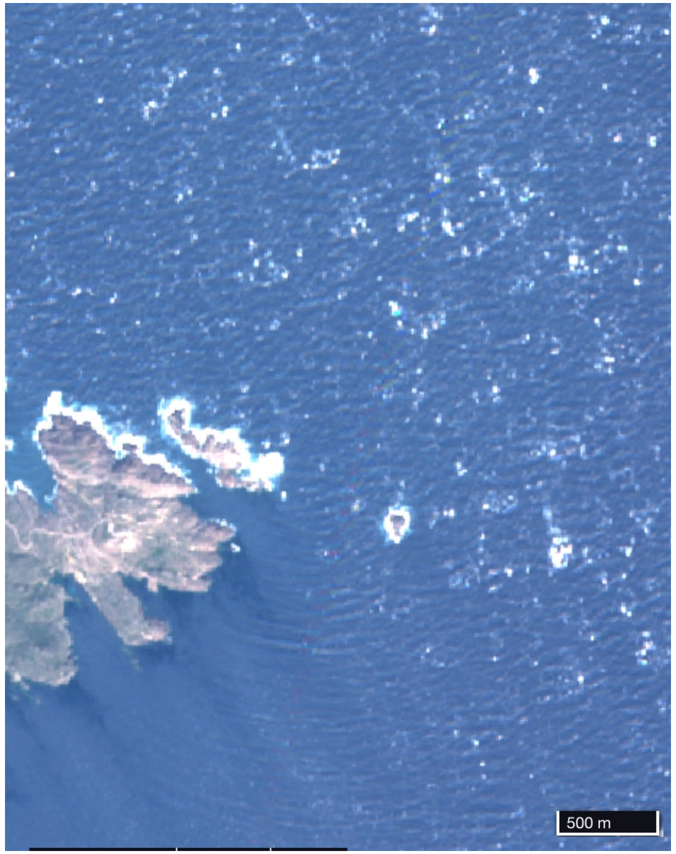
SWOT and wind-generated waves

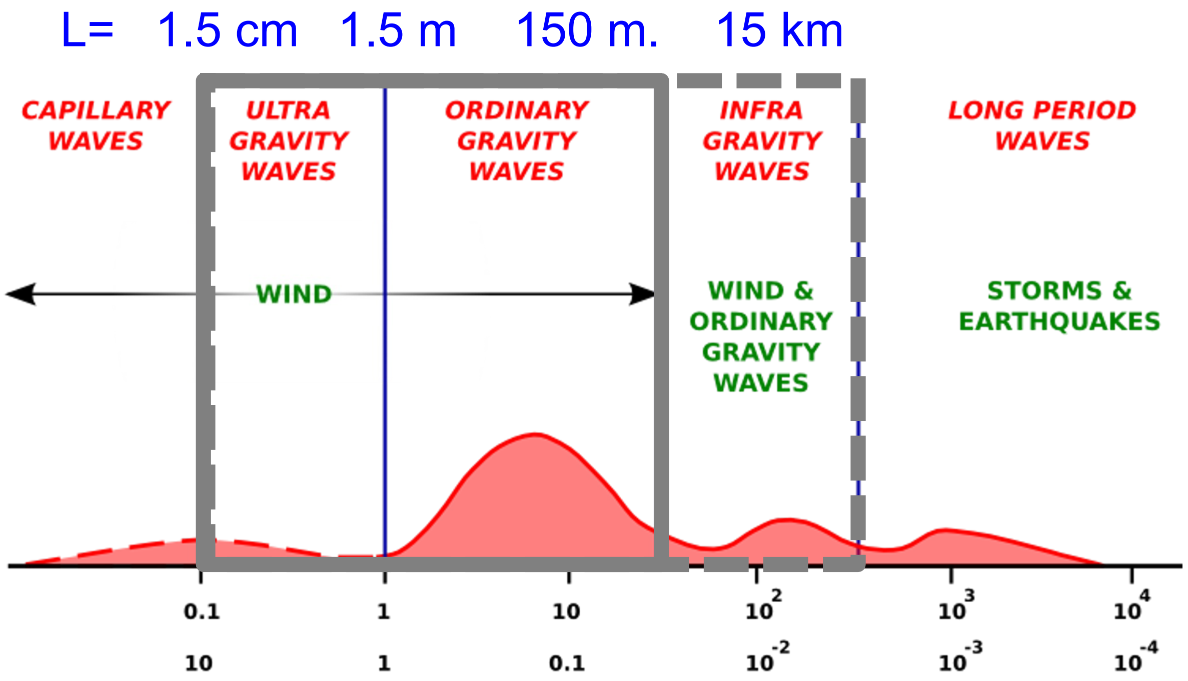
Fabrice Ardhuin (LOPS / CNRS)

Main message: **currents** impact **wave height** (Hs / SWH) and **mean square slope** -> radar backscatter (NRCS / σ_0)
so there should be some **consistency** between **SLA**, **SWH** and $\boldsymbol{\sigma_0}$ maps
Long term: using all measured parameters to estimate current gradients … and other things!
always good to have wave spectra because (almost) all wave quantities are derived from there

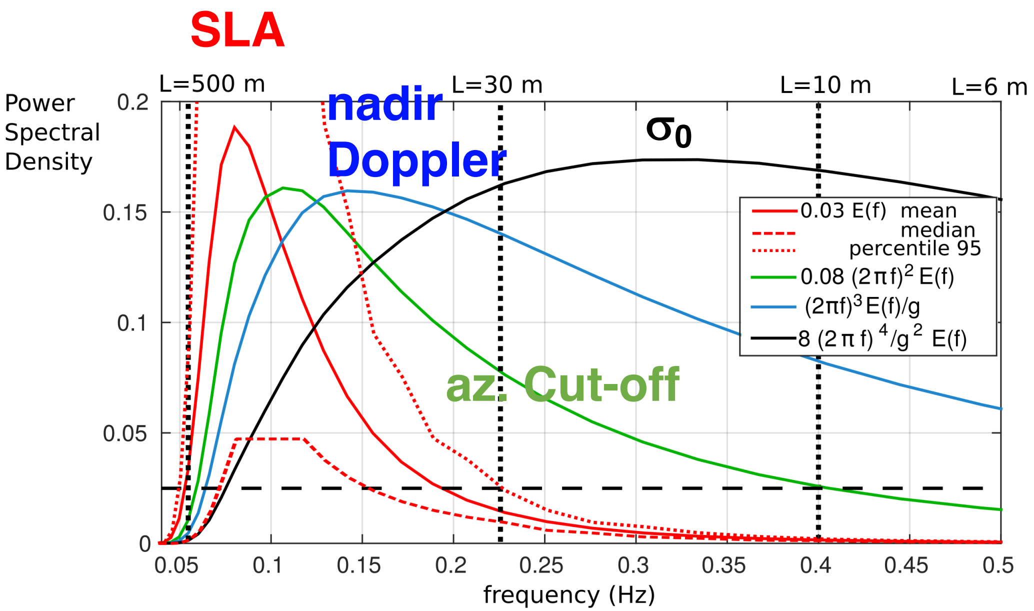


Sentinel 2 imagery, 2023/04/02

1. Wave scales: underlying wavelengths L



Average PSDs over global ocean



Large wavelengths will show up in SWOT data:

- actual swell with some effective along-track wavelength (see Villas-Boas et al., GRL 2022)

- infragravity waves (Ardhuin et al. 2013) **https://bit.ly/WW3SWOT**

1. Wave scales: wave dispersion

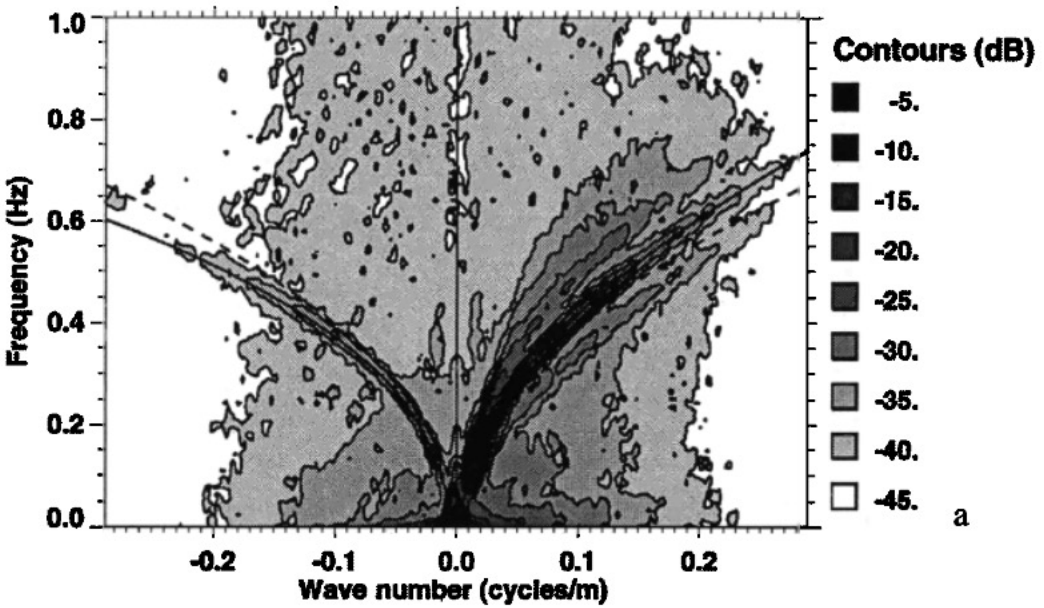
$$\sigma^2 = gk \tanh(kD)$$

$$\omega = \sigma + \mathbf{k}\cdot\mathbf{U}$$

$$C = \frac{\sigma}{k} + 2\int_{-D}^{0} \mathbf{k}\cdot\hat{\mathbf{u}}\frac{\cosh(2kz+2kD)}{\sinh(2kD)}\mathrm{d}z$$

(Kirby & Chen JGR 1989)

DUGAN ET AL: WATER DEPTH AND SURFACE CURRENT RETRIEVALS



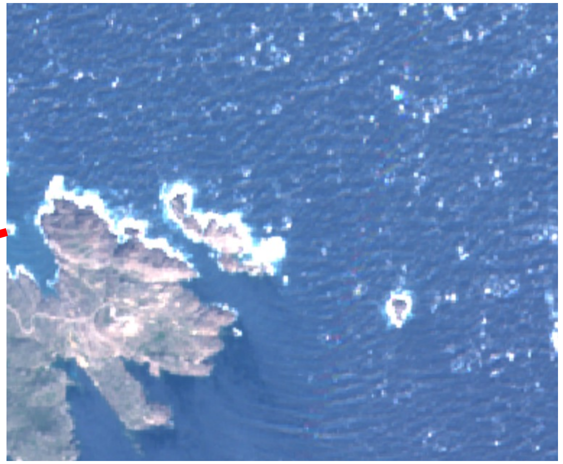
(Dugan et al. JGR 2001)

Inverting dispersion for U and the profile û is the basis of all surface remote sensing for currents.

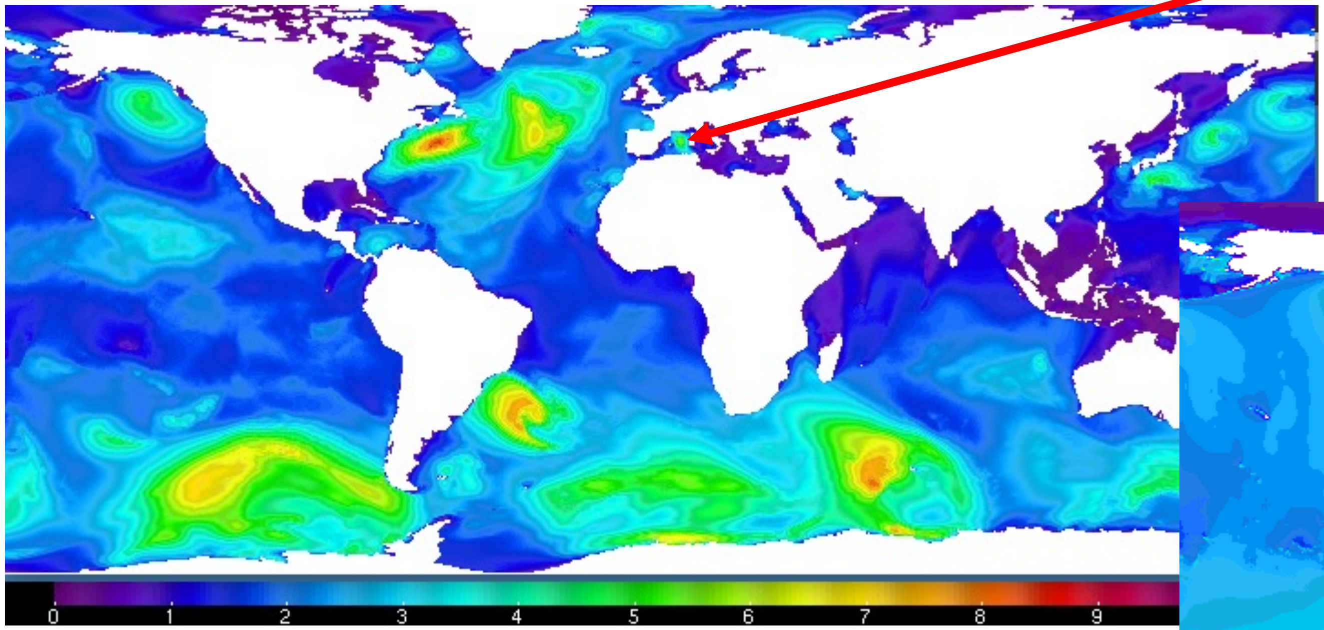
- HF radars (Barrick et al. 1977), X-band radars (Young et al. 1985)
- movies (Dugan et al. 2001, Lenain et al. GRL 2023)
- pair of images or radar looks (Kudryavtsev et al. JGR 2017, ….)
- pulse pair (Rodriguez 2019, Osina et al., in prep)
- sequence of n=3 or more images … (Ardhuin et al. JGR 2021)

1. Wave scales: infragravity waves

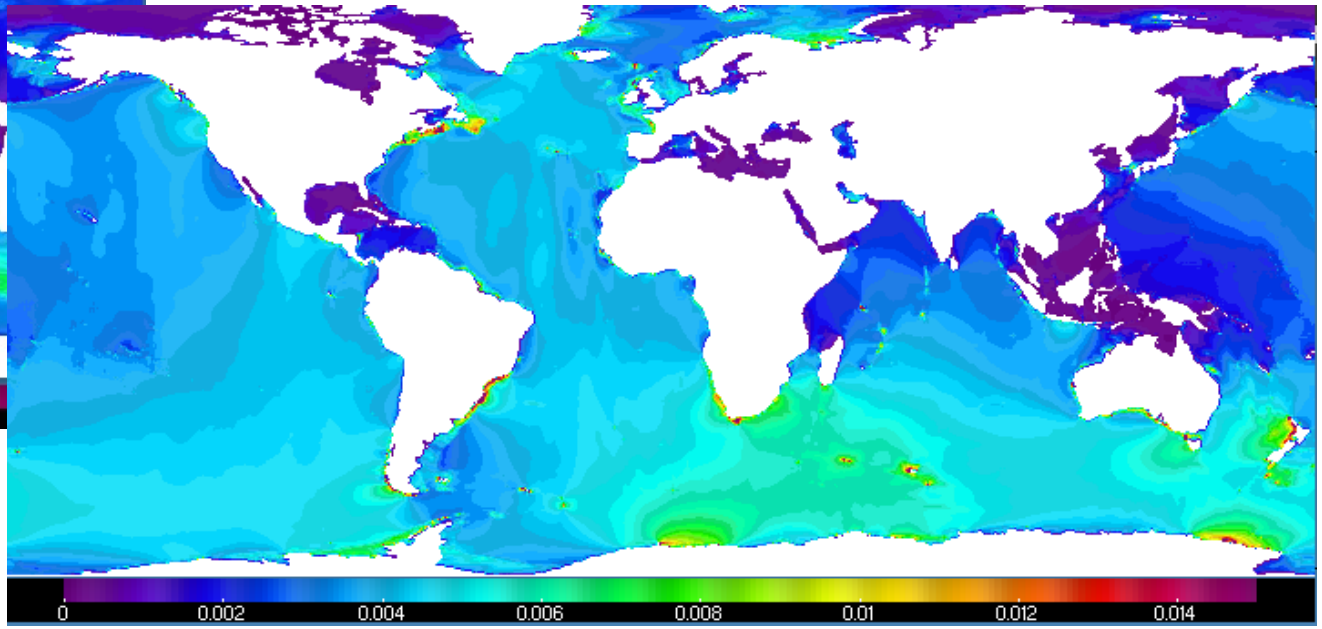
Model was validated using bottom pressure recorders up to 2008 (see Rawat et al. GRL 2014)
If you have bottom pressure records with dt < 20 s, let me know!
Links to wave hindcasts: https://bit.ly/WW3SWOT



Hs (0 to 10 m) for 12:00 April 2, 2023

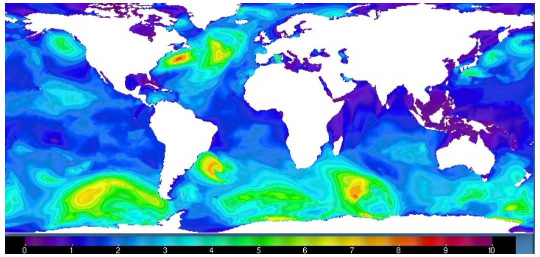


H_{IG} (0 to 15 mm) for 12:00 April 2, 2023



1. Wave scales: wave height variations are caused by …

- At large scales: wind history & fetch



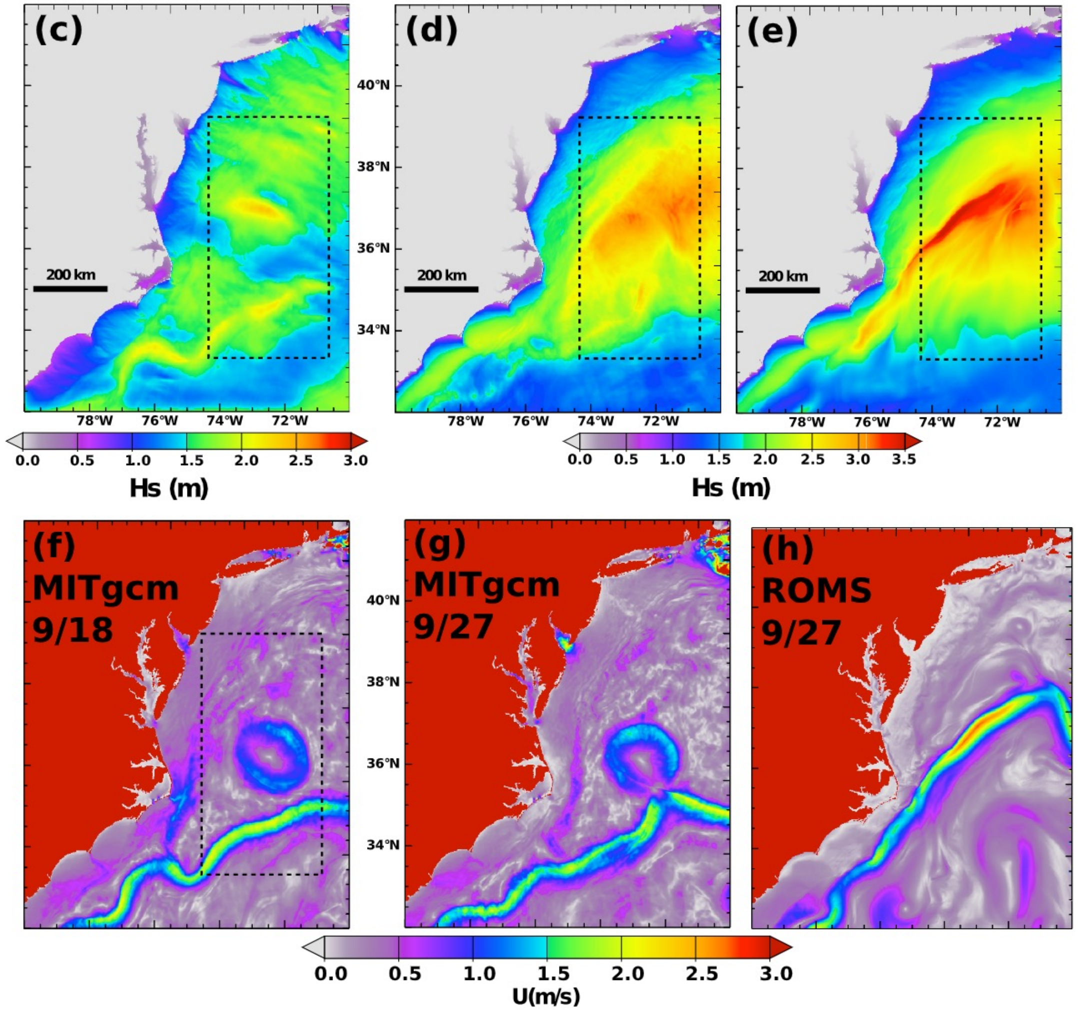
- At “small scales”: Currents (probably dominant at 10 km < L < 150 km)

Evidence in nadir altimetry (Quilfen et al. RSE 2017, Quilfen & Chapron GRL 2019, Marechal & Ardhuin JGR 2021)

Strongest effects at scales < 50 km, mostly due to refraction (Ardhuin & al. JGR 2017, Villas-Boas et al. JPO 2021)

Spectrum of Hs linked to spectrum of current

Effect is not completely local
Important for navigation safety



1. Wave scales: wave envelope

From a spatial map we can define a local amplitude and phase.

The local amplitude varies at all scales.

At "**small scales**" the PSD of the envelope is dominated by wave group effects, which are a function of the wave spectrum.

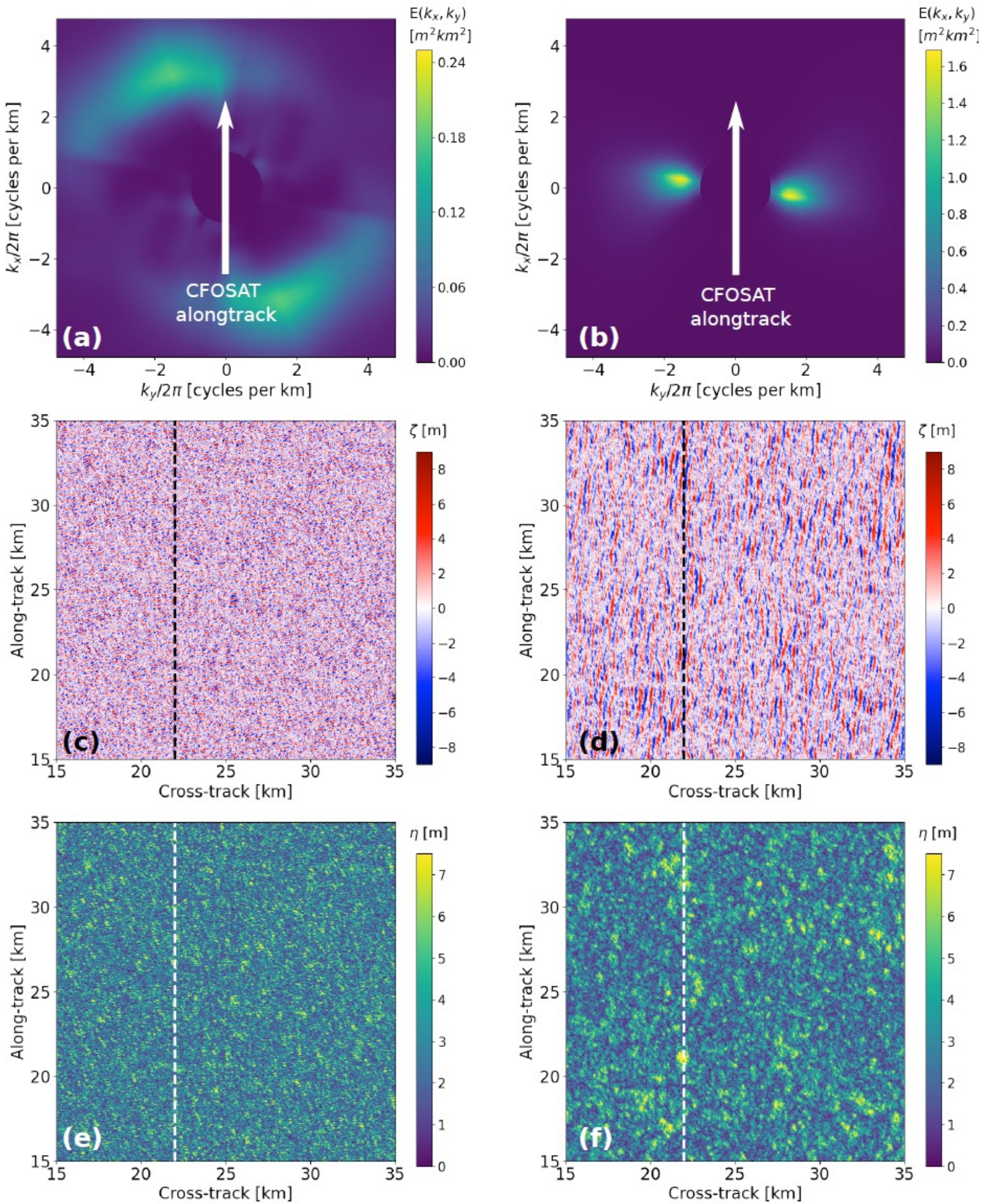
Wave groups actually contribute to very large scales also, the PSD around k=0 is a function of only 2 numbers:

Hs

Q_{kk} (spectral peakedness)

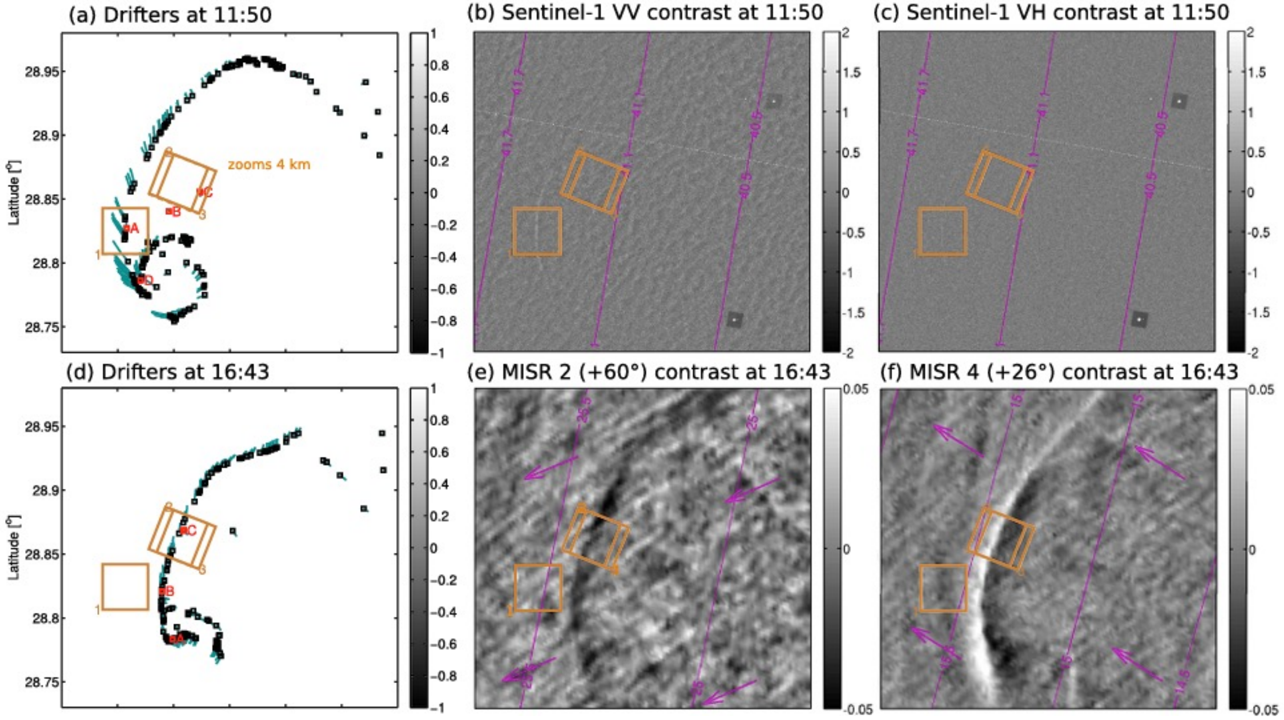
For any observing system, groups give random fluctuations: from spectra we can predict the rms value of Hs caused by groups

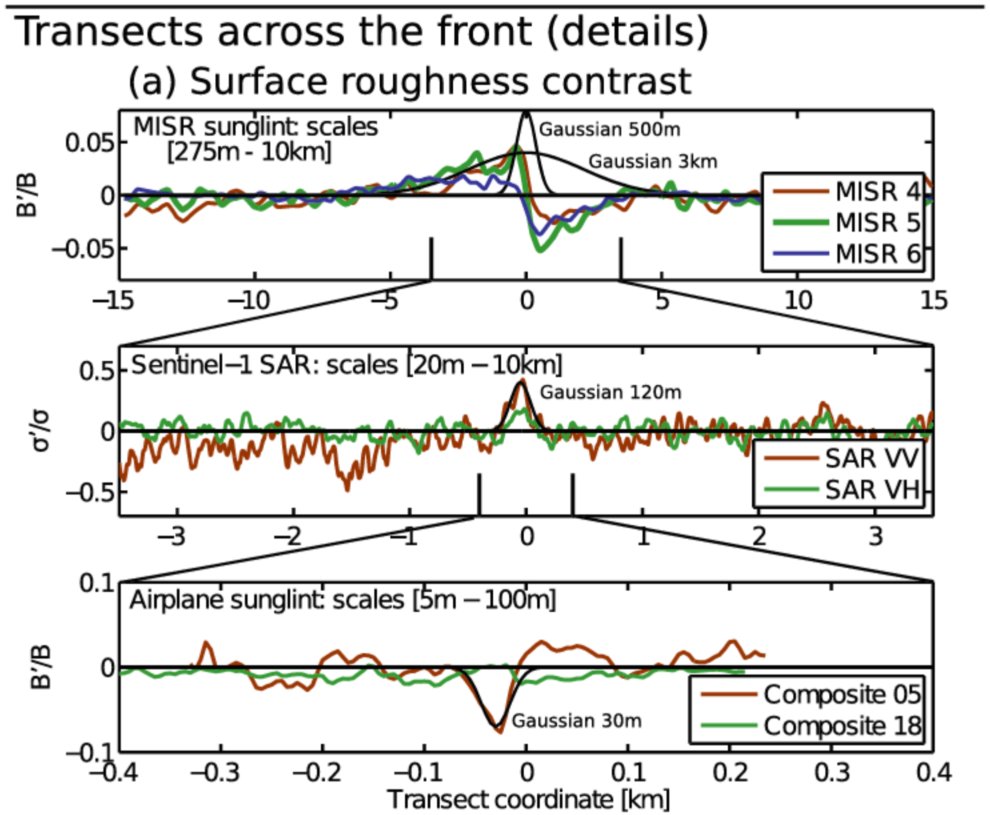
(De Carlo et al. JGR 2023)
see poster



1. Wave scales: mean square slope (mss) and σ_0

- σ_0 for near nadir is ~ 1/mss
- mss is driven by wind at scales > 1 km, with some wave age variations.
- O(10%) mss gradients occur at current fronts
- For SWOT, this should be due to divergence (Kudryavtsev et al. 2005, 2012, Rascle et al. 2017, 2020 …)





(b) Surface roughness contrast summary

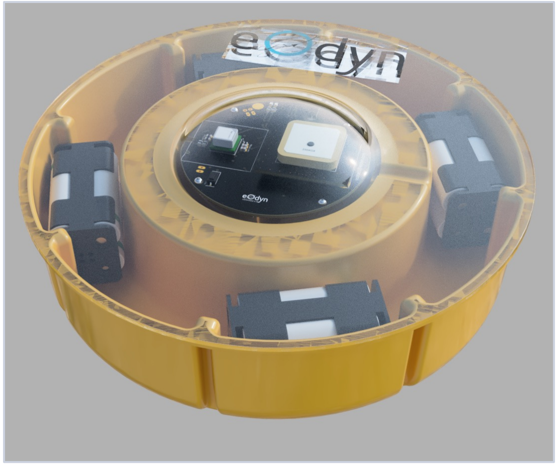
Data	Observed scales	Frontal width 80%	Frontal width 50%	Frontal width 20%	Contrast at scales [5m 100m]	Contrast at scales [275m 10km]
MISR 4, 5, 6, 7	[275m 10km]	600 m	1200 m	3500 m	Undef	~5%
SAR VV	[20m 10km]	70 m	110 m	230 m	Noise	~5%
SAR VH	[20m 10km]	100 m	200 m	300 m	Noise	~1%
Airplane C5	[5m 100m]	15 m	30 m	50 m	~6%	Undef

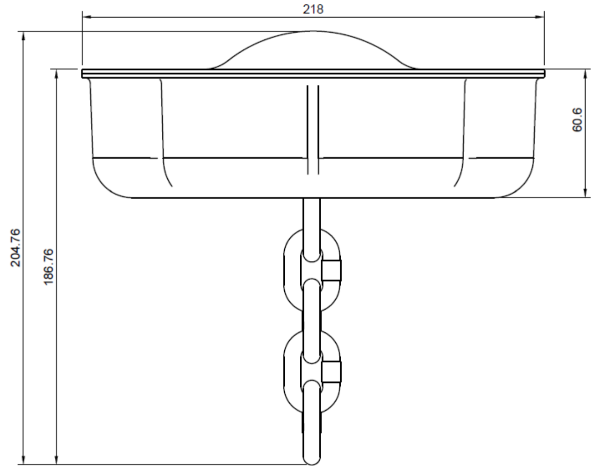
MELODI Drifters for SWOT Cal/Val Campaign

Alexei Mirnov (eOdyn)

MELODI drifter: *Miniature buoy for real-time sea surface tracking*

Dedicated for real-time measurement of sea state variables i.e. **sea surface current** and **wave parameters**





- Buoy overview
  - Satellite Connected
  - Small size (~20 cm in diameter), weight (> 1 kg)
  - Low profile with reduced wind drag
  - Real-time data visualization
  - Onboard full data log on SD card
  - Cost-effective conception

- Measured parameters
  - Wave data sampling 3Hz
  - GPS displacements every 10 min
  - Significant wave height every 30 min
  - Omnidirectional wave spectrum (0.02-0.8 Hz) every 1h

SWOT calibration and validation campaigns in the Mediterranean sea

Alexei Mirnov (eOdyn)

C-SWOT / WENSWOT

- Date : 21/03 to 18/04/23
- 2 buoys deployed

C-SWOT buoy trajectories

Atalante & Téthis II Ships in Mahon Port @Shom

Photo of buoys before the deployments

BioSWOT-Med

- Date : 21/04 to15/05/23
- 15 buoys deployed

Bio-SWOT buoy trajectories

Measurement data and Results

Alexei Mirnov (eOdyn)

Temporal experimental series and analysis

- ***Hs*** every 30 min
- Omnidirectional **wave spectra** every 1h
- ***u*** and ***v*** components of sea surface current

Collocated auxiliary numerical model data:

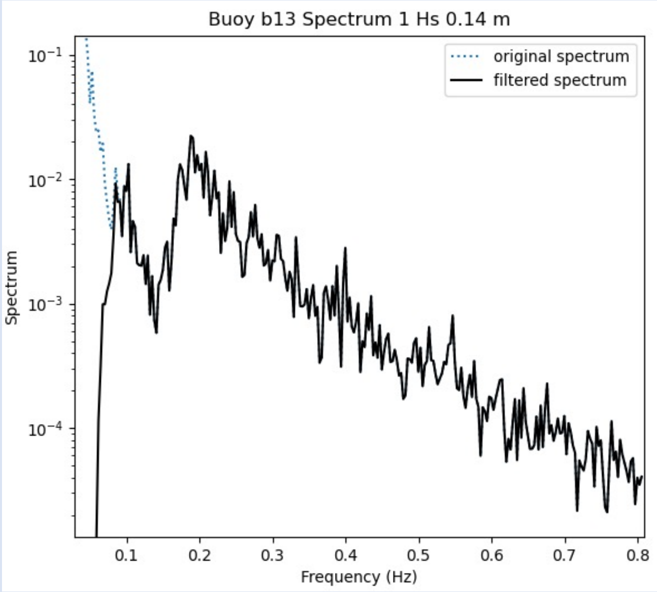
- CMES sea surface total **current**
- ECMWF 10m **wind**
- WW3 **significant wave height** estimations

Data availability:

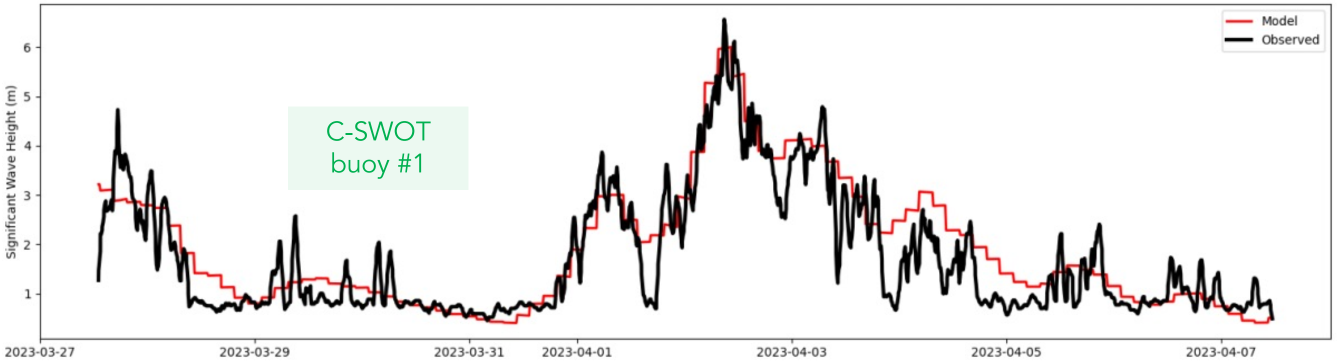
Integral collection of C-SWOT/BioSWOT data (in total 17 buoys) available in NetCDF file through PO.DAAC

Sea surface current components

Wave spectrum example



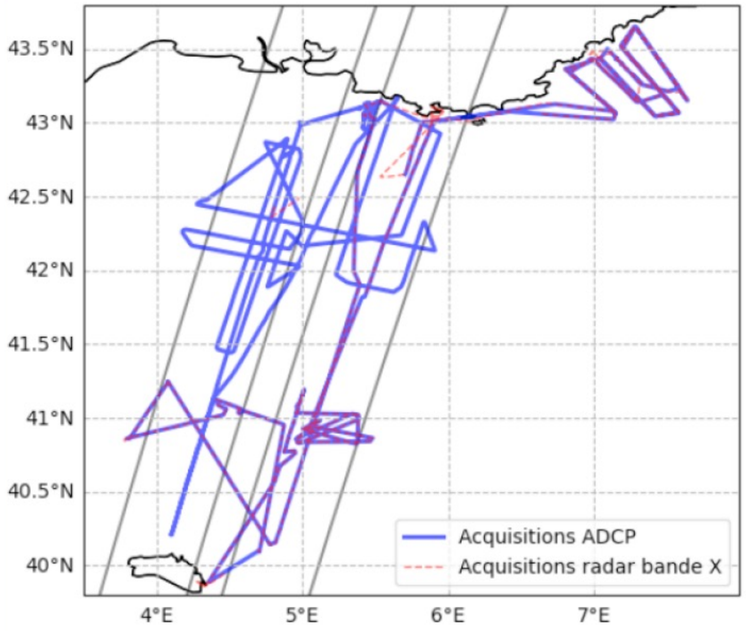
Significant wave height (Hs) compared to WW3 output

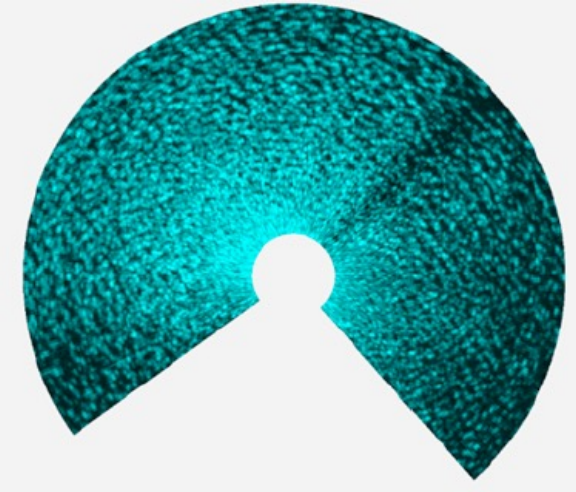


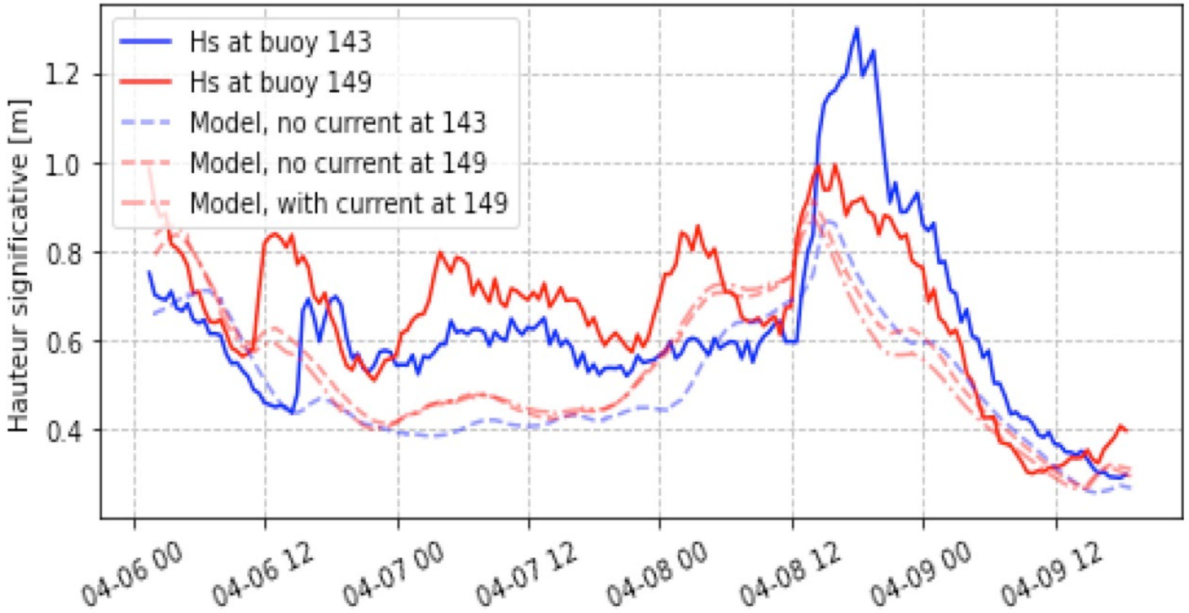
More waves around C-SWOT / WEMSWOT

Thomas Rouet
Fabrice Ardhuin
Franck Dumas
Pierre Garreau
Mickael Accensi

- 5 Spotter buoys from R/V l'Atlante
- X-band radar using MIROS Wavex system







More waves around C-SWOT / WEMSWOT

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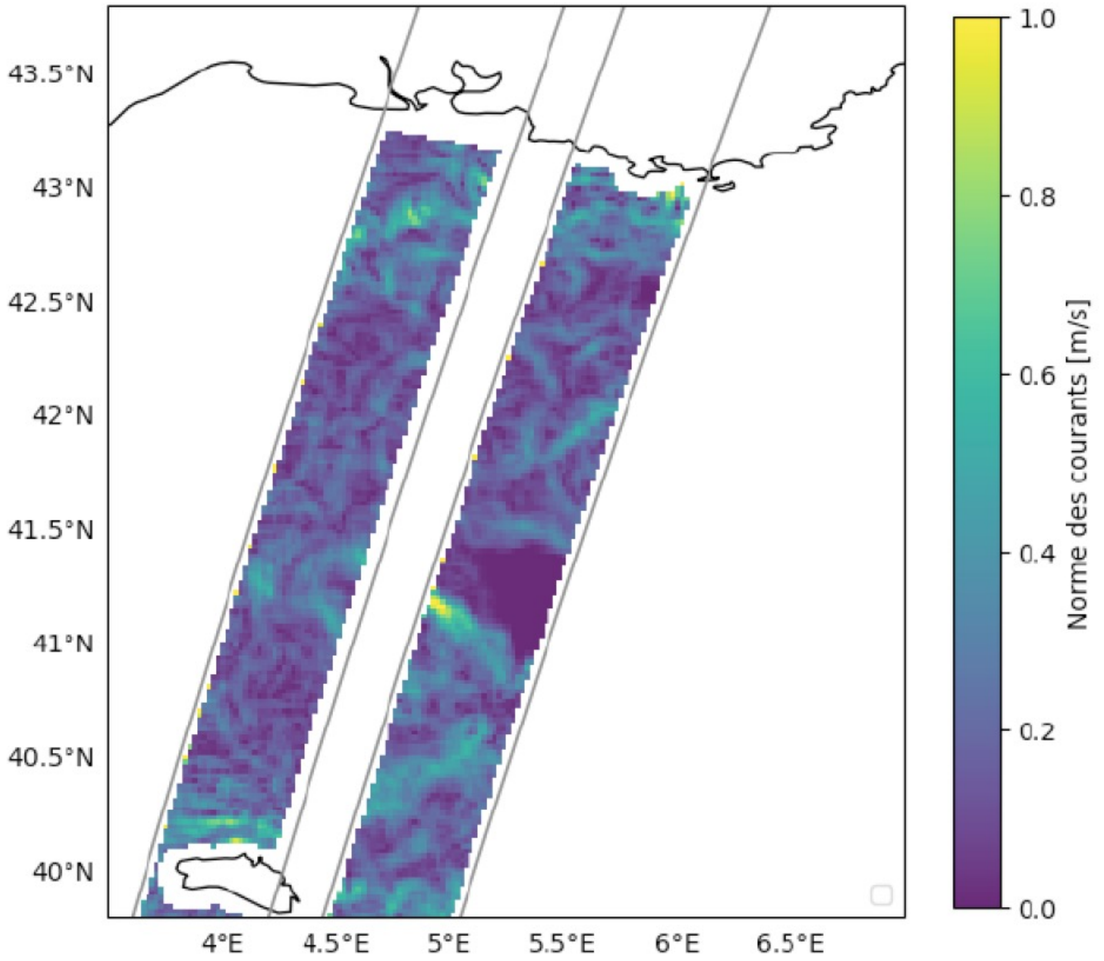
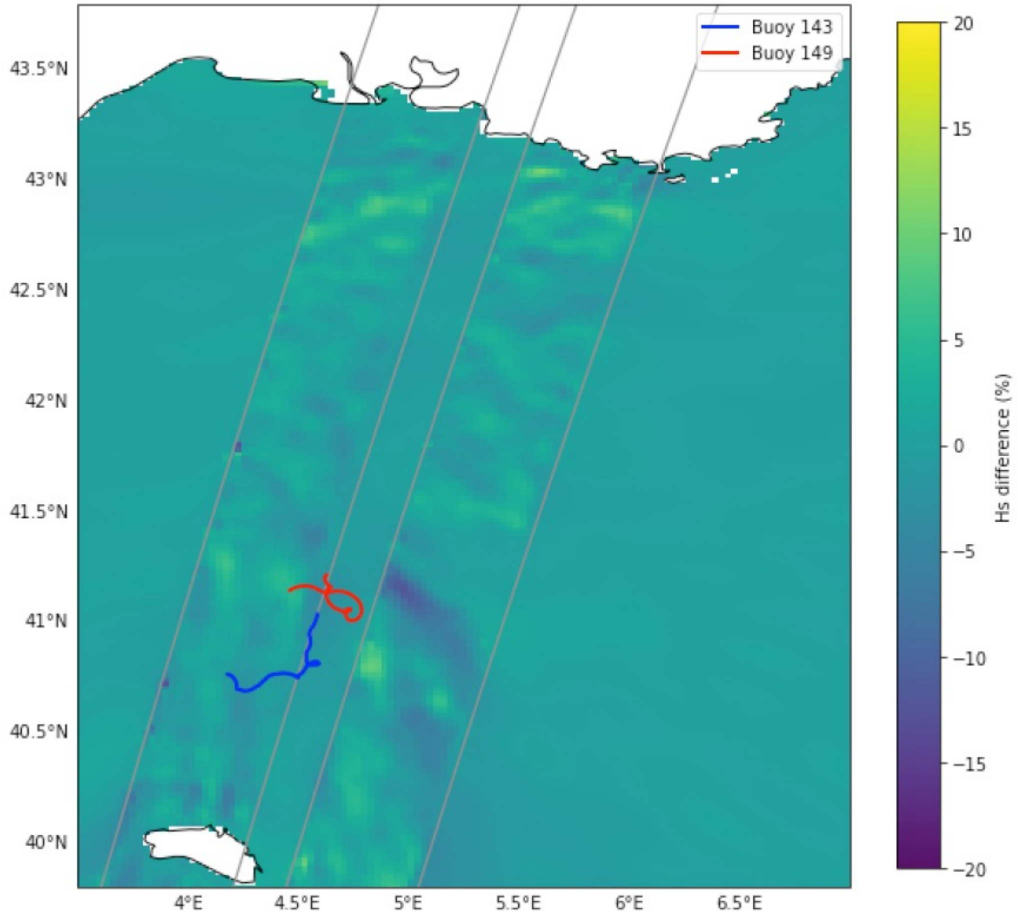
Mickael Accensi

Effect of currents on waves?

Preliminary model runs forced by “SWOT currents” (see poster shown Tue / Wed)
(U,V derived by P. Garreau from geotiff images)



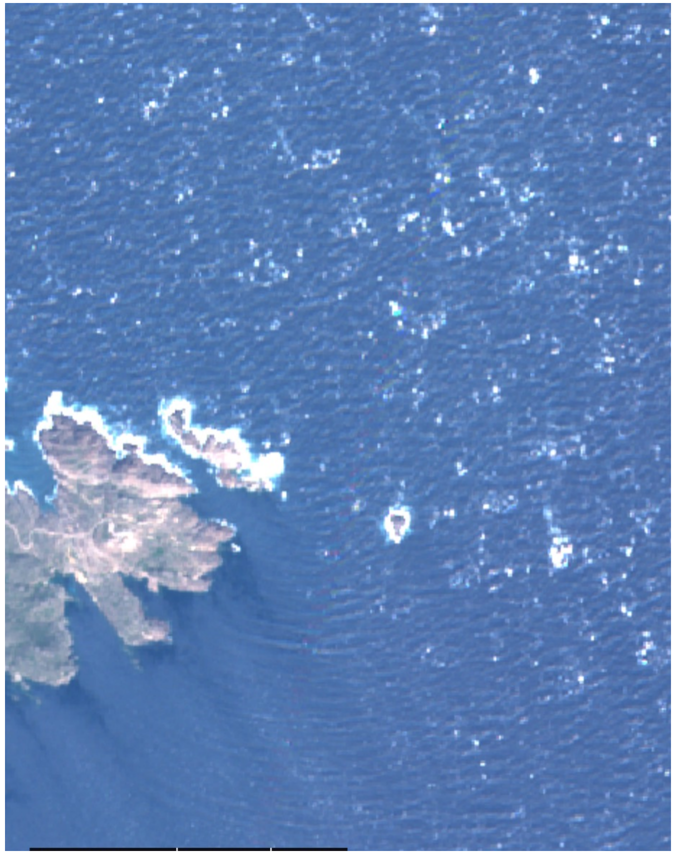


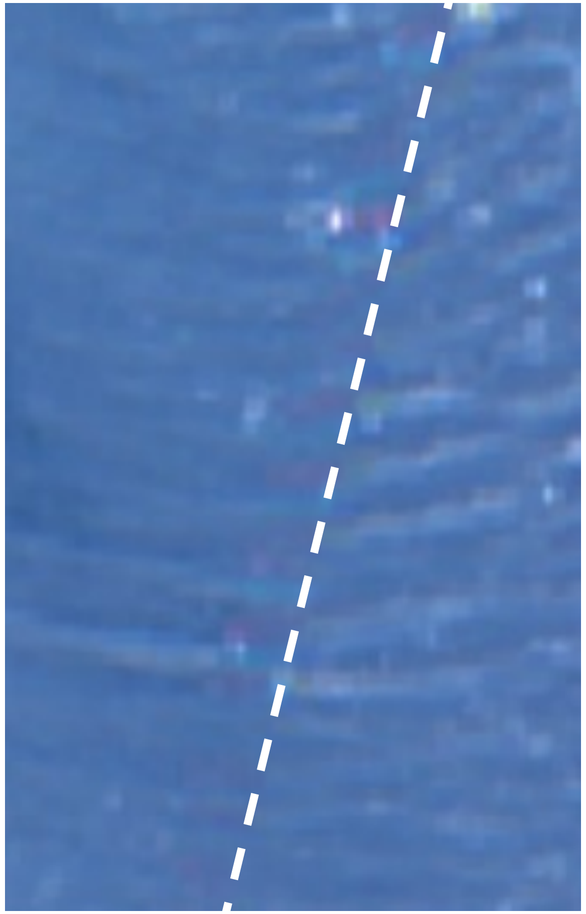
Sentinel 2 imagery for surface current

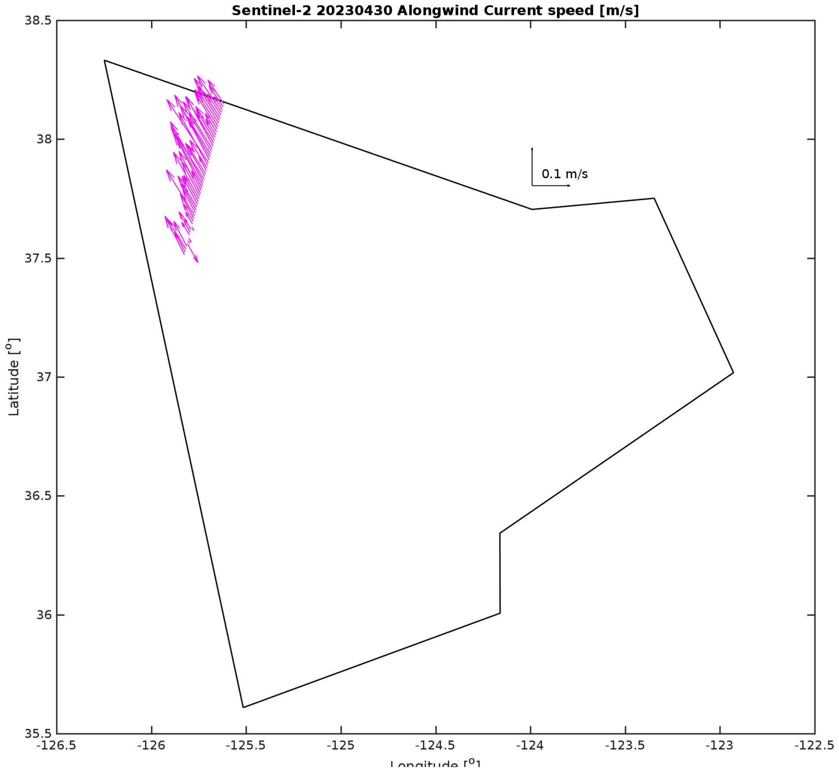
Nicolas Rascle, Fabrice Ardhuin (LOPS), Renaud Binet et al. (CNES), Luc Lenain (UCSD-SIO)
(thanks to ESA for funding as part of STREAM EE11 activities)

Following analysis of L1C data (Kudryavtsev et al. 2017, Yurovskaya et al. 2019),
first analyses of overlapping S2 data in L1B products (2 km wide overlap with delta-t up to 4 s)

- Tests on image over S-MODE areas:
30 April 2023, and 27 April 2023





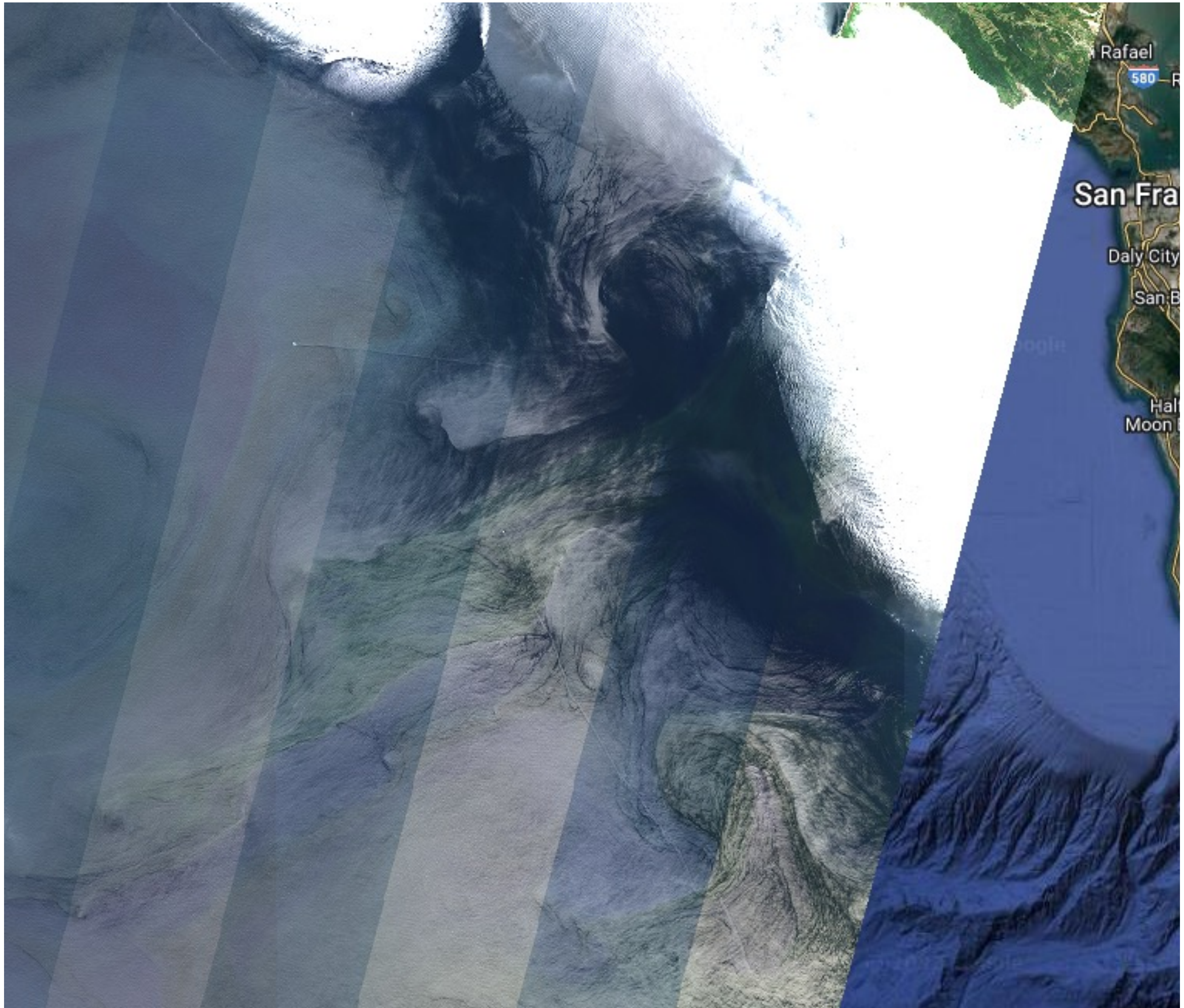


Sentinel 2 imagery for surface current

Nicolas Rascle, Fabrice Ardhuin (LOPS), Renaud Binet et al. (CNES), Luc Lenain (UCSD-SIO)

- Tests on image over S-MODE areas:
27 April 2023

(PhD work
 of Alexandra Cuevas at MIO)



National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Modular Aerial Sensing System (MASS) in support of SWOT Cal/Val and the S-MODE mission

Luc Lenain, Nick Statom,
Luke Colosi, Evan Harris

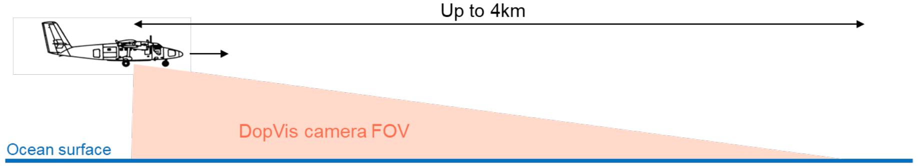
Scripps Institution of Oceanography

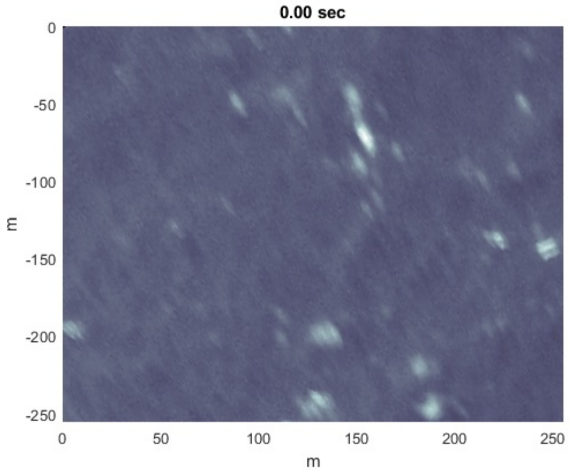
SWOT Science Team Meeting 2023

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

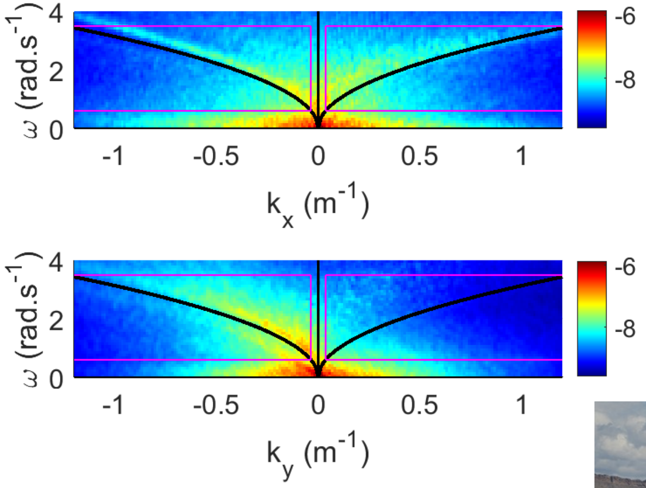
What about Wave-Current interaction? MASS DoppVis “surface currents“ sensor flown during S-MODE IOP2 on second aircraft

DoppVis instrument concept: Capturing upper-ocean current profiles (first few meters) along the track of the aircraft through observations of the spatio-temporal evolution of surface waves (**dispersion relationship method**), following the work of Dugan et al. (2001) and more recently the Fugro ROCIS team.

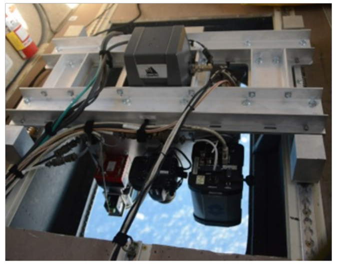




3D Spectra



Invert for upper ocean currents and shear (vertical and horizontal)

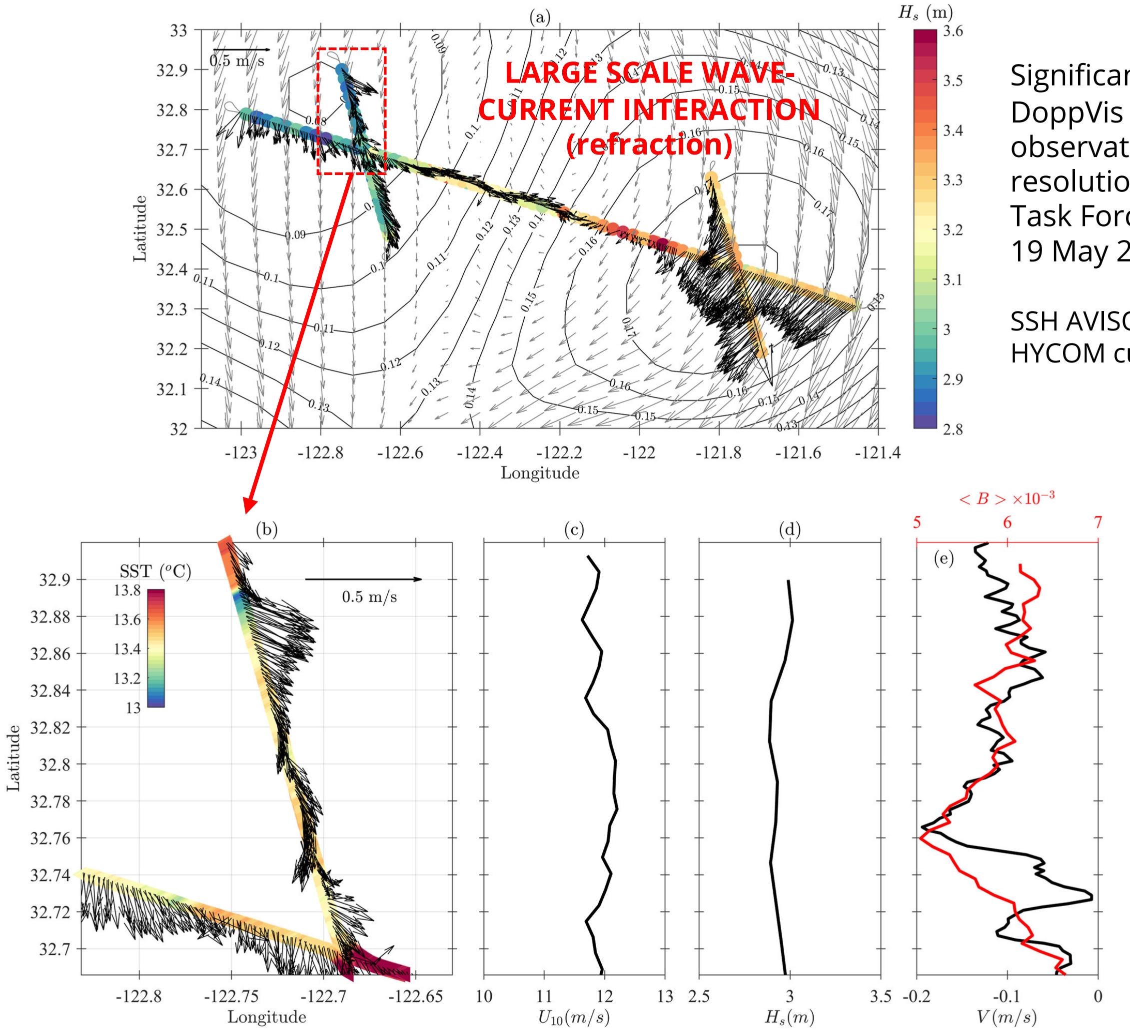


Horizontal resolution: 128-1000m
Depth range: 0.5-3m (wave conditions dependent)
*here depth-averaged currents

See Lenain et al. (2023) & Freilich et al. (2023) for details

Airborne Remote Sensing of Upper-Ocean and Surface Properties, Currents and Their Gradients From Meso to Submesoscales from MASS

- S-MODE IOP2 processing on-going - Showing here examples of observations collected during previous experiments



Significant wave height H_s and DoppVis surface current observations (250 m along-track resolution) collected during the Task Force Ocean experiment on 19 May 2021

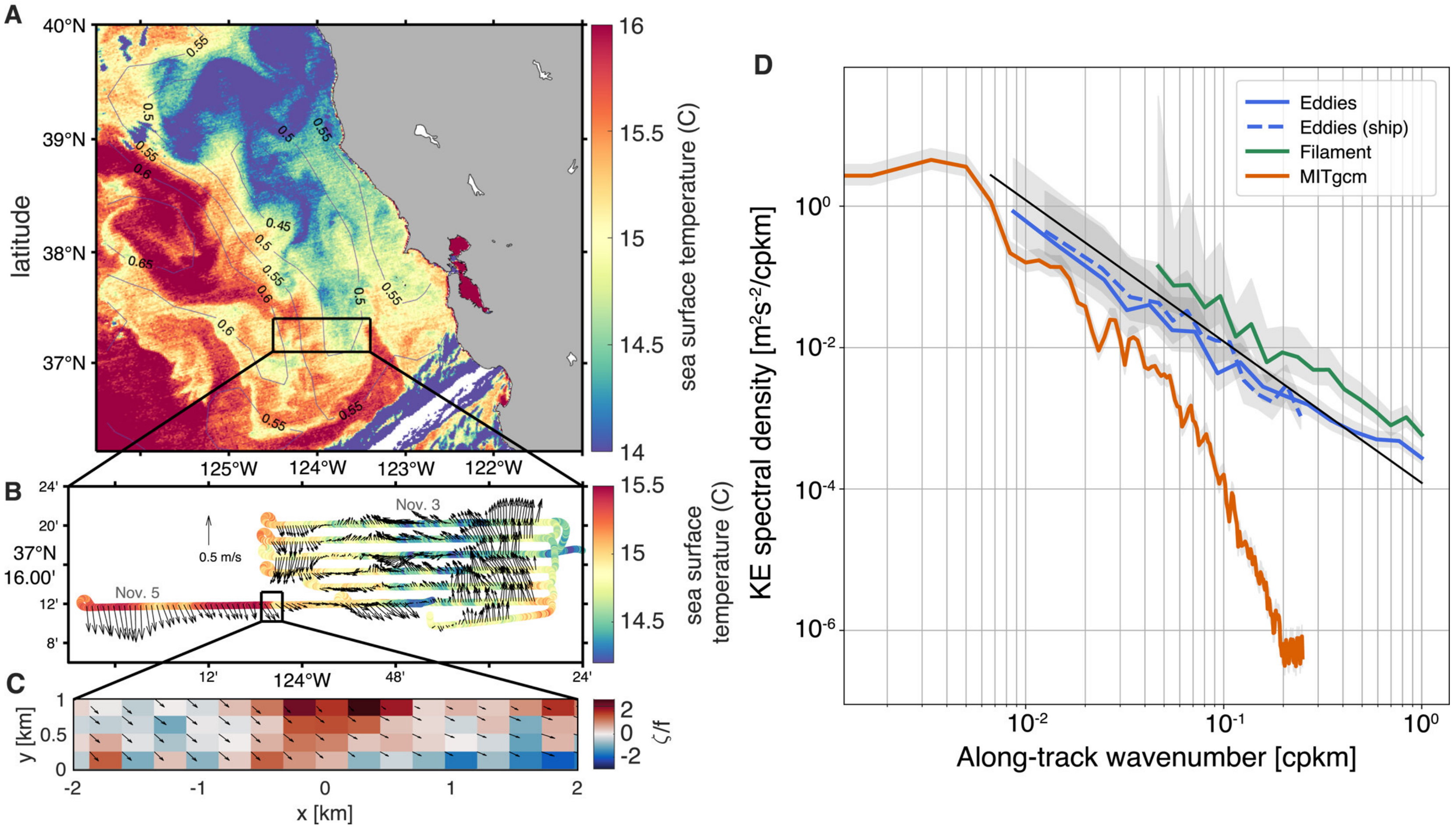
SSH AVISO: black contours
HYCOM currents: gray quivers

LOCAL WAVE-CURRENT INTERACTION

mean spectral Saturation & North component of currents

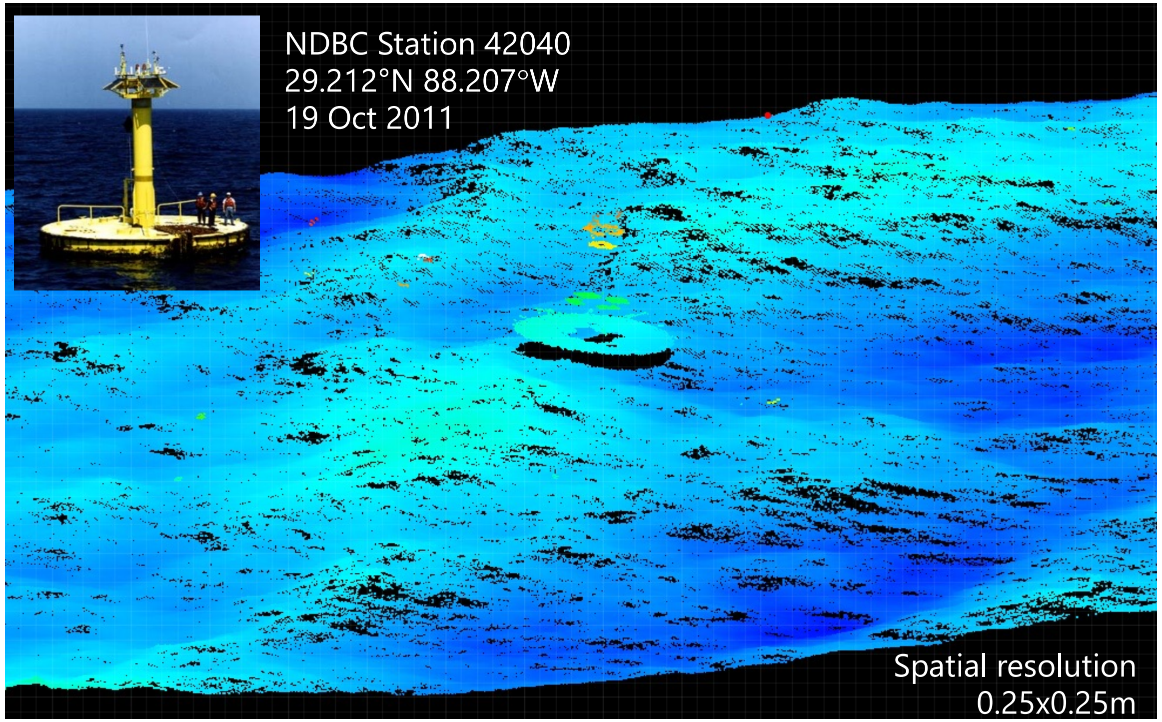
See Lenain et al. (GRL 2023) & Freilich et al. (GRL 2023) for details

Characterizing the transition to submesoscale dynamics using DoppVis

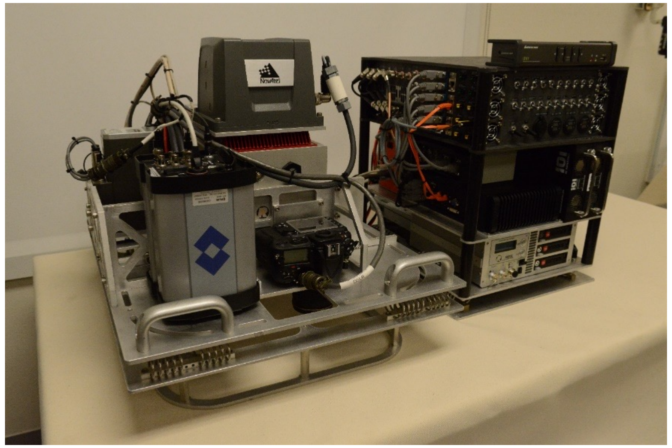


See Lenain et al. (GRL 2023) & Freilich et al. (GRL 2023) for details

SIO Modular Aerial Sensing System (MASS)



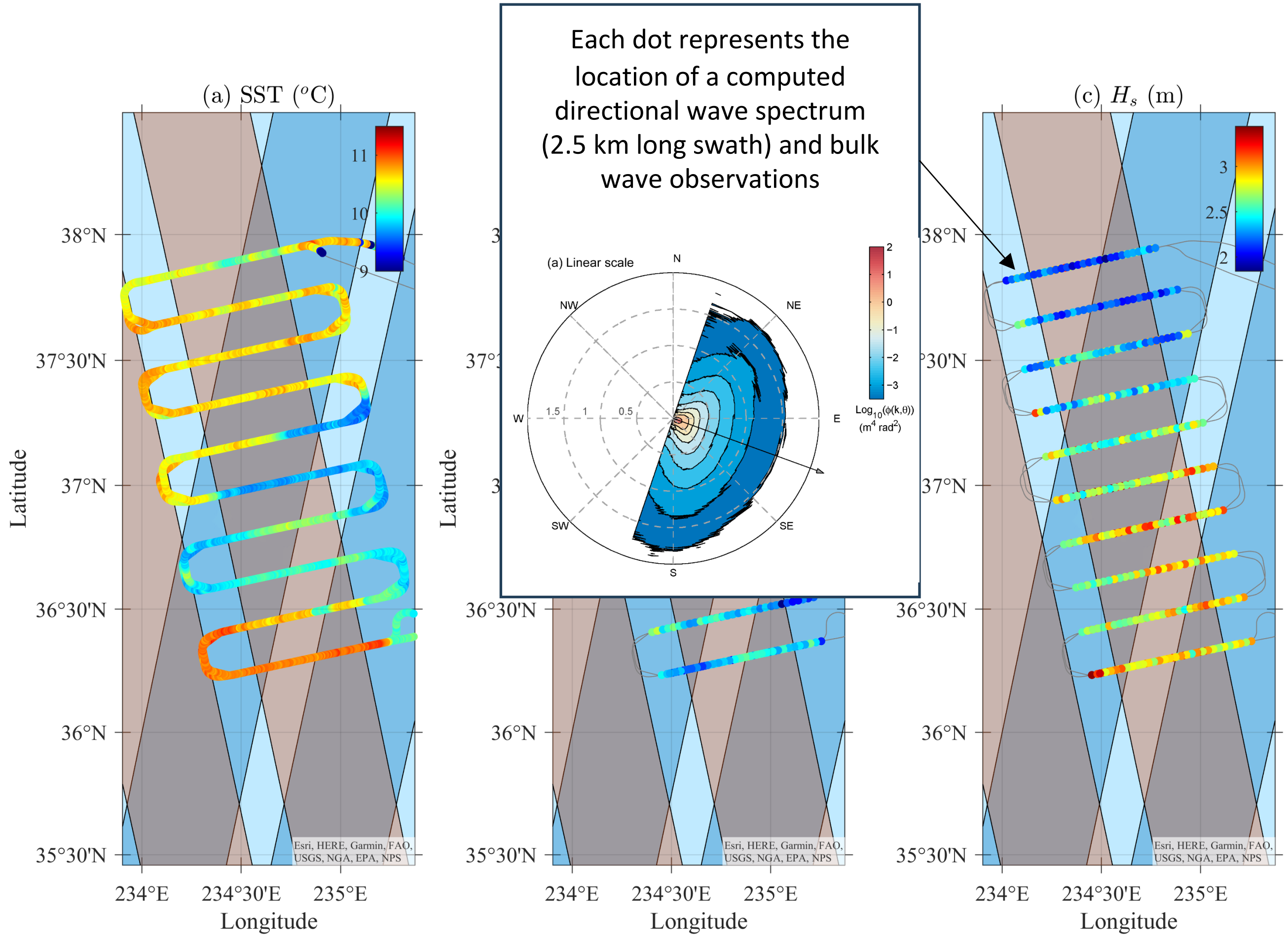
Example of surface elevation as measured from the MASS during a 2011 experiment in the Gulf of Mexico, flying above NDBC buoy #42040. (wind~12m/s, Hs = 3.1m)



Instrumentation		**Measurement**
Scanning Waveform Lidar	Riegl Q680i	Surface wave, surface slope, directional wave spectra (vert. accuracy ~2-3cm), **surface winds**
Long-wave IR Camera	FLIR SC6700 (SLS)	Ocean surface processes, wave kinematics and breaking, frontal processes
High-Resolution Video	JaiPulnix AB-800CL	Ocean surface processes, wave kinematics and breaking, frontal processes
Hyperspectral Camera	Specim EagleAISA	Ocean surface and biogeochemical processes
GPS/IMU	Novatel SPAN-LN200	Georeferencing, trajectory
DoppVis		**Surface currents, vertical shear, wave breaking statistics**

SWOT Phase I – March 30 2023 – SST, SSHA, Hs

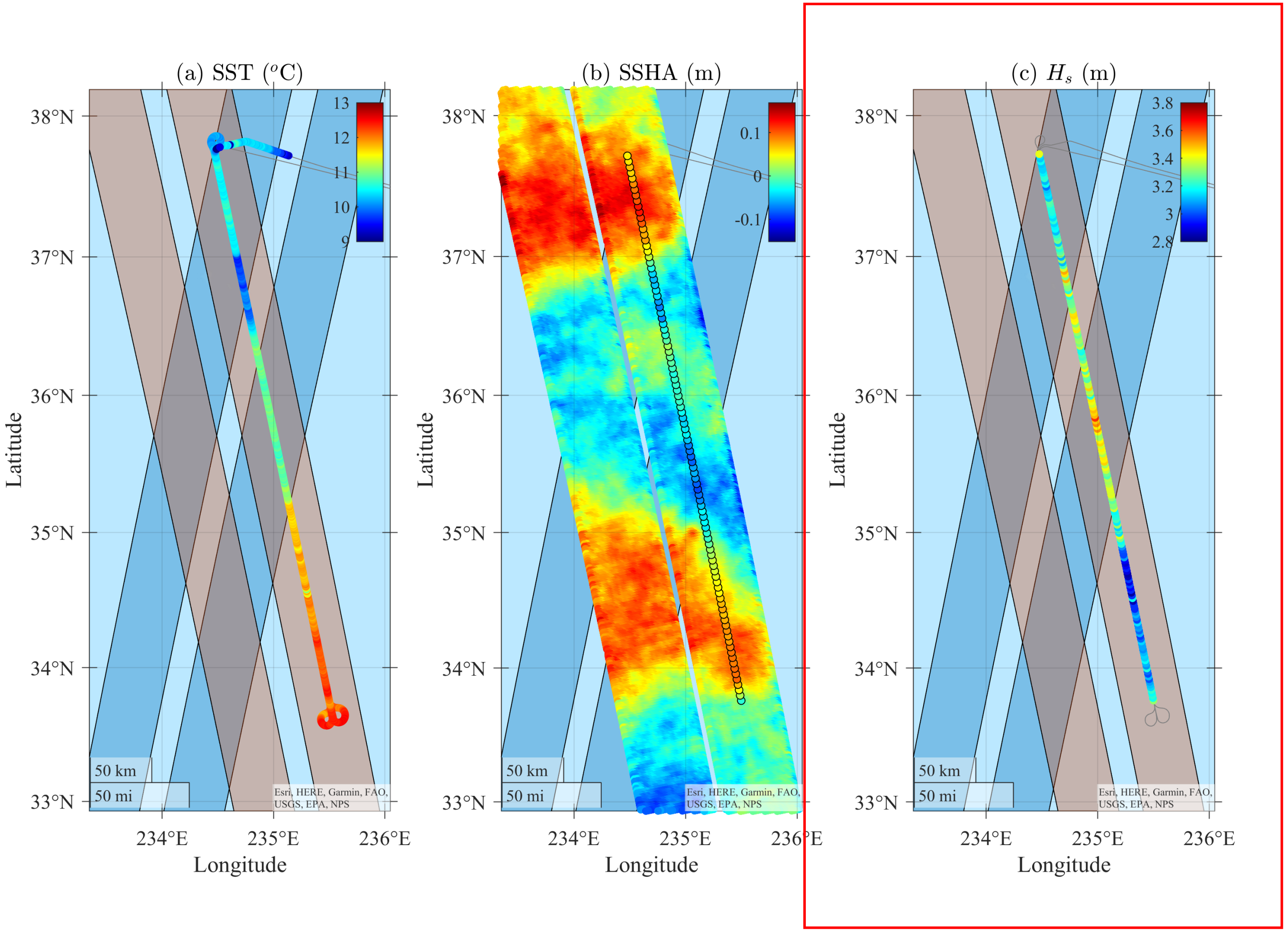
2.5km resolution products



Phase I – April 3 2023 – SST, SSHA, Hs

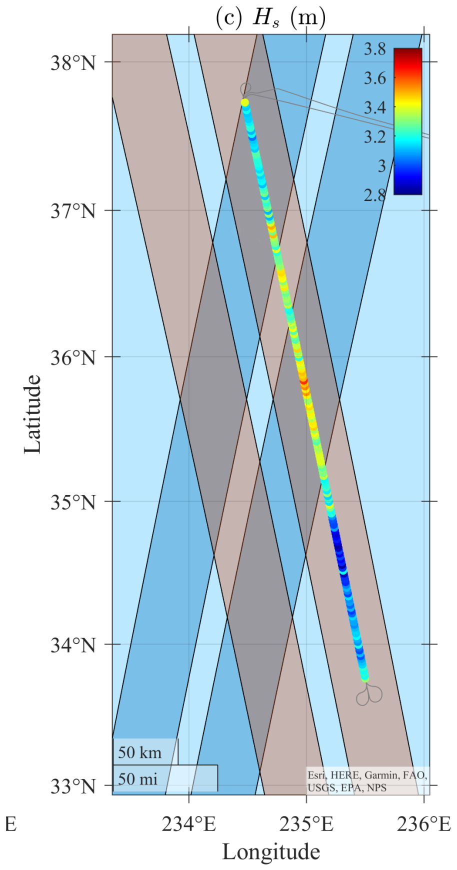
2.5km resolution products

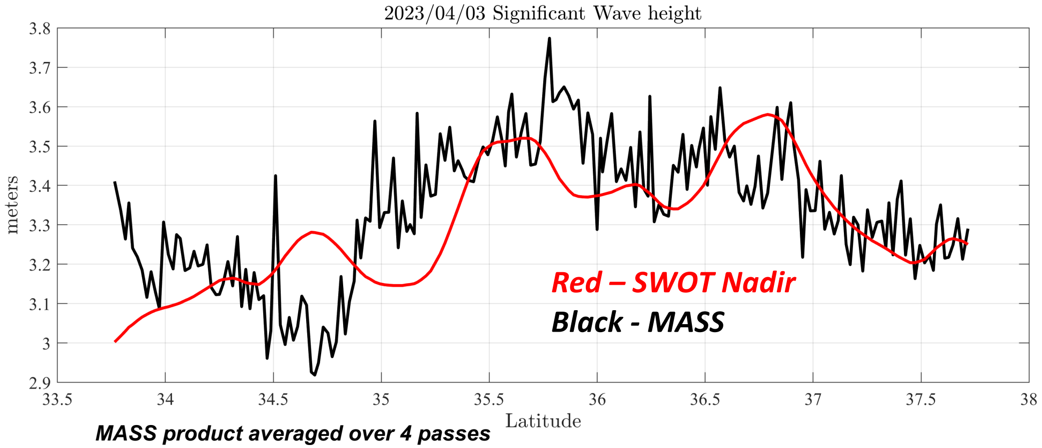
- Collect data for in situ cross comparison and left swath spectral validation



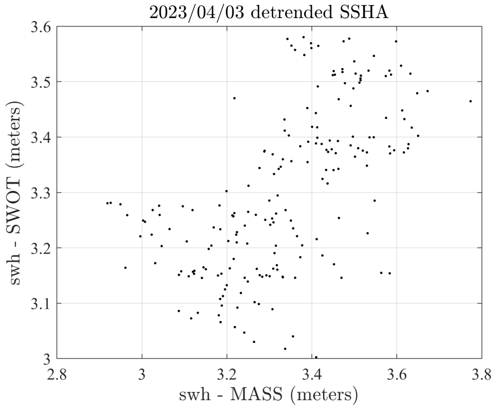
Phase I – April 3 2023 – SST, SSHA, Hs

2.5km resolution products





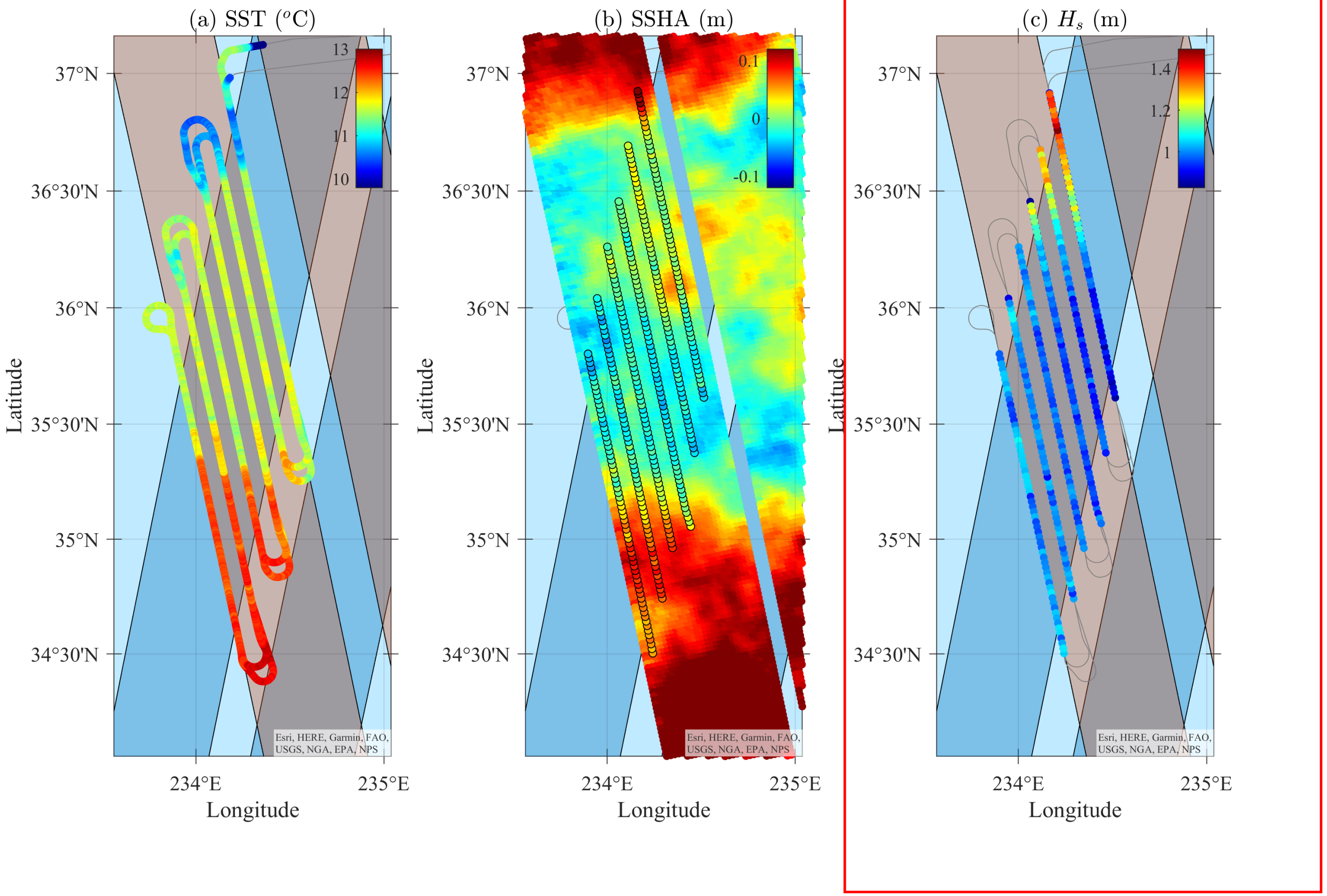
MASS product averaged over 4 passes



SWOT Phase I – April 6 2023 – SST, SSHA, Hs +SWOT preliminary data

2.5km resolution products

- Collect data for right swath spectral dependence vs. cross track and phenomenological investigation.
- Preliminary SWOT observations (offline processing) with empirical cross-swath correction.



Summary

- We report here on the MASS surveys conducted as part of the post-launch SWOT CalVal and S-MODE IOP2 experiment.
- A total of 27 combined flights were collected from two aircraft instrumented with the MASS in the footprint of SWOT.
- MASS measurement of 2-D SSH under the SWOT swath enables direct comparison with SWOT data for SWOT calibration, validation, and troubleshooting.
- We presented a novel instrument, DoppVis, capable of measuring surface currents down to 250m (and less!) horizontal resolution along with the standard remote sensing observations collected from the MASS.
- These types of combined observations can enable the development of better physical understanding of the transition from mesoscale to submesoscales processes and wave-current interactions