Meteorological Service Singapore
Centre for Climate Research Singapore

Radar Precipitation and Rain-Gauge Adjustment Techniques

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Typhoon Committee Roving Seminar

12 November 2019

Lecture Topics

<u>Topic B</u> – Rain gauge and radar data processing for QPE/QPF

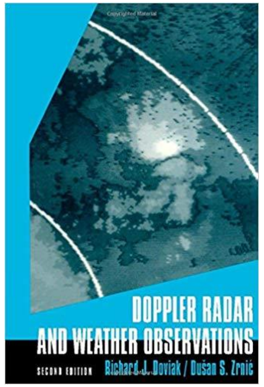
Goal: Scrutinise the radar processing chain for accurate QPE and QPF

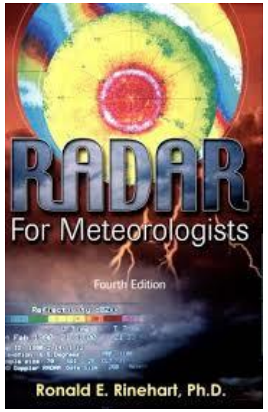
1. Radar and Rain-Gauge Data Quality and Processing
2. **Radar Precipitation and Rain-Gauge Adjustment Techniques**
3. Radar-Based Nowcasting and Verification Techniques

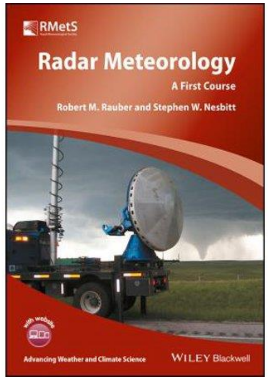
Reading Material:

- Doviak, Richard J, and Dusan S. Zrnic, 1993, ***Doppler Radar and Weather Observations***, Second Edition, San Diego, Academic Press, Inc., 562pp
- Rinehard, R. E., 2004, ***Radar For Meteorologists***, Fourth Edition, 2004
- Rauber, Robert & Nesbitt, Stephen. (2018). ***Radar Meteorology: A First Course.*** 10.1002/9781118432662.

Examples from SAWS and MSS Radar networks.







Outline

Radar Precipitation

- Reflectivity Extraction
- Precipitation Estimation
  - ZR explain ZR relationship (Textbook) also factors influencing rainfall
  - Dual ZR
  - HKO ZR calibration
  - DP
- Accumulation smoothing
- Rain gauge adjustments
  - MFB
  - Multiplicative
  - Kriging

Useful Tools

PYTHON:

- **wradlib**: wradlib.org/tag/python
- **PyART**: arm-doe.github.io/pyart/
- **rack**: baldrad.fmi.fi/software/rack/doc/rack/html/index.html
- **Baltrad**: git://git.baltrad.eu/
- **LROSE**: https://github.com/NCAR/lrose-core

R:

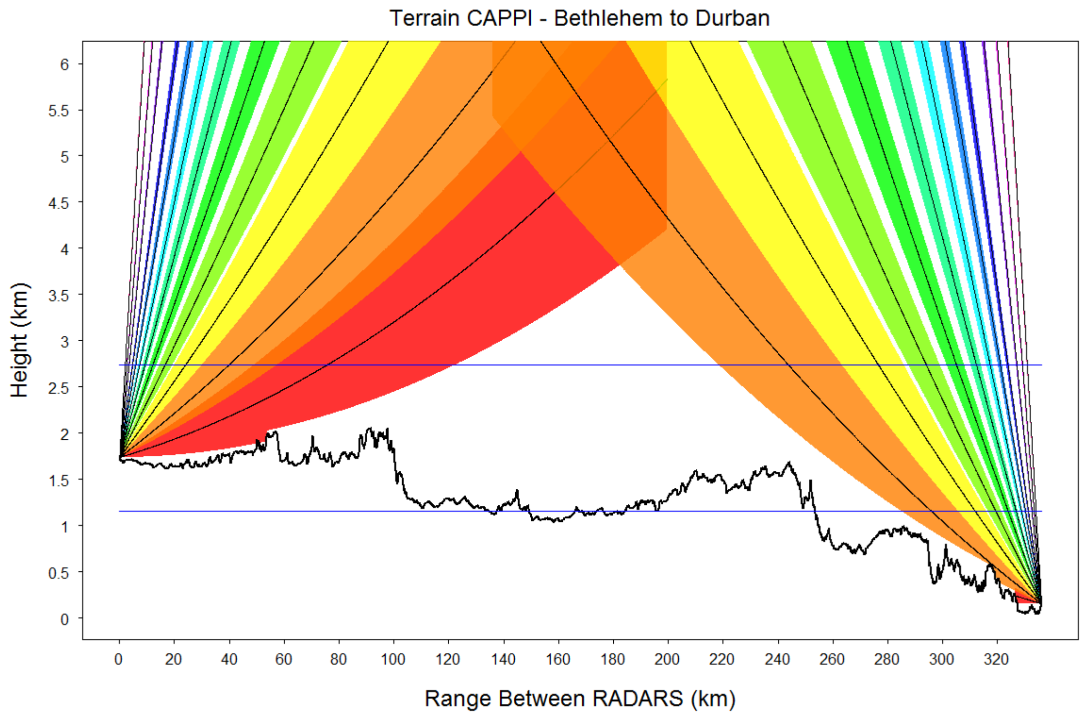
- **gstat** package (interpolation tools)

Reflectivity Extraction

Reflectivity for Precipitation

Multiple Methods:

- Single Radar → PPI
- Single Radar → CAPPI
- PPI → Composite PPI
- CAPPI → Composite CAPPI
- 3D Composite → CAPPI
- 3D Composite → Surface Intensity
- 3D Composite → Layer Intensity (Max,Mean,Median)



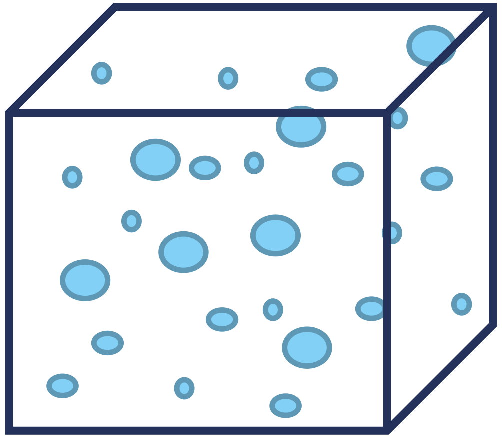
Precipitation Estimation

Precipitation Theory – Drop Size Distribution

- Precipitation measured with distrometre
- Precipitation Diameter (size) in millimetres
- Concentration number per volume usually m^{-3}
- Can define exponential or gamma distribution
- Rainfall Rate can then be expressed in terms of drop size distribution (DSD)

$$N = \sum_j n(D)\,\Delta D_j$$

Sample Volume (V_C)



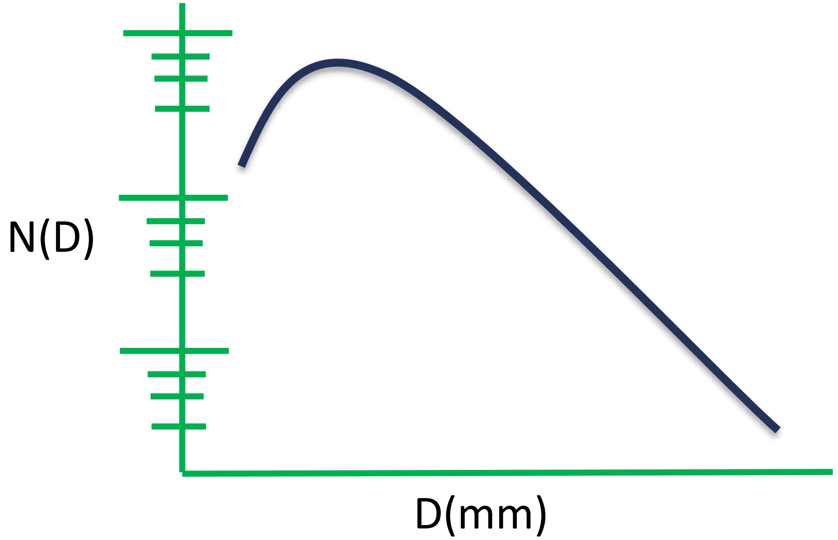


Figure 13.5 A Parsivel optical disdrometer

Z-R Relationship

Terminal Velocity Approximated

- Rinehart (2004) chapter 4 and 5.

$$Z = \frac{\sum_j D_j^6}{V_c} \quad \text{and} \quad R = \frac{\sum_j R_j}{V_c} = \frac{\pi \sum_j D_j^3 W_j}{6V_c} \; ; \quad W_t = aD$$

- Thus within a sample volume reflectivity and rain rate are approximately:

$$Z \propto \sum D^6 \qquad \text{and} \qquad R \propto \sum D^4$$

- Its true that,

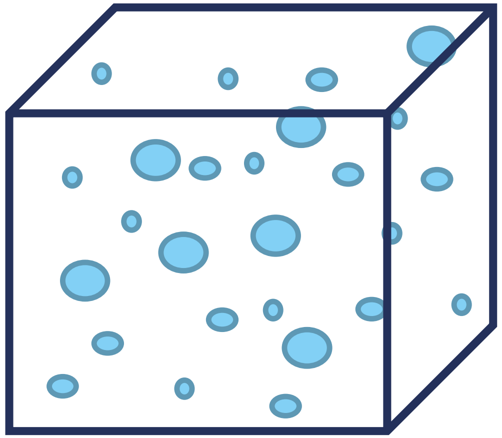
$$D_j^6 = \left(D_j^4\right)^{1.5}$$

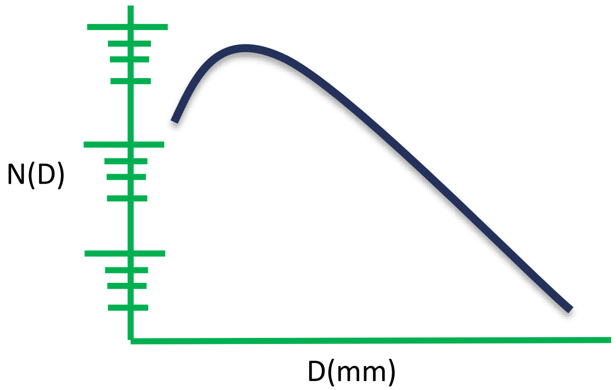
- However,

$$\sum_j D_j^6 \neq \left(\sum_j D_j^4\right)^{1.5}$$

- **No mathematical relationship** between the radar reflectivity factor and the rain rate.
- Empirical studies comparing measured radar reflectivity factors and rain rates in different types of weather systems suggest that relationships of the form:

Sample Volume (V_c)





$$Z = aR^b$$

Rauber, Robert & Nesbitt, Stephen. (2018). ***Radar Meteorology: A First Course.***

Precipitation Estimation

Challenges:

- Bright Band (ice versus water clouds);
- Dielectric constant (water = 0.93, ice = 0.197)

$$Z = \frac{\pi^5 |K^2| \sum D^6}{\lambda^4}$$

- Anomalous propagation (temperature inversion);
- Attenuation;
- Geometric issues:
  - beam blocking,
  - beam height (rainfall drift, overshooting),
  - beam broadening (inhomogeneous DSD);
- Absolute calibration.

Assumptions:

- Rayleigh Scattering:

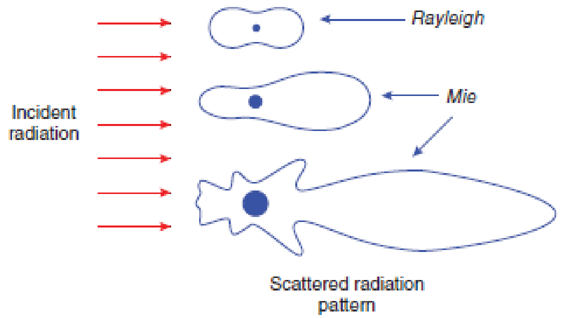


Figure 1.15 Scattered radiation pattern for progressively larger spherical particles. The distance is proportional to the amplitude of the scattered radiation

- Homogenous DSD within sample volume
- All Hydrometeors = Water
- Constant fall velocity

Z-R realtionships: $Z = aR^b$

Well known Z-R relationships:

Table 13.1 Legacy Z–R relationships used by the WSR-88D radars

Default	$Z = 300R^{1.4}$
Rosenfeld tropical	$Z = 250R^{1.2}$
Marshall–Palmer	$Z = 200R^{1.6}$
East Cool Season	$Z = 130R^{2.0}$
West Cool Season	$Z = 75R^{2.0}$

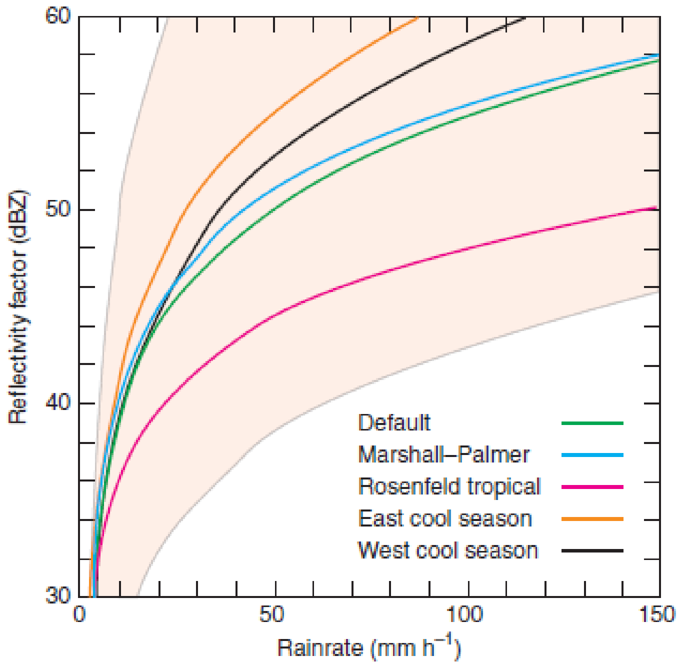


Figure 13.11 The relationship between the reflectivity factor and rainfall rate for the five legacy WSR-88D Z–R relationships (solid lines). The shading denotes the range of relationships for 69 other Z–R relationships in the published literature

Classify Z-R relationships:

Table 4. Reflectivity-rain rate (Z-R) relationships of the nine rain events for different rain types.

Rain event	Date	C		T	ST	ALL
1	09/01/98	$Z=330.74\ R^{1.25}$		$Z=149.44R^{1.55}$	$Z=182.61\ R^{1.43}$	$Z=192.13\ R^{1.40}$
2	28/01/98	$Z=129.87\ R^{1.58}$		$Z=175.36R^{1.48}$	$Z=295.49\ R^{1.13}$	$Z=179.87\ R^{1.48}$
3	05/04/98	$Z=411.68\ R^{1.27}$		$Z=248.71.03R^{1.34}$	$Z=142.63\ R^{1.59}$	$Z=212.52\ R^{1.42}$
6	18/05/98				$Z=445.89\ R^{1.29}$	
8	10/06/98	$Z=645.09\ R^{1.12}$		$Z=139.83\ R^{1.43}$	$Z=309.47\ R^{1.57}$	$Z=325.63\ R^{1.30}$
9	25/09/98	$Z=318.10\ R^{1.29}$		$Z=232.33\ R^{1.31}$	$Z=271.04\ R^{1.34}$	$Z=256.87\ R^{1.33}$
Rain event	Date	C1	C2	T	ST	
4	09/05/98	$Z=240.83\ R^{1.30}$	$Z=394.10\ R^{1.26}$	$Z=122.77\ R^{1.54}$	$Z=277.21R^{1.43}$	$Z=285.33\ R^{1.31}$
5	12/05/98	$Z=407.11\ R^{1.27}$	$Z=218.06\ R^{1.46}$	$Z=172.70\ R^{1.58}$	$Z=352.04\ R^{1.43}$	$Z=311.92\ R^{1.34}$
7	07/06/98	$Z=286.19\ R^{1.24}$	$Z=189.85\ R^{1.42}$	$Z=174.59\ R^{1.40}$	$Z=321.65\ R^{1.52}$	$Z=380.69\ R^{1.19}$
AU-SG		**$Z=328.64\ R^{1.29}$**		**$Z=173.24\ R^{1.42}$**	**$Z=309.20\ R^{1.39}$**	-

Kumar, L. S., Lee, Y. H., Yeo, J. X., & Ong, J. T. (2011). Tropical rain classification and estimation of rain from ZR (reflectivity-rain rate) relationships. Progress In Electromagnetic Research, 32, 107-127

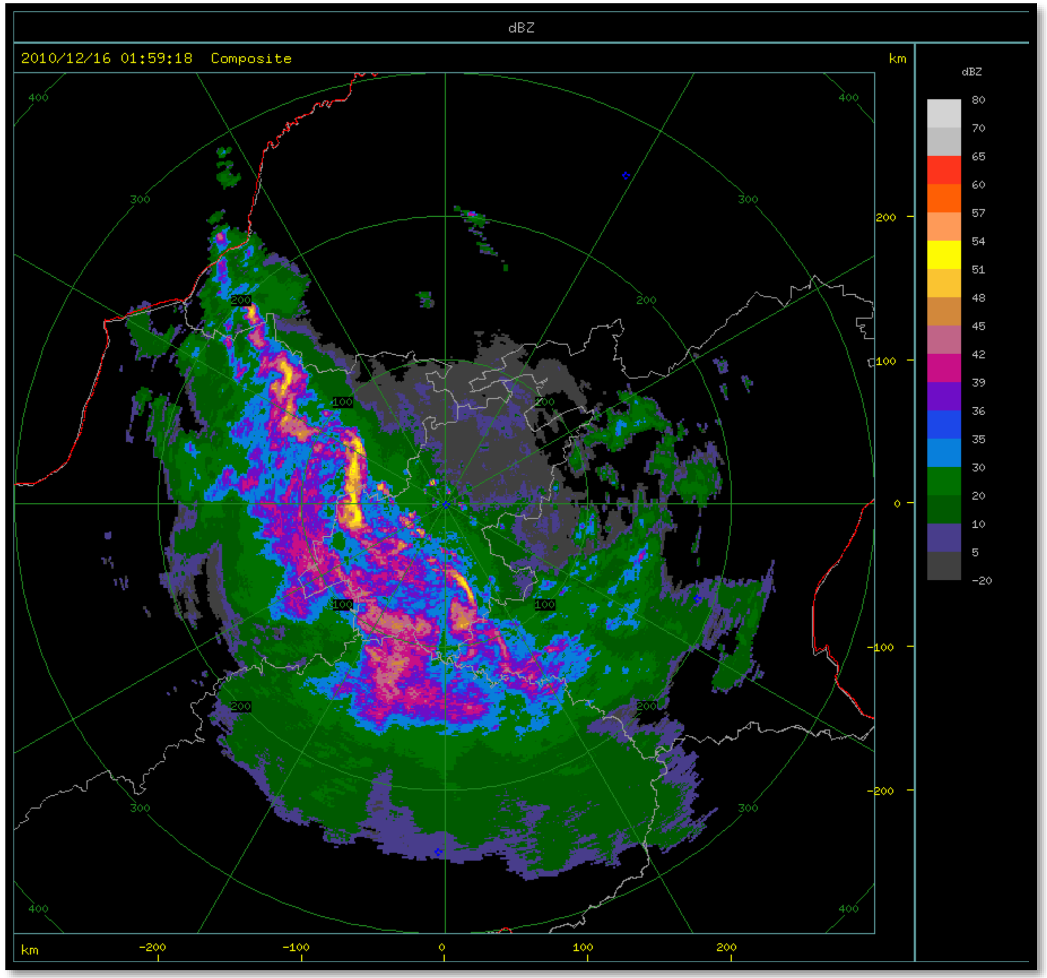
Dynamic Z-R relationships:

- Compare with Real-Time rain gauge data
- Linear regression method to find a and b - HKO

$$dBZ_i = b10\log R_i + 10\log a$$

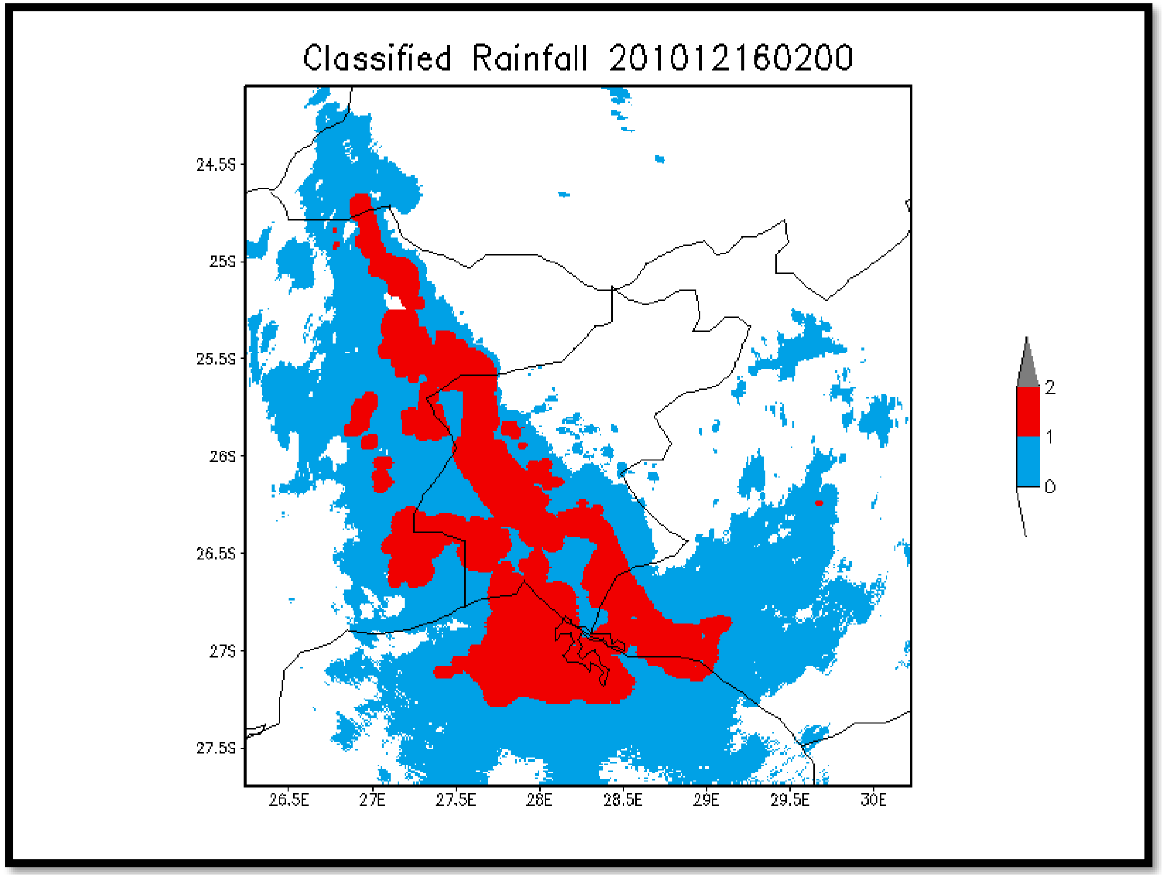
Rauber, Robert & Nesbitt, Stephen. (2018). ***Radar Meteorology: A First Course.***

Dual Z-R relationships (classification)



2D Classification (Conv/Strat)   Stratiform = $(Z = 200R^{1.6})$

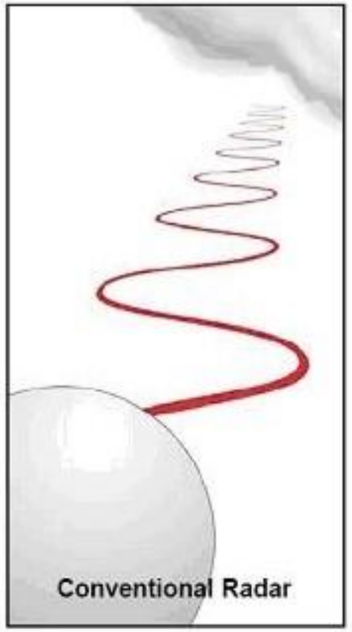
Dual Z-R relationship   Convective = $(Z = 300R^{1.4})$

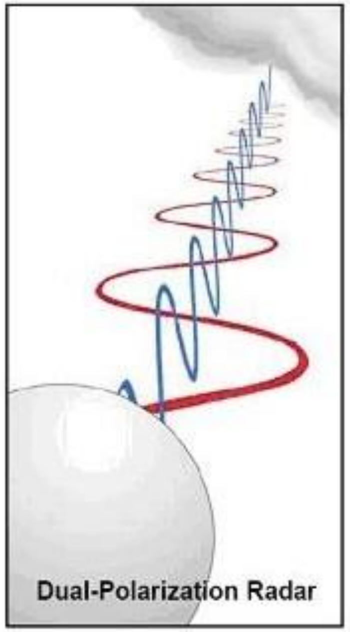


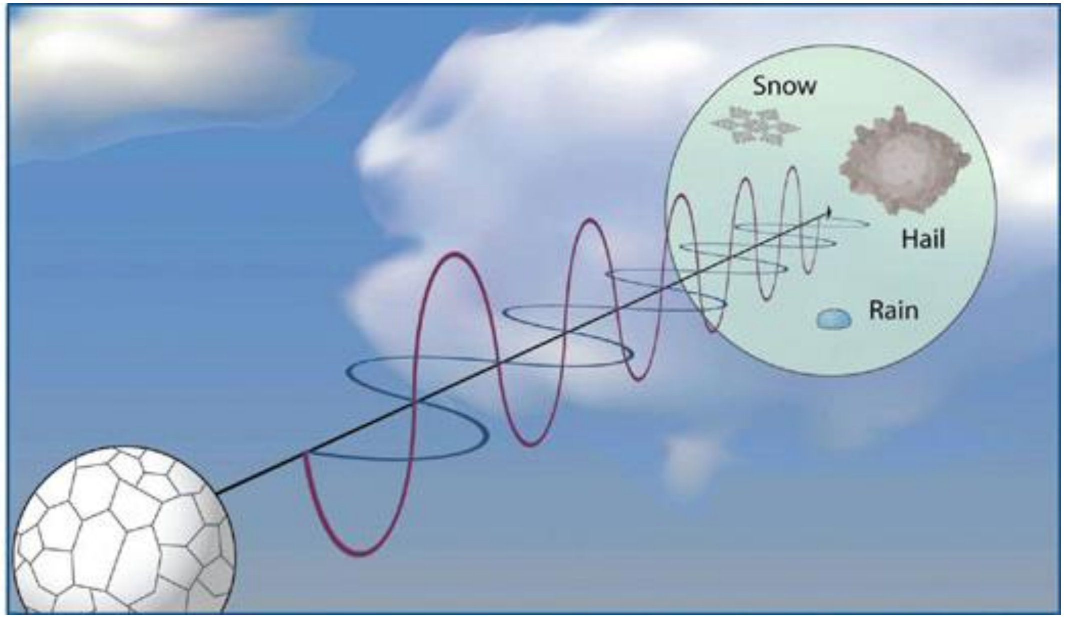
Steiner, et al. (1995)

Dual-Polarization Radars

- Additional information about the precipitation characteristics of clouds by essentially controlling the polarization of the energy that is transmitted and received
  - Most weather radars transmit and receive radio waves with a single, horizontal polarization
  - Polarimetric radars, on the other hand, transmit and receive both horizontal and vertical polarization simultaneously





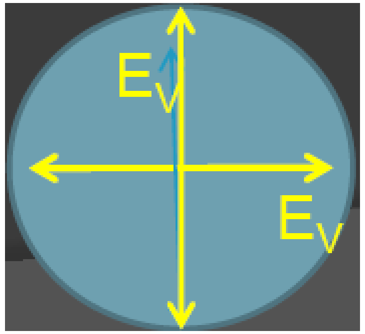


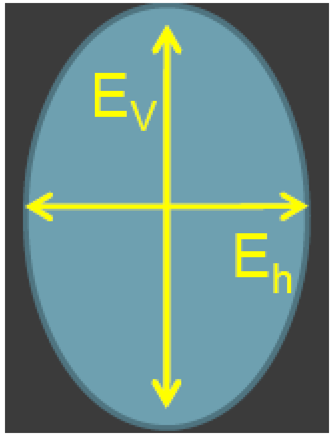
Dual-Polarization Radars

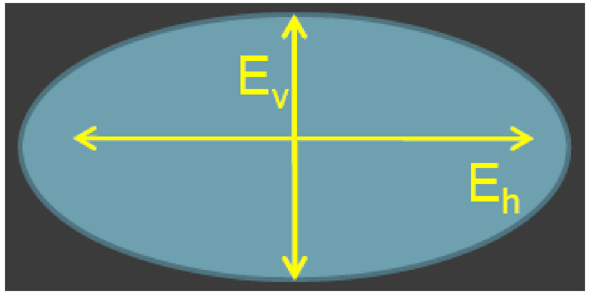
- **Differential Reflectivity:**

$$Z_{DR} = 10 \log_{10} \left[\frac{Z_h}{Z_v} \right]$$

  – ZDR > 0 - horizontally-oriented mean profile of hydrometeor
  – ZDR < 0 - vertically-oriented mean profile of hydrometeor
  – ZDR ~ 0 - nearly circular mean profile of hydrometeor







- **Correlation Coefficient:**
  – Correlation between Zh and Zv (RhoHV)
  – Round = 1.0

Dual-Polarization Radars

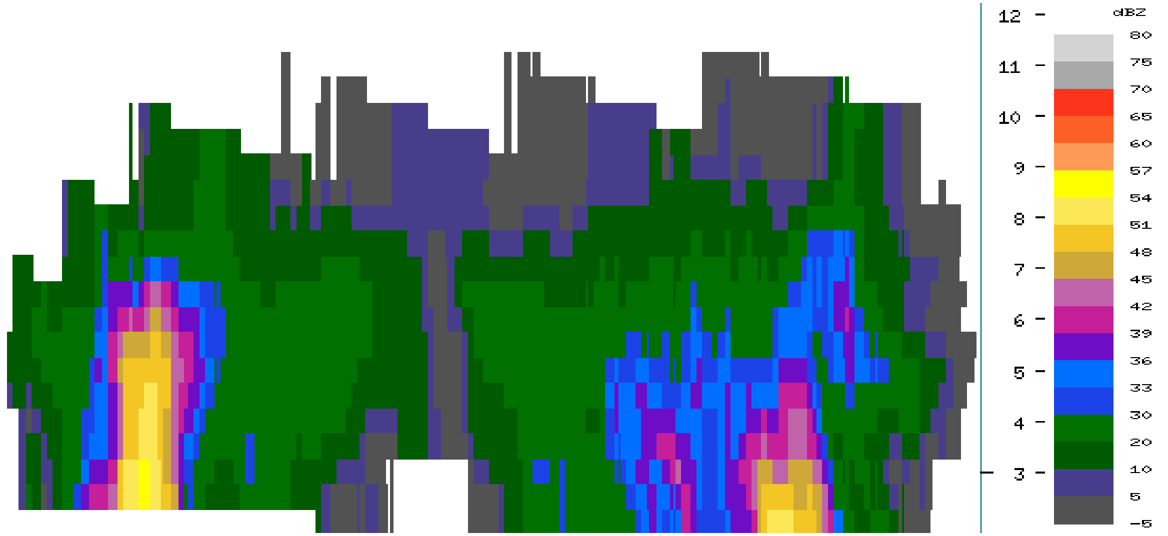
- **Specific Differential Phase**
  - A comparison of the returned phase difference between the horizontal and vertical pulses
  - This phase difference is caused by the difference in the number of wave cycles (or wavelengths) along the propagation path for horizontal and vertically polarized waves
  - It should not to be confused with the Doppler frequency shift, which is caused by the motion of the cloud and precipitation particles
  - Unlike the differential reflectivity, correlation coefficient, which are all dependent on reflected power, the specific differential phase is a "propagation effect“
  - It is a very good estimator of **rain rate**

$$\Phi_{DP} = \arg\left[\frac{1}{N}\sum_{i=1}^{N} V_i H_i^*\right]$$

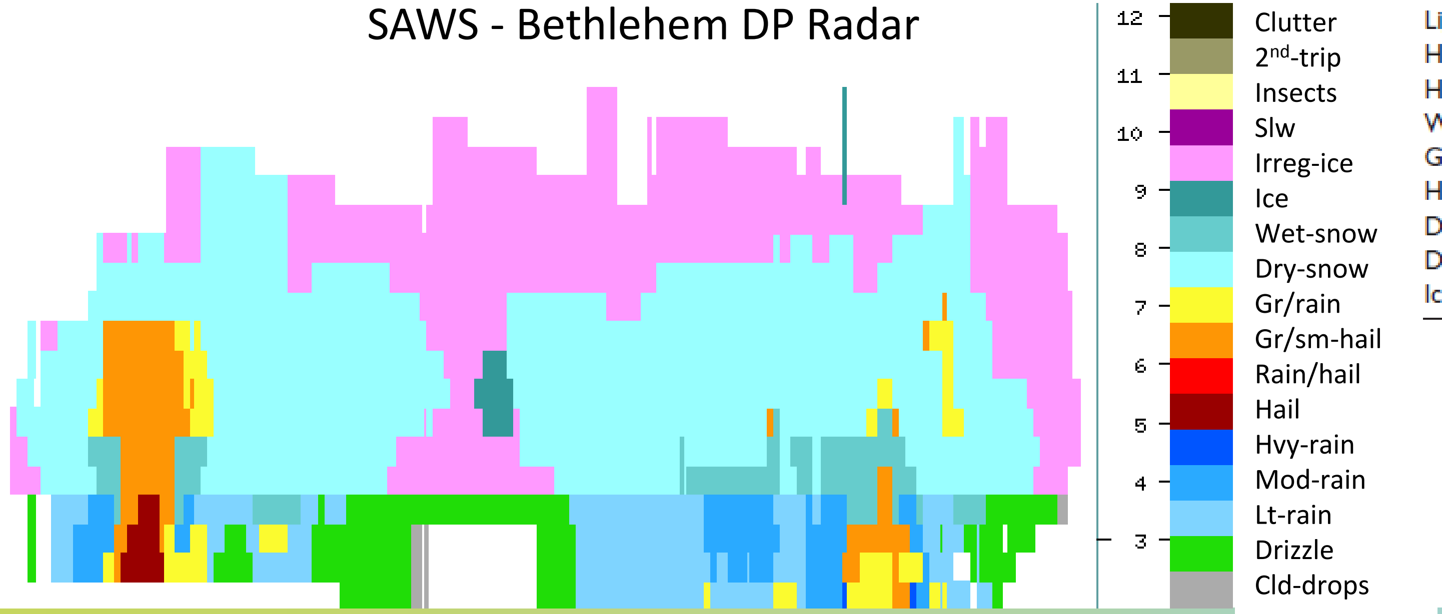
$$K_{DP} \approx \frac{1}{2}\frac{\Delta\Phi_{DP}}{\Delta r}$$

- K_{DP} is much stronger correlated to the rain rate than is Z or Z_{DR}
- Furthermore it is more or less independent of attenuation and partial beam blocking

Dual-Pol Particle Classification



SAWS - Bethlehem DP Radar



Dual-Pol Precipitation Estimation:

$$R(Z_H) = (1.7 \times 10^{-2}) Z_H^{0.714}$$

$$R(K_{DP}) = 44.0 |K_{DP}|^{0.822} sign(K_{DP})$$

$$R(Z_H, Z_{DR}) = (1.42 \times 10^{-2}) Z_H^{0.77} Z_{dr}^{-1.67}$$

Table 13.3 WSR-88D equations used in precipitation algorithm as a function of hydrometeor class

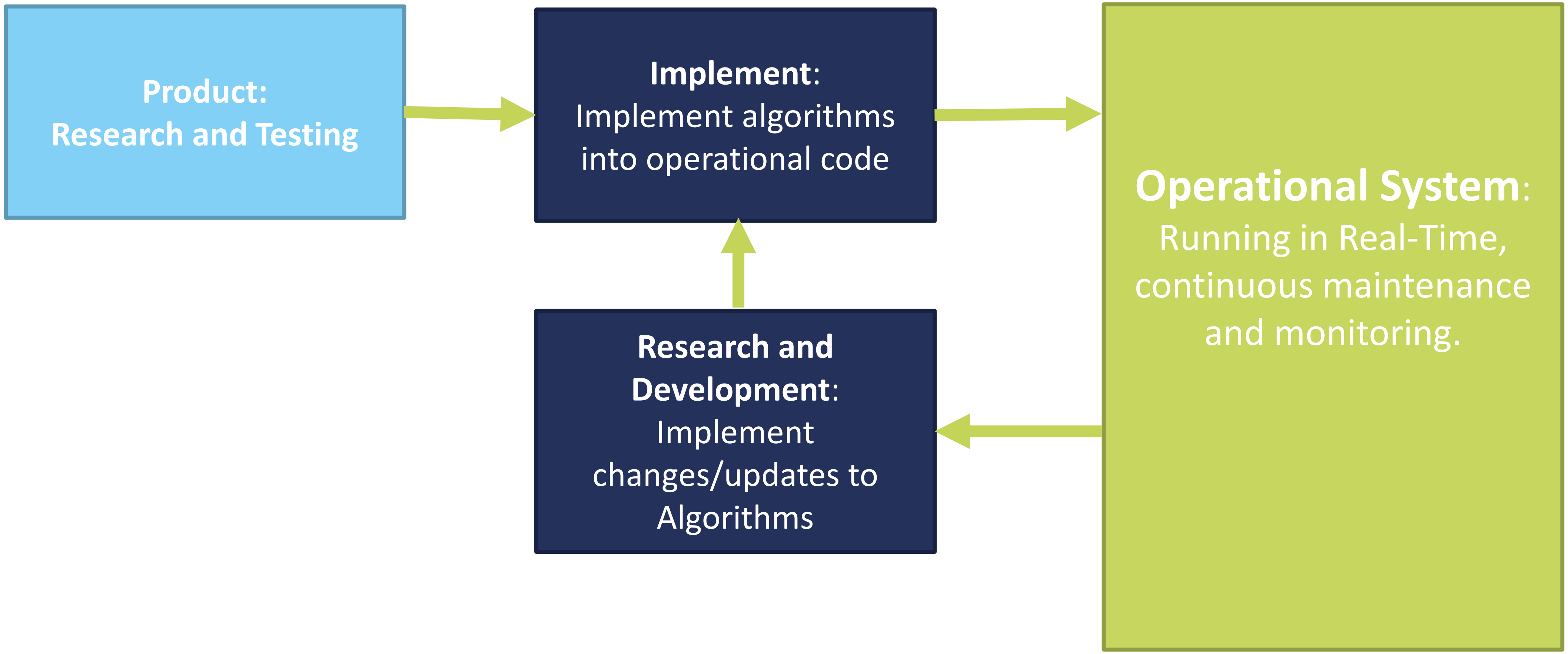
Hydrometeor class	Variables in precipitation rate equation
Non-meteorological echo (BI, ND)	None, no precipitation
Light to moderate rain (RA)	$R(Z_H, Z_{DR})$
Heavy rain or big drops (HR, BD)	$R(Z_H, Z_{DR})$
Hail mixed with rain below melting layer top (HA)	$R(K_{DP})$
Wet snow (WS)	$0.6 \times R(Z_H)$
Graupel (GR)	$0.8 \times R(Z_H)$
Hail, mixed with rain above top of melting layer (HA)	$0.8 \times R(Z_H)$
Dry snow (DS) below the top of melting layer	$R(Z_H)$
Dry snow (DS) above the top of melting layer	$2.8 \times R(Z_H)$
Ice crystals	$2.8 \times R(Z_H)$

Active Research Topic. Methodology updated continuously

Best to apply to Polar coordinate first and then convert to Cartesian coordinates

Rauber, Robert & Nesbitt, Stephen. (2018). ***Radar Meteorology: A First Course.***

Operational Research Model

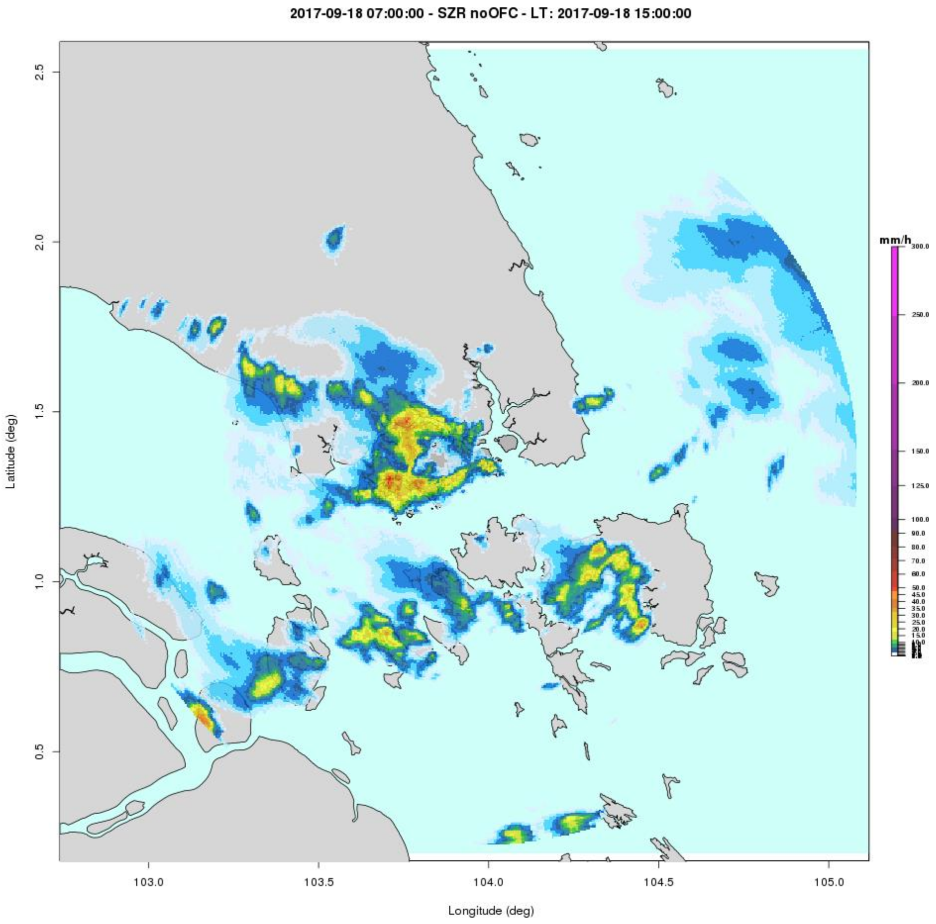


Operational QPE (CCRS)

Research Product – Setup:

- **Radars:** Changi and Seletar Merge
- **Domain:** 525X531 pixel, ±125km, 500m resolution
- **CAPPI:** 3D CART – 500m – 4500m median
- **Quality Control:** Cut second trip, Ships, Non-Met echoes, Speckle, Threshold extremes (min 15dBZ, max 53dbz), Gabella, Interpolate Missing Values
- **QPE:** Single Z-R, $z = 328.64R^{1.29}$
- **Bias Adjustment:** MFB, Temporal Smoothing, Conditional Merging

1 Hour Accumulation



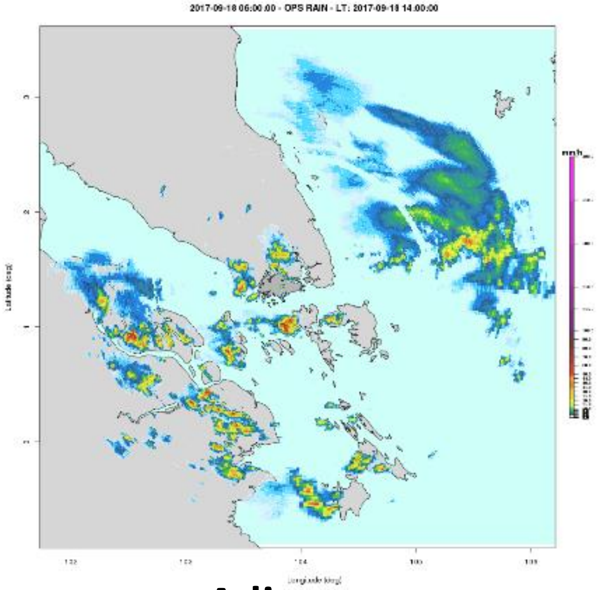
Some Known Issues

Current Operational Product

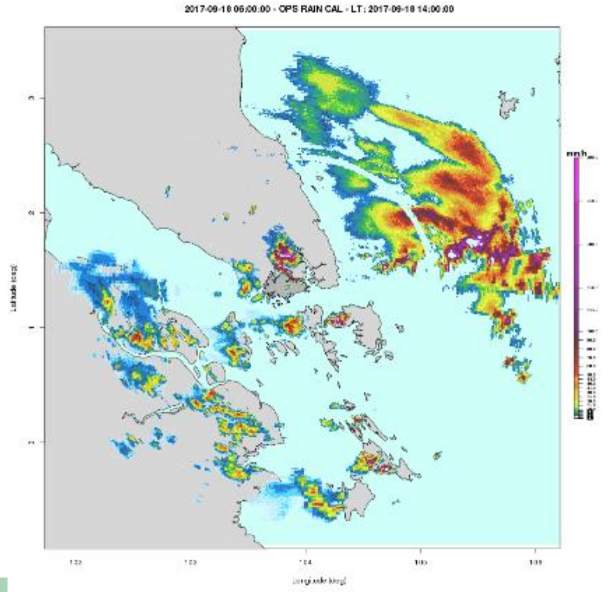
- Uses one radar (Changi S-band) only
  - Cone of silence
  - Ground Clutter
- Rain Gauge adjustment only works when rainfall within Singapore.
  - Radar under-estimate (calibration)

Calibration Bias Adjustment

No Adjustment

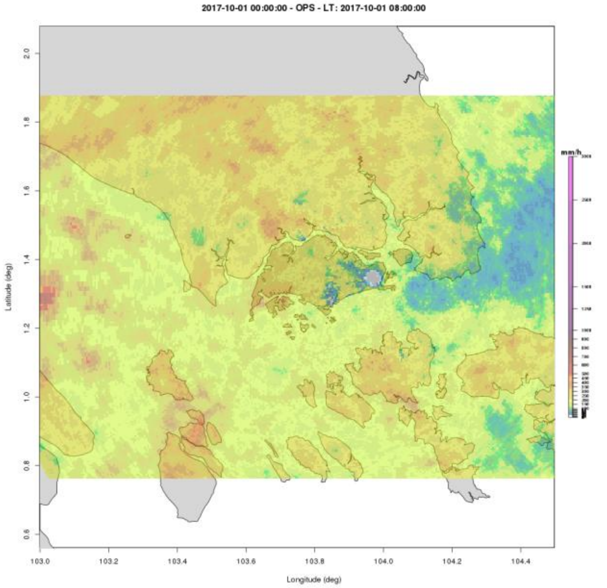


Adjustment

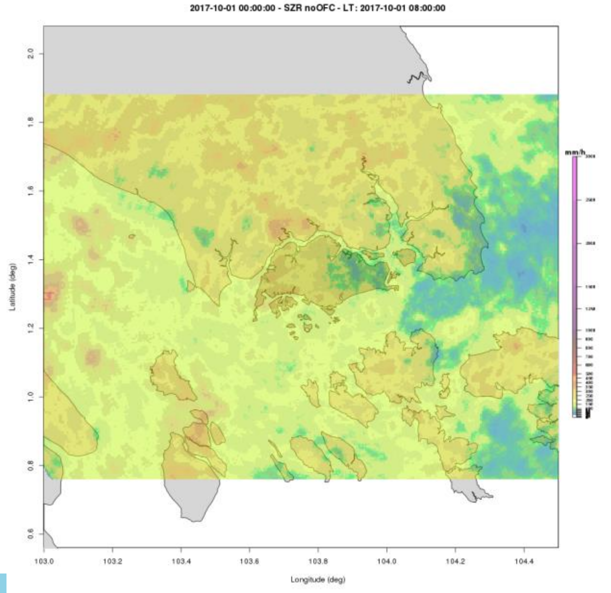


30 Day Accumulation

Changi Only



Composite

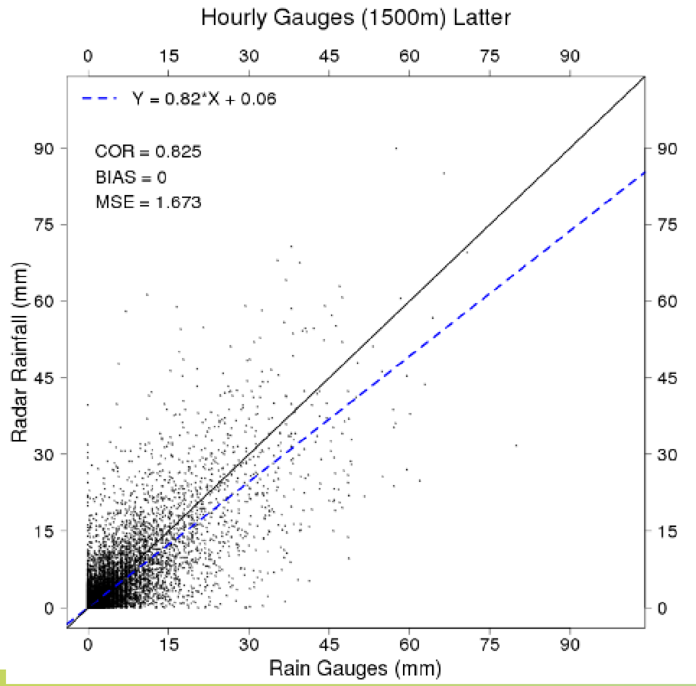


Quantitative Precipitation Estimation (QPE)

Continuous Variable Verification Scores

https://www.cawcr.gov.au/projects/verification/

- Scatter and boxplots
- Linear Model
- Error Scores
- Cross Validate when using gauge data



$$Correlation\ coefficient = \frac{\sum(R-\bar{R})(G-\bar{G})}{\sqrt{\sum(R-\bar{R})^2}\sqrt{\sum(G-\bar{G})^2}}$$

$$Mean\ Error\ (Bias) = \frac{1}{N}\sum_{i=1}^{N}(R_i - G_i)$$

$$Multiplicative\ Bias = \frac{\frac{1}{N}\sum_{i=1}^{N} R_i}{\frac{1}{N}\sum_{1=1}^{N} G_i}$$

$$Mean\ Absolute\ Error = \frac{1}{N}\sum_{i=1}^{N}|R_i - G_i|$$

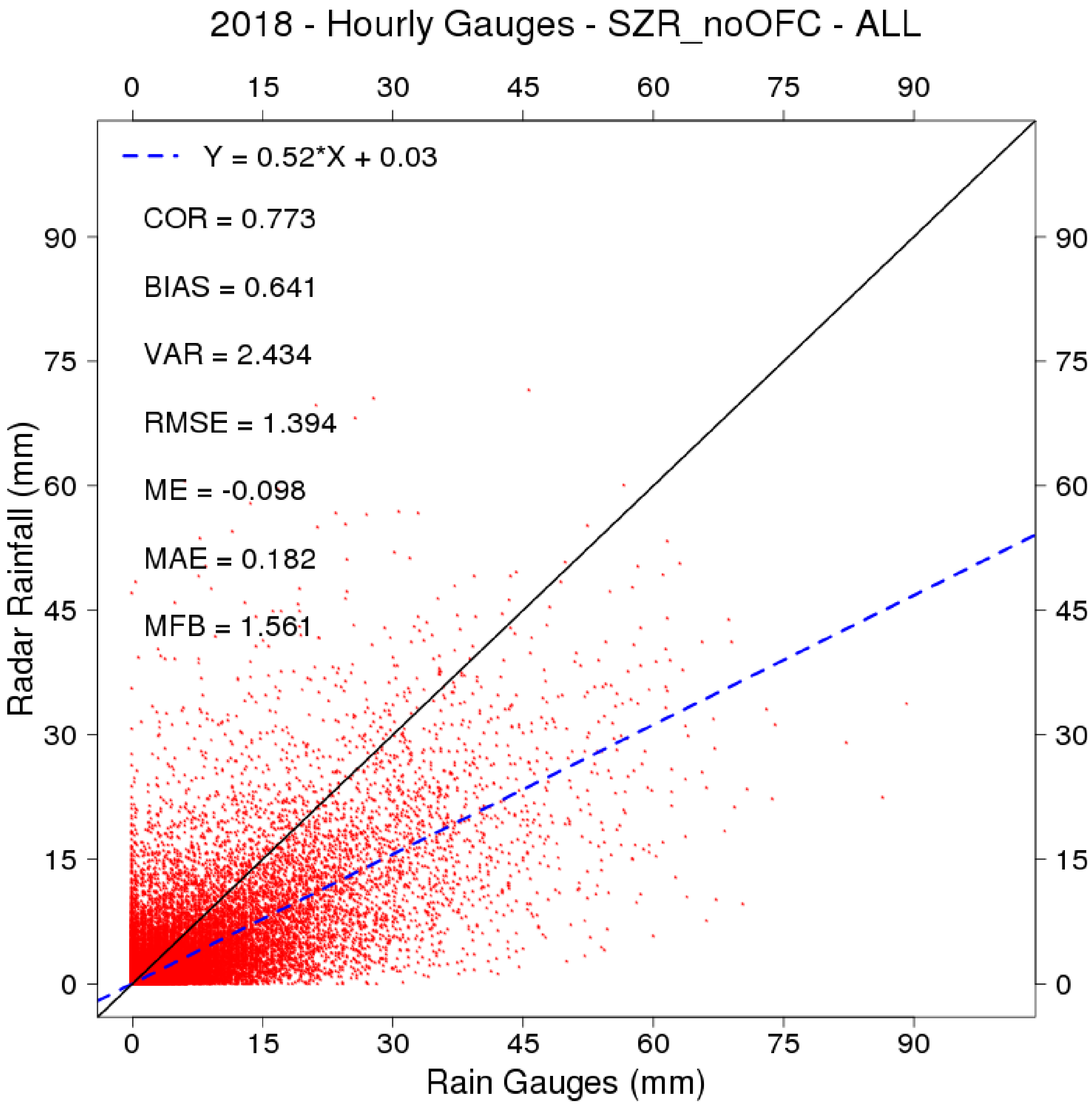
$$Root\ Mean\ Square\ Error = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(R_i - G_i)^2}$$

QPE - verification

Baseline

- Radar, Rain gauge matching technique:
  - 3X3 Average for rainfall drift.
- Verification period: 2018

- Can test QC procedure
- Can test different estimation techniques for improved results



Mean Field Bias Adjustments

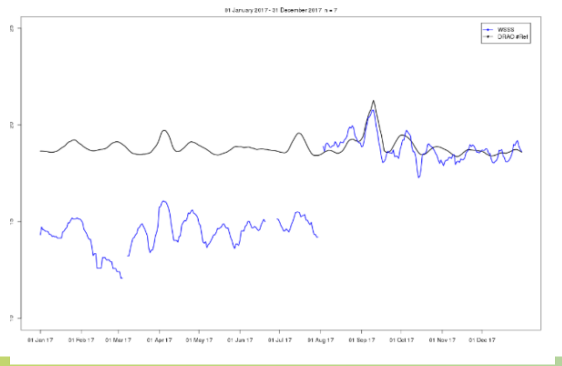
Quantitative Precipitation Estimation (QPE)

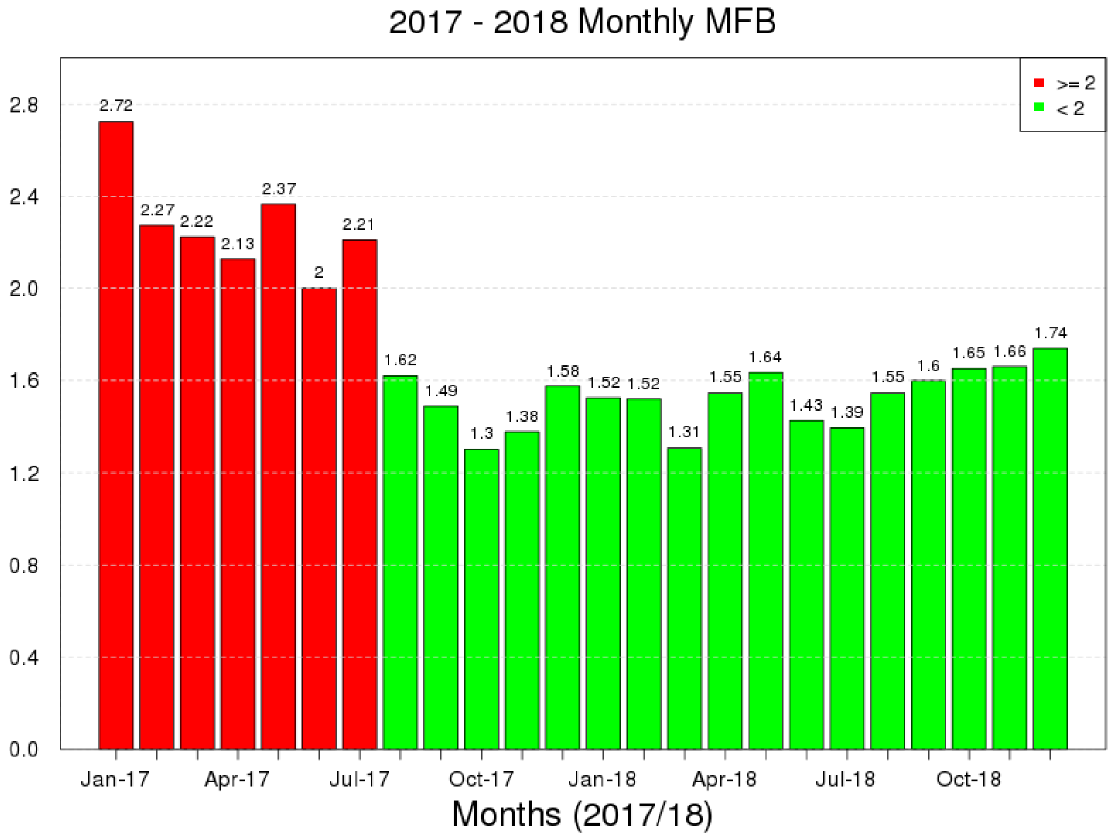
Mean Field Bias

- Need to apply MFB to correct for radar calibration bias.

$$MFB = \frac{\sum_{i=1}^{N} G_i}{\sum_{1=1}^{N} R_i}$$

- Applied on a month to month basis
- Similar to sun calibration results

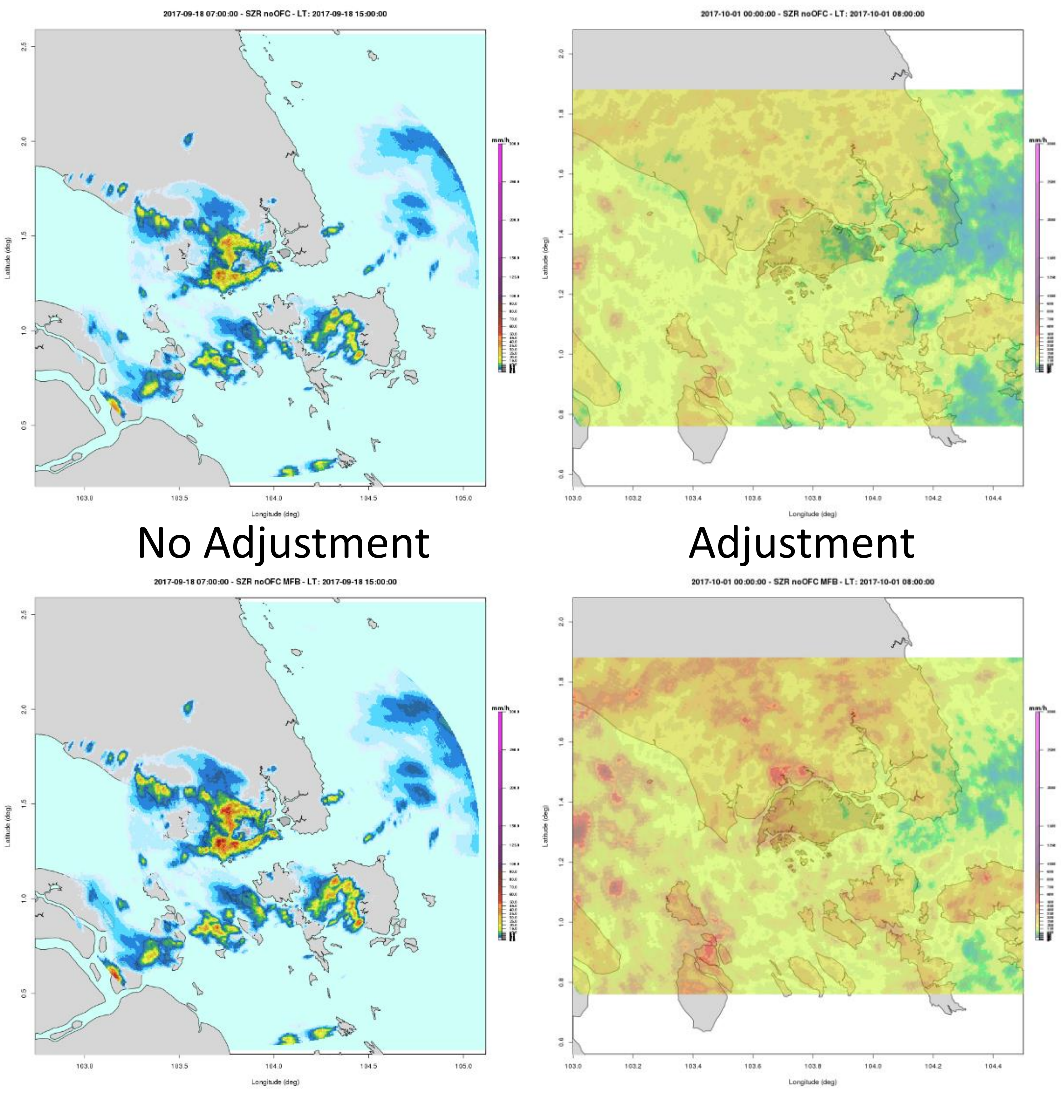




Quantitative Precipitation Estimation (QPE)

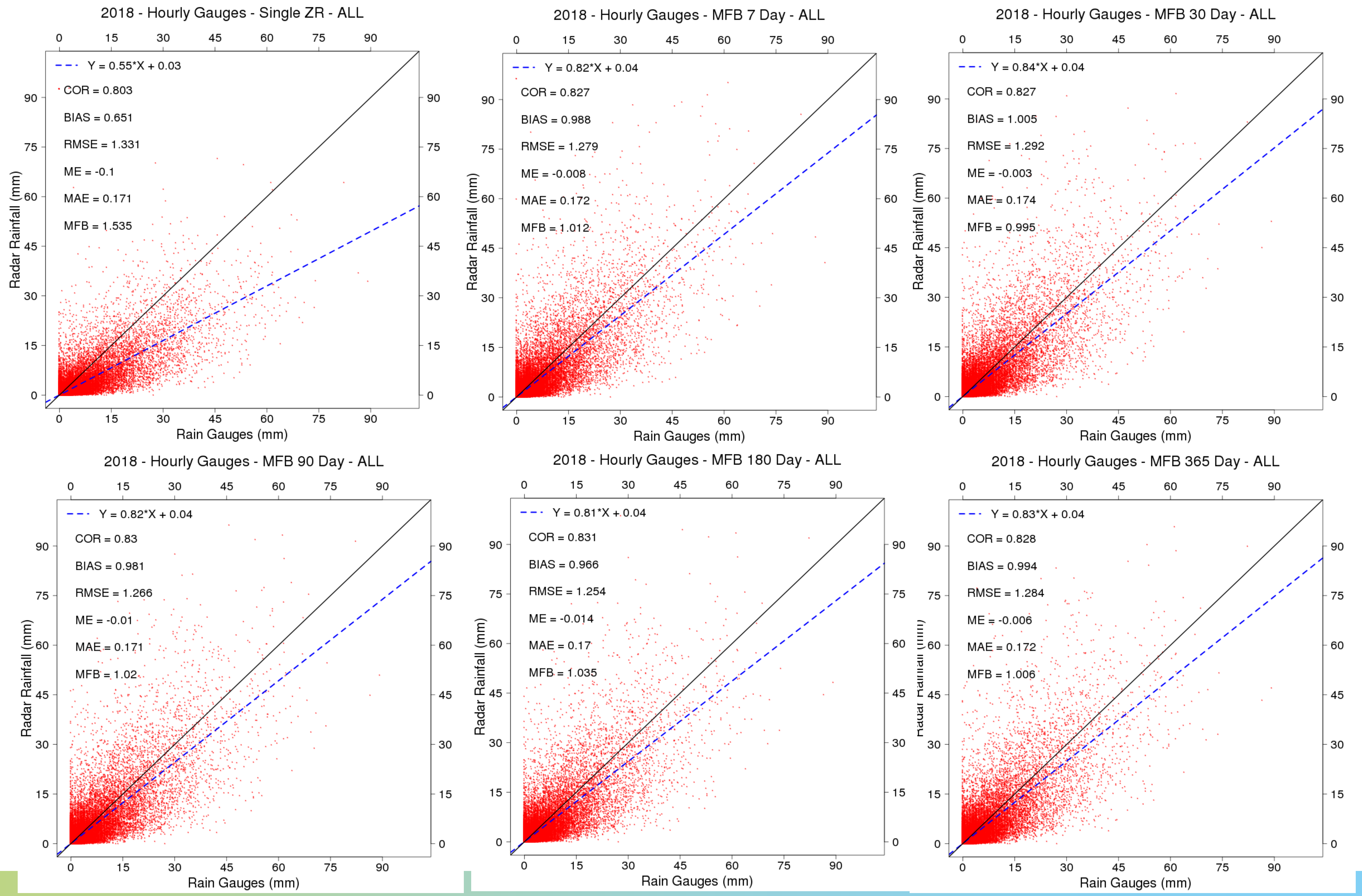
Research Product – MFB adjusted

- Hour Accum
- 30 Day Accum



Rolling MFB Scores

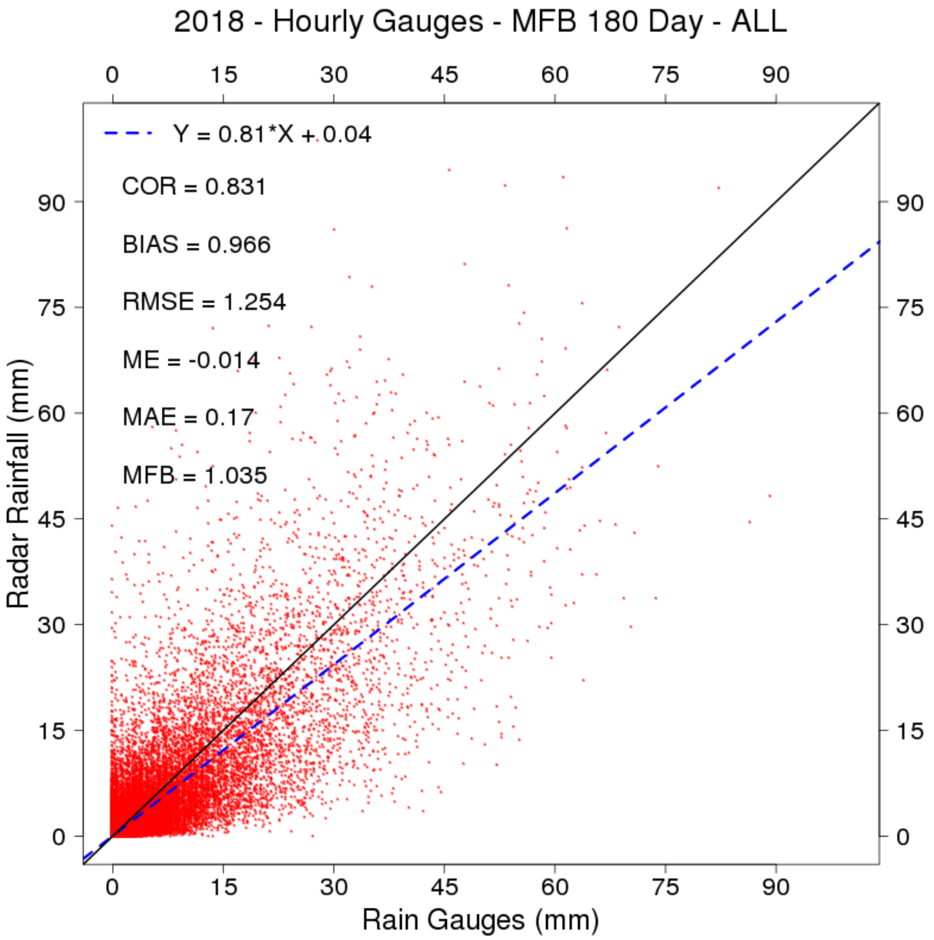
- 2018
- Calibration shift
- Need to find balance
- Previous time step
- Rolling average

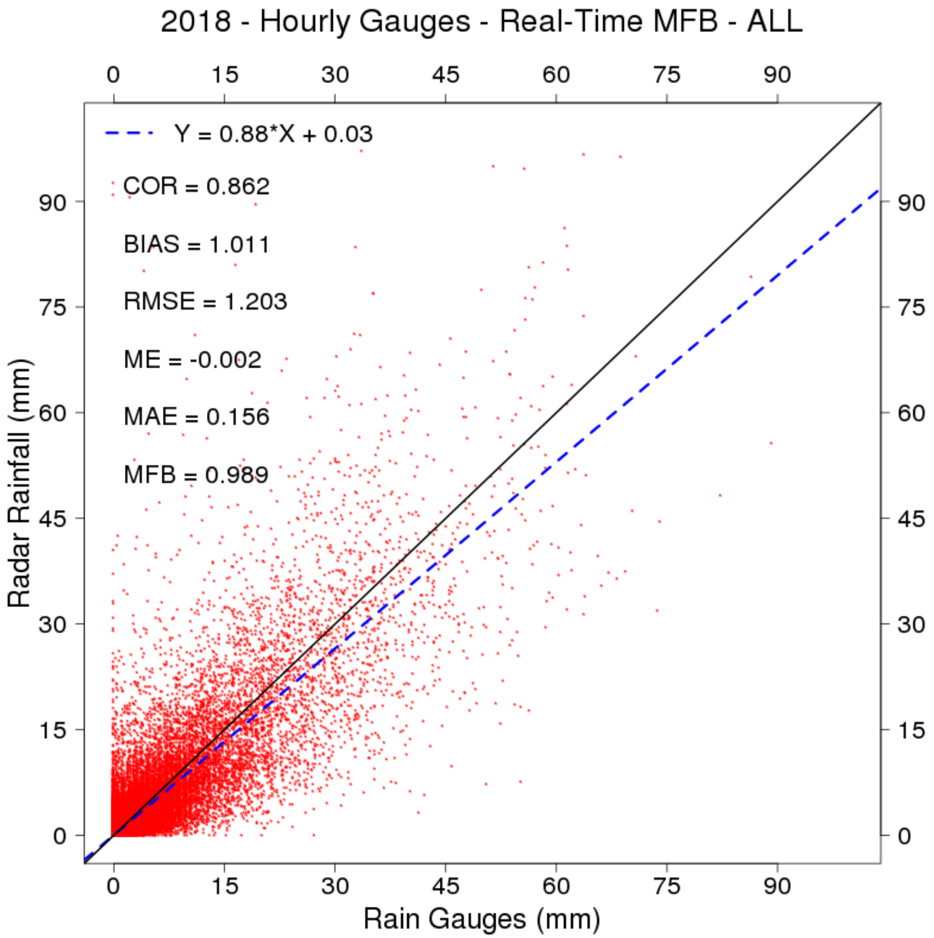


Real-Time MFB

Real-Time better
Need to update as gauge data become available

Applying static MFB will result in smaller shift

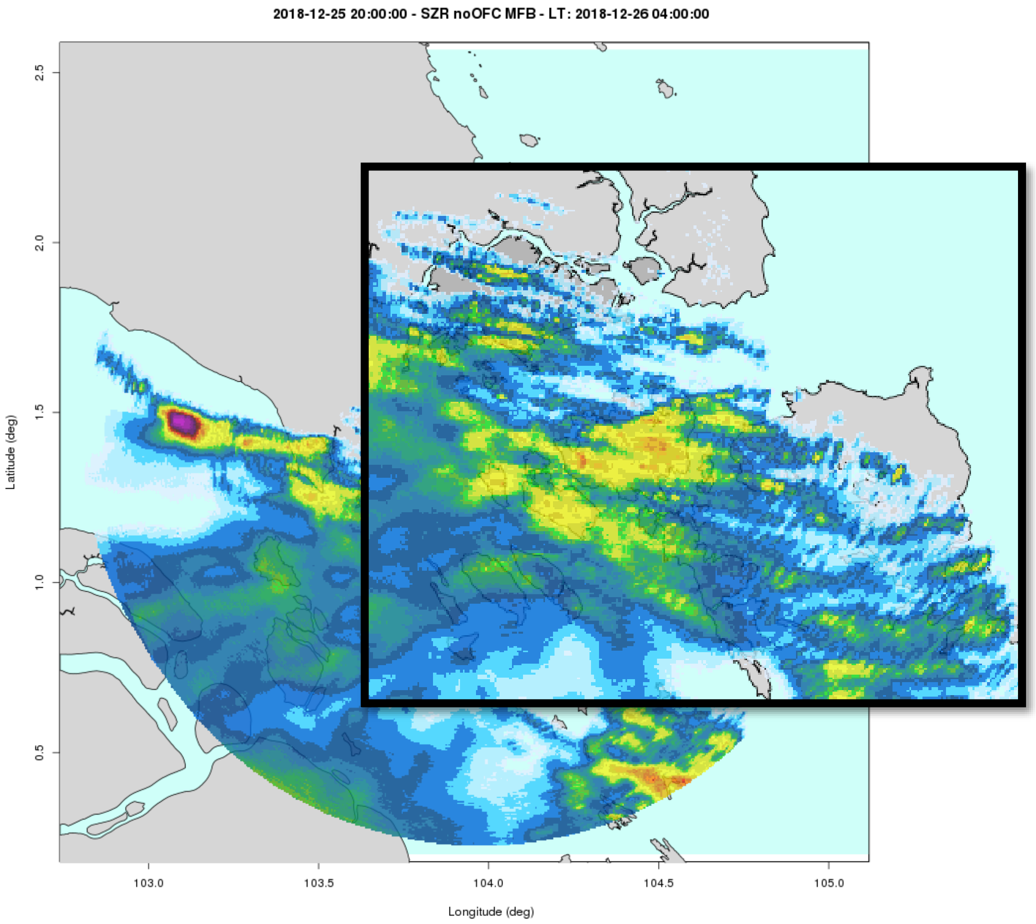


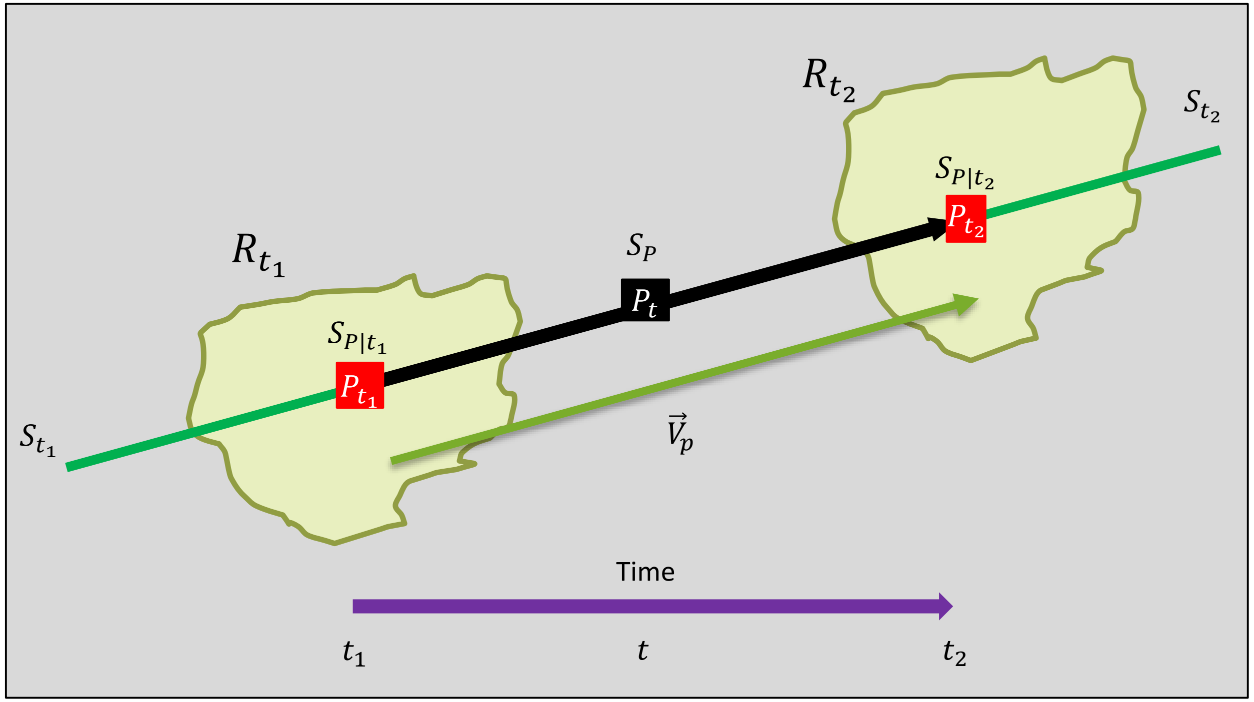


Smoothing Accumulation Biases

Accumulations (QPE)

Research Product – Spatial Smoothing of Temporal Bias





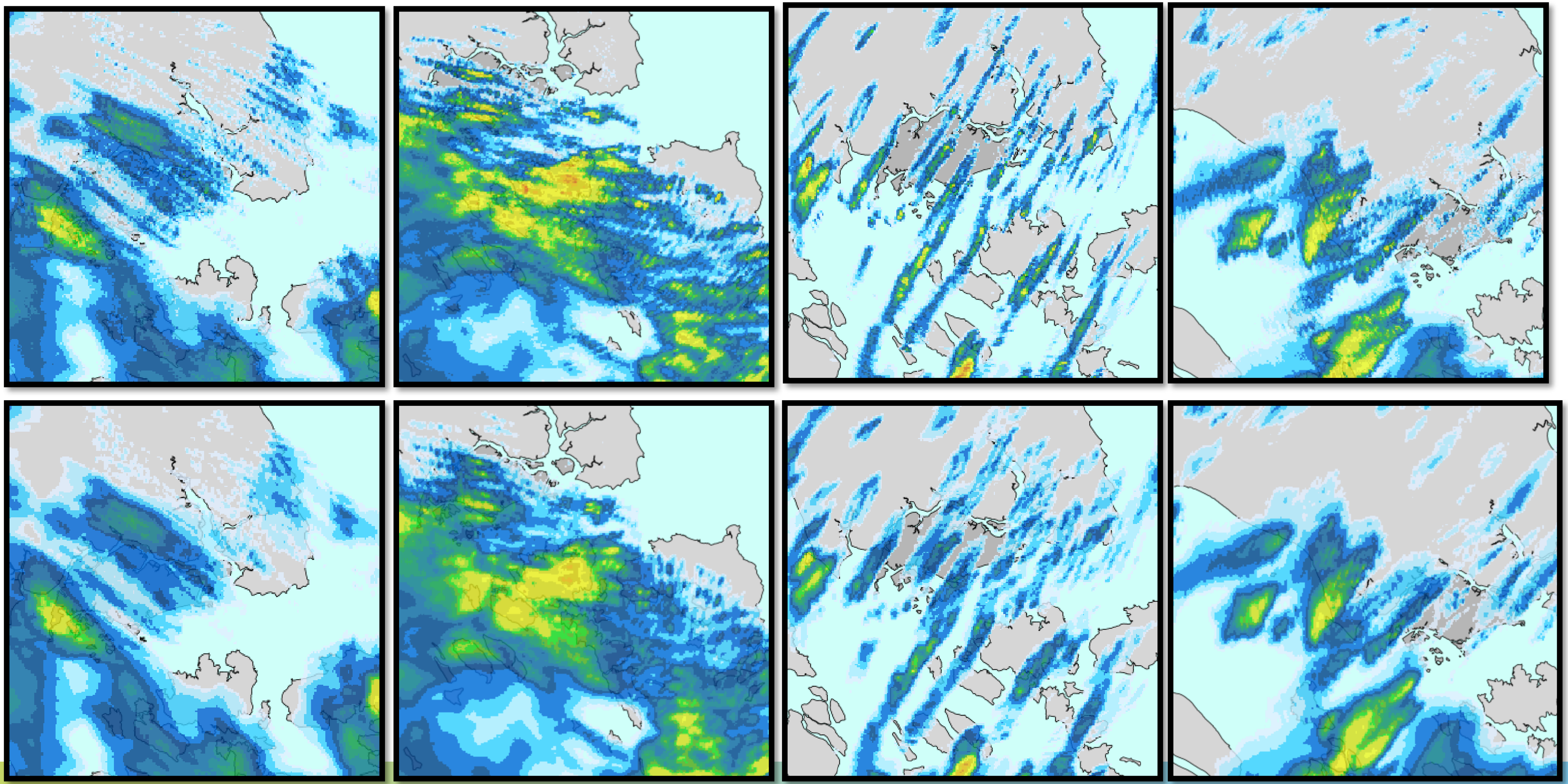
$$A_P = \frac{1}{\overrightarrow{V_P}}\left(\int_{S_{t_1}}^{S_{P|t}} \left|\frac{S_{t_1} - S_P}{\Delta s}\right| R(S_P)ds + \int_{S_{P|t}}^{S_{t_2}} \left|\frac{S_{t_2} - S_P}{\Delta s}\right| R(S_P)\,ds\right)$$

Quantitative Precipitation Estimation (QPE)

Before and After - Temporal Smoothing

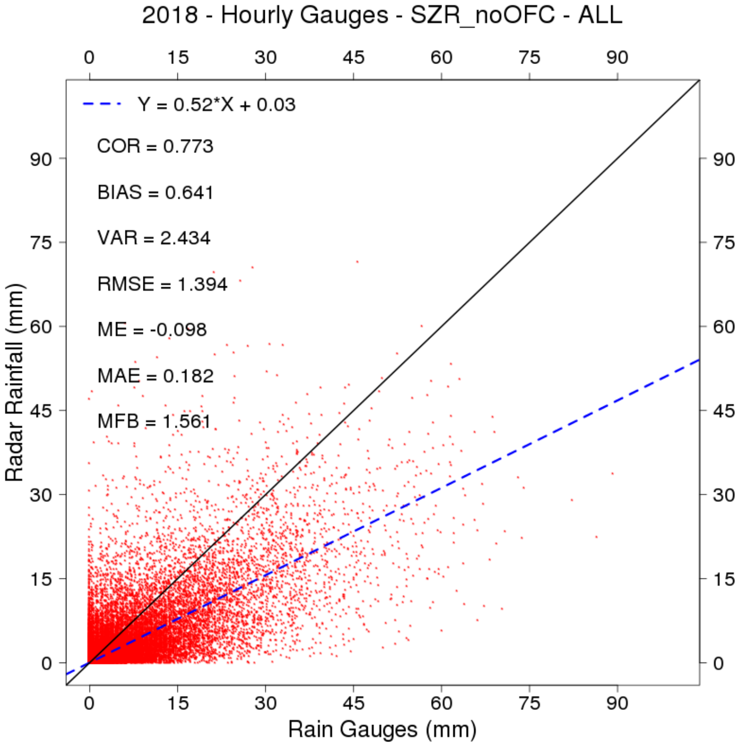
Before

After

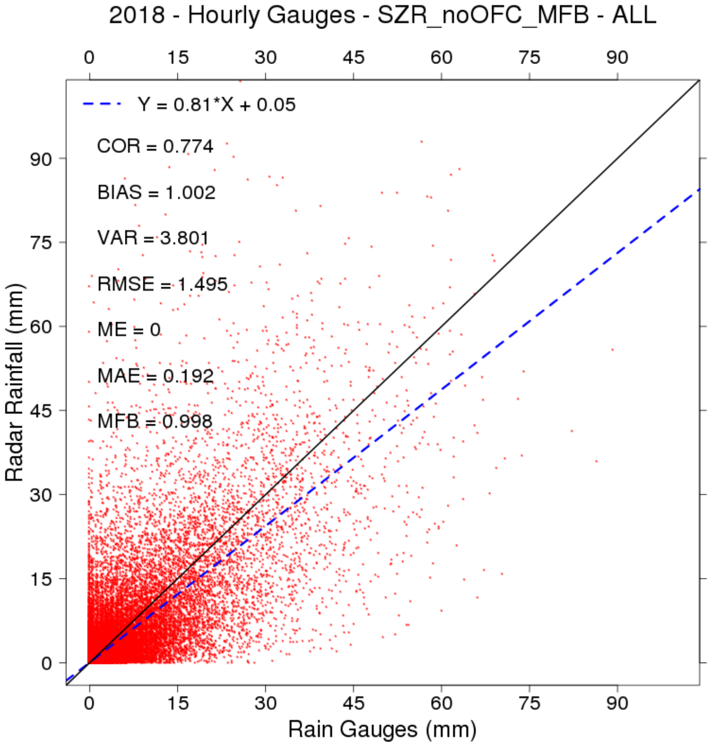


Verification (QPE)

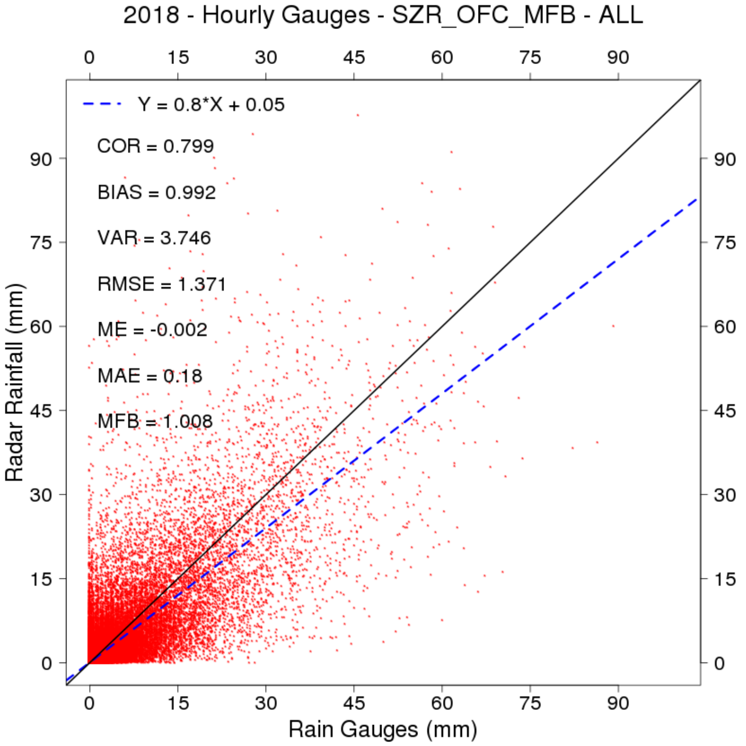
No Adjustment



MFB Adjusted



MFB & Temporal Smooting



- Work on Optical flow may improve results

Merging Radar and Rain Gauge Measurements

Quantitative Precipitation Estimation (QPE)

Conditional Merging with Gauge data

From Sinclair & Pegram (2005):

1. $Z(s) = G_k(s) + \varepsilon_G(s)$
2. $\mathrm{R}(s) = R_k(s) + \varepsilon_R(s)$
3. $\mathrm{M}(s) = G_k(s) + \varepsilon_R(s)$

- $\varepsilon_G(s) \approx \varepsilon_R(s)$, if they are highly correlated.
- The variance of $\varepsilon_G(s)$ and $\varepsilon_R(s)$ depend on distance from gauge location
- Will work well where there is a dense gauge network.
- i.e. Outside of Singapore MFB will be the best possible adjustment

1D Case

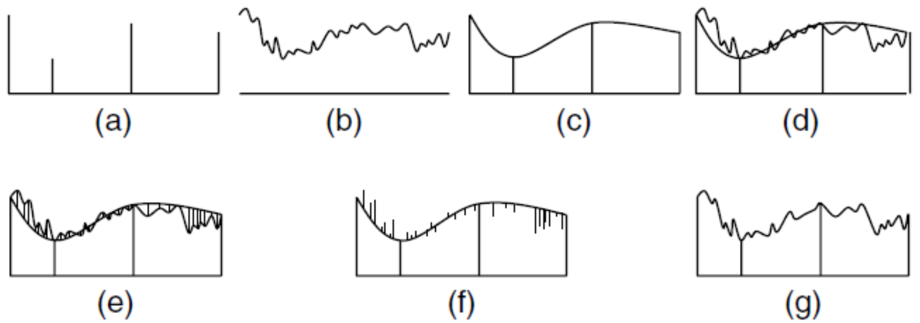
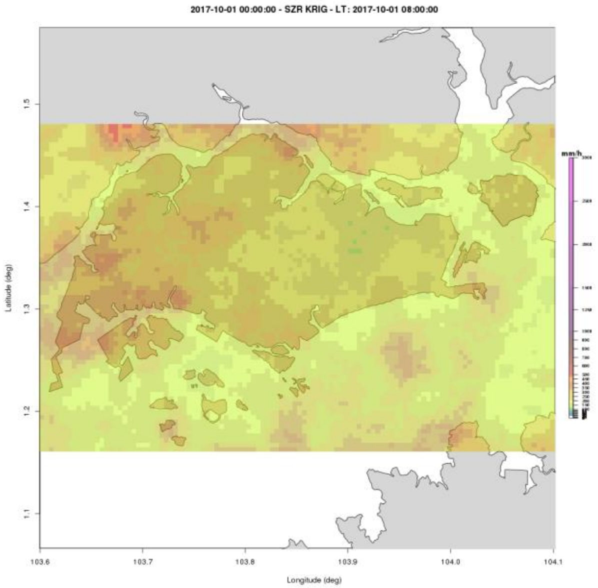
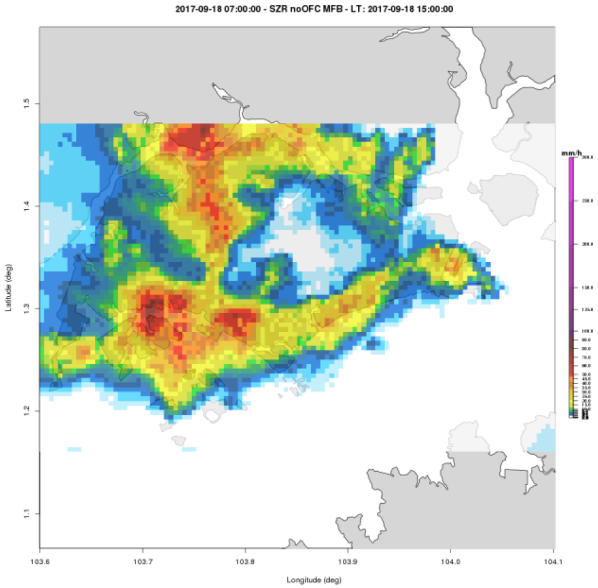


Figure 1. The conditional merging process. (a) The rainfall field is observed at discrete points by rain gauges. (b) The rainfall field is also observed by radar on a regular, volume-integrated grid. (c) Kriging of the rain gauge observations is used to obtain the best linear unbiased estimate of rainfall on the radar grid. (d) The radar pixel values at the rain gauge locations are interpolated onto the radar grid using Kriging. (e) At each grid point, the deviation C between the observed and interpolated radar value is computed. (f) The field of deviations obtained from (e) is applied to the interpolated rainfall field obtained from Kriging the rain gauge observations. (g) A rainfall field that follows the mean field of the rain gauge interpolation, while preserving the mean field deviations and the spatial structure of the radar field is obtained

Gauge Interpolation

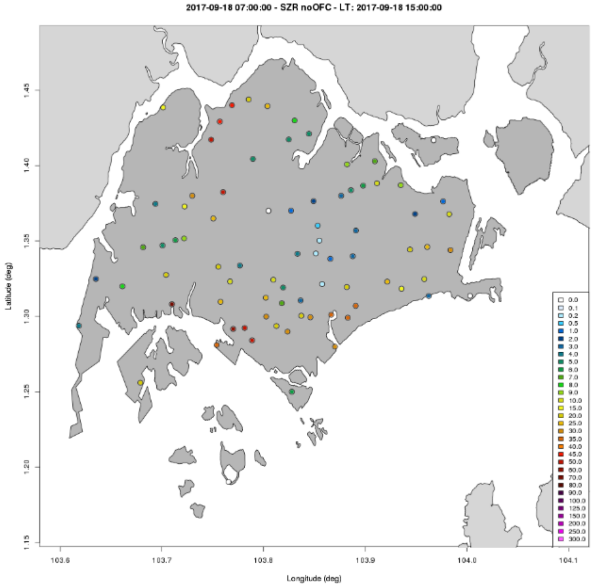
- Many Interpolation methods.
- Kriging one of the most popular.
- Need to consider accumulation period when interpolating gauge data.
- Need to be mindful of precipitation type Conv or Strat when working at hourly time periods

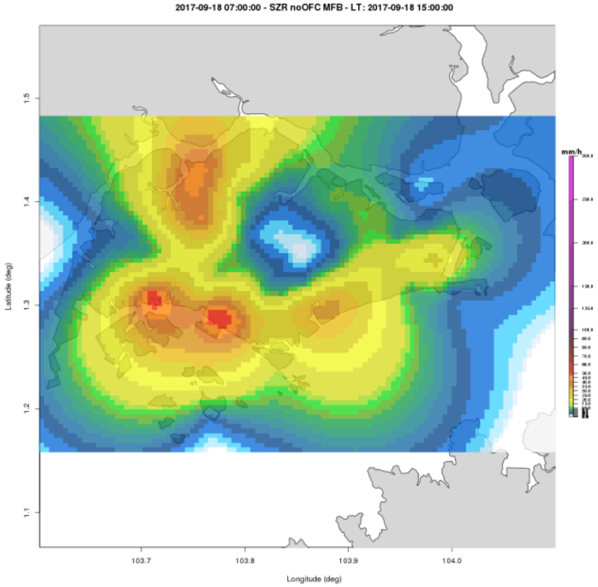




Gauge Observation

Gauge (Krig)

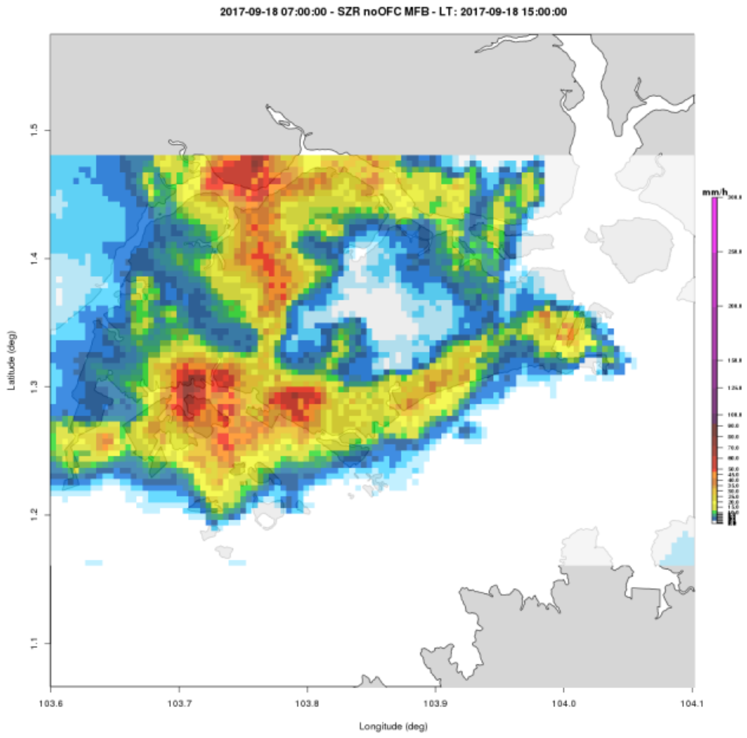


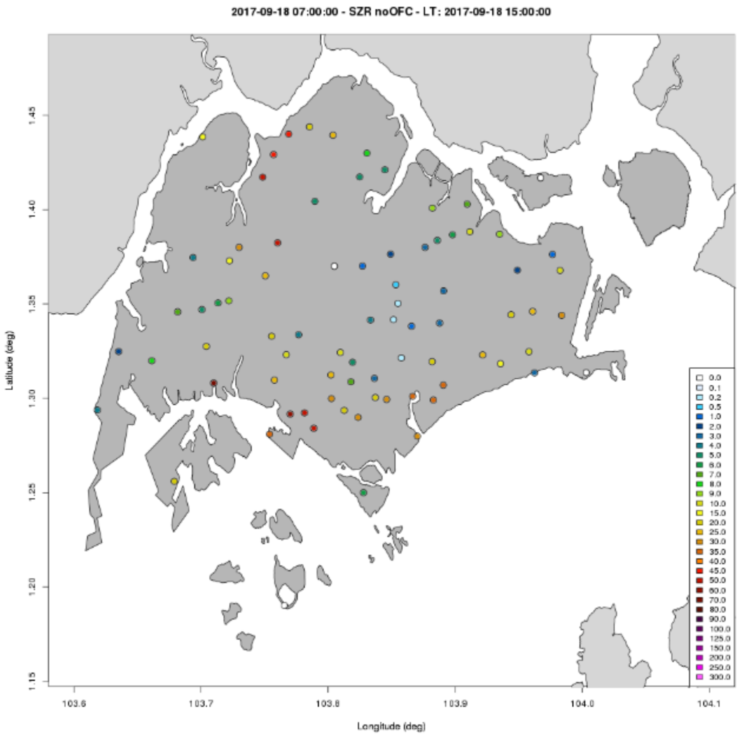


Radar interpolation

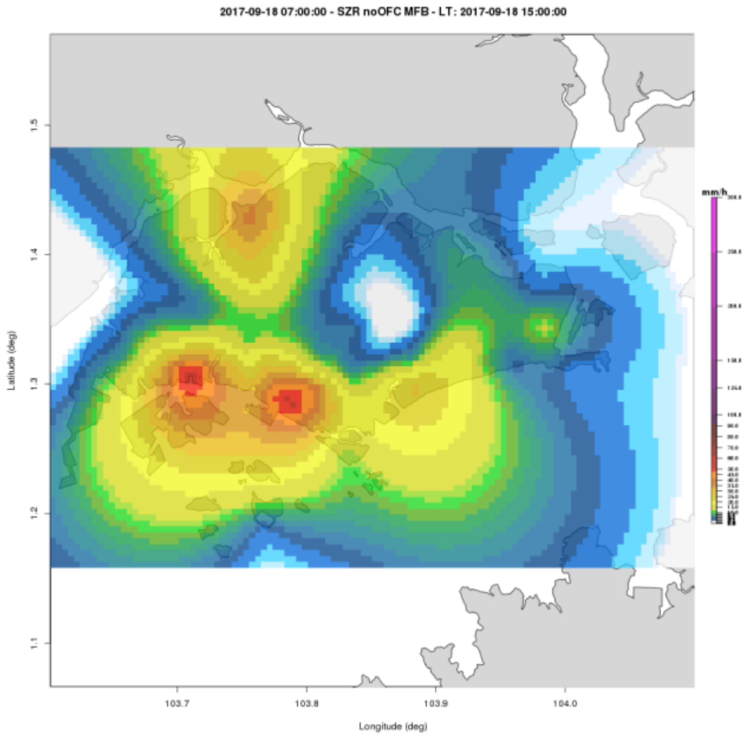
Calculate semi-variogram from radar data and apply to gauge data.

Radar Observation



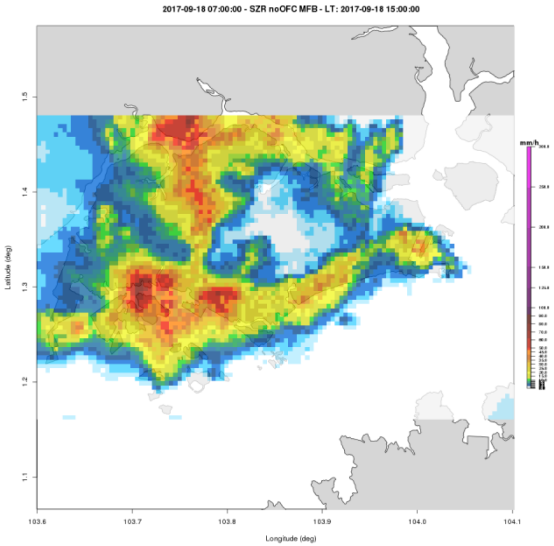


Radar (Krig)



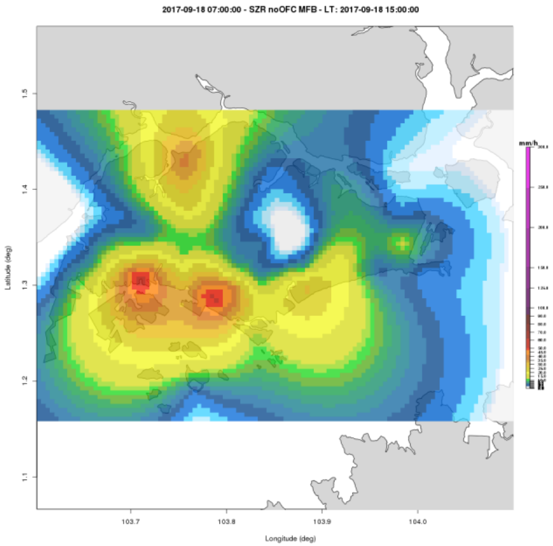
Conditional Merging with Gauge data

Radar Observation



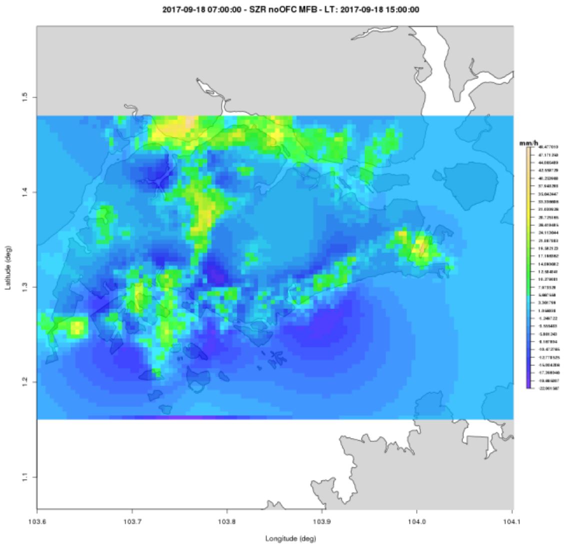
(-)

Radar (Krig)

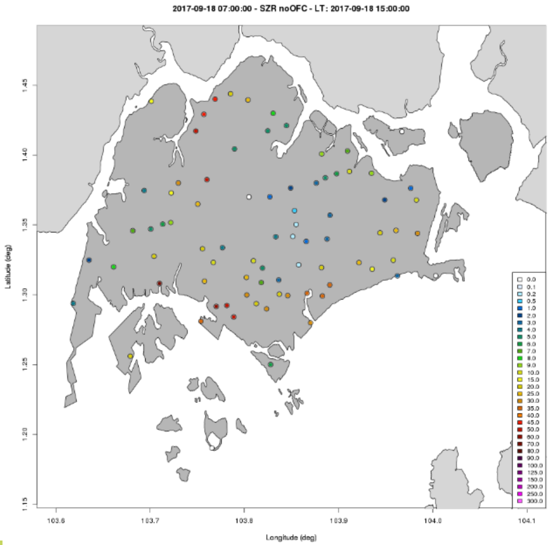


(=)

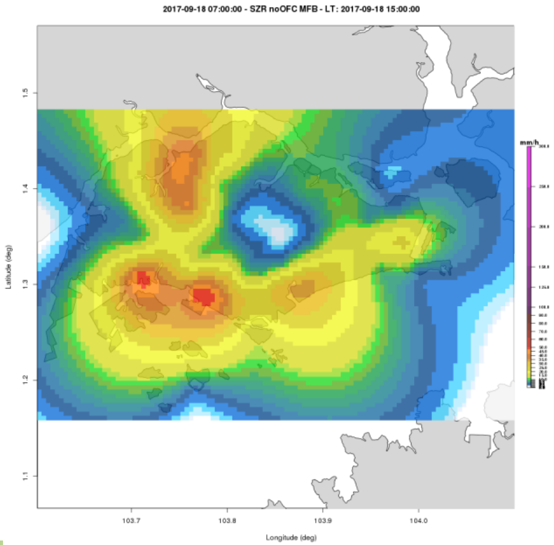
Error



Gauge Observation



Gauge (Krig)



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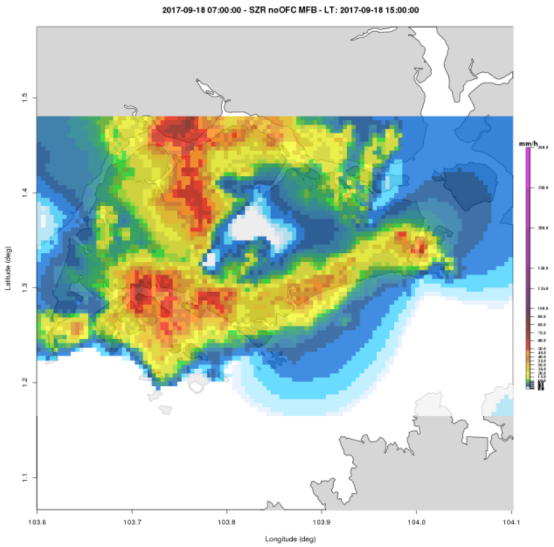
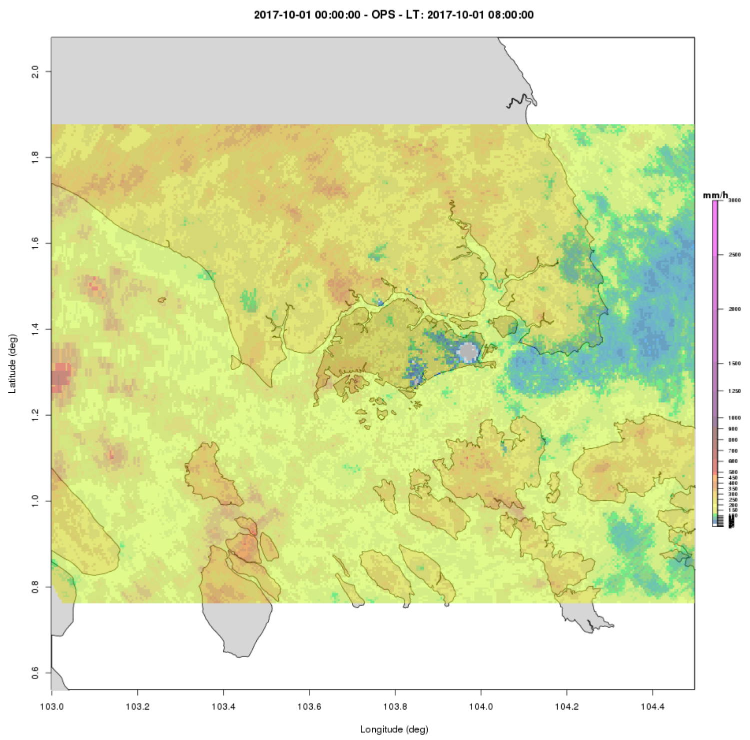
Merge



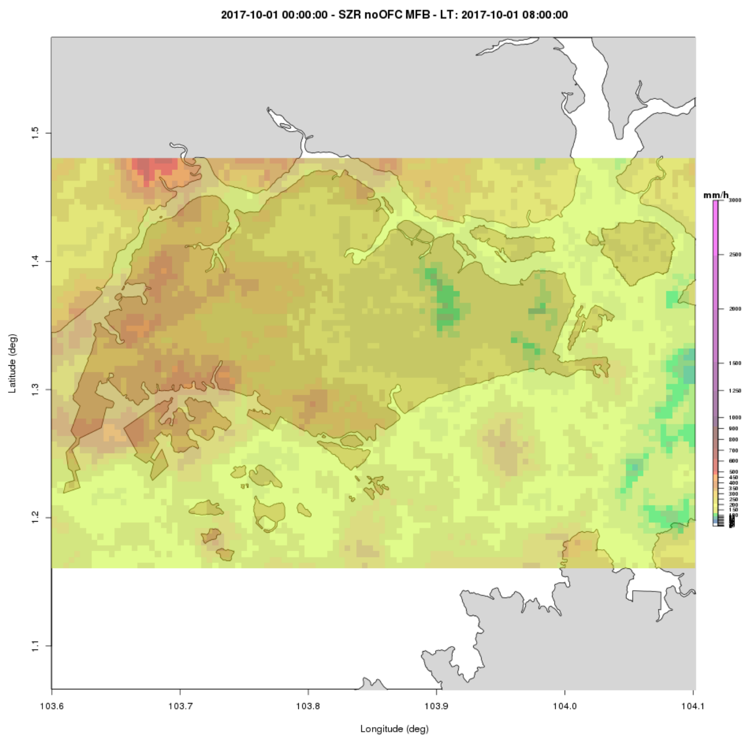
Quantitative Precipitation Estimation (QPE)

30 Day Accumulation Comparison

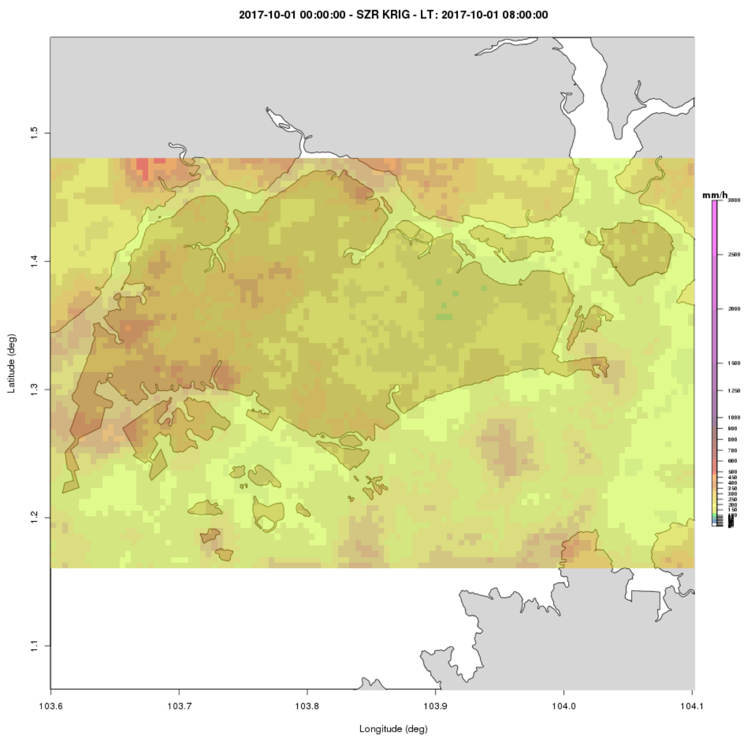
Operational Product



MFB Product



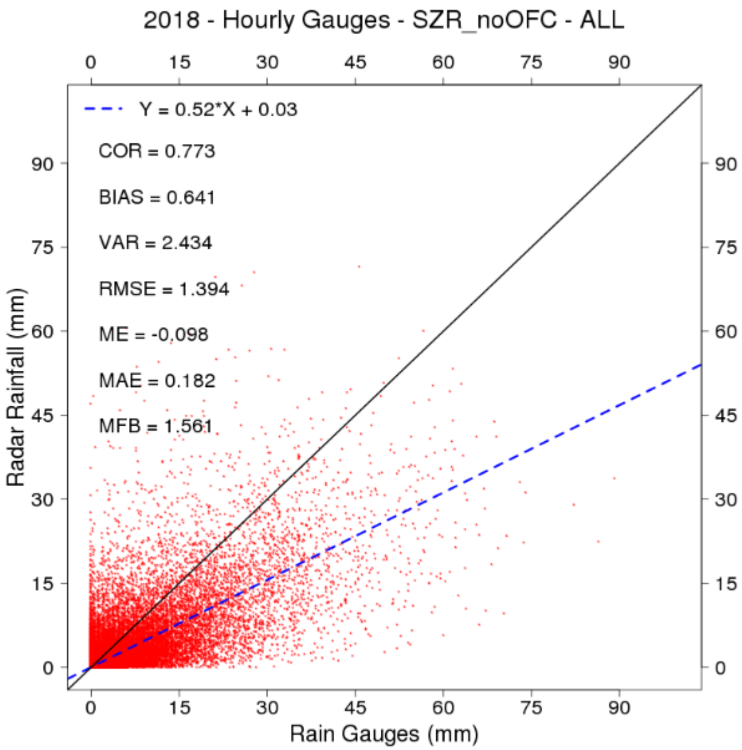
Merge Product



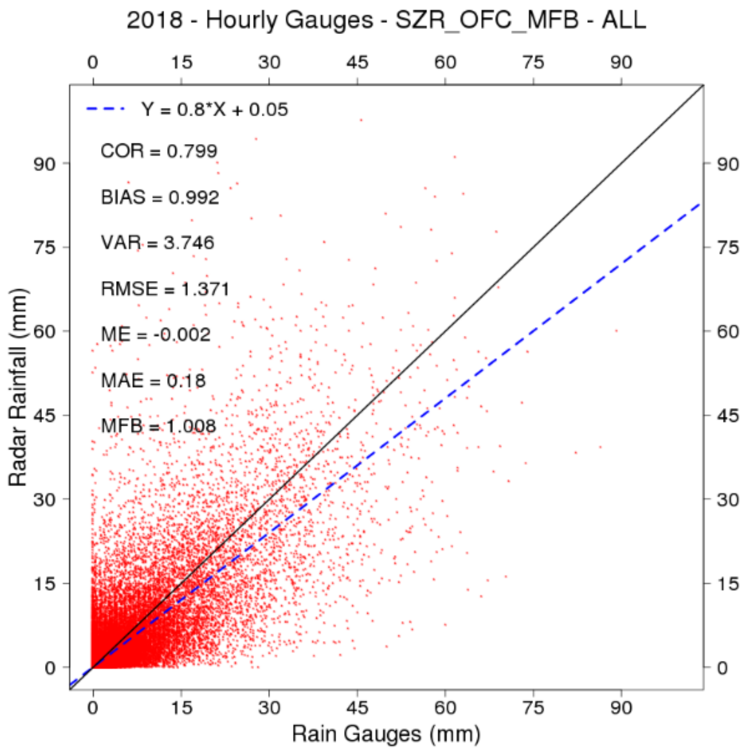
September 2017

Verification (QPE)

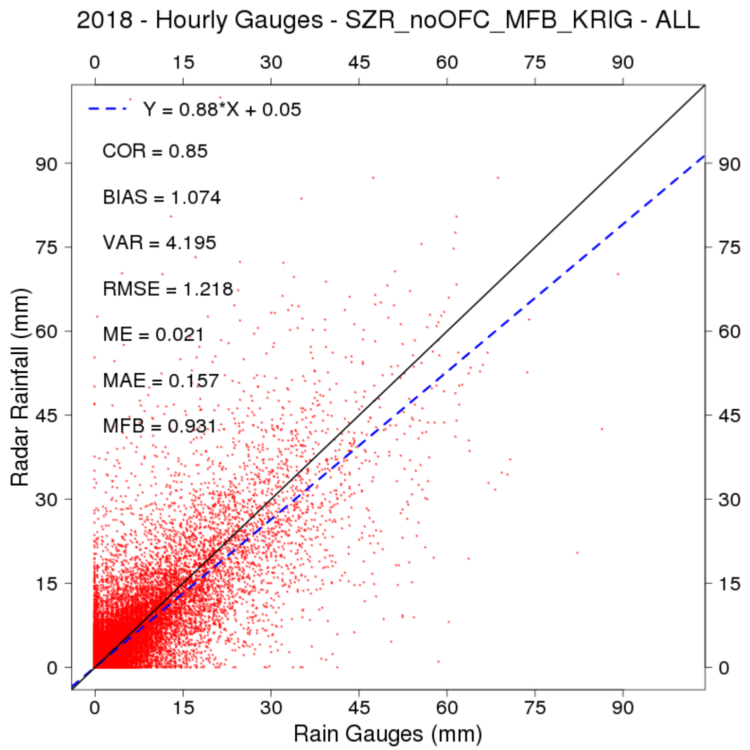
No Adjustment



MFB & Temporal Smooting



MFB & Krig Adjusted



Summary - Radar Product Processing

Data Format Conversion
RB5 → ODIM HDF5
Polar Coordinates

Data Processing

Radar Products

QPE

- **PID,**
- **QPE,**
- **Storm Structure,**
- **VIL,**
- **ETOPS,**
- **VAD,**
- **IVAP,**
- **Gust Front Detection**
- **Layer Turbulence**
- **Etc.…**

Satellite Products

Lightning Products

NWP

Useful for nowcasting

- A massive amount of information can be extracted from 3D radar data and products

- Accuracy of products depended on scan strategy
- For example: 3D products depended on the number of elevation scans;
- Gust front detection on clear-air return

- This can provide sufficient information for ANN

Thank You

Questions?

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Centre for Climate Research Singapore

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