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Short-range rainfall forecast in Hong Kong

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Abstract

Studies have shown that many landslides in Hong Kong are rainfall-induced. While efforts are at hand to stabilize the slopes and to implement various preventive measures such as better drainage design, the ultimate starting point for any emergency response and preparedness plans is a reliable assessment and prediction of the rain situation.

In this paper, we will introduce some operational practices currently adopted at the Hong Kong Observatory on the prediction of severe rainstorm events. These include the main forecasting tools based on numerical weather prediction (NWP) systems and guidance derived from weather radar observations. Performance as well as limitations of these tools will be discussed. Potential and possibilities of further improvement towards more accurate and extended quantitative precipitation forecast (QPF) will be evaluated.

1. Introduction - Rain-related Warnings

If heavy rain over a certain amount has fallen or is expected to fall generally over Hong Kong, the Observatory will issue rainstorm warnings to alert the public about the occurrence of heavy rain. The three levels of warnings of AMBER, RED and BLACK correspond to increasing hourly rainfall intensity of 30, 50 and 70 millimetres. These warnings are typically short-lived (in the order of several hours), reflecting urban flash flooding due to concentrated rainfall in confined location and of limited duration, blocking roads and creating havoc for pedestrians as well as vehicular traffic.

Other alerts tied in with rainfall amounts include Landslip Warnings and Special Flood Announcement for northwestern New Territories. The considerations here are more on prolonged and widespread heavy rain, and the accumulation of rainfall over an extended period of time. For Landslip Warnings in particular, the warning criteria are essentially based on rolling 24-hour rainfall amounts. In practice, however, decision-making on the "if"s and "when"s of issuing or cancelling the warning boils down to an assessment of the rainfall situation in the next few hours, in the knowledge that so much rain has already fallen over the territory in the previous 20 hours or so.

All these warnings carry with them profound economic and societal impact. And in operating these warnings, reliable quantitative precipitation forecast (QPF) several hours ahead is of prime importance. In this paper, we will present some of the QPF methods and strategies currently in operational use at the Observatory. Preliminary verification results will be provided, performance evaluated, limitations assessed, and finally future possibilities will also be explored.

2. QPF by Nowcasting

For a fast-developing rainstorm in the vicinity of Hong Kong, typically in the matter of a couple of hours, forecasters have to react quickly and decisively based on latest observation and information, an operational process that has become known as "nowcasting". A computer system designed for nowcasting purpose would essentially be an automated or semi-automated (man-machine interactive) tool to assist forecasters in monitoring and assimilating the latest weather information (radar, satellite, or other real-time observations as may be the case), providing objective assessment and analyses, and making predictions in terms of local precipitation trends.

At the Observatory, a nowcasting system SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) was put into operation in 1999. The first phase of SWIRLS is to make use of both radar and raingauge data to monitor and predict local rainfall distribution trends in the next couple of hours (Fig.1). The SWIRLS outputs have been shown to be very useful for provision of real-time rainfall information to the public, media and government decision-makers, formulation of nowcasting strategies, operation of warnings, as well as for physical initialization in numerical weather prediction (Section 3).

2.1 Rain movement on the pixel scale

TREC (Tracking Radar Echoes by Correlation) is one of the main algorithms developed in Phase I of SWIRLS (Li et al. 1999). Radar echoes are the returned signals from rain droplets in the atmosphere. By comparing two consecutive radar scans at 6-minute intervals, motion vectors of radar echoes at the same level down to the pixel scale can be derived. Short-term forecast of movement of rain cells, say in the next one or two hours, is obtained by extrapolation based on the smoothed field of TREC vectors.

The main advantage of TREC is that it requires only information from one single radar at two different observation times. Results have shown that TREC is able to reproduce realistic wind fields in major weather systems such as squall lines and spiral rainbands of tropical cyclones. The TREC analysis is updated every six minutes from the latest radar scan, and the resultant projection of rain movement will also be updated accordingly.

Now that we have an estimate of where the rain clouds are going to be, the next question is the amount of surface rainfall along the storm path. Conventionally, the Marshall-Palmer relationship is used to convert echo intensity (i.e. reflectivity, Z) to rainfall rate, R. However, the relationship is much generalized and does not apply well in many cases. In SWIRLS, actual rainfall data from over 100 raingauges in Hong Kong are used to calibrate radar reflectivity in real time. The Marshall-Palmer formula is retained only as a first guess, or as a fallback if no raingauge data are available. As the rain event unfolds and local raingauges start to register data, the Z-R relationship will also be adjusted and updated in time (and ideally, becoming more representative as well in the process).

In the course of extrapolation, we also have to address the issue of changes in echo intensity (which is highly non-linear and can fluctuate drastically in minutes). In SWIRLS, there are basically three options in estimating echo intensity in the following two hours:

(a) Assuming no change as from the latest scan (i.e. persistence). Though simplistic, it gives better continuity in forecasts. In cases where generation and dissipation of rain balance out in the long term, it even gives a reasonable forecast.

(b) Assuming linear extrapolation from the three latest scans. Results may still be acceptable in the first hour. But given the short life cycle of rain cells, linear extrapolation soon becomes rather unrealistic and the projected rainfall amounts after the first hour tends to be over-predicted.

(c) From the three latest scans, fit an idealized profile to the observed intensity trend. A crude attempt to rectify the runaway effect of linear extrapolation.

2.2 Rain movement on the storm scale

While TREC analysis can be done at a resolution down to the pixel scale of around 250m to 1 km, severe rainstorms are often organized systems of embedded convective cells that move at an angle to the general flow in association with synoptic scale weather systems or some mesoscale perturbations. For instance, individual cells in the summer southwest monsoon typically move northeastwards in the direction of the prevailing wind (Fig. 2a); but a squall line of organized convective cells is often found to have a southward component as well that is closely linked to the movement of the monsoon trough (Fig. 2b). To address the problem, the correlation method is extended to the tracking of echo groups (i.e. GTrack) (Li et al. 2000). The objective is to depict system movement and to resolve the interaction of multiple systems. The grouping of adjacent echo pixels is accomplished through an ellipse-fitting process. The fitted ellipses with echoes above some chosen thresholds are labeled and their attributes computed for tracking purposes in successive radar images. Again through linear extrapolation, the derived vectors of past system movement are then used to estimate future storm positions in, say, an hour's time.

As yet, operational SWIRLS warnings are still based on QPF from TREC and raingauge analyses. The GTrack option, entering its first season of operation in 2001, will be assessed in terms of system robustness and forecast reliability. If the results are positive, then future SWIRLS warnings may also take into account information gleaned from GTrack analysis. Unlike the embedded rain cells which can have quite a volatile life history, the overall rainstorm system organized on the larger scale tends to move more steadily. Preliminary observations suggest that 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.

3. QPF by NWP

For rainstorm forecasts in the longer term (say 3 hours or more), the NWP (numerical weather prediction) products become an important reference for forecasters. NWP methods are mathematical models of physical equations that simulate the evolution of the atmosphere. If the model predicts a considerable amount of surface rainfall over grid points in the vicinity of Hong Kong, then forecasters will naturally be alerted to the possibility of inclement weather and will monitor closely the development of significant weather systems during the period of interest.

Global NWP products regularly received at the Observatory include outputs from the European Centre for Medium-Range Weather Forecasts (ECMWF), the United Kingdom Meteorological Office (UKMO) and Japan Meteorological Agency (JMA). But to zoom in on the local situations, particularly with respect to short-term forecasts, the Observatory is also running a 20-km resolution Operational Regional Spectral Model (ORSM) nested in a 60-km resolution outer domain, producing timely forecasts for forecasters' early reference.

3.1 ORSM features

ORSM ingests an enormous amount of meteorological data at the analysis step. Forecast output from previous model run is taken as a first-guess, providing a background field that will be adjusted in accordance with the latest observational data. To improve short-term rainfall forecasts, a physical initialization scheme is adopted to inject moisture information derived from: (a) rainfall analysis based on local information from radars and raingauges; and (b) cloud cover and cloud top temperature from JMA's geostationary meteorological satellite. After completing the data assimilation and analysis processes, time integration will proceed to produce forecasts up to 24 hours (at 20-km domain) or 48 hours (at 60-km domain) ahead (Lam et al. 2000).

Model outputs are readily displayed as sets of graphics for easy reference. However, to speed up the interpretation process in evolving rainstorm scenario, certain tools such as automated warnings of rainstorm signals and thunderstorms have also been purposely developed to assist the forecasters in formulating response strategies (Figs. 3 and 4) (Wong et al. 1999).

3.2 Rain index

Since the 20-km ORSM is run 8 times a day during the summer season, a more elaborate presentation method has been introduced in 2001 in an effort to extract more information from consecutive model runs. The forecast rainfall fields of the latest model runs valid at the same time are displayed together to provide a combined value-added pattern. This enables forecasters to visualize where and how various rainfall forecasts have agreed or disagreed. Presumably, different model runs start with slightly different initial conditions. So the spread of the forecast rainfall patterns is potentially a measure of how sensitive are the model forecasts to the initial input, a kind of approach that is akin to "ensemble prediction". From this, forecasters can have a feel for the confidence level inherent with each rainstorm prognosis. From the overlapping forecast rain region, forecasters can also pinpoint and isolate in an objective manner the high-risk areas.

4. Performance and Limitations

In practice, SWIRLS forecasts are probably only useful for the first couple of hours. Beyond that, forecasters have to start looking to NWP output for guidance. To provide forecasters with a coherent picture of the overall situation, a combined SWIRLS and ORSM warning panel has been set up to integrate and summarize rainstorm-related alerts coming out from the two systems (Fig. 5). Some preliminary verification results for automated rainstorm warnings issued by SWIRLS (Lai et al. 2000) and ORSM for the 2000 rain season have been computed. Threat scores are 0.18 for SWIRLS amber warning and 0.21 for 20-km ORSM rainstorm days (amber, red or black). The results are comparable with QPF performance statistics published by other meteorological centres, and indicated that such techniques are at least better than random forecasts.

Operationally, there have been confirmed cases in which both SWIRLS and ORSM have demonstrated a positive impact on the decision-making process during rainstorm episodes. It has been shown that when the advective process is dominant and when there are no volatile changes in echo intensity, the systems generally perform well. This typically happens with lesser rainstorms at, say, the amber level. For red and black rainstorms, there are as yet not enough cases to make verification statistically meaningful. But intuitively, these would be events that involve explosive development in rain intensity, and hence less likely to be handled well by the techniques currently in use. SWIRLS has to go beyond linear extrapolation of the obvious and to explore the possibility of seeing the unseen. And ORSM, even at 20-km resolution, is still too crude in terms of resolving convective cells of a few kilometres in dimension. At such fine scale, modelling approach will have to advance to the next generation of NWP models - from hydrostatic models such as ORSM to Non-Hydrostatic Models (NHM).

5. Future Possibilities

5.1 Short-term rain intensity changes

A further study of TREC and GTrack reveals that the major problem in QPF in severe rainstorm situations is how to estimate echo intensity changes and to resolve the interaction of multiple systems. It is often observed that rain tends to be locally enhanced at points of merging or intersecting rainbands, or when a rainband moves over a pre-existing convergence line. The ability to recognize at an early stage a developing pattern that is conducive to heavy rain occurrence will therefore be very useful. Instead of relying solely on forecasters' experience and vigilance, attempts have been made to develop some automated pattern recognition methods as applied to sequence of radar echo maps using artificial neural networks (ANN). Programming effort has been completed and the algorithm satisfactorily tested with selected historical cases. More rainstorm cases will be collected over the next couple of years to boost the training set so that the ANN system as a whole will become even more robust.

Another approach is to carry out frequently updated local scale analysis in the hope of capturing the existence of hidden convergence lines in the vicinity of Hong Kong. It will make use of NWP outputs as background and will incorporate locally available observations as far as possible to produce a physically meaningful interpretation of ambient conditions. This allows forecasters to assess critically the state of the atmosphere in terms of chance of convection. One can also see that with such an analysis system in place, there will be a stronger link between nowcasting and NWP, with both feeding off one another in carrying the prognostic process forward.

5.2 NHM

For a local scale analysis to be effective, the companion NWP model that provides the background field needs to be run at a compatible resolution. As already mentioned, finer details down to a resolution of a few kilometres would also be required to depict small scale weather systems such as thunderstorm cells. The Observatory is currently exploring the feasibility of adapting non-hydrostatic models for operational rainstorm forecasting and is experimenting with some open community models for case studies and performance assessment.

5.3 The final frontier

Constant efforts have been made to improve the accuracy and reliability of rainfall forecasts. On one hand, we try to pull as much useful information out of the available data as possible, so that timely warnings can be issued through nowcasting techniques and more quality input can be prepared for NWP model's consumption. On the other hand, there is also a constant effort to keep up to date with the latest knowledge, ideas and technology in the hope of overcoming the shortcomings of the existing tools. But in the pursuit of all these, a meteorological service and the community it serves must not lose sight of the issue of cost-effectiveness. How far are we prepared to go in search of better forecasts?

While telecommunication cost is coming down and computers are getting ever more powerful, observational data are becoming more expensive, especially those obtained through :w-situ measurement and human operation. Critical information such as moisture distribution in the atmosphere is notoriously difficult to obtain, especially for data sparse region over the oceans and remote terrain. It can be envisaged that in the coming years, there will be a continuing surge towards more sophisticated remote sensing devices within the meteorological community in search of more comprehensive coverage of such data, both globally and over specific areas of interest.

Even with unlimited resources, is there a final frontier for QPF? "Predictablity" is a term that more or less defines to what extent in time a certain weather system on a certain length scale can be realistically forecast. In a nutshell, the smaller the system, the shorter is the effective forecast range. Larger scale systems spanning thousands of kilometres can now be confidently forecast using NWP models up to one or two weeks ahead. Mesoscale systems such as fronts and tropical cyclones can be predicted in terms of days. But for smaller systems such as squall lines and thunderstorms, we are talking about very short life cycle of events and a predictability limit of hours or even minutes. In that sense, location-specific QPF several hours ahead is well nigh an impossible task. But for decision-makers, an acceptable alternative may exist in the form of probability forecasts. Ensemble forecasts, for those with ample computing resources, are attracting more interest from both researchers and operational forecasters. Failing that, rainstorm risk can also be quantitatively or qualitatively assessed through model-derived statistics. But then with probability forecasts, as the cynics rightly point out, all scenarios are probable and one can never be sure. The forecasters may congratulate themselves for forecasting 30% rain instead of 70% if, as it turns out, there is actually no rain. But for the man in street, the forecast, be it 30% or 70%, will probably still be perceived as wrong if the expected rain never materializes!

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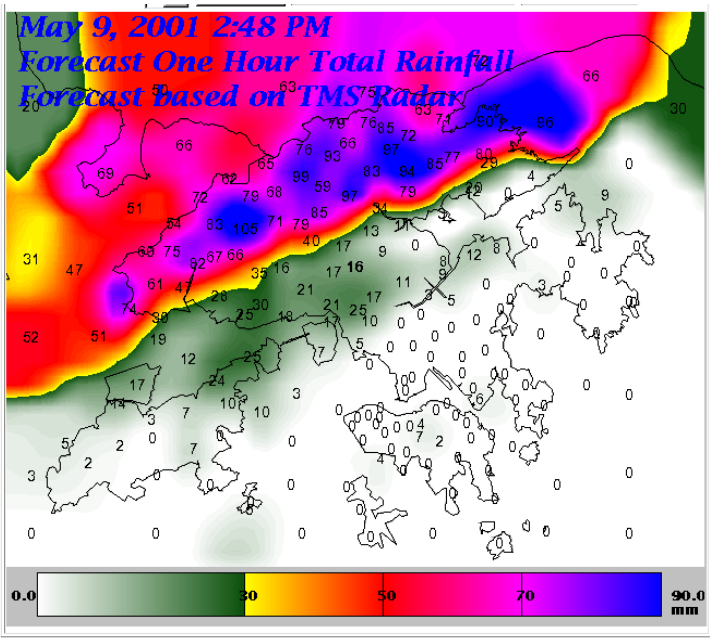

Figure 1 One-hour Rainfall Forecast by SWIRLS, predicting the occurrence of heavy rain over the northern part of the New Territories.

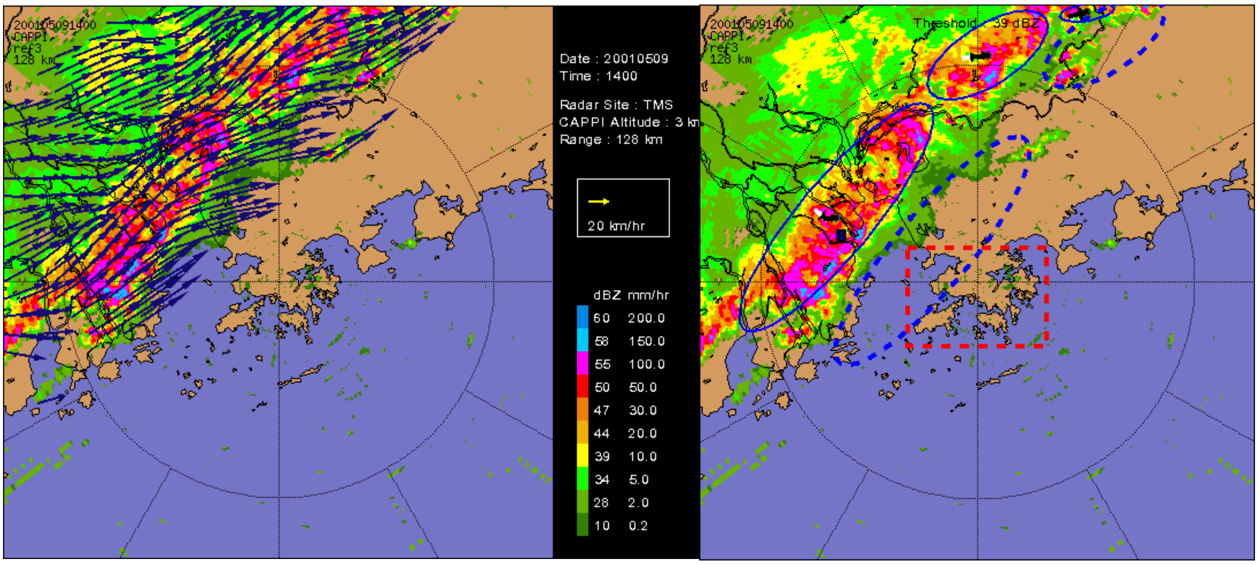

Figure 2 (a) Motion vectors produced by TREC, showing a rainband in perturbed southwesterly flow.

(b) Same radar image as in (a), but GTrack analysis also indicating southeastward 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.

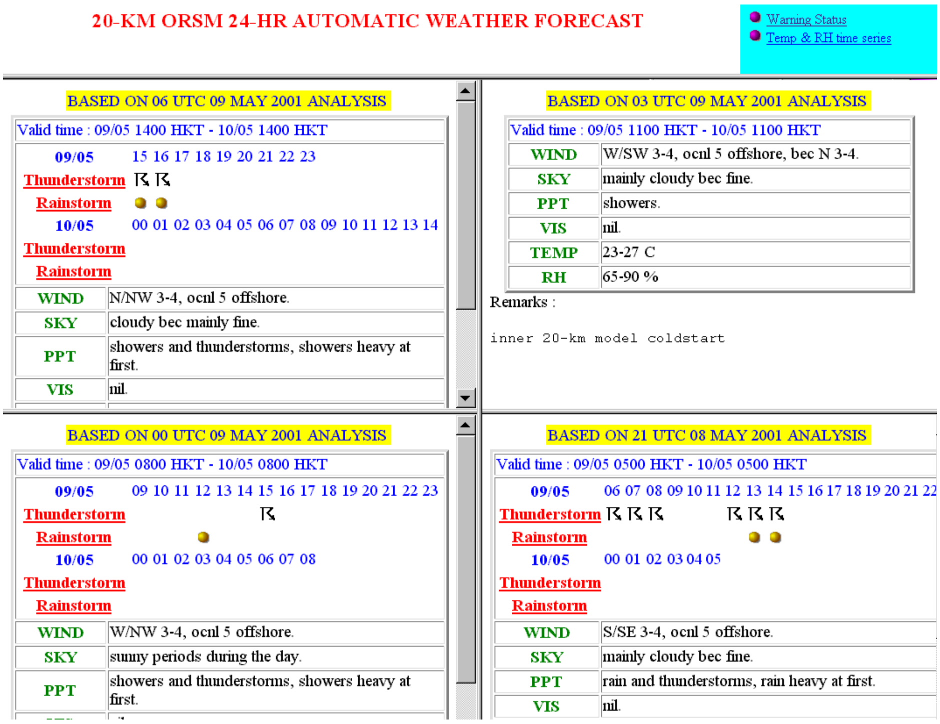

Figure 3 Automatic forecasts and warnings generated by 20-km ORSM.

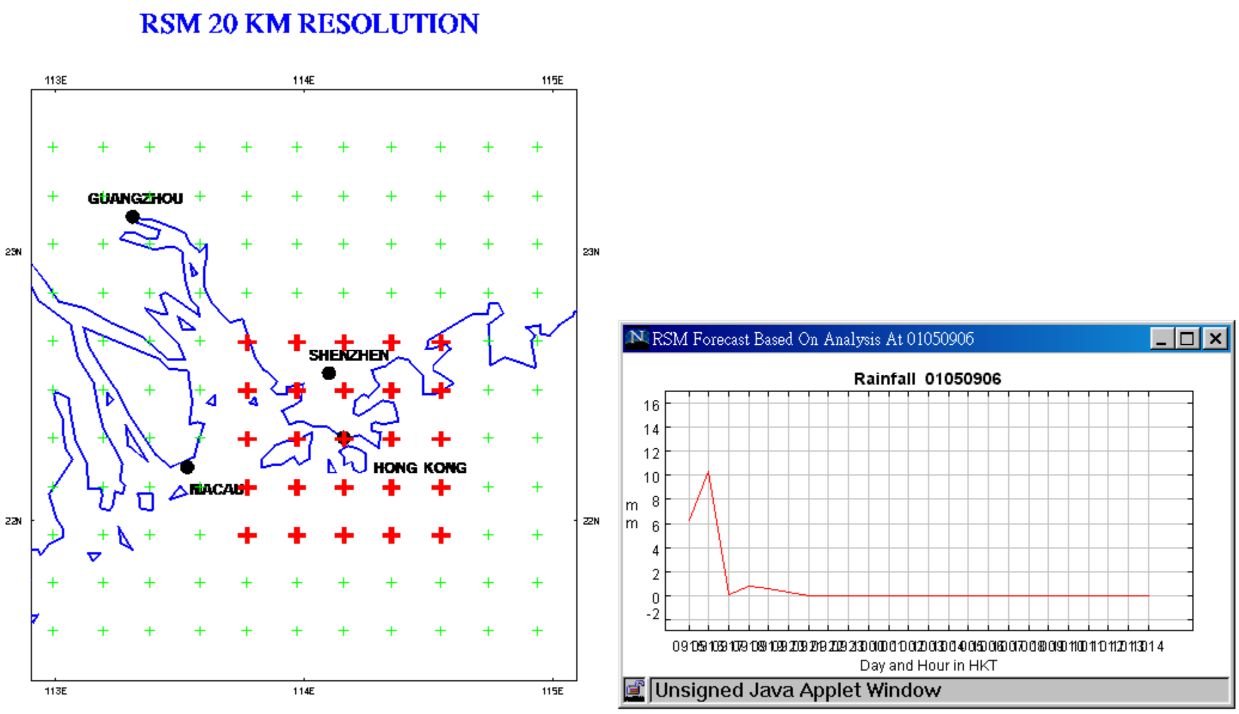

Figure 4 Graphical interface showing time series of 20-km ORSM predicted rainfall (right) over any of the 25 model grid points in the vicinity of Hong Kong (left).

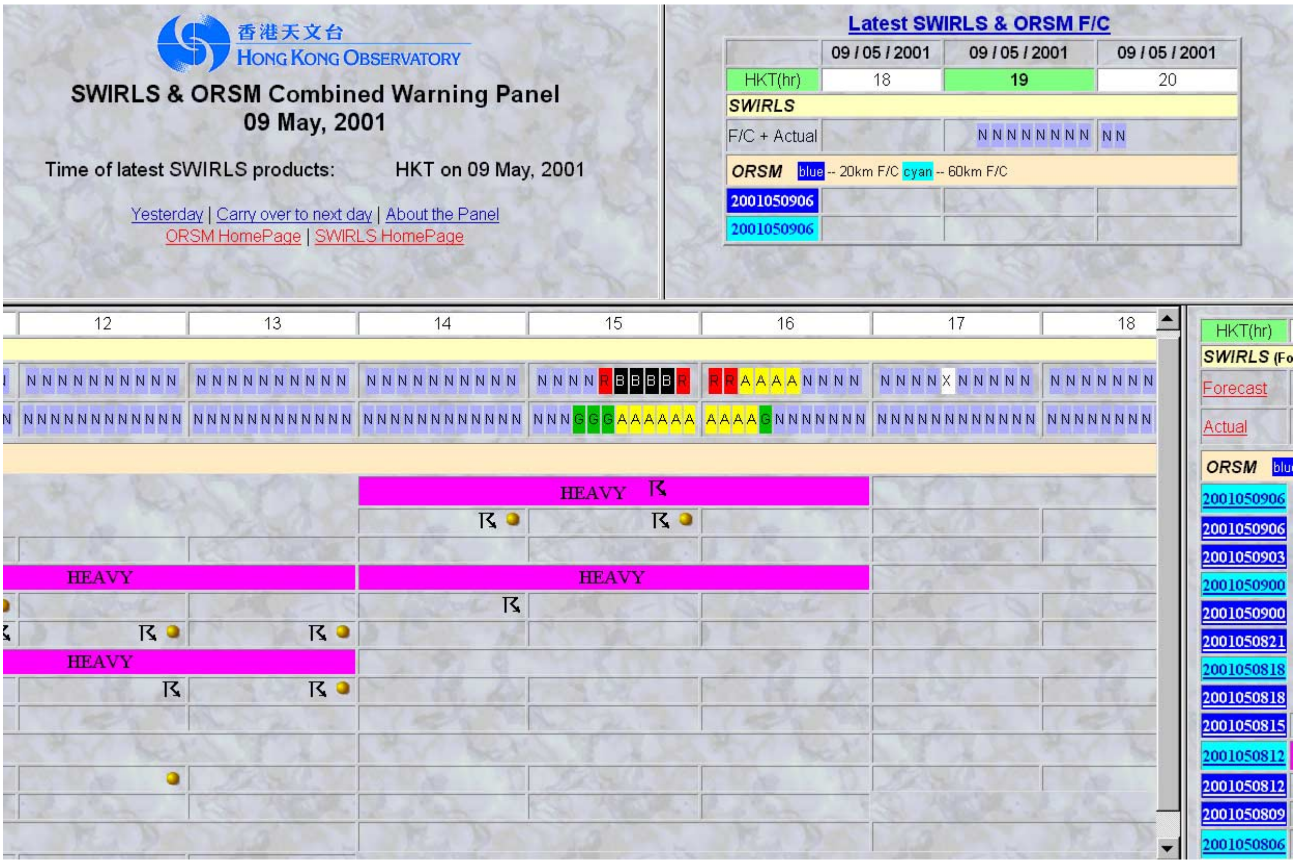

Figure 5 SWIRLS and ORSM combined warning panel.