Introduction to Radar Based Nowcasting

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香港天文台
HONG KONG OBSERVATORY

What We Need…

Actual

Quantitative Precipitation Estimate (QPE)

Forecast

Quantitative Precipitation Forecast (QPF)

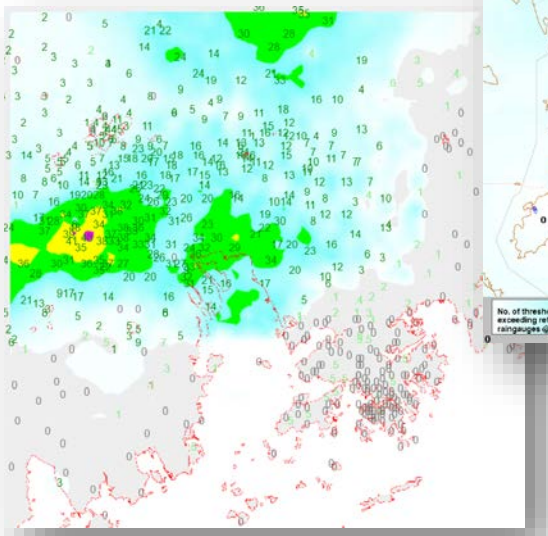
Severe Weather

Lightning, Gust, Hail

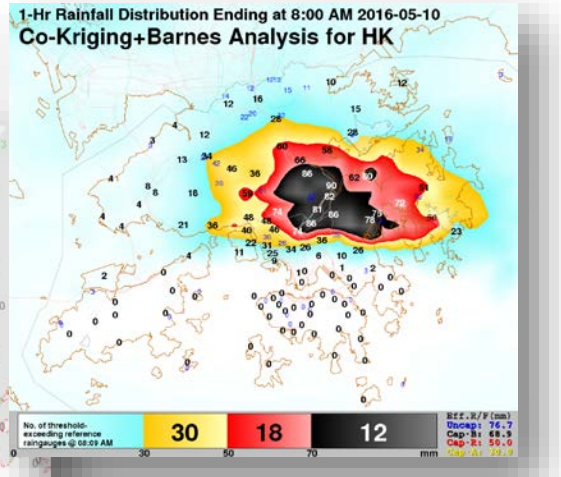
Services

Forecasts & Warnings

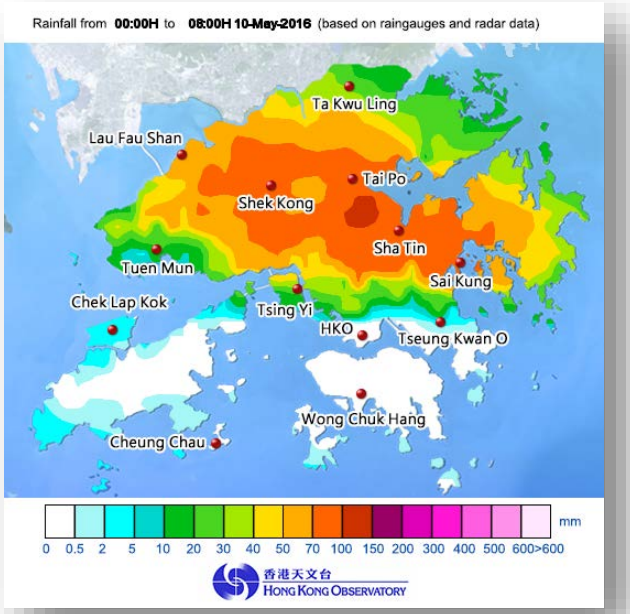
Actual (QPE) Products



Regional Rainfall Map
on GIS for Forecasters

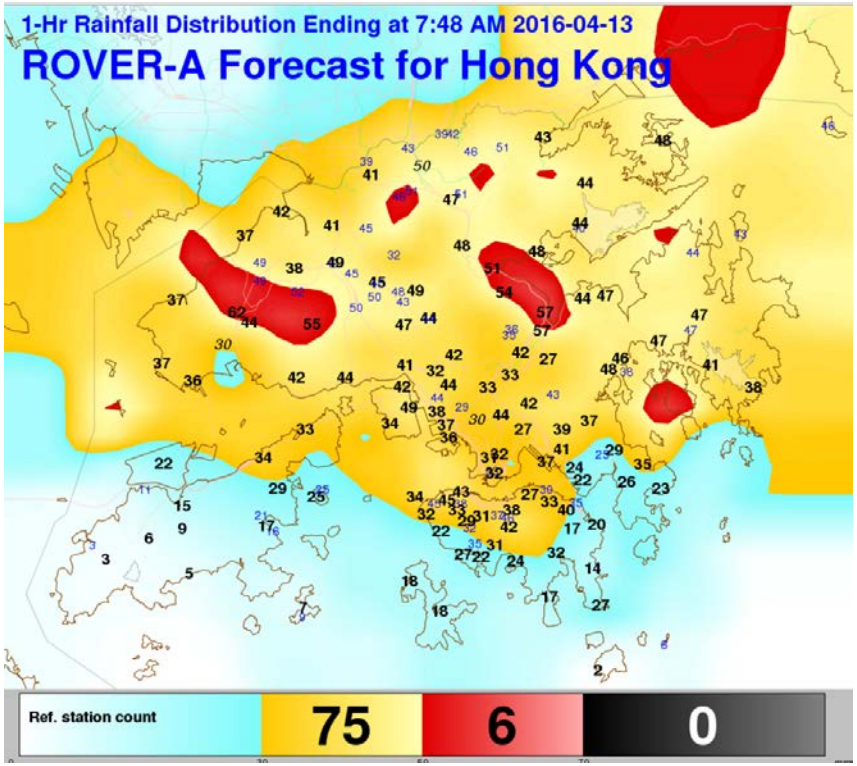


Local Rainfall Map
for Forecasters

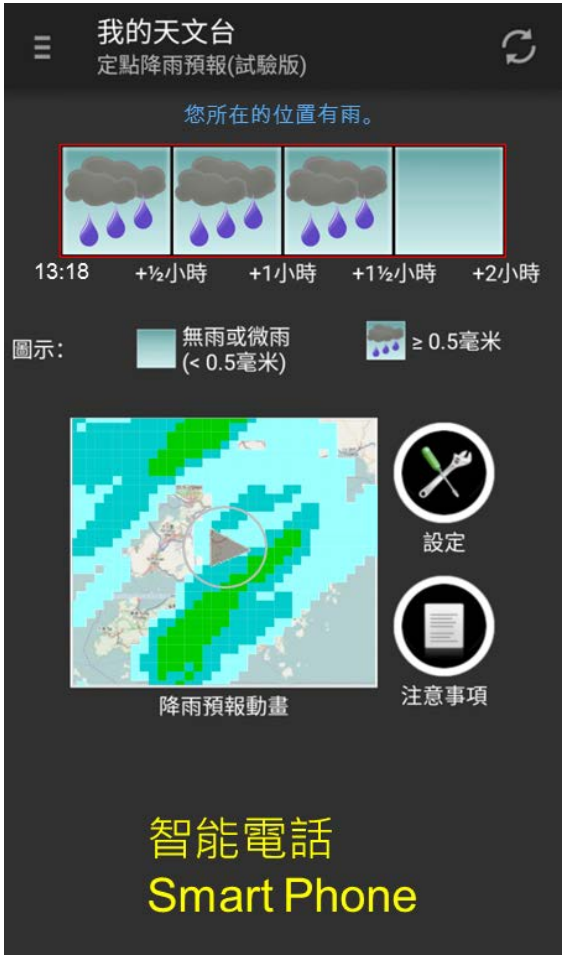


Local Rainfall Map
for the Public

Forecast (QPF) Products

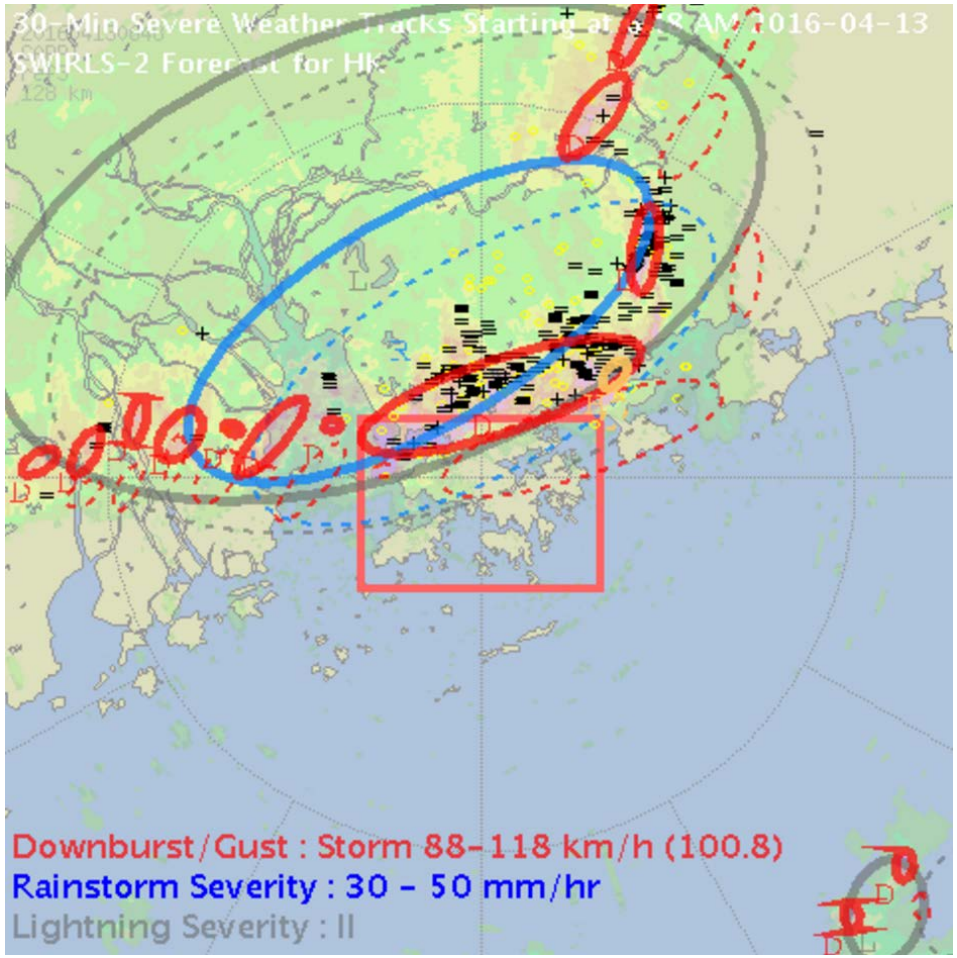


For Forecasters

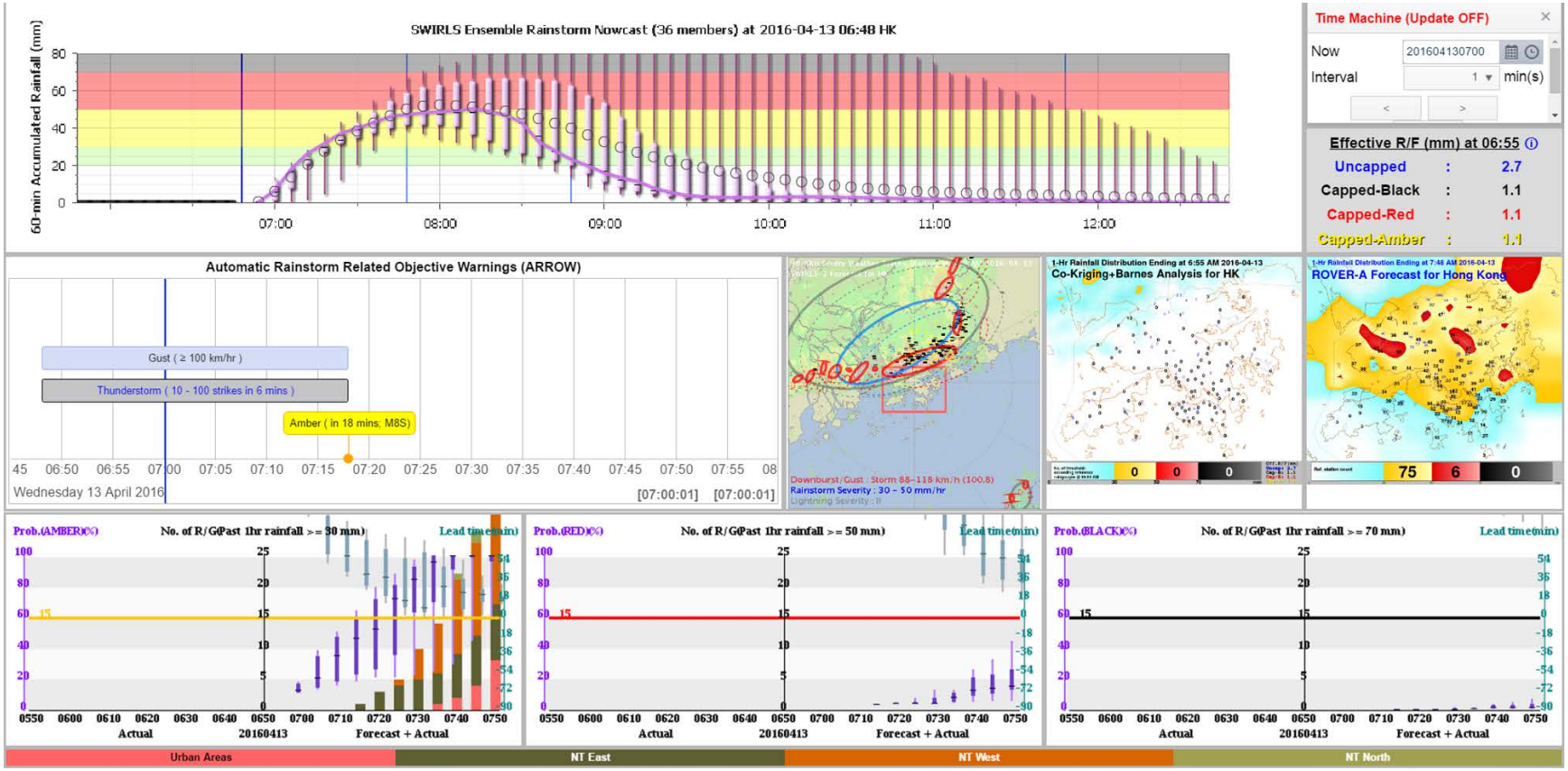


For Public

Severe Weather Products

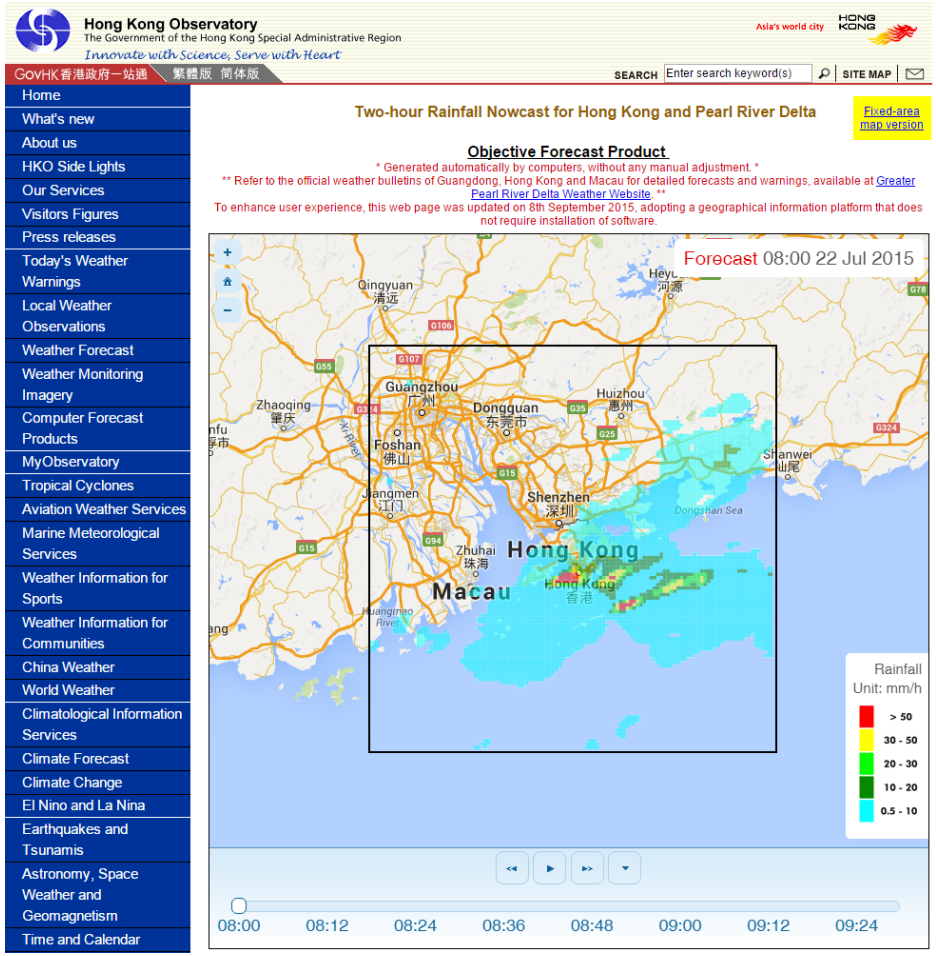


Services



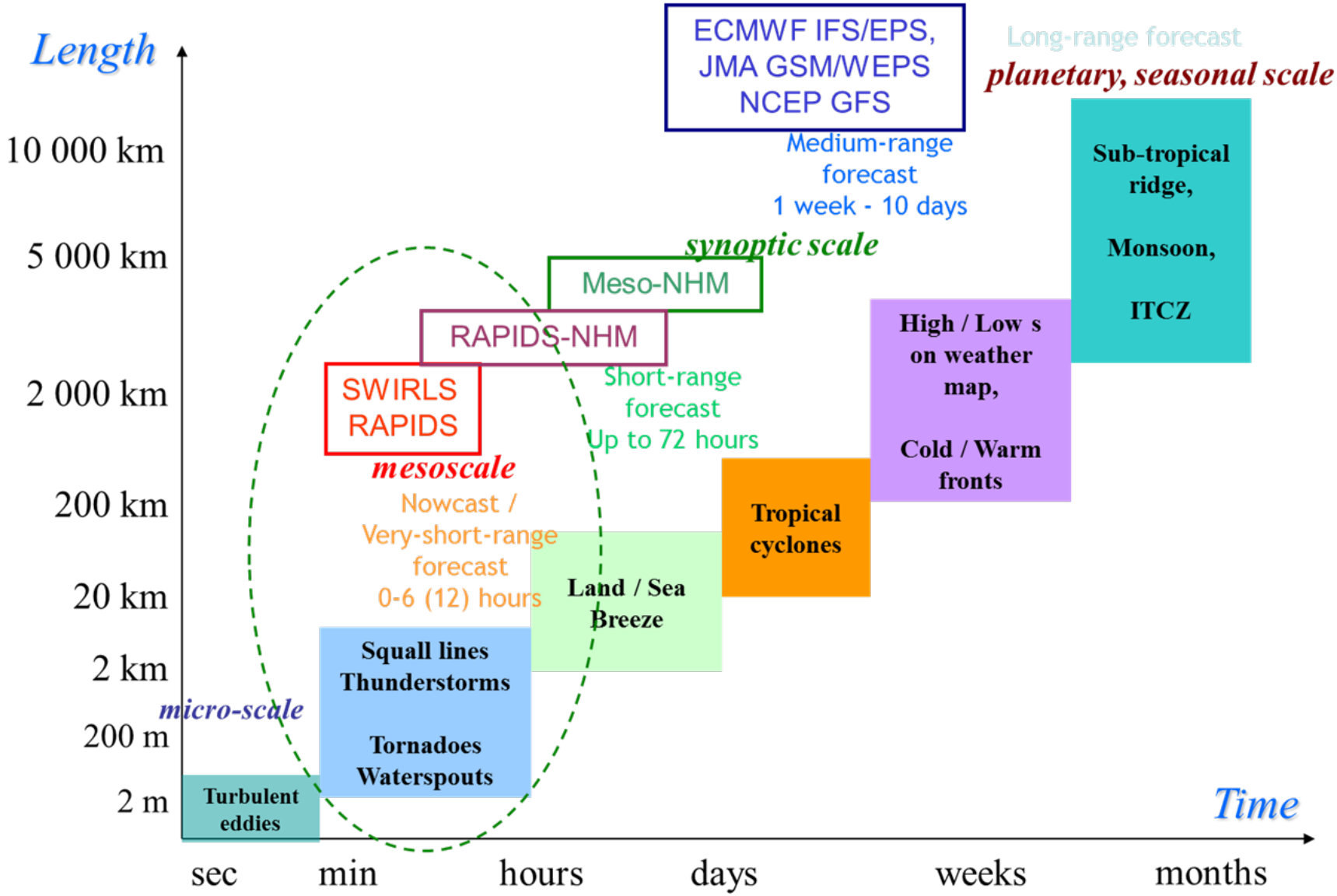
For Internal Customer (Forecasters)

Services



For Public

Scale matters …



WEATHER WARNINGS

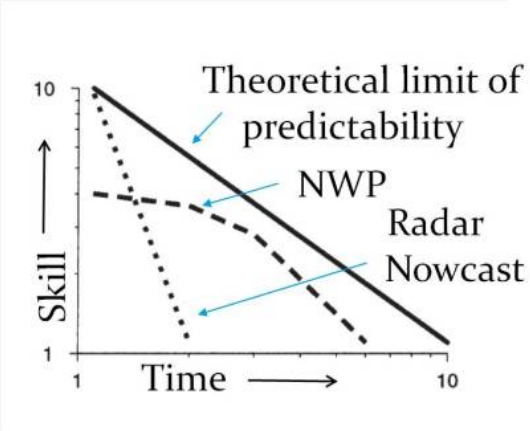
Radar-based vs NWP-based

Radar-based

- Basically Image Processing
  - Correlation-based
  - Optical flow
  - Convolutional LSTM
- Good for first few hours
- Skills deteriorates rapidly afterwards

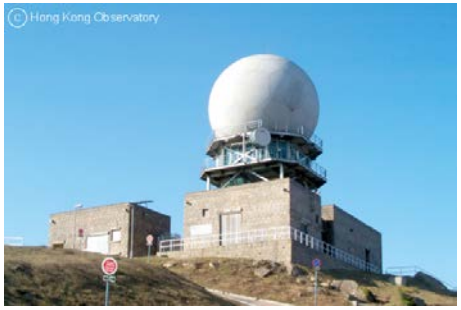
NWP-based

- Based on *Primitive Equations*
- Not so good for first few hours due to spin-up problem
- More skillful than Radar-based afterwards



Rain Gauge vs Radar vs Satellite

Rain Gauge

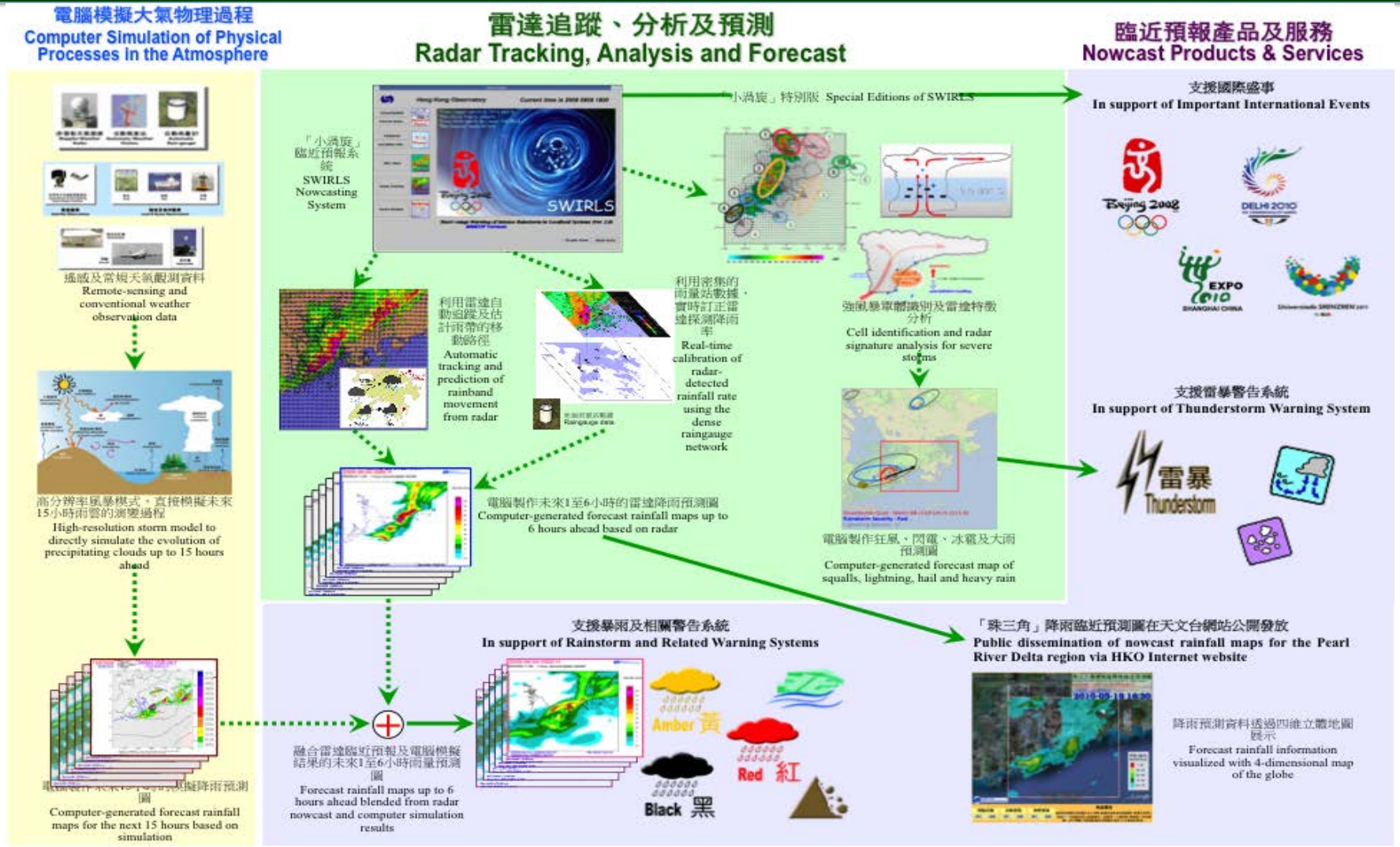


Radar

Satellite

Type	In-situ	Remote Sensing	Remote Sensing
Accuracy	Best	Moderate	Worst
Spatial Resolution	Discrete	Continuous, up to 200 m	Continuous, up to 500 m
Spatial Coverage	At point only	Regional, effective up to 256 km (radius)	Half the Globe (geostationery)
Cost	Cheap as single unit Expensive as network	Expensive to operate	Expensive to launch Cheap to use

SWIRLS – HKO Rainstorm Nowcasting System



SWIRLS –
Short-range Warning of Intense Rainstorm in Localized Systems

- ACTUAL :- Quantitative precipitation estimation (QPE)
  - radar-based, raingauge-based and blending with satellite cloud images
- TREND :- Retrieval of echo motion
  - tracking by maximum correlation (TREC)
  - tracking by optical flow
  - object-oriented tracking of storm motion
- FORECAST :- semi-Lagrangian advection to extrapolate radar reflectivity up to 6 / 9 hours
- OUTPUTS :- computation of gridded precipitation nowcast (QPF) and locations of storm objects on convective wind gust, lightning and hail, support to decision making
- UNCERTAINTY :- probabilistic QPF and blending with convection-permitting NWP model
- PRODUCTS :- nowcasting products for internal users and public

QPE – Rainfall Calibration Module

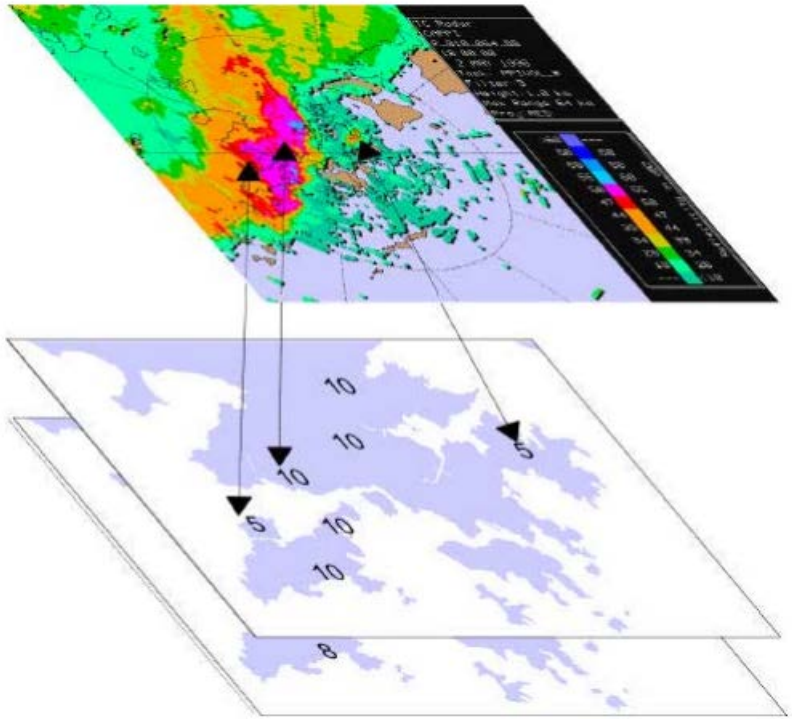
- Schematic diagram showing the calibration of radar reflectivity using real-time raingauge measurement.

- Z-R relation for converting reflectivity to rainfall rate

$$Z = aR^b$$

$$dBZ_i = b\, dBG_i + 10\log(a)$$

- Gridded rainfall analysis computed by Barnes successive correction or more advanced co-kriging algorithm



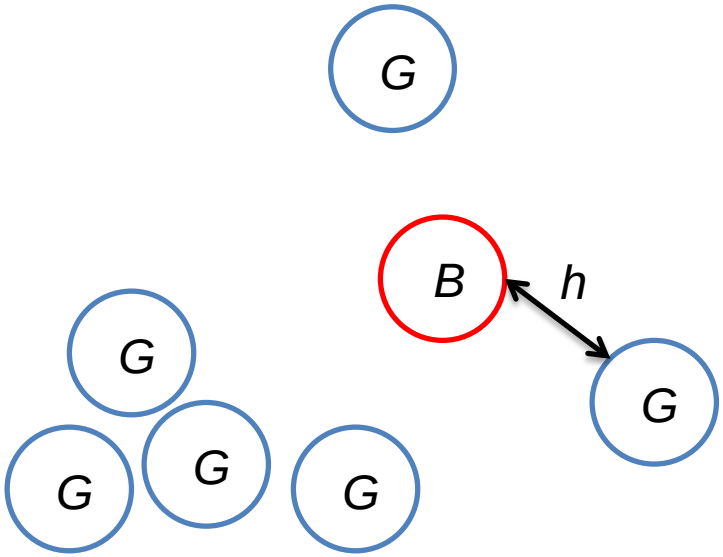
Barnes Analysis

- grid-point analysis by Barnes method
  - interpolation with Gaussian weighting according to distance between data & estimation point
  - consider correction using residuals and grouping of rainguages

$$B(x_0) = \frac{\sum_{i=1}^{N_0} w_i G_i}{\sum_{i=1}^{N_0} w_i}$$

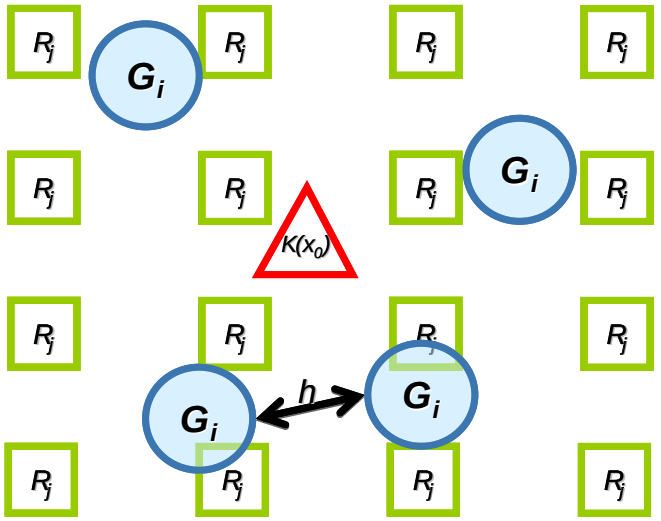
$$w_i = \exp\left(\frac{-h_i^2}{L^2}\right)$$

B : barnes estimation (mm)
L : radius of influence
N_0 : number of gauge report
G_i : i-th gauge report (mm)
w_i : weight of i-th gauge
h_i : distance between gauge and estimation point



Co-kriging Analysis

Symbol	Meaning	Unit
$K(x_0)$	rainfall estimated by Kriging/Co-Kriging at location x_0	mm
$\sigma^2(x_0)$	the corresponding estimation variance at location x_0	mm^2
N_0	number of rain gauges in the neighbourhood of x_0	-
M_0	number of radar grid points in the neighbourhood of x_0	-
G_i	data reported at the i-th rain gauge located at x_i, $i = 1,\cdots,N_0$	mm
R_j	data observed at the j-th radar grid point located at x_j, $j = 1,\cdots,M_0$	mm
$\lambda_i(x_0)$	weight of the i-th rain gauge data w.r.t. x_0	-
$\lambda_j(x_0)$	weight of the j-th radar data w.r.t. x_0	-
$\Gamma_{GG}(x_a,x_b)$	semivariogram of rain gauge data between any two locations x_a and x_b	mm^2
$\Gamma_{RR}(x_a,x_b)$	semivariogram of radar data between any two locations x_a and x_b	mm^2
$\Gamma_{GR}(x_a,x_b)$	cross-semivariogram of rain gauge data at x_a and radar data at x_b	mm^2
$\mu_{G,R}(x_0)$	are the two Lagrange multipliers accounting for the two unbiasedness constraints on the gauge or radar weights w.r.t. location x_0	mm^2



co-Kriging estimate: $K(x_0) = \sum_{i=1}^{N_0} \lambda_i(x_0) G_i + \sum_{j=1}^{M_0} \lambda_j(x_0) R_j$

seek to minimize: $\sigma^2 = E\left\{\left[K(x_0) - G(x_0)\right]^2\right\}$

subject to constraints: $\sum_{i=1}^{N_0} \lambda_i(x_0) = 1$ & $\sum_{j=1}^{M_0} \lambda_j(x_0) = 0$

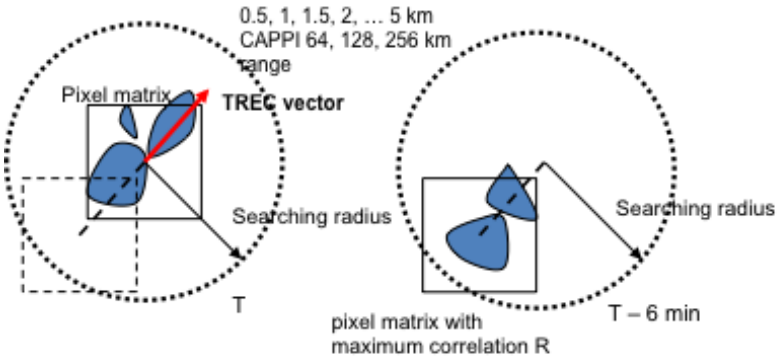
Solution:

$$\sum_{i=1}^{N_0} \lambda_i(x_0)\gamma_{GG}(x_n,x_i) + \sum_{j=1}^{M_0} \lambda_j(x_0)\gamma_{GR}(x_n,x_j) + \mu_G(x_0) = \gamma_{GG}(x_n,x_0), \quad \text{for } n = 1,\cdots,N_0$$

$$\sum_{i=1}^{N_0} \lambda_i(x_0)\gamma_{RG}(x_m,x_i) + \sum_{j=1}^{M_0} \lambda_j(x_0)\gamma_{RR}(x_m,x_j) + \mu_R(x_0) = \gamma_{RG}(x_m,x_0), \quad \text{for } m = 1,\cdots,M_0$$

Radar echo tracking in SWIRLS

Maximum Correlation (TREC)



where Z_1 and Z_2 are the reflectivity at T+0 and T+6min respectively

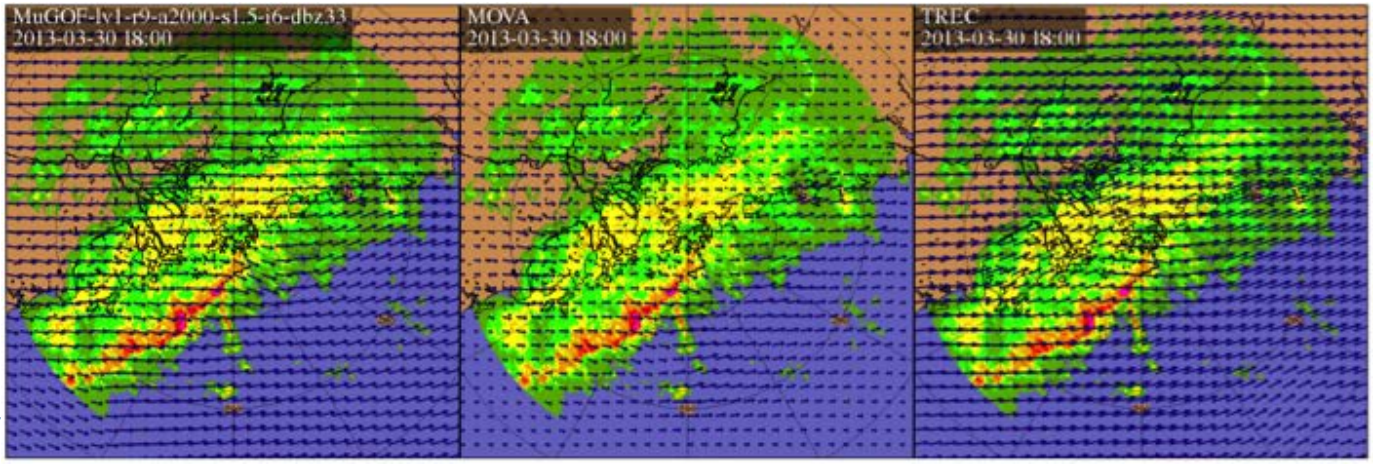
$$R = \frac{\sum_k Z_1(k) \times Z_2(k) - \frac{1}{N}\sum_k Z_1(k)\sum_k Z_2(k)}{\left[\left(\sum_k Z_1^2(k) - N\overline{Z_1}^2\right)\times\left(\sum_k Z_2^2(k) - N\overline{Z_2}^2\right)\right]^{1/2}}$$

Optical Flow

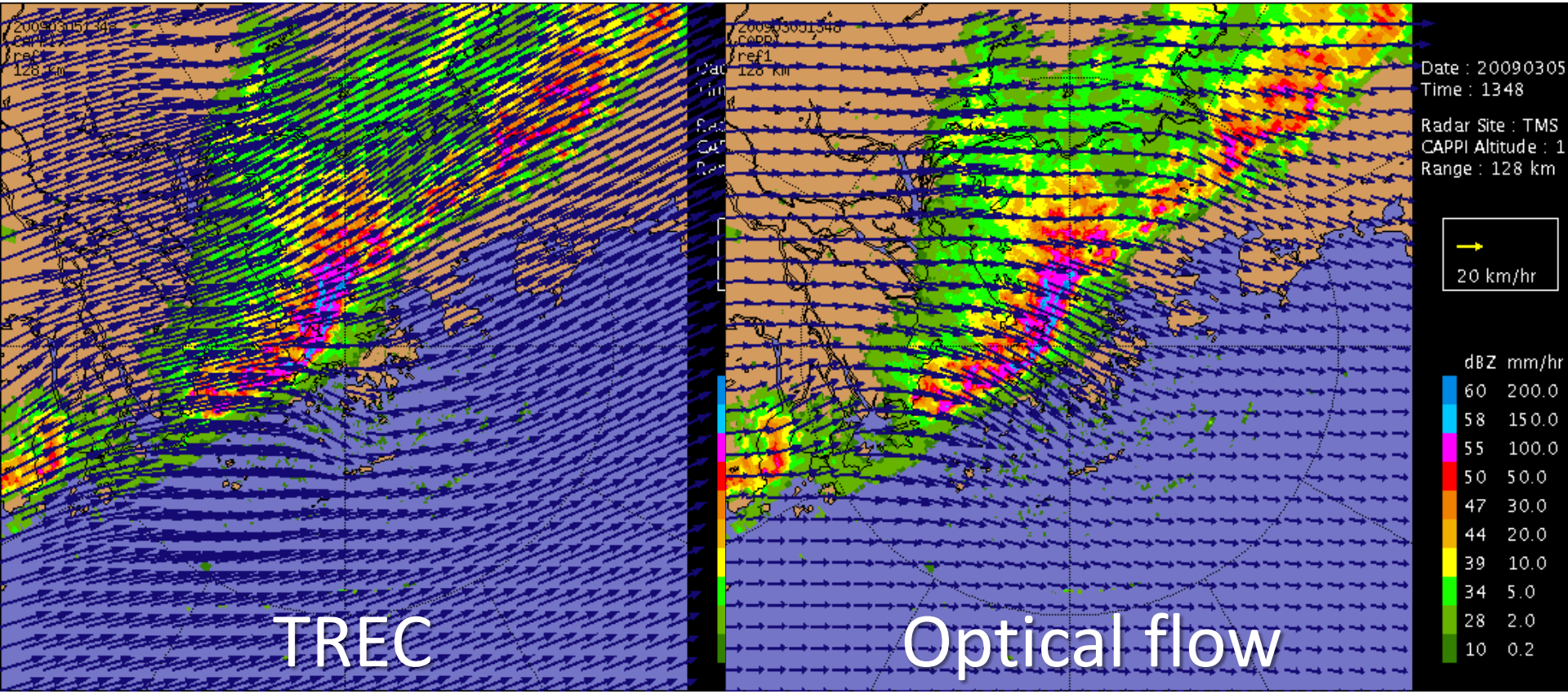
Given I(x,y,t) the image brightness at point (x,y) at time t and the brightness is constant when pattern moves, the echo motion components u(x,y) and v(x,y) can be retrieved via minimization of the cost function:

$$J = \iint \left[\frac{\partial I}{\partial t} + u\frac{\partial I}{\partial x} + v\frac{\partial I}{\partial y}\right]^2 dx\,dy$$

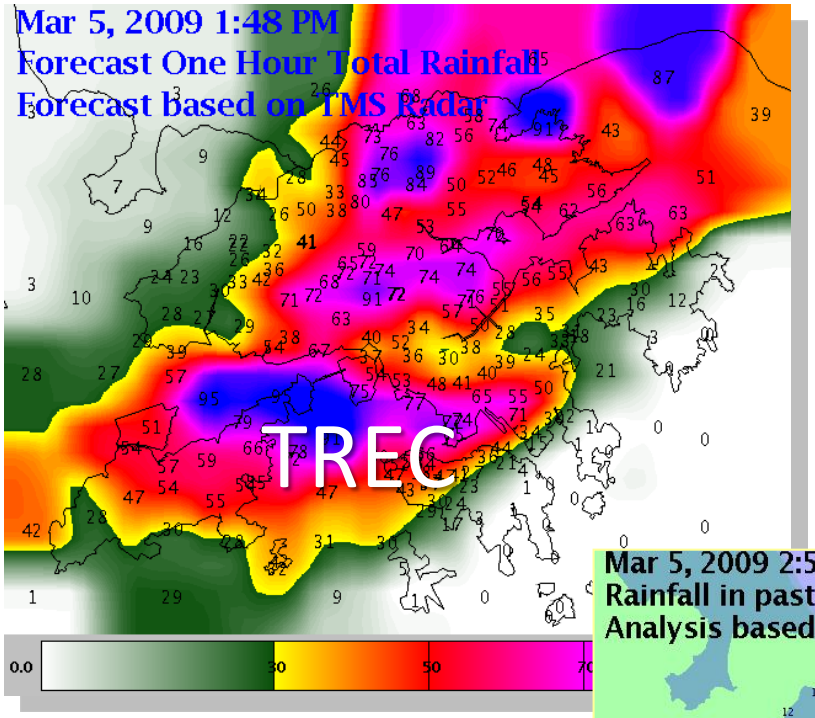
$$\nabla J = 0 \Rightarrow (u, v)$$

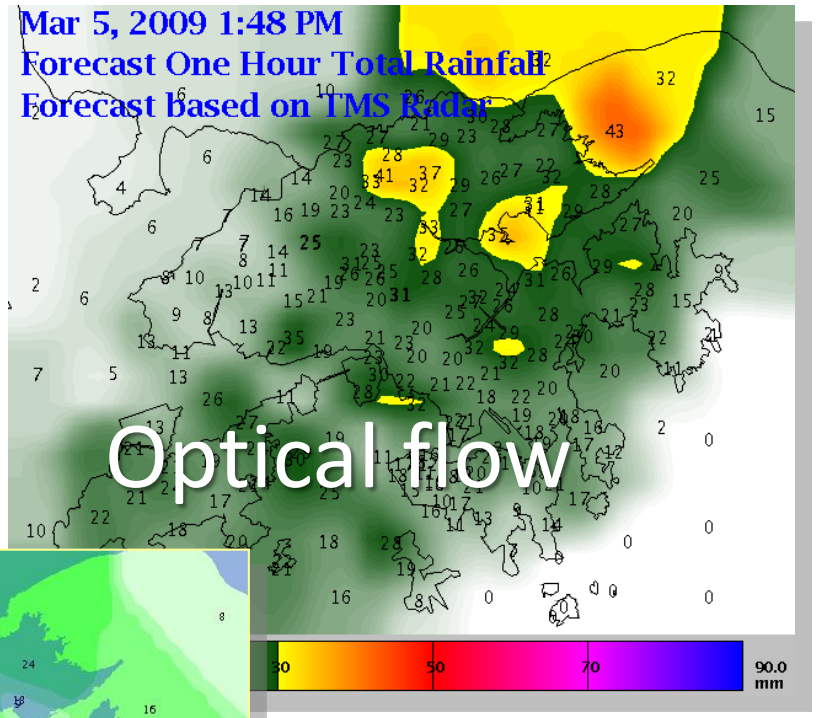


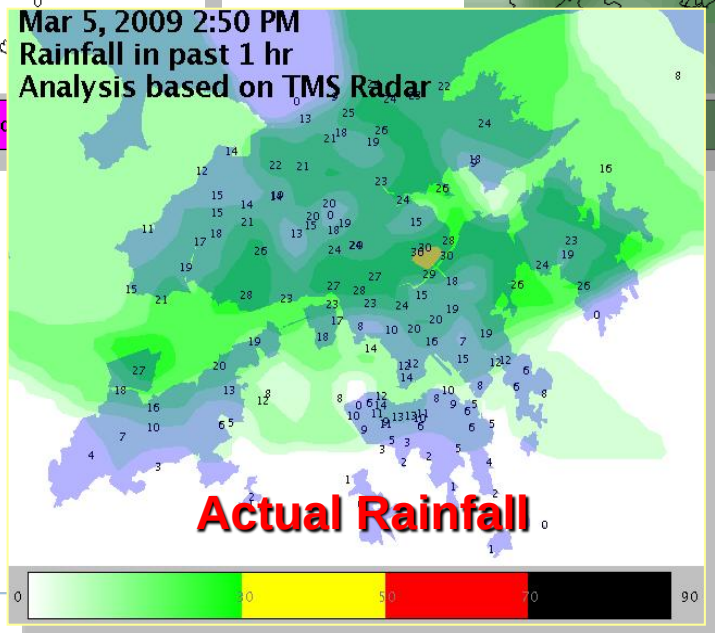
Comparison of echo tracking



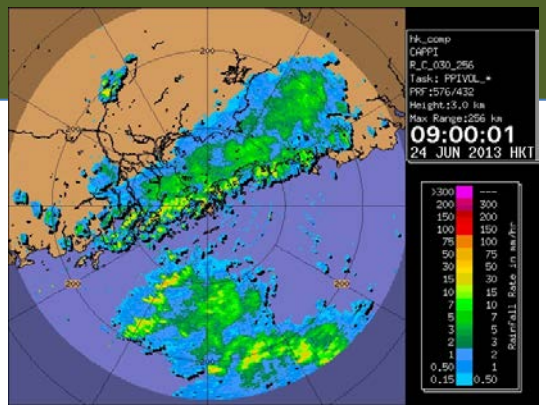
1-hr Quantitative Precipitation Forecast (QPF)

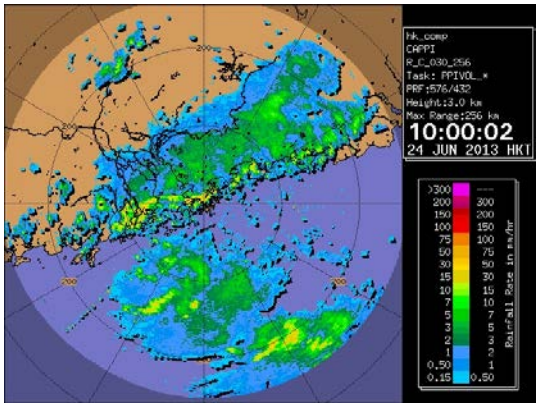


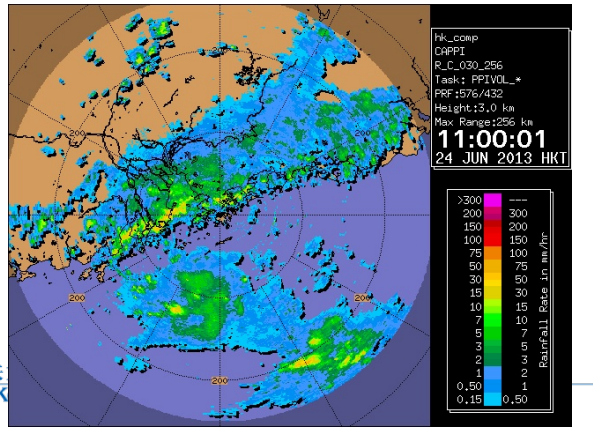


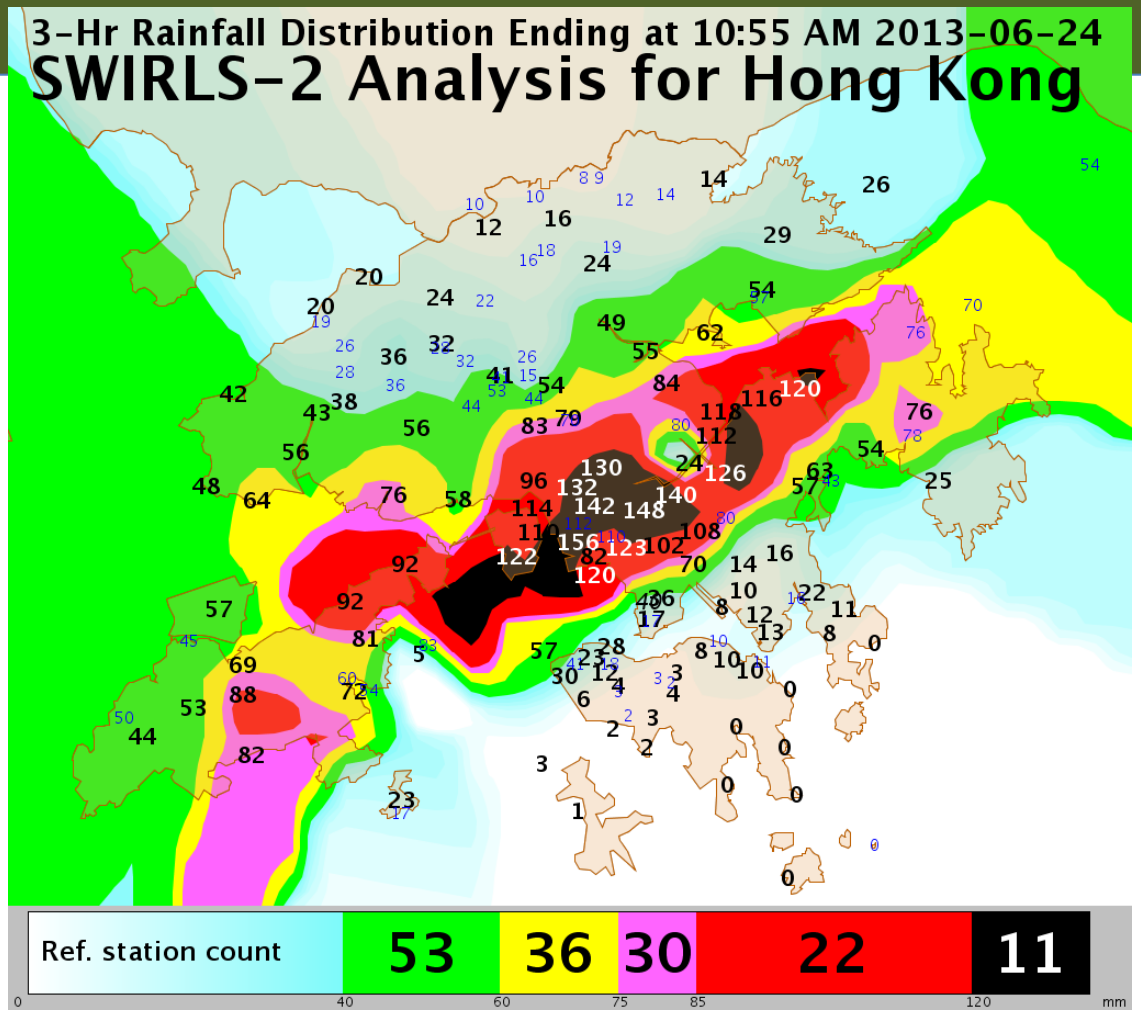


Rainfall nowcast from SWIRLS





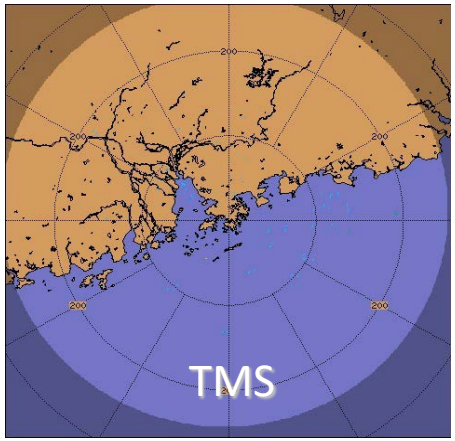




Multi-Sensor QPE/QPF

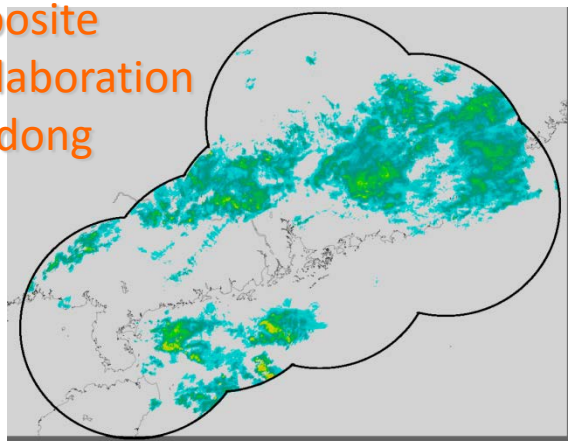
512 km

512 km



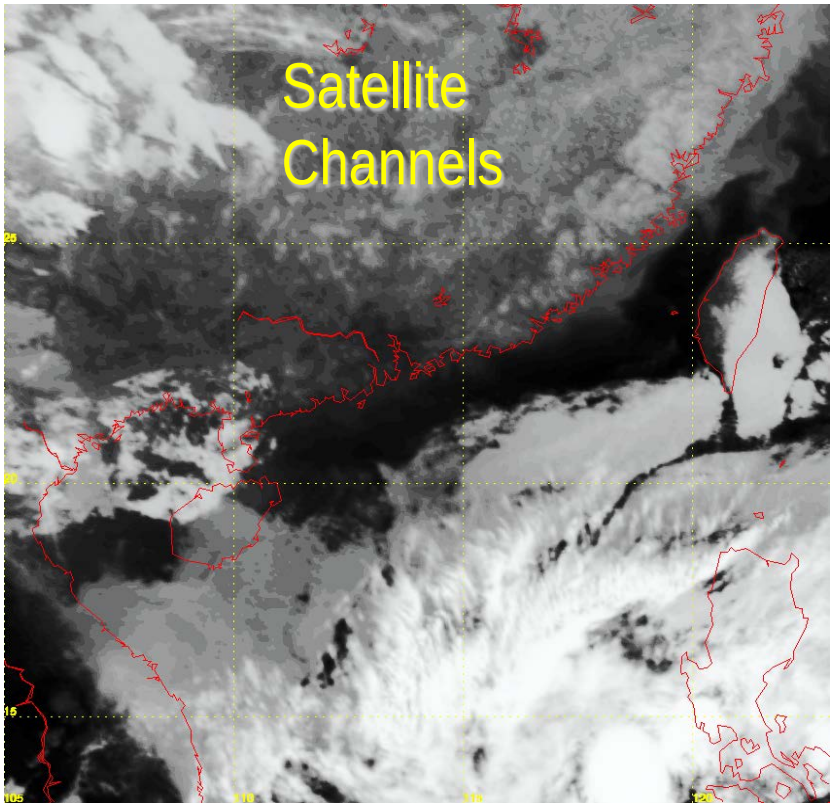
Radar composite through collaboration with Guangdong

904 km



1158 km

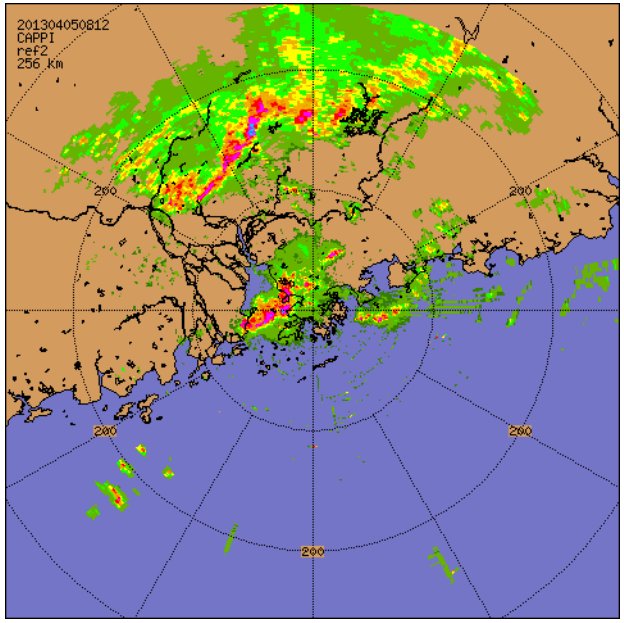
1728 km



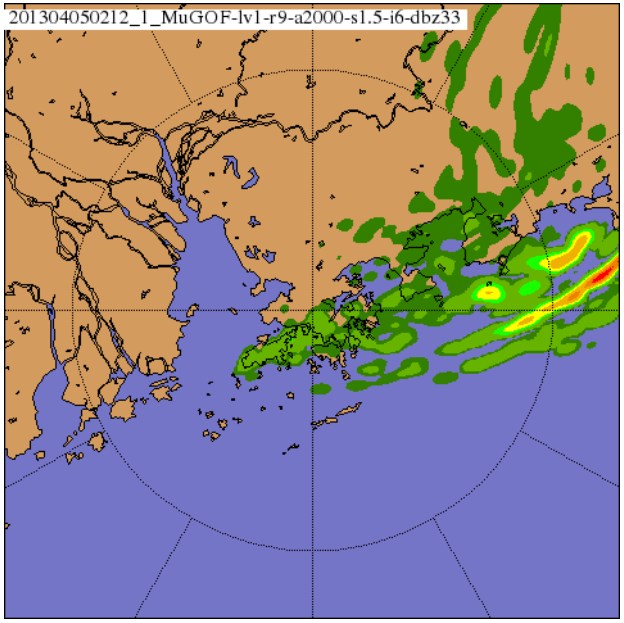
1804 km

9-hour Nowcast of Radar Reflectivity

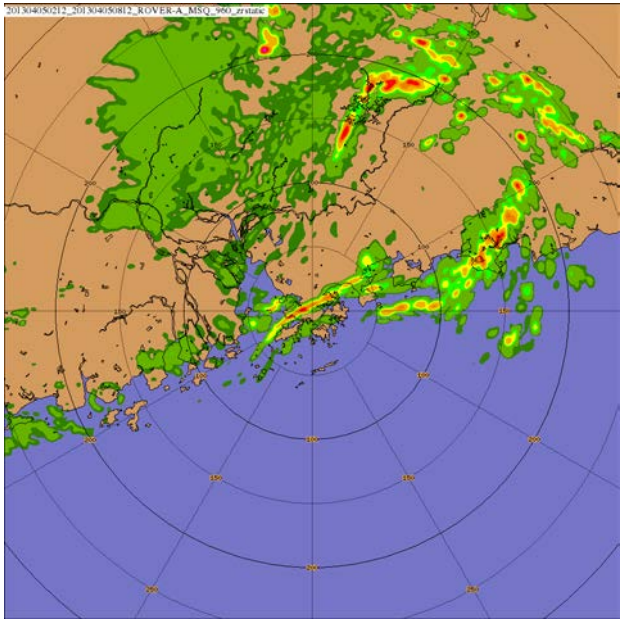
Base Time : 2013-04-05 02:12 HKT (6 hour forecast)



Actual



Extrapolate with only Hong Kong Radars



Extrapolate with Multi-Sensors

Decision Support - SWIRLS Integrated Panel

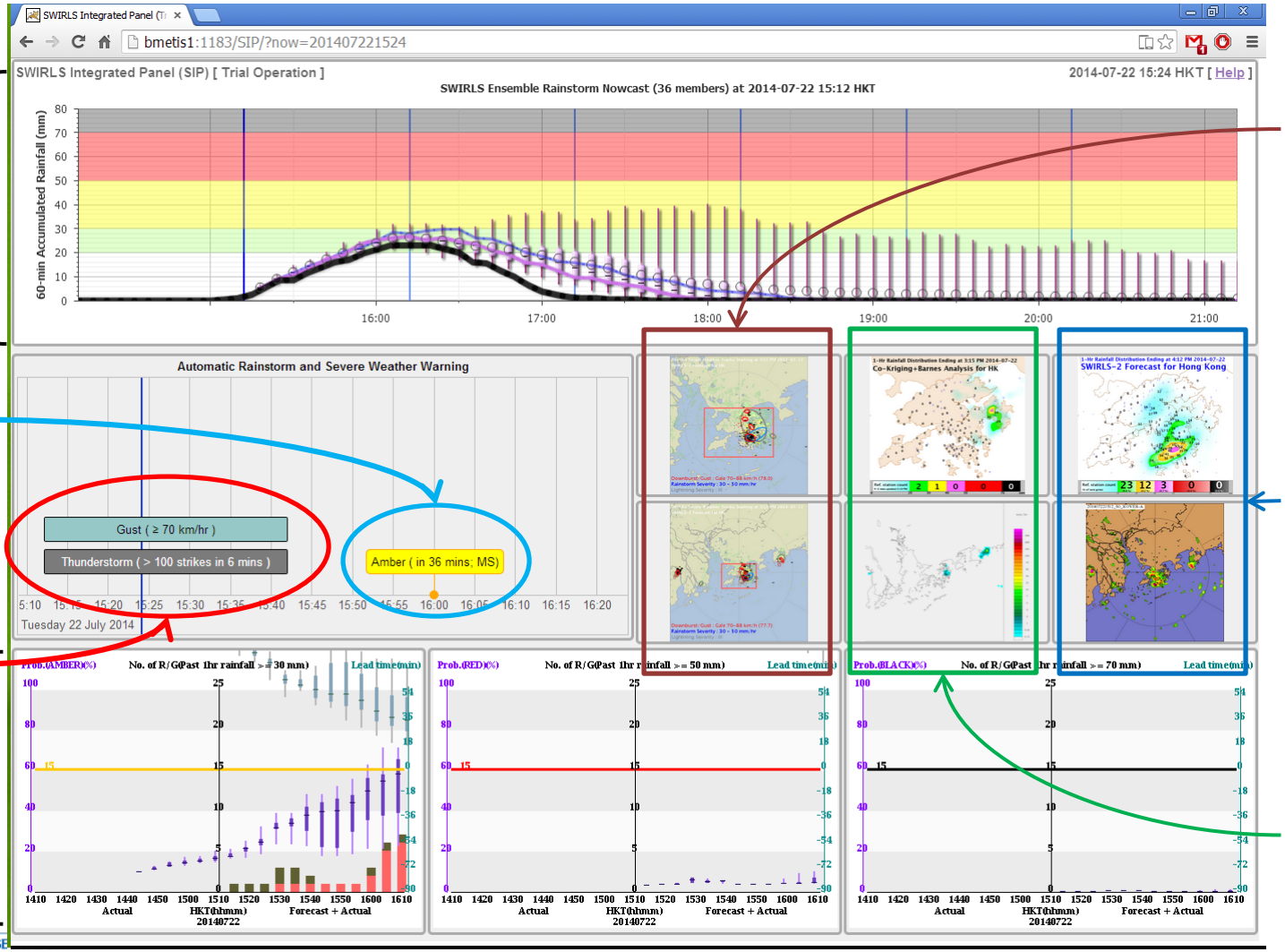
Sample Time : 2014-07-22 15:24

SWIRLS Ensemble Rainstorm Nowcast (SERN)

Amber expected in 36 minutes with criteria M and S met

Thunder-storm with high gusts expected during this period

SWIRLS Rainstorm Viewer



SWIRLS Severe Weather Viewer

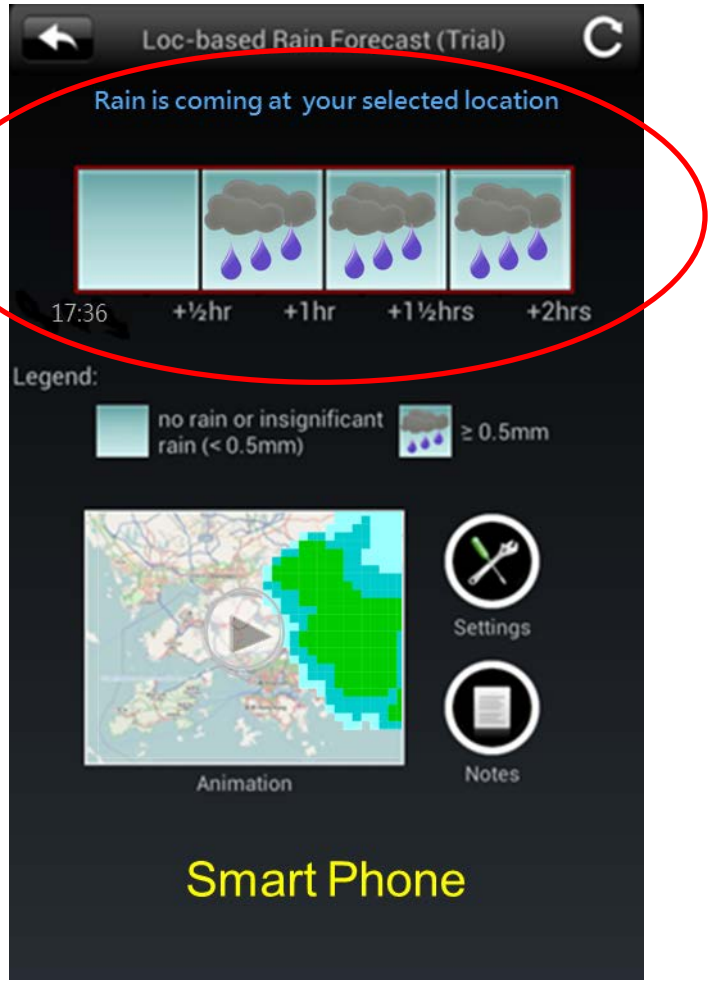
Forecast Rainfall (QPF)

Actual Rainfall (QPE)

香港天文台 HONG KONG OBSE

Location-based Nowcasting Service

- Available on “MyObservatory” mobile app
- rainfall nowcast for the next 2 hours at your location
  - data from SWIRLS QPF
- personalized automatic alerting service based on user location and expected rainfall



Location-specific Nowcasting Service

- Personalized & customizable:
  - update frequency
  - notification intervals
  - range of detection
  - forecast location
    - as set on a map

Integration with GIS

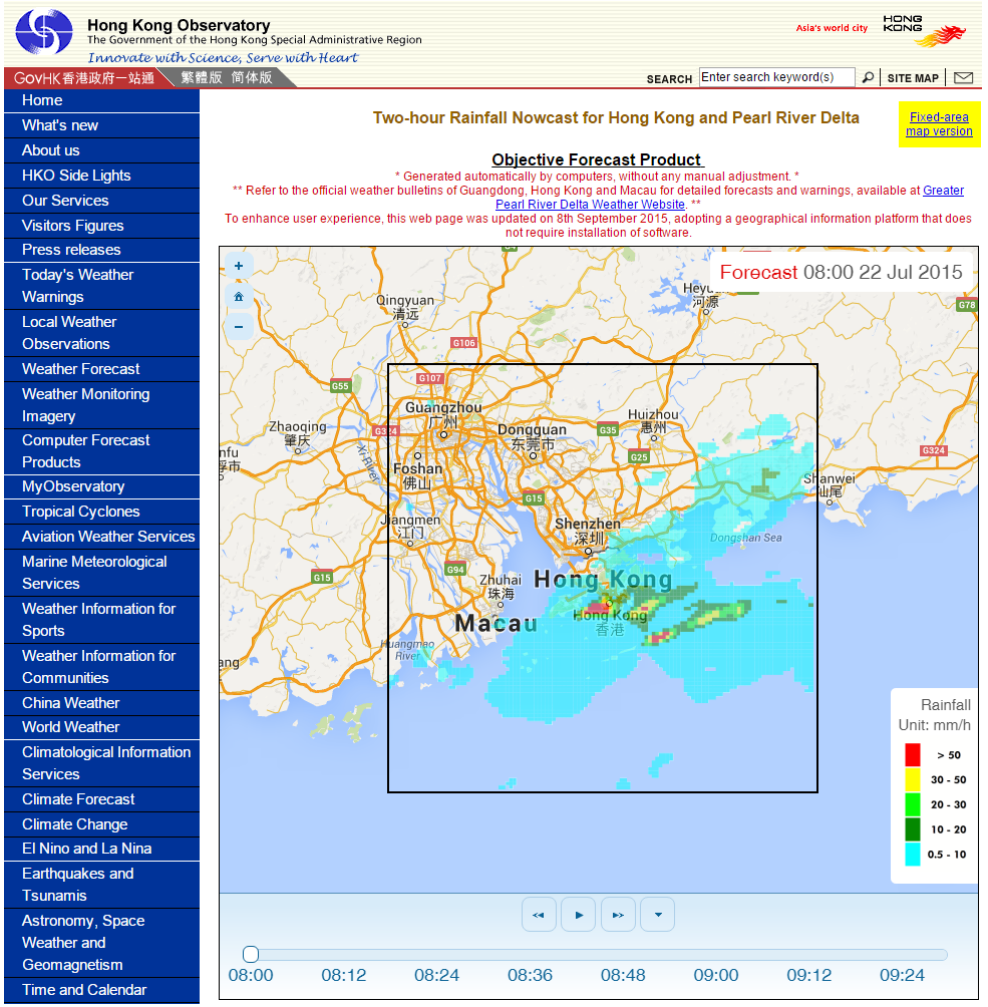
- Internet website：

  http://www.weather.gov.hk/nowcast/prd/api/

- forecast rainfall maps over the Pearl River Delta region in the next 2 hours

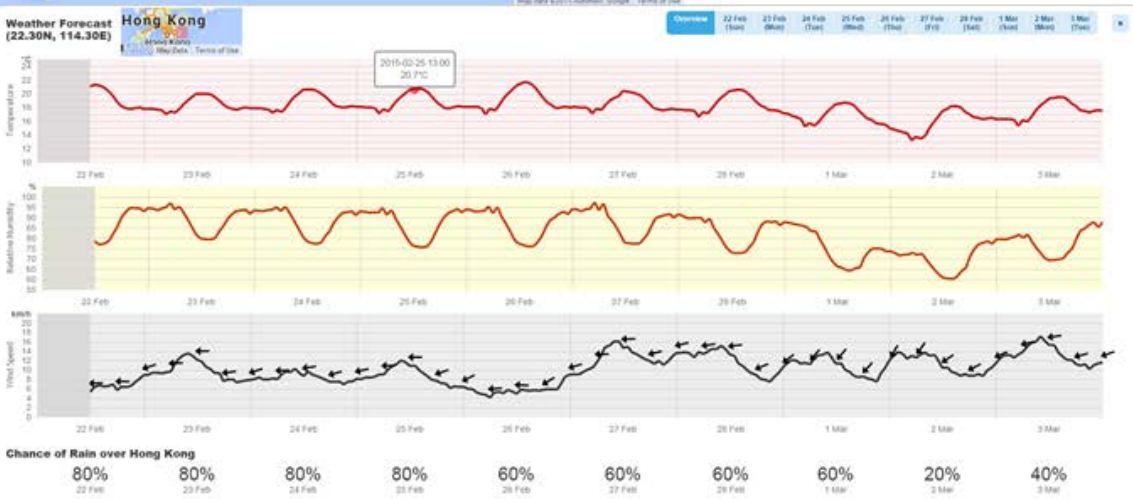
- updated every 12 min

- downloadable as KML files



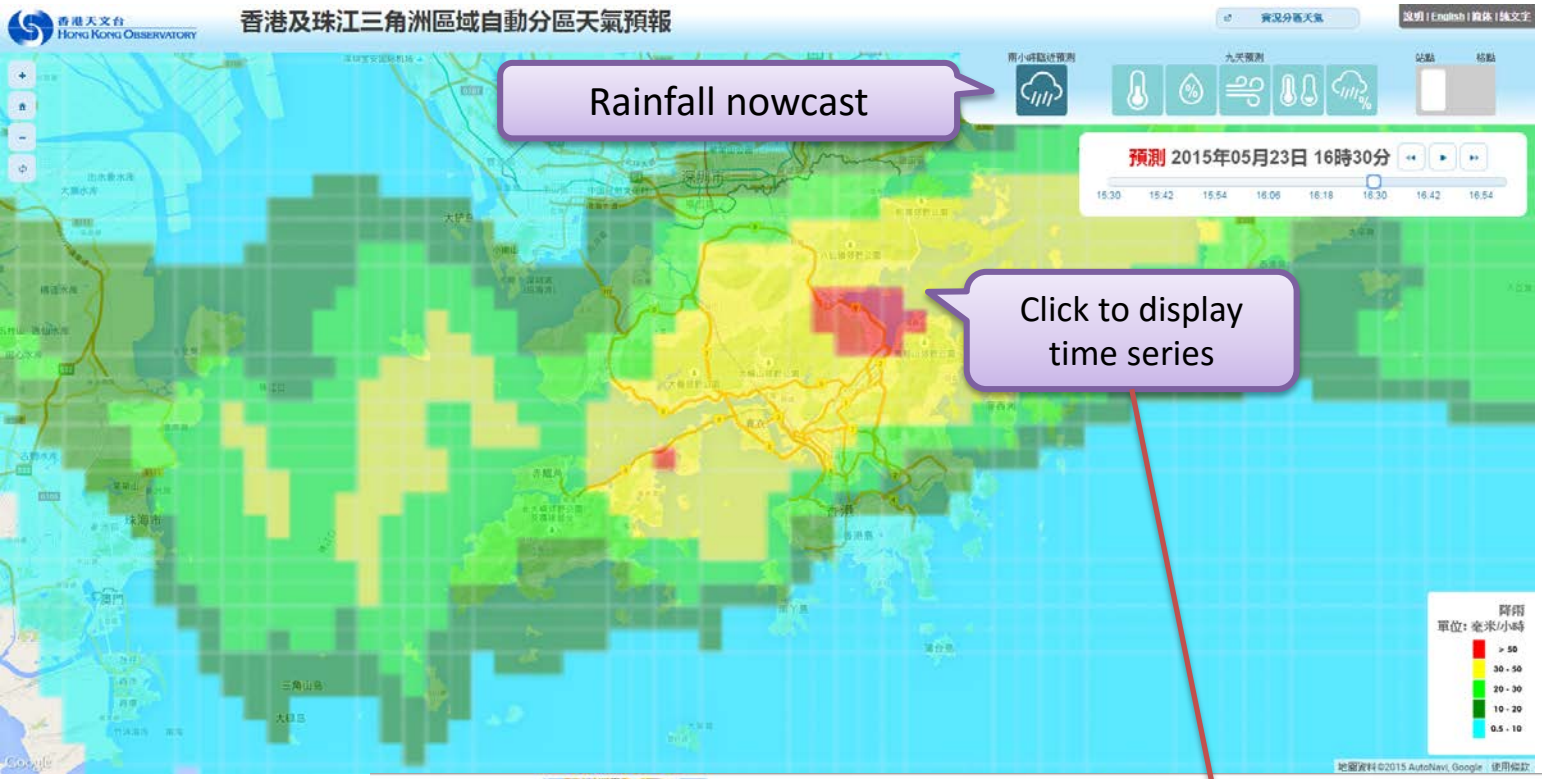
Rainfall Nowcast on Automatic Regional Weather Forecast website

Click on station or grid to show weather forecasts



http://maps.weather.gov.hk/ocf/

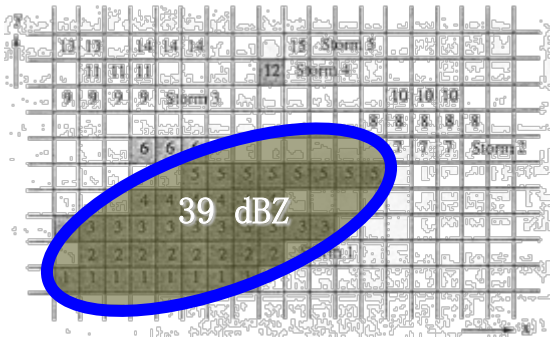
Rainfall Nowcast

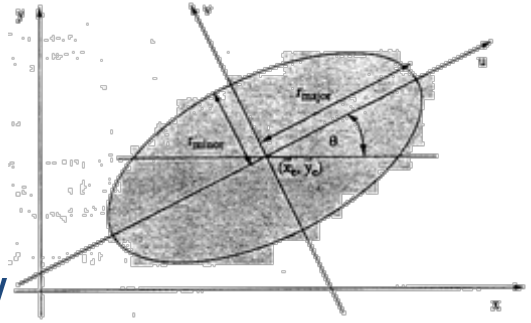


Provide image and animation sequence of rainfall forecast map over HK and Pearl River Delta for the next 2 hours

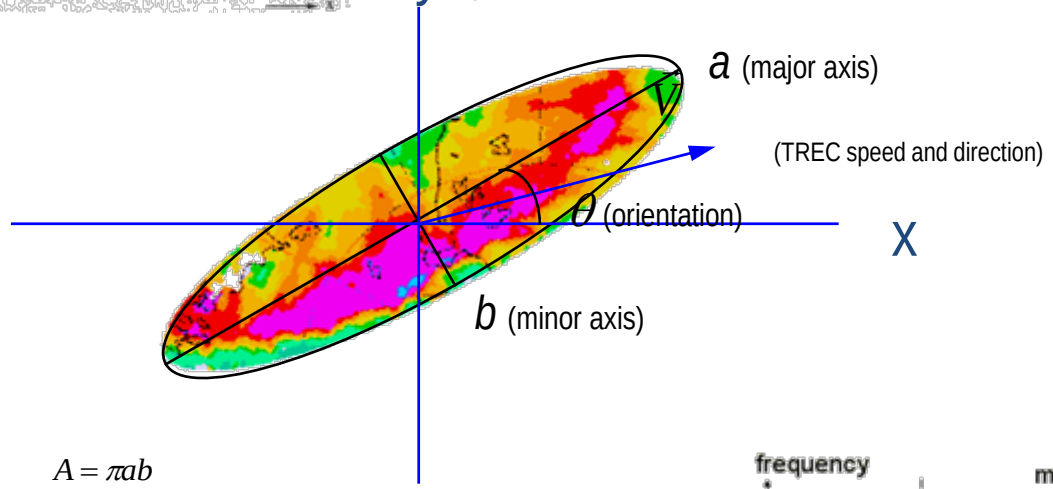
網址：http://maps.weather.gov.hk/ocf/index_uc.html

Cell Tracking in SWIRLS



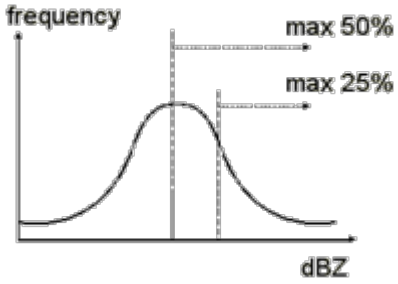


Group echo identification



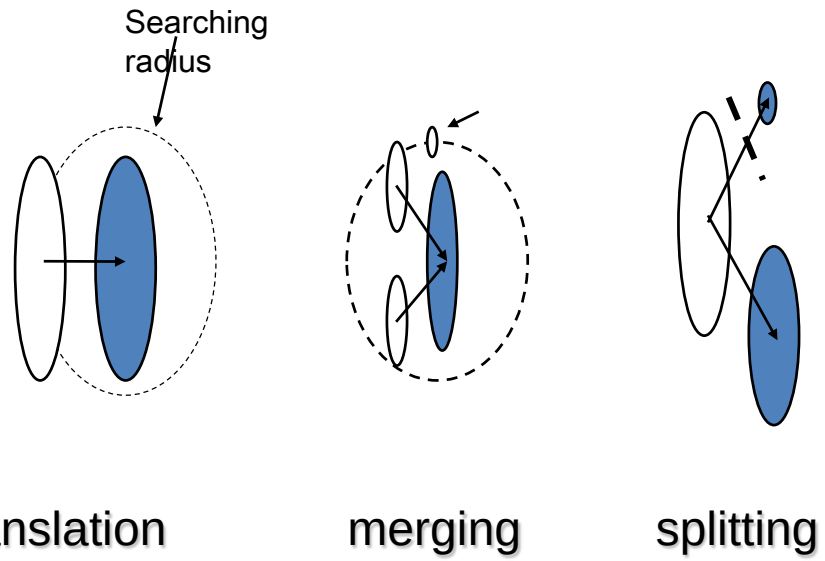
area	$A = \pi ab$
eccentricity	$\varepsilon = \sqrt{a^2 - b^2}\,/\,a$
perimeter	$P = 4aE(\pi/2, \varepsilon)$
orientation	$\theta = \tan^{-1}(b/a)$
total intensity	$I = \sum_{ellipse} dbZ \times \Delta A$

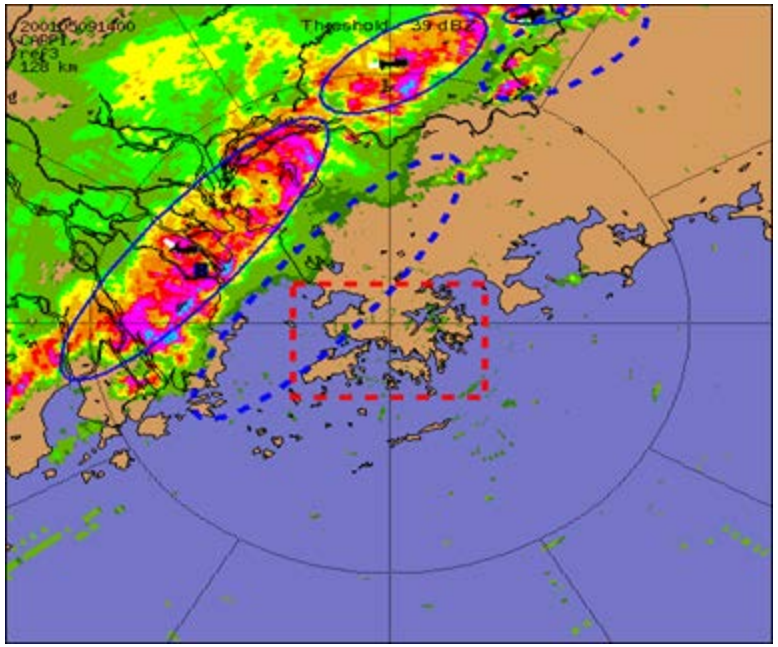
max dBZ <--> max rainfall
ave dBZ <--> ave rainfall
ave (max50% rainfall)
ave (max25% rainfall)



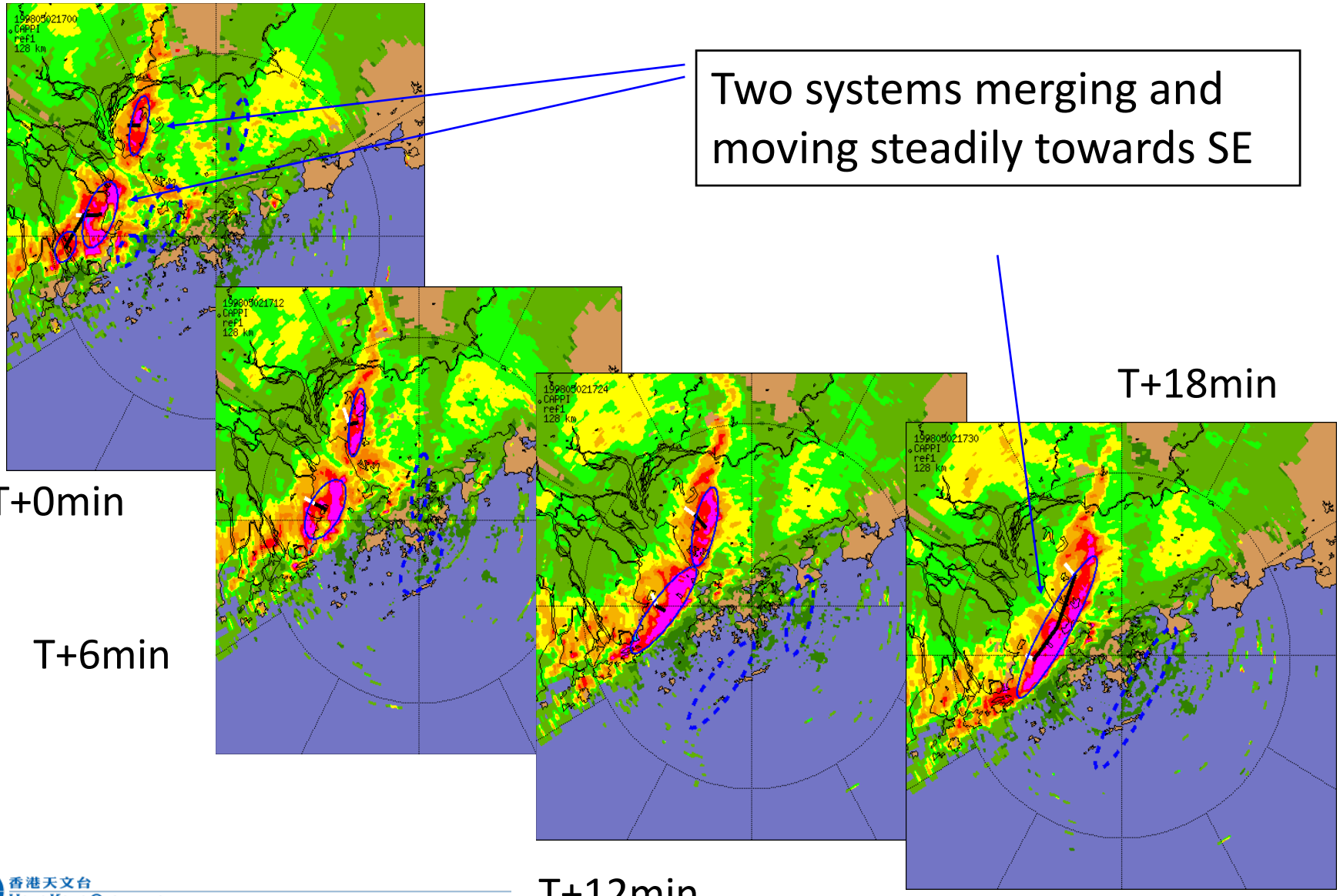
Tracking Capabilities

Based on moving speed, size, overlapping area





Application to squall-line



Lightning Conceptual Model

- +/–ve charges carried by ice and graupel respectively
- charges separated vertically by updraft
- Important distribution in the mixed layer from 0°C to -20°C:

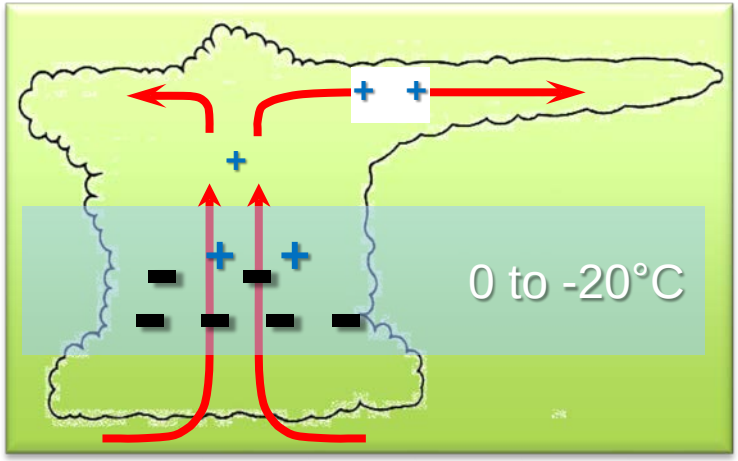


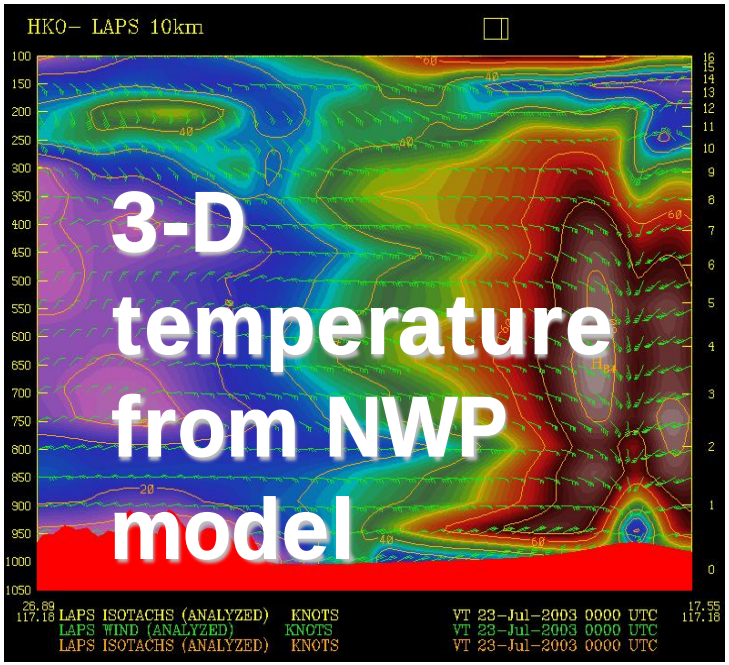
Table II – Summary of the conceptual model for lightning initiation.

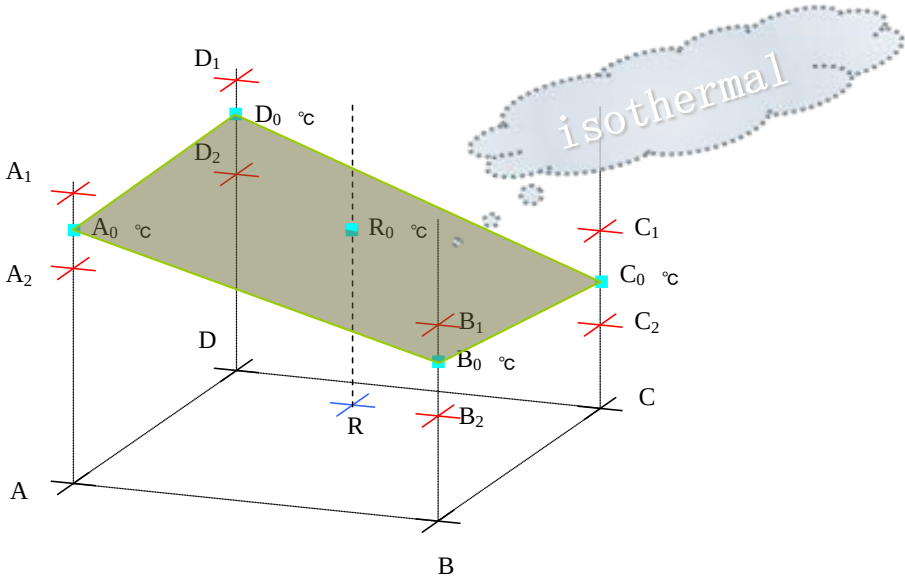
Isothermal Layers	(i) Shallow Cu			(ii) Towering Cu			(iii) mature Cb			(iv) decaying Cb		
	D	H	E	D	H	E	D	H	E	D	H	E
below –40°C							⇑	*	ρ	⇑	*	ρ
–20 to –40°C				⇑	*	ρ	⇑	*	ρ	⇑	*	
–10 to –20°C	⇑	*		⇑⇓	* △	σ	⇑⇓	* △	σ		*	
0 to –10°C	⇑	💧		⇑	* 💧		⇑⇓	* △ 💧	σ		*	
above 0°C	⇑	💧		⇑	💧		⇑⇓	△ 💧	σ	⇓	△	
near surface	→←			→←			← →			← →		

Note : Headings D, H and E stand for vertical dynamics, hydrometeors and electric charges respectively. Other symbols are explained in the main text of Section 2.

Isothermal Reflectivity

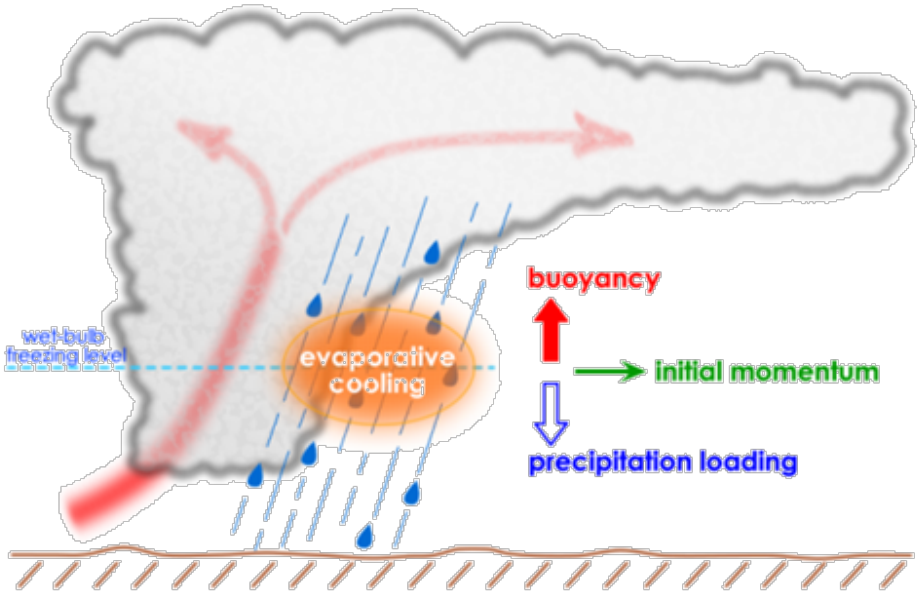
- 3D temp & height fields from hourly-updating model analysis
- interpolate to radar grid (cartesian)
- interpolate reflectivity to isothermal levels



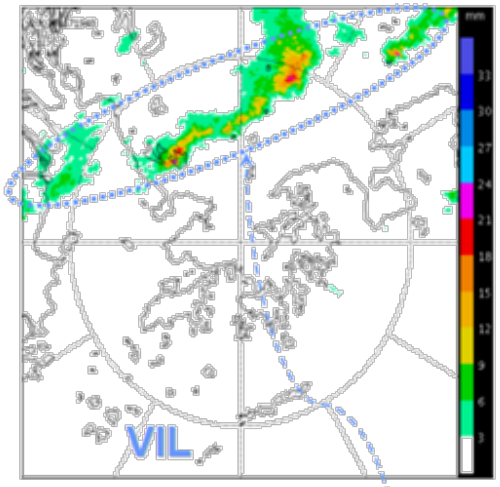


Downburst Conceptual Model

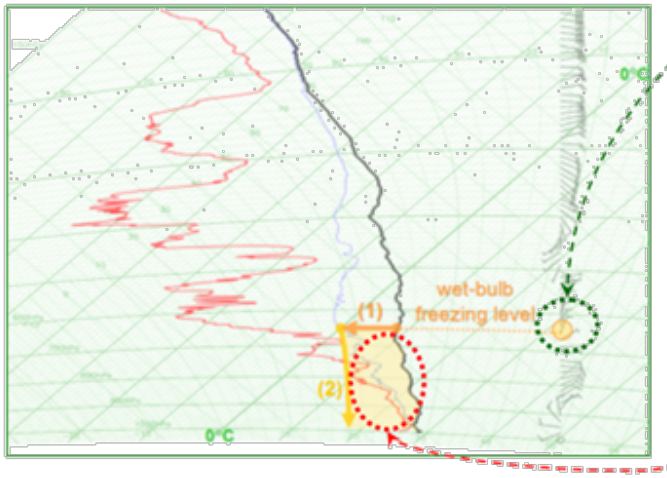
Conceptual model of convective downdraft due to raindrops evaporative cooling of air parcel in the rain shaft



Vertically integrated liquid (VIL) water data derived from radar reflectivity data.



Tephigram with a positive Downdraft Convective Available Potential Energy (DCAPE, the yellowish shaded area). Process (1) isobaric cooling by evaporation of raindrops; Process (2) pseudo-adiabatic descent if favoured.



$$v_s^2 = U_{\text{BUOY}} + v_H^2 + U_{\text{LOAD}}$$

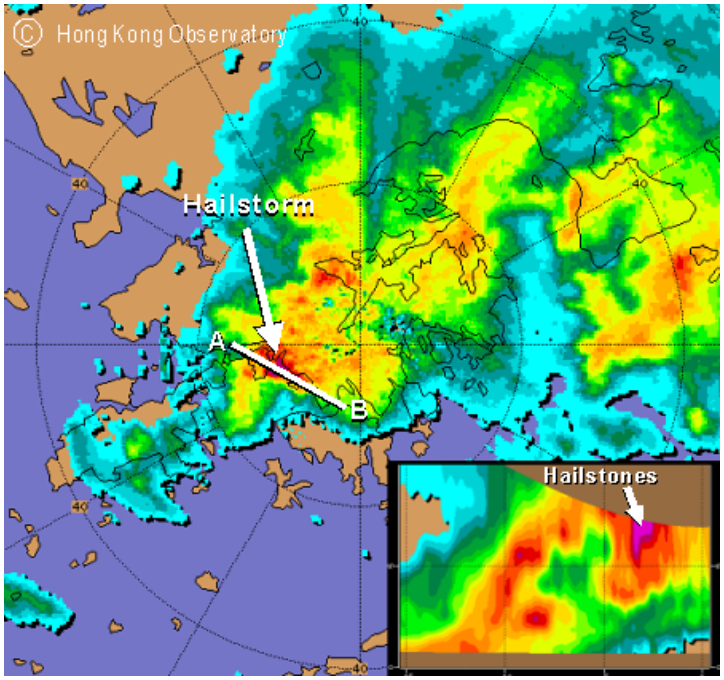
buoyancy | initial mom. | precip. loading

$$U_{\text{BUOY}} = \min\left\{\int_{P_F}^{P_S} R_d\left[T_v^{(\text{ambient})} - T_v^{(\text{parcel})}\right] d\ln p \ , \ v_{\max}\right\}$$

$$U_{\text{LOAD}} = -2\int_0^H L dz = 2g\int_0^H r_l dz = 20.3 \times \text{VIL}$$

Other Severe Weather Nowcast Algorithms

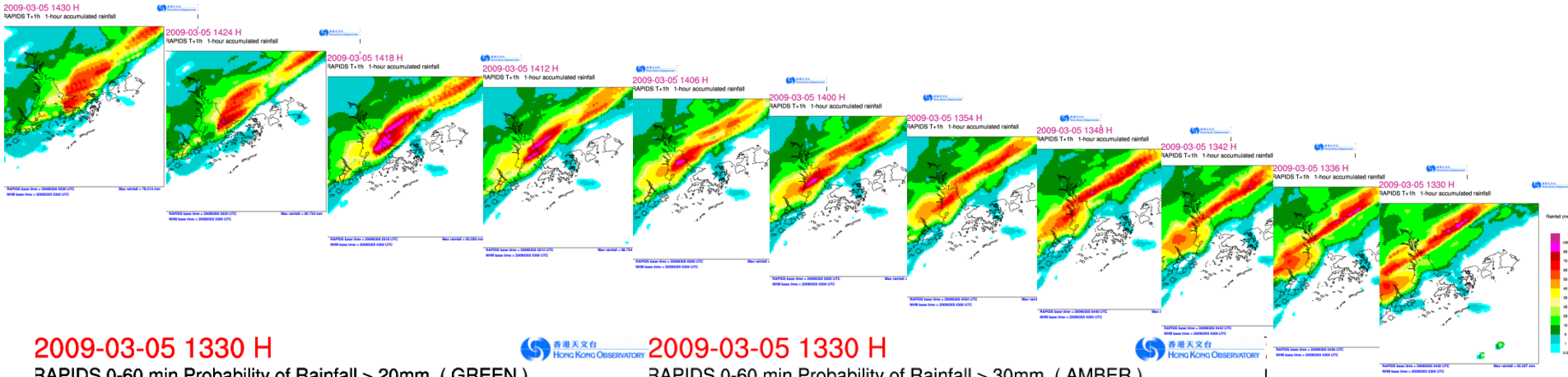
- Hail
  - 60-dBZ TOPS > 3 km
  - 0-2km VIL < 5 mm



- probability of precipitation
  - Time-lagged ensemble of blending QPF

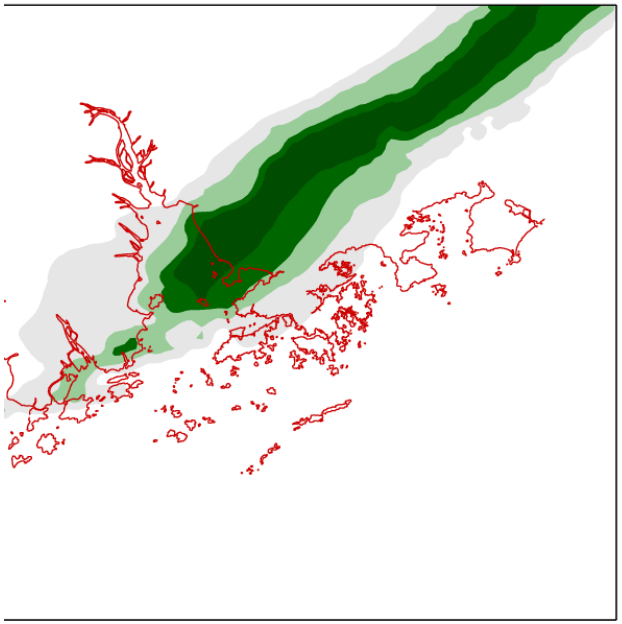
- probability of lightning threat
  - time lagged ensemble of extrapolated sub-zero reflectivity fields based on optical flow

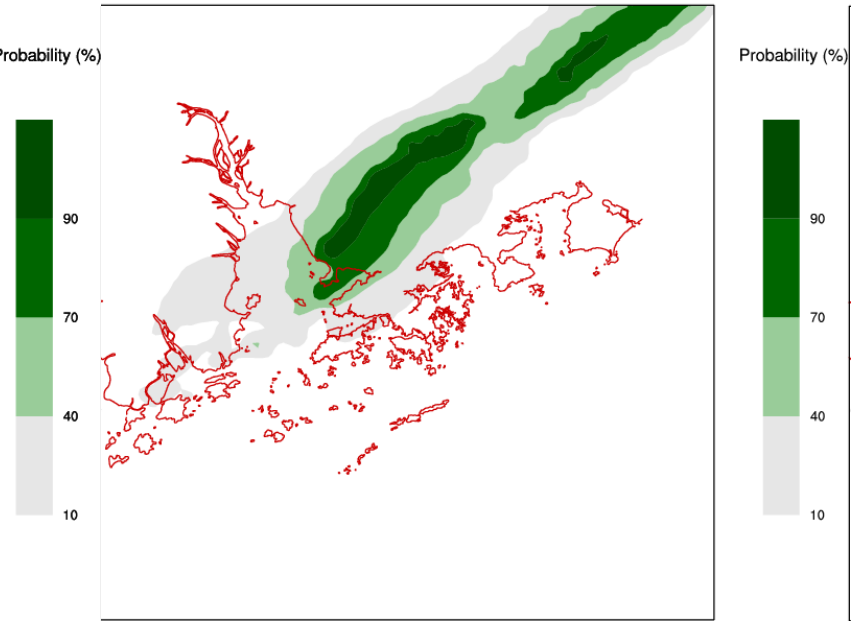
PoP by Time-lagged Ensemble



2009-03-05 1330 H

RAPIDS 0-60 min Probability of Rainfall > 20mm (GREEN)





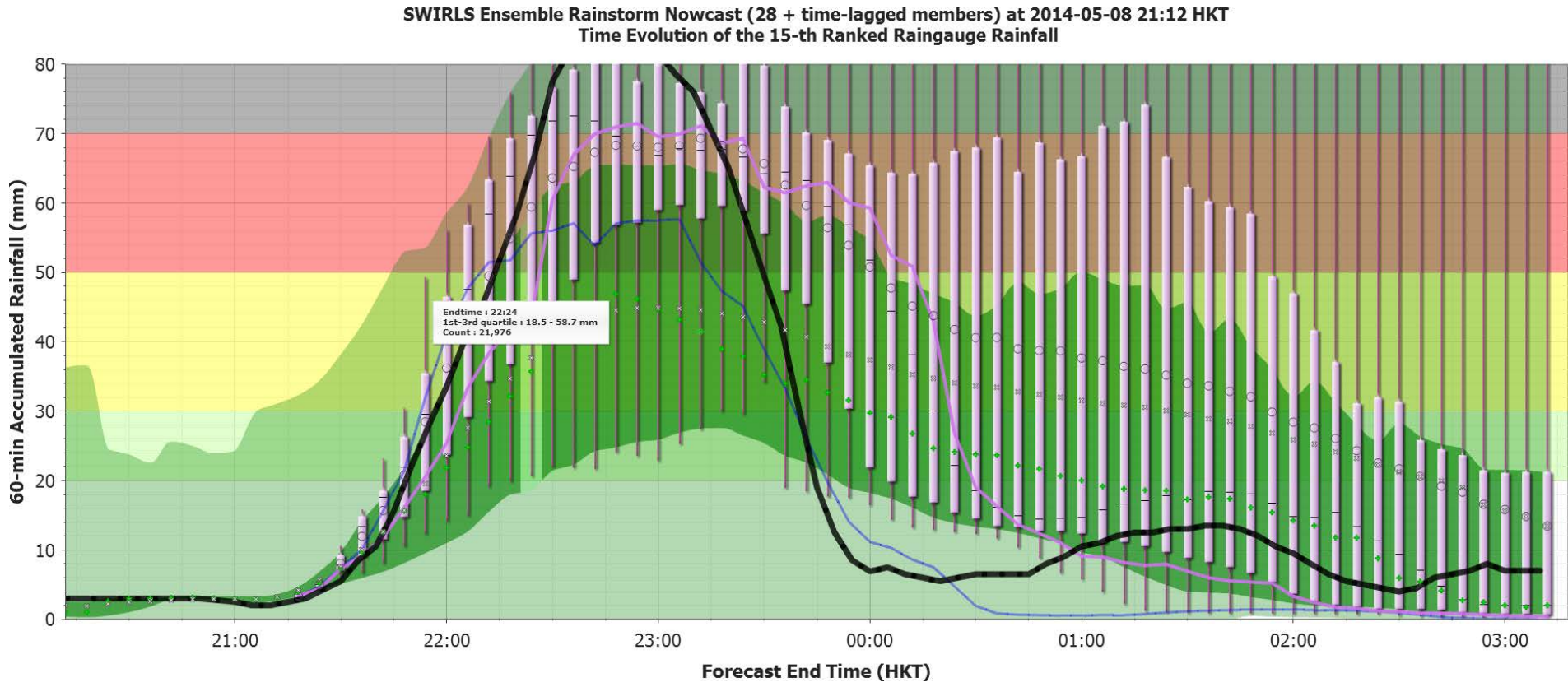
2009-03-05 1330 H

RAPIDS 0-60 min Probability of Rainfall > 30mm (AMBER)

Aggregate latest 10 RAPIDS QPF according to exponential decreasing weights

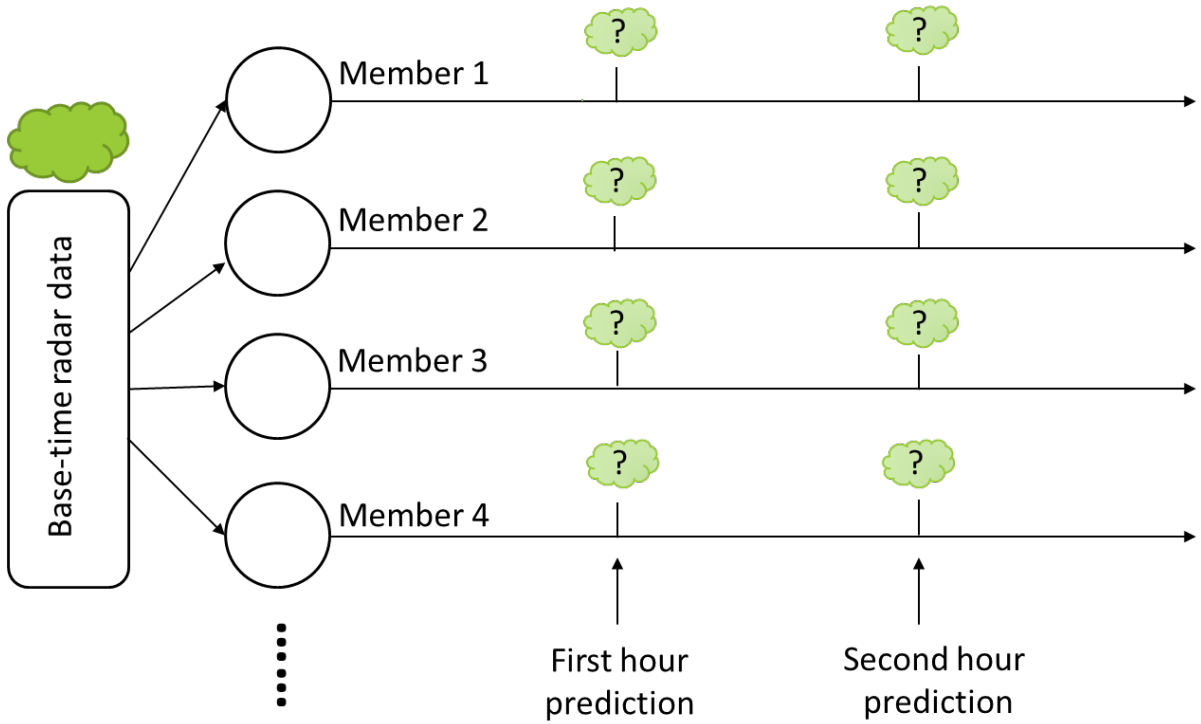
Probabilistic nowcast of precipitation
SWIRLS Ensemble Rainstorm Nowcast (SERN)

Spread of radar rainfall nowcast via selecting various parameters in echo motion retrieval



Design of SWIRLS Ensemble Rainfall Nowcast

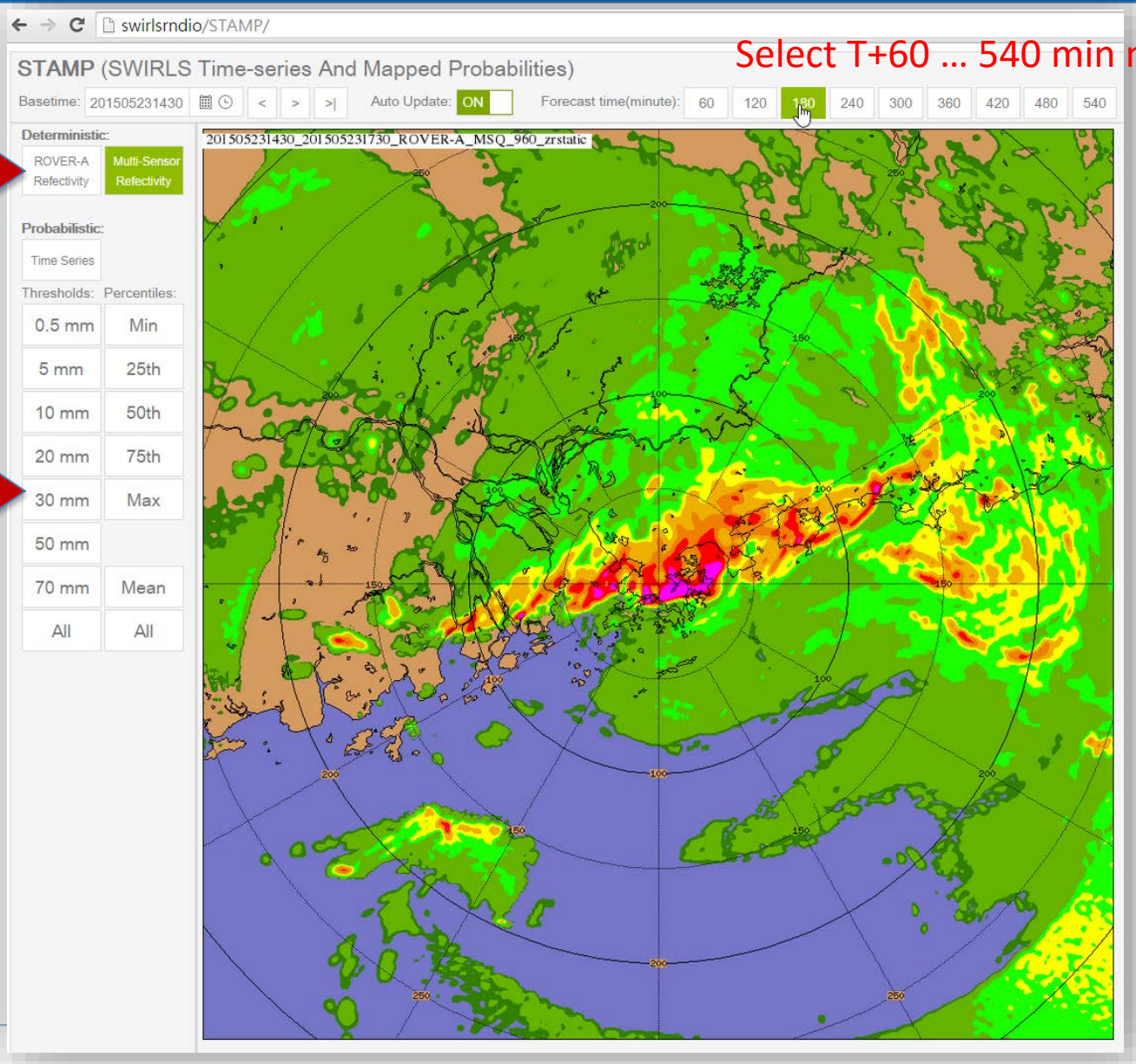
- By tuning parameters in optical flow computation, 36 sets of configurations have been experimented to generate rainfall nowcast ensemble of 36 members.



STAMP - Integrated Display of SWIRLS Deterministic and Probabilistic

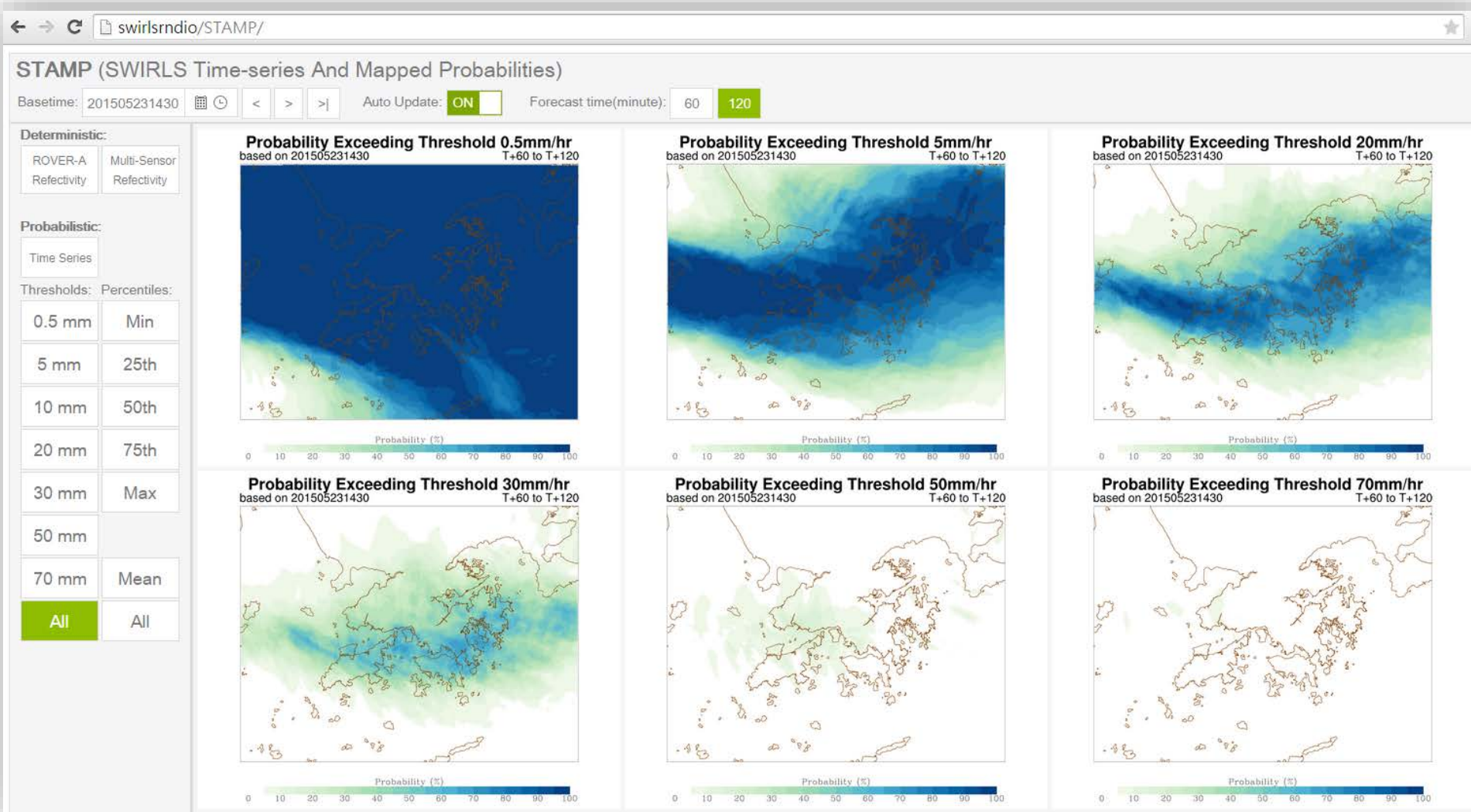
Radar-based / Multi-Sensor Deterministic

Probabilistic Products

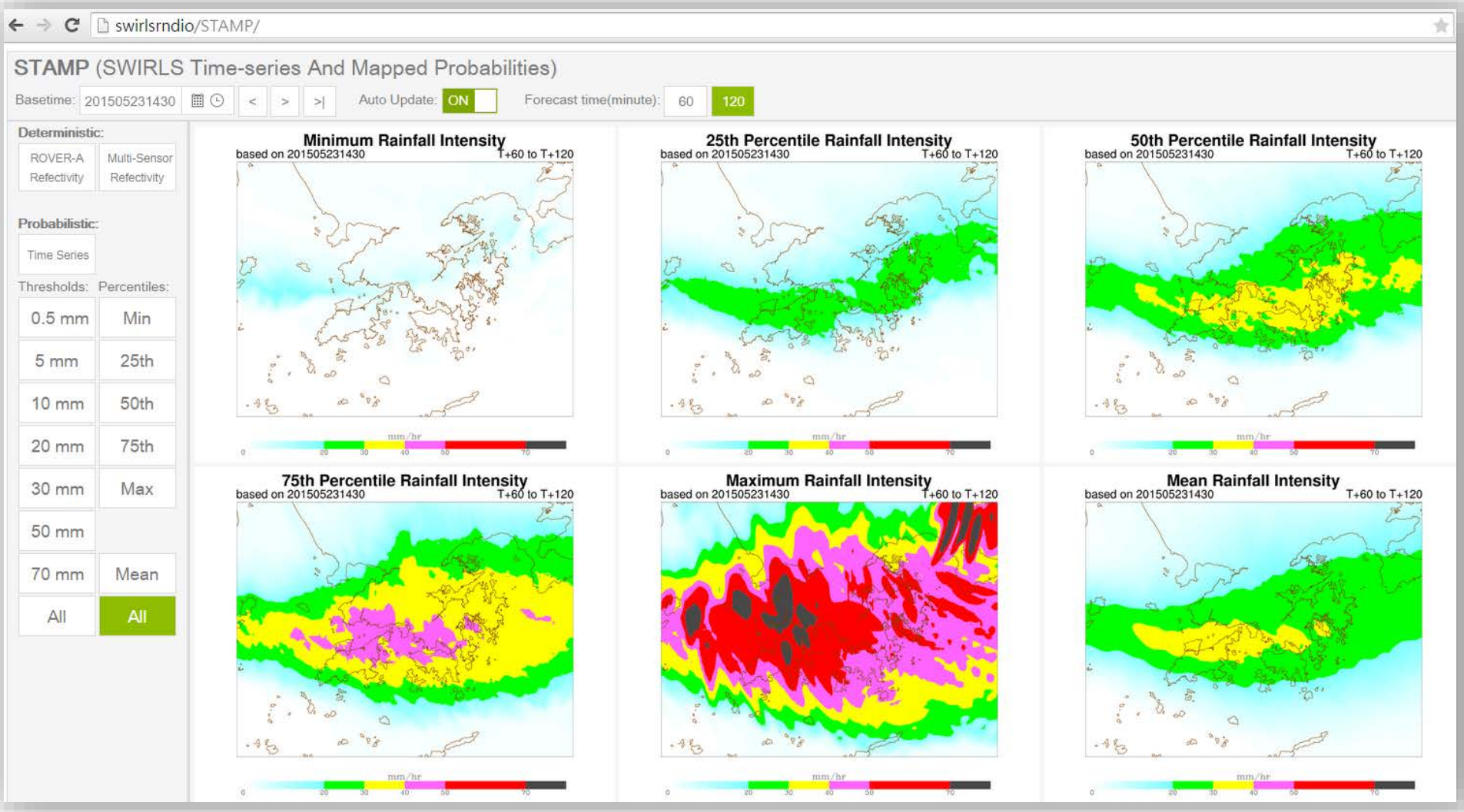


Select T+60 … 540 min nowcast

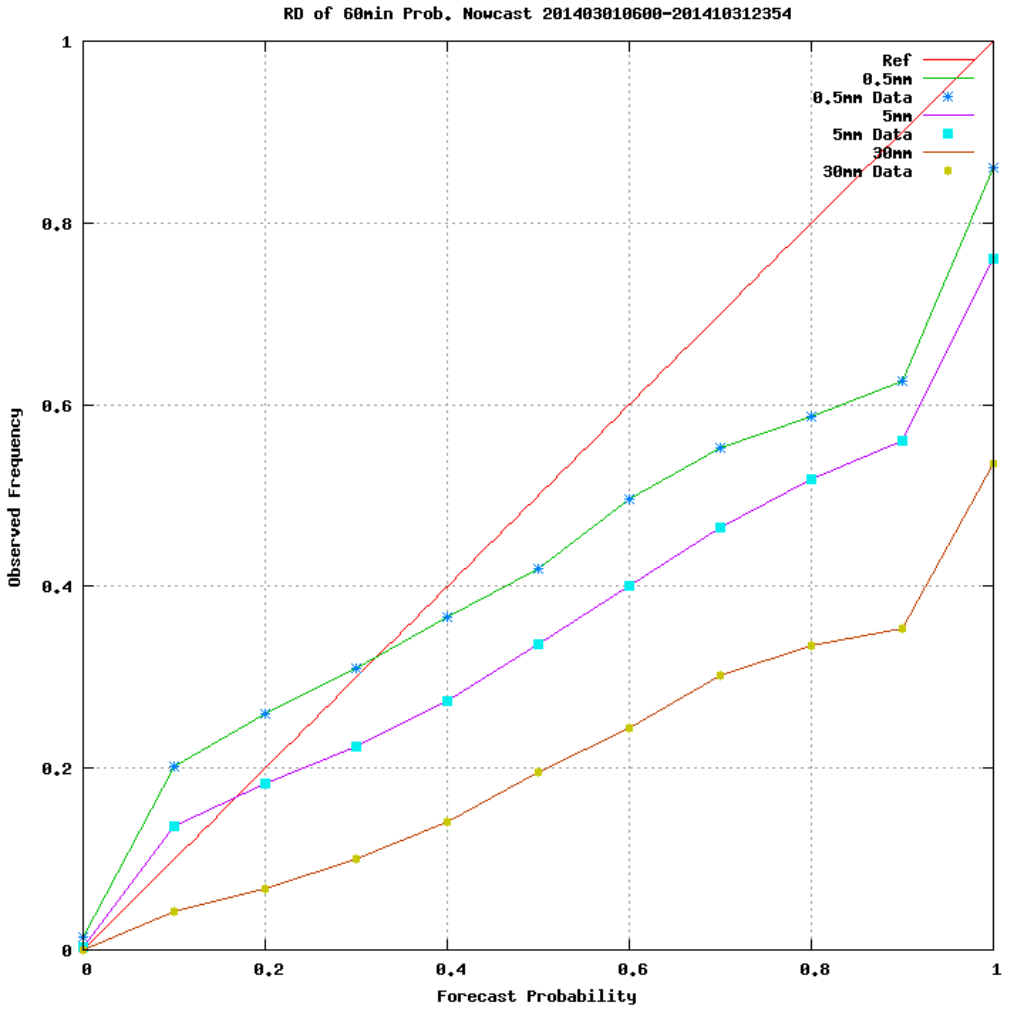
Probabilities of rainfall exceeding 0.5/5/20/30/50/70 mm per hr



Precipitation at different percentiles



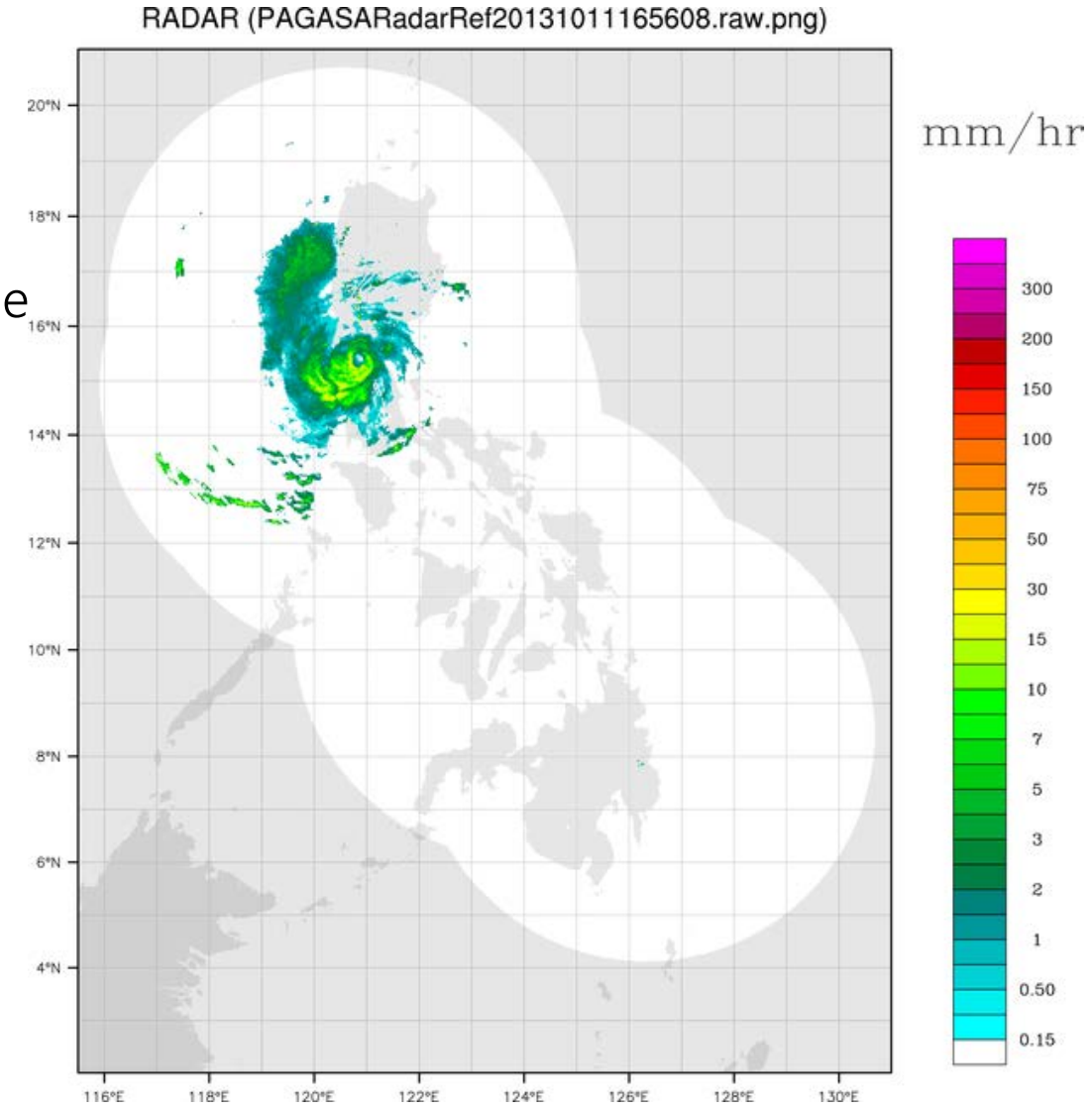
Reliability diagram (1-hr rainfall forecast) Mar – Oct 2014



Collaboration on TC rainfall nowcast

- Radar mosaic from PAGASA

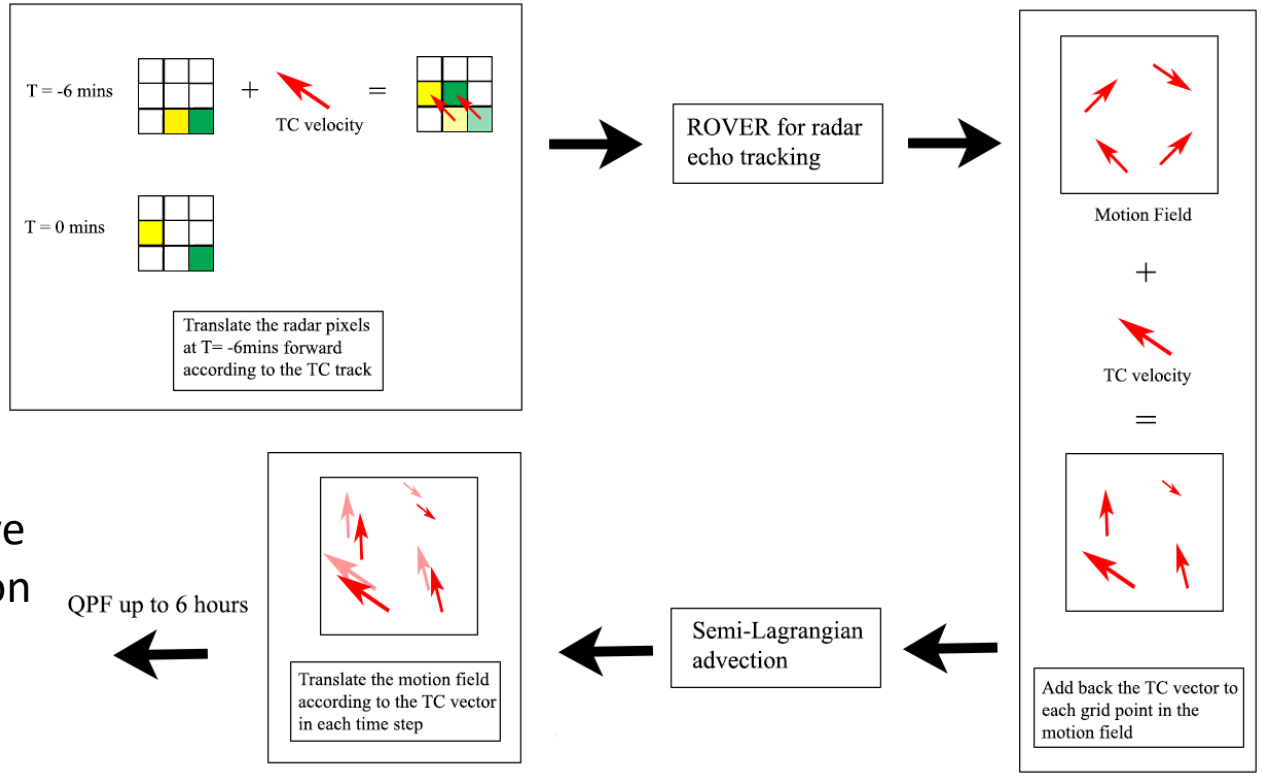
- Attachment programme unde ESCAP/WMO Typhoon Committee Research Fellowship Scheme



TC Module in SWIRLS
Typhoon Committee Research Fellowship 2012

- Enhancement Method:

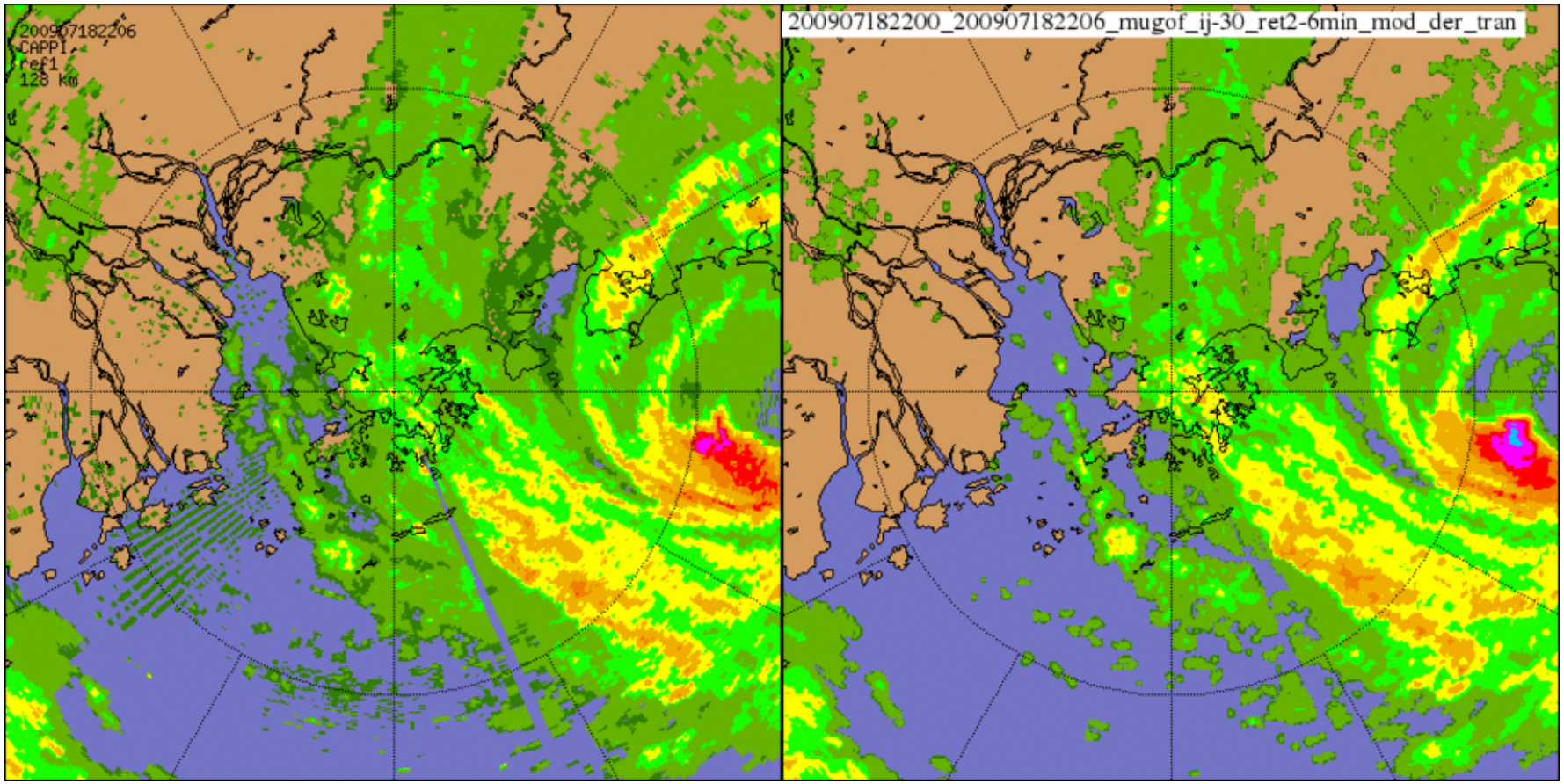
Separate the motion of TC before radar echo tracking



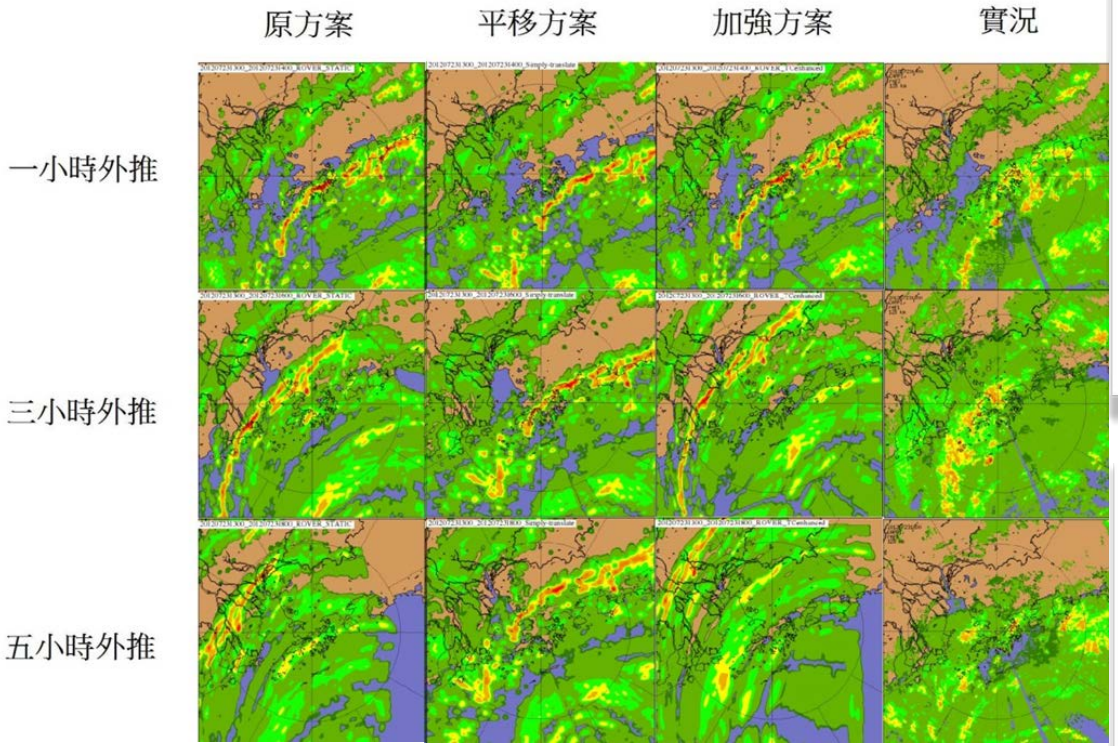
TC Nowcast Module

ACTUAL

Forecast using TC Module

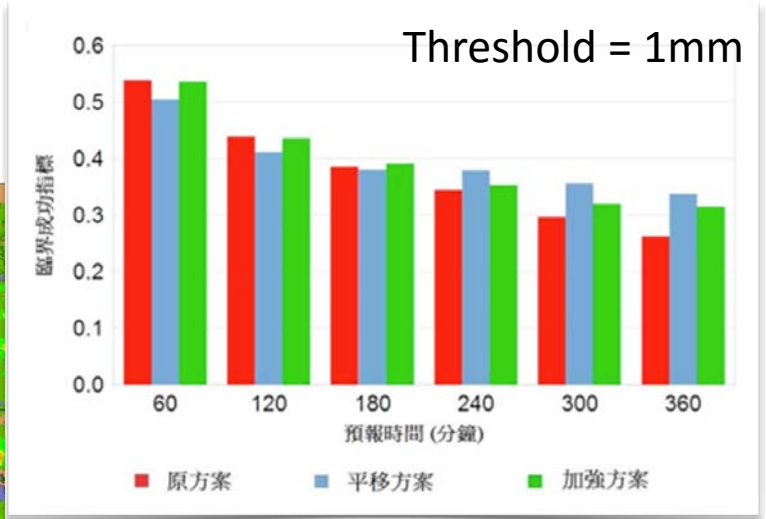


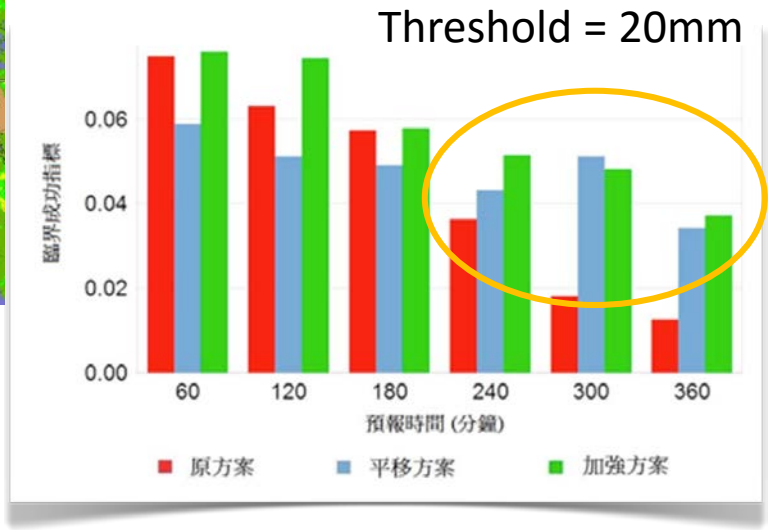
Performance of SWIRLS TC Module



Severe Typhoon Vicente
13HKT on 23 July 2012

Verification (15 Cases in 2003-2012)





Blending Nowcast with NWP

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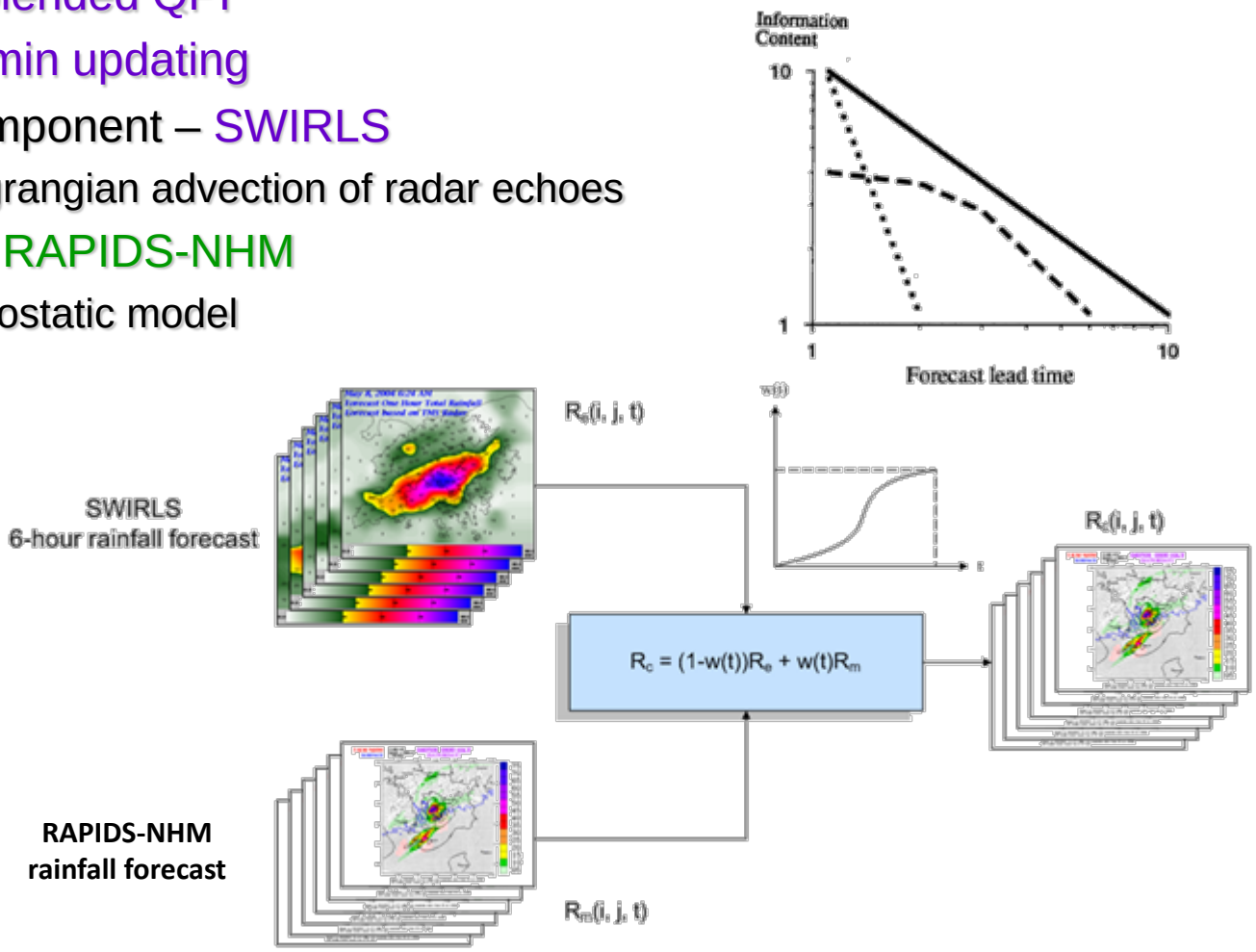
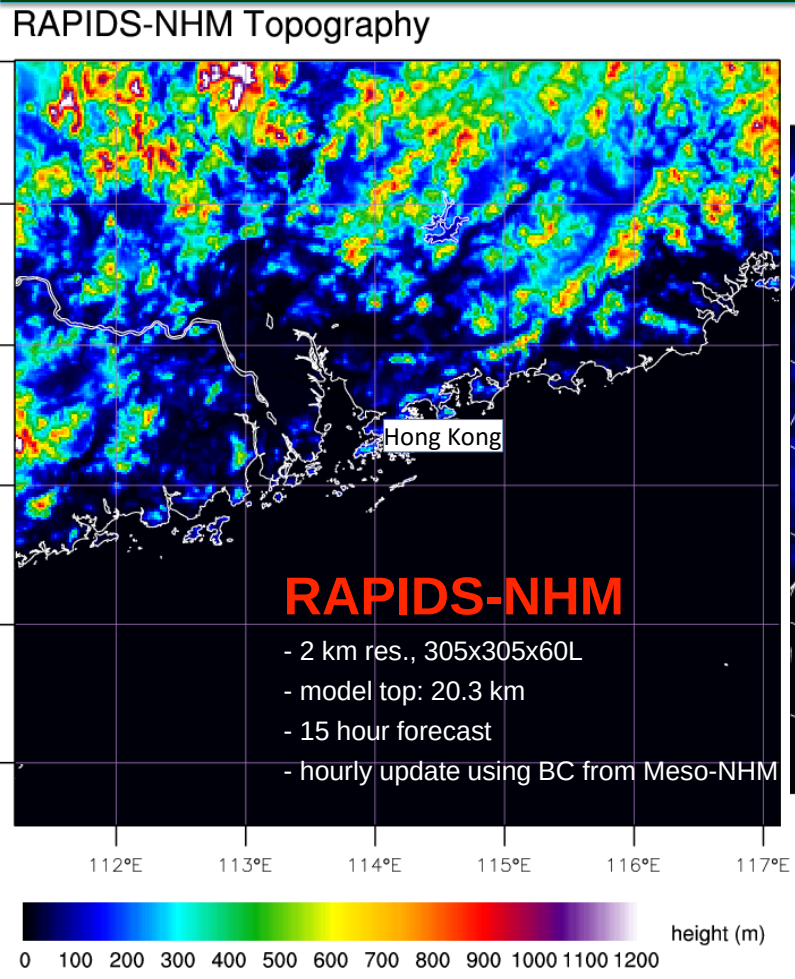
RAPIDS

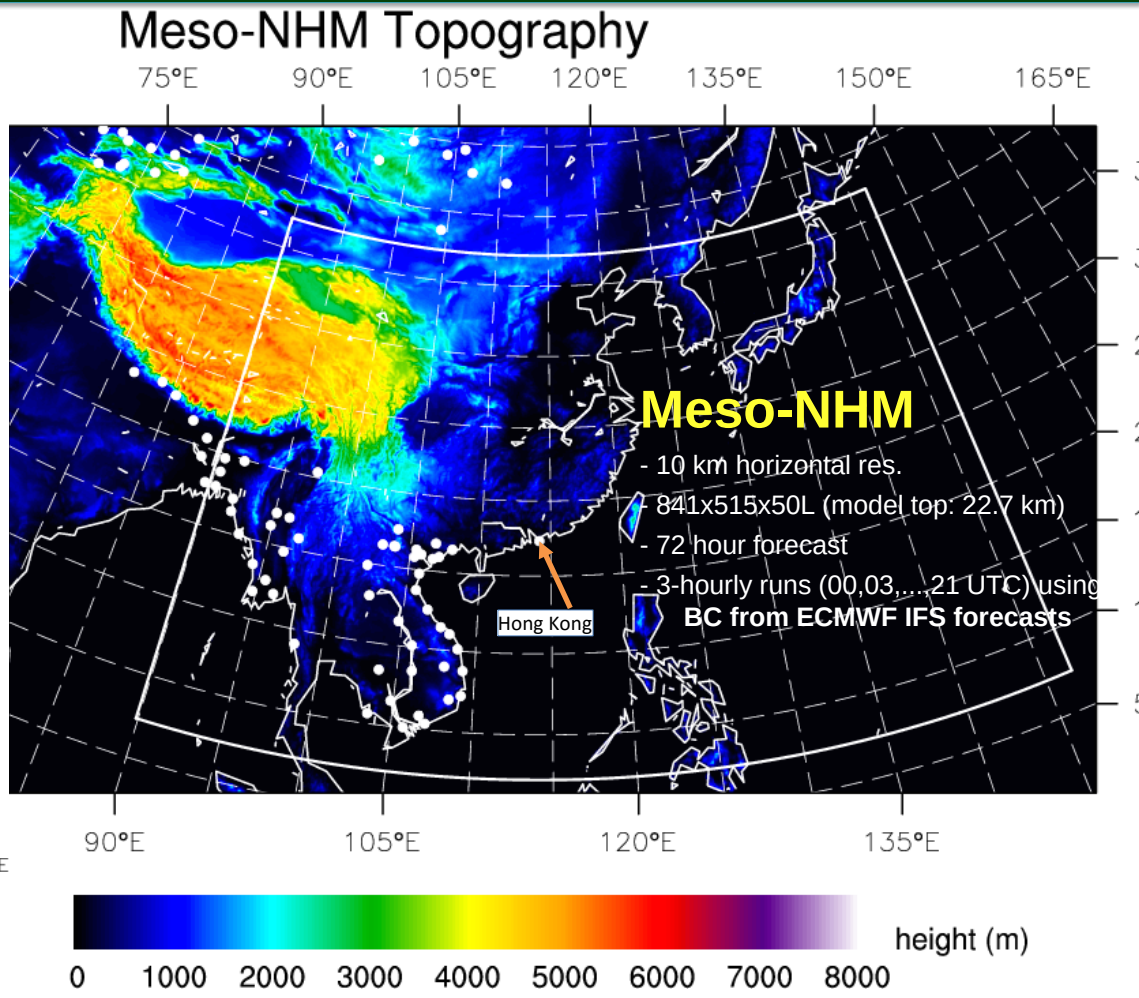
Rainstorm Analysis and Prediction Integrated Data-processing System

- provide 1-6 hours blended QPF
- 2-km resolution, 6-min updating
- NOWCASTING component – SWIRLS
  - QPF by semi-Lagrangian advection of radar echoes
- NWP component – RAPIDS-NHM
  - QPF by non-hydrostatic model



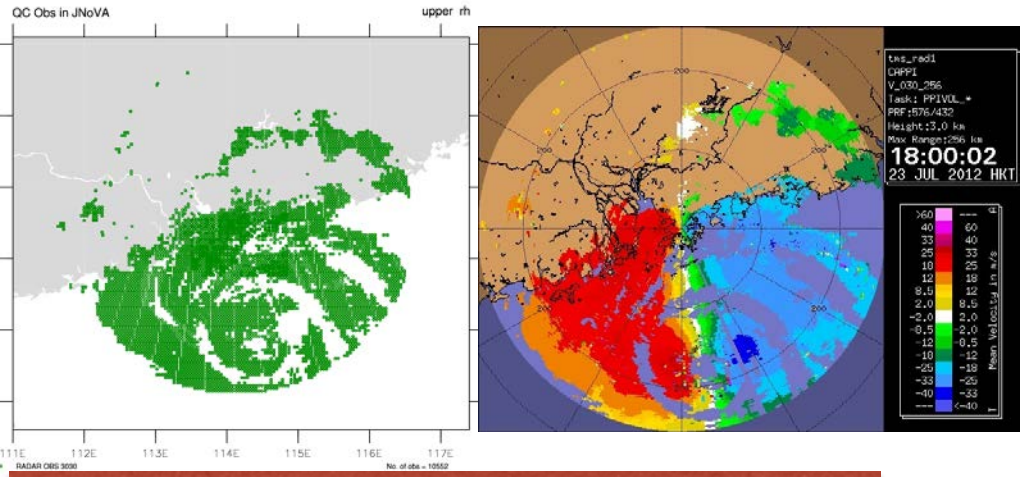
Mesoscale and Convection-permitting NWP System in Hong Kong Observatory



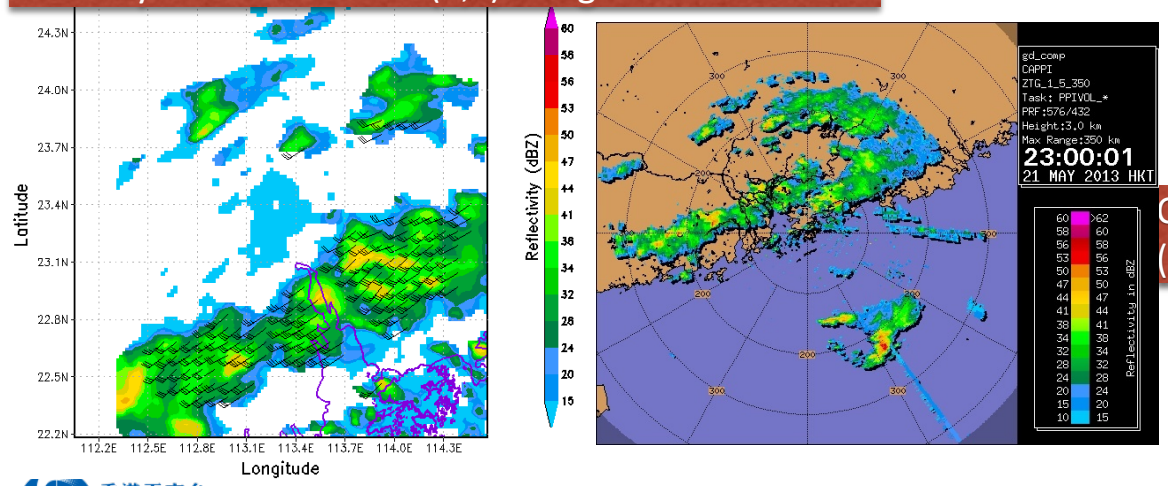


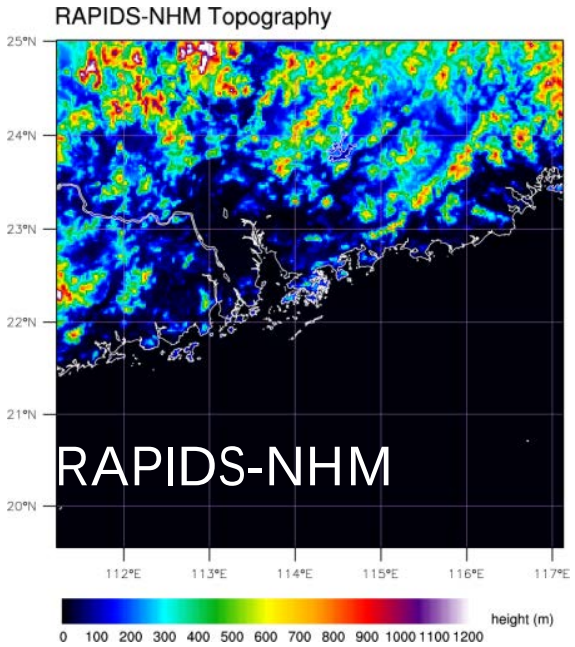
Data Assimilation of Radar Observations in RAPIDS-NHM

Doppler velocity from radars in HK



multi-layer wind retrieval (u,v) using radar mosaic





CAPPI reflectivity volume for 1D retrieval (mosaic from HK + Guangdong radars)

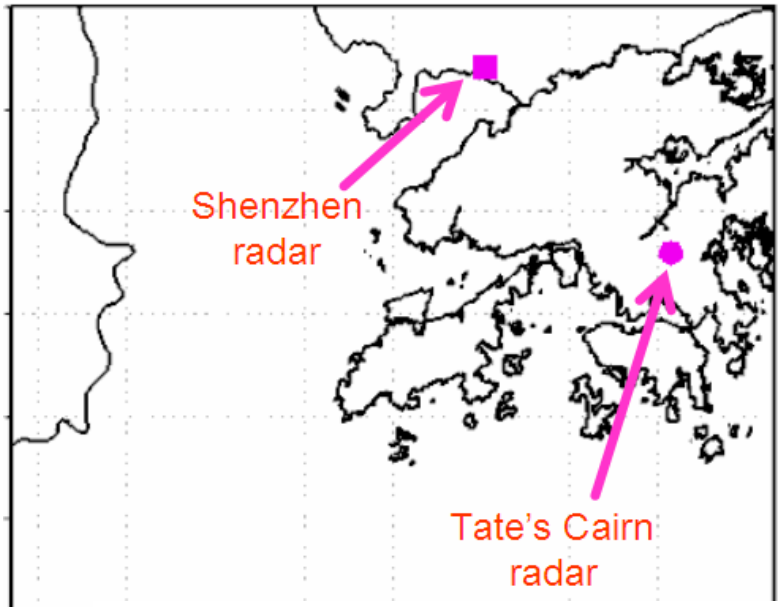
Radar retrieval wind

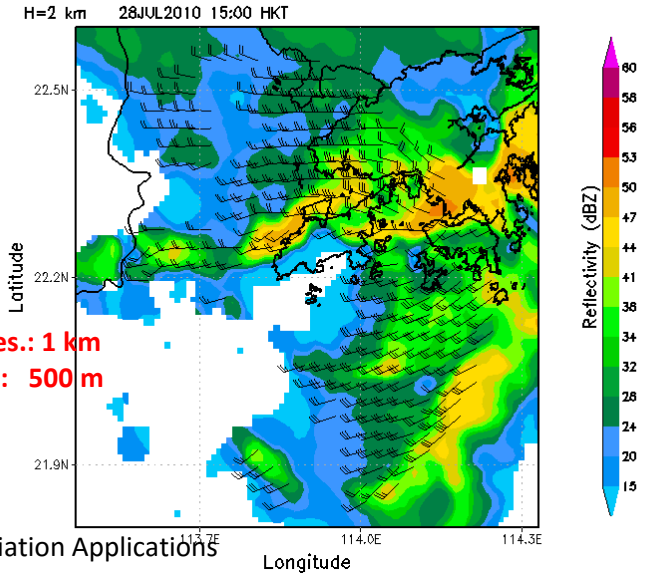
- Based on Doppler velocity from Hong Kong and radars in Shenzhen and Guangzhou

- Minimization of cost function to obtain (u,v,w):

$$J = J_O + J_B + J_D + J_S$$

  - J_O is proportional to the square of difference between the observed radial velocity and the radial velocity derived from retrieved 3D wind field;
  - J_B is proportional to the square of difference between the retrieved 3D wind field and the background;
  - J_D is the anelastic mass constraint term; and
  - J_S is the smoothness constraint of retrieved wind field using Laplacian of wind components.

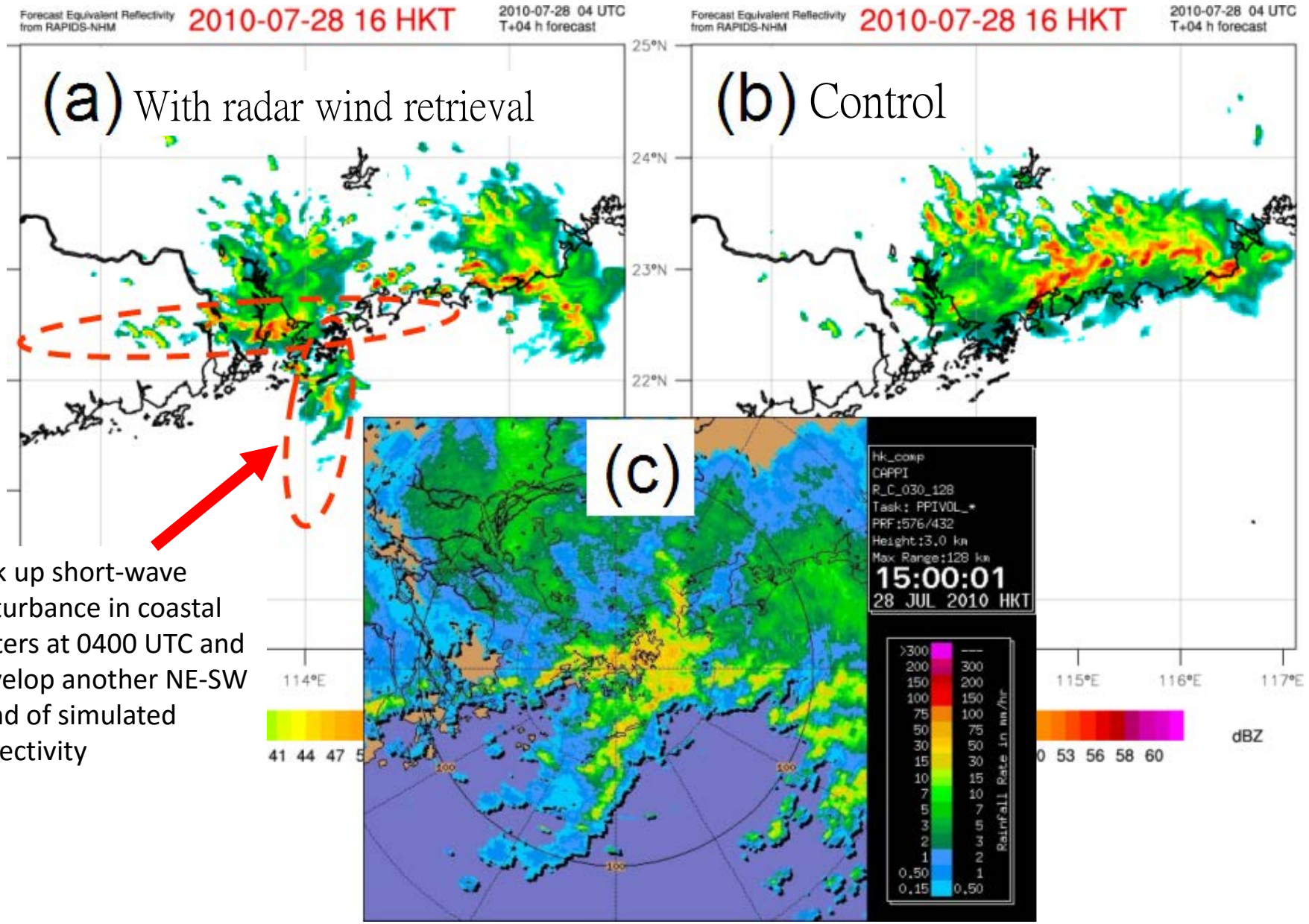




Horizontal res.: 1 km
Vertical res.: 500 m

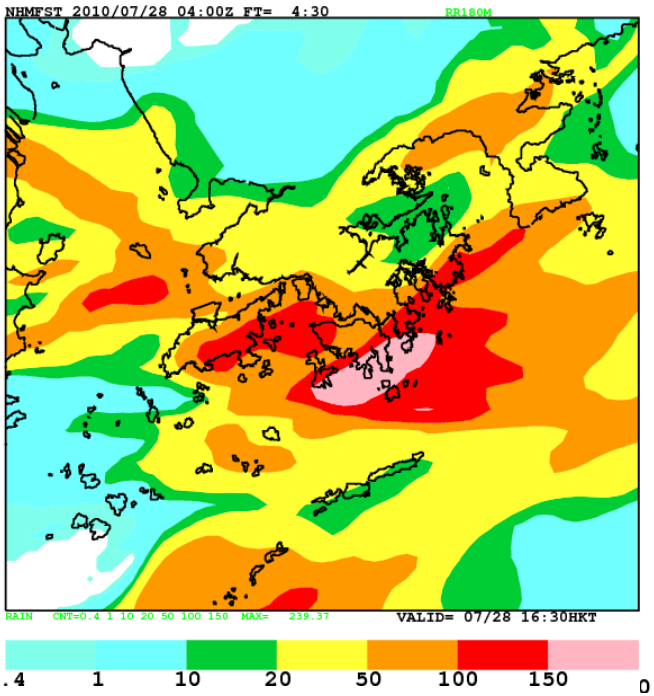
Reference:
Data Assimilation of Weather Radar and LIDAR for Convection Forecasting and Windshear Alerting in Aviation Applications
Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications (Vol. II), 2013, pp 527-554
DOI 10.1007/978-3-642-35088-7_22

4 hour forecast from RAPIDS-NHM

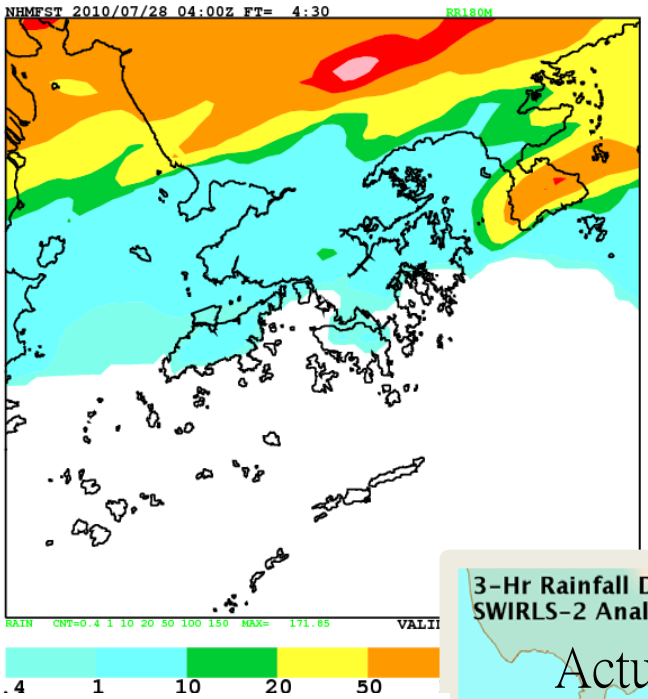


Pick up short-wave disturbance in coastal waters at 0400 UTC and develop another NE-SW band of simulated reflectivity

Impact on QPF

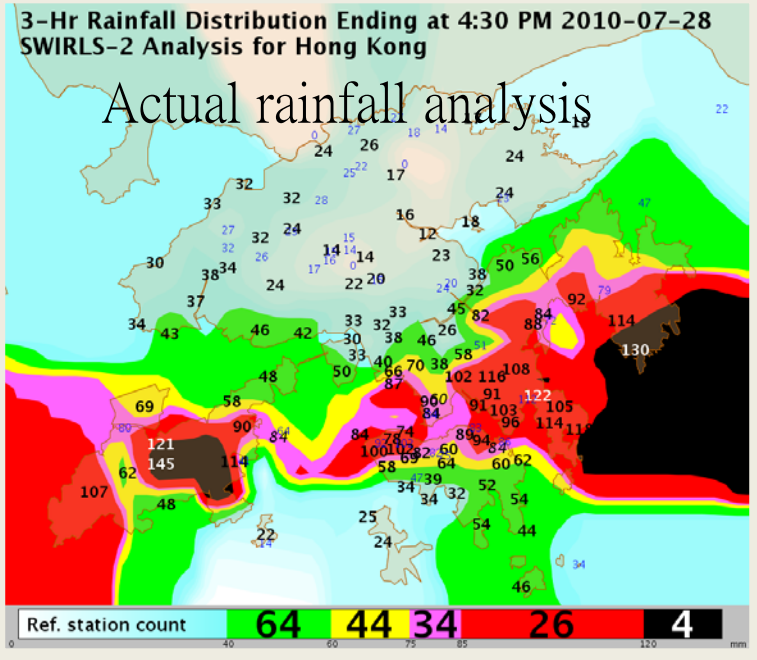


With radar wind retrieval

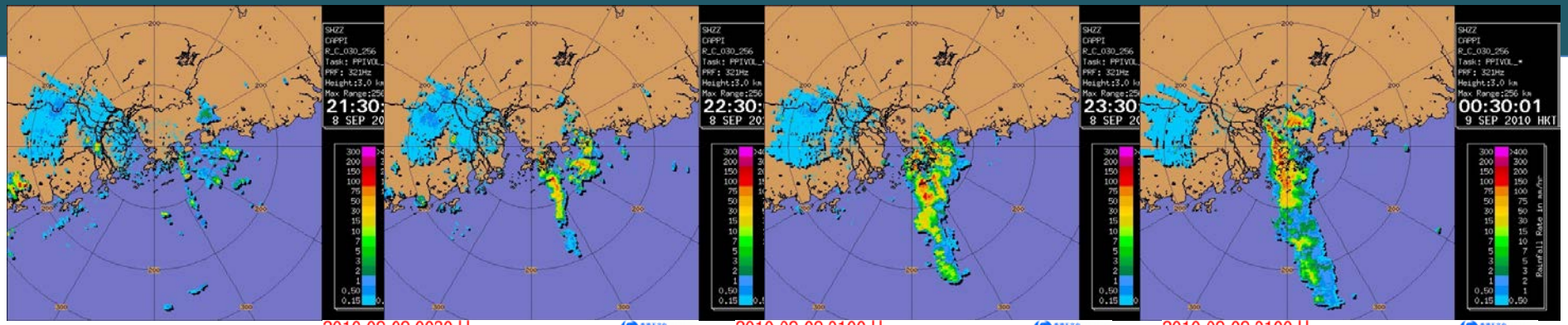


Control Expt (no radar)

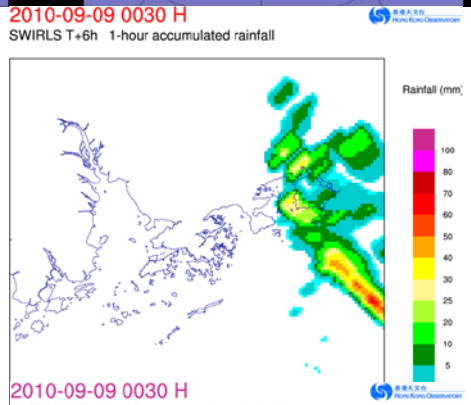
RAPIDS-NHM
3-hr acc. rainfall ending at 1630H

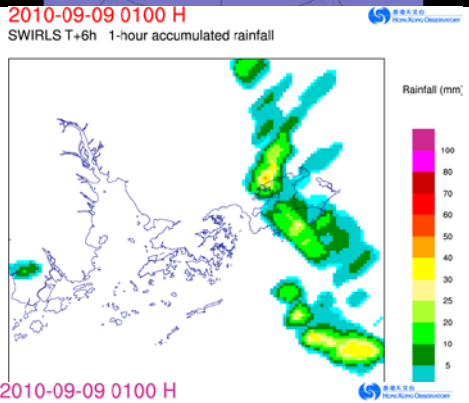


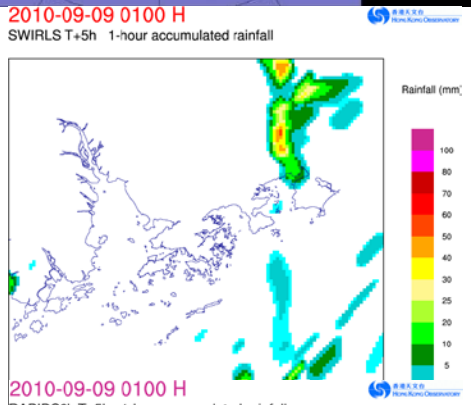
Blending Nowcast and NWP



SWIRLS nowcasts for 00:30 – 01:00H





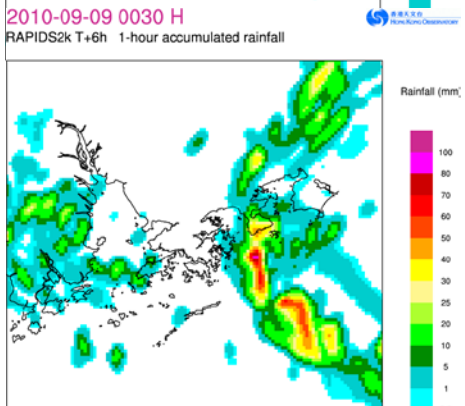


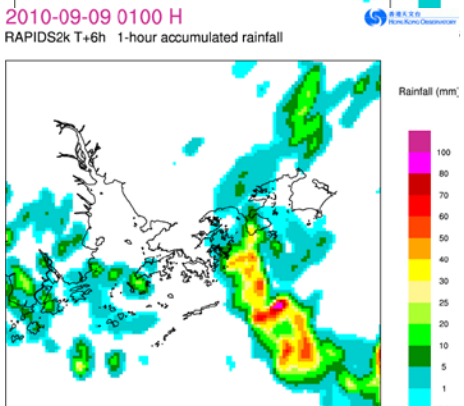
Blending

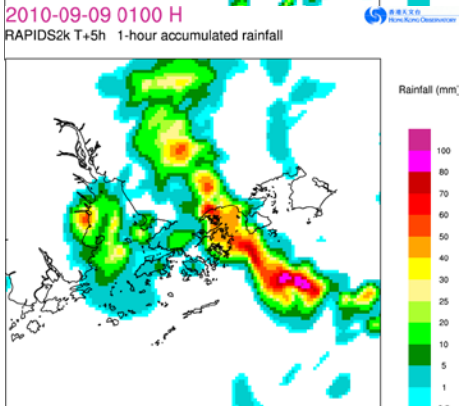
SWIRLS

+

NWP







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Summary

- Radar data in SWIRLS nowcasting system
  - Quantitative precipitation estimates
  - Quantitative precipitation nowcast (0-9 hr)
  - Severe weather parameters (lightning, hail, downburst)
- Use of radar data in convection-permitting NWP model (RAPIDS-NHM)
  - Improve very-short-range forecast
- Blending of nowcast and NWP rainfall (RAPIDS)

Thank you very much

Dr. Tin
HKO's Mascot