ROYAL OBSERVATORY, HONG KONG

Technical Note No. 87

IDENTIFICATION OF GUST FRONT CASES IN HONG KONG USING DATA FROM AUTOMATIC WEATHER STATION OF THE ROYAL OBSERVATORY

by

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Abstract

The objectives of this study are to identify gust fronts which occurred in Hong Kong over a period of about a year and to describe their characteristics. Data such as wind, pressure and temperature recorded by a network of automatic weather stations were employed in the analysis. An algorithm for analysis was developed and criteria for the identification of gust front cases were set. Characteristics of the identified gust fronts were also discussed.

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1. Introduction

A gust front is the leading edge of an outward-moving airflow which is induced by the evaporatively cooled downdraft from a thunderstorm. As the cool, dense outflow spreads out into the relatively warm and less dense environmental air, horizontal convergence is produced at the outflow edge. Properties of gust front and its associated flows have been studied through analyses of observations (Charba 1974, Goff 1976, Wakimoto 1982, Mahoney 1988) and numerical modeling studies (Mitchell and Hovermale 1977). However, the gust front was rarely explicitly defined in the literature. In a paper from Wakimoto (1982), a gust front was defined as "the leading edge of a mesoscale pressure dome followed by a surge of gusty winds on or near the ground. A gust front is often associated with a pressure jump, a temperature drop, and/or heavy precipitation". Figure 1 shows the schematic structure of a gust front.

Winds behind the gust front are often nearly perpendicular to the front. During the passage of a gust front, an observer on the ground typically experiences a sequence of meteorological events, namely pressure rise, wind shift, increase in wind speed, temperature drop and sometimes followed by rainfall.

A gust front may last several hours and propagate tens of kilometers from the parent storm, and commonly lasts long after the parent storm has dissipated. Typical gust fronts are more than 12 km in length with propagation speeds ranging from 5 to 20 ms^{-1} (Uyeda and Zrnic 1985). A gust front system is usually 0.5 to 2 km deep, depending on the strength and distance from the downdraft source.

Gust fronts are distinguished from cold fronts which are typically much deeper, more long-lived and have broader horizontal extent. They are also distinguished from sea breeze fronts which are weaker and not directly coupled to upper air dynamics.

2. Analysis Method

Taking a typical speed of about 10 ms^{-1}, a gust front would cross the Hong Kong territory in about one to two hours and bring sudden changes in meteorological variables such as wind direction, wind speed, pressure and temperature with a time scale of about ten minutes at any particular point. In view of this time scale, one-minute data from a network of twenty nine automatic weather stations (AWS) operated by the Royal Observatory were employed for analysis. Figure 2 shows the distribution of the AWSs. The occurrence of gust fronts in Hong Kong during a period of more than one year was studied, no matter whether it was fine or bad weather, for the sake of completeness.

The process of identification of a gust front was divided into stages. During the first round, possible gust front events were short-listed under a set of criteria with the aid of computer programs. The algorithm and criteria employed will be discussed in the next section.

In the second round, in order to have a clearer picture of each event, distribution of wind, temperature and pressure of each selected event were plotted on maps at ten or fifteen-minute intervals. The evolution of meteorological conditions of each event was analysed carefully. The existence of a gust front was subjectively determined and its location and movement were derived from detailed analysis of various meteorological parameters. Radar pictures were also studied to provide more evidence to help with the identification.

To supplement the spatial analysis, anemographs were also studied for the identification of gust front cases. They showed wind data in a continuous manner rather than discrete one-minute average as in the case of AWS data. However, it took a lot of time to study the roll charts of one year for so many stations. Nevertheless, the study of the anemographs gave further insight into the time scale and magnitude of gusts which facilitated the setting of criteria in this study.

3. Algorithm

The algorithm employed was based on the fact that a gust front brings abrupt changes in wind direction, increases in wind speed, pressure rise and temperature drop as it passes a station. The magnitudes of these changes have been discussed by others (Wakimoto 1982, Mahoney 1988) but their findings varied from case to case and might not be applicable to the situation in Hong Kong. Since there was no published study on the quantitative description of gust front cases in Hong Kong, it was necessary to determine the criteria in this study.

If the criteria were too loose, many false events would be reported, even on fine days. On the other hand, if the criteria were too stringent, some genuine gust front cases might be missed. Several fine days and several thunderstorm occasions were selected for testing of the algorithm and tuning of the criteria.

After a number of experiments, the following criteria for the first round of screening were selected:

For at least two stations, if each experiences:

(a) (i) a change in wind direction of 90° or more, with wind speed not less than 8 ms^{-1}
or
(ii) an increase in wind speed of 8 ms^{-1} or more

AND

(b) (i) a pressure rise of 0.8 hPa or more
or
(ii) a temperature drop of 2 °C or more

within a period of 10 minutes and the change lasts for at least 3 minutes, the event will be considered as a possible gust front case.

Since some of the gust front occasions might not be accompanied by both a pressure rise and a temperature drop, the criteria did not require both of them to occur. The requirement for sustained changes over at least three minutes should filter out those sudden and transient changes which might be due to disturbance such as turbulence. If the above criteria were met by only one station within an hour, the event would be considered as a false event since the length of a gust front should not be so short in length that it triggered off changes at only one station.

4. Results

One-minute AWS data from 1 May 1993 to 31 May 1994 were first analysed using the algorithm discussed in section 4. Twenty one events were short-listed in the first round. Table 1 shows when these events occurred.

Distributions of wind, temperature and pressure over the territory of all events were plotted for detailed analysis. Regions with velocity convergence and contrast in pressure or temperature were searched. If the length of the region was more than 10 km and the weather condition favoured the formation of gust front, the event would be identified as a gust front case. The possible existence of velocity convergence region owing to land-sea breeze and the decrease of temperature owing to diurnal variation was borne in mind during the selection process. Eventually, nine out of the twenty one events were identified as gust front cases. The remaining twelve events were non-gust front events such as land-sea breezes or turbulence. The characteristics of the nine cases are summarized in Table 2. Appendix I gives a snapshot of the gust front, daily weather map, description of synoptic background and selected meteorological observations on each of those days.

As an example, Figure 3 shows the evolution of a gust front in case 940503 (the number representing the year, month and day of the event). The estimated location of the gust front and its direction of movement at 15-minute intervals were plotted. The gust front was located such that stations with almost opposite wind directions lay on different sides of the front. It should be noted that this line of convergence in velocity was in general not exactly the same as the line determined by considering contrast in pressure or temperature.

More than half of the cases happened around noon. They mainly occurred in May, June and September, that is, the transition months in Hong Kong with frequent thunderstorms. Synoptic charts of all cases were reviewed. No signs of cold front were observed for all the gust front cases. A trough of low pressure was found near Guangdong in five cases (all May cases and the 930604 case). Tropical disturbances were observed in the South China Sea for the two cases in September. For case 930616, the south China coast was under the influence of the southwest monsoon. Heavy rain fell over Hong Kong with a daily rainfall over 250 mm recorded at Sai Kung. This rainstorm was discussed by others (Lam 1994, Song 1994) in synoptic, mesoscale and nowcasting aspects. For case 940319, a rain band associated with one upper-air trough affected the territory after the arrival of a northerly replenishment.

No case was found during late-autumn and winter although there were cold fronts crossing Hong Kong during this period. This might be because the changes in meteorological variables accompanying cold fronts were not as sharp as those required by the criteria.

Except case 940517, observers at RO and King's Park recorded thunderstorms or spherics during the passage of the gust front. Radar pictures showed that rain echoes moved across Hong Kong in all cases. Snapshots of radar are shown in

Appendix I. Direction of movement and time of arrival of rain echoes were close to those of gust fronts identified from AWS data.

For all cases, wind speed, wind direction, pressure and temperature were fairly uniform over the territory before the gust front arrived. The arrival of the gust front brought wind shift, pressure rise and temperature drop to the first station it met. The front moved in a direction which was roughly the same as that of the surface wind behind it.

The propagation speed of each gust front was estimated by measuring the distance it travelled in the time period when it traversed the territory. It was found that the speed of gust fronts studied ranged from 3 ms^{-1} to 17 ms^{-1}, with an average of 9 ms^{-1}. Maximum 1-minute mean wind accompanying gust fronts varied from 16.2 ms^{-1} to 27.7 ms^{-1}, with an average of 21 ms^{-1}. It should be noted that in most cases (such as case 940503) wind speed is low immediately behind the gust front, which is a line of convergence of velocity. The average location of the maximum wind was about ten kilometers behind the gust front.

The average values of maximum pressure rise and maximum temperature drop within ten minutes were 1.5 hPa and 4.0 °C respectively. The values of maximum changes within an hour that were more representative of the ultimate changes are also shown in Table 2.

The gust front in the 930616 case had the lowest propagation speed of 3 ms^{-1}. However, it gave rise to a very high one-minute mean wind (24 ms^{-1}) and a pressure rise of 2.7 hPa in 10 minutes. This pressure rise was the highest among all cases. The low propagation speed was quite extraordinary since the propagation speed of gust fronts was reported by other authors to be generally proportional to maximum wind speed (Wakimoto1982). A study of radar pictures showed that another intense storm cell developed to the southwest ahead of the gust front. Figure 4 shows the development of these storm cells. The retarded motion of the gust front associated with storm cell labelled "A" might be due to the head-on approach of airflow from the other storm cell labelled "B".

Time series plots showing the changes of meteorological variables at some stations and anemograph traces of conventional anemometers at Kai Tak Airport for cases 930509 and 940503 were shown in Figures 5 and 6 respectively. They illustrate the abrupt change in wind direction, pressure and temperature during the passage of a gust front. For case 930509 (Figure 5(a)), pressure began to rise before wind direction changed at Sha Lo Wan (SHA) while pressure rose after wind direction had changed at Ta Kwu Ling (TKL). It appeared that there was no definite sequence of changes of meteorological variables, contrary to the findings of other researchers as described in section 1. For most cases, wind direction and pressure would return to the original values within a few hours after the passage of gust fronts.

The restoration of meteorological variables after the passage of gust front was found to be gradual and varied greatly from case to case. The wind direction tended to return to the original value but sometimes chaotic wind patterns were observed during the transition. Other study (Mahoney 1988) also found that the time taken for wind speed and direction to return to their original states varied from case to case. The restoration within a few hours after the frontal passage distinguished the gust front cases from cold front or cold surge cases in which changes would persist for a much longer period.

It was found that the majority of the gust fronts came from the north of the territory rather than the south of the territory. Case 930923 was the only case in which gust front came from the south of the territory. The gust (16 ms^{-1}) and pressure rise (0.5 hPa within an hour) were also the lowest among all cases. The temperature drop was also the second lowest. This might be the result of the predominance of severe thunderstorms generated by solar heating inland. It might also be a consequence of the structure of severe storms preferred by the climatological vertical wind and temperature profiles. This remains to be studied.

5. Discussion

In this study, nine gust fronts were identified within a period of thirteen months. A greater number might have actually occurred as the criteria used in this study might filter off some genuine cases. In the analysis, cases with only one weather station having changes in meteorological variables were discarded. Some of them might be very weak gust fronts while some others might have passed on the periphery of the territory. However, checking all these cases by subjective judgment would require an enormous amount of effort since there are quite a number of them. Therefore, this study only aimed at searching for cases with significant changes and cases with fronts passing through a large part of the territory.

To study weak gust fronts or those passing on the periphery of the territory, a denser and larger AWS network is required. Furthermore, it would be better if more stations could be equipped with pressure sensor since pressure rise is an important feature of gust front passage.

Some of the events selected in the first round of automatic screening involved changes in meteorological variables at only two to three stations. These turned out on detailed analysis to be land-sea breezes or turbulence. In each of the nine gust front cases, more than five stations reported sudden changes in meteorological variables. The criteria in the first round of screening can be made stringent such that only cases with, say, five or more stations meeting the criteria would be selected. This would greatly reduce the number of non-gust front cases selected in the initial screening.

From detailed analyses, the most consistent and easily identifiable gust front signature is convergence in the velocity field. Thus, another approach to identify gust front could be to trace the regions of convergence in radial velocity, say, measured by the Doppler Weather Radar at Tate's Cairn. Furthermore, by taking vertical sections through storms, Doppler radar could reveal structure of gust fronts. Recent work by Lee *et al* (1996) is an example in this respect.

Using the automatic detection algorithm developed in this project, more data from other years can be analysed to study the characteristics of gust fronts in Hong Kong.

6. Conclusion

Criteria for identification of gust fronts in Hong Kong using AWS data were developed. With the aid of computerized criteria, nine gust fronts within a period of thirteen months were identified and their characteristics were briefly discussed. The average propagation speed of these gust fronts was found to be 9 ms^{-1} and the maximum 1-minute mean wind accompanying these gust fronts had an average of 21 ms^{-1}. Average values of maximum pressure rise and maximum temperature drop within ten minutes were found to be 1.5 hPa and 4.0 °C respectively. It was also found that the number of gust fronts moving from north to south across the territory was much larger than that from south to north.

With suitable modification and fine tuning, the criteria developed in this study could be adopted in the future to detect the arrival of gust fronts fully automatically.

7. Acknowledgments

I would like to thank Miss Wendy Tung, a voluntary student helper in 1994, for her assistance in the analysis of the cases. I would also like to thank Messrs C.Y. Lam, C.M. Shun and C.C. Fu for their comments on the report. The assistance of Mr. S.T. Chow, Mr. T.F. Lee and Miss Y.K. Sing in the preparation of some of the figures is much appreciated.

8. References

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Table 1 Months in which the events short-listed in the first round took place

Year	1993								1994				
Month	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Frequency	4	4	4	0	4	0	1	0	0	0	1	1	2

Table 2 Characteristics of the identified gust front cases

Case (yymmdd)	Time (HKT)	Maximum 1-minute mean wind / ms^{-1}	Maximum pressure rise/hPa within		Maximum temperature drop/ °C within		Propagation speed / ms^{-1}	Propagation direction	Thunderstorm reported/ Spheric recorded
			10 mins	60 mins	10 mins	60 mins			
930502	1200-1310	22.1	2.3	2.8	5.0	5.8	11	SE	Yes
930509	1245-1530	16.2	0.9	1.8	4.4	6.2	4	SSW	Yes
930604	1330-1420	27.7 (21.7)	1.7	1.7	4.1	5.0	17	ESE	Yes
930616	0745-1215	24.0 (19.1)	2.7	3.9	3.6	5.1	3	SW	Yes
930916	1730-1915	19.7 (18.2)	0.9	1.7	3.4	5.3	7	SW	Yes
930923	1120-1300	16.0	0.5	0.5	3.1	4.1	7	NNW	Yes
940319	0440-0600	18.5	1.6	3.6	2.7	4.0	10	SE	Yes
940503	0715-0845	18.2 (14.0)	1.9	2.3	4.6	6.0	8	S	Yes
940517	1530-1650	25.0	1.3	2.7	5.0	7.8	10	SE	No
	Mean	20.8 (19.0)	1.5	2.3	4.0	5.5	8.6		

Notes: 1. Some of the maximum 1-minute winds were recorded from Tai Mo Shan (930604, 930916 and 940503) or Green Island (930616) which were not so representative owing to topographical reasons. The second higher values recorded at these four stations are shown in the brackets. The mean of these four values and the highest values in the other five cases is also shown in bracket.

2. As maximum gusts were not available from AWS data retrieved from magnetic tapes, maximum one-minute mean winds were shown instead.

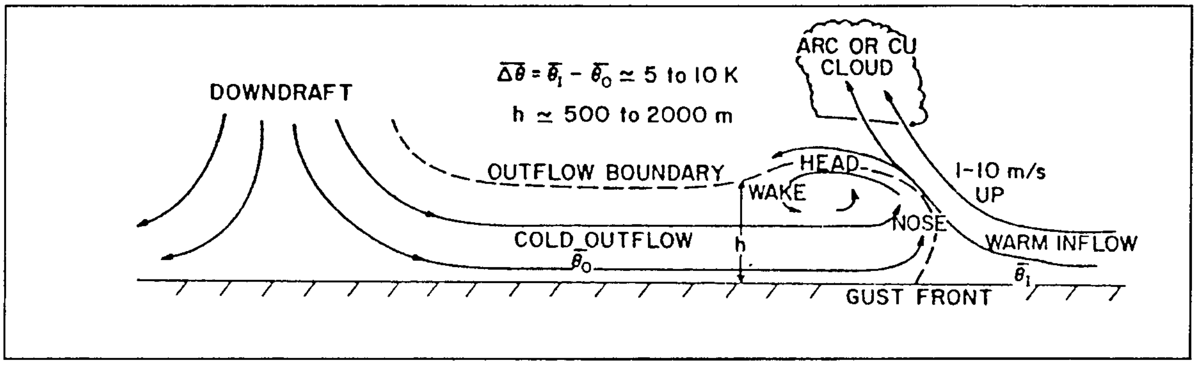


Figure 1 Schematic diagram of a thunderstorm outflow
(Adapted from Goff 1976 and Wakimoto 1982)

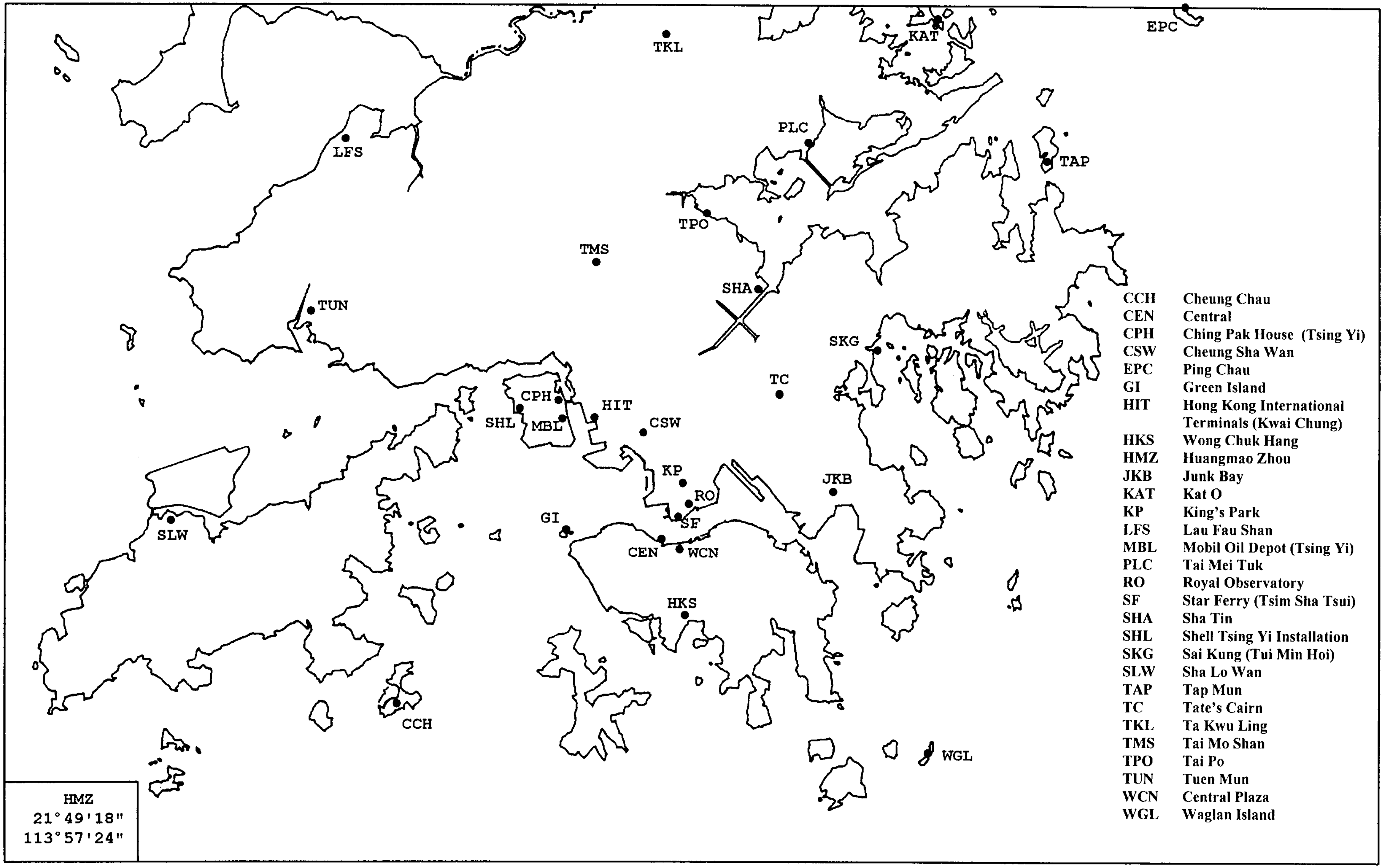


Figure 2 Distribution of automatic weather stations in Hong Kong

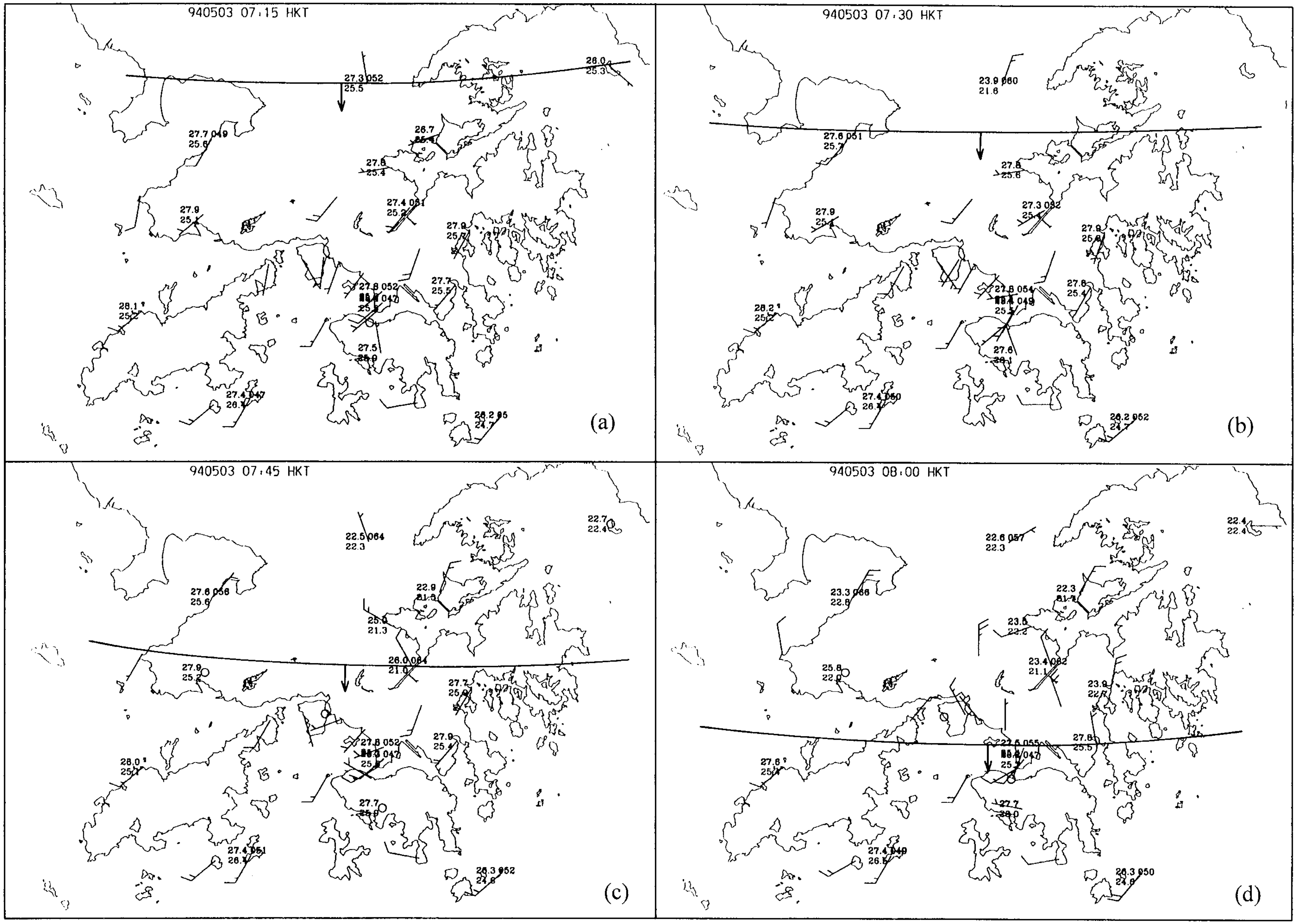


Figure 3 Evolution of gust front in case 940503 (a) 7:15 (b) 7:30 (c) 7:45 (d) 8:00
(Arrow indicates direction of gust front movement)

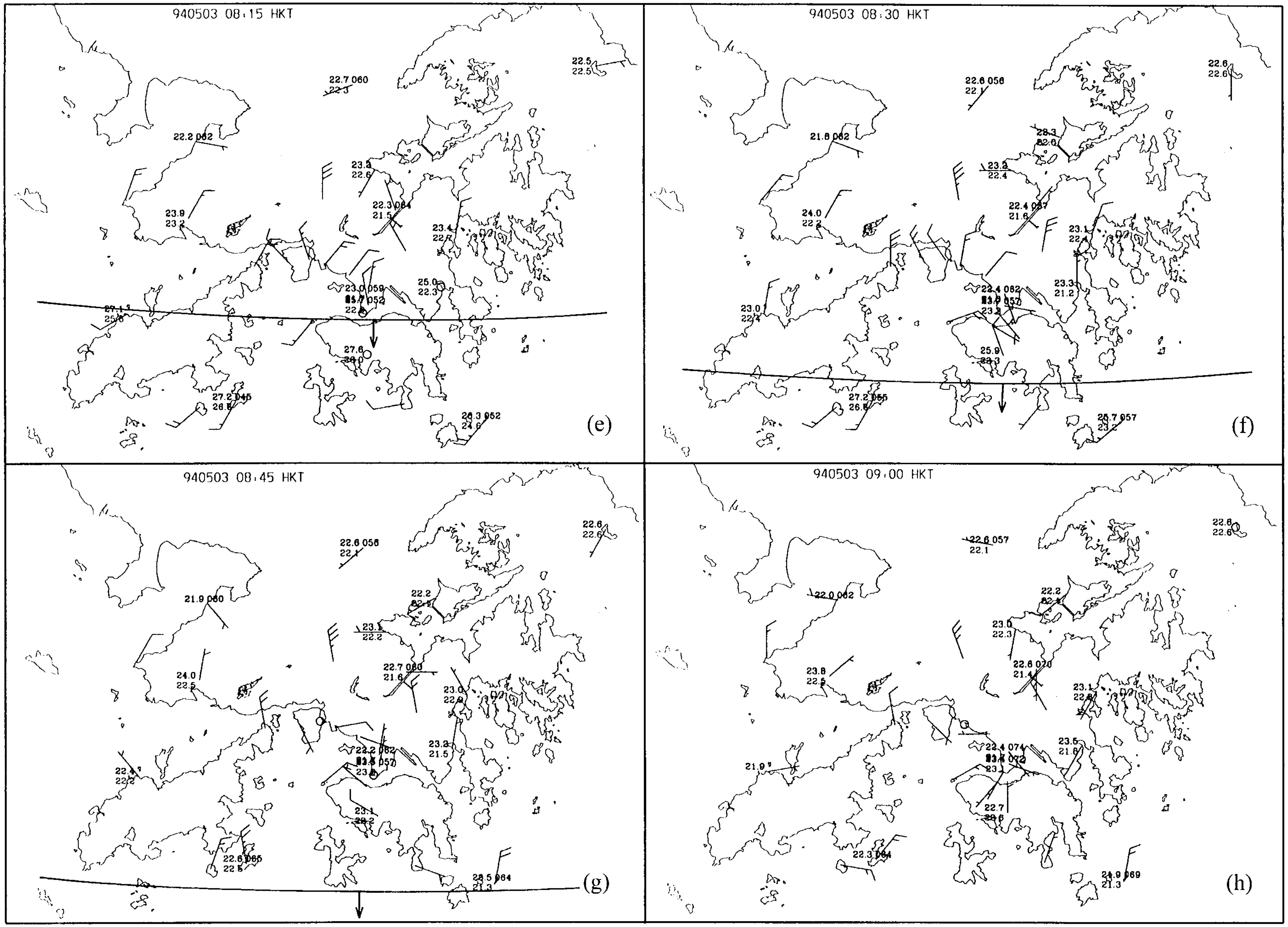


Figure 3 (Cont'd) Evolution of gust front in case 940503 (e) 8:15 (f) 8:30 (g) 8:45 (h) 9:00
(Arrow indicates direction of gust front movement)

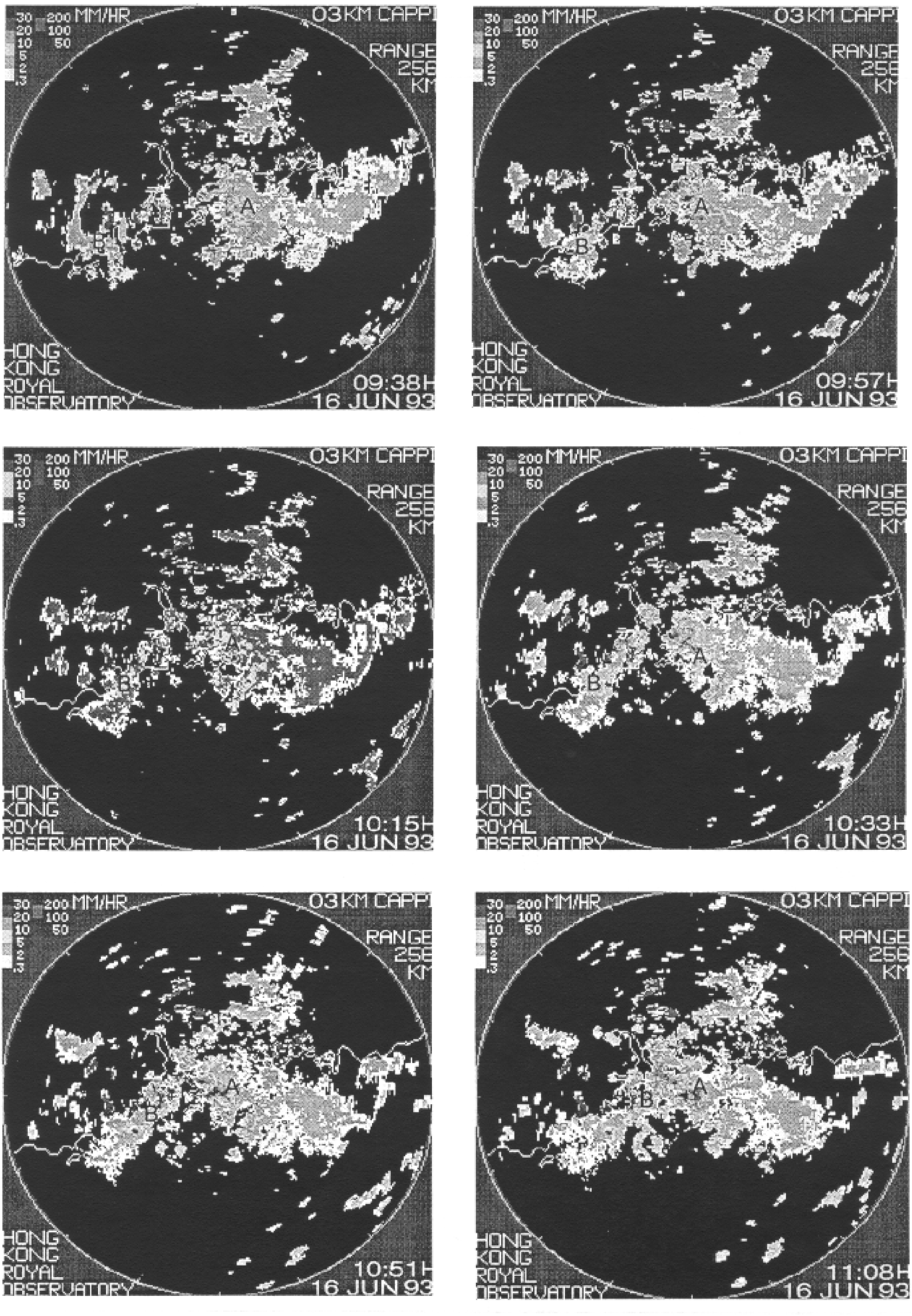


Figure 4 Development of two storm cells (A and B) in case 930616

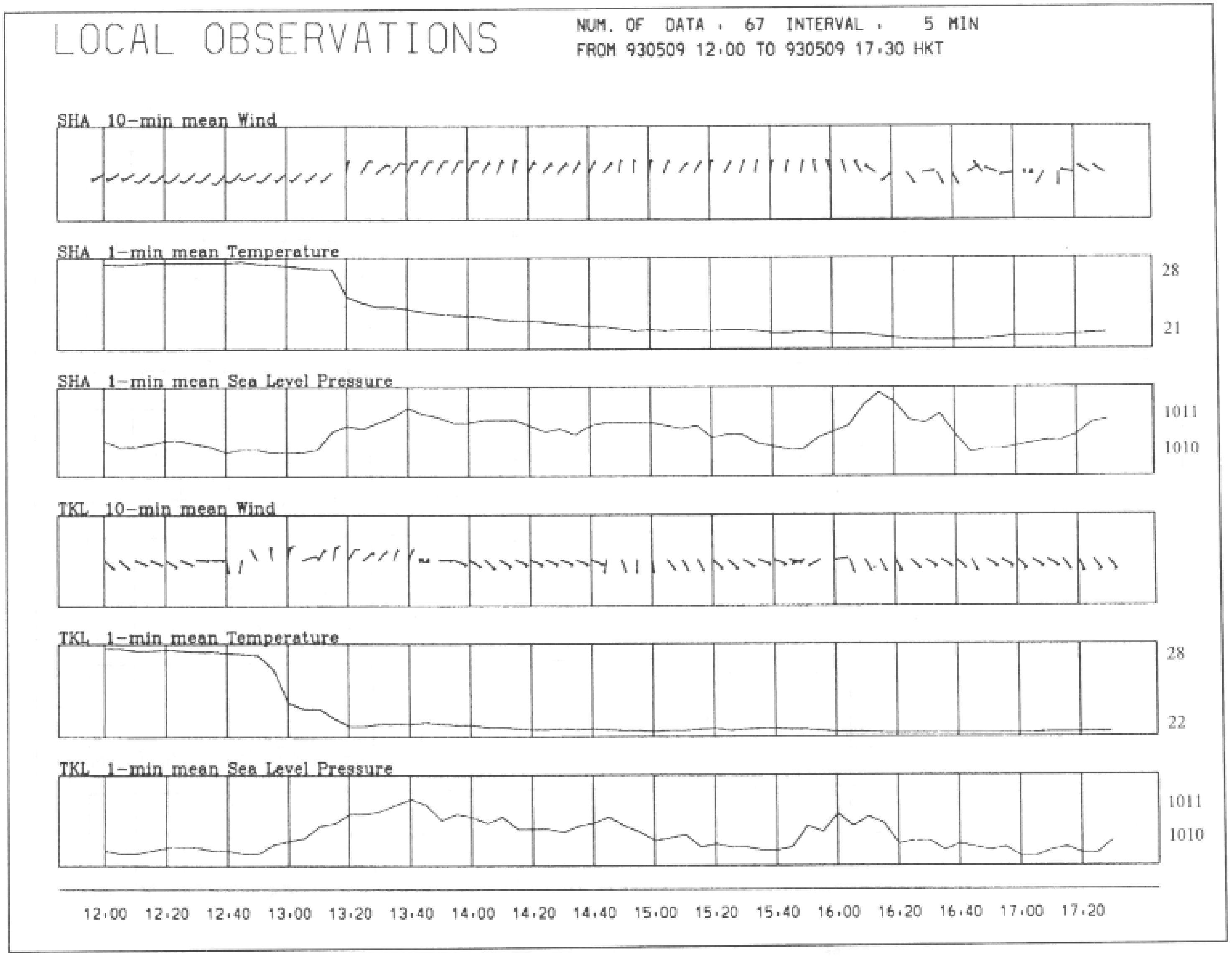


Figure 5 (a) Time series at Shatin (SHA) and Ta Kwu Ling (TKL) for case 930509

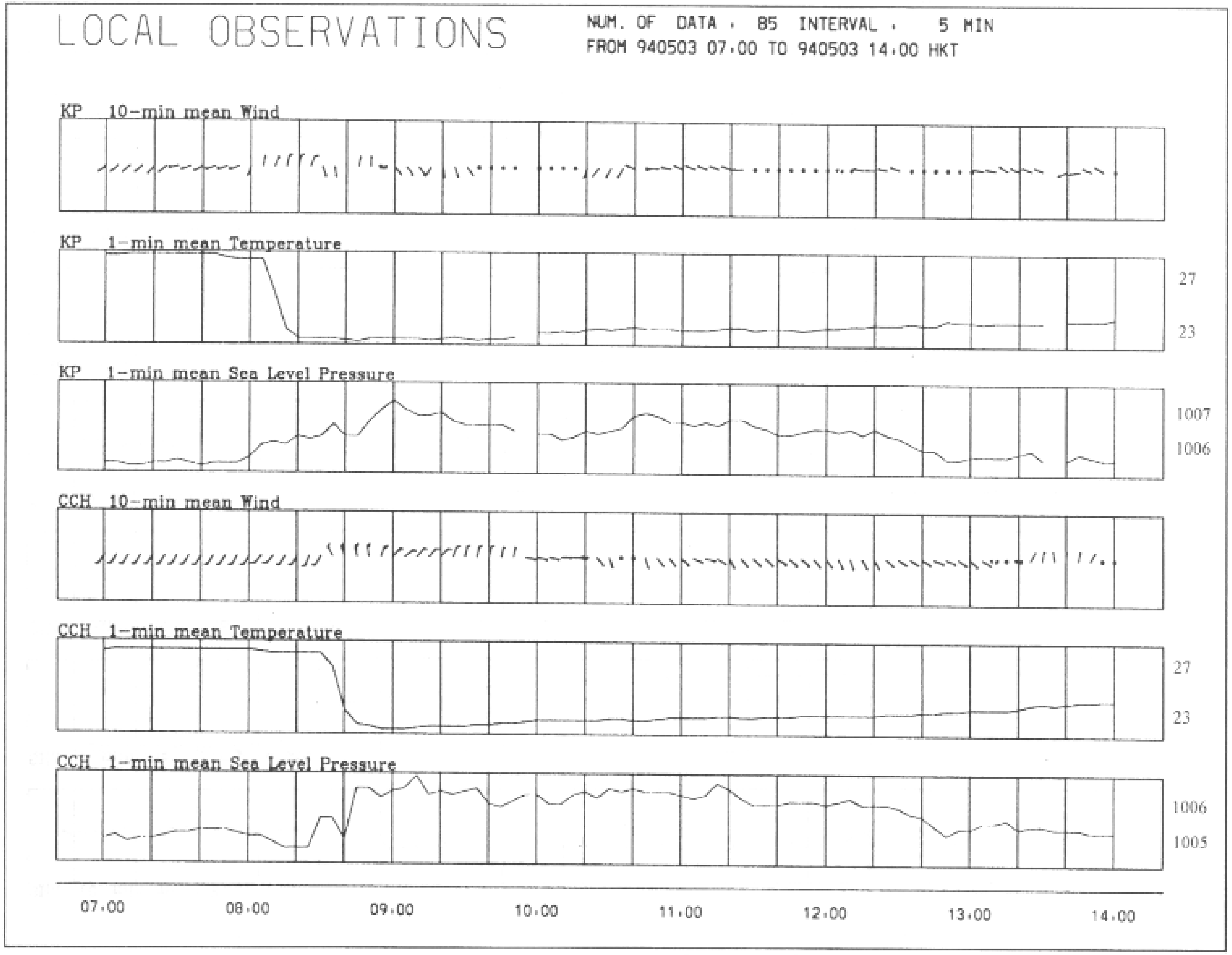


Figure 5 (b) Time series at King's Park (KP) and Cheung Chau (CCH) for case 940503

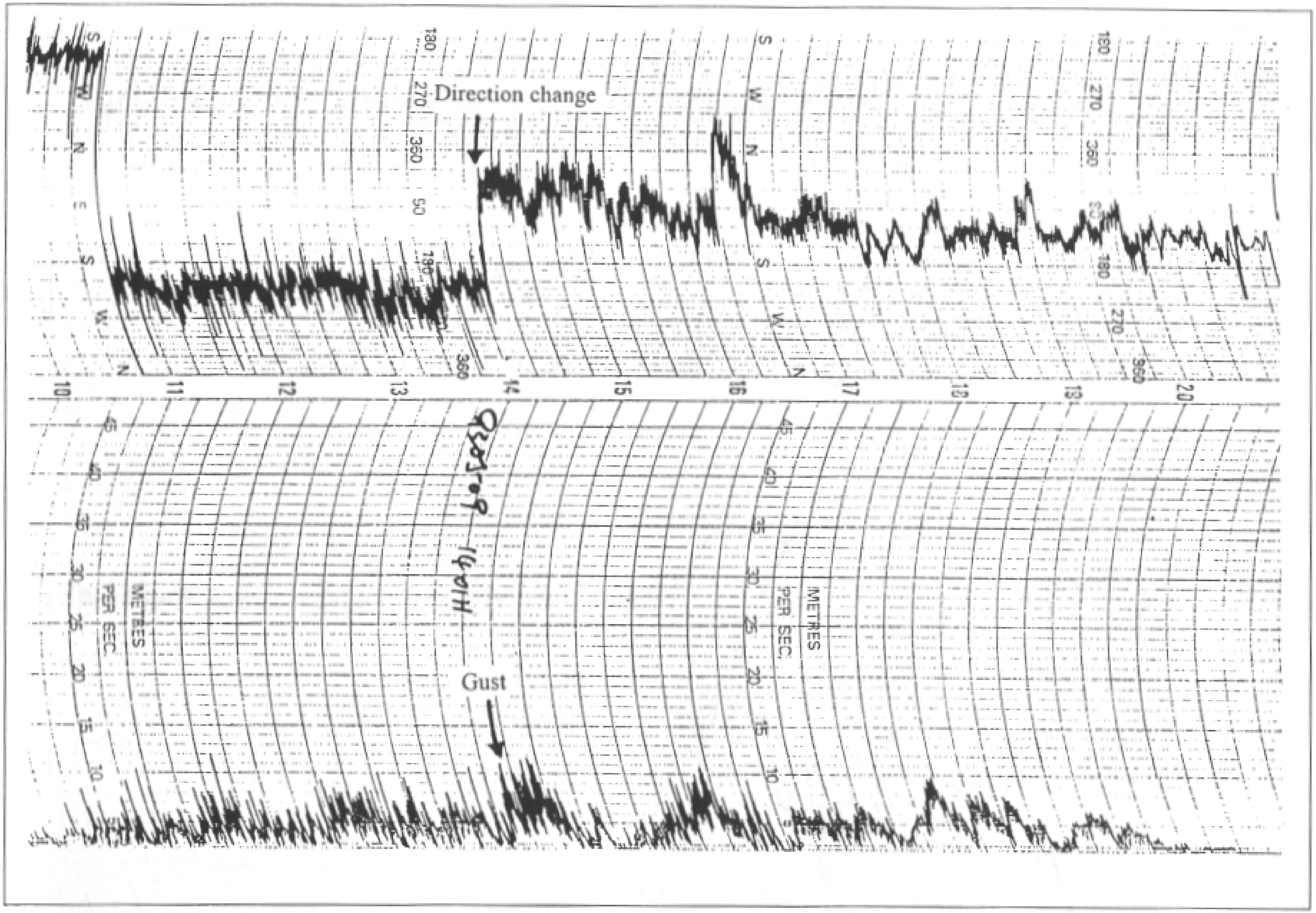


Figure 6 (a) Anemograph of conventional anemometer at southeast of runway of Kai Tak Airport for case 930509

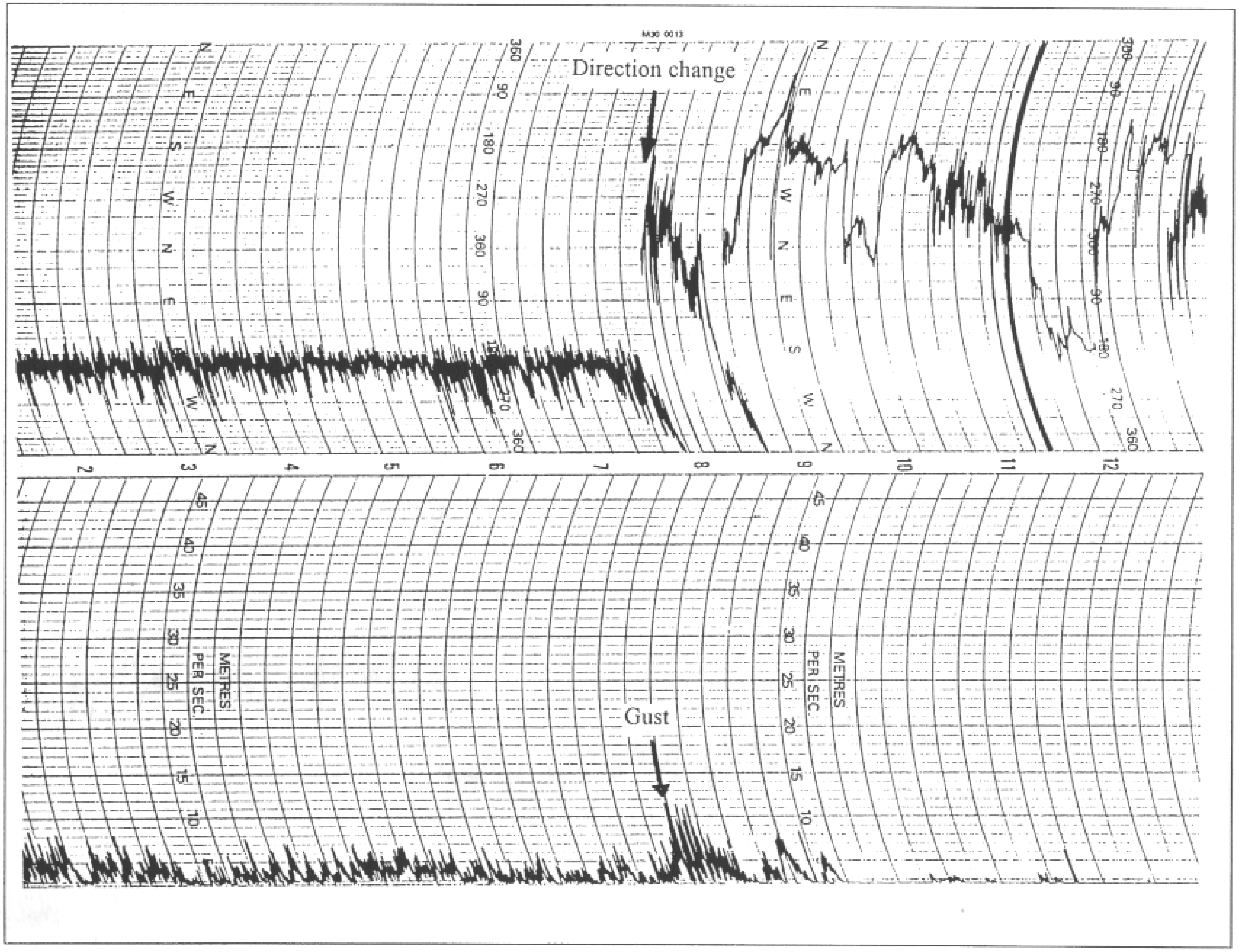
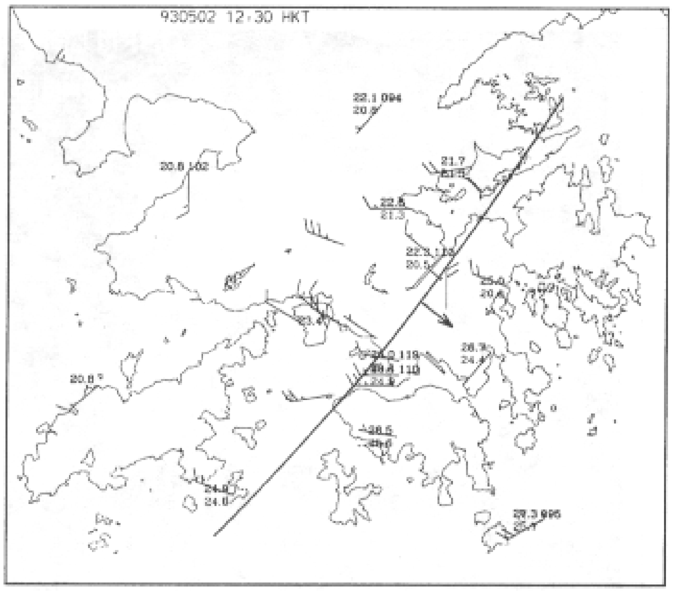
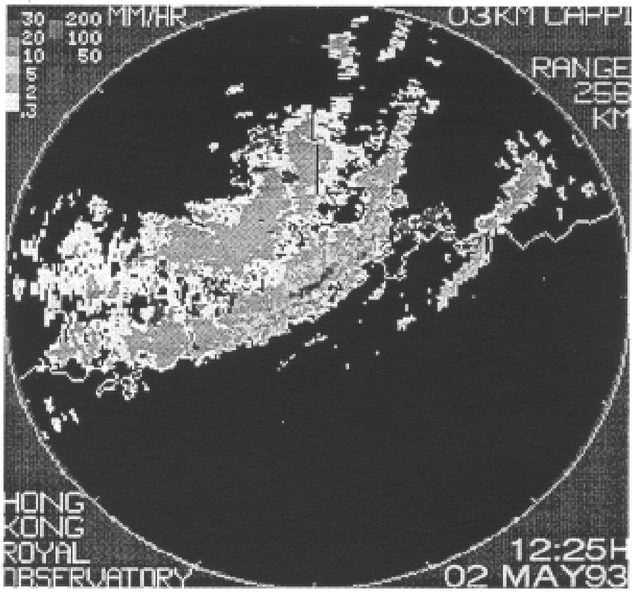


Figure 6 (b) Anemograph of conventional anemometer at northwest of runway of Kai Tak Airport for case 940503

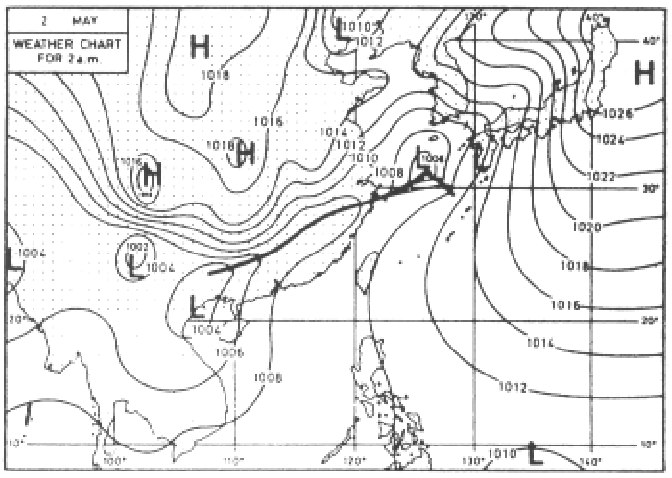
Case 930502 **Appendix I**

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

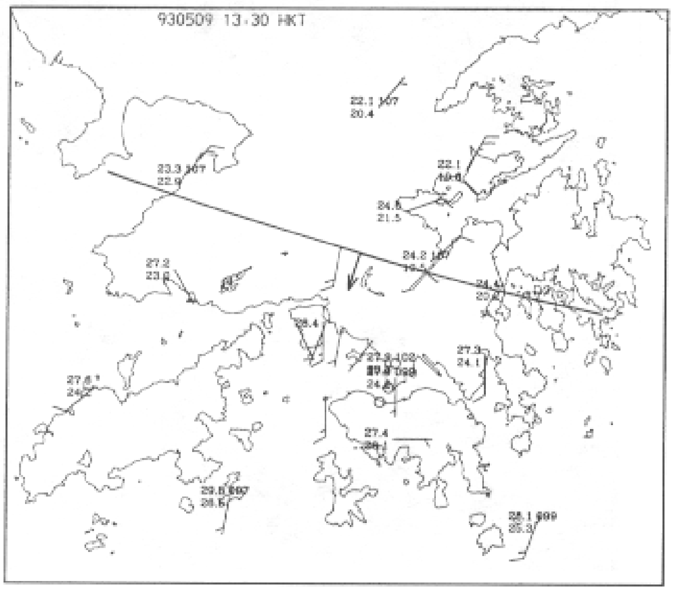
A trough of low pressure over Guangdong moved south towards the coast, bringing intense thunderstorms and heavy rain to Hong Kong.

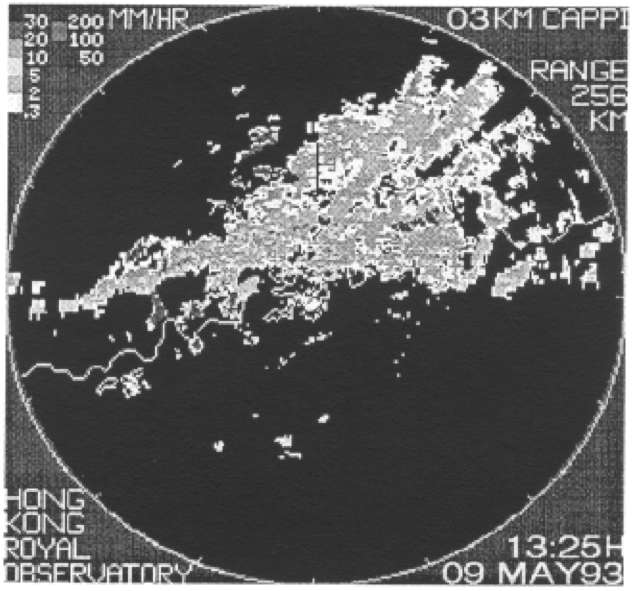
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1009.2	28.3	24.9	22.1	23.1	90	92

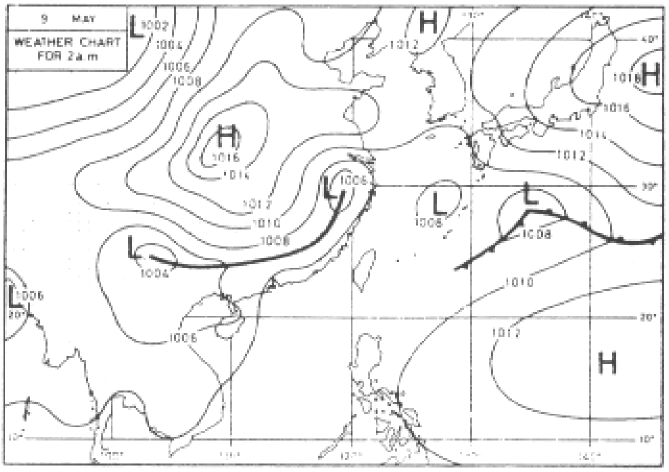
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
31.1	0.9	4.96	2.5	210	20.3

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

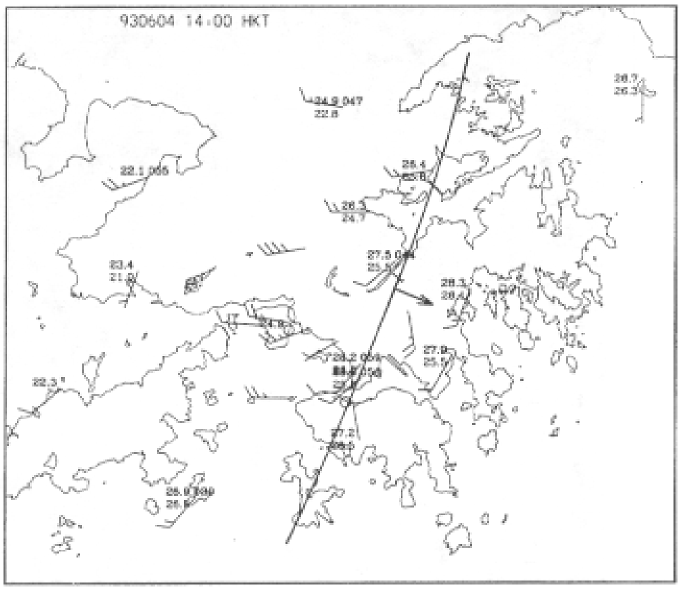
A trough passed through the territory bringing torrential rain and squally thunderstorms to Hong Kong.

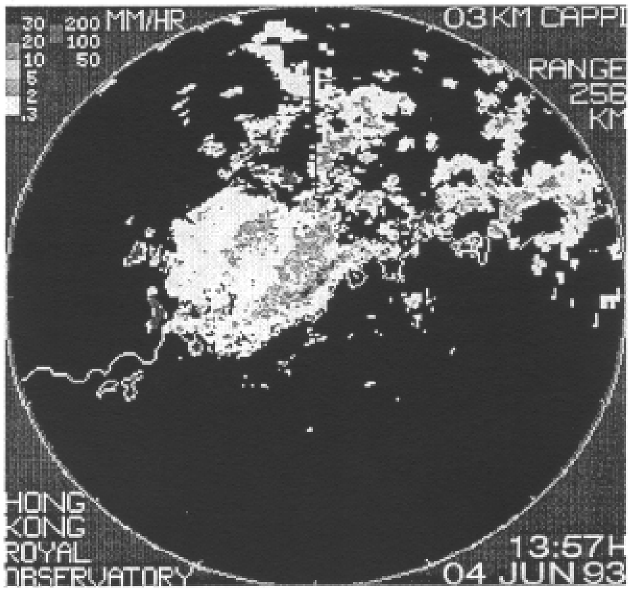
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1009.9	28.9	25.5	22.1	23.1	87	84

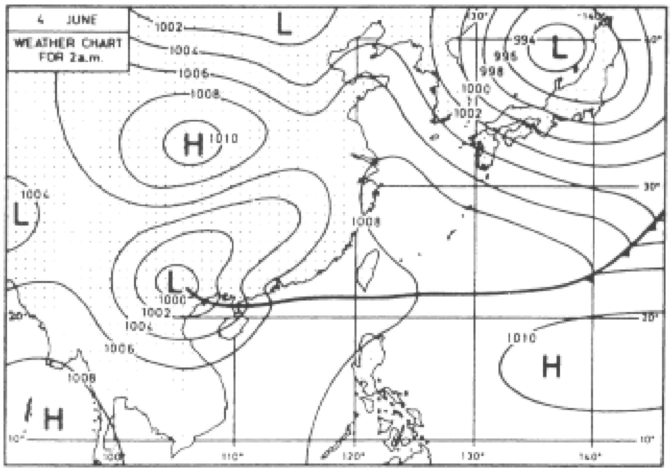
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
54.5	2.0	6.57	5.5	210	17.4

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

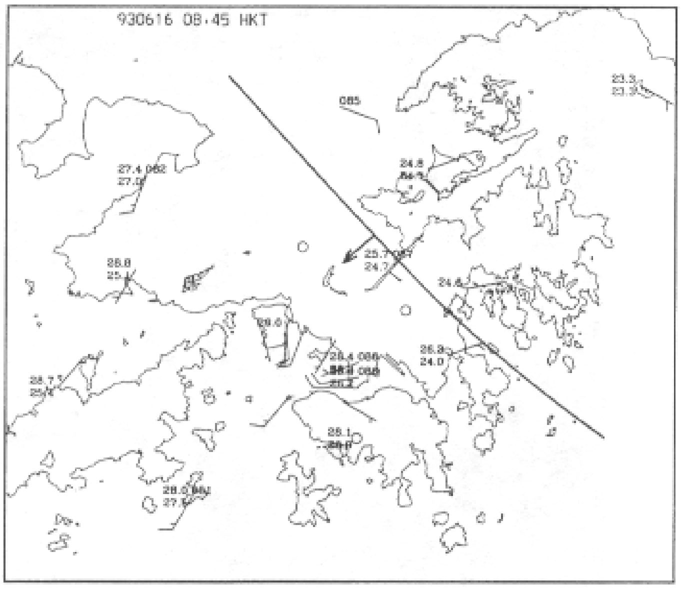
A trough over the northern part of the South China Sea brought rainy weather to Hong Kong.

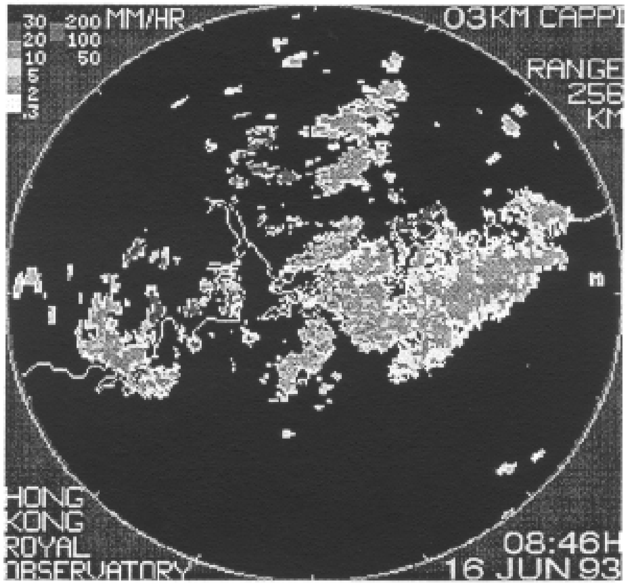
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1004.7	29.6	27.4	23.6	25.1	88	94

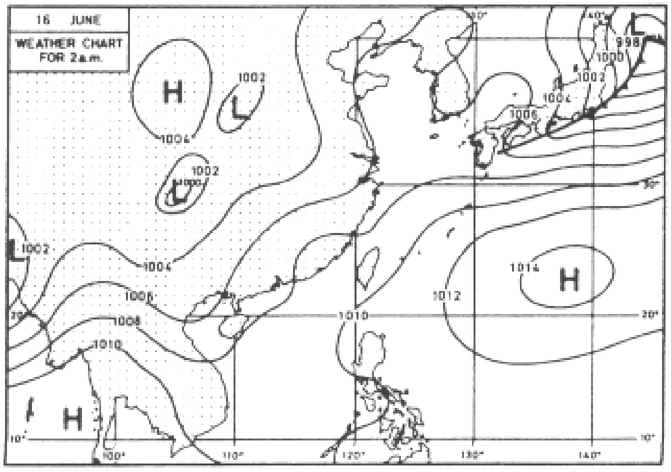
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
7.5	0.9	5.18	1.5	230	27.2

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

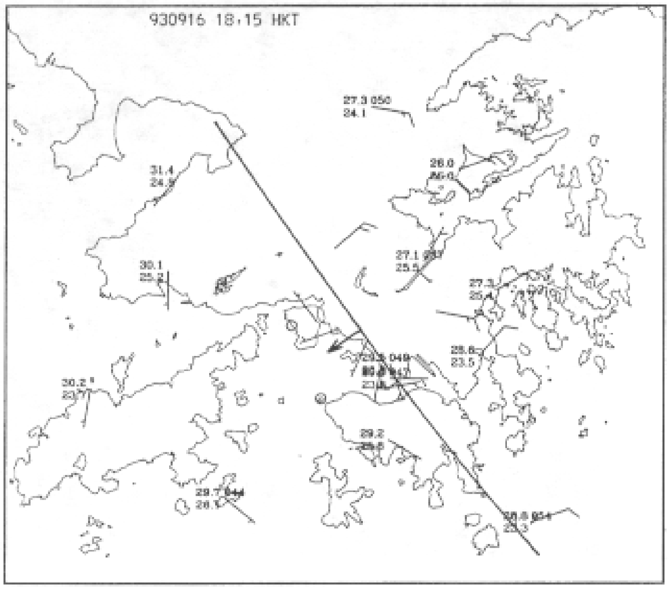
Under the influence of the southwest monsoon, intense convective storm cells developed near Hong Kong resulting in thundery and heavy rain which lasted from morning till afternoon.

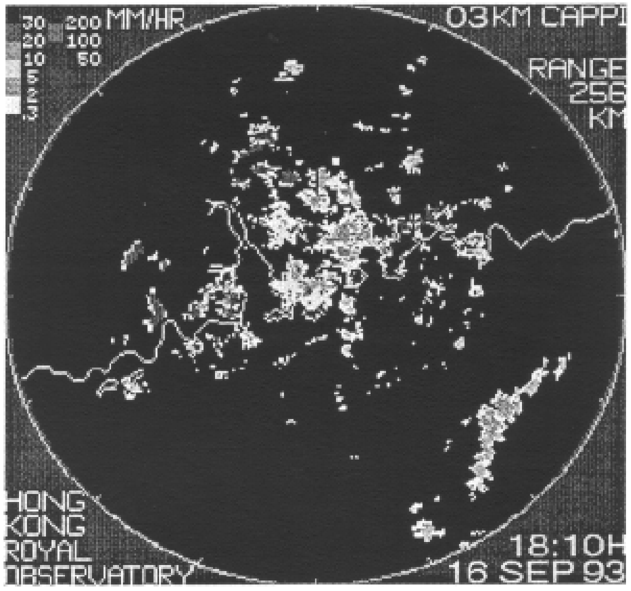
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1008.7	29.1	26.1	23.7	24.8	93	97

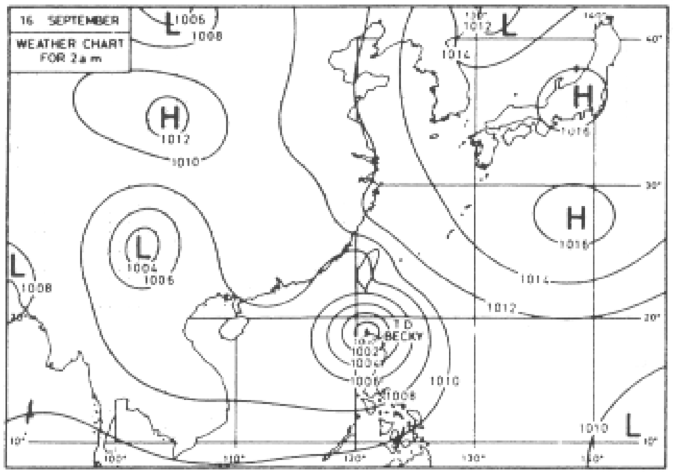
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
153.0	-	0.68	0.4	210	16.3

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

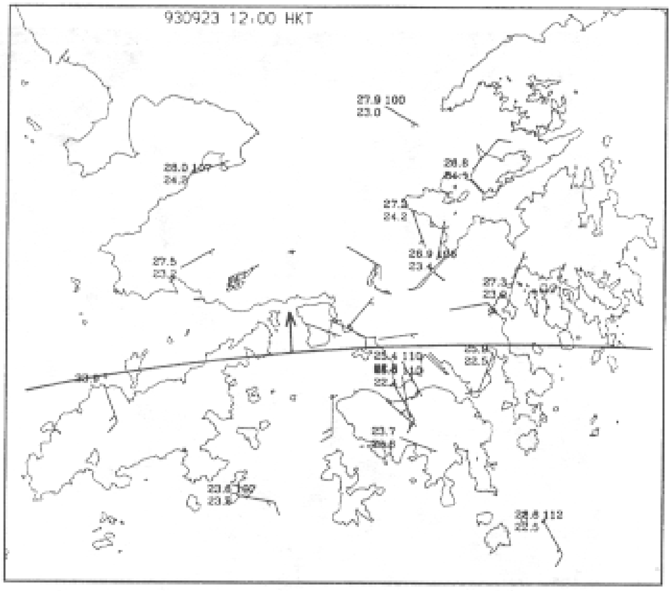
Formed as a tropical depression over the waters to the northeast of Luzon on 15 September, Becky traversed Luzon and intensified to a tropical storm on the morning of 16 September. It then adopted a northwestward course and winds picked up from the northeast as Becky moved closer to Hong Kong. Thunderstorms developing inland by land heating affected Hong Kong in the evening.

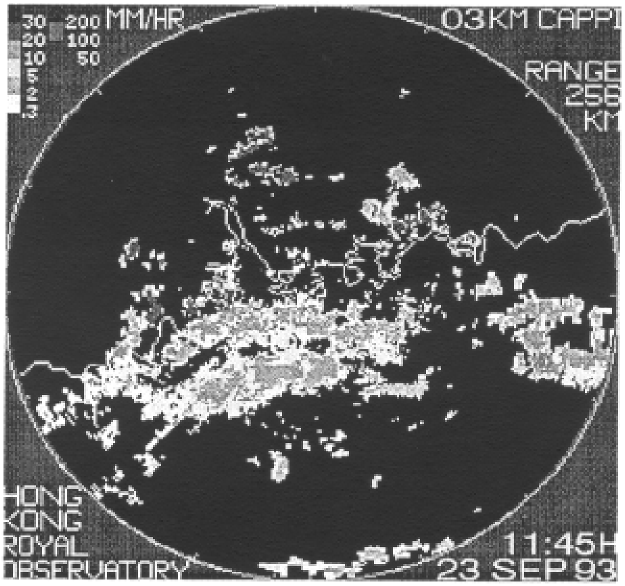
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1006.7	31.1	28.7	26.6	23.8	75	47

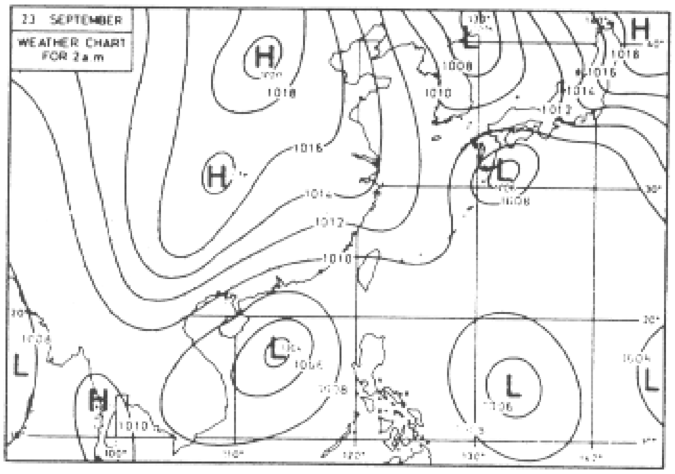
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
0.3	8.4	16.62	2.7	030	17.4

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

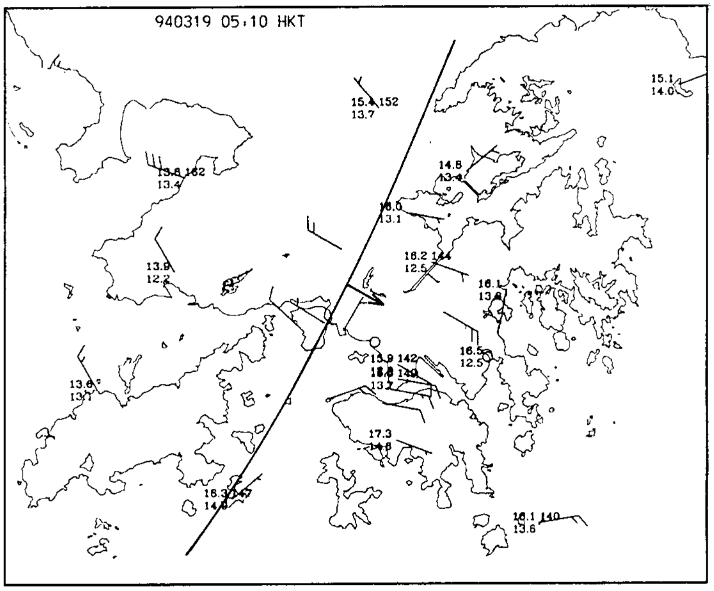
An area of disturbance over the South China Sea developed into a tropical depression named Dot in the afternoon. Its rainband moved slowly and affected Hong Kong.

Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1009.2	27.7	26.0	23.9	24.1	89	85

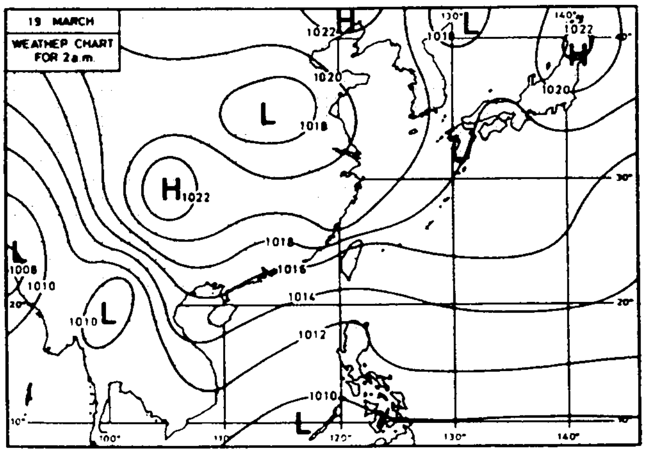
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
43.0	1.0	4.43	2.6	080	29.4

Snapshots of Gust Front



No Radar picture was available during the passage of gust front

Daily Weather Map



Synoptic Background

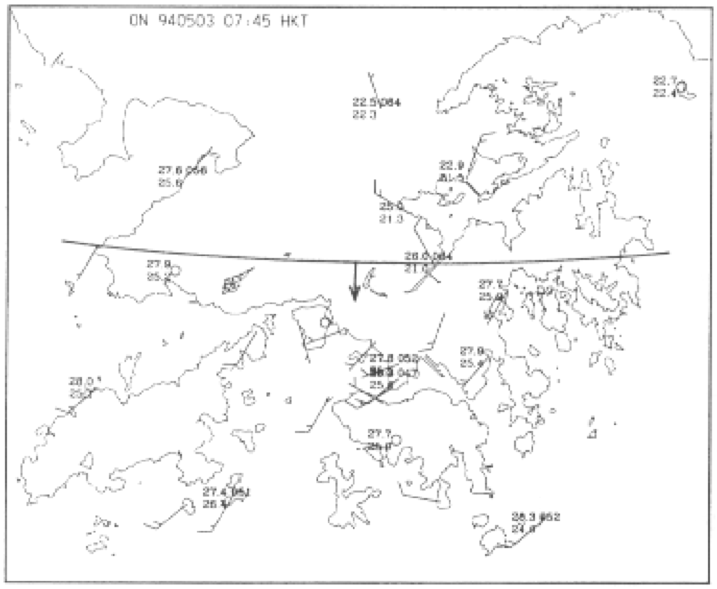
After a cool northerly replenishment reached the South China coast, rain band associated with an upper-air trough affected Hong Kong.

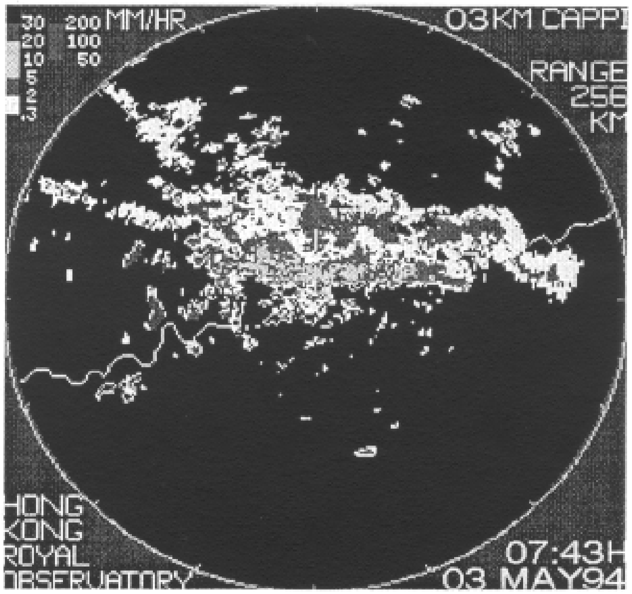
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1015.6	19.1	16.5	13.7	12.9	80	86

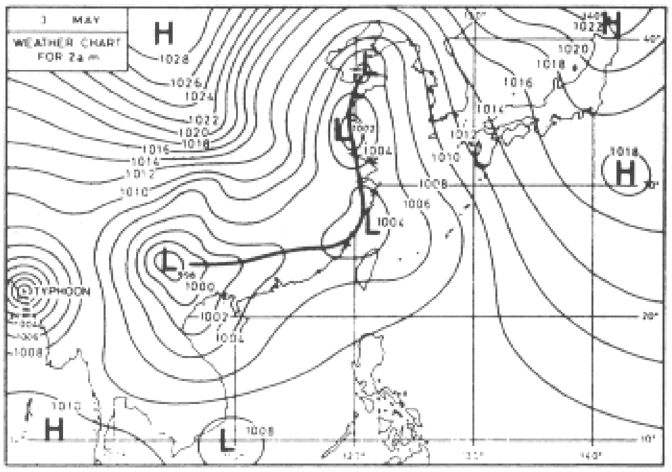
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
18.5	1.5	9.02	2.0	010	23.8

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

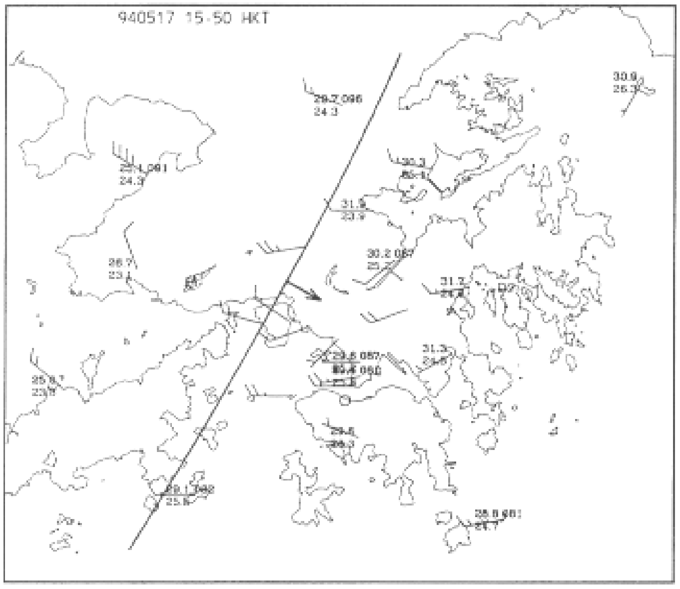
With the moving in of a trough of low pressure from Guangdong, weather was unsettled with widespread heavy rain and intense thunderstorms.

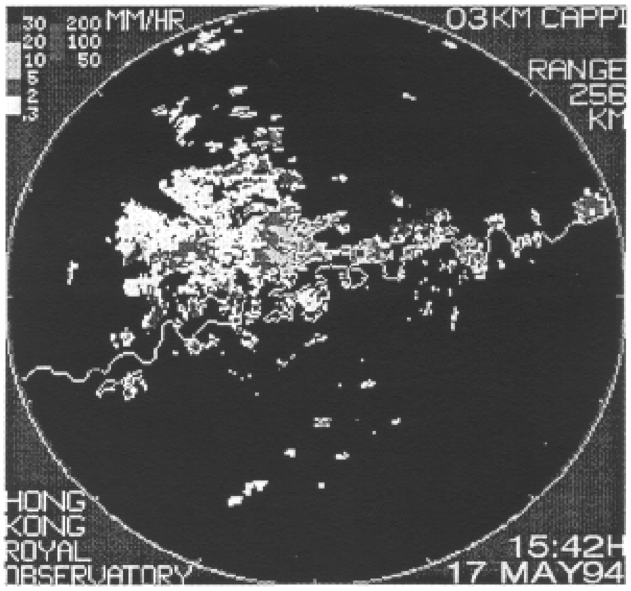
Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1005.0	28.8	26.2	23.2	23.9	87	94

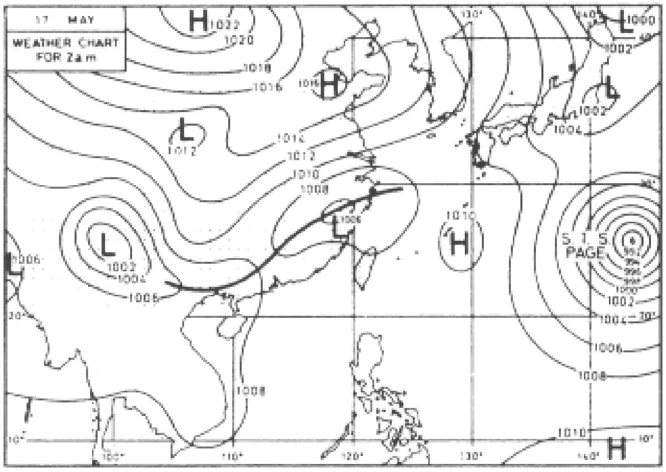
Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
86.8	-	2.80	3.0	230	18.6

Snapshots of Gust Front





Daily Weather Map



Synoptic Background

Severe squall developed along a trough of low pressure which moved across Hong Kong.

Summary of Selected Meteorological Observations of Hong Kong

Mean Pressure	Air Temperature			Mean Dew Point	Mean Relative Humidity	Mean Amount of Cloud
	Max.	Mean	Min.			
hPa	°C	°C	°C	°C	%	%
1008.9	32.4	28.6	26.1	24.2	77	74

Total Rainfall	Total Bright Sunshine	Daily Global Solar Radiation	Total Evaporation	Prevailing Wind Direction	Mean Wind Speed
mm	hours	MJ/m^2	mm	degrees	km/h
0.2	6.6	18.39	5.1	250	17.1