Advancing QuikSCAT Wind and Rain Retrieval

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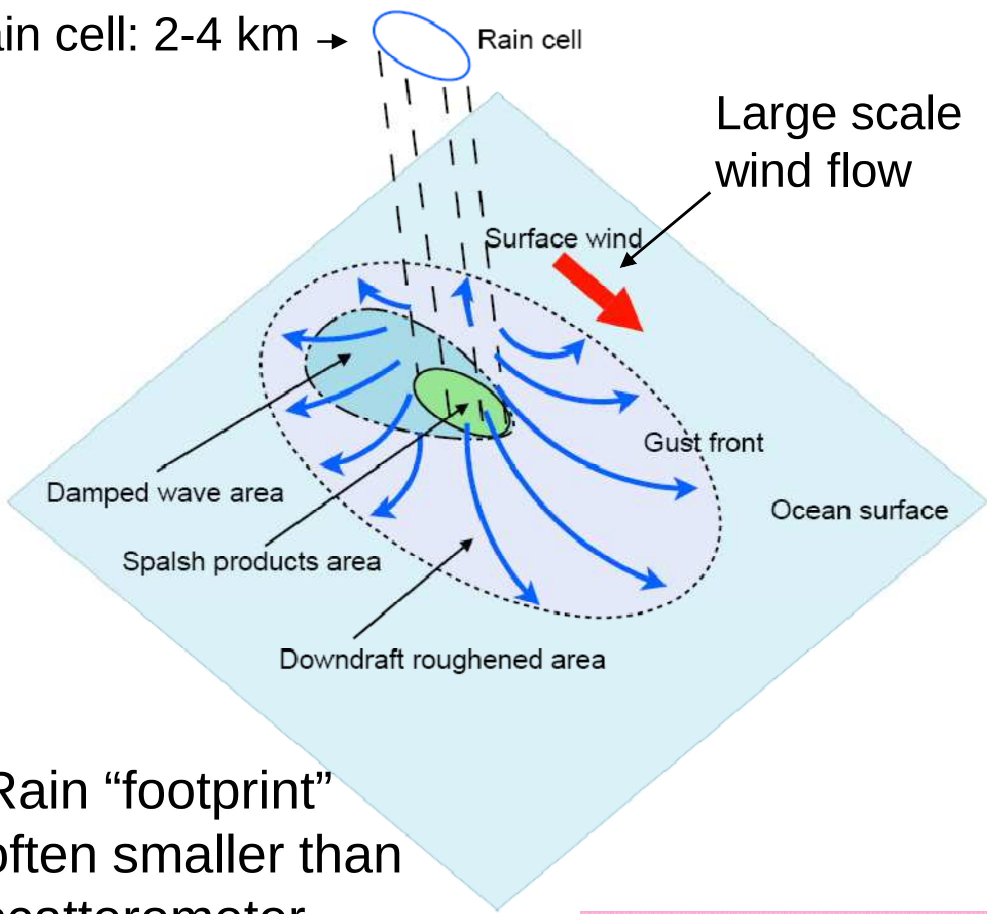
Outline

- QuikSCAT Land/Ice Climate Record (*Poster*)
  - 10 years of Earth observations

- Rain effects on scatterometer measurements
- Retrieval methods: Simultaneous Wind/Rain (SWR), Rain-only (RO), Wind-only (WO)
  - Emphasis on scatterometer-only methods (for application with QuikSCAT)
- Bayes estimator selection & prior distributions
- Results

Surface Effects of Rain on Radar Measurements

Rain cell: 2-4 km →



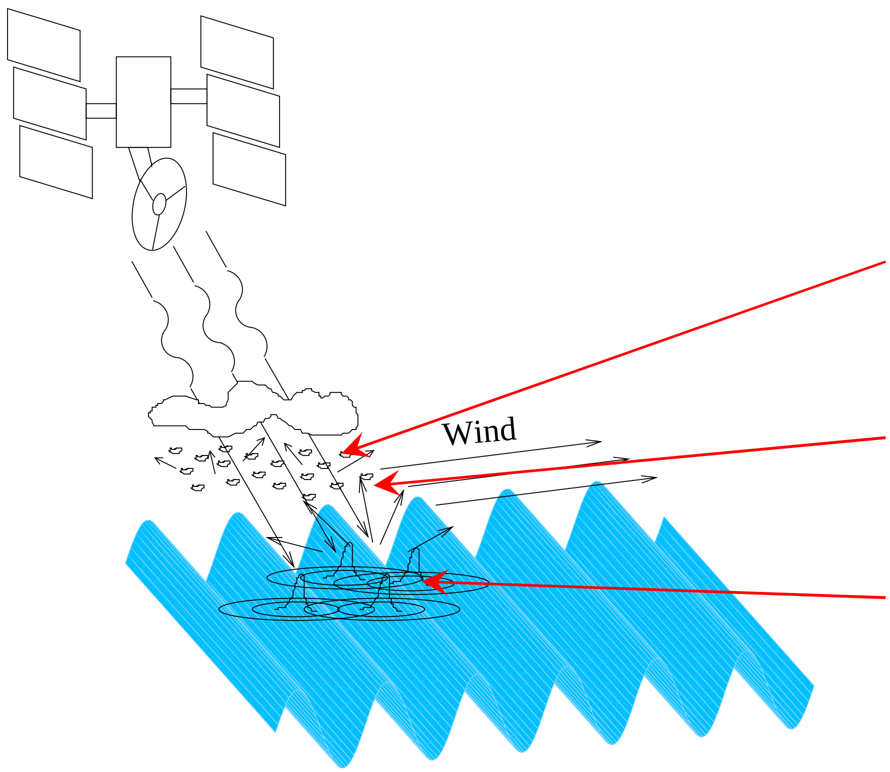
Large scale wind flow

Rain "footprint" often smaller than scatterometer footprint

- Splash products scatter the scatterometer signal (surface scattering from rain splash)
- Turbulence under the water attenuates the Bragg wave spectrum (Bragg scattering)
- Sea surface roughness also affected by the airflow associated with rain cell
- Atmospheric backscattering and attenuation (volume scattering from rain)

What is the "wind" do we want to measure?

Rain/Wind Backscatter Model



- Model for measured backscatter σ_M^o

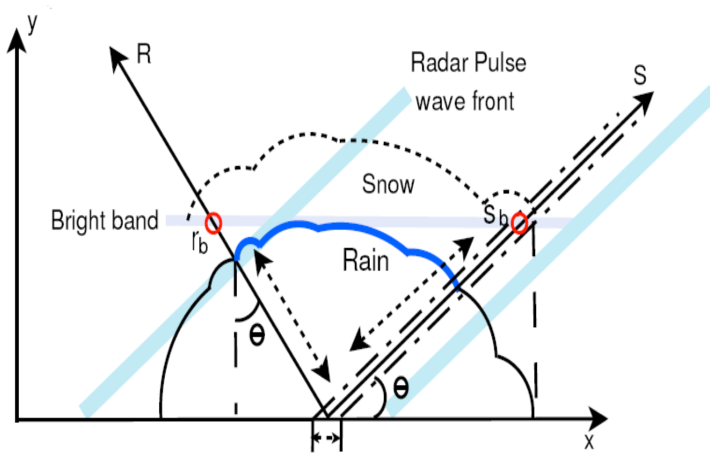
$$\sigma_M^o = \left(\sigma_W^o + \sigma_{sr}^o\right)\alpha_R + \sigma_R^o$$

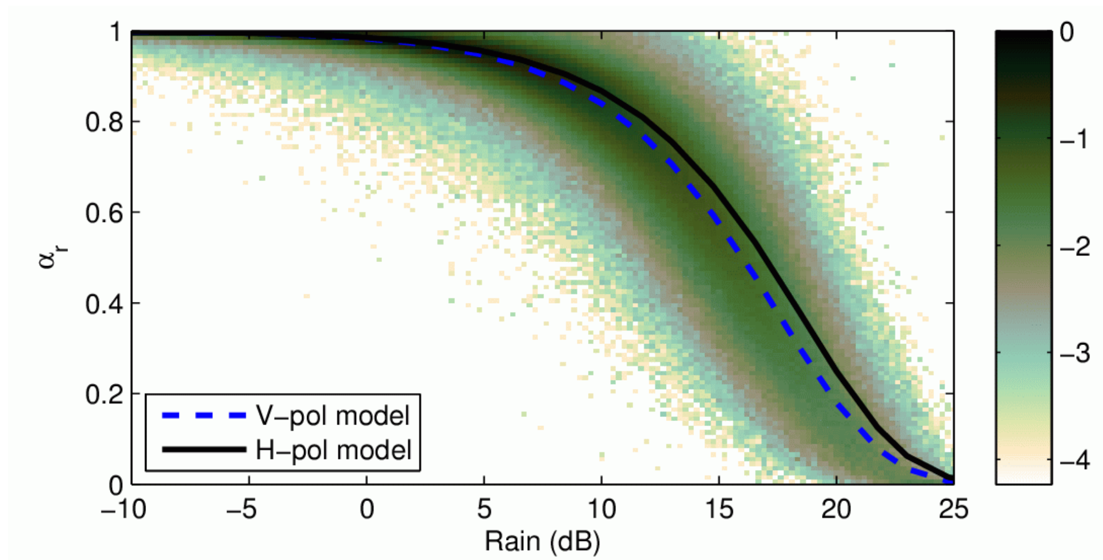
- Radar signal scattered by falling droplets σ_R^o
- Surface signal attenuated by atmospheric rain α_R
- Surface wind-induced σ_W^o backscatter perturbed by rain striking the water σ_{sr}^o

Simplified equivalent model: $\sigma_M^o = \sigma_W^o \alpha_R + \sigma_S^o$

Attenuation Model

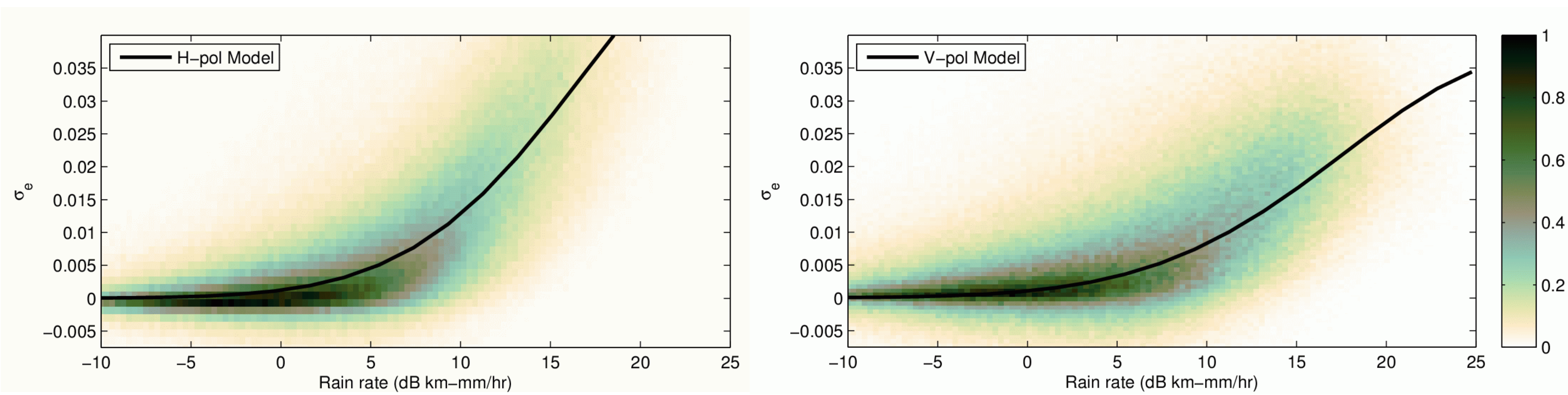
- Derived from collocated TRMM-PR or AMSR and QuikSCAT measurements
- Model as quadratic function of rain rate in dB
- Beam filling & 3-D effects





Effective Surface Scattering Model

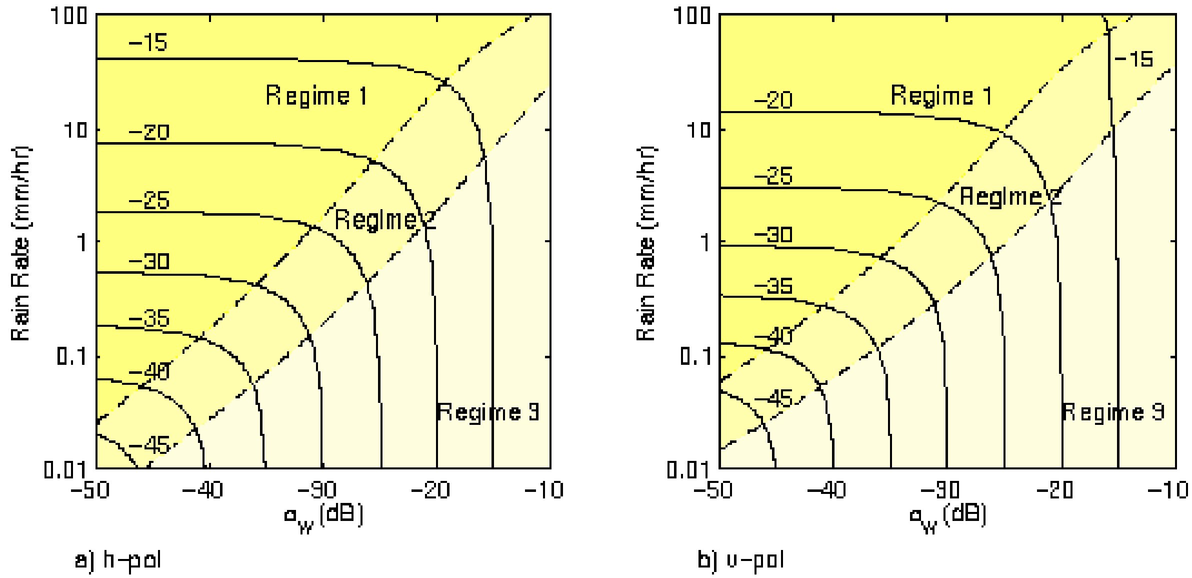
- Derived from collocated TRMM-PR or AMSR and QuikSCAT measurements
- Model as quadratic function of rain rate in dB



- *Assume conventional wind GMF*

Wind Rain Backscatter Regimes

$$\sigma_M^o(s,\chi,R,\ldots) = M(s,\chi,\ldots)\,\alpha_R(R) + \sigma_{eff}(R)$$



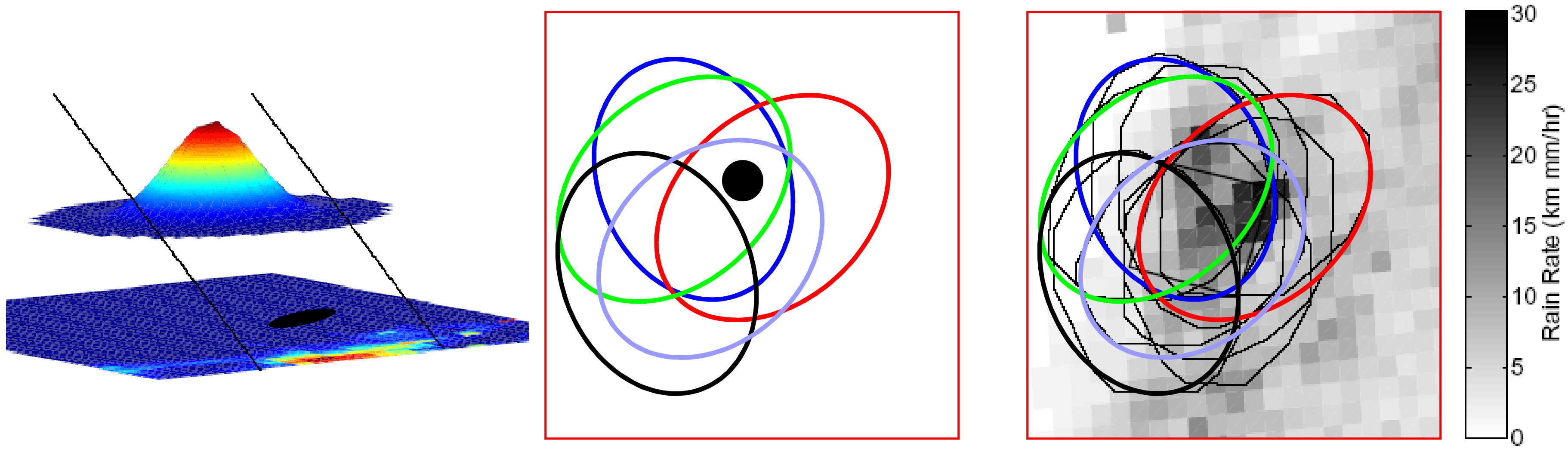
- Regime 1: rain dominates wind backscatter – poor quality wind estimates (10% of rain cases*)
- Regime 2: both wind and rain important – can retrieve wind and rain rate (34% of rain cases*)
- Regime 3: rain effects insignificant – wind estimates unaffected by rain (56% of rain cases*)

- Note: globally, about 4% of all QuikSCAT data effected by rain

* From collocated TRMM PR and QuikSCAT data in tropics

Simultaneous Wind/Rain Retrieval

- Scatterometer-only rain estimation is possible for QuikSCAT inner swath
  - Rain direction estimates have greater variability than wind-only retrieval (noisier wind when estimating rain)
  - SWR is an effective rain flag
- Beam-filling effects and mis-collocation of sigma-0 measurements increases variability



Ku-band: D.W. Draper and D.G. Long, Simultaneous Wind and Rain Retrieval Using SeaWinds Data, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 42, No. 7, pp. 1411-1423, 2004.

C-band: C. Nie and D.G. Long, A C-Band Scatterometer Simultaneous Wind/Rain Retrieval Method, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 46, No. 11, pp. 3618-3632, 2008.

Wind and Rain Retrieval

Wind/rain model: $\sigma_M^o = \sigma_W^o \alpha_R + \sigma_S^o$

- Noise model

$$p(\sigma_M^o \mid s, d, r) = \prod_k \frac{1}{\sqrt{2\pi\varsigma^2}} \exp\left\{-\frac{1}{2}\frac{(\sigma_M^o - \sigma_P^o)^2}{\varsigma^2}\right\}$$

$$\varsigma^2 = (1 + K_{pc}^2)(\alpha_R^2 \sigma_W^2 (1 + (1 - 2\alpha_R + \alpha_R^2)K_{pa}^2)(1 + K_{pm}^2) + \sigma_E^2 (1 + K_{pe}^2)) - \sigma_P^{o2}$$

$$K_{pc}^2 = \sqrt{\alpha + \frac{\beta}{\sigma_P^o} + \frac{\gamma}{\sigma_P^{o2}}}$$

- SWR Maximum Likelihood Estimation

$$(\hat{S}, \hat{D}, \hat{R})_{MLE} = \arg\max(s, d, r \mid \sigma_M^o)\left\{-\frac{k}{2}\log(2\pi\varsigma^2) - \frac{1}{2}\sum_k \frac{(\sigma_M^o - \sigma_P^o)^2}{\varsigma^2}\right\}$$

Estimator Limitations

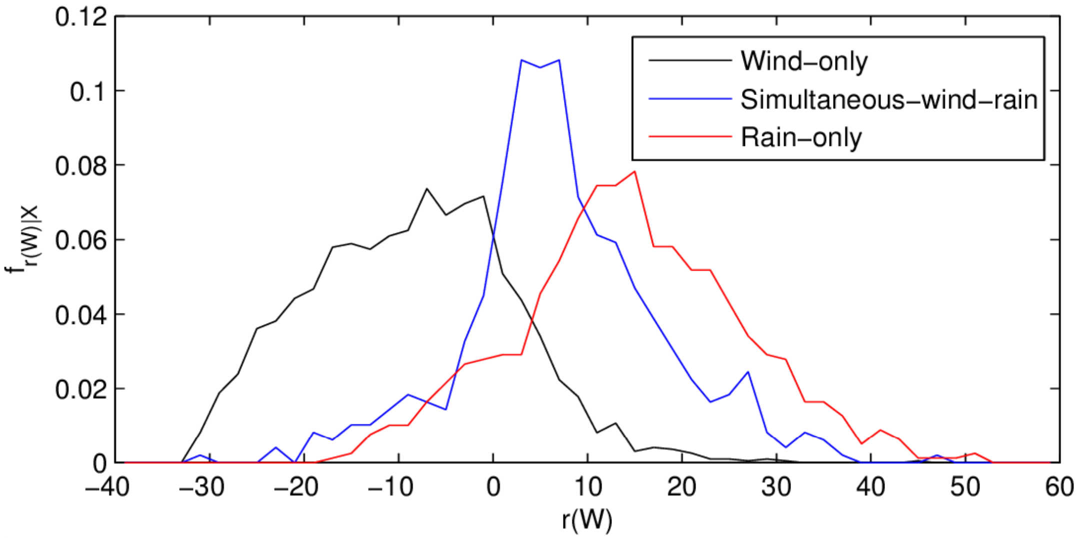
- *Simultaneous wind/rain (SWR)* retrieval performance can be poor under unintended conditions, i.e. w/o both rain and wind
  - *Wind-only (WO)* retrieval better when no rain
  - *Rain-only (RO)* retrieval better when rain dominates backscatter
- Each estimator is best in a certain regime
  - How to decide which regime to use?

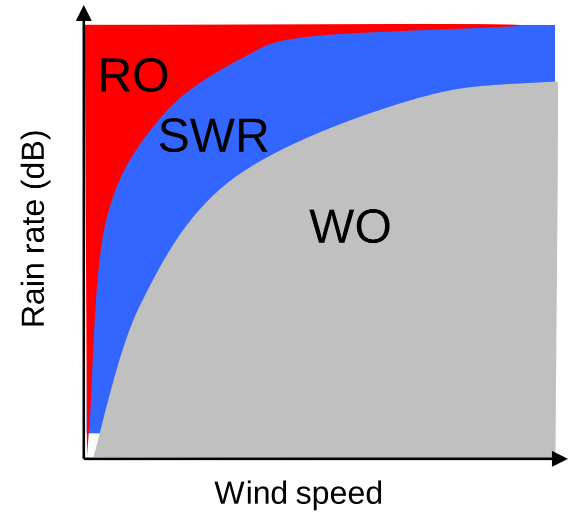
Problem

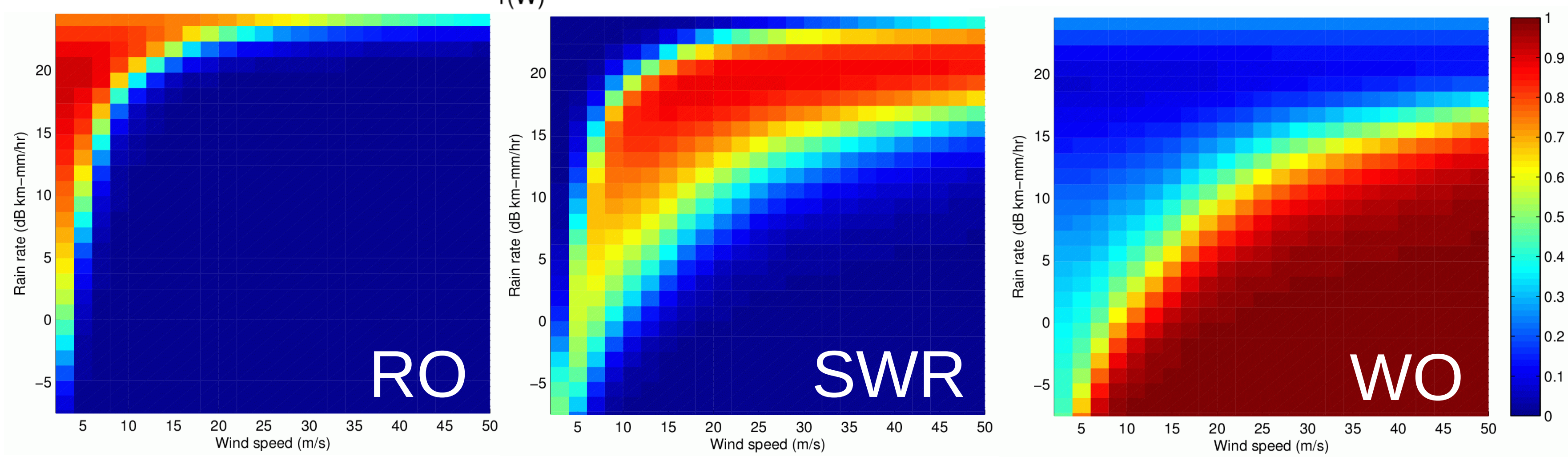
- Selecting best estimator to use

- Possible mechanisms:
  - Compare to true wind/rain
  - Use scattering regime calculated by SWR
  - Likelihood Ratio test
  - *M-ary Bayes decisions*

Estimator Regimes







Bayes Decision Overview

- Risk function

$$R(\vartheta, \phi(x)) = \sum_X L[\vartheta, \phi(x)]\, f_{X|\theta}(x \mid \vartheta)$$

- Bayes risk function

$$r(F_\theta, \phi) = \int_\theta R(\vartheta, \phi(x))\, f_\theta(\vartheta)\, d\vartheta$$

$$r(F_\theta, \phi) = \int_\theta \sum_X L[\vartheta, \phi(x)]\, f_{X|\theta}(x \mid \vartheta)\, f_\theta(\vartheta)\, d\vartheta$$

- Variable Descriptions
  - Parameter: ϑ
  - Observations: x
  - Decision rule: $\phi(x)$
  - Loss function: $L[\vartheta, \phi(x)]$
  - Priors: $f_\theta(\vartheta)$, $f_{X|\theta}(x \mid \vartheta)$

- Bayes Decision $\phi_B = \arg\min_\phi r(F_\phi, \phi)$

Loss Function

- Definition

$$L[\vartheta,\phi_i(x_j)] = C(\vartheta,x_j)(\eta\delta_{ij} + \mu(1-\delta_{ij}))$$

$\delta_{ij} = 1$ when $i = j$

$$C(\vartheta,x_j) = (\vartheta - x_j)^2$$

- Weight Error according to decision

$$(\eta\delta_{ij} + \mu(1-\delta_{ij}))$$

- Normalization matrix N

$$(\vartheta - x_j)^2 = (\vartheta - x_j)^T N(\vartheta - x_j)$$

Bayes Estimator Selection

$$r(F_\theta,\phi_i)=\int_\theta \sum_{j=1,3} L[\vartheta,\phi_i(x_j)]\, f_{X|\theta}(x_j\,|\,\vartheta)\, f_\theta(\vartheta)\, d\vartheta$$

$$r(F_\theta,\phi_i)=\int_\theta \sum_{j=1,3} C(\vartheta,x_j)[\eta\delta_{ij}+\mu(1-\delta_{ij})]\, f_{X|\theta}(x_j\,|\,\vartheta)\, f_\theta(\vartheta)\, d\vartheta$$

$$r(F_\theta,\phi_i)=\int_\theta C(\vartheta,x_i)[\mu+(\eta-\mu)\, f_{X|\theta}(x_i\,|\,\vartheta)]\, f_\theta(\vartheta)\, d\vartheta$$

$$r(F_\theta,\phi_i)=\int_\theta (\vartheta-x_i)^2[\mu+(\eta-\mu)\, f_{X|\theta}(x_i\,|\,\vartheta)]\, f_\theta(\vartheta)\, d\vartheta$$

$$\phi=\arg\min_i r(F_\theta,\phi_i)$$

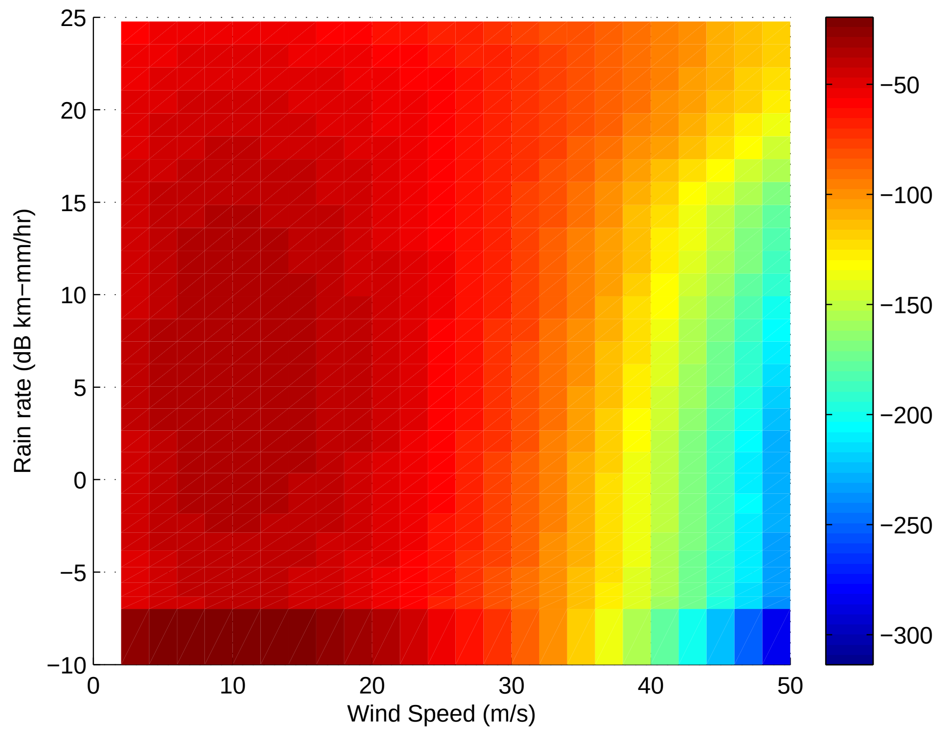
Application to Wind and Rain Estimation

- Choose normalization N
- Calculate wind-rain prior $f_\theta(\vartheta)$
- Estimate conditional prior $f_{X|\theta}(x_i \mid \vartheta)$
- Choose weights to meet performance criteria

Wind-Rain Prior Estimate Method

- NCEP winds
  - Numerically predicted
  - Low resolution, temporally and spatially
  - Known biases
    - Underestimate high wind speed compared to QuikSCAT
- TRMM PR rain rates
  - Measured rain
- Assume:
  - Uniform distributed wind direction
  - Weibull distributed wind speed

$$10\log_{10}(f_\theta(\vartheta))$$



Conditional Prior $f_{X|\theta}(x_i \mid \vartheta)$

- Probability of an estimator having minimum squared error given the wind conditions
  - Possible priors
    - Tabulate estimator performance
    - Use noise model to determine probability of a regime for each wind condition
- Noise model
  - Signal to interference ratio (SIR) of wind and rain

Conditional Prior

- Rain Fraction

$$r(S,\chi,R) = \frac{M_{RO}(R)}{M_{WO}(S,\chi)\alpha(R)}$$

- A threshold on rain fraction determines estimator boundaries

$$X = \begin{cases} 0: & r(S,\chi,R) < A \\ 1: & A < r(S,\chi,R) < B \\ 2: & r(S,\chi,R) > B \end{cases}$$

- Noise model gives conditional prior

$$f_{x|\theta}(x_0 \mid \vartheta) = P(r(S,\chi,R) < A)$$
$$f_{x|\theta}(x_1 \mid \vartheta) = P(A < r(S,\chi,R) < B)$$
$$f_{x|\theta}(x_2 \mid \vartheta) = P(r(S,\chi,R) > B)$$

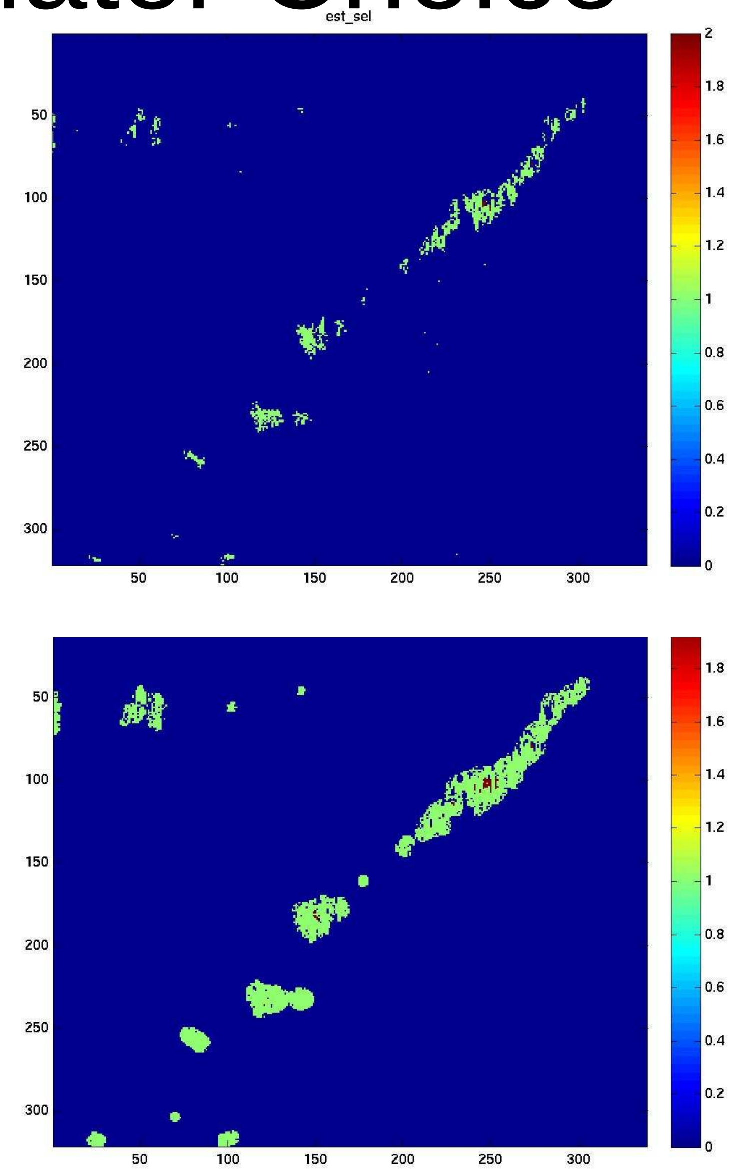
Choose Weights

- Performance criteria can include
  - Rain false alarm rate or probability of detection (SWR only used when rain rate is above a threshold)
  - Speed accuracy in raining/non-raining conditions

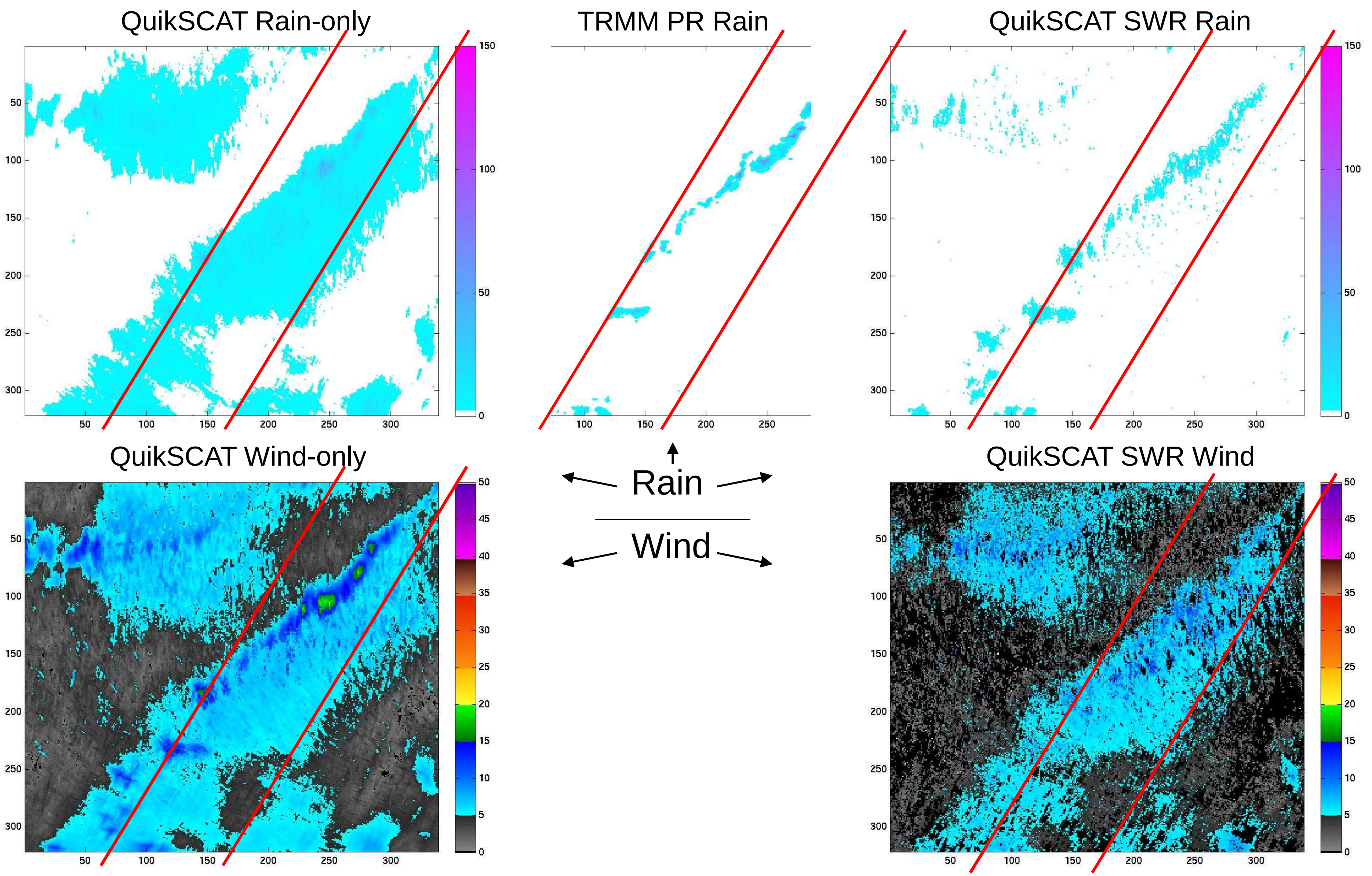
$$(\eta\delta_{ij} + \mu(1-\delta_{ij}))$$

Smoothing of Estimator Choice

- Estimator selection sensitive to noise
  - Slight noise changes result in selected estimator changes
- Spatial filtering with threshold
  - Correct for differences in the number of ambiguities

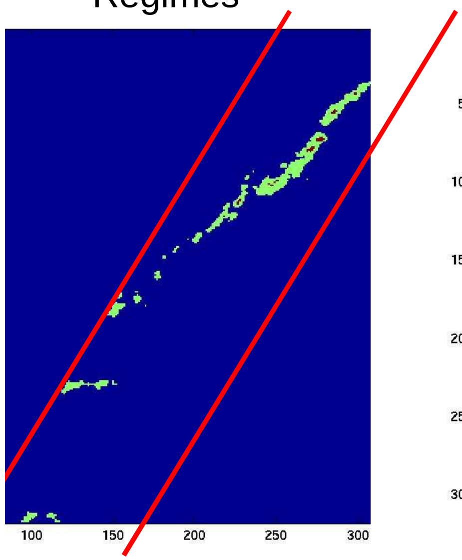


UHR Case Study

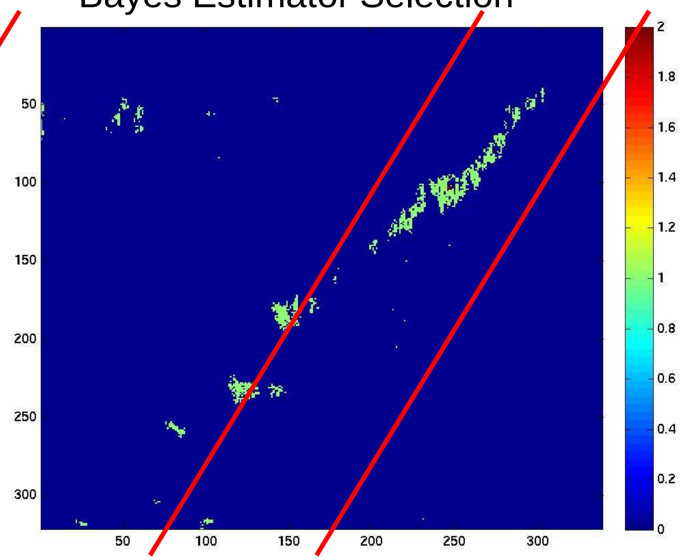


Bayes Estimator Results

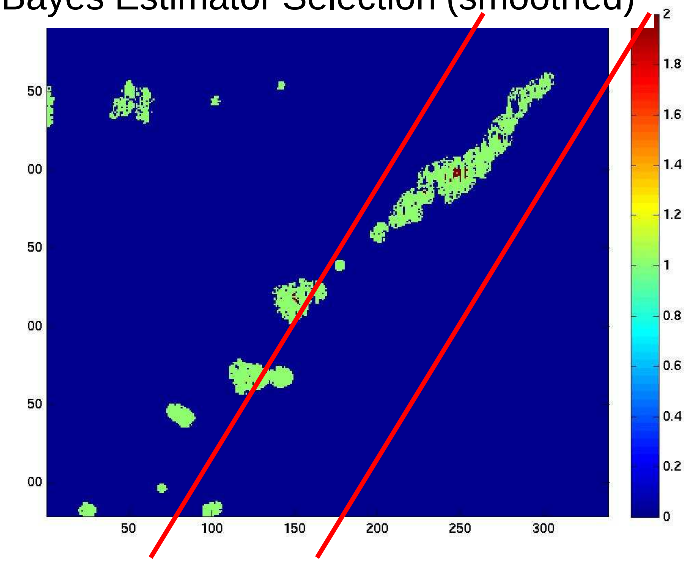
Regimes



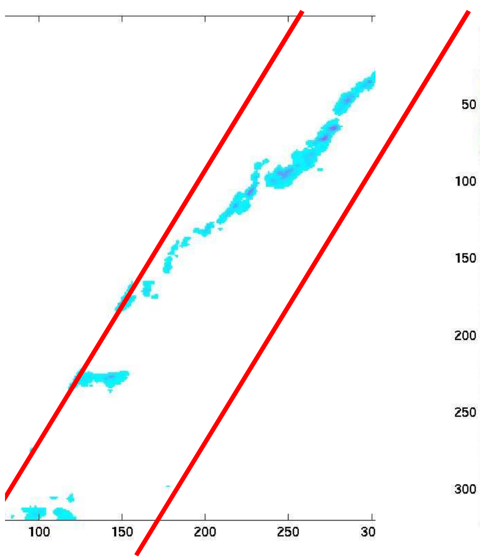
Bayes Estimator Selection



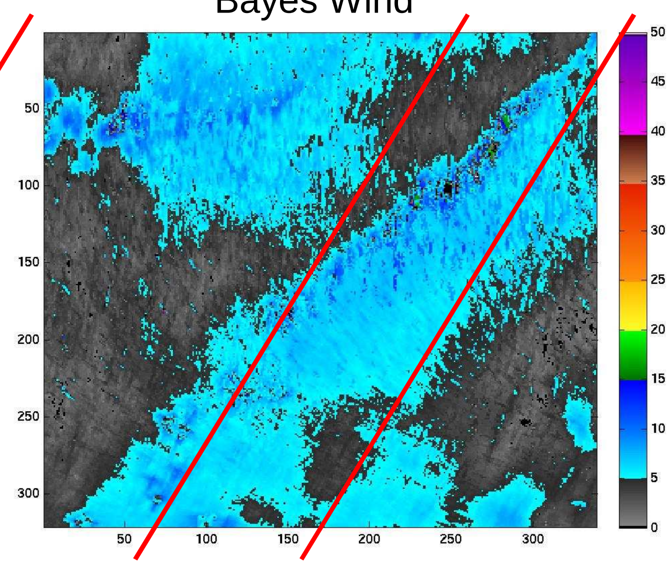
Bayes Estimator Selection (smoothed)



TRMM PR Rain



Bayes Wind



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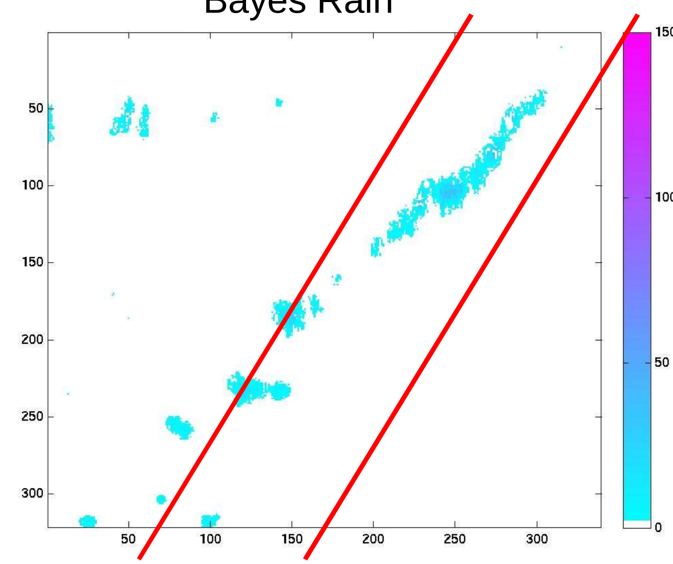

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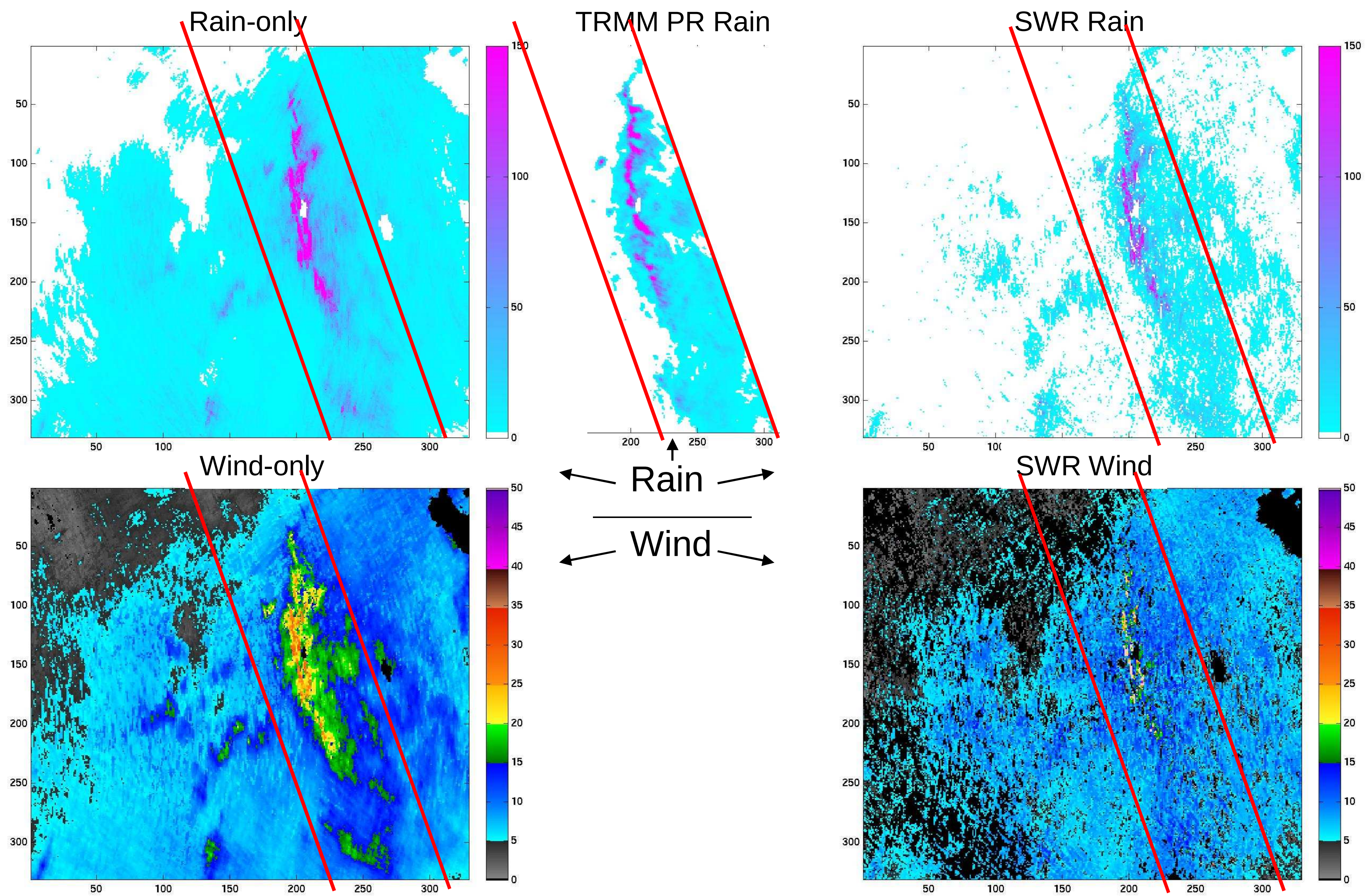
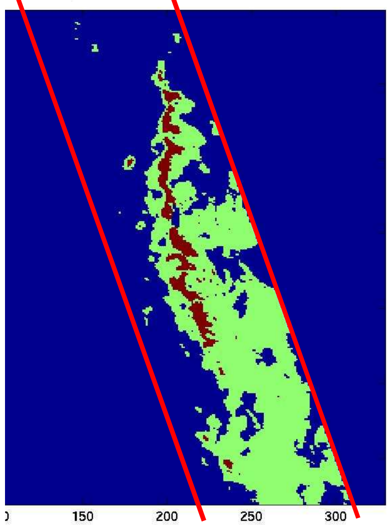


Bayes Estimator Results

Regimes



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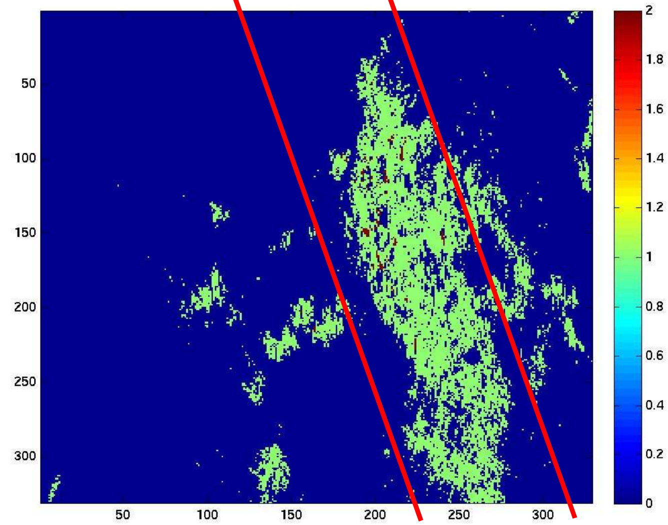

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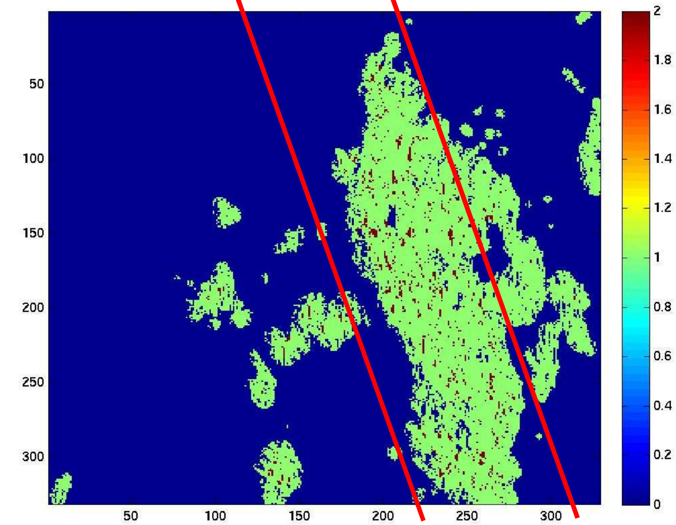

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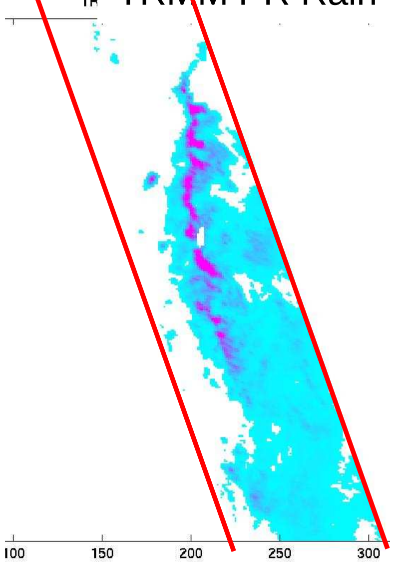
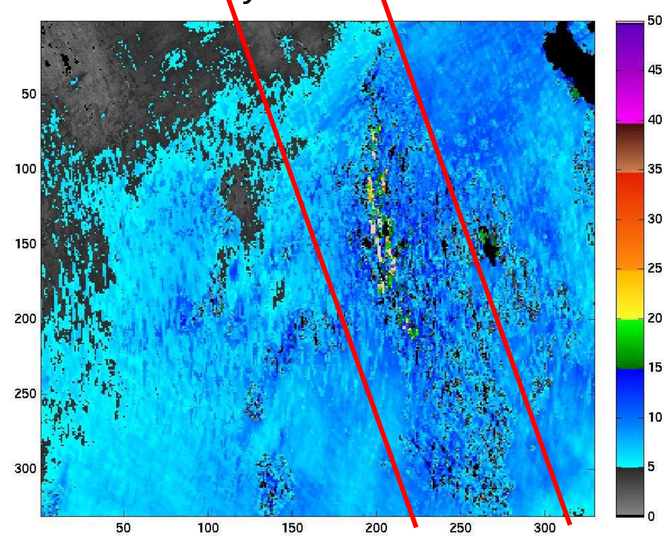


Bayes Wind



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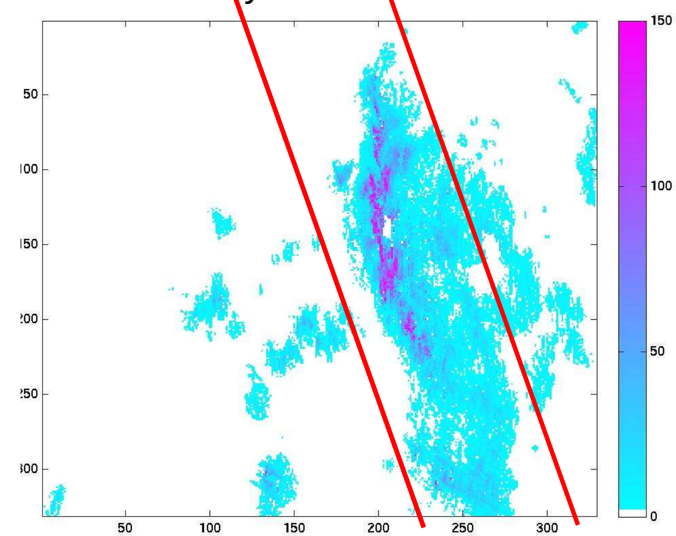

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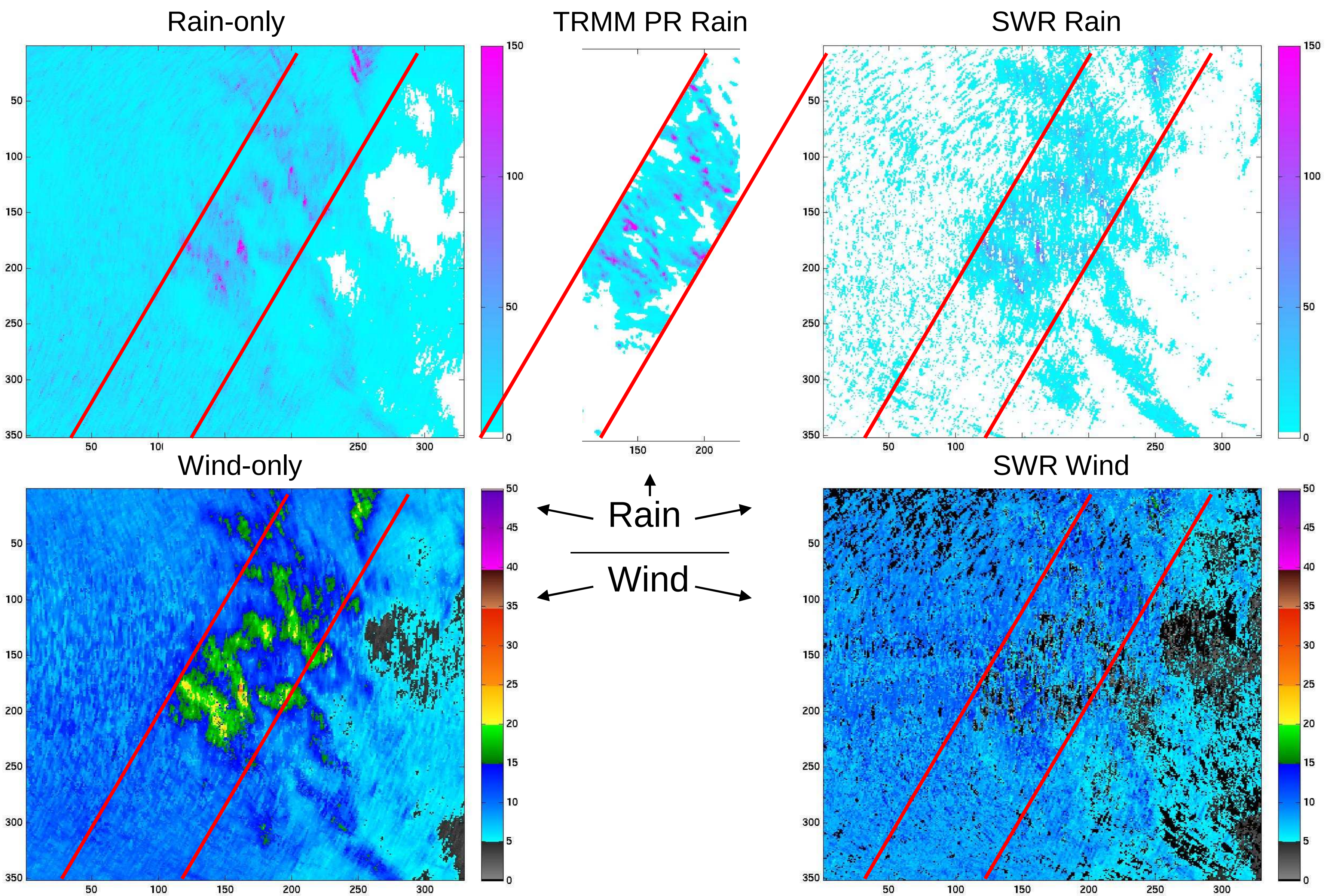
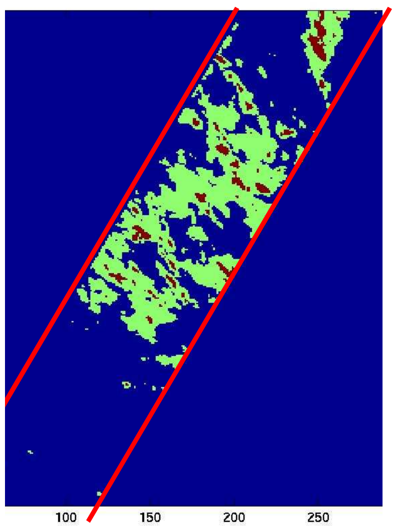


Bayes Estimator Results

Regimes



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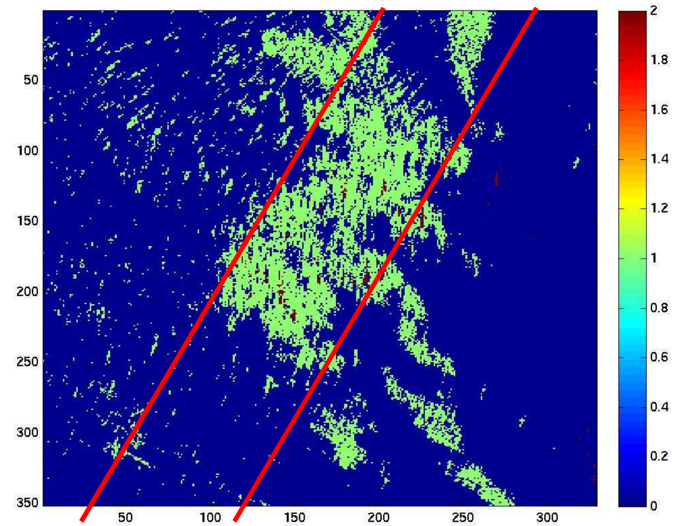

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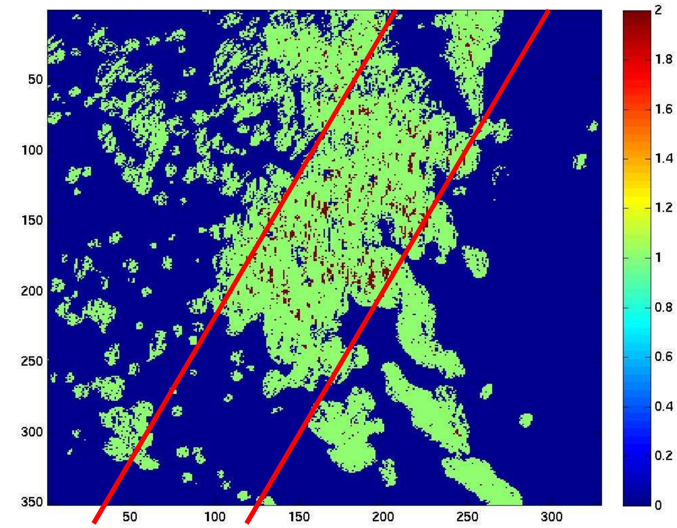

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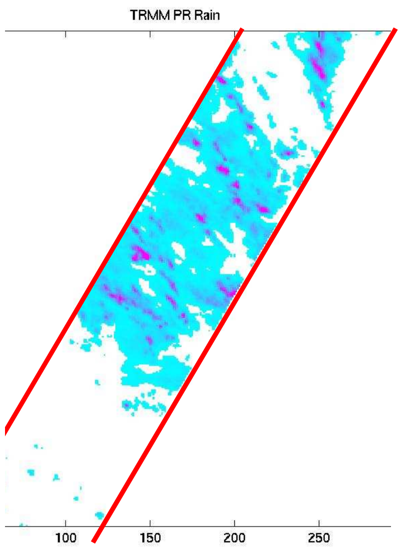

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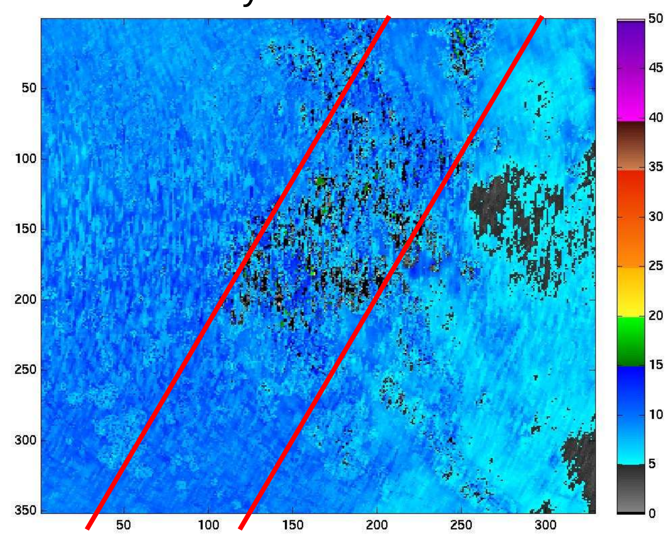

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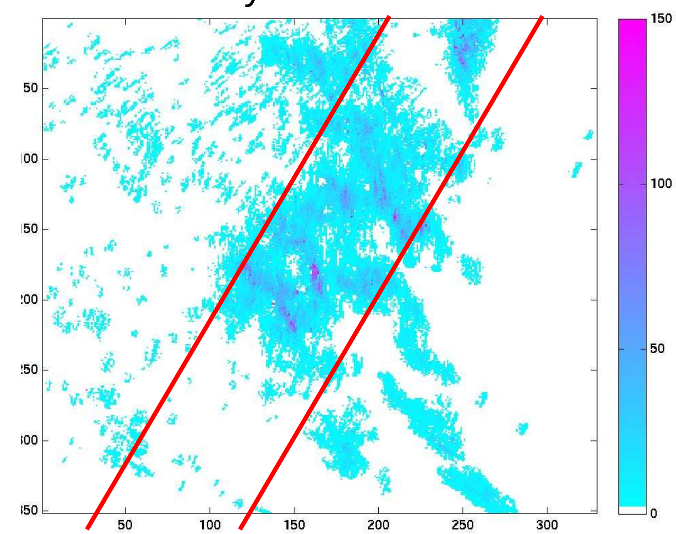

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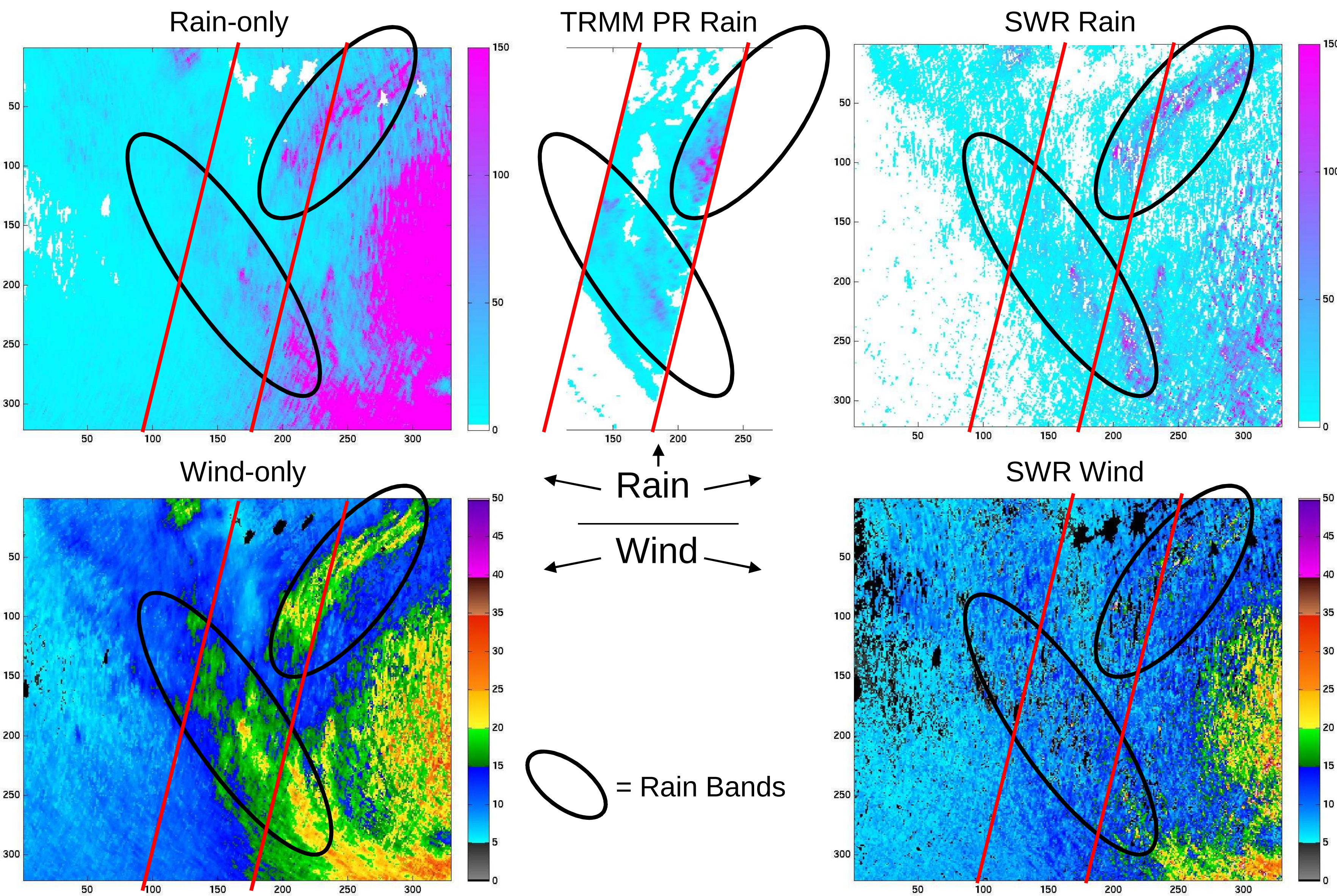

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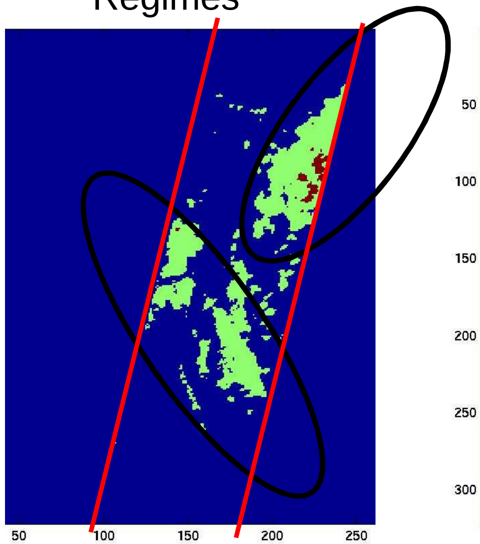

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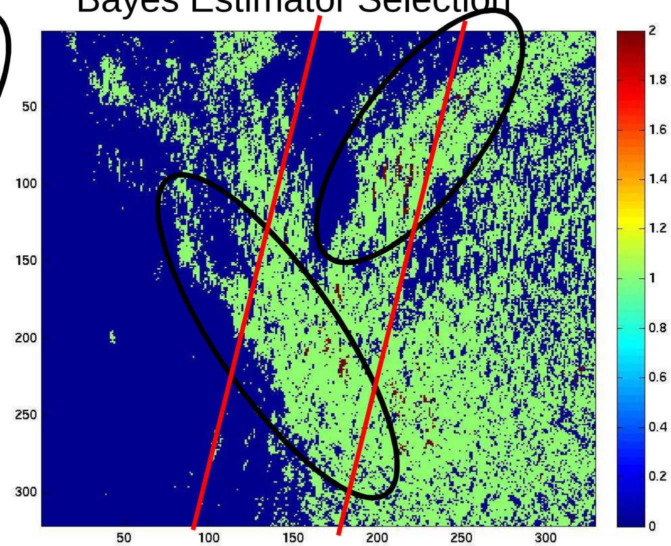

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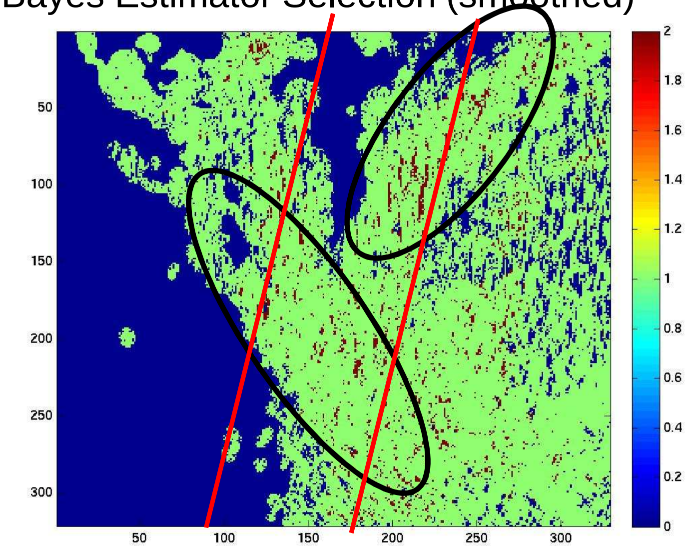

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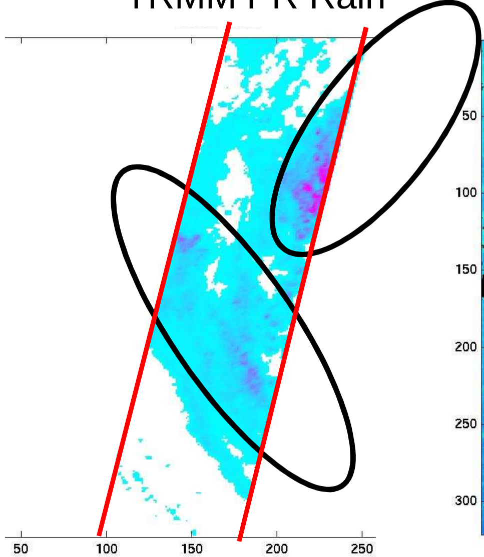
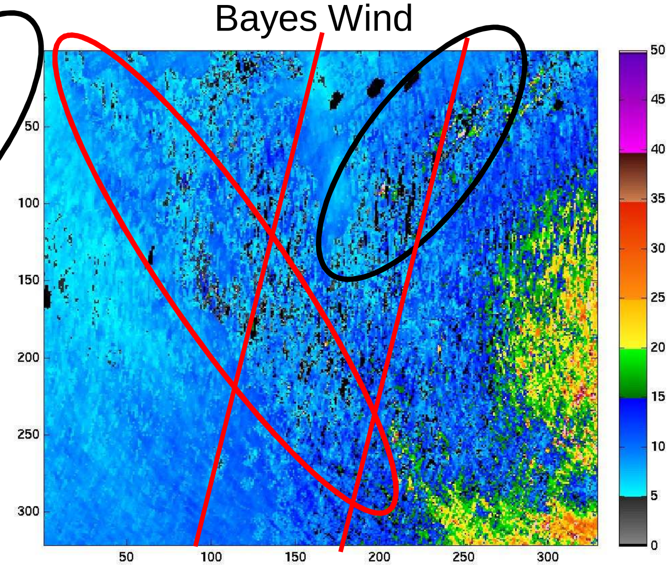


Bayes Wind



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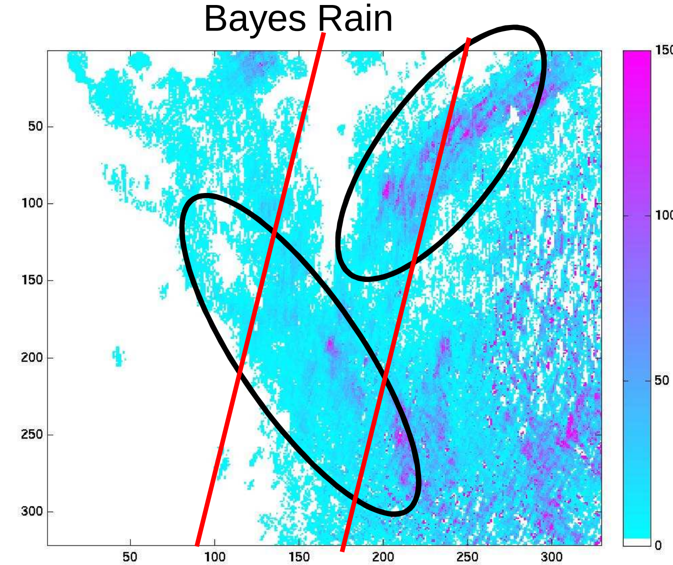


UHR

Summary Wind Speed Statistics

Sample set

	Bias mean(NCEP - X)	RMSE $(\text{mean}((\text{NCEP} - X)^2))^{1/2}$
WO wind Rain > 0	1.89	5.22
Bayes wind Rain > 0	-0.096	4.98
SWR wind Rain = 0	-2.35	5.73
Bayes wind Rain = 0	-1.52	2.75

Summary

Benefits

- Computationally simple
  - Expected error can be pre-computed for all wind-rain vectors
- Estimates selected in correct operating regimes

Limitations

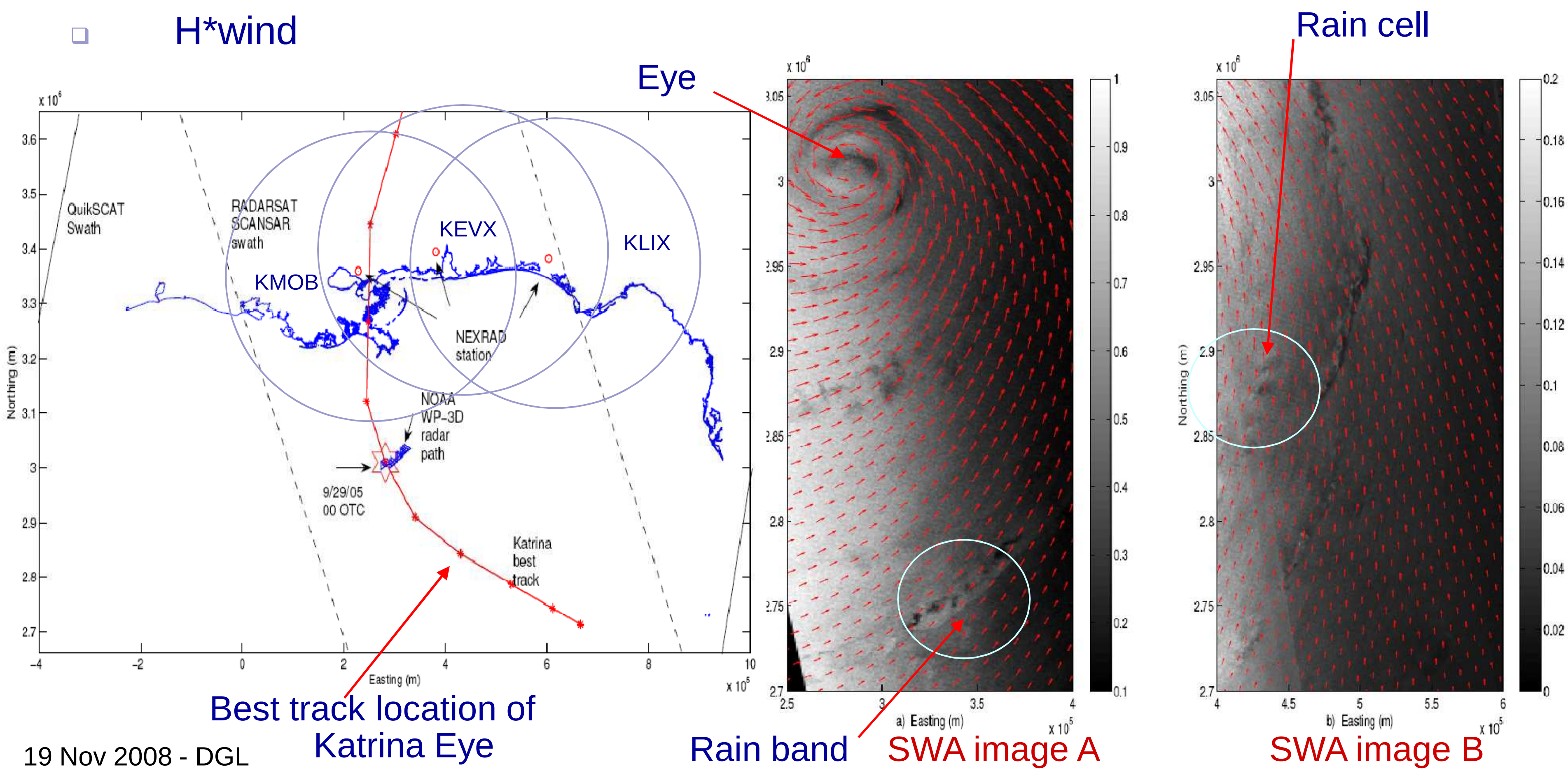
- Determining priors
  - Model for wind-rain distribution
  - Model for regime given wind-rain vector
  - True wind data non-existent
- Wind-Rain error-scaling
  - Physical wind-rain relationship difficult to quantify
- Estimator computation
  - All estimators always fully computed

Conclusions

- Preliminary results promising
  - Reduced bias and MSE
  - Visually good rain estimates, improved wind estimates
  - Effective as a rain flag
- Prone to noise
  - Mitigated with spatial filtering
- Ongoing accuracy and refinement studies

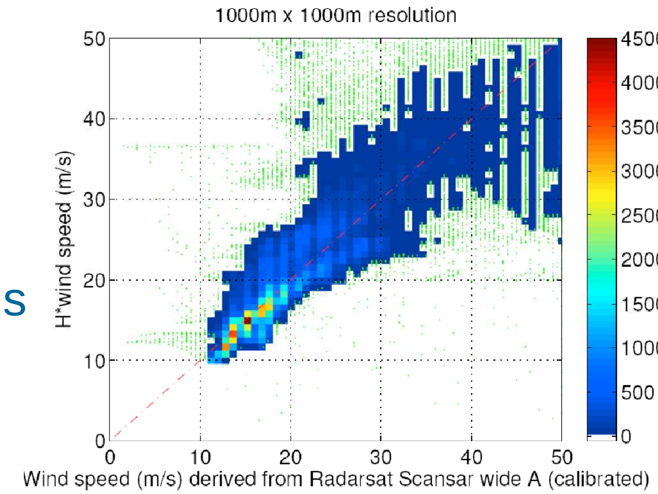
Coincident SAR/Scatterometer Set

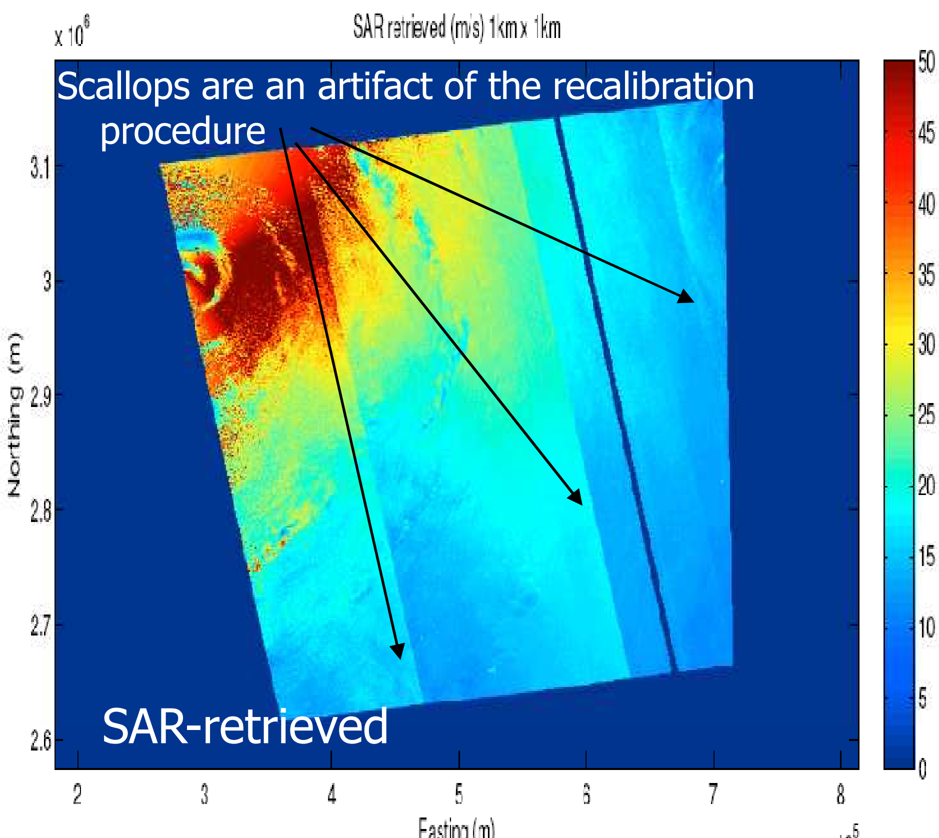
- C-band RADARSAT ScanSAR images 9/29/05 ~00 OTC
- NEXRAD
- QuikSCAT (within few mins)
- H*wind

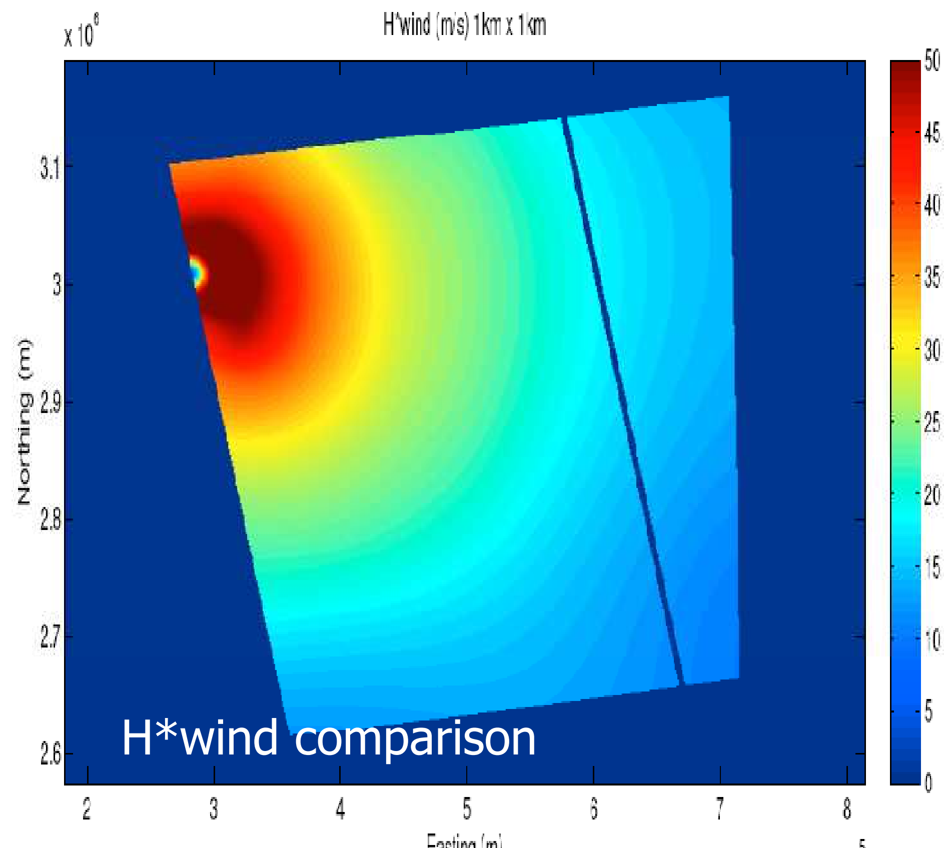


Retrieved SAR Winds

- “Recalibrate” sigma to CMOD5 GMF using H*Winds
- Uncertainty/error in H*wind field direction
- Limitation of GMF at high winds, Rain effects







C. Nie and D.G. Long, "RADARSAT ScanSAR Wind Retrieval under Hurricane Conditions," in J. Butler and J. Ziong, eds. "Earth Observations Systems VII", *Proceedings of SPIE*, Vol. 6677, doi:10.1117/12.732600, 10 pp., 26-28 Aug 2007.

Rain Atmospheric Attenuation and Backscatter on SAR Measurements

- Atmospheric attenuation factor
- Path integrated attenuation (PIA) in dB
- Atmospheric attenuation
- Volume backscattering coefficient
- Observed volume backscattering cross-section
- Atmospheric backscatter

Simultaneous Wind-Rain Retrieval

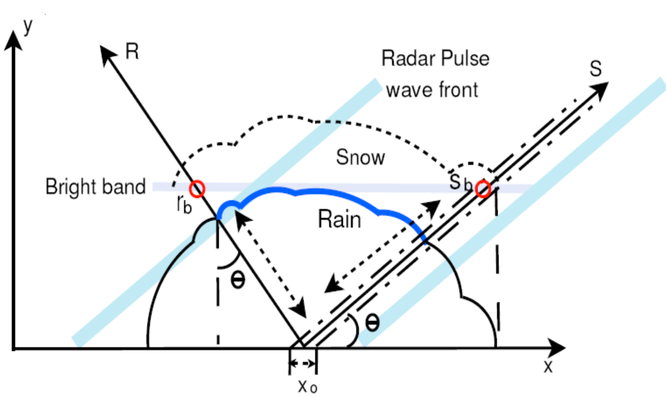
- Measurement model $\sigma^o = M_R(S,\chi,P,\omega,I,R) + noise$

$$p(\sigma^o \mid S,\chi,R) = \prod_k \frac{1}{\sqrt{2\pi\varsigma^2}} \exp\left\{-\frac{1}{2}\frac{(\sigma^o - M_R(S,\chi,P,\omega,I,R))^2}{\varsigma^2}\right\}$$

- MLE – log-likelihood function

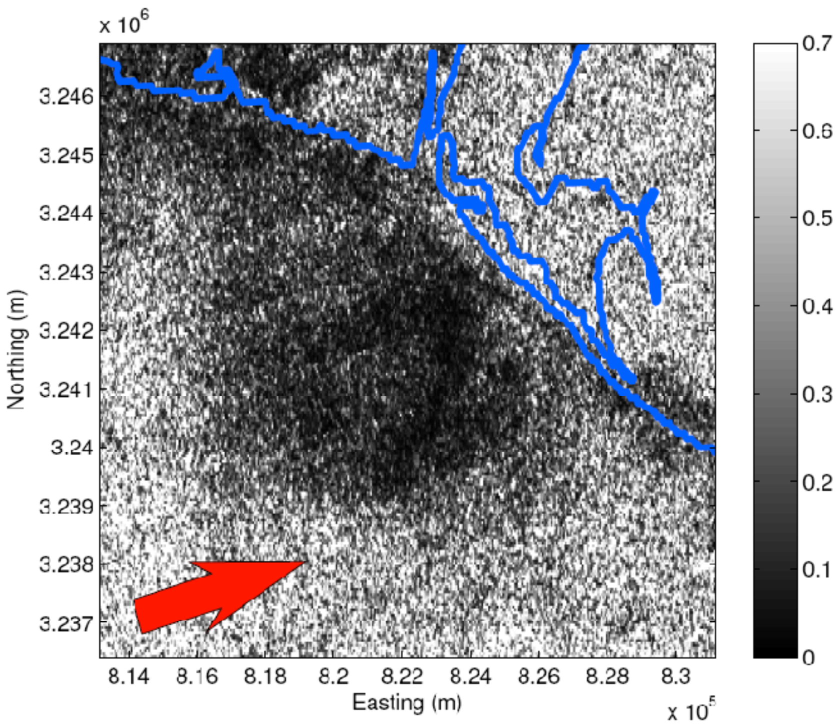
$$(\hat{S},\hat{\chi},\hat{R})_{MLE} = \arg\max(S,\chi,R \mid \sigma^o)\left\{-\frac{k}{2}\log(2\pi\varsigma^2) - \frac{1}{2}\sum_k \frac{(\sigma^o - M_R(S,\chi,P,\omega,I,R))^2}{\varsigma^2}\right\}$$

- UHR implementation



Rain cell at incidence angles between 22 and 23.6 degrees

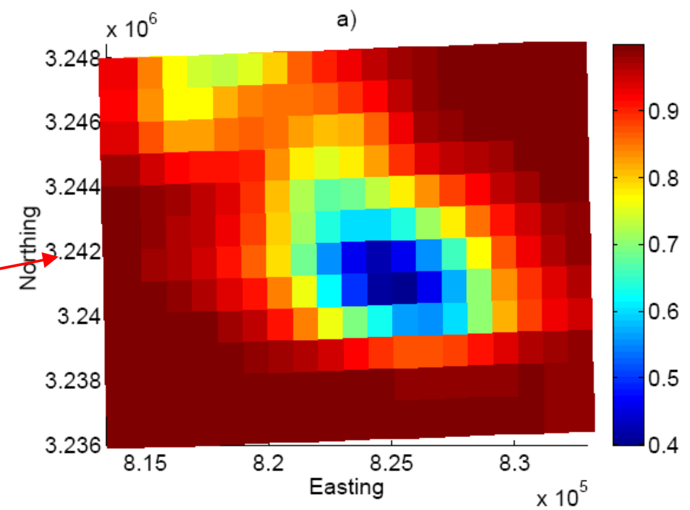
(C-band)



SAR signature of rain cell

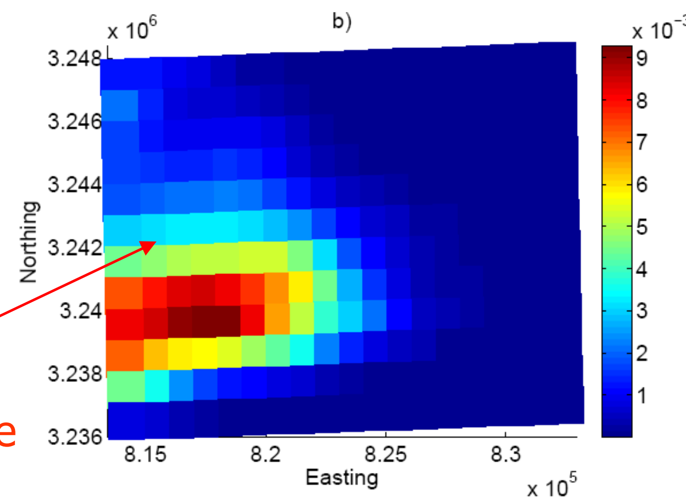
Attenuation

Significant at heavy rain



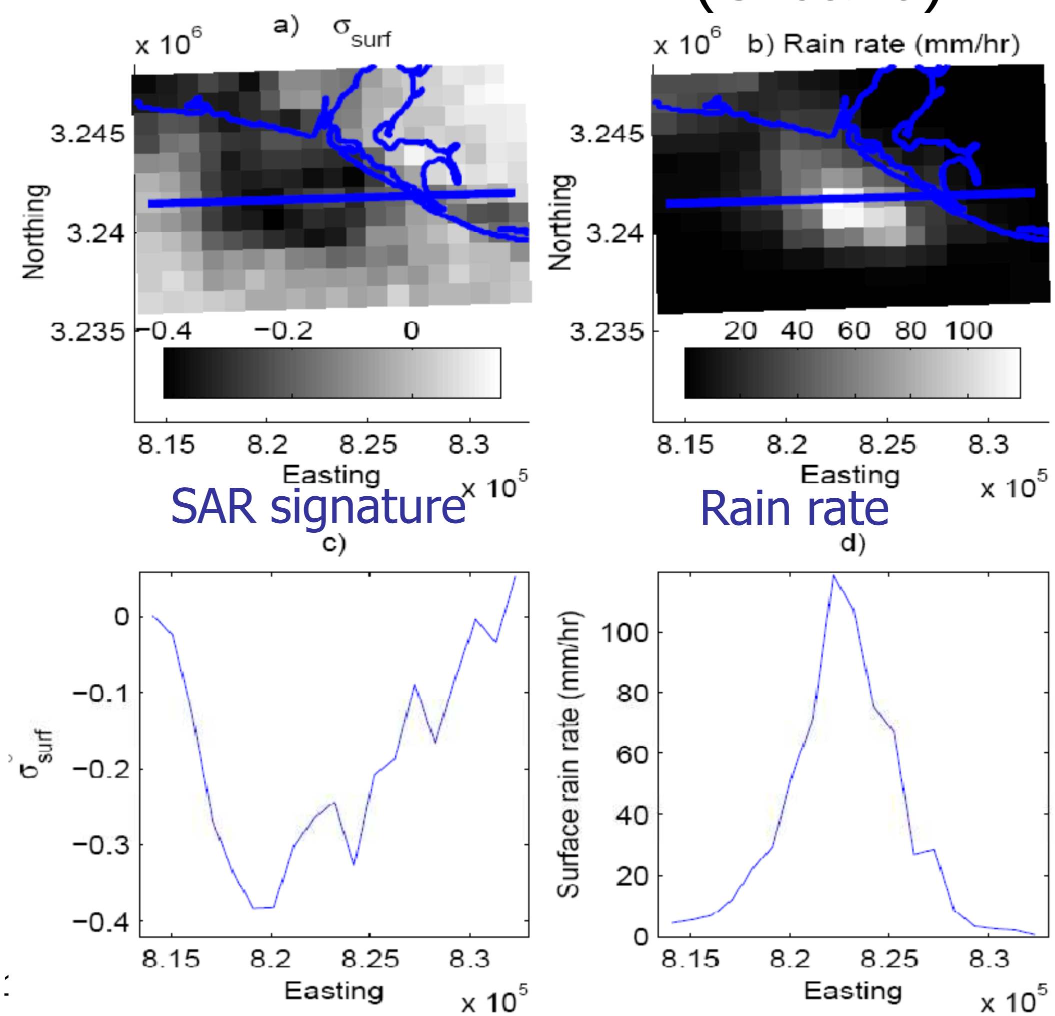
Atmospheric backscatter

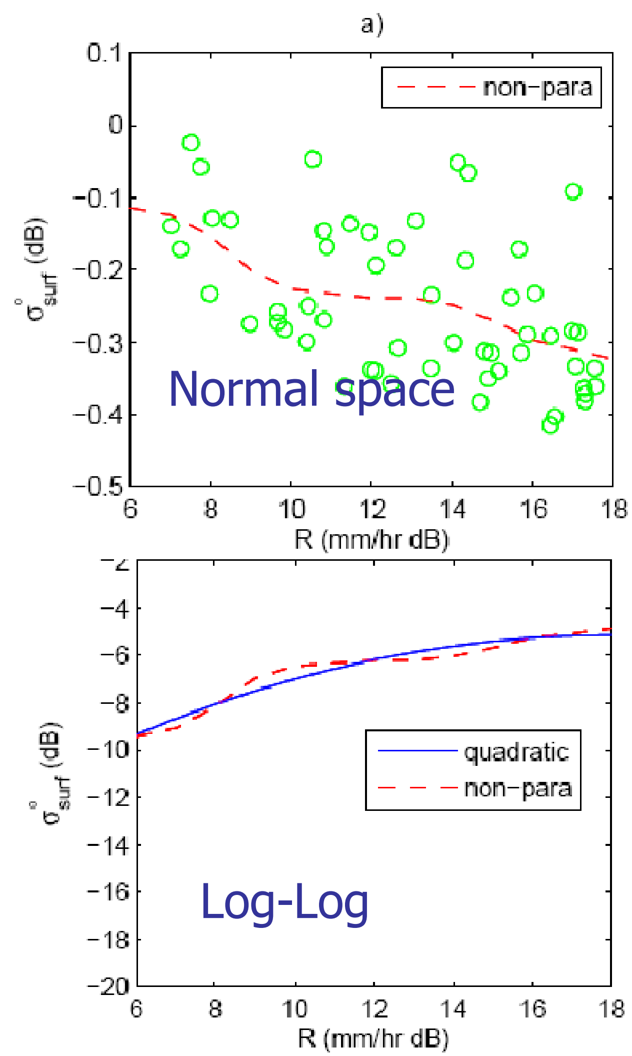
Insignificant at low incidence angle



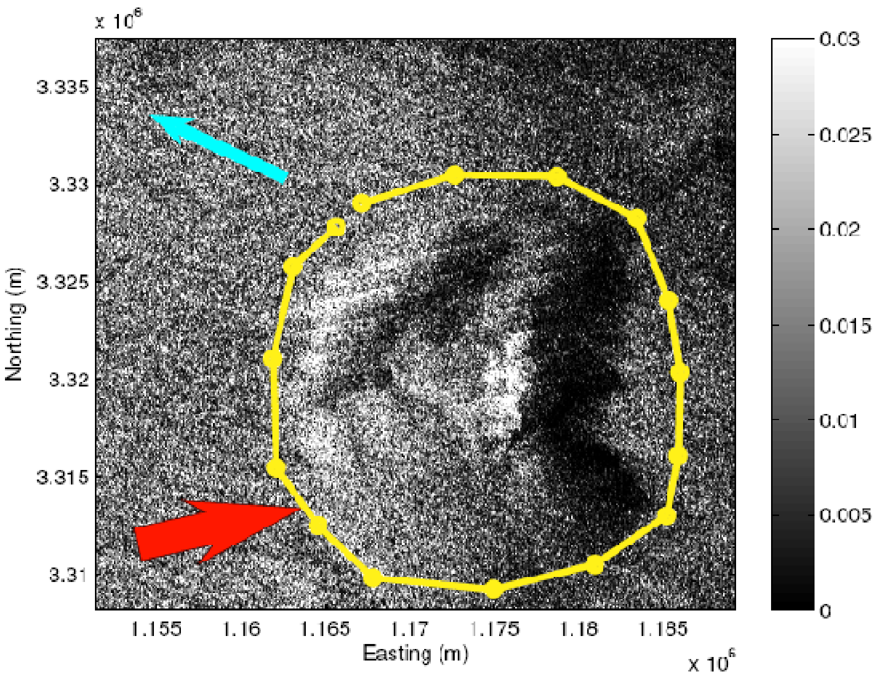
Rain cell at incidence angles between 28 and 31.7 degrees

(C-band)



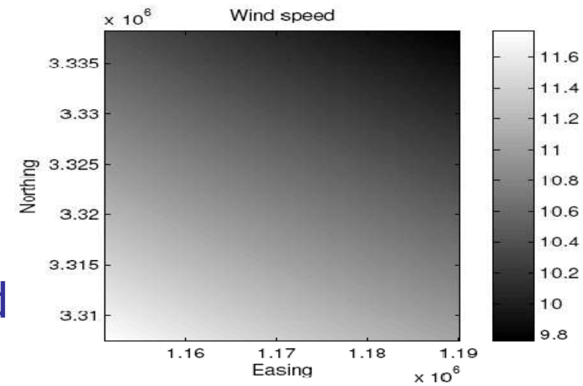


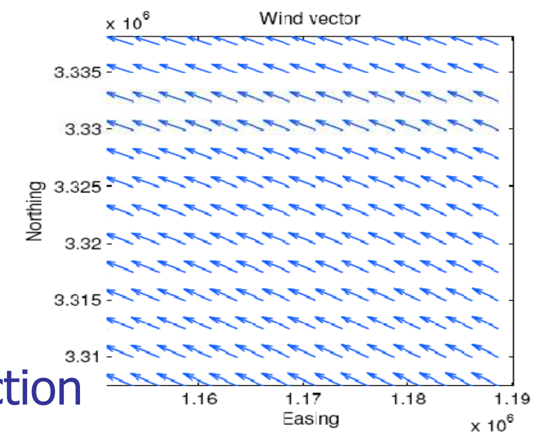
Rain cell at incidence angles between 44 and 45.7 degrees
(C-band)



SAR signature of rain cell

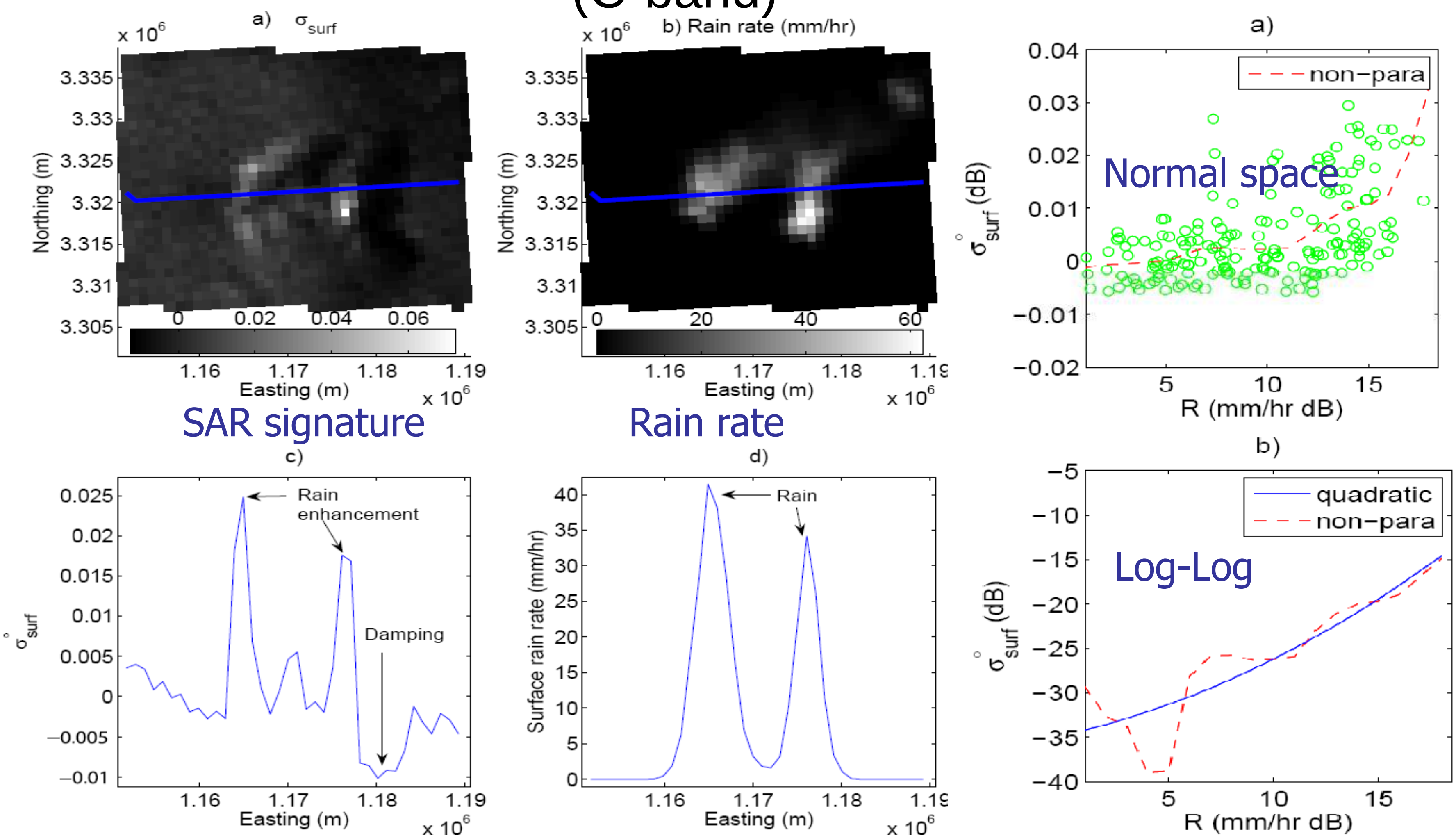
Wind speed





Wind direction

Rain cell at incidence angles between 44 and 45.7 degrees (C-band)



Problem Setup

- Variable Descriptions
  - Parameter: ϑ
  - Observations: x
  - Decision rule: $\phi(x)$
  - Loss function: $L[\vartheta, \phi(x)]$
  - Prior: $f_\theta(\vartheta)$, $f_{X|\theta}(x \mid \vartheta)$

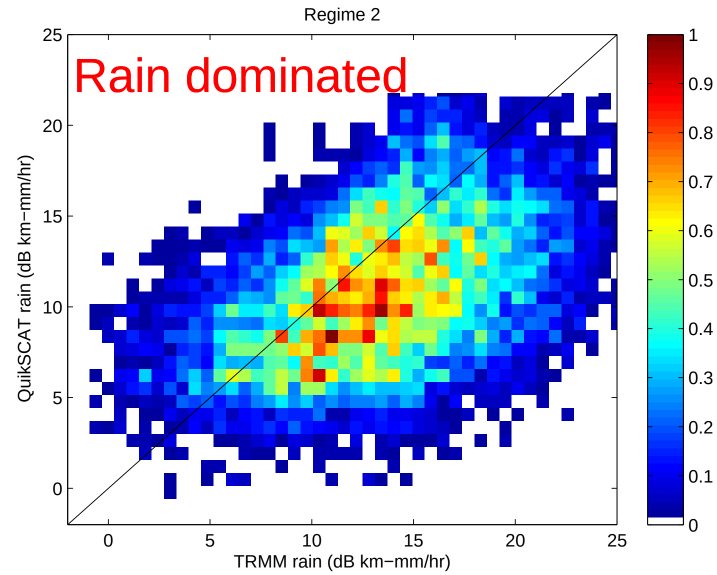
- Estimator Selection
  - True Wind/Rain Vector
  - Estimates: $x_j = \hat{\vartheta}_j : j \in \{0,1,2\}$

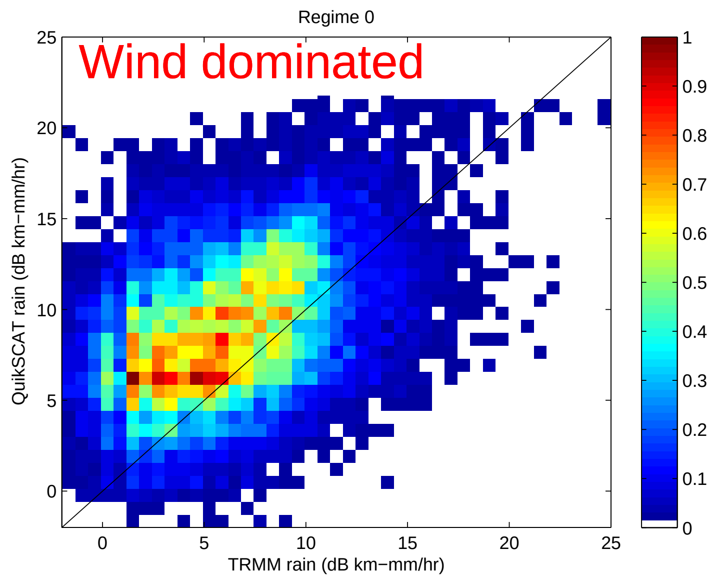
$$\phi_i(x_j) \Rightarrow \hat{\vartheta}_i$$

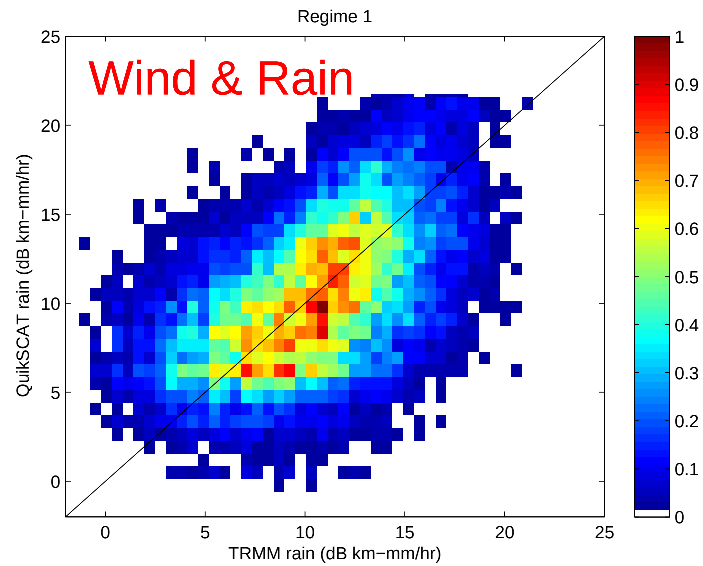
$$L[\vartheta, \phi_i(x_j)]$$

UHR SWR Rain Accuracy

- TRMM vs. QuikSCAT rain rates
- High variance –
- Regime 0 – biased high, wind backscatter mapped into rain space
- Regime 1 – unbiased wind & rain
- Regime 2 – biased low, rain backscatter mapped into wind space







UHR SWR Co-location Examples