An Overview of Nowcasting Development, Applications, and Services in the Hong Kong Observatory

LI Ping-Wah* (李炳华), WONG Wai-Kin (黄伟健), CHEUNG Ping (张 冰), and YEUNG Hon-Yin (杨汉贤)

Hong Kong Meteorological Society and Hong Kong Observatory, 134A Nathan Road, Kowloon, Hong Kong

(Received May 7, 2014; in final form July 30, 2014)

ABSTRACT

The Hong Kong Observatory (HKO) has been developing a suite of nowcasting systems to support operations of the forecasting center and to provide a variety of nowcasting services for the general public and specialized users. The core system is named the Short-range Warnings of Intense Rainstorm of Localized Systems (SWIRLS), which is a radar-based nowcasting system mainly for the automatic tracking of the movement of radar echoes and the short-range Quantitative Precipitation Forecast (QPF). The differential, integral (or variational), and object-oriented tracking algorithms were developed and integrated into the nowcasting suite. In order to predict severe weather associated with intense thunderstorms, such as high gust, hail, and lightning, SWIRLS was enhanced to SWIRLS-II by introduction of a number of physical models, especially the icing physics as well as the thermodynamics of the atmosphere. SWIRLS-II was further enhanced with non-hydrostatic, high resolution numerical models for extending the forecast range up to 6 h ahead. Meanwhile, SWIRLS was also modified for providing nowcasting services for aviation community and specialized users. To take into account the rapid development of lightning events, ensemble nowcasting techniques such as time-lagged and weighted average ensemble approaches were also adopted in the nowcasting system. Apart from operational uses in Hong Kong, SWIRLS/SWIRLS-II was also exported to other places to participate in several international events such as the WMO/WWRP Forecast Demonstration Project (FDP) during the Beijing 2008 Olympics Games and the Shanghai Expo 2010. Meanwhile, SWIRLS has also been transferred to various regional meteorological organizations for establishing their nowcasting infrastructure. This paper summarizes the history and the technologies of SWIRLS/SWIRLS-II and its variants and the associated nowcasting applications and services provided by the HKO since the mid 1990s.

Key words: nowcasting, thunderstorm, lightning, aviation weather, high resolution numerical weather prediction

Citation: Li Ping-Wah, Wong Wai-Kin, Cheung Ping, et al., 2014: An overview of nowcasting development, applications, and services in the Hong Kong Observatory. *J. Meteor. Res.*, **28**(5), 859–876, doi: 10.1007/s13351-014-4048-9.

1. Introduction

1.1 History

Nowcasting by definition is a collection of very short-range forecasting from zero up to a few hours ahead that starts from a "detailed description of the current weather", and is made possible by fully utilizing all observations available, in particular remote sensing data from radar, satellite, lightning, GPS, wind profiler, etc. (e.g., Browning, 1982; Conway, 1998). This is the forecast range when forecasters and frontline staff often have to make critical operational decisions in the face of rapidly developing weather situations. Due to the high spatial and temporal resolution and update frequency of the advanced meteorological instruments, nowcasting can provide a very detailed and informative four-dimensional description of the current state as well as a short-term evolution of the atmosphere. Nowcasting capability has therefore become a vital and specialized subject that affects daily forecasting operations as well as decision-making processes in weather services (Liljas, 1998). Nowcast-

*Corresponding author: pwli@hko.gov.hk.

ing also supplements the gap in numerical weather prediction where the latter has lower skill in the first few hours of the model run when its performance has not yet stabilized.

The first international symposium dedicated to nowcasting was held in Hamburg, Germany, in 1981 as part of the International Association of Meteorology and Atmospheric Physics Third Scientific Assembly (European Space Agency, 1981). The major topics discussed in the symposium were observations and very-short-range forecasts up to 2 h ahead. The second symposium of the same series was held in Norbert, Norway, in 1984. Lam (1984) presented a paper on using digital radar to study the evolution of rainstorm to provide short-term forecast of rainfall over the Hong Kong territory. In his paper, he employed nowcasting technique to predict the surface rainfall up to 3 h ahead for rain-bearing systems such as tropical cyclone and monsoon trough based on manual extrapolation of radar echoes shown on radar screen. Though the performance was not very satisfactory at that time, Lam's ground work in fact laid down the foundation of nowcasting research and development of the Hong Kong Observatory (HKO) in the following decades.

Affected by a couple of heavy rainstorms which brought significant flooding to Hong Kong, the HKO decided to implement a Rainstorm Warning System in 1992 to warn the public of intense rainstorm. The Rainstorm Warning System operated at that time had very limited prediction power as warnings were issued mainly based on actual rainfall amount recorded. However, there were great demands from the public for a warning system that was based on forecast. To meet the demands of the public, HKO went forward to develop an automatic system which could quantitatively forecast the amount of precipitation over the territory. Then, the HKO's nowcasting research and development began to enter its rapid development era.

1.2 The first generation nowcasting system–SWIRLS

The Rainstorm Warning System was enhanced in 1998 to bring in the forecast element. The new system was operated based on the recorded or predicted rainfall amounts to issue either Amber, Red, or Black Rainstorm Warning (respectively representing more than 30-, 50-, and 70-mm h^{-1} rainfall that would affect significant parts of the territory) to warm the public of various severity of the rainstorm. To achieve that, the observatory developed the first generation nowcasting system, named SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems), in 1996 and put the system in operation in 1998. SWIRLS consists of: (1) simple automatic tracking of radar echoes by the technique Tracking Radar Echoes by Correlation (TREC), (2) dynamical correlation of radar Z-R relation, (3) extrapolation of the existing radar echoes by simple advection scheme, and (4) audio-visual situational display for alarming the potential of Amber, Red, and Black Rainstorm Warnings. Though the system design was relatively simple, it turned out to be rather useful for forecasters' reference under rainstorm situations (Lai and Li, 1999).

Borrowing the success story, SWIRLS in 2001 was subsequently enhanced for issuance of other rainfall related warning services, namely, the Landslip Warning and Special Announcement on Flooding in the northern New Territories, in cooperation with the Civil Engineering Department and Drainage Department of the Hong Kong Special Administrative Region, respectively. Meanwhile, there were also demands on extending the forecast range from 1–2 h to a longer lead time. To achieve that, the HKO also developed the mesoscale numerical weather prediction (NWP) model called the Non-Hydrostatic Model (NHM) adapted from the Japan Meteorological Agency (JMA) (Saito et al., 2006) for the prediction of rainstorms in 6–12 h ahead. On top of the direct model output, the model grids were phase-shifted by using pattern matching skill based on actual radar echo images to adjust the position of the forecast rainfall field. Meanwhile, SWIRLS was also enhanced with improved advection scheme borrowed from the global models, namely, the semi-Lagrangian advection (SLA) scheme, and successfully extended the extrapolation advection time up to 6 h ahead. The primary advantage of SLA is that any flows especially those with curving features could be maintained in long run while the simple advection scheme cannot maintain the curving structure of the forecast field soon after the forecast is started. By incorporating the enhanced SWIRLS and the phase-adjusted NHM rainfall field, an extrapolation-model-blended system, namely, Rainstorm Analysis and Prediction Integrated Data-processing System (RAPIDS), was put into operational trial in 2005. It was one of the blended nowcasting systems put in real-time operation in the world by that time.

1.3 SWIRL-II

To meet demands for alerting hazards associated with severe storms, SWIRLS was further enhanced with the capability of predicting lightning, hail, squall threats as well as probability of heavy precipitation. The first three capabilities were developed as additional modules based on object-based nowcasting techniques. The enhanced system, named SWIRLS-II, participated in the WMO/WWRP Forecast Demonstration Project (FDP) held in the Beijing Olympic Games in 2008 (B08) and Shanghai Expo in 2010 (Cheng et al., 2011; WMO, 2012). During the FDPs, SWIRLS-II was demonstrated to be one of the best performed nowcasting systems in the world (WMO, 2009; Wilson et al., 2010).

SWIRLS II also contains a new module for predicting the probability of heavy precipitation by employing the time-lagged ensemble technique for the NHM. The two components were combined into one graphical situational display named SWIRLS Panel for Integrated Display of Alerts on Severe Storms (SPIDASS). SPIDASS was put into operation in 2008. There were two more occasions where SWIRLS "participated" in, namely, the Commonwealth Games held in India in 2010 (Srivastava et al., 2012) and the Universiade held in Shenzhen, China in 2011. During those events, the HKO provided the SWIRLS software respectively to Indian Meteorological Department and Shenzhen Meteorological Bureau with the software implemented and executed by the local personnel. HKO provided training and overseas instructions for the implementation and execution of the software.

In the following paragraphs, we will highlight the major technology of the various nowcasting systems and the respective services. We will also mention about the ongoing development of the HKO's nowcasting research and services towards the end of this paper.

2. Nowcasting technology

SWIRLS is a radar-based rainstorm nowcasting system which consists of three major components: (1) automatic tracking of radar echoes, (2) dynamical correlation of Z-R relation, and (3) extrapolation of the radar echoes (Li et al., 2000; Li and Lai, 2004a, b).

2.1 Automatic radar echo tracking

In generic terms, automatic radar echo tracking methods can be classified into: (a) differential tracking, (b) integral tracking, and (c) object-based tracking:

(a) Differential tracking. Tracking Radar Echoes by Correlation (TREC) belongs to this type (Rinehart, 1979) (Figs. 1a–c). The essence of this method is to divide the whole radar image into a number of boxes based on some pre-defined box size (representing the spatial scale) and search the neighbouring boxes to determine the most similar box via maximizing the correlation R:

$$R = \frac{\sum_k Z_1(k) \times Z_2(k) - \frac{1}{N}\sum_k Z_1(k)\sum_k Z_2(k)}{\left[\left(\sum_k Z_1^2(k) - N\bar{Z}_1^2\right) \times \left(\sum_k Z_2^2(k) - N\bar{Z}_2^2\right)\right]^{1/2}},$$

where $Z_1(k)$ and $Z_2(k)$ are respectively the radar reflectivity at pixel k at two consecutive radar scan, e.g., in 6-min separation. Though simple, this method has many merits including: capable of capturing small-scale movement, capable of capturing divergence and circulation motion, and flexible in capturing various scales by choosing different box sizes in the correlation exercise. The major disadvantage lies in the fact that this approach could easily miss out the large-scale movement of the whole system.

(b) Integral tracking. Two algorithms called MOVA (Multiscale Optical flow by Variational Analysis) (Wong et al., 2009) and ROVER (Real-time Optical flow by Variational method for Echoes of Radar)

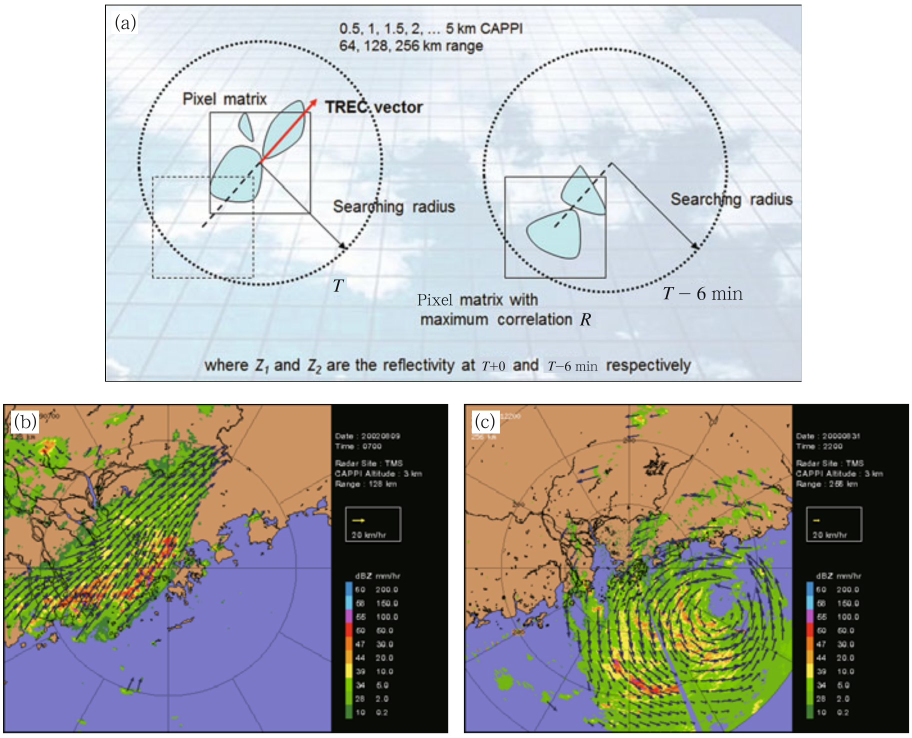

Fig. 1. (a) Schematic diagram about the algorithm of TREC, (b) sample TREC wind field of a thunderstorm, and (c) sample TREC wind field of a tropical cyclone.

(Cheung and Yeung, 2012) developed in the HKO belong to this type. In essence, both methods employ optical flow technique (Aubert et al., 1999) that attempt to retrieve echo motion (u, v) from successive radar images by minimizing the cost function:

$$J_I = \iint \left(\frac{\partial I}{\partial t} + u\frac{\partial I}{\partial x} + v\frac{\partial I}{\partial y}\right)^2 \mathrm{d}x\mathrm{d}y,$$

where I is the radar reflectivity at location (x, y) and t applies to two or three adjacent time levels (6 min in our case to align with the radar volume scanning scheme). To improve the quality of the motion vector, a constraint term J_s is used to attain the smoothness of the vector field via minimizing the square norm of the divergence of the resulting vector field, namely,

$$J = J_I + J_S,$$
$$J_S = \gamma \iint \Big[\left(\frac{\partial^2 u}{\partial x^2}\right)^2 + \left(\frac{\partial^2 u}{\partial y^2}\right)^2 + 2\left(\frac{\partial^2 u}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2 v}{\partial x^2}\right)^2 + \left(\frac{\partial^2 v}{\partial y^2}\right)^2 + 2\left(\frac{\partial^2 v}{\partial x \partial y}\right)^2\Big] \mathrm{d}x\mathrm{d}y.$$

The dimensionless coefficient γ, in the order of 10^{-1}, is to control effect of the smoothness term in the minimization process. In MOVA, the cost function is applied 7 times to various scales (resolution) of the radar images to capture the motion fields. The final motion field is obtained by adding all the motion fields on various subscales, with some predetermined weighting factors obtained through experience. The merits of MOVA/ROVER are that the motions of various scales can be treated in one go and they can capture better the system scale motion in comparison with the differential tracking method (Figs. 2a and 2b). ROVER has several enhancements over MOVA in terms of robustness against noise as inherited from the local features, and allowing tunable parameters to obtain better tracking results in squall lines and tropical cyclones. The major limitation of these methods lies on the fact that the tunable parameters which connect different scale motions are empirical, requiring a large amount of historical cases to be optimized for robustness in operational use.

(c) Object-based tracking. This method groups the radar reflectivity image above pre-defined threshold into simple geometrical objects (circle, ellipse,

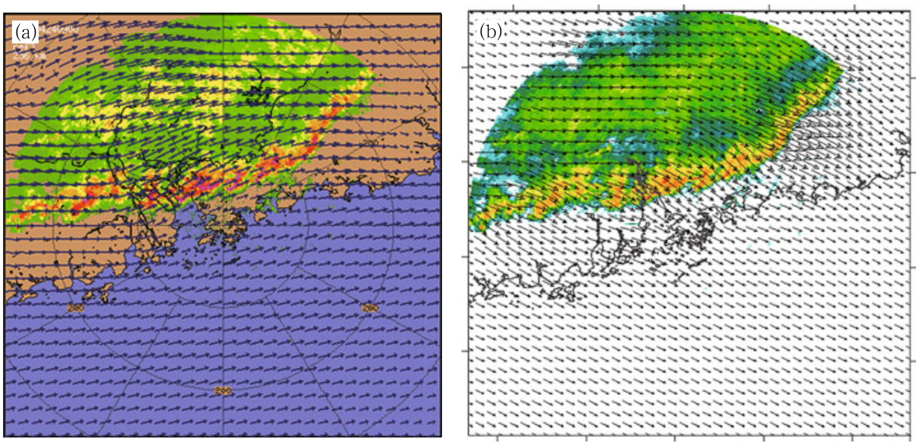

Fig. 2. (a) Individual cell moving towards northeast by TREC and (b) large-scale motion moving towards southeast by MOVA.

polygon, etc.) and track their respective movement via various matching methods (Dixon, 1995). In SWIRLS, there is a component named GTrack (Li and Lai, 2004a) which identifies congregated radar pixels over some pre-defined intensity values and encircles the pixels by using ellipses (Figs. 3a and 3b). Once the ellipses (or cells) are identified, a number of cell parameters are calculated, including the arithmetic and weighted mean positions, average cell intensity, maximum intensity, 90th percentile intensity, and the derived geometric parameters such as the length and inclination angle of the major and minor axes. Tracking of the parent and daughter cells are achieved by searching all possible cell positions in the previous image within a maximum allowable range and identifying the nearest cell with similar cell parameters, i.e., minimum change of the above cell parameters in time. From that, we can determine the so called GTrack vector, which represents the displacement of the centroid of the associated ellipse between successive images. Short-term forecast of the cell's future position is then made by linear extrapolating the current cell by moving along the respective GTrack vector. When two smaller cells are identified within the pre-defined searching radius from a cell with nearly the combined size of the two cells at the previous step, they may be treated as the merger. In reverse, if a large cell falls within the searching radii of two smaller cells at the present time, they may be treated as splitter. In the splitter case, only the most similar cell will be associated with its parent cell and tracked along their respective GTrack vector. The major merits of this method include: capable of capturing well the movement of the whole system, and easily tracing the evolution of the objects identified. The well-known disadvantages are: it cannot maintain the structure of any circulat-

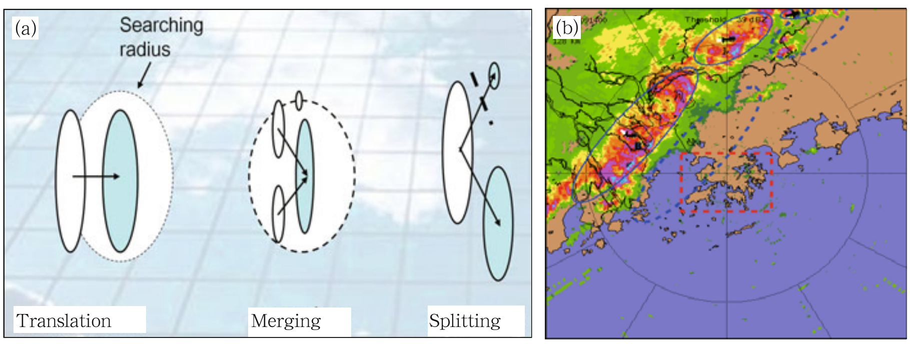

Fig. 3. (a) GTrack uses ellipses to identify and track the movement of the radar echo "objects" and (b) the current (solid line) and predicted (dashed line) positions of the radar echo "objects."

ing/rotating motion including tropical cyclone or meso-cyclone and it cannot handle merging and splitting of the objects, hence limiting its forecasting capability to very short time. The severe weather module of SWIRLS-II (Figs. 6a and 6b) was built mainly based on the object-based tracking approach.

2.2 Extrapolation of radar echoes

The extrapolation method adopted in SWIRLS is the semi-Lagrangian advection (SLA) scheme. It is the Robert's type of three iteration scheme used in most of the global NWP models (Robert, 1982). In SWIRLS implementation, bi-cubic interpolation and flux limiter are used. The advantages of this scheme include: numerical stability and non-dispersive. Experience also demonstrates that it can retain the rotation feature of motion field up to several hours ahead while most of the simple advection schemes do not possess this desirable feature (Figs. 4a and 4b). This feature allows one to perform extrapolation up to several hours ahead.

2.3 Dynamic Z-R relation

This module is relatively straight forward but utmost crucial for obtaining accurate quantitative nowcast. Through minimizing the discrepancy between the real-time surface raingauge data with the radar CAPPI reflectivity aloft (say at 2-km altitude), the parameters a and b in the radar-rainfall $Z = aR^b$ relation can be calibrated in real time. This is particularly useful for capturing the development of a rainstorm during its different evolution stages. The dynamically adjusted Z–R relation can also reflect the rainfall accumulation of storms moving at different speeds. Through the updated Z–R relation, the extrapolated radar reflectivity field would be translated into the surface rainfall to provide realistic quantitative precipitation forecast.

2.4 Severe weather nowcasting modules

To enhance SWIRLS's capability for nowcasting severe weather associated with thunderstorms, several new features were implemented in SWIRLS-II. SWIRLS-II tracks and predicts severe weather objects that may lead to cloud-to-ground (CG) lightning, damaging thunderstorm squalls, and hail (Yeung et al., 2009). The following paragraphs will focus on the identification and nowcasting of these three kinds of threats.

(a) Lightning nowcast

SWIRLS-II makes use of conceptual models to help select the critical precursors to identify severe weather. For CG lightning, SWIRLS-II employs the conceptual model so-called DELITE (Detection of cloud Electrification and Lightning based on Isothermal Thunderstorm Echoes) (Yeung et al., 2007) algorithm to select parameters most relevant to the microphysical processes leading up to the electrification of a cumulus cloud as shown in Fig. 5a. In DELITE, the main source of electric charges is assumed to be

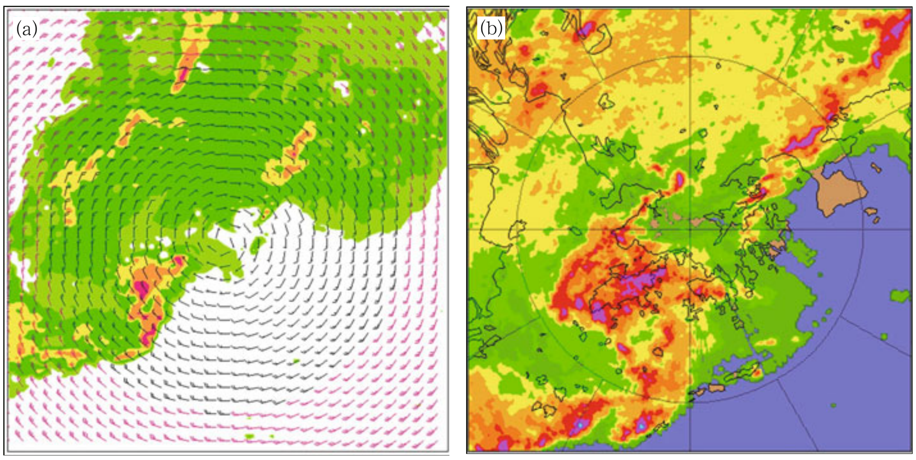

Fig. 4. (a) An ideal circulation pattern preserves after 6-h forecast time by using SLA and (b) 6-h rainfall forecast of a storm case by using SLA.

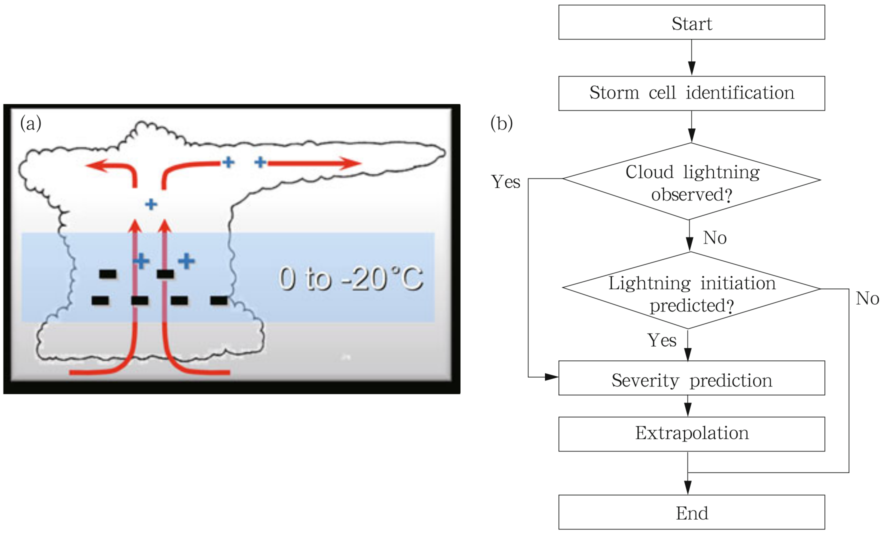

Fig. 5. (a) DELITE's conceptual model of an electrifying cumulus cloud and (b) flow chart of the DELITE algorithm.

located in the mixed-phase layer between 0 and –20℃ in a cumulus cloud. Prior to electrification, the updraft is expected to separate the charge carriers vertically according to their weights. Being heavier, the negative charge carriers (i.e., graupels) are expected to reside mainly in the mixed-phase layer. The updraft is also expected to pump super-cooled rain water into this layer and wet the carriers. The resulting radar echoes detectable in this layer therefore provide an important clue.

To retrieve radar reflectivity at constant temperature levels, the thermal profile of the troposphere must be known in near real time. In DELITE, such information comes from either numerical weather model analysis or the latest available radiosonde data. Besides isothermal reflectivity, the storm height and the total amount of rain water in a cloud column are also identified as favourable factors. While the former is taken as a proxy for updraft strength, the latter indicates the availability of hydrometeor to form charge carriers and release latent heat. The other radar predictors used in DELITE include echo top height, vertically integrated liquid (VIL), and 0℃, –10℃, and –20℃ isothermal reflectivities. Nowcasting of CG lightning initiation will be triggered if these five radar parameters simultaneously exceed their prescribed thresholds, which may be determined by optimizing either the prediction skill or lead time of alerts by using historical thunderstorm cases. In-cloud or cloud-to-cloud (CC) lightning observation is taken as an independent precursor to CG lightning initiation. The logical flow of the DELITE algorithm is summarized in Fig. 5b.

(b) Nowcasting of downburst and squalls

Nowcasting of downburst and squalls in SWIRLS is based on the BLAAST (Buoyancy contribution and Loading effect of rain water to Air parcel Acceleration in Squally Thunderstorms; Yeung et al., 2008) algorithm that was developed with reference to the following conceptual model. The descending force that creates a thunderstorm downburst is attributed to the net effect of buoyancy and water loading on an air parcel. In BLAAST, the former is calculated from radiosonde data as the downdraft convective potential available energy which is estimated from radar VIL. When the parcel is dry, rain drops falling through its volume will evaporate, cool, and reduce its buoyancy. A downburst is considered triggered if the resultant force acting on the air parcel is pointing downward. The maximum wind inducible on the ground is estimated by converting all the potential energy (due to buoyancy and water loading combined) and initial kinetic energy (associated with the horizontal motion) of the descending parcel into wind energy at the ground level. The originating level of a downburst is assumed to be the wet-bulb freezing level and the maximum amount of the buoyancy energy convertible into wind energy is treated as a tunable parameter determined by optimizing the prediction skill.

The above severe weather analyses are object oriented. The threat areas are first identified as elliptical cells in the corresponding interest fields with values greater than or equal to some prescribed thresholds. The detailed cell identification technique follows the GTrack algorithm of SWIRLS. For lightning and downburst, the interest fields are 3-km CAPPI and 0–5-km VIL, respectively. The prescribed thresholds adopted by SWIRLS are 25 dBZ and 5 mm, respectively. After identification, the DELITE and BLASST algorithms are applied accordingly to analyze if the corresponding weather alerts have to be triggered.

(c) SWIRLS-II products suite

For severe thunderstorms, the major results are visualized as an image product called the Severe Weather Map. Figure 6a shows an example issued in real time for a squall line that traversed Hong Kong on 5 March 2009. On the map, textual alerts with quantitative details were printed at the bottom, as the threat areas were intersecting or expected to intersect the warning zone (the red rectangle in Fig. 6a) for Hong Kong. SWIRLS-II outputs its products on the map through its client workstation installed in the forecasting office, as well as a web page named SPIDASS (SWIRLS Panel for Integrated Display of Alerts on Severe Storms) dedicated for severe weather alerts. As shown in Fig. 6b, the main panel of SPIDASS provides a compact view of all alerts arranged in rows and colour-coded for different severity levels. Embedded on these colour codes are hyperlinks to the corresponding Severe Weather Maps and rainfall maps.

2.5 Extended nowcasting: Extrapolation-model blended approach

Owing to its intrinsic limitation, linear extrapolation along the TREC wind can only provide reliable forecast up to 1–2 h ahead, for persisting thunderstorms. In order to extend the forecast range and to capture the development and dissipation of thunderstorms, an extrapolation-model-blending approach is adopted to enhance SWIRLS. In this approach, radar linear extrapolation products are blended dynamically with outputs from a high horizontal resolution (5 km) NWP model, namely, the RAPIDS (Li et al., 2005; Wong et al., 2009). Volume radar reflectivity data are ingested into NHM via the LAPS data analysis system (Albers et al., 1996) to improve the model initial moisture field. Recently, Doppler radar radial wind

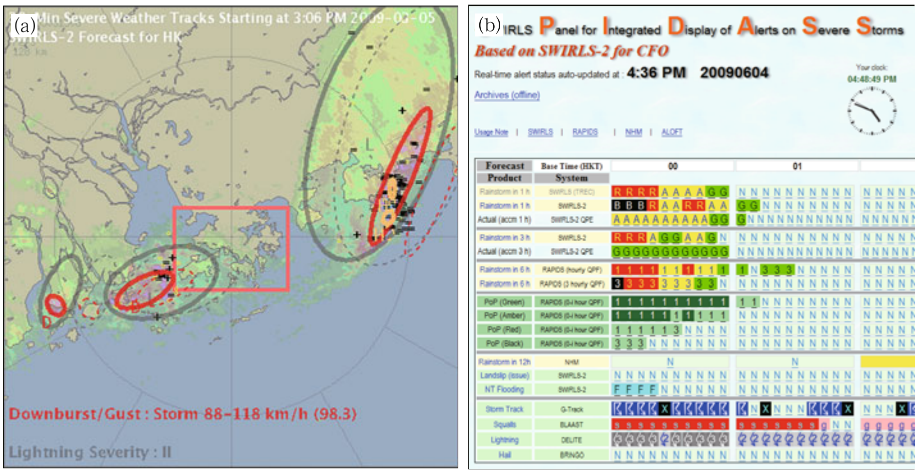

Fig. 6. (a) Severe Weather Map of SWIRLS issued at 0306 HKT (Hong Kong Time) 5 March 2009. Red and grey ellipses indicate the analyzed threat areas of severe wind gust and CG lightning respectively. Dashed ellipses indicate the forecast positions of the threat areas at 30 min. Small yellow "o", black "=", and black "+" symbols mark the locations of actual cloud-to-cloud, negative CG, and positive CG lightning, respectively. (b) Screen shot of SPIDASS on 4 June 2009. Lightning and severe squall alerts are shown respectively on the second and third rows from the bottom (upper rows refer to rainstorm related alerts).

and three-dimensional (3D) radar wind are also ingested in the 3DVAR data assimilation system (Wong et al., 2011) for improving the model initial condition (see Section 4).

The algorithm in the SWIRLS-NHM consists of the following procedures: (1) obtain SWIRLS radar reflectivity, and convert it into surface precipitation using dynamic reflectivity-rainfall (Z–R) relation; (2) obtain precipitation forecast from the NHM; and (3) perform the blending process (Fig. 7). The whole blending involves sophisticated procedures, which can be described as follows:

(1) Phase correction. To tackle the problem of spatiotemporal errors in the model precipitation forecast, phase correction is applied to the direct model output. Location departure in the forecast precipitation patterns from NHM is estimated with respect to the actual radar-rainfall distribution (i.e., radar-estimated rainfall calibrated against rain gauges). Variational technique is adopted, which minimizes the root mean square error of the forecast rainfall field from a previous model run (usually initialized at 1–2 h before) and the actual precipitation distribution (Wong et al., 2009). When there is large difference between the model QPF and actual precipitation distribution, the variational method would fail to converge. Under this situation, no phase correction will apply to the QPF and the algorithm will continue with procedure (2) below.

(2) Calibration of the intensity of model QPF. The intensity of model precipitation is corrected according to the radar-based quantitative precipitation estimate (QPE).

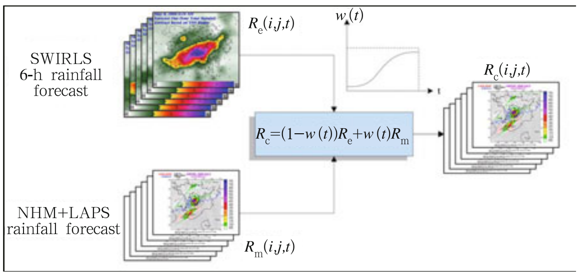

Fig. 7. Schematic diagram showing the components of the SWIRLS-NWP blending approach.

(3) Blending of calibrated model QPF with the radar nowcasting, with larger weighting assigned to the nowcasting component at short lead times and increasing weighting to the NWP component as lead time increases to 6 h.

The blended forecast precipitation is then converted back to forecast radar reflectivity at the grid points, based on the dynamic Z–R conversion formula. Figure 8 shows the comparison between SWIRLS simple extrapolation (1–6-h forecasts) and the SWIRLS-NHM blended forecasts for the case of 4 June 2009 (1–6-h forecasts). The right panels of the figure are radar-based QPE at the respective forecast hours. It appears that the rainfall forecasts produced by simple extrapolation overestimate the rainfall beyond 2 h. The blended approach, however, produces forecast precipitation field resembling that based on the radar echoes. This example demonstrates that the SWIRLS-NHM blending system could produce more reasonable forecasts, making it a feasible approach to extend the skill of the thunderstorm nowcasting beyond the first couple of hours.

2.6 Performance of the nowcasting systems

Figure 9 shows some verification skill scores, namely, Probability of Detection (POD) and Critical Success Index (CSI) of the gridded QPF from the ROVER optical flow (red), TREC (blue), SWIRLS-NHM blended nowcast (green), and direct RAPIDS-NHM outputs (orange) during the rainy season from mid March to July 2014. In general, the optical flow method can give a higher skill than TREC. The blending of nowcast (using QPF based on ROVER tracking) with the high-resolution RAPIDS-NHM improves the skill further throughout the 6-h lead time.

3. Nowcasting applications and services

3.1 Airport lightning alerting

SWIRLS and SWIRLS-II were mainly designed for providing rainstorm-related nowcasting and warnings for the general public. SWIRLS was also adapted to provide services for specialized users. The first spe-

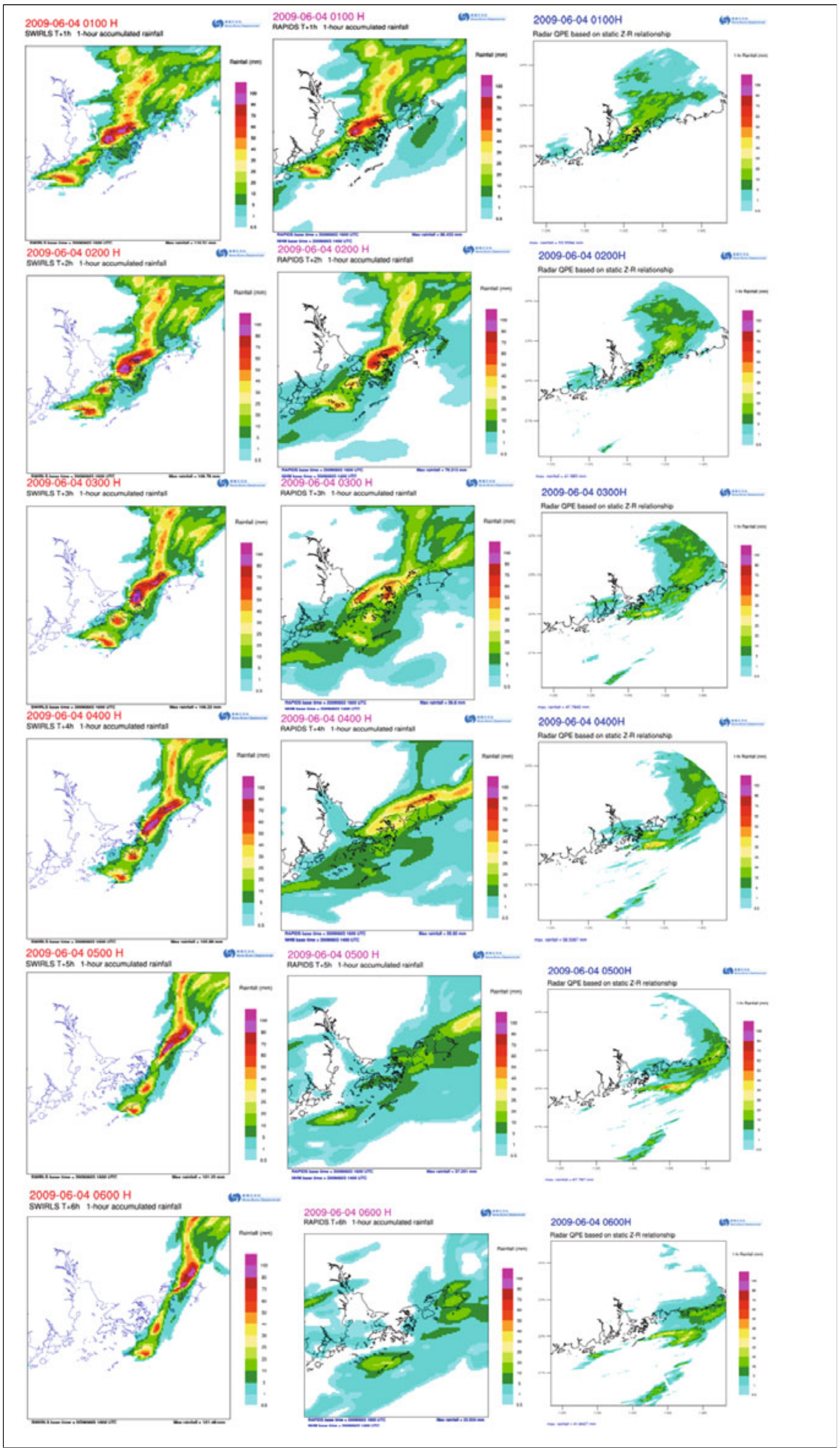

Fig. 8. An example showing the comparison between the effects of SWIRLS simple extrapolation and blending of SWIRLS and NHM rainfall forecast. Figures from top to bottom are 1-, 2-, $\cdots$, 6-h simple extrapolation (left column) and the blended precipitation (middle column) forecasts. Figures on the right show the corresponding radar-based QPE (on different scales).

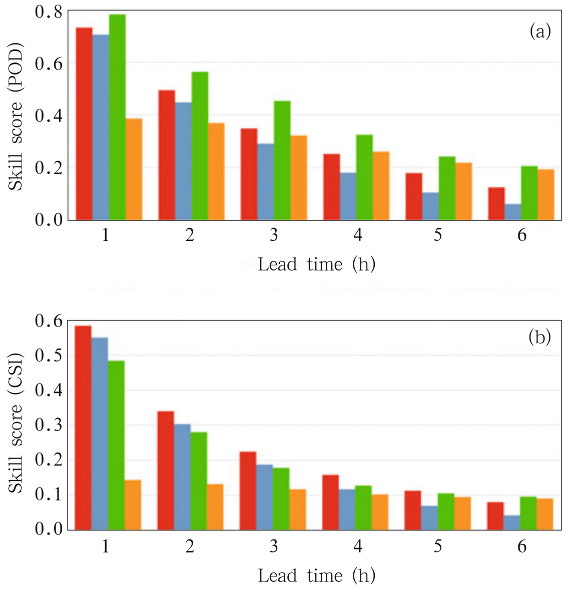

Fig. 9. (a) POD and (b) CSI of grid-based verification of QPF from ROVER tracking (red), TREC (blue), blended forecast (green), and RAPIDS-NHM (orange).

cialized user was the aviation community. At the request of the Airport Authority (AAHK) of the Hong Kong International Airport (HKIA), the HKO developed a novel lightning nowcasting system, namely, the Airport Thunderstorm and Lightning Alerting System (ATLAS), based on the SWIRLS technology, to detect and predict CG lightning over and in the vicinity of the airport so as to alarm the ground operators for avoiding lightning strikes. ATLAS combines the HKO lightning location information system, which detects lightning strikes up to a 300-km radius of Hong Kong, and the TREC wind field analyzed by SWIRLS, and extrapolates the movement of CG lightning strikes along the TREC wind by a modified semi-Lagrangian advection scheme.

In order to take into account the rapid varying and stochastic nature of lightning (transient and sporadic), ATLAS is equipped with two ensemble algorithms to enhance the performance of the extrapolation results. The first one is named the Weighted Ensemble (WE) algorithm, which collects all available 12-min CG forecasts, assigns different weightings (linearly decreasing backward with time), and sums them up to arrive at a total score (Fig. 10a). When the score is forecasted to be above some pre-defined threshold (optimized for highest POD and lowest FAR), the system will automatically issue Amber or Red alert. WE is proved to be rather effective for alerting persistent and wide-spread thunderstorms. ATLAS is also equipped with another ensemble algorithm, named the Time Lagged Ensemble (TLE), which sums the 1-min forecasts valid at the same time from the twelve 1-min forecasts provided in the past 12 minutes to come up with the total score. A similar set of weighting factors as in WE is applied during the summation process. TLE is proved to be more skilful in predicting rapidly developing, small or wide-spread thunderstorms than WE. Figure 10b shows a snapshot of the ATLAS product. The update time of ATLAS product is every 1 minute. ATLAS has been put into operation at HKIA

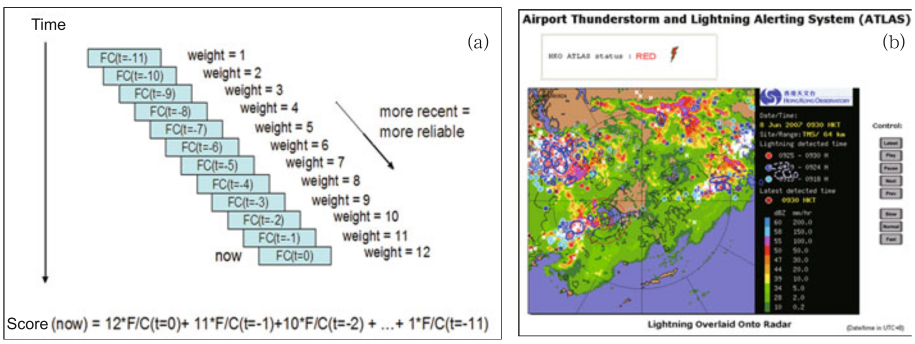

Fig. 10. (a) Schematic diagram of WE algorithm. The weighting factors are linearly decreasing with time, i.e., the latest forecast is allocated 12 marks while the oldest forecast is allocated 1 mark. (b) A snapshot of ATLAS webpage. The top panel shows the latest ATLAS alert status while the bottom panel shows the actual position of the CGs (ellipses with solid line) and the predicted CGs (ellipses with dashed line). 12-min forecast is in blue while 30-min forecast is in grey.

since 2008 and is the only such automatic lightning alerting system in the airports over the world up to the time of writing.

Depending on the distances of the observed or predicted CG locations, ATLAS will trigger either Amber or Red lightning warning (Amber when CG lightning is detected within 10 km or predicted within a 5-km radius of the HKIA; Red when any CG lightning is detected or predicted to affect 1 km from the passenger or cargo terminal of the airport). Whenever the system issues Red lightning warning, all ground operations at the airport will be suspended.

3.2 Convection nowcasting for air traffic control and management

SWIRLS technology was also deployed to predict significant convection to affect the significant points including the aircraft holding points within the HKIA terminal area. Another system named Aviation Thunderstorm Nowcasting System (ATNS) was developed in 2008 for this application (Fig. 11) (Li, 2009; Li and Wong, 2010). The core of ATNS is the modified SWIRLS adapted for aviation use to automatically track the past movement and forecast the future location of storms that may block the intended flight path or significant areas/points in the air space for the next 60 minutes. The output of the system is disseminated to the Civil Aviation Department of Hong Kong for integrating with their new generation flight control system. They are also provided to local Air Traffic Control (ATC) and Air Traffic Management (ATM) authorities for continuously assessing the air space and runway air traffic capacity. In case a significant portion of the holding points are predicted to be affected by intense convection, ATC/ATM will issue capacity notification to the airport community including uplinking to the cockpits for their contingency measures including slow-down, holding, go-around or even flight re-scheduling. ATNS is updated automatically every 6 minutes.

3.3 Nowcast for public utilities

Furthermore, SWIRLS technology was also deployed for the development of a Lightning Nowcasting System (LiNS) for providing up to 2 h ahead accumu-

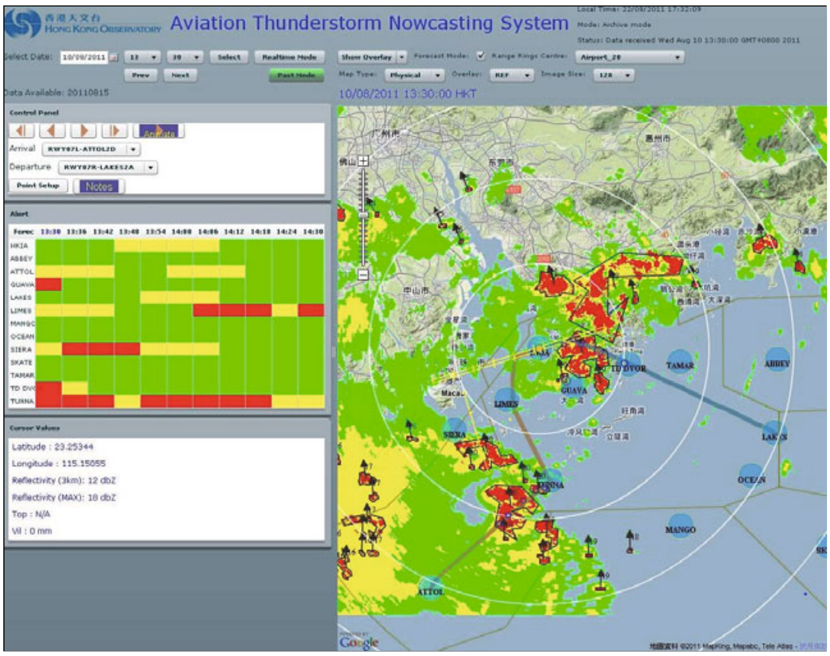

Fig. 11. The display panel of the Aviation Thunderstorm Nowcasting System (ATNS). The red, yellow, and green colour pixels on the right hand side respectively represent intense, medium, and mild intensity storms. The blue circles represent the significant points/holding points in the airspace near HKIA. The bar chart on the left hand side presents nowcast of the aviation impact on aircraft at various significant points/holding points up to 1 h ahead at 6-min intervals.

lative lightning number prediction for a local electric power company. LiNS is an advanced nowcasting system, which is constructed with fully ensemble nowcasting technique. The full ensemble members are generated by varying the correlation box size and the searching radius to come up with a series of TREC wind fields representing the radar echo motions on different spatial scales (Fig. 12a and Section 2.1a). Similar to ATLAS, in order to capture the rapid development of lightning strikes, LiNS also includes in the ensemble the whole series of nowcast members predicted in the previous time step, 6 min ago in our case. Lastly, in order to take into account the growth and dissipation of the storm, LiNS also includes another series of nowcast members by multiplying linearly or nonlinearly the trend of the storm intensity. Altogether, the LiNS contains a total number of 48 nowcast members, i.e., 16 multiple-scale TREC wind nowcasts based on the current radar image, 16 linear or nonlinear trended multiple-scale TREC wind nowcasts based on the current radar image, and 16 multiple-scale TREC wind nowcasts based on the previous radar image. By using this grand ensemble, it is hoped that the inherent prediction uncertainty due to spatial, temporal, and growing/dissipation variability of significant convection activities could be addressed.

LiNS predicts the distribution of total CG lighting strikes over some major zones of the territory where the outdoor power network is exposed to air and hence vulnerable to CG lightning strikes (Fig. 12b). It is the first operational nowcasting system of this kind in the world. LiNS began to provide service to local utility company in 2012.

3.4 Mobile nowcast rainfall services

To further promote the service coverage to more public users, the HKO nowcasting rainfall products have been developed to provide (1) Pearl River Delta rainfall nowcast webpage since 2008 and (2) location-specific rainfall nowcast on the HKO's mobile apps named MyObservatory since 2011 (Woo, 2013). Both products can be accessed with mobile device and are rather popular, particularly the latter, which receives rather high hit counts during rainy days (Figs. 13a and 13b). Besides the rainfall products, the associated rainstorm warnings are also made available on various media forms for rapid dissemination, including radio and television broadcast, automatic telephone enquiry system, Internet webpage, as well as mobile apps for smart phones and social networking platforms such as Twitter.

4. Ongoing high resolution numerical model development

As part of the nowcasting component for the provision of storm growth and dissipation and for extending the nowcast range beyond 2 h from the observation time, the numerical modeling component has been

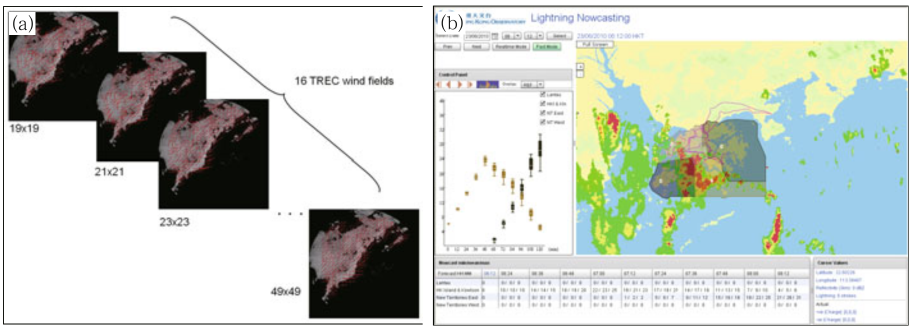

Fig. 12. (a) By changing the box sizes, eTREC generates motion vectors for different scale motions. LiNS uses the 16 motion fields to track and predict the movements of the CG distribution to generate an ensemble lightning distribution. (b) LiNS webpage. Hong Kong is divided into four zones. The white figures on each zone represent the forecast hourly CG stroke numbers. The colour patches (red, yellow, and green) represent the storm intensity. The bar chart on the left represents the forecast accumulative CG stroke number, including the spread, in the next 120 minutes, at 12-min intervals. The table at the bottom provides detailed figures about the forecast maximum, minimum, and average CG stroke numbers in each zone for ease of reference.

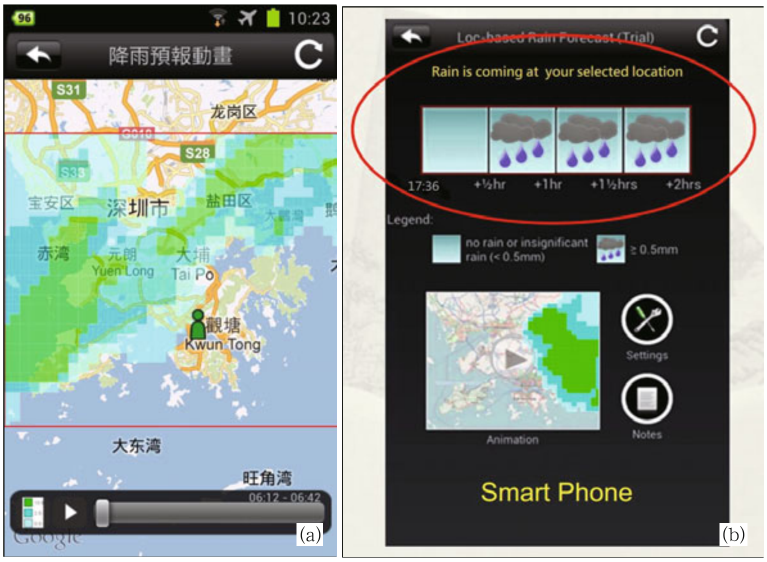

Fig. 13. (a) Rainfall nowcast map animation showing on the mobile phone. (b) Location specific rain alert available on mobile phone. Whenever there is rain forecast to affect the user's location, the apps will pop up with a message to alert the approaching rain.

undergoing continuous improvement. For instance, the RAPIDS-NHM was enhanced by assimilating Doppler weather radar data far back in 2005. The data assimilation system was also replaced by the 3DVAR system in 2010 in a new generation mesoscale NWP model system using NHM running with increased horizontal resolutions (Wong, 2011). Besides, the model was also configured to run by taking boundary conditions from multiple global models, including ECMWF and JMA global NWP models. In 2011, it was also enhanced to ingest dual-Doppler 3D radar retrieved winds to improve its initial wind field analysis. Evaluation demonstrated that ingestion of the mesoscale observations from surface observations and ground-based remote sensing data could improve both the analysis field as well as the QPF. Meanwhile, the horizontal resolution of the RAPIDS-NHM has been increased to 2 km with the model cycle updated every hour.

As convection could evolve rapidly, a single deterministic model run might not be able to predict correctly the time and position of the rainfall. In order to capture the possible scenarios of convective development, once again time-lagged ensemble technique is employed to aggregate all available RAPIDS-NHM forecasts from current and previous hourly runs (Fig. 14). Improved model QPF within South China and the Pearl River Delta domains can be obtained by choosing suitable percentile of model QPFs from the ensemble members. To further improve the representativeness of convection in the model, a fine-resolution modeling system with sub-kilometer horizontal resolution, named the Aviation Model (AVM) (Wong et al., 2013) has been put into trial. Besides general convection forecast, it is also used to provide enhanced aviation forecast applications. For instance, Fig. 15 shows the simulated radar reflectivity generated by AVM in comparison with the actual radar reflectivity image. With sub-kilometer resolution, the model simulated reflectivity becomes commensurate, at least qualitatively, with the observed radar reflectivity. AVM is operated at hourly updated configuration and the model convection forecasts are generated with a rapid output schedule, i.e., model forecasts are output at intervals of a few minutes instead of an hour. The rapidly-output model forecasts can be used to blend with the radar-based nowcasting products to form a seamless, high resolution nowcast product from 0 h to a few hours ahead, with a 6-min interval to align with the radar-based extrapolation. Furthermore, time-lagged ensemble of AVM model consensus from the most recent and all available previous runs can be constructed to indicate the potential of growth and decay of the

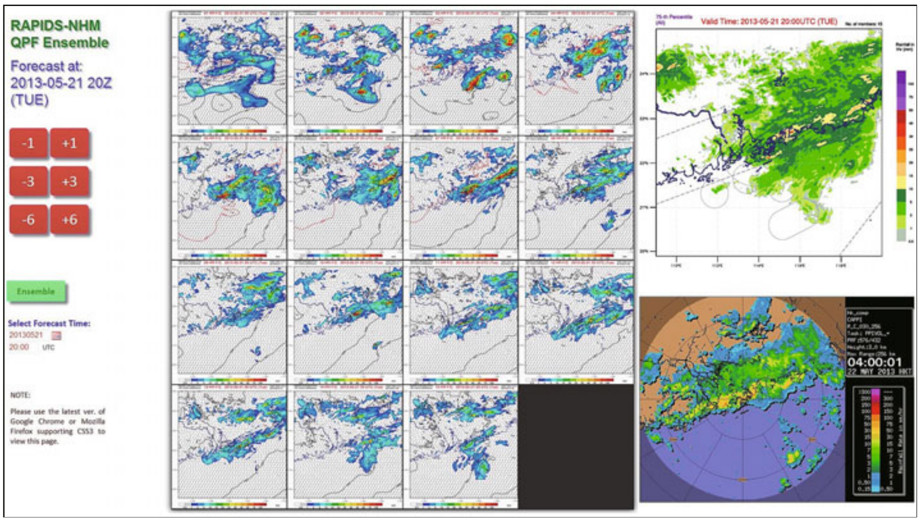

Fig. 14. Stamp map (left) showing forecast hourly rainfall (color) and mean sea level pressure (contour) from the hourly updated RAPIDS-NHM forecasts all valid at 2000 UTC 21 May 2013. The 75th percentile of the gridded rainfall from these time-lagged ensemble members is shown on top right. Radar CAPPI reflectivity (at 0400 HKT) is given on bottom right.

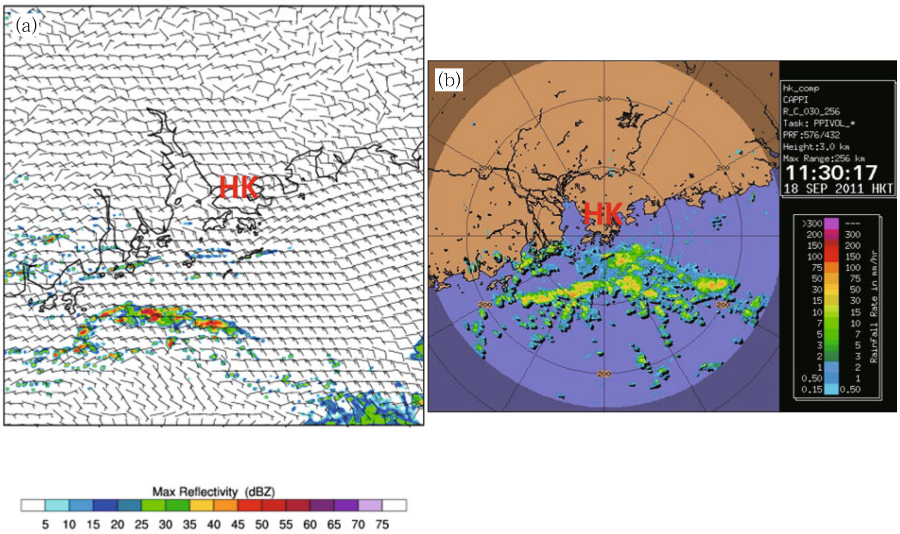

Fig. 15. (a) Simulated radar reflectivity from the Aviation Model and (b) actual CAPPI radar reflectivity.

rapidly evolving convection over Hong Kong and the adjacent areas.

5. Conclusions and future development

The HKO has developed various nowcasting systems, including SWIRLS/SWIRLS II, ATLAS, ATNS, LiNS, etc. and applied the systems to various applications and provided nowcasting services to the public and specialized users. There are still many areas where these nowcasting systems are undergoing enhancement for further improving the performance as well as providing better services.

As mentioned in Section 2.1b, the integral tracking methods perform better in capturing the larger-scale motion of the convection systems. Hence, SWIRLS-II has been upgraded by adopting the ROVER tracking algorithm in 2012. Meanwhile, as have been pointed out a couple of times in the above paragraphs, the "transient and sporadic" nature of convective cells, which might have different evolution cycles, is rather difficult to be handled by just one single initial radar echo intensity and motion field analysis. To tackle this, SWIRLS-II was also enhanced by adopting the ensemble method, i.e. by perturbing the optimization parameters of ROVER, plus using the time-lagged ensemble skill, to generate an ensemble consisting of 144 members of nowcast rainfall fields (Fig. 16). From this grand ensemble, probability of rainfall nowcast was generated. This product is under trial operation at the HKO.

Furthermore, as the forecast period is extended, the radar-rainfall correlation analysis (i.e., the Z-R relation) should also cover a broader area. To achieve that, the surface rainfall analysis was enhanced by the co-Kriging method to replace the traditional Cressman analysis. Subsequently, the rainfall analysis would also be extended to use satellite image for providing an even larger area rainfall analysis. After these enhancements, one should be able to obtain a more realistic, longer lead time QPF via extrapolating the calibrated satellite images (radar-satellite analysis). The co-Kriging algorithm was developed in 2011 while the extrapolation of the calibrated satellite imagery is still under development (Yeung et al., 2012).

The nowcasting development will not stop with the conventional observational instruments. The HKO has continuously been exploring the use of emerging technologies for nowcasting research and development. Two efforts most spent are: (1) GPS-PWV (precipitable water vapor) (Cao et al., 2006) and (2) microwave radiometer (Chan, 2009). A GPS-PWV system has already been set up for real-time monitoring of water vapor content over a number of GPS receiver stations scattering around Hong Kong. The time-trace of the atmospheric GPS-PWV contents helps to provide information about the accumulation/dispersion of water vapor content, which is the essential ingredient for the growth/dissipation of thunderstorms. Meanwhile, microwave radiometers have also been put into operation for real-time monitoring of the atmospheric instability to provide precursor-like information for the formation/dissipation of local thunderstorms. The HKO will continue to study their effectiveness by integrating the data into the existing nowcasting systems for further improving the performance. Efforts will also be spent in improving the blending technology between the radar-based extrapolation products with the high resolution numerical models for further improving the performance of the seamless 0–6-h nowcast products and services.

Acknowledgment. The authors would like to thank the following persons for contributing in the research and development of the HKO's nowcasting

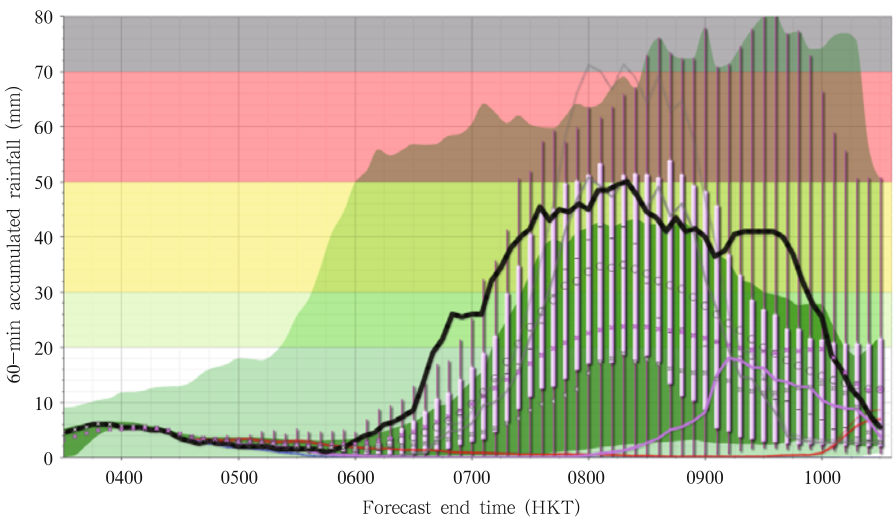

Fig. 16. Sample SWIRLS ensemble rainstorm nowcast. The box and whisker plot represent the nowcast spread at each forecast valid time while the black curve represents the actual rainfall.

systems, applications and services: E. S. T. Lai, H. T. Poon, C. C. Lam, S. T. Chan, K. Y. Chan, T. L. Cheng, D. S. Lau, S. M. Tse, and W. C. Woo. Special thanks go to C. Y. Lam for initiating the nowcasting projects, B. Y. Lee and C. M. Shun for continuously supporting the project, and S. Y. Lau for reading the manuscript. NHM is developed on the basis of the NPD/MRI Non-Hydrostatic Model of the Japan Meteorological Agency. The AVM is developed based on the Advanced Research WRF (ARW) of National Center of Atmospheric Research.

REFERENCES

Albers, S. C., J. A. McGinley, D. L. Birkenheuer, et al., 1996: The Local Analysis and Prediction System (LAPS): Analyses of clouds, precipitation, and temperature. *Wea. Forecasting*, **11**, 273–287.

Aubert, G., R. Deriche, and P. Kornprobst, 1999: Computing optical flow via variational techniques. *SIAM J. Appl. Math.*, **60**, 156–182.

Browning, K. A., 1982: *Nowcasting*. London, Academic Press, 256 pp.

Cao, Y. C., Y. Q. Chen, and P. W. Li, 2006: Wet refractivity tomography with an improved Kalman-filter method. *Adv. Atmos. Sci.*, **23**, 693–699.

Chan, P. W., 2009: Nowcasting applications of a microwave radiometer in Hong Kong. Preprint, 8th International Symposium on Tropospheric Profiling: Integration of Needs, Technologies and Applications, Delft, The Netherlands, S11-P02-1. [Available online at http://www.knmi.nl/∼apituley/files/istp8/data/1643742.pdf].

Cheng Tsz-lo, Dai Jianhua, and Yeung Hon-yin, 2011: Applications of SWIRLS nowcasting system in the Shanghai Expo 2010. Preprint, 28th Chinese Meteorological Society Annual Meeting, Xiamen, China. (in Chinese)

Cheung, P., and H. Y. Yeung, 2012: Application of optical-flow technique to significant convection nowcast for terminal areas in Hong Kong. The 3rd WMO International Symposium on Nowcasting and Very Short-Range Forecasting, 6–10 August 2012, Rio de Janeiro, Brazil.

Conway, B. J., 1998: An overview of nowcasting techniques. SAF Training Workshop-Nowcasting and Very Short Range Forecasting, 9–11 December 1998, Madrid, Spain, EUMETSAT, 34–33.

Dixon, M., and G. Wiener, 1993: TITAN: Thunderstorm identification, tracking, analysis and nowcasting—A radar-based methodology. *J. Atmos. Oceanic Technol.*, **10**, 785–797.

European Space Agency, 1981: Nowcasting: Mesoscale observations and short-range prediction. Proceedings of an International Symposium, 25–28 August 1981, Hamburg, Germany (Part of the IAMAP Third Scientific Assembly), 415 pp.

Hong Kong Observatory, 2012: Thunderstorm Warning. Hong Kong Observatory webpage: http://www.weather.gov.hk/wservice/warning/thunder.htm.

Lai, E. S. T., and P. W. Li, 1999: Preliminary performance evaluation of a rainstorm nowcasting system. Proceedings of the Forth International Conference on East Asia and Western Pacific Meteorology and Climate, Hangzhou, China, 390–400.

Lam, C. Y., 1984: Digital radar data as an aid in nowcasting in Hong Kong, nowcasting-II, Mesoscale observations and very-short-range weather forecasting. Proceedings of the Second International Symposium on Nowcasting, Norrköping, Sweden, 249–253.

Li, P. W., W. K. Wong, K. Y. Chan, et al., 2000: SWIRLS—An Evolving Nowcasting System. Technical Note No. 100, Hong Kong Observatory, 33.

——, and E. S. T. Lai, 2004a: Applications of radar-based nowcasting techniques for mesoscale weather forecasting in Hong Kong. *Meteor. Applications*, **11**, 253–264.

——, and E. S. T. Lai, 2004b: Short-range quantitative precipitation forecasting in Hong Kong. *J. Hydrology.*, **288**, 189–209.

——, W. K. Wong, and E. S. T. Lai, 2005: RAPIDS—A new rainstorm nowcasting system in Hong Kong. WMO/WWRP International Symposium on Nowcasting and Very-short-range Forecasting, 5–9 September 2005 Toulouse, France. [Available online at http://www.meteo.fr/cic/wsn05/].

——, 2009: Development of a thunderstorm nowcasting system for Hong Kong international airport. First AMS Aviation, Range, Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, Phoenix, Arizona, p16. [Available online at https://ams.confex.com/ams/89annual/techprogram/paper_146911.htm].

——, and W. K. Wong, 2010: Development of an advanced aviation nowcasting system by including rapidly updated NWP model in support of air traffic management, preprints. AMS Aviation, Range, Aerospace Meteorology, Atlanta, Georgia, 5.3. [Available online at https://ams.confex.com/ams/90annual/techprogram/paper_159847.htm].

Liljas, E., 1998: COST-78 co-operations on SAFs. In SAF Training Workshop-Nowcasting and Very Short Range Forecasting, 9–11 December 1998, Madrid, Spain, EUMETSAT, 23–33.

Rinehart, R. E., 1979: Internal storm motions from a single non-Doppler weather radar, NCAR/TN-146+STR, 262 pp.

Robert, A., 1982: A semi-Lagrangian and semi-implicit numerical integration scheme for the primitive meteorological equations. *J. Meteor. Soc. Japan*, **60**, 319–325.

Saito, K., T. Fujita, Y. Yamada, et al., 2006: The operational JMA nonhydrostatic mesoscale model. *Mon. Wea. Rev.*, **134**, 1266–1298.

Srivastava, K., S. Y. Lau, L. H. Y. Yeung, et al., 2012: Use of SWIRLS nowcasting system for quantitative precipitation forecast using Indian DWR data. Mausam Quart. J. Meteor., Hydrol. Geophy., **63**, 1–16.

Wilson, J. W., Y. Feng, M. Chen, et al., 2010: Nowcasting challenges during the Beijing Olympics: Successes, failures, and implications for future nowcasting systems. *Wea. Forecasting*, **25**, 1691–1714.

Wong, W. K., 2011: Development of operational rapid update non-hydrostatic NWP model and data assimilation system in the Hong Kong Observatory. Technical Reports of the Meteorological Research Institute No. 65: International Research for Prevention and Mitigation of Meteorological Disasters in Southeast Asia, 87–100.

——, L. H. Y. Yeung, Y. C. Wang et al., 2009: Towards the blending of NWP with nowcast-operation experience in B08FDP. 2nd WMO International Symposium on Nowcasting and Very-Short-Range Forecasting, 30 August–4 September 2009, Whistler, Canada.

——, M. K. Or, P. W. Chan et al., 2011: Impact of radar retrieval winds on data assimilation and forecast of a mesoscale convective storm using non-hydrostatic model. 14th AMS Conference on Mesoscale Process, American Meteorological Society, 31 July–4 August 2011, Los Angeles, USA. 8.4. [Available online at https://ams.confex.com/ams/14Meso15ARAM/webprogram/Paper190629.html].

——, C. S. Lau, and P. W. Chan, 2013: Aviation Model: A fine-scale numerical weather prediction system for aviation applications at the Hong Kong international airport. *Adv. Meteor.*, 2013, Article ID 532475, 11.

Woo, W. C., 2013: Location-based rainfall nowcasting service for public. Preprint, European Geosciences Union General Assembly 2013, 7–12 April 2013, Vienna, Austria. EGU2013-2767. [Available online at http://meetingorganizer.copernicus.org/EGU2013/EGU2013-2767.pdf].

World Meteorological Organization (WMO), 2009: WMO Report on Overview of the Beijing 2008 Olympics Project–Part I: Forecast Demonstration Project, 130 pp.

——, 2012: WMO Report on Final Review Meeting for the World EXPO 2010 Nowcasting Services (WENS) Demonstration Project and Capacity-Building Workshop, 14–18 November 2011, Shanghai, China, 26 pp.

Yeung, L. H. Y., E. S. T. Lai, and S. K. S. Chiu, 2007: Lightning initiation and intensity nowcasting based on isothermal radar reflectivity—A conceptual model. The 33rd International Conference on Radar Meteorology, 6–10 August 2007, Cairns, Australia, 11A.7. [Available online at https://ams.confex.com/ams/pdfpapers/123157.pdf].

——, ——, and P. K. Y. Chan, 2008: Thunderstorm downburst and radar-based nowcasting of squalls. Fifth European Conference on Radar in Meteorology and Hydrology, 30 June–4 July 2008, Helsinki, Finland.

——, W. K. Wong, P. K. Y. Chan, et al., 2009: Applications of the Hong Kong Observatory nowcasting system SWIRLS-2 in support of the 2008 Beijing Olympic Games. 2nd WMO International Symposium on Nowcasting and Very-Short-Range Forecasting, 30 August–4 September 2009, Whistler, B. C., Canada.

——, C. Man, S. T. Chan et al., 2012: Application of radar-raingauge co-kriging to improve QPE and quality control of real-time rainfall data. *Weather Radar and Hydrology*, International Association of Hydrological Sciences Publication No. 351, 231–236.