A MODEL IN SPATIAL AND TEMPORAL DOMAIN TO PREDICT RADAR RAINFALL DATA

Nazario D. Ramirez-Beltran,

Luz Torres Molina, Joan M. Castro, Sandra Cruz-Pol, José G. Colom-Ustáriz and Nathan Hosanna

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Introduction

- Rainfall is one of the most difficult elements of the hydrological cycle to be predicted and large uncertainties occur in the flood warning process.

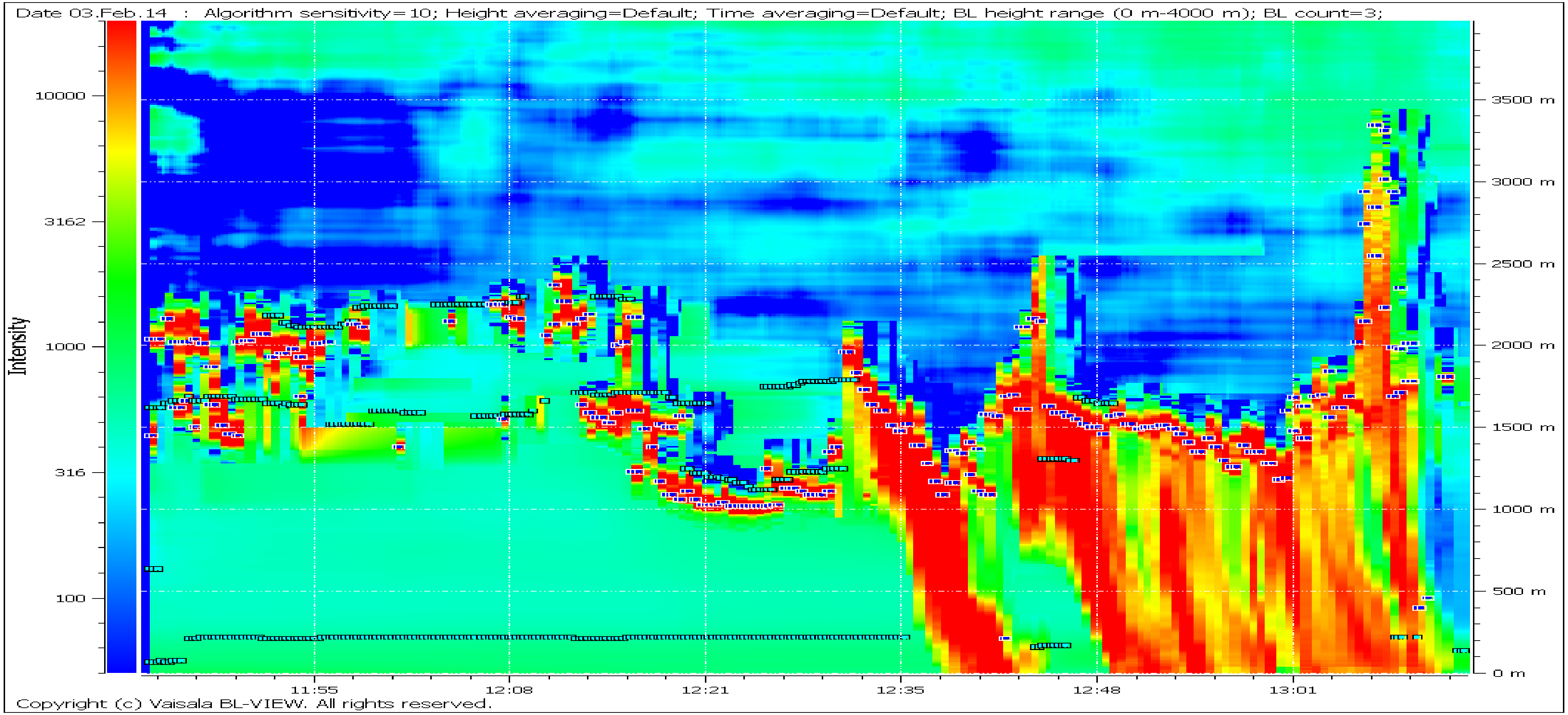
- The spatial and temporal rainfall forecasting algorithm was derived with the purpose of being coupled to a hydrological numerical model to forecast flash floods on real time.

Motivation

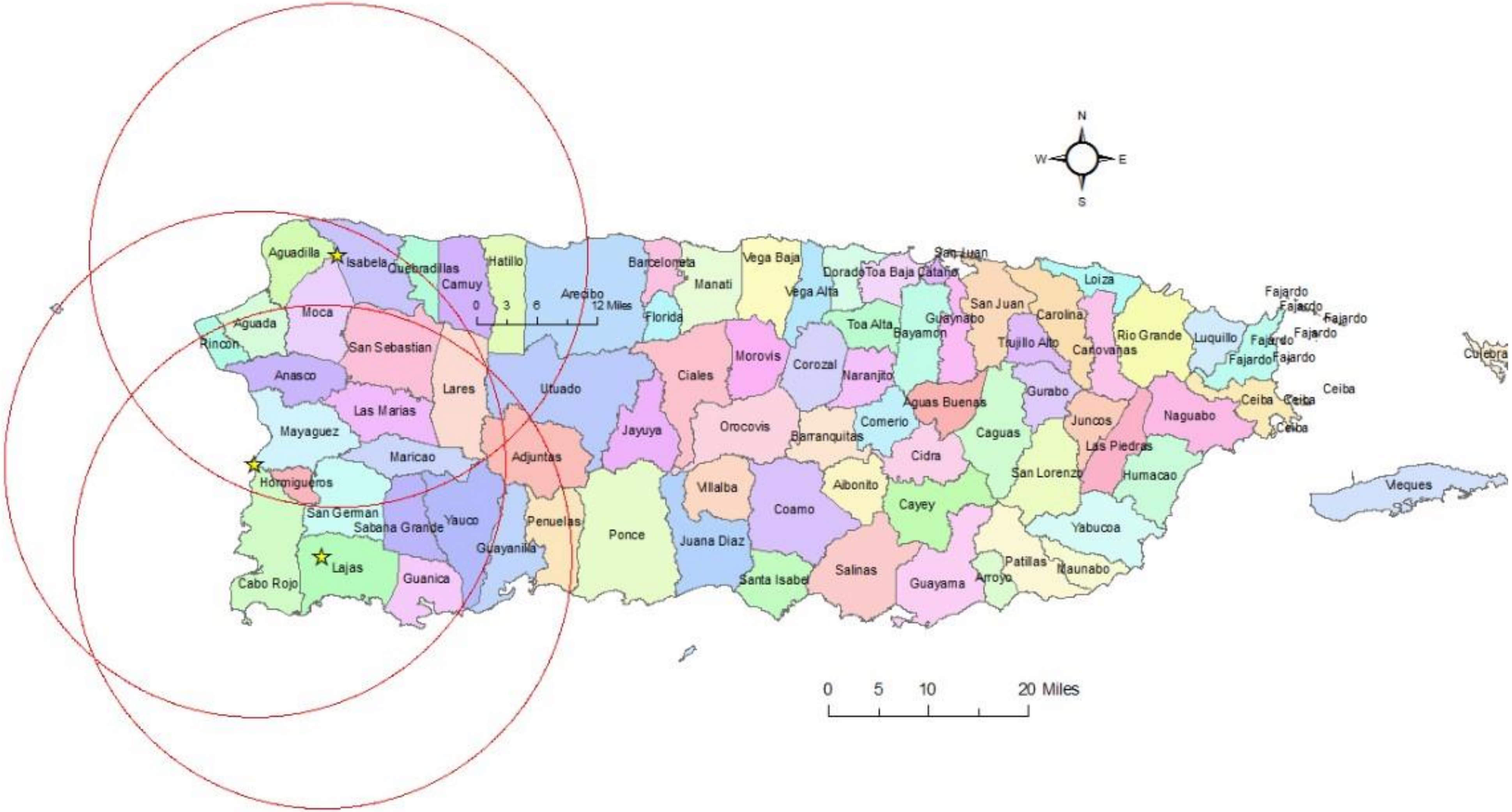
- **Practical bases**

  - Puerto Rico is heavily affected by rainfall due to warm-top convective processes that are induced by local sea breeze- and/or orographic features and also by tropical storms and cold fronts.
  - Some storms in the western part of PR are missed because NEXRAD radar is located about 104 km away from the studied area and
  - Reflectivity is measured at about 3 km above the surface due to Earth curvature and mountains

Ceilometer backscattering profile for a storm that occurred in Puerto Rico in February 3, 2014. (Lidar Laboratory NOAA-CREST UPRM).



Location and spatial coverage of TropiNet Radars



Motivation

- **Theoretical bases**
  - (NOAA/NWS) in a near-term forecast period the numerical weather prediction models currently have lesser precipitation forecast skills than extrapolation of current radar rainfall observations (Van Horne, 2003; Wilson 2004; Thorndahl, et al. 2010)
  - There is a large amount of mathematical tools to model and forecast a single or a few points throughout time.
    - Time series models (ARIMA and ARMA) Burlando et al. 1992; 1996)
    - Point process (Rodríguez-Iturbe et al. 1984; 1987; Cowpertwait et al. 2007)
    - Artificial Neural Networks (Toth et al. 2000)
    - Regression with time series models (Ledolther, 2000)
  - However to represent and forecast the variation of a process throughout time and spatial domain the tools are vary limited
    - Kalman filter
    - Vector ARIMA models
    - Canonical correlation

Methodology

1. Forecast rainfall areas

2. Predict the growth and decay of rainfall intensity

Identification of rainfall cells

- A threshold is used to select the rainy pixels

- A meridional and zonal searching method is conducted to identify contiguous rain pixels, which will be referred as rainfall cells.

Tracking rainfall cells

- It is expected that in a short time period (~10 min) a rain cloud behaves approximately as a rigid object and the cloud rain pixels moves in a constant speed and direction.
- Let $C_{\tau_1,t-1}(x_{t-1}, y_{t-1})$ and $C_{\tau_2,t}(x_t, y_t)$ be the centroids of a rain cell at time $t-1$ and t, respectively.
- The distance among centroids for all possible path ways were computed and a combinatory linear optimization problem is solved to find the minimum distances among each pair of centroids and determine the same rain cell in the two consecutive radar images.

The motion vector

- The meridional and zonal displacement between two consecutives centroids of the same cell is estimated as follows:

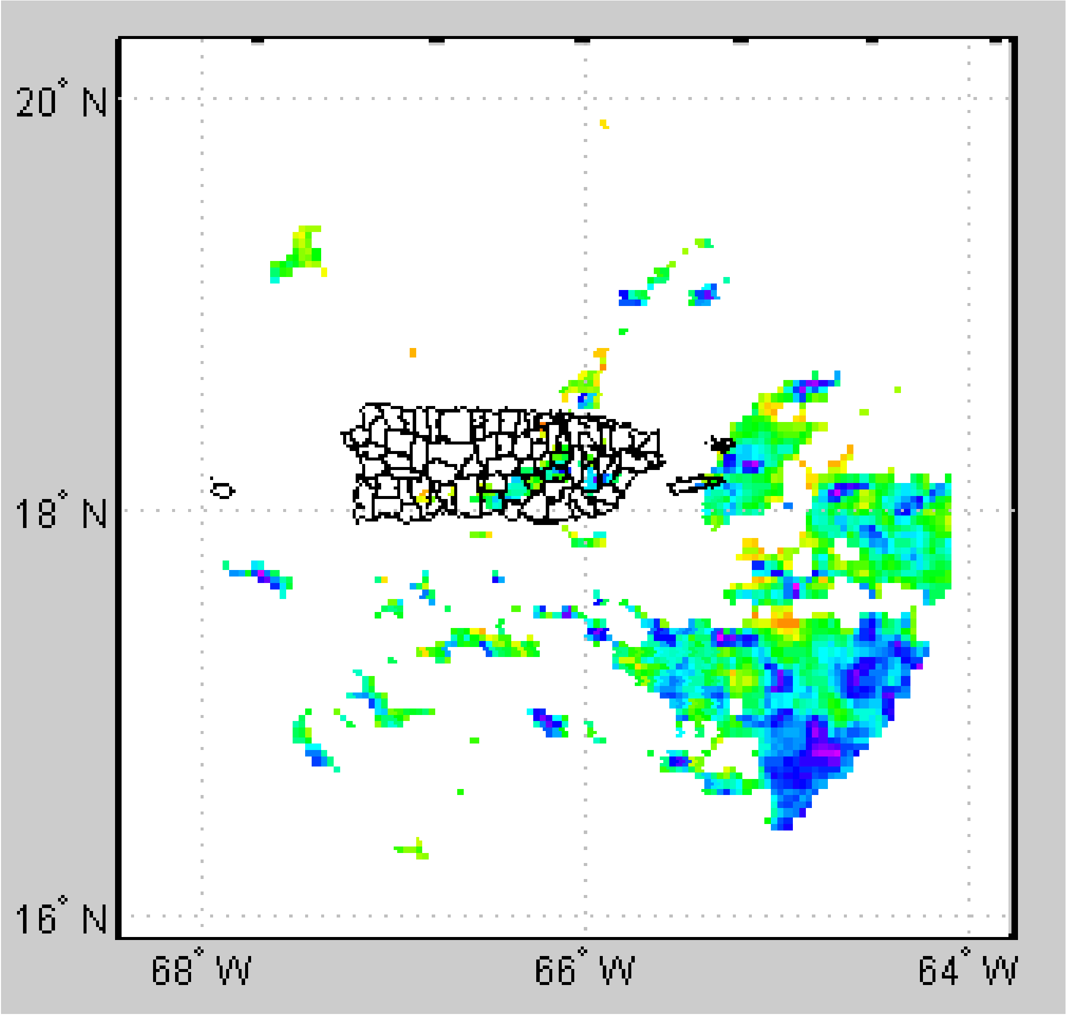
$$\Delta x = x_t - x_{t-1} \quad \text{and} \quad \Delta y = y_t - y_{t-1}$$

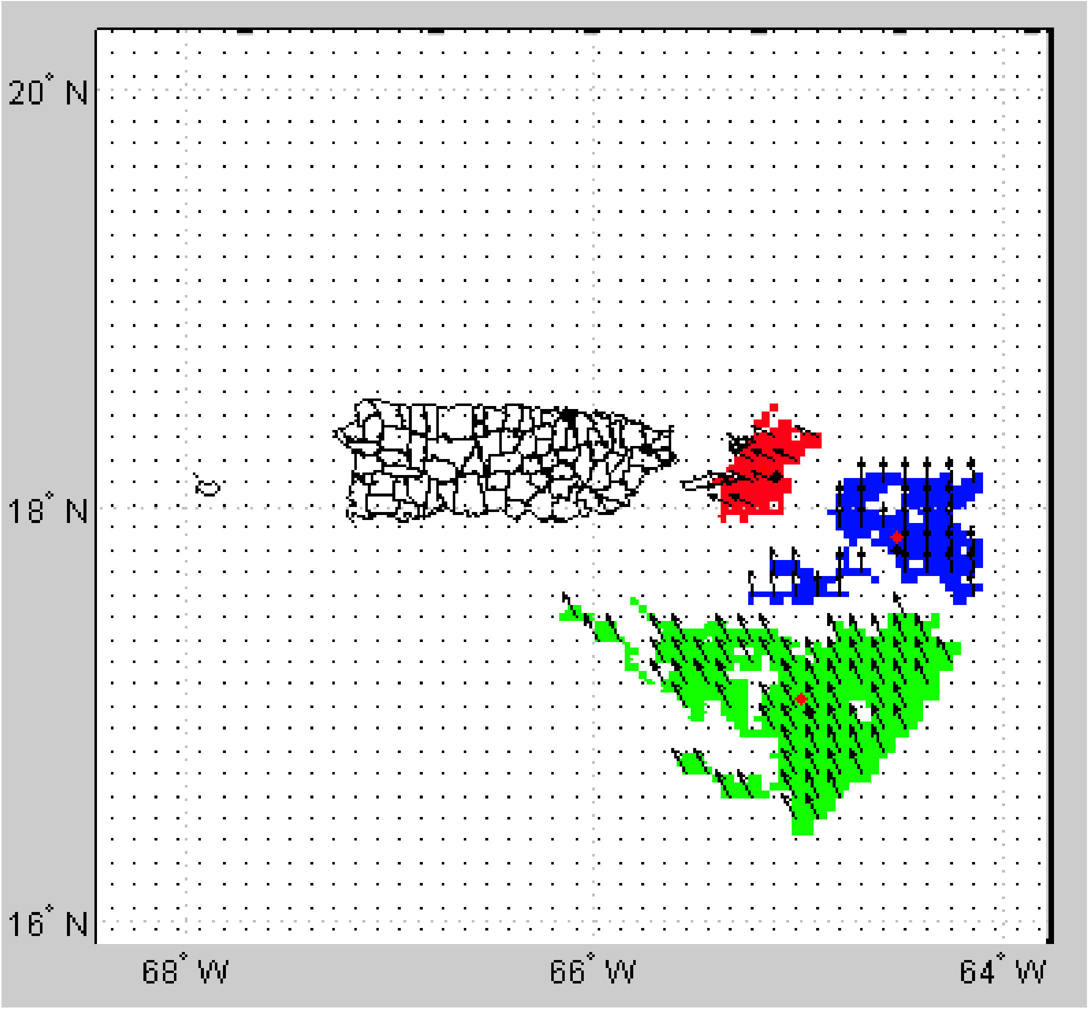
$$m = \sqrt{(\Delta x)^2 + (\Delta y)^2} \quad \text{and} \quad \theta = \arctan\left(\frac{\Delta y}{\Delta x}\right)$$

$$P_{t+1}(k,l) = P_t(i + \Delta x, j + \Delta y)$$

The cloud motion vector

Tropical storm: October 27, 2007 (at 1000 UTC)





Characteristics of the Rainfall Process

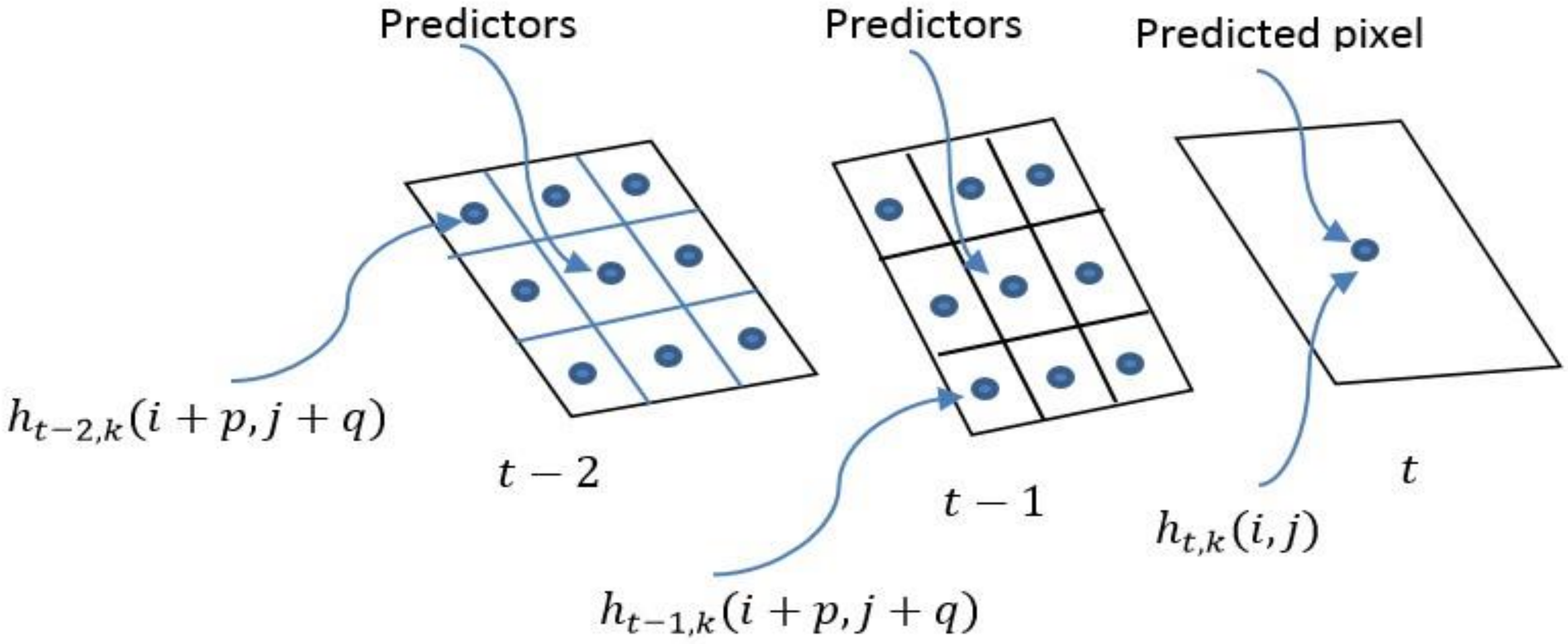
- The rainfall process exhibits significant changes in time and space, and it can be characterized as a non-stationary stochastic process.

- To face the non-stationary characteristic of the process, different models are developed at different times and space.

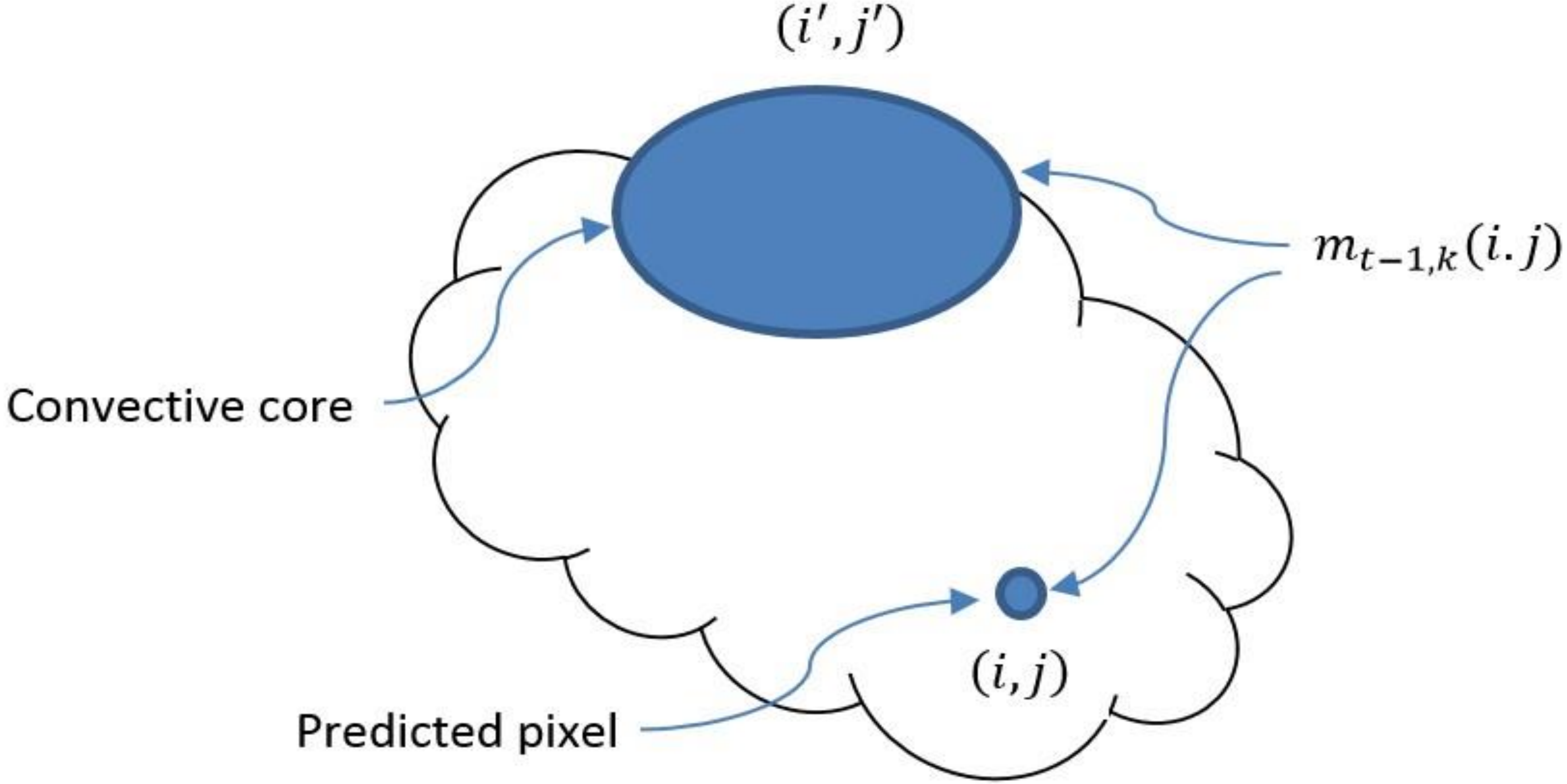
- The stochastic characteristics of the process are represented by a quassy autoregressive model.

Estimation of rain rate at a given space and time requires consideration of cloud status at the current time and also at consecutive previous points in time.

Because a cloud rainfall event is the result of a complex thermodynamic process that starts with nucleation of cloud drops, continues with drop growth, and finishes with water drop precipitation.



Pixel is influenced by the convective core



Model in time and space domain

$$h_{t,k}(i,j) = \alpha_{t,k} + \left(\beta_{t,k} - \alpha_{t,k}\right)\phi_{t,k} \left\{1 - e^{-\left[\delta_{1,t,k}\bar{h}_{t-1,k}(i,j) + \delta_{2,t,k}\bar{h}_{t-2,k}(i,j) + \delta_{3,t,k}m_{t-1,k}(i,j)\right]}\right\} + \varepsilon_{t,k}(i,j)$$

$\delta_{i,t,k} \geq 0, \quad i = 1,2,3$ and $0 < \phi_{t,k} \leq 1.1$

$$\bar{h}_{t-1,k}(i,j) = \frac{1}{\eta}\sum_{p\in A}\sum_{q\in A} h_{t-1,k}(i+p, j+q) \qquad A = \{\, 0, \pm 1, \dots, \pm \mathrm{s}, \quad \text{and } \mathrm{s} < a\}$$

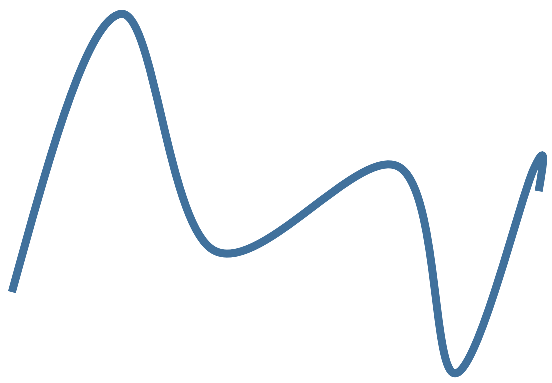
$$m_{t-1,k}(i,j) = \frac{\sum_{p\in A}\sum_{q\in A} h_{t-1,k}(i+p,j+q)}{\sum_{p\in A}\sum_{q\in A} h_{t-1}(i'+p,j'+q)} \qquad A = \{\, 0,\ \pm 1, \dots, \pm \mathrm{s},\ \text{and } \mathrm{s} < a\}$$

Initial and final point

- **Initial point**

$$y_{t,k}(i,j) = \delta_{1,k}\bar{h}_{t-1,k}(i,j) + \delta_{2,k}\bar{h}_{t-2,k}(i,j) + \delta_{3,k}m_{t-1,k}(i,j) + \xi_{t,k}(i,j)$$

$$y_{t,k} = -\ln\left(1 - \frac{h_{t,k} - \alpha_{t,k}}{\beta_{t,k} - \alpha_{t,k}}\right), \qquad \alpha_{t,k} < h_{t,k} < \beta_{t,k}$$

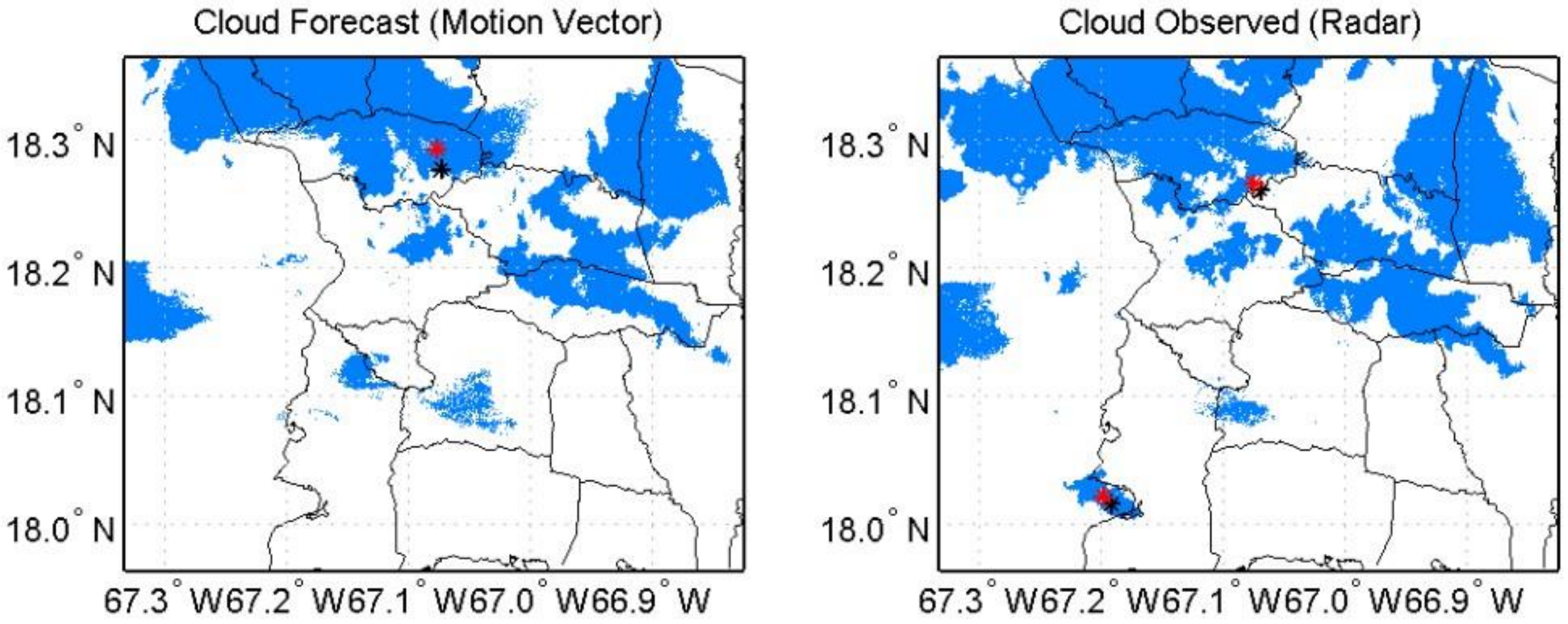


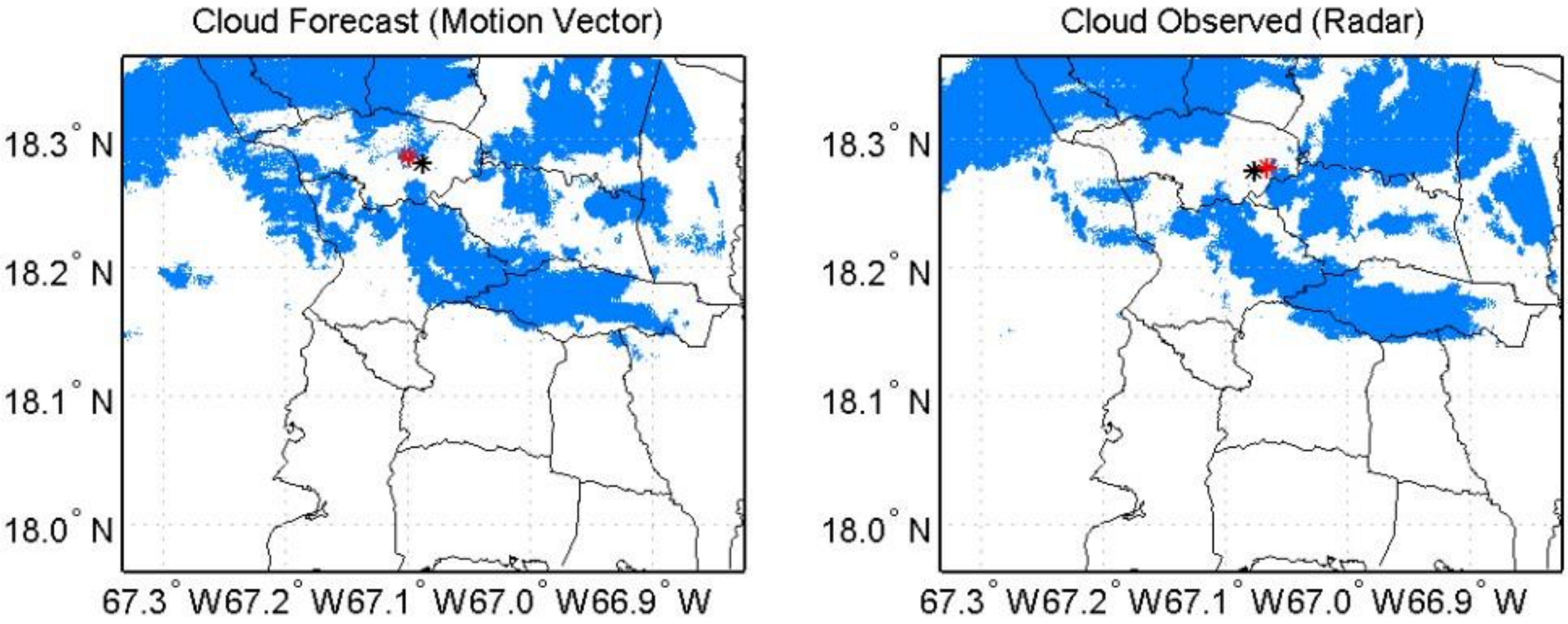
$$z_{t,k}(i,j) = \phi_{t,k}x_{t,k}(i,j) + \nu_{t,k}(i,j)$$

$$x_{t,k}(i,j) = 1 - e^{-\{\hat{\delta}_{1,t,k}\bar{h}_{t-1,k}(i,j) + \hat{\delta}_{2,t,k}\bar{h}_{t-2,k}(i,j) + \hat{\delta}_{3,t,k}m_{t-1,k}(i,j)\}}$$

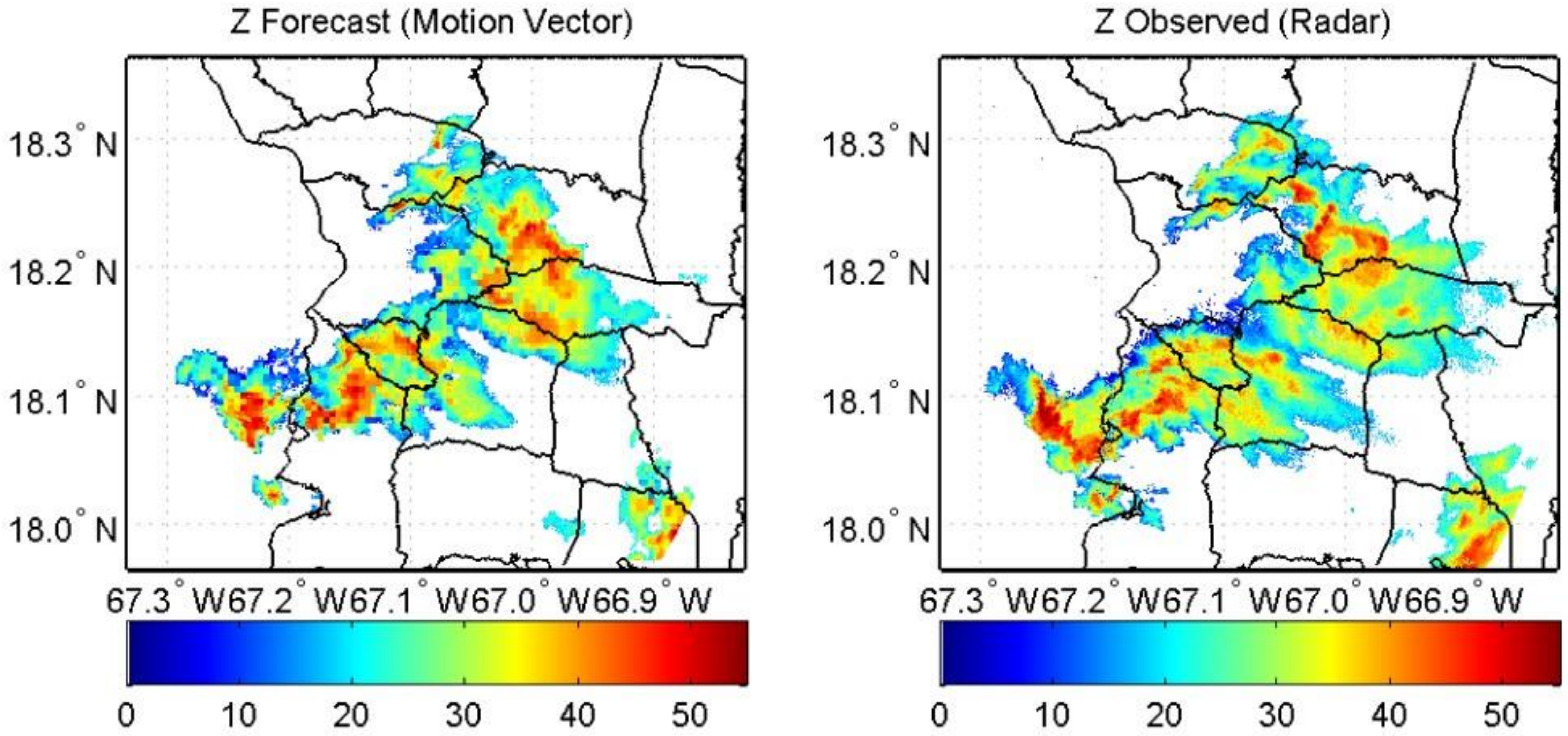
$$z_{t,k}(i,j) = \frac{h_{t,k} - \alpha_{t,k}}{\beta_{t,k} - \alpha_{t,k}}, \qquad \alpha_{t,k} < h_{t,k} < \beta_{t,k}$$

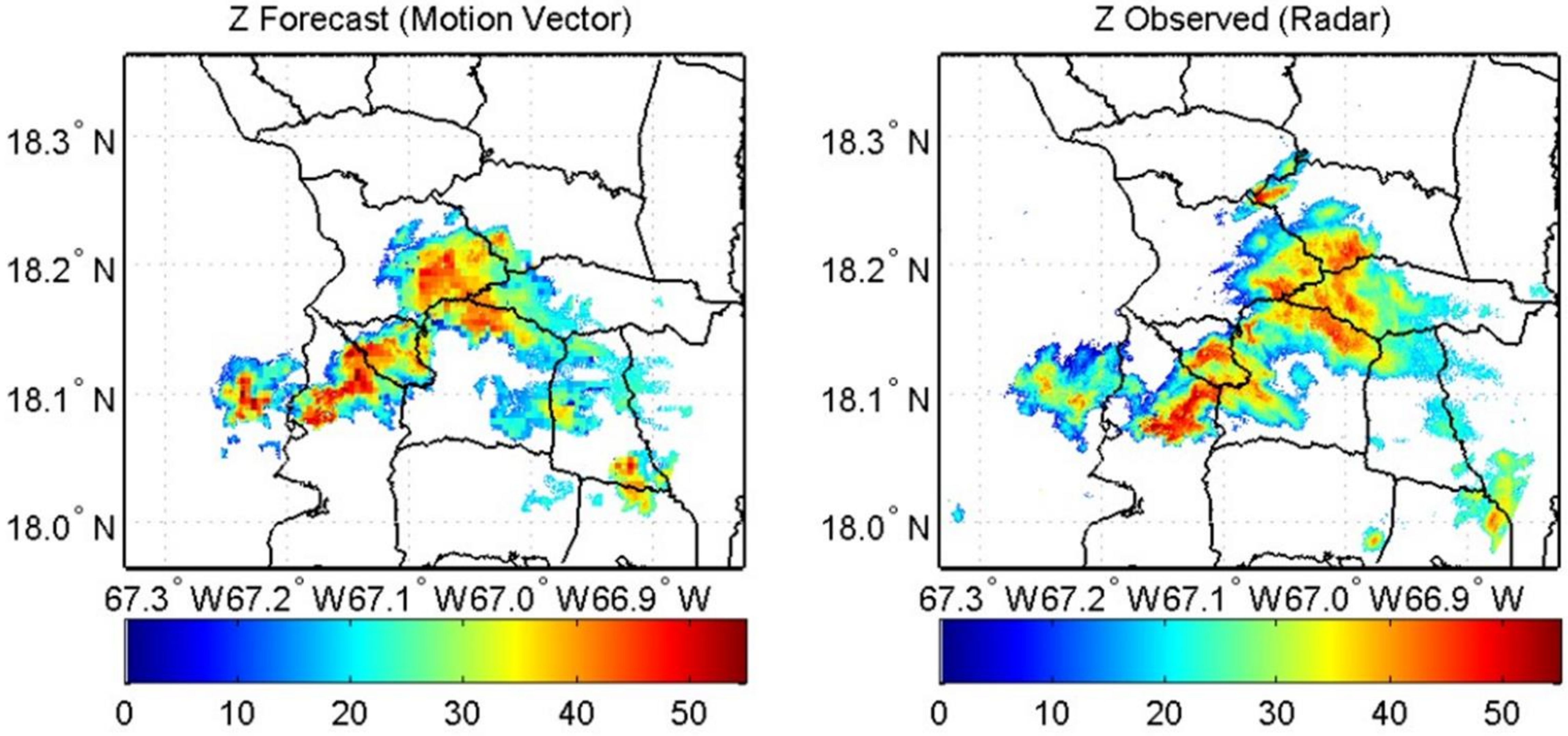
- **Final point: Sequential Quadratic Programming Algorithm**


Cloud Forecast (Motion Vector)
Cloud Observed (Radar)
18.3° N
18.2° N
18.1° N
18.0° N
67.3° W
67.2° W
67.1° W
67.0° W
66.9° W



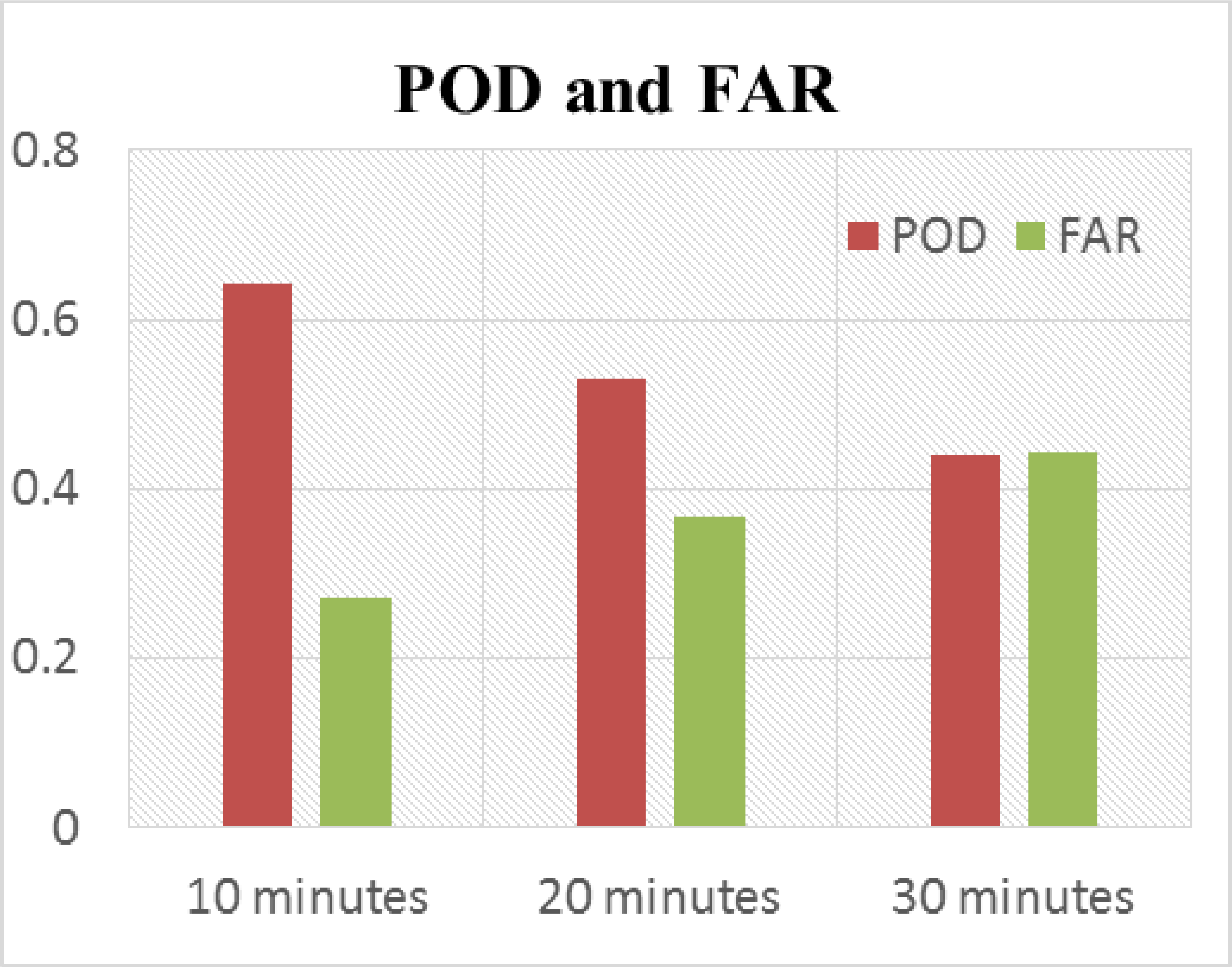
Cloud Forecast (Motion Vector)
Cloud Observed (Radar)
18.3° N
18.2° N
18.1° N
18.0° N
67.3° W
67.2° W
67.1° W
67.0° W
66.9° W


Z Forecast (Motion Vector)
18.3° N
18.2° N
18.1° N
18.0° N
67.3° W 67.2° W 67.1° W 67.0° W 66.9° W
0
10
20
30
40
50
Z Observed (Radar)
18.3° N
18.2° N
18.1° N
18.0° N
67.3° W 67.2° W 67.1° W 67.0° W 66.9° W
0
10
20
30
40
50


Z Forecast (Motion Vector)
Z Observed (Radar)
18.3° N
18.2° N
18.1° N
18.0° N
67.3° W
67.2° W
67.1° W
67.0° W
66.9° W
0
10
20
30
40
50

Numerical example

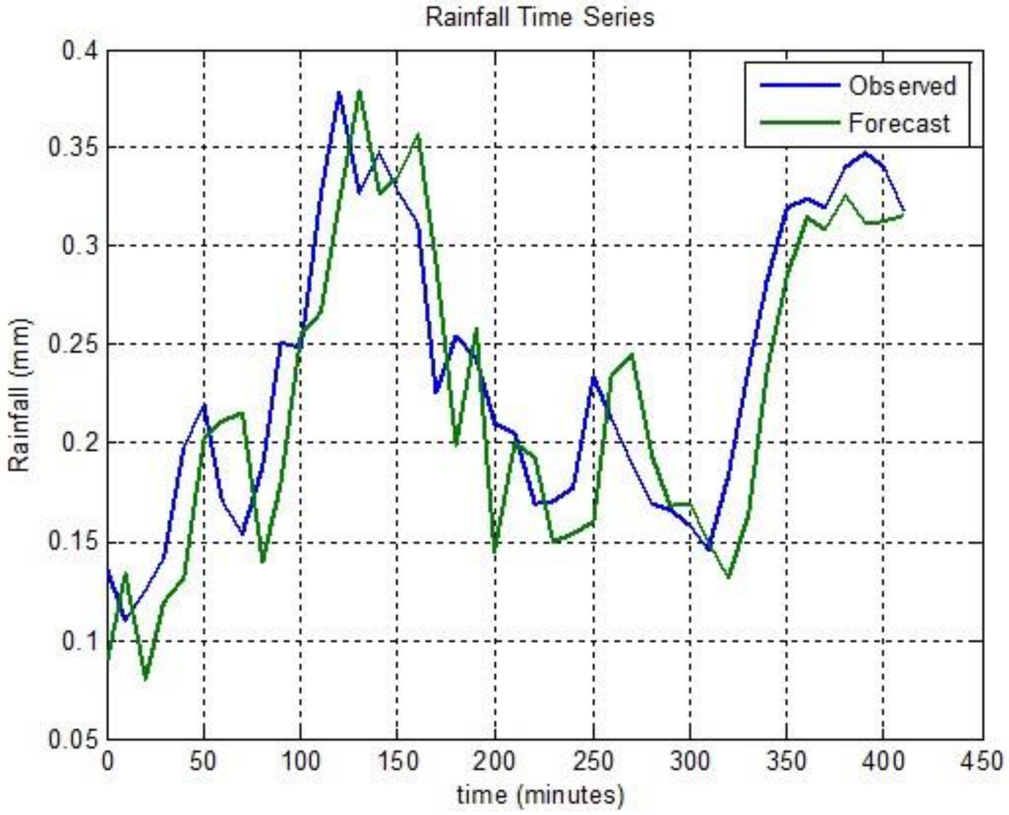
Parameter	Initial Point (Linear Regression)		Nonlinear Regression
	Estimation	T-statistics	Final Estimation
$\delta_{1,t,k}$	0.03546	0.65098	0.00507
$\delta_{2,t,k}$	0.06596	2.89453	0.47448
$\delta_{3,t,k}$	-2.47237	-1.01741	0.00012
$\phi_{t,k}$	2.18039		0.81903
$RMSE_t$	**29.51233**		**2.01960**

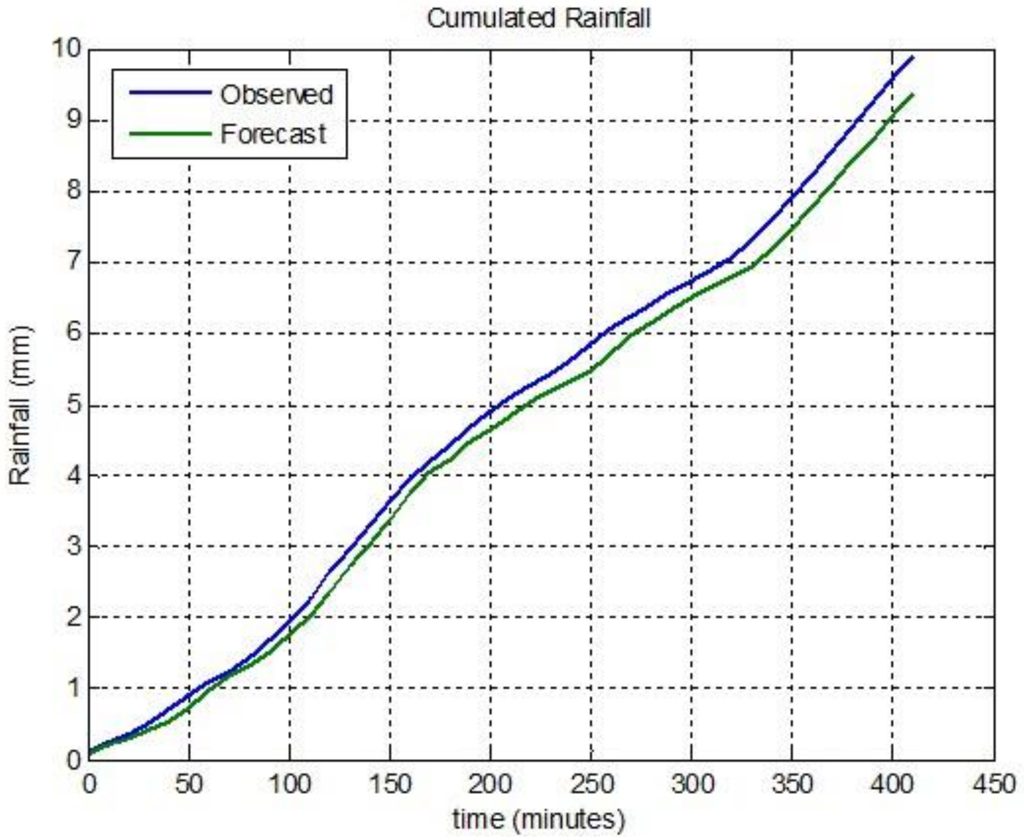

POD and FAR
0.8
0.6
0.4
0.2
0
POD
FAR
10 minutes
20 minutes
30 minutes

Prediction errors

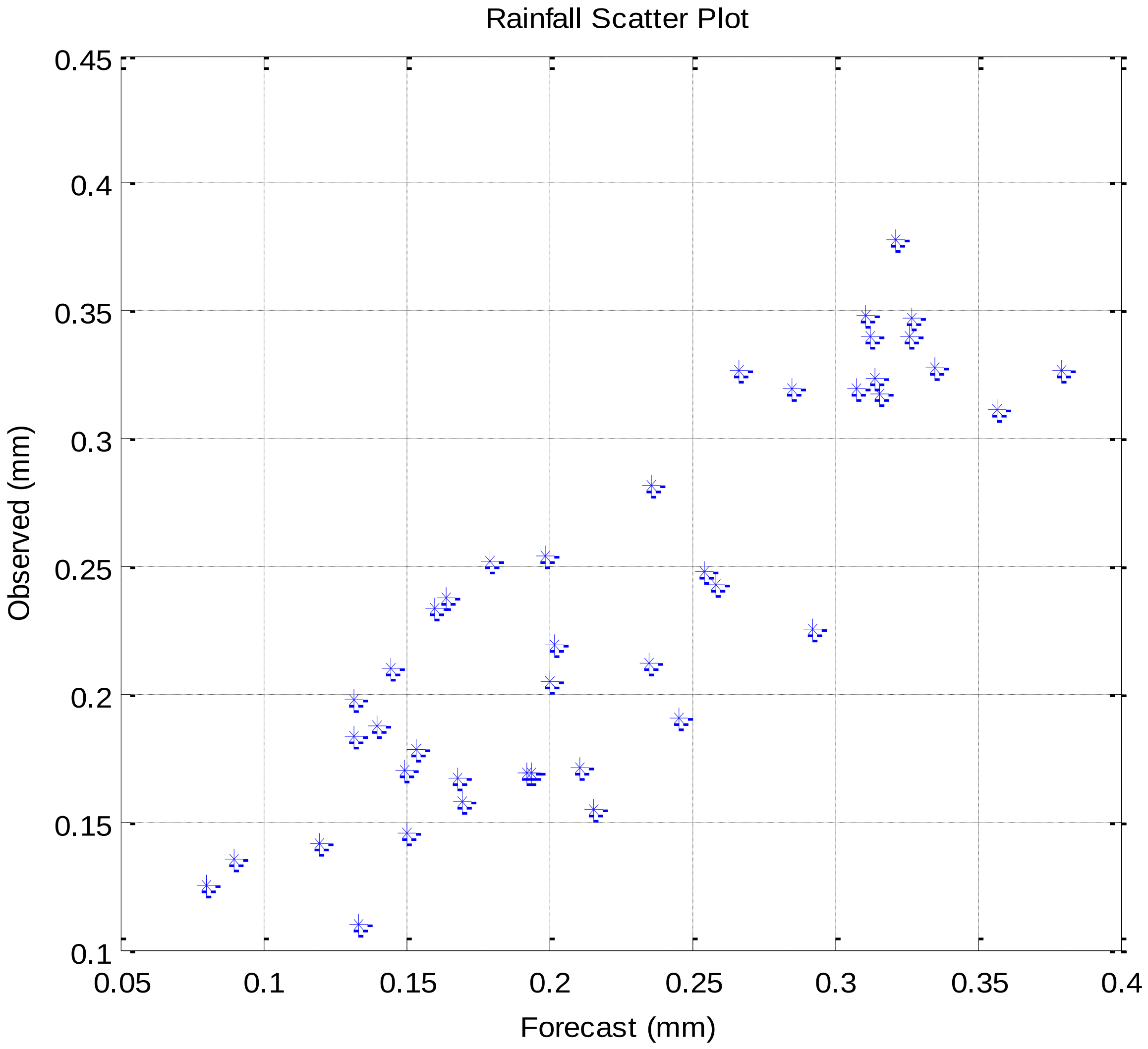
	10 minutes		20 minutes		30 minutes	
Rainfall Event	Average RMSE (mm)	Average BR	Average RMSE (mm)	Average BR	Average RMSE (mm)	Average BR
1	0.04	0.95	0.14	0.91	0.21	0.83
2	0.01	0.97	0.03	0.98	0.03	0.97
3	0.01	1.03	0.03	1.12	0.04	1.19
4	0.06	0.95	0.15	0.92	0.36	0.86
5	0.03	0.97	0.06	0.92	0.15	0.84
Average	**0.03**	**0.97**	**0.08**	**0.97**	**0.16**	**0.94**

- Left panel shows the average rainfall for all rain pixels during each time interval (10 minutes).
- The right panel shows the accumulated precipitation for all rain pixels during 7 hours of a rainfall event that occurred on March 28, 2012.
- The blue line represents the observed (TropiNet) data and the green line represents the forecasts at 10 minutes lead time.



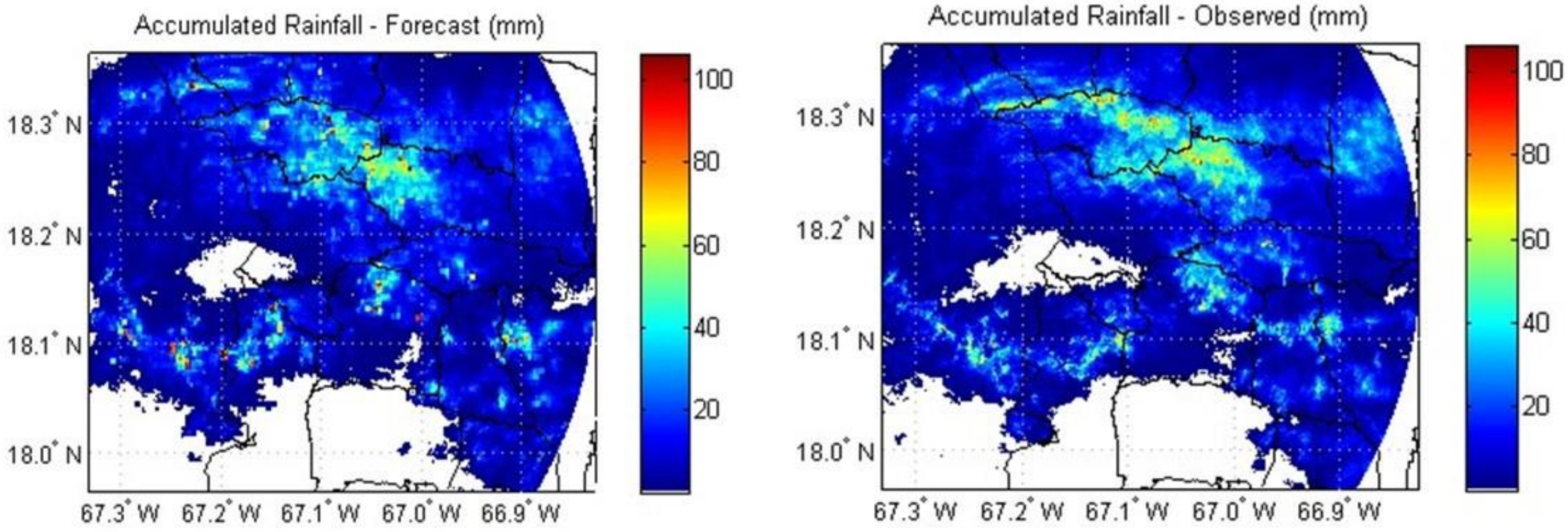


Observations vs Forecasts



Rainfall accumulated during 7 hours for the event that occurred in Puerto Rico on March 28, 2012.

Left panel show the accumulated predicted rainfall (mm) for a 10 minutes lead time and right panel show TropiNet observed accumulated rainfall (mm).



Conclusions future work

- The major contribution of this research is the postulated model that represents the spatial and temporal variation of rainfall rate.

- The proposed model will run in a server of 32 processors that were acquired by the project.

- The proposed real time algorithm will be assimilated by a hydrological model to predict flash flood.

- Develop a prototype algorithm to run in the new generation of GOES (GOES-R, 2016).
- GOES-R 16 bands, 5 min. and (500 m visible and 1000 m IR)
- Rainfall estimation for hurricanes and tropical storm.

Acknowledgements

- The National Oceanic and Atmospheric Administration: Cooperative Remote Sensing Science and Technology Center (NOAA-CREST) also supported this research under grant NA11SEC4810004.
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- NSF MRI ECCS-0821331 “Development of a Meteorological Radar Network for Puerto Rico's West Coast of PR".

Studied storms

Date	Duration (UTC)	Storm Type	Storm Impacts
March 28, 2012	7 hr. 16:27-23:58	Stationary trough	Impacts rivers, water on the road, and significant rainfall accumulation
March 29, 2012	6 hr. 00:36-06:53	Stationary trough	Impacts rivers, water on the road, significant rainfall accumulation
April 30, 2012	5 hr. 17:55-22:21	Convective storm	Numerous showers over western Puerto Rico at the afternoon
October 10, 2012	5 hr. 16:10-21:43	Convective storm	Some urban flooding
February 12, 2014	7 hr. 16:00-23:29	Heavy convective storm	Reduced visibilities and ponding of water on roadways and low lying areas