# Bayesian rain estimation and correction for Ku-band scatterometers

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**IOVWST meeting, Nanjing, Dec. 1st, 2023**

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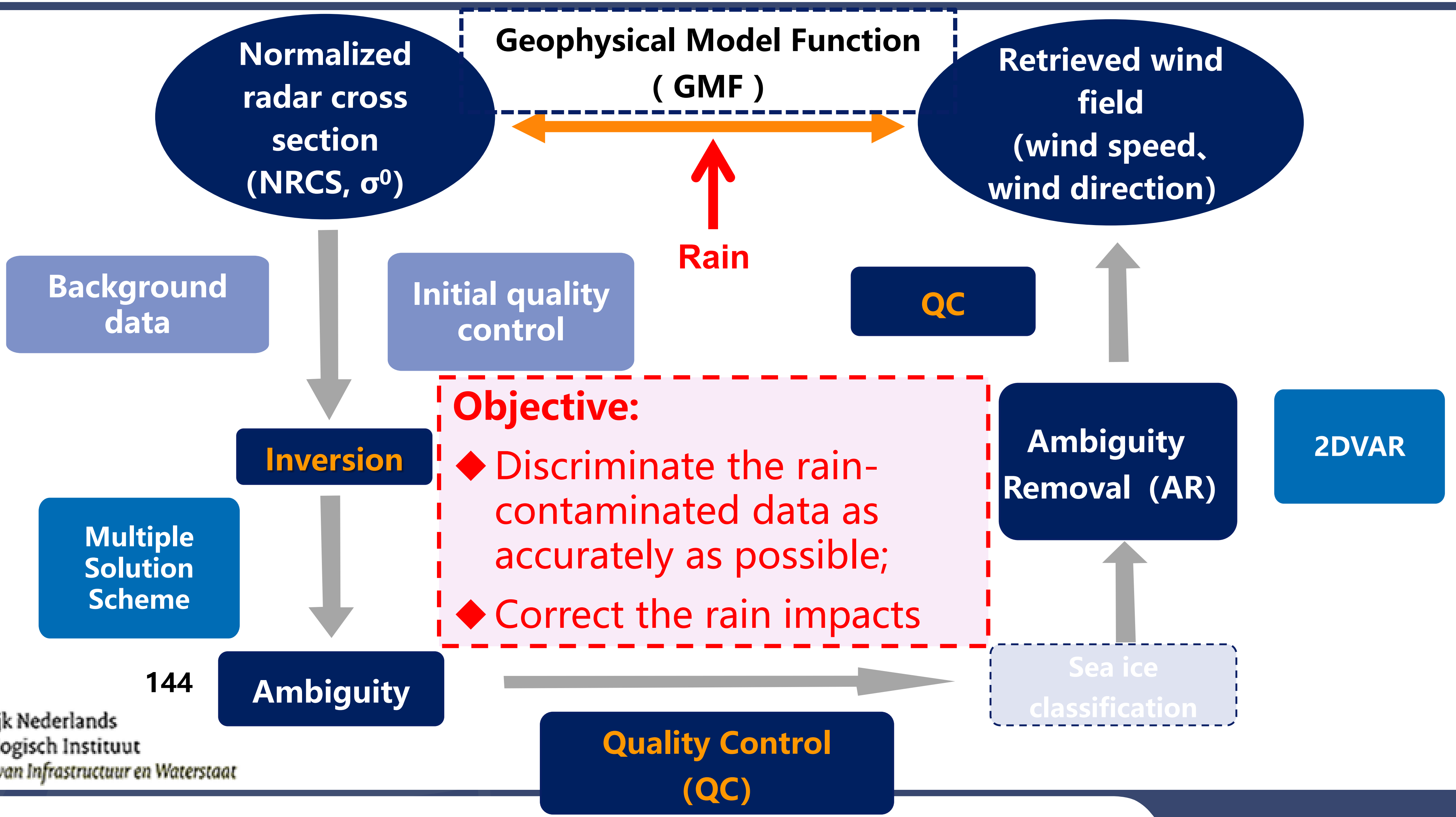
# Background

## Scatterometer wind retrieval procedure

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# Data and collocation method

NSMC NCSW

**ASCAT** (-A/B/C) ⟷ $25/\sqrt{2}\ km$, $30\ mins$ ⟷ **HSCAT** (HY-2C) ⟷ area-weighted, $5\ mins$ ⟷ **GPM** (3IMERG)

- November 2020 - September 2021
- within ±20° latitude

After QC, the accepted ASCAT winds are generally not affected by rain and can be seen as the true sea surface wind field reference

ASCAT + HSCAT → Preliminary QC → Eliminate the PDF biases → ASCAT-HSCAT collocation data

HSCAT + GPM → Preliminary QC → Calculate the average rain rate for each WVC → HSCAT-GPM collocation data

$$RR_{WVC} = \frac{\sum_i RR_{i,GPM} \times A_{i,GPM}}{\sum_i A_{i,GPM}}$$

| Bayesian method |
|---|
| SR: 2,860,974<br>NR: 1,694,335 |

| Bayesian method |
|---|
| SR: 3,555,645<br>NR: 2,038,307 |

ASCAT-HSCAT collocation data + HSCAT-GPM collocation data → ASCAT-HSCAT-GPM collocation data

| Rain model |
|---|
| SR: 425,363 |

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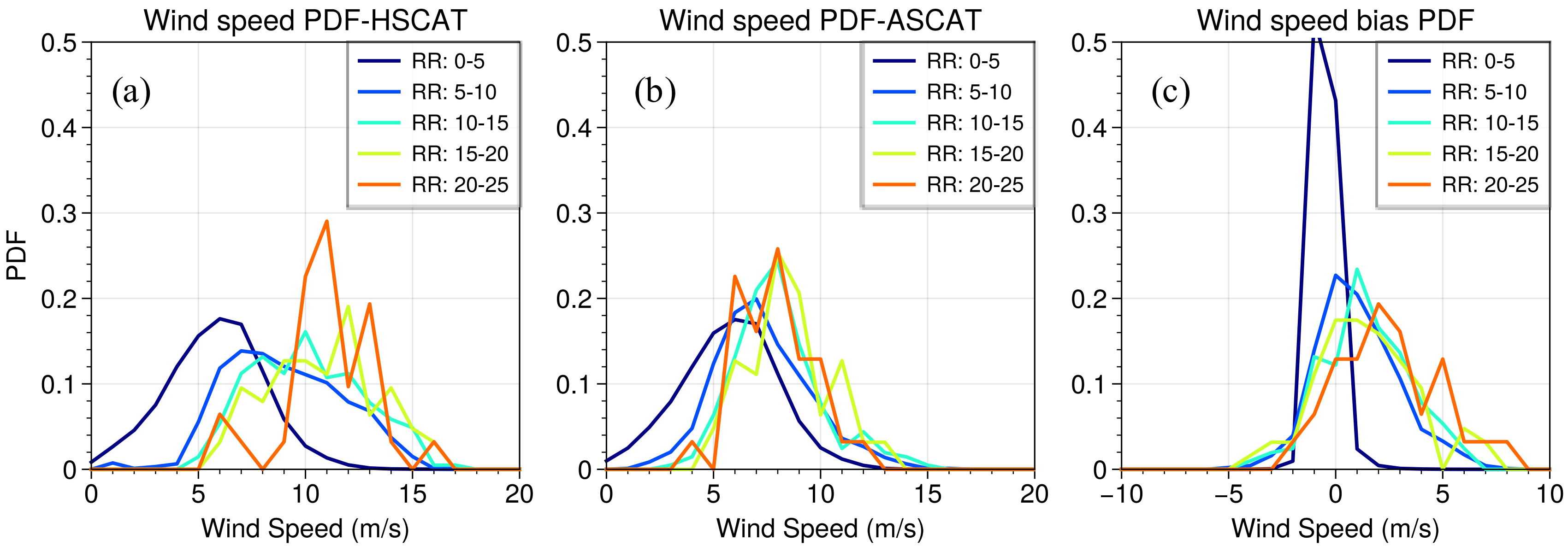
# Rain effects on retrieved wind fields




Wind speed PDFs of HSCAT (panel (a)), ASCAT (panel (b)) and the wind speed bias (HSCAT-ASCAT) PDFs (panel (c)) under different rain rate bins.

| Rain rate (mm/h) | Mean bias (m/s) | Mean standard deviation(m/s) | Mean bias (deg) | Mean standard deviation(deg) | VRMS | Collocation numbers |
|---|---|---|---|---|---|---|
| 0-5 | 0.05 | 0.46 | -0.32 | 25.36 | 1.50 | 424100 |
| 5-10 | 1.67 | 1.89 | 4.68 | 53.47 | 7.09 | 938 |
| 10-15 | 2.12 | 2.04 | 3.53 | 58.12 | 8.66 | 205 |
| 15-20 | 2.22 | 2.29 | -1.38 | 49.92 | 8.35 | 63 |
| 20-25 | 3.15 | 2.41 | 11.67 | 50.15 | 8.87 | 31 |
| 25-30 | 3.51 | 3.45 | 11.41 | 41.00 | 8.91 | 10 |
| 30-35 | 3.06 | 2.36 | 15.51 | 49.34 | 9.77 | 7 |
| 35-40 | 2.26 | 1.31 | 6.92 | 40.54 | 7.48 | 5 |

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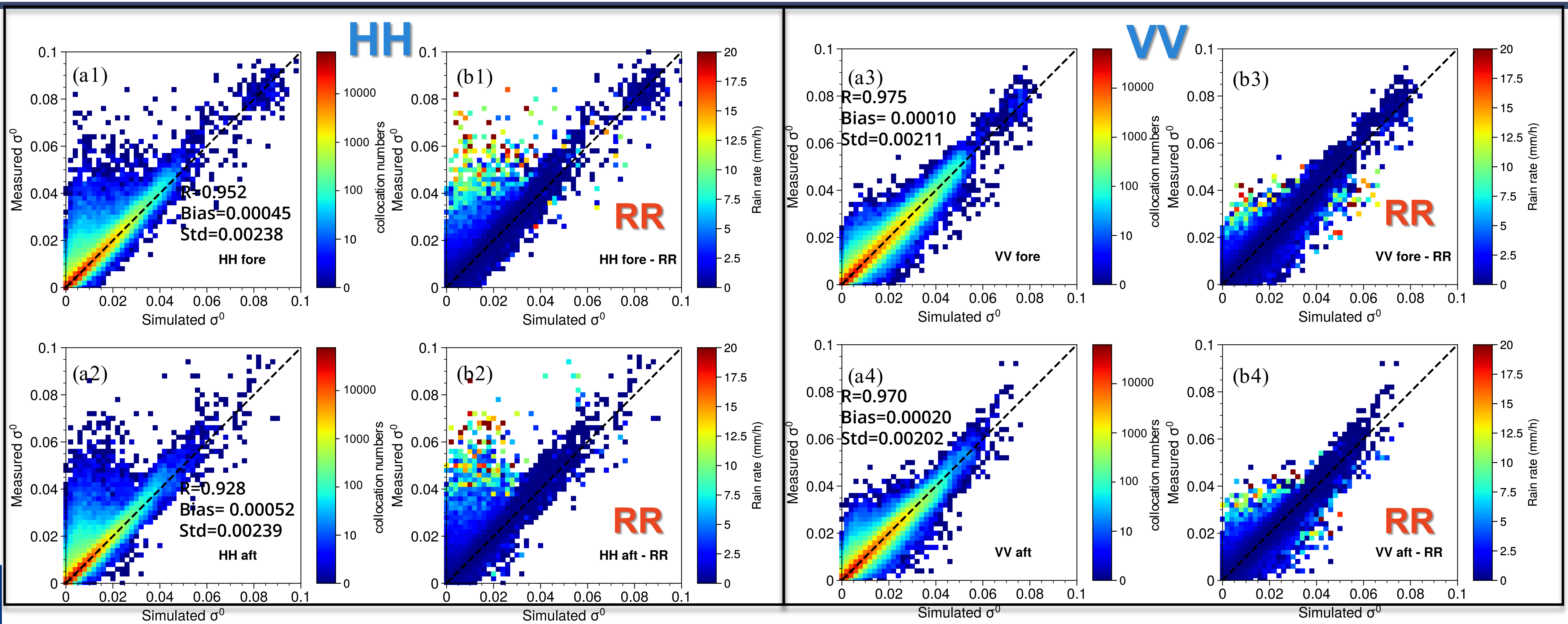
# Rain effects on scatterometer NRCS




Sample-density scatterplot of measured and simulated $\sigma^0$ (left) and the corresponding rain rates (right) for each beam. Panel (a1) and (b1) are of $\sigma^0_{fore\_HH}$; panel (a2) and (b2) are of $\sigma^0_{aft\_HH}$; panel (a3) and (b3) are of $\sigma^0_{fore\_VV}$; panel (a4) and (b4) are of $\sigma^0_{aft\_VV}$.

# Contents

*Ke Zhao, Ad Stoffelen, Jeroen Verspeek, Anton Verhoef and Chaofang Zhao. Bayesian Algorithm for Rain Detection in Ku-band Scatterometer Data. IEEE Transactions on Geoscience and Remote Sensing, 2023.*



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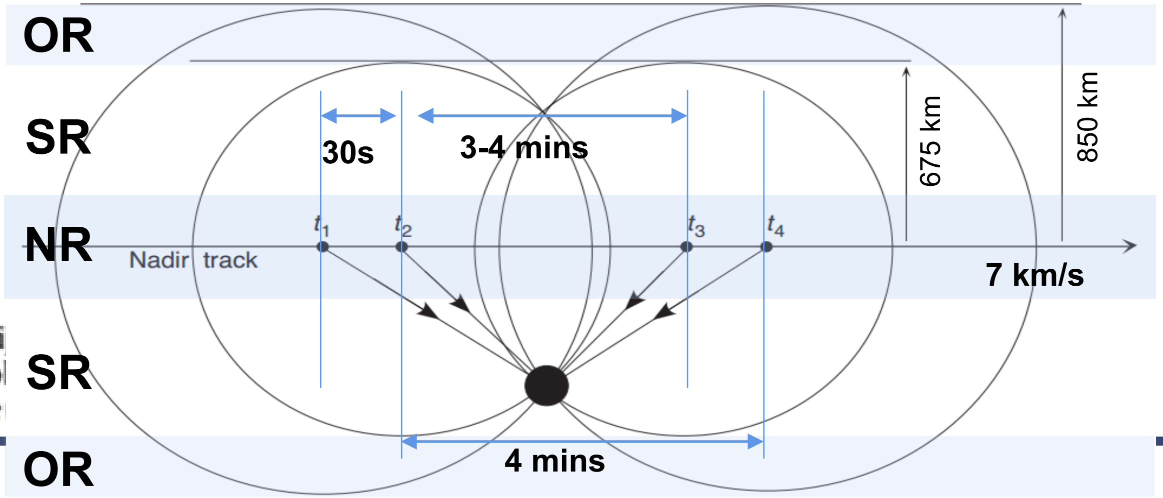
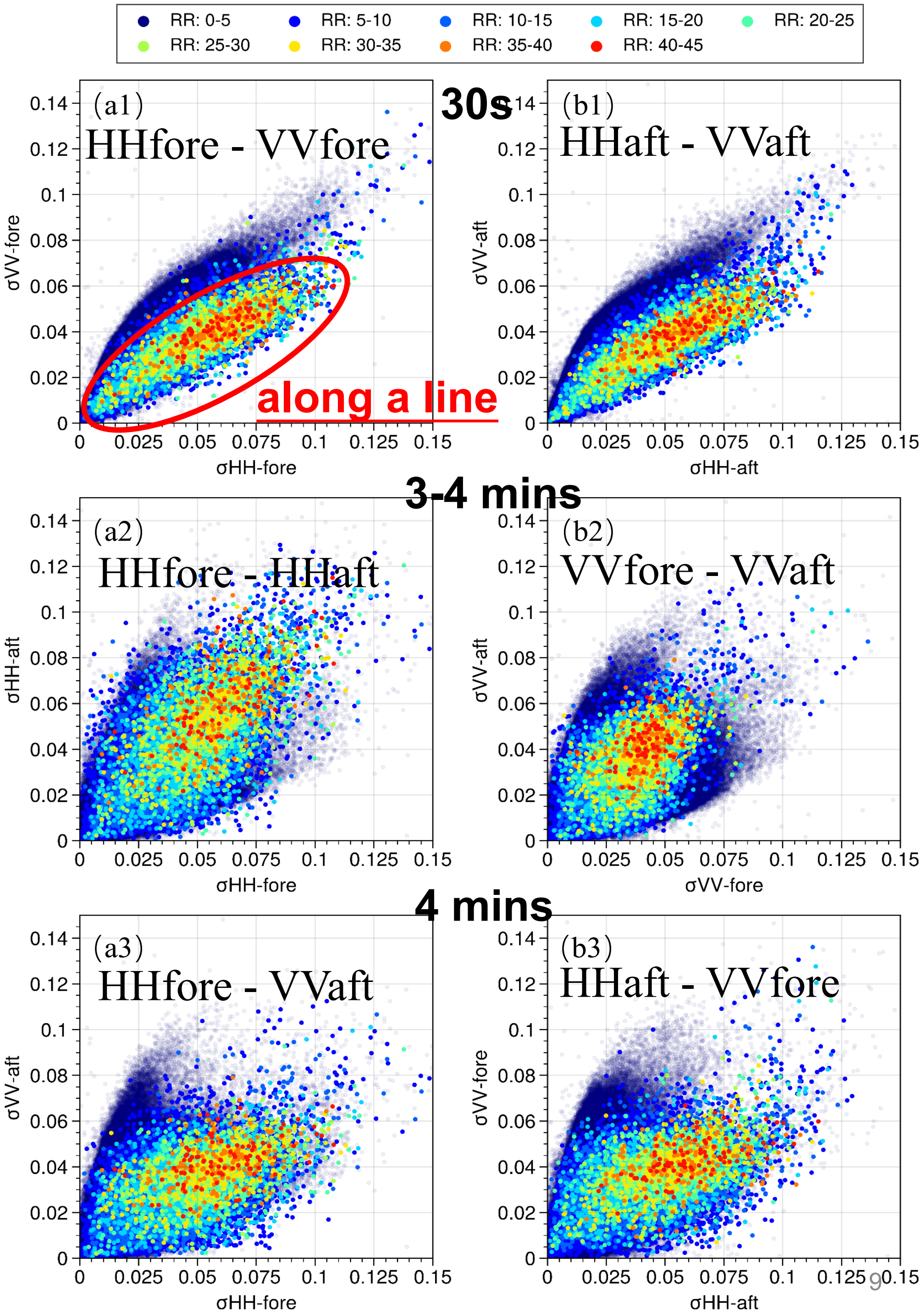
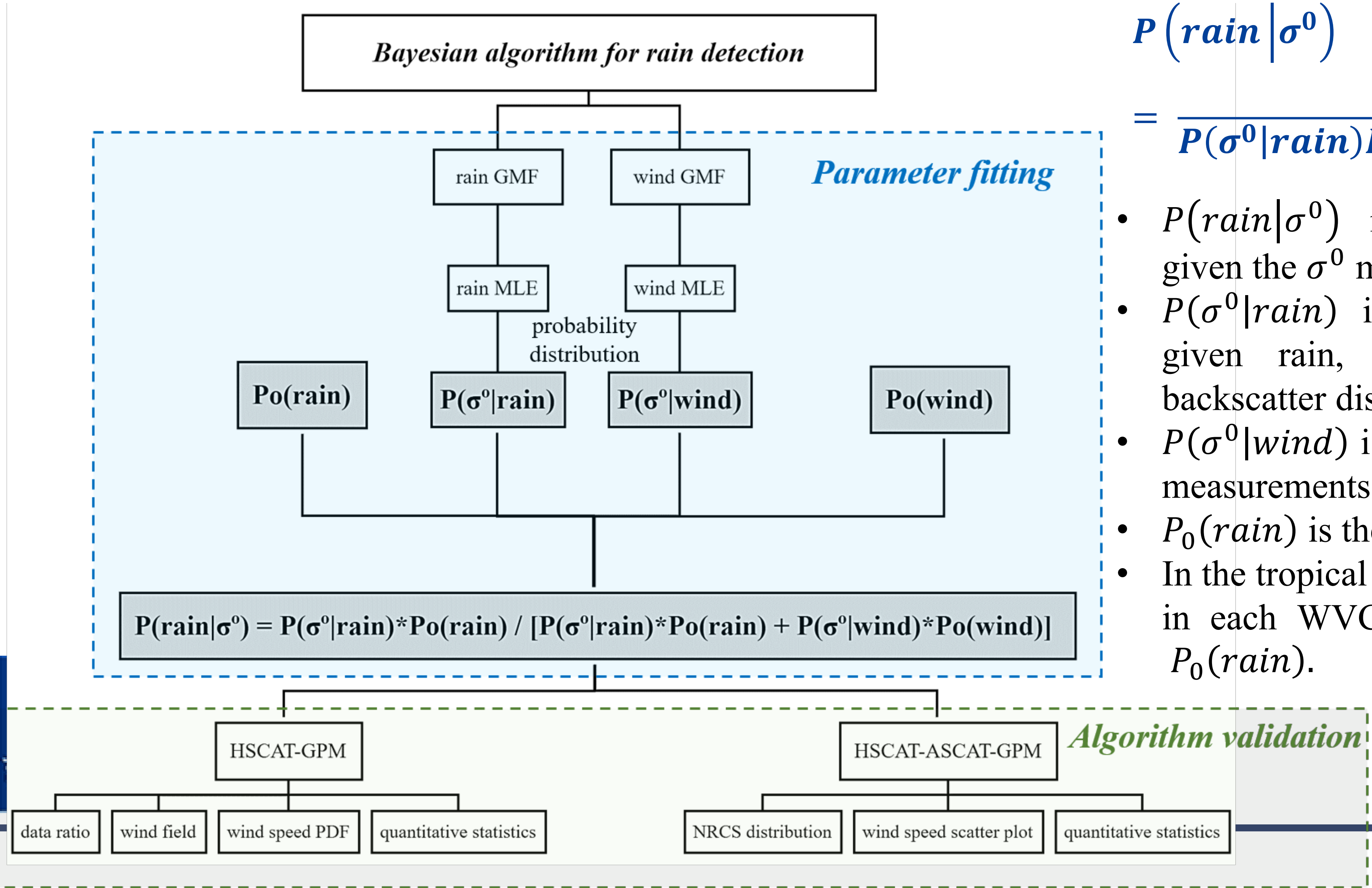
- Rain clouds in the atmosphere and rain drops hitting the sea surface affect scatterometer received backscatter signal, which will contribute differently to different polarizations.
- Adopting the Bayesian methodology to calculate posterior rain probabilities in each WVC.
- Pure rain backscatter distributes around the linear rain GMF with Gaussian distribution in four-dimensional measurement space.



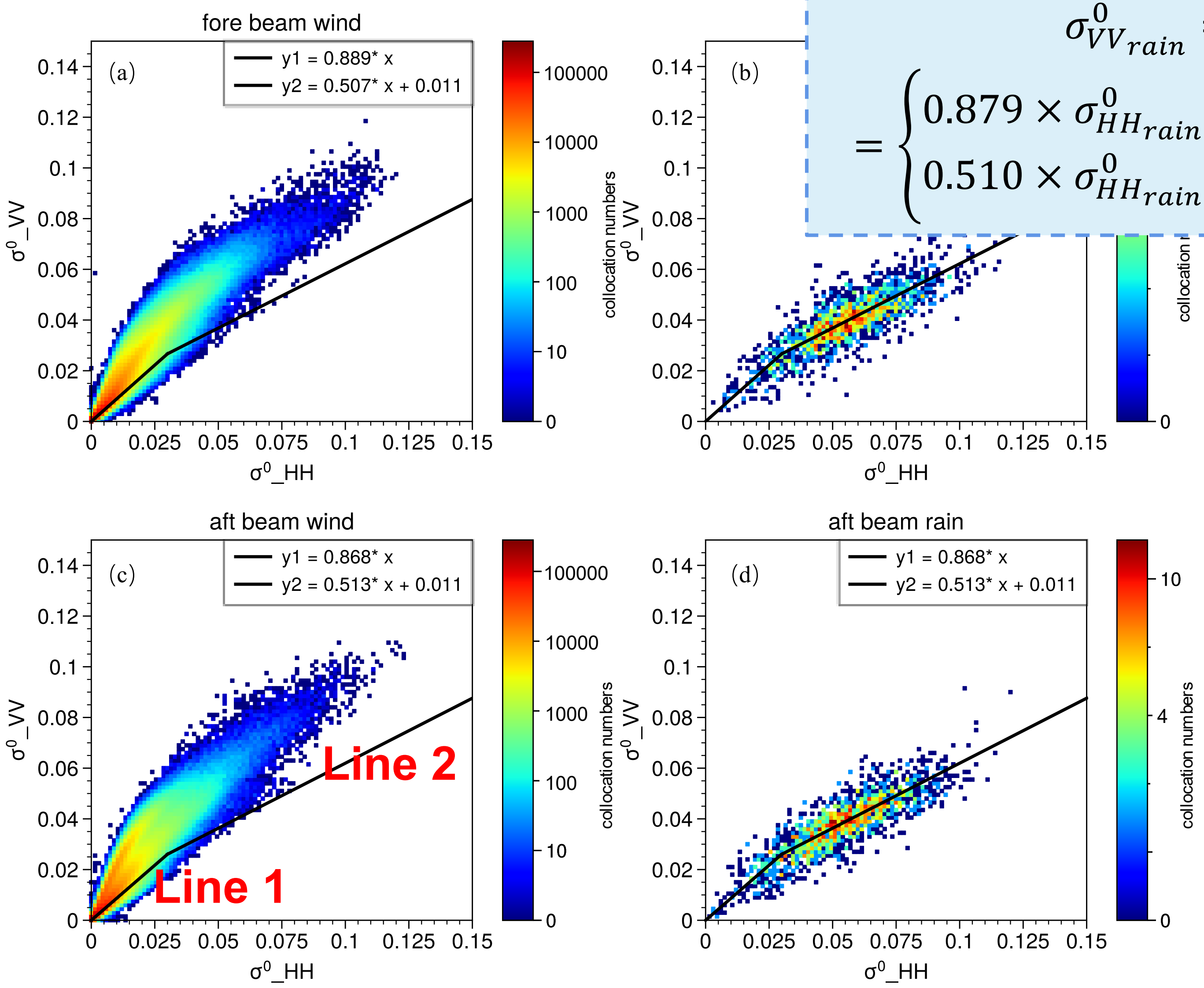
# the posterior probability of rain




$$P\left(rain\middle|\sigma^0\right) = \frac{P(\sigma^0|rain)P_0(rain)}{P(\sigma^0|rain)P_0(rain) + P(\sigma^0|wind)P_0(wind)}$$

- $P\left(rain|\sigma^0\right)$ is the posterior probability of rain given the $\sigma^0$ measurements.
- $P(\sigma^0|rain)$ is the conditional probability of $\sigma^0$ given rain, which is the rain contaminated backscatter distribution about a **rain GMF**.
- $P(\sigma^0|wind)$ is the distribution of ocean backscatter measurements about the ocean wind GMF.
- $P_0(rain)$ is the prior rain probability.
- In the tropical region, we assume two possible states in each WVC: rain or no rain. $P_0(wind) = 1 - P_0(rain)$.

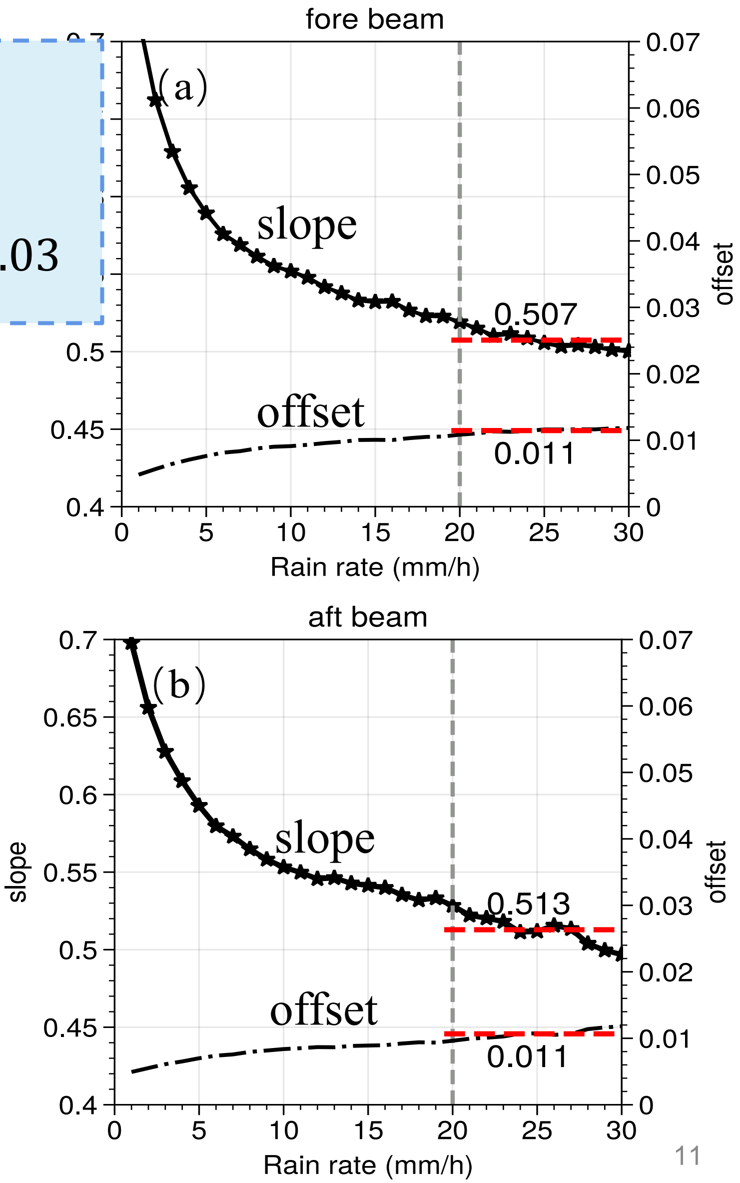
# Rain GMF




$$\sigma^0_{VV_{rain}} = f\left(\sigma^0_{HH_{rain}}\right) = \begin{cases} 0.879 \times \sigma^0_{HH_{rain}}, & \sigma^0_{HH_{rain}} \le 0.03 \\ 0.510 \times \sigma^0_{HH_{rain}} + 0.011, & \sigma^0_{HH_{rain}} > 0.03 \end{cases}$$

Wind σ0 distribution and rain-contaminated σ0 distribution in HH–VV space for fore and aft beams. (left)

Slopes (left y-axis) and offsets (right y-axis) of the Line2 when RRs are higher than the x-axis values. (right)



# Maximum Likelihood Estimators (MLEs)

the **Euclidean distance** of backscatter measurements to the modeled values by the geophysical model function

## Wind MLE

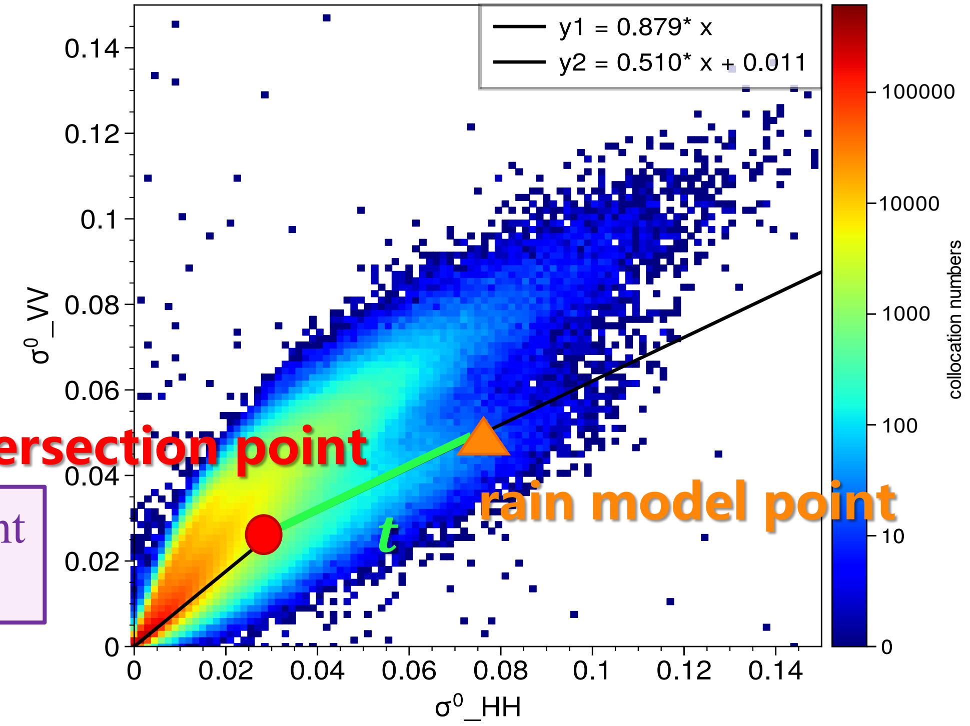
$$MLE_{wind} = \frac{1}{\langle MLE \rangle} \sum_{i=1}^{n} \frac{\left(\sigma^0_{obs,i} - \sigma^0_{wind,i}\right)^2}{var\left[\sigma^0_{wind,i}\right]}$$

## Rain MLE

$$MLE_{rain} = \sum_{i=1}^{n} \frac{\left[\left(\sigma^0_{obs,i} - \sigma^0_{rain,i}\right)\right]^2}{var\left[\sigma^0_{rain,i}\right]} + \frac{\left[(t - average\_t)\right]^2}{cmix \times var[t]}$$

The distribution of pure rain backscatter distances to the rain model point

The rain model point distribution along the line



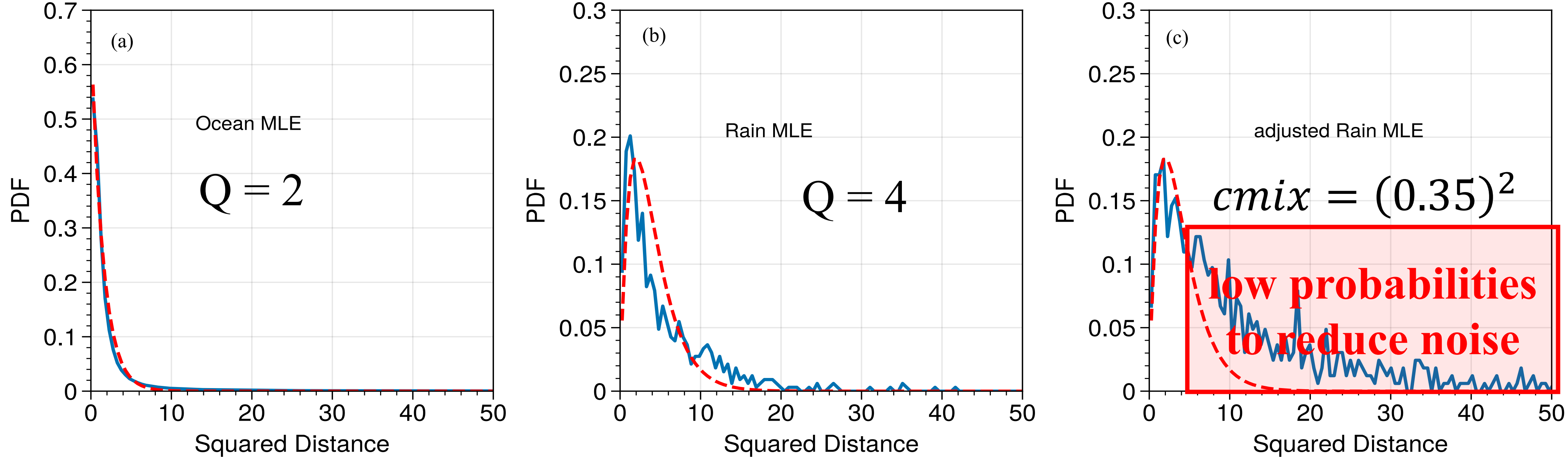

- n is the number of views per cell (n = 4 in sweet swath).
- $\sigma^0_{obs,i}$ is the i-th observation in each WVC.
- $\sigma^0_{wind,i}$ and $\sigma^0_{rain,i}$ are the corresponding respective wind and rain GMF simulated values.
- $\langle MLE \rangle$ is the expected MLE for a WVC.
- $var\left[\sigma^0_{wind,i}\right]$ and $var\left[\sigma^0_{rain,i}\right]$ is the measurement Gaussian error variance.
- $t$ is the distance of the corresponding rain GMF point from the line intersection point.

# Probability distribution of wind and rain backscatter

both wind/rain measurements obey a Gaussian distribution around each GMF → MLEs represent sums of squared standard Gaussian variables → obey Chi-square distribution with different degree of freedom (Q)

$Q = 2$ → $$P(\sigma^0|wind) = \frac{1}{L} e^{-MLE_{wind}/L}$$

$Q = 4$ → $$P\left(\sigma^0 \middle| rain\right) = \frac{MLE_{rain}}{4} \times e^{-MLE_{rain}/2}$$




Observed (blue solid lines) and expected (red dashed lines) MLE distributions to (a) ocean wind and (b) rain GMF for all collocation data when cmix = 1. Blue line in (c) represents the adjusted rain MLE distribution normalized to the expected MLE peak value when cmix = $(0.35)^2$.

# Algorithm implementation

$$p\left(rain \middle| \sigma^0\right) = \frac{p(\sigma^0|rain)P_0(rain)}{p(\sigma^0|rain)P_0(rain)+p(\sigma^0|wind)P_0(wind)}$$

$$\sigma^0_{VV_{rain}} = f(\sigma^0_{HH_{rain}}) = \begin{cases} 0.885 \times \sigma^0_{HH_{rain}}, & \sigma^0_{HH_{rain}} \le 0.03 \\ 0.505 \times \sigma^0_{HH_{rain}} + 0.011, & \sigma^0_{HH_{rain}} > 0.03 \end{cases}$$

$$MLE_{wind} = \frac{1}{\langle MLE \rangle} \sum_{i=1}^{n} \frac{\left(\sigma^0_{obs,i} - \sigma^0_{wind,i}\right)^2}{var\left[\sigma^0_{wind,i}\right]}$$

$$p(\sigma^0|wind) = \frac{1}{L} e^{-MLE_{wind}/L}, \qquad L = 1.5$$

$$P_0(wind) = 1 - P_0(rain)$$

$$MLE_{rain} = \sum_{i=1}^{n} \frac{\left[\left(\sigma^0_{obs,i} - \sigma^0_{rain,i}\right)\right]^2}{var\left[\sigma^0_{rain,i}\right]} + \frac{[(t - average_t)]^2}{cmix \times var[t]}$$

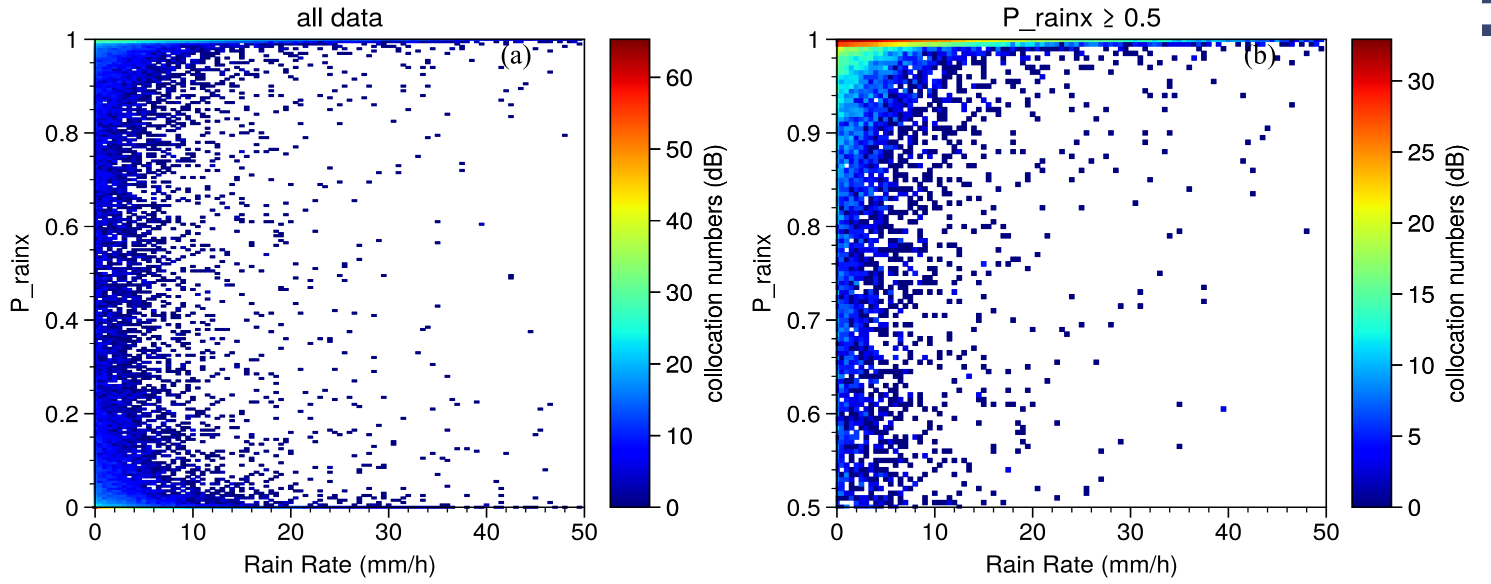
$$P(\sigma^0|rain) = \frac{MLE_{rain}}{4} \times e^{-MLE_{rain}/2}$$

$$P_0(rain) = 0.0002$$

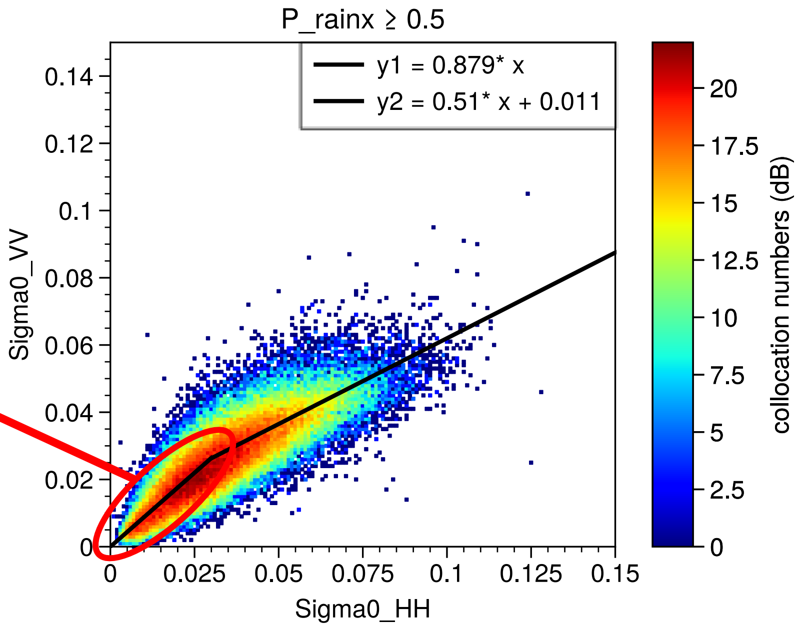
**Rain events can be assumed to occur randomly without favoring specific locations or times.**

# Algorithm Validation

- The average rain rate of the rejected dataset flagged by the current QC method (Rn) is about 2 mm/h and the corresponding average posterior probability is about 0.46.
- When the posterior probability is higher than or equals to 0.5, the data are flagged as poor-quality winds




- Still many points are located **close to the wind backscatter distribution**. That also reflects the aliasing issue and some good quality data are **mis-flagged** by the P flag.

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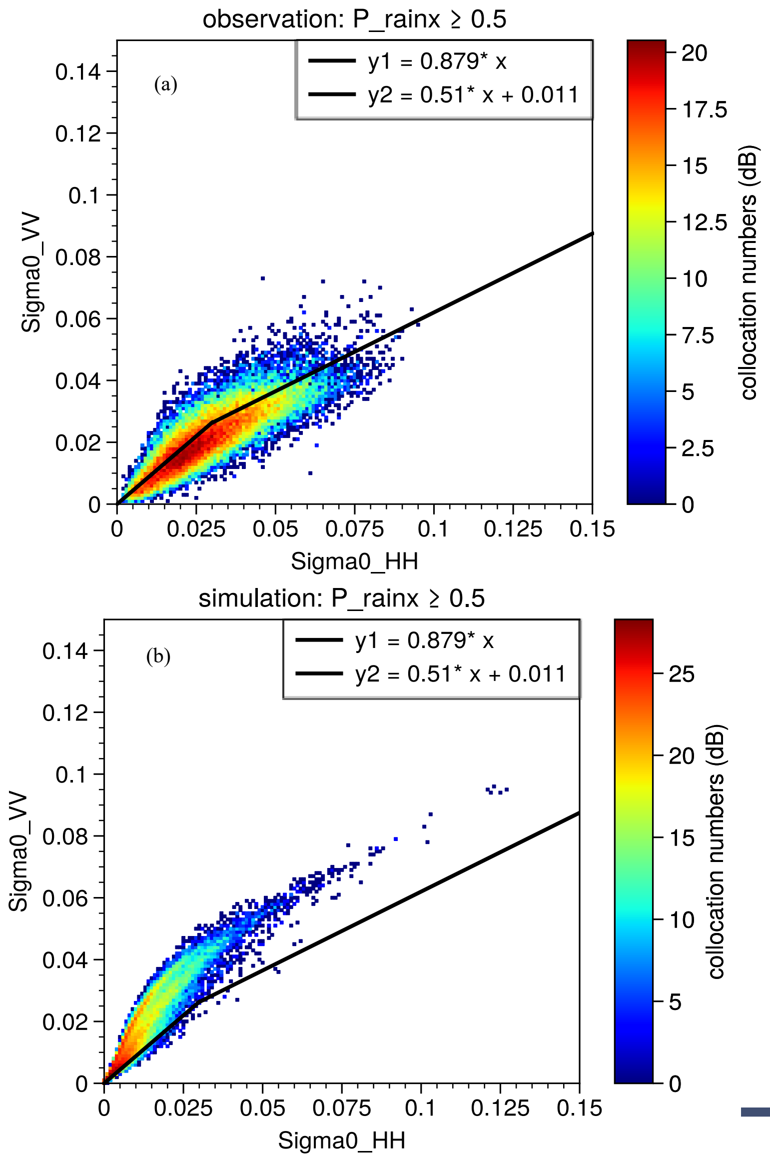
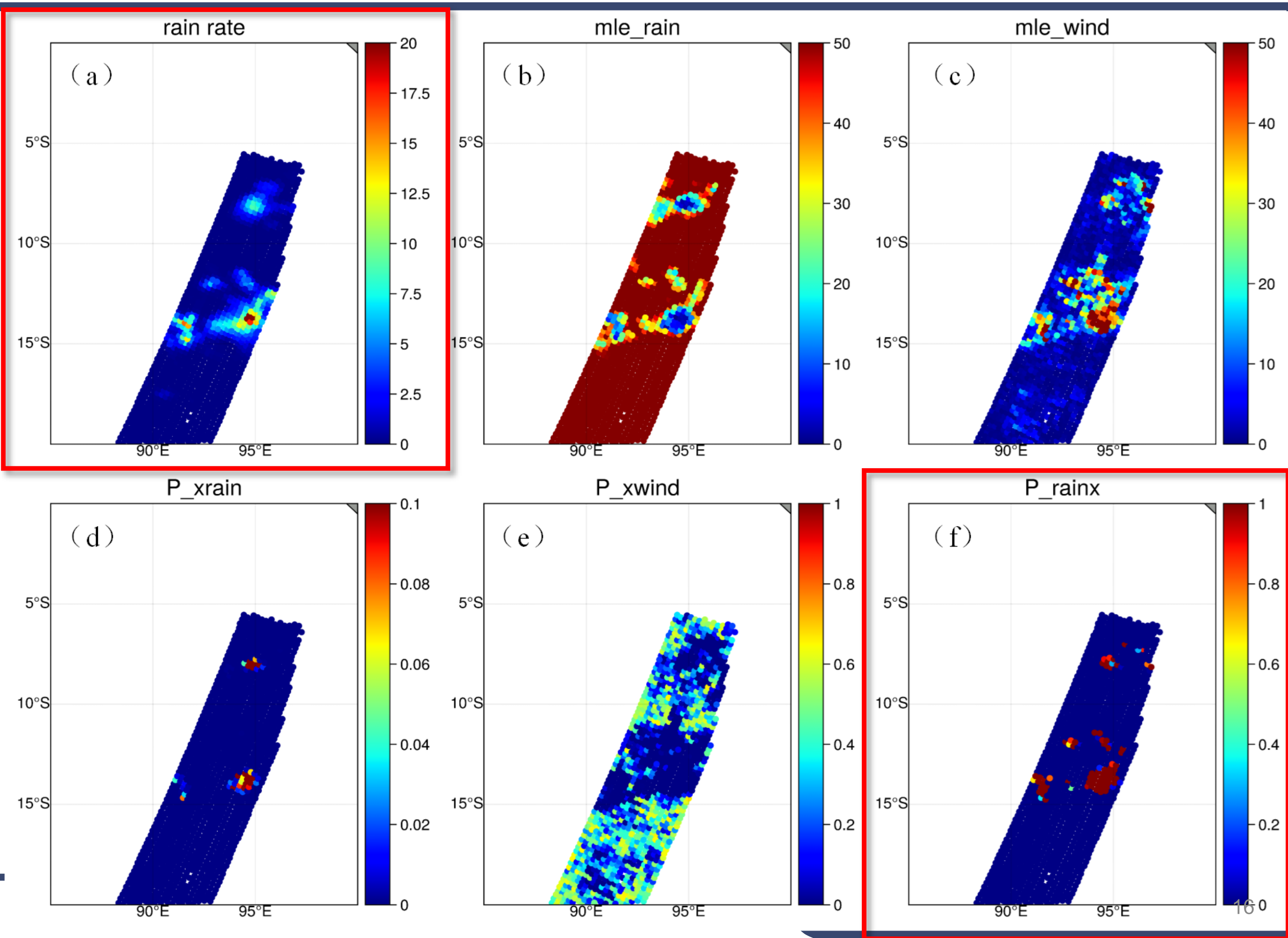
# Algorithm Validation



# Algorithm Validation

Ku-band QC

**KNMI flag**

$$MLE = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(\sigma^0_{i,measure} - \sigma^0_{i,model}\right)^2}{\left(K_{pi}\cdot\sigma^0_{i,model}\right)^2} \qquad Rn = \frac{MLE}{<MLE>}$$

*M. Portabella and A. Stoffelen, 2001; M. Portabella, 2002*

**Operational quality control method**

**Joss flag**

$$Joss = 2DVAR\ analysis\ wind\ speed - selected\ wind\ speed$$

$$Joss > 0.33 \times (2DVAR\ analysis\ wind\ speed - 5),$$

$$2DVAR\ analysis\ wind\ speed \leq 11\ \mathrm{m/s}$$

*X. Xu and A. Stoffelen, 2019. X. Xu, A. Stoffelen, W. Lin, and X. Dong, 2020.*

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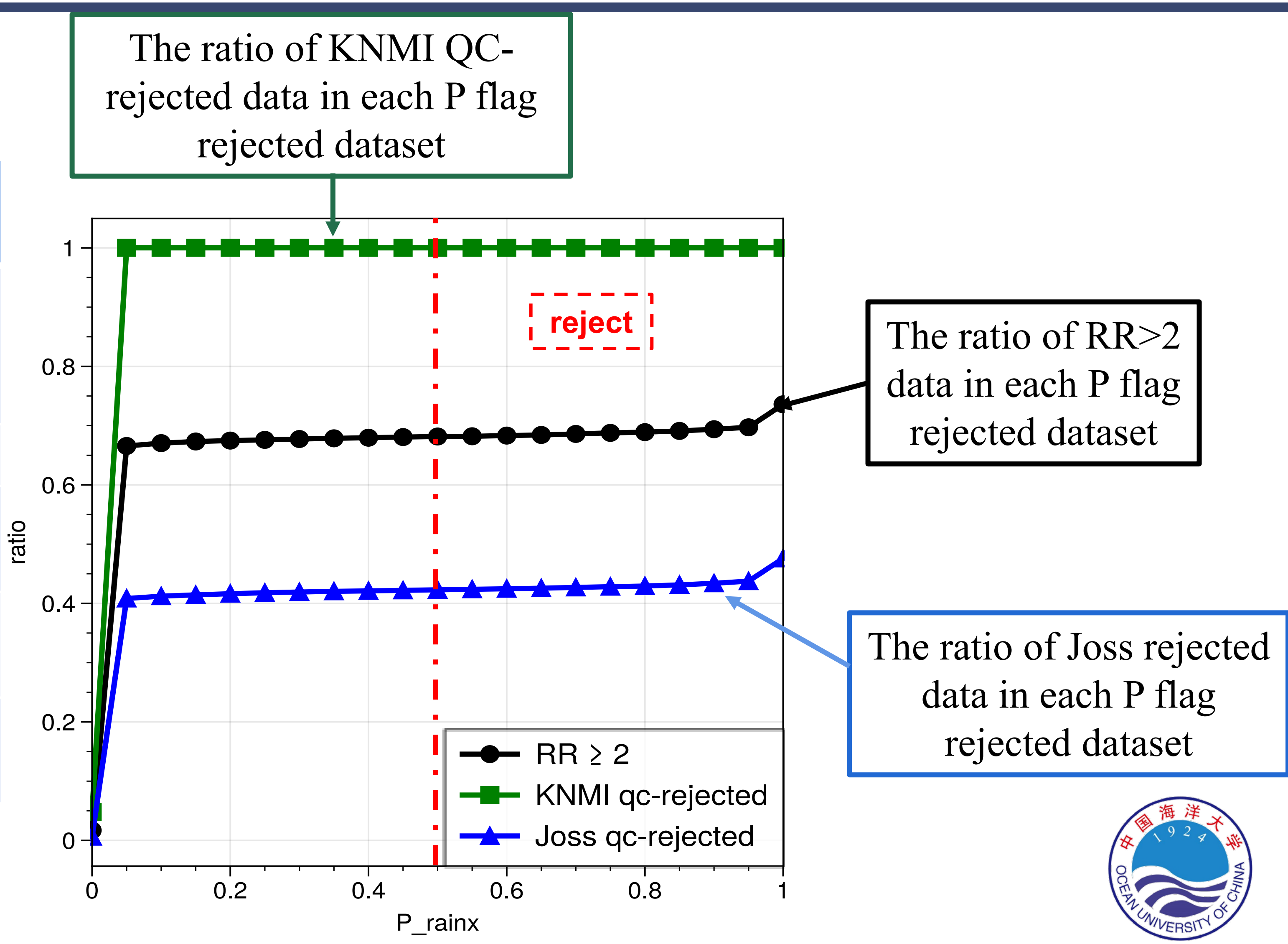
# Algorithm Validation

| | KNMI flag | P flag | Joss flag |
|---|---|---|---|
| Rejected numbers (rejected ratio) | 171,894 (4.83%) | 35,363 (0.99%) | 29,762 (0.84%) |
| RR ≥ 2 mm/h | 26.53% | 68.16% | 69.24% |
| Mean rain rate (mm/h) | 2.05 | 5.76 | 6.35 |
| Mean wind speed (m/s) | 7.56 | 9.55 | 11.65 |
| Mean standard deviation (m/s) | 2.82 | 2.65 | 2.41 |

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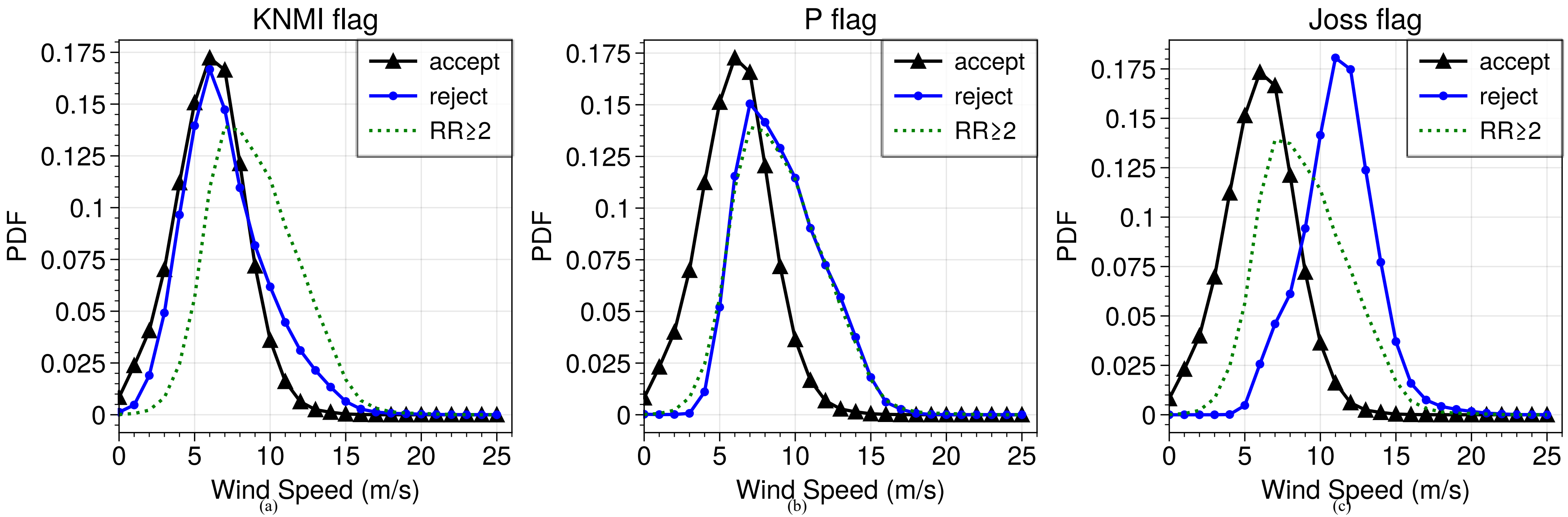
# Algorithm Validation




- KNMI flag ensures the best quality of the accepted winds at the cost of a high false alarm rate.
- The rejected winds by Joss are the most likely affected by rain.
- P flag has lower missing rate than Joss and lower false alarm rate than KNMI flag.

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*Ke Zhao, Ad Stoffelen, Jeroen Verspeek, Anton Verhoef and Chaofang Zhao. A Conceptual Rain Effect Model for Ku-band Scatterometers. IEEE Transactions on Geoscience and Remote Sensing, 2023.*



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# Rain model introduction

## The classic model VS The conceptual model

**The classic model**

$$NRCS_m = (NRCS_w + NRCS_{sr}) \times \alpha_r + NRCS_{ar}$$

surface effect ($NRCS_{sr}$); atmosphere effect ($NRCS_{ar}$)

$$NRCS_m = NRCS_w \times \alpha_r + NRCS_{rain}$$

- The physical mechanisms are complex and hard to quantify theoretically
- Didn't eliminate the SST effects
- Using model winds as the $NRCS_w$ may introduce unexpected errors

Huddleston, J., Stiles, B, 2000; Wentz, F.; Smith, D., 2000; Figa, J., Stoffelen, A. 2000; Portabella, M., Stoffelen, A, 2002; Mears, C.; Stiles, B.W., Yueh, S.H., 2002; Hilburn, K.; Draper, D.W., Long, D.G.,2004; Wentz, F., Smith, D., Ashcroft, P. ,2006; Nie, C., Long, D.G. ,2008; Stiles, B.W., Dunbar, R.S. ,2010; G. Zhang et al., 2016; O. Olabisi and E. J. I. Oladeji, 2018; X. Zhao et al., 2022.

**The conceptual model**

$$NRCS_{measurement} = A \times NRCS_{rain} + (1-A) \times NRCS_{wind}$$

- Assume $A$ is the rain area fraction in one WVC. The WVC accumulated rain rate is relative with $A$, $A = g(RR)$.

$$\boldsymbol{\Delta NRCS = NRCS_{measurement} - NRCS_{wind} = g(RR) \times (NRCS_{rain} - NRCS_{wind})}$$

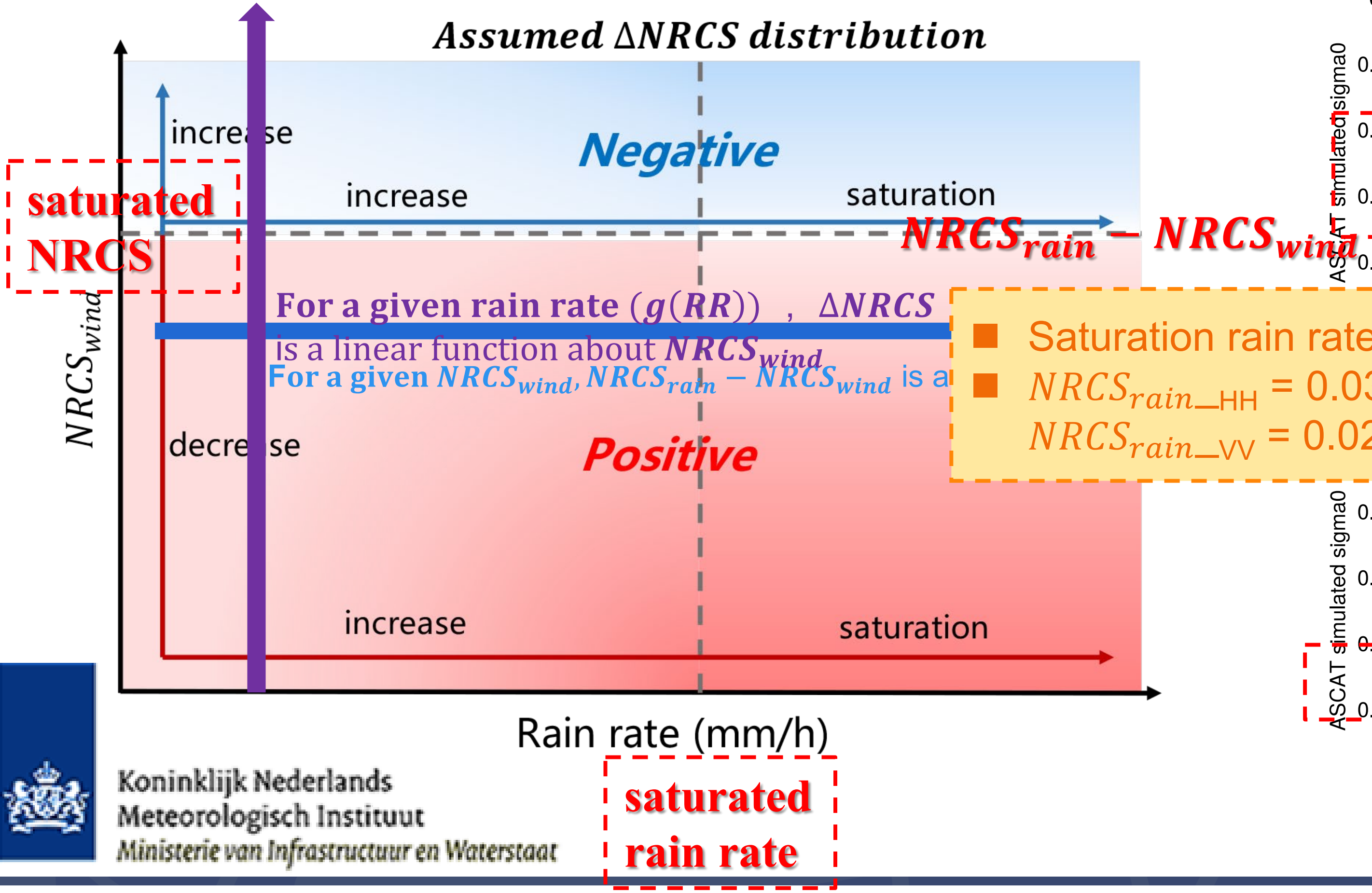
- In the tropics, sub-WVC moist convection dominates the rain effects in WVCs.
- Differences between C- and Ku-band scatterometers are dominated by precipitating cloud effects.

Fois, F.,2015 ;W. Lin, M. Portabella, A. Stoffelen, A. Verhoef, and A. Turiel,2015; X. Xu and A. Stoffelen, 2019. X. Xu, A. Stoffelen, W. Lin, and X. Dong, 2020.

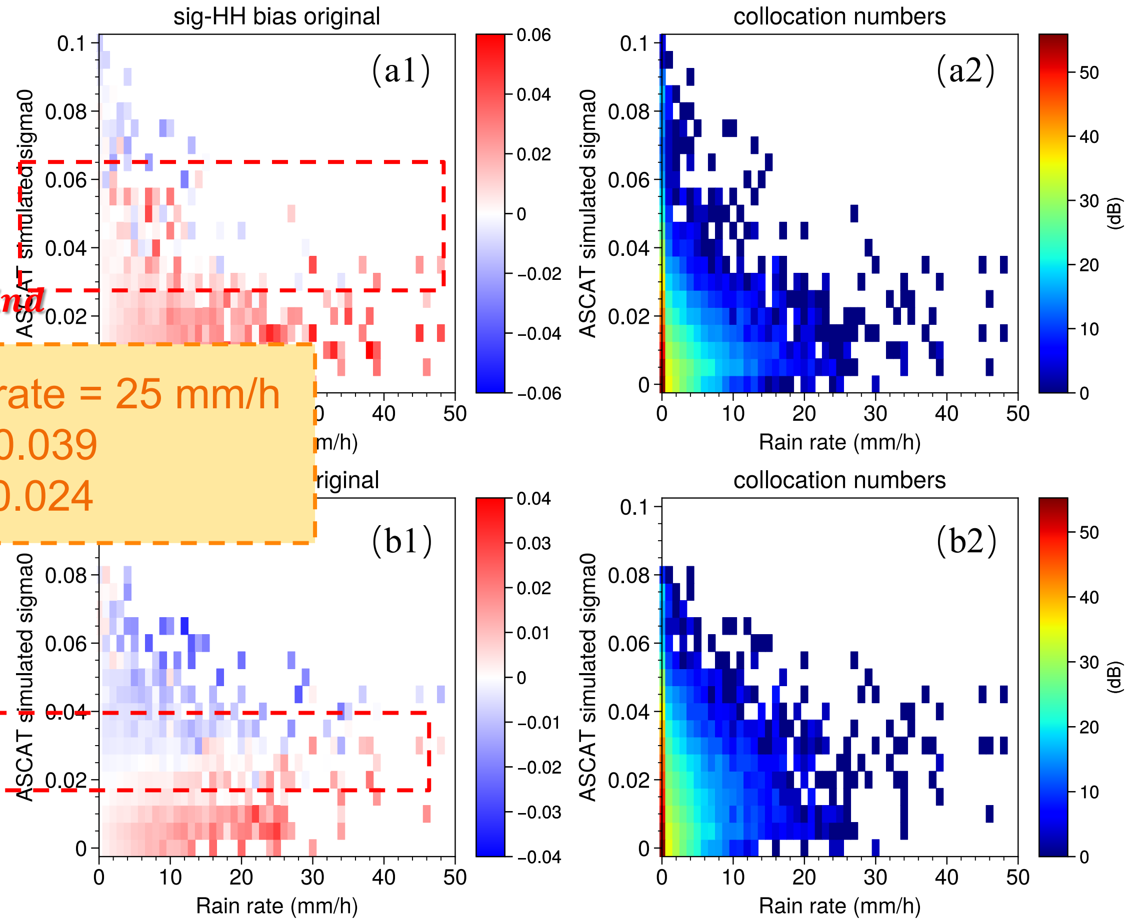
# The conceptual model

$$\Delta NRCS = NRCS_{measurement} - NRCS_{wind} = g(RR) \times (NRCS_{rain} - NRCS_{wind})$$

$$g(RR) \in [0, 1]$$




- Saturation rain rate = 25 mm/h
- $NRCS_{rain\_HH}$ = 0.039
  $NRCS_{rain\_VV}$ = 0.024

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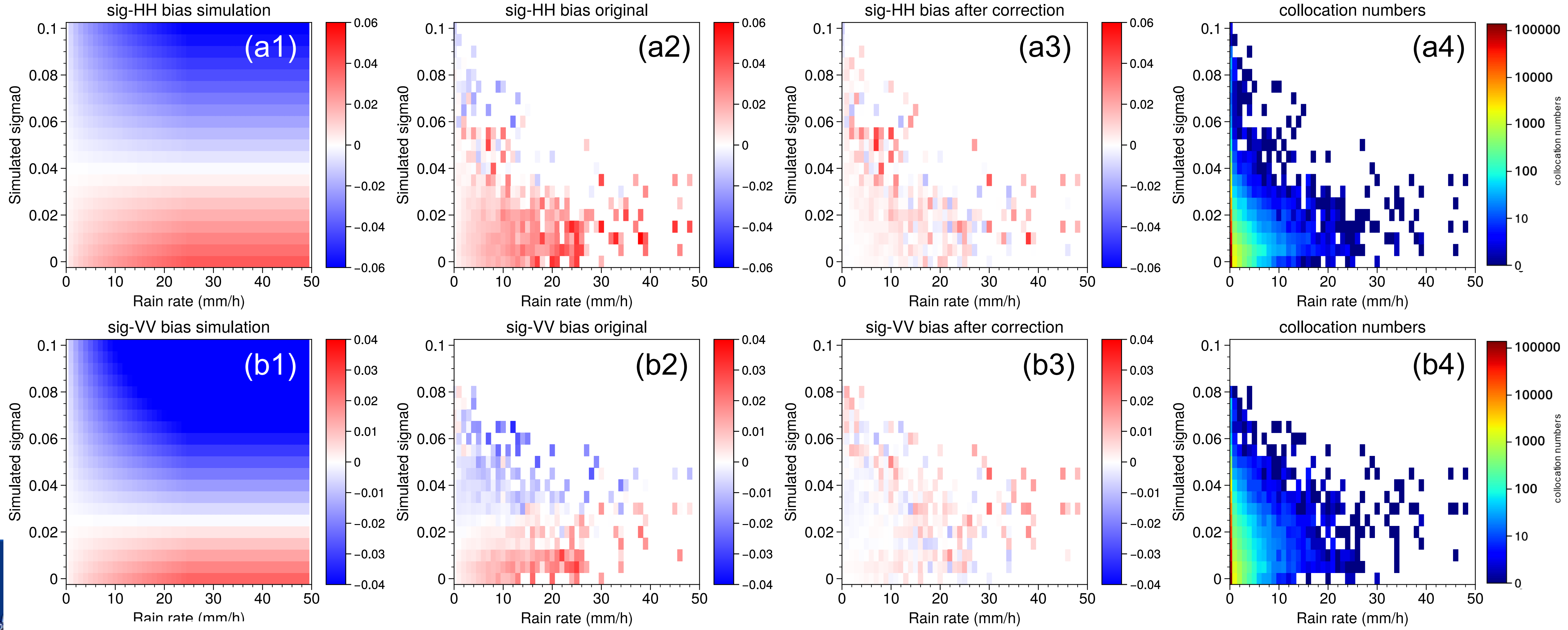
# Model validation



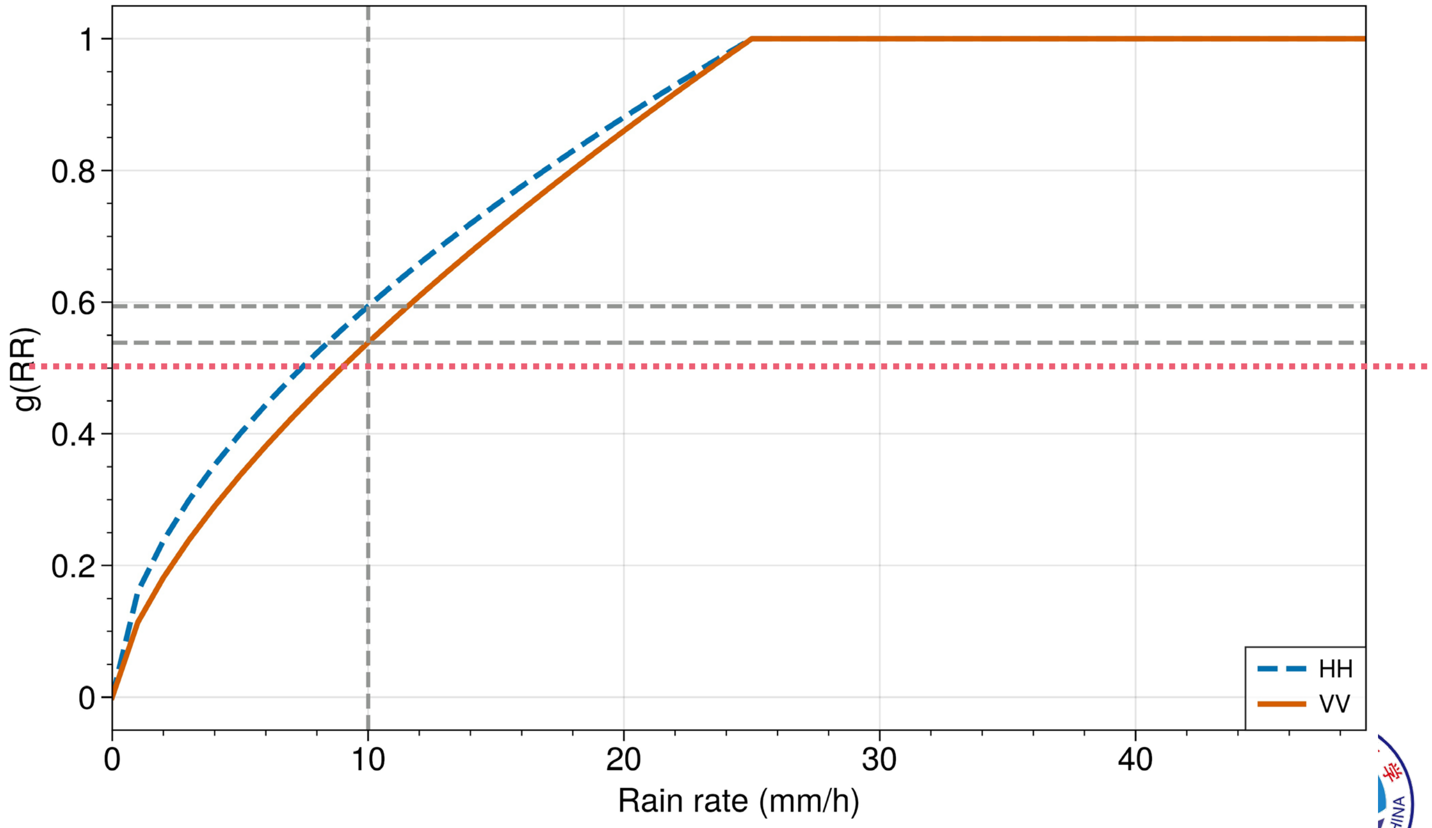

model before after

$\Delta NRCS$ histograms before and after correction

# Preliminary correction

$$f(bias) = NRCS_{measurement} - NRCS_{wind} - \Delta NRCS(RR, NRCS_{wind})$$
$$= NRCS_{measurement} + (1 - g(RR)) \times NRCS_{wind} - g(RR) \times NRCS_{rain}$$

- For a given rain rate, $f(bias)$ is a function of $NRCS_{wind}$.
- Find a possible true sea surface wind NRCS solution by minimizing the absolute value of $f(bias)$.
- The less available wind information is will cause a large computation error.
- When rain rates are less than 10 mm/h, this model can much reduce the rain effects.

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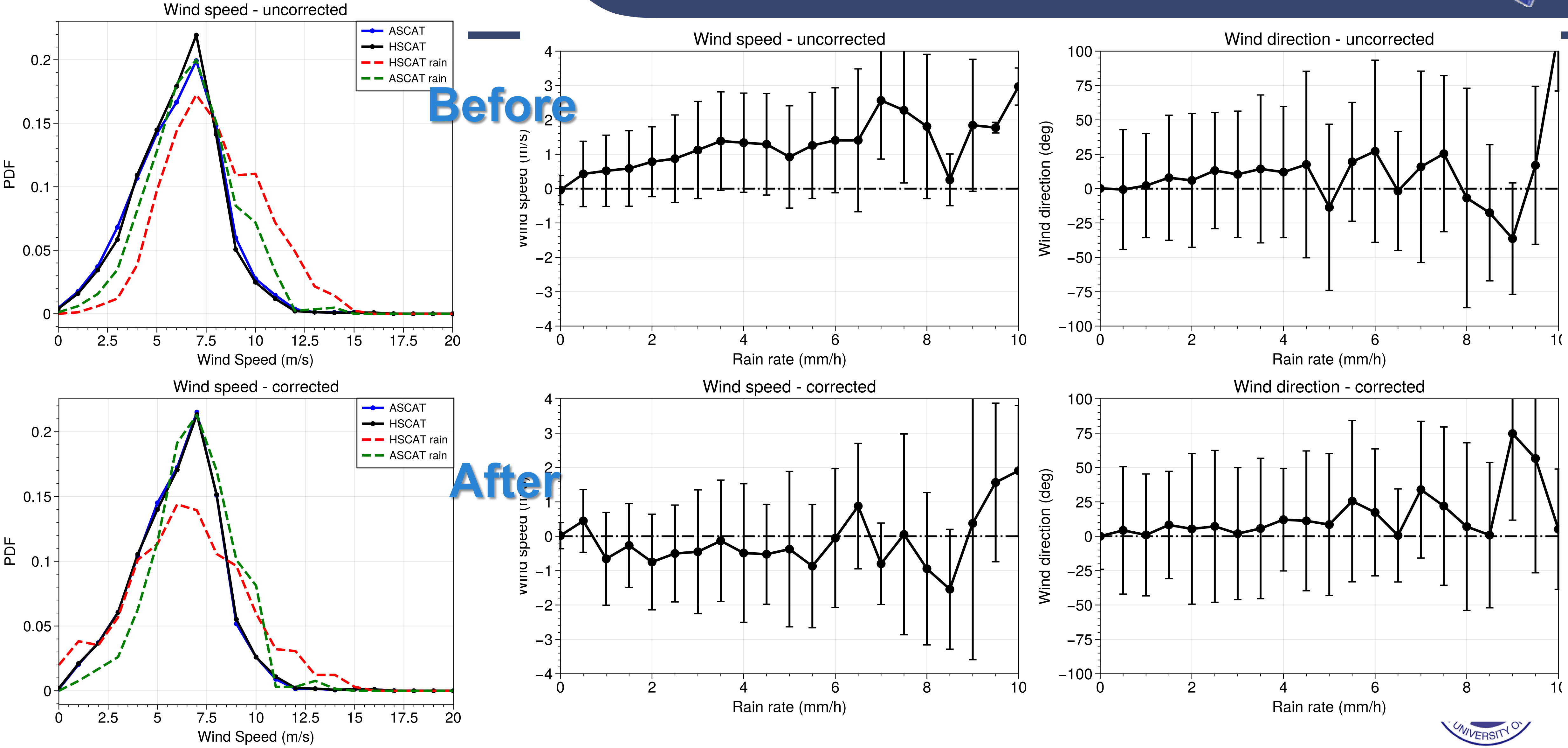
# Preliminary correction



# Contents

- Rain effects on HY-2C measurements
- Bayesian algorithm for rain detection
- A Conceptual rain effect model
- Summary and outlook

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# Summary & Outlook

**Summary:**

◆ Ku-band scatterometers are much more affected by rain than C-band scatterometers, due to the shorter wavelength.

◆ HH polarization radar views are more sensitive to rain than VV polarization views.

◆ A Bayesian method can be applied for the HY-2C scatterometer data to identify rain-contaminated data.

◆ Scatterometer received signals are mixed ocean surface wind and precipitating cloud responses. If a WVC is full of precipitating clouds, no effective sea surface wind signal can be received.

◆ A loop-search method to minimize the bias between the corrected NRCS and $NRCS_{wind}$ can be applied to the wind retrieval procedure without C-band data collocation.

**Outlook:**

□ The model can be further tested outside the tropical region and the correction method can be refined further.

□ Different QC flags have their advantages and disadvantages. The combination of all flags is important for wind retrieval under rainy conditions and in marine and atmospheric applications.

□ The dual-frequency wind radar **WindRAD** on FY-3E is a powerful instrument to explore rain effects for its unique **C-band and Ku-band simultaneous observation**.

# Thanks for your attention!

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