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Recent developments and applications of the SWIRLS nowcasting system in Hong Kong

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RECENT DEVELOPMENTS AND APPLICATIONS OF THE SWIRLS NOWCASTING SYSTEM IN HONG KONG

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ABSTRACT

The Hong Kong Observatory's nowcasting system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) has undergone a major upgrade to version 2 in 2010 with new and refined prediction algorithms, expanded warning support, as well as new weather services for the public. There are several special versions of SWIRLS that supported the 2008 Beijing Olympic Games, the 2010 Shanghai World EXPO and the 2010 New Delhi Commonwealth Games. Performance statistics and user feedbacks showed that the products of SWIRLS have been useful in supporting both the weather warning operations and public nowcasting service. Recent development and application experience will be shared in this article. Some thoughts on meeting the nowcasting challenges will also be put forward.

1. INTRODUCTION

Following the external deployment to Beijing for the WMO Beijing 2008 Olympics Forecast Demonstration Project (B08FDP; WMO 2009) and a parallel internal trial at the Hong Kong Observatory, the second-generation nowcasting system of the Observatory SWIRLS-2 (Yeung *et al.* 2009) has been formally put into operation in 2010. Compared with its original version, which is radar-based and targeted mainly for imminent rainstorms (Li *et al.* 2000; Li & Lai 2004), the second generation was much enhanced including new and refined prediction algorithms, expanded scope of warning support, as well as introduction of new service for the public. It has also grown from a relatively simple system with local flavours to a sophisticated system that could be adapted for use in other operational environments with significantly different severe weather climatology.

In respect of severe weather prediction, SWIRLS comprises a whole suite of nowcasting sub-systems and algorithms. Major modules include the optical-flow and correlation based radar-echo tracking methods (Cheung & Yeung 2012), radar QPE based on real-time calibrated Z-R (Li *et al.* 2000; Li & Lai 2004), blended QPE based on co-Kriging of radar and raingauge information (Yeung *et al.* 2011), rainfall extrapolation by semi-Lagrangian advection (Staniforth & Cote 1991; Li & Lai 2004), nowcast-NWP QPF blending (Wong *et al.* 2009), centroid-based thunderstorm cell identification and tracking (Li *et al.* 2000; Li & Lai 2004), cloud-to-ground lightning initiation nowcast (Yeung *et al.* 2007), thunderstorm severe squalls (Yeung *et al.* 2008) and hail nowcasting based on conceptual models (Yeung *et al.* 2009). Major developments introduced in recent years are highlighted and described in Section 2.

In terms of weather warnings, SWIRLS now supports rainstorm warning, landslip warning, flood alerting, as well as thunderstorm warning that covers lightning, severe wind gust and hail. For the early alerts on rainstorm, the maximum lead time has been extended to 6 hours. Details are presented in Section 3.1 below. Besides public weather warnings, the radar reflectivity nowcasts have also been applied to nowcasting of convection in support of air traffic control. The details will be presented in a separate paper submitted by Cheung and Yeung (2012) to this symposium.

The introduction of public nowcasting service is one of the key driving forces behind the upgrade of SWIRLS to version 2. Participation in international events helped accelerate the research-to-service process. Sections 3.2 and 3.3 summarize the key messages and findings along these lines. In Section 3.4, a brief account of forecast performance

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is given. Section 4 discusses the various challenges and opportunities in rainfall nowcasting and outline the possible ways forward. Lastly, Section 5 concludes this paper.

2. RECENT ADVANCES

2.1 Radar-Echo Tracking by Optical Flow

In SWIRLS, the original radar-echo tracking algorithm is based on the TREC method (Tracking of Radar Echoes by Correlation; Tuttle & Foote 1990). The movement of radar echoes between two consecutive CAPPI scans is derived by maximizing the cross-correlation between small blocks of radar echoes on the two scans. The method is good for tracking the movement of localized systems in short duration, say one or two hours. For longer period out to 6 hours as required in B08FDP, TREC has been found to be inadequate, notably for rainfall systems with different moving directions in the large and small scales. A classic example is squall line. While individual echoes within the squall line move towards the northeast following the southwesterly winds ahead of a short-wave trough in the upper westerlies, the squall line as a whole move towards the southeast, closely aligning with the southeast advancement of the short-wave trough.

With a view to improving the tracking of radar echoes, Wong *et al.* (2009) and Wong (2012) introduced a Multi-scale Optical flow by Variational Analysis (MOVA) scheme in the SWIRLS nowcasting system. It is based on the popular optical flow approach and a multi-level cascade computation to analyze echo-motion at different spatial scales. MOVA had been applied in SWIRLS to support various international events, including the 2008 Beijing Olympics (Yeung *et al.* 2009; Wong *et al.* 2009), the 2010 Shanghai World EXPO (WMO 2012), as well as the 2010 Commonwealth Games in New Delhi, India (Srivastava *et al.* 2012). Starting from 2010, MOVA has been adopted as the operational radar-echo tracking scheme for quantitative precipitation forecast (QPF) of SWIRLS in Hong Kong. Its performance is summarized in Section 3.4 below. Research and development works are also underway at the Observatory to further enhance the optical-flow based tracking. Further details can be found in a separate paper submitted by Cheung & Yeung (2012) to this symposium.

2.2 Co-Kriging QC and QPE

In the original version of SWIRLS, there were two schemes for gridded rainfall analysis, namely the raingauge-only Barnes interpolation method and the radar

(a)

(b)

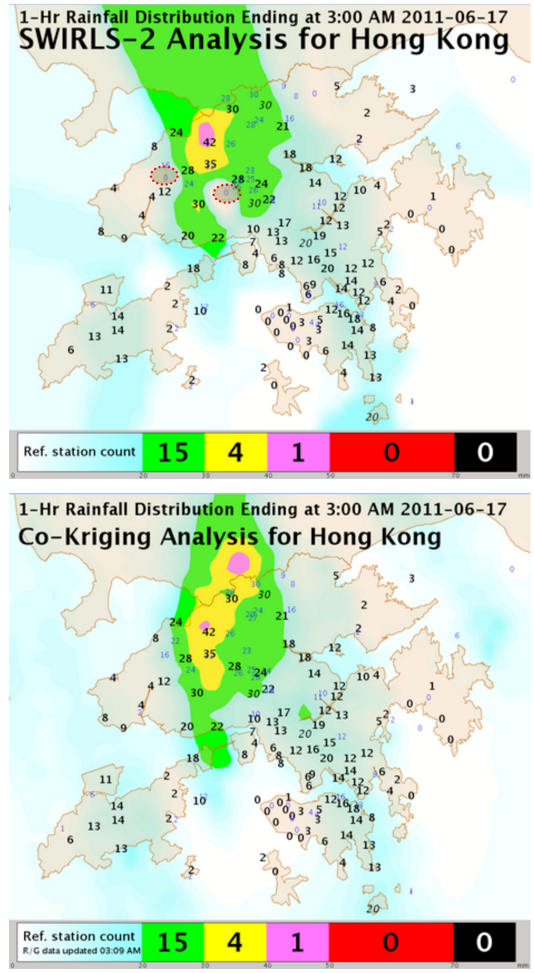

Fig. 1 A real-time example of co-Kriging raingauge data quality control and rainfall isohyet analysis valid at 3:00 pm on 17 June 2011: (a) based on the operational Barnes analysis method without data quality control; (b) based on co-Kriging QPE after co-Kriging raingauge data QC. The dashed ellipses in (a) marked the two raingauges that reported false zeroes.

reflectivity-based QPE. The former method is good for estimating the absolute value of rainfall on the ground but the major problem is that surface raingauge network is usually not dense enough to describe the spatial distribution in sufficient details. For the latter approach, rainfall rate is the main object of analysis and it is obtained through the Z-R relation $Z = a \cdot R^b$.

Treating a and b as adjustable parameters, this conversion formula can be calibrated every 5 minutes. Approximating the surface rainfall rate by the latest available short-duration rainfall accumulation G registered by raingauges, a linear regression analysis can be performed on the logarithms of G and Z to determine the dynamical values of a and b as best fitting parameters. When the spatial extent of the rainfall system is extensive, this calibration method can be effective. However, during the start of a rainfall event or when the rainbands cover only a limited number of raingauges, the number of data pairs available for the dynamic regression analysis would be limited, which would in turn affect the quality of data fitting. Moreover, the Z-R calibration may also depend on range due to radar beam broadening and power loss in far range.

During the last couple of years, Yeung *et al.* (2010; 2011) developed a new rainfall analysis scheme based on the co-Kriging geostatistical technique to combine both the raingauge and radar data. In their formulation, raingauge data are treated as the primary source of rainfall information and radar reflectivity-converted rainfall plays a secondary role to provide detailed information on the spatial structure of the rainfall systems. The co-Kriging QPE scheme is further applied to the quality control (QC) of raingauge measurements. The co-Kriging QC/QPE system has been put into operational trial since May 2011. Fig. 1 shows an example of real-time raingauge data QC and rainfall isohyet analysis based on the co-Kriging method. As marked on Fig. 1(a) by dashed ellipses, two false zeroes seriously affected the rainfall analysis in the stormy area. With proper discard of such problematic data through the application of co-Kriging QC procedure, the resulting rainfall isohyet map based on co-Kriging QPE much better reflected the coverage of the rainstorm. Notice that the blended use of radar rainfall by co-Kriging analysis also helped improve the intensity estimation over gauge-void region, e.g. the yellow/purple patch just to the north of the Hong Kong border.

The current implementation of the co-Kriging QPE algorithm requires significant computation power. Development work is under way to optimize the numerical algorithm so that it can be extended to cover a large domain. If that becomes achievable, the initial field required by QPF algorithm may be switched to use co-Kriging QPE which is considered superior than the pure reflectivity-based radar QPE.

2.3 Blending with NWP

For rainfall prediction beyond the first couple of hours, forecast errors mainly come from the inability to forecast the initiation, growth and decay processes of precipitation systems solely by tracking movement of radar echoes. To properly address this problem, high-resolution NWP is required to simulate such physical processes. Yet due to the well-known spin-up problem with NWP models, the nowcast-NWP rainfall blending is considered a better approach in practice. At the Observatory, a rainfall blending system called RAPIDS (Rainstorm Analysis and Prediction Integrated Data Processing System; Wong & Lai 2006) has been in trial operation and deployed to Beijing in support of the Beijing 2008 Olympics (Wong *et al.* 2009). It is updated at 6-min intervals, in synchronization with the radar-extrapolated QPF from SWIRLS. For the NWP input, the Non-Hydrostatic Model (NHM; Saito *et al.* 2007) of the Japan Meteorological Agency (JMA) is used. Before blending with nowcasts, the NWP QPF is pre-processed to correct for phase errors and intensity errors (Wong *et al.* 2009). To represent the inherent uncertainties, a time-lagged ensemble approach is used to post-process the blended QPF for generating probabilities of precipitation (PoP) at various thresholds of interest.

In 2011, the NHM was upgraded to 2-km horizontal resolution. In an attempt to ease the spin-up problem, NHM is initialized through a two-stage data assimilation procedure: (1) retrieval of humidity profiles over raining areas using radar reflectivity; and (2) 3-dimensional variational data assimilation of the retrieved humidity profiles by the JNoVA-3DVAR system (Honda *et al.* 2005). During data assimilation, all other available observations, including radar, satellite, GPS and AWS, etc, are ingested in an hourly update cycle.

3. APPLICATIONS & PERFORMANCE

3.1 Severe Weather Warnings

In Hong Kong, the products of SWIRLS have been extensively used to aid warning decision making by forecasters. Fig. 2 shows a screen shot of the main webpage called SPIDASS (SWIRLS Panel for Integrated Display of Alerts on Severe Storms) dedicated for the display of all the severe weather alerts generated from SWIRLS and RAPIDS. As shown in Fig. 2, SPIDASS provides a compact view of different alerts (in rows) with their status colour-coded for different severity levels and aligned vertically according to issue times. For example, the first row of colour codes indicates that the 1-hour forecast for rainstorm status from 00:00 to 01:00 local time was changing from category "R" through "A" and "G" (which refer to widespread and persistent hourly rainfall reaching thresholds of 50, 30 and 20 mm) to "N" (meaning non-rainstorm) as the actual rainstorm weakened and departed during the period.

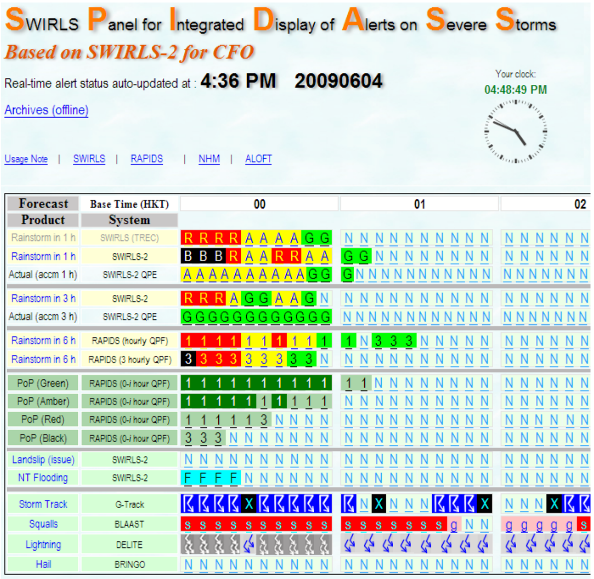

Fig. 2 Screen shot of SPIDASS in the early hours on 4 June 2009. Refer to the main text in Section 3.1 for descriptions of various alerting products.

The next 6 rows are also rainstorm alerting products with lead times increasing to 3 and 6 hours for early alerts to forecasters. The middle four rows represent PoP at thresholds 20, 30, 50, 70 mm/h respectively calculated from the time-lagged ensemble of RAPIDS. Different probability ranges are represented by different green shadings. The numeric codes refer to different lead times in hours. These PoP alerting products are included to supplement the deterministic rainstorm alerts displayed in the upper rows and indicate the degree of consistency/confidence of the deterministic alerts. The next 2 rows show the alerting status of landslide (with status symbol "L" if triggered) and flooding (with status symbol "F" as shown in Fig. 2).

The bottom four rows refer to alerting status of thunderstorms (with status symbol if the tracks traverse Hong Kong) and the associated severe weather, including severe squalls (with possible status symbols of "g", "s" or "h" for gale, storm or hurricane force wind), cloud-to-ground (CG) lightning (with three possible severity levels , , and) and hail (with status symbol). Besides colour-coded alerting status, the threats of severe weather can also be visualized on maps for forecasters' appreciation of the geo-locations of the concerned weather. Fig. 3 shows an example of the Severe Weather Map of SWIRLS for thunderstorms near and over Hong Kong on 5 March 2009.

Selected QPF data and map products are also provided to other government departments, including the

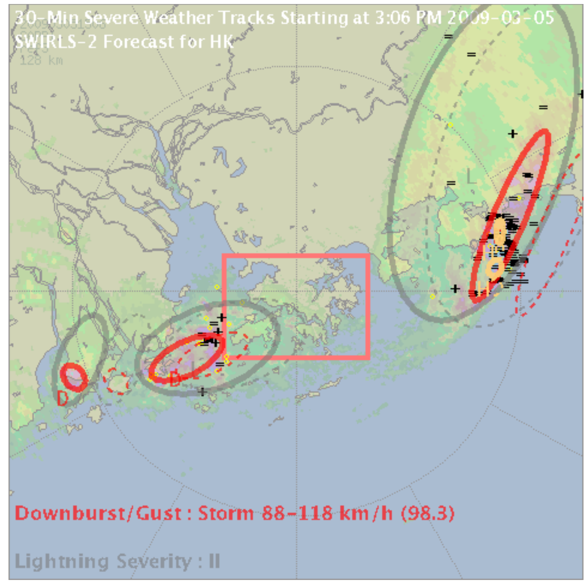

Fig. 3 Severe Weather Map of SWIRLS issued at 3:06 pm on 5 March 2009. Red and grey ellipses indicate the analyzed threat areas of severe wind gust and CG lightning respectively. Dashed ellipses indicate the forecast positions of the threat areas in 30 minutes. Small yellow "o", black "=" and black "+" symbols mark the locations of actual cloud-to-cloud, negative CG and positive CG lightning respectively.

Geotechnical Engineering Office and the Drainage Services Department, for better appreciation of the impending heavy rain in support of their operations in relation to landslip and flooding.

3.2 Nowcast Service for the Public

At the public service front, visual impact and user-friendly delivery of weather products are of paramount importance. Since late 2008, the first 2-hour QPF from SWIRLS has been used to provide a web service called "Rainfall Nowcast for the Pearl River Delta (PRD) Region". The high-resolution QPF from SWIRLS is smoothed to 2-km resolution for the production of rainfall isohyet maps. Such forecast rainfall maps are formatted using the Keyhole Markup Language (KML) for visualization using the desktop application Google Earth or directly on the Internet webpage via the Google Earth API/plugin. Fig. 4 shows a screen shot of the product on 22 May 2011. Users could easily perform zoom-in and zoom-out, configure panoramic view and animate the forecast maps of rainfall distribution. Since its introduction, webpage access statistics have been increasing with an accumulative total number of page hits exceeded 12 million by the end of 2011. With such a public embracement and the huge potential noticed from other mobile applications developed by the Observatory, work is underway to develop

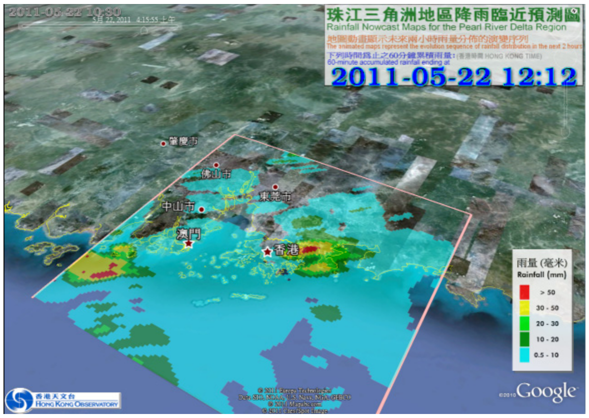

Fig. 4 Screen shot of the "Rainfall Nowcast for the PRD Region" product disseminated on 22 May 2011.

and launch a mobile version of rainfall nowcast products targeting to provide smart-phone users with location-specific rainfall nowcast information.

3.3 Deployment to Other Places

After the participation in the WMO/WWRP B08FDP project (Yeung *et al.* 2009), HKO was invited to contribute SWIRLS in several others international events. The first one was the 2010 Shanghai World EXPO Nowcasting Services (WENS) project (WMO 2012) under the auspicious of WMO Public Weather Services. In WENS, all nowcasting systems deployed in Shanghai had to be operated throughout the entire EXPO period from May to Oct 2010. It presented an even bigger challenge than B08FDP in terms of the duration of deployment. According to the Shanghai Meteorological Bureau, a total of 30 severe weather warnings were issued, encompassing thunderstorms, strong winds and heavy rain. Due to resource and time constraints, the Shanghai version of SWIRLS was reduced with nowcast-NWP blending sub-system skipped. For radar inputs and pre-processing, the needed data streams were provided by the Severe Weather Automatic Nowcasting (SWAN; Feng 2012) system of the China Meteorological Administration. Contrary to the real-time forecast verification performed during the 3-week operational period of B08FDP, the assessment on WENS nowcast products was performed subjectively by forecasters on a regular and systematic manner. It was noted that each forecaster seemed to have favourite products of his/her own and there was no clear consensus as to which system was the most popular or useful. In terms of subjective scores, SWIRLS was ranked the top overall and the severe weather products of SWIRLS were reported to be very much liked by the forecasters.

(a)

(b)

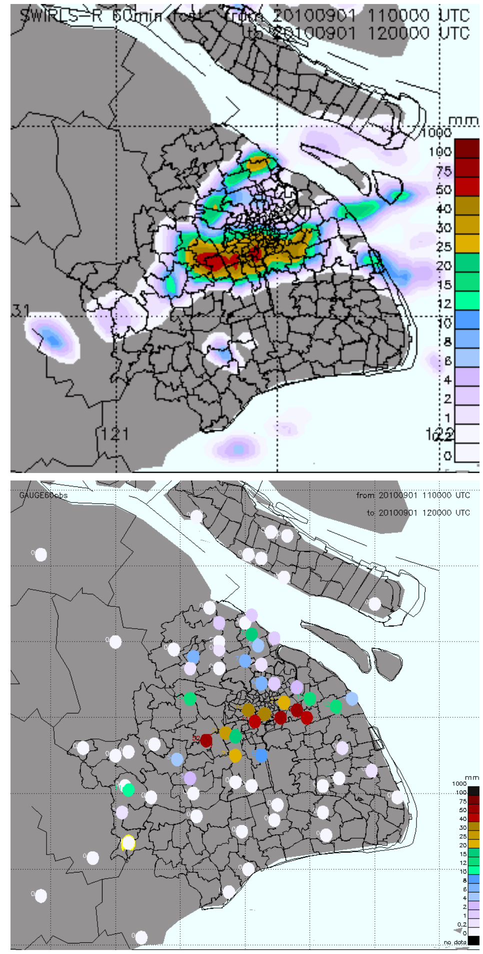

Fig. 5 Real-time example of localized heavy rain forecast for Shanghai on 1 September 2010: (a) 1-hour nowcast by SWIRLS issued at 19:00 local time; (b) actual 1-hour accumulated rainfall ending at 20:00 local time reported by raingauges.

Fig. 5 shows an example of localized heavy rainfall successfully predicted by SWIRLS on 1 September 2010. In Fig. 5(a), hourly rainfall exceeding 50 mm (red or darker colours) was predicted over and near the EXPO site (centre of the map) at 19:00 local time and later verified by actual observed rainfall as shown in Fig. 5(b).

At the request of the India Meteorological Department, SWIRLS was also installed in India in support of the New Delhi Commonwealth Games, a project almost running in parallel with the WENS operation. One major lesson learnt from developing the India version of SWIRLS was on the impact of radar update cycle on radar tracking. Different from the 6-minute update cycles in Hong Kong and in Mainland China, the Indian radars run on a 15-minute (and later revised to 10-minute) cycle. This presented a major challenge to the radar-echo tracking methods of SWIRLS and substantial algorithm tunings were required. The application of SWIRLS and the results of tunings were reported recently by Srivastava *et al.* (2012).

3.4 Performance

Fig. 6(a) summarizes the probability of detection (POD), false alarm ratio (FAR) and critical success index (CSI) of the "Rainfall Nowcast for the PRD Region" product for 2010-2011. The radar QPE was taken to be the ground truth for verification. The "PRD" verification domain is a square with area approximately 240 km x 240 km centred at the main radar site of Hong Kong. It is noted that the "rain" or "no rain" forecast as discriminated by the 0.5-mm threshold scored about 70% POD at 1-hour lead time, dropping to about 50% at the end of the 2-hour forecast period. Also noted in Fig. 6(a) is the higher skill attained in the smaller "HK" domain (the dashed curves refer) covering just the territory of Hong Kong. This could be attributed to the better radar measurement and higher applicability of the dynamic Z-R calibration in closer ranges to the radar.

At higher thresholds and longer lead times, the POD and CSI dropped significantly. And in these regimes, the blended QPF finds its slightly better performance. Fig. 6(b) shows the CSI of the MOVA-based QPF of SWIRLS at the lead time of 6 hours (red bars). Starting from a low value of about 0.12, it drops further quickly to a vanishing value at high rainfall thresholds. Also shown are the blended QPF from RAPIDS (blue) and its NWP component (green). Apparently, the CSI of RAPIDS QPF at T+6h out performed its parent forecasts for threshold values up to about 20 mm. However, it should be remarked that the advantages of RAPIDS QPF at shorter lead times (not shown) and higher thresholds are not obvious. This is because the absolute skill level of the current model QPF from NHM is actually still rather low (0.12 or less) throughout the 6-hour period so that inclusion of such information does not add significant benefit to the blended QPF.

For rainstorm warning verification, an event-based approach is adopted. Although the warning criterion for intensity is high (hourly rainfall at 30 mm or above), the spatial criterion (widespread) is not very restrictive which requires only a certain number of raingauges attaining the intensity criterion. Compared with the QPF verification, which is a strict grid-to-grid checking, the spatial criterion in rainstorm warning is much relaxed. It is therefore not surprising that the QPF of

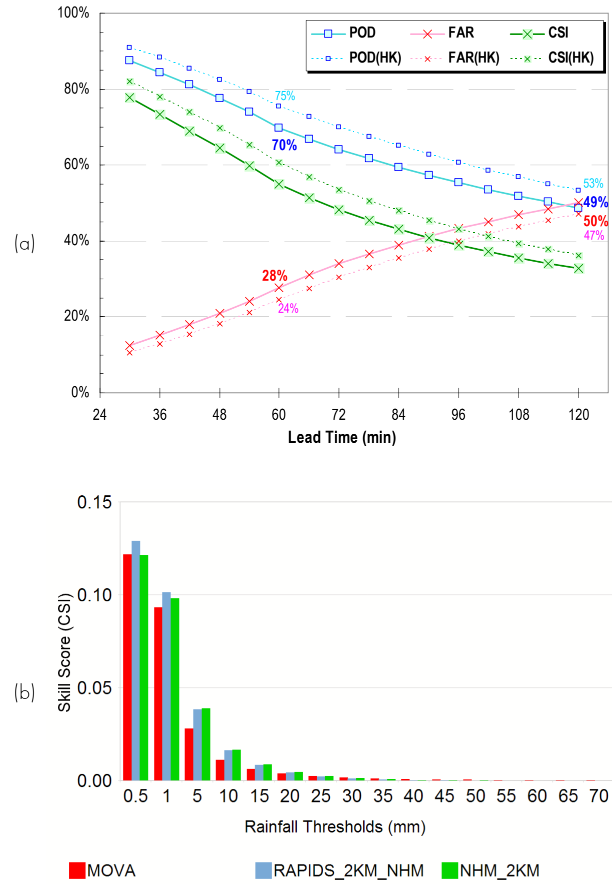

Fig. 6 Verification results of SWIRLS QPF for 2010-2011 over the "PRD" domain: (a) POD (blue), FAR (red) and CSI (green) in the first two hours of prediction at the 0.5-mm threshold (note: dashed curves refer to the smaller "HK" domain); (b) CSI at the lead time of 6 hours (red histograms labeled "MOVA"). Also shown in (b) are CSIs of the blended forecast from RAPIDS (blue) and the underlying 2-km NHM QPF (green).

SWIRLS is still useful when applied to rainstorm prediction. In fact, verification results for a total of 50 rainstorms in 2008-2011 indicate that the overall POD and FAR were about 82% and 62% respectively. The averaged lead time was about 48 min. For the more severe rainstorm categories of Red or Black (hourly rainfall at 50 mm and 70 mm or above respectively), the performance was considerably less satisfactory. In some sense, this is not surprising as such intense rainstorms often involved violent convective developments even in the first hour of prediction, far beyond the capability of extrapolation nowcast and the current generation of NWP QPF. Moreover, it should be noted that these two categories belong to rare events and the currently used POD and FAR may not be the most effective measures to assess the predictions of such.

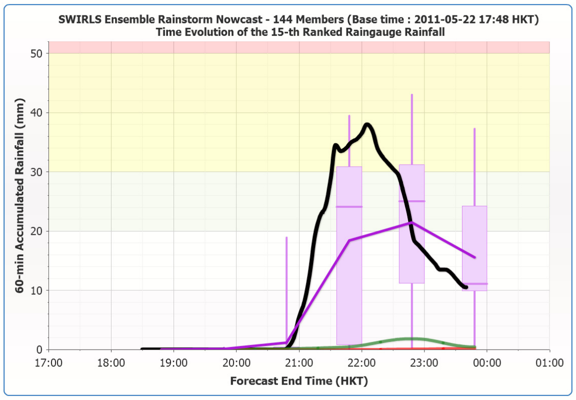

Fig. 7 Illustrative example of ensemble rainstorm nowcasting. The y-axis refers to the value of the key rainfall parameter (i.e. the "15-th ranked raingauge rainfall) most critical to the Observatory's rainstorm warning criteria. Different background colours indicate different warning thresholds. The black curve and the purple box-whisker diagrams represent respectively the actual and predicted values of the key rainfall parameter. Also shown are the existing extrapolation nowcasts based on TREC (green curve) and MOVA (red curve).

4. DISCUSSION & OUTLOOK

Although the merits of the blended QPF looked marginal as indicated in the performance statistics, case by case inspection indicated that RAPIDS did outperform extrapolation nowcast significantly when the model could capture correctly the mesoscale circulations responsible for the rainfall initiation, growth and decay processes. The low skill level stemmed from the NHM QPF which could in turn be attributed largely to the model spin up problem. Further effort will be invested to improve on this issue through better assimilation of more remote-sensing data and actual rainfall observations.

Apart from blending, Fig. 6 actually reveals a potential gain by improving the rainfall nowcast in the shorter range of 2 or 3 hours. Case studies showed that much improved CSI could be achieved by a better representation of the larger scale motion field, which controls the advection of radar echoes in the longer lead times. Motion tracking using satellite imageries at hourly intervals can be one direction. In situations of tropical cyclone (TC) where the resultant motion of rain echoes will be difficult to be tracked accurately by automatic algorithms, the use of subjective TC track information analyzed by human forecasters may also be considered. To effectively use the larger scale motion field in extrapolation type nowcast, work is under way to modify the semi-Lagrangian advection scheme of SWIRLS so that the finer scale motion field obtained from automatic tracking of radar echoes will also be moved along by the larger scale motion field.

Another critical factor that leads to the quick depreciation in QPF skill is the evolution of storms, which often involves large uncertainties in terms of both location and intensity. Ensemble nowcasting with a probabilistic product representation is a means to deal with such inherent uncertainties. As there is no simple ground truth to quantify the location errors of QPF, the modeling of such errors is non-trivial. As an alternative approach, a poor-man ensemble obtained by perturbing the controlling parameters around some "optimal" setting in the tracking algorithm may be pursued.

Fig. 7 illustrates an example of ensemble rainstorm nowcast currently under development at the Observatory. As shown in the figure, both the ensemble median (purple horizontal bar) and mean (deep purple curve) are closer to the verifying observation (black curve) compared with the existing deterministic predictions based on TREC (green curve) and MOVA (red curve) throughout the 6-hour period of prediction. This much improved result is partly due to the reduction of location error by the averaging effect of ensemble and partly attributable to the improved tracking method itself (Cheung & Yeung 2012).

The remaining gap is mainly due to the errors from intensity change as well as the limited spatial coverage of the weather radars in Hong Kong. To improve on the latter issue, expanded radar coverage has been realized in early 2012 through collaboration and data exchange with the China Meteorological Administration. For ensemble prediction of intensity change, further research effort will be devoted to the study of the intensity evolution of historical rainstorms so that representative intensity perturbations could be drawn in accordance with past statistics. Satellite data will also be explored for real-time extraction of information on storm evolution.

5. CONCLUDING REMARKS

The second-generation of SWIRLS has found its applications not only in the forecasting office but also in the public weather services for Hong Kong, as well as in a number of international events. Recent statistics indicated that SWIRLS QPF is useful in support of a public service but with rooms for further enhancement in terms of heavy rain prediction in the longer lead time. Continuing effort will be devoted to such enhancement.

As with the B08FDP, participation in international events with on-site tests and trials brought new challenges to the nowcasting algorithms and revealed issues not readily noticeable from the operation in Hong Kong alone. All of these have shed light on the direction for further enhancement of the system. The external deployments also served to benchmark the capability and functionality of SWIRLS against other state-of-the-art nowcasting systems in the world. Noting the silent reward from nowcasting technology exchange and experience sharing, the Observatory will welcome further collaborations from members of the meteorological community.

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