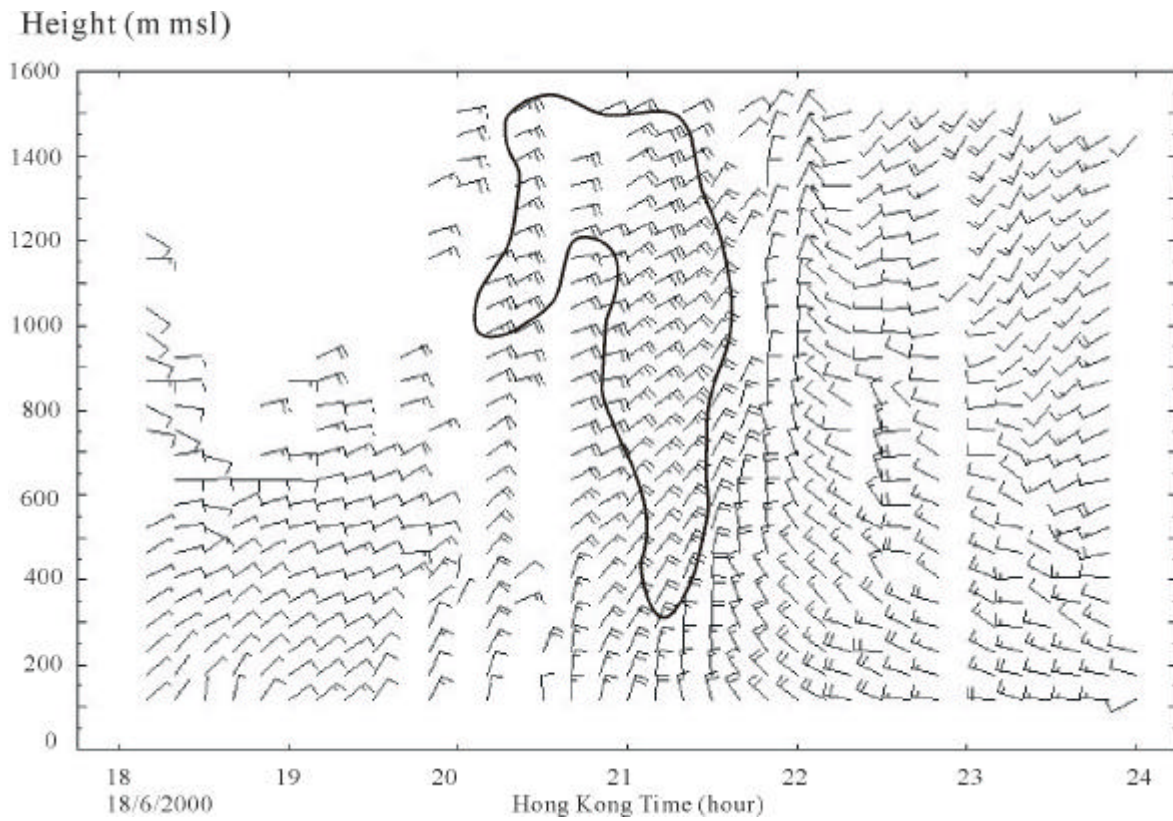


Figure 13 Wind profiler data for the period 08 to 16 UTC 18 June 2000 at 10-minute intervals Sha Lo Wan stations in Hong Kong. The solid line is the isotach of 10 m/s. Adapted from Leung *et al.* (pers. comm.)

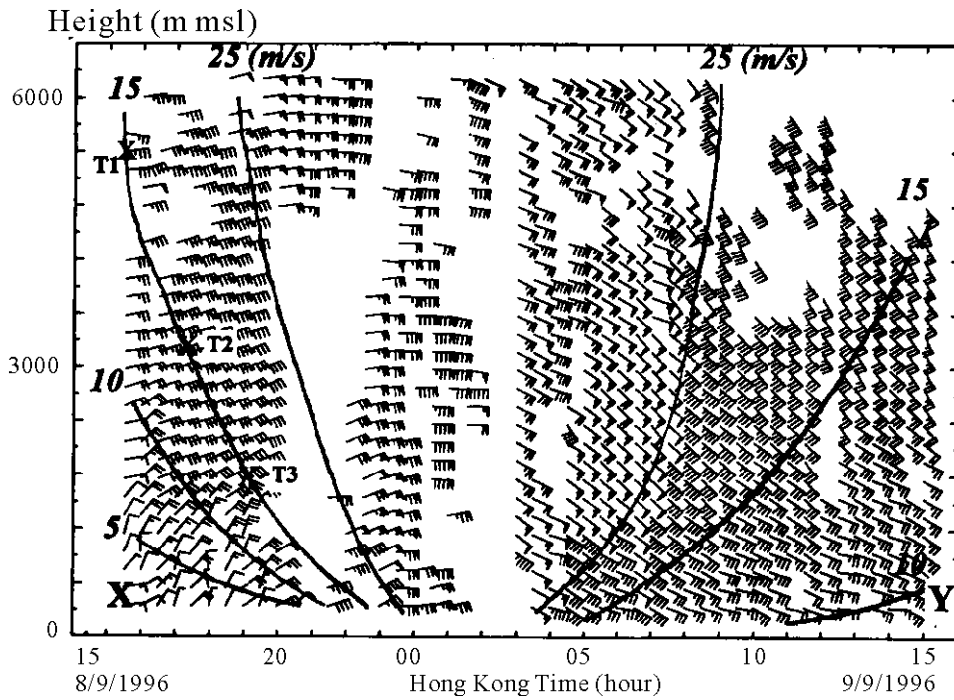


Figure 14 Wind profiler data for the period 07UTC 8 September 1996 - 07 UTC 9 September 1996 at 30-minute intervals during the passage of Typhoon Sally across the northern part of the South China Sea. Adapted from Yeung (1998).

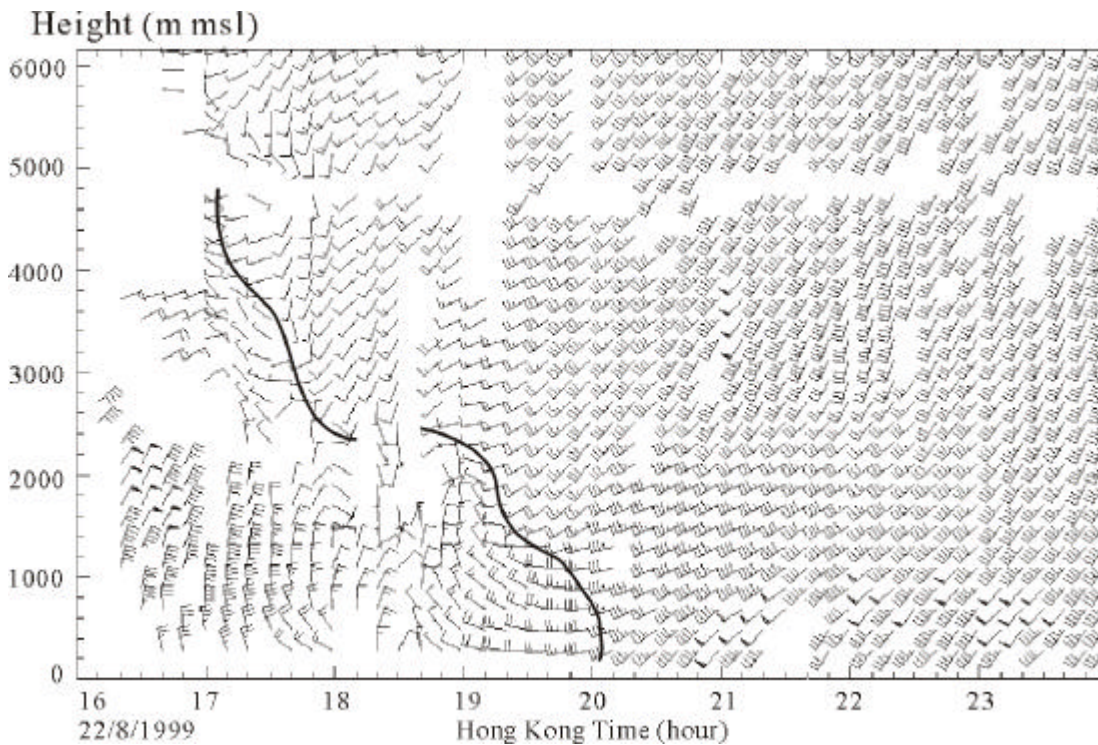


Figure 15 Wind profiler data at Sham Shui Po station in Hong Kong for the period 08 - 16 UTC 22 August 1999 (16-24H Hong Kong Time) at 10-minute intervals. The solid line delineates northwesterly winds from southwesterlies. Adapted from Lam (2000).

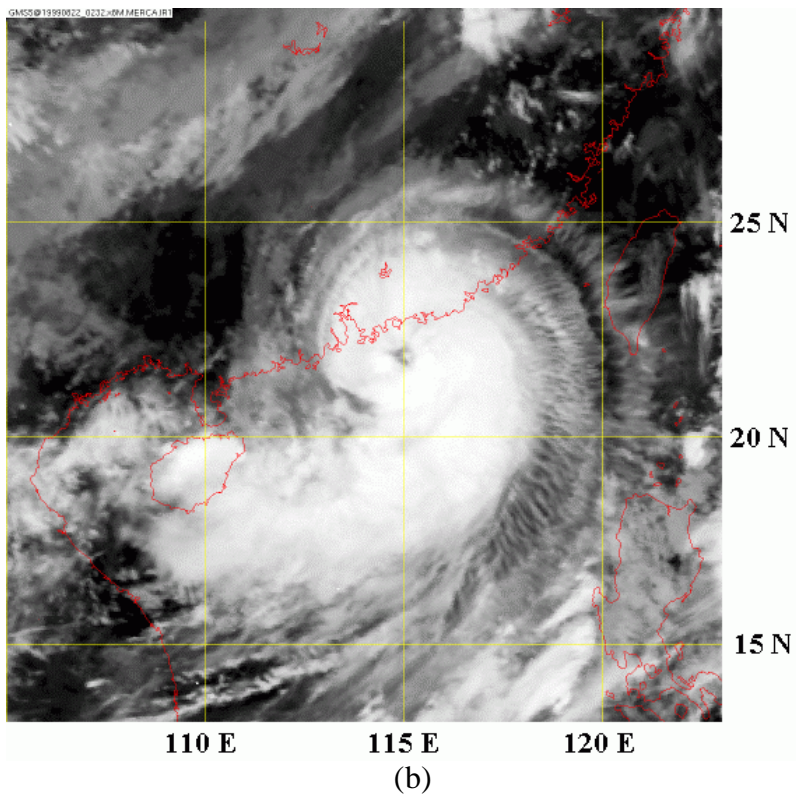
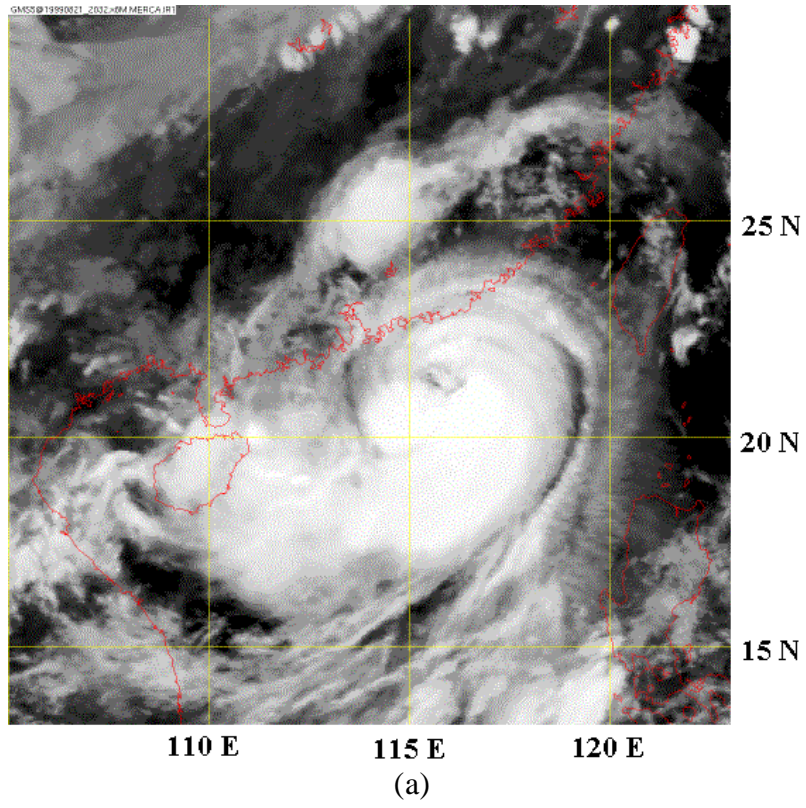


Figure16 IR satellite imageries for (a) 21 UTC 21 August and (b) 03 UTC 22 August 1999. Adapted from Lam(2000).

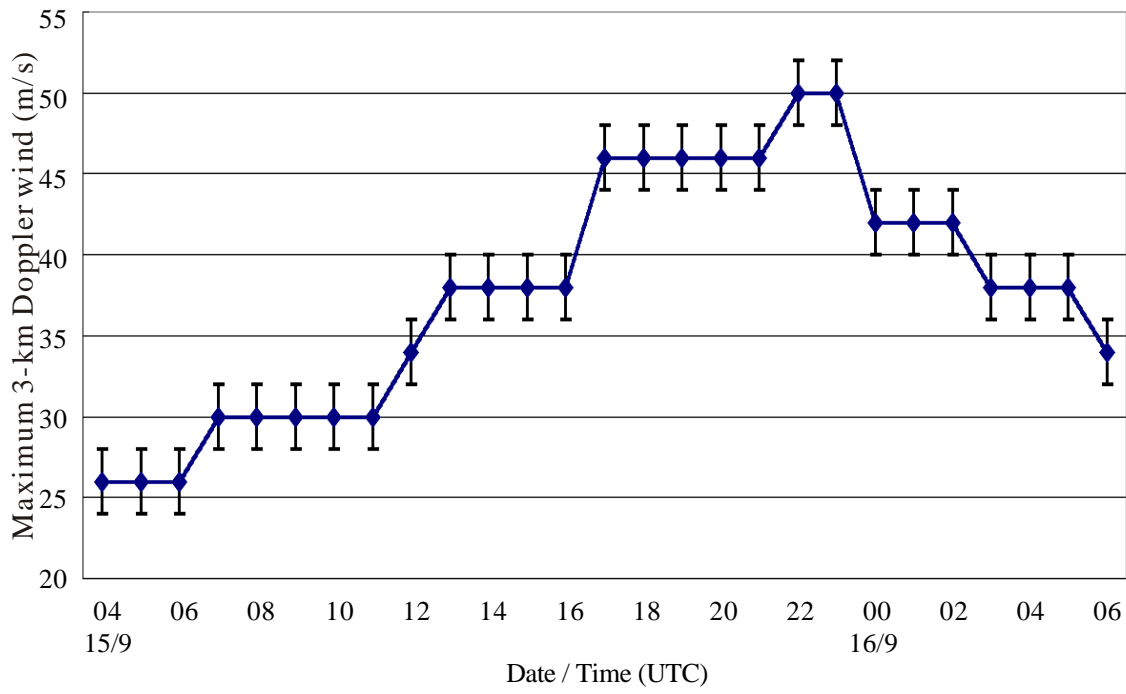


Figure 17 Maximum 3-km Doppler wind of York on 15 & 16 September 1999. Adapted from Lee *et al.* (2000).

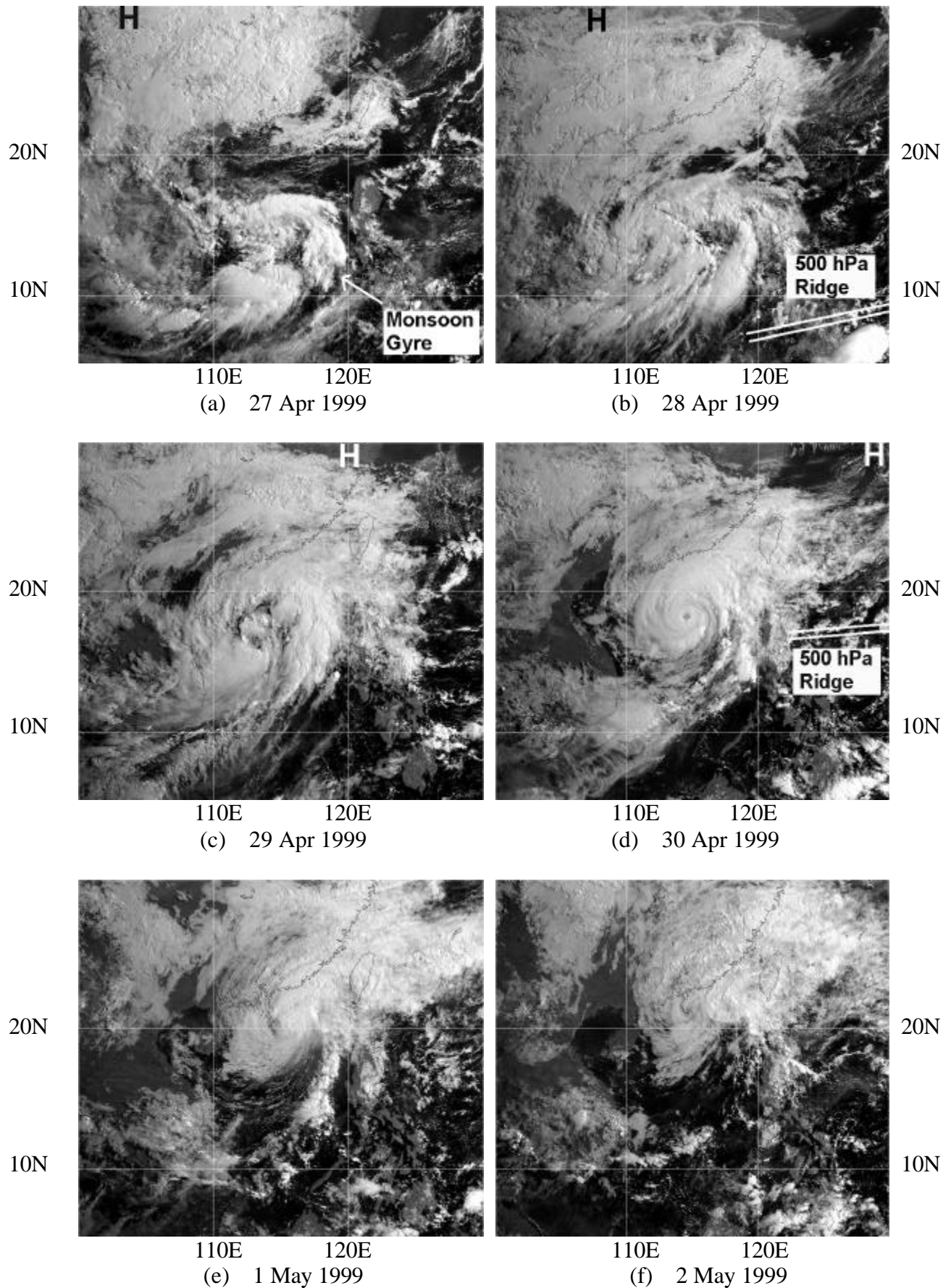
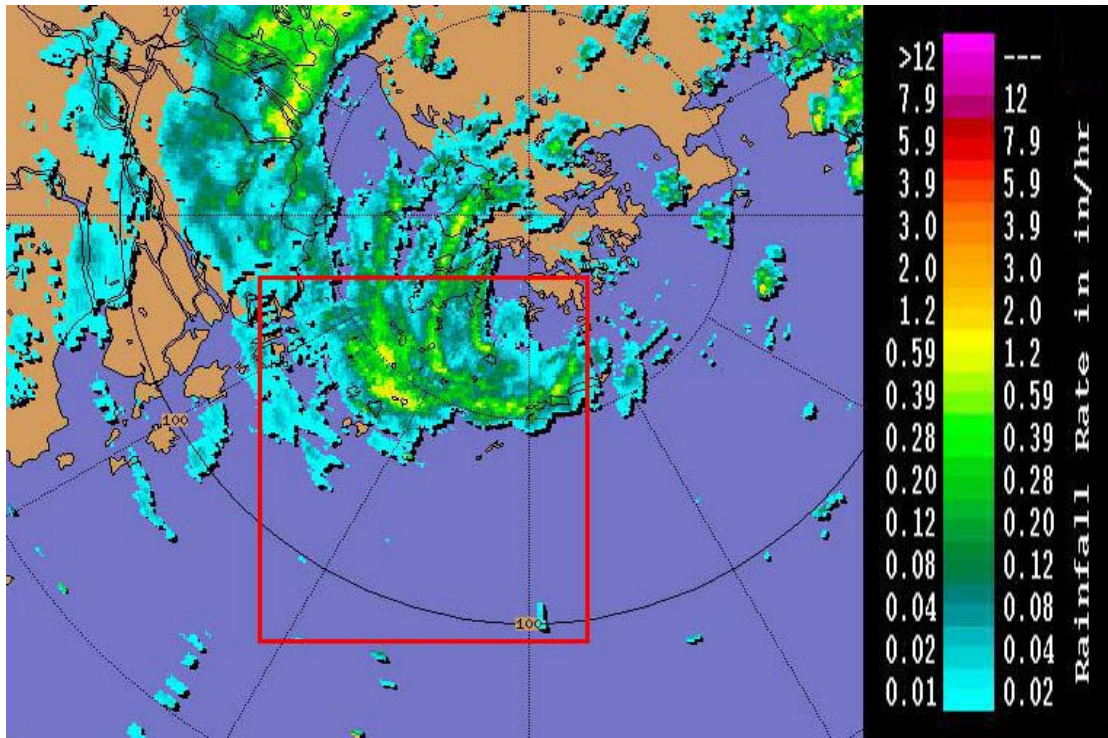
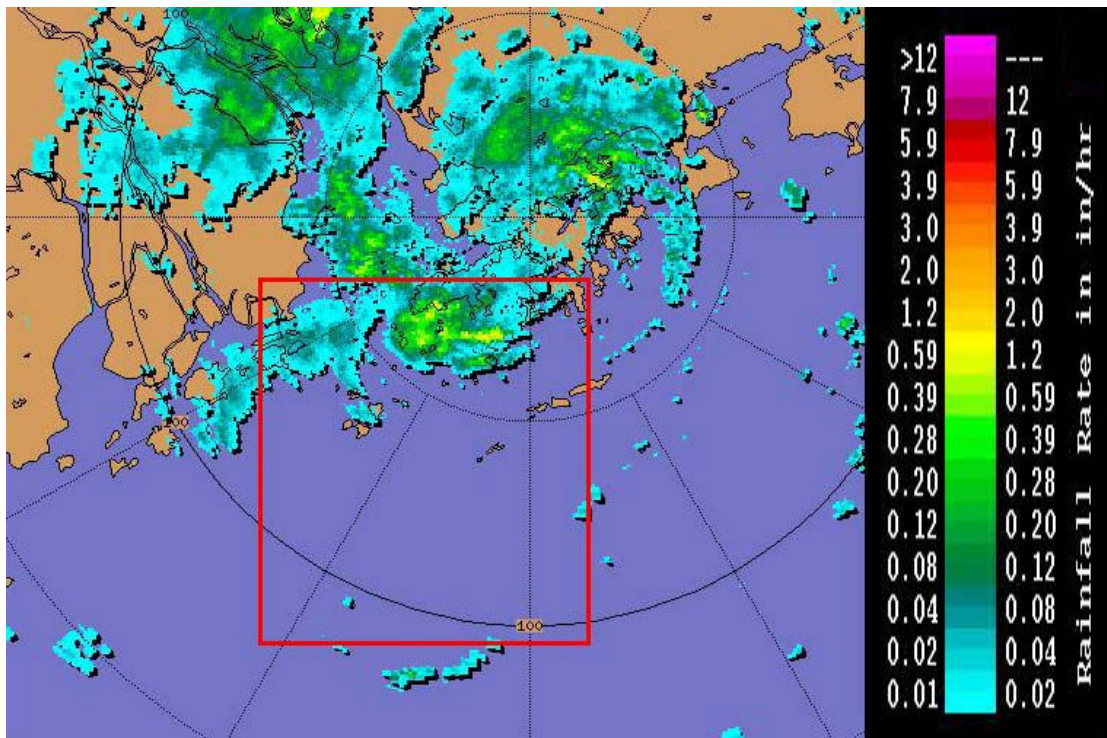


Figure 18. IR satellite imageries from 00 UTC 27 April to 2 May 1999 at 24-hour intervals. Adapted from Lam *et al.* (pers. comm.)



(a)



(b)

Figure 19 2-km CAPPI radar reflectivity. (a) At 1300 UTC before landfall of the midlevel tropical depression and (b) at 1400 UTC 18 June 2000 after landfall. Adapted from Leung *et al.* (pers. comm.)