Application of microwave radiometer and wind profiler data in the estimation of wind gust associated with intense convective weather

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Abstract. Estimates of the wind gusts associated with intense convective weather could be obtained using empirical relationships such as GUSTEX based on radiosonde measurements. However, such data are only available a couple of times a day and may not reflect the rapidly changing atmospheric condition in spring and summer times. The feasibility of combining the thermodynamic profiles from a ground-based microwave radiometer and wind profiles given by radar wind profilers in the continuous estimation of wind gusts is studied in this paper. Based on the results of a 4-month trial of a microwave radiometer in Hong Kong in 2004, the estimated and the actual gusts are reasonably well correlated. It is also found that the wind gusts so estimated provide better indications of the strength of squalls compared with those based on radiosonde measurements and with a lead time of about one hour.

1. Introduction

Situated in a subtropical coastal area, Hong Kong occasionally experiences intense wind gusts associated with convective weather, such as downburst of thunderstorm and gust front, in the spring and summer every year. In the forecasting of wind gusts, reference has been made by the weather forecasters at the Hong Kong Observatory (HKO) to the radiosonde measurements and gust estimates are determined using empirical relationships like GUSTEX [1]. However, radiosonde data are only available a few times a day and may not be updated fast enough to catch the rapidly evolving atmospheric conditions in intense convective weather.

Measurements by remote-sensing meteorological instruments provide basically continuous monitoring of the dynamic and thermodynamic conditions of the troposphere. In Hong Kong, a network of boundary-layer type radar wind profilers (locations in Figure 1) measures the upper-air winds every 10 minutes up to a height of 9 km above ground. Continuous measurement of the temperature and humidity within the troposphere has also been made in field experiments of ground-based, multi-channel microwave radiometers. For instance, in the study of 2004 [2], the radiometer data were demonstrated to vividly reveal the rapid evolution of humidity profiles of the atmosphere (up to 10 km above ground) and the thermodynamic data turned out to be very useful in the nowcasting of the occurrence of thunderstorms and the number of lightning flashes.

The radiometer data in 2004 are examined in this paper from the perspective of nowcasting of the wind gusts associated with intense convective weather. For that purpose, they are combined with the upper-air wind data from the network of radar wind profilers in Hong Kong to provide continuous update of GUSTEX (every 10 minutes). This gust estimate is then compared with the actual gust measurements by the dense network of surface anemometers in Hong Kong (locations in Figure 1).

This paper is organized as follows. Section 2 gives a brief account of the gust estimation based on radiometer and wind profiler data. Section 3 compares the gust estimates with the actual gust measurements in the thunderstorm days during the field experiment of the radiometer in Hong Kong in 2004. Two case studies are given in Section 4. The conclusions of the paper are drawn in Section 5.

2. Wind gust estimate

GUSTEX is based on WINDEX developed in [3]. WINDEX is modified in [1] and given by:

$$WI = 5\,[H_m R_q (L_{max}^2 - 30 + q_l - 2\,q_m)]^{0.5} \quad (1)$$

where WI is the WINDEX in knots, H_m is the height of the melting layer in km, L_{max} is the maximum lapse rate from the ground to the freezing layer in K/km, q_l is the mean mixing ratio of water vapour between the ground and 1 km above in g/kg, q_m is the mixing ratio of water vapour at the melting layer in g/kg, and $R_q = q_l/12$.

GUSTEX also considers the downward transport of horizontal momentum in the upper air. It is modified in [1] and given by:

$$GU = \alpha_1\, WI + \alpha_2\, \rho U_{max} \quad (2)$$

where GU is GUSTEX in knots, U_{max} is the maximum wind speed between 900 and 500 hPa levels in knots, $\rho=\rho_{max}/\rho_{990}$ in which ρ_{max} is the air density at the pressure level at which U_{max} occurs and ρ_{990} is the air density at 990 hPa level. α_1 and α_2 are constants to be determined empirically.

In [1], the empirical constants in equation (2) were determined from the high wind gust cases at the Hong Kong International Airport between 2001 and 2005. The upper-air temperature, humidity and wind data were taken from the twice-daily radiosonde measurements. Besides determining the empirical constants from the least-square linear fit between GUSTEX and the actually measured wind gust from the surface anemometer stations, the upper bound GU_{max} and the lower bound GU_{min} of the wind gust estimate are also calculated. The relevant equations are summarized below:

$$GU = 0.12\, WI + 0.93\, \rho U_{max} \quad (3)$$
$$GU_{max} = 0.30\, WI + 0.93\, \rho U_{max} \quad (4)$$
$$GU_{min} = -0.05\, WI + 0.93\, \rho U_{max} \quad (5)$$

In equation (1), if L_{max}^2 is less than 30, WI is taken as 0 and, from equations (3) to (5), $GU = GU_{max} = GU_{min}$ in this case.

In the present study, the zenith mode measurements by the microwave radiometer are used to retrieve the temperature and humidity profiles up to 10 km above ground. These profiles are then employed to determine the thermodynamic parameters in equations (3) to (5), such as the height of the melting layer, water vapour mixing ratio, lapse rate, etc. The only complication in this calculation is that the radiometer data are only available at fixed heights above ground, instead of fixed pressure levels. The height and the pressure are related using hydrostatic approximation. The maximum wind speed and the corresponding height above ground are obtained by considering the wind profiles from all the four radar wind profilers in Hong Kong. At a particular moment, the maximum wind among the four profilers is selected in the calculation of GUSTEX as well as its upper and lower bounds.

IOP Conf. Series: Earth and Environmental Science **1** (2008) 012042 doi:10.1088/1755-1307/1/1/012042

3. Comparison between wind gust estimate and the actual gust measurements

The performance of the wind gust estimate determined from the above method (viz. radiometer and wind profiler data) is compared with the actually measured gust by the dense network of surface anemometers in Hong Kong in 14 thunderstorm episodes between March and June 2004. A thunderstorm episode is defined as a period of time (normally a few hours or more) in which thunderstorm has been reported by the weather observers at HKO Headquarters and/or Hong Kong International Airport. In general, the GUSTEX itself (equation (3)) could underestimate the actual gust measurement at times. For practical applications, the upper bound of wind gust estimate (equation (4)) may be more useful in giving the weather forecaster an idea about how large the gust could attain. As such, GU_{max} is considered in the comparison.

The scatter plot of the maximum wind gust actually measured by the surface anemometers and the largest value of GU_{max} within an hour prior to the maximum gust occurrence for the thunderstorm episodes under study is given in Figure 2(a). The two datasets are found to have good correlation and the latter is only larger than the former by about 20% on average from the least-square linear fit. There are two outlier points in Figure 2(a) (encircled in red in the scatter plot). In both cases, the upper-air winds from the wind profilers are too strong to result in over-estimation of wind gusts.

For comparison of performance, the corresponding scatter plot based on the GU_{max} estimated from radiosonde measurements is shown in Figure 2(b). In this plot, the upper bound of GUSTEX determined from the radiosonde data just prior to the maximum gust occurrence is used, which could be as many as 12 hours earlier (because there are only two radiosonde ascents every day in Hong Kong with both wind and temperature/humidity profiles). Compared to the radiometer/wind profiler plot, the radiosonde plot has weaker correlation and on average the wind gust estimate is 63% larger on average. There are also two outlier points in Figure 2(b) (encircled in red in the scatter plot). In both cases, the upper-air winds measured by the radiosonde are too strong to result in over-estimation of the wind gusts. Overall speaking, the GU_{max} estimated from radiometer/wind profiler data has superior performance and could be useful in the nowcasting of wind gust associated with intense convective weather with a lead time of about one hour.

4. Case studies

Two convective weather cases within the study period in 2004 are discussed in detail in this Section on how the wind gust estimate performs. The first case occurred on 8 May 2004. Synoptically, a strong southerly airflow between a westerly wave to the west of Hong Kong and the subtropical ridge to the east affected the Pearl River Estuary (location in Figure 3(a)) within the boundary layer. At 200 hPa, divergent flow occurred over the south China coast (location in Figure 3(a)) ahead of a deep westerly wave. From the 256-km radarscope, bands of strong echoes with southwest-to-northeast orientation moved from western coast of Guangdong across Hong Kong. Thunderstorms were reported over the territory between 2 and 8 a.m. on that day (Hong Kong time, which is equal to UTC + hours). The first band of heavy rain affected Cheung Chau (location in Figure 1) at about 3:42 a.m. (Figure 3(a)), bringing wind gust of 18.9 m/s, the largest over Hong Kong. The second band affected Waglan Island (location in Figure 1) at about 7:04 a.m. (Figure 3(b)), bringing the maximum wind gust of 26.2 m/s. The time series of maximum wind gust over the surface weather stations in Hong Kong in that morning as well as the GUSTEX, GU_{max} and GU_{min} are given in Figure 3(c). For the two events of the passage of strong radar echoes, the maximum wind gusts lie between the largest values of GU and GU_{max} within an hour prior to each event. As such, the wind gust estimates based on radiometer and wind profilers are considered to be useful in nowcasting the actual strength of the gusts.

It is noted that, after the occurrence of squalls at the surface, the wind gust estimates may remain at rather high values, such as between 4 and 4:30 a.m. on 8 May 2004. This is because of the appearance of strong winds at the upper air after the passage of the squall near the surface.

The second case occurred on 17 April 2004. Synoptically, a trough of low pressure at the surface over the south China coast brought unsettled weather to the region. On the 256-km radarscope, a band of intense echoes with north-northeast to south-southwest orientation moved across Hong Kong in the afternoon on that day. Thunderstorms were reported in Hong Kong at 5 and 6 p.m. At the times shown in Figures 4(a) and (b), high wind gusts were recorded at Cheung Chau (15.1 m/s) and Waglan Island (17 m/s) respectively. The time series of the highest wind gust in Hong Kong together with the various wind gust estimates are given in Figure 4(c). The largest values of GUSTEX and GU_{max} within an hour before the high wind gust events provide reasonable estimates on the gusts that could be attained. As in the previous case, after the occurrence of squalls at the surface, the wind gust estimates may remain at rather high values, such as after 6:30 p.m. on 17 April 2004. This is again because of the appearance of strong winds at the upper air after the passage of the squall near the surface.

5. Conclusions

The performance and application of wind gust estimates based on remote-sensing instruments, viz. radiometer and radar wind profilers are studied in this paper. The GUSTEX originally developed for radiosonde data is adopted here. Compared to the twice-daily balloon ascents, the continuous measurements of temperature, humidity and wind from the remote-sensing instruments better capture the rapid evolution of the troposphere in convective weather conditions. As such, the wind gust estimates so determined has improved correlation with the maximum gusts actually measured by the network of surface anemometer stations in Hong Kong. From two case studies of typical intense convection in the summer, the gust estimates are found to be useful in the nowcasting of high winds associated with thunderstorms.

The present study is based on the field experiment data of a ground-based microwave radiometer in Hong Kong in 2004 only. The amount of data involved is rather limited. A permanent unit of radiometer has recently been set up in Hong Kong and a larger set of data accumulated over the years would then be employed to evaluate the performance of the wind gust estimates determined from radiometer and wind profiler measurements for operational use.

References

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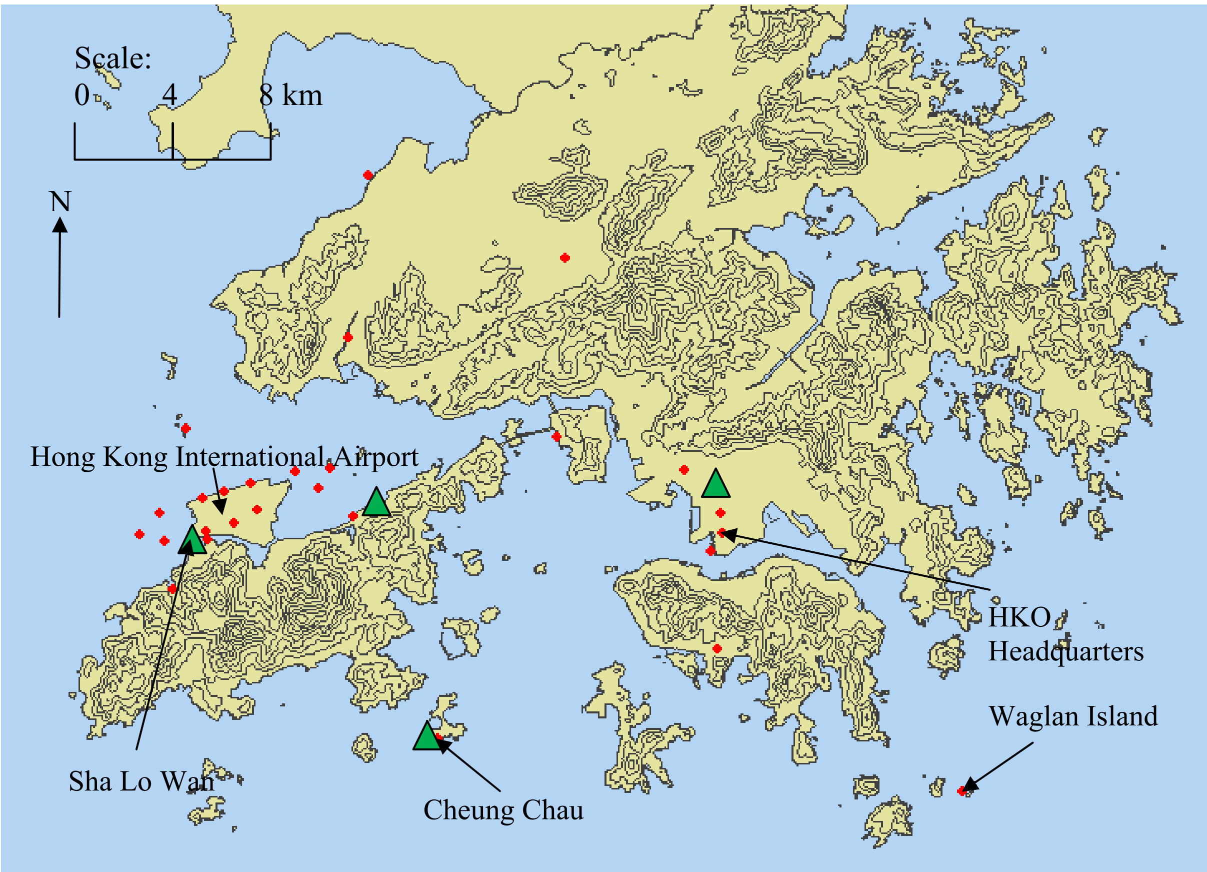
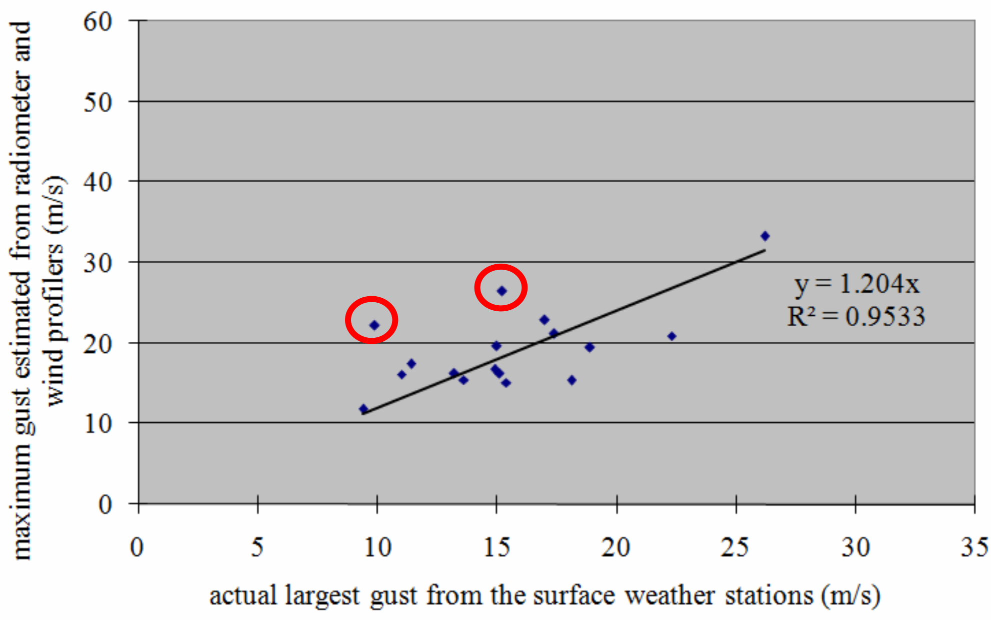
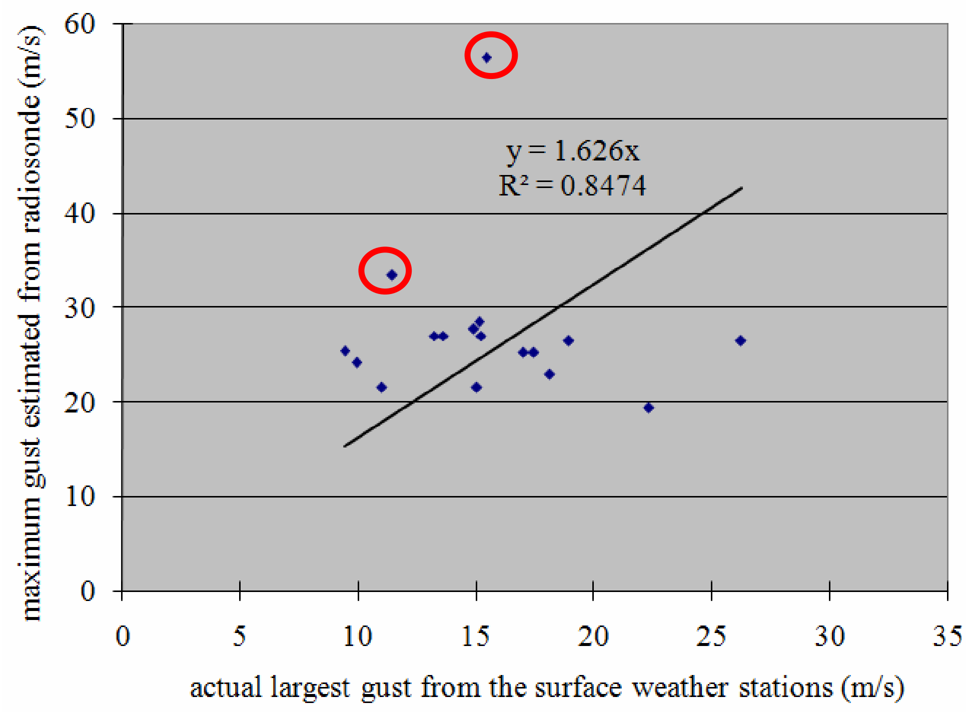


Figure 1. The network of surface anemometers (red dots) and radar wind profilers (green triangles) in Hong Kong. The radiometer has been placed at HKO Headquarters, Cheung Chau and Sha Lo Wan during the experiment. Height contours are in 100 m.



(a)



(b)

Figure 2. (a) The scatter plot of the maximum gust estimated from microwave radiometer and radar wind profiler data against the largest value of the actually measured gust from the surface anemometer stations in the 14 thunderstorm episodes in 2004 of the current study. (b) is the corresponding scatter plot based on the maximum gust estimated from the radiosonde data. In (a) and (b), the outliers are encircled in red.

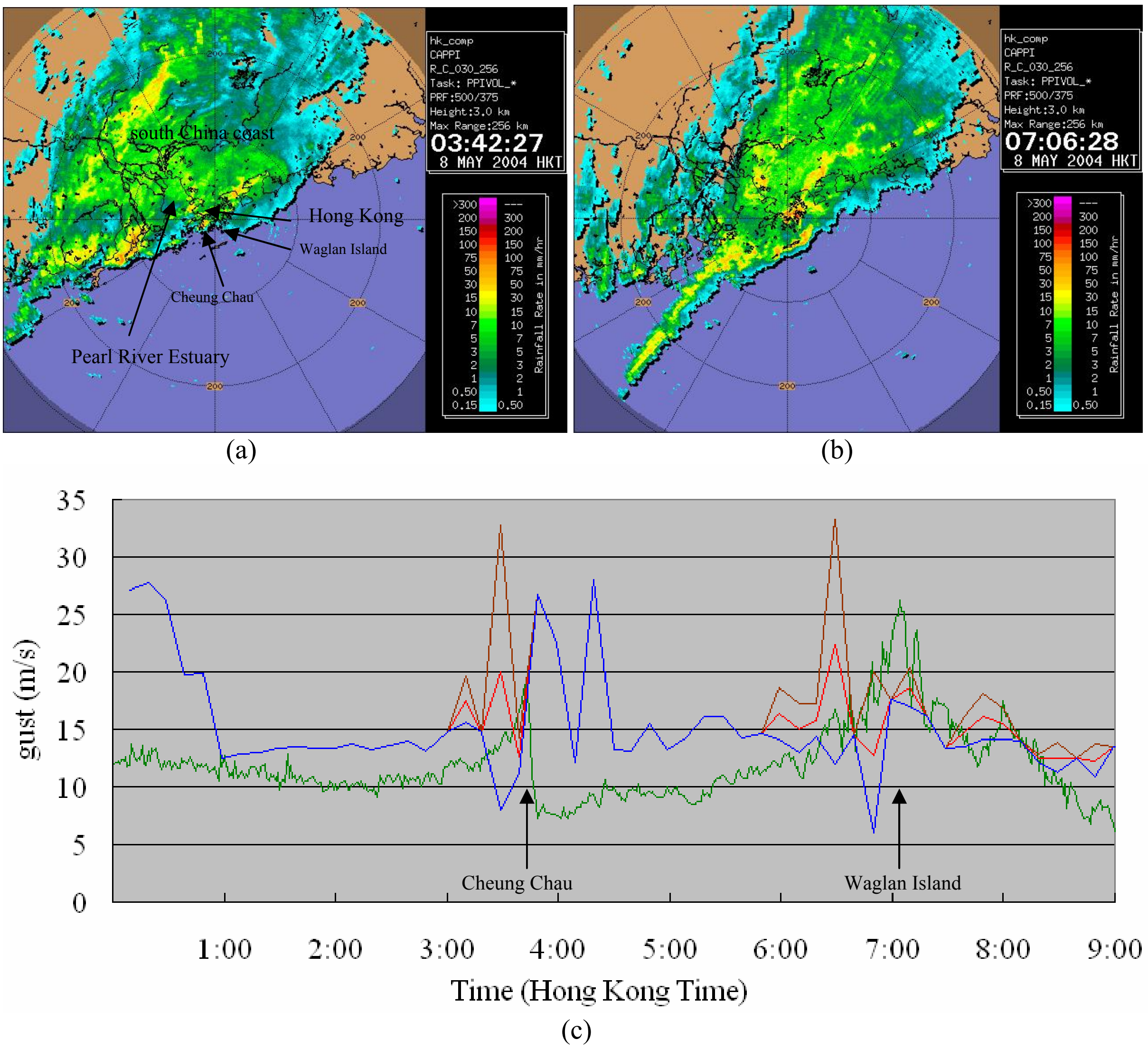
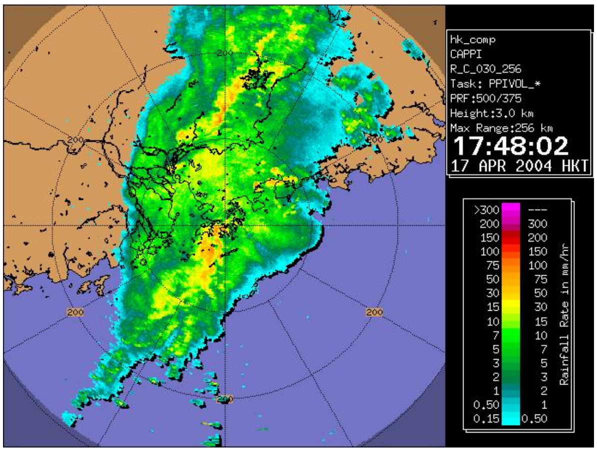
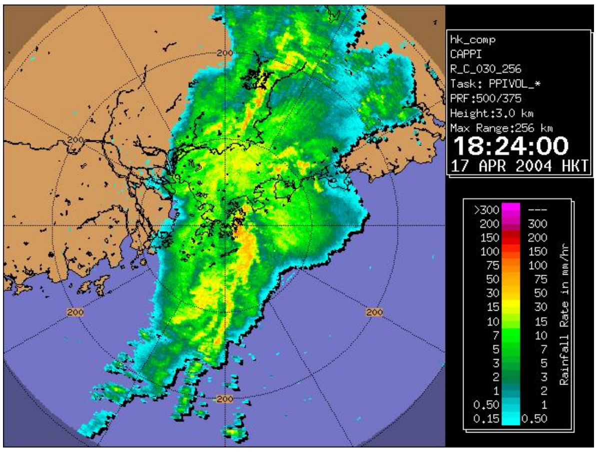


Figure 3. (a) and (b) are the 256-km radarscope images of Hong Kong at 3 km above mean sea level at 3:42 and 7:06 a.m., 8 May 2004 respectively. (c) is the time series of the largest value of the actually measured wind gust from the surface anemometers (green), GU_{min} (blue), GU (red) and GU_{max} (brown).



(a)



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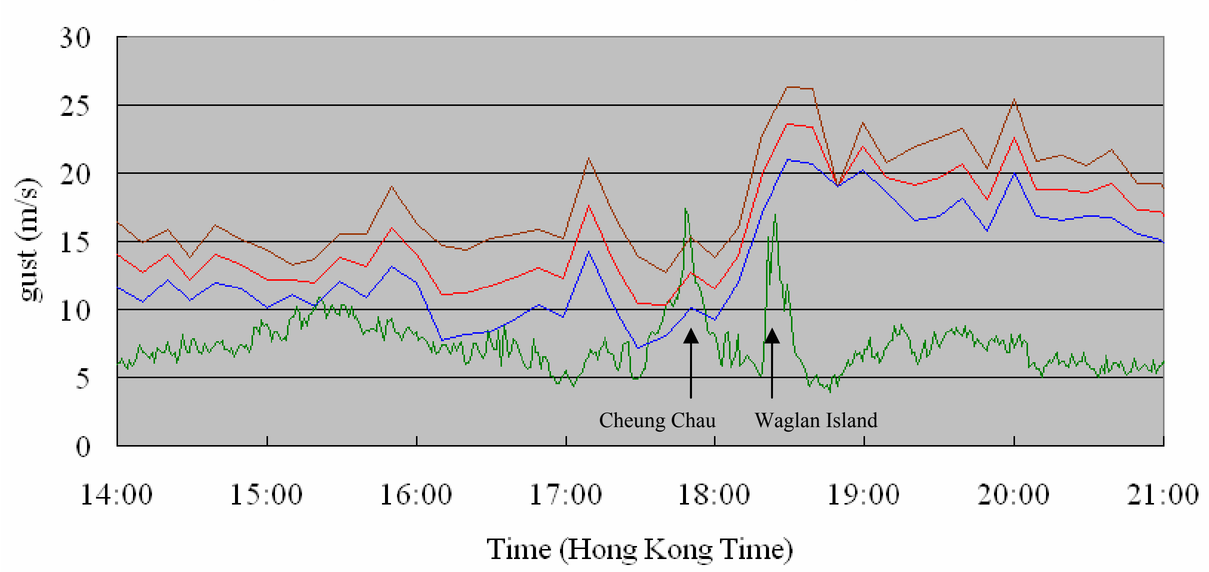

(c)

Figure 4. (a) and (b) are the 256-km radarscope images of Hong Kong at 3 km above mean sea level at 5:48 and 6:24 p.m., 17 April 2004 respectively. (c) is the time series of the largest value of the actually measured wind gust from the surface anemometers (green), GU_{min} (blue), GU (red) and GU_{max} (brown).