Nowcasting – the Means for Meeting the Severe Weather Challenge

Linus H.Y. Yeung
Hong Kong Observatory

Abstract

With Hong Kong's population spreading geographically more evenly, the occurrence of severe weather anywhere in the territory can pose a significant threat to people or businesses. Inclement weather may also cause chaos with social and economic consequences in the increasingly complex yet weather-sensitive transport infrastructure. There is a growing demand in recent years on shorter-range and regional forecasts, as well as a popular call for "pre-warnings" of severe weather. However, severe weather such as rainstorms are often volatile and erratic in nature, with typical life spans ranging from tens of minutes to several hours. To make accurate and reliable prediction of them, even with a very short lead time, is a notorious challenge that forecasters have faced up to for many years.

By examining the scientific constraints inherent to weather prediction and the characteristics and impacts of the typical rainstorms in Hong Kong, the Observatory has found that nowcasting (i.e. prediction of imminent weather several hours ahead) is an appropriate strategy and successfully developed an automated system called SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems) to meet the longstanding challenge. SWIRLS is radar-based, very high resolution, fast updating and tailor-made for the prediction of detailed rainfall distribution over Hong Kong up to 3 hours ahead. Forecast verification results of 2001-2005 indicate that SWIRLS has been effective in support of rain-related warning operations in Hong Kong and performed most satisfactorily in the alerts of Amber rainstorm and landslip. To improve further on the forecast range of rainstorms and to cater for severe weather such as lightning and severe squalls, several promising directions have been identified, including (a) replacing the existing simple forecasting scheme of SWIRLS by a more advanced scheme called Semi-Lagrangian Advection; (b) optimal blending of nowcast and model forecast through a new forecasting system on trial called RAPIDS (Rainstorm Analysis and Prediction Integrated Data-processing System); (c) a multi-sensor, multi-discipline and customer-centric development approach.

1. Introduction

The fast pace of economic development locally and across the border has brought about rapid changes to the society and the environment. Hong Kong's population has been dispersing over the territory and the transportation infrastructure has become increasingly complex. The occurrence of severe weather, even at locations away from the urban hub, can affect or threaten a significant number of people or businesses. Inclement weather may also cause chaos in the increasingly complex yet weather-sensitive public transport infrastructure, leading to serious social and economic disruptions as the links between communities and business areas are blocked. However, severe weather such as rainstorms are often volatile and erratic in nature. To make accurate and reliable prediction of them, even for a very short lead time, is a notorious challenge that forecasters have faced up to for many years.

In this paper, nowcasting (i.e. the prediction of imminent weather events in the next several hours) is presented as an effective means to meet the challenge. In Section 2, an overview of the typical characteristics of heavy rainstorms associated with different weather systems will be presented and their impact on Hong Kong assessed. After exploring the scientific aspects of such phenomena in Section 3, the concept of "nowcasting" is explained in Section 4, in particular the design and strategies adopted by the Hong Kong Observatory's automated nowcasting system, SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems). The applications and performance of SWIIRLS in support of rain-related warning operations are presented in Section 5. Finally, the further development of SWIRLS and other nowcasting applications in Hong Kong will be discussed in Section 6.

2. Rainstorm Characteristics and Impact on Hong Kong

In southern China, the synoptic weather systems bearing heavy rain include monsoon troughs, active southwesterly monsoon flow, converging southerly flow on the western flank of the Pacific ridge, tropical cyclones and land-sea breezes. According to a recent study by Li and Lai [1], rainstorms in Hong Kong can be subjectively stratified into seven representative types according to the prevailing synoptic conditions and their radar signatures. In order of decreasing occurrence frequency, they are quasi-stationary southwesterly rainbands (QU), cross-type rainbands (X), land-sea breeze storms (LS), squall-lines or bow echoes (SQ), tropical cyclone rainbands (TC), southeasterly rainbands (SE) and supercells (SU). Fig. 1 shows examples of these rainstorm types as seen on radar.

Rainstorms vary in intensity, translational speed, spatial coverage and shapes, and hence the amount of rainfall produced over Hong Kong. Hence, different rainstorm scenarios can lead to different impact. Analyses based on data in 2001-2005 indicate that while all seven types could lead to Amber rainstorms (refer to Table I for reference criteria), only the QU, SE, SQ and X types could produce Red rainstorms, and only QU and X could trigger Black rainstorms (see Table I). It is interesting to note that the TC type hardly triggers any Red or Black rainstorms despite the huge destructive power of tropical cyclone. For flooding in the northern part of Hong Kong, all but SE type could be a trigger. Except for the fast moving SU and SQ, all other types could give rise to landslides.

3. Science of Weather Predictions

Weather systems exist over a wide range of space and time scales. Fig. 2 shows the cascade of scales associated with commonly observed weather systems. Roughly speaking, their sizes vary logarithmically with their life spans. As shown in Fig. 2, a waterspout is of microscale (2 km or less) whereas a jet stream stretches out to the macroscale (200 km or more); and in between these two lies the mesoscale where many high-impact weather systems belong. As yet, there are no unanimous definitions for the mesoscale boundaries and Fig. 2 is a compromised view of various authors [2],[3]. But a review of the rainstorm scenarios in the previous section suggests that most rainstorms bringing high-impact weather to Hong Kong are at the mesoscale or smaller.

As can be seen in Fig. 2, all types of weather systems essentially lie on a diagonal. This means that in a short time frame, say one hour, we will only see changes of those systems with sizes at 2 km or smaller. For systems at larger spatial scale, short-term temporal changes are much less noticeable. The implication on forecasting strategy is profound — no single forecasting tool can work effectively across scales. (Ideally, a perfect global numerical weather prediction (NWP) model at ultra-high resolution, say 1 metre or even less, may be able to do the job. But such an ideal model does not and most likely will not exist for fundamental and practical reasons. Data are simply not available at such a fine resolution. And at 1-metre resolution, the computational requirement is roughly of the order 10^8 terabytes of memory, far exceeding the capacity of any computer at present or in the foreseeable future.)

Perhaps more important is the issue of predictability. Predictability generally refers to the extent to which future states of a system may be predicted based on the knowledge of current and past states of the system. Since knowledge of the system's past and current states is generally imperfect, as are the models themselves that utilize this knowledge to produce a prediction, errors of state estimation and prediction are unavoidable. For weather prediction, it has been shown in the 1960s by Edward N. Lorenz [4],[5] that the atmosphere is a chaotic system (a nonlinear system that exhibits erratic behavior in the sense that very small changes in the initial state of the system rapidly lead to large and apparently unpredictable changes in the later state) and any forecast method has an intrinsic limit of predictability. Generally speaking, the predictable range diminishes with the scale of the weather system. For example, forecasting synoptic weather systems at the macroscale by NWP models is known to have a predictability of around 2 weeks [6]. For individual convective elements, say a single-cell thunderstorm at the mesoscale or microscale, the predictability is about one hour or less [7]. For larger and more organized convective storms, their predictability could be a little longer depending on the underlying large-scale forcing [6].

Given the constraints mentioned, meteorologists in practice employ tailor-made prediction tools to tackle the weather prediction problem category by category. For example, in tropical cyclone forecasting, it typically takes one week or so for a tropical disturbance to mature into a typhoon and to traverse the oceans towards land or high latitudes where it dissipates or transforms to a cold core cyclone. As such, the relevant prediction tool has to have the capability to make a forecast out to the medium range, to effectively handle the complex non-linear dynamics and thermodynamics involved, and to include the full set of microphysics to describe the evolution of the cyclone and its environment. In reality, global NWP models with horizontal resolution typically at 20 to 60 km are used for the forecasting of tropical cyclone evolution. Yet even at such high resolution, these models are still too coarse for the prediction of rainstorms at smaller scales. In the following sections, “nowcasting” as a forecasting tactic for mesoscale weather features will be introduced and its effectiveness examined.

4. Nowcasting and SWIRLS

Given the volatile nature of mesoscale systems and a small forecast area such as Hong Kong, a forecasting tool at high spatial resolution, of the order of one kilometre or less, and with the ability to detect, analyze and forecast at short turn-around time is a must for effective rainstorm prediction. Nowcasting techniques, tools that are based on linear extrapolation for a forecast range up to several hours, presents one effective strategy to meet the challenge, as demonstrated by the Observatory’s operational nowcasting system SWIRLS.

SWIRLS meets the high-resolution requirement by resorting to remote sensing data, namely Doppler weather radar which has a radial data spacing of the order of 1 kilometre and an angular resolution of 1 degree. To retain all the small scale features, SWIRLS is based on the simplicity of linear extrapolation of the latest radar information. In this way, nonlinear magnification of errors by complicated physical models is avoided. The down side is that growth and decay of rainstorm systems are ignored. To compensate for this and to cope with the predictability constraint, SWIRLS updates the forecast as rapidly as the observations go so as to ensure that the latest developments will be captured as soon as they appear on the radar.

The workflow of SWIRLS is outlined in Fig. 3. The weather radar detects precipitating regions in its neighbourhood by sending out electromagnetic wave pulses (microwave frequency) and picking up the returned signals, or echoes, as reflected by the rain drops. By computing the time delay between the outbound and inbound signals, locations of the precipitation are estimated with reasonable accuracy. Fig. 4 shows a schematic of how radar works. Radar by itself only measures the strength of the returned signals in terms of power level (dBZ). SWIRLS converts this signal power *Z* into rainfall intensity *R* by using the following logarithmic relation:

$$Z = aR^b,$$

or equivalently,

$$\log Z = \log a + b \log R.$$

The parameters *a* and *b* in the above relationship depend on precipitation types and can vary case by case. SWIRLS estimates and updates these two parameters in real-time by best-fitting the radar echo intensities with rainfall data measured on the ground by a dense network of raingauges in Hong Kong (see Fig. 5 for an illustration).

To perform the linear extrapolation, SWIRLS derives the motion vectors of the radar echoes by a technique called TREC (Tracking of Radar Echo by Correlation). Essentially, two consecutive radar images are compared and cross-correlations between the echoes calculated. Echo pairs with the highest cross-correlations are tracked to produce a field of smoothed motion vectors. Radar echoes are then advected linearly in space at steps of 6 minutes according to the estimated TREC vectors (as illustrated in Fig. 6). At each time step, the real-time calibrated *Z-R* relation is applied to the transported radar echoes to estimate the forecast rainfall distribution. This extrapolate-estimate procedure is repeated and the rainfall distribution accumulated until the end of the desired cumulative period. Currently, SWIRLS generates forecasts of 1-, 2- and 3-hour cumulative rainfall distributions updated at 6-minute intervals. More detailed description of SWIRLS design and capability is given in [8] and [9].

5. SWIRLS in Support of Warning Operation

The Observatory currently operates three rainstorm-related warning systems, namely Rainstorm Warning (RW), Landslip Warning (LW) and Thunderstorms Warning. Quantitative precipitation estimates and forecasts generated by SWILRS are particularly useful for operating RW and LW which are based on exceedance of prescribed rainfall thresholds.

The RW system is primarily designed to warn territory-wide short-duration intense rainfall and the warning criteria for the three categories of warnings, namely Amber, Red and Black, are rainfall intensities of at least 30, 50 and 70 mm/hr respectively. For low-lying areas with poor drainage in the northern part of Hong Kong, a special announcement of flooding (SAF) risks is broadcast based on warning criterion similar to that for the Red RW, i.e. 1-hour rainfall reaching 50 mm or more but specifically over the northern part of Hong Kong.

Landslides are typically associated with prolonged rain events. An individual rain event itself may not trigger a RW but a chain of events may bring about accumulated rainfall significant enough to trigger a landslide. Currently, the LW criteria devised by the Geotechnical Engineering Office (GEO) are based on 24-hour accumulated rainfall with vulnerable areas as weighting factors. Operationally, the 24-hour rainfall is inferred from the past 21-hour actual rainfall augmented by a forecast of accumulated rainfall for the next three hours. When a threshold number of landslips is likely to occur based on such estimates, the LW will be issued.

Table I summarizes the reference warning criteria for the above rain-related severe weather phenomena in Hong Kong. As noted from Table I, the warnings have different requirements on the spatial, temporal and intensity distributions of the triggering rainstorm systems. Nowcasting tools are used to operate these warning services. The 1-hour and 3-hour rainfall products of SWIRLS are tailor-made for RW and LW respectively. To offer timely decision support to the forecasters, audio and visual alerts (see Fig. 7) are provided based on SWIRLS' forecast rainfall data.

SWIRLS has been in operation for over 5 years since 1999. Fig. 8 shows its performance in Red and Amber RW cases in 2004-2005, and flooding (for northern part of Hong Kong) and LW cases in 2001-2005 (because of its infrequent occurrences over the past five years, Black RW is not verified). In the histogram, the solid colour bars in blue, orange and green indicate the probability of detection (POD), false alarm rate (FAR) and critical success index (CSI) respectively. The striated bar in purple shows the percentage of ideal lead (PIL) time achieved by the alerts. According to the underlying forecast ranges, the ideal lead time for RW, LW and flooding announcement are 1 hour, 3 hours and 1 hour respectively.

As seen from Fig. 8, Red and Amber RW achieve the highest POD and PIL at the expenses of FAR. Because of the higher impact of Red RW, the spatial criterion for triggering the alert is purposely tuned towards higher detection rate and longer lead time. In operation, the same criterion is also applied to Amber. The consequences are that Red RW alert scores a higher FAR and a lower CSI than Amber. As far as forecast skill (in terms of CSI) is concerned, guidance on LW scores the highest due to the incorporation of 21-hour actual rainfall information. The error of 3-hour rainfall forecast of SWIRLS is thereby "diluted" to some extent. Despite its high POD and CSI, the PIL of LW alert is just over 50%. This is a reflection of the fact that SWIRLS is not able to predict rainstorm development with any skills beyond, say, one and a half hour due to its implicit assumption of rain intensity persistence. Amongst the four, the flooding announcement for the northern part of Hong Kong on average shows the poorest performance mainly because of its demanding warning criteria (intense rainfall over a specific region within Hong Kong; see Table I).

In daily operation, forecasters on the bench would apply the nowcast products in a smarter way. For example, they will not rely on a single piece of forecast guidance but instead look for a consistent signal from the rapidly updating forecasts and alerts of SWIRLS. Forecasters will usually check the corresponding forecast rainfall maps and the actual situation on the radar screen to judge if intensity persistence is a valid assumption and whether allowance should be allowed for in terms of location errors in the forecast rainfall distribution. Fig. 9 and Fig. 10 show two rainstorm cases, resulting in a Red RW/flooding announcement and a Black RW respectively. In both cases, the detailed spatial distribution and rain intensity did not satisfactorily match the actual situations; but the sequence of rapidly updated forecasts from SWIRLS were sufficiently informative to help forecaster decide and issue timely warnings in both cases.

6. Further Developments of Nowcasting Techniques in Hong Kong

Forecast beyond 3 hours is extremely unreliable with SWIRLS because of the validity of linear extrapolation and the assumption of rain intensity persistence. One way to improve on the linear extrapolation methodology is to adopt a more sophisticated method of transporting the radar echoes along a flow field by means of Semi-Lagrangian Advection (SLA). The major advantage of SLA is that the transport of radar echoes is performed in a moving (Lagrangian) frame of reference. In other words, the scheme is by design flow-following. In actual implementation (see Fig. 11 for an example), the transport of echoes is achieved by back-tracing upstream in the flow to the last time step for the echoes (black ellipse in Fig. 11) that would arrive at the location of interest at the current time step (dashed blue ellipse in Fig. 11). When identified, such upstream echoes will be moved bodily to the current location of interest following the flow. SLA is also known to be a robust computational method against numerical errors and instabilities during time integration. These two characteristics of the SLA scheme will potentially allow SWIRLS to integrate forward in time out to 6 hours with a more realistic forecast rainfall distribution. Fig. 12 shows a comparison between the SLA-based and linear extrapolation-based forecasts.

SLA alone would not help SWIRLS to overcome the inherent predictability constraint. One possible solution to get around this is to resort to NWP models. Among the practical problems discussed in Section 3, a more subtle issue relates to the model spin-up problem. Due to the use of imperfect and imbalanced atmospheric analysis fields as initial conditions for NWP model, it takes some time for the model to adjust and respond to the initial forcing. The consequence is that the model usually does not produce the amount of rainfall it should have produced in the first few hours of simulation, effectively creating a blind spot in the nowcasting range.

For this reason, the skills of nowcasting and NWP systems in general exhibit opposite trends in time as illustrated in Fig. 13. But then, would a complementary use of nowcast and NWP output leads to a more skillful forecast as hinted by the envelop curve in Fig. 13? Along this line of thought, one technically feasible strategy is to optimally blend the forecasts from nowcasting system and NWP model in a linear fashion:

$$F_{\mathrm{opt}} = w_{\mathrm{now}} \cdot F_{\mathrm{now}} + w_{\mathrm{NWP}} \cdot F_{\mathrm{NWP}} ,$$

where *F*'s represent forecast fields and *w*'s refers to the weights used to combine the two different forecast fields. A new system called RAPIDS (Rainstorm Analysis and Prediction Integrated Data-processing System) has been developed upon this notion and is currently under trial at HKO. In actual implementation, F_{NWP} comes from an advanced high-resolution non-hydrostatic model (NHM) currently being tested in HKO, which is capable of simulating convections explicitly and thus more realistically. Before performing the blending, F_{NWP} also has to be adjusted for location and shape errors. RAPIDS performs such adjustments automatically via image transformation methods. The weights w_{x} at different lead times are given by a smoothed step function (see Fig. 14) such that SWIRLS will be weighted more heavily in the near range while increasing weights will be shifted to the model forecast towards the end of the forecast period. The parameters in the weighting function are dynamically adjusted according to real-time validation of SWIRLS and NHM performances.

RAPIDS has been under operational trial since April 2005. The example shown in Fig. 15 illustrates how an optimally blended rainfall map is produced by RAPIDS. A forecast verification has been performed based on a data set comprising of 16 rainstorm cases in May-Aug 2005 [10]. As shown in Fig. 16, the forecast skills of SWIRLS-SLA and NHM follow the expected trends plotted in Fig. 13. As a preliminary assessment, RAPIDS has met its design objectives, attaining improved skill scores at the forecast range of 3-4 hours.

To further improve on rainstorm forecasting, both SWIRLS and NHM have to be enhanced. For examples, introducing growth-decay capability to SWIRLS and employing more advanced data assimilation technique to ease the spin-up problem of NHM are future possibilities. Whether nowcasting technique could be applied to high impact weather beyond 1 hour is yet another difficult issue requiring further studies. One possible direction to proceed is to take into account the uncertainties of the initial conditions and present the forecasts in a probabilistic representation.

Apart from quantitative precipitation forecasts, HKO has also started research on forecast of high-impact weathers related to severe thunderstorms, including lightning and severe squalls. This calls for the development of new radar analysis techniques and severe weather detection and tracking algorithms. To supplement the radar data, use of other types of remote-sensing data such as lightning and satellite data are also being explored.

On the service front, HKO's severe weather warning systems have been evolving over the years to meet the increasing demand of the public. A good warning system should (a) be easy to understand; and (b) facilitate collective and effective response by the public [11],[12]. Warning systems are more than just a set of definitions of different "warning status" or warning criteria. Consideration has to be given to optimal utilization of forecast products by users and customers. From this angle, one way to enhance the applications of SWIRLS and RAPIDS products is to incorporate more customer-centric information. Following this line, presenting nowcasting information over a GIS (geographical information system) platform is worth pursuing.

Another important consideration in forecast development work is the multi-disciplinary approach. As discussed in previous sections, SWIRLS' development effort in the past has been focused on rain, landslides and flooding, which are intimately connected with the operational and research activities of other government departments including Drainage Services Department and GEO. Recently, HKO has also embarked on a research study on the nowcasting application of GPS (global positioning system) satellite data supplied by Lands Department. It is interesting to note that HKO is focusing on the part of the GPS signal that has been regarded by colleagues in Lands Department as "noises"! Information, technology and experience sharing will no doubt lead to a win-win-win situation for the forecasters, other special users and the public at large.

Acknowledgement

The author would like to thank Mr KH Yeung, Mr Edwin ST Lai and Mr ST Chan for their valuable comments on the manuscript, as well as Mr CK Chow for compiling the verification statistics.

References

[1]. Li, P.W. & Edwin S.T. Lai, 2005: Typical Characteristics of Heavy Rain over Coastal Areas of Southern China – A Radar Perspective. *Proceedings Workshop on Meteorology and Climate over South China*, 5-8 December 2005, City University of Hong Kong.

[2]. Orlanski, I., 1975: A Rational Subdivision of Scales for Atmospheric Processes. *Bulletin of American Meteorological Society ,* **56**, No.5, pp527-530.

[3]. Thunis, P. & R. Bornstein, 1996: Hierarchy of Mesoscale Flow Assumptions and Equations. *Journal of Atmospheric Science,* **53**, No.3, pp380-397.

[4]. Lorenz, E., 1963: Deterministic Nonperiodic Flow. *Journal of Atmospheric Science*, **20**, pp 130-141.

[5]. Lorenz, E., 1969: The Predictability of Flow Which Possesses Many Scales of Motion. *Tellus*, **21**, pp 289–307.

[6]. Kalnay, E., 2003: *Atmospheric Modeling, Data Assimilation and Predictability*, Cambridge University Press.

[7]. Emanuel, K., 1994: *Atmospheric Convection*, Oxford University Press, Inc.

[8]. Li, P.W. & Edwin S.T. Lai, 2004: Short-range Quantitative Precipitation Forecasting in Hong Kong, *Journal of Hydrology*, **288**, pp 189-209.

[9]. Li, P.W. & Edwin S.T. Lai, 2004: Applications of Radar-based Nowcasting Techniques for Mesoscale Weather Forecasting in Hong Kong, *Meteorological Applications*, **11**, pp 253-264.

[10]. 黃偉健・黎守德，2006：「激流」(RAPIDS)暴雨預報系統—「小渦旋」與數值天氣預報模式的融合。*第二十屆粵港澳氣象科技研討會*，中國・澳門，2006 年 1 月 18-20 日。

[11]. Lam C.Y., 2004: The Weather Aspect of Disaster Planning and Preparedness in Hong Kong. *Symposium on Planning and Preparedness for Weather-related Disasters*, Hong Kong, China, 29-30 March 2004.

[12]. Lam C.Y. & W.L. Ginn, 2002: Changing User Requirements for Severe Weather Warnings and the Response Strategies of the Hong Kong Observatory. *WMO Commission for Basic Systems, Technical Conference on Data Processing and Forecasting Systems*, Cairns, Australia, 2-3 December 2002.

Table I – Reference warning criteria for rain-related severe weather phenomena in Hong Kong as of 2005.

Warning	**Spatial Criteria**	**Temporal Criteria**	**Rainfall Criteria**
Amber RW	widespread	persistent	30 mm/hr or more
Red RW	widespread	persistent	50 mm/hr or more
Black RW	widespread	persistent	70 mm/hr or more
LW	weighted by vulnerable areas	prolonged	24-hour rainfall → 15 landslides or more
SAF	northern NT	-	~50 mm/hr or more

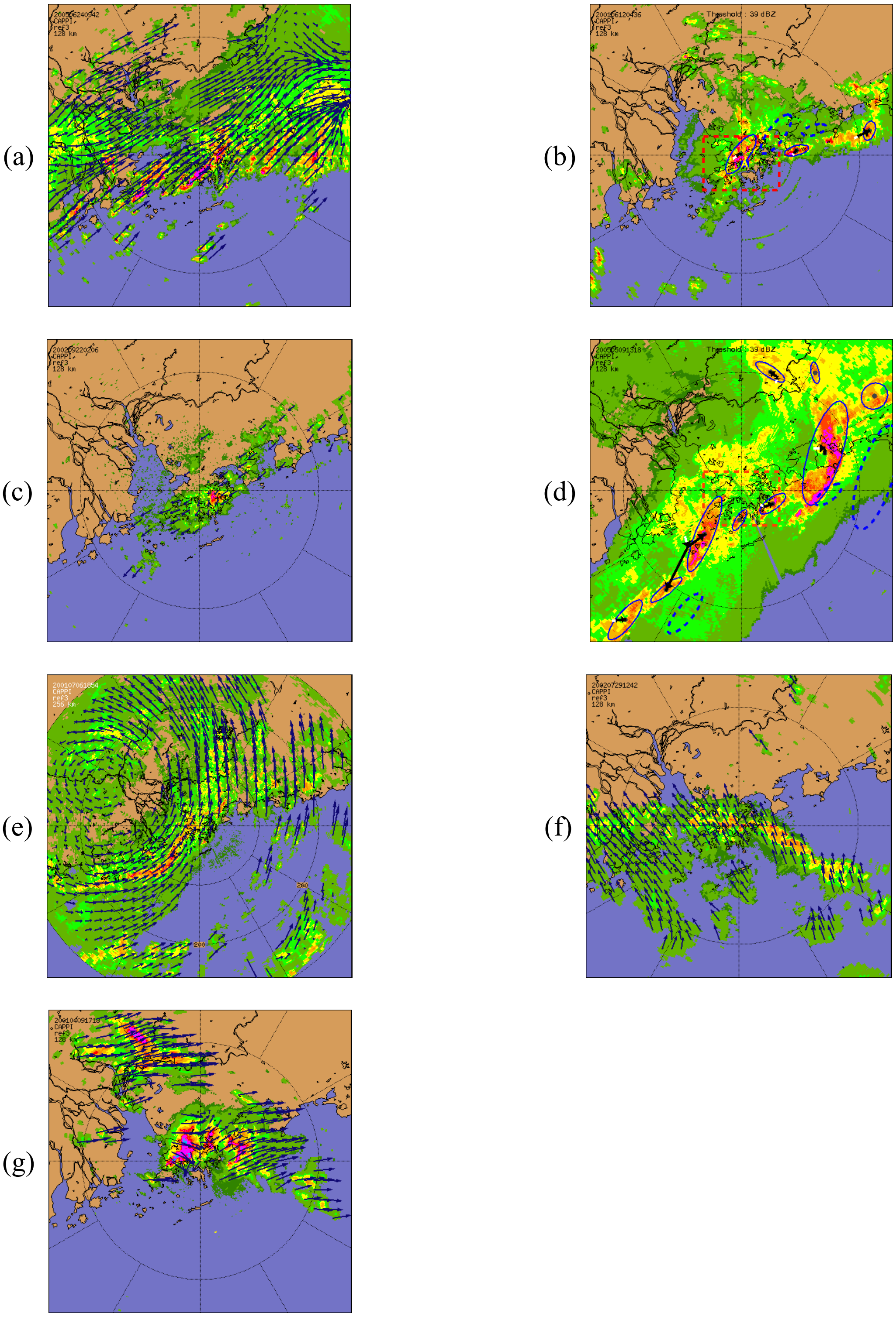


Fig. 1 Typical radar signatures of seven types of high-impact rainstorms in Hong Kong: (a) QU, (b) X, (c) LS, (d) SQ, (e) TC, (f) SE and (g) SU. Arrows and ellipses on the diagrams indicate local flow directions (TREC vectors; see Section 4) and organized rainband structures respectively.

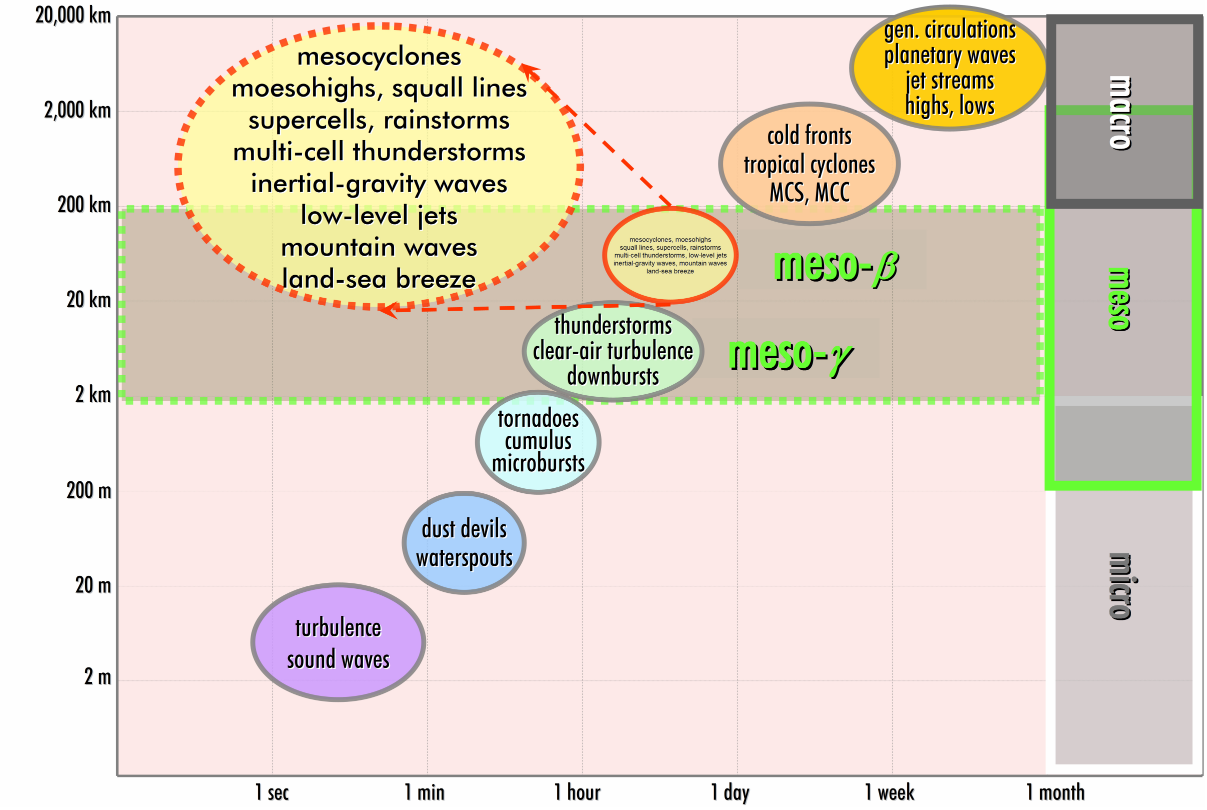


Fig. 2 Temporal and spatial scales of typical observable weather systems. From top to bottom, the overlapping rectangles on the right indicate the spatial ranges of the macro-, meso- and microscale respectively. The dashed oval shows a magnified view of the meso-β (20-200 km) weather phenomena.

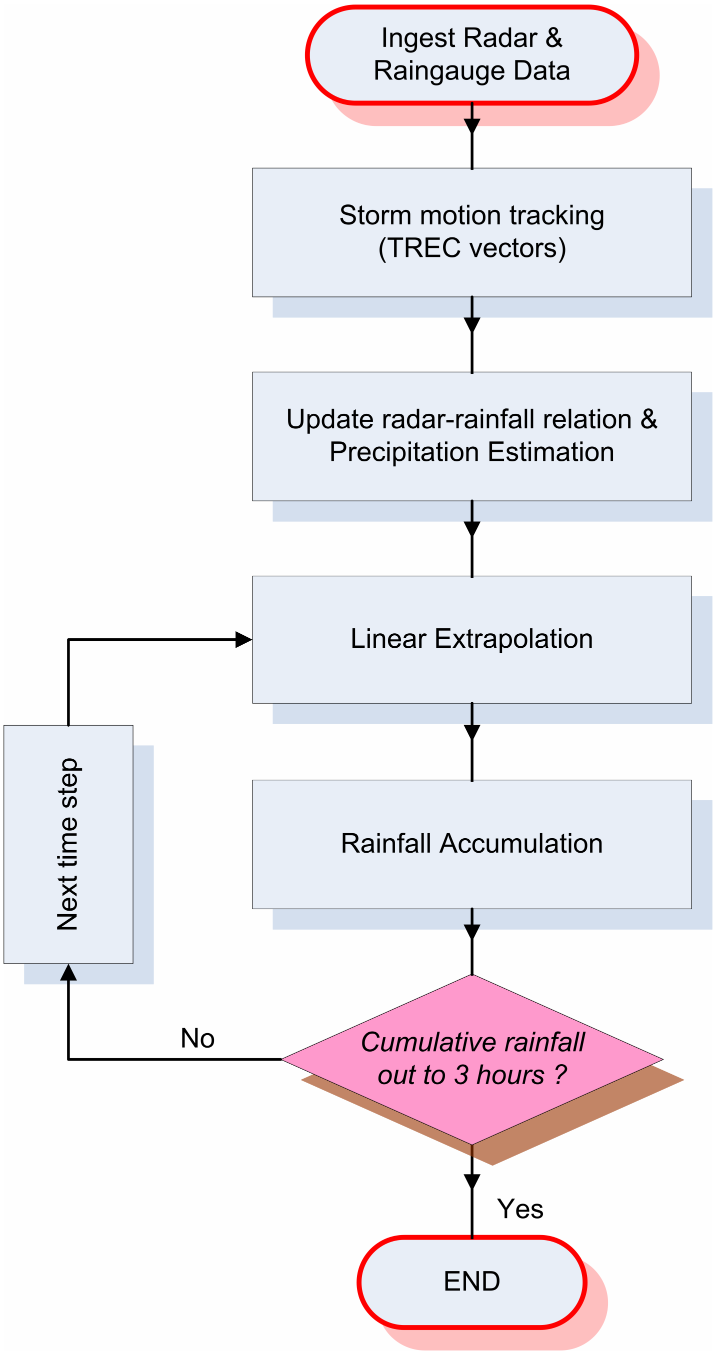


Fig. 3 Workflow of SWIRLS rainfall forecast.

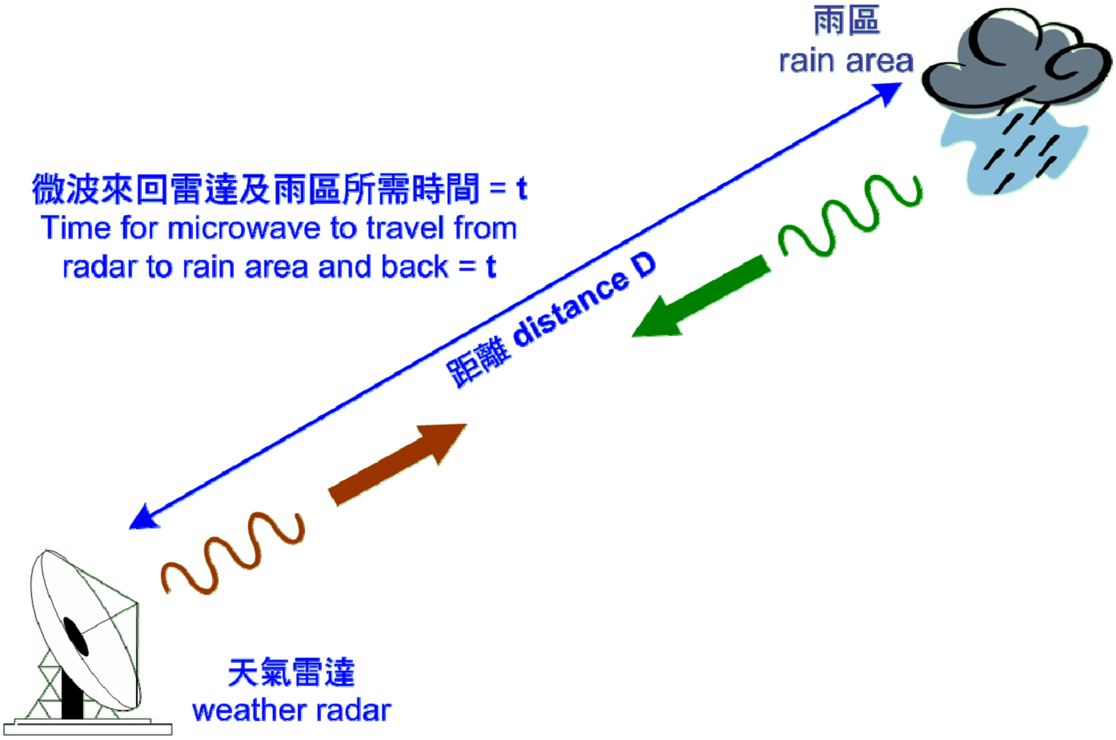


Fig. 4 Working principle of a weather radar: $D = \frac{1}{2} \cdot c \cdot t$, where c is the speed of light.

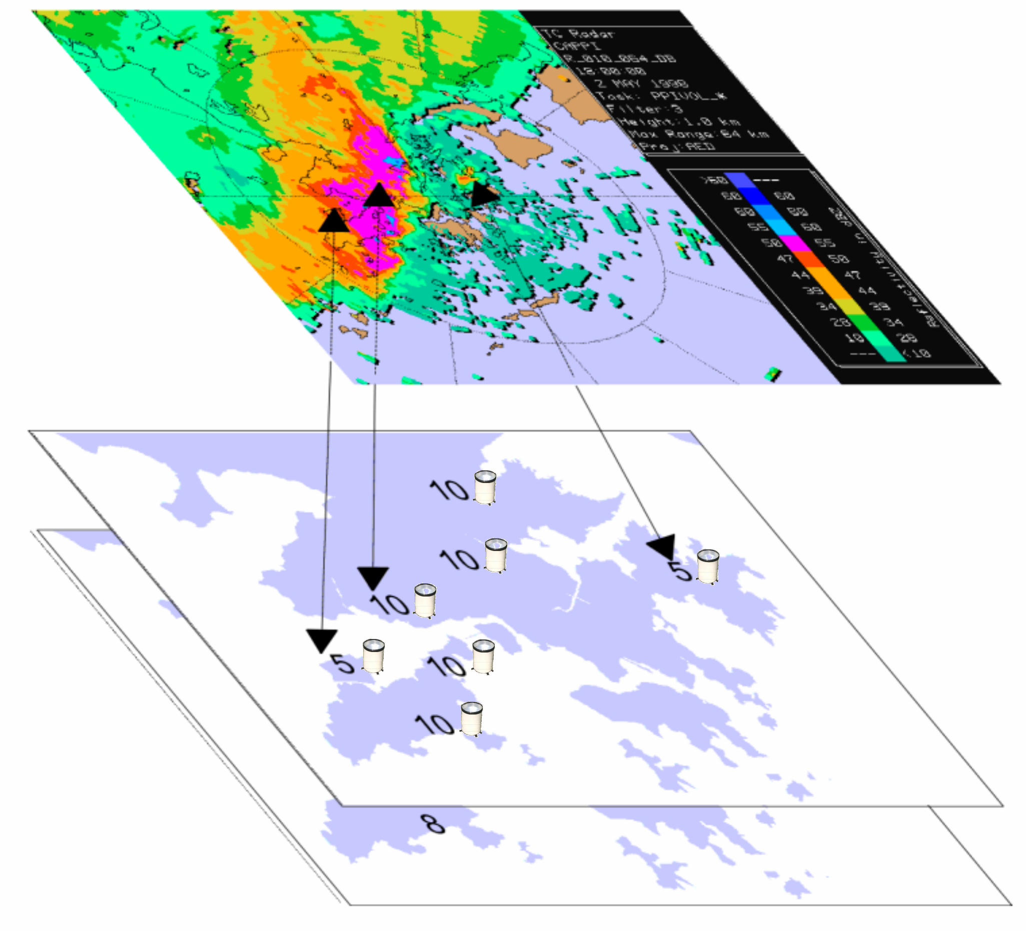


Fig. 5 Real-time calibration of radar signals by rainfall data collected by surface raingauges.

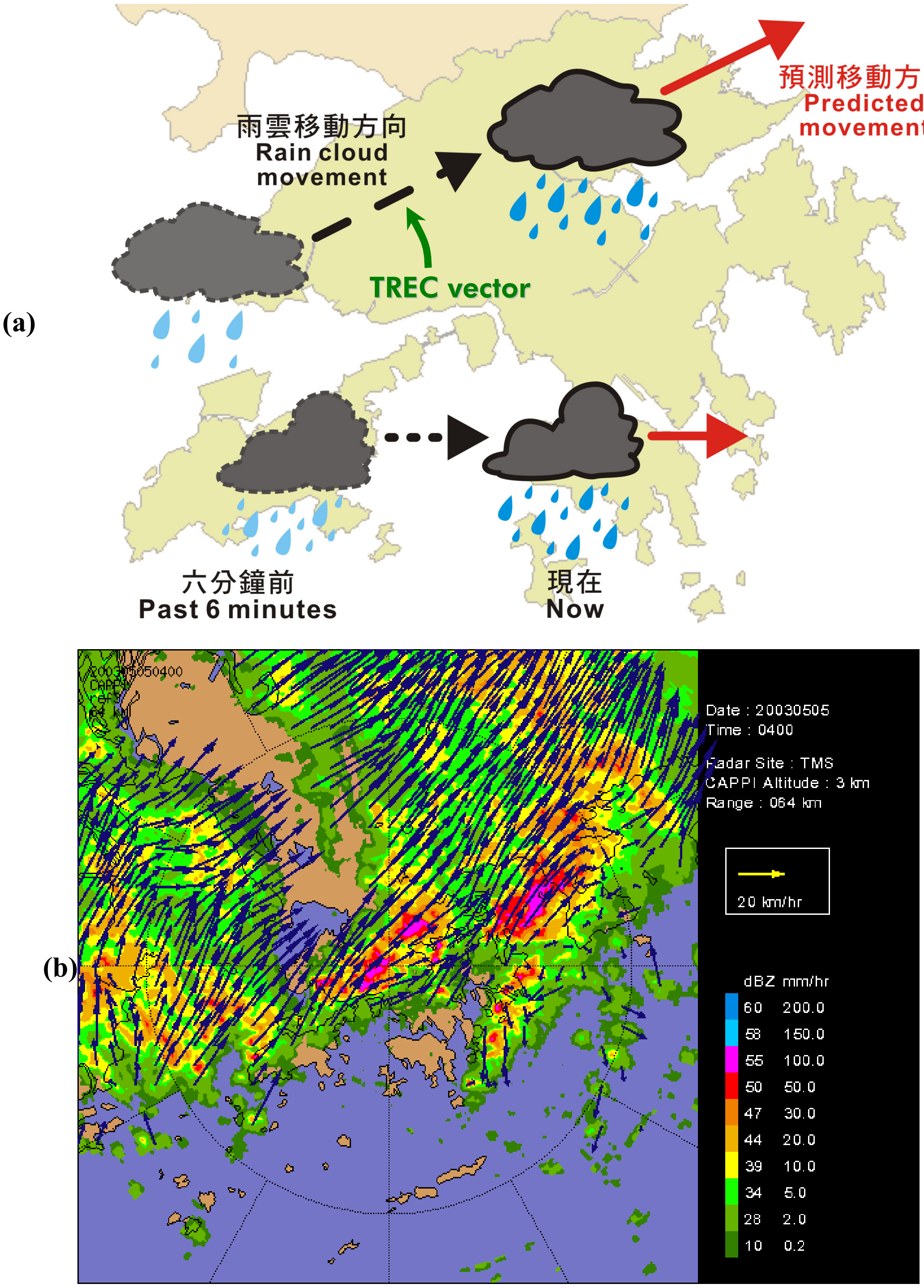
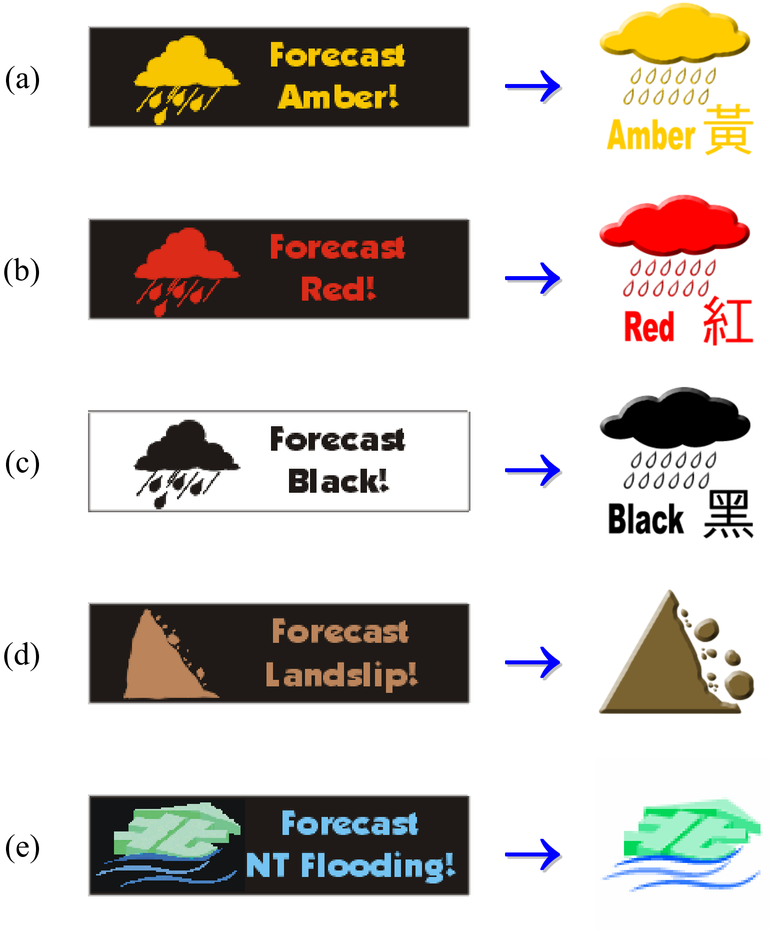
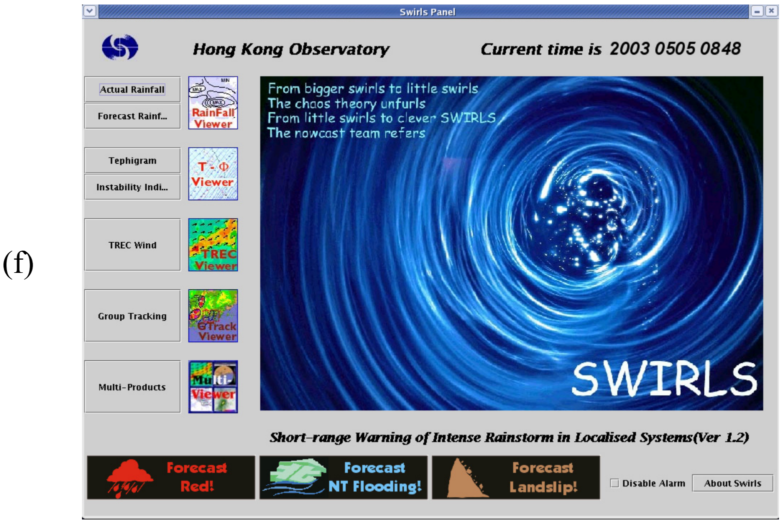


Fig. 6 Nowcasting by linear extrapolation of radar echoes based on the TREC technique. (a) Conceptual model. (b) Actual TREC motion field (5 May 2003, 4:00 am).





From bigger swirls to little swirls
The chaos theory unfurls
From little swirls to clever SWIRLS
The nowcast team refers

Short-range Warning of Intense Rainstorm in Localised Systems(Ver 1.2)

Fig. 7 SWIRLS warning guidance products. Visual alerts from top to bottom corresponding respectively to (a) Amber RW, (b) Red RW, (c) Black RW, (d) LW and (e) SAF. (f) appearance of the alerts as displayed on the front panel of SWIRLS's graphical user interface.

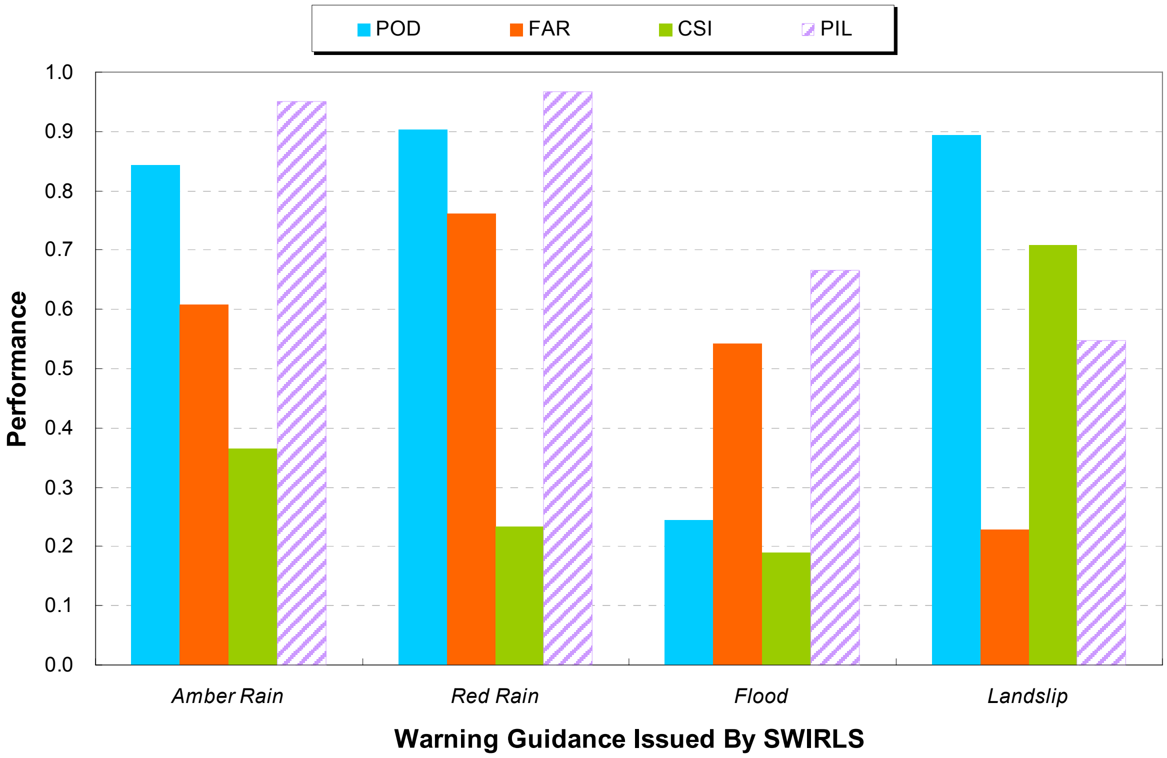


Fig. 8 Performance of SWIRLS forecasts in terms of warning guidance. The acronyms POD, FAR, CSI and PIL stand respectively for the probability of detection, false alarm rate, critical success index and percentage of ideal lead time respectively (see Section 5 in main text). Statistics of Rain guidance are based on data in 2004-2005, whereas Flood and Landslip encompass a larger data set from 2001 to 2005 in order to have statistically significant sample sizes.

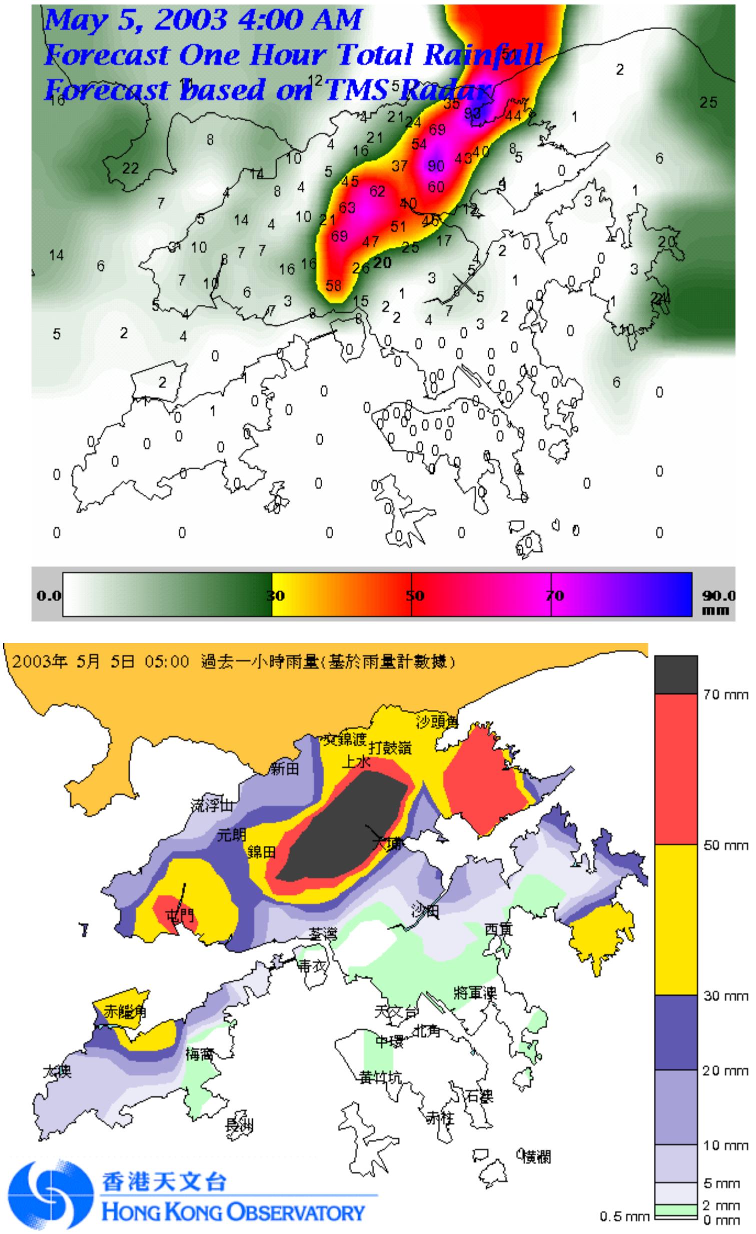


Fig. 9 Rainstorm on 5 May 2003 leading to both SAF and Red RW. SWIRLS one-hour forecast rainfall map (top) issued at 4 am compares favourably with the actual one-hour rainfall distribution (bottom) ending at 5 am.

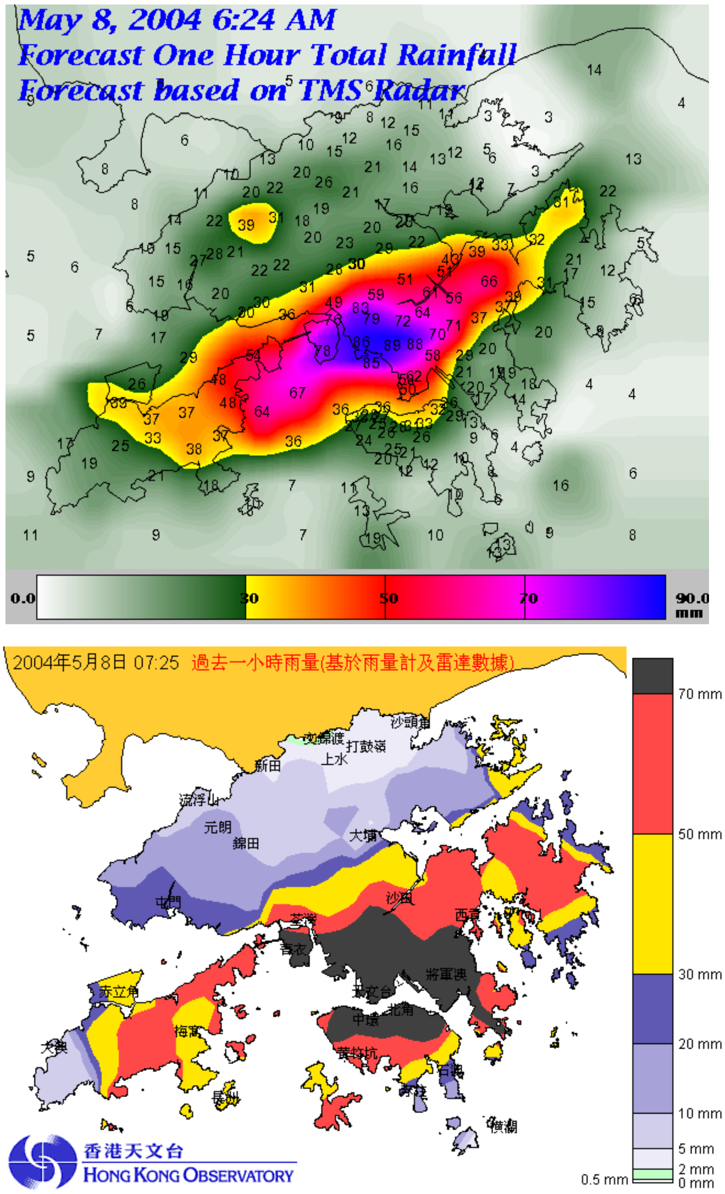


Fig. 10 Rainstorm on 8 May 2004 leading to a Black RW. SWIRLS one-hour forecast rainfall map (top) issued at 6:24 am compares favourably with the actual one-hour rainfall distribution (bottom) ending at 7:25 am.

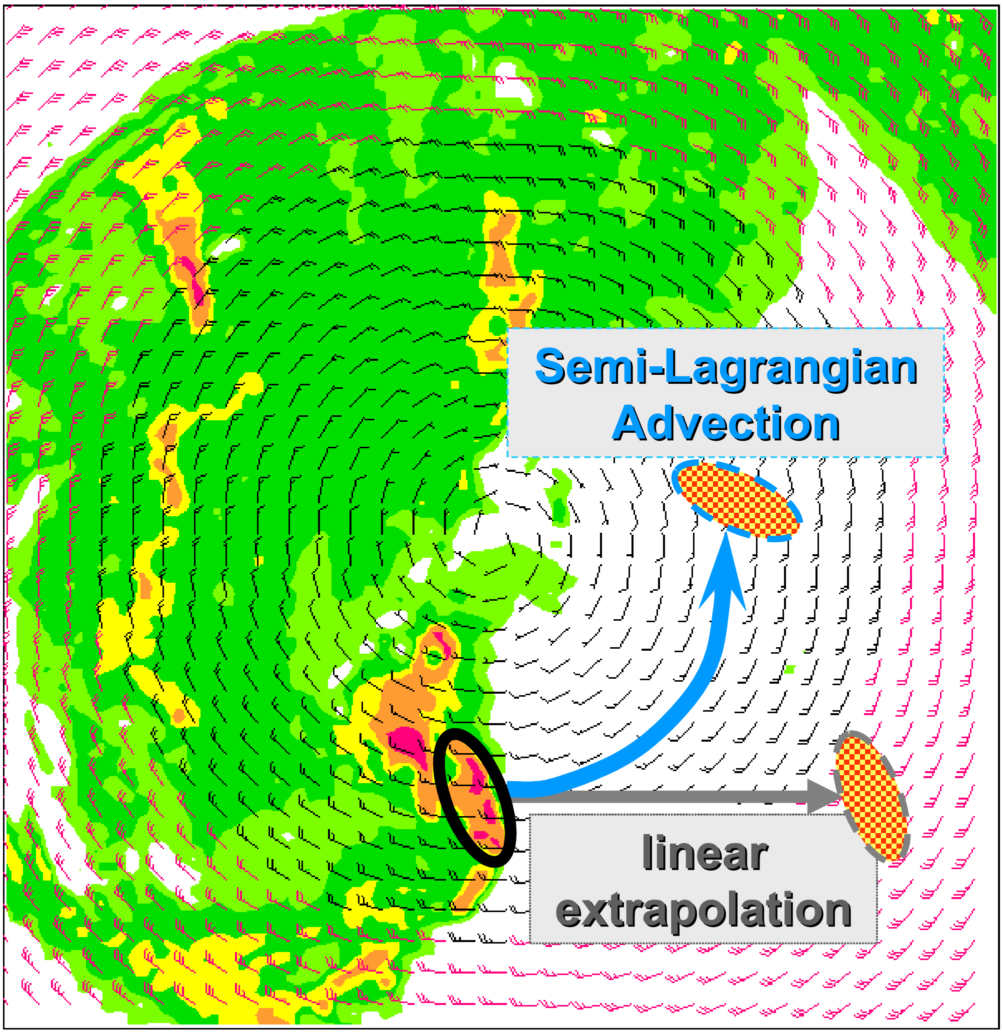


Fig. 11 Semi-Lagrangian advection scheme (blue annotations). Also shown in grey is the linear extrapolation method. The black and the dashed ellipses indicate respectively the current and forecast positions of the selected radar echoes (coloured areas). The wind barbs at the background represent the motion field at the current time.

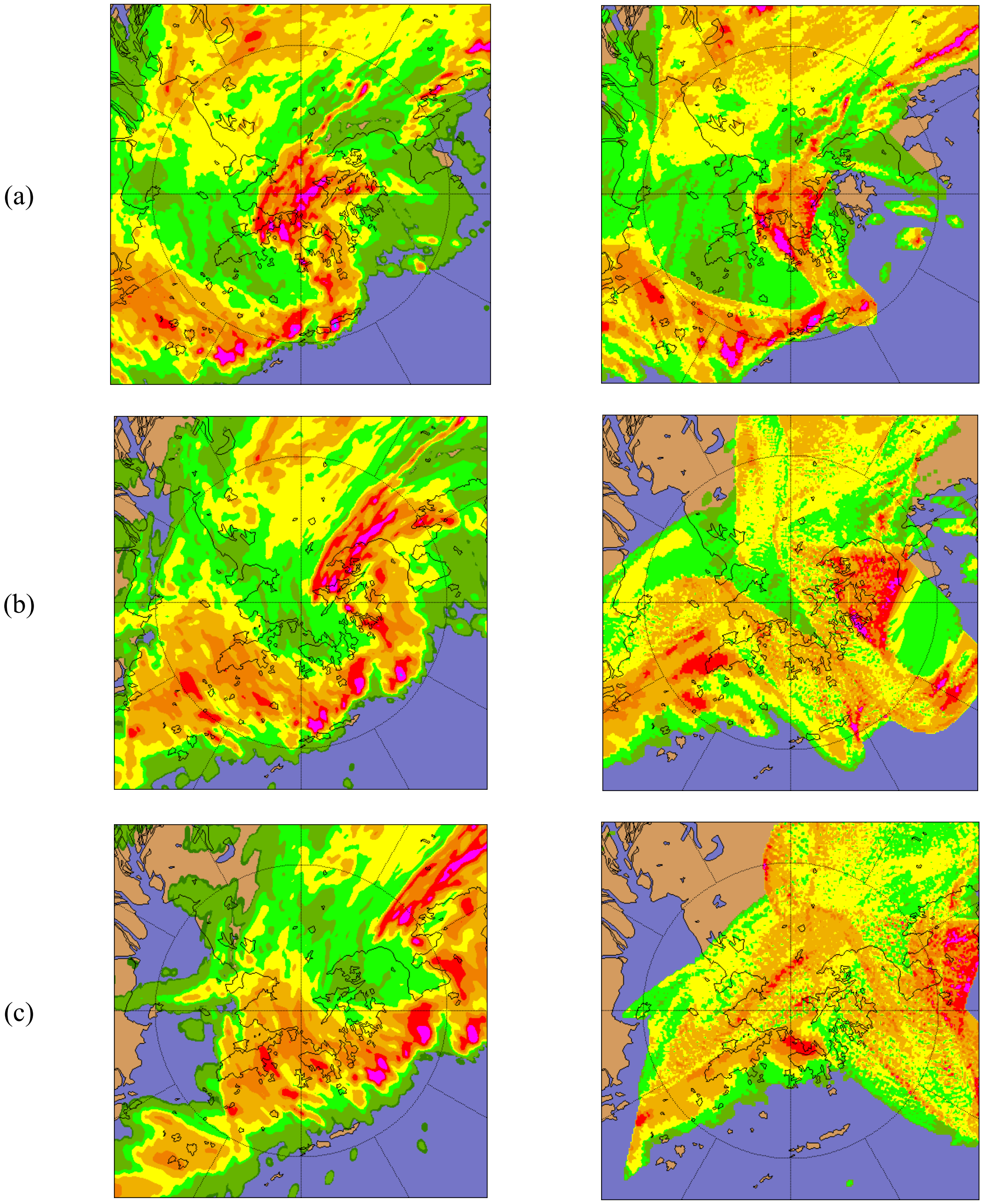


Fig. 12 Comparison between forecasts based on SLA scheme (left) and linear extrapolation (right) method. Rows from top to bottom refer to different forecast range: (a) 1 hour, (b) 2 hours and (c) 3 hours.

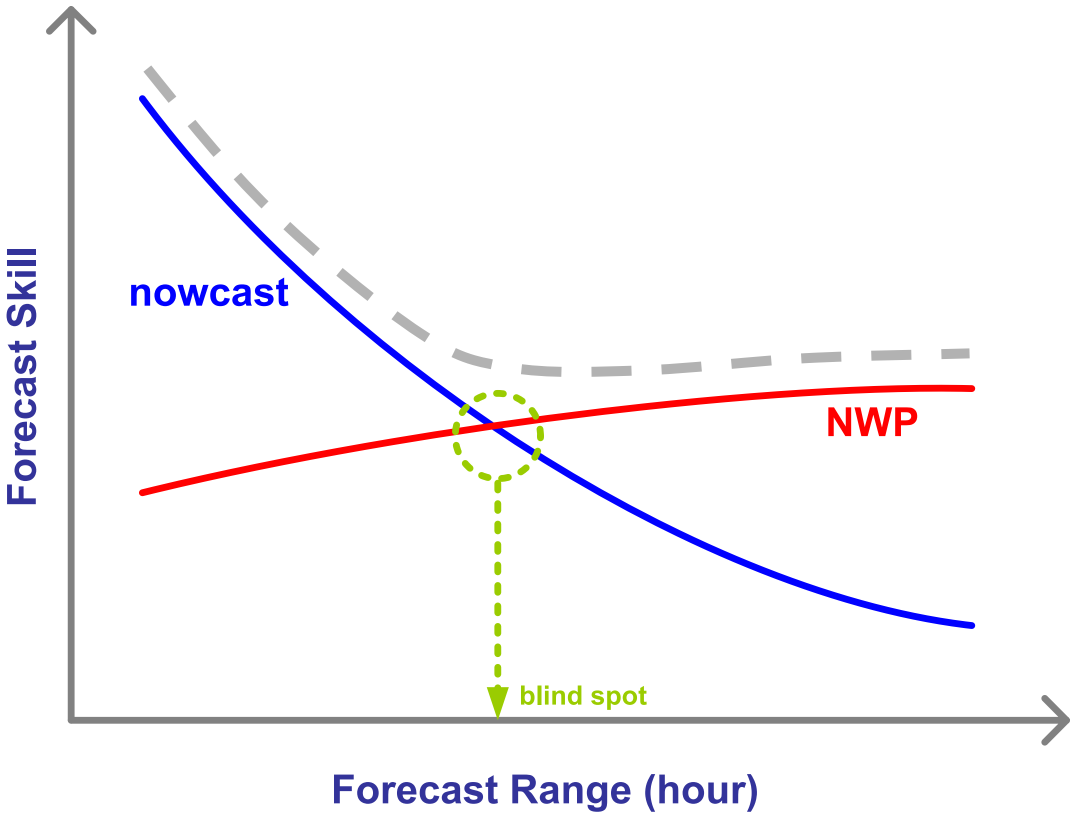


Fig. 13 Expected skill trends for nowcast and NWP forecast. The dashed grey curve represents an envelop of the two skill trends.

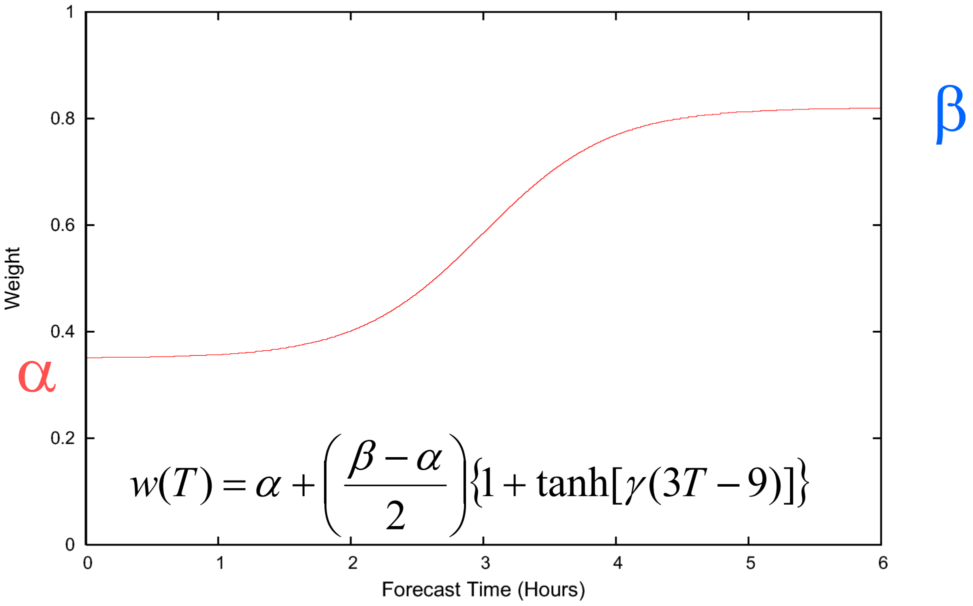


Fig. 14 Weighting function for blending NWP forecast ($w_{\mathrm{NWP}} = w$) and nowcast ($w_{\mathrm{now}} = 1 - w$). The starting and ending values, α and β, are determined from past forecast performance whereas the parameter γ determines the steepness of the mid-section of the curve and is set to be 1.

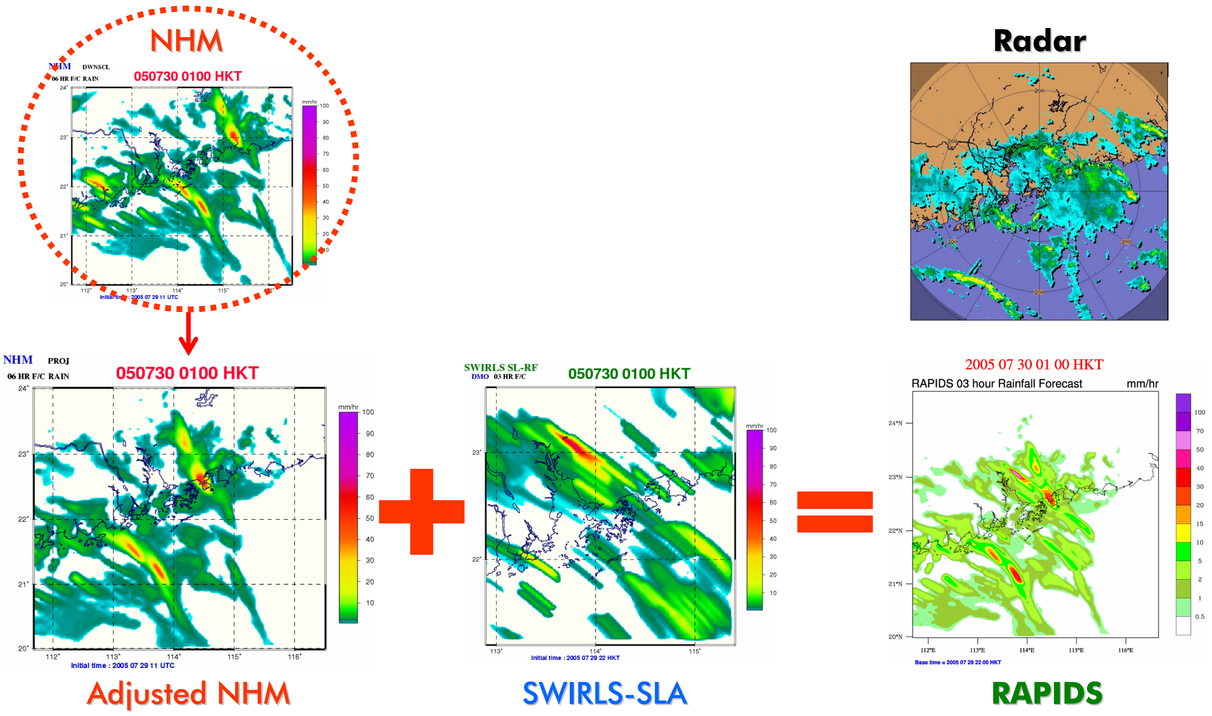


Fig. 15 RAPIDS algorithm illustrated by a real example on 30 July 2005.

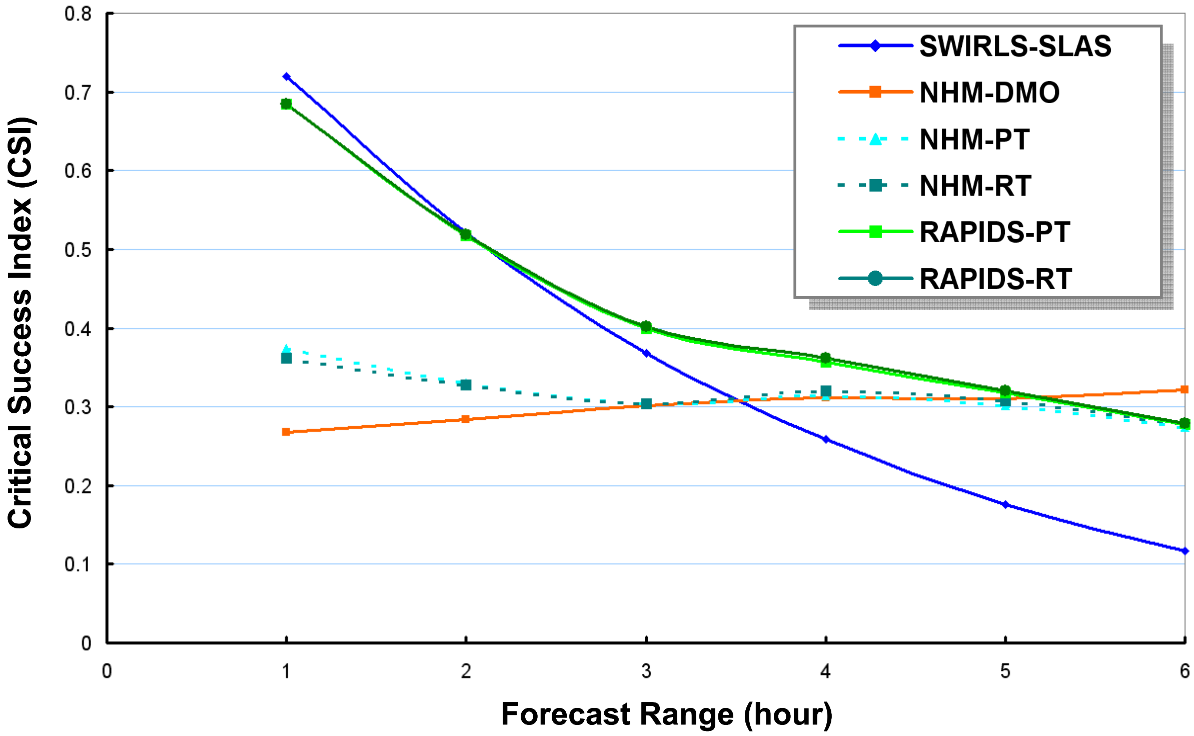


Fig. 16 Forecast skill comparison of RAPIDS (green solid lines) and SWIRLS semi-Lagrangian version (blue line) in terms of critical success index (CSI). Also shown are the orange and the dashed lines, representing respectively the skills of the direct-model output (DMO) and the adjusted products from NHM. The subscripts RT and PT refer to the two different methods, namely rigid transform and projective transform, used by RAPIDS to adjust the forecast rainfall distributions.