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From Radar Echoes to Landslip Warnings

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FROM RADAR ECHOES TO LANDSLIP WARNINGS

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Abstract

The Hong Kong Observatory has been operating weather radars to monitor the location and development of rain within several hundreds of kilometers from Hong Kong since 1959. Radars have the advantage of filling gaps in rainfall information in areas where ground-based observations are sparse. Increasingly, radar data are used as a quantitative forecasting tool at the Observatory. Lately, its SWIRLS nowcasting system has been deployed to support the issuance of Landslip Warnings. The performance and limitations of the system are presented. Future challenges on the intelligent engineering application of remote-sensing technology for extended quantitative precipitation forecast are also discussed and evaluated.

1. INTRODUCTION

The occurrence of landslips is related to the physical condition of soil and rock, the underground water action and the micro-topography in a region. The Hong Kong Observatory (HKO) is involved in the issuance of local Landslip Warnings because rainfall plays an important part in influencing the underground water action. The Geotechnical Engineering Office (GEO) of the Civil Engineering Department is the other partner in the warning process. To monitor the location, movement and development of rain areas, weather radars are indispensable, in addition to the dense local network of raingauges.

The HKO has operated weather radars for more than 40 years to monitor rain areas in the vicinity of Hong Kong. Doppler weather radars have the added ability to measure the velocity of approach/departure of rain drops. Currently, HKO operates two Doppler weather radars. The new one, which was installed in 1999, is located at Tai Mo Shan. The old one is situated at Tate's Cairn and serves mostly as a backup. A radar-based nowcasting system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems), which was developed in-house at HKO, was also put into operation in 1999. It provides local analysis and forecasts of rainfall up to 3 hours ahead. It gives support to forecasters in formulating nowcasting strategies and in operating rainstorm and landslip warnings.

2. FROM RADAR ECHOES TO RAINFALL ESTIMATION

A weather radar scans a volume of the atmosphere and detects rain in the atmosphere, by sending out pulses of microwave from its antenna. When a radar pulse encounters rain drops or ice particles, part of its energy is reflected back to the antenna. The time delay in the returned echoes gives information on the distance of the rain area from the radar. Rain intensity is deduced from this distance and the received signal strength.

The radar measures power return which is expressed as a reflectivity factor Z. Theoretically, Z is proportional to the dimension of rain drops to the sixth power. In practice, the reflectivity factor is converted to a radar estimate of rainfall rate, R, through an empirical Z-R relation :

$$Z = aR^b \quad (1)$$

where a and b are determined by fitting Z against rainfall measured by raingauge observations.

Using observations from a variety of different storm types, a and b are estimated. For stratiform rain, a = 200 and b = 1.6 in eqn. (1) forms the conventional Marshall-Palmer equation (Marshall *et al.*, 1948). Other relations include those for orographic rain (a=31, b=1.71) and thunderstorm rain (a=486, b=1.37) (Battan, 1973). Literature review shows that there is no “one-size-fits-all” Z-R relation that works for every precipitation situation. The Marshall-Palmer relation is often used when no other relationship is known (Cataneo, 1969), despite its well known limitations. When rainfall data are based solely on weather radar observations, the uncertainty is high particularly over complex terrain (Dinku *et al.*, 2002).

In Hong Kong, SWIRLS allows changing Z-R relationship for different precipitation situations. Rainfall observations from a dense local network of raingauges (currently over 100) are used to calibrate radar reflectivity in real time for obtaining a better estimate of rainfall than that from the Marshall-Palmer relation. As such, the Z-R relationship will be adjusted in time as the rain event unfolds. If rain has not fallen as yet over any of the raingauges, the latest Z-R relationship from the previous rain episode will be used as first guess.

To optimize the values of the parameters a and b in eqn.(1), radar reflectivity is correlated every five minutes with the rainfall recorded by the raingauges underneath, which serve as the “ground truth”. 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) in which radar-rainfall estimation can be achieved with reasonably accuracy within a short distance (say, within 30 km from radar) through a suitable choice of spatial and temporal resolution in the calculation. Details of the radar-raingauge adjustment can be found in Li *et al.* (2000).

3. RADAR-BASED NOWCASTING OF RAIN

3.1 Echo movement

Radar echoes can be tracked by a correlation method. Motion vectors of radar echoes at the same level down to the pixel scale are derived by comparing two successive CAPPI (Constant Altitude Plan Position Indictor) reflectivity fields at 6-minute intervals. Figure 1 shows schematically the computation of TREC vectors to represent the motion of reflectivity echoes. The reflectivity field at an earlier time is divided into a number of equally sized boxes containing 2-D array of pixels. Computations are repeated for all possible arrays found at consecutive time to determine the array with the highest correlation, and the centre of this second array will be the end point of motion vector or the TREC vector. Spatial consistency check and an objective analysis using modified Cressman weighting function (Cressman, 1959) is then applied on the TREC vectors. Based on the smoothed TREC vectors, the short-term forecast of movement of rain cells in the next couple of hours is obtained by moving the rain echoes following the TREC vector pattern.

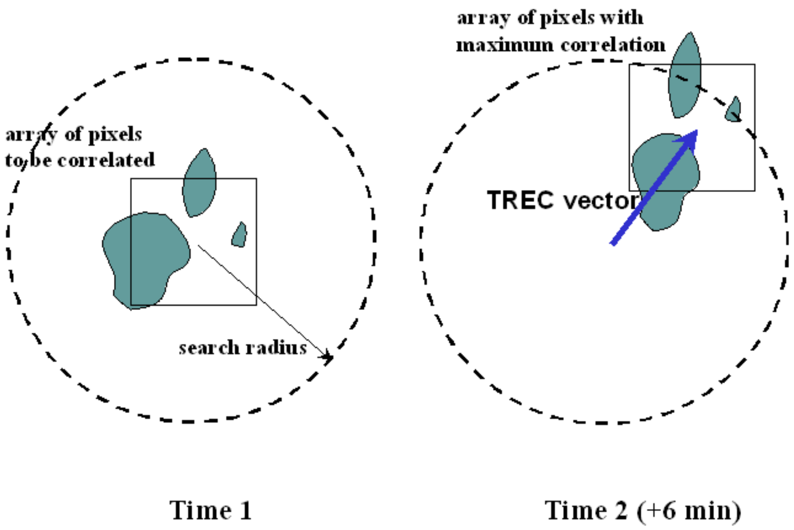


Figure 1 – Schematic diagram showing the computation of the TREC vector to represent the motion of reflectivity echoes. The pixel array at Time 1 is correlated with all pixel arrays of the same size within the search radius at Time 2. The centre of the array at Time 2 with maximum correlation coefficient designates the end point of the TREC vector.

The TREC wind analysis is updated every six 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. Results from case studies showed that TREC is able to reproduce realistic wind fields in weather systems like spiral rainbands of tropical cyclones (Fig.2) and squall lines. Figure 3(a) shows an example of motion vectors produced by TREC for a rainband in perturbed southwesterly flow 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.

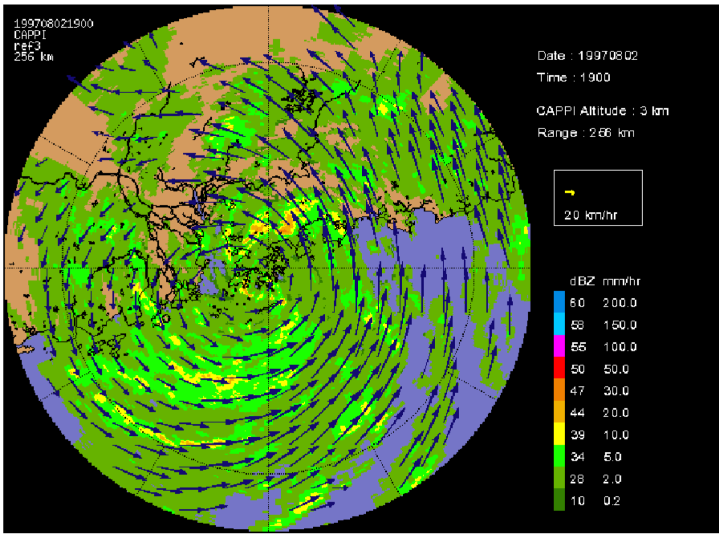


Figure 2 – TREC wind analysis of Typhoon Victor (9712) over Hong Kong at 1900 HKT on 2 August 1997.

There is another module for estimating echo movement in SWIRLS called GTrack (Group Tracking). 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. In fact, GTrack is an “object-oriented” technique for tracking the movement of a storm as a total entity. The GTrack option is still being assessed for system robustness and reliability. Preliminary observations suggest that as long as the rainstorm systems are well-defined, rainstorm system movement can be reliably tracked and their short-term positions in the next couple of hours well handled. Figure 3(b) shows the GTrack analysis of the same case as in Fig.3(a). In this case, GTrack indicated the southeastward movement of rainband as a whole towards Hong Kong in spite of the fact that individual small-scale features were moving northeastward. To the operational forecaster, this would be an important piece of information relevant to short-range forecasting. If long-term results are positive, then the future SWIRLS warning algorithm may be adjusted to take into account information from the GTrack analysis.

(a) (b)

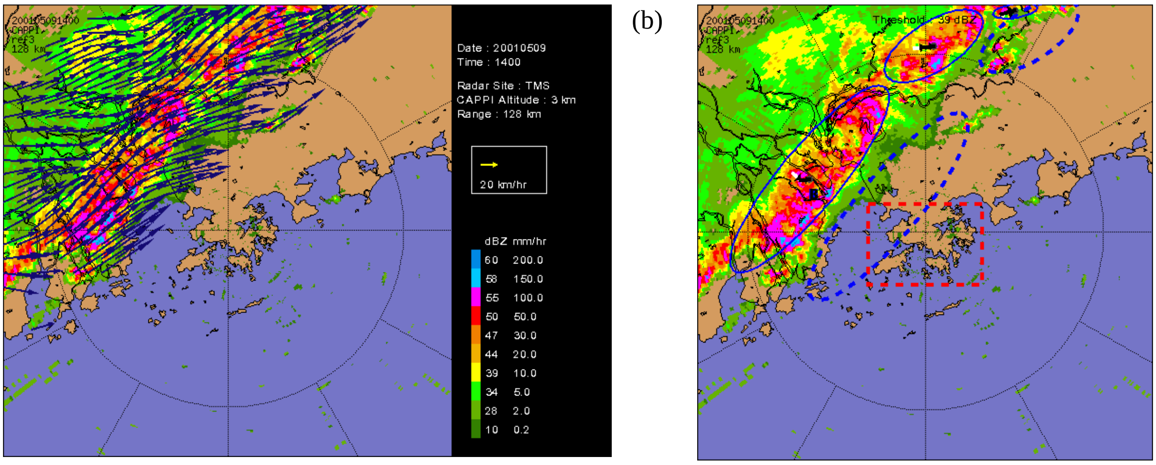


Figure 3 – (a) Motion vectors produced by TREC showing a rainband in perturbed southwesterly flow. (b) Same radar images as in (a), but GTrack analysis also indicating southwestward movement of rainband as a whole towards Hong Kong. Solid lines are the storms as identified by GTrack and dashed ellipses are 1-hour forecast position of echo groups.

3.2 Echo intensity

To derive SWIRLS forecast rainfall, the next step is to estimate the intensity change of the echoes. TREC winds can also serve as a basis for estimating the extent of growth and decay associated with each echo pixel. As the TREC vector traces the trajectory of individual echoes, the difference in echo intensity along the flow between two successive radar scans can be deduced. The information on the change in echo intensity can be utilized in the rainfall forecast.

At present, two options are available in the operational set-up of SWIRLS to estimate echo intensity. The first option assumes no change in intensity as from the latest radar scan, and the second imposes an idealized intensity profile on the intensity trends as deduced from the latest radar scans. The latter provides a crude “first-order” method by applying an idealized empirical intensity profile in Gaussian form. The details of the echo intensity profiling scheme are given in Li *et al.* (2000). Though superficially simplistic, the former gives a better continuity in forecasts, or indeed even more reasonable estimates in some cases, when rain intensification and decay balance out on a larger scale. Operational experience also 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. For special cases of rapid echo development, studies on rainfall enhancement judging from the signature pattern of radar echoes using Artificial Neural Network and Hough Transform Module was attempted and the results showed initial promises (Lai *et al*., 2000).

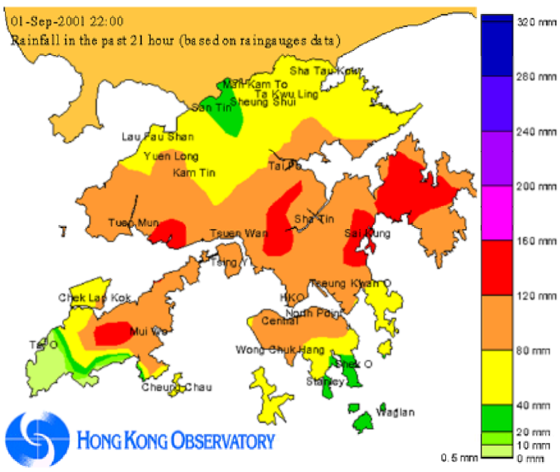
The forecast radar reflectivity is converted into rainfall over raingauge positions using the adjustable Z-R relationship as described in Section 2.

4. LINK TO LANDSLIP RISK ASSESSMENT

HKO has been operating a 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 (Quantitative Precipitation Forecast) 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.

Subsequent to a review conducted by GEO in 1999, the geographical factor has been included in the operational assessment of landslip risk. Raingauges are assigned to represent specified areas with past history of reported landslides. Taking into account the factor of such vulnerable areas, SWIRLS was designed to trigger an automatic alarm to the forecaster when the sum of likely landslips from all the contributing raingauges exceeds a pre-defined threshold. Figure 4 shows the distribution of 21-hour rainfall observations and 3-hour SWIRLS rainfall forecast in connection with a landslip event on 1 September 2001. In this case, SWIRLS triggered a landslip alert to the forecaster at 2154 H and the rainfall criteria was eventually met at 2220 H, giving a lead time of around half an hour.

(a)



(b)

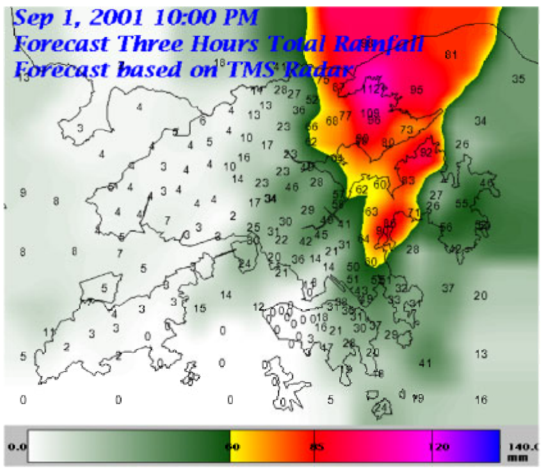


Figure 4 – (a) 21-hour accumulated rainfall observations ending at 2200 H on 1 September 2001.
(b) 3-hour rainfall forecast by SWIRLS ending at 0100 H on 2 September 2001.

5. VERIFICATION STATISTICS

The verification of the SWIRLS landslip alert was performed using the datasets in 2001 and 2002 (Chan *et al*., 2003). There were a total of 15 cases. Figure 5 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 the 15 cases, 12 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 1 was a false alarm in which the rainfall never reached the criterion. The average lead time was around 1.2 hours, one third of the cases falling in the 1-2 hours bracket.

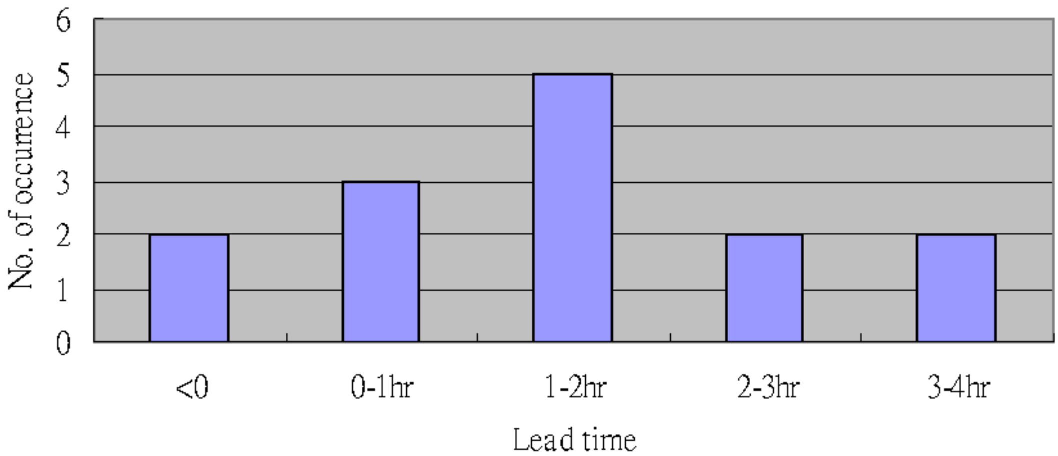


Figure 5 - The numbers of SWIRLS landslip alerts with specified lead times before the warning criterion was reached.

In the two 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 (Probability Of Detection) is 0.86 and the FAR (False Alarm Rate) is 0.08. The CSI (Critical Success Index) is as high as 0.80. It is evident from the performance indices that the SWIRLS landslip alert is a robust guidance to help objectively assess the landslip risk, and to facilitate the decision making regarding landslip warnings.

6. OTHER INTELLIGENT USE OF REMOTE-SENSING TECHNOLOGY

For rainstorm forecasts beyond a few hours, NWP (numerical weather prediction) products become an indispensable reference for forecasters. NWP is based on mathematical models of the physical equations that describe the evolution of the atmosphere. In running the HKO's ORSM (Operational Regional Spectral Model), radar data are ingested into the model calculations through the technique of physical initialization so as to improve short-term rainfall forecasts especially in the first few hours. The moisture information derived from the rainfall analysis based on local Doppler weather radars and raingauges (together with cloud cover and cloud top temperature from geostationary meteorological satellite of Japan Meteorological Agency) are utilized in the ORSM. It has been demonstrated that the assimilation of radar data in the ORSM is beneficial to rainfall forecast in the first 6 to 12 hours (Lam *et al*., 1999). Other remote-sensing data such as wind profiler (equivalent to vertically pointing radar) data are also ingested in the ORSM. After completing the data assimilation and analysis process, time integration will proceed to produce forecasts up to 24 hours (at 20-km model resolution) or 48 hours (at 60-km model resolution) ahead (Lam *et al*., 2000).

The assimilation of TREC winds is being tested in the ORSM and ARPS (Advanced Regional Prediction System currently under operational trial at 6 km resolution) (Lam *et al*., 2003). Wind velocity data derived from the newly acquired lidar installed at the airport will also be tested in the future.

7. CONCLUDING REMARKS AND LOOKING AHEAD

The radar-based nowcasting system of the HKO, SWIRLS, has demonstrated its capability in providing reliable guidance to forecasters for making decisions in respect of Landslip Warnings. Taking into account the geographical distribution of vulnerable areas, 3-hour rainfall forecasts by SWIRLS combined with previous 21-hour rainfall observations form the basis for landslip risk assessment. The verification results in 2001-02 show that the average lead time of the SWIRLS automatic landslip alert is around an hour or so.

There are limitations to the accuracy achievable in the rainfall forecast. A major cause of errors in radar-derived rainfall is the utilization of the Z-R relation ignoring the details of the drop size distribution and the vertical variation of reflectivity. Another limitation comes from the applicability of a simple technique like TREC in different weather situations. It is a non-trivial task to represent the combined effect of motions on a range of spatial scales, in order to represent echo movement in an optimal way in the TREC method. Furthermore, rapid fluctuations in small scale features render location-specific rainfall forecasts even just minutes ahead uncertain to a significant degree. There is a natural barrier of unpredictability which is not easy to cross.

Looking ahead, on the meteorological side, the future trend will be the merging of radar-based nowcasting with a high-resolution NWP system with a view to extending the forecast range of quantitative precipitation forecasting. NWP provides the scientific basis for real intelligent use of ever-increasing remote-sensing data in weather forecasting. Emerging opportunities include multiple radars in the Pearl River Estuary, satellites carrying microwave sensors or radars, GPS satellites which yield moisture information also, etc. Together they would enable a better start for model forecast over a larger domain. As for the presentation of forecast product, the introduction of probability forecast, which contains information on uncertainties, could facilitate decision makers assessing risks arising from weather-induced disasters. In spite of the best of theories and techniques in the world, it is always beneficial to adopt an engineering approach in the design of a QPF nowcasting system tailor-made for the specific locale, both in terms of rain characteristics and operational warning requirement.

On the engineering side, changing land use and improvement to slopes brings about changes in the correlation between rainfall and landslide density. HKO and GEO will maintain close contact and review the threshold values every year before the rain season starts.

Echoes on the radarscope stand only for the first layer of information derived from remote sensing using microwave. It is useless until the signals are interpreted in terms of rainfall measured on the ground and the echo movements intelligently deduced and extrapolated. By working closely with engineers, the second layer of information is transformed into a warning relevant to the man in the street. That of course has always been the ultimate purpose of meteorology.

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