Analysis of Wind and Sea State Signatures in Wind Scatterometry

- For Further Improvements in High Wind Scatterometry

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Overview

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2. Metrics for Scatterometer Wind and Sea State Parameters
3. Experiments and Results
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Research Motivation

- Brief on principle of wind scatterometry

Scatterometer

Well-calibrated real aperture radar that is capable of providing accurate Normalized Radar Cross Section (NRCS) measurements.

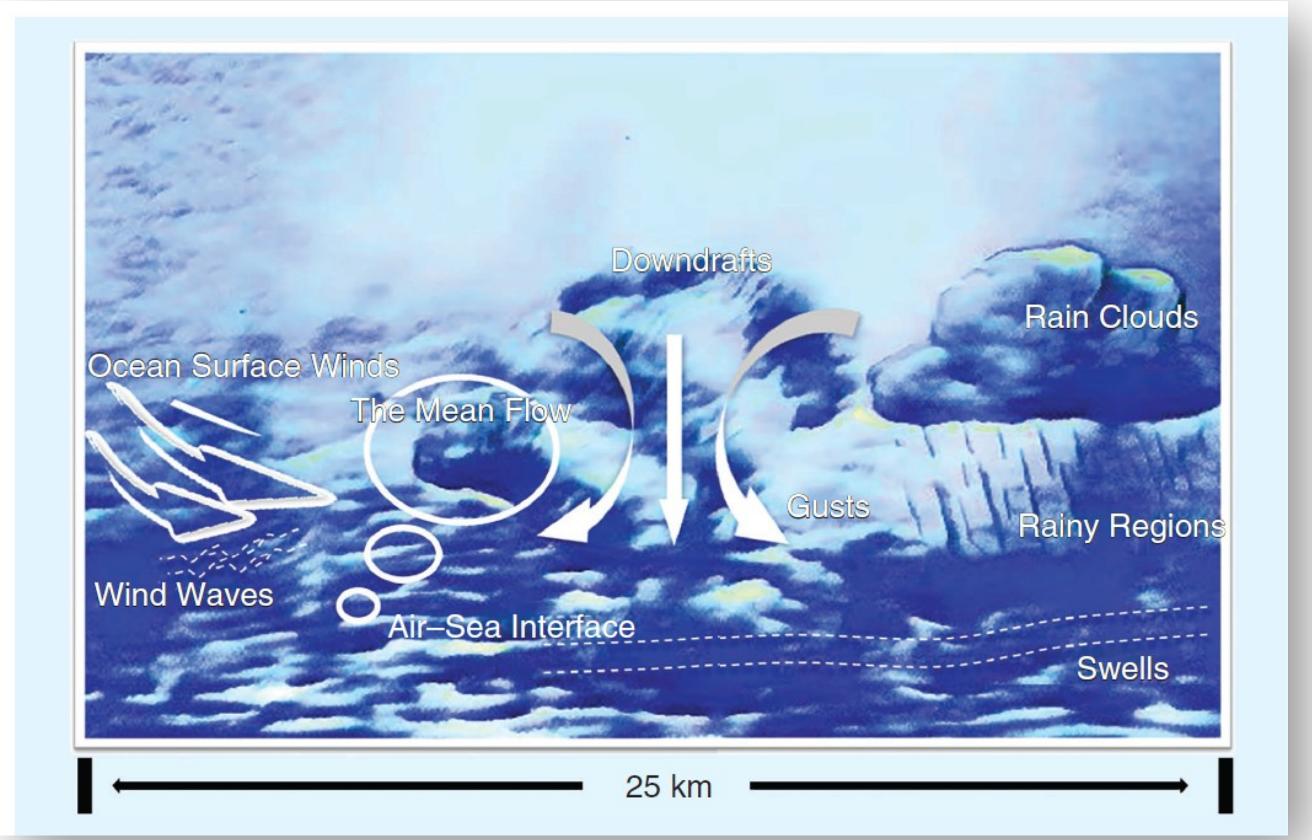
GMF

The Geophysical Model Function is an empirical model that maps 10-m stress-equivalent ocean vector wind to NRCS for a given observing geometry, polarization and e.m. wave frequency.

Wind Inversion

Apply a maximum likelihood estimation (MLE) for wind vector inversion, using NRSC values that fall into a Wind Vector Cell (WVC)

However, the actual scene, even after abstracting.



Rain convections can now be well QC-ed.

The well-developed wind retrieval procedure is the result of much effort:

E.m. method derived equation

- Early stage GMF predicts Ku-band scatterometer wind only up to about 11 m/s. (Skylab)

Early Stage

After SASS (1978)

- The first calibration results from SASS (onboard 1978 satellite) reaches 18m/s.

With first remote sensing data

More scatterometers till now and are improving

- Elaborated calibration with buoy and NWP data
- Development of quality control (QC) techniques.

Improved winds

Air-sea interaction to resolve the scientific question back to the beginning

- Role air mass density and SST
- Wind stress product, curl, divergence

What can be derived

As measurements and application requirements develop:

01 Extremes from scatterometers: different sea states from normal condition (sea states: features of waves and swells)

02 More in-situ observations: collocated measured wave parameters in addition to model information

03 New techniques for measuring the complicated scene: to extract better wind and extra information about the observed scene

From the state-of-art scatterometers: *what* has exactly been obtained

It is timely to revisit sea state (wave) effects in wind scatterometry

Metrics for Scatterometer Wind and Sea State Parameters

Energy balance: wind input, wave feedback, and surface roughness (total energy) related sea state parameters:

Energy balance equation:

$$\frac{\partial E}{\partial t} + (V_g + U_d)\frac{\partial E}{\partial x} = I + W + D$$

Wave age from the speed of the peak wave that relates to the dominant wave period (1/frequency):

$$\beta = \frac{C_p}{u_{10s}}, \; C_p = \frac{gT_p}{2\pi}$$

The slope parameter in significant wave height and wave period:

$$\delta = \frac{H_s}{C_p T_p} = \frac{2\pi \cdot H_s}{g T_p^2}.$$

Ocean Surface Roughness:

- The energy that forms the sea surface energy spectrum is governed by energy balance equation, the first equation. Where E: Total energy, Vg: Group velocity, Ud: Wind-driven current speed.
- The energy flux is linked to wave-wind interaction, dissipation, and wave energy losses (the right side of equation).
- NRCS is related to the spectrum of short waves (< 1 m)

01

02

Key parameters to establish the surface spectrum for varied sea states:

- Short waves generated by the breaking of waves: linked to longer waves.
- Wave age and peak speed: the development stage of ocean waves
- Significant wave height and slope (period): depict wave form from long wave spectra.

Metrics for Scatterometer Wind and Sea State Parameters

when emphasizing scatterometer obtained winds, they are related to the stress transforming wind input (instantaneous energy input):

$$\tau =< \rho_a > C_{DN} u_{10s} \mathbf{u}_{10s}$$

(Wind stress)

$$C_{DN} = \frac{-\overline{uw}}{G\, u_{10N}^2} = \frac{-\overline{uw}\;\rho_a}{G\, u_{10s}^2 \langle \rho_a \rangle}$$

(Drag coefficient)

$$u_{10s} = \sqrt{\frac{\rho_a}{\langle \rho_a \rangle}}\, u_{10N}$$

(Neutral drag representation)

$$G_r = \frac{u_g}{u_M}. \quad G_{\mathrm{diff}} = u_g - u_M.$$

(Gustiness in ratio and difference forms)

The stress transforming wind input:

- Wind stress τ is obtained in the first equation and depends on the aerodynamic ocean roughness, which is obtained from scatterometer observations (as NRCS)
- Meanwhile, the drag C can be obtained in the second equation, with a neutral drag representation.

01

02

Wind variability is linked to Gustiness:

- Gustiness G, is involved in the wind input to the waves, represents wind variability, and associated with sea state.
- Obtained in two formats mentioned in existing scientific literature.

Metrics for Scatterometer Wind and Sea State Parameters

Wind GMF:

$$\sigma(u,\theta,\phi,p)=\left[a(u,\theta,p)+b(u,\theta,p)\cos(\phi)+c(u,\theta,p)\cos(2\phi)\right]$$

where *Φ* is the angle between the radar look-direction and the wind direction, and the coefficients *a*, *b* and *c* are found by inverting the above equation at up-wind, cross-wind, and down-wind looks.

The sea state parameters not directly related to scatterometer winds are not, or to an extent empirically integrated, and can be captured by:

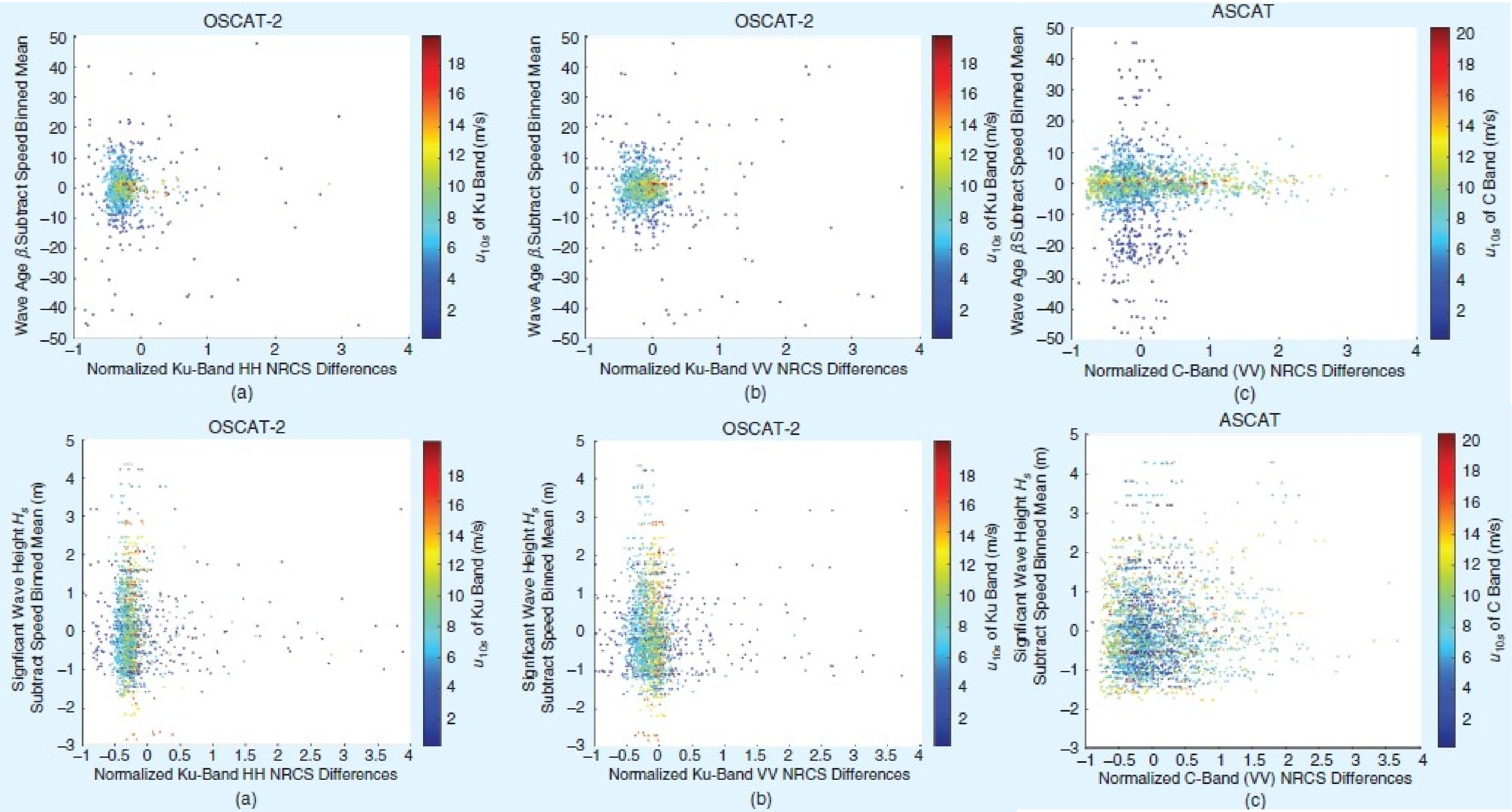
The components of a normalized Euclidean distance vector of the observations to the wind GMF model:

$$\sigma_{\mathrm{nor},i}=\frac{\sigma_i^o-\sigma_{\mathrm{sim\_}i}}{\sigma_{\mathrm{sim\_}i}}$$

where σ_i^o represents the ith NRCS within the WVC and N represents its total number; $\sigma_{\mathrm{sim\_}i}$ is the simulated value corresponding to σ_i^o. The $\sigma_{\mathrm{sim\_}i}$ are obtained from the GMF by applying the polarization, frequency, and observing geometry of σ_i^o and the evaluated wind vector of the WVC during the MLE minimization

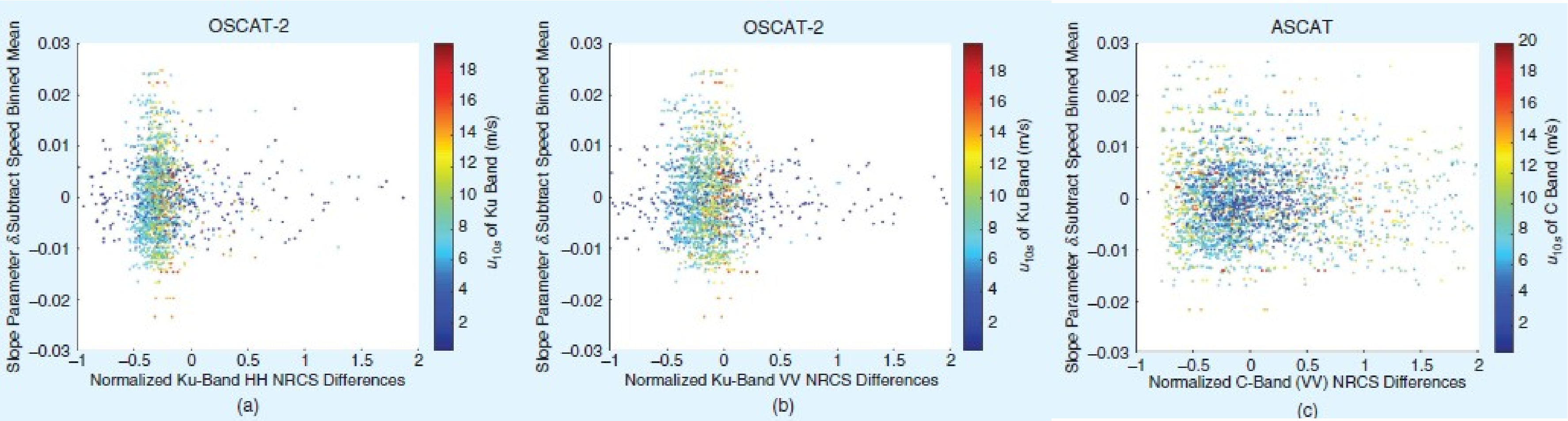
Experiments and Results

Experiments: To investigate signals contributed other than winds, we check the normalized residuals from wind GMF model against the sea state parameters from NDBC buoys. (Rain effects are identified by GPM collocations and not shown)

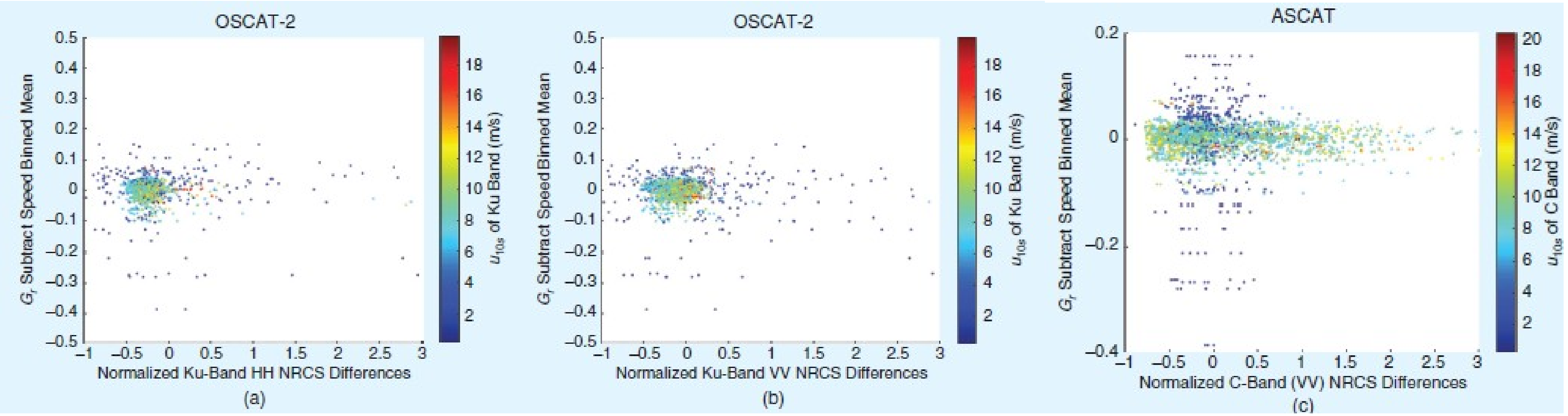


Wave age against normalized residuals and winds, Ku hh, Ku vv and C vv

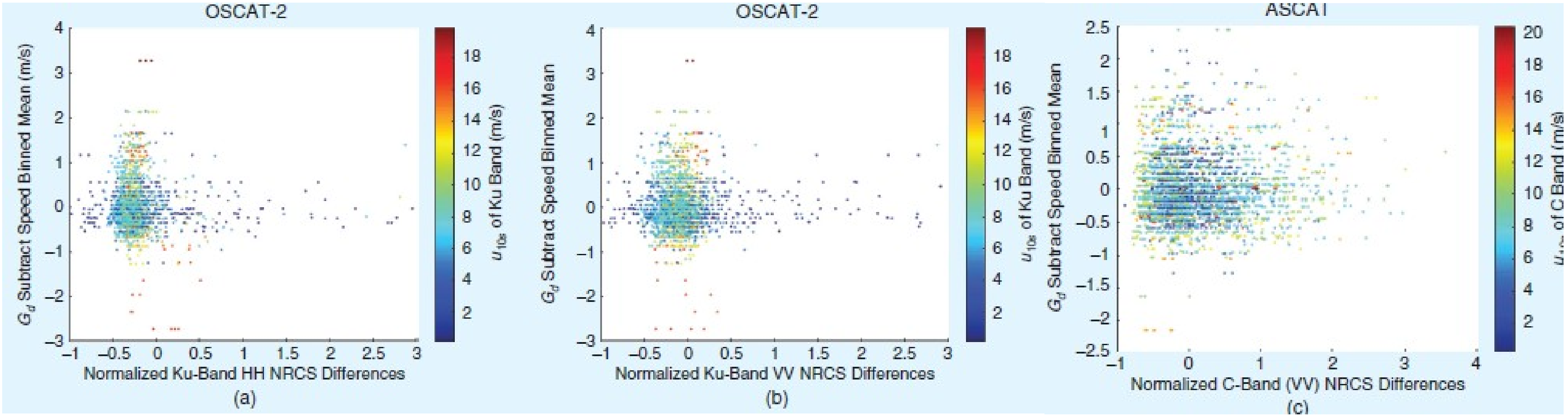
Significant wave height against normalized residuals and winds, Ku hh, Ku vv and C vv



Slope parameter against normalized residuals and winds, Ku hh, Ku vv and C vv



Gustiness in ratio from against normalized residuals and winds, Ku hh, Ku vv and C vv



Gustiness in difference from against normalized residuals and winds, Ku hh, Ku vv and C vv

The High Wind Case

In Tropical Cyclones:

01

Wave age

Waves are fetch-limited such that the input wind affects the significant wave height. This contrasts with fully developed seas with long fetches, where the wave growth becomes vanishingly small.

02

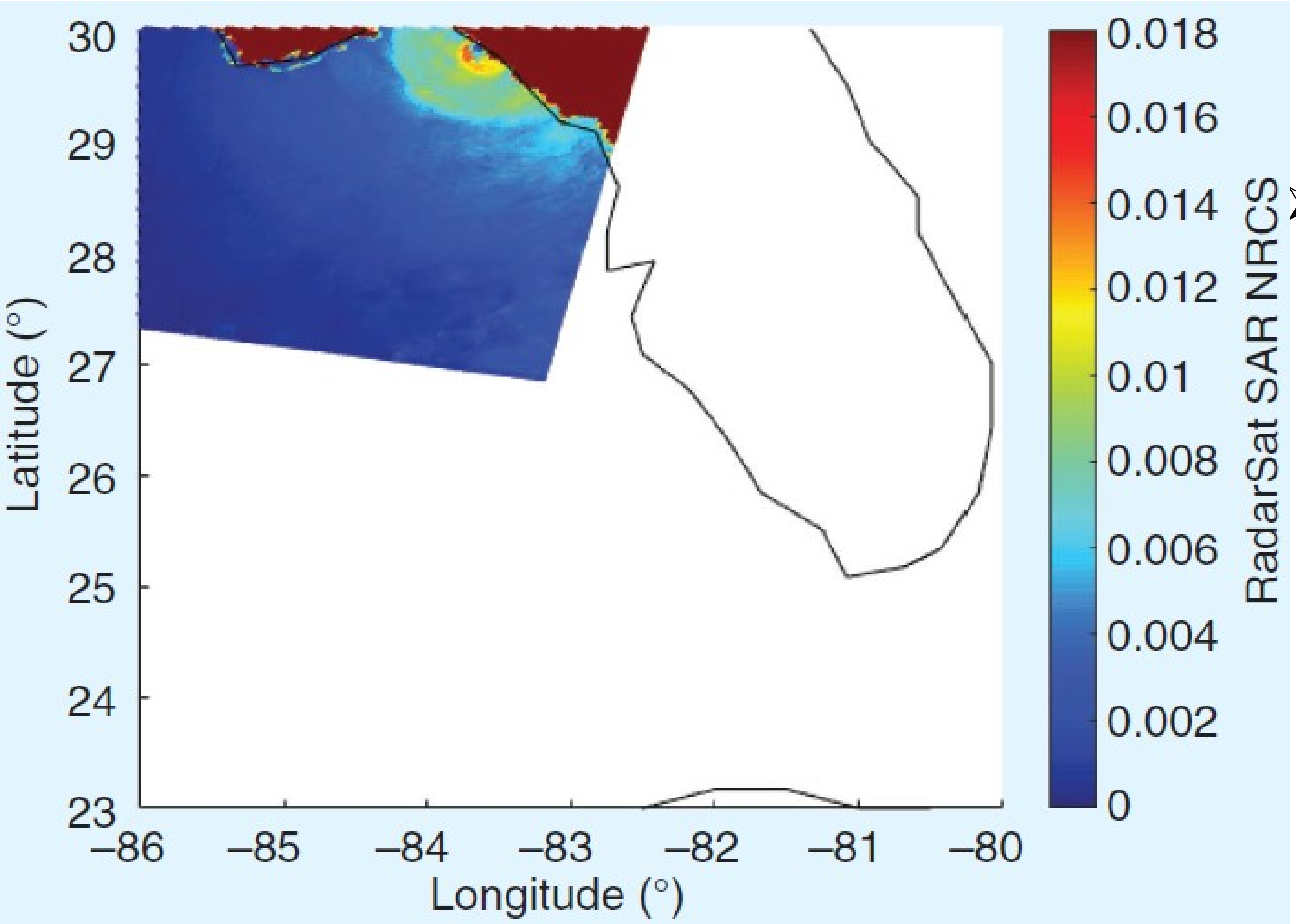
Direct input to long waves

In additional to centimeter waves, wind input can be empirically linked to significant wave height and the dominant wave period in a power equation in these cases.

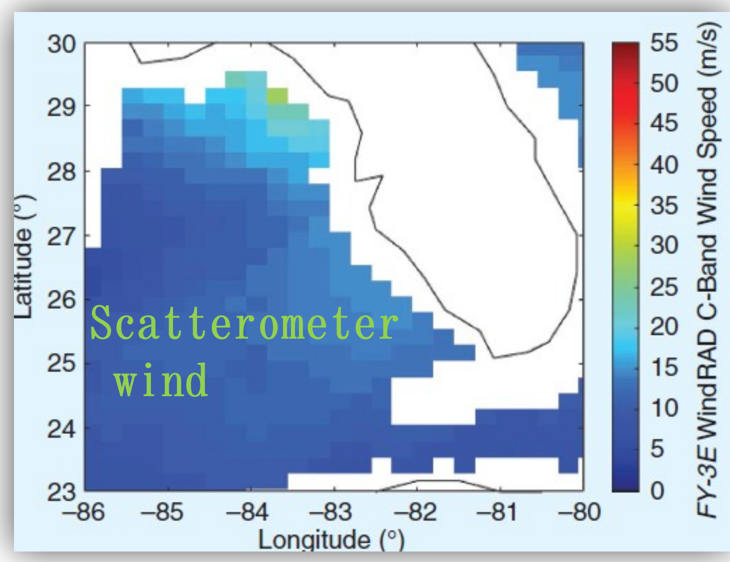
A pressing question:

Whether the overall principles mapping winds to the NRCS can be different in high-wind circumstances in young (not fully developed) and old (fully developed) seas.

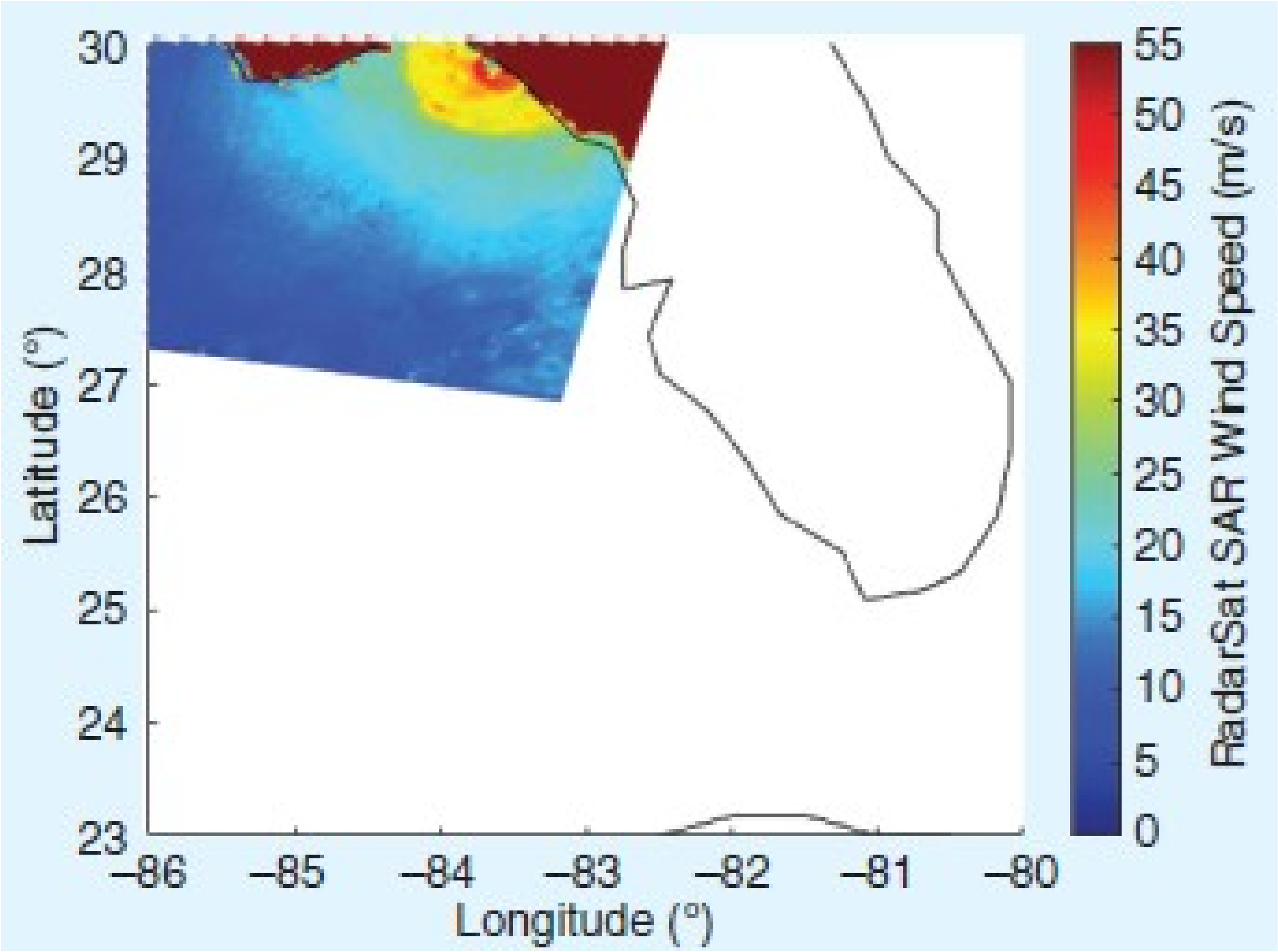
The High Wind Case: Hurricane Idalia

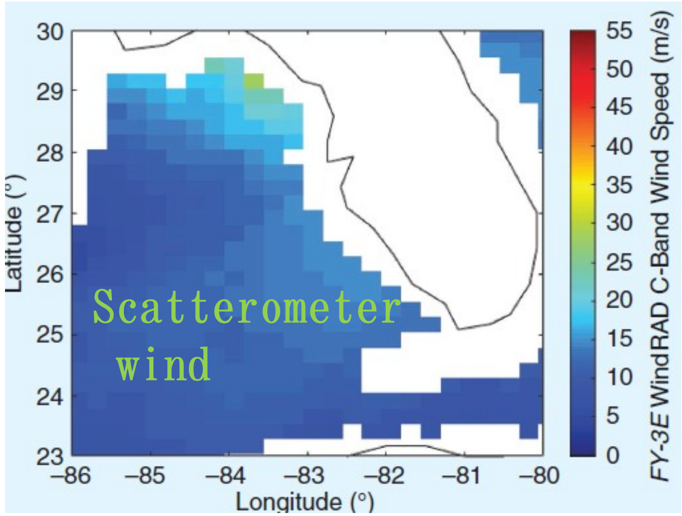


- In the collocated regions of scatterometer and SAR winds, the spatial resolution of scatterometers is lower than that of SAR observations.
- Due to this, a lack of detailed representation by scatterometer winds can be observed, in contrast with the SAR wind: scatterometer winds have lower maxima due to their larger footprint.



A High Wind Case: Hurricane Idalia





- The symmetric and dense structure of a major hurricane is easy to observe.
- Comparing the north and south, differences due to the fetch condition are not observed.
- GMF wind direction effects appear, as the stronger radial symmetry in the inner core than outer region.
- In the coarser resolution from scatterometer, the symmetric features of wind are also quite obvious.
- Wave conditions do not affect scatterometer high winds.
- GMF requires further improvement.

Key Findings and Future Directions

Take home findings:

01.

Geophysical elements that depend on surface vector wind are well incorporated into empirical GMFs, and hence, the mapping of wind-induced NRCS values in a WVC to the mean flow above the air–sea interface works well.

02.

Longer waves and nonlocal sea state effects may be neglected. Factors other than waves inducing deviations from GMFs are confirmed to be rain and SST, which can be labeled or corrected.

03.

The hurricane case confirms that the NRCS sea state dependency is small and also difficult to observe.

Key Findings and Future Directions

Future directions:

For high winds

- GMF modification can be done, however is complex for the Ku band due to rain.
- Cross-pol for Ku band could also be helpful.

To better define ocean surface conditions

- Future Doppler measurements observing wave motion and currents.

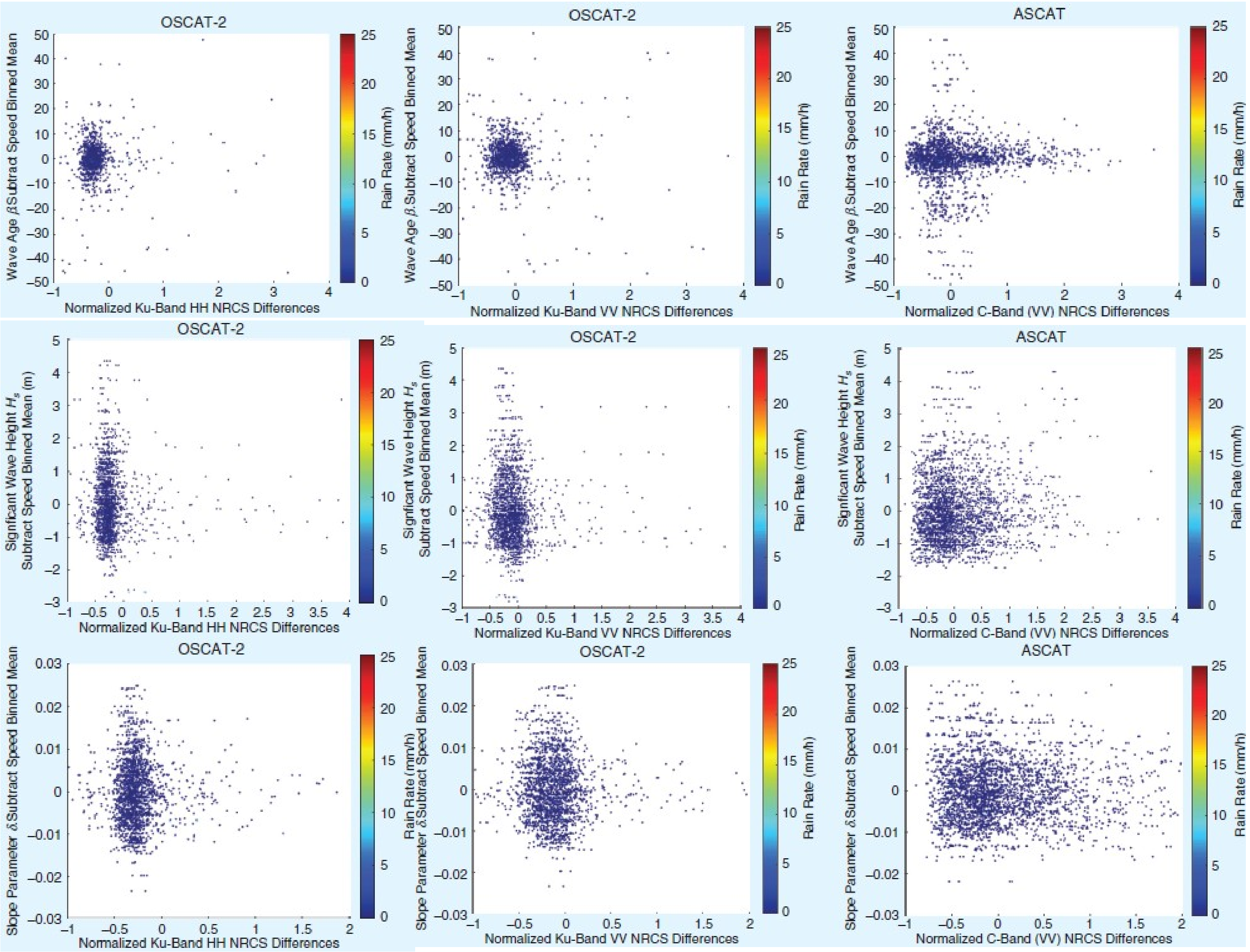
Related content and references in the paper:

X. Xu and A. Stoffelen, "Wind and Sea State Signatures in Wind Scatterometry: An analysis,“ in IEEE Geoscience and Remote Sensing Magazine, online published: Dec., 2024. doi: 10.1109/MGRS.2024.3501472. (https://ieeexplore.ieee.org/document/10811669)

Thank you!

Questions and suggestions?

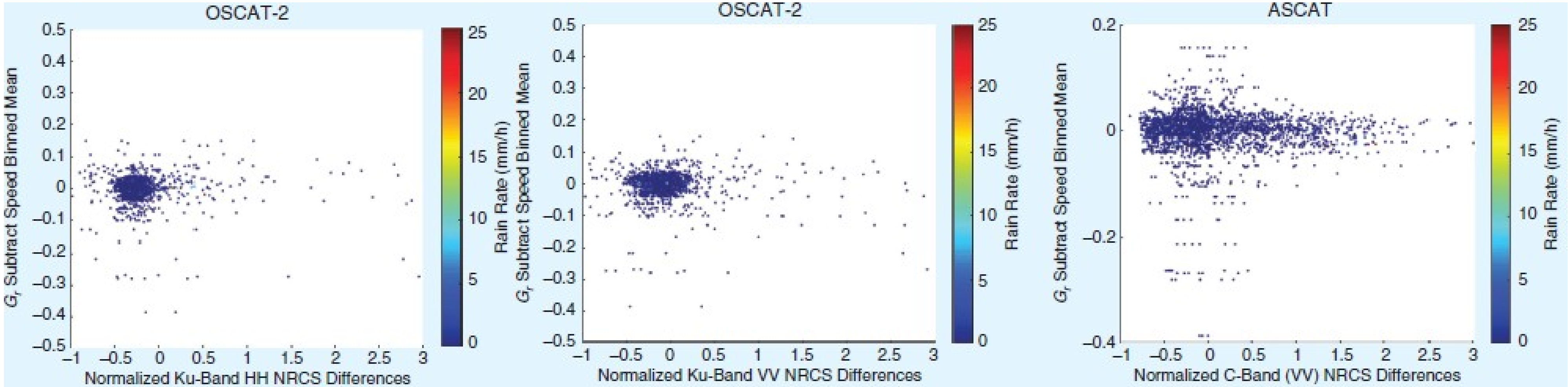
Rains:



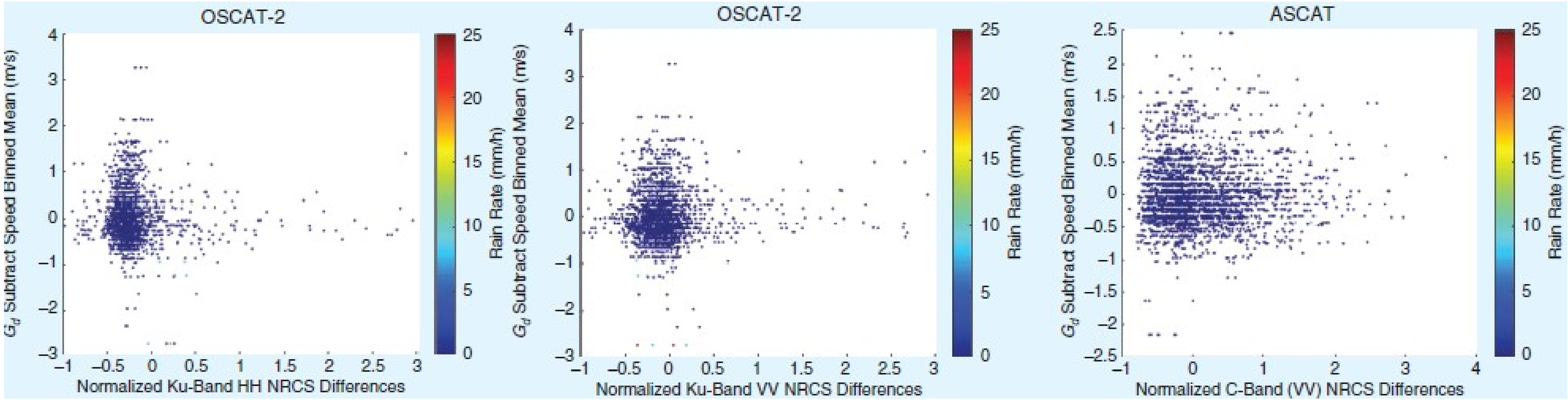
Wave age

Significant Wave Height

Slope Parameters



Gustiness in ratio form



Gustiness in difference form

There are mainly two reasons in addition to the rain condition that may cause the anomalies:

- 1) The first relates to the dynamic part in the momentum transfer induces significant motion variance. This can be a large variance in the dominant wave direction as well as significant dispersion in the wind and dominant wave directions.
- 2) The second concerns the thermomechanical, i.e., local temperature gradients may cause convective variability. This can be presented by the differences between the air and ocean surface temperatures.

Specific cases please refer to the published paper.