Probabilistic QPF & Impact-based Forecasting / Warning

WC Woo, Hong Kong Observatory

Typhoon Committee Roving Seminar 2019

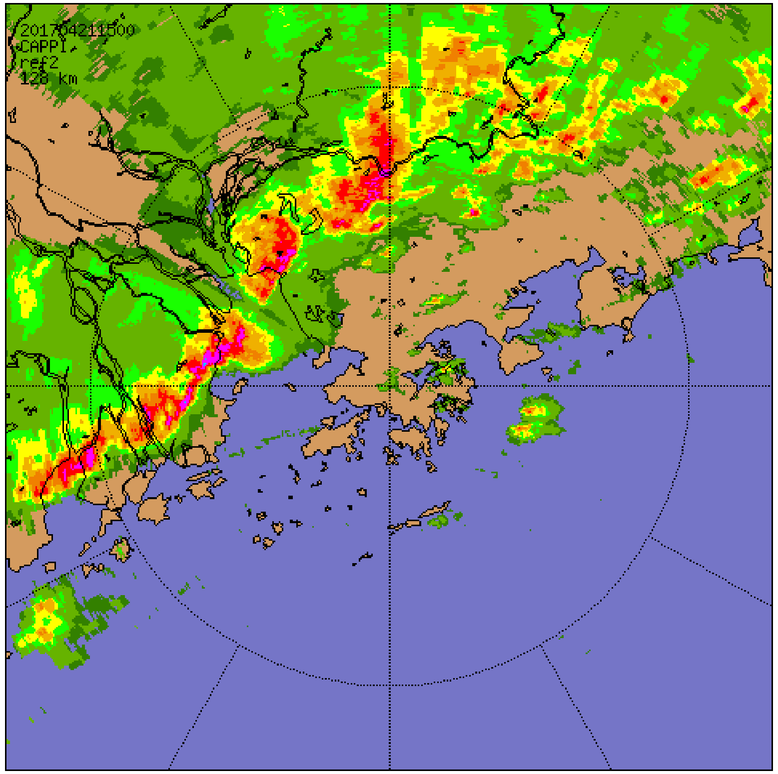
Beijing, China

12 November 2019

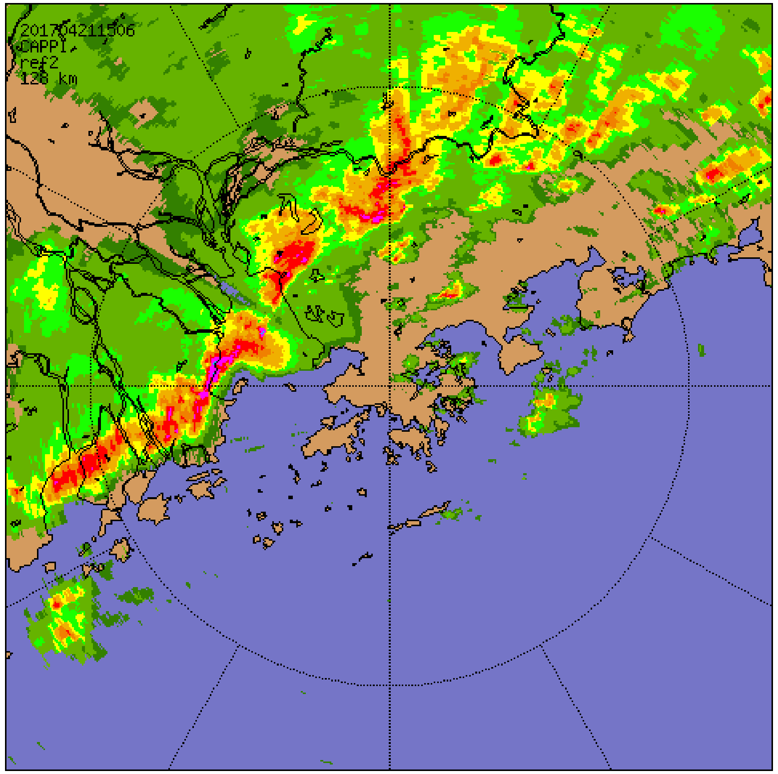
Quantitative Precipitation Forecast (QPF)

Principle of Radar-based Rainfall Nowcast

3:00pm

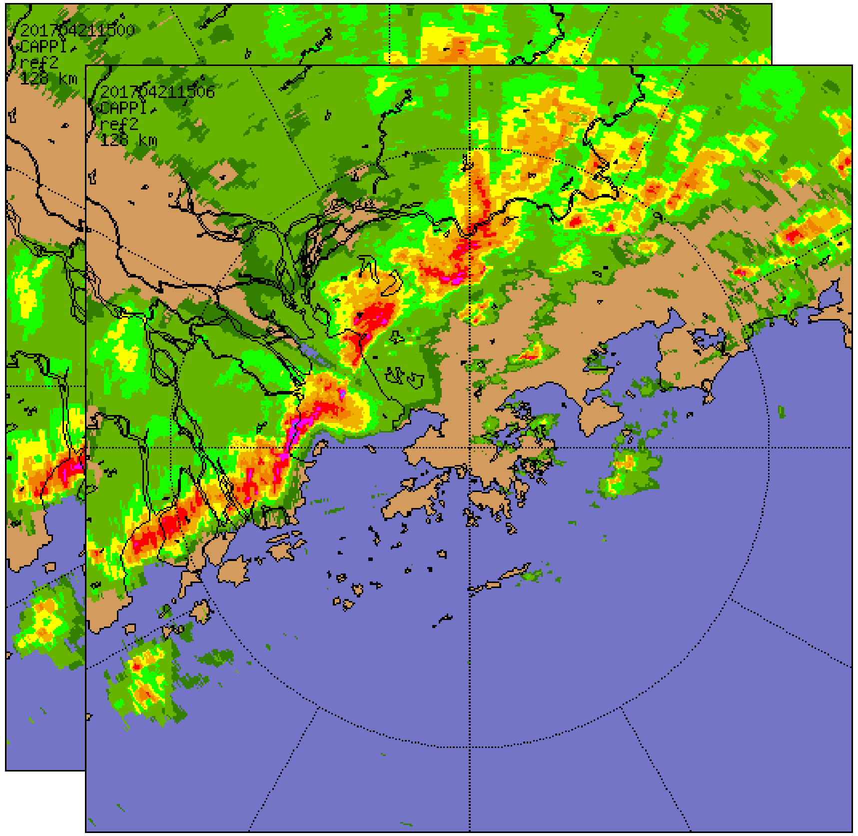


3:06pm

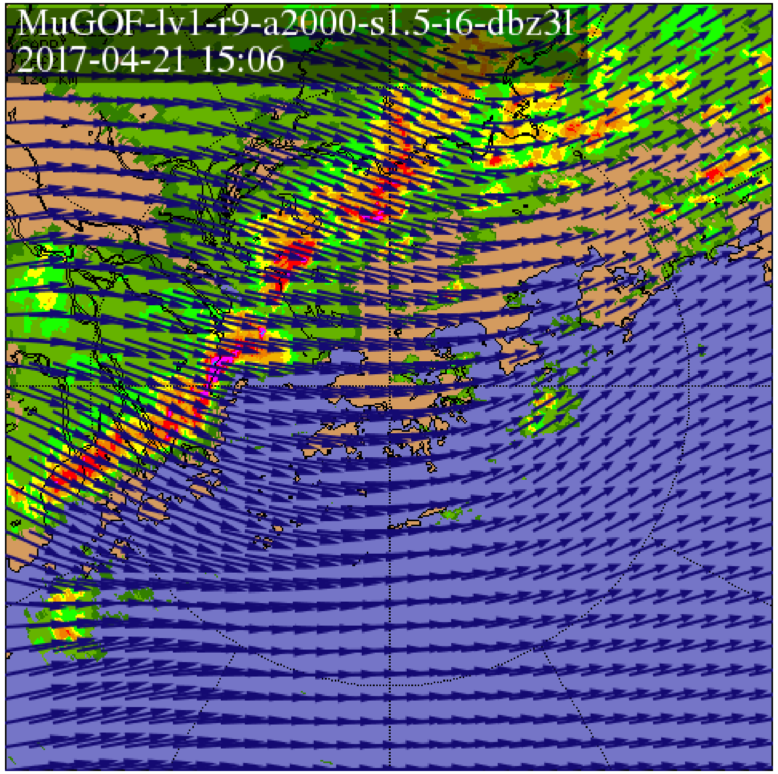


Generation of Motion Field

Consecutive Radar Images

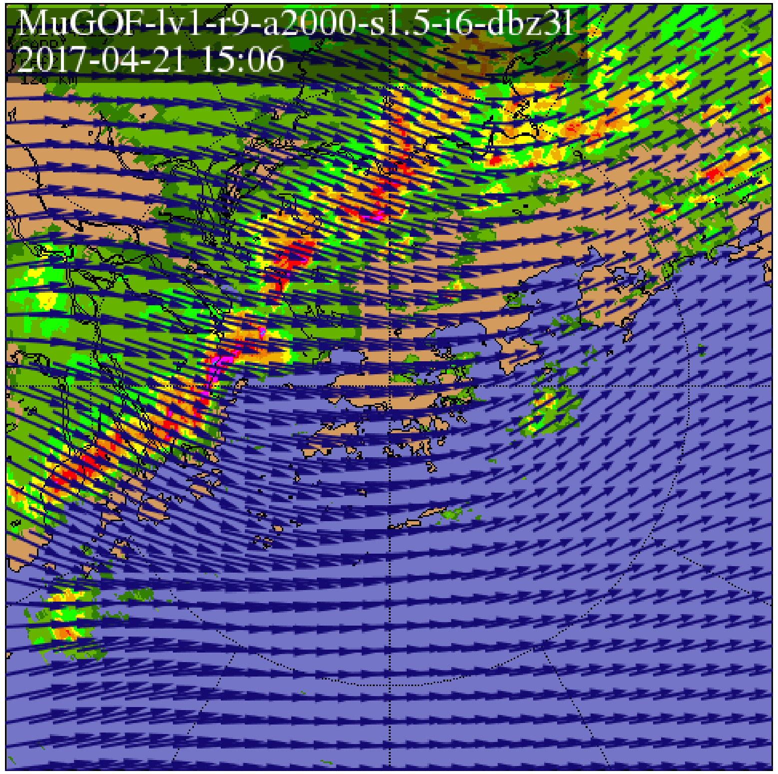


Motion Field

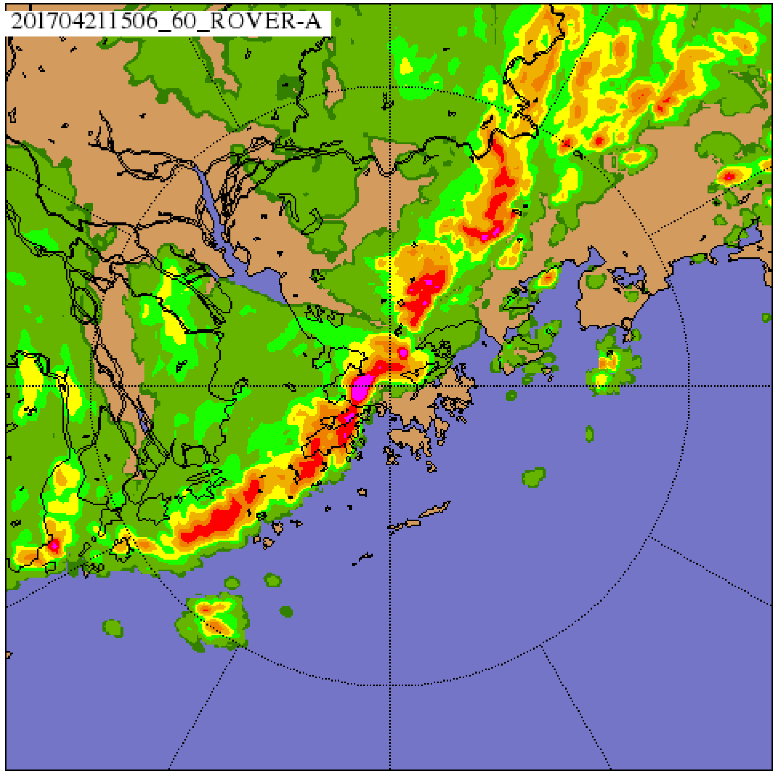


Rainfall Nowcast by Extrapolation

Analysis



1 Hour Forecast



Radar Echo Tracking

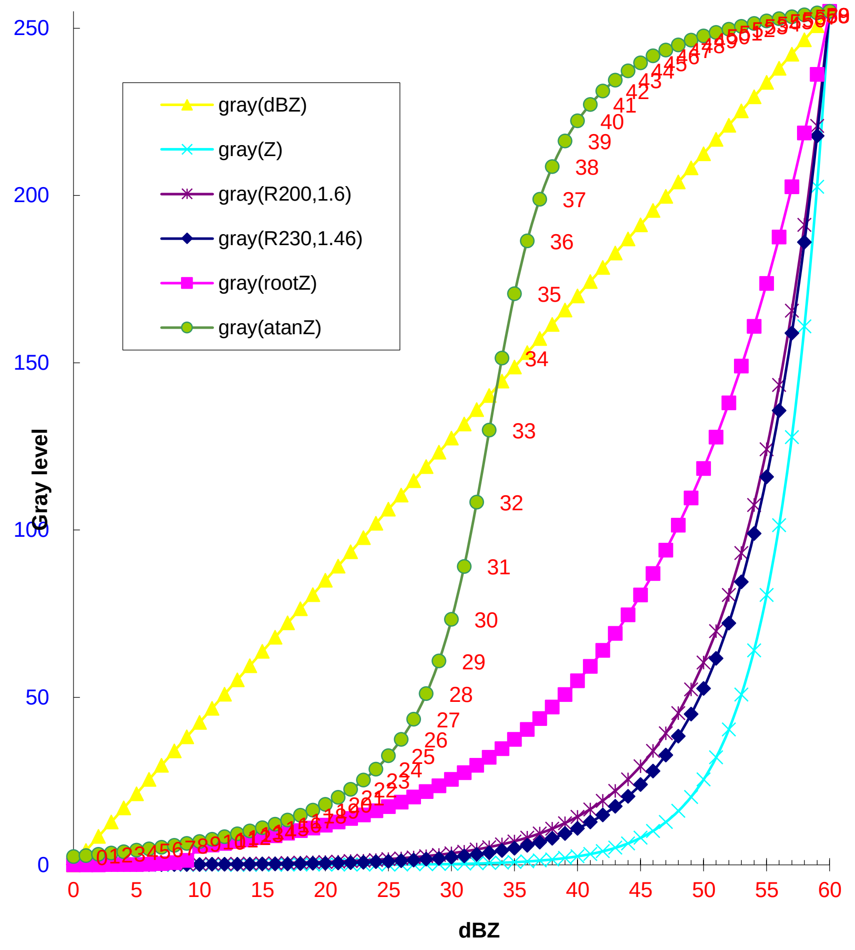
- Correlation-based
  - TREC / Co-TREC / MTREC
- Variational Optical Flow
  - MOVA / ROVER
- Deep Learning
  - ConvLSTM / ConvGRU / TrajGRU
- References:
  - *Operational Application of Optical Flow Techniques to Radar-Based Rainfall Nowcasting (Link)*
  - *Deep Learning for Precipitation Nowcasting: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

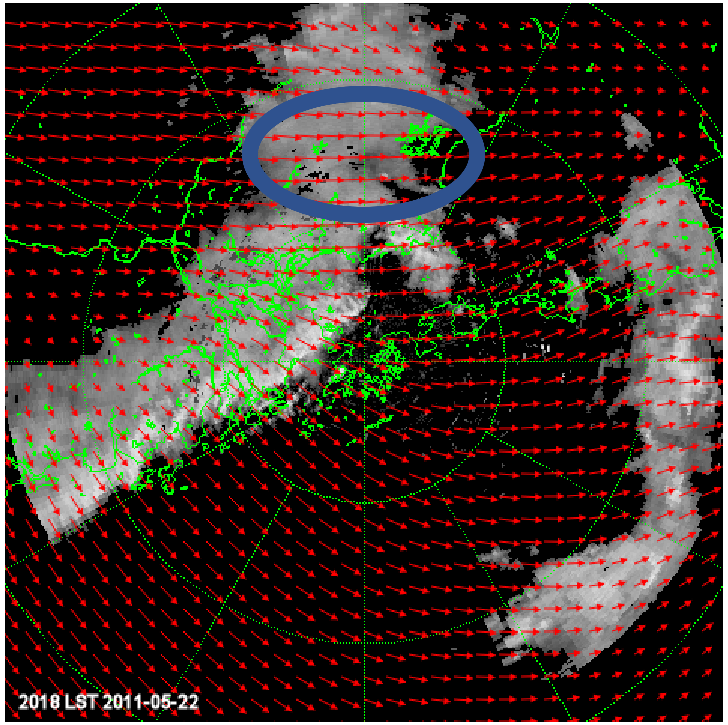
Enhancing Radar Images

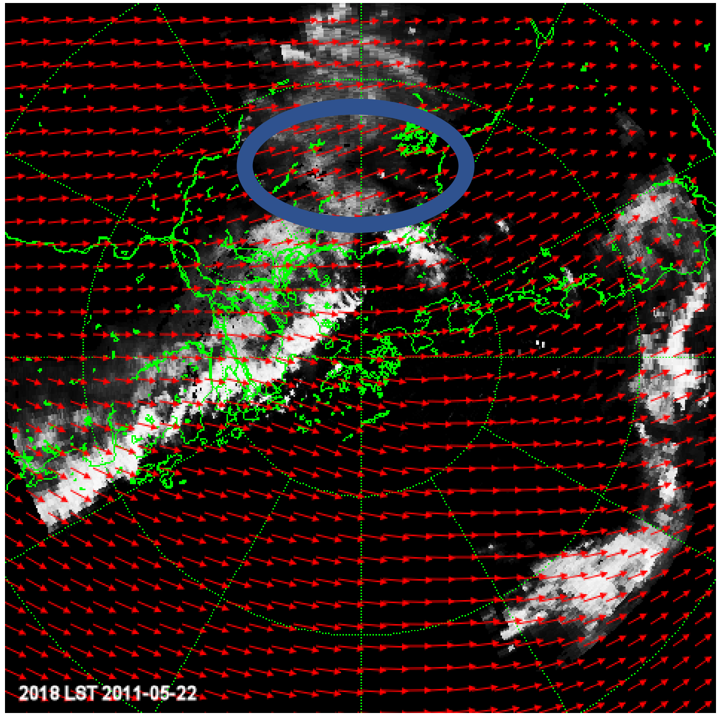
- Bowler et al. (2004): Radar or rain rate field is typically noisy and pre-smoothing is needed for a stable calculation of the partial derivatives.
- Highlight echoes from the convective regime with high dBZ values and play down echoes with intensity of less interest.



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

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 *Kρ* a Gaussian kernel with standard deviation *ρ*.
Compared with
the global variational methods

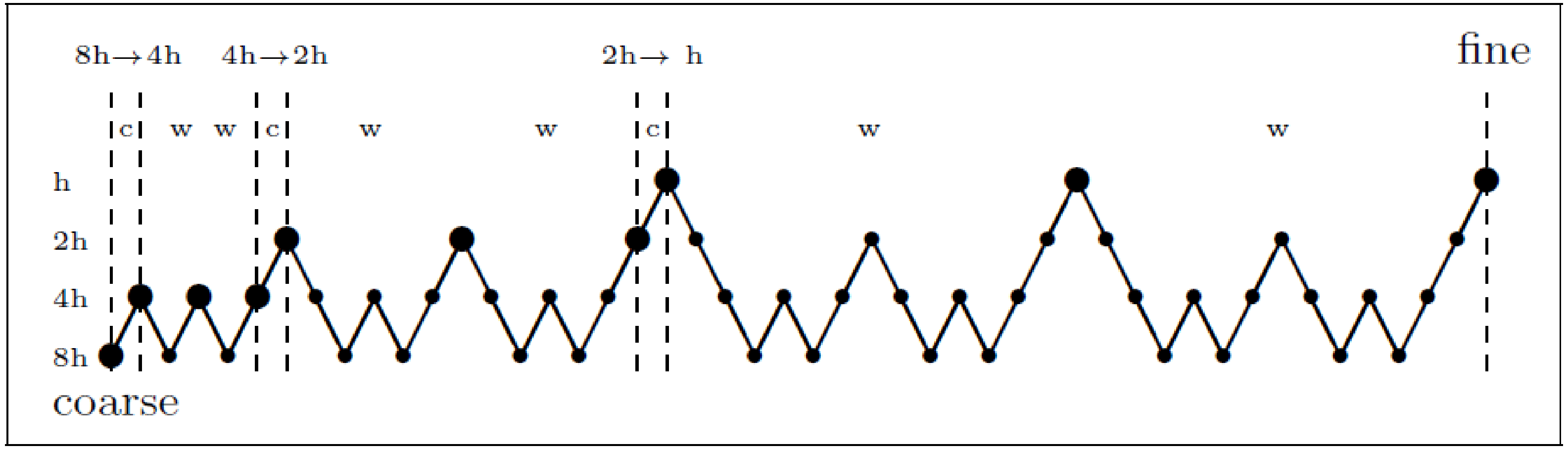
$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} K_\rho * (I_x I_x) & K_\rho * (I_x I_y) \\ K_\rho * (I_y I_x) & K_\rho * (I_y I_y) \end{pmatrix}^{-1} \begin{pmatrix} -K_\rho * (I_x I_t) \\ -K_\rho * (I_y I_t) \end{pmatrix}$$

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

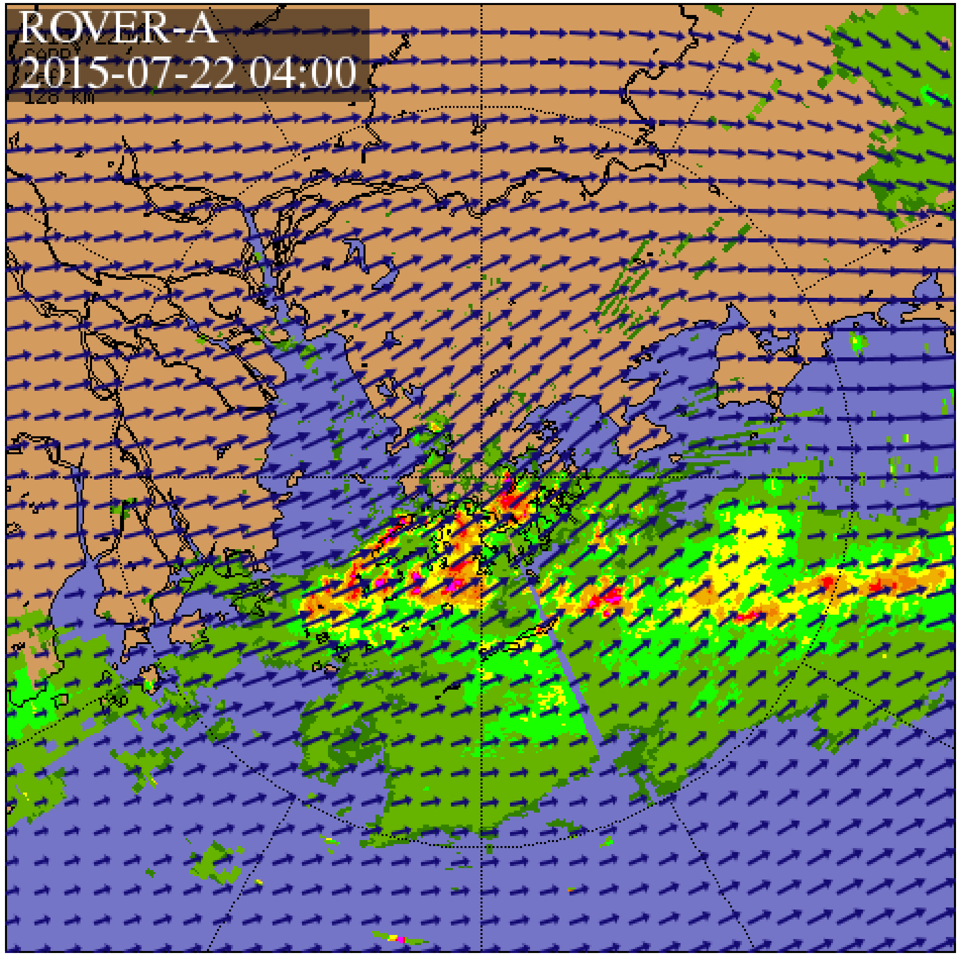
Local Scheme + Global Scheme

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.



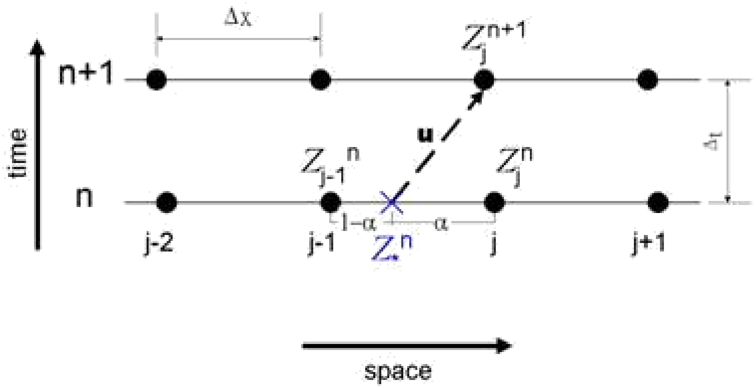
Motion Field - Product of ROVER (Radar Echo Tracking)

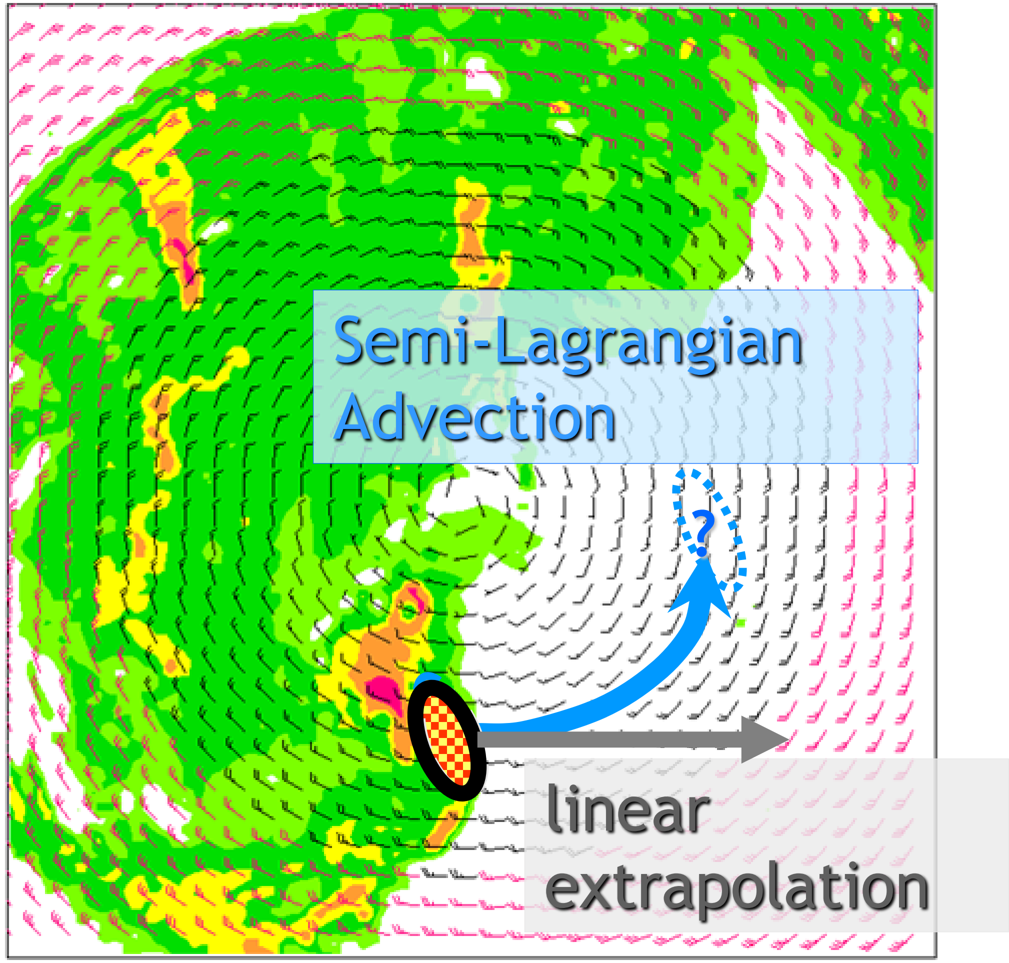


Forecast by Extrapolation

- 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

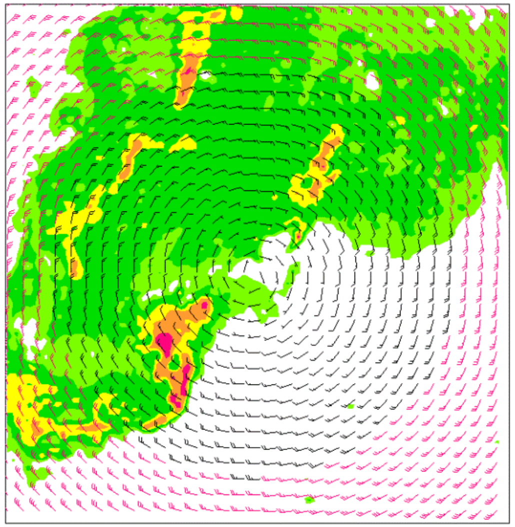
$$\frac{dZ}{dt} = \frac{\partial Z}{\partial t} + \mathbf{u}\frac{\partial Z}{\partial x} = 0$$





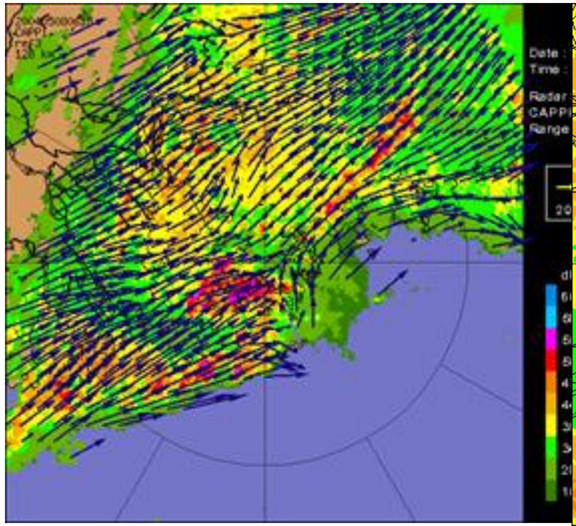
SWIRLS SLA Examples

- circulation pattern preserved →

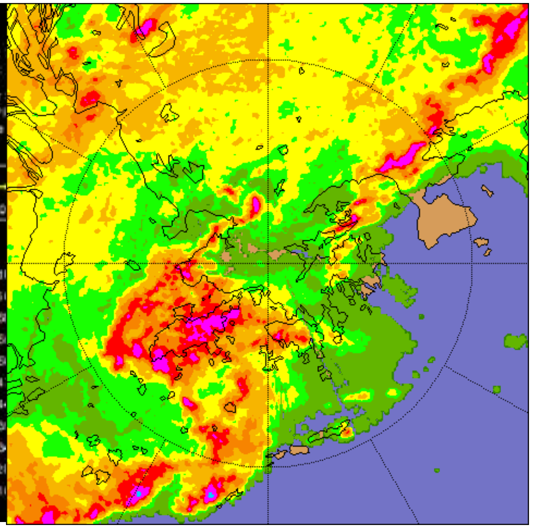


Forecast reflectivity – pure rotation
Up to 6 hr (6-min interval)

- numerically less dissipative ↓



TREC wind



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

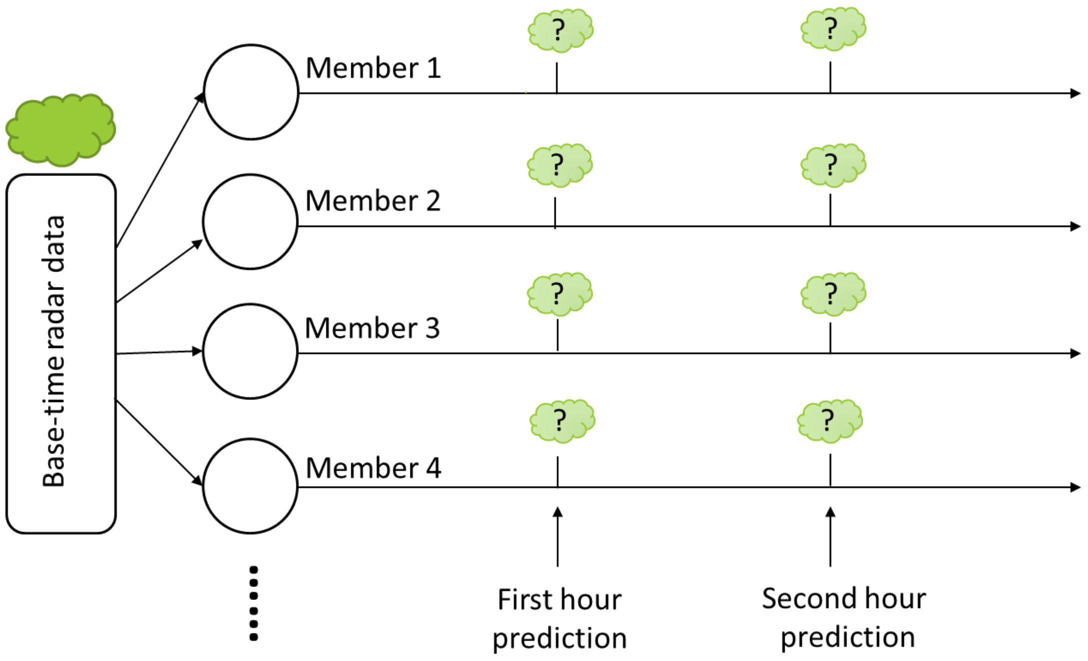
Probabilistic QPF

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.



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

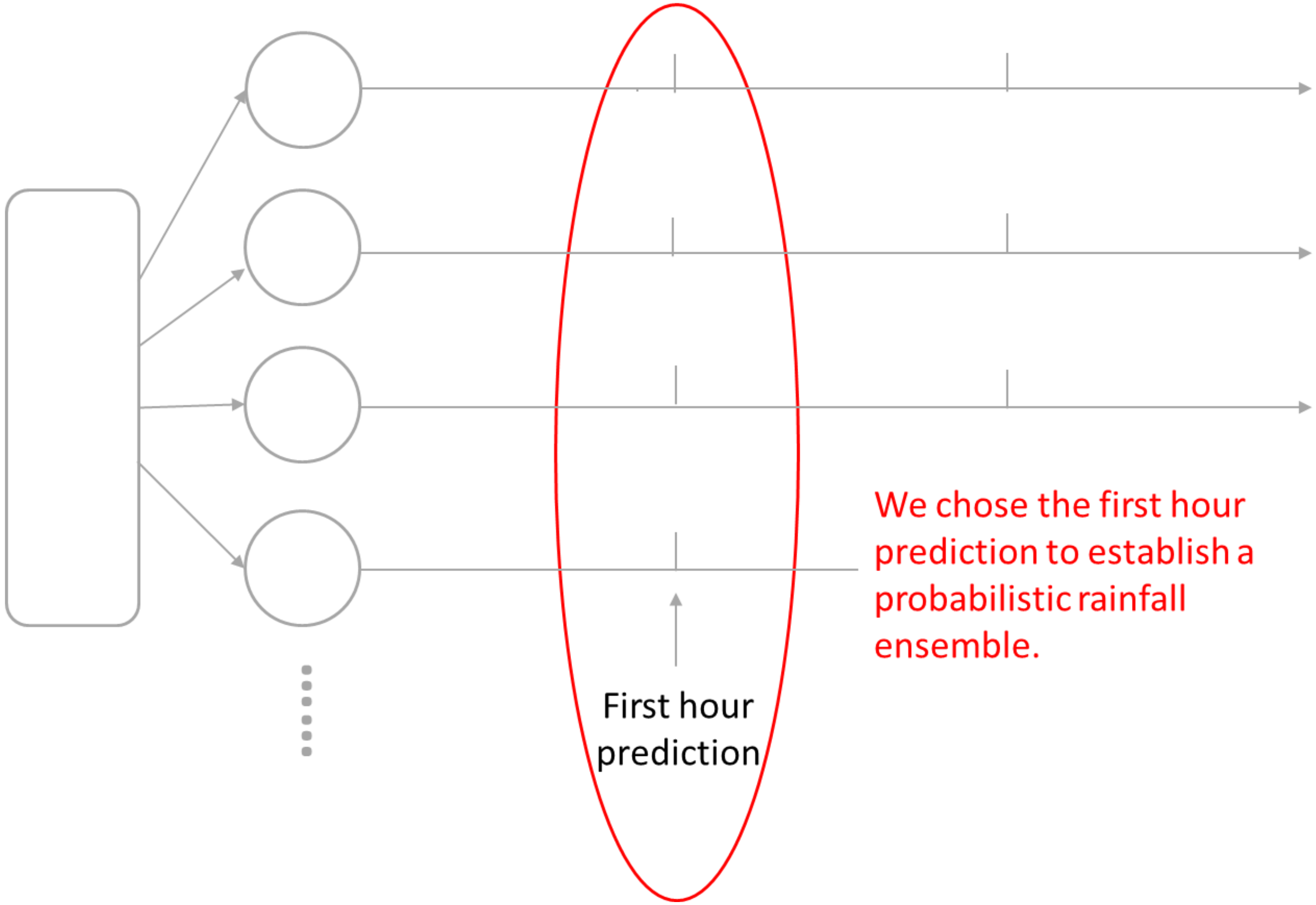
SERN
SWIRLS
Ensemble
Rainfall
Nowcast

36-Members list

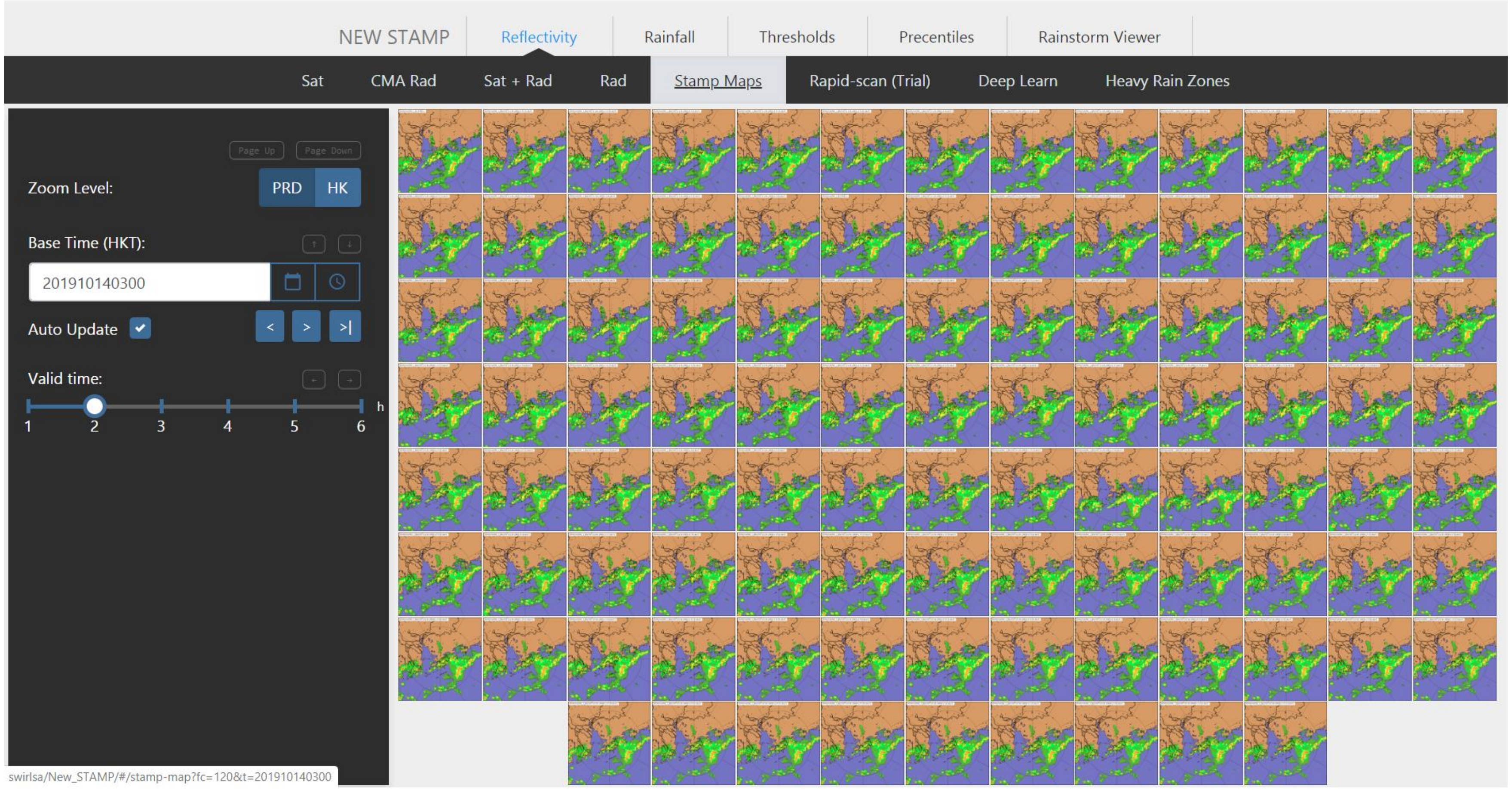
[edit]

```
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
```

Probabilistic QPF (PQPF)



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
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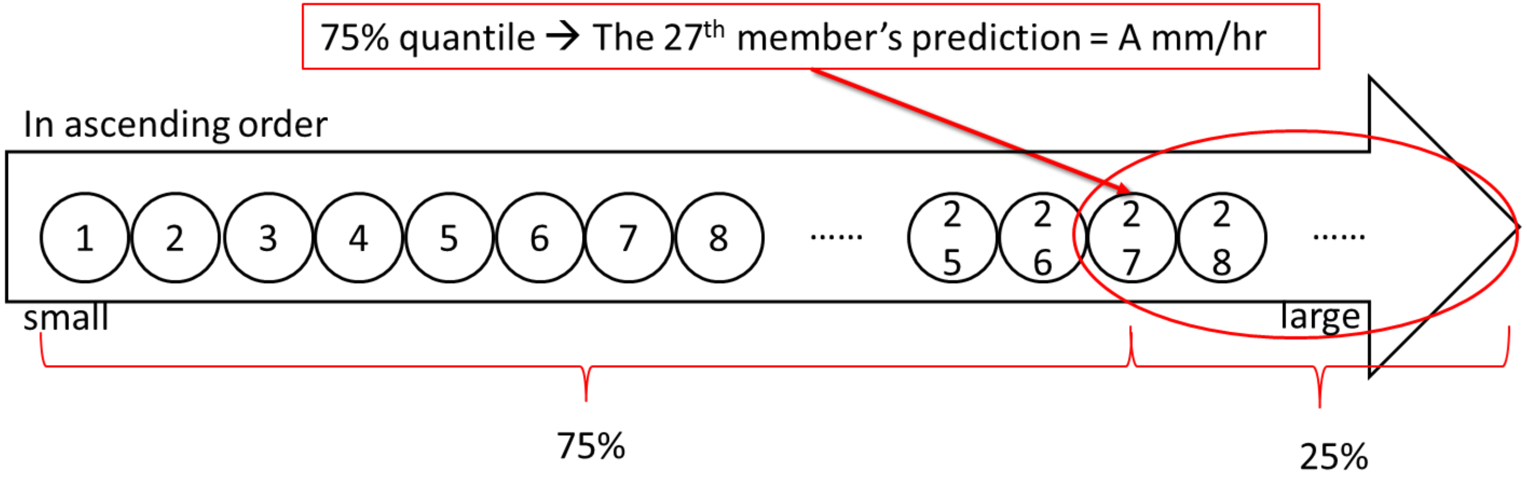
PQPF Product 1
Rainfall Intensity Contour Map

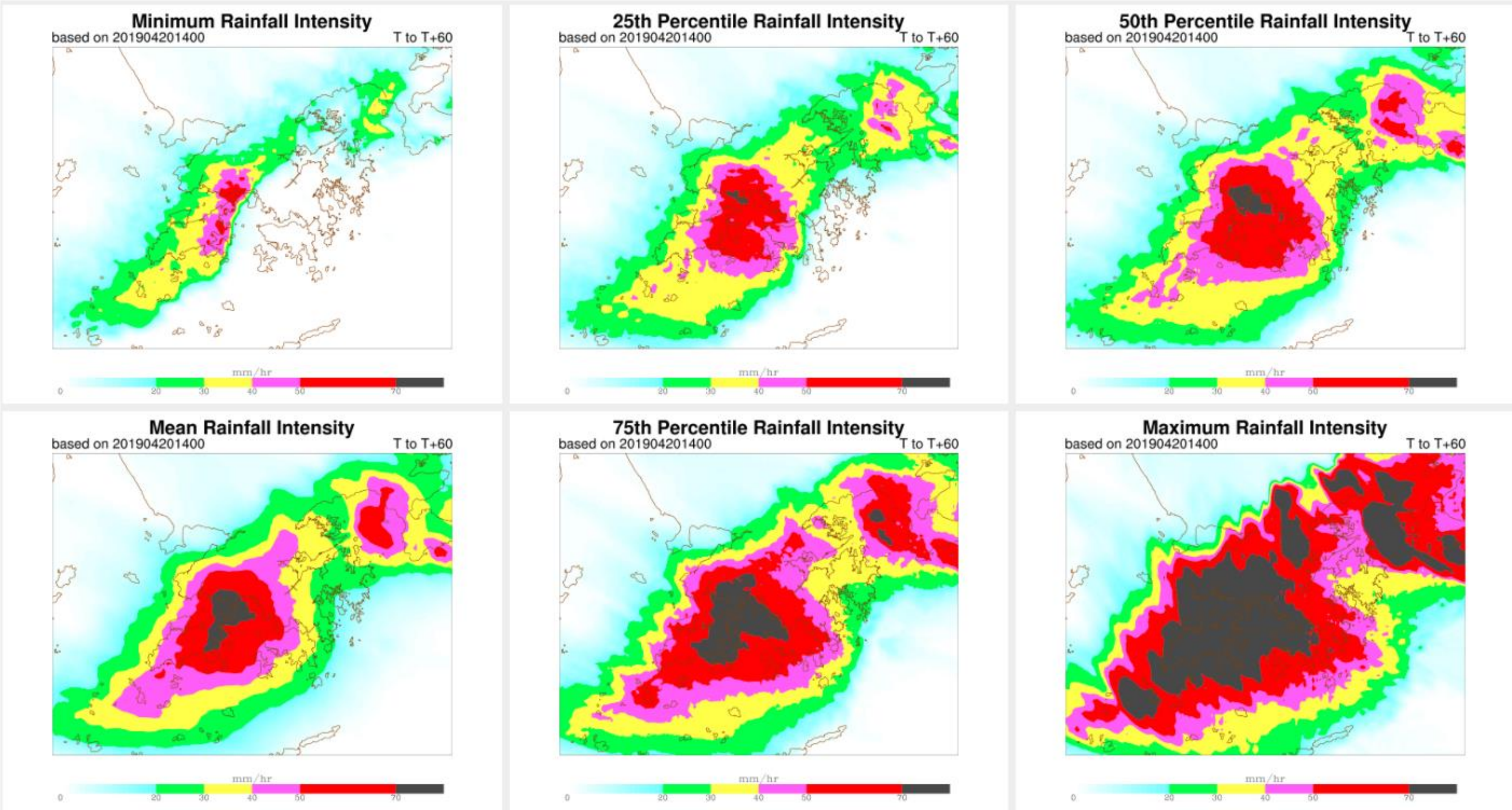
- For Specific Exceedance Probability:



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

Rainfall Intensity at Fixed Percentile



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

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

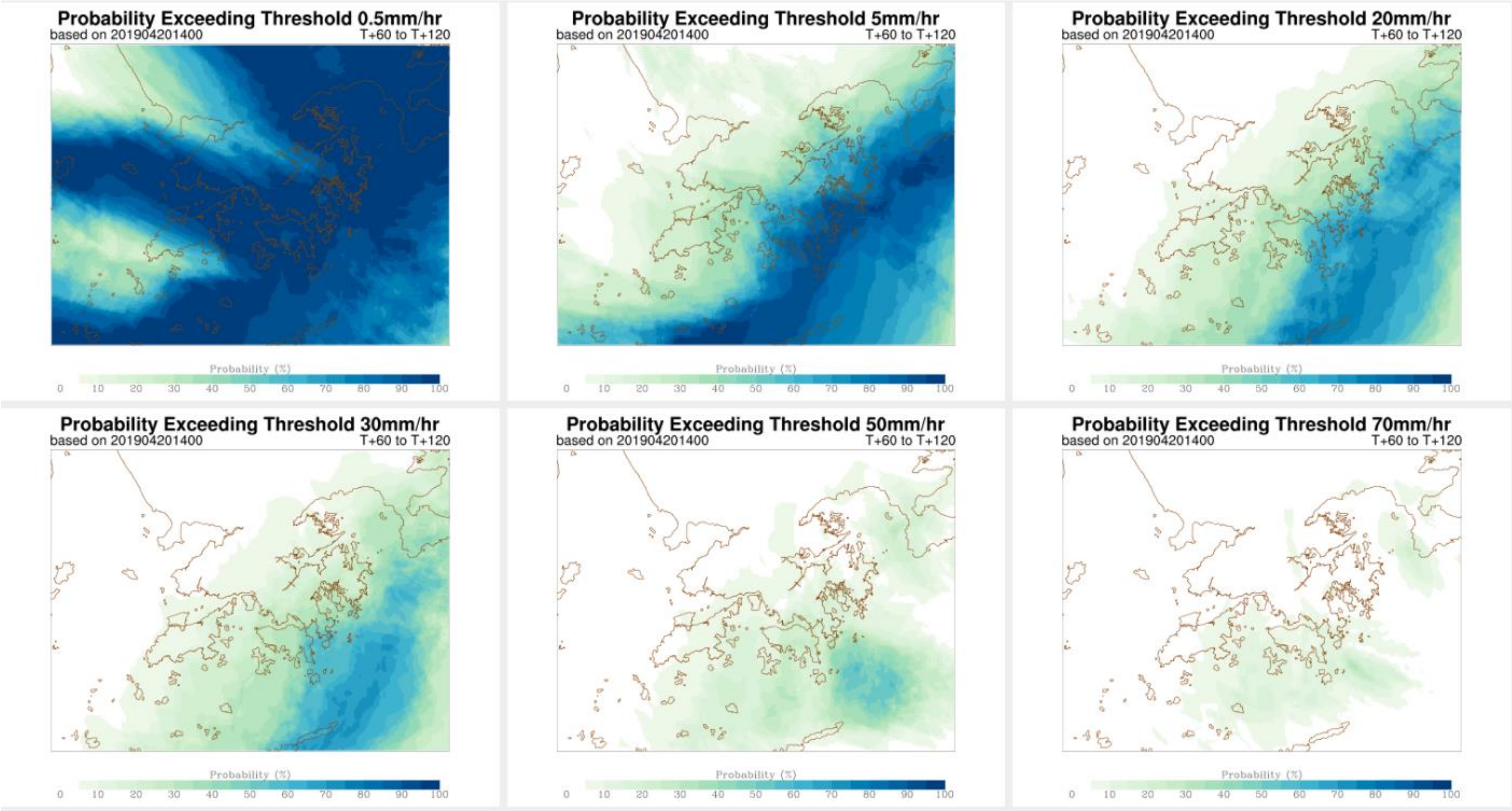
Selected thresholds:

0.5mm/hr

5mm/hr

30mm/hr

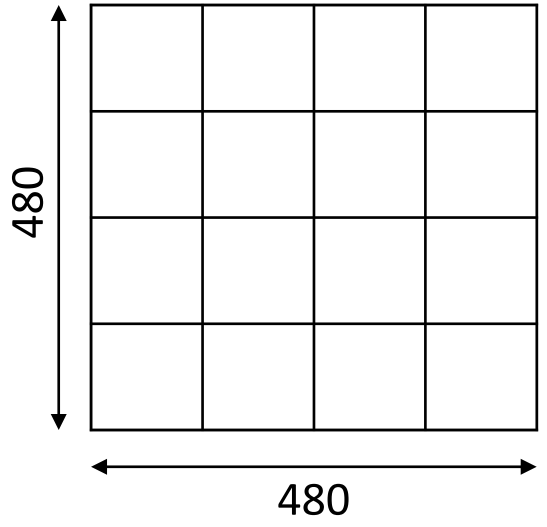
Probability of Exceeding Fixed Intensity



Verification and Analyses

Verified against Radar QPE data:

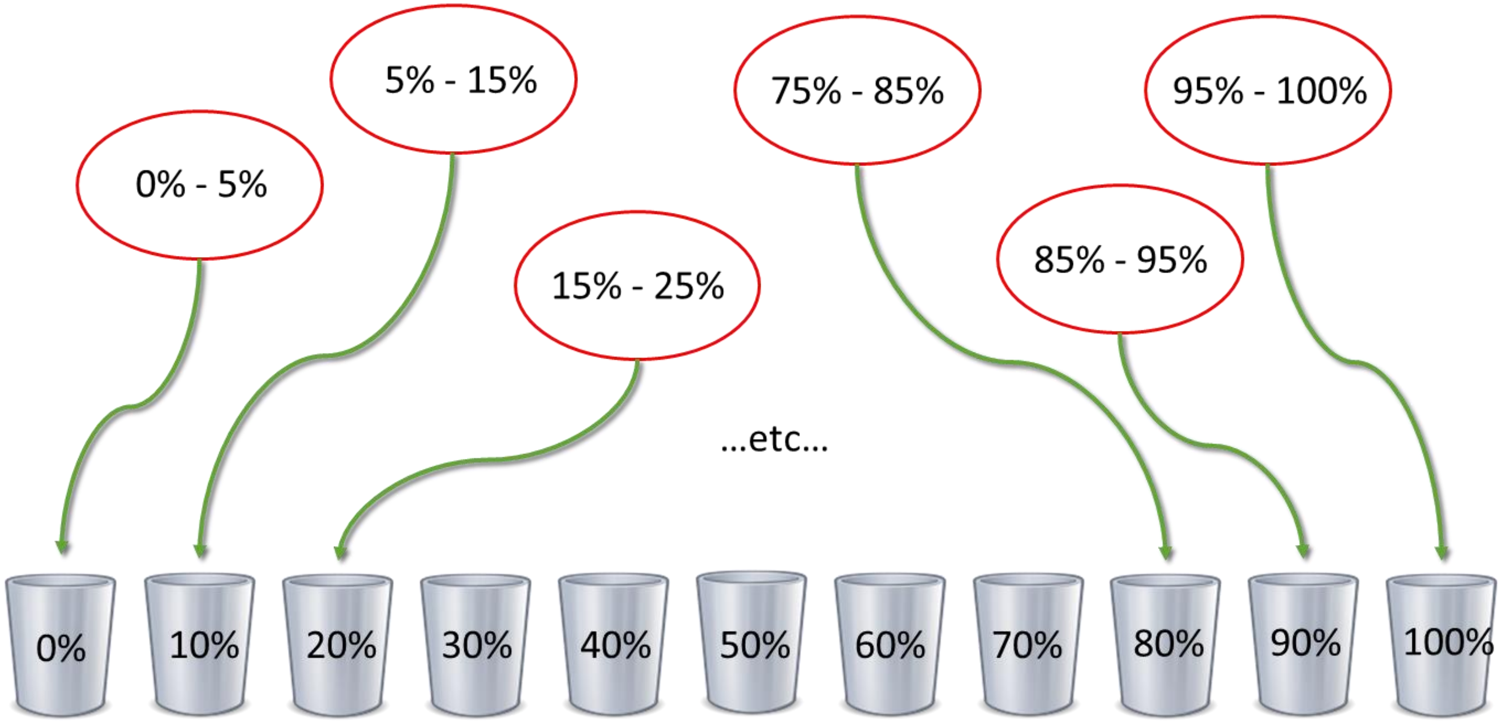
- resolution 480X480 pixels
- Generated every 6 minutes



One datum for each grid

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.

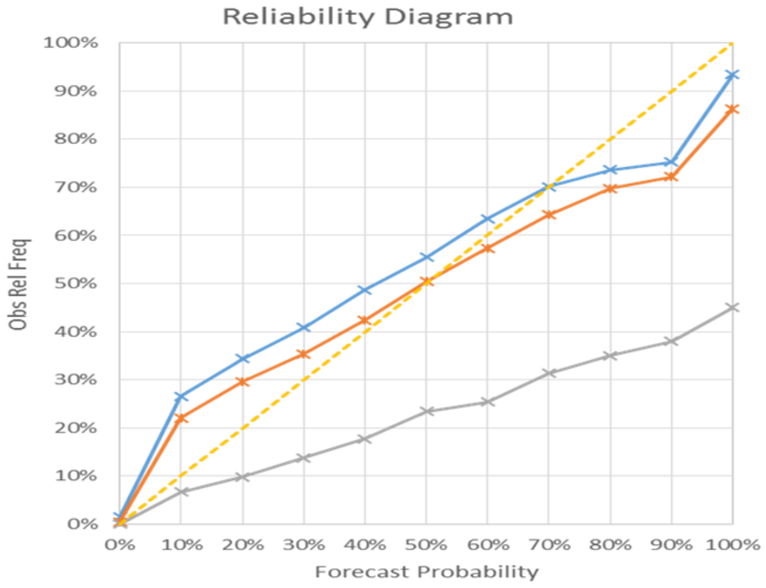
10%	10%	10%	10%	10%
10%	10%	10%	10%	10%

10-events actual occurrences

N	N	N	Y	N
N	N	N	N	N

Expected to happen once out of 10 times

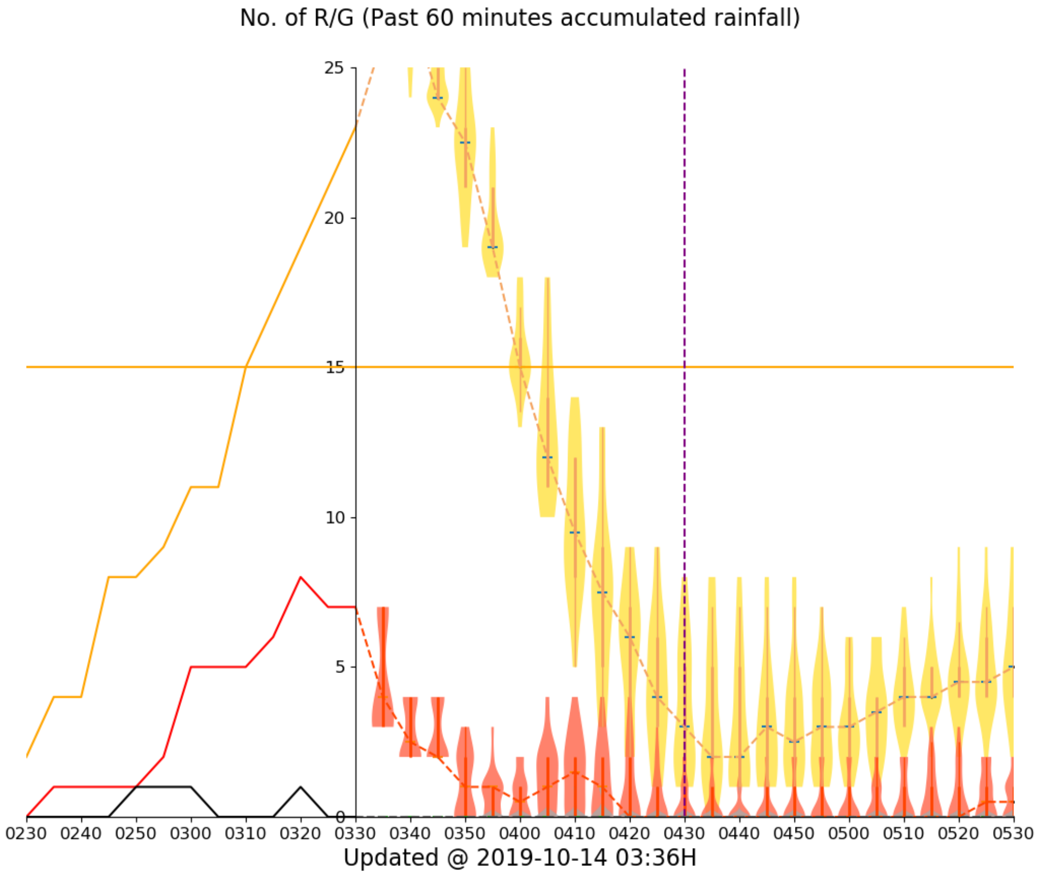
→observed relative frequency = 1/10 =10%



forecast probability = observed relative frequency

→ the probability forecast is perfectly reliable

Probability in Time Series



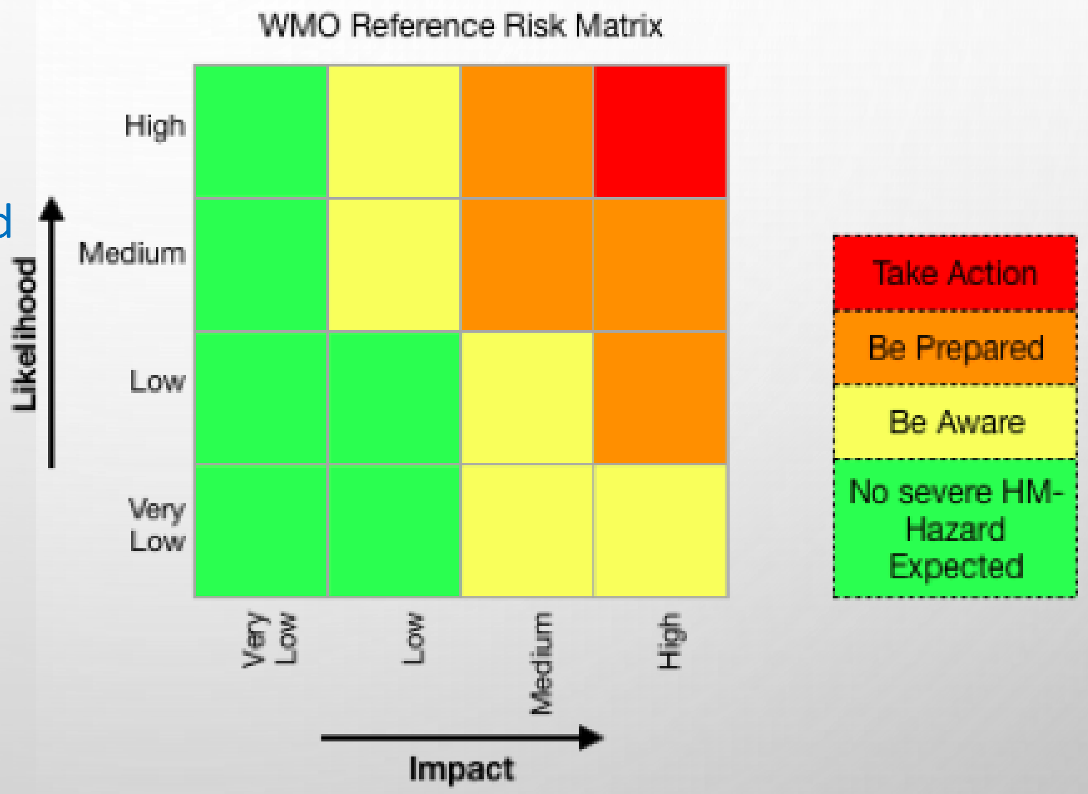
Impact-based Forecasting / Warning

Status of IBFWS Implementation

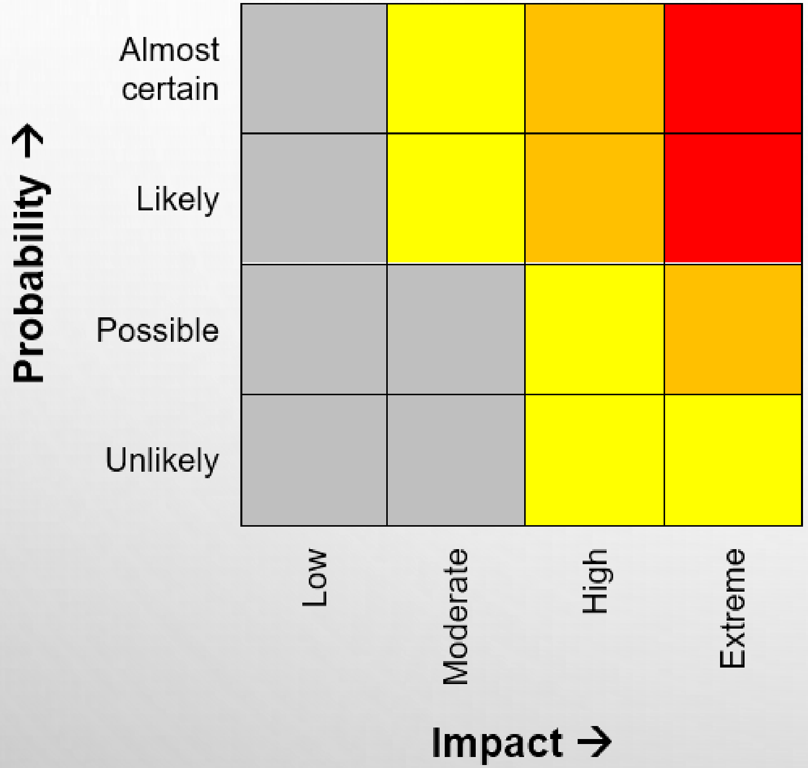
- IBFWS implemented / being implemented
  - *e.g. UK, Australia, France, Canada, Korea*
- Developing from other IBFWS
  - *Mongolia from MeteoAlarm, Indonesia from WRN of NWS*
- Hazard/weather oriented early warnings
  - *Japan, China, Hong Kong*
- Direct impact forecast/warning
  - *UK, Japan, Korea (developing)*

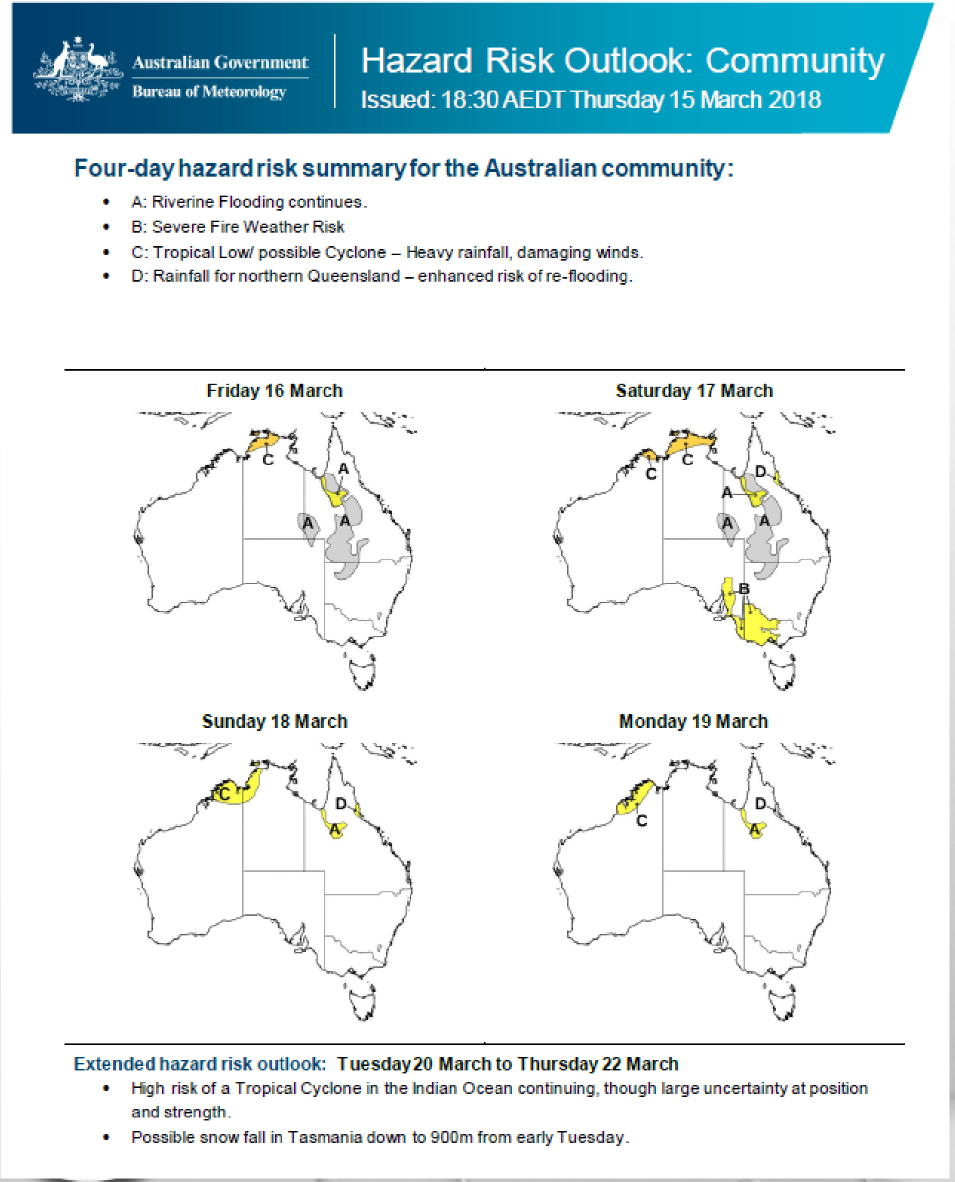
UKMO

- Direct impact forecasting developed for some impacts, e.g. flooding, vehicle overturning (due to high winds), …
- Emergency responders defined the levels of impact
- Forecasters to provide an expected level of impact and a likelihood of this impact (on a subjective basis)
- Thresholds are no longer used to trigger warnings (but may form part of the decision process)



BoM - Australia





Australian Government
Bureau of Meteorology

Hazard Risk Outlook: Community

Issued: 18:30 AEDT Thursday 15 March 2018

Four-day hazard risk summary for the Australian community:

- A: Riverine Flooding continues.
- B: Severe Fire Weather Risk
- C: Tropical Low/ possible Cyclone – Heavy rainfall, damaging winds.
- D: Rainfall for northern Queensland – enhanced risk of re-flooding.

Friday 16 March **Saturday 17 March**

Sunday 18 March **Monday 19 March**

Extended hazard risk outlook: Tuesday 20 March to Thursday 22 March

- High risk of a Tropical Cyclone in the Indian Ocean continuing, though large uncertainty at position and strength.
- Possible snow fall in Tasmania down to 900m from early Tuesday.

BoM Example

Australian Government
Bureau of Meteorology

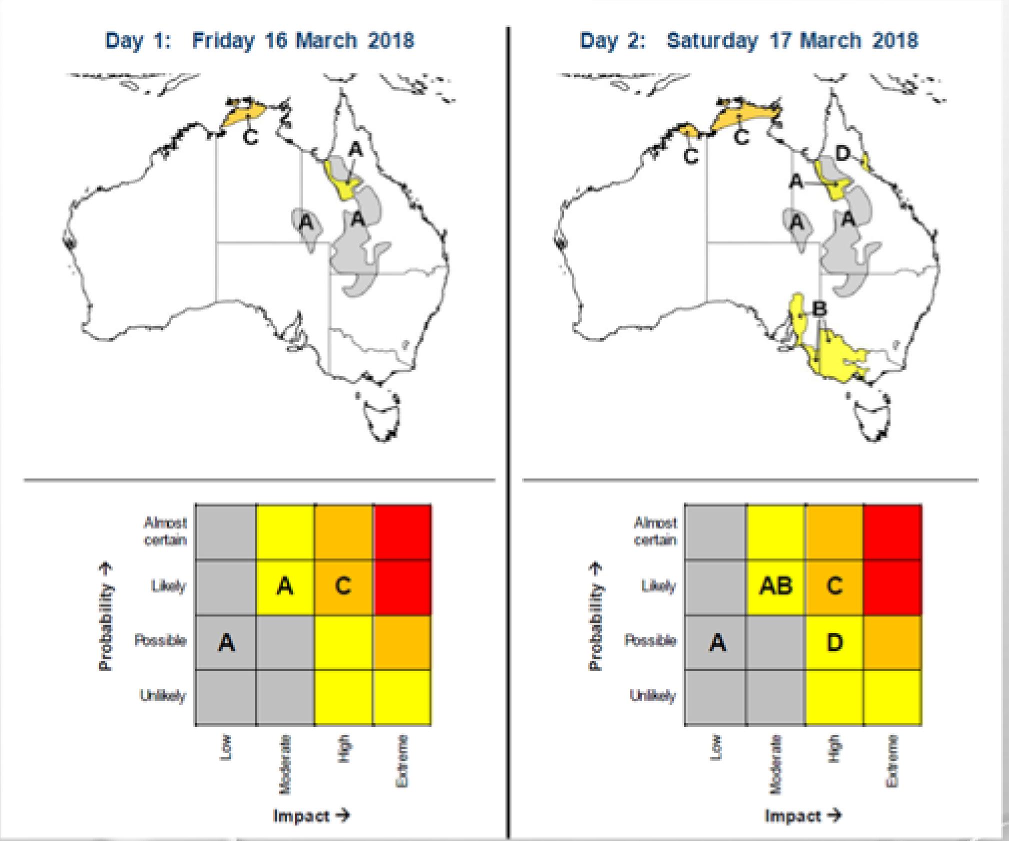
National Hazard Community Impact
Tropical Cyclone Marcus

Impact probability-based communication strategy.

Contingency planning

BEFORE

- A: Riverine flooding
- B: Severe fire weather
- C: Tropical Low/ Possible Cyclone
- D: Heavy rainfall



- **C: Tropical Low/ Possible Tropical Cyclone**
- Heavy rainfall, possible flash flooding
- Possible damaging wind gusts near the low or TC
- Risk to Darwin (NT capital city ~106,000 people).
- Risk of damage to property and agriculture.
- Increased demand of emergency services.

BoM Example – Risk Assessment Process

Community Impact and Risk Assessment

HAZARD COMMUNITY IMPACT				
Tier	0	1	2	3
Impact level	LOW	MODERATE	HIGH	EXTREME

Hazard

Life

Property

Delivery of services/util

Emergency services

Transport

Day-to-day activities

Agriculture

Land/vegetation

HAZARD PROBABILITY				
Tier	0	1	2	3
Probability level	UNLIKELY	POSSIBLE	LIKELY	ALMOST CERTAIN
Forecast likelihood	Not current official forecast policy Long term forecast period Computer model guidance very inconsistent Outlier forecast scenario Other forecast scenarios remain very likely	Not current official forecast policy Medium-long term forecast period Computer model guidance very inconsistent Other forecast scenarios considered to remain possible or Current official forecast policy Short- long term forecast period Computer model guidance remains uncertain Other forecast scenarios considered to remain possible	Current official forecast policy Short-medium term forecast period Majority of computer model guidance in agreement, although some uncertainty remains Other forecast scenarios now considered unlikely C	Current official forecast policy Short term forecast period/event imminent All computer model guidance in very close agreement Other forecast scenarios considered extremely unlikely/impossible

Total score:
(sum all elements) 2

Hazard probability assessment:

0	TIER 0	UNLIKELY	
1	TIER 1	POSSIBLE	
2	TIER 2	LIKELY	C
3	TIER 3	ALMOST CERTAIN	

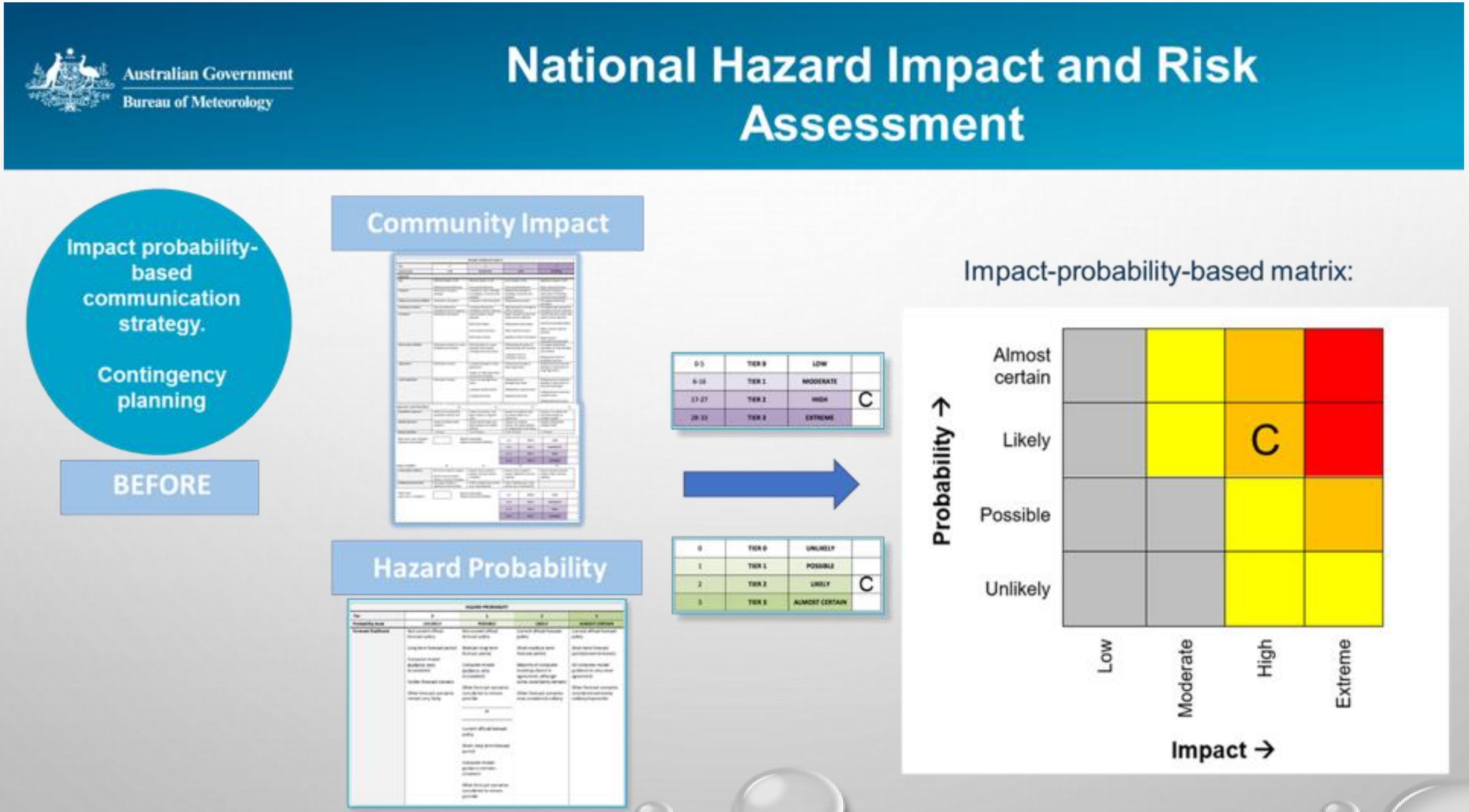
+2	+3
al cities. on a C	Impacts on a capital city. Less likely impact on multiple capitals.
le impacts ulti-states.	Impacts widespread/ multiple states.
	> 24 hours

TIER 0	LOW	
TIER 1	MODERATE	
TIER 2	HIGH	C
TIER 3	EXTREME	

	+3
ther recovery	Recent extreme weather impact, major recovery ongoing
or travel mas/NY)	

TIER 0	LOW	
TIER 1	MODERATE	
TIER 2	HIGH	C
TIER 3	EXTREME	

BoM Example



Australian Government
Bureau of Meteorology
National Hazard Impact and Risk Assessment
Impact probability-based communication strategy.
Contingency planning
BEFORE
Community Impact
Hazard Probability
C
C
Impact-probability-based matrix:
Almost certain
Likely
Possible
Unlikely
Probability →
C
Low
Moderate
High
Extreme
Impact →

BoM Example

Australian Government
Bureau of Meteorology

National Hazard Operational Impact
Tropical Cyclone Marcus

Impact probability-based communication strategy.

Contingency planning

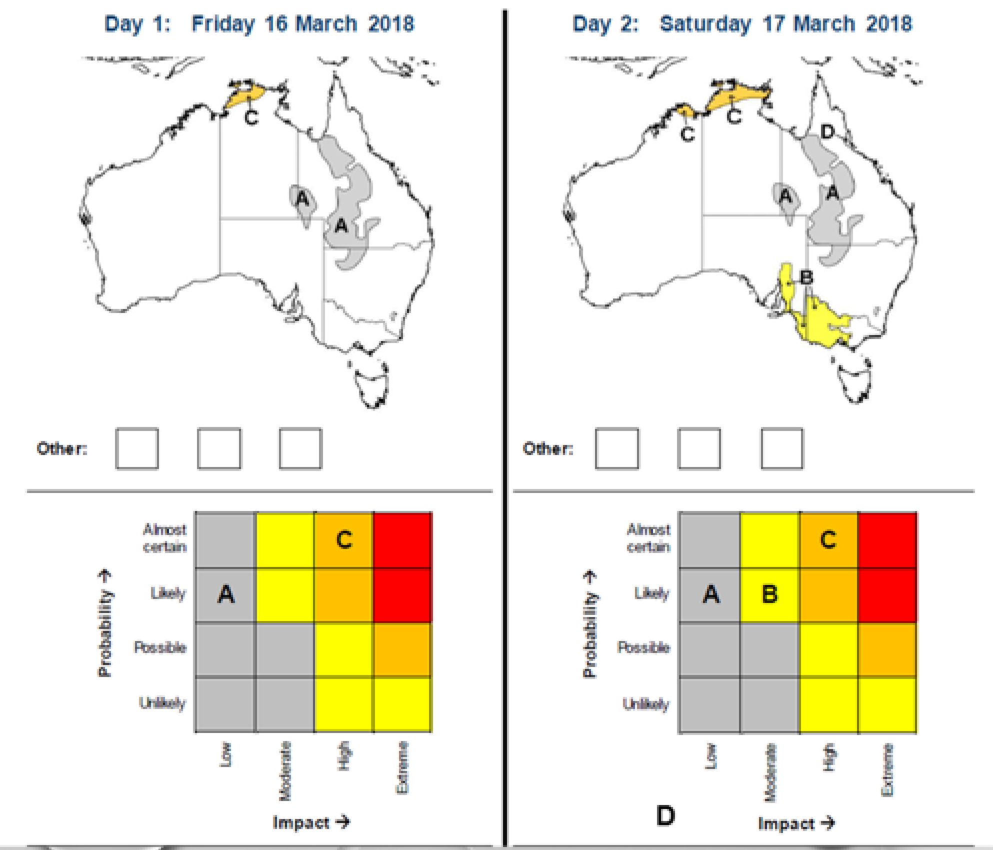
BEFORE

A: Riverine flooding

B: Severe fire weather

C: Possible Tropical Cyclone

D: Heavy rainfall



C: TCWC Activation – NT

- High risk of TC in the Arafura Sea from Friday
- Populated Areas, TC - Coastal Impact.
- Additional staff required.

Meteo-France : Vigilance EWS

- Does not rely on risk-matrix
- Still uses thresholds:
  - *dependent on local climatology*
  - *regularly reviewed*

4 colours/levels of risk :

Red **: absolute awarness.**
Exceptionally intense meteorological phenomena have been forecasted. Follow orders and any advice given by your authorities under all circumstances, be prepared for extraordinary measures.

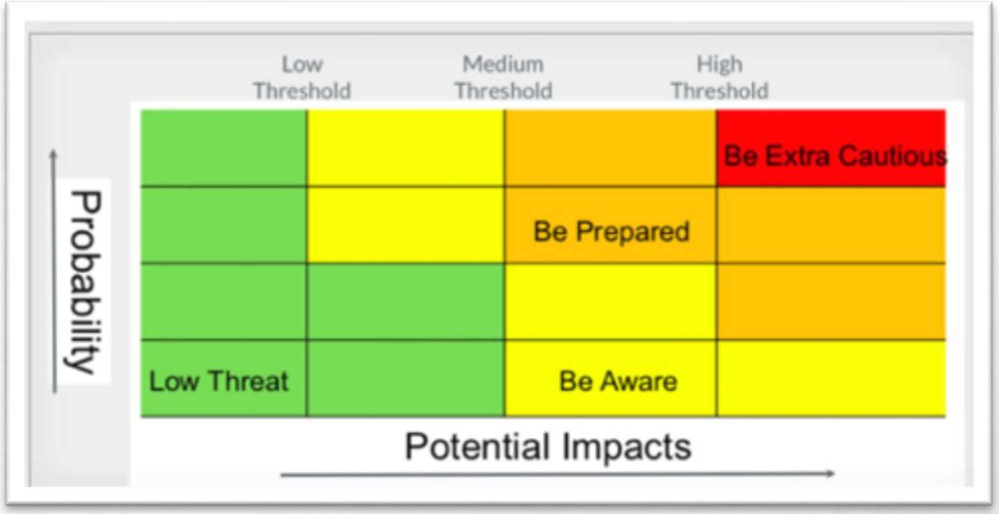
Orange **: Be very vigilant !**
The weather is dangerous. Unusual meteorological phenomena have been forecasted.

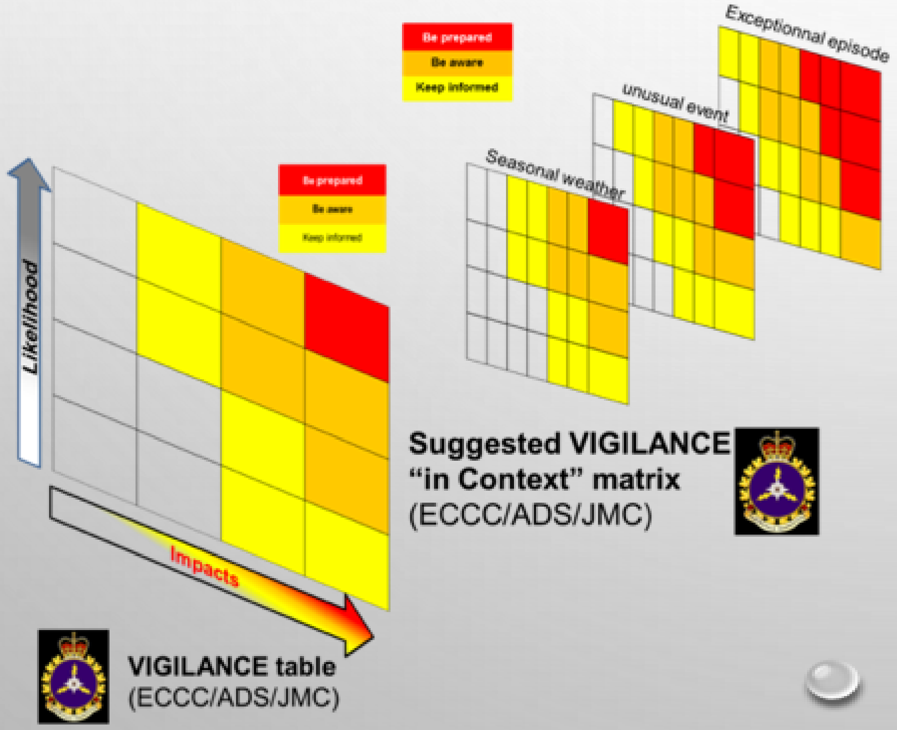
Yellow **: Be attentive** if you intend to practice activities exposed to meteorological risks.

Green **: No particular awareness** of the weather is required.

Met Service Canada

Attempted to improve over UK's version to cater for low-prob high-impact events





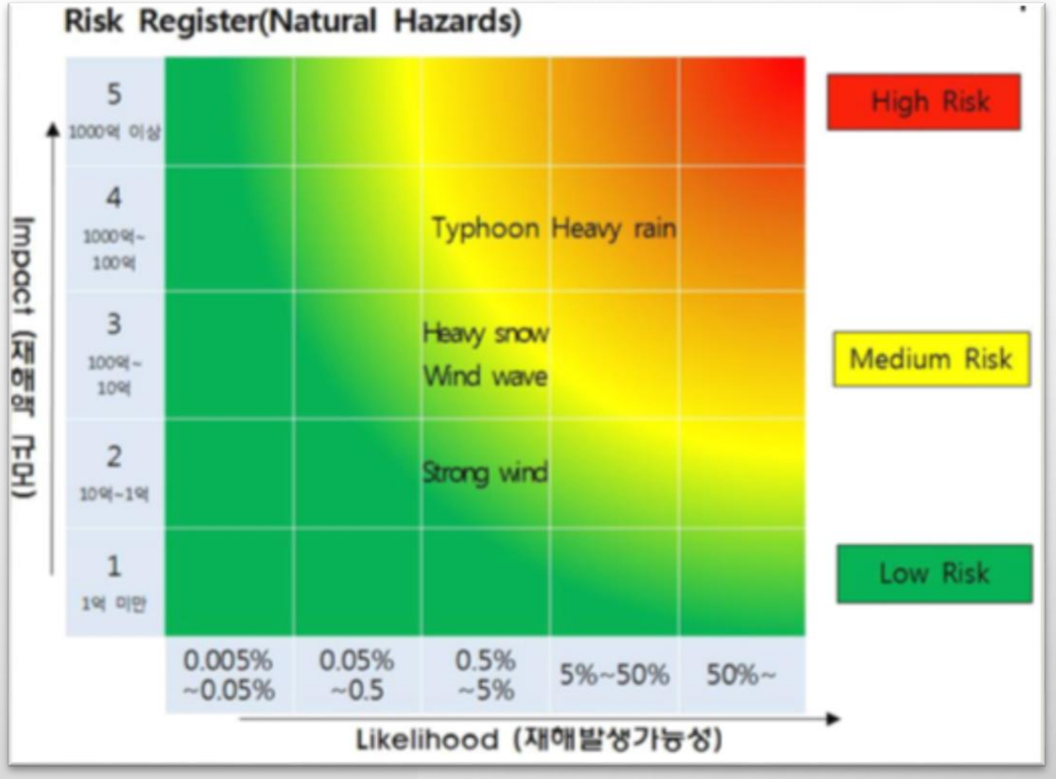
Risk matrix varied for different extreme events based on EFI:

Seasonal
➔ unseasonal
➔ exceptional

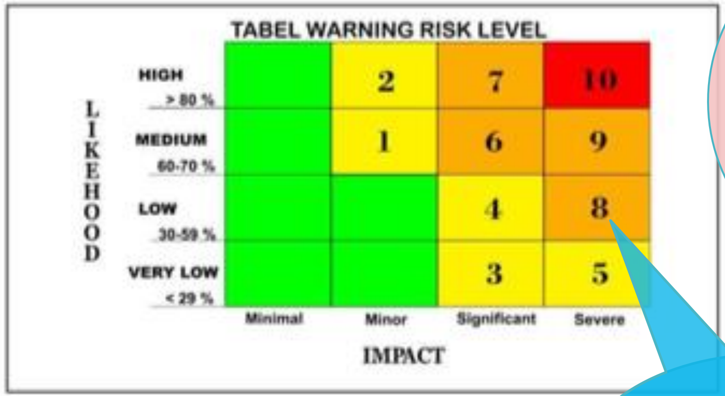
KMA

- Axes swapped
- Colour gradient
  - *Diagonal symmetric*
  - *with 5 x 5 tiles*
- Non-linear scale
- Likelihood

  = impacted days/(365 x 12 yrs)



BMKG - Indonesia



TABEL WARNING RISK LEVEL

LIKEHOOD	Minimal	Minor	Significant	Severe
HIGH > 80 %		2	7	10
MEDIUM 60-70 %		1	6	9
LOW 30-59 %			4	8
VERY LOW < 29 %			3	5

IMPACT

Risk levels ordered by numbers

N.B. Numerical levels to supplement risk colours

Detailed description of weather impact

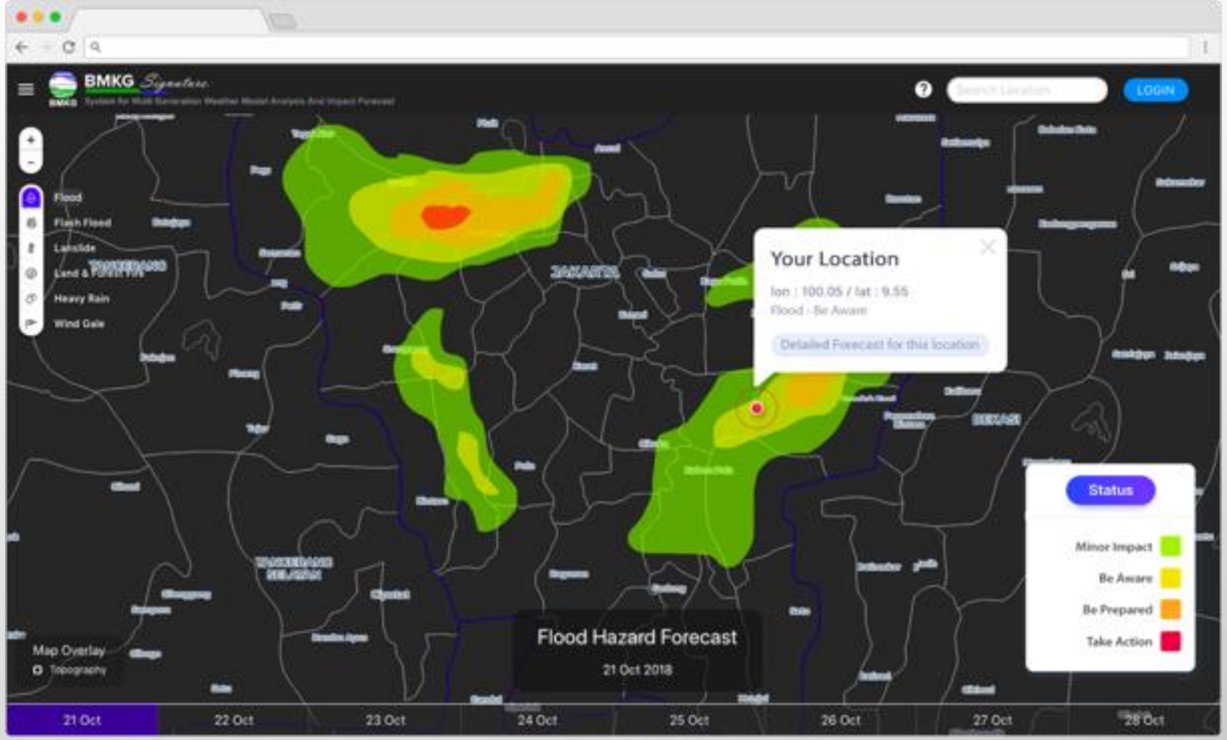
TABEL MATRIKS DAMPAK DAN MATRIKS RESPON

WARNING RISK	DESKRIPSI DAMPAK CUACA	RESPON DISASTER MANAGEMENT BPBD: DESKRIPSI RESPON	KETERANGAN	LEVEL
	[illegible]	[illegible]	[illegible]	[illegible]
1	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible]	[illegible]	[illegible]	
3	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible]	[illegible]	[illegible]	
5	[illegible]	[illegible]	[illegible]	
6	[illegible]	[illegible]	[illegible]	
7	[illegible]	[illegible]	[illegible]	
8	[illegible]	[illegible]	[illegible]	
9	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]	

Response

Public Product - BMKG Example

- Colour coded risk maps to indicate “hot spots”
- CAP messages for more specific uses
- Road map:
  - *Pilot operation in 2019, with CAP*
  - *National implementation by 2021*



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An Example of TC Impact Study

DATA COLLECTION – impact data

Source of Impact data:

- Annual damage survey conducted by HKO to government department and public utilities
- HKSAR government Press Release
- Newspaper

REPORT ON DAMAGE CAUSED BY CYCLONES, FLOODS AND DROUGHT
(This report should cover the total damage caused by typhoons and heavy rainfall, and associated storm-surges, floods, landslides.**)**

Period: from 1 JANUARY 2017 to 31 DECEMBER 2017

Prepared by: SA(D)13

Date prepared: 27 Jul 2018

For consistency, please use the following where necessary:

… data are not available or not separately reported
amount is negligible or nil
N/A item is not applicable

I. GENERAL	**Sequence No.**	1	2	3	4	5	6	7	8	9	10	11	
1. Type of disaster Sequence number/code name of the typhoon and/or type of disaster caused by it or by a combination of weather disturbances such as rainfall, strong winds, storm-surges, floods and landslides		Merbok	Roke	Hato	Pakhar	Mawar	TD Sep	Khanun	Rainstorm /Landslip	Rainstorm /Landslip	Rainstorm	Rainstorm /Landslip	
2. Date of period of occurrence		11-13 Jun	22-23 Jul	22-23 Aug	26-27 Aug	2-4 Sep	23-24 Sep	14-16 Oct	24 May	13 Jun	17 Jun	17 Jul	
3. Name of regions/areas seriously affected													

II. HUMAN DAMAGE	**Unit**												
4. Dead and missing	persons												
5. Injured	persons				1	1							
6. Homeless	persons families			4 1	8 2								
7. Affected [1]	persons families			148 66	8 2			2					
8. Total	persons families			152 67	17 4	1		2					

Source of Meteorological data:

- Wind Speed: Maximum hourly wind and max gust of the 8 reference stations for the issuance TC signals
- Rainfall: Rainfall recorded at Hong Kong Observatory Headquarters when a TC is within 600 km range + subsequent 72 hours after the TC dissipation or moving out of the 600 km range of HK;

Regression analysis – methodologies

- Simple and Multiple Linear Regression
  - All combinations will be attempted.
  - Reject the model if the variable is insignificant at 5% level
  - Reject the model if $R^2 < 40\%$ (i.e. less than 40% are explained)
  - Select the model with the highest R^2 as the 'BEST' model

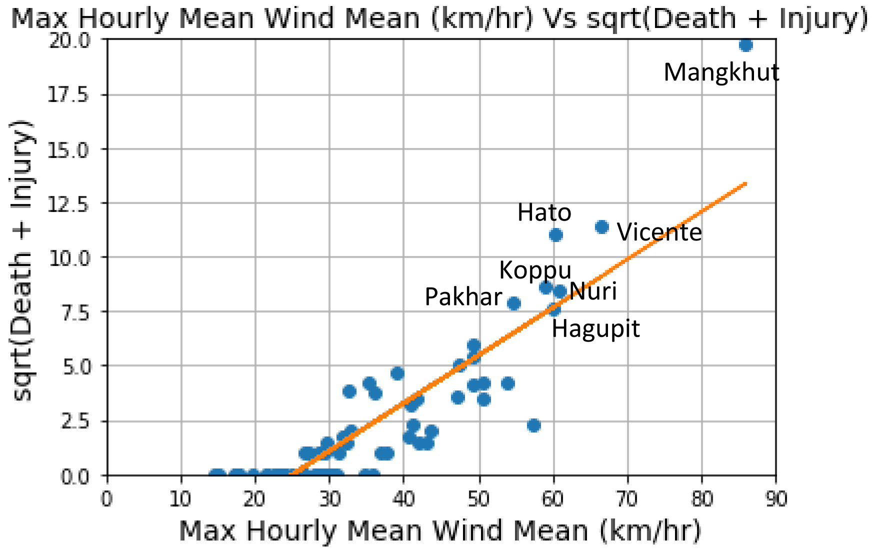
Regression analysis – Tropical cyclone

Name	max	Date start	Date end	Max Gust Mean (km/hr)	Max Hourly Mean Wind Mean (km/hr)
MANGKHUT	10	14/09/2018	17/09/2018	159.500	86.000
VICENTE	10	21/07/2012	24/07/2012	120.875	66.625
NURI	9	20/08/2008	23/08/2008	110.625	61.000
HATO	10	22/08/2017	23/08/2017	122.250	60.250
HAGUPIT	8	22/09/2008	24/09/2008	114.625	60.125
KOPPU	8	13/09/2009	15/09/2009	106.625	59.000
MOLAVE	9	17/07/2009	19/07/2009	98.375	57.500
PAKHAR	8	26/08/2017	27/08/2017	112.000	54.750
PRAPIROON	3	01/08/2006	04/08/2006	106.333	54.000
NIDA	8	31/07/2016	02/08/2016	92.625	50.625

Regression analysis – tropical cyclone

- Impact on Life

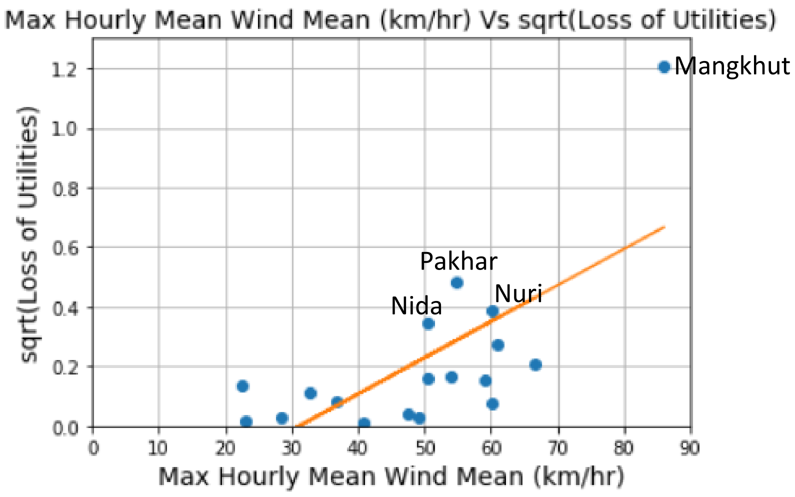
Response Variable	Good ?	Explanatory Variable 1	Explanatory Variable 2	Regressed Equation	R^2
Death + Injury (Y)	Good	Max Hourly Mean Wind (km/hr) (X)	N/A	$\sqrt{Y} = \begin{cases} 0.2195X - 5.5212 & X > 25.15 \\ 0 & otherwise \end{cases}$	0.79



Regression analysis – tropical cyclone

- Impact on Utilities (adjusted based on inflation rate) (unit: Million in US dollars, 7.8 HKD = 1 USD)

Response Variable	Good ?	Explanatory Variable 1	Explanatory Variable 2	Regressed Equation	R^2
Loss of Utilities (Y)	OK	Max Hourly Mean Wind (km/hr) (X)	N/A	$Y^{0.5} = \max\{0.0121X - 0.3788, 0\}$	0.49

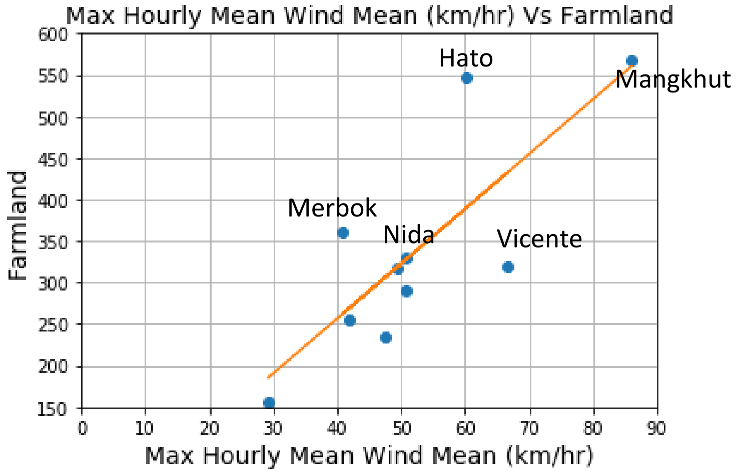


Remark
The data is reported by different companies (i.e. inconsistent) every year and is usually incomplete.

Regression analysis – tropical cyclone

- Impact on Agriculture (Farmland, unit: Hectares)

Response Variable	Good ?	Explanatory Variable 1	Explanatory Variable 2	Regressed Equation	R^2
Farmland (Y)	OK	Max Hourly Mean Wind (km/hr) (X)	N/A	$Y = \begin{cases} 6.6030X - 7.7354 & X > 1.17 \\ 0 & otherwise \end{cases}$	0.64

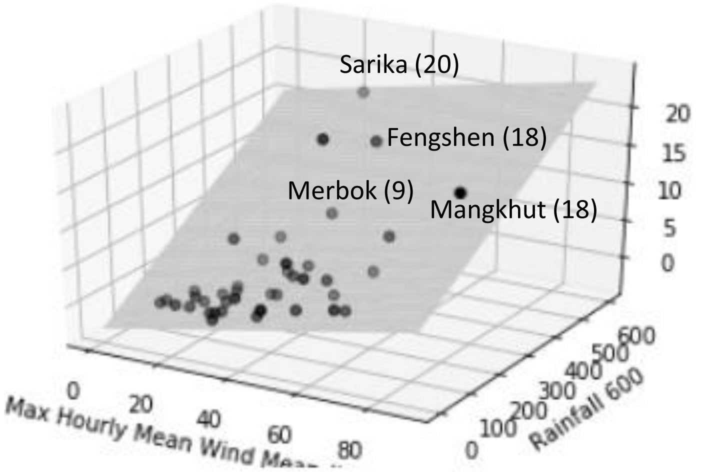


Remark
All possible outliers are excluded. Only 10 data points are used.

Regression analysis – tropical cyclone

- Impact on Land/vegetation (unit: number of reports)

Response Variable	Good ?	Explanatory Variable 1	Explanatory Variable 2	Regressed Equation	R^2
Landslide Reports (Z)	OK	Max Hourly Mean Wind (km/hr) (X)	Rainfall 600 (Y)	$Z = \max\{[0.0883X + 0.0314Y - 3.1873] + 1, 0\}$	0.52



Remark
The model works well for large values but not small. 20/43 cases have 1 landslide report only.

Regression analysis – tropical cyclone

- Summary:

Aspect	Response Variable	Good ?	Explanatory Variable 1	Explanatory Variable 2	Regressed Equation	R^2
Life	Death + Injury (Y)	Good	Max Hourly Mean Wind (km/hr) (X)	N/A	$\sqrt{Y} = \begin{cases} 0.2195X - 5.5212 & X > 25.15 \\ 0 & \mathit{otherwise} \end{cases}$	0.79
Delivery of services/utilities	Loss of Utilities (Y)	OK	Max Hourly Mean Wind (km/hr) (X)	N/A	$Y^{0.5} = \max\{0.0121X - 0.3788, 0\}$	0.49
Agriculture	Farmland (Y)	OK	Max Hourly Mean Wind (km/hr) (X)	N/A	$Y = \begin{cases} 6.6030X - 7.7354 & X > 1.17 \\ 0 & \mathit{otherwise} \end{cases}$	0.64
Land/vegetation	Landslide Reports (Z)	OK	Max Hourly Mean Wind (km/hr) (X)	Rainfall 600 (Y)	$Z = \max\{[0.0883X + 0.0314Y - 3.1873] + 1, 0\}$	0.52

SUMMARY

- Statistical relationships between impacts and weather has been analyzed with a view to develop impact-based forecasts
- Preliminary results suggested that statistical relationship exists between maximum hourly mean wind and (1) death and injury, (2) economic loss of utilities, (3) area of farmland affected