香港天文台
HONG KONG OBSERVATORY

SWIRLS QPE, QPF and Probabilistic Nowcast

WMO VCP Workshop on Nowcasting, Seamless Forecasting and Warning Services

29 May 2018

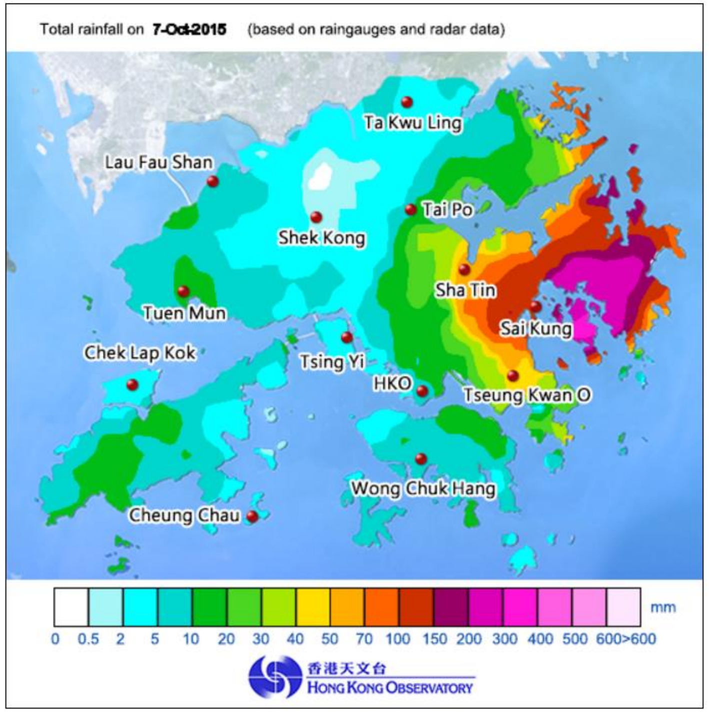
Quantitative Precipitation Estimation (QPE)

What is QPE?

Daily Rainfall distribution [past 3 months]

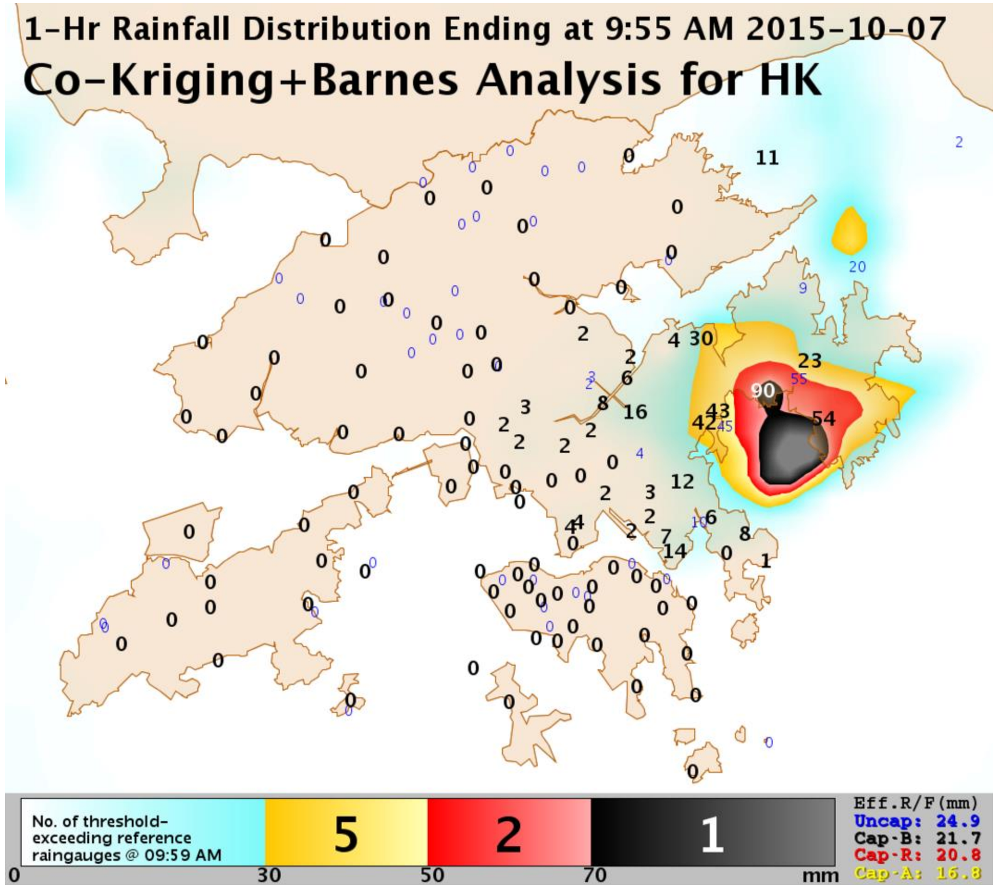
Select date: 7 Oct View << >>

Isohyet chart for 7 Oct 2015

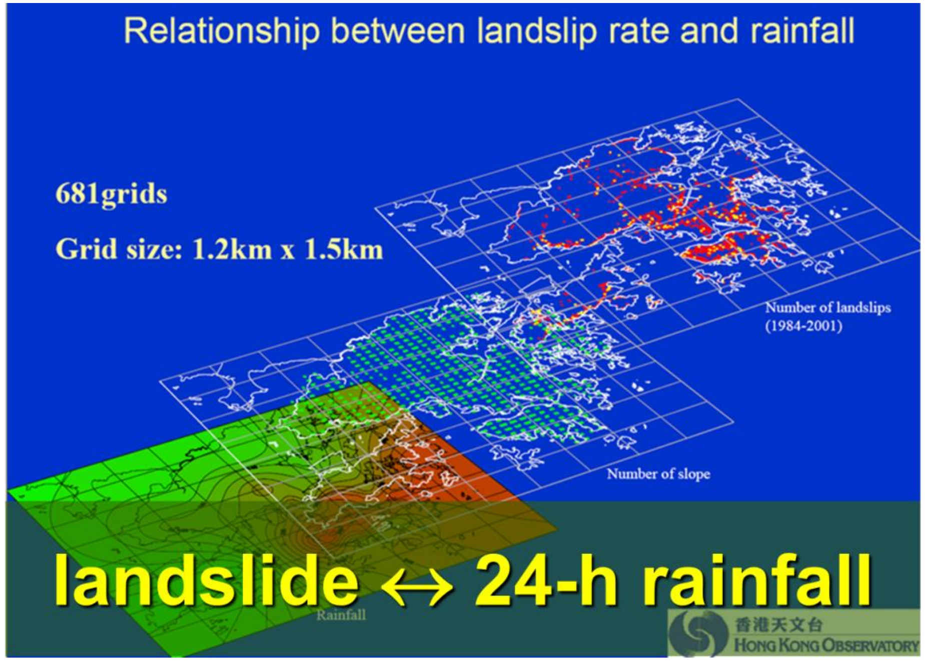


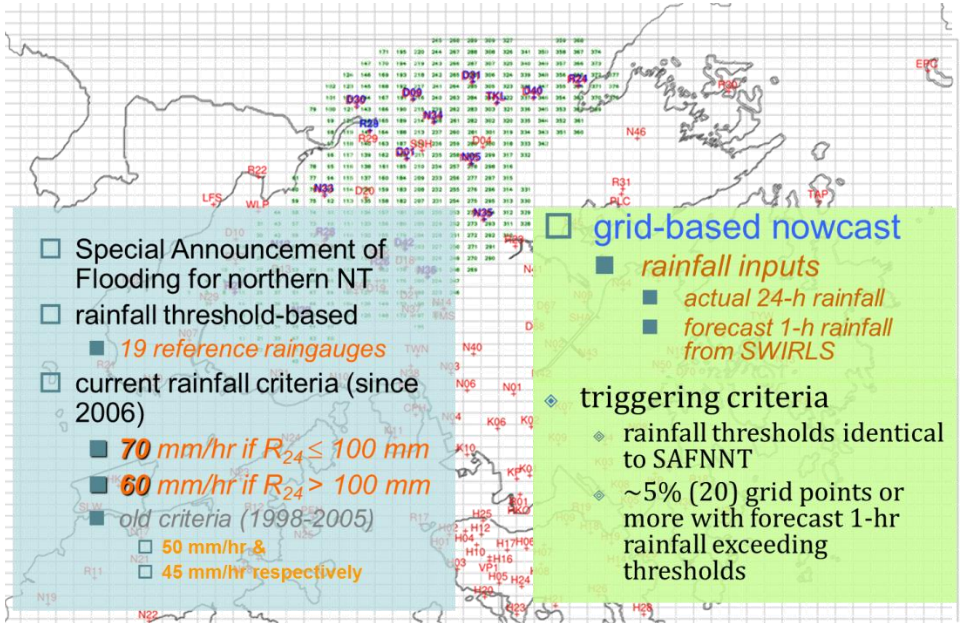
For Public

For Forecasters



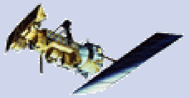
QPE for Engineering Departments





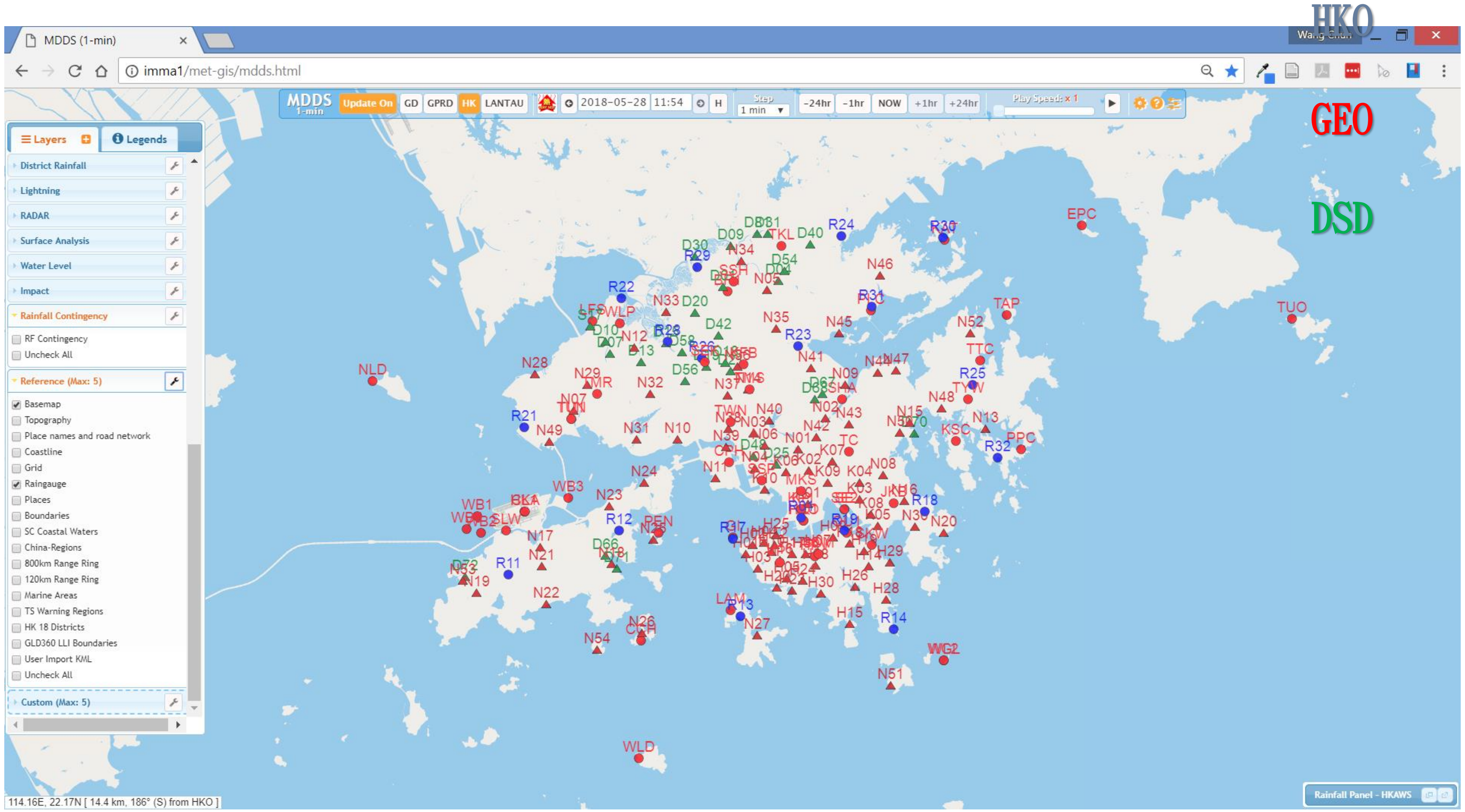
香港天文台 HONG KONG OBSERVATORY

Observations for QPE

Data Source	Quality	Temporal Resolution	Spatial Resolution	Coverage
Rain Gauge 	Very High In-situ continuous measurement	Continuous	Only available on the spot	Depends on the network
Radar 	Medium Depends on Z-R relationship	Sampled 6-min Scan 10 samples / hour	Quite good, about 0.5 km	Medium Typically up to ~250km
Satellite 	Low Requires conversion from reflectance to reflectivity	Sampled Himawari-8 6 samples / hour	Not so fine, but improving rapidly	High A satellite and scan half the globe

香港天文台 HONG KONG OBSERVATORY

Rain Gauge Network in Hong Kong

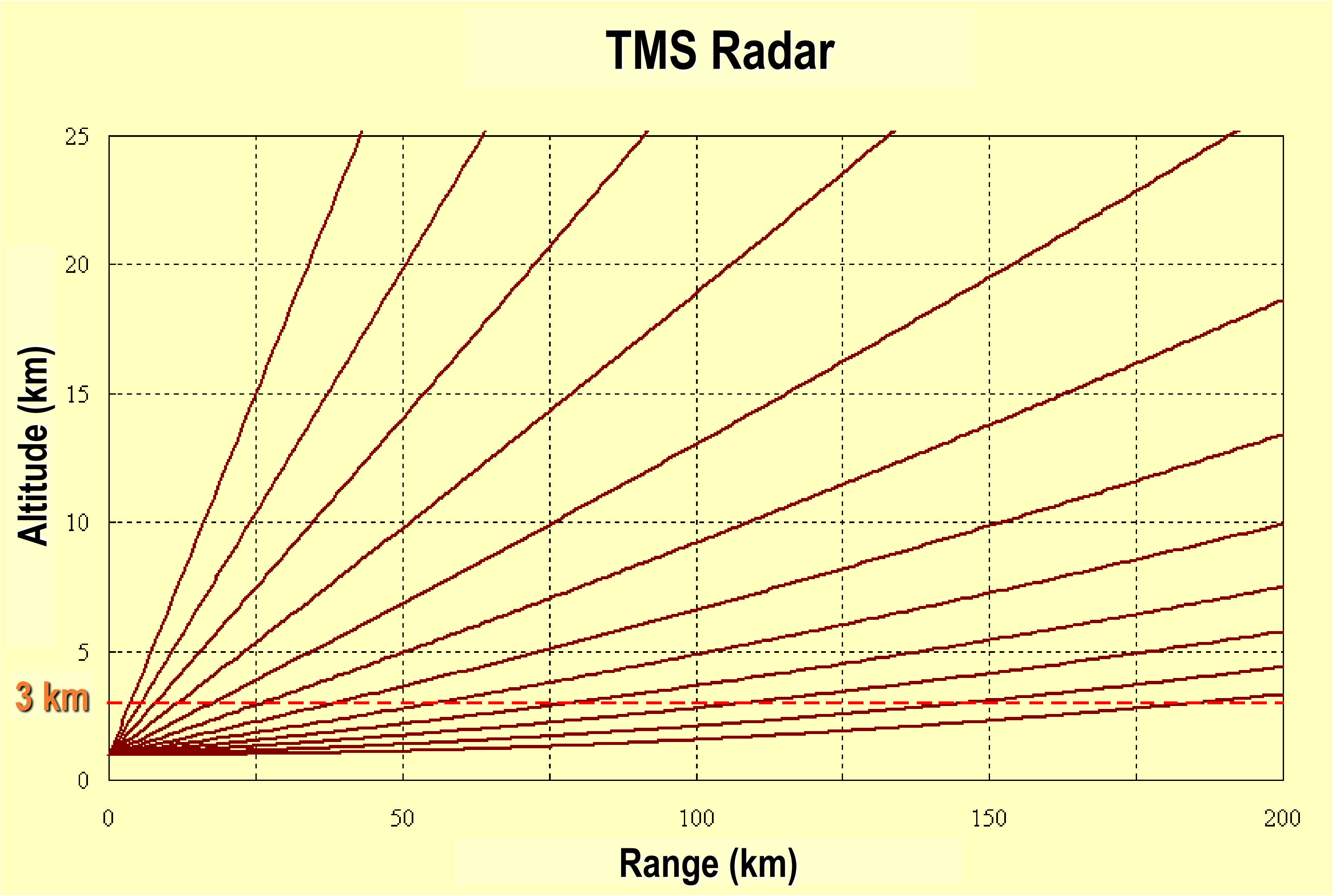


Total no. > 160, updated every 1 or 5 min

Doppler Weather Radars

香港天文台 HONG KONG OBSERVATORY

Vertical Coverage Pattern

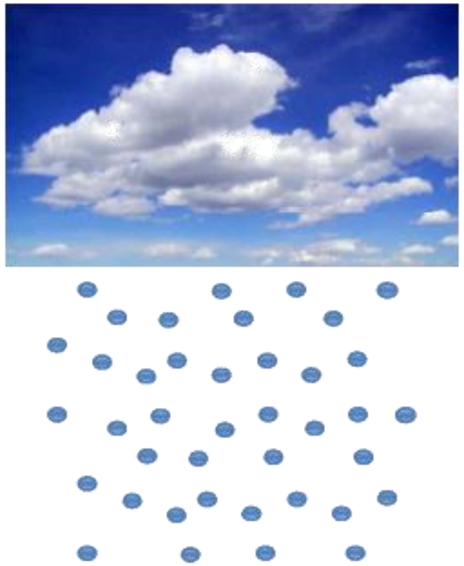


Drop-size Distribution

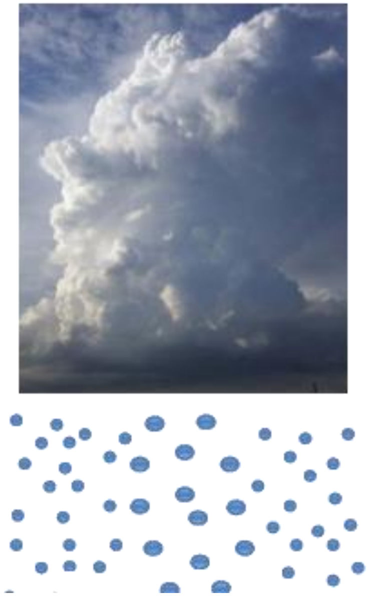
Z-R relationship for each rain-cloud

- Parameters '*a*' and '*b*' varies on rain drop size distribution.

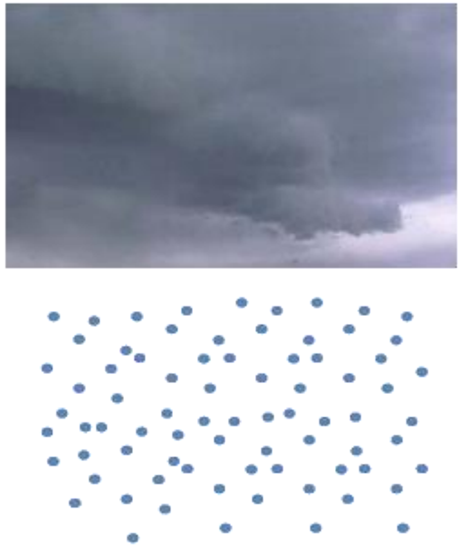
Cumulus



Cumulonimbus



Nimbostratus



Basic Principle

In rain, radar measures reflectivity, which is the sixth moment of drop size distribution:

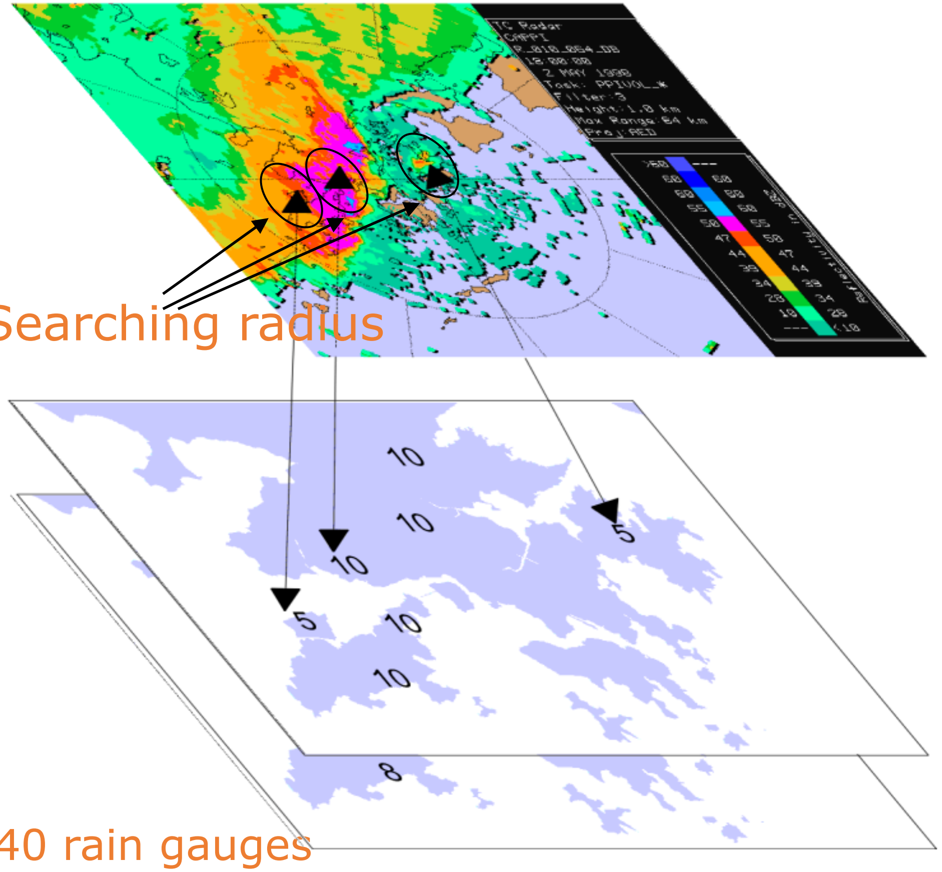
$$Z = \int_0^\infty N(D) D^6 dD$$

While rain rate is given by:

$$R = c \int_0^\infty N(D) V(D) D^3 dD$$

Thus, if we know the DSD with enough accuracy a relationship between *Z* and *R* can be established.
Experience shows that a power law is a good approximation to this relationship: $Z = aR^b$

Radar QPE



- Z-R relationship for converting reflectivity to rainfall rate

$$Z = aR^b$$

- seek (a, b) to minimize:

$$\sum_{i=1}^{140} (dBG_i - dBZ_i)^2$$

- where

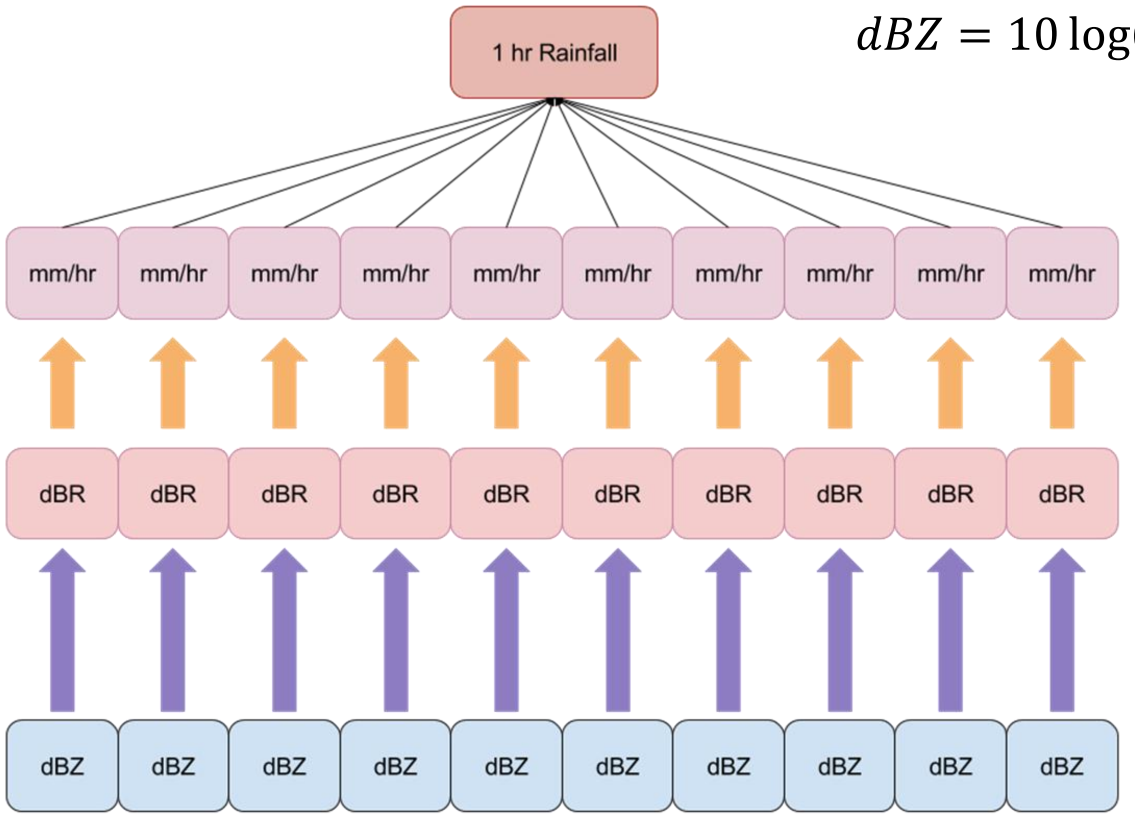
$$dBG_i = 10 \log R_i$$

From Radar Reflectivity to Rainfall

$$Z = aR^b$$

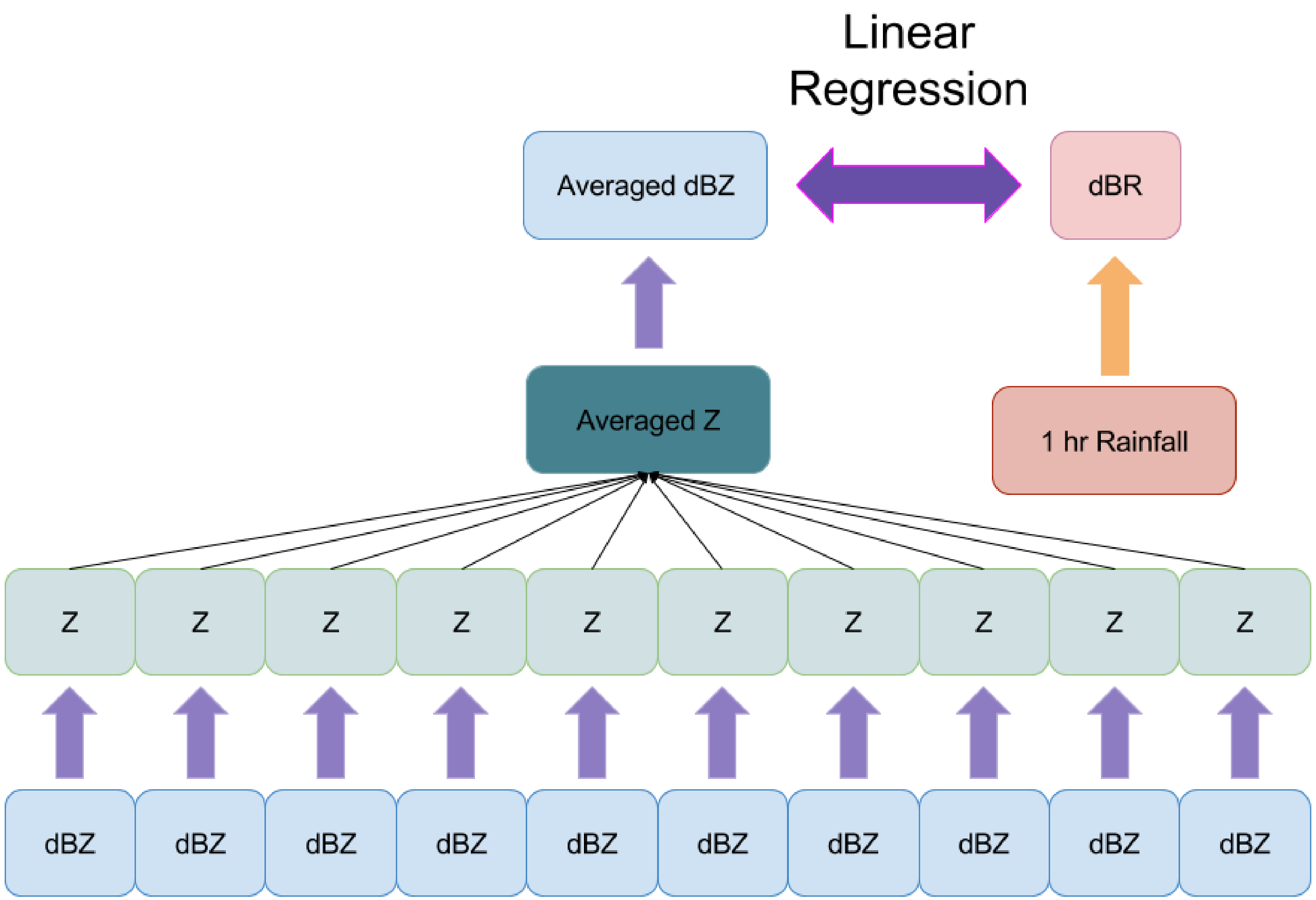
$$\downarrow$$

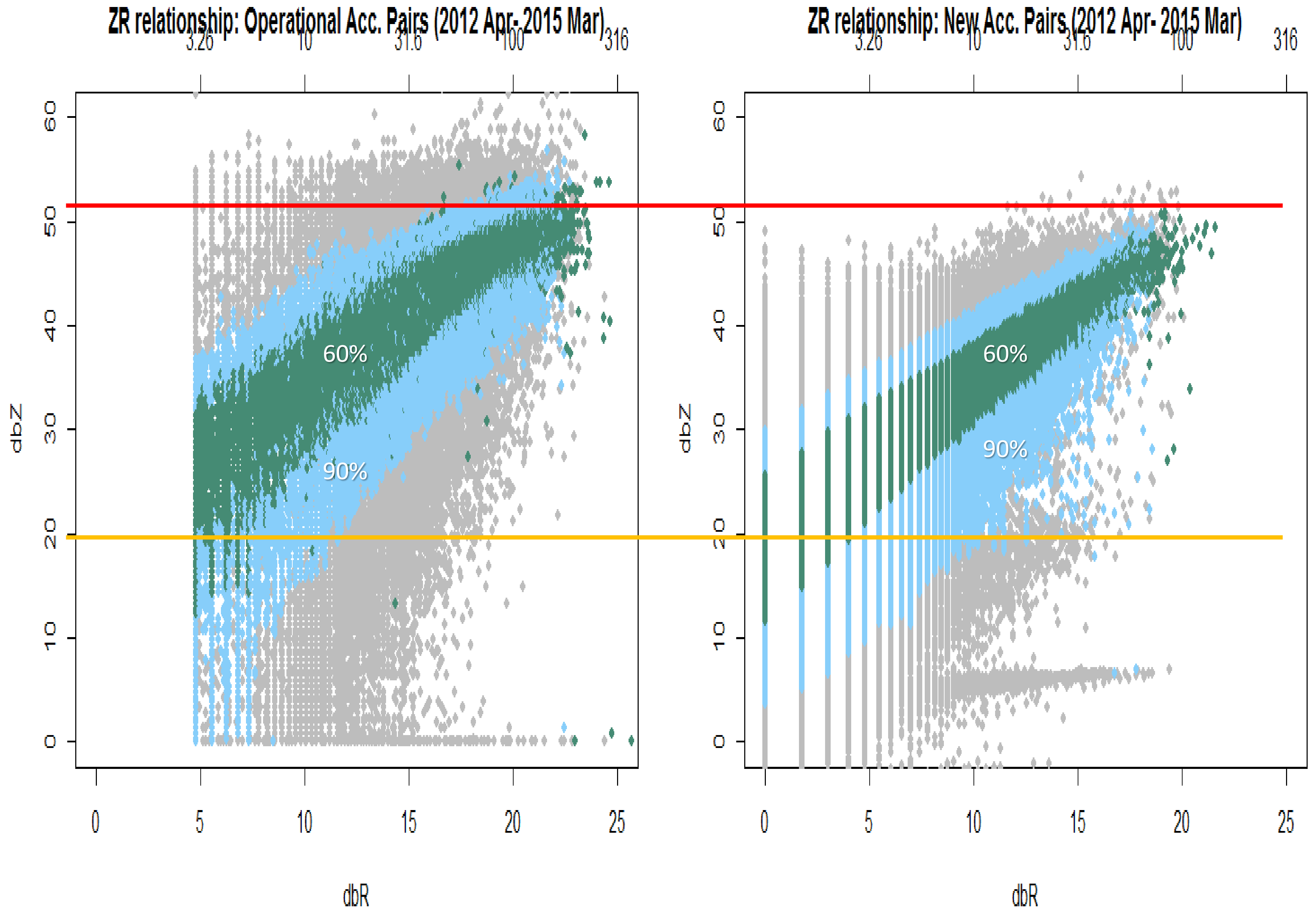
$$dBZ = 10\log(a) + bdBR$$



Radar Images → Every 6 Minutes

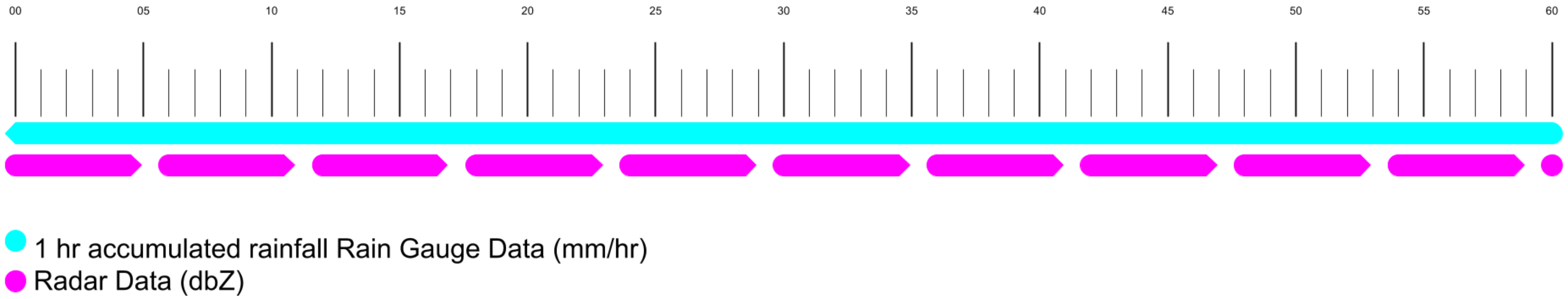
Correlation between ZR data




ZR relationship: Operational Acc. Pairs (2012 Apr- 2015 Mar)
ZR relationship: New Acc. Pairs (2012 Apr- 2015 Mar)
3.26
10
31.6
100
316
60%
90%
dbZ
dbR
0
5
10
15
20
25
30
40
50
60

Algorithm to compute a,b value

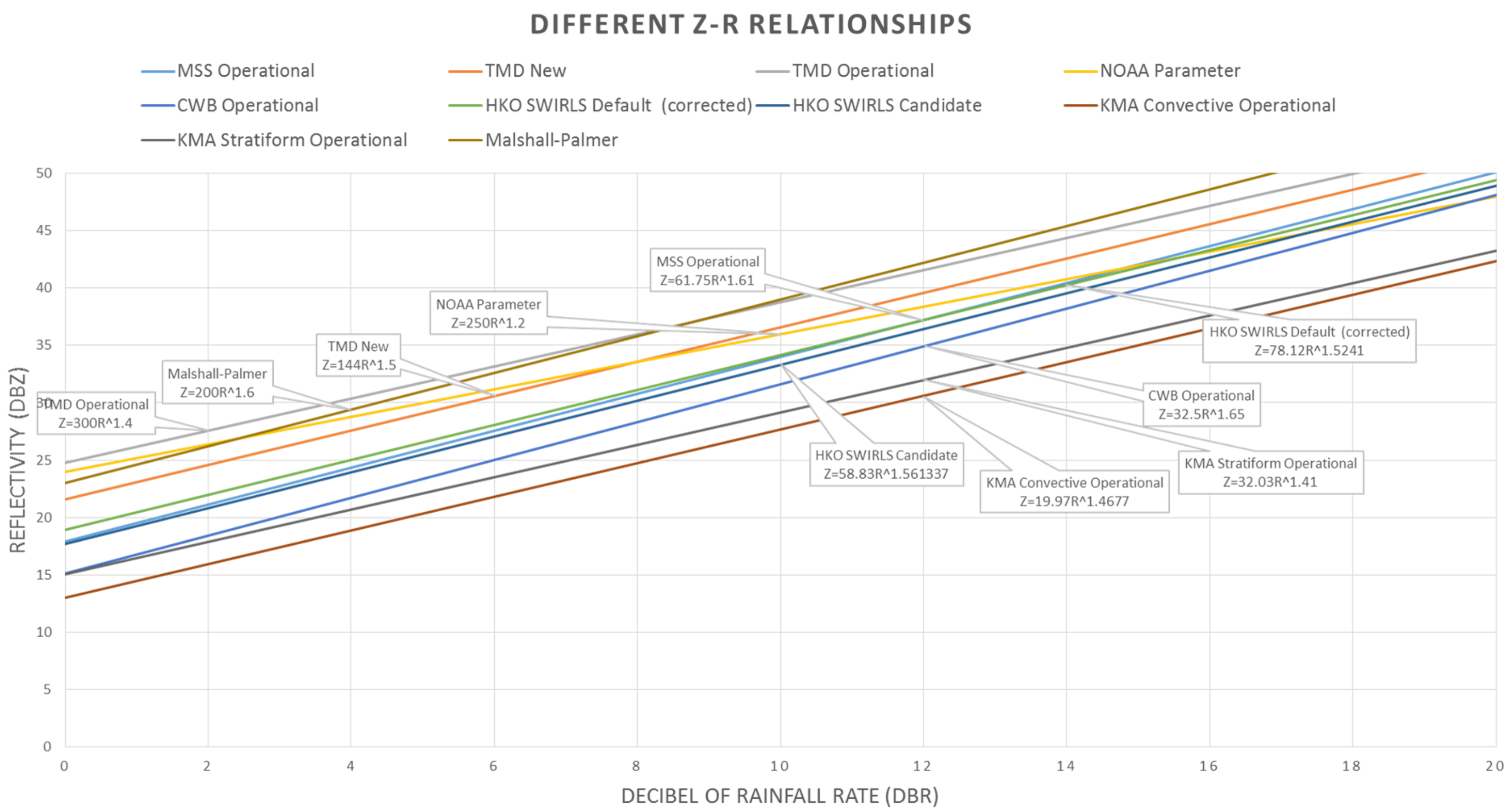
- Period: 12Apr – 15Mar
- **Geometric Mean** of 10 Radar Images from the last 1hr is used as the average dbZ corresponding to the 1-hr accumulated rainfall



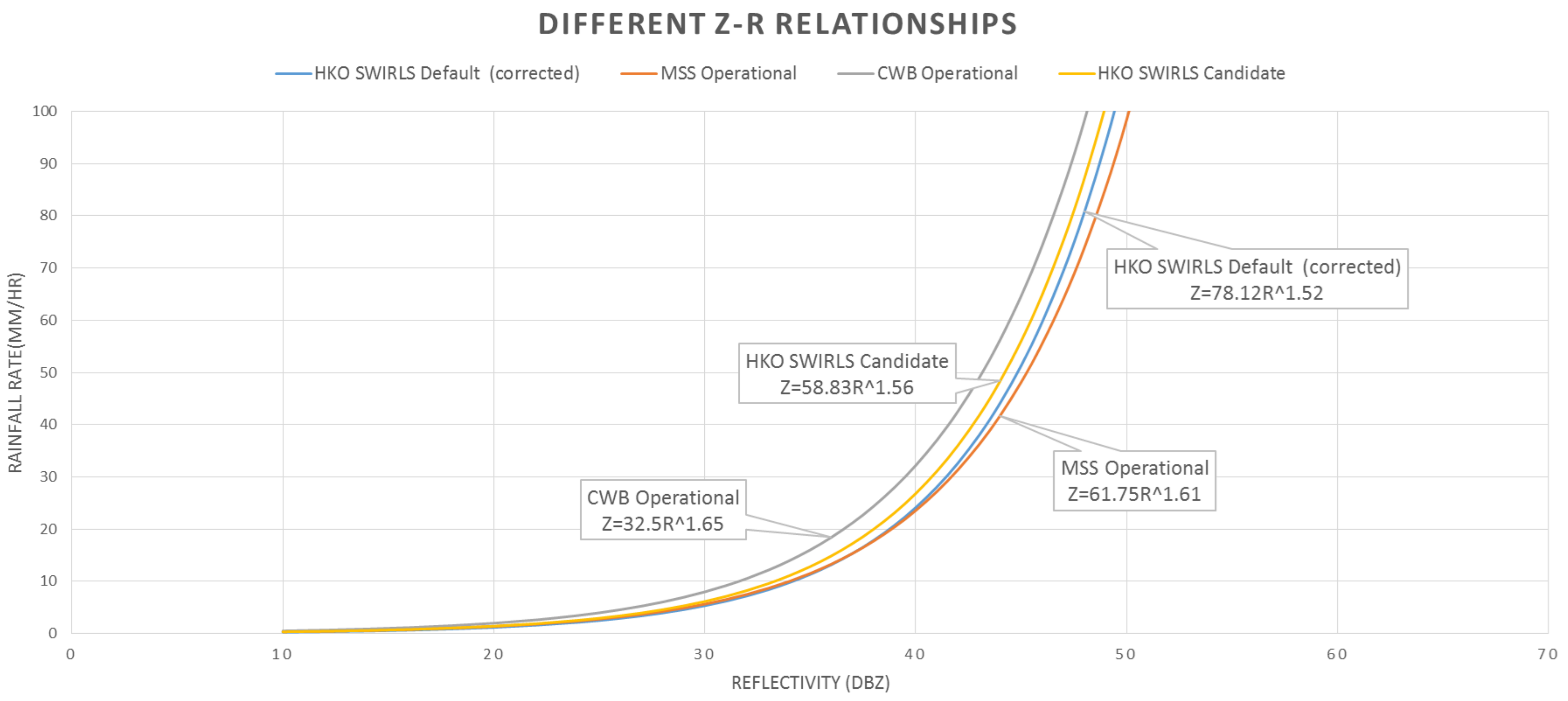
- $\boldsymbol{Result: Z = 58.53R^{1.56}}$

香港天文台
HONG KONG OBSERVATORY

Z-R in other Meteorological Services



Best Four Z-R relationships

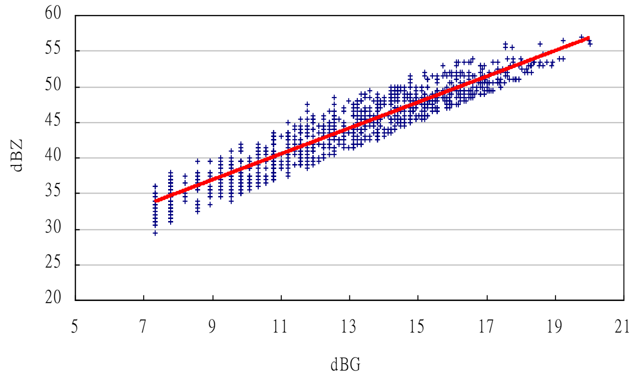


Dynamic Z-R Calibration

- least square matching (Zawadzki 1987)
- based on latest radar reflectivity and raingauge data
- linear regression to find a & b:

$$\underbrace{dBZ_i}_{y} = \underbrace{b}_{m}\,\underbrace{10\log R_i}_{x} + \underbrace{10\log a}_{c}$$

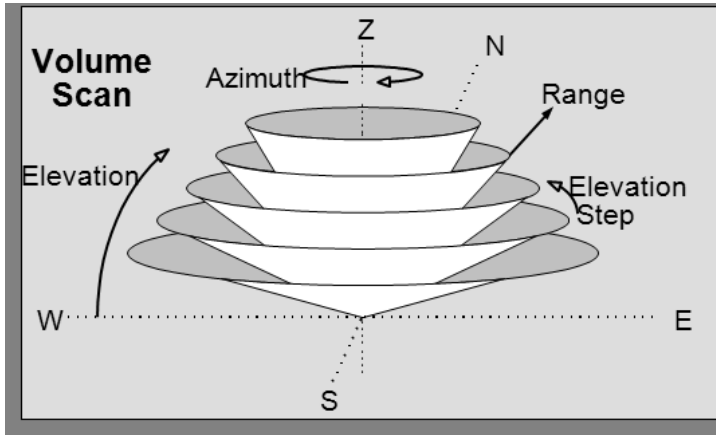
- updated every 5 min
- rainfall accumulations estimated by integrating the rainfall rates at different times
- requires:
  - a dense raingauge network
  - default values for a & b

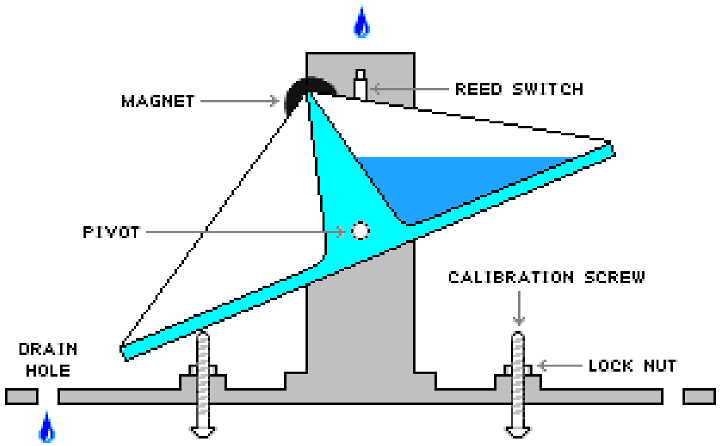


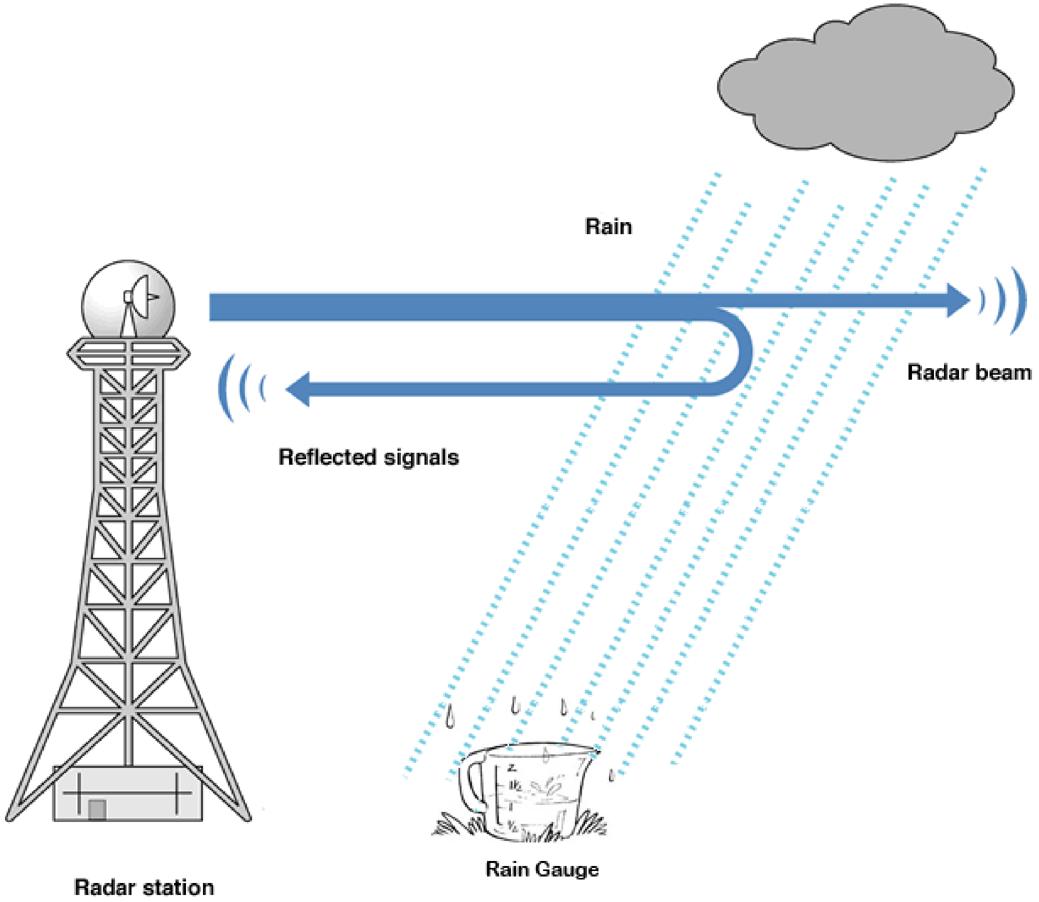
Dynamic Calibration in Hong Kong

- Default values:
  a = 58.53, b = 1.56
- 10 mins raingauge accumulated R/F surrounding the radar scanning time are used to calculate the a, b by using Least Square Method.
- Iteration stops when the program achieve a good correlation between Gauges and Radar measurements.

Uncertainties in Z-R







Z-R Pairing Methods

- **TMM**: Traditional matching method
- **PMM**: Probability matching method
- **WPMM**: Window probability matching method
- **WCMM**: Window correlation matching method
- Reference:
  - *Development of a window correlation matching method for improved radar rainfall estimation*
    https://www.hydrol-earth-syst-sci.net/11/1361/2007/hess-11-1361-2007.pdf

TMM: Traditional Matching Method

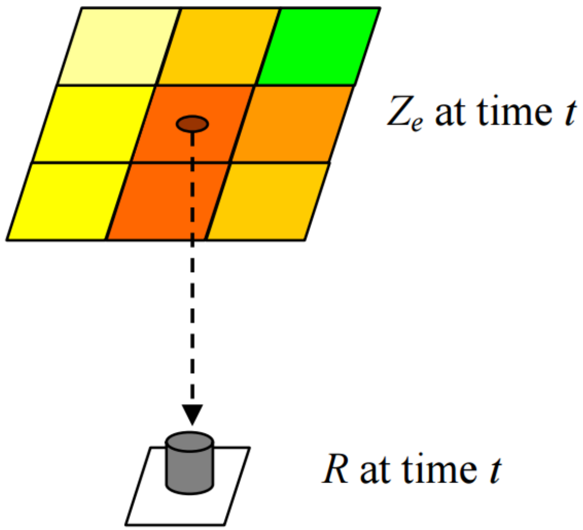


Fig. 2. The traditional $Z_e - R$ matching method (TMM).

- Based on the assumption that raindrop captured by certain radar grid point will fall vertically into the rain gauge right under the grid point

香港天文台
HONG KONG OBSERVATORY

PMM: Probability Matching Method

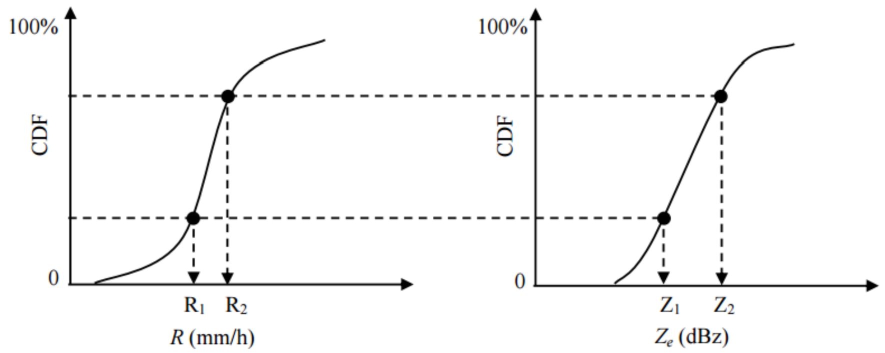


Fig. 3. The probability matching method (PMM).

- Consider cumulative distribution function (CDF) of radar reflectivity and rain gauge rainfall rate
- Match reflectivity and rainfall rate at the same percentile

WPMM: Window Probability Matching Method

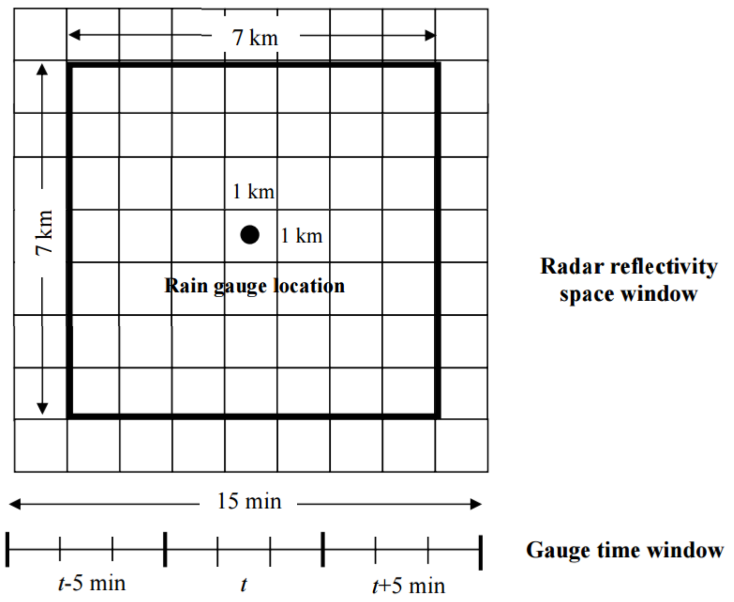


Fig. 4. The window probability matching method (WPMM).

- Reduces geometrical mismatch and synchronization error by introducing time window and space window

WCMM: Window Correlation Matching Method

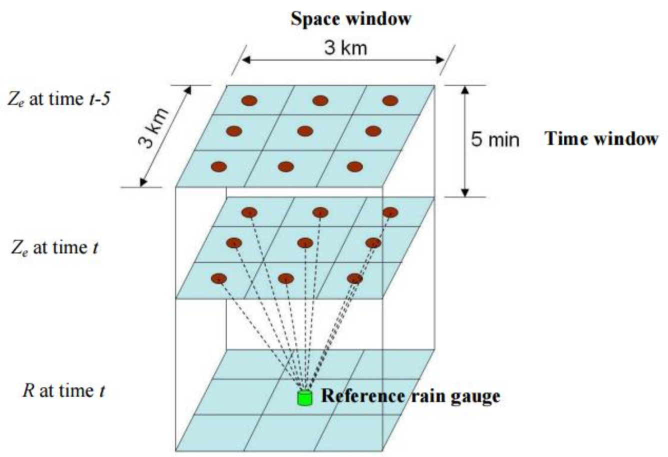
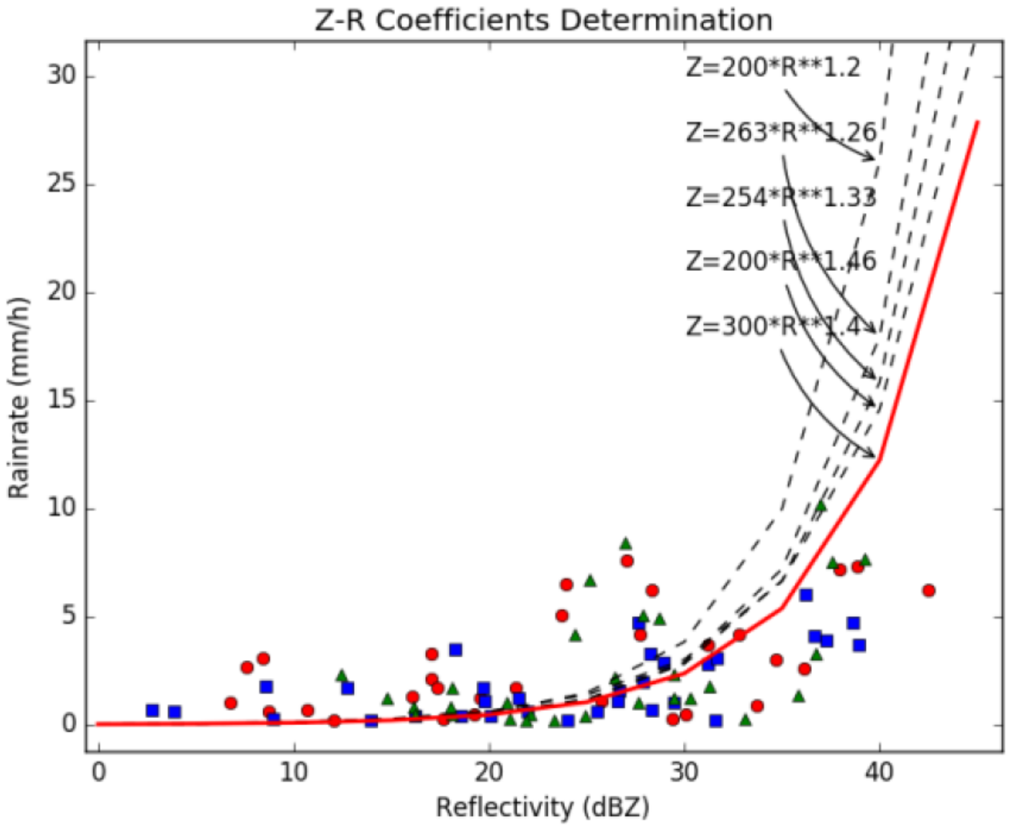


Fig. 5. The concept of the window correlation matching method (WCMM).

- Attempts to identify the highest correlation Z-R pairs from the space and time windows by searching through the reflectivity grid point and singling the one that gives closest standard score

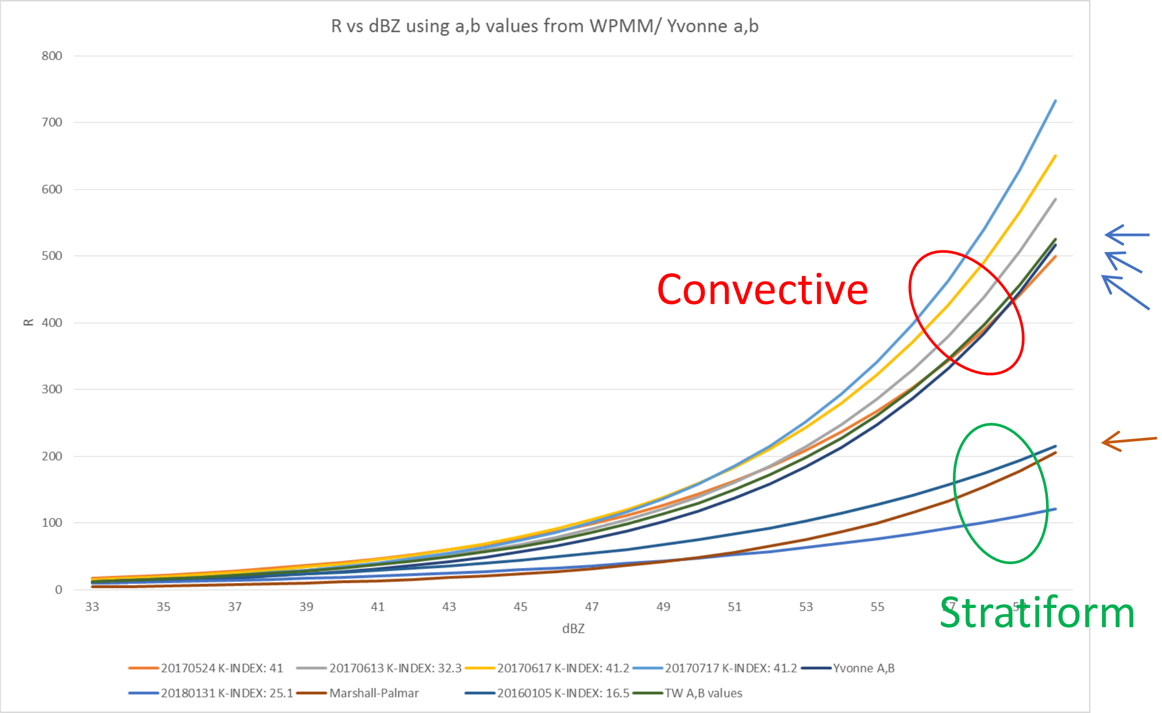
Shanghai's Method



香港天文台
HONG KONG OBSERVATORY

Z-R of Rainstorms and Stratiform Rains

2017.07.17 K-index: 41.2
2017.06.17 K-index: 41.2
2017.06.13 K-index: 32.3



CWB
HKO (since 2017, a.k.a. Yvonne a-b)
2017.05.24 K-index: 41.0

2016.01.05 K-index: 16.5
Marshall-Palmer
2018.01.31 K-index: 25.1

Other Possible Approaches

- Two-segment Linear Regression
- Quadratic Regression
- Disdrometer Network
- Machine Learning
- Real-time Bias Correction
- (wradlib) Adjusting radar-base rainfall estimates by rain gauge observations (Link)
- An Integrated Approach to Error Correction for Real-Time Radar-Rainfall Estimation (Link)

Methods for QPE

- Barnes
  - Relatively simple
  - Easy to implement
- Co-Kriging
  - Minimize errors
  - More computational intensive

香港天文台
HONG KONG OBSERVATORY

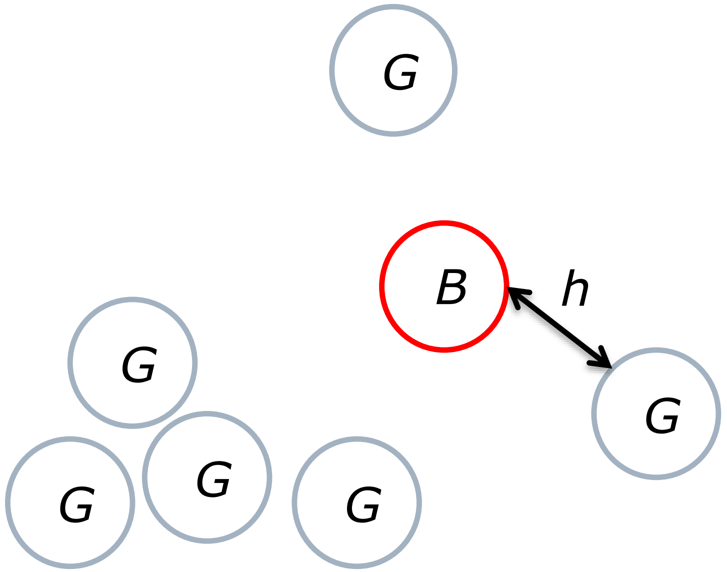
Barnes QPE with Raingauges only

- grid-point analysis by Barnes method
  - *interpolation with Gaussian weighting according to distance between data & estimation point:*

$$B(x_0) = \frac{\sum_{i=1}^{N_0} w_i G_i}{\sum_{i=1}^{N_0} w_i} \qquad w_i = \exp\left(\frac{-h_i^2}{L^2}\right)$$

  - *plus correction using residuals*
- ***L*** is arbitrary
- problems:
  - *boundary*
  - *over/undershoot*
    - **eased by post-processing**

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

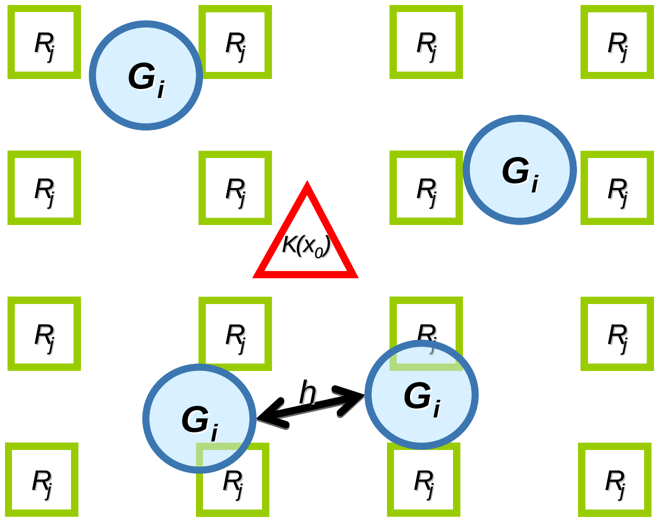


Co-Kriging QPE with Raingauge and Radar Data

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:

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

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

Co-Kriging QPE Raingauge & Radar

Empirical Variograms & Cross-variogram:

$$\gamma_{GG}(h) = \frac{1}{2P_1(h)} \sum_{k=1}^{P_1(h)} \left[G(x_k + h) - G(x_k) \right]^2$$

gauge–gauge variation

$$\gamma_{RR}(h) = \frac{1}{2P_2(h)} \sum_{k=1}^{P_2(h)} \left[R(x_k + h) - R(x_k) \right]^2$$

radar–radar variation

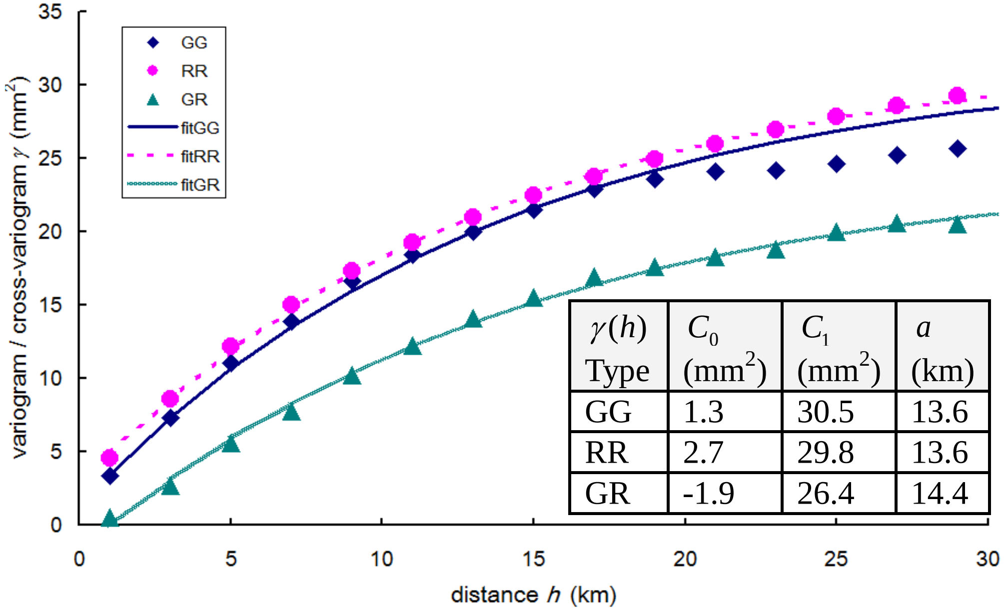
$$\gamma_{GR}(h) = \frac{1}{2P_3(h)} \sum_{k=1}^{P_3(h)} \left[G(x_k + h) - G(x_k) \right]\left[R(x_k + h) - R(x_k) \right]$$

gauge–radar cross-variation

Modeling Variogram:

$$\gamma(h) = \begin{cases} 0 & \text{if} \quad h = 0 \\ C_0 + C_1\left(1 - e^{-h/a}\right) & \text{if} \quad h > 0 \end{cases}$$

where $C_0 = \text{nugget}$, $C_1 = \text{sill}$, $a = \text{range}$

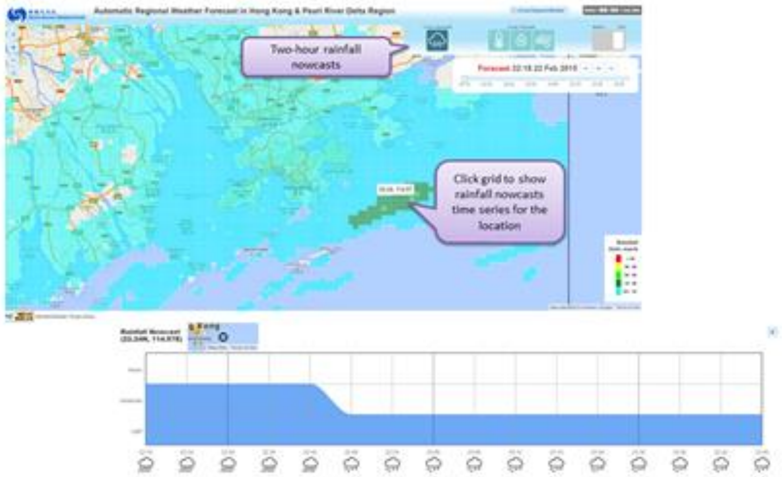


$\gamma(h)$ Type	C_0 (mm^2)	C_1 (mm^2)	a (km)
GG	1.3	30.5	13.6
RR	2.7	29.8	13.6
GR	-1.9	26.4	14.4

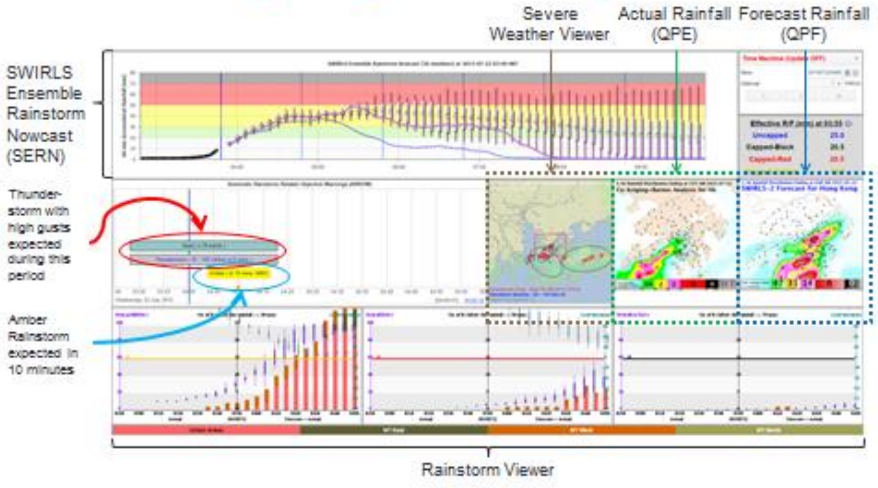
Quantitative Precipitation Forecasts (QPF)

What is QPF?

Rainfall Nowcast integrated with Automatic Regional Weather Forecast



SWIRLS Integrated Panel (SIP) for the Hong Kong Observatory

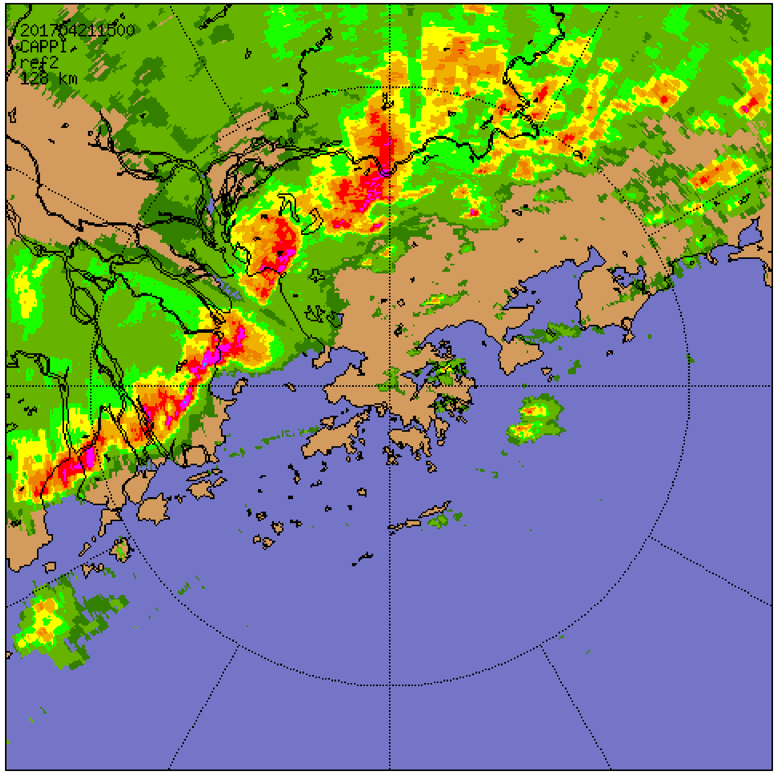


QPF

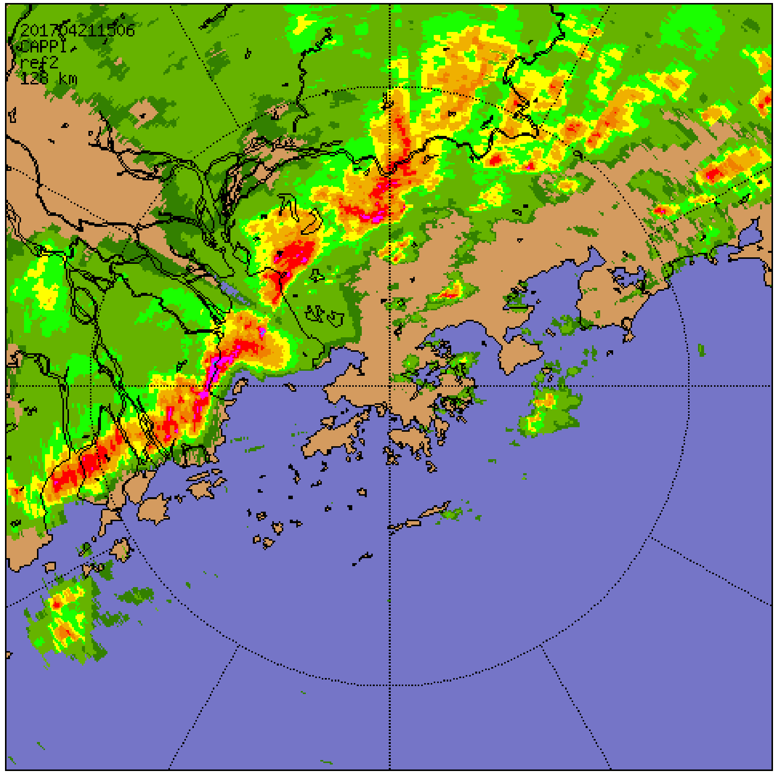
- Objective
  - Predict rainfall amount at particular area/ point
- Steps
  - Compare two successive radar images and analyze the motion field with variational optical flow;
  - Predict the evolution of radar echoes with semi-Lagrangian advection of radar echoes; and
  - Convert forecast radar reflectivity to rainfall intensity with static / dynamically calibrated Z-R relationship.

Principle of Radar-based Rainfall Nowcast

3:00pm

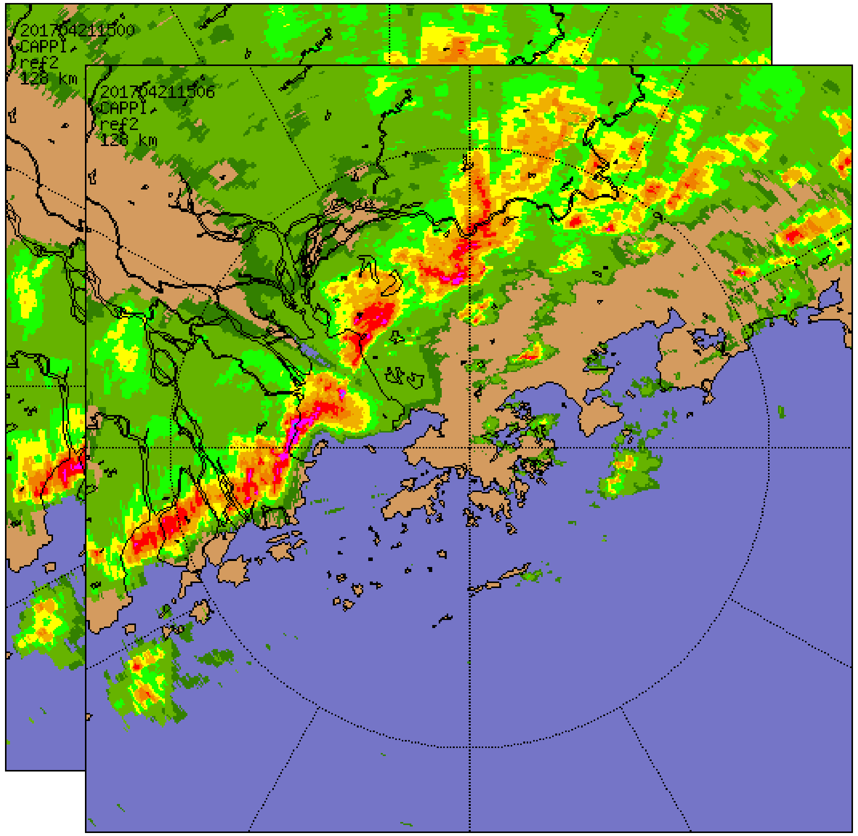


3:06pm

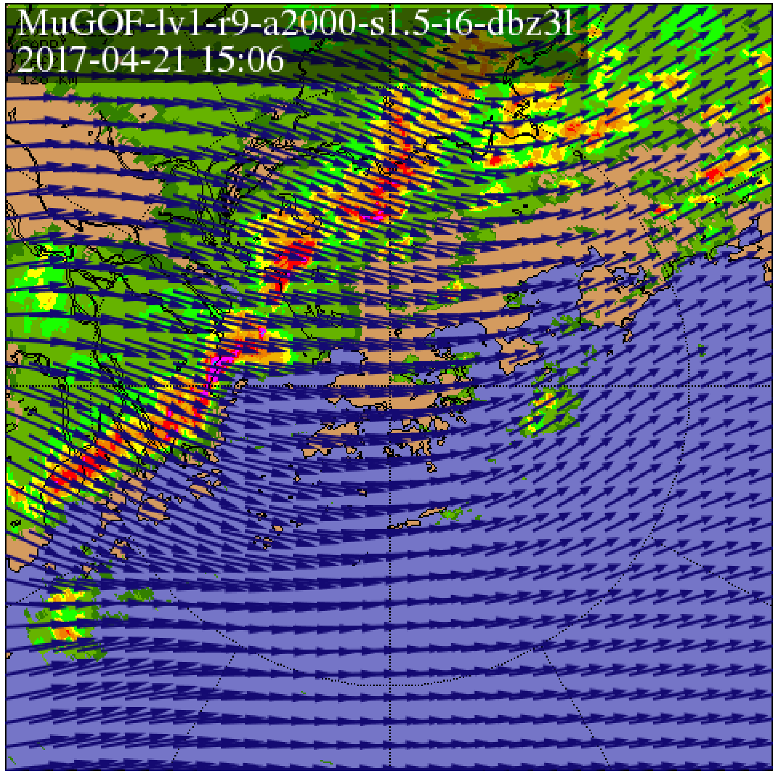


Generation of Motion Field

Consecutive Radar Images



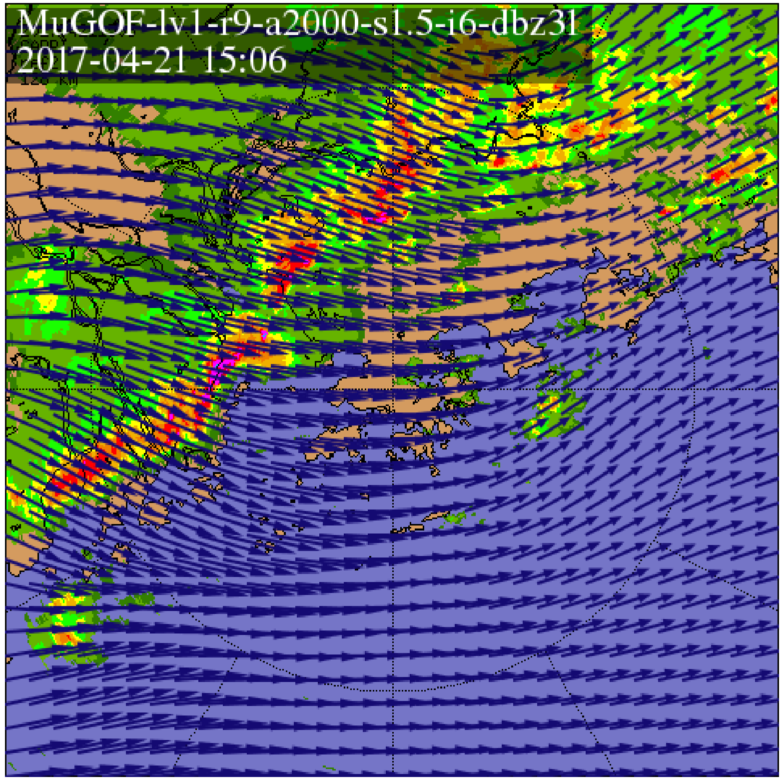
Motion Field



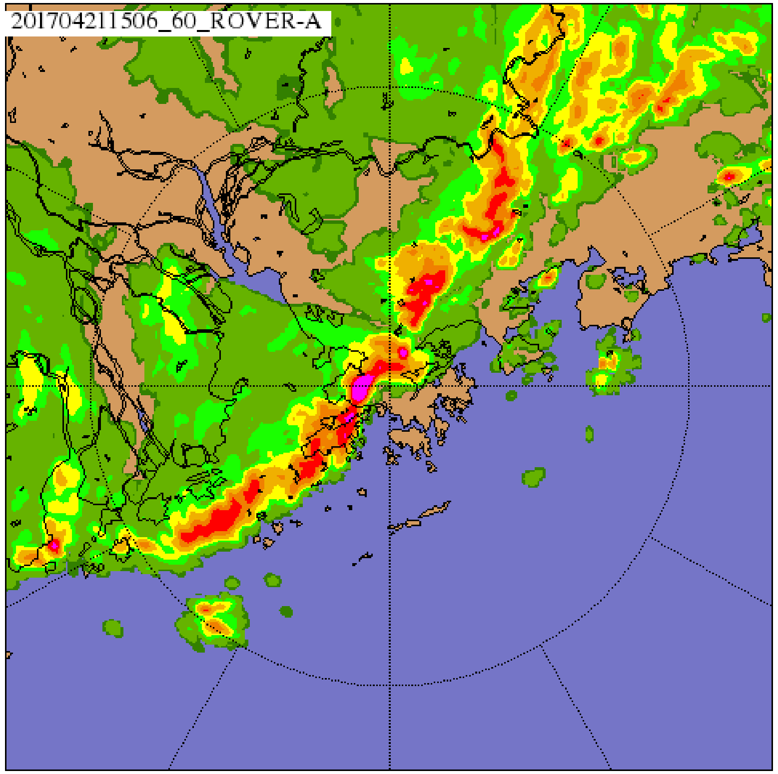
香港天文台 HONG KONG OBSERVATORY

Rainfall Nowcast by Extrapolation

Analysis



1 Hour Forecast



Radar Echo Tracking

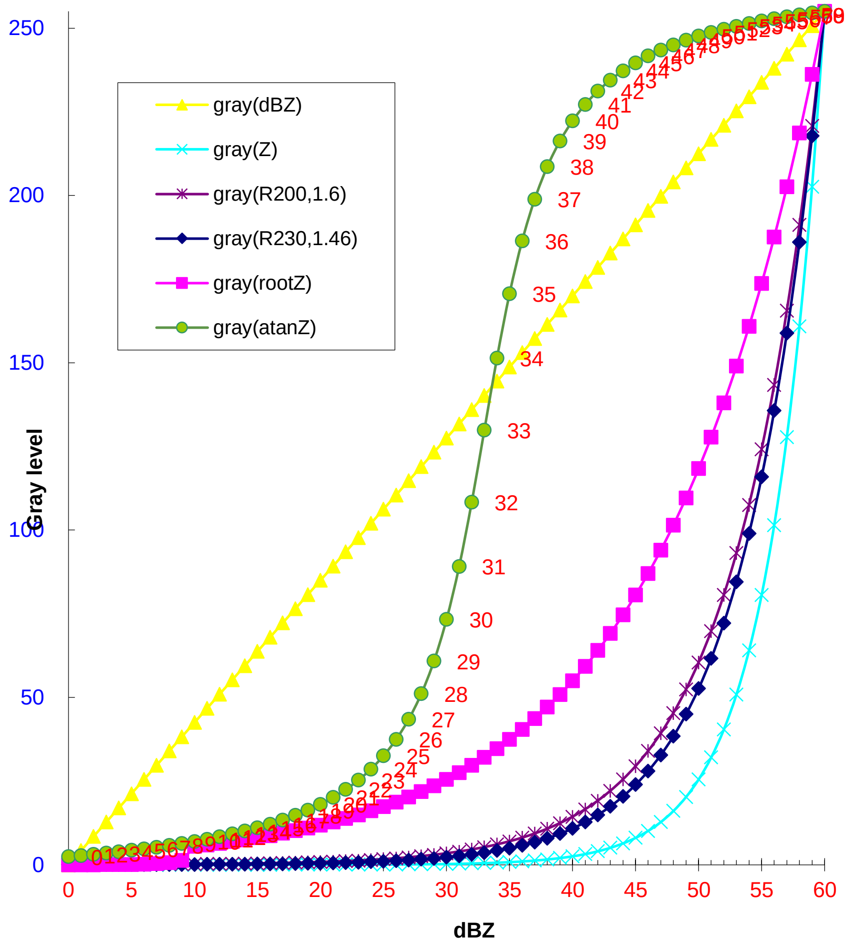
- Correlation-based
  - TREC / Co-TREC / MTREC
- Variational Optical Flow
  - MOVA / ROVER
- Deep Learning
  - ConvLSTM / ConvGRU / TrajGRU
- References:
  - *Operational Application of Optical Flow Techniques to Radar-Based Rainfall Nowcasting (Link)*
  - *Deep Learning for Precipitation Nowcasting: A Benchmark and A New Model (Link)*

Variational Optical Flow

- “ROVER“ - Real-time Optical-flow by Variational method for Echoes of Radar –
  - Enhance Radar images
  - Derive Motion Field based on the “VarFlow” algorithm developed by Bruhn et al. (2003 & 2005)

Enhancing Radar Images

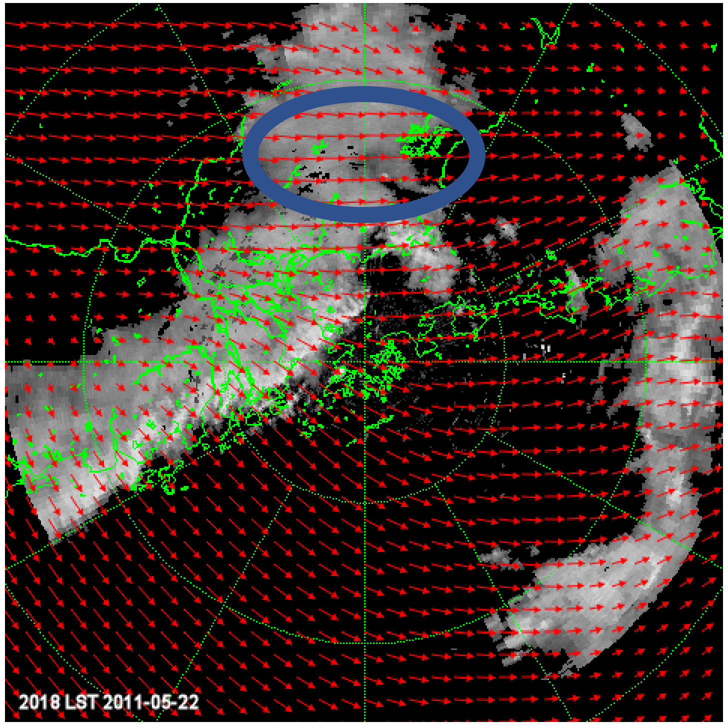
- Bowler et al. (2004): Radar or rain rate field is typically noisy and pre-smoothing is needed for a stable calculation of the partial derivatives.
- Highlight echoes from the convective regime with high dBZ values and play down echoes with intensity of less interest.

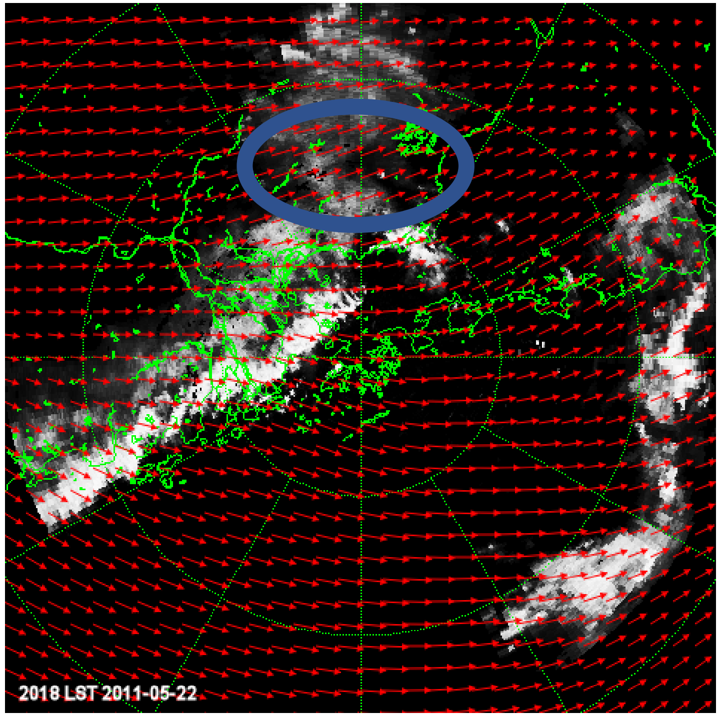


$$G(Z) = \tan^{-1}\left(\frac{Z - Z_c}{\zeta}\right)$$

香港天文台
HONG KONG OBSERVATORY

Enhancement of Radar Images





OPTICAL FLOW

- Assumption:

$$\frac{\partial I}{\partial t} + u\frac{\partial I}{\partial x} + v\frac{\partial I}{\partial y} = 0$$

- Variational Formulation

$$J = J_o + \alpha \cdot J_v$$

$$J_o = \iint \left[\frac{\partial I}{\partial t} + u\frac{\partial I}{\partial x} + v\frac{\partial I}{\partial y} \right]^2 dxdy$$

$$J_v = \begin{cases} J_{\mathrm{HS}} \\ J_{\mathrm{WW}} \end{cases}$$

where

$$J_{\mathrm{WW}} = \iint \left[\left(\frac{\partial^2 u}{\partial x^2}\right)^2 + \left(\frac{\partial^2 u}{\partial y^2}\right)^2 + 2\left(\frac{\partial^2 u}{\partial x \partial y}\right) + \left(\frac{\partial^2 v}{\partial x^2}\right)^2 + \left(\frac{\partial^2 v}{\partial y^2}\right)^2 + 2\left(\frac{\partial^2 v}{\partial x \partial y}\right) \right] dxdy \quad \text{(WW80)}$$

$$J_{\mathrm{HS}} = \iint \left[|\nabla u|^2 + |\nabla v|^2 \right] dxdy \quad \text{(HS81)}$$

in original HS formulation

FORMULATION BY BRUHN ET AL 2003

$$I_x(q)\cdot u + I_y(q)\cdot v = -I_t(q) \qquad \text{where } q \in \Omega$$

Adopting a least-square principle and applying weights to different points in the neighbourhood through Gaussian convolution, it can be solved with the following solution, where the operator $*$ denotes convolution and $K\rho$ a Gaussian kernel with standard deviation ρ. Compared with
the global variational methods

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} K_\rho * (I_x I_x) & K_\rho * (I_x I_y) \\ K_\rho * (I_y I_x) & K_\rho * (I_y I_y) \end{pmatrix}^{-1} \begin{pmatrix} -K_\rho * (I_x I_t) \\ -K_\rho * (I_y I_t) \end{pmatrix}$$

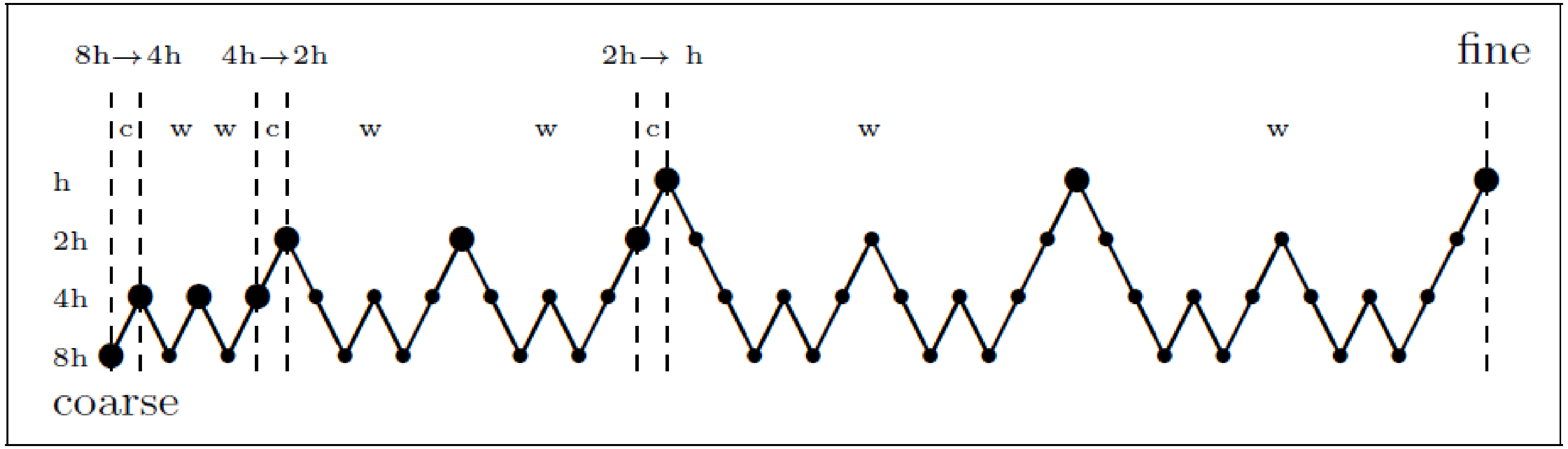
$$J_{\mathrm{HS}} = \iint \left[|\nabla u|^2 + |\nabla v|^2 \right] dxdy \qquad \text{(HS81)}$$

Local Scheme + Global Scheme

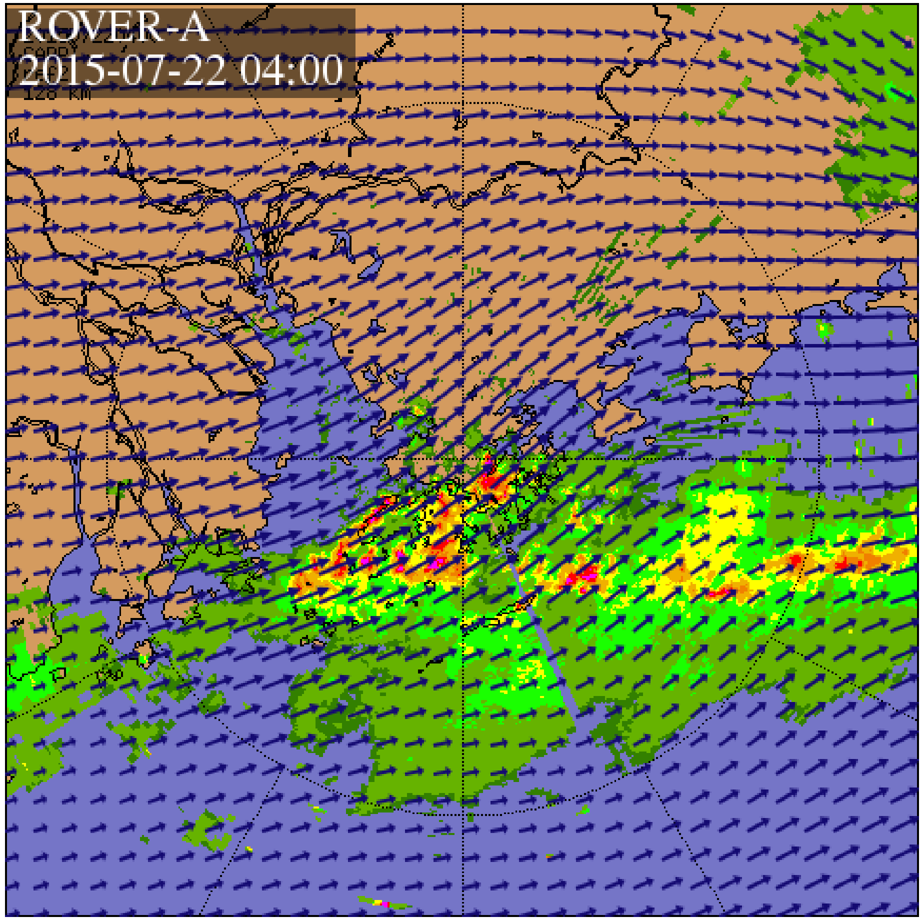
香港天文台
HONG KONG OBSERVATORY

FORMULATION BY BRUHN ET AL 2003

Bi-directional with errors at all coarser levels of the grid hierarchy corrected before going down to the next finer level.



Motion Field - Product of ROVER (Radar Echo Tracking)



Parameter Tuning & Ensemble

ROVER depends on tunable parameters:

Parameter	Significance	Value adopted in ROVER
σ	Gaussian convolution for image smoothing	9
ρ	Gaussian convolution for local vector field smoothing	1.5
α	Regularization parameters in the energy function	2000
L_f	the finest spatial scale	1
L_c	the coarsest spatial scale	7
T_r	the time interval for tracking radar echoes	6

SERN
SWIRLS
Ensemble
Rainfall
Nowcast

36-Members list

[edit]

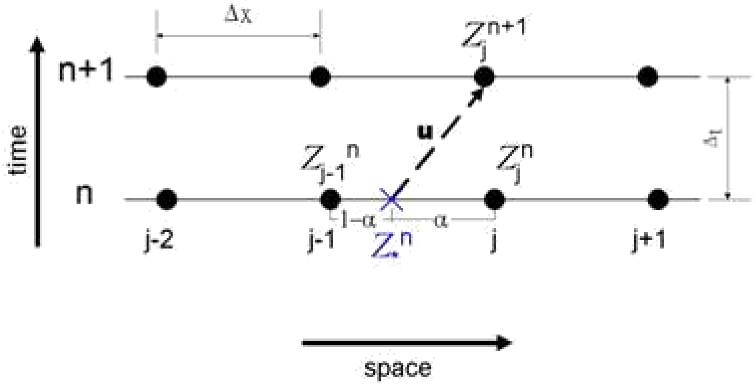
```
for dbz in 33
for lv in 1 2
for rho in 9
for alpha in 2000 10000
for sigma in 1.5 2.5 3
for interval in 6 12 30
```

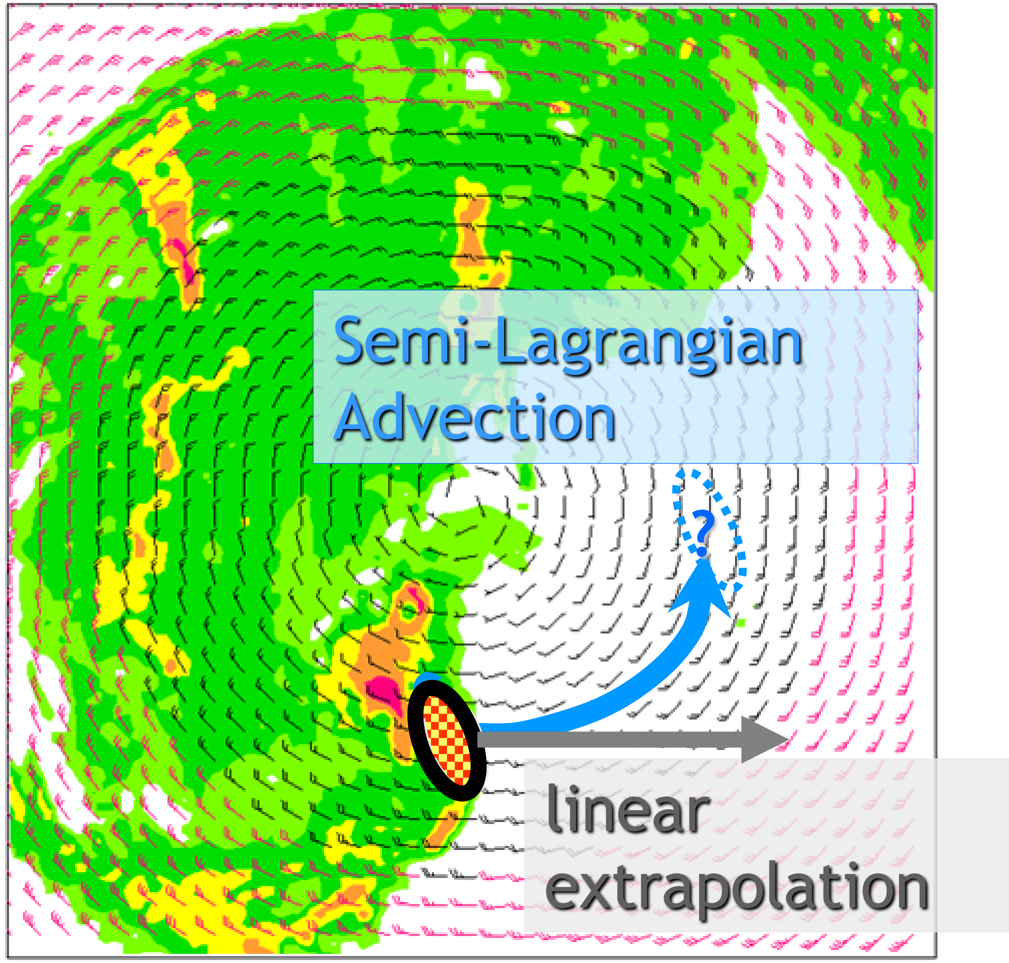
香港天文台 HONG KONG OBSERVATORY

Forecast by Extrapolation

- Semi-Lagrangian Advection (SLA)
  - Robert scheme (3 iterations to find origin point)
  - Bi-cubic interpolation
  - Flux limiter (local max, min constraint)
  - One-way nesting
  - resolution 1.1 km -> 0.5 km

$$\frac{dZ}{dt} = \frac{\partial Z}{\partial t} + \mathbf{u}\frac{\partial Z}{\partial x} = 0$$

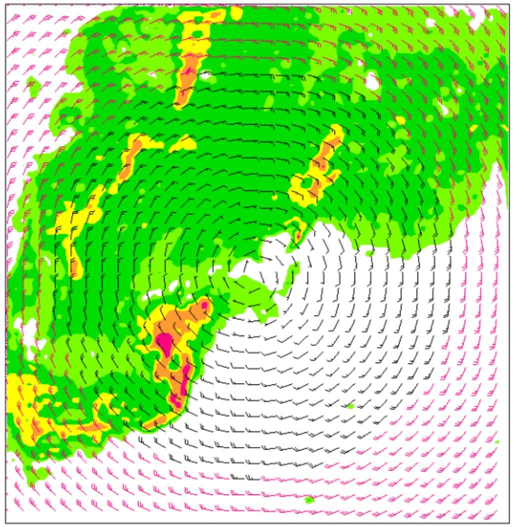




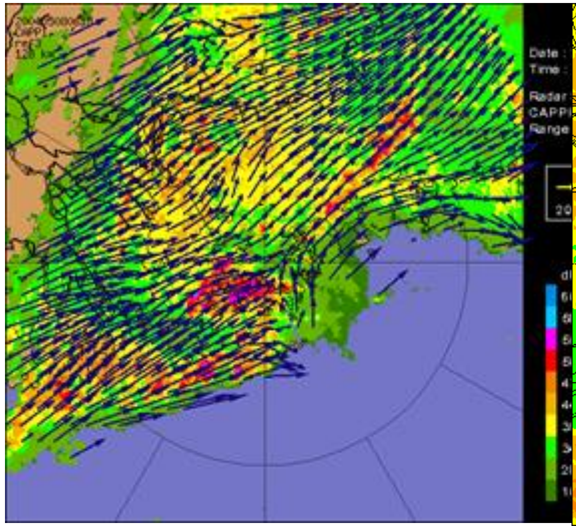
香港天文台
HONG KONG OBSERVATORY

SWIRLS SLA Examples

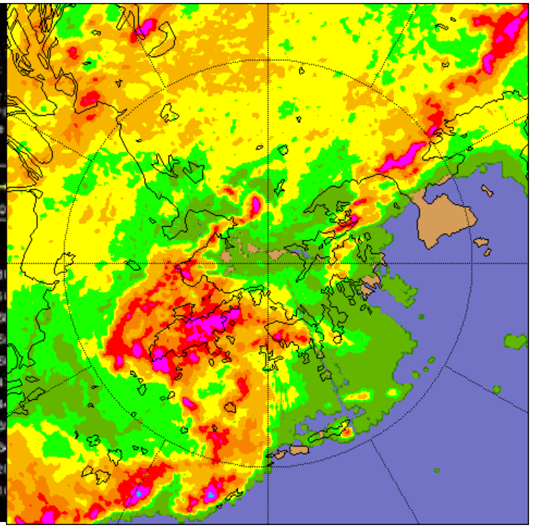
- circulation pattern preserved →
- numerically less dissipative ↓



Forecast reflectivity – pure rotation
Up to 6 hr (6-min interval)



TREC wind



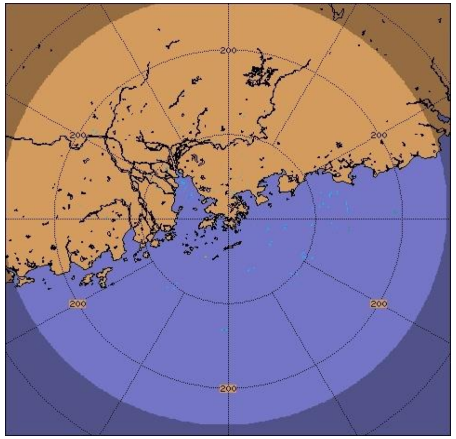
Forecast reflectivity – TREC wind
Up to 6 hr (6-min interval)

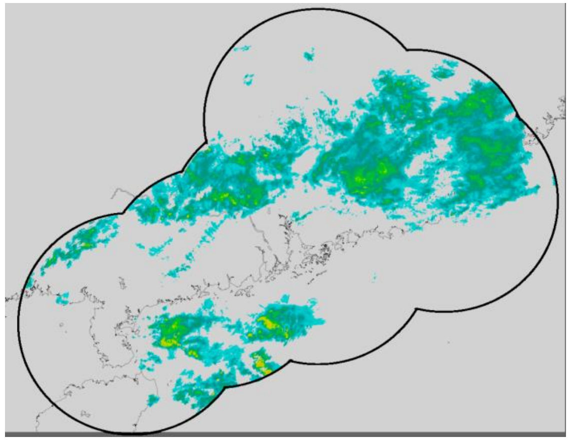
香港天文台
HONG KONG OBSERVATORY

Multi-Sensor QPF

512 km

512 km

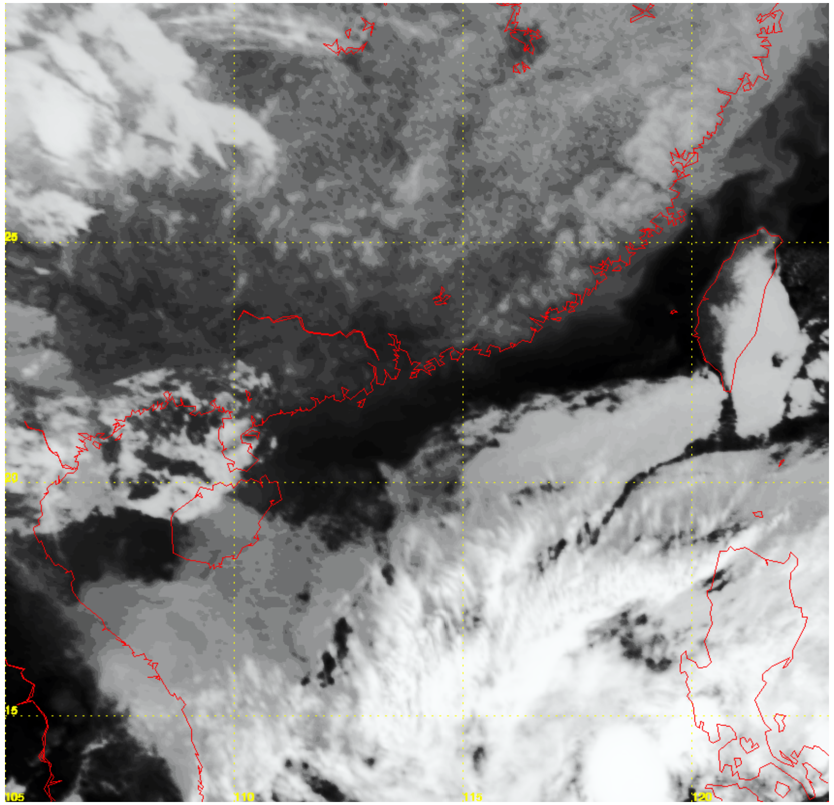




904 km

1158 km

1728 km

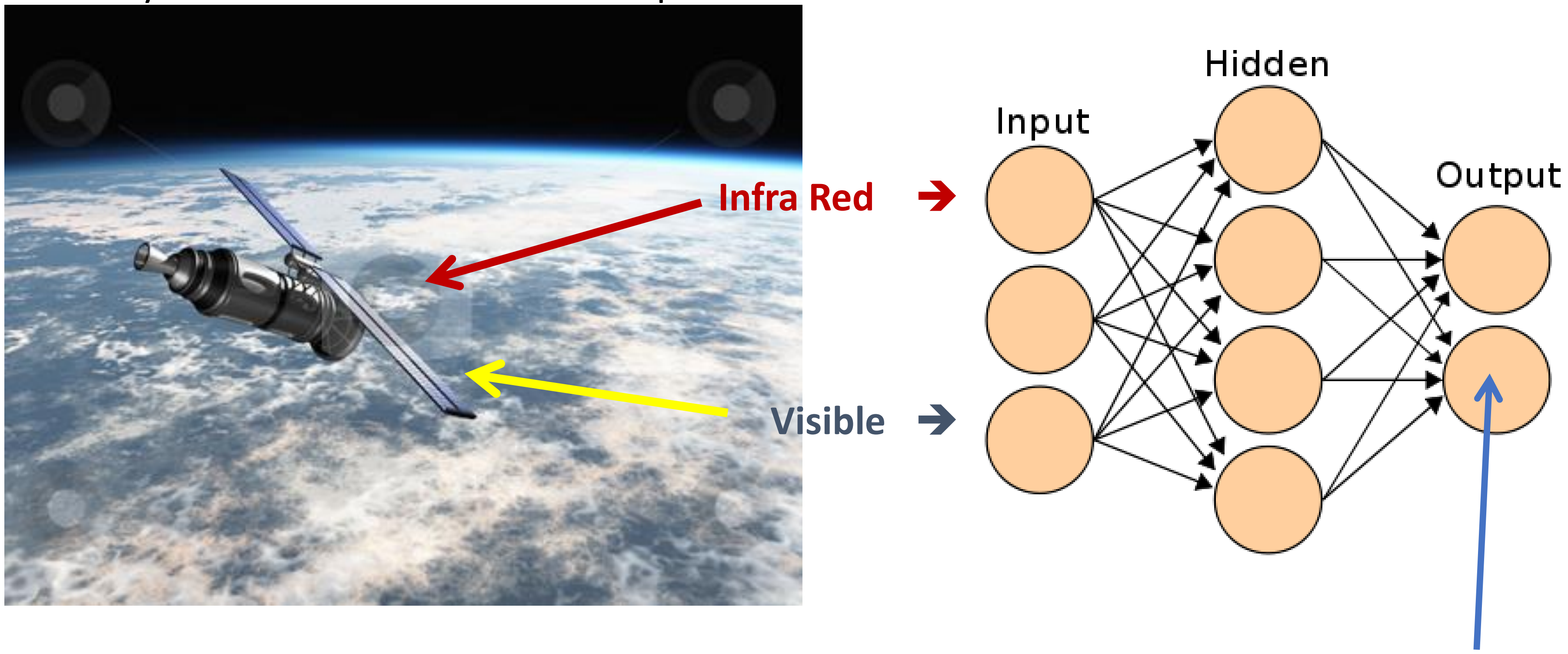


1804 km

Multi-Sensor QPF

- Indirect measurement on precipitation
- Only reflect conditions of cloud top

Artificial Neural Network



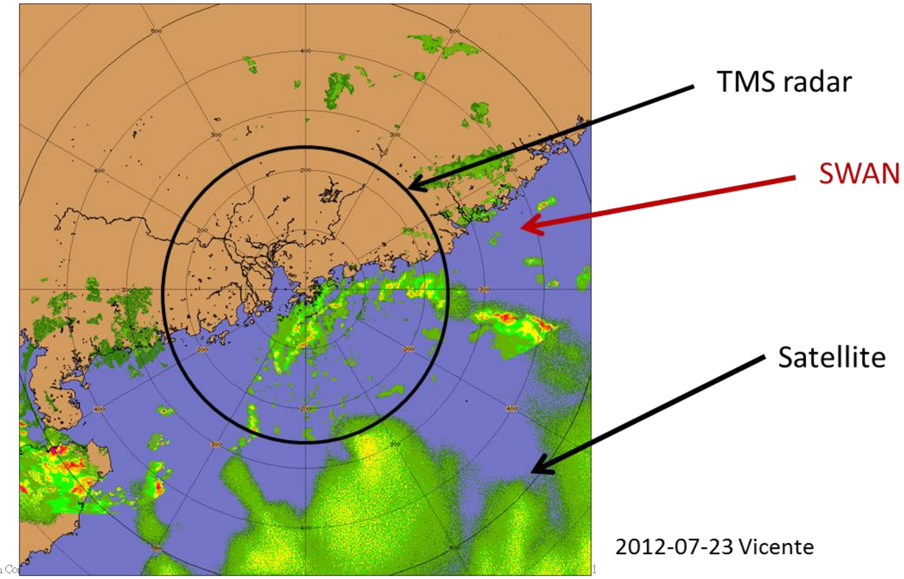
Total 23 inputs (IR, VIS values and their structures)

Focus on strong echoes of reflectivity while training the network

Composite

	TMS radar	SWAN	Satellite
Dimension	512km x 512km	1158km x 904 km	1804km x 1728km
Temporal Resolution	6min	6min	1hr

- After projection, all data have the same spatial resolution of **1km/pixel**
- Satellite data are advected by its own motion field to 6-min interval data



2012-07-23 Vicente

Probabilistic QPF

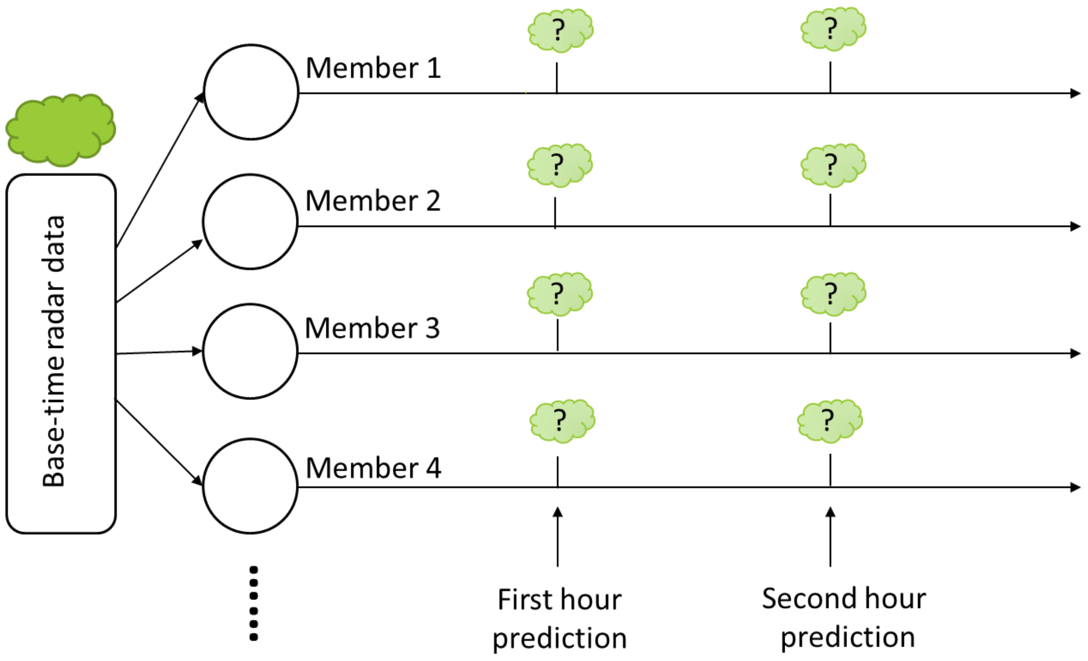
香港天文台 HONG KONG OBSERVATORY

Why?

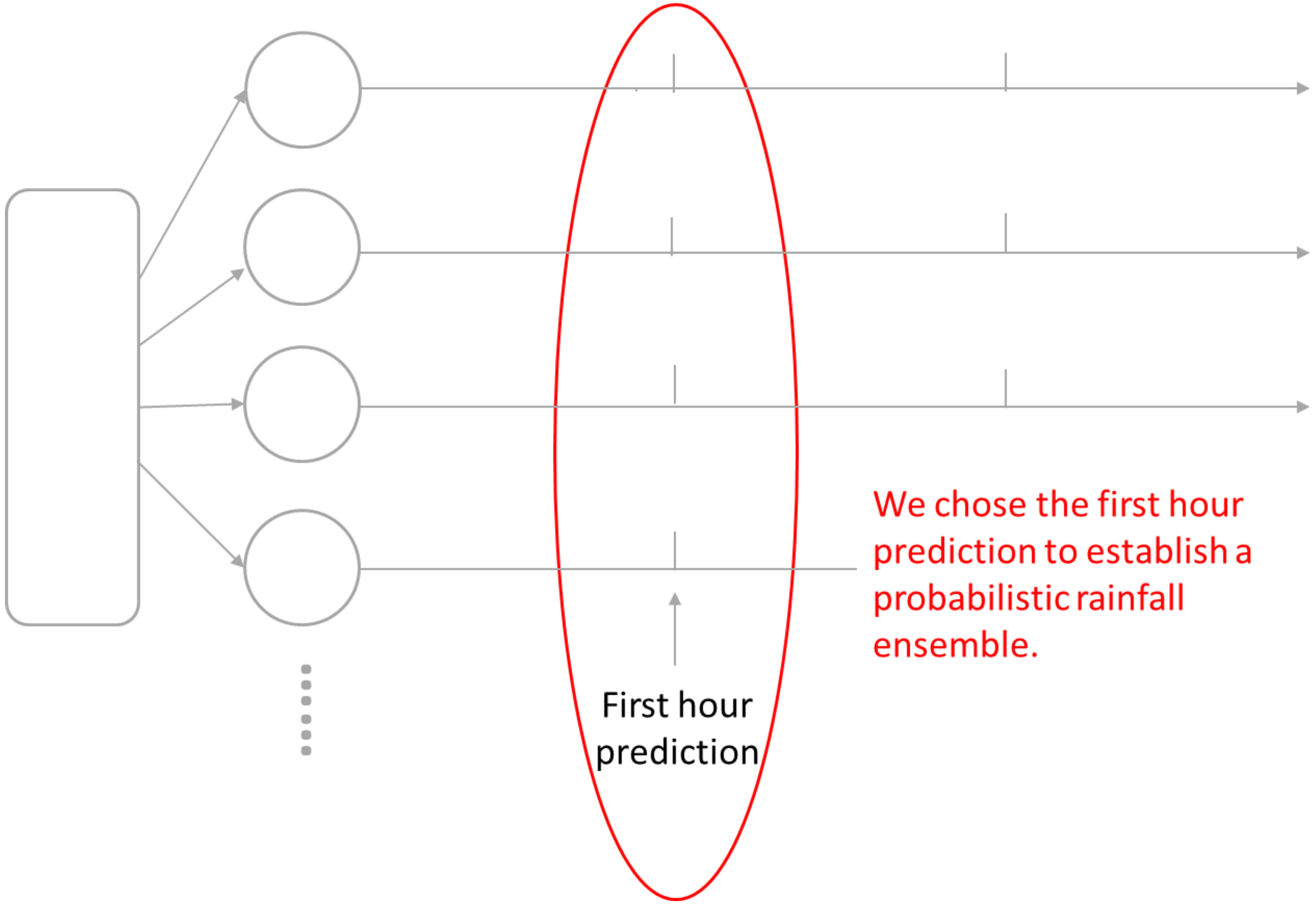
1. Better support for Rainfall Warning System
2. Facilitate cost-benefit analyses
3. More tailored to the needs of organizations under various operational constraints

SWIRLS Ensemble Rainfall Nowcast

- By tuning the 6 parameters, 36 sets of parameters have been experimented, i.e. ensemble of 36 members.

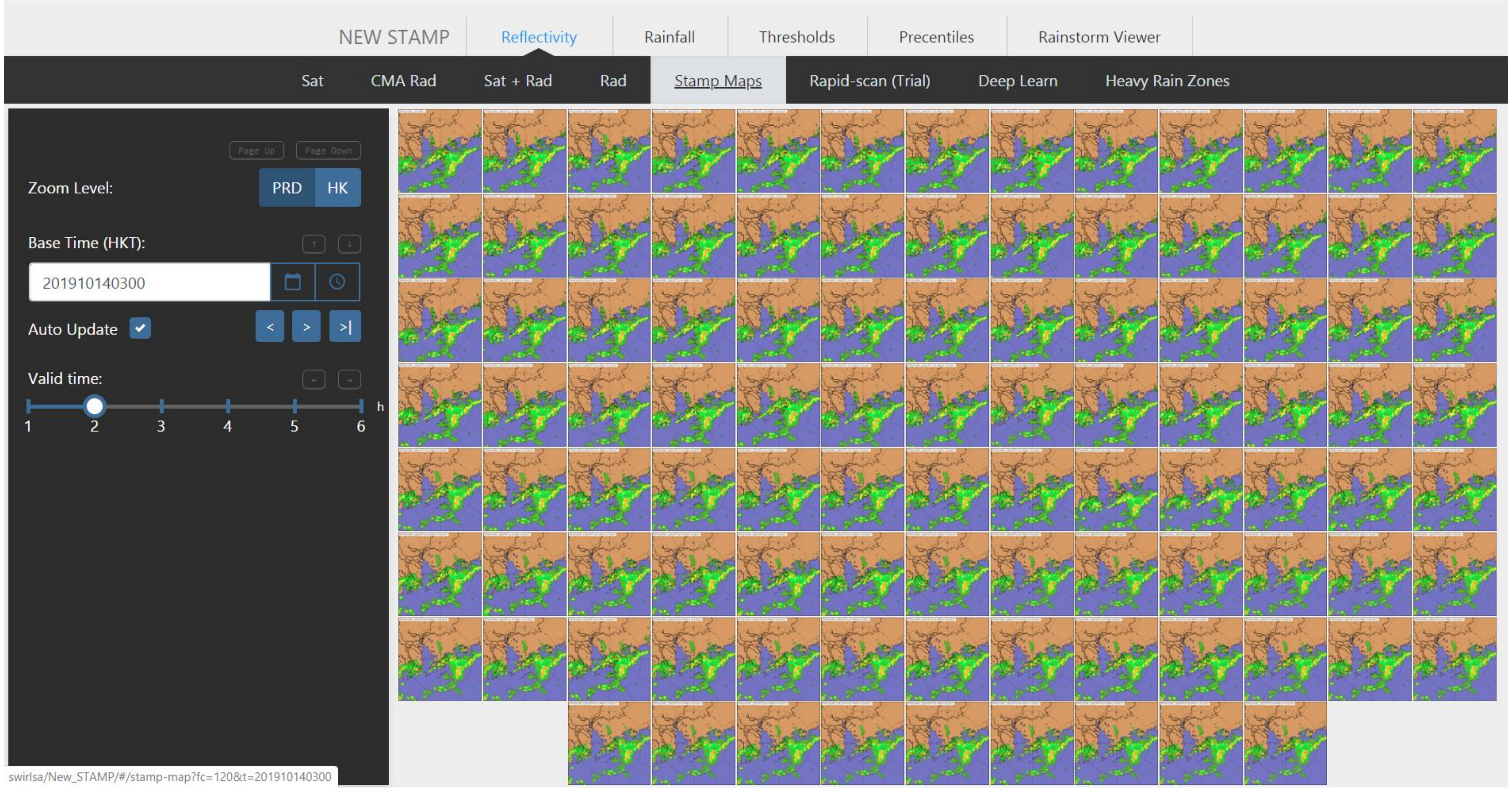


Probabilistic QPF (PQPF)



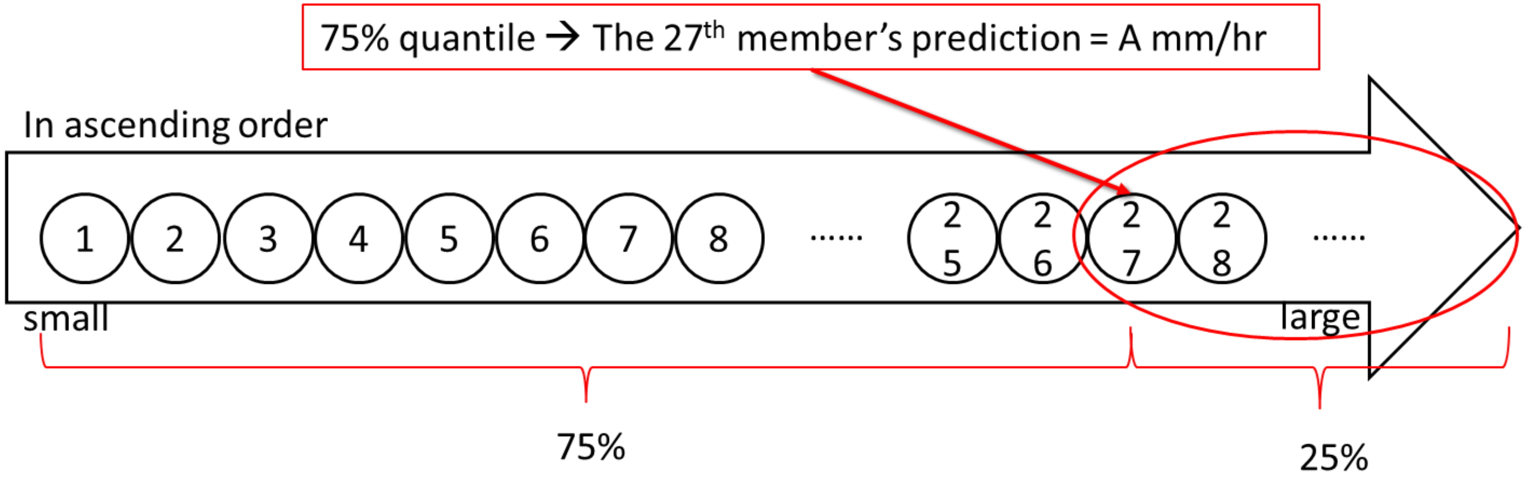
We chose the first hour prediction to establish a probabilistic rainfall ensemble.

Stamp Map


NEW STAMP
Reflectivity
Rainfall
Thresholds
Precentiles
Rainstorm Viewer
Sat
CMA Rad
Sat + Rad
Rad
Stamp Maps
Rapid-scan (Trial)
Deep Learn
Heavy Rain Zones
Page Up
Page Down
Zoom Level:
PRD
HK
Base Time (HKT):
201910140300
Auto Update
Valid time:
1
2
3
4
5
6
h
swirlsa/New_STAMP/#/stamp-map?fc=120&t=201910140300

PQPF Product 1
Rainfall Intensity Contour Map

- For Specific Exceedance Probability:

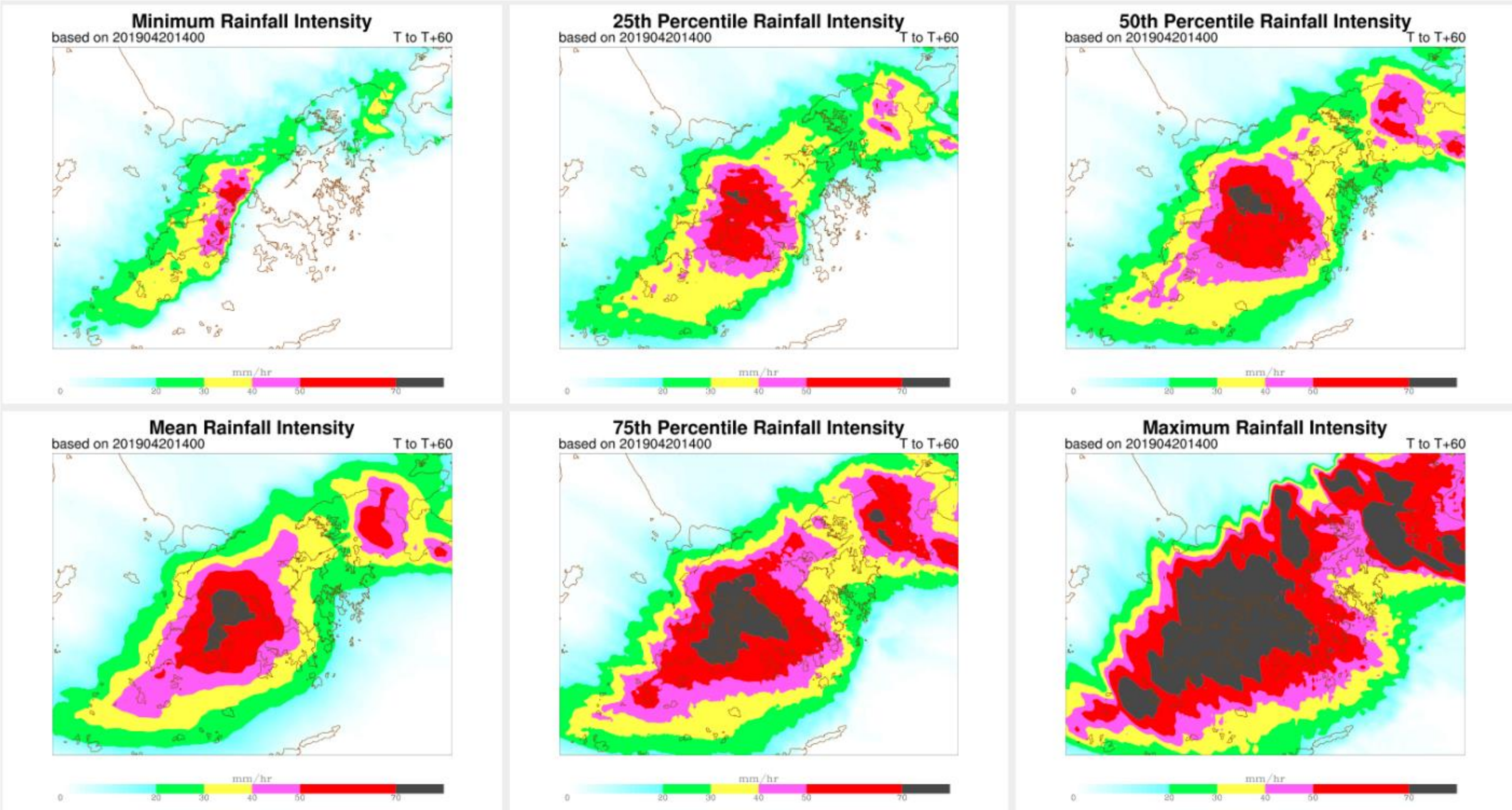


25% of the member predict hourly rainfall greater than A mm/hr
→ 25% probability of rainfall exceeding A mm/hr

The 75% quantile has a 25% exceedance probability

HONG KONG OBSERVATORY 香港天文台

Rainfall Intensity at Fixed Percentile



香港天文台 HONG KONG OBSERVATORY

PQPF Product 2
Probability Contour Map

- For Specific Intensity Threshold

36 members produce 36 hourly rainfall predictions

Set a rainfall intensity threshold to make Yes/No decisions:
If :

No. of Yes = Y

No. of No = N

Then probability of the hourly rainfall exceeds a certain threshold is given by

$$\text{Probability} = \frac{Y}{Y+N}$$

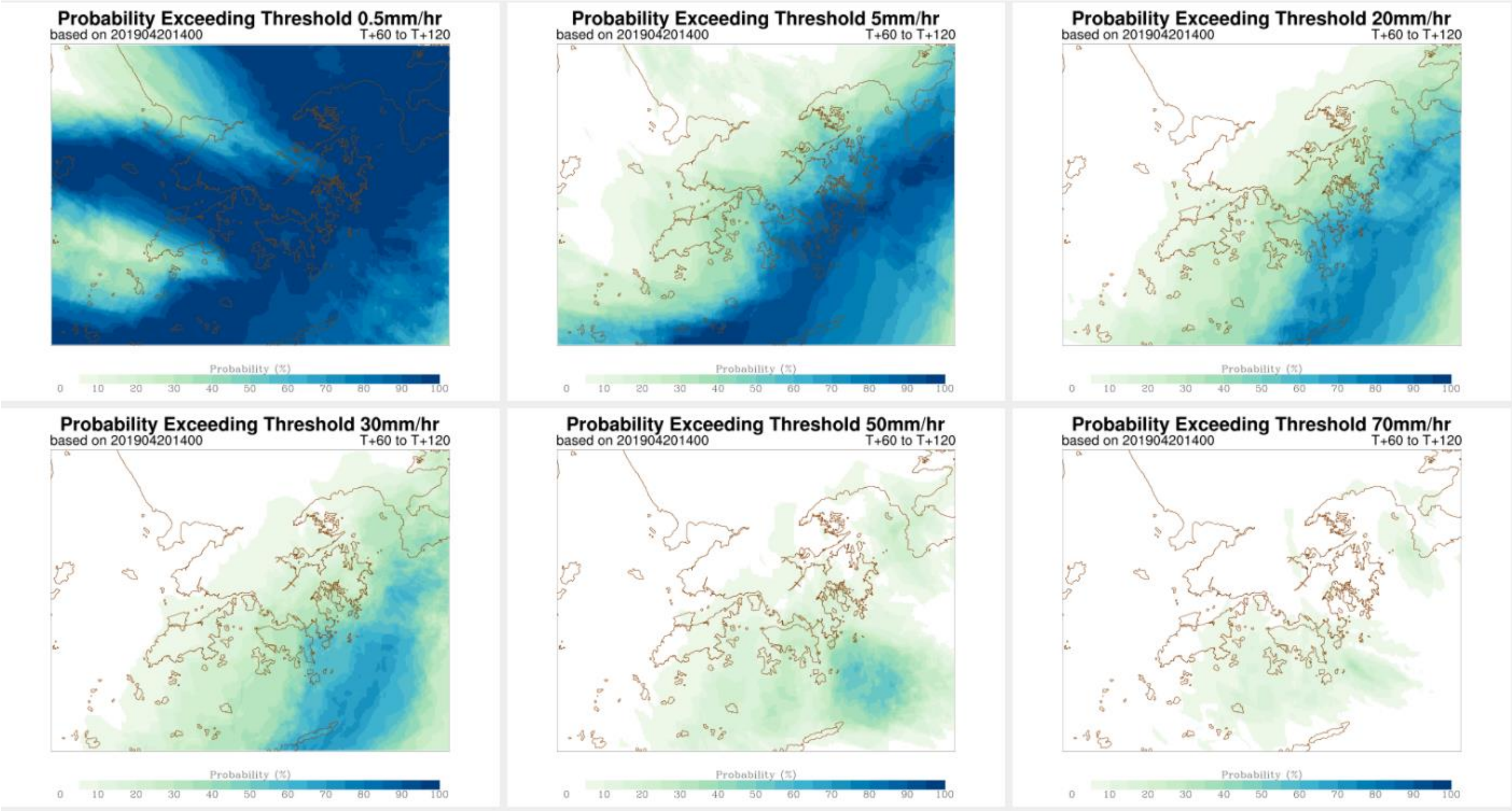
Selected thresholds:

0.5mm/hr

5mm/hr

30mm/hr

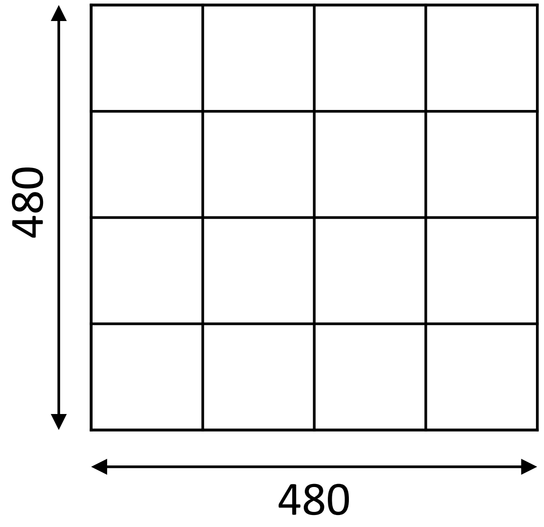
Probability of Exceeding Fixed Intensity



Verification and Analyses

Verified against Radar QPE data:

- resolution 480X480 pixels
- Generated every 6 minutes

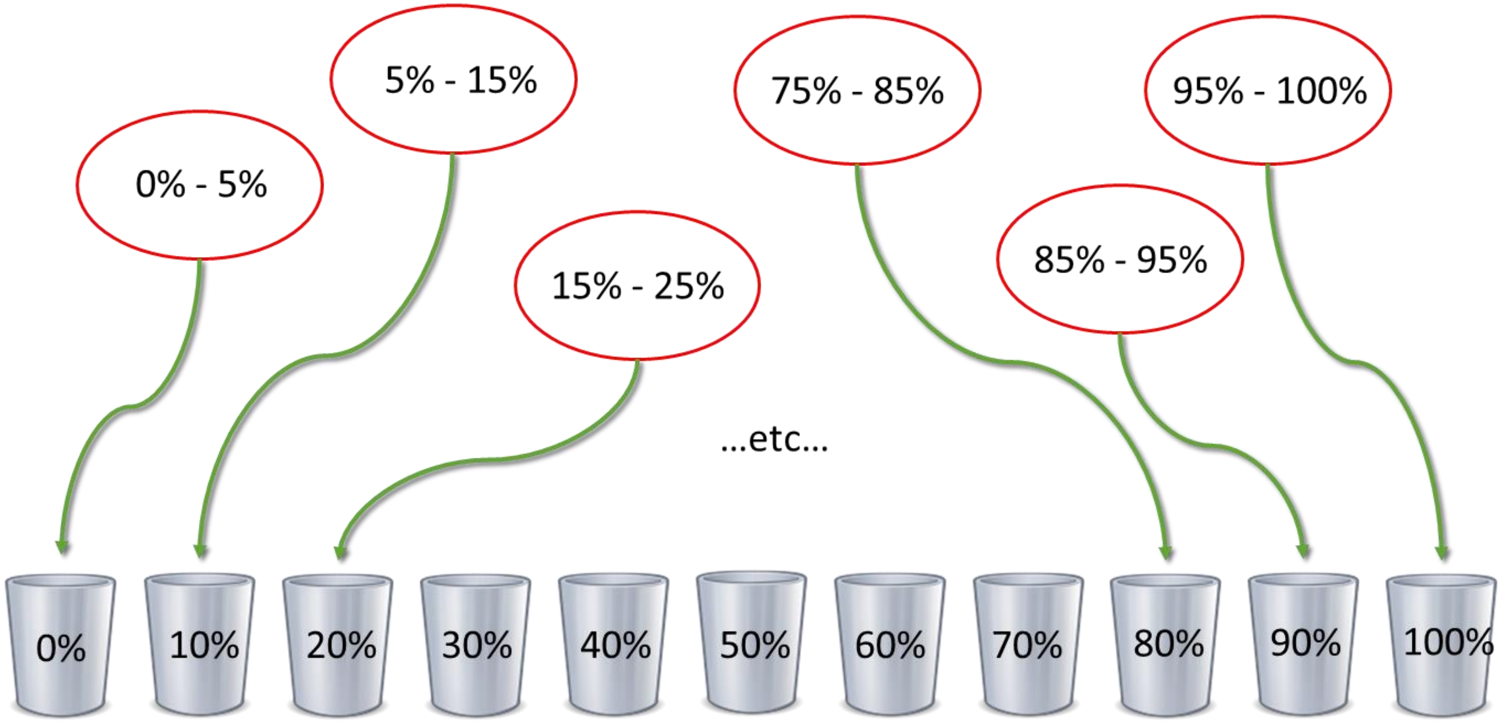


One datum for each grid

香港天文台 HONG KONG OBSERVATORY

Verification and Analyses

Divide the range of forecast probability into 11 bins : 0% -5%, 5%-15%, etc.



Verification and Analyses

Reliability Diagram - *degree to which the model forecast probabilities agree with the observed frequencies*

Interpretation– A 10-event example

10 events predicted prob.

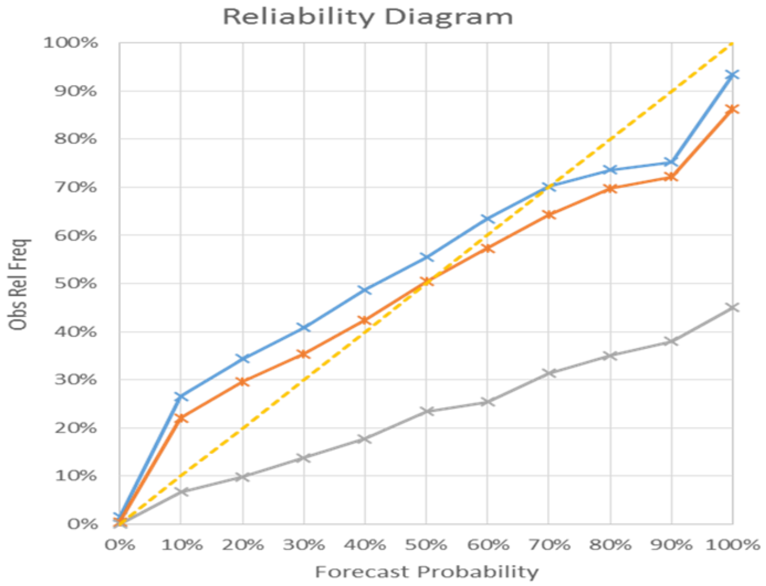
10%	10%	10%	10%	10%
10%	10%	10%	10%	10%

10-events actual occurrences

N	N	N	Y	N
N	N	N	N	N

Expected to happen once out of 10 times

→observed relative frequency = 1/10 =10%

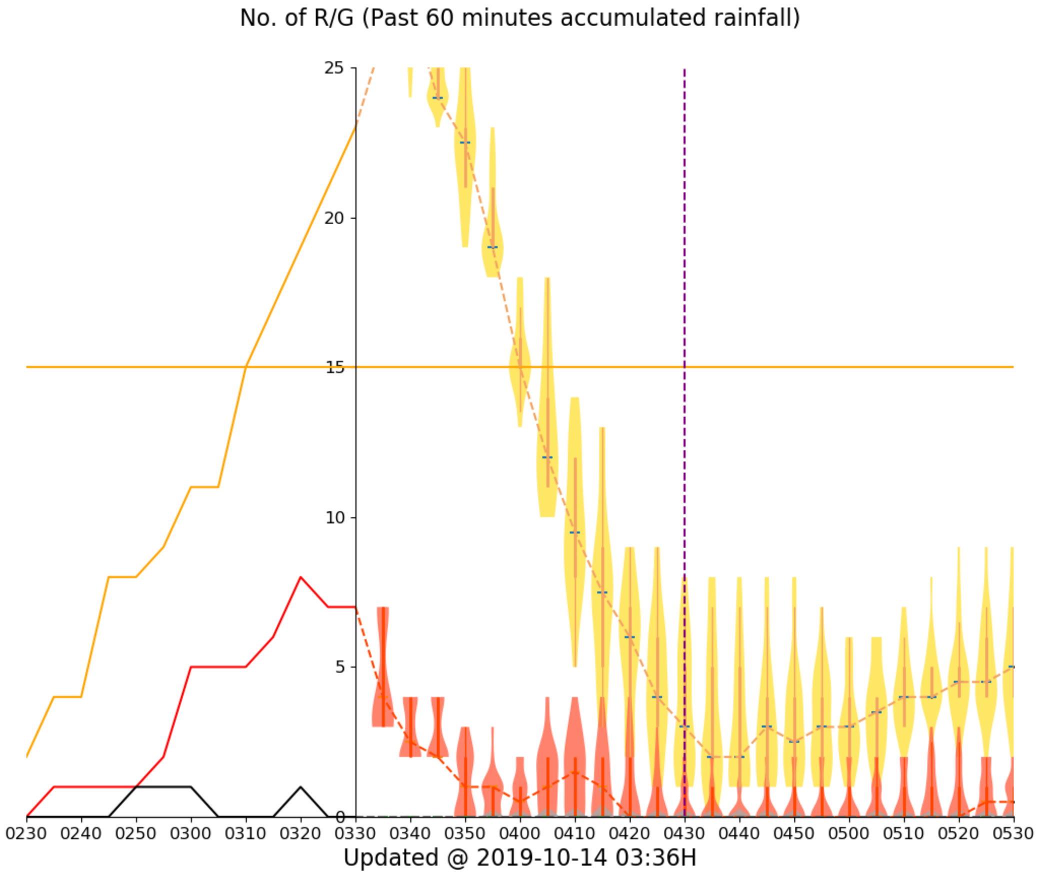


forecast probability = observed relative frequency

→ the probability forecast is perfectly reliable

香港天文台
HONG KONG OBSERVATORY

Probability in Time Series



SWIRLS Applications

香港天文台
HONG KONG OBSERVATORY

Rainstorm Warning System

- designed with 3 levels of severity to alert the public about the occurrence of *widespread heavy rain which is likely to persist* and bring about major disruptions of different scales
- to ensure a state of readiness within the essential services to deal with emergencies
- different levels of impact requiring different responses:

rainfall ≥ 30 mm

- may develop into RED or BLACK signal situations
- flooding in some low-lying and poorly drained areas
- *should reduce exposure to risks such as flooding*

rainfall ≥ 50 mm

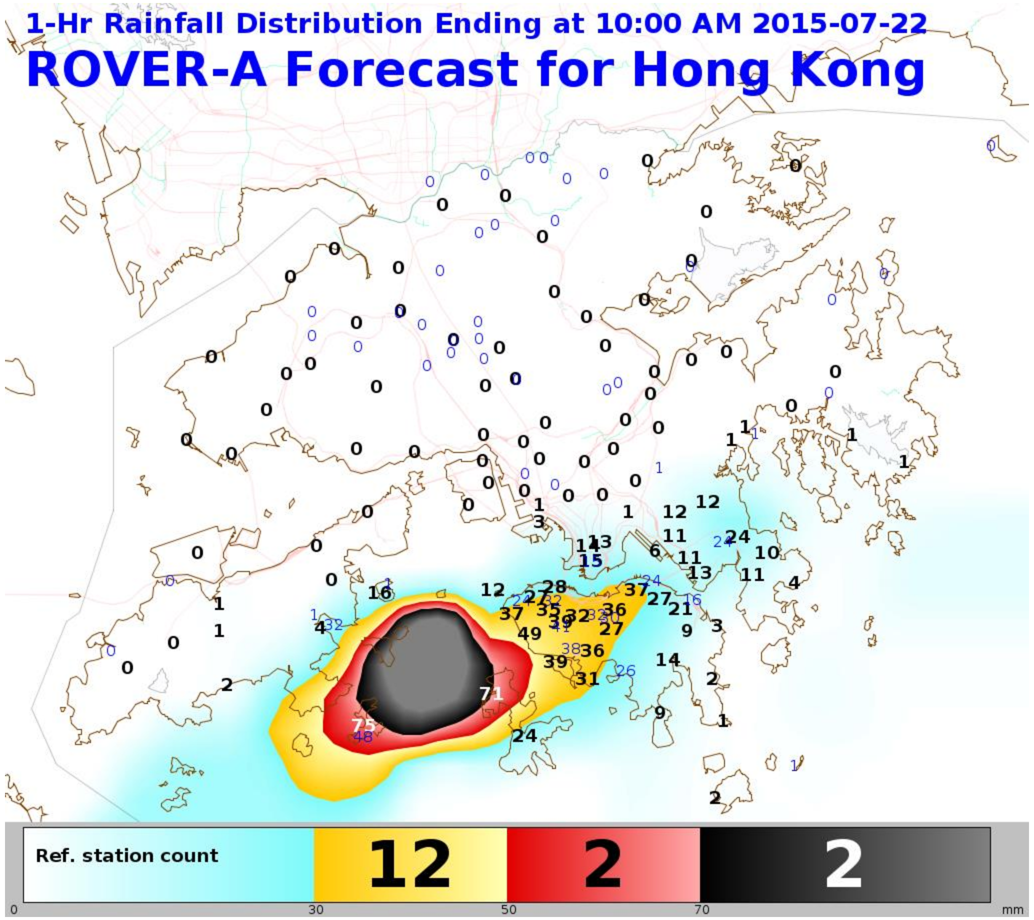
- (RED or BLACK) serious road flooding and traffic congestion are likely
- gov. depts., transport operators & other public sectors to response
- *students to stay in safe places (either home or school)*

rainfall ≥ 70 mm

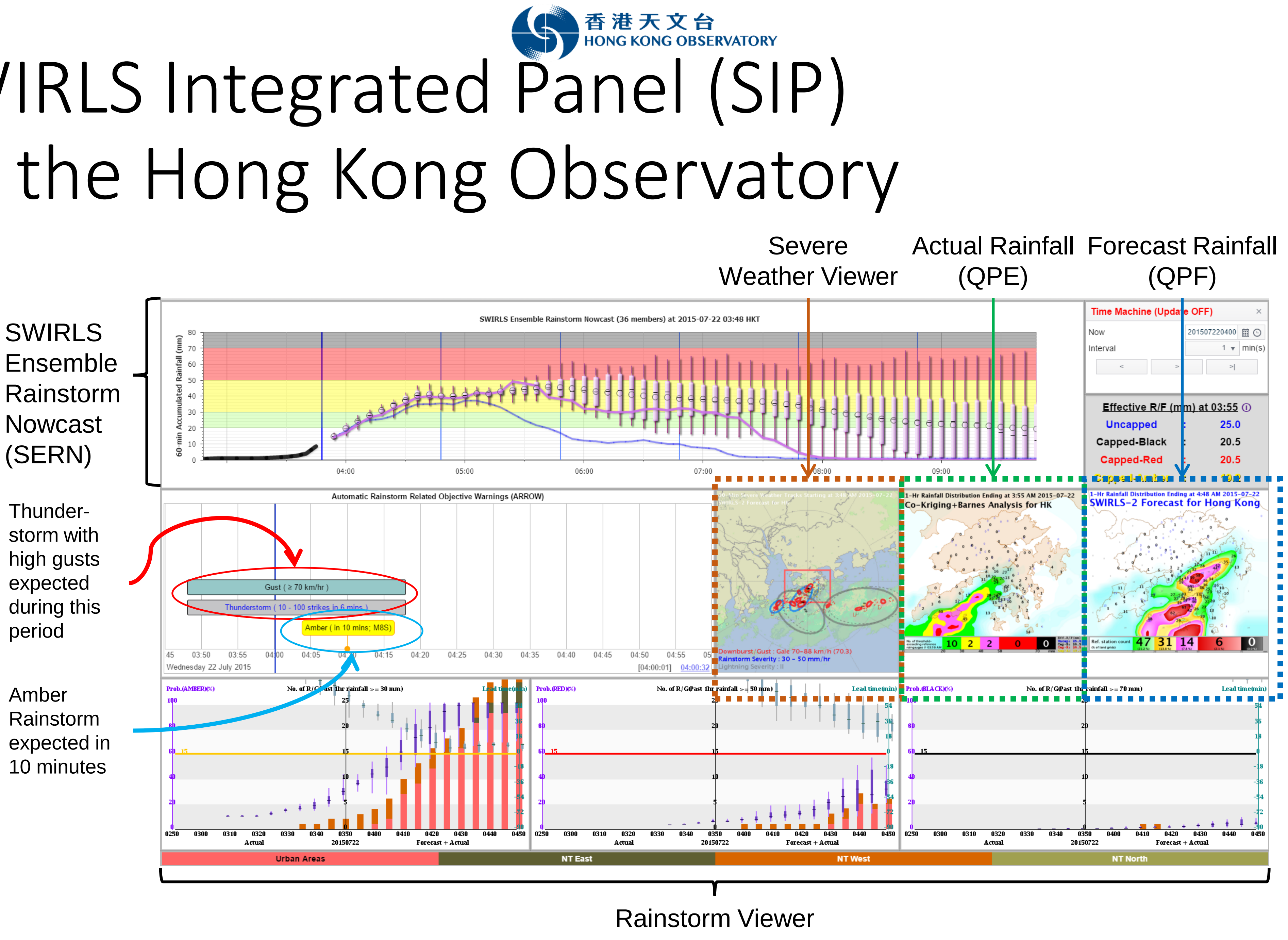
- *stay indoors or take safe shelter until the heavy rain has passed*
- *employees working in exposed areas should stop work and take shelter*

http://www.weather.gov.hk/wservice/warning/rainstor.htm

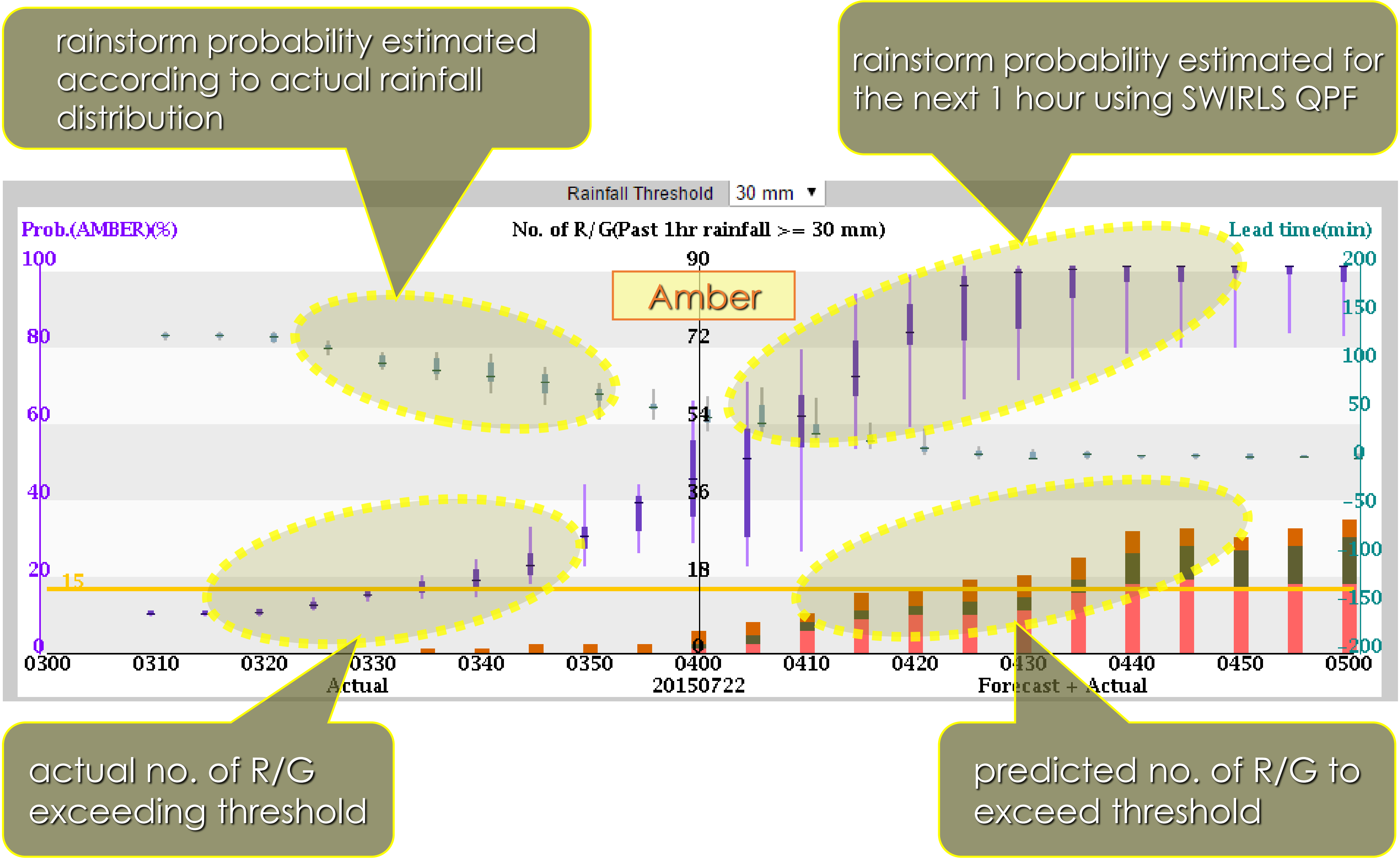
Counting Rain Gauges



SWIRLS Integrated Panel (SIP) for the Hong Kong Observatory

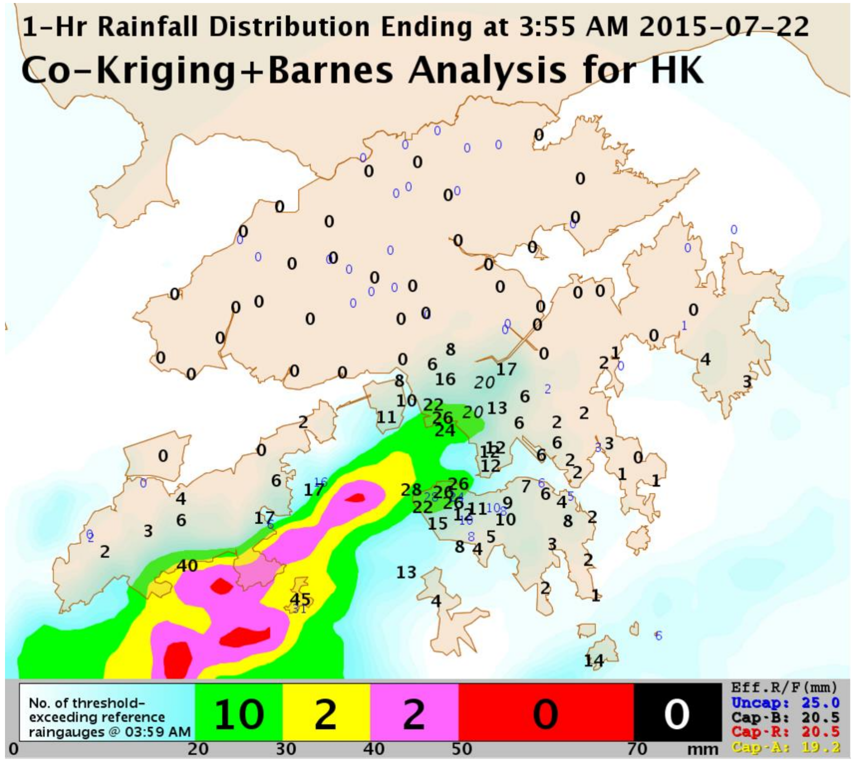


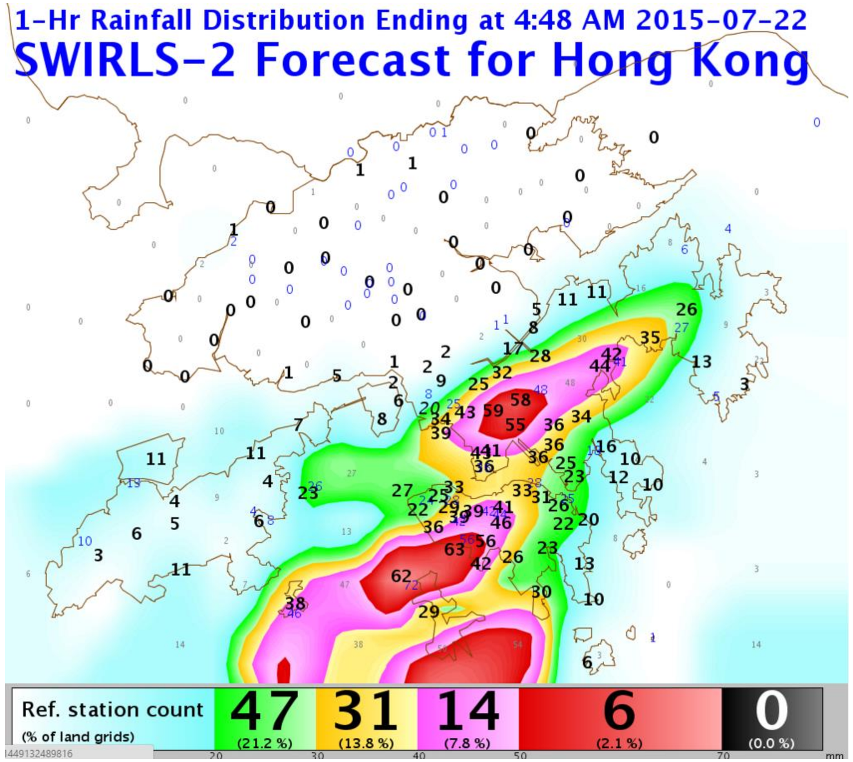
SWIRLS Rainstorm Viewer for the Hong Kong Observatory



香港天文台
HONG KONG OBSERVATORY

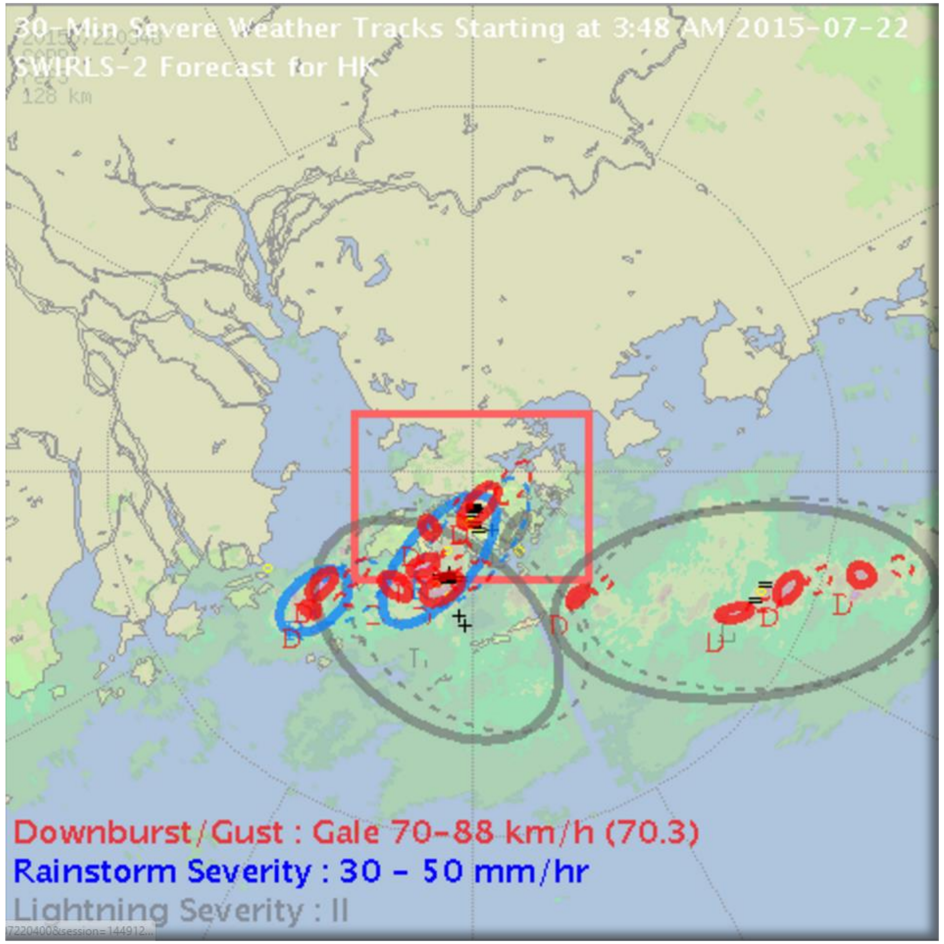
QPE/QPF Chart





香港天文台
HONG KONG OBSERVATORY

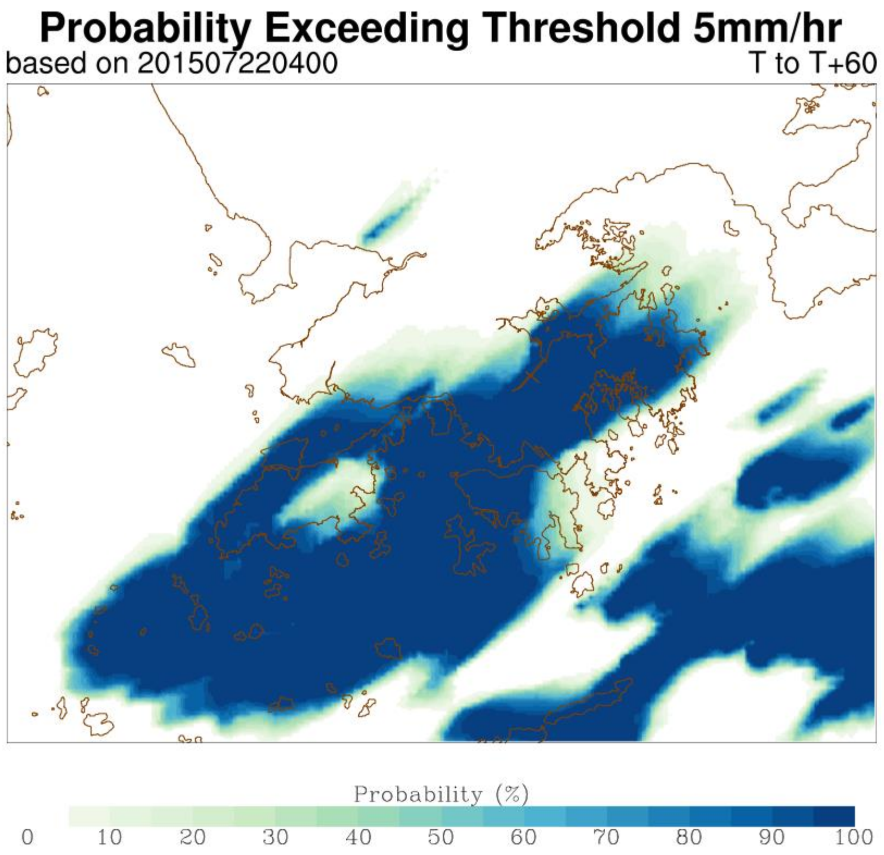
Severe Weather Map

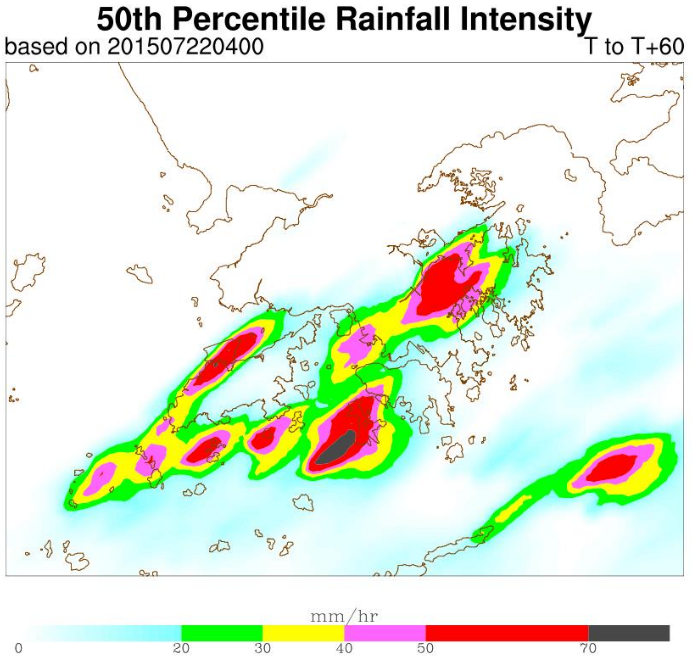


Legend

- area with hail potential
- 30-min forecast location of hail
- area with severe gust potential
- 30-min forecast location of severe gust
- area with rainstorm potential
- 30-min forecast location of rainstorm
- area with lightning potential
- 30-min forecast location of lightning
- —/⊥ detected -ve CG lightning location
- detected CC lightning location
- Warning area

Probabilistic Rainfall Nowcast



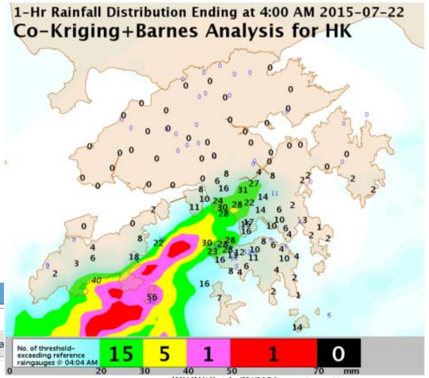


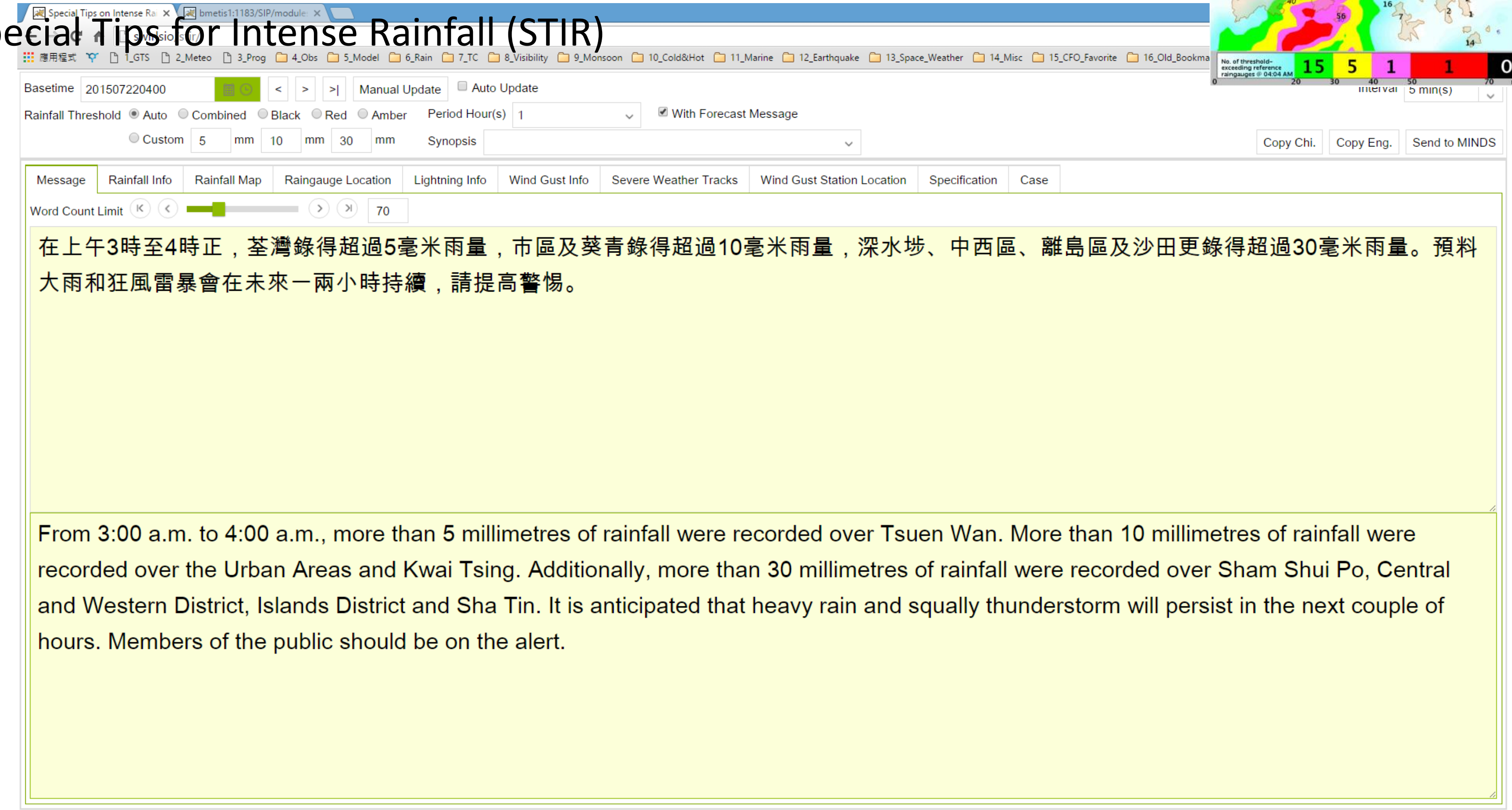
Based on SERN (SWIRLS Ensemble Rainfall Nowcast)

香港天文台
HONG KONG OBSERVATORY

Textual Description of QPE/QPF

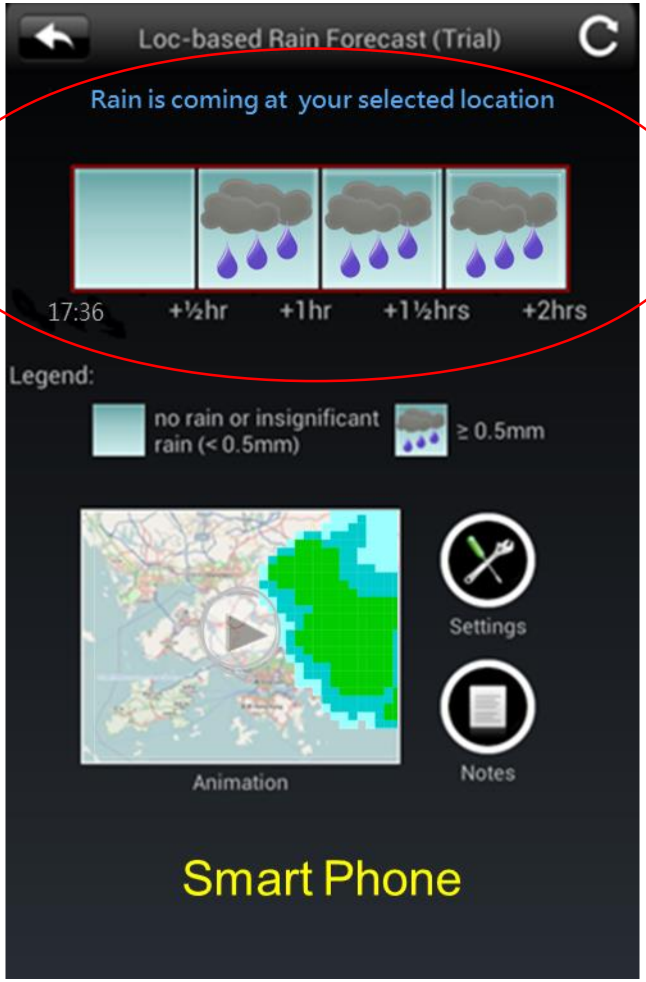
Special Tips for Intense Rainfall (STIR)





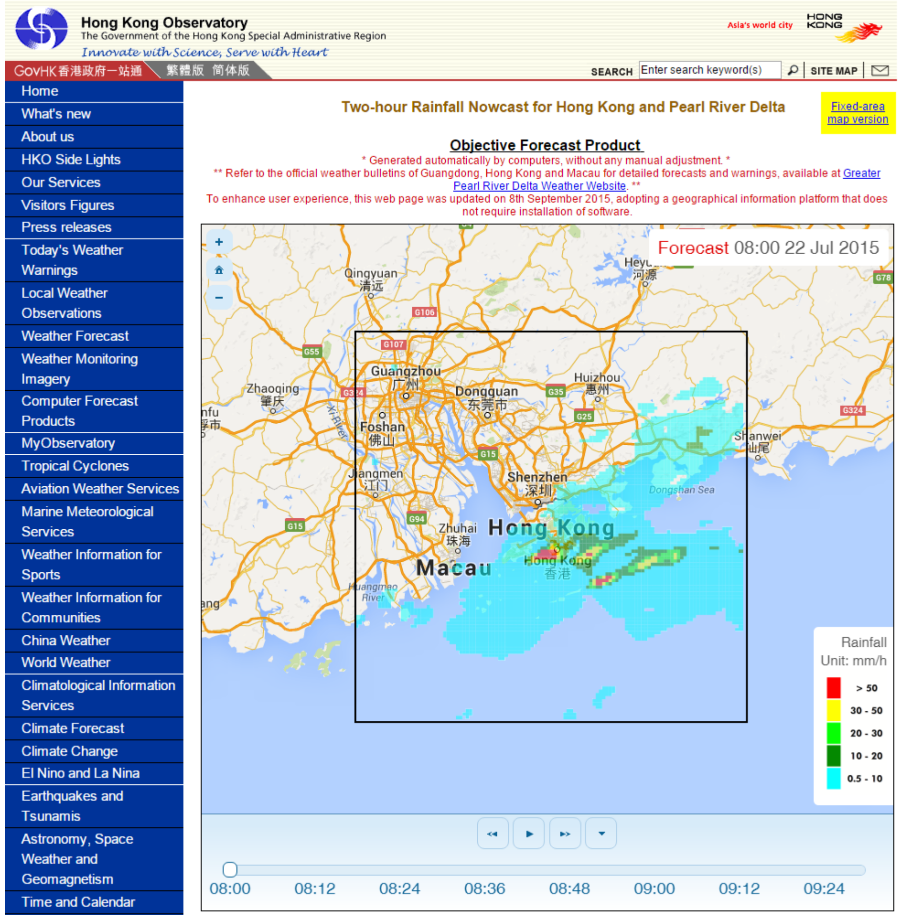
Rainfall Nowcast with Apps

- Rainfall Forecast in half hour interval in the next two hours
- Actively notify users upon change in state



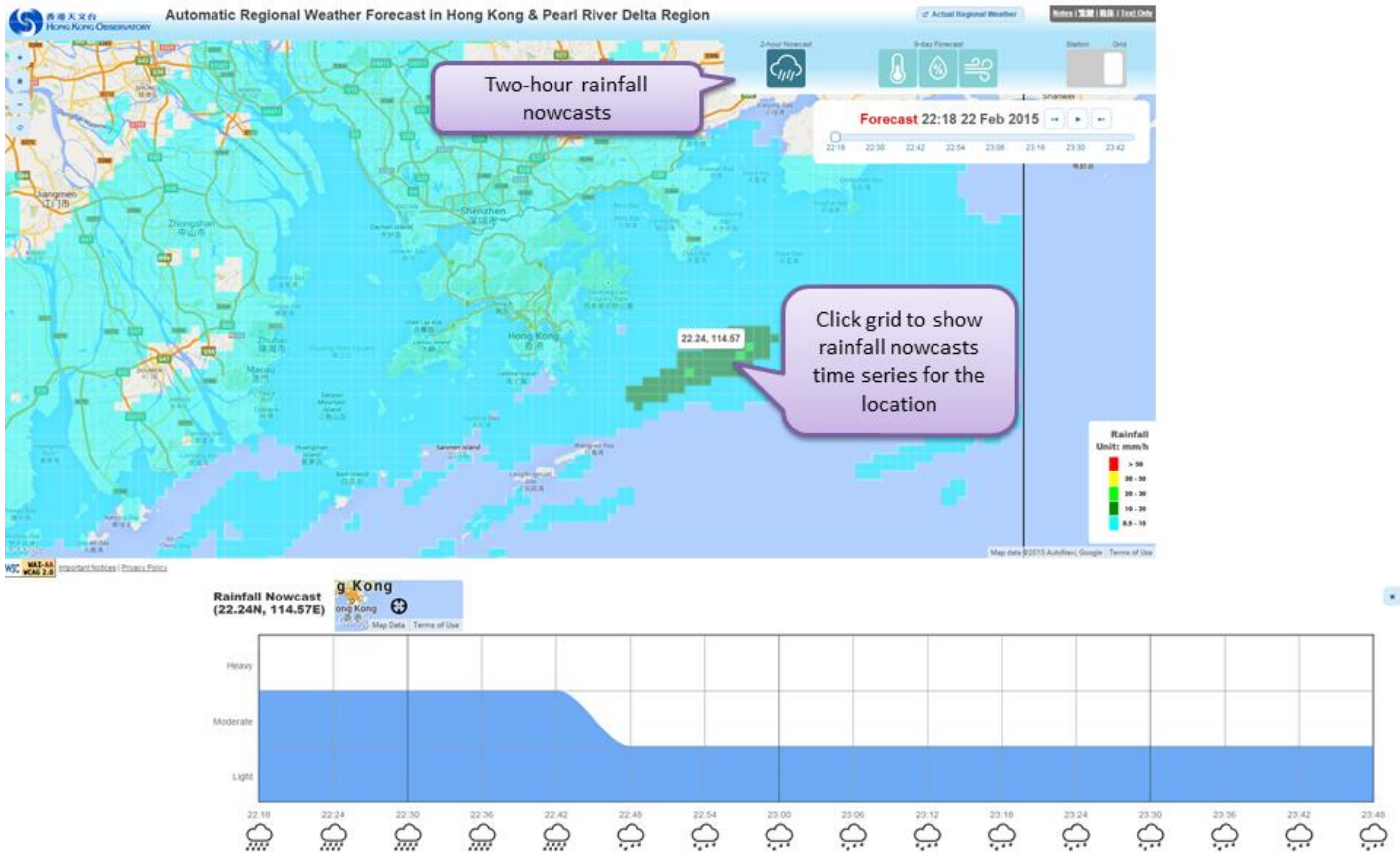
香港天文台
HONG KONG OBSERVATORY

Rainfall Nowcast for the Public



香港天文台
HONG KONG OBSERVATORY

Rainfall Nowcast integrated with Automatic Regional Forecast



The End

Thank You!