GNSS+R 2025
Leiden, NL 23-25 April 2025

The Sensitivity of GNSS-R Ocean Surface Wind Speed to Wind Transience

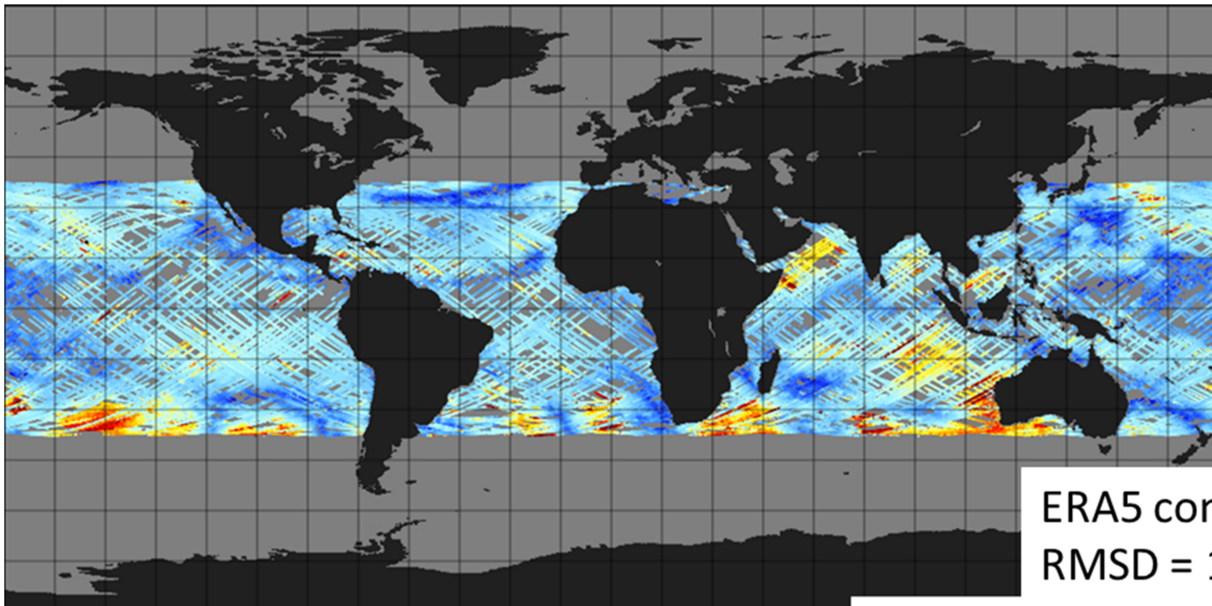
Chris Ruf[1], Darren McKague[1], Anthony Russel[1],
Dorina Twigg[1], April Warnock[2]

1. University of Michigan, Ann Arbor, MI USA
2. SRI International, Ann Arbor, MI USA

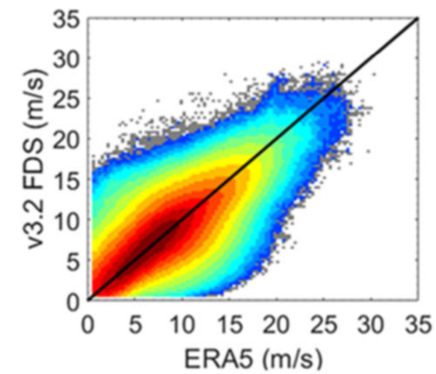
CYGNSS Mission Overview

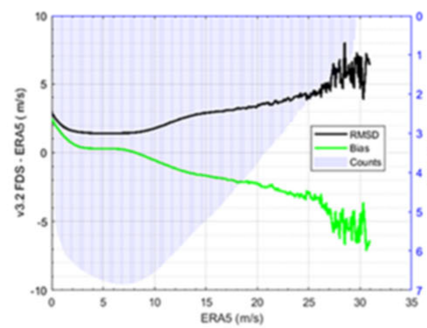
- Original Mission Objectives
  - Measure ocean surface wind speed in all precipitating conditions with sufficient frequency to resolve tropical cyclone rapid intensification
- Flight Segment Design
  - Eight satellites in low earth orbit at 35^o inclination, each carrying a modified GPS receiver for bistatic radar measurement of GPS signals scattered by the Earth surface
- Expanded Science Scope (measurements over land)
- Mission Timeline
  - Launch 15 Dec 2016
  - Science Phase E since Mar 2017
  - One of eight satellites lost Nov 2022
  - Currently in extended Phase E with 7 of 8 operating nominally

CYGNSS Global Wind Speed (FDS v3.2)



ERA5 comparison to CYG FDS v3.2
RMSD = 1.7 m/s, Bias =-0.2 m/s





Relationship between GNSS-R Measurement and Ocean Surface Conditions

- Bistatic link equation gives scattered power received as a function of ocean surface scattering cross section, $\boldsymbol{\sigma_0}$

$$P_g^R(\tau, f) = \frac{\lambda^2}{(4\pi)^3} \iint_A \frac{(P_T G_T)\boldsymbol{\sigma_0}\, G_R}{\left(R_{x,y}^R\right)^2 \left(R_{x,y}^T\right)^2 L_{a1} L_{a2}} \Lambda_{x,y}^2(\tau) S_{x,y}^2(f) dxdy$$

- Scattering cross section is related to the mean square slope of surface height (R is Fresnel reflection coefficient)

$$\sigma_0 = \frac{|R|^2}{mss}$$

- MSS is the second moment of the surface height spectrum

$$mss = \iint_{\kappa<\kappa_{\text{cutoff}}} \kappa^2\, \Psi(\vec{\kappa}) d^2\kappa$$

Differences between GNSS-R and Traditional Ocean Wind Scatterometers

- Scatterometers are primarily sensitive to the capillary wave portion of the roughness spectrum at the Bragg resonant wavelength of the backscattered microwave signal. Capillary waves are closely coupled to the local wind speed at the time of the radar observation.
- GNSS-R is sensitive to the integrated roughness spectrum over both capillary and longer waves
  - In fully developed seas, the shorter and longer portions of the roughness spectrum are in equilibrium and both GNSS-R and scatterometers are sensitive to the local wind
  - In young (underdeveloped) seas, GNSS-R is sensitive to longer portions of the roughness spectrum that are not forced by the local wind at the time of the observation, and a correction for this sensitivity is necessary (typically using ancillary SWH information from a model)
- GNSS-R is very weakly sensitive to wind direction
  - Poor ability to detect wind direction (*bad*)
  - Little dependence of wind speed error on wind direction (*good*)

Wind Speed Assessment Paper
Sea State Sensitivity of Wind Speed Retrieval

- **Recent publication assessing CYGNSS wind speed data products**

  Ruf, C., M. Al-Khaldi, S. Asharaf, R. Balasubramaniam, D. McKague, D. Pascual, A. Russel, D. Twigg, A. Warnock (2024). Characterization of CYGNSS Ocean Surface Wind Speed Products. *Remote Sensing*, 16, 4341, doi: 10.3390/rs16224341.

- **Paper outline:**

  1. & 2. Introduction & Materials and Methods

  3. Results

     3.1 Intercomparisons with Reference Wind Speeds

     3.2 Triple Colocation Validation

     3.3 Sampling Properties

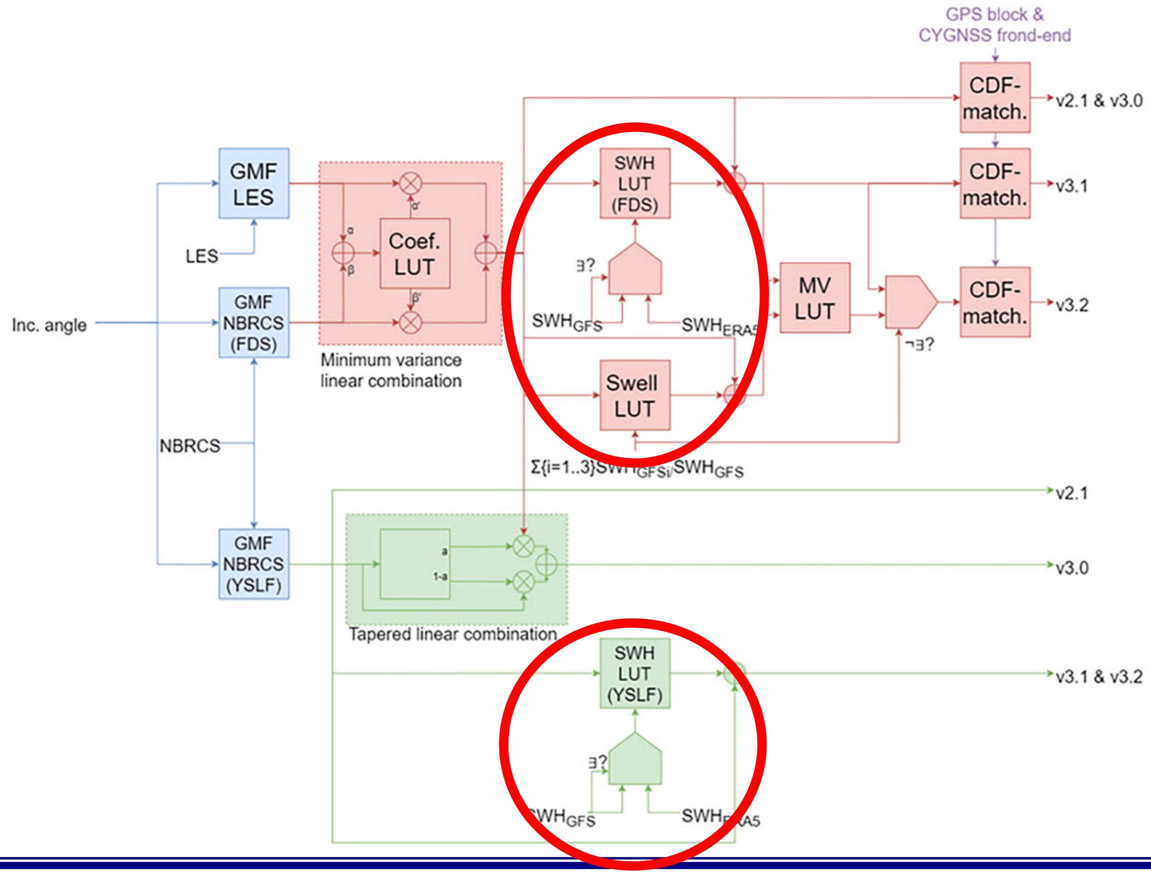
     3.4 Sensitivity to Significant Wave Height

     3.5 Sensitivity to Wind Speed Transience

  4. & 5. Discussion & Conclusions

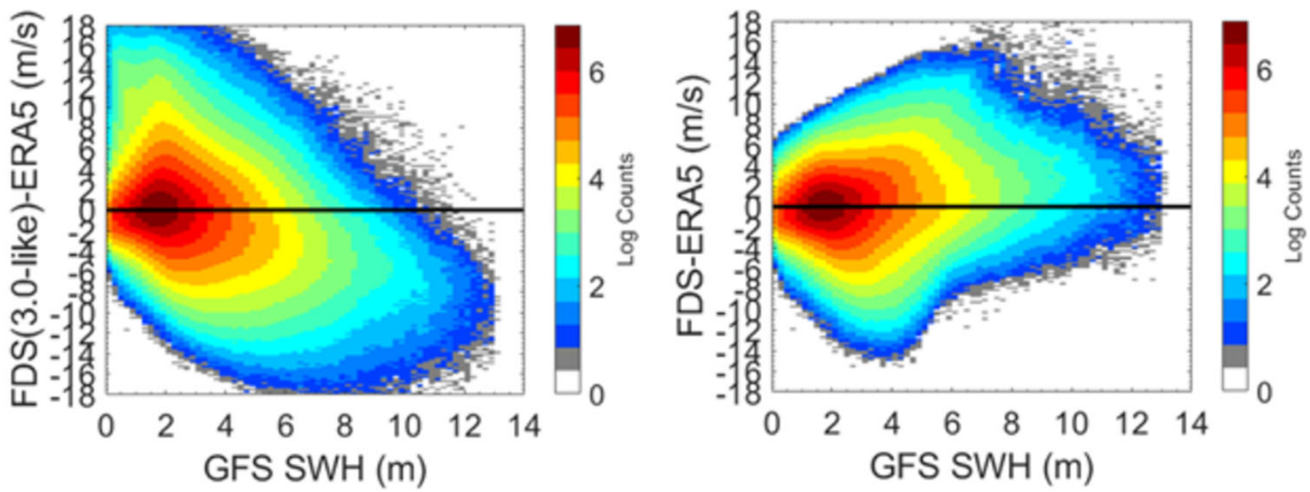
Correcting for SWH Dependence

- Level 2 wind speed processing flow: Fully Developed Seas (FDS) (red) and Young Seas with Limited Fetch (YSLF) (green).



Effectiveness of SWH Correction

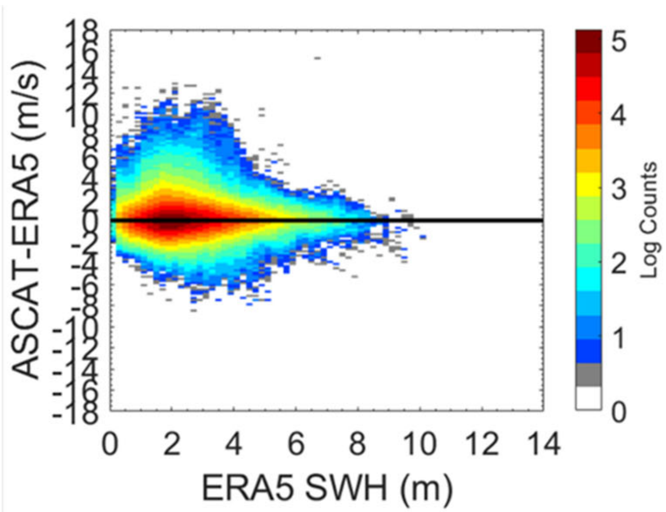
- ❖ **Dependence of CYGNSS wind speed error on SWH**
  - ❖ **(a) FDS wind speed product without SWH correction**
  - ❖ **(b) FDS wind speed product with SWH correction**



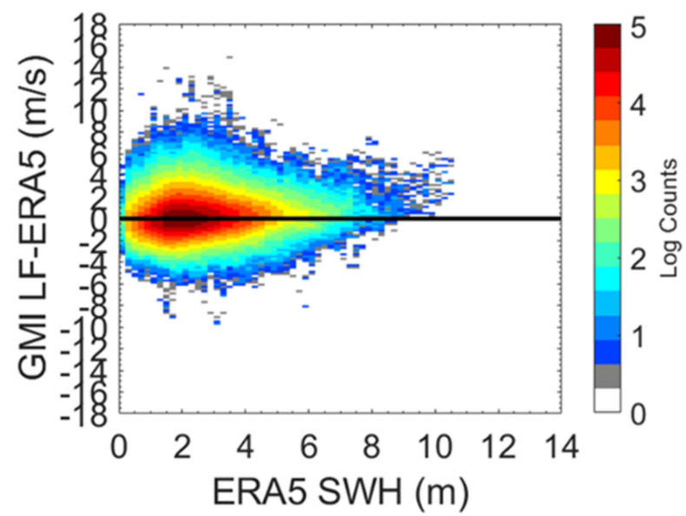
(a) (b)

Sensitivity (or lack thereof) to SWH by other Remote Sensing Modalities

- **Dependence of wind speed bias on SWH for other types of sensors**
  - **(a) ASCAT (backscatter radar – Bragg resonant with capillary waves)**
  - **(b) GMI (microwave radiometer – fractional foam coverage)**



(a)



(b)¶

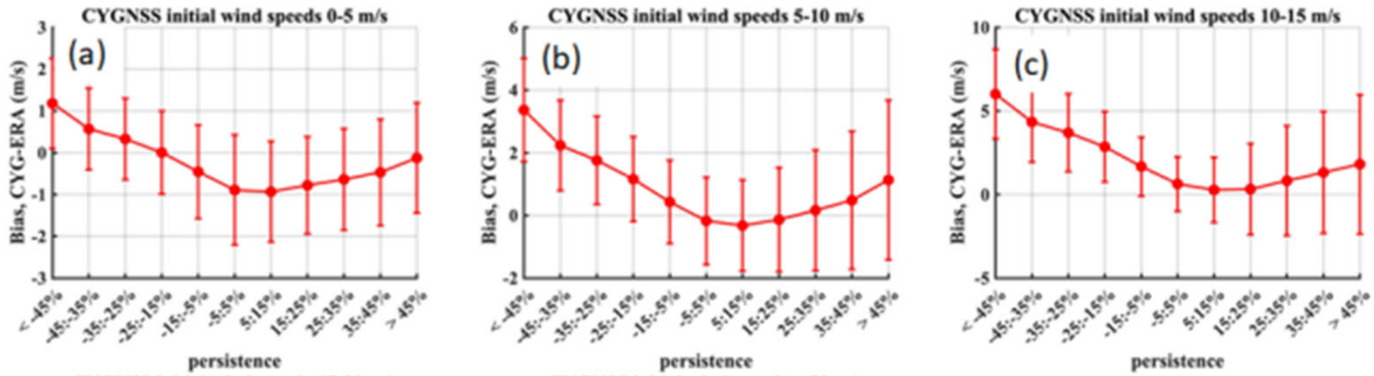
Transient Wind Speed

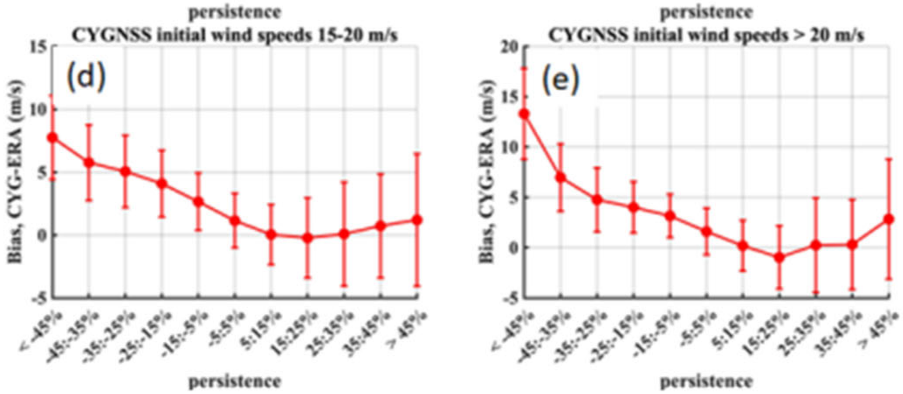
- A young sea state is characterized by an imbalance between the short and long wave portions of the ocean roughness spectrum
- Young seas can occur when the wind is changing.
- Wind speed transience is defined to quantify the change in wind speed prior to a remote sensing observation

$$\mathrm{transience}(t) = \frac{\mathrm{windspeed}(t) - \mathrm{windspeed}(t - 2\mathrm{hr})}{\mathrm{windspeed}(t)}$$

Dependence of GNSS-R Retrieval Bias on Wind Transience

- Bias in CYGNSS wind speed as a function wind speed transience for wind speed ranges of (a) 0–5 m/s, (b) 5–10 m/s, (c) 10–15 m/s, (d) 15–20 m/s, (e) >20 m/s. Transience<0 implies prior winds were higher in the past. Error bars are the stdev of samples in each wind speed and transience bin.





Bias is the average (FDS–ERA5) difference for all of CY2022.

Impact of Transience Bias on Global Performance Statistics

- Dependence of wind speed bias (CYGNSS–ERA5) on wind transience at typical and high wind speeds
- Note low frequency of occurrence of high wind speeds
- Note low frequency of occurrence of high transience winds
- Note high retrieval bias in high wind/high transience corner case

Wind Speed Range (m/s)	**5-10 m/s**			**>20 m/s**		
% of Samples	62%			0.02%		
Transience Range	**t<-25%**	**t>-25, t<25%**	**t>25%**	**t<-25%**	**t>-25, t<25%**	**t>25%**
% Samples @Wind Speed (FDS/ERA5 matchup)	3.27%	94.88%	1.85%	2.93%	95.38%	1.69%
FDS – ERA5 Bias (m/s)	2.32	0.00	0.40	9.48	2.05	1.34

Summary

- GNSS-R "measurements" of ocean surface wind speed are actually measurements of ocean surface roughness over a range of the roughness spectrum
- The shorter (capillary wave) portion of the roughness spectrum responds quasi-instantaneously to the local wind speed
- A "fully developed sea" implies that an equilibrium exists between the shorter and longer portions of the roughness spectrum
  - This occurs if the winds have blown in the same direction at the same speed for a sufficiently long time (1-2 hrs)
- Biases in the retrieved wind speed due to anomalous short-to-long wavelength portions of the roughness spectrum can be corrected. using SWH information
- Biases can also occur if the seas are underdeveloped (a.k.a. "young") because the winds have recently changed