Meteorological Service Singapore
Centre for Climate Research Singapore

Radar-Based Nowcasting and Verification Techniques

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Typhoon Committee Roving Seminar

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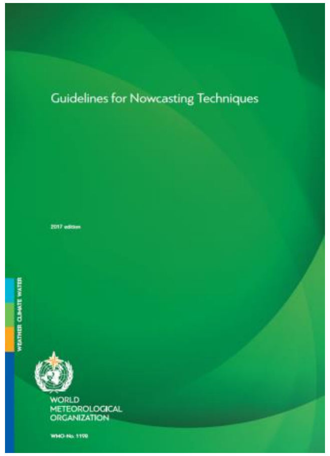
Lecture Topics

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

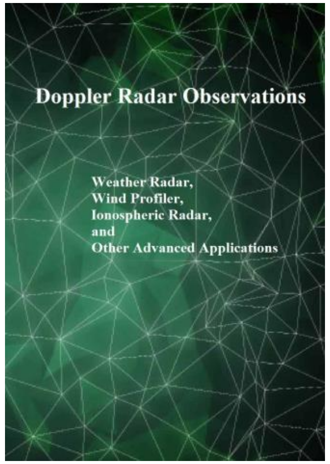
Goal: Scrutinise the radar processing chain for accurate QPE and QPF

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:

- Wang, Yong, Estelle De Coning, Wilfried Jacobs, Paul Joe, Larisa Nikitina, Rita Roberts, Jianjie Wang, et al. 2017. “Guidelines for Nowcasting Techniques.” *WMO.* https://library.wmo. int/opac/doc_num.php?explnum_id=3795
- Pierce, Clive, Alan Seed, Sue Ballard, David Simonin, and Zhihong Li. 2012. “Nowcasting.” In *Doppler Radar Observations - Weather Radar, Wind Profiler, Ionosperic Radar, and other Advanced Applications*, by Joan Bech and Jorge Luis Chau, 97-142.



Examples from SAWS and MSS Radar networks.

Outline

Radar Precipitation

- Intro and outline
- Nowcasting
  - Object based tracking
  - Field Advection
  - Growth and Decay (stochastic and ANN model)
  - NWP
  - Blending
- Verification
  - CT performance diagram
  - Spatial (FSS, SAL, etc)
- Some Operational considerations
- Summary

Useful Tools

PYTHON:

- **LROSE**: https://github.com/NCAR/lrose-core
- **pySTEPS**: https://github.com/pySTEPS
- **SwirlsPy**: https://docs.com-swirls.org/

R:

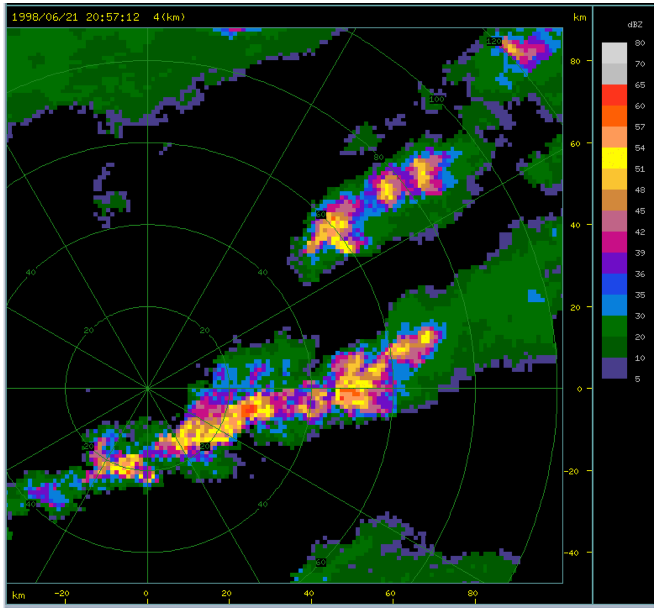
- **SpatialVx** package (Spatial Verification Tools)
- **Verification** package (Standard Verification Tools)

Nowcasting

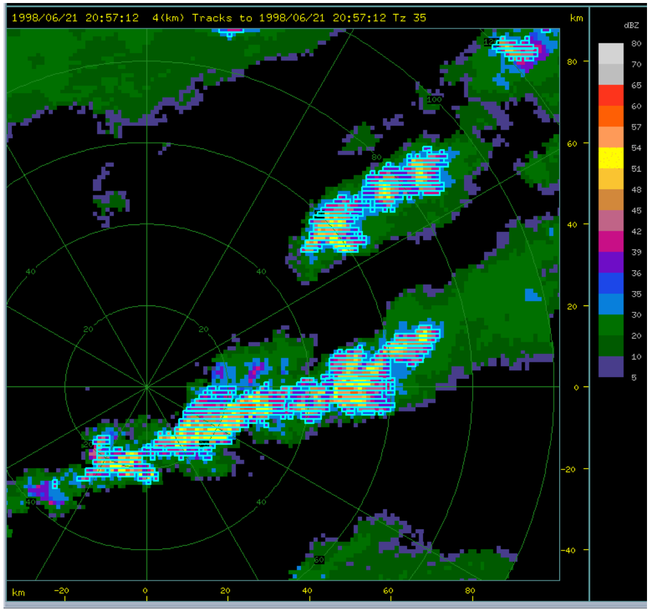
Object-Based (Cell) Tracking

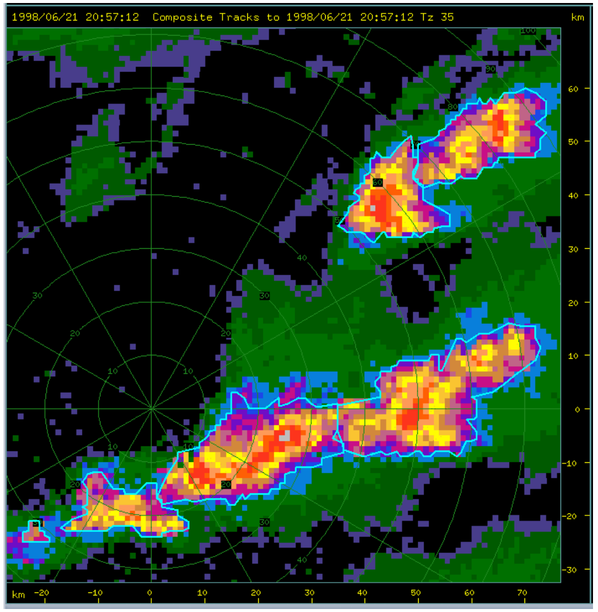
Thunderstorm **I**dentification **T**racking **A**nd **N**owcasting:

- **TITAN** (NCAR). https://github.com/NCAR/lrose-titan
- Identifies thunderstorm through single threshold
  - Typically 30dBZ
- Dual Threshold also possible (Useful for squall lines)



- **Storm Properties can be calculated**:
  - Volumetric centroid
  - Volume (km3)
  - Mean area (km2)
  - Precipitation flux (m3/s)
  - Mass (ktons)
  - Max, Mean dBZ
  - Etc… (Many more)





Object-Based (Cell) Tracking

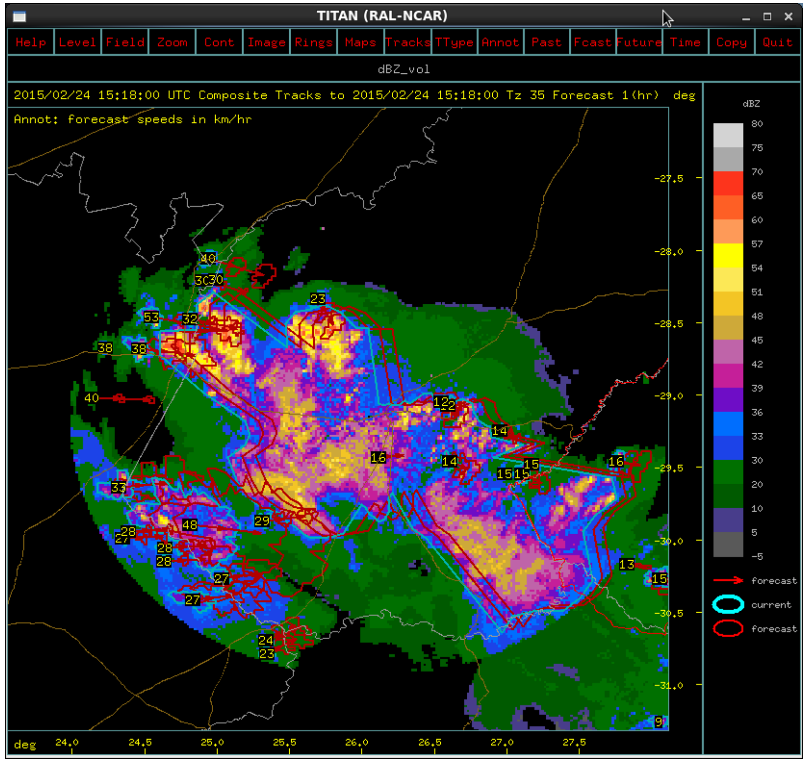
Bloemfontein - 24 Feb 2015

- Convective Classification
- Texture algorithm:

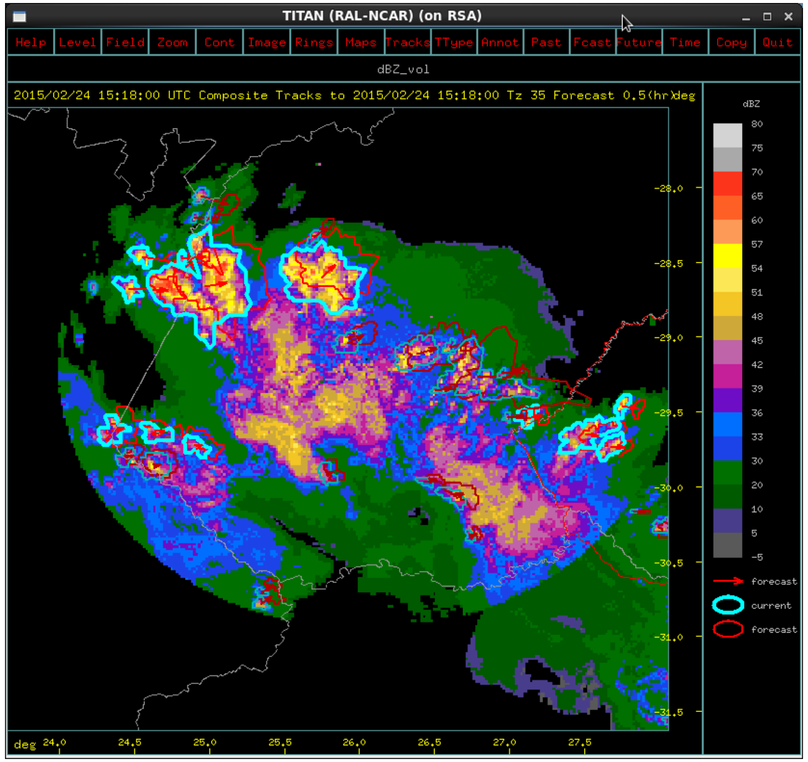
$$texture = \sqrt{sdev(dbz^2)}$$

- Improves hail metrics and warnings

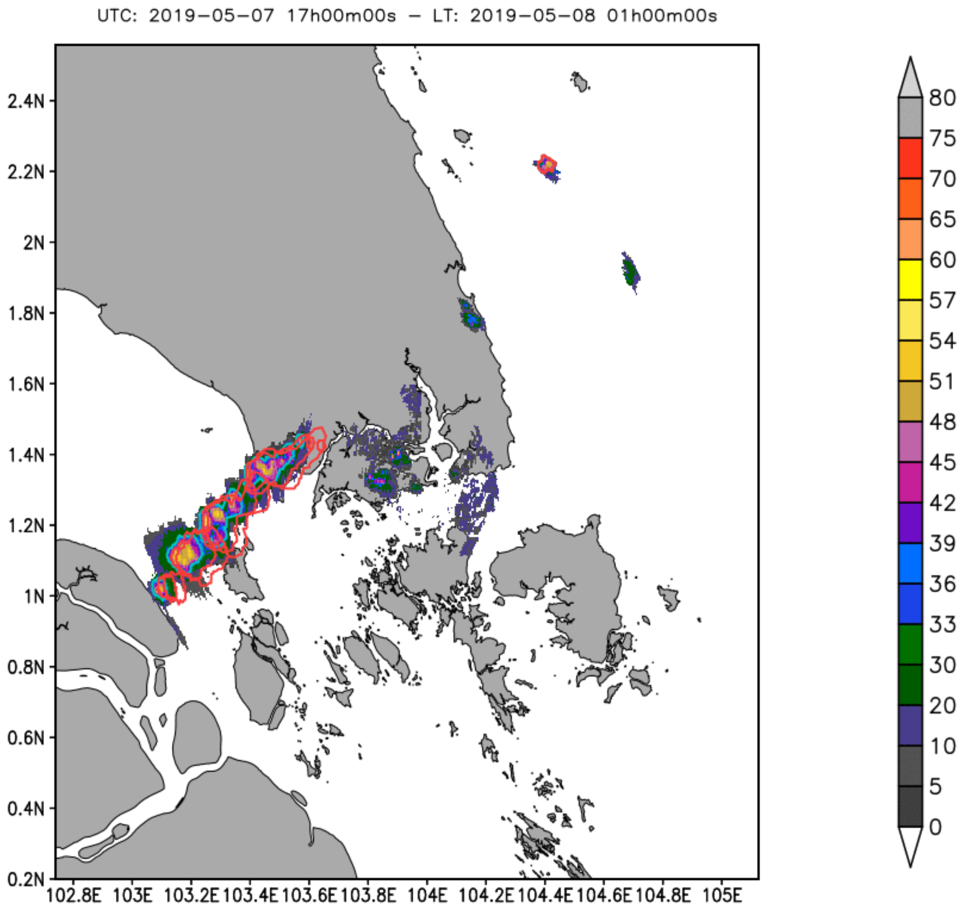
Threshold only 30dBZ



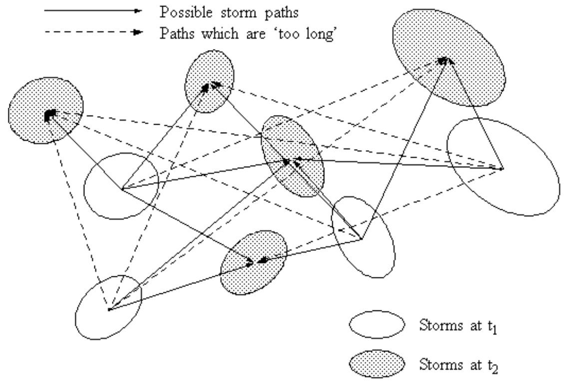
Threshold (30dBZ) + convective classification

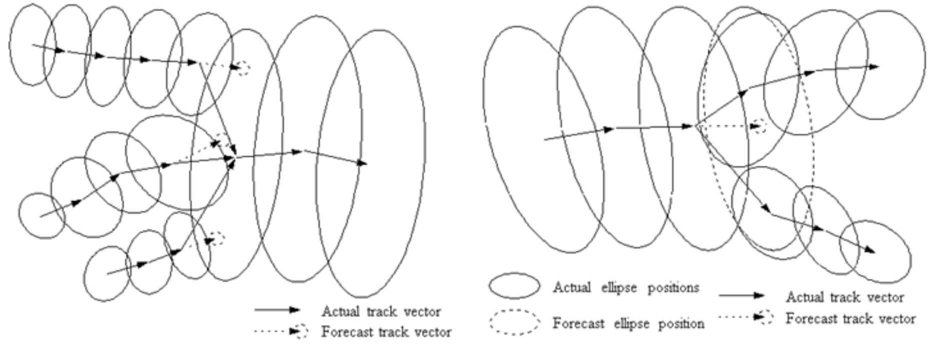


Object-Based (Cell) Tracking



- Need at least 2 time steps
- Matching using overlaps and optimization.
- Handles storm merging and splitting.

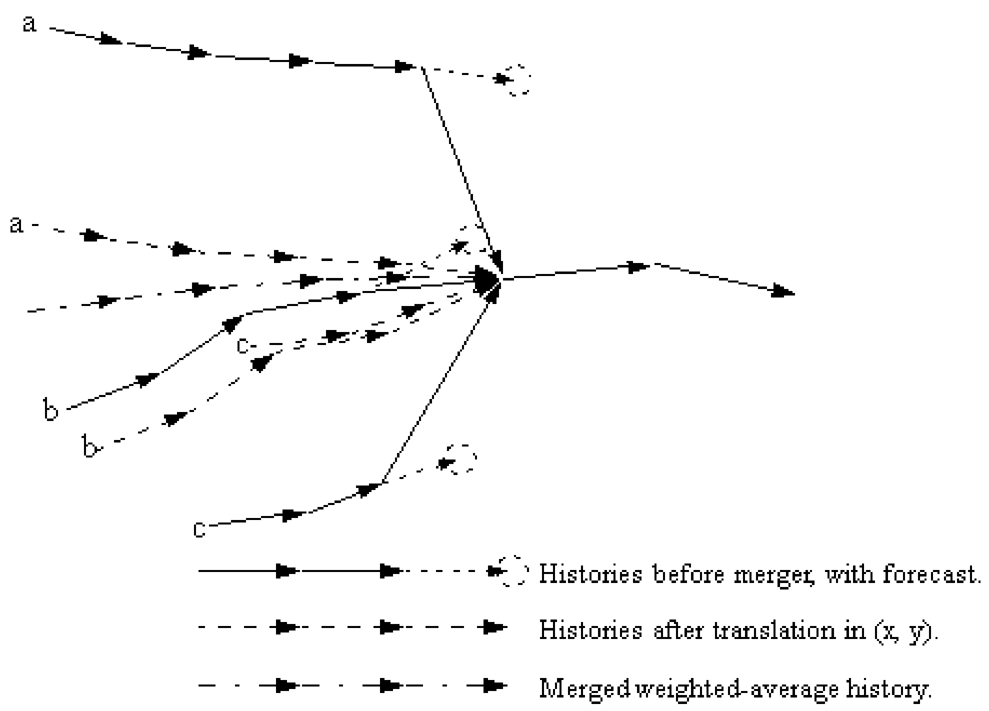


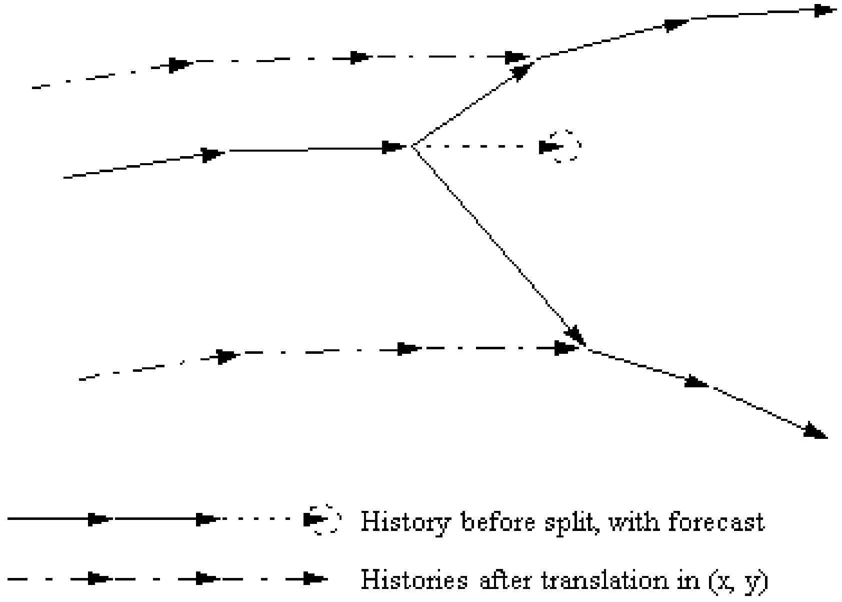


Object-Based (Cell) Tracking

- Extrapolation for forecasting
- Assumes:
  - Storm move in straight line
  - Linear trend for growth and decay
  - Random departures from above behaviour
- Weight linear fit on time-history of storm. (More is better)

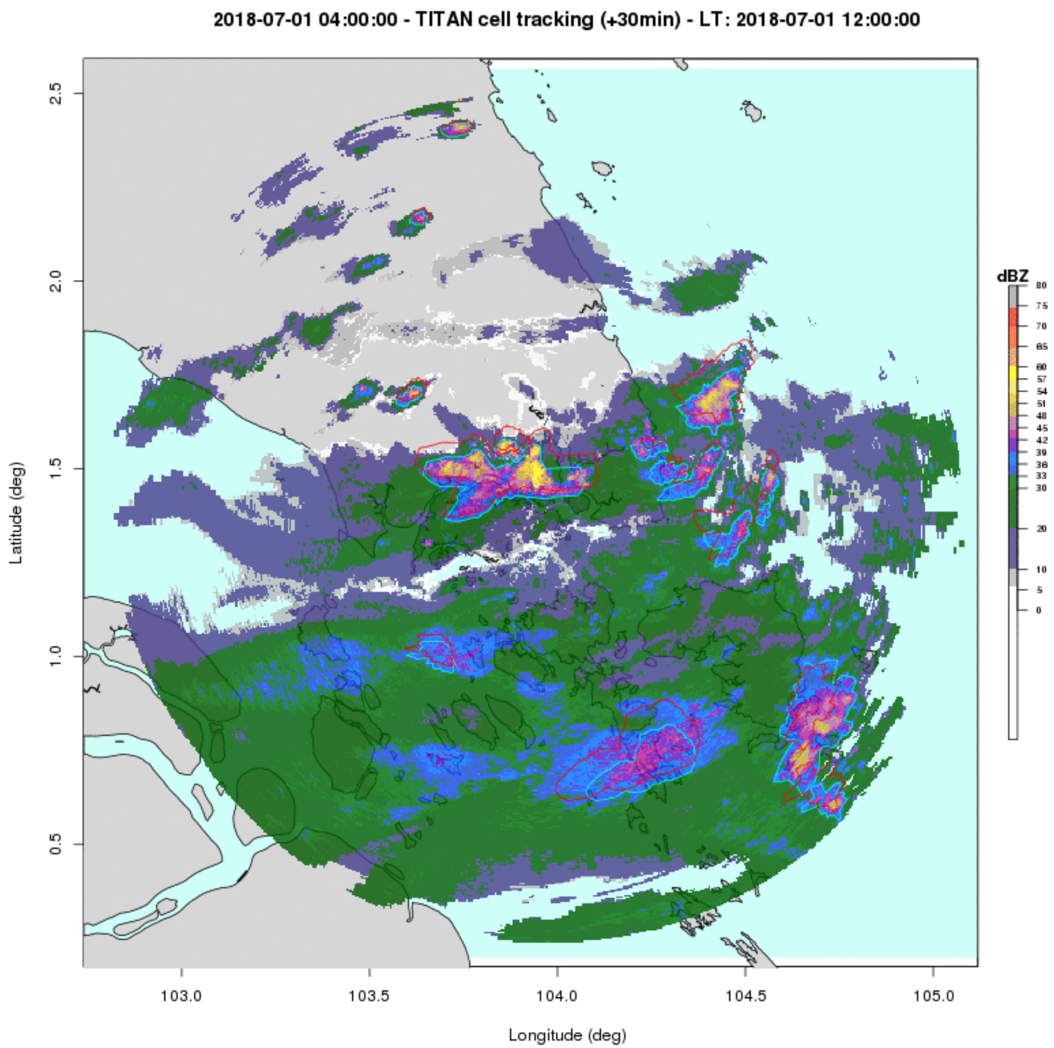
- Experimenting with cascading for larger features
- Merge tracks weighted average of parent tracks
- Split the forecast is a copy of the history of the parent.





Object-Based (Cell) Tracking

- Possible to isolate convective cores in large systems such as MCC
- Some Bright Band interference

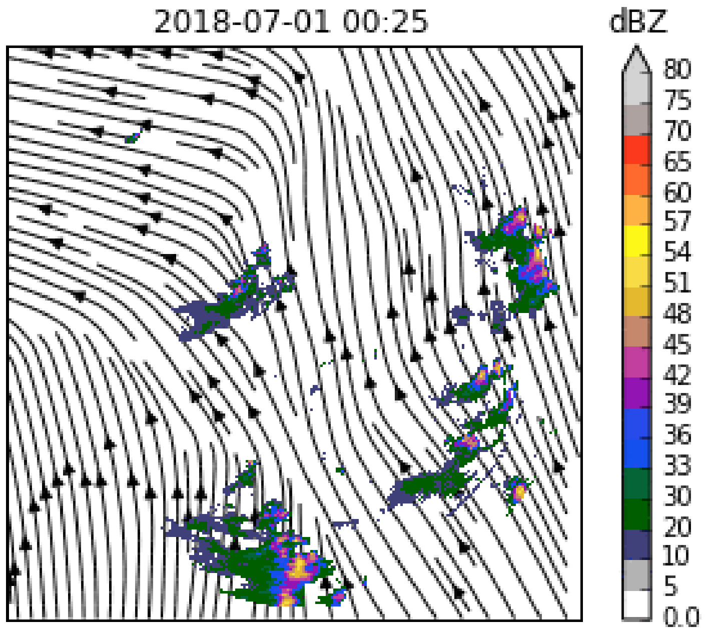


Field Advection (Extrapolation):

- Motion vectors calculated from current and previous radar images.
- Results can be noisy due to temporal variability of reflectivity.
- Using additional time steps can help smooth vectors.
- Linear or Rotational flow.
- Methods (pySTEPS, SwirlsPy):
  - COTREC (SWIRLS)
  - Vibrational Echo Tracking (VET) (MAPLE)
  - Optical Flow:
    - Open CV (Lukas-Darts
    - Rover
- Semi-Lagrangian backward interpolation scheme to extrapolate reflectivity.
- Does not consider growth and decay.
- Sensitivity to settings, weather type and domain.
- Consider computation efficiency.
- RainyMotion, constant motion vector for domain (Benchmark)

$$D_t Z = u\frac{\delta Z}{\delta x} + v\frac{\delta Z}{\delta y} + \frac{\delta Z}{\delta t} = 0$$

Solve using Minimize Least Squares



Motion vector calculations

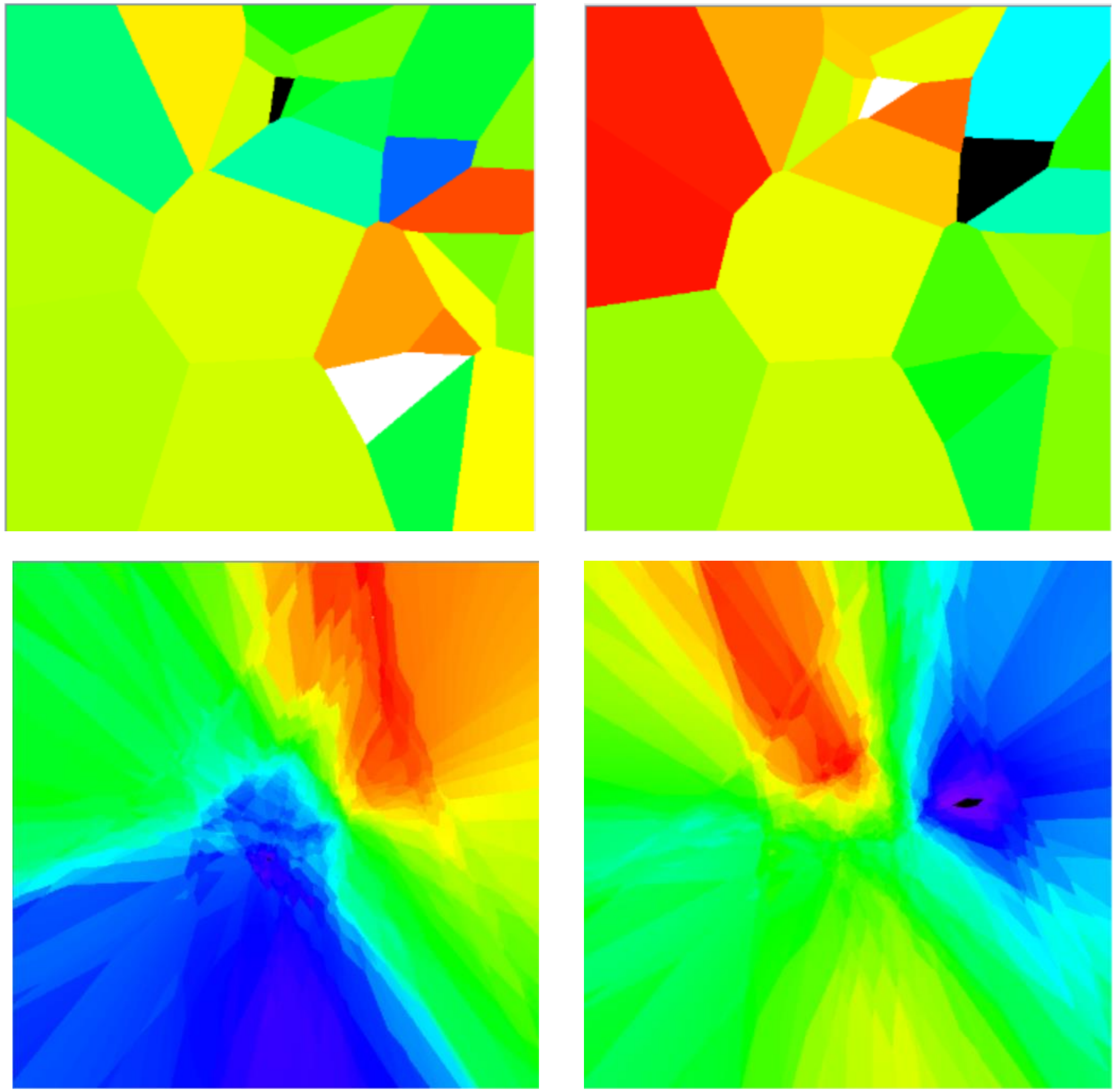
- Sensitivity study on optical flow parameters:
  - Box window size
  - Interpolation methods
  - Max speed
  - Etc.

- Different weather types may require different settings

UWND VWND

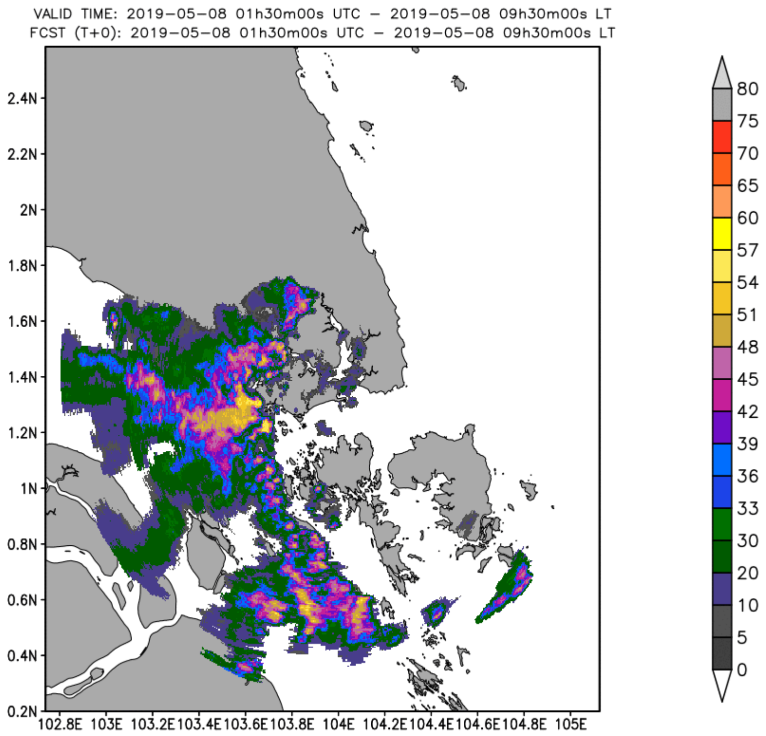
Nearest Neighbour

Inverse Distance Weighting

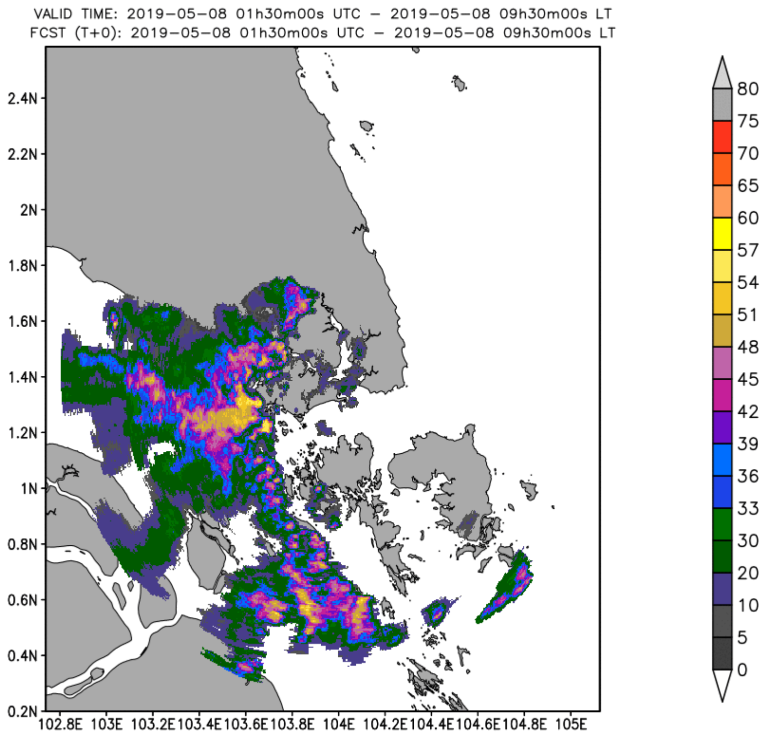


Nowcasting Methods: Optical Flow Extrapolation

Observed



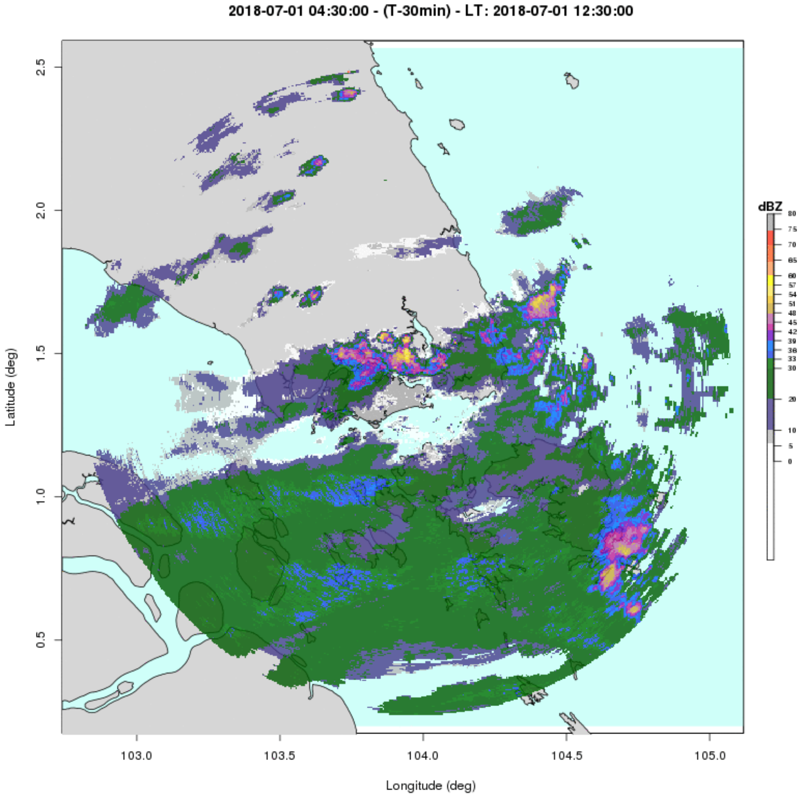
Forecast



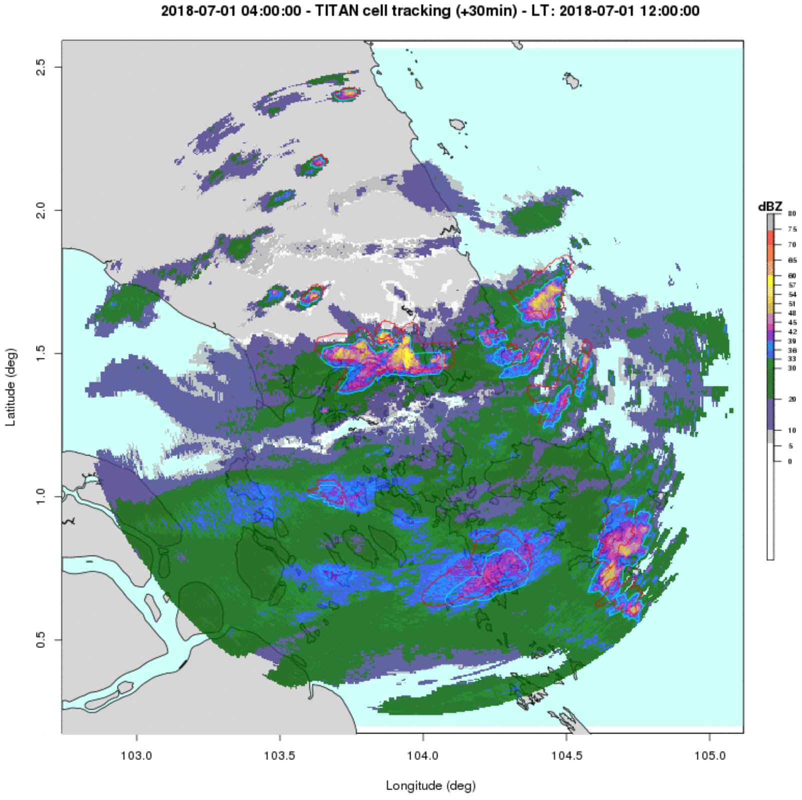
- 3 hour extrapolation
- Advection appears to be slower than the observed

Challenge in the Tropics

Extrapolation at 0430 UTC (T-30min – T+120min)

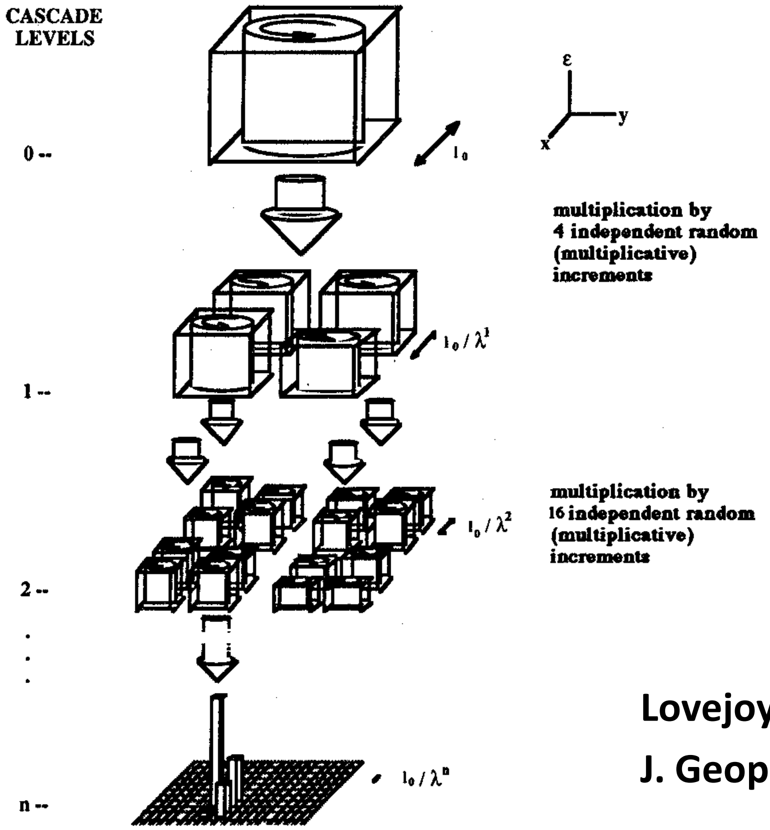


TITAN cell tracking at 0400 UTC – 0500 UTC (30min forecast track)



Growth and Decay

- Rainfall has a scaling structure in both space and time
- Multiplicative cascades can model this behaviour
- *The Weather and Climate*, Lovejoy and Schertzer, 2013, Cambridge University Press
- Statistical Approach (Stochastic Noise)



Lovejoy et al., 1987

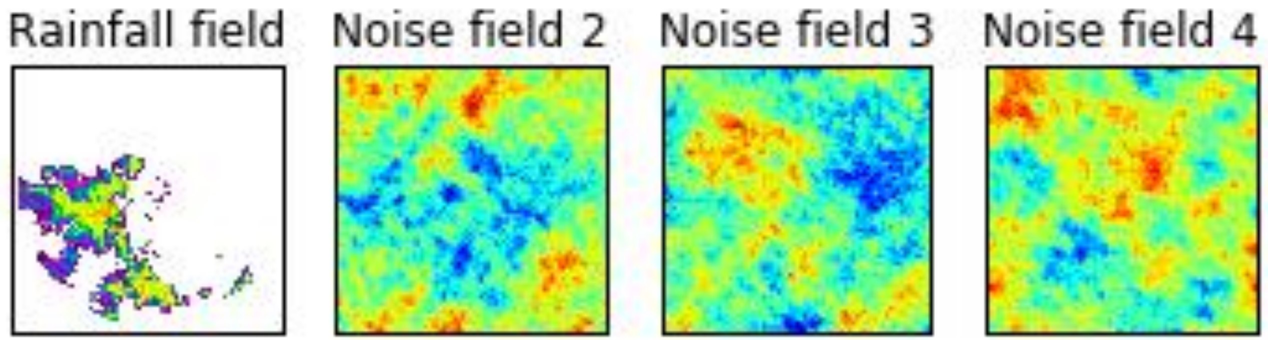
J. Geophys. Res.

pySTEPS - Decomposition

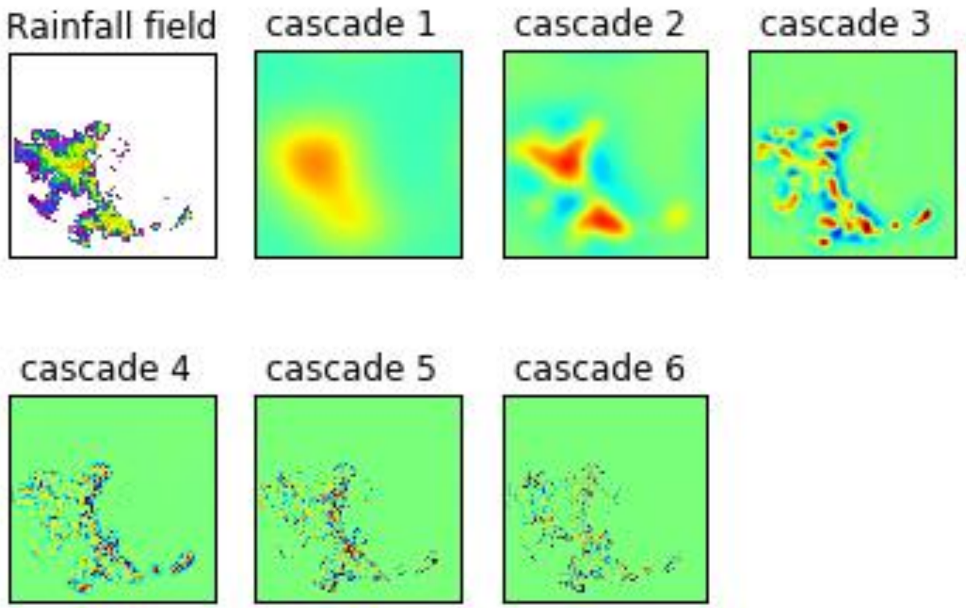
- Cascade Decomposition
- Optical Flow vectors for each cascade level.
- Semi-Lagrangian Extrapolation.
- Growth and decay:
  - Large Scale features to persist.
  - Stochastic noise.

- Fourier Domain
- Auto-Regressive Model

Stochastic Noise Generation:

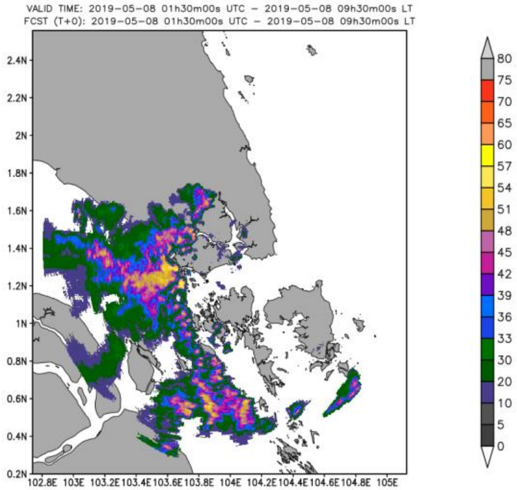


Multiplicative Cascades:

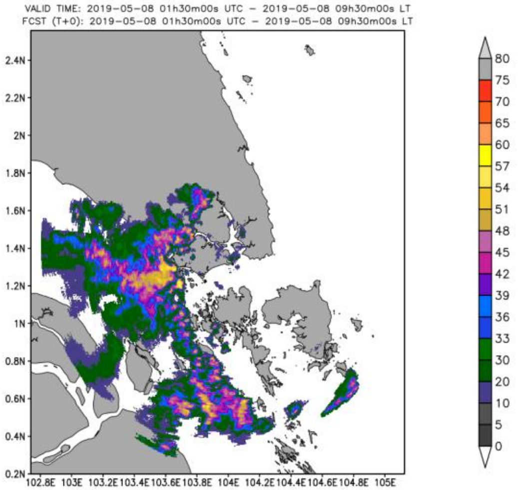


pySTEPS

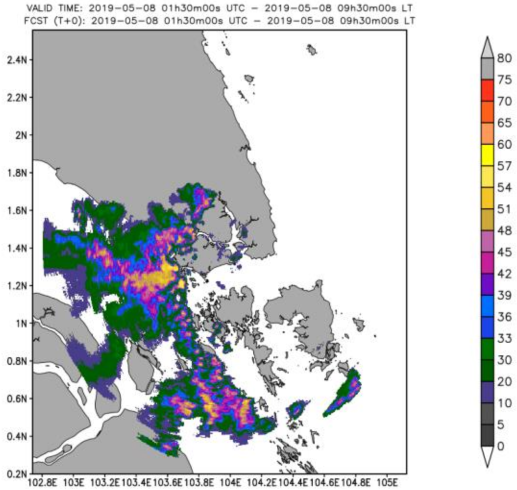
Observed



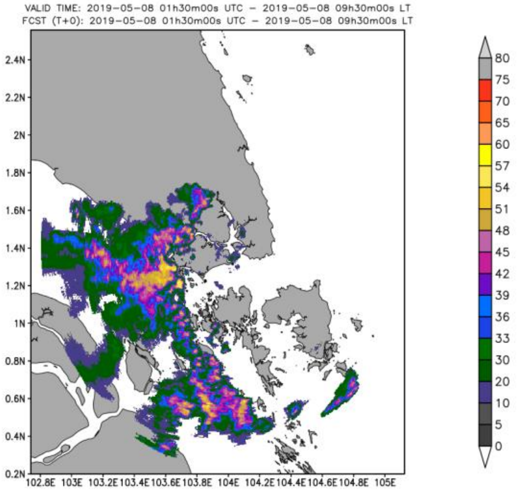
Ensemble 1



Ensemble 2



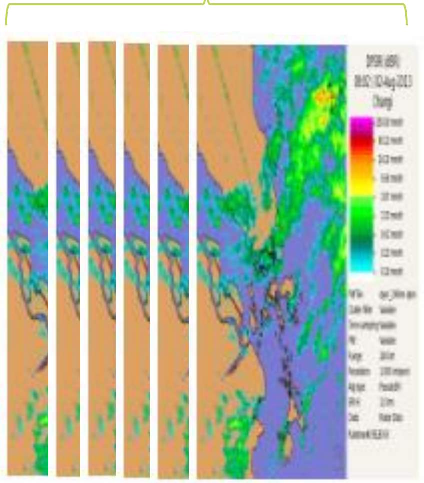
Ensemble 3



- 3 hour forecast
- Stochastic noise makes is possible to produce ensemble
- Probabilistic forecast now possible
- Will require a study on how to approach different weather systems

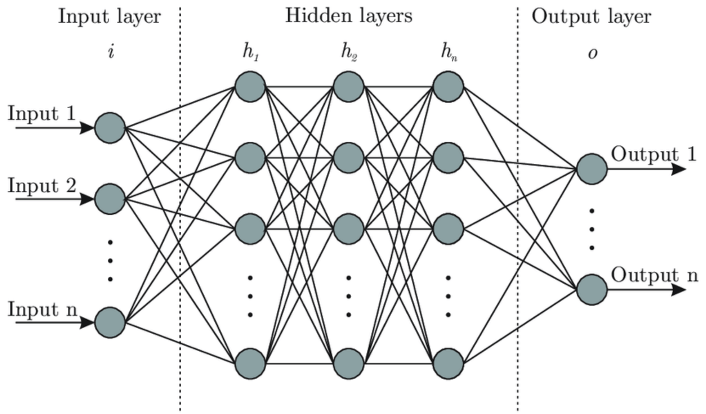
Artificial Neural Network (ANN) Nowcaster

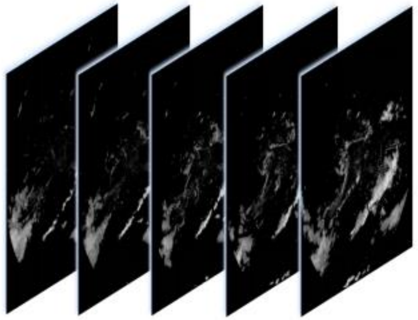
Radar data for the previous 50 minutes (10 frames)



Input: observed radar maps up to current time

Deep learning algorithm





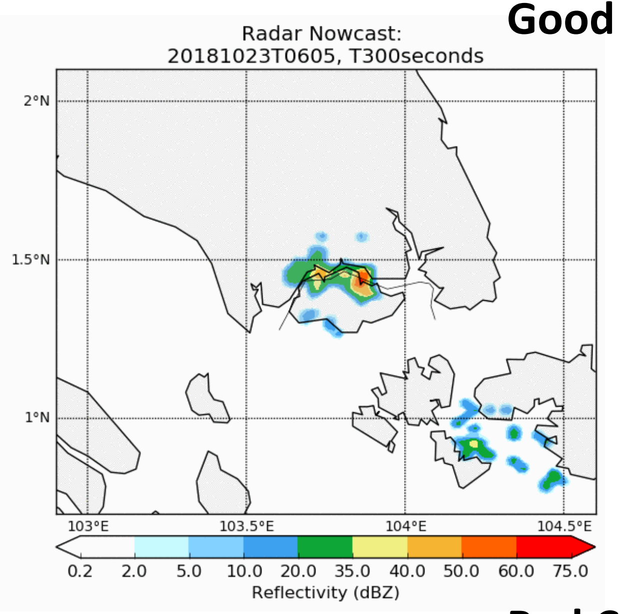
Output:
Predicted radar maps for 0-3 hours, depending on the weather systems

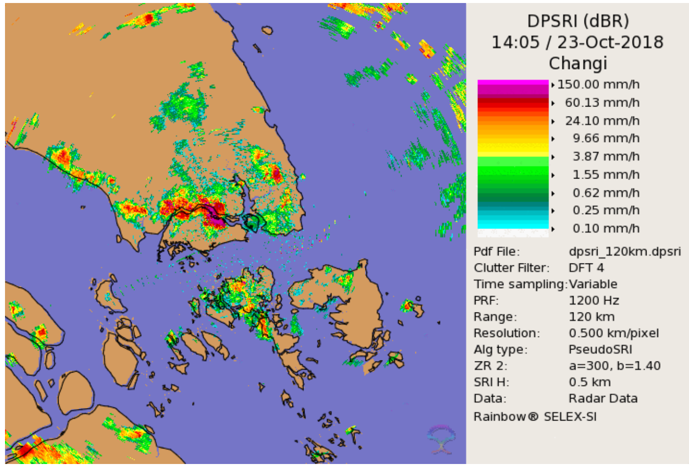
Why DLM ?

- Learn the nonlinear characteristics in real time
- Provide the possibility of predicting thunderstorms before they appear from radar

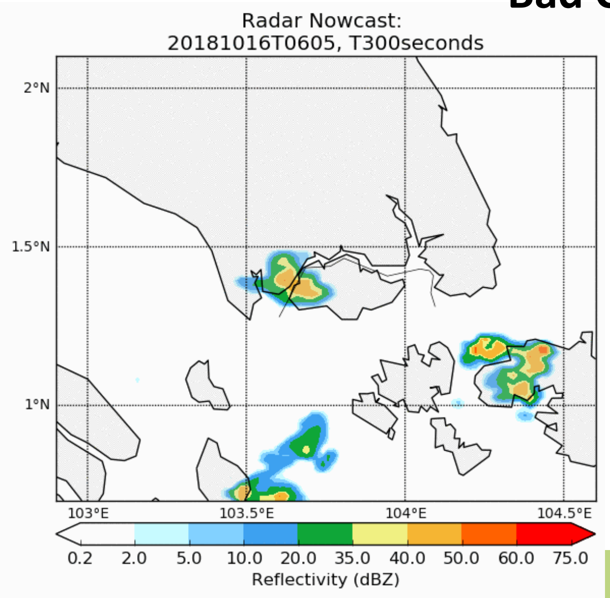
Artificial Neural Network (ANN)

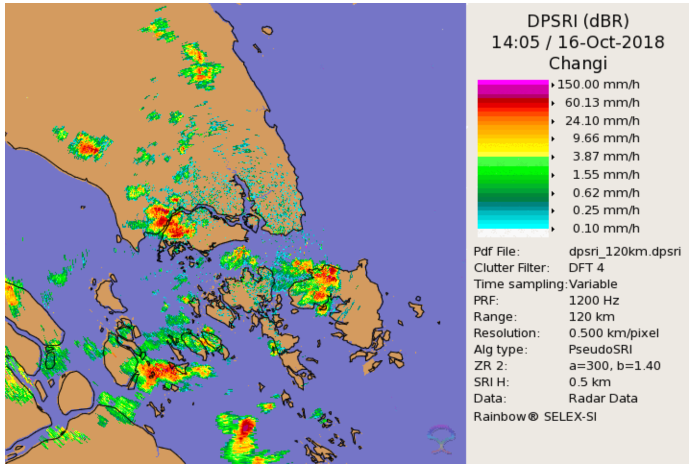
Good Case





Bad Case





Date	Intensity	Movement	Spatial Distribution
6/10/2018	Under-forecast	OK	Ok
7/10/2018	NA	NA	NA
8/10/2018	Under-forecast	OK	OK
11/10/2018	Under-forecast	OK	Under-forecast
12/10/2018	Under-forecast	OK	Under-forecast
16/10/2018	Over-forecast	Wrong	Over-forecast
23/10/2018	Ok	Ok	Ok
25/10/2018	NA	NA	NA
27/10/2018	NA	NA	NA
28/10/2018	NA	NA	NA
29/10/2018	Under-forecast	OK	Under-forecast
10/11/2018	Under-forecast	OK	Ok
11/11/2018	Under-forecast	OK	Under-forecast
28/11/2018	NA	NA	NA
1/12/2018	Ok	Wrong	Under-forecast
2/12/2018	Under-forecast	OK	Under-forecast
5/12/2018	Ok	OK	Under-forecast
7/12/2018	NA	NA	NA
8/12/2018	NA	NA	NA
10/12/2018	Under-forecast	OK	Under-forecast
11/12/2018	Under-forecast	OK	Under-forecast
12/12/2018	Under-forecast	Wrong	Under-forecast
19/12/2018	NA	NA	NA
20/12/2018	NA	NA	NA
31/12/2018	Under-forecast	OK	Under-forecast
5/1/2019	NA	NA	NA
8/1/2019	Under-forecast	OK	Under-forecast
13/1/2019	NA	NA	NA

- Current setup not ideal.
- ANN will require a different processing approach and thus needs to be redeveloped.

- ANN requires excessive amounts of data.
- Needs this info to model storm initiation, evolution and movement.

Contribution: WSD

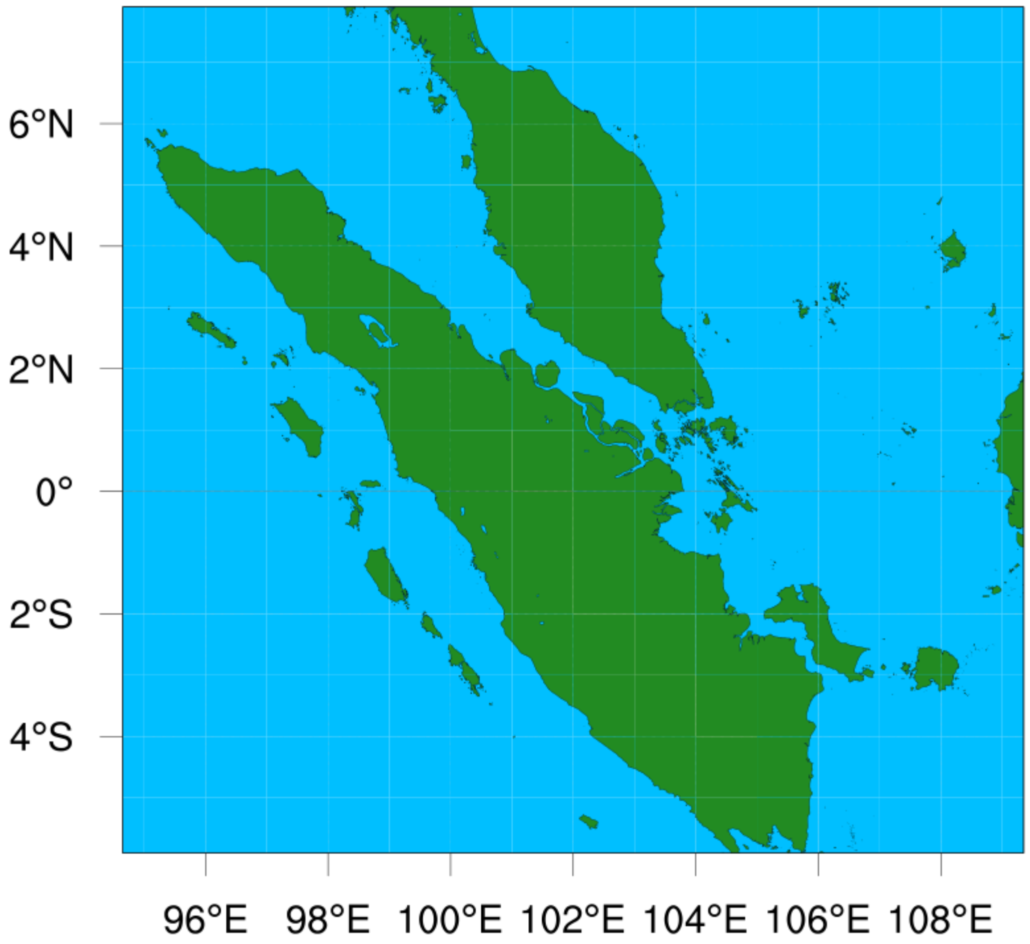
Numerical Weather Prediction (NWP)

Considerations:

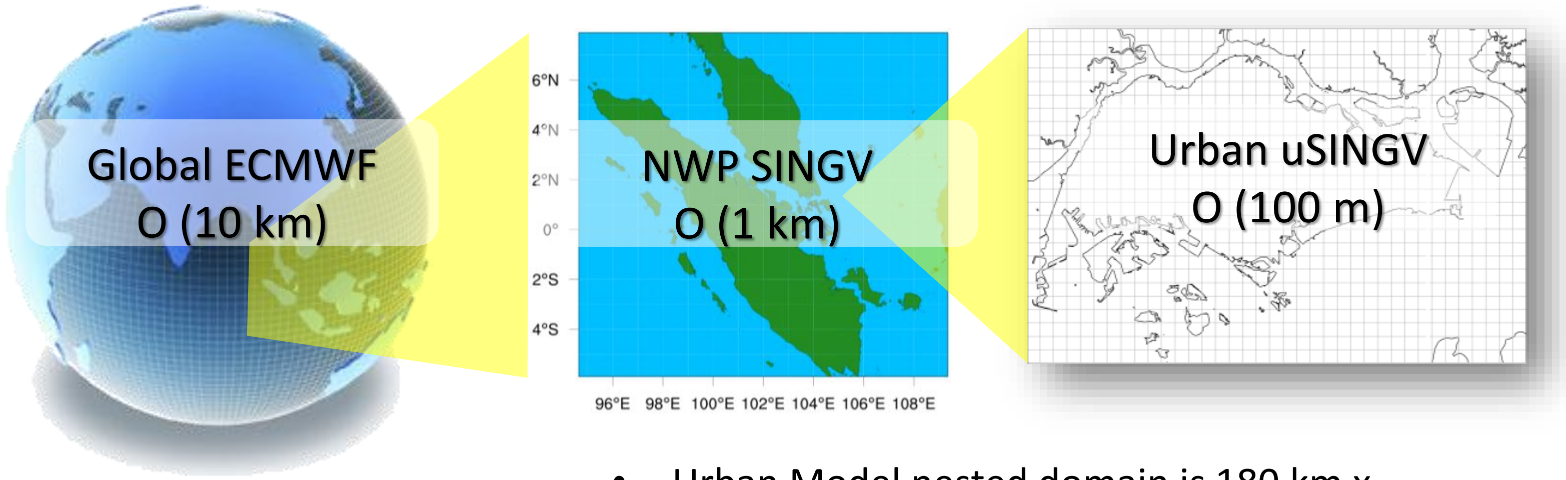
- Domain Size
- Initial condition for regional model
- High resolution
  - Convective resolving
  - Urban area (land use)
- Data Assimilation
  - 3D-VAR or 4D-VAR
- Cycling (Cold vs Warm start, Spin-up)
- Forecast length (typical 48 hour for regional domain)

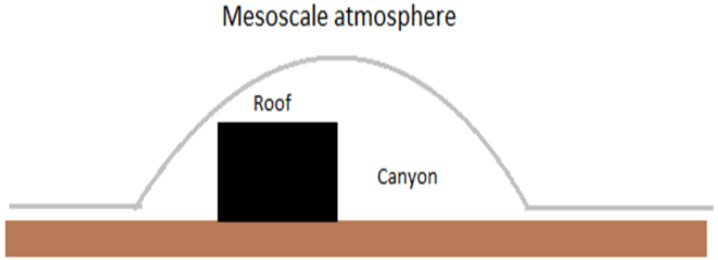
- For nowcasting, important to get your precipitation, humidity, winds and temperature observation right.
- Accurate initial conditions one of the biggest problems

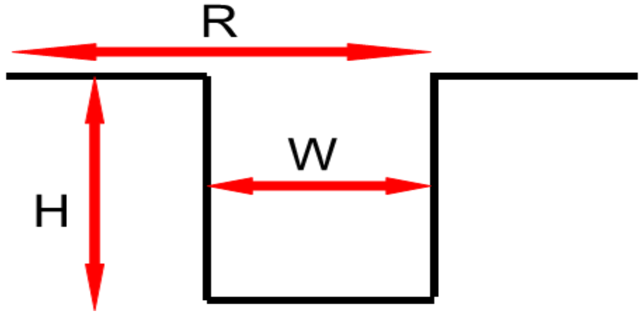
Regional version of Met-Office Unified Model - SINGV 1.5km



NWP – High Resolution Urban Model for Singapore







- Urban Model nested domain is 180 km x 180 km in horizontal and extends up to 40 km up in the atmosphere, centred over Singapore.
- Initial and boundary conditions come from ECMWF NWP model.

Urban morphology and land-use

- Morphological parameters W/R, H/W, H are calculated from 2D topographic data provided by Singapore Land Authority (LOD2).
- ESA CCI land-use data (~ 300 m) with some modifications making it more appropriate for Singapore.

Future Work:

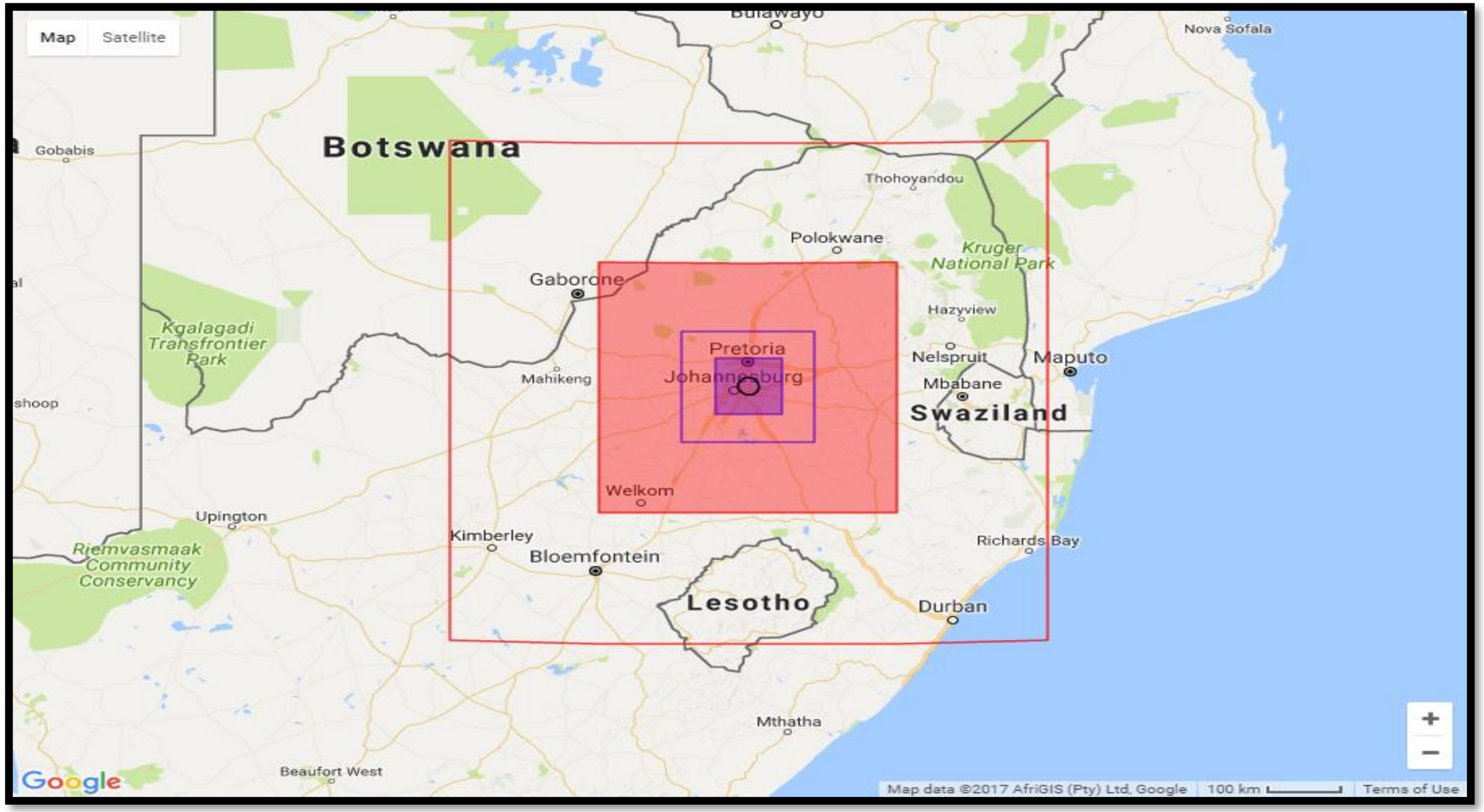
- Model geared more towards a nowcasting setup:
- Hourly cycle (Warm start)
- Data Assimilation (3D-VAR):
  – Himawari-8 radiances [AMV’s]
  – Radar derived rain-rates [Radial Velocities]
- Forecast range up to 6 hours
- High Resolution (300m) - Nested

NWP – South Africa Mesoscale Modelling Experiment

- Investigating a convective scale model run at 300m over ORTIA
- Nesting Suite vn10.4 (upgrade to vn10.6) – dynamically downscaled to regional domain
- Regional domain with ORTIA at center (-26.136S, 28.241E)
- Tropical configuration with additional moisture conservation
- Initialized by GA (Global Atmosphere) at 17 km resolution
- Parent domain: 1.5 km resolution (300 x 300 grid points)
- Child domain: 300 m resolution (300 x 300 grid points)
- Vertical resolution of 70 levels; model top at 38.5 km
- Lead-time 36-hours but initialized at 00, 06, 12 and 18 UTC to compensate for spin-up which then equates to 24-hours forecasts.

High Resolution Mesoscale Modellin

- Convective scale model (300 m) using the UK Met Office Unified Model
- Investigating a convective scale model run at 300m over ORTIA

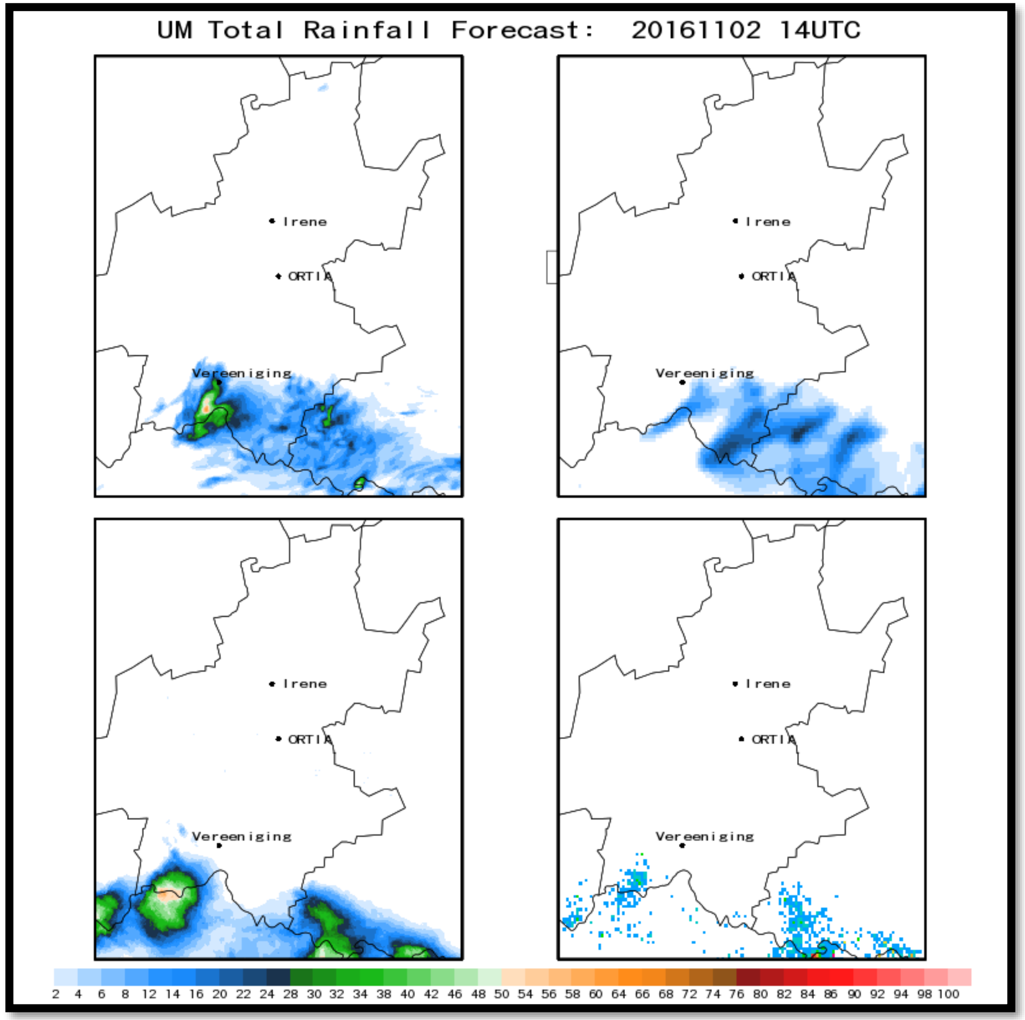


- Model simulations for 2016-11-02
- Storm moved over OR Tambo Int. Airport – Flooding of airport access roads and parking structures
- Severe impact on airport operations

- Red (1,5 km) & Purple (300 m)
- 300x300 (shaded) & 600x600 (non-shaded)
- Black circle ORTIA aerodrome

Information courtesy Stephanie Landman

Unified Model (300m)



UM 300m
1 Hour Accum

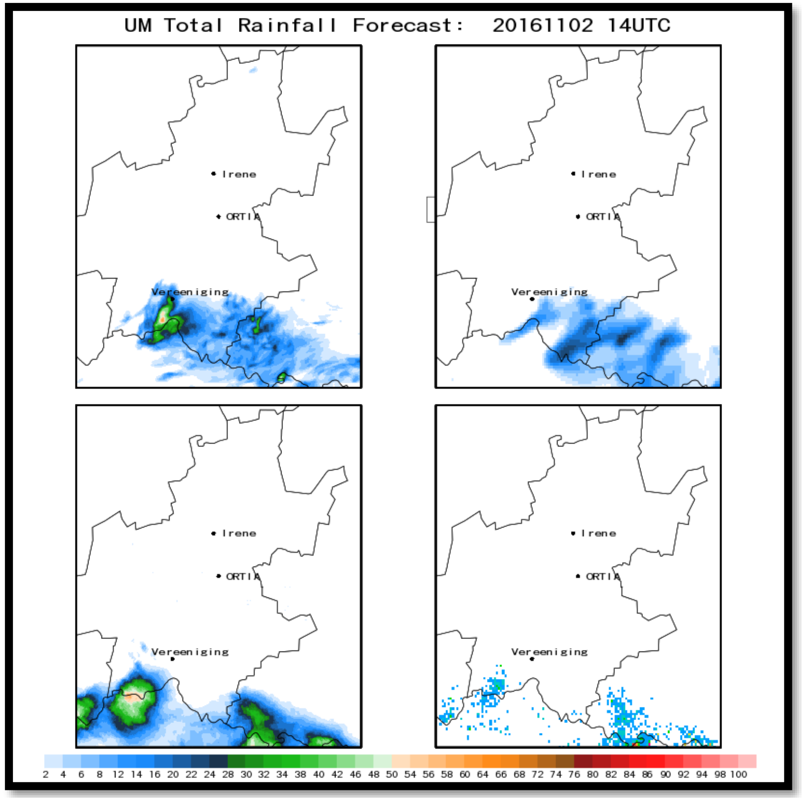
UM 1.5km
1 Hour Accum

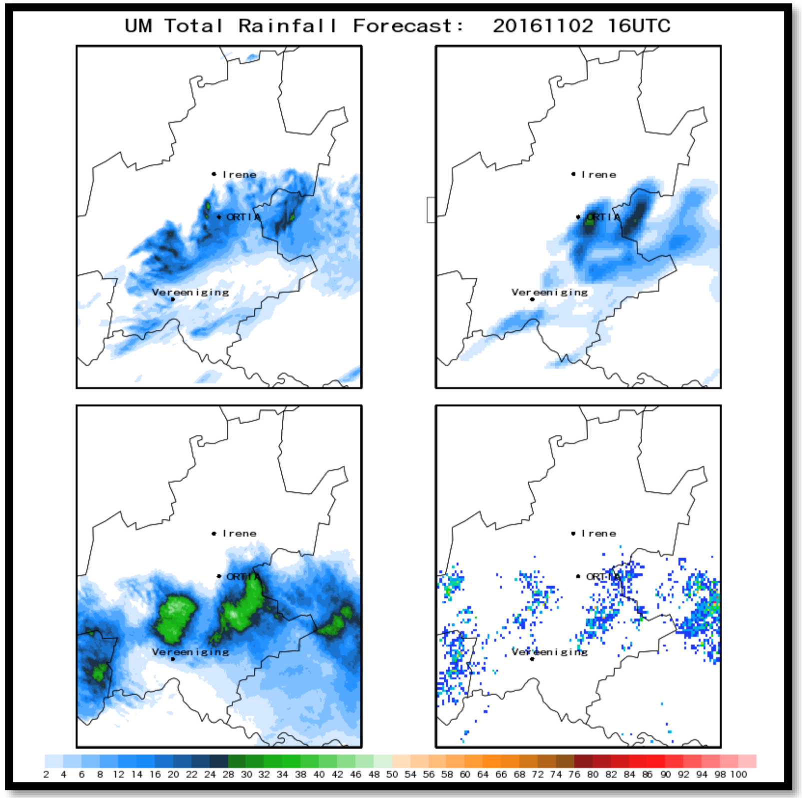
Radar 500m
1 Hour Accum

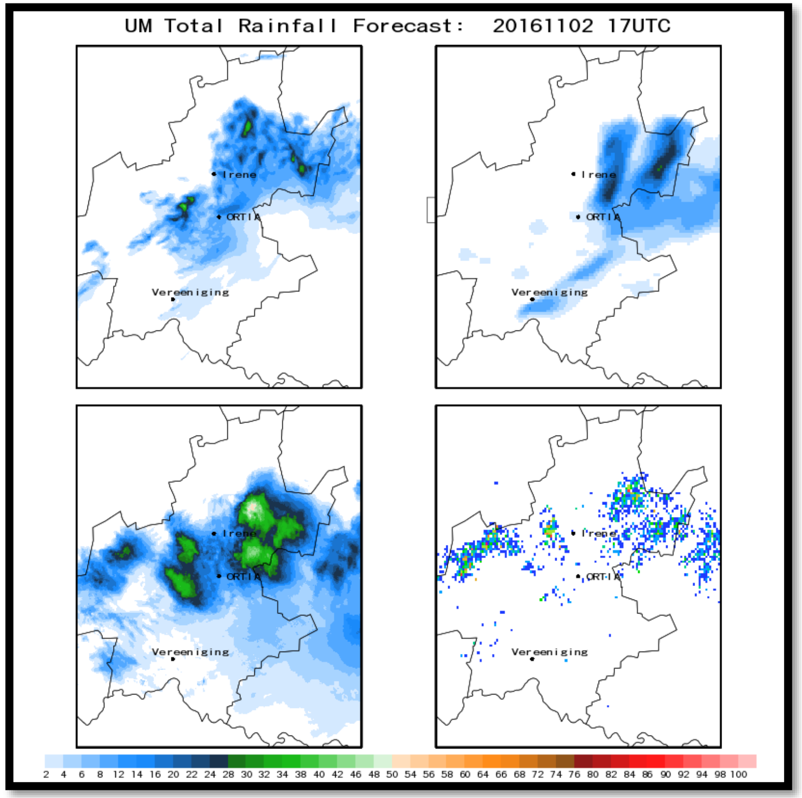
Lightning C-G
1 Hour Accum

Information courtesy Stephanie Landman

Unified Model (300m)

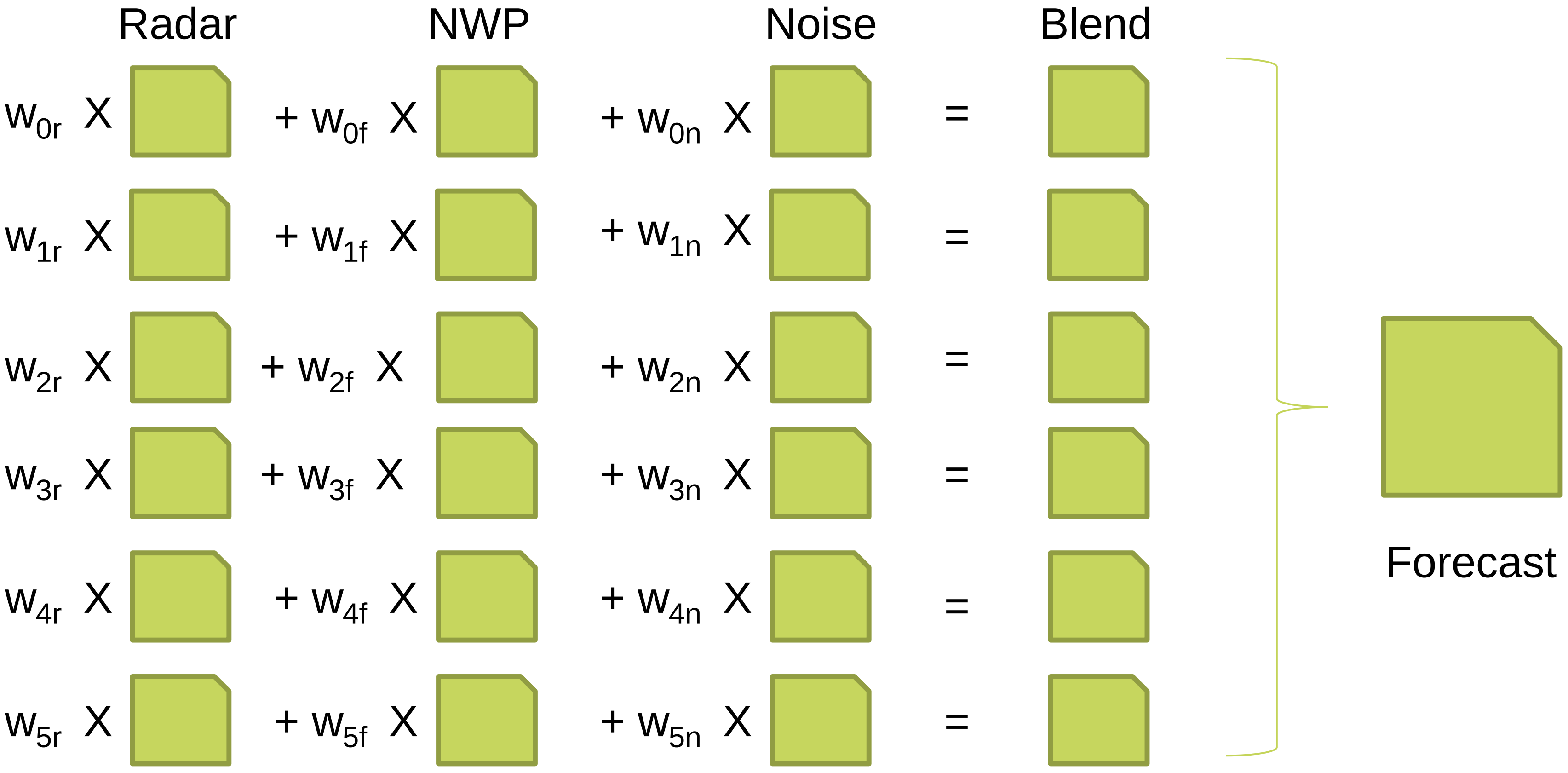






Radar and NWP Blending
BoM – STEPS system

- Need to merge Radar with NWP to include dynamical evolution of the atmosphere
- NWP downscaled to be statistically equivalent to rain analysis
- Weight are calculated from the expected skill (variance) of the advection and NWP forecasts



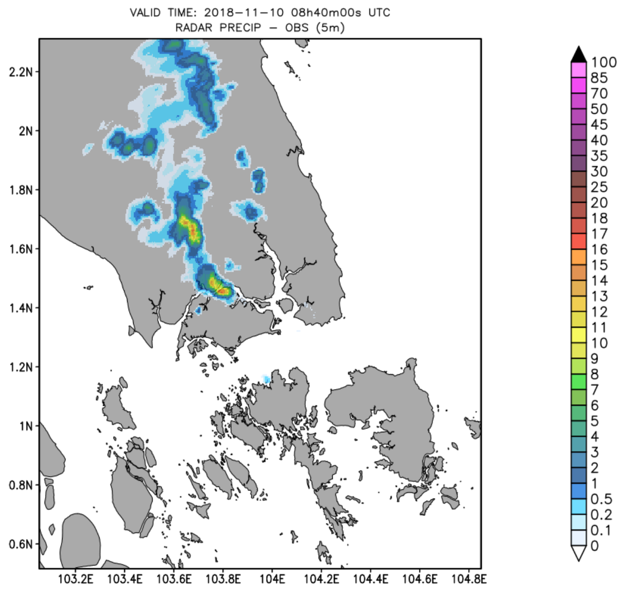
Blending

Flooding event at forecast time.

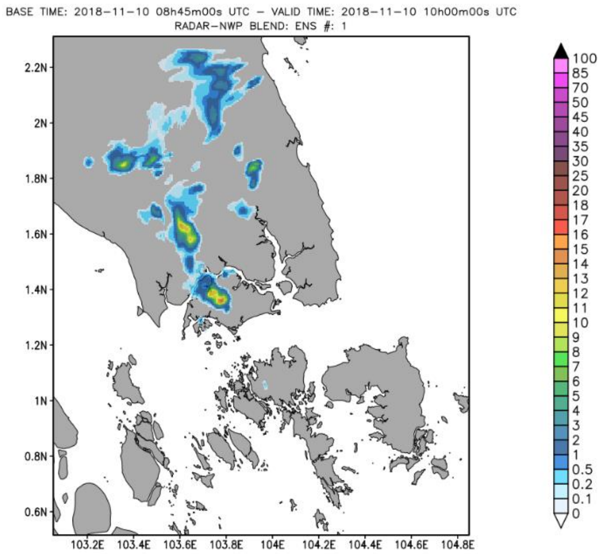
Radar Time: 2018-10-10 08h45 UTC
NWP initialisation time: 2018-10-09 12Z

SINGV-DS 1.5km

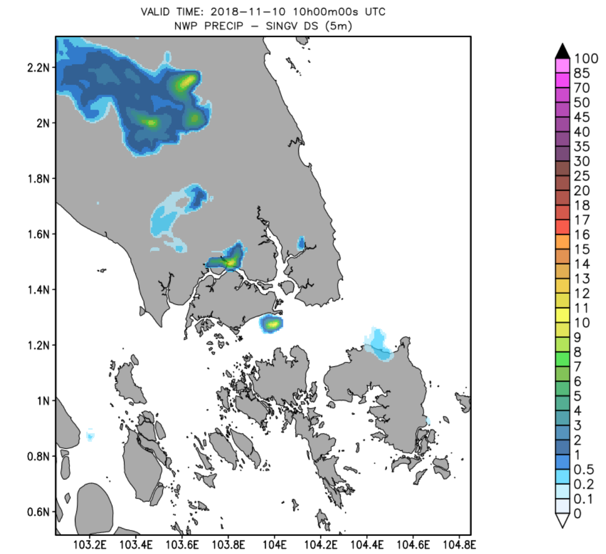
Forecast Time: 2018-10-10 10h00 UTC



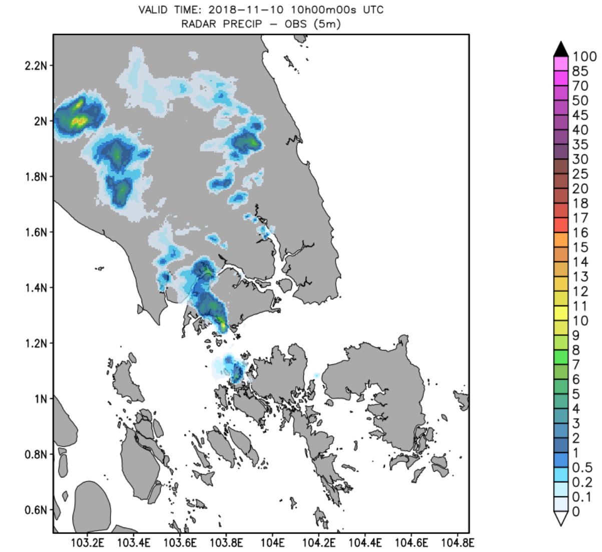
Advection



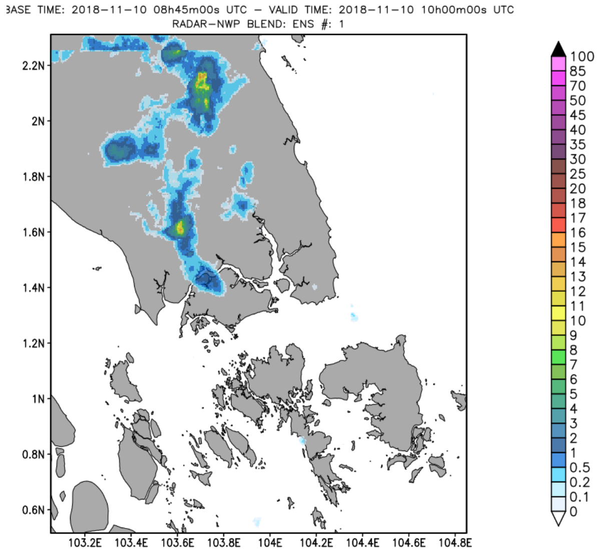
NWP



Blend



Obs Radar



Radar Nowcasting: Future Work

- Goal: Blending

Radar Extrapolation: Advection → **Growth and Decay: pySTEPS ANN** → **NWP: Nowcasting Setup**

Lead-Time: 0 – 6 hours

- Sensitivity study with nowcasting parameters
- Improve on verification technique.
  - Compensate for domain
  - Classification of dBZ

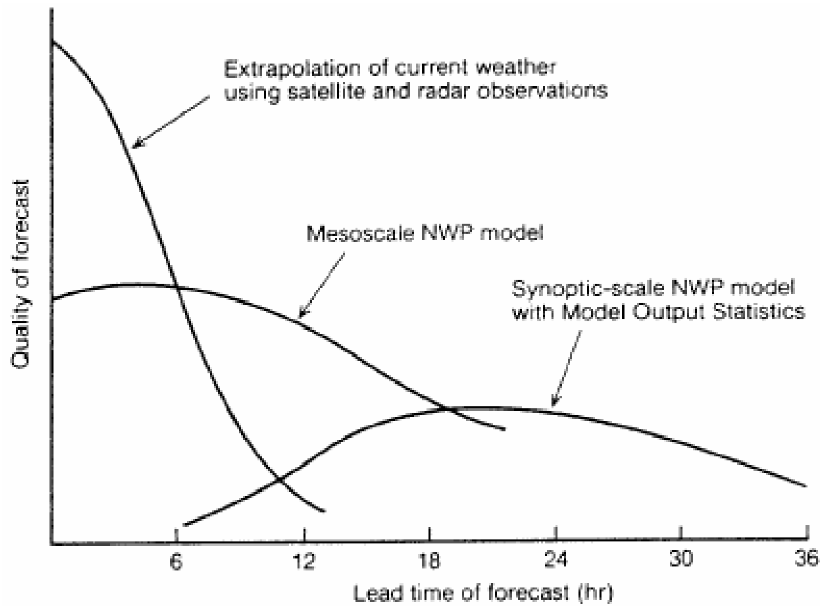


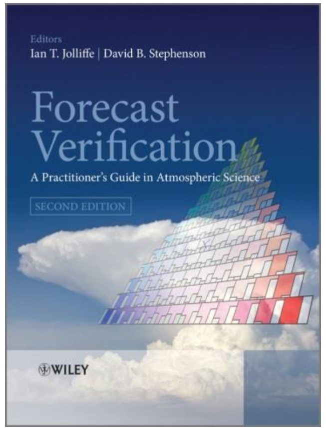
Fig. 1. A schematic diagram after Browning (1980) conceptualizing the relationship between forecasting methodology, skill and forecast range.

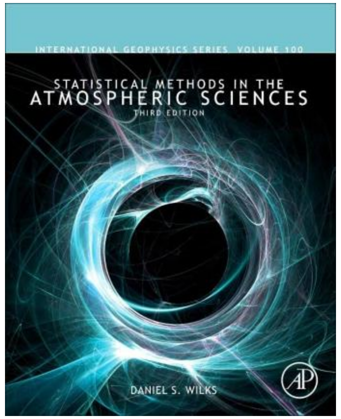
Verification

Why Verify?

To answer questions on:

- Model performance with forecasting the weather (location, type, etc.)
- Administrative (choice of model / continuous monitoring)
- Scientific understanding (improve model dynamics/parametrization)
- Economic (Disaster management / Decision support)





References:

- CAWCR verification website (Beth Ebert): http://www.cawcr.gov.au/projects/verification/
- Jolliffe IT and Stephenson DB (2011) *Forecast Verification: A Practictioner's Guide in Atmospheric Science (2nd Ed)*. Wiley.
- Wilks DS (2011) *Statistical Methods in the Atmospheric Sciences (3rd Ed)*. Academic Press.
- Casati, B., Wilson, L. J., Stephenson, D. B., Nurmi, P., Ghelli, A., Pocernich, M., Damrath, U., Ebert, E. E., Brown, B. G. and Mason, S. (2008), Forecast verification: current status and future directions. *Met. Apps*, 15: 3–18.
- WMO research programme: https://www.wmo.int/pages/prog/arep/wwrp/new/Forecast_Verification.html

What makes a good forecast?

- A forecast must have Consistency, be of good Quality and be of Value
- Need to determine or VERIFY that a forecast has these qualities.

- Forecast Attributes:
  - Bias (deviate from the mean observations)
  - Association (linear relationship or correlation),
  - Accuracy (difference from the observed error),
  - Skill (compared to some reference, climatology or persistence),
  - Reliability (agreement between observed and forecast values),
  - Resolution (resolve events into subset of events),
  - Sharpness (extreme values),
  - Discrimination (higher prediction frequency for specific outcomes),
  - Uncertainty (variability)

- Ground Truth – Normally from observations or reanalysis. Consider the limitations of the observation.

Verification Methods

Standard:

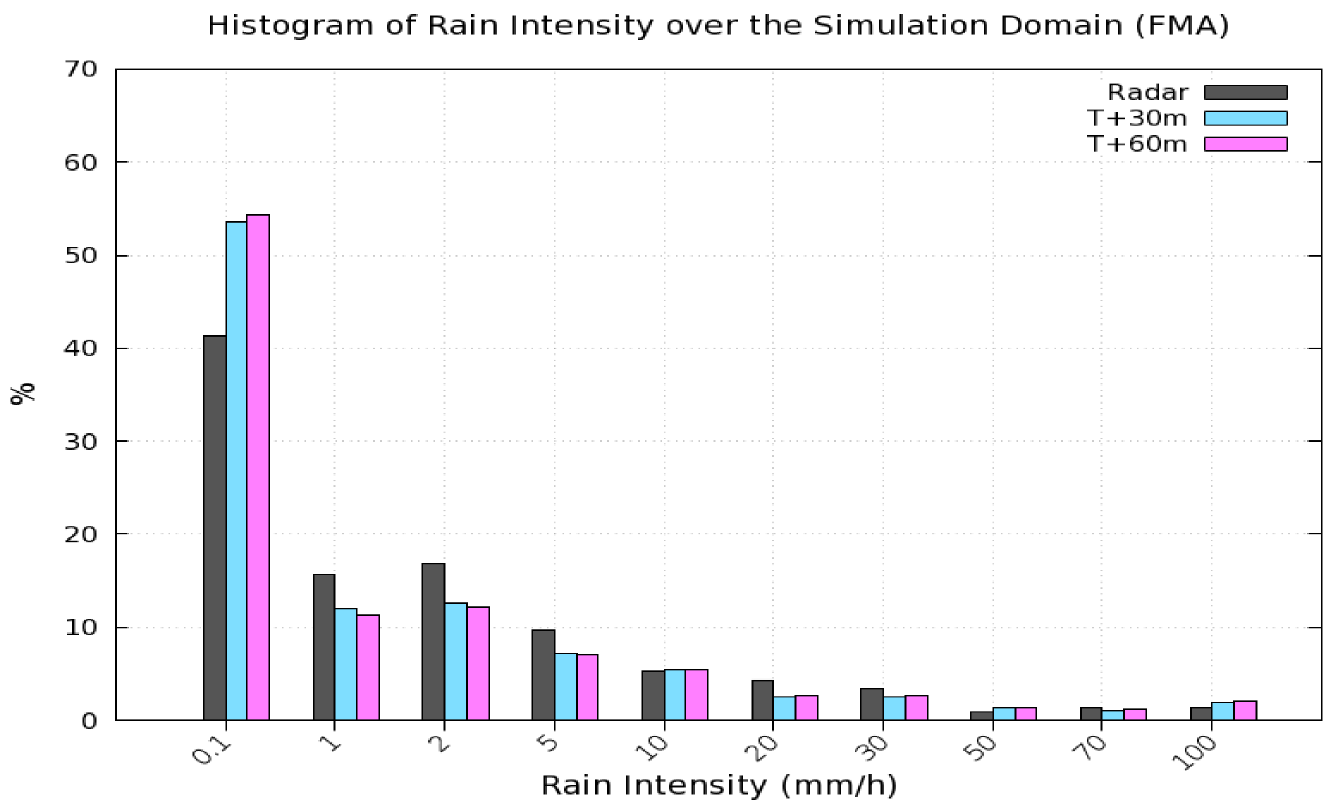
- Dichotomous (yes/no) forests
- Multi-category forecasts
- Continuous variable
- Probabilistic forecasts (Brier Skill Score)

Diagnostic (scientific):

- Spatial Forecasts
- Probabilistic forecasts, including ensemble prediction systems (Rank Histogram)
- Rare events (EDS, SEDI, SEDS)

Verification - Histograms

- Univariate Statistics; Good place to start.
- Frequency histograms
- Separate into different thresholds
- Good way to gee how model performs at different intensities



Performance Diagram (based on CT scores)

		Observed	
		Yes	No
Forecasted	Yes	a	b
	No	c	d

$$POD = \frac{a}{a+c}$$

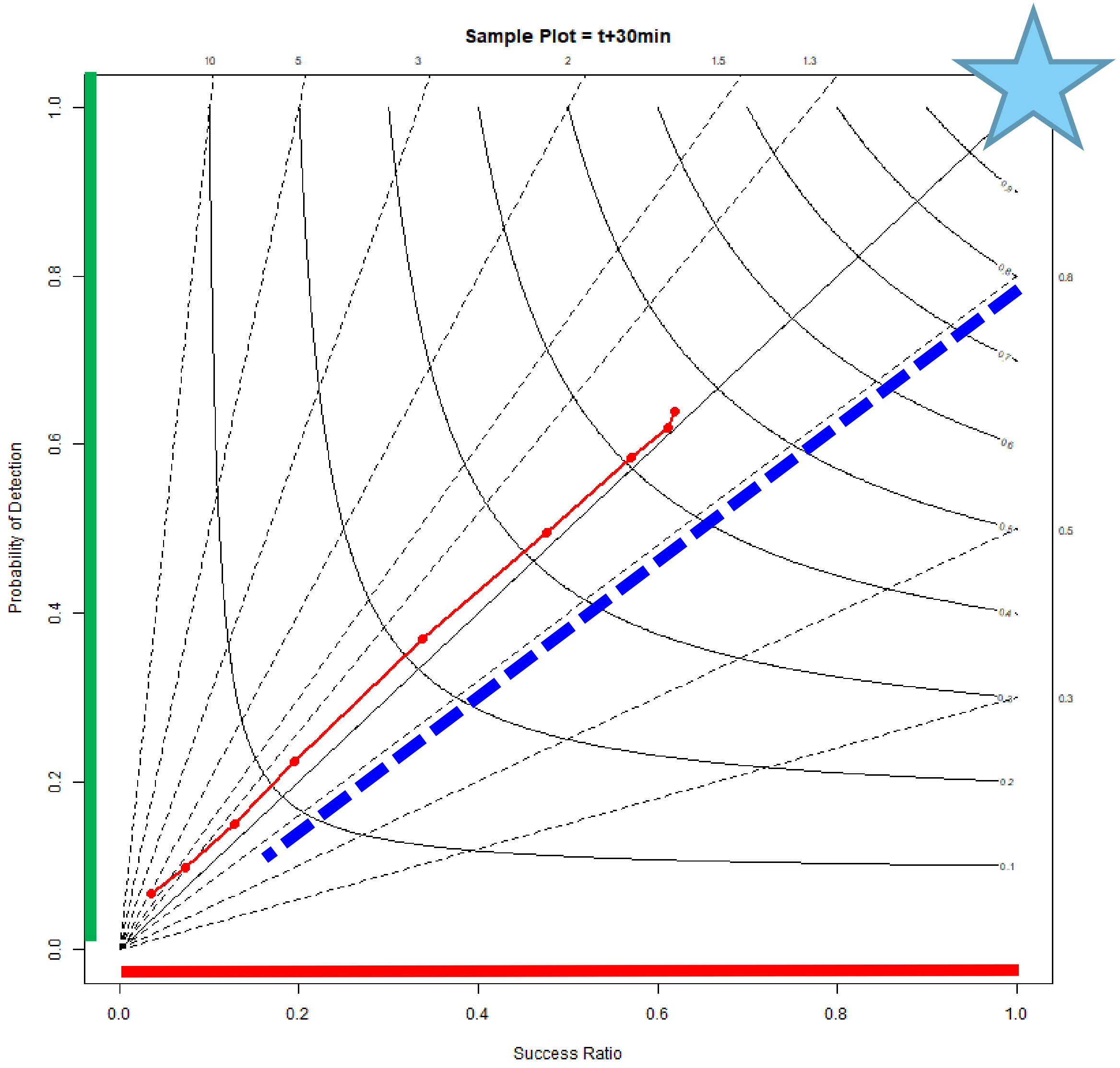
$$Bias = \frac{a+b}{a+c}$$

$$SR = \frac{a}{a+b}$$

$$CSI = \frac{a}{a+b+c}$$

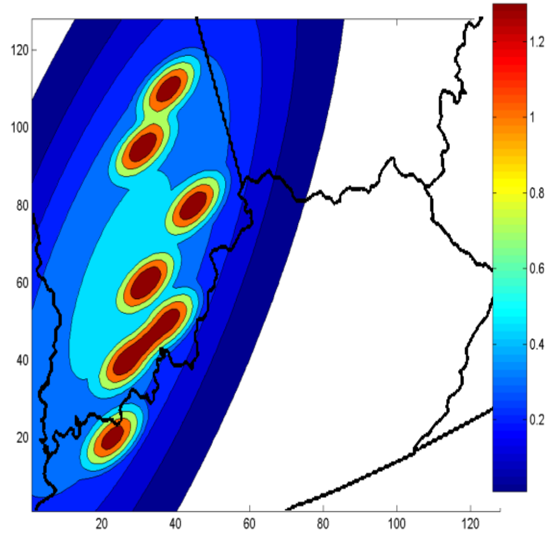

Perfect Forecast

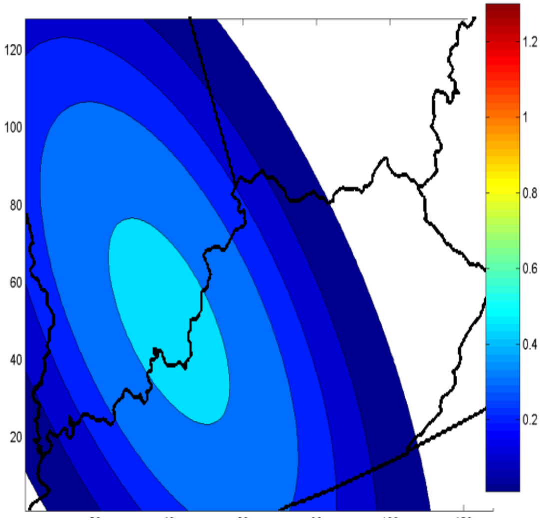
Spatial Forecasts:
Double penalty problem when comparing grid cell to grid cell



Which is the better forecast?

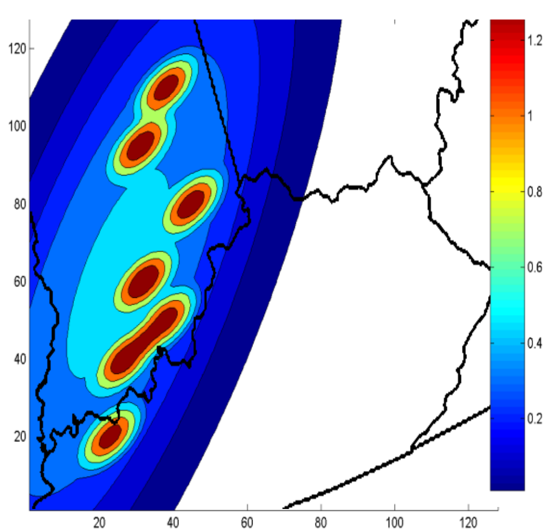
OBSERVED

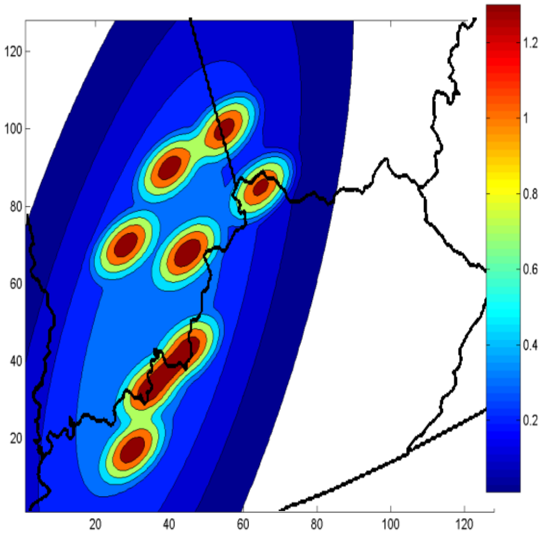




FCST #1: smooth

OBSERVED





FCST #2: detailed

From Baldwin 2002

Information courtesy Barbara Brown, NCAR

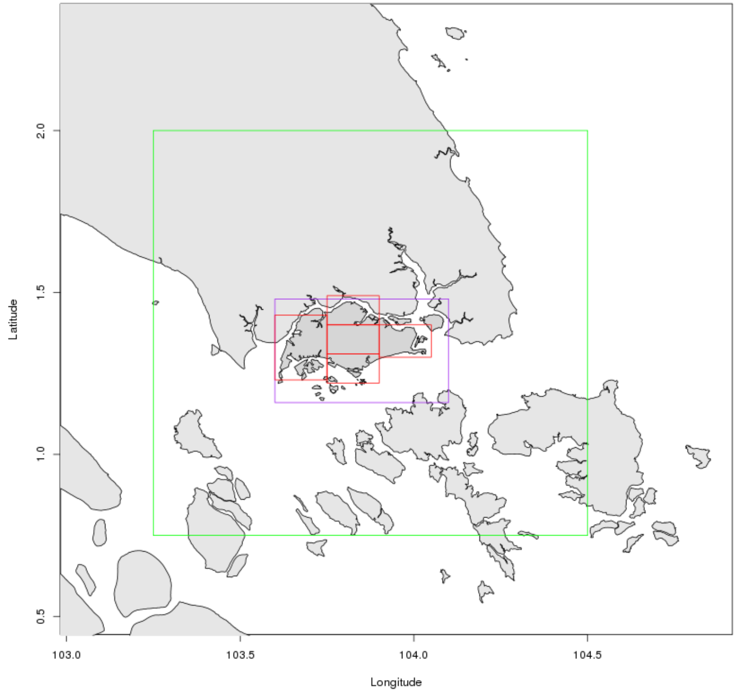
CT Score for grid comparison

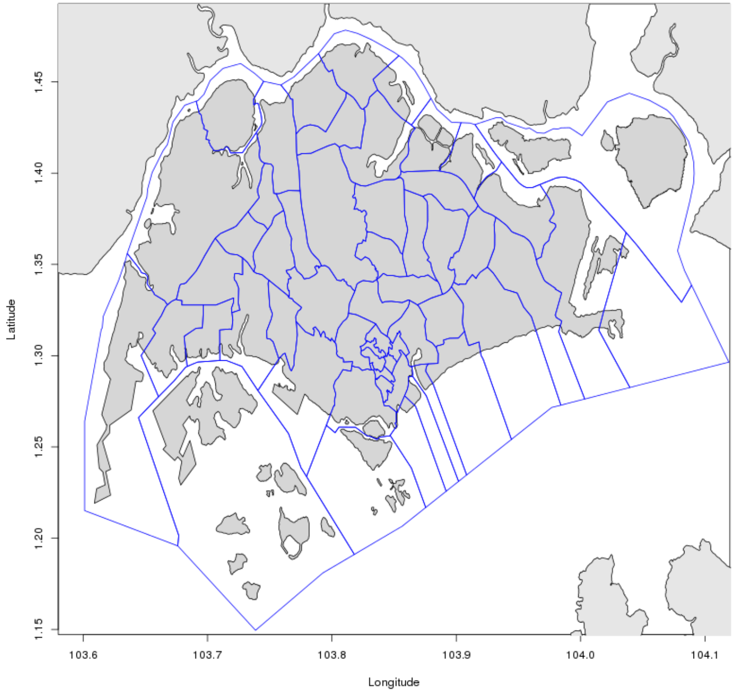
Verification Measure	Forecast #1 (smooth)	Forecast #2 (detailed)
Mean absolute error	*0.157*	0.159
RMS error	*0.254*	0.309
Bias	0.98	0.98
CSI (>0.45)	*0.214*	0.161
GSS (>0.45)	*0.170*	0.102

From Baldwin 2002

Neighbourhood Techniques

- Define Domains of interest (Scale dependent)





		Observed	
		Yes	No
Forecasted	Yes	a	b
	No	c	d

$$POD = \frac{a}{a+c}$$

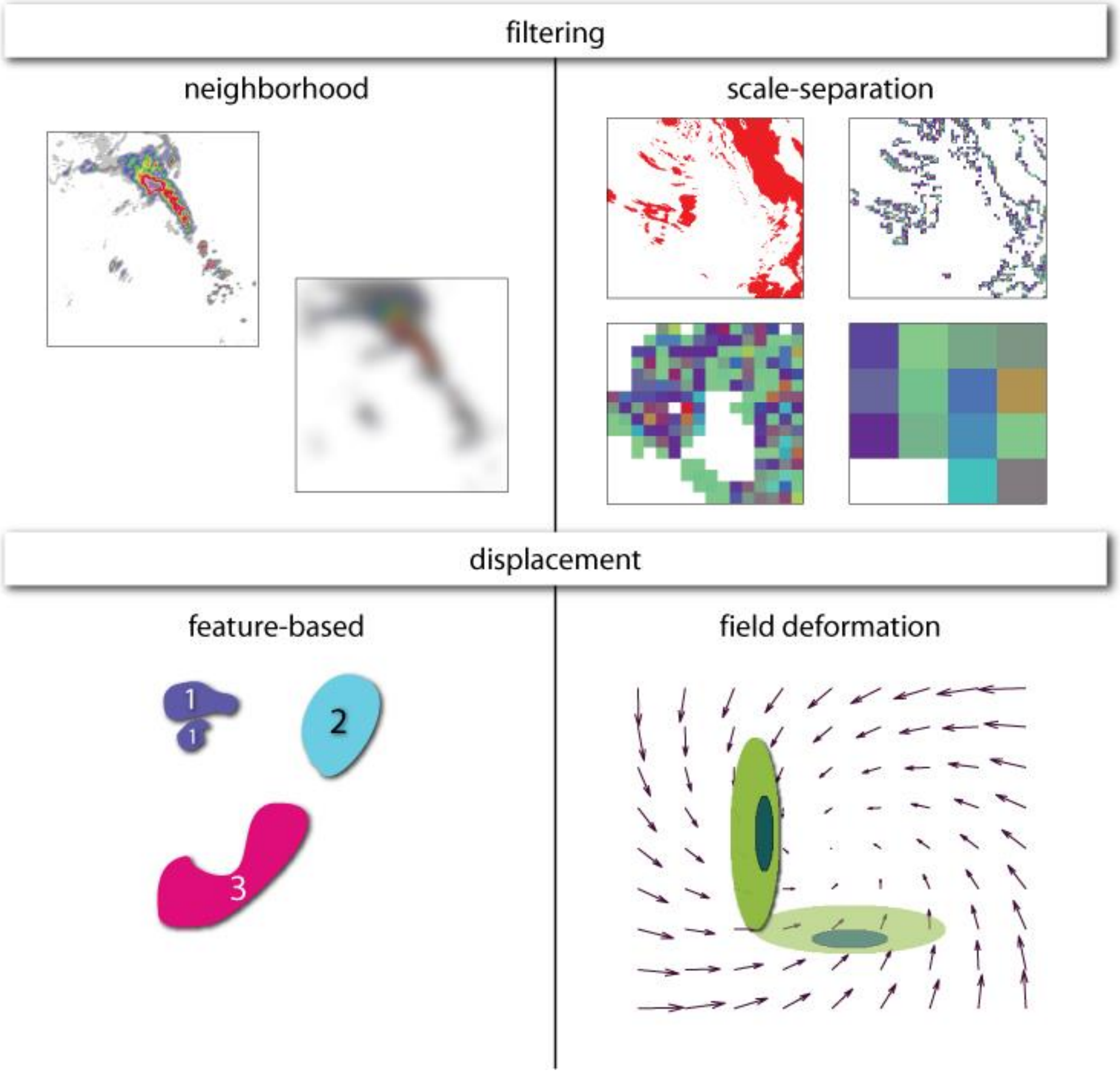
$$Bias = \frac{a+b}{a+c}$$

$$SR = \frac{a}{a+b}$$

$$CSI = \frac{a}{a+b+c}$$

Spatial Verification Approaches

- To address limitations of traditional approaches
- Goal is to provide more useful information about forecast performance

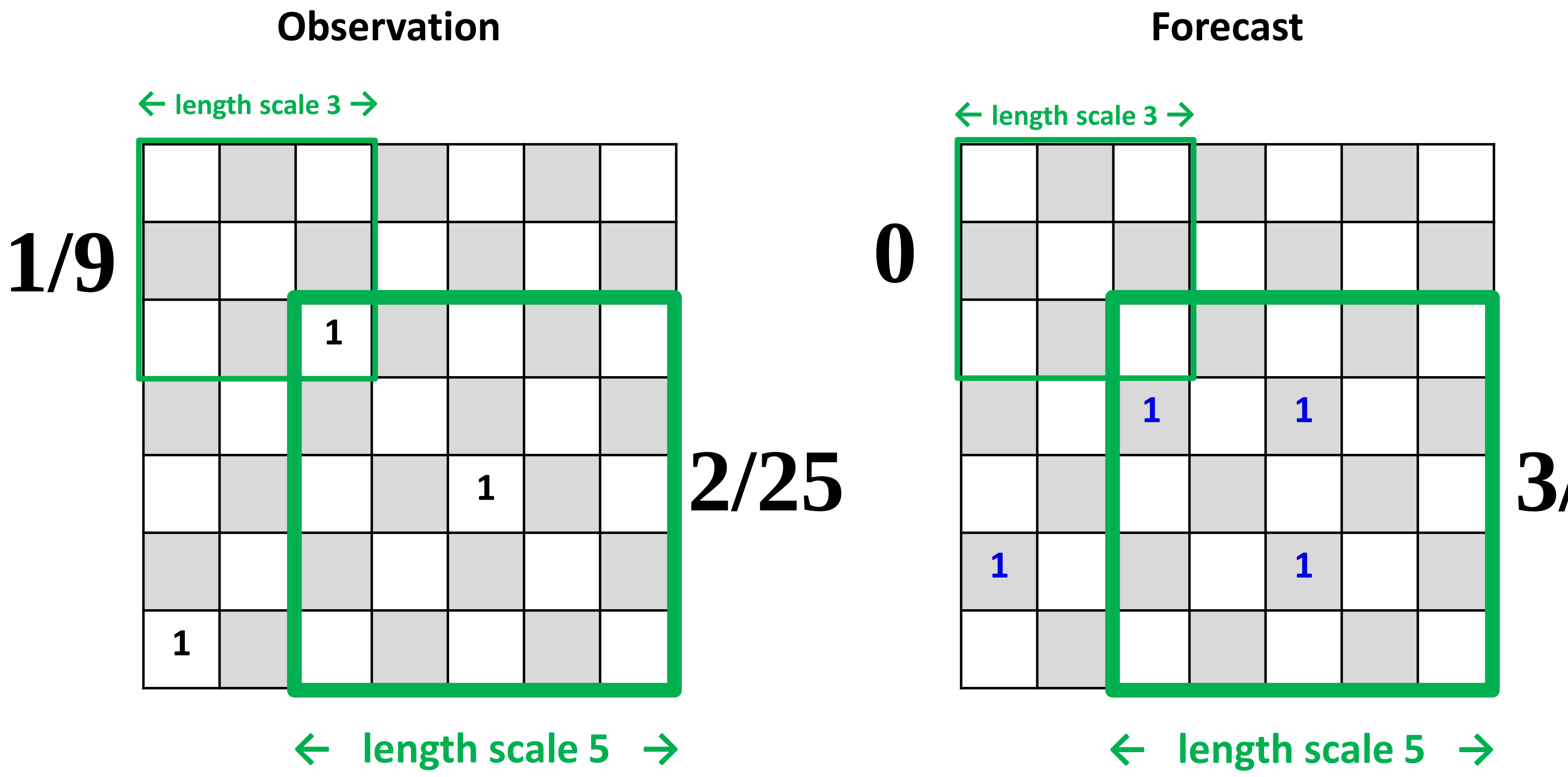


Fractions Skill Score (FSS)

$$\boldsymbol{Fractions\ Skill\ Score_{(n)} = 1 - \frac{MSE_{(n)}}{MSE_{(n)r}}}$$

Roberts, N. M. and Lean, H. W. (2008)

$$\left.\begin{aligned} MSE &= \frac{1}{N}\sum_{i=0}^{N}[F_i - O_i]^2 \\ MSE_r &= \frac{1}{N}\sum_{i=1}^{N}[F_i^2 + O_i^2] \end{aligned}\right\}$$



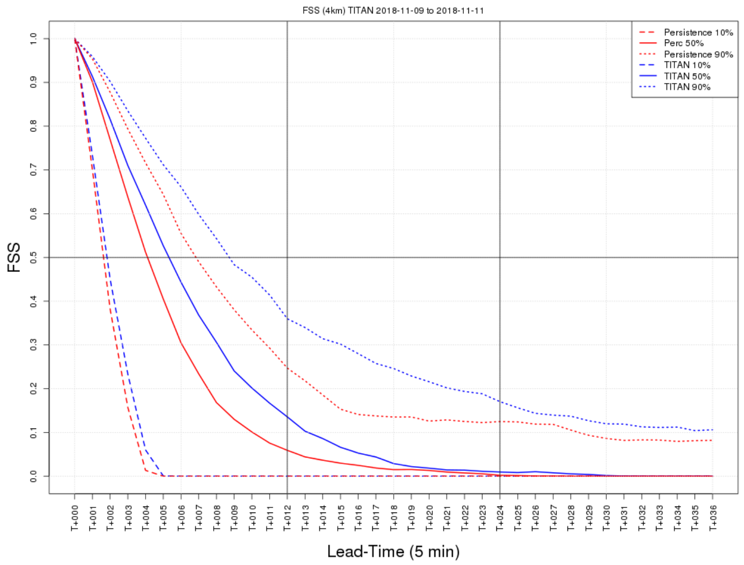
n = Length scale

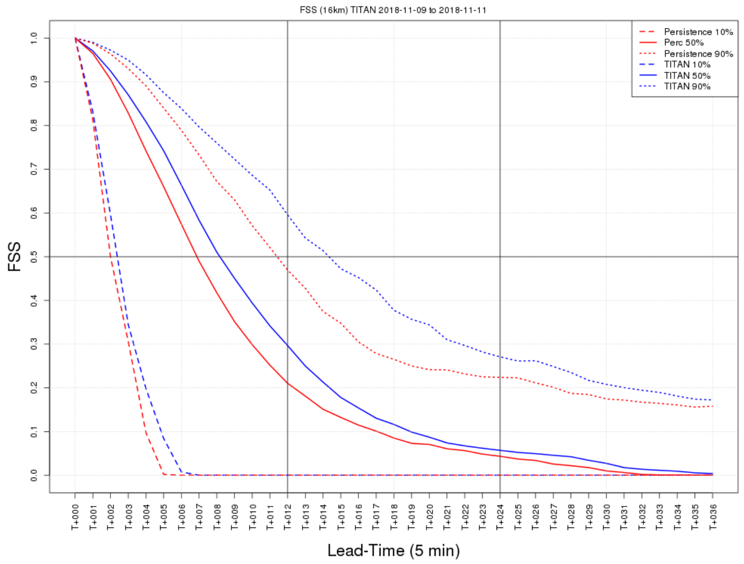
Length scale are selected so that n x n grid box doubles in size with each iteration (i.e. 2 km → 270 km)

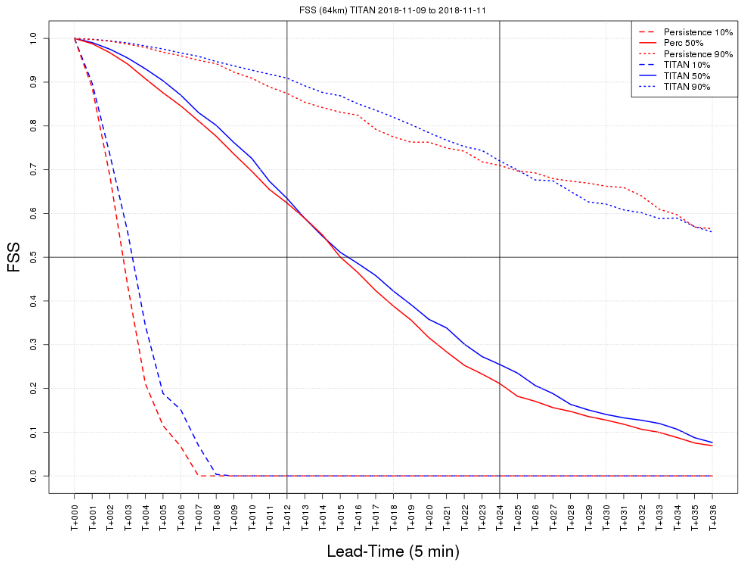
Back

TITAN FSS

- FFS Scores for TITAN cell tracking
- 3 day period 2018-11-09 to 2018-11-11
- TITAN (blue) compared to Persistence (red)
- 10th, 50th and 90th percentile plot for the evaluation period
- Length scales 4km, 16km and 64km

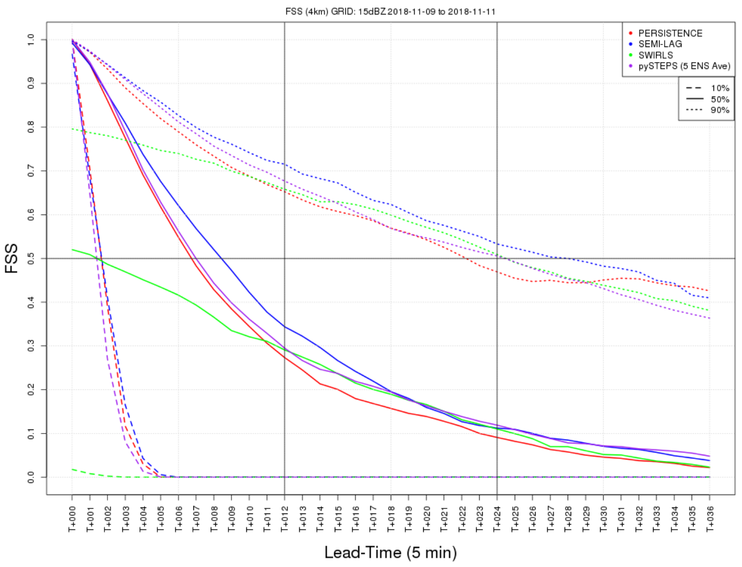


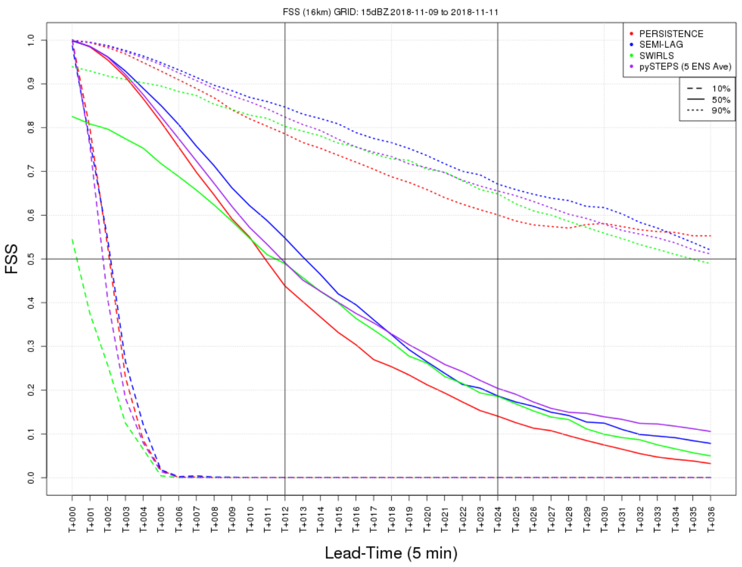


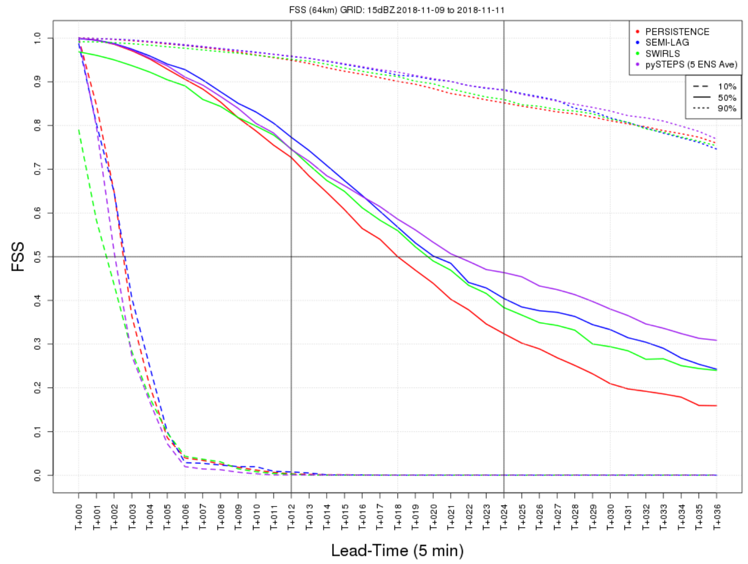


FSS Scores Nowcasting systems

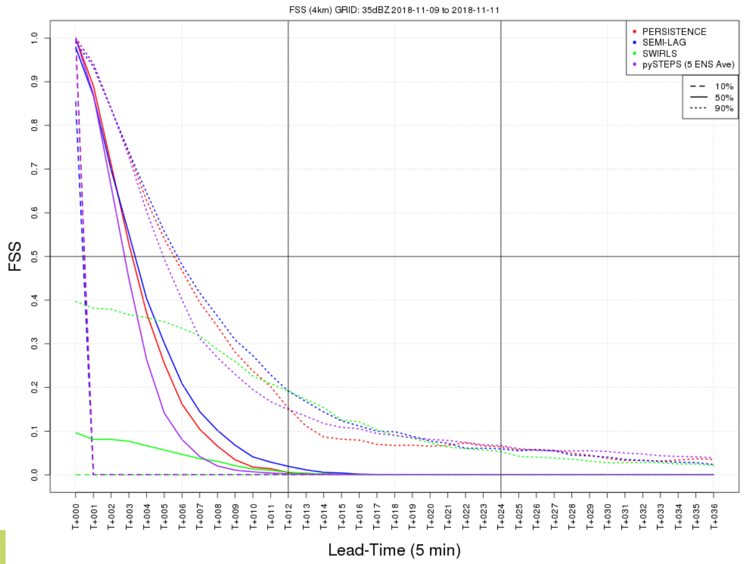
15 dBZ

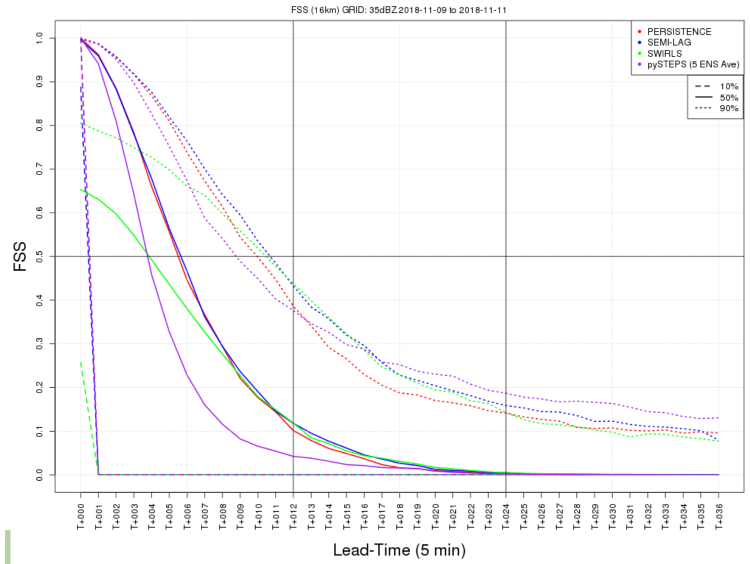


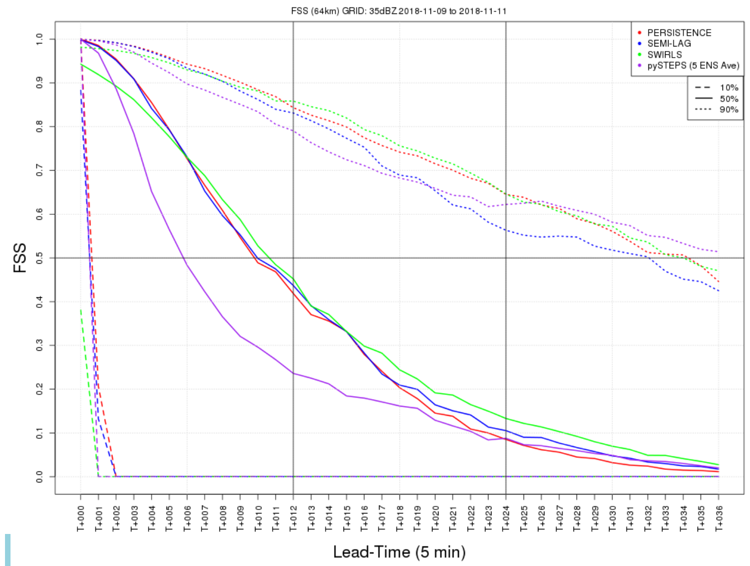




35 dBZ

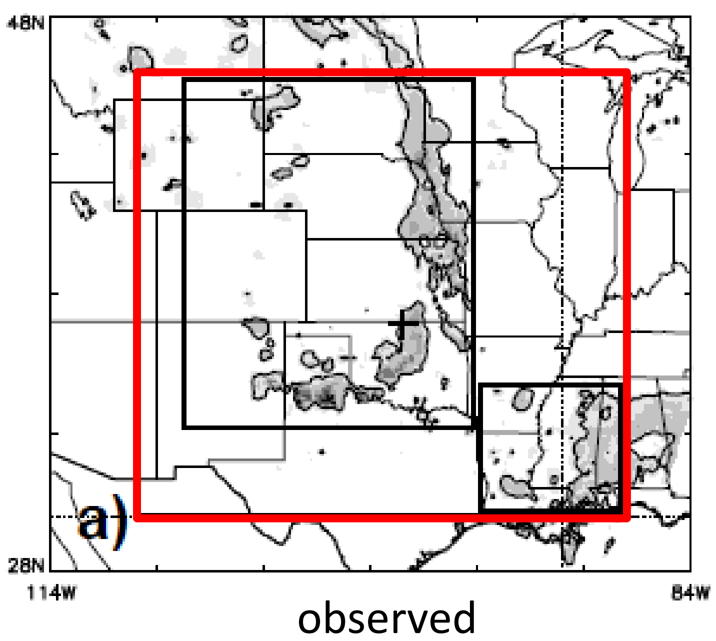


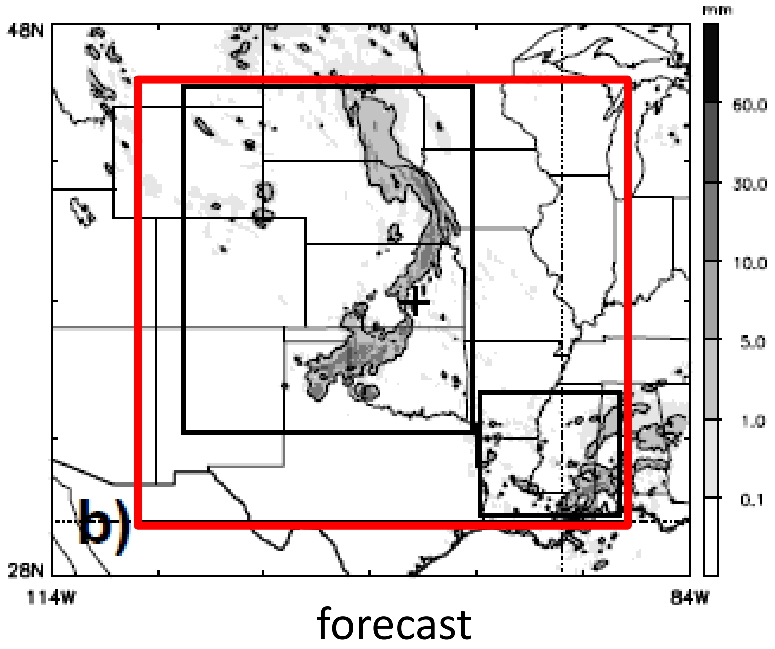




Structure-Amplitude-Location (SAL)

Wernli et al., Mon. Wea. Rev., 2008

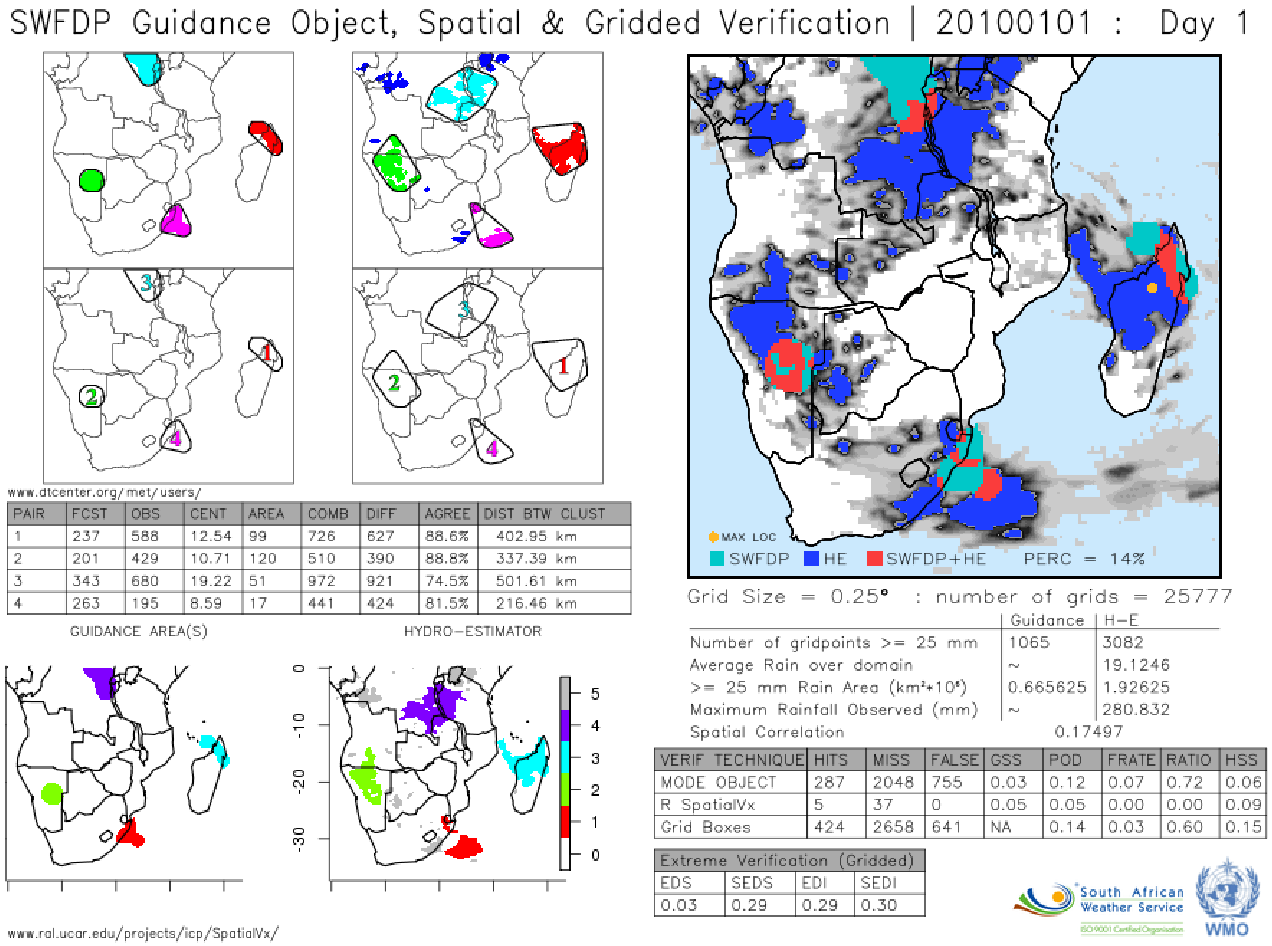




1. Is the domain average precipitation correctly forecast? A = 0.21
2. Is the mean location of the precipitation distribution in the domain correctly forecast? L = 0.06
3. Does the forecast capture the typical structure of the precipitation field (e.g., large broad objects vs. small peaked objects)? S = 0.46

(perfect=0)

Mode – SpatialVx



PAIR	FCST	OBS	CENT	AREA	COMB	DIFF	AGREE	DIST BTW CLUST
1	237	588	12.54	99	726	627	88.6%	402.95 km
2	201	429	10.71	120	510	390	88.8%	337.39 km
3	343	680	19.22	51	972	921	74.5%	501.61 km
4	263	195	8.59	17	441	424	81.5%	216.46 km

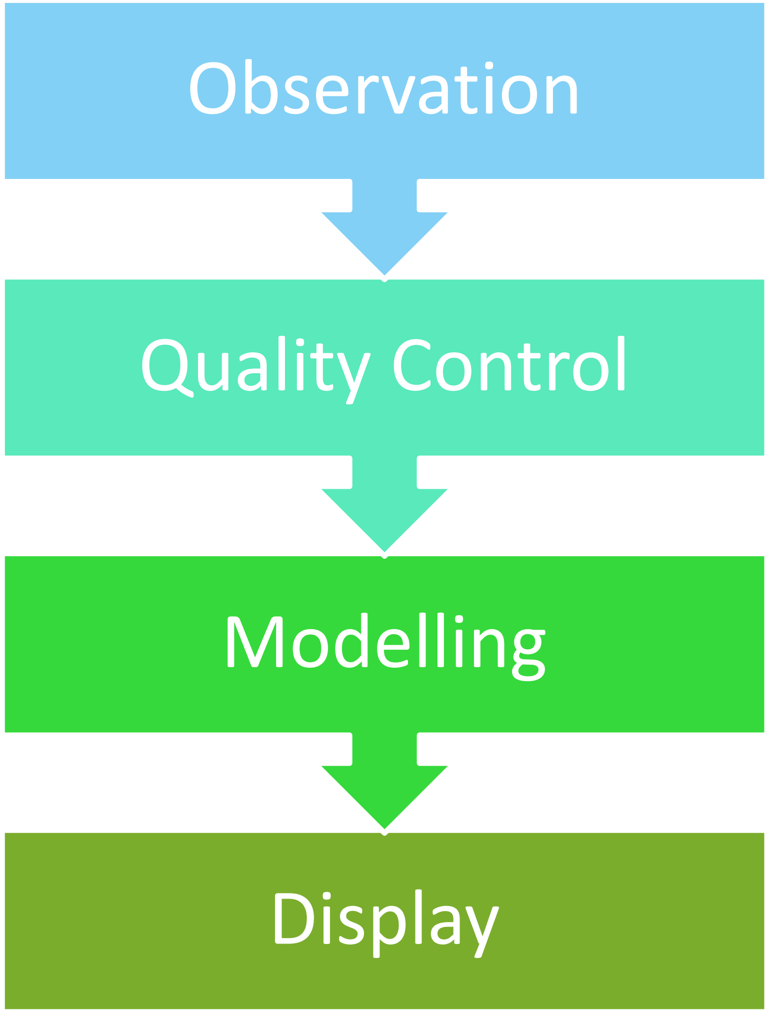
VERIF TECHNIQUE	HITS	MISS	FALSE	GSS	POD	FRATE	RATIO	HSS
MODE OBJECT	287	2048	755	0.03	0.12	0.07	0.72	0.06
R SpatialVx	5	37	0	0.05	0.05	0.00	0.00	0.09
Grid Boxes	424	2658	641	NA	0.14	0.03	0.60	0.15

Extreme Verification (Gridded)			
EDS	SEDS	EDI	SEDI
0.03	0.29	0.29	0.30

Information courtesy Stephanie Landman

Operational Requirements

Operational: Considerations



- Data point for incoming data (Availability, Latency).
- Data Format (HDF5, RB5, IRIS, NETCDF, MDV, etc.)
- Distinguish between online/offline data.
- Distinguish between research/operational.
- Processing of data to radar, nowcasting, verification, etc. type products (Server, HPC).
- Archiving and Database management.
- Visualisation (Webpage, Software).
- House Keeping.

Summary

Scrutinise the radar processing chain for accurate QPE and QPF:

- Data Acquisition
- Data Quality Monitoring
- Data Quality Control
- Data Processing
- QPE and Rain Gauge adjustments
- Nowcasting:
  - Object based tracking
  - Field advection
  - Growth and Decay (Statistical and Machine Learning Methods)
  - NWP
  - Blending for seamless nowcasting
- Verification:
  - Operational
  - Scientific
- Operational Considerations (Team Effort)

Thank You

Questions?

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