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Numerical Simulation of a Severe Squall Event in Hong Kong

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1. INTRODUCTION

In the summer, Hong Kong, located over the coastal area of southern China, is occasionally affected by tropical squall lines associated with troughs of low pressure, southwest monsoon or tropical cyclones. The high wind gusts in the severe squall events could be hazardous to aircraft operation as well as activities of the general public.

This study examines the possibility of forecasting severe squalls using a numerical weather prediction model for a squall line case in Hong Kong on 9 May 2005. A brief description of the event is given in Section 2. The model configuration is described in Section 3, with the simulation results presented in Section 4. Section 5 discusses a physical approach adopted to estimate the wind gust based on the model results. A brief summary of the effect of cloud-top turbulent mixing in the simulation result is presented in Section 6. Section 7 gives the conclusions of this study.

2. BRIEF DESCRIPTION OF THE EVENT

A trough of low pressure affected the inland area of southern China in the morning of 9 May 2005. A squall line developed in the strong southwesterly flow ahead of the trough and moved southeastward to Hong Kong. It swept across the territory between noon and 1 p.m. (local time = UTC + 8 hours), bringing gusts of about 20 m/s to the Hong Kong International Airport (HKIA) and more than 30 m/s to some other places in Hong Kong (Figure 1). The largest gust was recorded at the container terminal at Kwai Chung (location in Figure 1), reaching 37.6 m/s. A more detailed account of the event could be found in Lam and Lam (2006).

On the radar display, a bow-shaped echo was observed when the squall line moved across Hong Kong (Figure 2). Strong southwesterly wind prevailed at the surface ahead of this intense radar echo with northwesterly flow at its rear (Figure 3). The passage of the squall line at a location showed up as a rapid change of the wind direction (from southwesterly to northwesterly) and a sharp peak in the wind speed (associated with the squall) in a matter of several minutes. Figure 4 gives a typical example of the wind trace of an anemometer in this event. It shows that the southwesterly flow ahead of the squall line was rather gusty, with a mean wind of about 10 m/s and the gust reaching 16 m/s or so. The squall line moved past that anemometer at about 12:18 p.m. and the gust reached a maximum of 21 m/s in the northwesterly flow. The wind remained northerly for about half an hour afterwards, and became significantly weaker and less gusty. The temperature at HKIA also dropped from a high of 27^{o}C to about 21^{o}C. This was the period when the cold pool behind the squall line affected the territory. Starting from around 1:20 p.m., winds turned to southeasterly and the temperature rose again after the passage of the cold pool.

Measurements from the wind profiler at Sham Shui Po (location in Figure 1) show that the northwesterly flow at the rear of the squall line extended up to about 1.5 km above ground (Figure 5). Further aloft, there was a southwesterly jet of about 31 m/s (60 knots).

3. MODEL CONFIGURATION

The Regional Atmospheric Modelling System (RAMS) version 4.4 (Cotton et al. 2003) is used in this study. It is nested with the 4D VAR version of the Regional Spectral Model (RSM) of the Observatory, which has a horizontal resolution of 20 km (Yeung et al. 2005). The 4D VAR RSM uses radar-based rainfall estimate to adjust the dynamic and thermodynamic fields of the model. The squall line is reasonably well analyzed in this model at the start of the simulation (8 a.m., 9 May 2005) because at that time it was located in the inland areas of the southern China, which is within the radar coverage of Hong Kong. In the 4D VAR RSM forecast, a bow-shaped heavy rain area moves across Hong Kong in the early afternoon of 9 May 2005 (Figure 6), consistent with the actual observations. However, the wind change in Hong Kong is not well simulated – southwesterly flow is forecast to prevail over the territory in the whole event and northwesterly squall is not predicted. This may be partly attributable to the coarse model grid.

Two nested runs of RAMS are performed with a horizontal resolution of 4 km (grid 1) and 1.33 km (grid 2). The model domains are shown in Figure 7. RAMS is again initialized at 8 a.m., 9 May 2005 and run for 8 hours. Cumulus parameterization is switched off for direct cloud scale simulations. Turbulent mixing at the top of the cloud/updraft is reduced by setting a flag in the turbulence module following the experience in the simulation of tropical cyclones (Mel Nicholls, private communication), in which dry Brunt-Vaisala frequency is used in the turbulence term instead of the moist one. The Smagorinsky turbulence scheme is employed, without the use of the turbulent kinetic energy (TKE) equation.

4. SIMULATION RESULTS

The RAMS simulation reproduces reasonably well the southeastward movement of the squall line.

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In the “radar” plot of the simulated surface rainfall in Grid 2 (Figure 8), an intense, bow-shaped “echo” is forecast to sweep across Hong Kong between noon and 1 p.m. of 9 May 2005, consistent with the actual observations. The updraft in this “echo” reaches a maximum of about 16 m/s (Figure 9), which is the magnitude to be expected in such a severe squall event.

At the surface, the model successfully simulates the strong southwesterly flow ahead of the squall line and the northwesterly flow at the rear of it. For instance, northwesterly wind of 15 m/s (29 knots) is predicted over HKIA after the passage of the squall line (Figure 10), consistent with the actual measurements. At the location of the R2C anemometer at HKIA in Figure 4, the wind direction change and the peak in wind speed associated with the squall line are reasonably well forecast (Figure 11). However, some discrepancies are observed between the actual and the forecast wind fields: (a) the arrival time of the squall line is later by about half a hour in the simulation, and (b) the cold pool behind the squall line is more widespread (not shown) and affects Hong Kong for much longer time in the model, e.g. the wind at HKIA (Figure 11) remains to be southwesterly to northwesterly for a couple of hours after the passage of the squall line.

The modelled winds at the location of Sham Shui Po wind profiler are given in Figure 12. The depth of the northwesterly flow behind the squall line is forecast to reach about 1.5 km, consistent with the actual data (Figure 5). The 60-knot southwesterly jet aloft is also well simulated. On the other hand, as observed in the simulated surface wind field, the west to northwesterly flow in the cold pool is forecast to last too long after the passage of the squall line.

5. GUST ESTIMATE

The wind gust estimate method in Brasseur (2001) is adopted in this study. It is based on the assumption that the air parcel at a given height could reach the ground if the mean TKE is greater than the buoyancy energy between the ground and the height of the parcel:

$$\frac{1}{z_p}\int_0^{z_p} e(z)dz \geq \int_0^{z_p} g\,\frac{\Delta\theta_V(z)}{\Theta_V(z)}dz \qquad (1)$$

where z_p is the height of the parcel considered, e the TKE, g the acceleration due to gravity, Θ_v the virtual potential temperature, and $\Delta\theta_v$ the variation of virtual potential temperature over a given layer. The gust is the maximum wind speed of all parcels in the boundary layer satisfying eq. (1).

Brasseur (2001) also gives a lower bound and an upper bound of the gust estimate. The lower bound is obtained based on the consideration of the local TKE instead of the mean TKE, with an equation similar to eq. (1) but replacing the left hand side by (2.5/11)$e(z)$. The upper bound is given by the maximum wind speed in the boundary layer. Following Brasseur (2001), the boundary layer depth is defined as the height where the TKE is 0.01 of the surface value.

Brasseur (2001) also discusses gust estimate in deep convection. Following his suggestion, the downdraft is also added to the horizontal wind speed in estimating the wind gust in this study.

Since TKE is not prognosticated in the model, it is calculated from the model variables using the following equation in Goyette et al. (2003):

$$TKE = \frac{1}{2}\left\{B_1 l_m\left[K_h S^2(Pr - Ri)\right]\right\}^{2/3} \qquad (2)$$

where B_1 is an empirical parameter fixed at 16.6, l_m the Blackadar mixing length, K_h the turbulent transfer coefficient for heat, S the vertical shear of horizontal velocity, Pr the Prandtl number and Ri the Richardson number.

The wind gust estimate at the location of R2C anemometer at HKIA is shown in Figure 11. It is generally consistent with the actual observation (Figure 4) with the upper bound reaching 20 m/s, close to the actual measurement of 21 m/s. Within the Hong Kong territory, the upper bound of the wind gust has a maximum value of 30 m/s based on the simulation results. Though it is smaller than the actual maximum gust observed (37.6 m/s), the gust estimate nonetheless provides a useful indication about the gust that could be attained in the present severe squall event (see the magnitude of gust in various places in Hong Kong in Figure 1).

Lam and Lam (2006) found that GUSTEX of Geerts (2001) gave a wind gust estimate of 25.2 m/s for the present event, which is even smaller than the gust estimated from the Brasseur (2001) method based on RAMS simulation. They proposed a modified GUSTEX using the wind at 700 hPa and the estimated gust value is closer to reality.

6. CLOUD-TOP TURBULENT MIXING

An experiment has also been carried out by retaining the default setting of cloud-top turbulent mixing in the simulation. The convective development turns out to be weaker. The maximum updraft is 12 m/s only, which is smaller than that in the model run without the cloud-top mixing. The arrival time of the squall line at Hong Kong is also later by an hour, with weaker northwesterly wind behind the squall line (14 m/s). The cloud-top turbulent mixing appears to have significant effect on the development of convection, the speed of propagation as well as the strength of rear inflow of the squall line in the simulation.

7. CONCLUSIONS

A numerical study of a severe squall event in Hong Kong on 9 May 2005 is studied using RAMS. The model is found to simulate successfully many aspects of the event, such as the development of a bow-shaped echo and the movement of the squall line. The wind gust is estimated from the simulation results using the method of Brasseur (2001) with the inclusion of downdraft. The maximum value of gust estimate, though smaller than the maximum gust observed in the event, provides a useful indication about the gust that could be attained due to the squall line and outperforms the other gust estimation methods like GUSTEX. The reduction of cloud-top turbulent mixing is found to have significant effect on the model results, such as the development of convection and movement of the squall line. Simulations would be performed for other squall line cases in the future to study the possibility of applying the method discussed in this paper to predict the wind gusts in severe squall events in operational weather forecasting.

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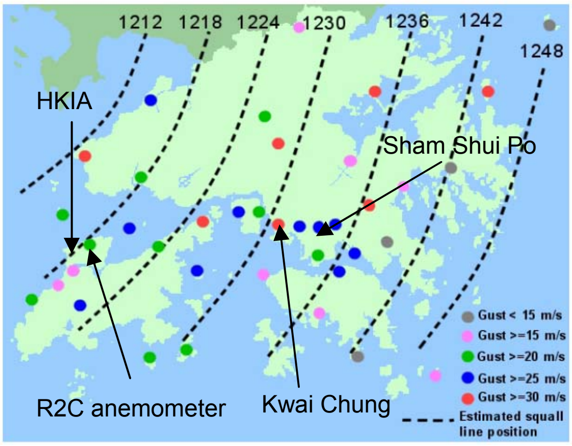

Figure 1 Location of the squall line in the 9 May 2005 event and the gust measured at various places in Hong Kong due to the squall line.

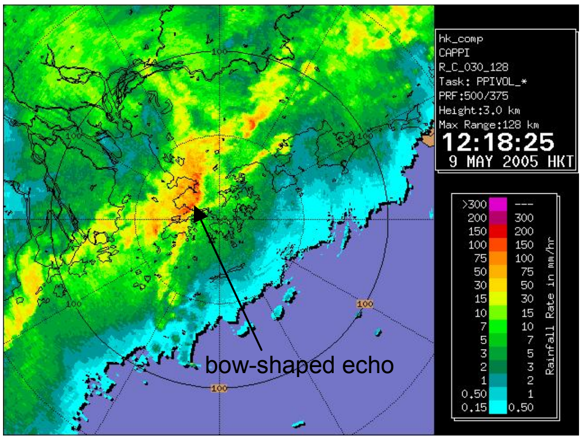

Figure 2 128-km range radar picture of Hong Kong at 12:18 p.m., 9 May 2005, showing the passage of the squall line across the territory.

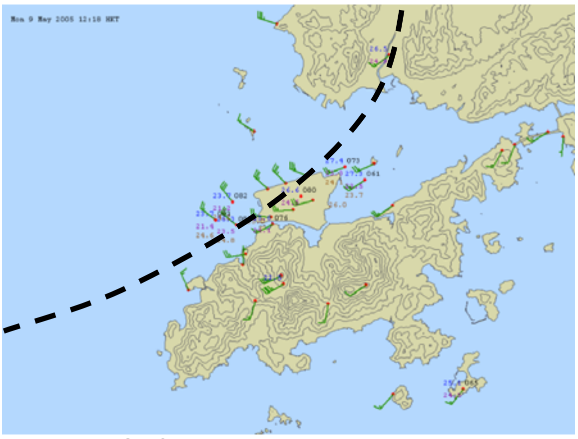

Figure 3 Surface observations at 12:18 p.m., 9 May 2005, with the estimated location of the squall line indicated by a dashed line.

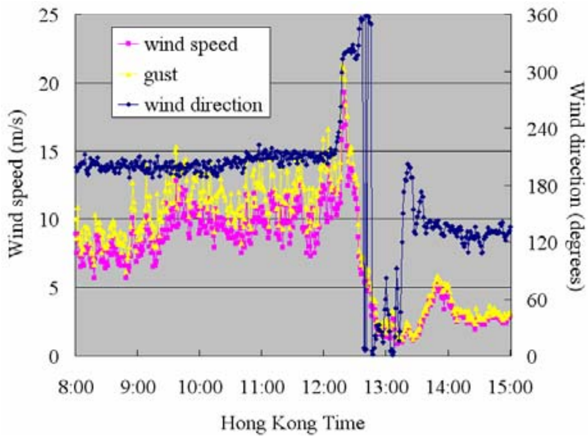

Figure 4 Wind data from the R2C anemometer (location given in Figure 1) in the severe squall event on 9 May 2005.

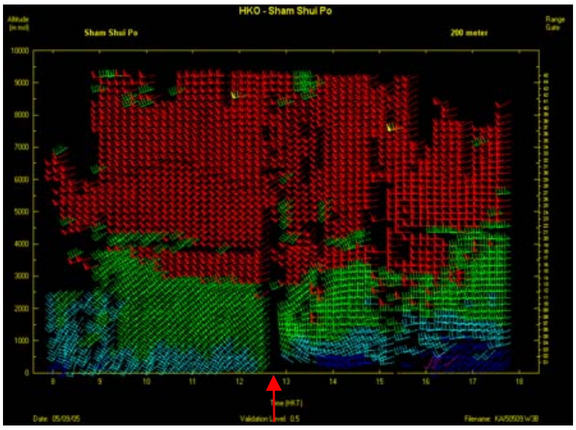

Figure 5 Upper-level wind data from the radar wind profiler at Sham Shui Po (location in Figure 1) on 9 May 2005. The time of squall line passage is indicated by an arrow.

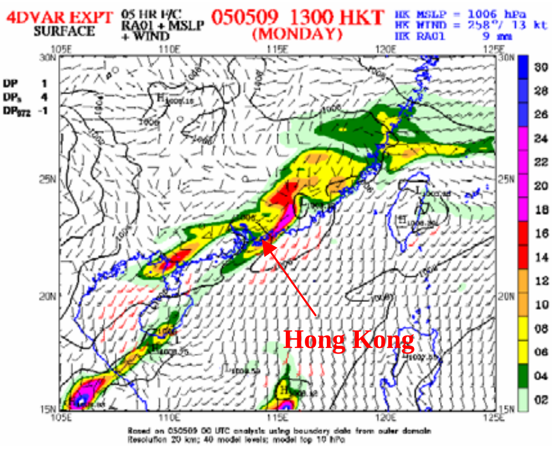

Figure 6 Simulated surface wind, pressure and hourly rainfall at 1 p.m., 9 May 2005 based on 4D VAR RSM model initialized at 8 a.m. on that day.

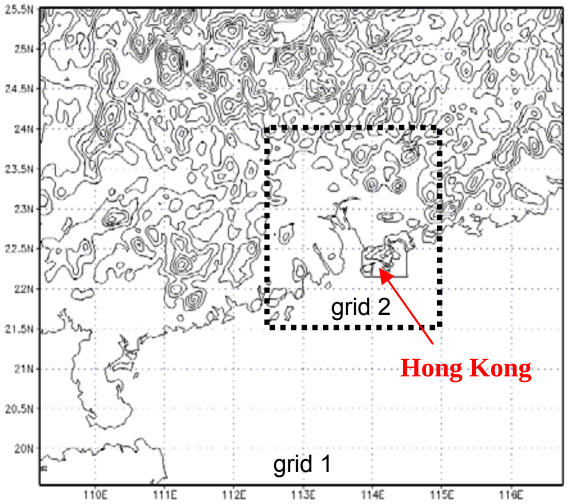

Figure 7 Model domains in RAMS simulation.

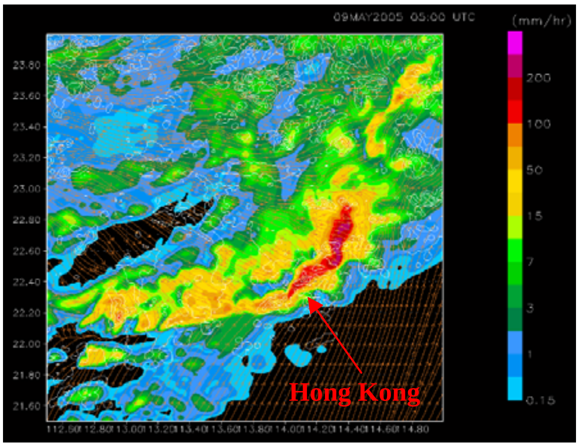

Figure 8 "Radar" plot of the simulated surface rainfall in Grid 2 of RAMS simulation at 1 p.m., 9 May 2005.

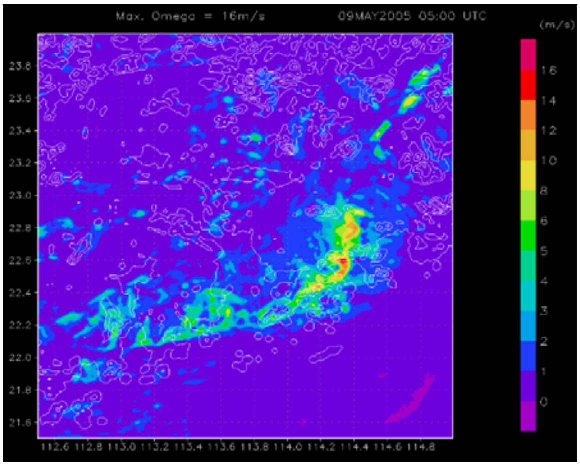

Figure 9 Maximum updraft strength simulated using RAMS at the same time as in Figure 8.

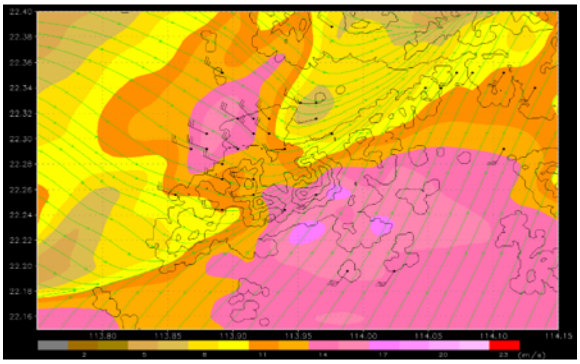

Figure 10 The simulated surface wind magnitude (colour shaded), streamlines (green lines) and winds at the anemometer locations (wind barbs) at 12:50 p.m., 9 May 2005.

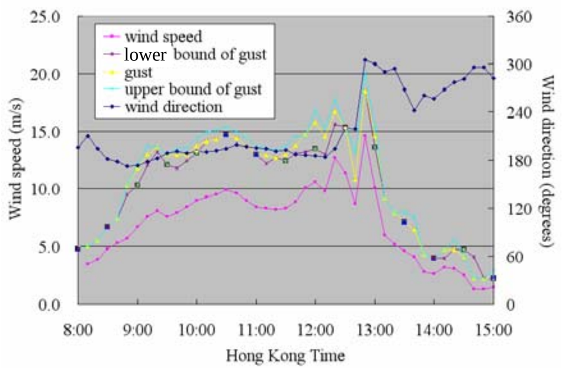

Figure 11 The simulated surface wind speed and direction from RAMS and the wind gust estimate from the Brasseur (2001) method at the location of R2C anemometer at HKIA.

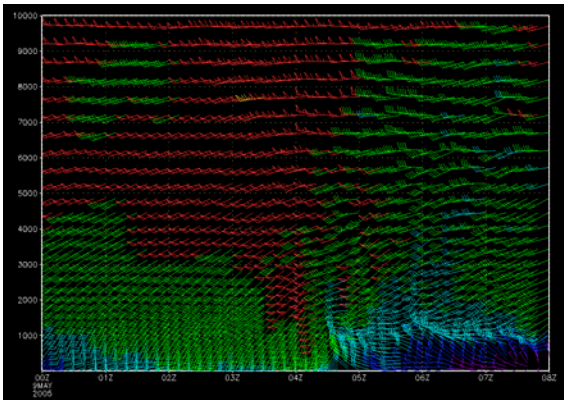

Figure 12 The simulated vertical wind profiles from RAMS at the location of Sham Shui Po wind profiler.