

NUMERICAL SIMULATION OF WIND GUSTS IN TERRAIN-DISRUPTED AIRFLOW AT THE HONG KONG INTERNATIONAL AIRPORT

P. Cheung *, C. C. Lam and P. W. Chan
Hong Kong Observatory, Hong Kong, China

1. INTRODUCTION

The Hong Kong International Airport (HKIA) is an island surrounded by complex terrain. To its south is the hilly Lantau Island with peaks rising to about 1000 m above mean sea level and with valleys as low as 400 m in between. Winds from the east to southwest could become turbulent and gusty after flowing over the Lantau terrain. The development of objective guidance for forecasting gust will be beneficial to aviation forecasters in support of their preparation of the aerodrome forecast (TAF), take-off and landing forecasts, as well as aerodrome warning of strong wind and gusts.

This study explores the feasibility of using a high-resolution numerical weather prediction (NWP) model to forecast gusts associated with terrain-disrupted airflow in two typical weather conditions of gusty winds at HKIA, namely, southwesterly flow, and east to southeasterly flow. The simulation of high gust associated with tropical cyclone was also studied in this paper. Nested model runs using the Regional Atmospheric Modelling System (RAMS) version 4.4 (Cotton et al., 2003) at a spatial resolution down to 200 m were conducted to simulate orographically enhanced high wind events. The simulation results are compared with surface anemometer observations in the vicinity of the airport. The effect of turbulence parameterization schemes on gust forecasting is also examined.

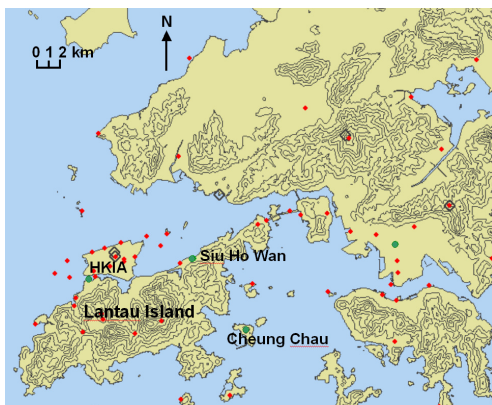


Figure 1. Land sea distribution and topography around HKIA. The locations of anemometer stations and wind profilers are marked by red and green dots respectively.

* Corresponding author address: Ping Cheung, Hong Kong Observatory, 134A, Nathan Road, Kowloon, Hong Kong, China; email: picheung@hko.gov.hk.

2. MODEL CONFIGURATION

The RAMS was run in three nested grids at a horizontal resolution of 4 km, 800 m and 200 m respectively (hereafter referred to as Grids 1 to 3). The model domains for the nested runs are shown in Figure 2. The boundary and initial conditions were provided by the forecasts and analysis of the Regional Spectral Model (RSM) of the Hong Kong Observatory (HKO) with a horizontal resolution of 20 km.

Topography data used in the RSM are extracted from the 30 arc-second Advanced Very High Resolution Radiometer (AVHRR) dataset from U.S. Geological Survey, while Grids 1 to 3 uses the 3 arc-second resolution data from Shuttle Radar Topography Mission (SRTM). Vegetation is also resolved at 3 arc-seconds with five classes, namely, crop/mixing farming, irrigated crop, evergreen broadleaf tree, desert (only applied to HKIA which is reclaimed land), and ocean.

The Mellor-Yamada Level 2.5 turbulence closure scheme (1982) was employed in the model runs. In Grids 2 and 3, the large eddy simulation (LES) to calculate large scale turbulent eddies explicitly and parameterize small turbulent eddies was also tested, and the results were compared with those using the Mellor-Yamada scheme.

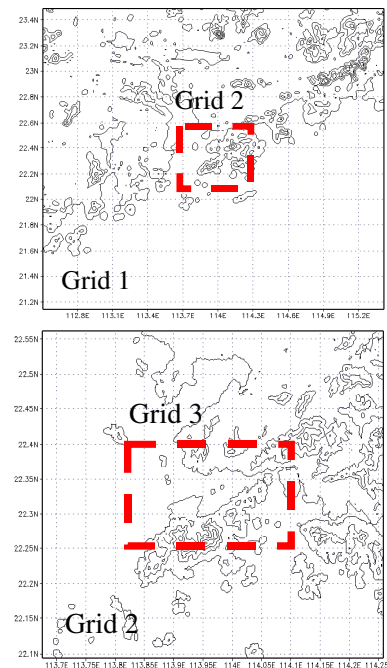


Figure 2. Model domains of the RAMS.

3. GUST ESTIMATION

The wind gust estimation method by Brasseur (2001) was 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:

$$\frac{1}{z_p} \int_0^{z_p} e(z) dz \geq \int_0^{z_p} g \frac{\Delta\theta_v(z)}{\Theta_v(z)} dz \quad (1)$$

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 eqn. (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. The boundary layer depth is taken as the height where the TKE is 0.01 of the surface value. In the estimation of gust in deep convection, the downdraft is also added to the horizontal wind speed.

TKE is a diagnostic variable and is calculated from the model variables using the following equation (Goyette et al., 2003):

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

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

The maximum gust estimated by the algorithm within the area marked in Figure 3 is taken to be the gust forecast by the model while the maximum gust recorded by the six anemometers along the runways serves as the actual gust observation for forecast verification.

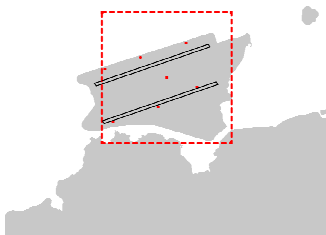


Figure 3. Area marked by the red box in which model data from 200-m RAMS were used for forecasting gust at HKIA. Red dots on HKIA mark the location of the six anemometers on the runways. The black dot marks the position where simulated vertical profiles were extracted for study in section 5.

4. MODELLED GUST

4.1 Strong southwesterly flow on 8 April 2008

A trough of low pressure developed over central China late on 7 April 2008 (Figure 4). The southwesterly flow over southern China was enhanced. Locally in Hong Kong, hilltop winds to the south of HKIA strengthened from the south up to around 15 m/s between 10-11 a.m. on 8 April. Southwesterly winds over HKIA freshened at around noon and gustiness also increased. The maximum observed gust over HKIA was about 15 m/s in the afternoon and evening of 8 April. Winds moderated near midnight. The trough of low pressure over central China and the southwesterly flow over southern China weakened afterwards.

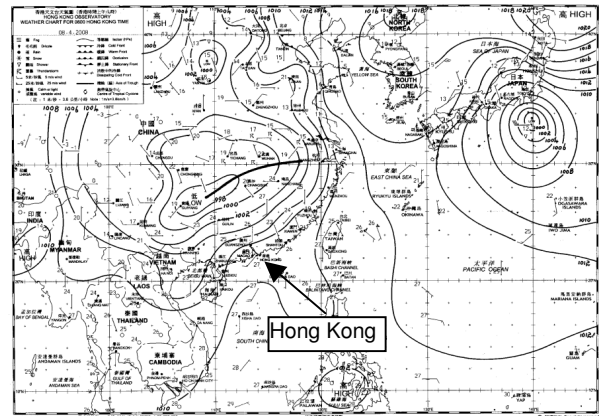


Figure 4. Mean sea-level pressure pattern at 8 a.m. on 8 April 2008.

RAMS could basically forecast the increasing trend of wind strength in the early morning (Figure 5). The maximum gust forecast from the model run initiated at 8 a.m. of 8 April was over-estimated by about 4 m/s compared with the observed maximum at HKIA.

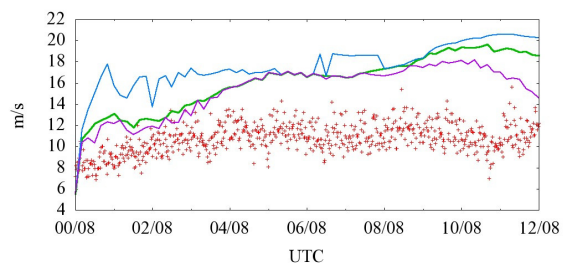


Figure 5. Time series of 12-h maximum gust forecast by 200-m RAMS with model initial time at 8 a.m. on 8 April 2008 (model forecast in green line, upper bound in blue line and lower bound in pink line) compared with the observed maximum at HKIA (data at 1-min intervals represented by red dots) (Local time = UTC + 8 hours).

4.2 Strong east to southeasterly flow on 10 April 2008

A ridge of high pressure developed over southeastern China later on 10 April 2008 and extended southwards on the following day (Figure 6). Surface easterlies strengthened at HKIA at about 6 a.m. on 11 April. Low level winds veered to the south at around 600 m as depicted by wind profiler data. The cool easterlies were shallow and a low level inversion developed between 400 and 800 m after the onset of easterlies (Figure 7). Figure 8 shows the vertical profile of low level winds in the upstream and downstream of the Lantau Island. Strengthening of low level southeasterly winds from around 10 m/s to 15 m/s was found between 200 m and 800 m when they passed over the hills over Lantau Island with height close to that of the inversion. The timing and strength of the strong low level southeasterlies matched with those of the observed maximum gusts at HKIA during 9 a.m. to 1 p.m. on 11 April. The strong southeasterlies on the hill tops were rather localised over the Lantau Island (Figure 9). The Froude number in this case was found to be 0.7-1 (taking the mean wind speed of 10 m/s, the Brunt-Väisälä frequency of 0.02 /s, and the height of hills on the Lantau Island ranging from about 500 m to 900 m). The flow on the upwind side was subcritical. Thinning and acceleration of airflow occurred on the upslope side and attained maximum at the crest when the Froude number was close to 1 (CAeM website). In case the Froude number equals to 1 at the crest, the flow will become supercritical and continue to accelerate as it descends the lee side until it adjusts back to the ambient subcritical conditions (Holton, 2004). The effect of topography apparently plays a significant role to the gusty condition in this type of east to southeasterly flow in the presence of a low level inversion close to the hill top.

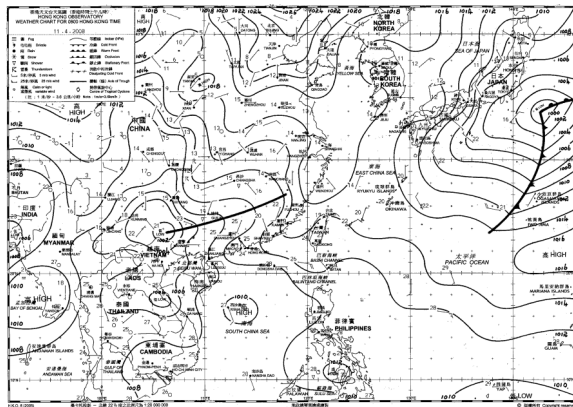


Figure 6. Mean sea-level pressure pattern at 8 a.m. on 11 April 2008.

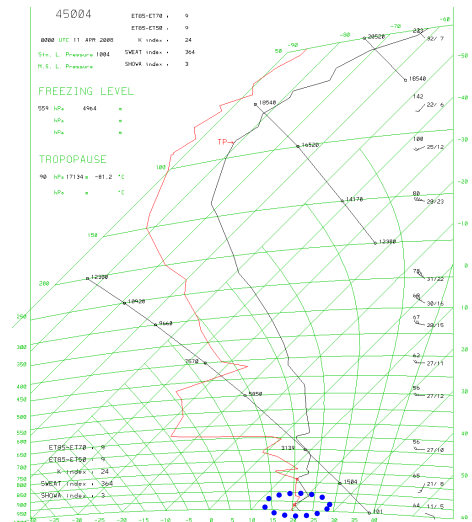
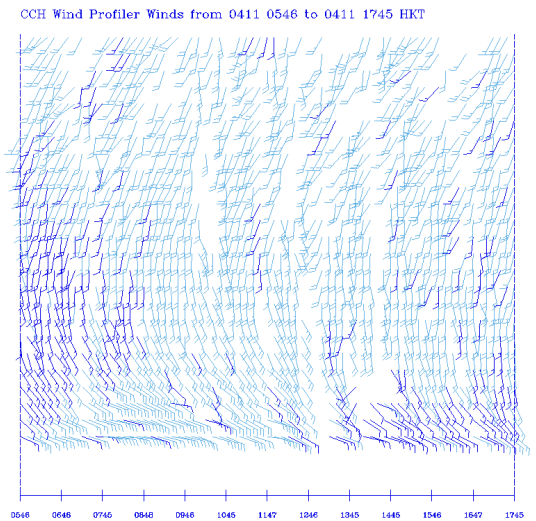


Figure 7. Ascent data of Hong Kong at 8 a.m. on 11 April 2008. A low level inversion near 950 hPa is circled in blue.

(a)



(b)

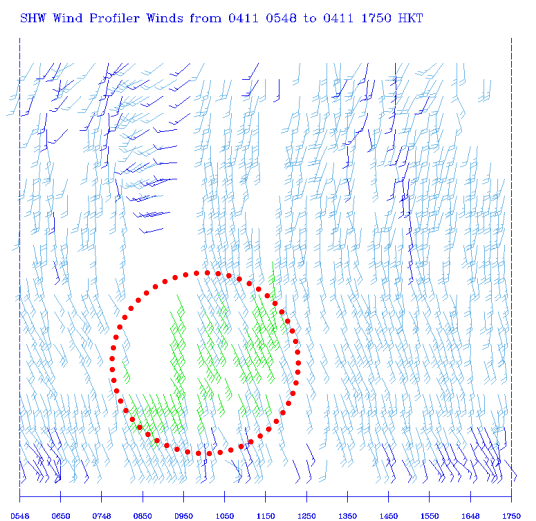


Figure 8. Low level wind profiler recorded on 11 April 2008 at (a) Cheung Chau (upwind side) and (b) Siu Ho Wan (downwind side). A low level jet (circled in red) appeared in the downwind area after strong southeasterly winds passed over the hills on the Lantau Island.

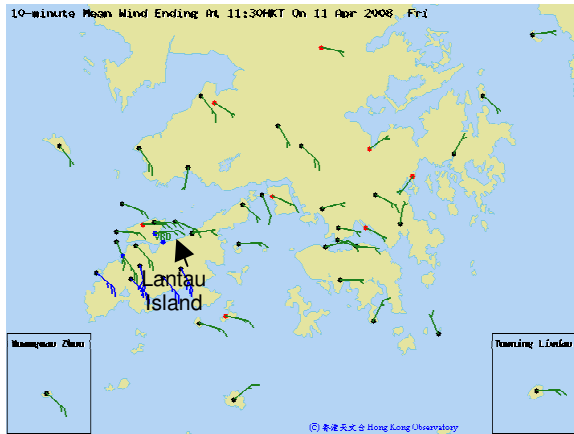


Figure 9. Wind distribution over Hong Kong at 11:30 a.m. on 11 April 2008.

The model forecast increasing gust about four hours earlier than observed at HKIA on the morning of 11 April. However, the model forecast maximum gust attained at around noon on that day was consistent with the observed, though the strength was over-estimated by about 2 m/s (Figure 10).

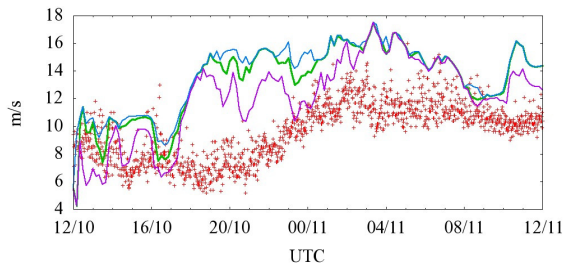


Figure 10. As in Figure 5, but for 24-h model forecasts initialised at 8 p.m. on 10 April 2008.

4.3 Tropical cyclone Neoguri on 19 April 2008

Neoguri formed as a tropical depression over the South China Sea and it tracked generally northwards skirting the northeastern tip of Hainan on the early morning of 19 April 2008 (Figure 11). It once intensified into a typhoon, but weakened to a tropical storm as it moved north-northeastwards towards the coast of Guangdong. Under the combined influence of Neoguri and the northeast monsoon, winds at HKIA were strong easterlies for most of the day on 19 April. When Neoguri passed to the west of Hong Kong at about 150 km, winds strengthened further from the south, reaching more than 15 m/s and gusting up to about 25 m/s during the evening of 19 April. Wind speed at HKIA momentarily decreased to about 2 m/s at around 6 p.m. just prior to strengthening from the south. It appears that this sudden drop in wind speed could not be well depicted in the model forecast (Figure 12).

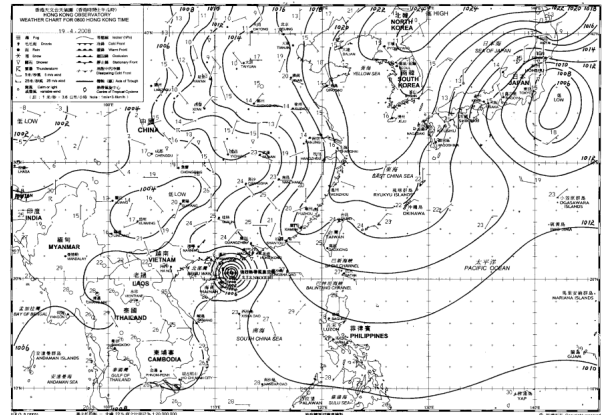


Figure 11. Mean sea-level pressure pattern at 8 a.m. on 19 April 2008.

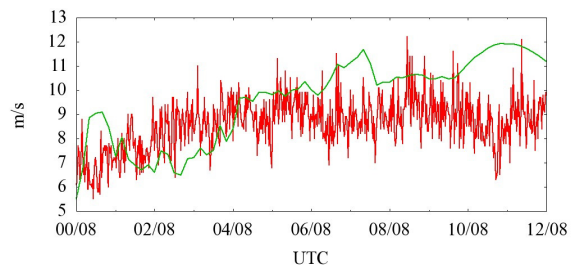


Figure 12. 24-h maximum surface wind forecast by 200-m RAMS within the red box in Figure 3 with model initial time at 8 a.m. on 19 April 2008 (green line) compared with the observed maximum 10-min mean wind on the runways at HKIA (red line).

Apart from the momentarily drop in wind speed, model maximum gust forecast was in general in good agreement with the observed maximum (Figure 13). The general increasing trend on the morning of 19 April and the decreasing trend after around 9 p.m. that day could be depicted by model forecast.

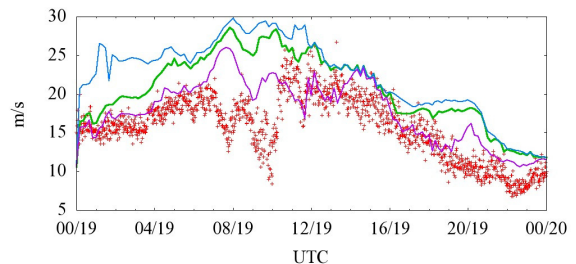


Figure 13. As in Figure 5, but for 24-h model forecasts initialised at 8 a.m. on 19 April 2008.

5. EFFECT OF TURBULENCE PARAMETRIZATION SCHEME

Gust forecasts from model runs utilizing LES as the turbulence parameterization scheme did not show significant difference as compared with those from the runs using Mellor-Yamada Level 2.5 turbulence closure scheme except for the case of strong east to southeasterly flow on 11 April 2008 (Figure 14). The first peak of maximum gust occurred at around midnight of 10 April could be depicted by the upper bound forecast from the model run using LES, but not the one using Mellor-Yamada Level 2.5 turbulence closure scheme.

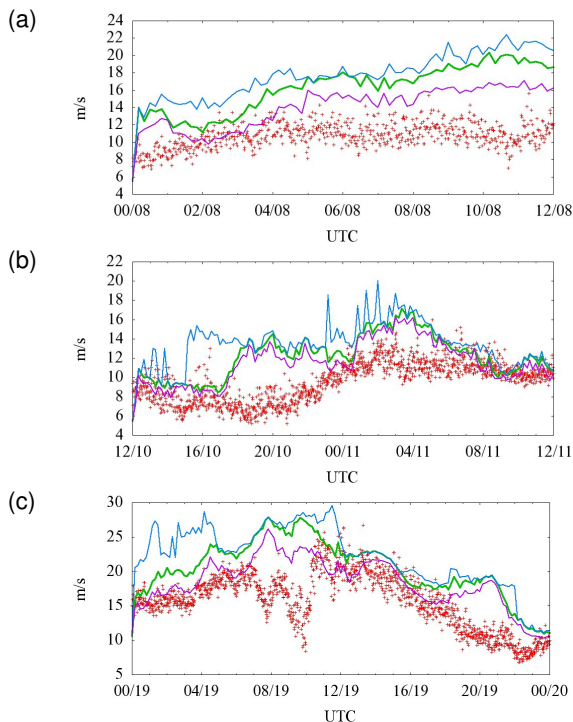


Figure 14. (a), (b) and (c) same as Fig. 5, 10, 13 respectively except for using LES instead of Mellor-Yamada Level 2.5 turbulence closure scheme in the model runs of 800-m and 200-m RAMS.

Since the upper bound of gust forecast is given by the maximum wind speed in the boundary layer whose depth is taken as the height where TKE is 0.01 of the surface value, the discrepancy suggested that the two turbulence parameterization schemes produced rather different vertical profiles of TKE. The vertical profiles of TKE and wind speed at HKIA (location marked by black dot in Figure 3) extracted from model forecasts at midnight of 10 April 2008 are shown in Figure 15. The Mellor-Yamada scheme estimated the boundary layer top at around 500 m, while that of the LES scheme was around 1400 m. Consequentially, winds of larger speed at higher levels were taken as the gust upper bound based on the LES scheme.

The vertical profiles of downdraft for the two schemes are also shown in Figure 15. The LES scheme successfully depicted the downdraft

associated with the accelerated descent of the supercritical air flow from around 500 m while the Mellor-Yamada scheme has no such indication. It should be noted that the downdraft is also considered in the gust estimation as described in section 3.

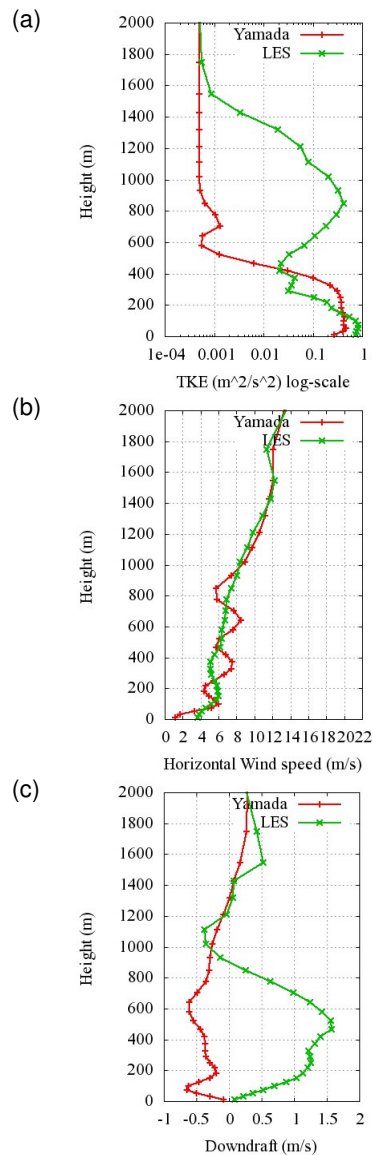


Figure 15. Vertical profiles of (a) TKE, (b) horizontal wind speed, and (c) downdraft at HKIA at the midnight of 10 April 2008. The TKE plot is in log-scale, red for the LES and green for the Mellor-Yamada scheme.

Further tests would be needed to yield conclusive results for the performance of two schemes in different types of weather pattern and the impact of turbulence parameterization scheme on model gust forecast.

6. CONCLUDING REMARKS

Cases of high gusts associated with terrain-disrupted airflow at HKIA in typical weather conditions of strong southwesterly flow, and east to southeasterly flow, as well as during the passage of tropical cyclone were studied with the use of 200-m RAMS. Model could generally depict the increasing

or decreasing trend of gusts, and that was consistent with the observed trend, though the timing could be a few hours earlier than the actual. The forecast gust strength was in general over-estimated by about 2-4 m/s. The effect of topography apparently plays a significant role to the gusty condition particularly in the case of strong east to southeasterly flow in the presence of a low level inversion close to the hill top. Model runs with the use of LES or Mellor-Yamada Level 2.5 turbulence closure scheme as the turbulence parameterization scheme shows similar results of gust forecasts except for the case of strong east to southeasterly flow in which the former produced better forecasts. The production of TKE and downdraft explained the discrepancy in the forecasts. The effect of turbulence parameterization scheme on gust forecast needs to be further examined with more cases. The use of high-resolution model in forecasting high gust events associated with terrain-disrupted airflow is promising. Further tests will be conducted to explore the model application in operational forecasting of gust.

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