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Seamless Weather Forecast from Minutes to Days to Support Air Travel

W.K. Wong, S.M. Tse & P. Cheung

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# Seamless Weather Forecast from Minutes to Days to Support Air Travel

WONG, W.K., TSE, S.M. and CHEUNG, P.

Hong Kong Observatory  
Hong Kong SAR, China

## Abstract

*Heavy rain is a great concern in Hong Kong as it has significant socio-economical impacts and is one of the important factors affecting air traffic. Active research on weather forecasting techniques and development of new products and services are being undertaken by the Hong Kong Observatory (HKO) to foster more effective support of aviation weather forecasts, and to ensure timely warning and alerting services, and to produce tailored-made products in fulfilling operational demands from various aviation users and stakeholders. This paper will describe the state-of-the-art technologies employed to predict the weather from a few tens of minutes to several hours ahead, also known as nowcasting; up to a few days in advance through the numerical weather prediction (NWP) models. To overcome difficulties in capturing and predicting high-impact weather phenomena like significant thunderstorms which are usually violent but short-lived, nowcasting techniques are used to provide robust and rapidly-updated guidance, in every several minutes, on identification and movement of thunderstorms. For forecasts of more extended period, NWP models that provides a more comprehensive representation of the dynamical and physical factors leading to the changes of weather systems are used to generate deterministic or probabilistic forecast products, or through their intelligent blending with nowcast via machine-learning approach or human-computer interaction. Using aviation applications as an example, concepts and general methodologies of these sophisticated forecasting methods will be outlined in the presentation. Merits and limitations of these approaches will then be discussed followed by projections on future development and technological enhancements.*

## Keywords

*Heavy rain, air traffic, nowcasting, numerical weather prediction (NWP)*

## 1. Introduction

In southern China, thunderstorms and organized significant convection develop in association with frontal systems in spring, and monsoon trough as well as tropical cyclones in summer. When significant convection or organized thunderstorms affects the Hong Kong International Airport (HKIA) and the Hong Kong Flight Information Region (FIR), disruption in air traffic for in-bound and out-bound flights could occur. The reduction in the number of arrivals means some of the arrivals will be held up in

the air unless prior measures have been taken by the personnel of the Air Traffic Control (ATC) as part of its planning of Air Traffic Flow Management (ATFM) to minimize the disruptions of air traffic flow.

With increasing air traffic in Hong Kong and nearby airports in southern China, close coordination between ATC flow control units of adjacent FIRs becomes more important. This is particularly essential in order to assure flight safety at top-most priority, as well as to reduce flight delays and diversions, and to maximize capacity and optimize the flow of air traffic within the FIR. If the timing and severity of the convective weather could be accurately forecast and provided to ATC, prior arrangements could be made in the planning of air traffic flow to optimize flight operations and also reduce the unnecessary fuel burnt due to holding, thus reducing release of carbon dioxide and aerosol to the atmosphere and impact on the climate. If reliable significant convection forecasts are provided to airlines, they can make sure the arrival flights will have sufficient fuel in case holding is required so as to ensure flight safety. They may also make informed and collaborative decisions on whether to delay departure of the arrival flights. The aforementioned requirements call for robust methods on identification of significant or organized thunderstorms, tracking of their movements and predicting their future locations and intensities in the next 6-12 hours. Potentials or likelihood of the occurrence of significant convections in a day or beyond will also be useful for airlines, aviation users and travellers to plan the flights and prepare for necessary measures to ensure smooth operations.

This paper discusses the recent development in HKO supporting the aviation weather services on significant convection forecasts. A brief review on strategy and challenges of significant convection forecast is given in Section 2. Concepts of nowcasting and numerical weather prediction (NWP) model will be discussed in Section 3 and Section 4 respectively. Techniques on using nowcast and NWP products to foster forecast supports on thunderstorms and significant convection are then covered in Section 5 followed by discussion on future developments in Section 6. A conclusion will then be given in Section 7.

## 2. Challenges in Forecasting Significant Convection

Weather forecast process and service involve four major stages, namely: (a) monitoring of the current meteorological situations via observations; (b) analysis of features and signatures conducive to development of

weather phenomena; (c) predicting evolution or development of weather system; and (d) dissemination of forecast, alerts and warnings to users in timely and effective channels. Traditionally weather forecasts are issued, usually in every few hours, by forecasters after assessing all the weather information that are usually issued every few hours. However, given that significant convections and organized thunderstorms are usually rapid changing, small in spatial scale (known as “storm-scale” covering size of weather systems from 2 to 20 kilometres), and short-lived (in about few hours), such forecasts tend to be very general and given in descriptive terms.

Lately with advances in the quality of automated forecasts, very short-range forecast or nowcast products and those based on numerical weather prediction (NWP) models become more viable. As described in the next two sessions, these products on the one hand have their advantages due to high update frequency (once every few minutes or every hour) to capture the storm movement or development. On the other hand, there are still limitations in the performance of these automated products compared with the skills of experienced forecasters.

### 3. Nowcasting of Significant Convection

#### 3.1 Monitoring and Nowcasting Techniques

Monitoring of weather phenomena including significant convections are performed via several meteorological observation platforms. For instance, synoptic stations, automatic weather stations and rain-gauges record the surface conditions. The Doppler weather radar is a vital instrument for monitoring severe weather due to high update frequency (every 6 minutes) and good resolution (a few hundred metres) and relatively large coverage. Through emission of microwave signals to the atmosphere and detection of their returns upon hitting raindrops, also commonly termed as radar echoes, location and intensity of rain drops can then be obtained (Figure 1). In Hong Kong, two weather radars located in Tai Mo Shan and Tate’s Cairn are used to detect precipitation and convective weather systems over Hong Kong and neighbouring coastal regions up to about a radius of 500 km of range from the radar sites. Another radar, called the Terminal Doppler Weather Radar (TDWR) in Tai Lam Chung, is used specifically for monitoring convective and severe weather occurring near HKIA. Furthermore, the Lightning Location Information System (LLIS) of the Observatory is used to detect lightning activities due to electrical discharges occurring in thunderstorms.

The above remote sensing instruments provide very frequent updates of observations. In case of weather radars, the 3-dimensional distributions of radar echoes are obtained in every 6 minutes. Tracking of thunderstorms can be made from successive radar

images over 6-minute interval, or longer, to get the storm movement (Figure 2). The Observatory’s nowcasting system - SWIRLS (Short-range Warning of Intense Rainstorms and Localised Systems) was developed [Li et al, 2000] to employ this echo tracking technique to forecast the radar rainfall pattern by advecting the echo distribution using the storm motion field.

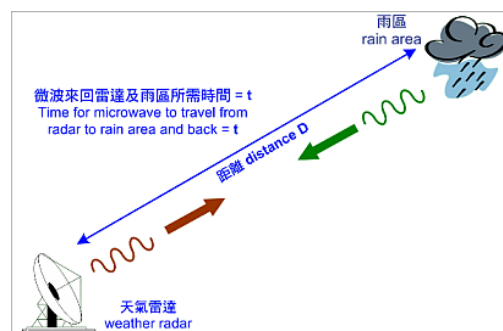


Fig.1 Basic principle of remote sensing of precipitation and thunderstorm using weather radar

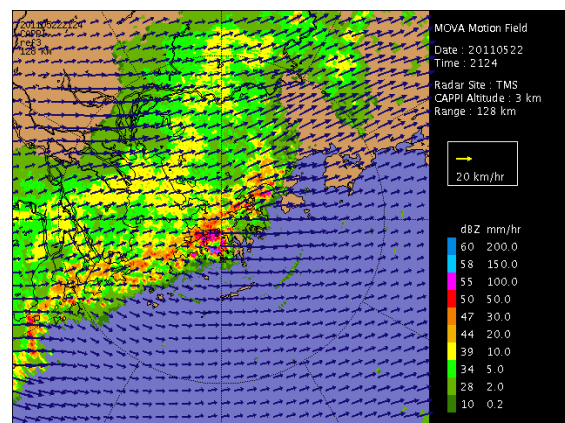


Fig. 2 Tracking of movement of radar echoes

#### 3.2 Thunderstorm Nowcasting

Built on the foundation of SWIRLS, the Observatory developed the Aviation Thunderstorm Nowcasting System (ATNS) for alerting thunderstorm and lightning near HKIA [Li, 2009]. ATNS was put into operational trial from March 2008 and was extended to cover the terminal area. The system provides the current storm area and forecast positions in one-hour ahead, in a time interval of every 6 minutes, of the thunderstorms affecting HKIA and the vicinity region. The arrival and departure routes are overlaid onto the thunderstorms. Various colours are used to represent the intensity levels of the thunderstorm (or severity of impact to aircraft) – red being severe, yellow being moderate and green being light. Besides the graphical presentation, a time series is provided to indicate the predicted impact of thunderstorms at various way-points of interest (top right-hand panel in Figure 3). Making use of the number of recorded lightning strokes from the LLIS, forecasts of lightning intensity around the airport region for sake of operation safety in

the airfield are available from the system called Airport Thunderstorm and Lightning Alerting System (ATLAS) [Li and Lau, 2008]. Using the product, ATM and

personnel of airport operations can obtain a more concise picture about the intensity and the locations to be affected by thunderstorms over the terminal area.

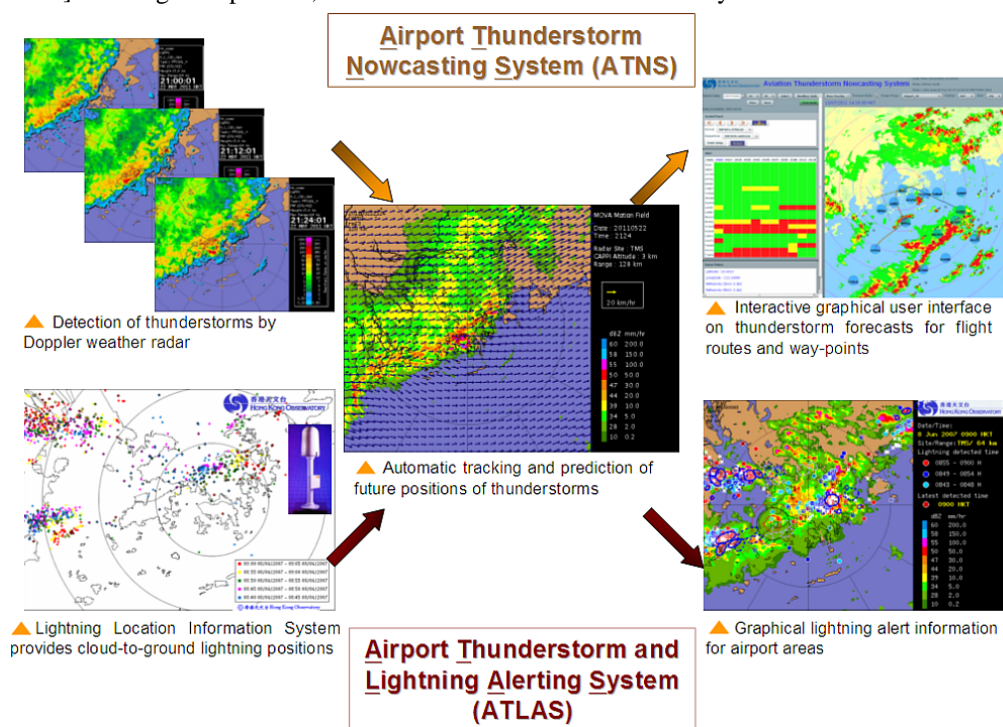


Fig. 3. Schematics of ATNS and ATLAS for nowcasting of thunderstorm and lightning.

#### 4. Forecast using Numerical Weather Prediction (NWP) Model

##### 4.1 Basic Principle of NWP

NWP model is a set of computer codes representing the governing equations of the atmosphere to predict its future states. Model weather forecasts are formulated by solving the governing equations of the atmospheric processes of winds, temperature, moisture and pressure. Analytical method is not permissible to determine the solutions of these governing equations due to their complexity. One of the common approaches adopted by NWP models to solve the governing equations is based on using a set of discrete grid points to represent the 3-dimensional atmosphere. Physical processes are computed on the grids to account for the effects due to exchanges of energy between the atmosphere and the land or sea surface, solar and terrestrial radiation, phase changes of water substance, cumulus convection and turbulence, etc. However, these physical processes are still too complex to be understood in full and, in practice, have to be simplified in order to obtain the model simulation results within available computation capacity to attain timely delivery of results to users.

##### 4.2 Mesoscale NWP Model System at HKO

Figure 4 describes a schematic of data flow in the current operational NWP system at HKO [Wong, 2011]. The core is a suite of mesoscale non-hydrostatic model (NHM) with two computation

domains running at horizontal resolution (spacing between two successive grid points) of 10-km and 2-km. The 10-km outer version covers Southeast Asia and the western Pacific while the 2-km inner version covers Hong Kong and its neighbouring areas in about 10 millions of grid points. Weather observations from surface synoptic weather stations, automatic weather station network, ships, buoys, radiosonde, aircrafts, and meteorological satellites are transmitted via the Global Telecommunication System (GTS), Internet, local and regional telecommunication links. The observations are processed through data quality control modules and input to the model system to compute the initial condition of model forecast. Errors in both measurements from the weather observations, as well as the NWP model are taken into account in the initial condition in order to generate an optimal atmospheric state for model prediction. Computation of model forecasts are then carried out on a high performance computer system to provide grid-point forecast of wind, temperature, humidity, pressure, cloudiness and precipitation - a total of about 10 forecast quantities per one grid point, for the next 72 hours (10-km model) and 15 hours (2-km model) ahead. To better capture the convective storms and mesoscale processes, NHM runs are performed every 3 hours for the 10-km model and once every hour for the 2-km model.

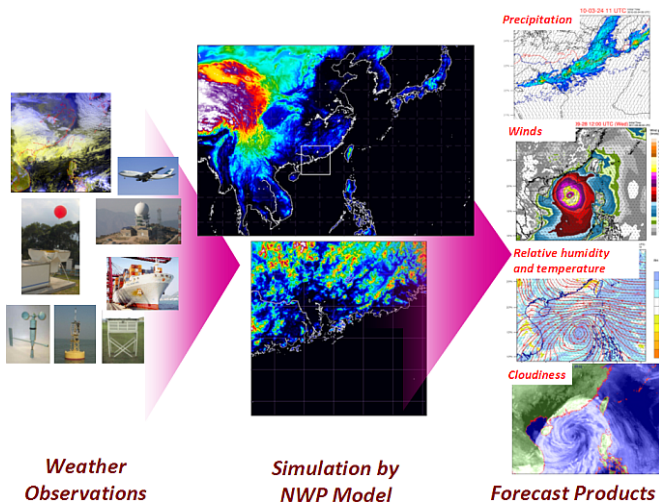


Fig. 4: Schematic of data flow in the NWP model system of HKO. The upper (lower) panel in the middle is the domain of 10-km NHM (2-km NHM).

#### 4.3 Other NWP Products

The Observatory has been receiving and making use of NWP data provided by major meteorological centres including Japan, the United Kingdom and the United States of America. These NWP model forecasts are made at the grid points (or through other mathematical methods) over the whole global atmosphere at about 16-40 km of grid spacing. Medium range forecasts up to 10 days ahead are obtained from the model runs performed at least twice a day (00 and 12 UTC – Coordinated Universal Time, 8 hours behind Hong Kong Time). These meteorological centres have much higher computation capacities that permit the model forecast operation in more advanced configurations, for example ingestion of many different types of meteorological satellite data to capture the global atmospheric condition, in particular over the oceans where number of surface and upper-air observation stations are very limited. The global NWP model forecasts are made available to other meteorological centres typically at least 6 hours after the model initial time. Besides the time latency, the model gridded data are provided at a coarser horizontal and vertical resolution than the full model configuration. These may be inadequate to delineate the development of significant convection as compared to the regional NWP model systems, as for NHM in HKO, that are running at higher spatial resolution (grid spacing at a few to 10 kilometres) with more rapidly-updated initial conditions (every 1 to 3 hours).

In addition to running a single model forecast (commonly called deterministic model forecast) as discussed above, the global NWP modelling centres operates an ensemble prediction system (EPS) – running the model with multiple instances of the atmosphere with slightly different initial conditions to simulate the effects of uncertainty in atmospheric

processes leading to development of possible scenarios of weather conditions like extreme rainfall. Currently, the EPS of these centres comprises of 50 members of model forecasts. Developments are underway in the Observatory on using the global NWP model products and EPS outputs to enhance the forecasts of precipitation, movement of tropical cyclones and other synoptic phenomena including cold surge.

## 5. Use of Nowcast and NWP

Both nowcasting and NWP techniques have their own merits and limitations in predicting significant convections. Radar-based nowcasting algorithms make use of tracking of convections and organized thunderstorms from radar scans in every 6 minutes, to produce relatively skilful prediction for the next tens of minutes or 1 hour when there is no significant change in the storm intensity and movement. However, as thunderstorms are usually short-lived, growth and decay of thunderstorms occur and hence the skill of nowcasting technique drops appreciably in 2-3 hours and beyond.

On the other hand, the NWP model incorporates physical and dynamical process that constitutes a better and complete representation of mesoscale processes. Hence the model products may provide indication on the development of storm. However, a number of factors could critically affect the model capability and accuracy in predicting convective storms in location, time and intensity. For instance, observations are usually insufficient to initialize all the model forecast quantities at all the grid points, especially those related to complex cloud process leading to storm development. The numerical methods employed to represent the full governing equations and physical processes can inevitably generate errors due to simplification made in order to allow feasible computation on available computer capacity.

Techniques to take advantages of both nowcast and NWP to provide better support in forecast of significant convection has been developed in the Observatory and will be illustrated in the following sections.

### 5.1 Blending of Nowcast and NWP

To improve the quality and enhance the reliability of the thunderstorm nowcasting, methodologies to incorporate the growth and dissipation of thunderstorm via NWP output have been developed. The so-called blending technique was formulated by combining SWIRLS radar-based rainfall nowcast and NHM output [Wong et al., 2009]. It has been put into operational trial and undergone some enhancements. A schematic is depicted in Figure 5 with the computation procedure outlined as follows: -

- (i) Phase correction: to tackle the problem of spatio-temporal errors in the direct model output of precipitation forecast. Location departure in the forecast precipitation patterns from NHM is estimated with respect to the actual gridded rainfall distribution derived from radar echoes;
- (ii) Calibration of intensity of model forecast rainfall: correction of the intensity of model precipitation based on radar-based quantitative precipitation estimate; and
- (iii) Blending of calibrated model rainfall forecast with the radar-based nowcast, with larger weighting assigned to the nowcast component at short lead times and increasing weighting to the NWP component as lead-time increases to 6 hours.

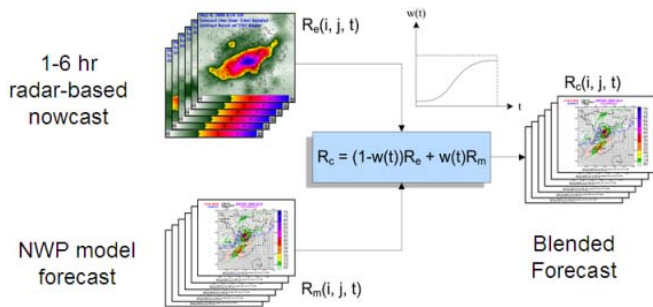


Fig. 5 Blending of nowcast and NWP

A case illustration on precipitation forecasts from nowcast-NWP blending and radar-based nowcast is shown in Figure 6. The passage of organized thunderstorms over Hong Kong during the overnight on 8 September 2010 was indicated in the blending forecast made at 18:00 HKT (i.e. 5 hours earlier). The forecast from the 2-km NHM, through phase correction procedure, indicated the passage of rain-band over Hong Kong and Pearl River Estuary at 23:00 HKT. On the other hand, without blending, major convections from the radar-based nowcast were located to the east,

due to a slower storm motion estimated at 18:00 HKT when the thunderstorms developed over inland Guangdong. However, there are still errors in timing and location in the blending forecast, as the phase correction applied was based on the comparison (steps (i) and (ii) above) made at the initial time of blending computation (i.e. 5 hours before 23:00 HKT). Changes in the phase errors and intensity calibration are not taken into account.

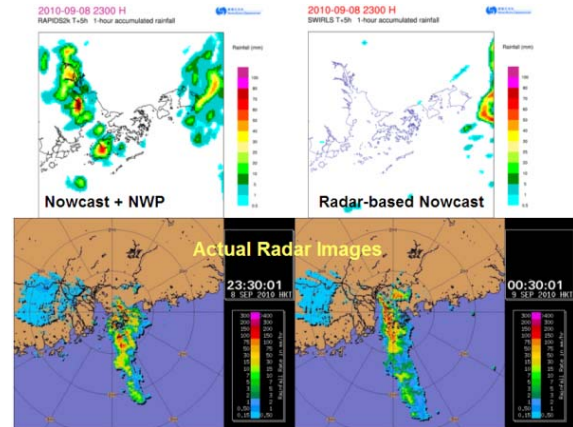


Fig. 6: Comparison of precipitation forecasts from nowcast-NWP blending and radar-based nowcast.

### 5.2 Incorporating Experience of Forecasters

In the above automatic blending method, the forecast products are available to forecasters once every 6 minutes in accordance with update frequency of radar image. In case when the automatic forecast products from nowcast, NWP model or their blending is not adequate to capture the actual storm development, forecasters' experience would be very valuable to improve the quality of forecast guidance and alerting service to the users.

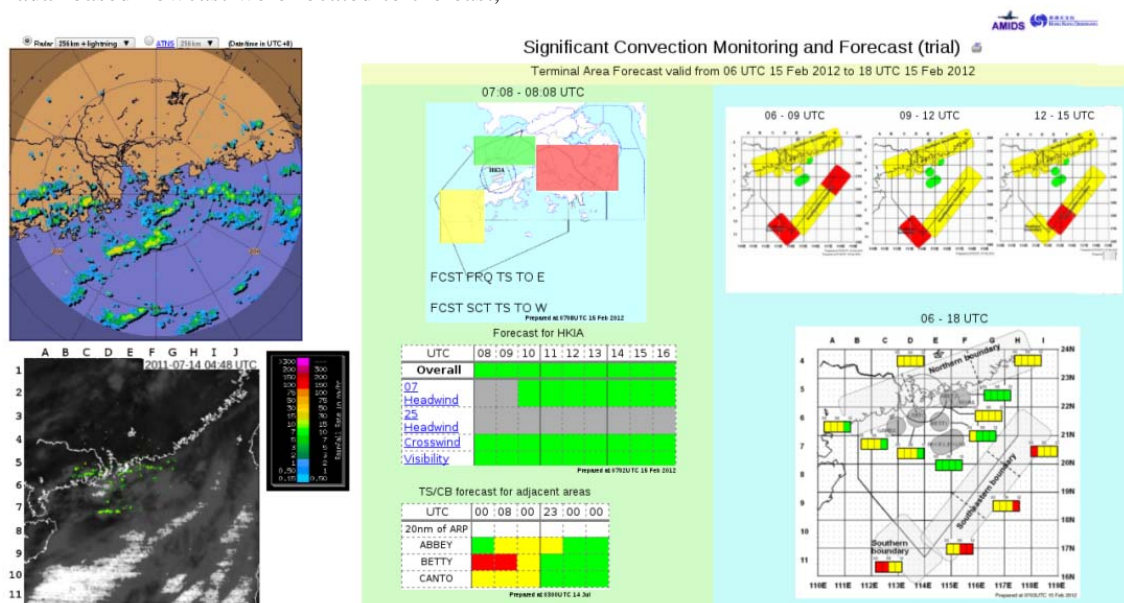


Fig. 7: Display of Significant Convection Monitoring and Forecast

To achieve this flexibility, a user-friendly interface is made available to forecaster to adjust the forecast from ATNS and NWP model outputs. Alerts on the convection intensity (red or yellow alerts) are first generated from NWP model outputs as a first-guess to forecasters. These alerting levels are derived from past model performance according to verification statistics. This “human-machine-mix” mode of operation not only utilizes the state-of-the art technology to enable rapid and frequent update of products based on the latest weather observations, but also the expertise of the forecasters based on their knowledge on the limitations of these automated products. To enable users to easily understand the product and make effective and informed decisions, the forecasts are presented in a graphical form with a succinct 3-tier colour scale indicating the chance of significant convection impacting ATM operations, viz. green, yellow and red colours respectively for low, medium and high impact (Figure 7). Short forecast message in the form of abbreviated plain language is also provided to facilitate dissemination of the information to pilots via ATC. The “human-machine-mix” could facilitate the provision of more frequently updated forecast and to accommodate specific requirements from users. With growing need for high spatial and temporal resolution forecast products which cannot be addressed by traditional forecast by forecasters, “human-machine-mix” products hold promise for future development. Again the experience gained could be extended to the development of new products for other sectors and even the general public.

## 6. Future Developments

Research and development are underway in the Observatory to further enhance the significant convection forecasts. These include the use of satellite data [Cheung et al, 2011], and combining radar data from the neighbouring cities to increase the detection coverage of such significant convections. Monitoring and tracking of movement of the thunderstorms can then be made over a wider area, paving the way for enhancement of thunderstorm nowcast over the way-points and whole Hong Kong FIR.

To enhance the skill of NWP model in the prediction of thunderstorm and significant convections, development will be made to ingest more observations (e.g. radar and satellites) in the model.

We would continue to reach out to the users and the aviation community to gather their views and feedback and to explore how these significant convection forecasts could be used more effectively. For instance, the graphical significant convection forecast (Figure 6) could be enhanced to generate textual message for forecasters’ reference. This is to facilitate

dissemination through social networks on the Internet such as Twitter to increase situation awareness of all stakeholders. The simplified text message can also be made available for access by pilot in the cockpit for making the necessary preparations ahead of encountering the significant convections.

In planning of flights across provinces or continents, route specific forecast on the occurrence of significant convection and other high-impact weather conditions like clear-air turbulence and icing potential could be useful for preparing safety measures and planning of alternative routes in advance. Figure 8 shows an example of the Observatory’s model forecast for the flight route from Hong Kong (HK) to Beijing (BJ). The 24 hour forecast cross section from 10-km NHM for upper-air from about 5.5 km to 12 km of altitudes (i.e. flight levels from 18000 feet - FL180, to 38000 feet – FL380) shows the wind barbs (red contours for wind speed), temperature (blue contours), areas with high moisture content (green) favourable for development of clouds or cumulus convection, and significant vertical wind shear (light purple) representing turbulent region. Along the route from HK to BJ in the model forecast, it would expect to encounter a high potential of significant clear-air turbulence (CAT) from 27 N to 31 N and on altitudes from FL250 to FL350 (denoted by T) due to large vertical wind shear and passage of a jet stream (i.e. narrow band of strong winds). Flying slightly further north, areas with high potential of convection development (region B) would be present according to the model forecast, and it agreed with the actual satellite image which clearly shows the presence of an area of significant convection (region A). This flight specific forecast would be explored after further refinements in the algorithms and the presentation.

## 7. Conclusion

HKIA is one of the busiest international airport in the world, 53.9 million passengers used the Airport and 3.9 million tonnes of air cargo passed through Hong Kong in 2011. If there is a 10-minute disruption of air traffic caused by significant convections, even when such are short-lived, about 1,000 passengers and 75 tonnes of air cargo will be affected. Timely and effective warning of the significant convections is therefore vital to ensure the smoothness in operation and flight safety, so that the impact to the aviation and related socio-economic activities could be minimized.

In this paper, the use of nowcasting technique and NWP model to forecast significant convection in aviation application has been discussed. Nowcasting technique and NWP model have their merits and drawbacks in depicting the potential of occurrence of organized thunderstorms. To meet the demands,

several developments have been carried out in the Observatory, for example the nowcasting system for thunderstorms, lightning and significant convection have been tailored for aviation purposes. The suite of significant convection forecasts is useful for raising situational awareness of the key stakeholders of the aviation community, facilitating effective planning and collaborative decision making before or when significant convective weather disrupts the smooth flow of air traffic, hence contributing to the safety,

regularity and efficiency as well as environmental sustainability of air navigation.

In addition, a high resolution NWP model system has been implemented to provide supports to simulate the mesoscale phenomena, as well as to enhance the skill of nowcasting techniques through the blending. Model outputs could also be utilised for future development of new products like the route specific forecast to help flight planning.

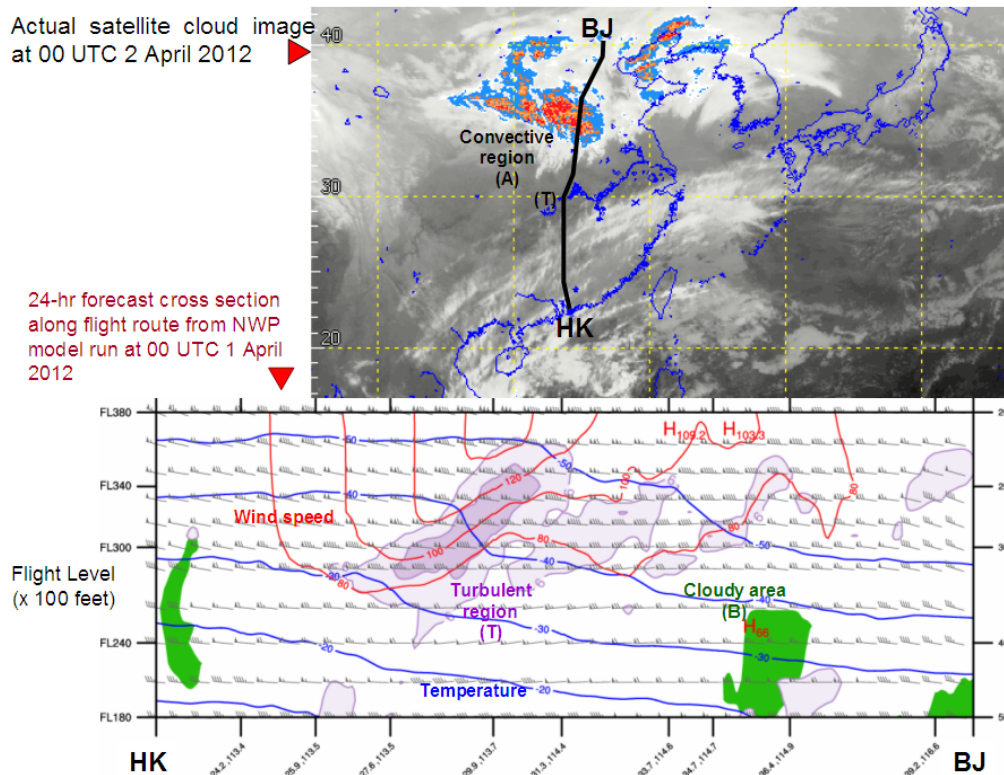


Fig. 8 A prototype route specific forecast for a flight from Hong Kong (HK) to Beijing (BJ).

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