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Merging Nowcasting and NWP in Weather Warning Operations,
with Special Reference to Landslides

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1. Introduction

In support of weather forecast and warning operations for different time frames, various forecast suites and visualization tools have been specially designed and implemented in the Hong Kong Observatory (HKO). These suites generate timely and easy-to-interpret analysis and forecast products to facilitate forecasters' formulation of forecast strategy and operation of weather warnings. Noting that accuracy, timeliness and effective communications are key factors leading to the success of a weather warning service, HKO strives to enhance the service by taking advantage of the latest advance of nowcasting and forecasting techniques together with the computer and communication technologies. In recent years, HKO has devoted much effort to the development of nowcasting and forecasting systems in support of an array of weather warnings. This paper describes how the suites of forecasting systems developed by the HKO support the operation of weather warnings in Hong Kong. Performance evaluation, limitations, challenges and opportunities in the future are also discussed.

2. Weather warnings in Hong Kong

HKO has a long history of operating severe weather warning systems. The warning systems have evolved over the years to meet the public's changing demand. Figure 1 summarizes the history of the severe weather warning systems operated by the HKO. In response to the growing need to warn of the hazardous phenomena associated with mesoscale rainstorms, HKO introduced short-range warnings for heavy rain in 1967. It has evolved into an array of warnings covering flooding and landslips as well. The Landslip Warning was introduced in 1983. A Rainstorm Warning System using different colors to warn different levels of heavy rain was introduced in 1992 after a severe rainstorm event of 8 May in the same year. When it was first introduced, issuance of the warnings was based on the actual amount of rainfall which has fallen generally over Hong Kong. Technological advancement gained from the development of nowcasting system and mesoscale modelling enabled the introduction of a forecast element into the rainstorm warning system later. The

system was revised in 1998 and now there are three levels of warning, viz. Amber, Red, Black, which means heavy rain exceeding 30 mm, 50 mm and 70 mm respectively has fallen or is expected to fall generally over Hong Kong in an hour. Key government departments and major transport and utility operators are put on alert if Amber rainstorm warning is issued. Over a 12-year period from 1992-2003, the annual occurrences of Amber, Red and Black rainstorms on average are 28, 4, and 1 respectively.

Special announcement for flooding over the northern part of Hong Kong and landslide warning were implemented for targeted groups of people who live or commute in low-lying areas and near precarious slopes respectively. All these warnings have profound impact on economic and societal aspects. Timely and reliable quantitative precipitation forecast (QPF) in the short range, especially several hours ahead, will be of prime importance.

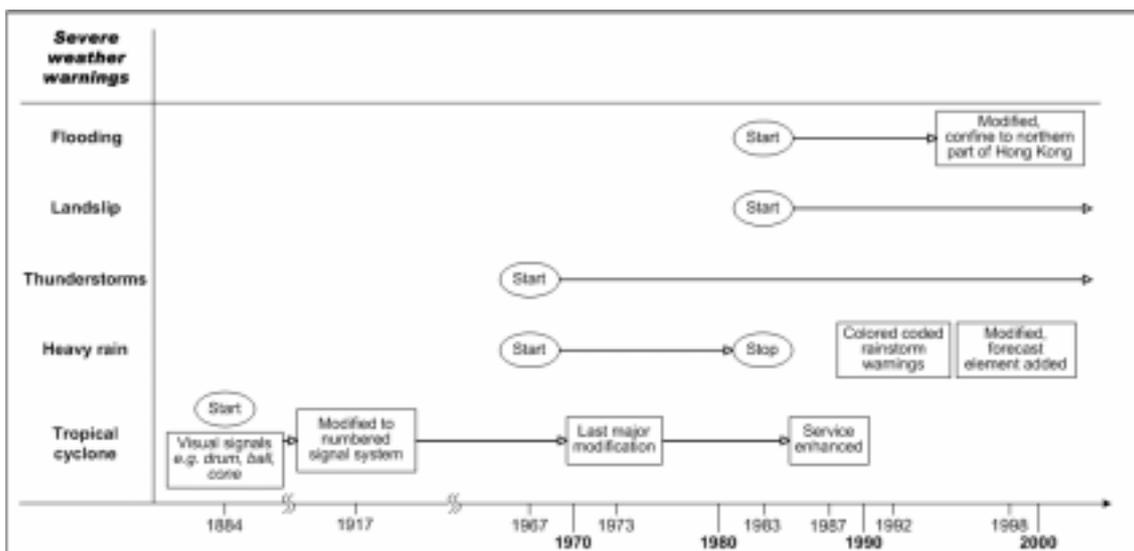


Fig. 1 History of severe weather warning systems in Hong Kong.

3. Rainstorm nowcasting system

Nowcasting covers the forecast range that forecasters often have to make critical operational decisions in rapidly developing weather situations. It has become an increasingly important and specialized subject that supports decision making in daily forecasting and warning operations. Nowcasting, according to the definition by Conway (1998), is forecasting with local detail, by any method, over a period from the present to a few hours ahead with the inclusion of a detailed description of the present weather.

A radar-based nowcasting system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems), which was developed in-house at HKO, was put into operation in 1999. It provides local analysis and forecasts of rainfall up to 3 hours ahead. It supports forecasters in formulating nowcasting strategies in operating the Rainstorm Warning System in Hong Kong. It also supports forecasters in operating the Landslip Warning System in collaboration with the Geotechnical Engineering Office (GEO) of the Civil Engineering Department of Hong Kong. HKO is responsible for providing a 3-hour rainfall forecasts for assessing the short-term trends in the running 24-hour accumulated rainfall, a parameter found to correlate well with landslip occurrence.

In SWIRLS, rainfall rate (R) is estimated from radar reflectivity factor (Z) through a dynamic empirical relation. It makes use of more than 100 raingauge data over Hong Kong to calibrate radar reflectivity in real-time using linear regression method. Radar CAPPI reflectivity data at 1-km height are used to correlate every five minutes with the rainfall recorded by the raingauges underneath within a searching area. The adjusted Z-R relationship is used subsequently in the forecast module, based on TREC (Tracking Radar Echoes by Correlation) winds, to convert the forecast radar reflectivity pattern into future rainfall figures at the raingauge positions. The procedures adopted largely follow Zawadzki *et al.* (1986) and details of the radar-raingauge adjustment can be found in Li *et al.* (2000).

The TREC wind analysis is updated every 6 minutes from the latest radar scan and the forecast movement of rain cells will also be updated accordingly. With suitably chosen box size, the TREC can reveal the rain movement on different spatial scales. Figure 2 illustrates an example of motion vectors produced by TREC for a rainband in perturbed southwesterly flow in a case of Amber Rainstorm as described in Lai *et al.* (2001). Individual rain echoes typically move northeastward in the direction of prevailing wind as shown by the TREC vectors in Fig.2. However, the rainband as a whole actually moved southeastward. To track and estimate the echo movement in a group, another module has been developed called GTrack (Group Tracking).

GTrack is an “object-oriented” technique for tracking the movement of a storm as a total entity. The pixels over some pre-defined intensity threshold are grouped in the form of an ellipse. The movement of ellipse centroids will be tracked between successive radar images. Figure 2(b) shows the GTrack analysis of the same case as in Fig.2(a). It clearly shows that GTrack is capable of indicating the southeastward movement of the rainband as a whole in spite of the fact that individual small-scale

features were moving northeastward. Unlike the embedded rain cells which can have a volatile life history, the overall rainstorm system organized on the larger scale tends to move more steadily. As long as the rainstorm systems are well-defined, system movement can be reliably tracked and their short-term positions in the next couple of hours well handled. To the operational forecaster, such information is very useful to rainstorm nowcasting and the operation of weather warnings related to heavy rain.

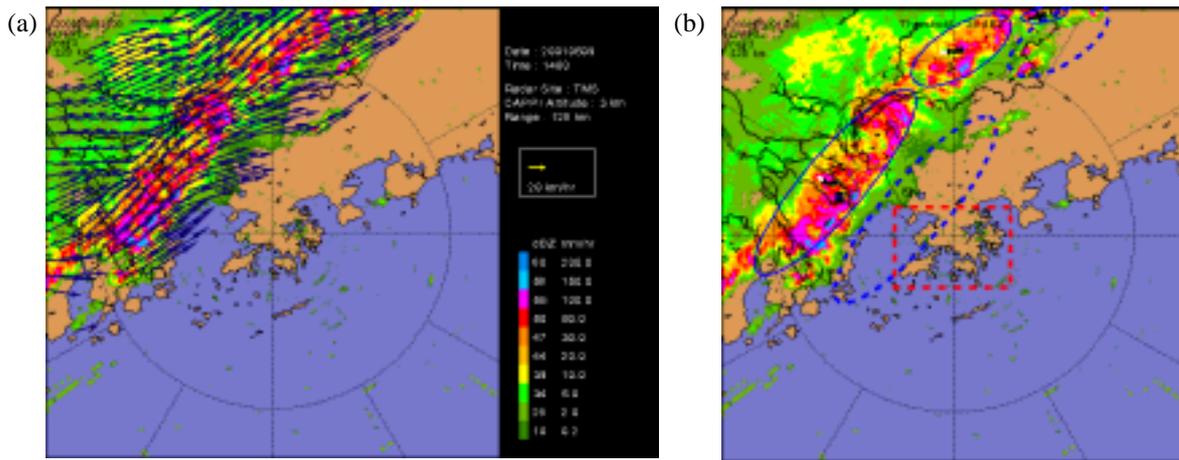


Fig. 2 (a) Motion vectors produced by TREC showing a rainband in perturbed southwesterly flow ; (b) Same radar images as in (a), but GTrack analysis also indicating southwestward movement of rainband as a whole towards Hong Kong. Solid lines are the storms as identified by GTrack and dashed ellipses are 1-hour forecast position of echo groups.

Through linear extrapolation, the TREC vectors of past echo movement are used to estimate future positions of rain echoes in the next 1-3 hours. Combining with the rain estimation from radar reflectivity and raingauge data and assuming no change in echo intensity, SWIRLS rainfall forecasts and automatic warnings up to 3 hours ahead will be provided to the forecasters every 6 minutes, around 10 minutes after radar observation time, in support of operational rain-related warnings. Operational experience suggests that reasonable rainfall forecasts can be achieved within the first three hours as long as the advective process is dominant and provided there is no volatile fluctuation in echo intensity.

A SWIRLS rainstorm nowcasting tool named “Rainstorm Viewer” has also been developed to facilitate the monitoring of rainfall trend and decision making for rainstorm warning in the next hour. Statistical method based on historical rainstorms statistics has been used in conjunction with SWIRLS QPF to generate probabilistic forecast of Rainstorm Warnings together with average lead time information every 6 minutes for the next hour. This is the first probabilistic

nowcasting tool for operational trial in 2003. A sample of the Rainstorm Viewer display is shown in Fig.3. Preliminary assessment is that the nowcasting tool provides additional useful guidance for the risk assessment of the occurrence of rainstorms.

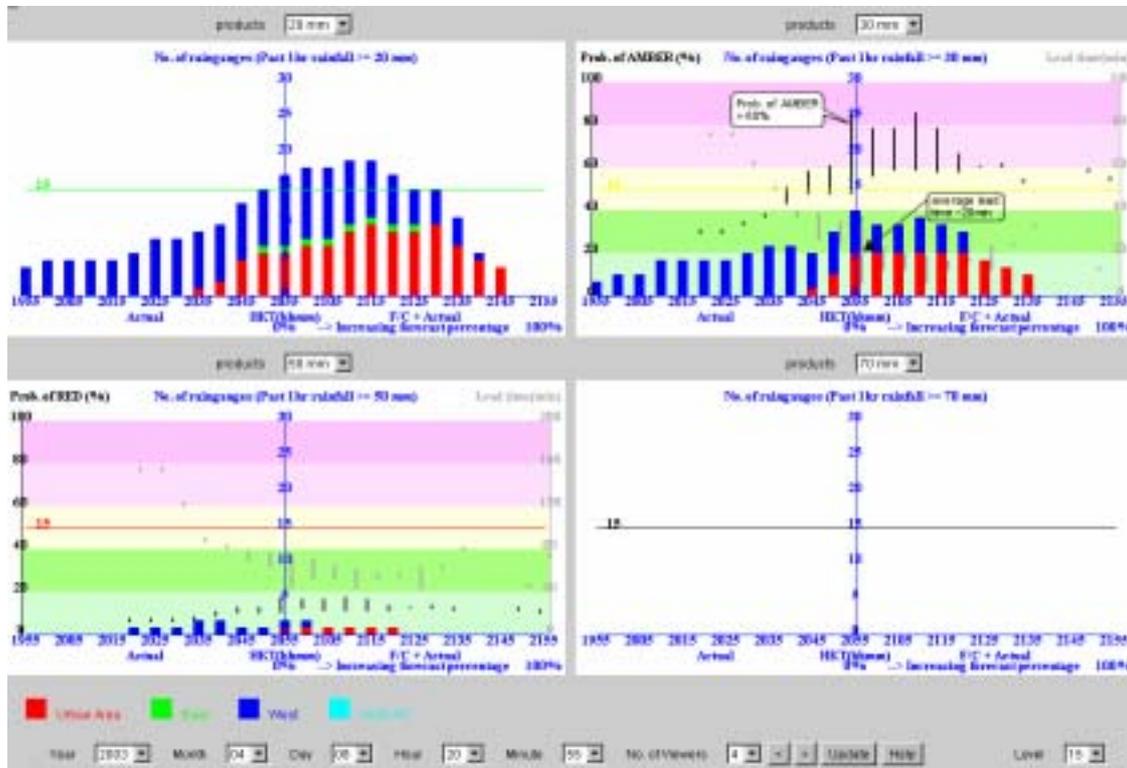


Fig. 3 Display of Rainstorm Viewer for an Amber Rainstorm on 8 April 2003.

4. Objective rainfall guidance from NWP models

In support of short-range forecasting operations, HKO operates a mesoscale hydrostatic model developed based on the RSM of the Japan Meteorological Agency (JMA). The HKO's ORSM (Operational Regional Spectral Model) was put into operation at 20-km and 60-km resolutions to provide 24-hour and 48-hour forecasts respectively in 1999. Both models are configured with 36 vertical levels (Lam *et al.*, 2000). The 20-km model is run in a 3-hourly analysis-forecast cycle and is one-way nested into the 60-km model. The data cut-off time is around 2 hours and the products are made available to the forecasters around 4 hours after model analysis time. The 60-km model is run in a 6-hourly analysis-forecast cycle with boundary data provided by JMA's Global Spectral Model forecasts. The data cut-off time is 3 hours and the products are made available around 5 hours after model analysis time. The model domain configurations are shown in Fig. 4. The forecast ranges for 20-km and 60-km ORSM have been extended to 42 hours and 72 hours respectively

in late 2003.

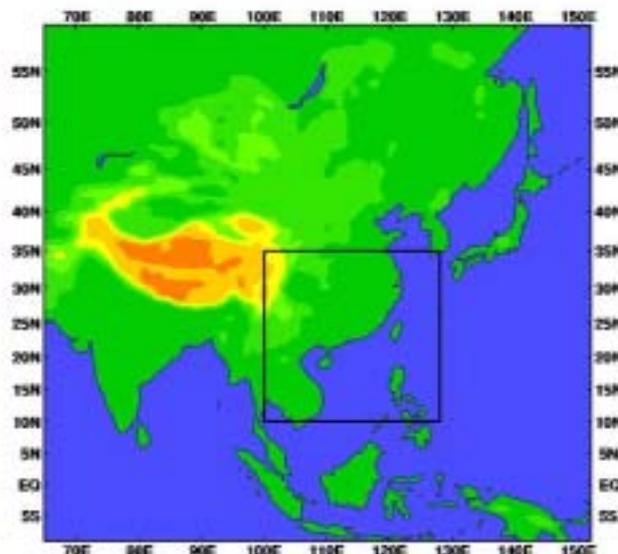


Fig. 4 Model domain of 20-km ORSM covering 10–35 N, 100-128 E (inner box) and 60-km ORSM (outer box) spanning 9 S – 59 N, 65-152 E.

In addition to the conventional surface and upper air observations, radar data is ingested into the model through physical initialization technique with a view to improving rainfall forecast, especially for the first few hours. Hourly rainfall analysis data, which is provided by the radar-based SWIRLS nowcasting system, is utilized in the model three hours before model analysis time so as to adjust the initial heating profile and dynamic forcing. As the rainfall analysis from radar and raingauges covers only a limited portion of the model domain, rainfall estimation based on information derived from the Geostationary Meteorological Satellite (GMS) such as cloud top temperatures and cloud cover are also used. Results from model impact studies show that physical initialization helps alleviate the spin-up problem in model simulation, especially for the first 6 hours of forecast, and produce more realistic QPF (Lam *et al.*, 1999).

Text forecasts mimicking those issued by forecasters including state of sky, wind direction and strength, maximum and minimum temperatures, visibility and categorical precipitation forecasts based on ORSM outputs are generated automatically. In addition, automatic warnings of rainstorms and thunderstorms are also produced based on calibrated model rainfall forecasts and model outputs of instability index, low level mixing ratio, vertical velocity, convergence and relative vorticity as well as upper level divergence in the vicinity of Hong Kong. The calibration of model rainfall was done by comparing model predicted rainfall with the



Fig. 7 SWIRLS-ORSM Combined Warning Panel Display for a rainstorm day.

As to the design of the forecast suites in support of weather warning operations, “blending” the nowcasting and NWP systems will be a direction to move in to complement with each other to achieve the optimal performance of rainfall forecasts given the recent scientific and technological advances.

Currently, SWIRLS generated rainfall analysis is utilized in the physical initialization process of the ORSM. Besides, SWIRLS derived TREC winds are also being tested for assimilation in the ORSM and ARPS (Advanced Regional Prediction System currently under operational trial at 6 km resolution) with a view to improving initialization of tropical cyclones and hence the associated wind and rain forecasts (Lam *et al.*, 2003). Preliminary assessment shows that TREC winds might have potential to improve forecast of rain and winds associated with landfalling tropical cyclones. The application of TREC winds in rainstorm cases will also be explored in the future.

Before the realization of a perfect model and a fast enough computer to support weather forecast and warning operations, radar-based nowcasting system is expected to remain as the key tool to support rain-related warning operations. To SWIRLS, enhancements could be made in the advection algorithm and use of rain intensity profile. To achieve the optimal performance, it is beneficial to adopt an engineering approach in the merging of the two systems. Information from model generated wind fields and model derived parameters can be used in the advection algorithm to handle the combined effect of motions on a range of spatial scales, and to enhance the intensity profile algorithm to cater for the growth and decay factors. Use of

empirical rules or supplementary methods based on statistical and pattern recognition techniques or forecasters' rules of thumbs can also be incorporated into the nowcasting system to achieve better performance in volatile rainfall pattern. In fact, studies on rainfall enhancement judging from the signature pattern of radar echoes using Artificial Neural Network (ANN) and Hough Transform Module (HTM) was attempted and the results showed initial promises (Lai *et al.*, 2000). ANN and HTM can serve as supplementary methods in SWIRLS. To establish empirical rules, satellite data such as GPS, SSM/I and TMS will be potentially useful. Besides, other factors like drop size distribution and the vertical variation of radar reflectivity as well as topography can also be included in the enhancement algorithms to improve rainfall forecast for the next couple of hours.

6. Applications to landslide risk assessment

HKO has been operating the Landslip Warning Service in collaboration with the GEO since 1983. The correlation between rainfall and landslide density has been carried out by GEO for the development of a set of Landslip Warning criteria. The running 24-hour rainfall is a promising parameter to correlate with the number of reported landslides. In the past, QPF was hampered by a lack of forecasting tool and the rainfall factor in the issuance of landslip warning relied solely on actual observations. Over the years, advancements in radar technology and nowcasting techniques have allowed HKO to introduce a forecast element in the Landslip Warning service. Starting 2000, HKO provides 3-hour QPF to assess the short-term trends in the running 24-hour accumulated rainfall by topping the 21-hour actual rainfall from raingauges with the 3-hour rainfall forecast. The estimation of rainfall distribution in the next 3 hours is again an extrapolation of echo movement along the TREC vectors, similar to those for the next one hour forecast.

Subsequent to a review conducted by GEO in 1999, the geographical factor has been included in the operational assessment of landslide risk. Raingauges are assigned to represent specified areas with past history of reported landslides. Those have a long history of landslide occurrences are assigned larger weightings, and vice versa for those with less historical occurrences. The number of likely landslide occurrences for each raingauge is then derived through statistical correlation. Taking into account the factor of such vulnerable area weighting factor, SWIRLS was designed to trigger an automatic alarm to the forecaster when the sum of likely landslips from all contributing raingauges exceeds a pre-defined threshold. As an illustration, the distribution of 21-hour rainfall observations and 3-hour SWIRLS rainfall forecast in connection with a landslide event on 5 May 2003 is shown in Fig. 8.

The QPF guidance is updated every 6 minutes and forecasters will be promptly alerted to possible landslip risks as the rain event unfolds and GEO staff immediately informed accordingly. In this illustrative case, SWIRLS triggered a landslip alert to the forecaster at 0542 H and the rainfall criteria was eventually met at 0840 H, giving a lead time of nearly 3 hours.

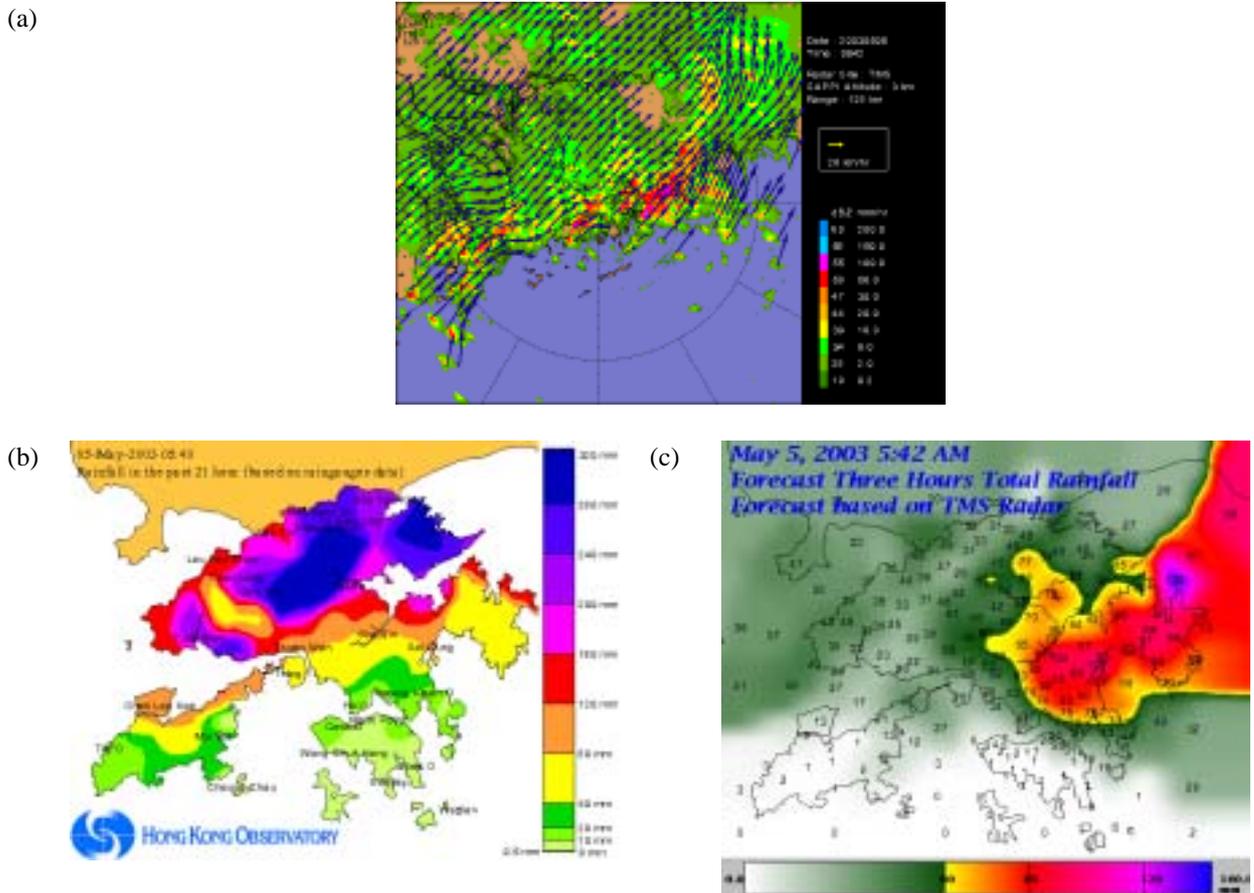


Fig. 8 (a) Motion vectors produced by TREC used to forecast the locations the rain echoes 3 hours ahead ; (b) 21-hour accumulated rainfall observations ending at 0540 H on 5 May 2003 ; and (c) 3-hour rainfall forecast by SWIRLS at that time.

7. Verification statistics

Knowing the highly variable nature of rainstorms and the current model skill in providing accurate forecasts of the locations, intensity and timing of rainstorms, it may be more practical from forecasters' application viewpoint to verify model generated rainstorm warnings at certain intensity range against the observed rainstorms based on the number of rainstorm days. Objective verification was performed using the dataset in 2001-2003. There was a total of 63 rainstorm days, including those for Amber, Red and Black rainstorms. The probability of detection (POD) is 0.82 which means the 20-km ORSM successfully provided early indications

of rainstorms in about 80% of the cases. However, noting that the forecast-based false alarm rate (FAR) is similarly high, extra methods have to be devised to provide forecasters with additional guidance on the reliability of NWP-based rainstorm forecasts. Verification of ORSM QPF was also done using a modified Contiguous Rain Area (mCRA) method. The original CRA method was proposed by Ebert and McBride (2000) as an object-oriented approach for verifying NWP daily rainfall forecasts. In CRA, model grids with QPF over some prescribed thresholds are identified and grouped together to form a forecast object. Verification results show that the model has its best skill in precipitation forecast at around 5 hours after model initial time. In spite of the inherent limitations in forecast accuracy, the overall model results have nonetheless proven to be functional and useful for producing early alerts of rainstorms for forecasters' reference.

With special reference to landslide application, the verification of the SWIRLS landslip alert was performed using the datasets in 2001-2003. There was a total of 22 cases. Figure 9 shows the distribution of the number of SWIRLS alarm occurrences for various lead times before the observed 24-hour accumulated rainfall reached the warning criterion. Among 22 cases, 15 were successes with a lead time of up to 4 hours; 2 were late but with a time lag of no more than 1 hour; and 5 was false alarm in which the rainfall never reached the criterion. The average lead time was around 1.3 hours, 7 of the cases falling in the 1-2 hours bracket.

In the 2 late cases, the SWIRLS either under-forecast the 3-hour rainfall or failed to forecast the location of heavy rain accurately. In the false alarm event, rapid weakening of radar echoes within 3 hours kept the actual rainfall below the landslip warning threshold.

From the contingency table based on the same set of verification data, POD is 0.88 and the FAR is 0.25. The CSI (Critical Success Index) is as high as 0.68. The performance indices suggest that the SWIRLS landslip alert is a robust guidance to help objectively assess the landslip risk, and to facilitate decision making regarding landslip warnings.

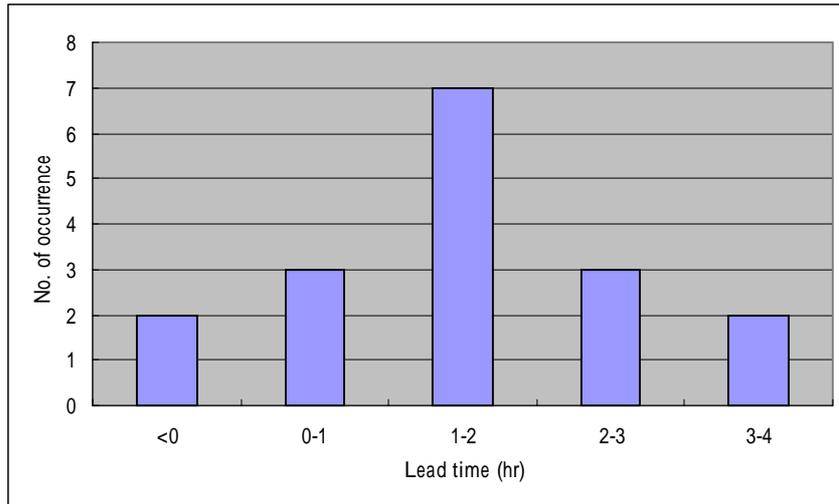


Fig. 9 The numbers of SWIRLS landslip alerts with specified lead times before the warning criterion was reached.

The development and implementation of SWIRLS and ORSM has definitely made a difference in generating useful objective rainfall prediction for guidance and reference. Early alerts of heavy rain are provided to the public through regular weather bulletins whenever possible. From the public viewpoint, opinion polls since 2000 on average considered nearly 80% of the Observatory's rainstorm warnings and forecasts as accurate, an increase of 3% compared to statistics for 1999 when the operation of SWIRLS and ORSM commenced in the latter part of the year.

8. Concluding remarks and looking ahead

Nowcasting was originally considered to involve the specification of initial state with forecast derived from extrapolation of initial conditions. It has been shown that SWIRLS nowcasting system exhibits useful predictive skill for QPF up to 3 hours ahead and support rain-related warnings. The verification results in 2001-2003 show that the POD of SWIRLS automatic landslip alert stands a high value of 0.88 and the FAR is just 0.25. The average lead time of the alert is around an hour or so. SWIRLS has been proven its capability in providing reliable guidance to forecasters for making decisions in respect of Landslip Warnings.

With the SWIRLS radar-rain gauge analysis rainfall assimilated through the technique of physical initialization, NWP-based QPF from ORSM becomes more realistic in the vicinity of Hong Kong especially for the first 6 hours of forecasts. The moisture information so derived from the radar-based nowcasting system is useful to NWP models. The wind information retrieved from radars will also be useful to initialize the model dynamical field. Preliminary numerical experiments

show the potential of the application of multiple levels of TREC wind data. The NWP-based QPF will be useful to provide trend forecast of rainfall and indications of rainstorm days. This allows forecasters to carry out rainstorm risk assessments at a much earlier time frame so as to make better arrangements and preparations for the coming rainstorms.

Looking ahead, it will be a general trend to blend nowcasting with NWP model forecasts to achieve an optimal performance of QPF at lead times of around 6 hours ahead. The “merged” product will be more skilful than either component of the state-of-the-art systems. In fact, this is basically an engineering approach which is believed to be the most practical way to obtain the best achievable results and to present an integrated coherent picture of the rainstorm forecasts for forecasters’ timely reference.

Limitations in model resolution and imperfect models render QPF difficult to come by. Although model resolution has increased dramatically over recent years, fairly crude parameterizations of convection that were designed for coarser models continue to be used in NWP. To improve model QPF, it may be necessary to run the models on grid scales that can explicitly resolve clouds so that cloud physical and dynamical processes can be more accurately represented with new moist physical schemes. As such, the validity of the hydrostatic assumption in ORSM will render it inapplicable for high resolution model run. There will be a gap between SWIRLS nowcasting system, which provides rainfall forecast with high spatial (5-km resolution for 64-km range of radar scan) and temporal (forecasts every 6 minutes in the first hour) resolution, and the ORSM (20-km resolution at the highest; forecasts every 3 hours).

Gearing towards more effective merging of nowcasting and high-resolution NWP model in supporting weather warnings operation, HKO has planned to develop a Rainstorm Analysis and Prediction Integrated Data-processing System (RAPIDS) to bridge the gap of very short-range forecast of rainstorms between SWIRLS and ORSM. RAPIDS will be a rapidly updated analysis and forecast system to provide forecasts at every hour up to around 6 hours ahead. A non-hydrostatic model (NHM) will form the key forecast component of RAPIDS. Before the implementation of a 3D variational data assimilation system in RAPIDS to better assimilate asynoptic remote-sensing data, LAPS (Local Analysis and Prediction System), which is the data analysis system currently being tested under the umbrella of SWIRLS, will be one of the candidates to couple with the NHM in RAPIDS. The system will run at 2-km resolution with the assimilation of mesoscale observations particularly ground-based

remote-sensing radar data and satellite data. Making better use of the emerging opportunities including multiple radars in the Pearl River Delta, satellites carrying microwave sensors or radars, GPS satellites, SSM/I and TMS data which carry moisture information, etc. will enable a better start for model forecast and provide useful information for incorporation into the nowcasting system through additional forecast rules and enhanced algorithms.

Another practical way with engineering approach to improve QPF using existing NWP models is the use of ensembles to generate multiple rain scenarios and probabilistic forecasts to cater for the uncertainties due to imperfect models or errors in initial conditions. The ensembles can be generated from multi-analysis systems, multi-models or multi-model runs. A Poor Man's ensemble of QPFs from a number of operational centers has been shown to perform well in the 1- to 2-day range (Ebert, 2001). In fact, the concept of generating probabilistic QPF also emerges from a smearing of the extrapolation forecast using nowcasting methods. A probabilistic nowcasting system has been developed in UK Met Office to quantify the uncertainties in the motion and evolution of radar observed rainfall fields (Bowler *et al.*, 2003). Probability forecasts will be useful to decision makers when the uncertainties cannot be explained by deterministic forecasts.

Operational weather centers may eventually need a super-ensemble end-to-end weather warnings decision support system which may include a cascade of forecast systems with tailor-made strategies and "many-way" interactions with a view to handle collectively weather systems across a spectrum of spatial and temporal scales and to display an ensemble picture of forecasts and warning alerts. The end-to-end decision support system may also include cost-loss models to translate forecast scenarios all the way to future outcomes of warnings including economic and societal impacts on the community. The ultimate goal is to achieve the optimal effectiveness of the warnings.

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