Forward Model Simulation of Swell Effects in SMAP Near-Coastal High-Resolution NRCS Data

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Motivation

- Radar observations of the sea surface can provide information on key geophysical parameters such as :
  - Wind speed + Wind direction
  - Ocean wave properties (effects are second order)

- Recent L-band radar systems have also demonstrated a wind retrieval capability based on empirically-derived Geophysical Model Functions (GMFs)
  - PALSAR (single pol, high spatial resolution)
  - Aquarius (multi-pol, multi-angle, resolution O (100 km))
  - SMAP (multi-pol, single angle, wind retrievals shown at ~ 30 km resolution)

- SMAP radar also provides a 1 km resolution product called "L1C data"
  - Do these provide additional higher resolution information on ocean winds or waves?
  - Can possible swell wave effects be modeled using approximate EM scattering models?

Objectives

1) **Forward model SMAP L1C data using approximate EM scattering models**
2) **Investigate the presence and impact of ocean swell waves on SMAP L1C data**

Outline

Motivation

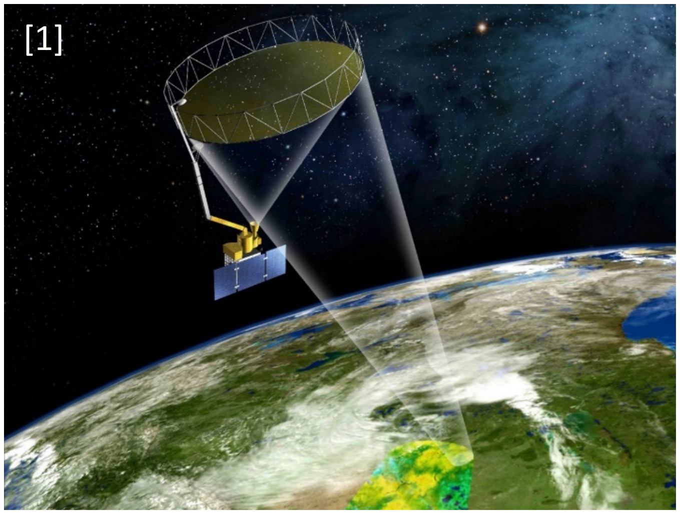
SMAP mission overview

Forward Modeling of SMAP L1C Data

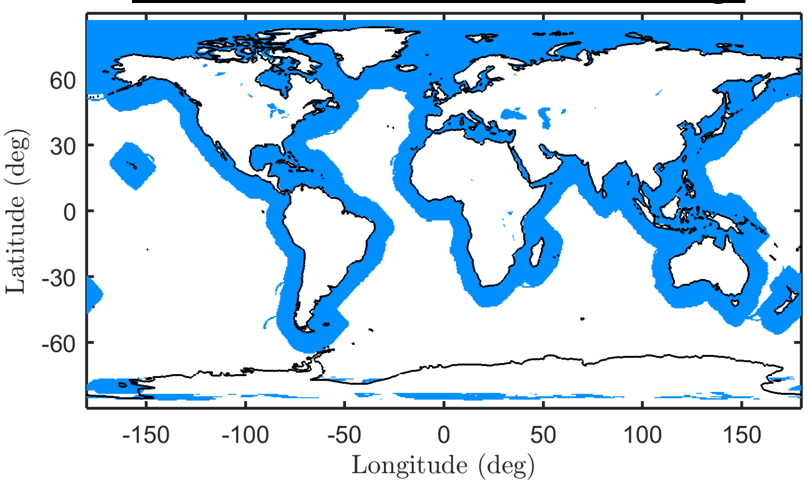
Results

Concluding remarks

Soil Moisture Active/Passive (SMAP) Mission



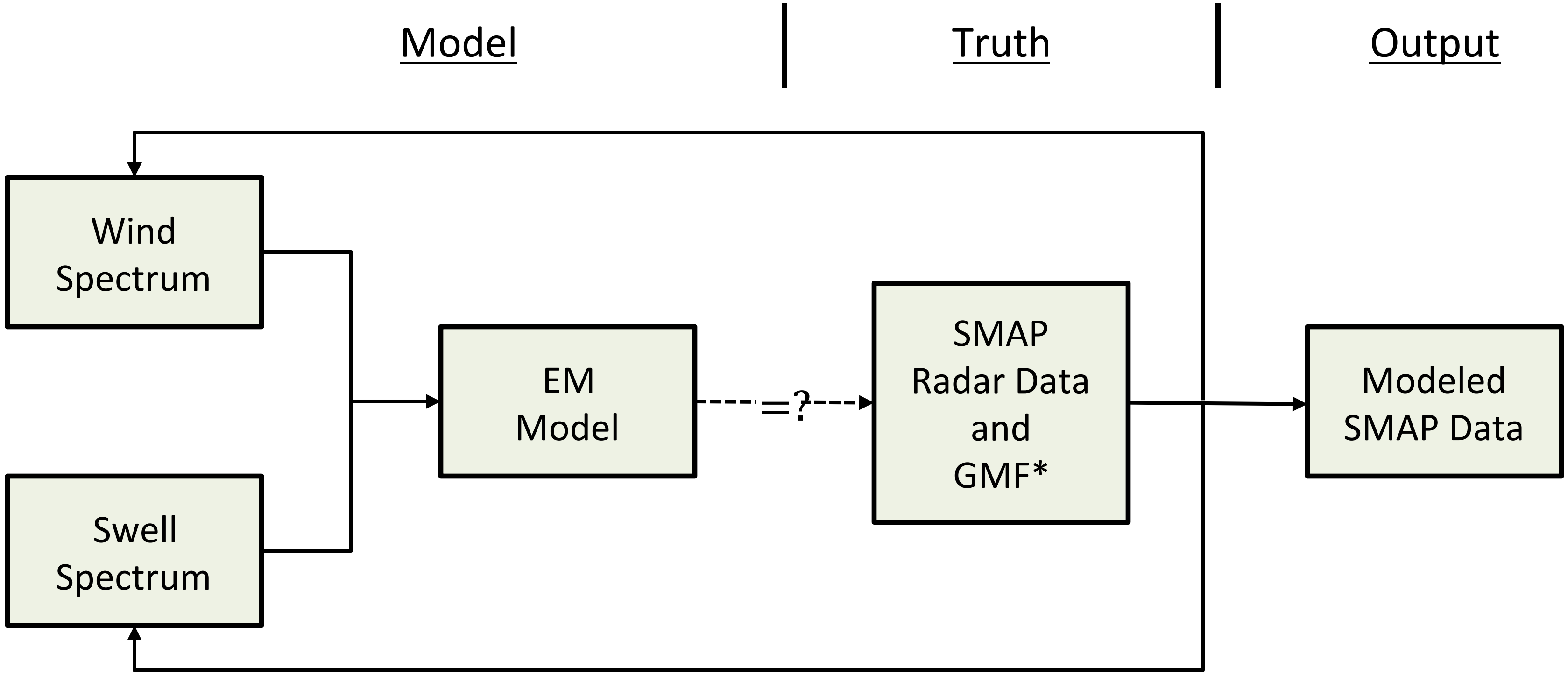
SMAP L1C Near-Coastal Global Coverage



- Objective: provide accurate soil moisture and freeze/thaw measurements over land surfaces
- L-band radar (1.26 GHz) and L-band radiometer (1.41 GHz)
- Global revisit rate: 2-3 days
- Multiple radar polarizations: HH, VV, HV (operated for ~ 3 months)
- Two high- and low-resolution SAR radar data products
  - L1B – 30 km multi-looked SAR imagery
  - L1C – 1 km multi-looked SAR imagery
- Over 3 TB of L1C data from the operation window available for analysis

[1] http://smap.jpl.nasa.gov/resources/59/

Forward Modeling Overview



- Wind Spectrum: Based on the Durden-Vesecky (DV) spectrum
- Swell Spectrum: Based on the JONSWAP spectrum
- EM Model: Two-scale (composite) model (co-pol); SSA2-HF (cross-pol)

- Represents swell effects as an additional slope contribution

Two-Scale Model (TSM)

- Two-scale Model

$$\sigma_{0,ij}^{SEA}(\theta) = \int_{-\infty}^{\infty} d(\tan\psi) \int_{-\infty}^{\infty} d(\tan\delta)\, \sigma_{ij}'(\theta')\, P(\tan\psi, \tan\delta)\, W(2k_0 \sin\theta')$$

  - ψ: In-plane tilting; δ: Out-of-plane tilting; θ: Incidence angle
  - $\sigma_{ij}'(\theta)$: Tilted, rotated backscatter coefficients combing first order SPM kernels in multiple polarizations
  - $P(\tan\psi, \tan\delta)$: Slope PDF of large-scale roughness due to wind
  - $W(\cdots)$: Spectrum model (based on the DV spectrum)
  - Cutoff wavenumber: $k_c = k_0/2$

- Integration over slope PDF performed numerically
  - Additional swell-induced contributions to slope variances can also be included

- Captures "tilt" effects on co-pol returns as well as tilt-induced creation of cross-pol backscatter
  - Neglects second order multiple scattering cross-pol contributions however

G. R. Valenzuela, "Theories for the Interaction of Electromagnetic and Oceanic Waves | A Review," *Boundary-Layer Meteorology*, vol. 13, no. 1, pp. 61-85, Jan 1978.

SSA2 (Second-order Small Slope) High-Frequency (HF) Approximation

- SSA2-HF Model
  - TSM does not account for second-order scattering effects
  - Use of SSA2 constrained by its computational complexity
  - Use SSA2-HF proposed by C. A. Guerin and J. T. Johnson in 2015

$$\sigma_{hv}^{0} = 4\pi |G|^2 \cot^2 \theta_i \; Q_H^4 \, W(\mathbf{Q_H}) s_y^2$$

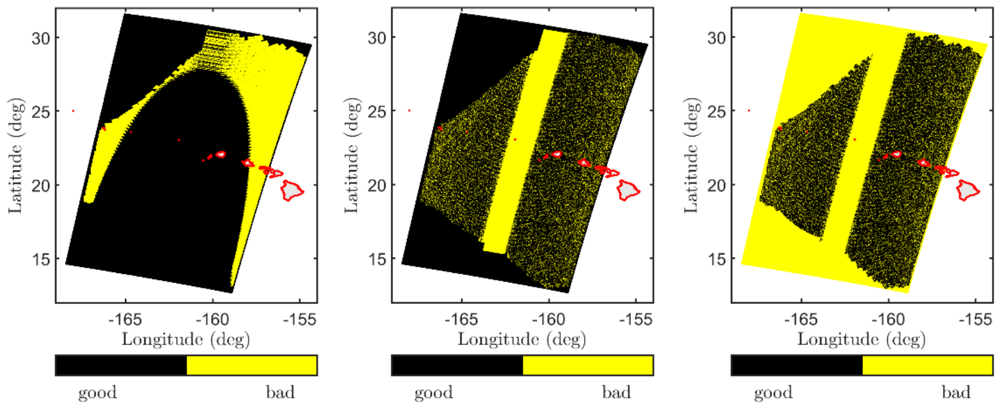
- $Q_H = 2k_0 \sin\theta_i$
- G: A function of permittivity
- s_y^2 : Cross-plane slope variance

$$s_y^2 = \int_0^{2\pi} \int_0^{k_0} k^2 \sin^2 \phi \, S(k,\phi) k\,dk\,d\phi$$

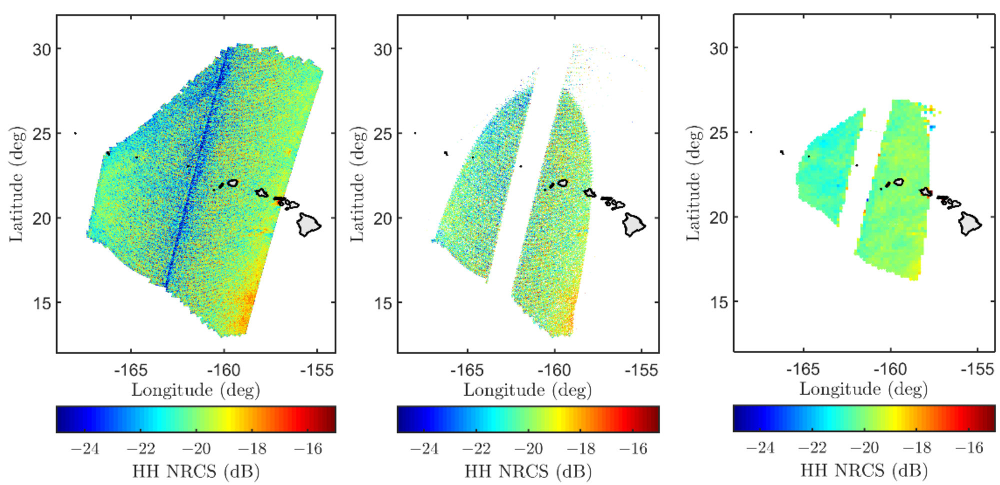
C. Guerin and J. T. Johnson, "A Simplied Formulation for Rough Surface Cross-Polarized Backscattering Under the Second-Order Small-Slope Approximation," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 11, pp. 6308-6314, Nov 2015

Truth Data – Constructing a NRCS vs. Wind Match-up Dataset

SMAP Quality Flags

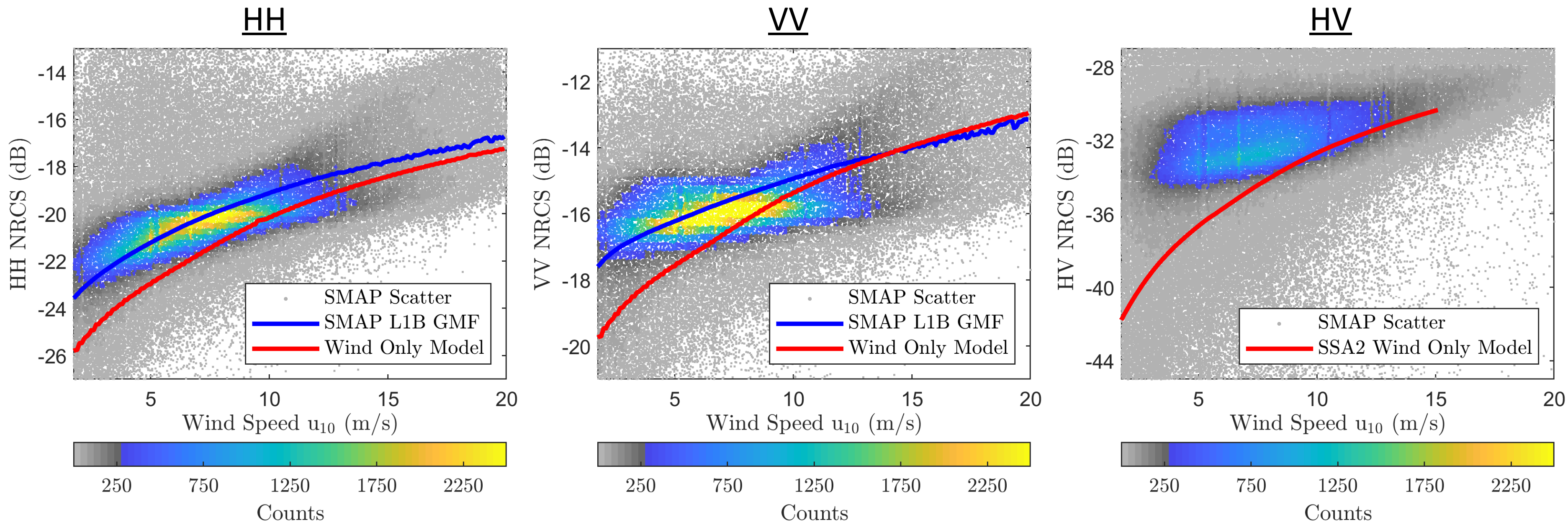


Data Processing Steps



- Apply SMAP Quality flags
- Use NOAA GFS operational winds through WW3 model
  - Available over multiple resolutions
  - Primarily use *glo_30m*
- Degrade SMAP spatial resolution to WW3 wind resolution using a nearest neighbor algorithm
- Apply user-defined spatial filters to minimize contamination due to land clutter and sea ice
- Results in a NRCS vs. Wind match-up dataset

Truth Data – SMAP-based Scatter plots and GMFs



- GMF: 2nd order cosine-series Zhou et. al, JSTARS 2017; based on SMAP L1B data
- GMF captures the SMAP backscatter NRCS scatter density data more accurately compared to TSM model predictions using the fully-developed wind-driven DV spectrum
  - Model underestimates; the dependence of this underestimation on polarization and wind speed indicate the presence of swell waves
  - GMF includes swell effects

Wind + Swell Model

- Model Assumptions:
  - Wind seas driven by local winds sources
  - Swell seas driven by remote winds sources
  - Two contributions are independent

$$S(k,\phi)=S_w(k,\phi)+S_s(k,\phi)$$

$$s_x^2 = s_{x,w}^2 + s_{x,}$$

$$s_y^2 = s_{y,w}^2 + s_{y,}$$

- Slope variances (second-order moments) add linearly

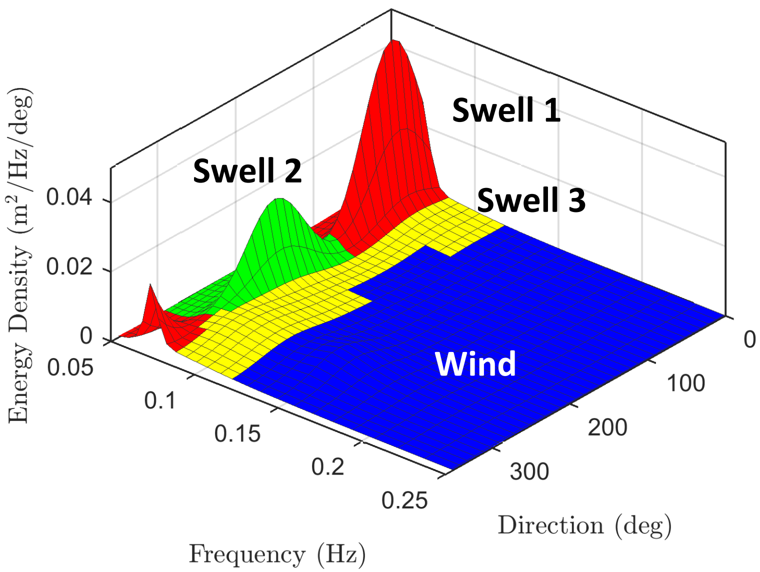
$$s_{x,y}^2 = \int_0^{2\pi} \int_0^{k_c} k^2 \{\cos^2\phi, \sin^2\phi\} S(k,\phi) k \, dk \, d\phi$$

- Captures swell-effects as an excess slope contribution
  - Introduces additional tilting of Bragg waves under TSM

- Need swell-only slope variances
  - Can leverage existing models (WW3, ECMWF, ect…), but MSS is not publically available
  - Compute 2-D swell-only spectrum $S_s(k,\phi)$

- Latter approach pursued

2D Swell Spectrum : JONSWAP Spectrum with WW3 Partitioned Data



Partition #	H_s [m]	T_p [s]	Λ [m]	ϕ [deg]	σ_ϕ [deg]	W_f
0	2.93	11.28	198.59	325.99	33.22	0.13
1	2.80	11.55	208.36	326.48	24.49	0.15
2	0.62	9.21	132.51	1.83	6.94	0
3	0.37	13.72	293.87	191.07	10.12	0
4	0.34	11.03	189.83	193.14	7.73	0

Total wave-field | Wind-sea partition | Swell-only partitions

- Swell spectrum definition:

$$S_s(f,\phi)=\sum_n S_{s,n}(f,\phi)$$

$$S_{s,n}(f,\phi)=1/f\, S_{s,n}(f)\Psi_s(f,\phi)$$

- 1D Spectrum – Use JONSWAP Spectrum:

$$S_s(f)=C_0\, g^2 (2\pi)^{-4} f^{-5} e^{-1.}$$

$$f=f/f_m$$

$$G=e^{-(f-f_m)^2/2\sigma^2 f_m^2}$$

- Spreading Function: Use $\cos^{2s}$ form

$$\Psi_s(f,\phi)=A_0 \cos^{2s}[(\phi-\phi_m)/2]$$

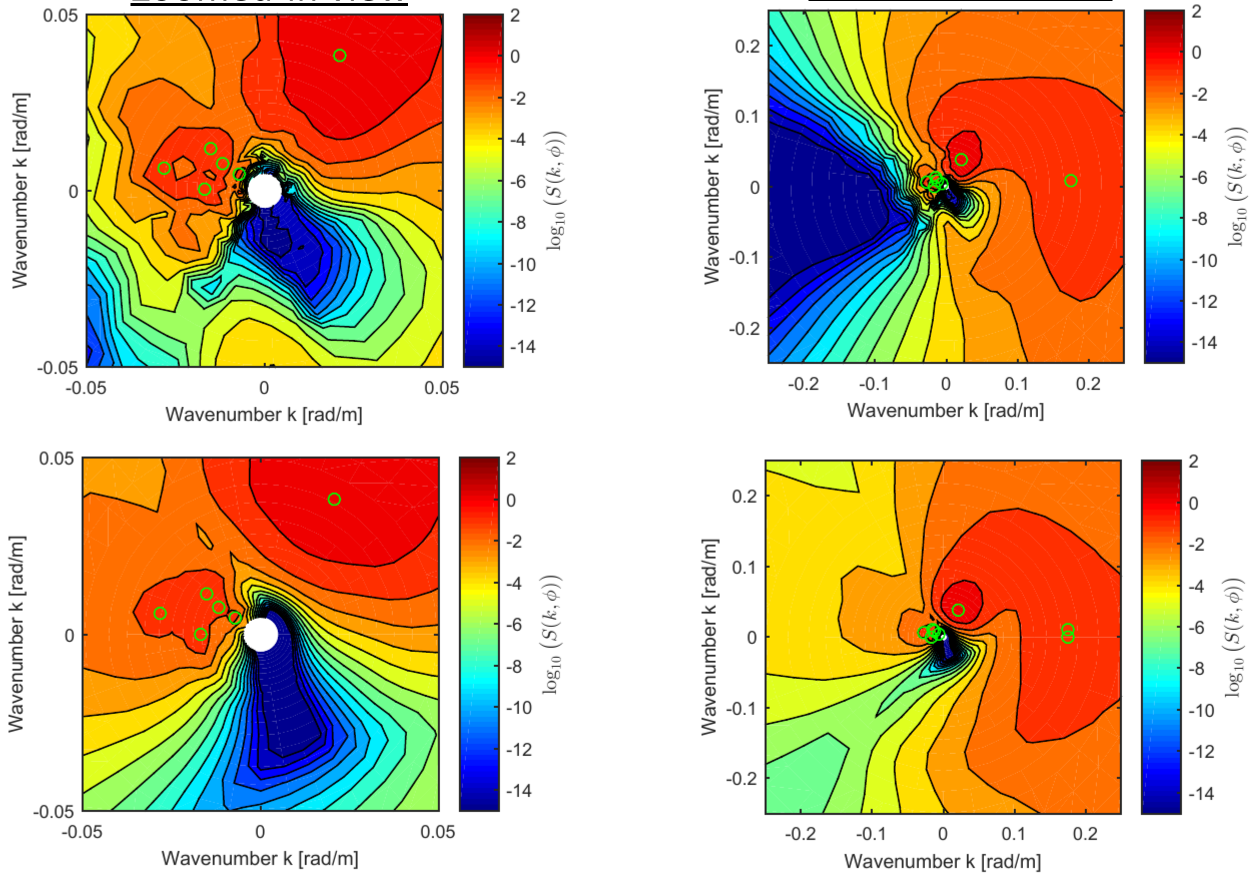
$$s=2/\sigma_\phi^2-1$$

Modeled 2D Swell Spectrum – Comparison with Buoy Spectra

Zoomed-in view | Zoomed-out view

Buoy Spectra
(Wind + Swell)

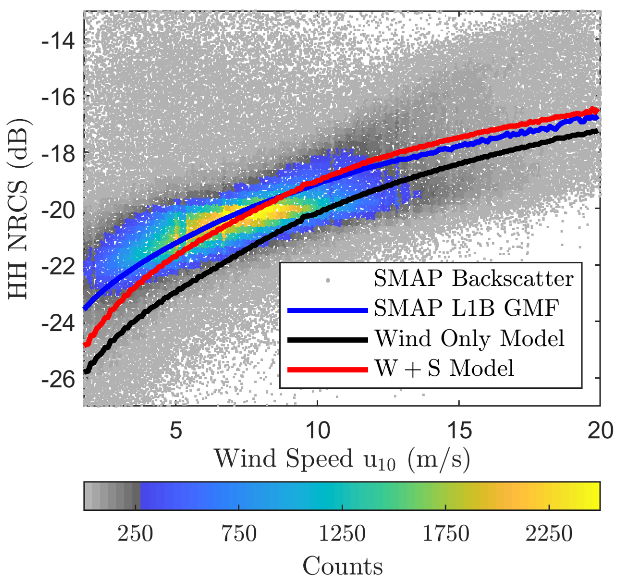
Modeled Spectra
(swell-only on left;
Wind + swell on right)



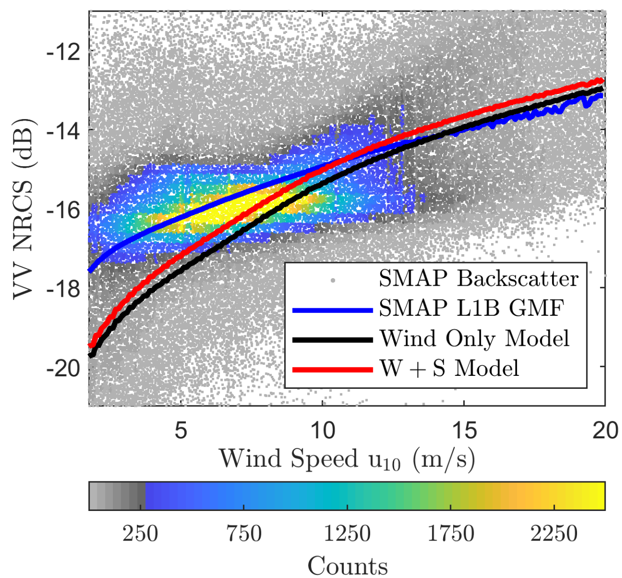
- Modeled swell-only spectra capture swell contributions reasonably accurately in both magnitude and direction. They can be numerically integrated to compute swell-only slope variances

Initial Results

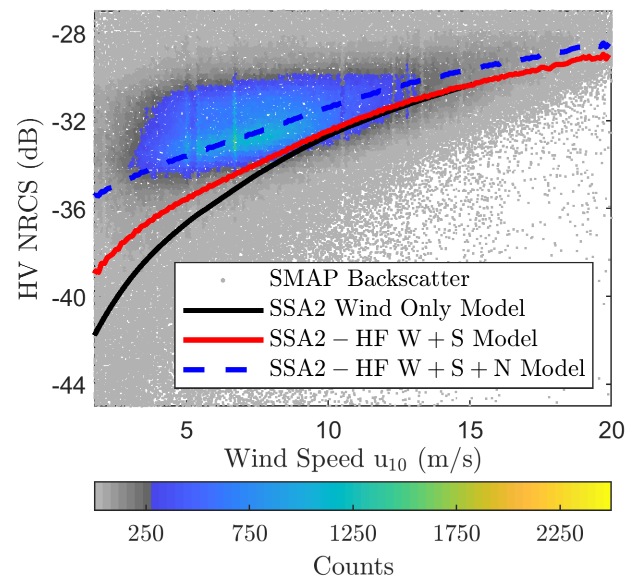
HH



VV



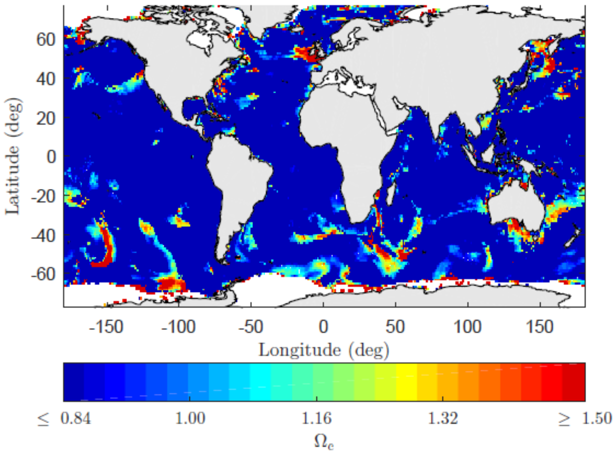
HV

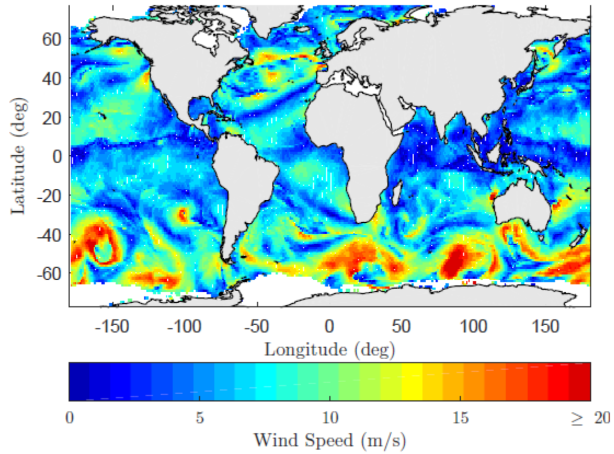


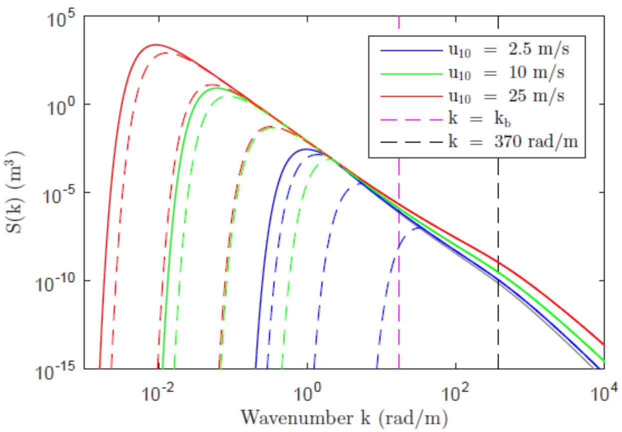
- All polarizations respond to swell in varying degrees
  - VV – very limited response to swell
  - HV – swell observations are limited by system noise (-38 dB noise added)
  - HH – clear response to swell—proceed further

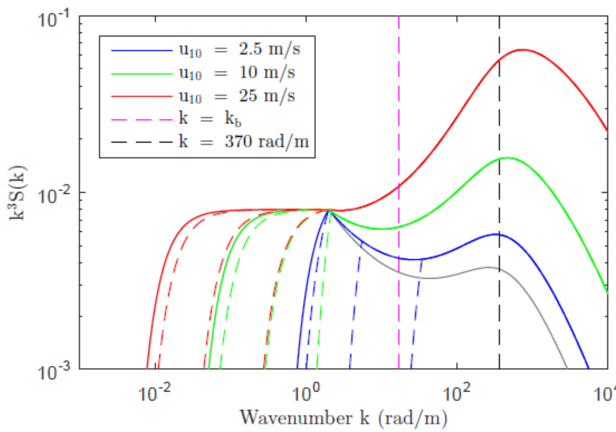
- Model refinements
  - Fetch limited seas and low wind correction term

Model Refinements



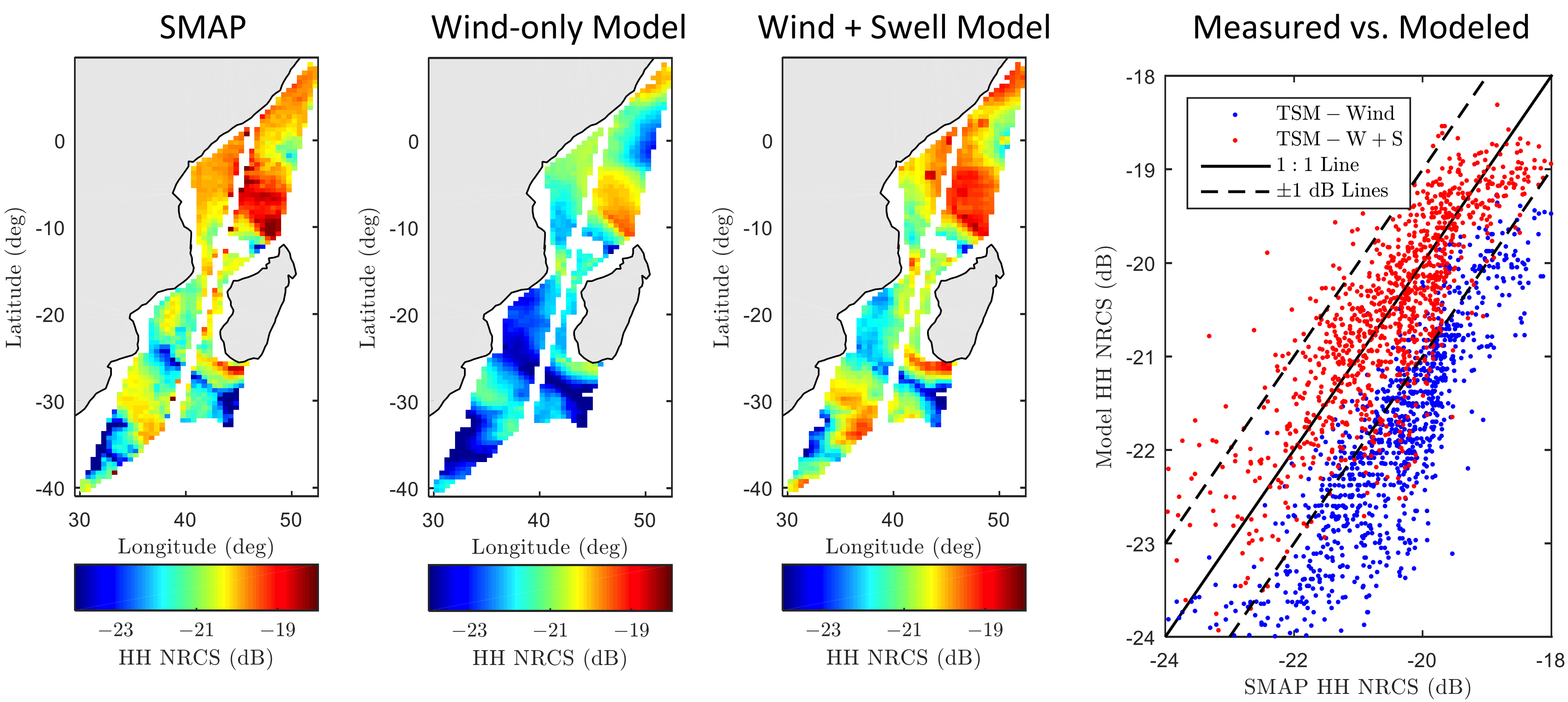






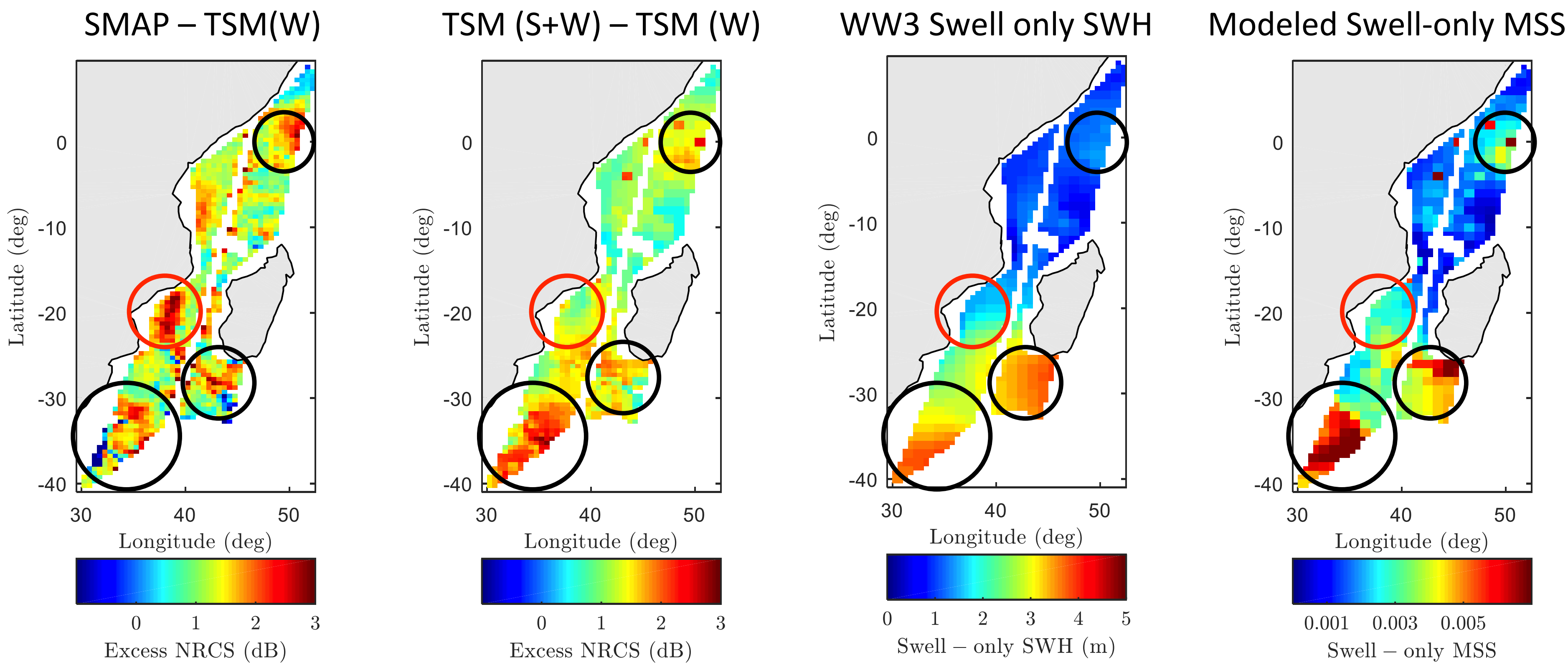
- Fetch-limited seas
  - Observed under high winds and over near-coastal regions
- Modeled using Ω_c
  - Elfouhaily Wave age parameter
  - $\Omega_c = 0.84$: Fully-developed
- Also added a low-wind correction term to the DV spectrum

Results: Model vs. SMAP NRCS Comparison For a Single Pass



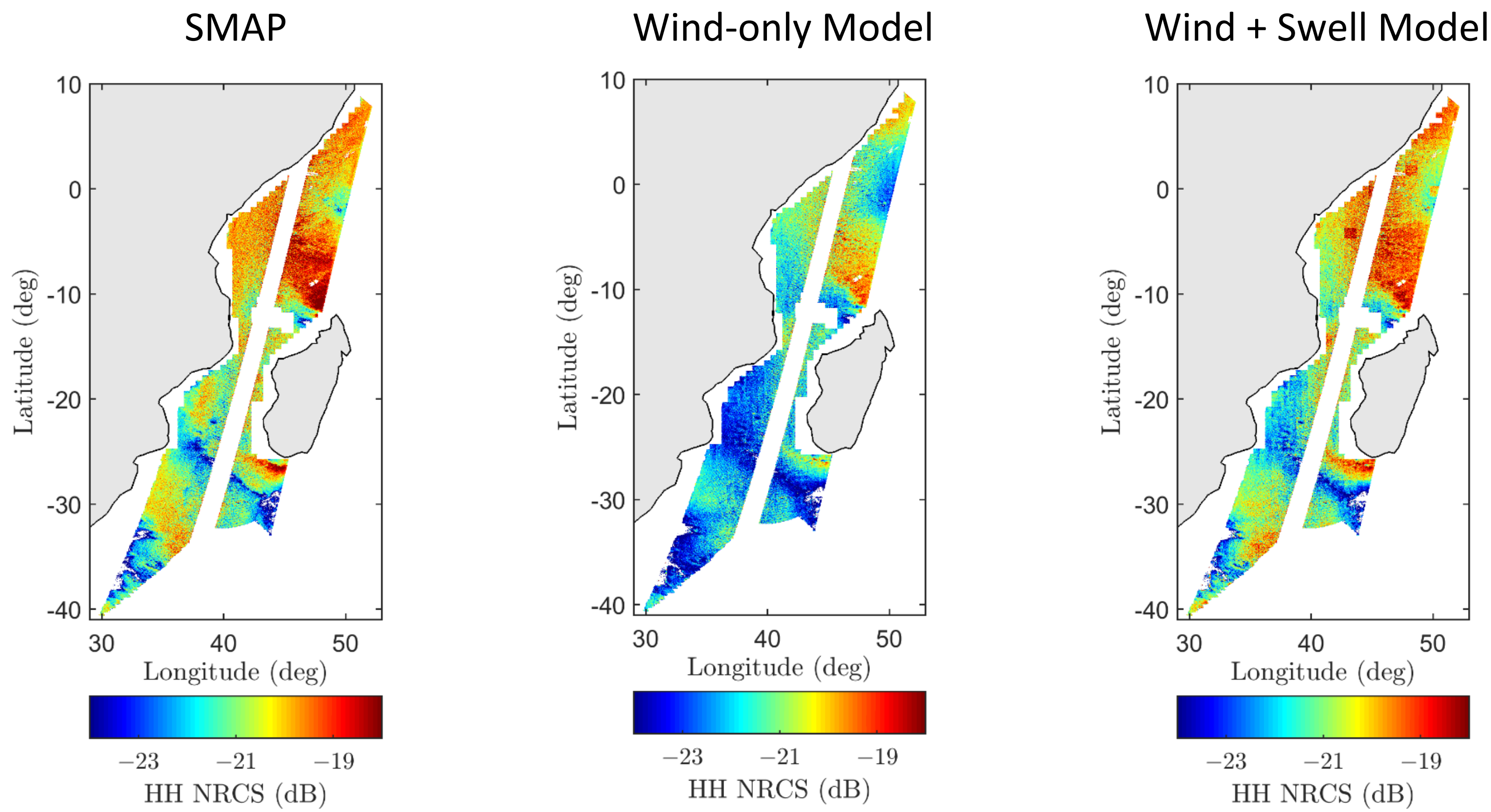
- Modeled NRCS values within ± 1 dB of SMAP data increases from 23% for wind-only mode to 85% for wind + swell model

Results: Swell Prediction Comparison



- Swell features present in SMAP data are captured by model results (indicated using black circles)
- SMAP also presents features that the WW3 model does not capture (red circles)
  - The prediction capability is ultimately limited by the quality of the WW3 predictions

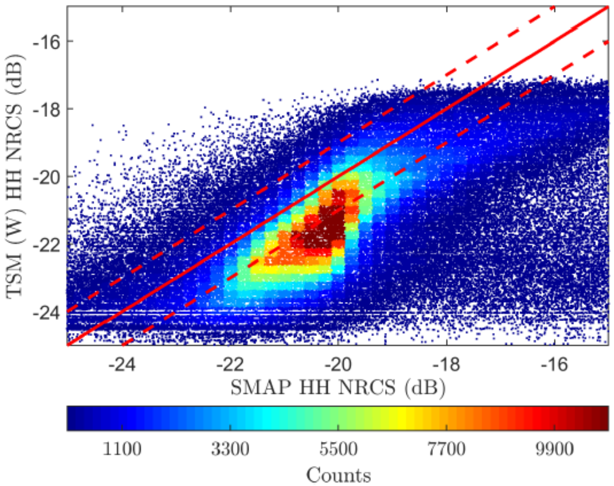
Results: Model Backscatter NRCS at SMAP L1C Resolution



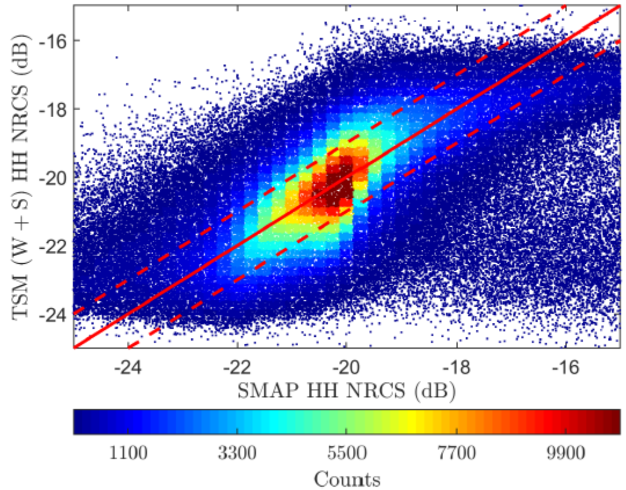
- High-resolution model results are in agreement with observations thus far

Cumulative HH Results

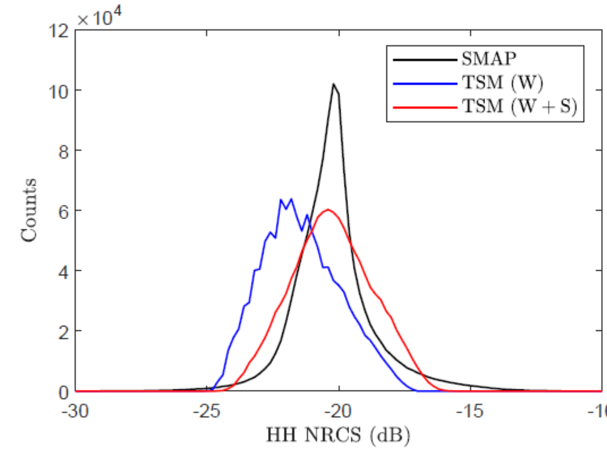
SMAP vs. Wind-only



SMAP vs. Wind + Swell



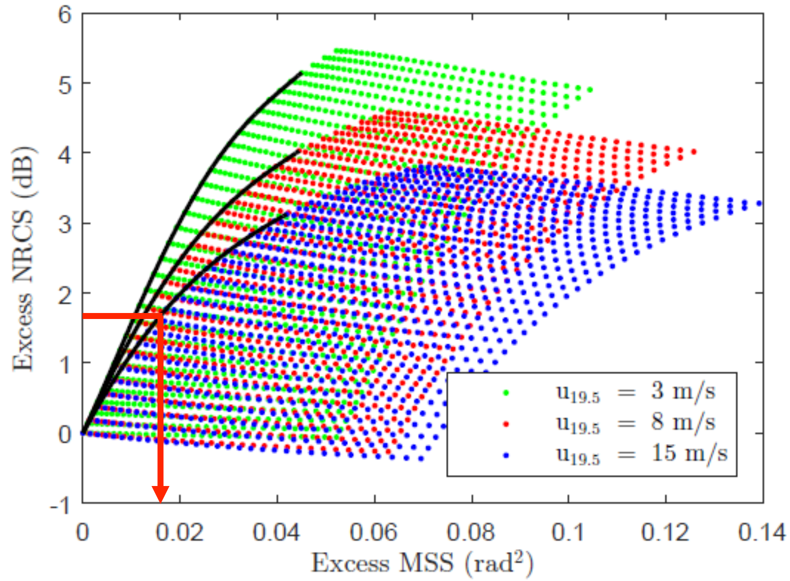
Distributions



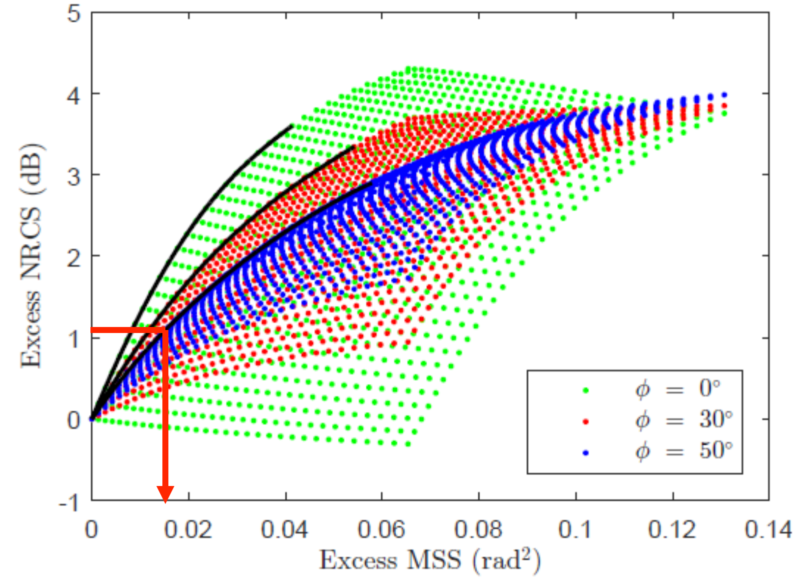
- Model predictions between ± 1 dB of SMAP measurements improve significantly
  - From 39% to 65%
- A mean NRCS increase of $2\ dB$ observed
- Wind + Swell model distribution mean aligns with SMAP mean
  - Variance is constrained by the wind model

Inverse Problem: Swell Retrieval

Excess MSS vs. Excess NRCS vs. Wind Speed

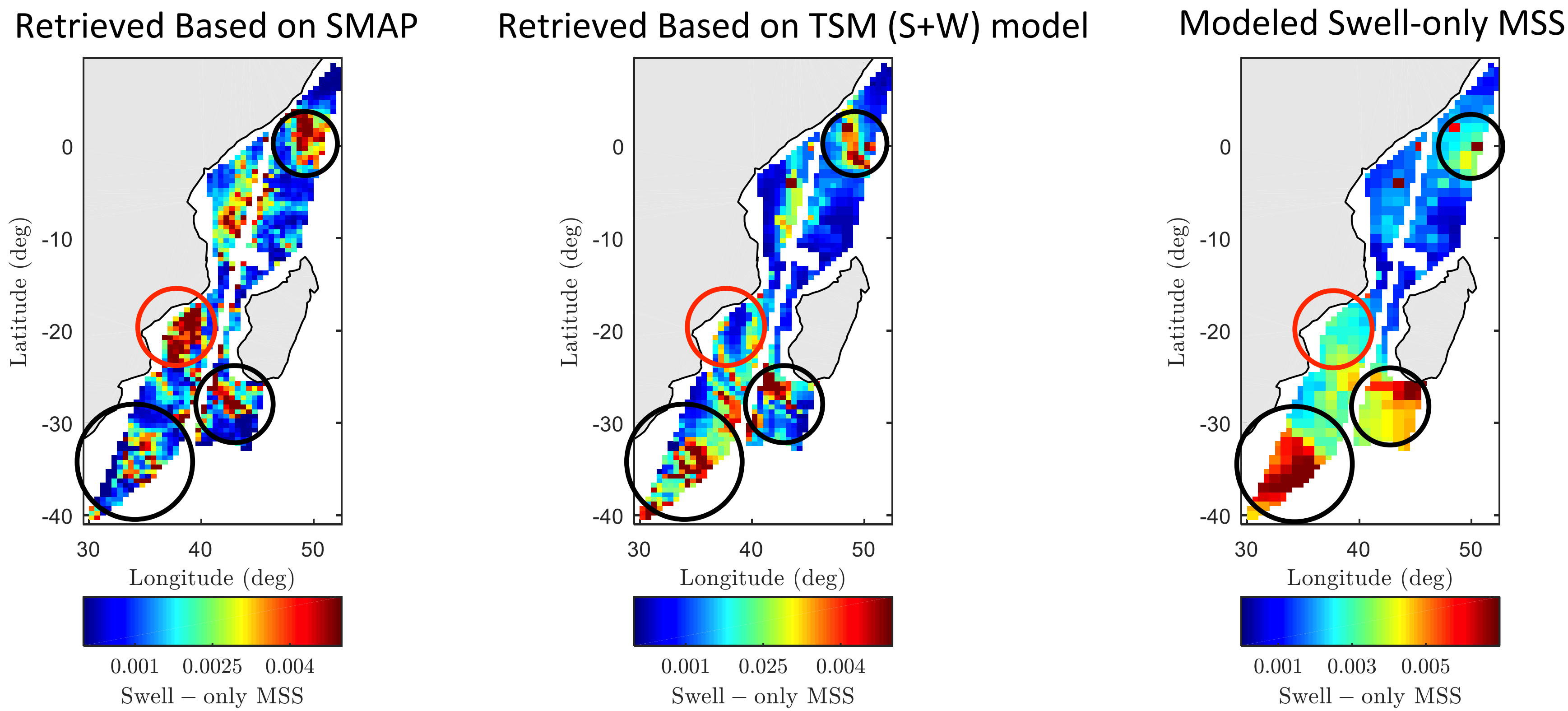


Excess MSS vs. Excess NRCS vs. Azimuth



- The SMAP and Wind + Swell model excess NRCS can be mapped to an excess swell
  - Many-to-one mapping
  - 2-D mapping space varies with wind speed and azimuth

Inverse Problem: Swell Retrieval – Initial Results



- Initial results are encouraging
  - Retrieved swell captures some of swell features
  - Note: Retrieved vs. modeled MSS scales are different
- More analysis required

Summary/Conclusions

- SMAP high-resolution (L1C) backscatter NRCS data over near-coastal regions modeled using physical models
  - TSM and SSA2-HF models used for backscatter NRCS modeling
- A combined wind + swell spectrum used to characterized the ocean surface
  - Wind: Durden-Vesecky-based spectrum
  - Swell: JONSWAP-based spectrum
  - Swell effects represented as an excess slope
- SMAP data forward modeled using the wind + swell model
  - The model improves backscatter NRCS predictions
  - Captures swell effects reasonably well
  - Initial indications for possible swell retrieval
- Future work:
  - Further refine the model increase the prediction accuracy
  - Compare and contrast modeled and retrieved swell MSS using those predicted by a numerical wave model

Thank You