Application of MM5 for Short-Range Aviation Forecasts Over Hong Kong

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1. Introduction

Mesoscale numerical models with explicit physical parameterization and high horizontal and vertical resolution have become a powerful tool for mesoscale meteorological research and for operational prediction. Because of the need to provide very short-range prediction of severe weather in the vicinity of the airport, aviation weather prediction has become a very important application of mesoscale models. In the past five years, the Penn State/NCAR mesoscale model, MM5, has been used for several projects related to aviation weather forecasts. These include the study of inflight and ground icing prediction of the Winter Icing and Storm Project (WISP), snowfall forecasts, and the ceiling and visibility prediction.

Recently, NCAR/UCAR through Weather Information Technologies, Inc. (WITI) has started a project to develop and deliver an Operational Wind Shear Warning System (OWWS) for the new airport at Chek Lap Kok (CLK) in Hong Kong. The OWWS will provide users, including pilots, airlines, the Air Traffic Service, airport operators, the Royal Observatory Hong Kong (ROHK) and others with alerts of topographically-induced wind shear and turbulence (TIWT). The OWWS will include two major components, an instrumentation and a modeling component. The instrumentation component will integrate products and convective wind shear alerts from the Terminal Doppler Weather Radar (TDWR) that will be installed at CLK, thereby providing a single source of wind shear and turbulence products and alerts. The modeling component will provide short-range prediction of the mesoscale airflow and thermodynamic structure in the vicinity of Hong Kong. The model forecasts will then be used as input to a topographically-induced windshear and turbulence detection and diagnosis algorithm to provide short-range prediction of TIWT. The MM5 model will be used for this purpose.

In this paper, we present some of the ongoing work in testing and evaluating the MM5 model for the OWWS project. In section 2, we will discuss the proposed model configuration and update cycle. The testing and evaluating of the MM5 modeling system on a few selected cases will be discussed in section 3. Concluding remarks and a plan for future work will be given in the final section.

2. Proposed Model Configurations for the OWWS Project

The role of the MM5 system in the OWWS project is to predict the mesoscale atmospheric conditions associated with TIWT events near Hong Kong and to provide daily forecasts for the region. In order to do so, several factors have been considered for the design of the model configurations.

To allow for maximum areal coverage and computational efficiency, a two-way nested domain structure is selected. The coarse mesh has to be large enough to ensure adequate regional upper-air and surface data coverage for analysis updates, to include various types of weather systems influencing Hong Kong, and to minimize possible forecast contamination from the lateral boundary conditions. The fine mesh with a grid distance less than 20 km is desirable for predicting a wide range of mesoscale weather systems that are of special forecast interest to Hong Kong and the OWWS. The model should also have adequate vertical resolution for the objectives of the OWWS project and for the selected physical parameterization. The model has to complete a 24-h forecast within 2 h in order to meet the operational requirements. An outer domain of sufficiently larger size is also needed so that a secondary configuration using fixed boundary conditions can be used when necessary.

Working under these constraints, the proposed MM5 modeling system for the OWWS project consists of two configurations. The first configuration is comprised of two domains with grid sizes of 54 km and 18 km. This configuration is used during normal operation when lateral boundary conditions are available from the US National Meteorological Center's (NMC) Aviation forecast (AVN). When lateral boundary conditions are not available from the NMC for five consecutive times, the second

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configuration, consisting of three domains (162 km, 54 km and 18 km), will be used. The 162-km domain will be used to provide lateral boundary conditions for the 54 km/18 km model. The proposed configurations are illustrated in Fig. 1. All model domains consist of 27 sigma levels.

The forecast/analysis cycle will use the previous MM5 12-h forecast as the first guess fields. The first guess fields are then enhanced with observations through objective analysis. The model's initial conditions are generated through a four-dimensional data assimilation procedure with Newtonian nudging. The MM5 forecasts will be 24 h in duration and generated with either a 6-h or a 12-h update cycle. Figure 2 shows a schematic diagram for a 12-h update cycle. The forecast is scheduled to complete in 2 h. With the accompanying lag time of the global forecast, this provides 17 h of usable MM5 forecast in a 12-h update cycle. The usable forecast can be extended if the 12-h old NMC AVN forecast is used to provide the lateral boundary conditions.

The physical processes to be included in MM5 are the predictions of ground temperature, surface fluxes of momentum, sensible and latent heat, the Blackadar multi-level PBL, explicit predictions of cloud/ice and rain/snow, a cumulus parameterization scheme, and a simple atmospheric radiation calculation. The non-hydrostatic version of the MM5 model will be used, which will allow for possible further grid nesting at 6 km and 2 km with a consistent model configuration. The proposed MM5 model will be run on a high-performance workstation.

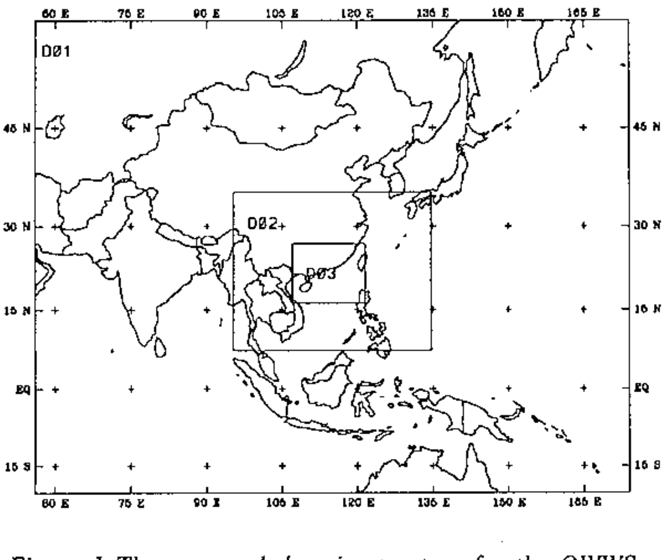

Figure 1 The proposed domain structure for the OWWS project. D01 denotes the 162-km domain, D02 the 54-km domain, and D03 the 18-km domain.

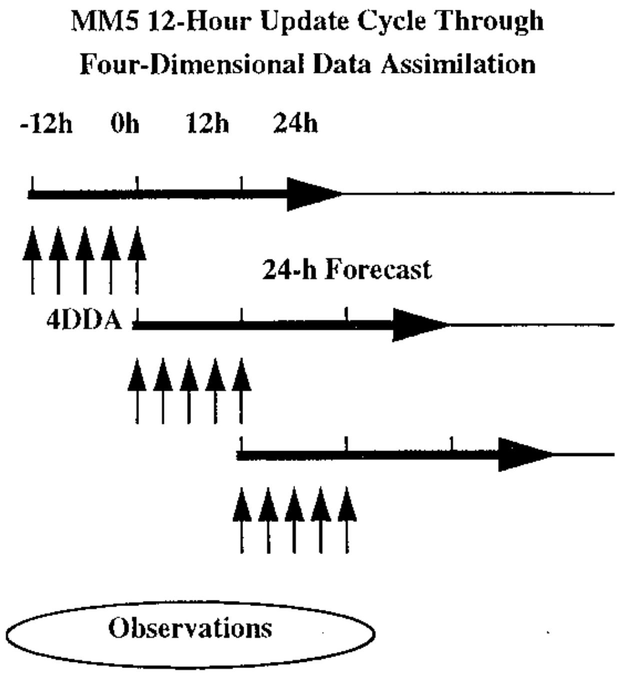

Figure 2 Schematic diagram to show a 12-h update cycle for generating a 24-h forecast.

3. Case Studies

In order to use MM5 reliably for the OWWS project, we need to test the model on a wide range of mesoscale weather systems in the subtropical regions in the vicinity of Hong Kong. The proposed model configuration is currently applied to a number of meteorological events that include heavy precipitation episodes, cases of moderate to severe turbulence on the north side of the Lantau island, Hong Kong, and a record-breaking cold air outbreak event (not shown). The preliminary numerical simulations of these cases indicate that the MM5 model possesses good forecast skills in predicting a wide range of mesoscale weather systems and environmental flow conditions that are conducive to TIWT in the region. However, many of the simulation details are sensitive to model physics, grid sizes and terrain resolutions. In the following subsections, three of these cases are used to demonstrate the ability as well as the sensitivity of the model when grid sizes are decreasing to tens and the few-kilometer range.

a. Sensitivity of precipitation forecasts to cumulus parameterization schemes

A severe convective precipitation event occurred in Hong Kong on 8 May 1992. The heavy rainfall occurred from the early morning to mid-afternoon hours on 8 May (local time). The event consisted of two severe convective episodes: a locally developed squall line, and a convective system that propagated into the Hong Kong area from southwest China. The squall line produced a record one-hour rainfall of 109.9 mm. The two precipitation systems together generated over 300 mm of rain on the Hong Kong island during a 12-h pericd beginning at 2000 UTC 7 May.

The MM5 model captured the second precipitation system reasonably well, while the model only gave a hint about the first locally-generated convective system. The model, with either the Grell or Kain-Fritsch cumulus parameterization scheme (CPS), produced fairly good overall precipitation forecasts over a 12-h period as the system moved southeastward passing through Hong Kong (not shown). However, the hourly precipitation structure from the two CPSs runs is quite different. Figure 3 shows the hourly rainfall fields as predicted by the two CPSs at 0600 UTC 8 May (18-h forecast) from the 18-km domain.

Tropical storm Russ was observed over the South China Sea on 4-8 June 1994. The storm tracked from the southeast to the south, and then to the west-southwest of Hong Kong during the period. The MM5 model was initialized at 0000 UTC 7 June and run for 24 h. Both the Grell and Kain-Fritsch CPSs were used in the simulations of Russ. The hourly predictions of the precipitation from the 18-km domain at the end of the 18 h with the Grell and Kain-Fritsch schemes are shown in Fig. 4. Again, significant differences are seen in the rainfall distribution. These results indicate that

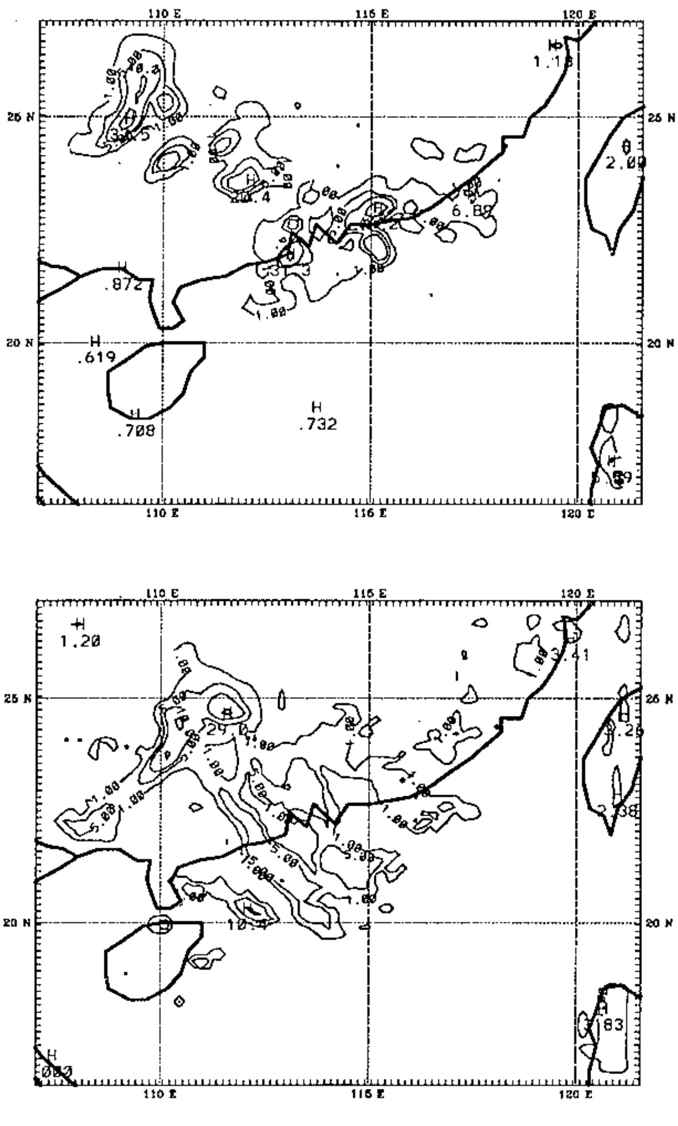

Figure 3 Simulated 1-h precipitation from the 18-km domain ending at 18 h of model integration (valid at 0600 UTC 8 May 1992) for runs with (a) Grell scheme and (b) Kain-Fritsch scheme. Contours are at 1, 5, 10, 25, 50 mm.

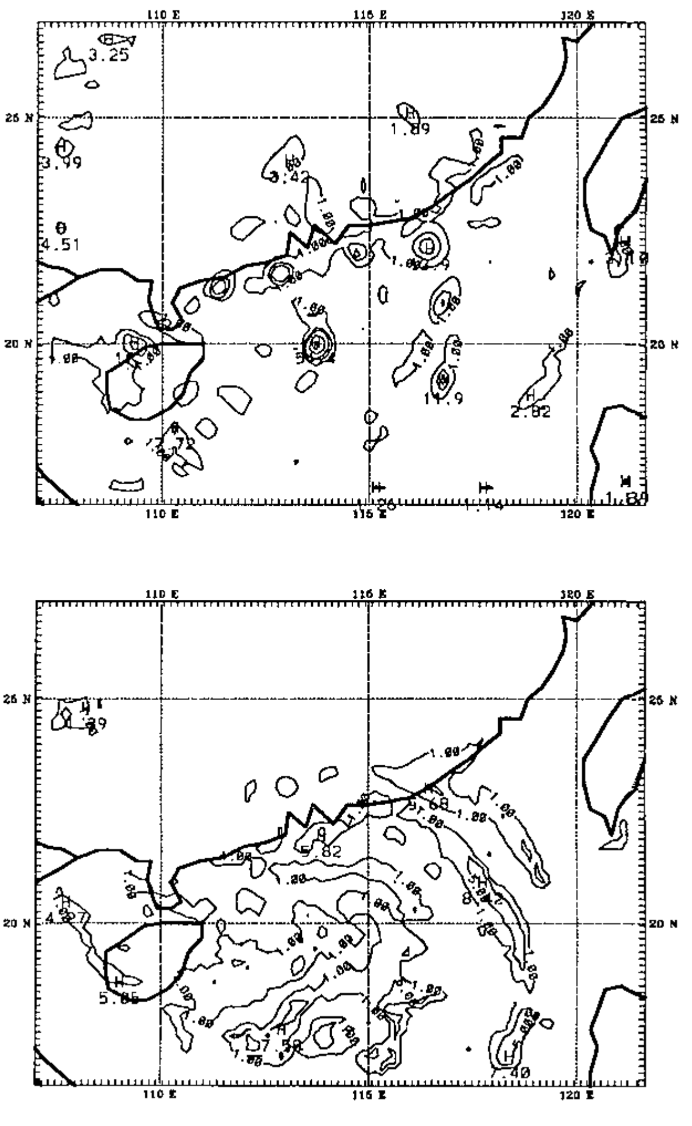

Figure 4 Simulated 1-h precipitation from the 18-km domain ending at 18 h of model integration (valid at 1800 UTC 7 June 1994) for runs with (a) Grell scheme and (b) Kain-Fritsch scheme. Contours are at 1, 5, 10, 25, 50 mm.

the prediction of precipitation systems over southern China is sensitive to the CPS used in the model.

b. Coupling of MM5 with a small-scale model

The model-based approach for forecasting TIWT consists of two components. The explicit prediction of TIWT is being tested with a small-scale model (Clark model; Clark 1977) which runs at a few hundreds of meters in grid length. The environmental conditions that are conducive to TIWT events are predicted with MM5. The coupling of these two models is achieved with MM5 providing soundings near Hong Kong to the Clark model.

A preliminary experiment was conducted in which a 6-h forecast sounding from MM5 for the tropical storm Russ case was provided to the Clark model, and the Clark model was run with the MM5 sounding and an observed sounding. The comparison of the MM5 sounding with the observed sounding shows that the MM5 predicted the stability and wind direction very well. The results from the Clark model also indicate that at a 500-m grid size, the simulated low-level flow fields from the MM5 sounding did as well as the run with the observed sounding (not shown).

c. Impact of terrain on the flow fields near Lantau

While the explicit prediction of TIWT is attempted using the Clark model in the OWWS, the MM5 model is also being tested with high horizontal resolution. The ability of the model to predict a correct response in the flow fields when Froude number, Fr = U/Nh (where U is the flow speed, N the Brunt Vaisalla frequency, and h the terrain height), is decreased to less than unity, was demonstrated in a high-resolution MM5 simulation of an observed TIWT case.

On 23 July 1981, moderate to severe turbulence was observed on the north side of the Lantau island. The ambient flow was characterized by an increase of strong low-level southerly flow on that day. The MM5 model was first run with triple nests at 54 km, 18 km and 6 km starting at 0000 UTC 23 July. The increase in the strength of the southerly flow was well-captured by the 6-km simulation. A 2-km model was then initialized from the 6-km model output in a one-way nesting mode at 0600 UTC 23 July and run for 12 h.

As the Fr decreased from larger than unity to about 0.6 by keeping the wind speed and stability unchanged but increasing the terrain elevation over Lantau, the low-level flow was deflected on the windward side of the obstacle, and moved around, instead of over, the Lantau island. There was also a flow reversal found on the windward side at the low levels. Figure 5 shows a simulated low-level wind field at 6-h model integration. Large-amplitude gravity waves can be seen on the lee side of the obstacle with wind speed reaching 34.5 m/s at the ground level 6 h into the forecast (Fig. 6). A critical level was located at about the 500 mb level (where the southerly flow

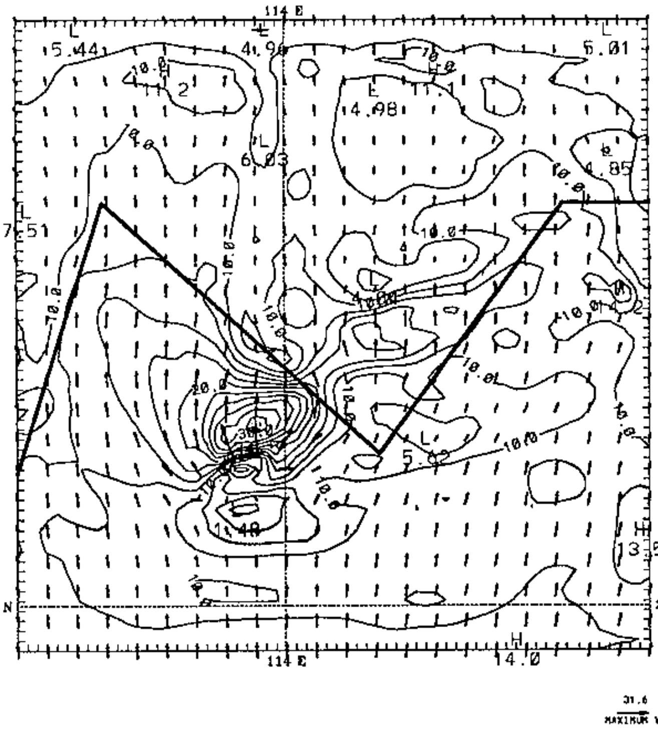

Figure 5 Simulated low-level wind field at 6 h into the 2-km model integration (valid at 1200 UTC 23 July 1981). Contour interval for the wind speed is 2.5 m/s.

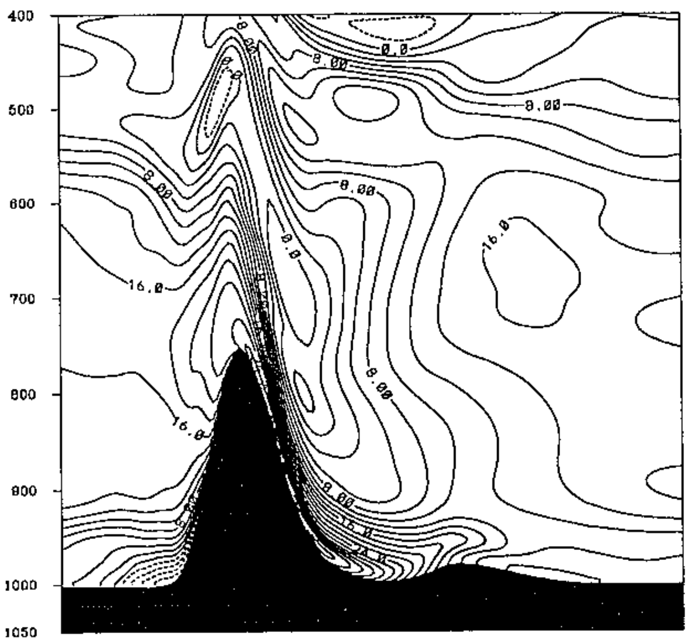

Figure 6 Cross-section plot of north-south component of the wind speed (m/s) at 6-h model integration (valid at 1200 UTC 23 July 1981). Contour interval is 2 m/s.

reversed to northerly), suggesting the possible occurrence of wave breaking. These non-linear responses of flow around obstacles when Fr becomes much less than unity is similar to the theoretical study of Smolarkiewicz and Rotunno (1989, 1990).

4. Summary and Future Work

Our experience with MM5 in support of the OWWS project shows that the MM5 model possesses good predictive skills over southern China, although there are also known forecast deficiencies for a given weather system studied. For instance, the local convective system associated with the May 8, 1992 event was underpredicted. The cold front moved too fast, and was too strong for the cold air outbreak event of January 1993 (not shown). The 24-h prediction of the lower-tropospheric wind at Hong Kong was off by 20-30 degrees in the tropical storm Russ case. These errors can be attributed to two major factors: model initial conditions and the model physical parameterization. The lack of sufficient observations over the South China Sea presents a great challenge to short-range numerical weather prediction in the vicinity of Hong Kong. The uncertainties in the planetary boundary-layer (PBL) parameterization and precipitation parameterization can also contribute significantly to the model forecast errors.

In the coming year, we will continue to test and evaluate the MM5 modeling system for the OWWS project. In particular, we will focus on three areas: (a) assimilating asynoptic data for model initialization, (b) testing and improving the PBL and precipitation parametrization, and (c) conducting semi-operational runs in the vicinity of Hong Kong.

To mitigate errors in the initial conditions, particularly for weather systems coming from the oceans, the inclusion of bogus data ingestion strategies (similar to the one currently used by the ROHK) in the MM5 data assimilation cycle should be examined. In the future, assimilation of satellite observations, and profiler and aircraft data should also be considered.

Implementing and testing additional PBL and precipitation parameterization schemes should be continued. It is possible that fine-tuning is required for all the existing schemes before they can be properly applied in the subtropical environment. Special attention needs to be given to the interaction between subgrid-scale cumulus parameterization and the grid-resolvable-scale precipitation parameterization to better simulate the development and evolution of mesoscale convective systems in this region.

Through semi-operational runs, we would be able to accumulate a sufficient number of cases to allow a statistically reliable evaluation of the MM5 modeling system in the vicinity of Hong Kong. This would allow us to identify the model systematic biases, and to have a better understanding of the performance of the MM5 modeling system. The verification results will provide directions for future model development. With the availability of high-performance workstations, work in this area will begin very shortly.

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