Observing the Ocean Surface and the Air-Sea Boundary Layer: Currents and their Gradients at the Submesoscale

Luc Lenain[1], Nicholas Pizzo[2], Mara Freilich[3]

(1) Scripps Institution of Oceanography, La Jolla, United States,
(2) University of Rhode Island, Graduate School of Oceanography
(3) Brown University, Department of Earth, Environmental & Planetary Science

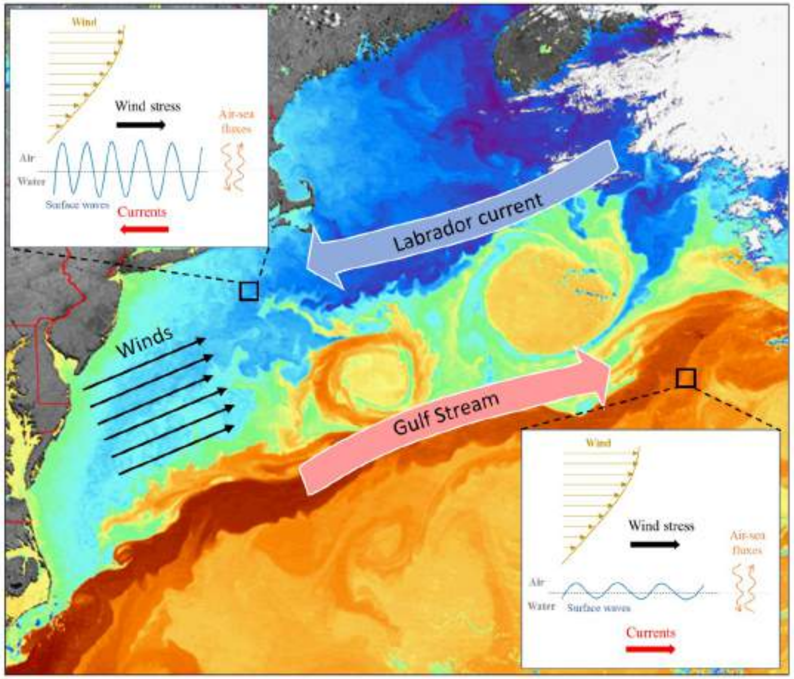
NASA Ocean Vector Wind Science Team (OVWST) meeting
Salt Lake City, UT - May 29-31 2023



Better understanding the coupling between the ocean and the atmosphere from meso to submesoscales

- Direct spatial and temporal observations of the lower atmosphere, sea surface and upper ocean are crucial for improved knowledge of air-sea interaction.

- However, the broad range of scales, or equivalently the strong spatial and temporal variability of theses interactions, make this a formidable theoretical, numerical and observational challenge.



Objectives

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

- Combine observations (e.g. from S-MODE & SWOT programs) with our theoretical understanding on ocean surface boundary layer processes from meso- to submesocales and shorter.

- Conduct process study modeling using high resolution ocean models and a wide range of hydrographic, wave, and wind forcing parameters used to bridge observations and empirical relationships to improve theoretical understanding of air-sea interaction processes.

- These techniques will be brought to bear to inform and interpret the next generation of remote sensing products and to better understand crucial air-sea interaction processes

NASA SWOT SUB-MESOSCALE OCEAN DYNAMICS EXPERIMENT S-MODE

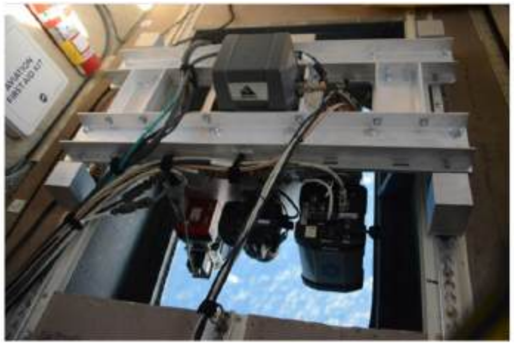
Observing submesoscale dynamics

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

Spatially and temporally co-located observations of wind, waves, and currents are necessary to understand the impacts of atmospheric forcing on submesoscale dynamics.

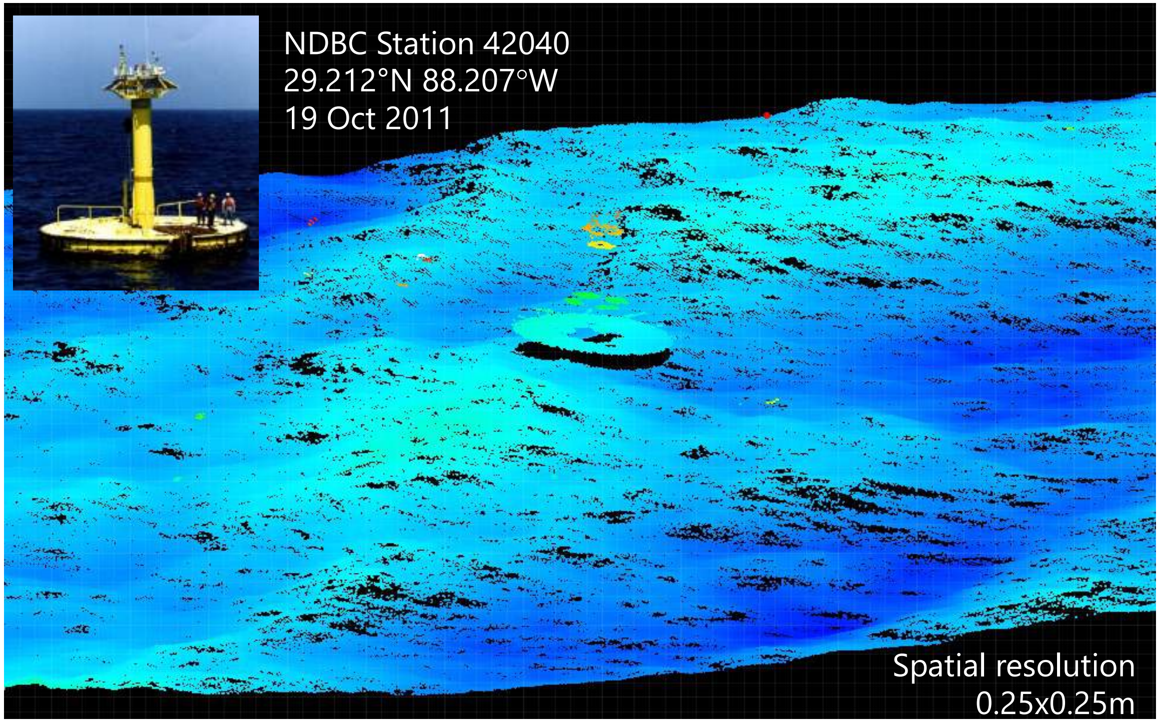
SIO MASS is an airborne instrument to simultaneously collect observations of sea surface temperature, ocean color, winds and mean-square slope, surface waves, wave breaking statistics, ocean topography, and **currents and upper-ocean shear** at horizontal scales ranging from **submeter to mesoscales**.


SIO Modular Aerial Sensing System (MASS)

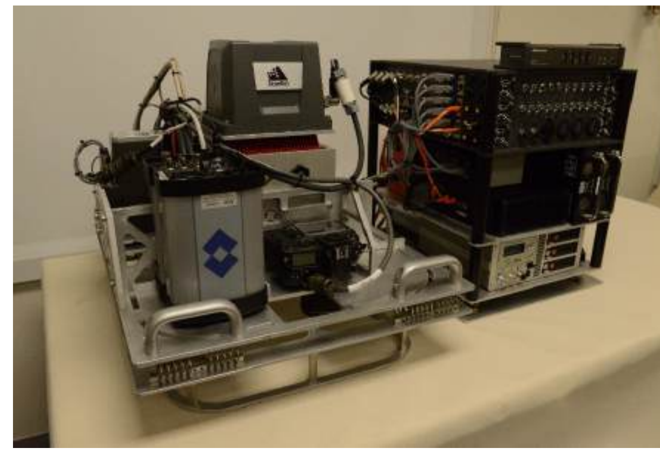


SIO Modular Aerial Sensing System (MASS: Melville et al. 2016)

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego



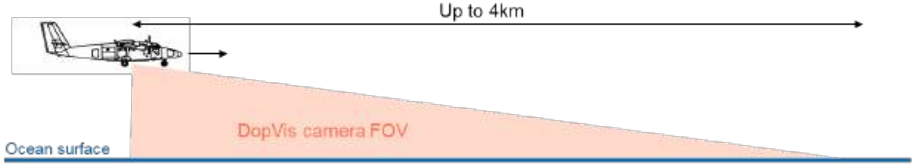
Example of surface elevation as measured from the MASS during a 2011 experiment in the Gulf of Mexico, flying above NDBC buoy #42040. (wind~12m/s, Hs = 3.1m)



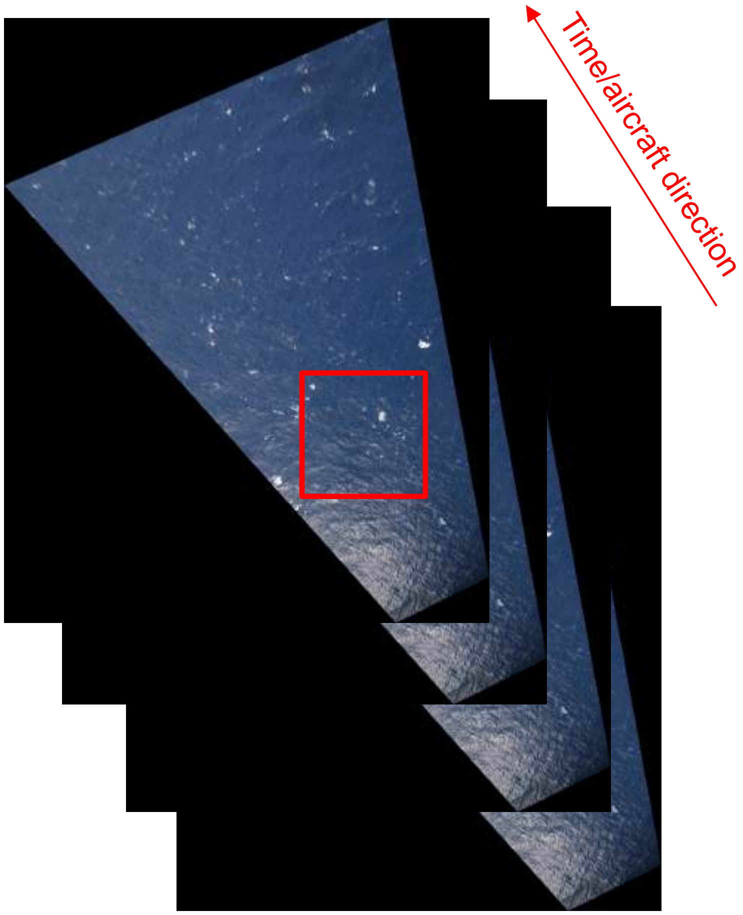
Instrumentation	Measurement	
Scanning Waveform Lidar	Riegl Q680i	Surface wave, surface slope, directional wave spectra (vert. accuracy ~2-3cm), **MSS & winds**
Long-wave IR Camera	FLIR SC6000 (QWIP)	Ocean surface processes, wave kinematics and breaking, frontal processes
High-Resolution Video	JaiPulnix 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 (NEW)		**Surface currents, vertical shear, wave breaking statistics**

MASS DoppVis instrument: Lenain et al. (2023)

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.

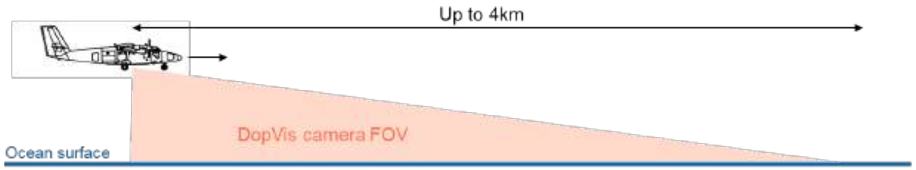


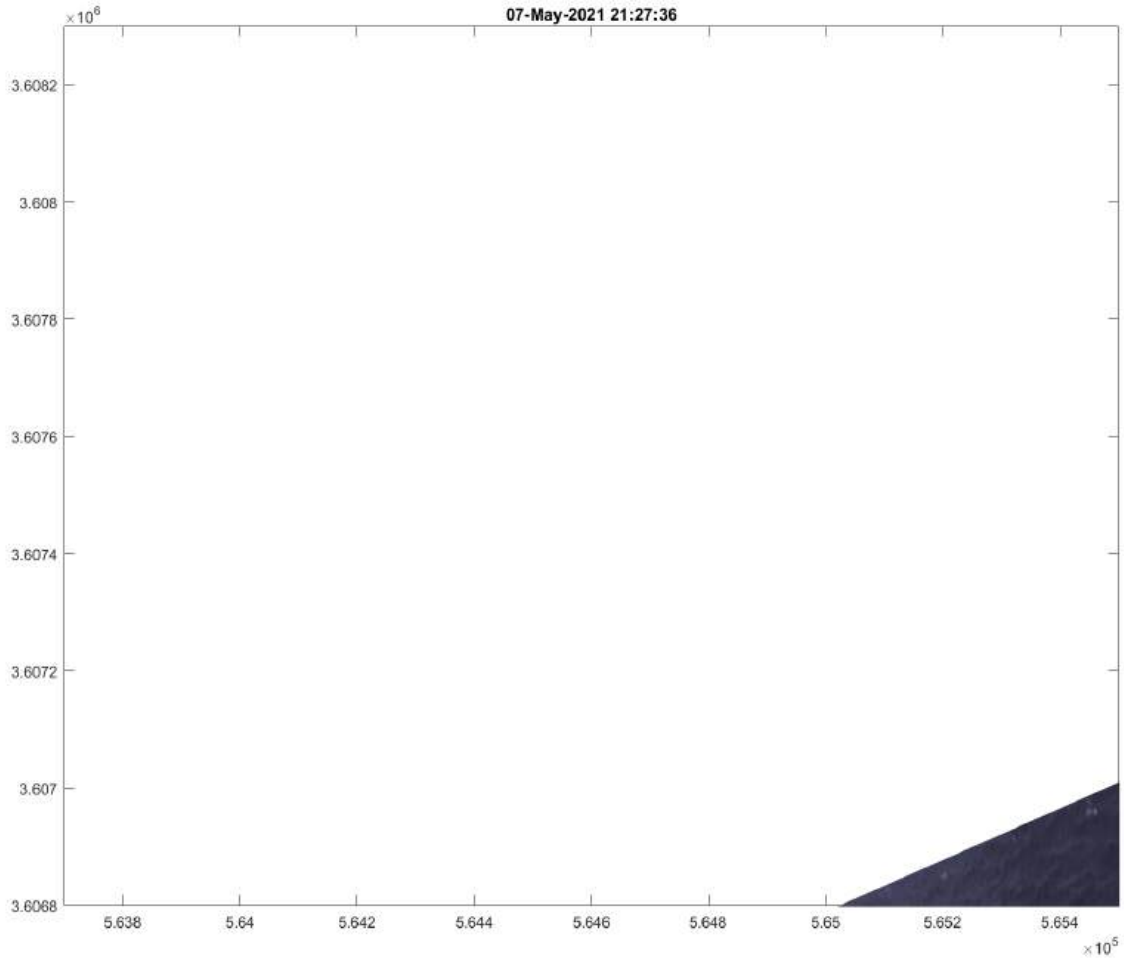
"Stack" georeferenced images together to identify overlapping region (256x256m squares)



MASS DoppVis instrument (Lenain et al. 2023)

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.

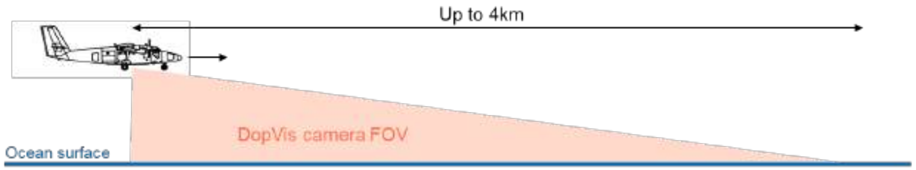


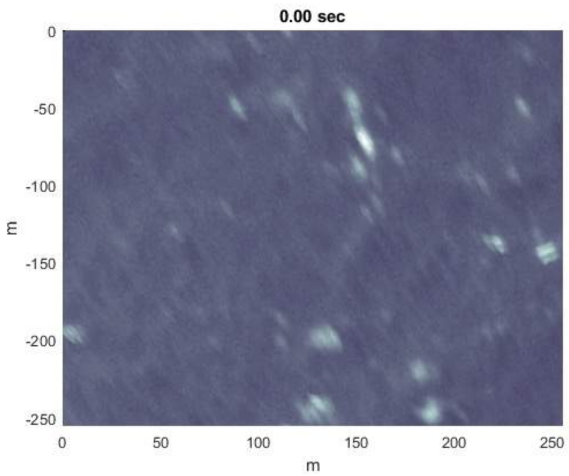


MASS DoppVis surface currents (Lenain et al. 2023)

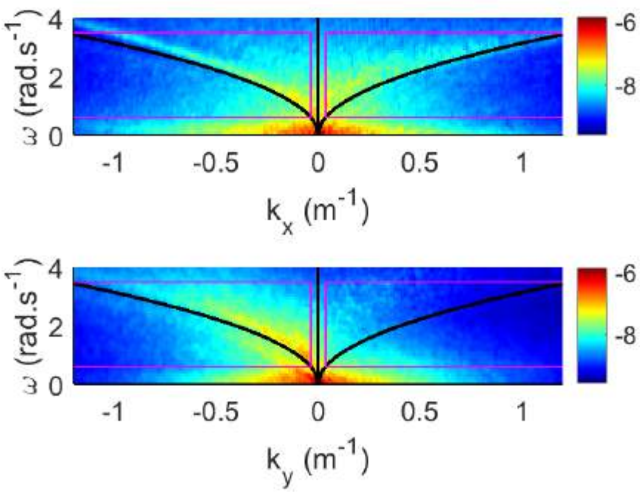
SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

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)

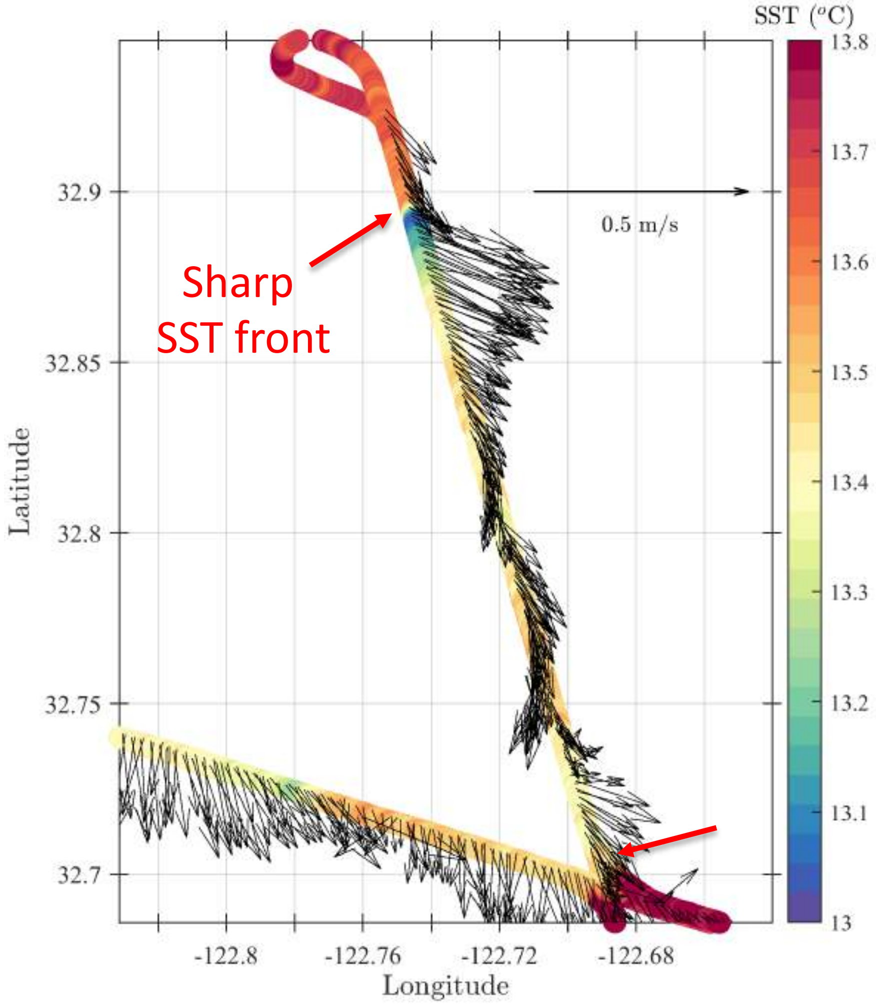
Horizontal resolution: 128-1000m
Depth range: 0.5-3m (wave conditions dependent)
*here depth-averaged currents

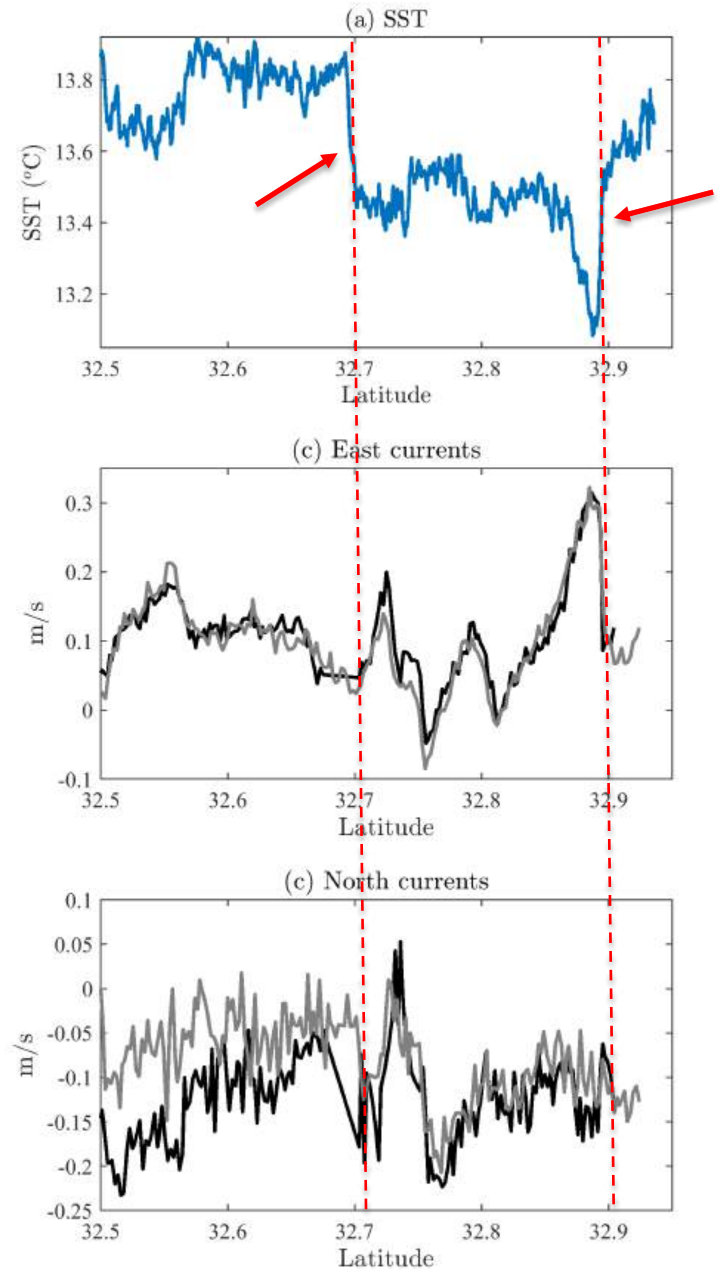
See Stewart & Joy (1974), Campana et al. (2016), Smeltzer et al. (2019) among others for more details on the approach

DoppVis and SST observations at high-resolution (250m along-track & depth-averaged 0.3-2.5m)

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

Very energetic submesoscale features
(few kms wavelength) and fronts

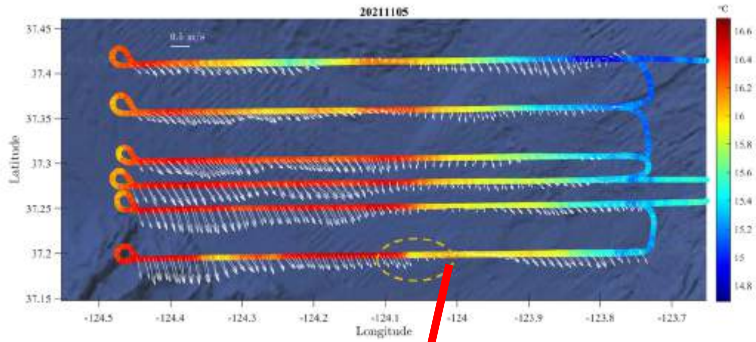




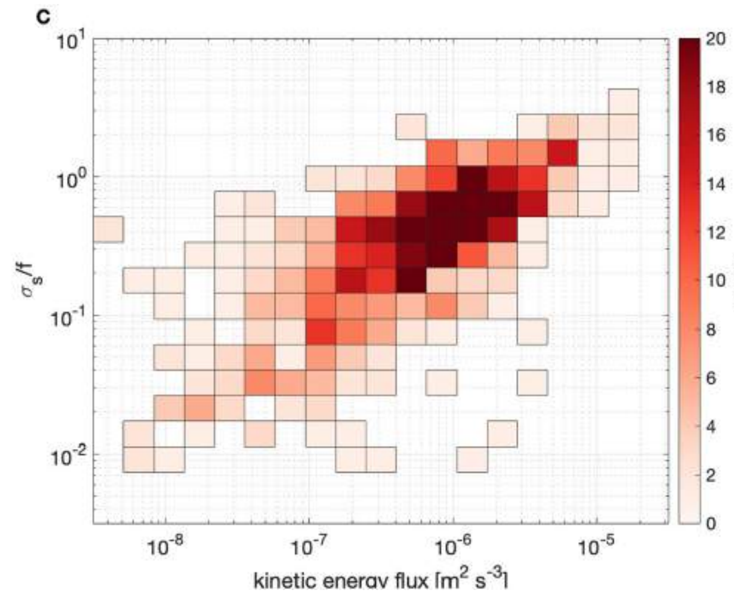
Combining SST imagery and DoppVis surface currents

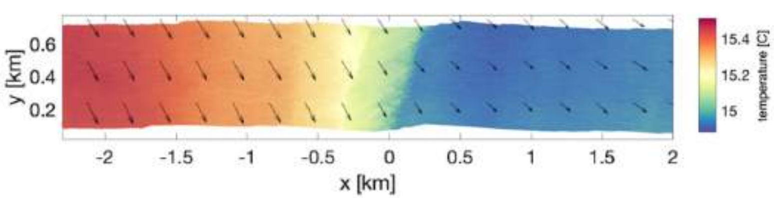
Higher resolution DoppVis current map + SST imagery

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego



Cross-scale kinetic energy flux is localized at submesoscale fronts





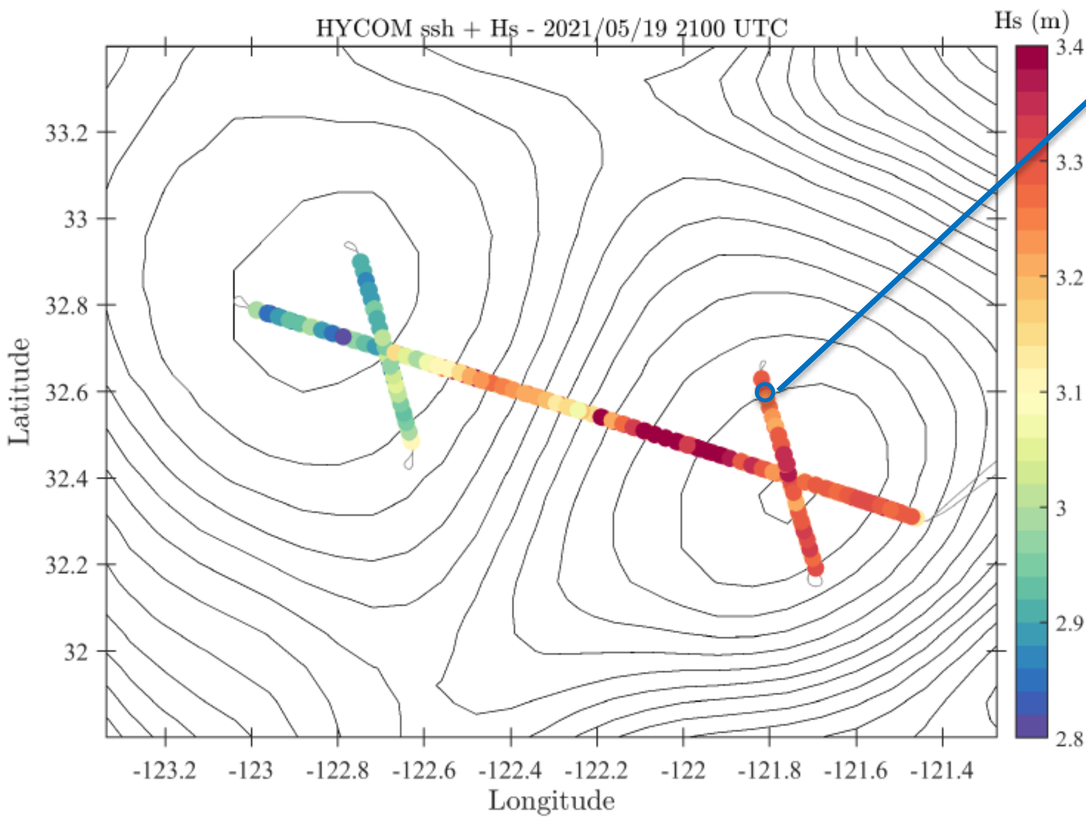
Spectral Energy Transfers (coarse graining approach)

Implications:

- *Magnitude of instantaneous kinetic energy flux has been underestimated by previous modeling and observational work.*
- *New understanding of kinetic energy flux mechanisms.*

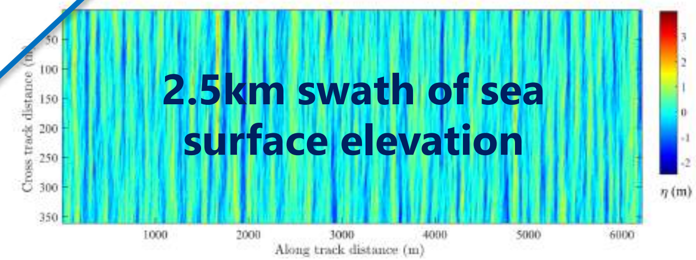
Freilich, M., Lenain, L., Gille, S. (2023). Characterizing the role of non-linear interactions in the transition to submesoscale dynamics at a dense filament.

Significant **spatial** variability in surface gravity wave properties

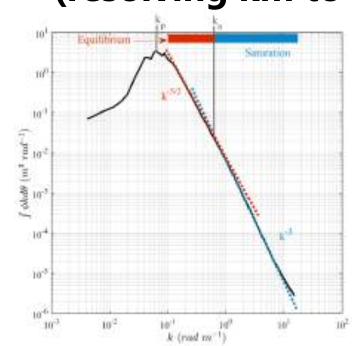


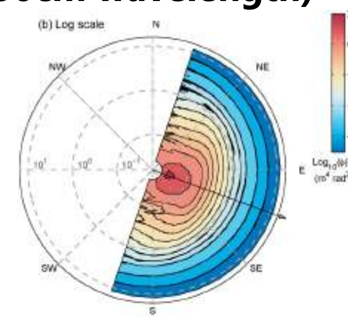
H_s computed using 2.5km long surface height segments

For each "point":



Directional and omnidirectional spectra (resolving km to 50cm wavelength)





+ bulk wave statistics and surface winds (Lenain et al. 2019)

Exploring the role of submesoscale current variability on wave spectral properties

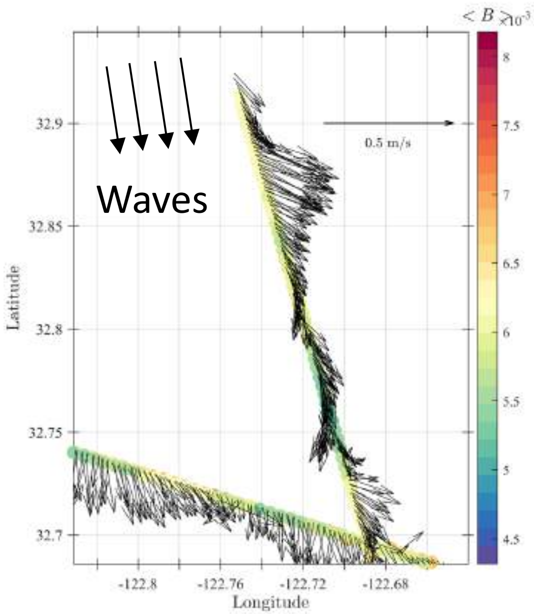
Currents modulate the properties of surface gravity waves through:

- **wave refraction** (e.g. Ardhuin et al. 2017, Romero et al. 2017, 2020, Villas Bôas et al. 2020)
- **local effects** (Rascle et al. 2016, Lenain & Pizzo 2021, Vrecica et al. 2022, Lenain et al. 2023)

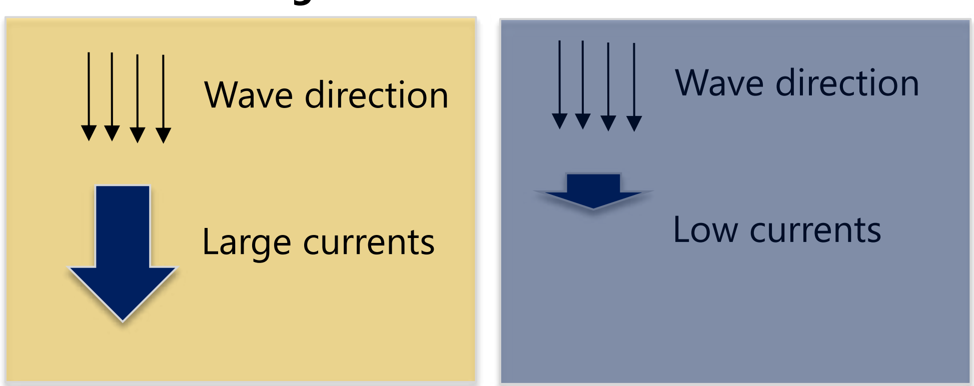
Exploring the role of submesoscale current variability on wave spectral properties (Lenain et al. 2023)

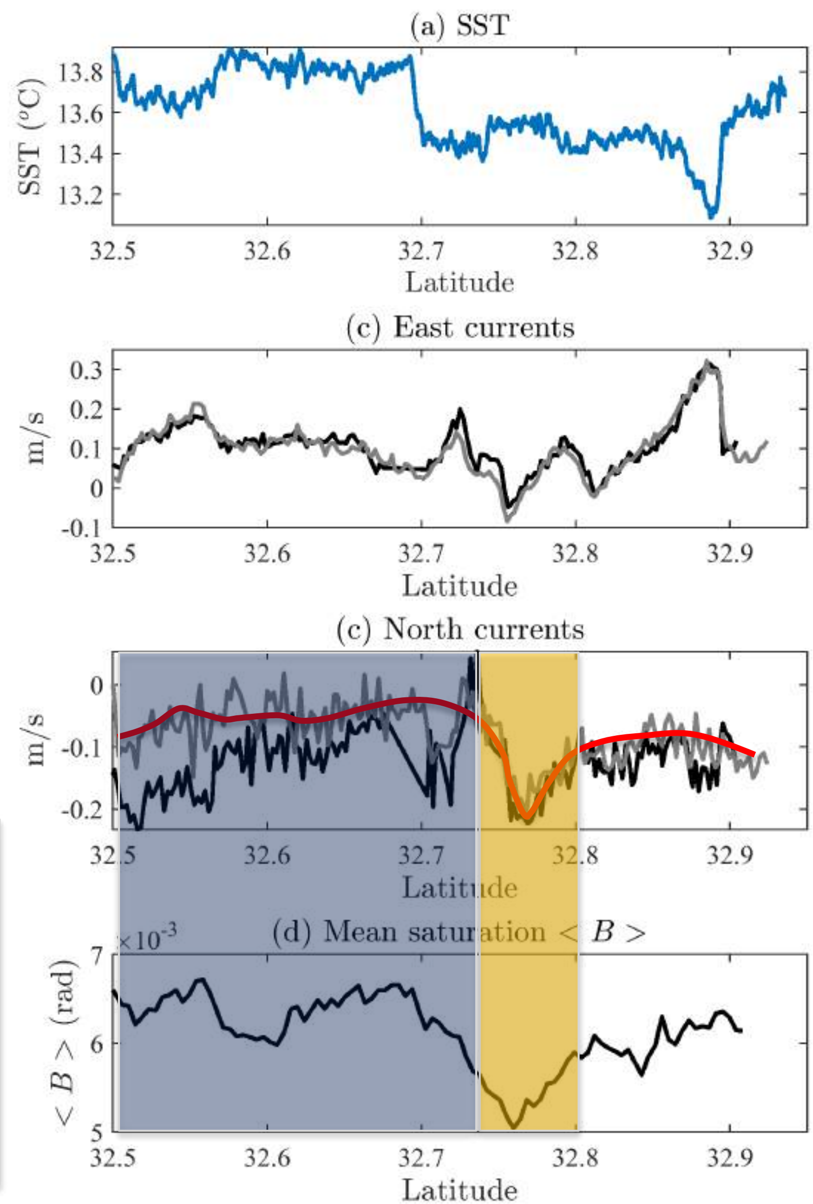
SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

Spectral saturation <B> computed for
k=1-5 rad/m (~1-6m)

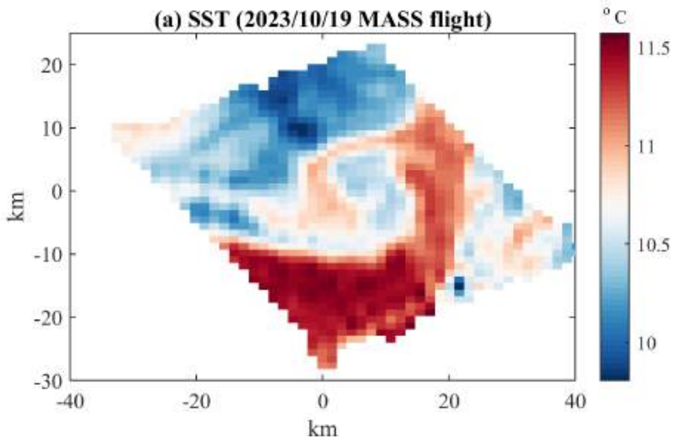


Modulation of saturation level through wave-current interaction



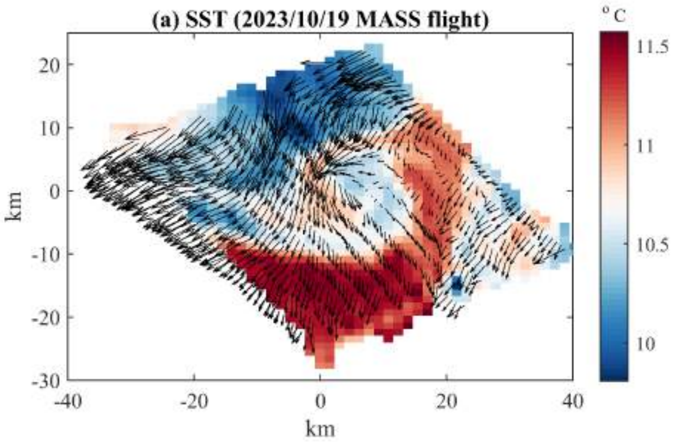


S-MODE IOP2 - April 19th 2023 MASS/DoppVis flight



Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)

S-MODE IOP2 - April 19th 2023 MASS/DoppVis flight

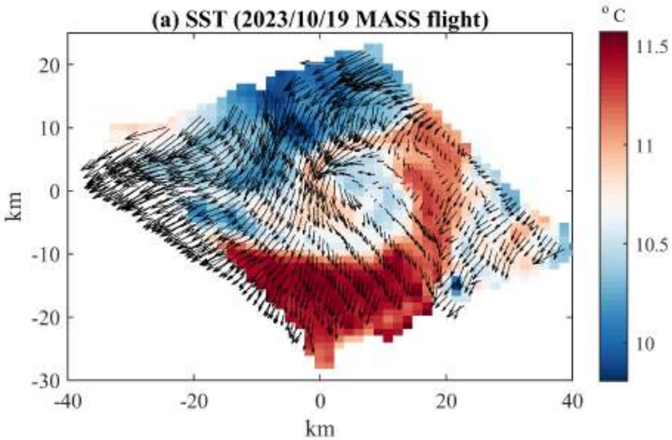


Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)

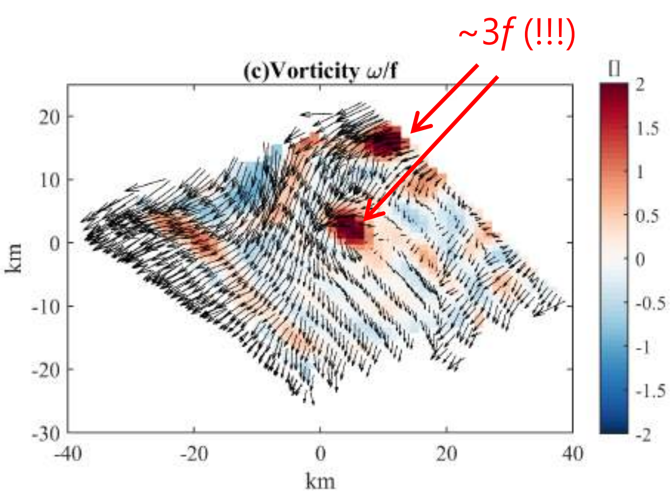
NASA S-MODE IOP2: observing the evolution of surface and near surface properties near two small-scale interacting eddies

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

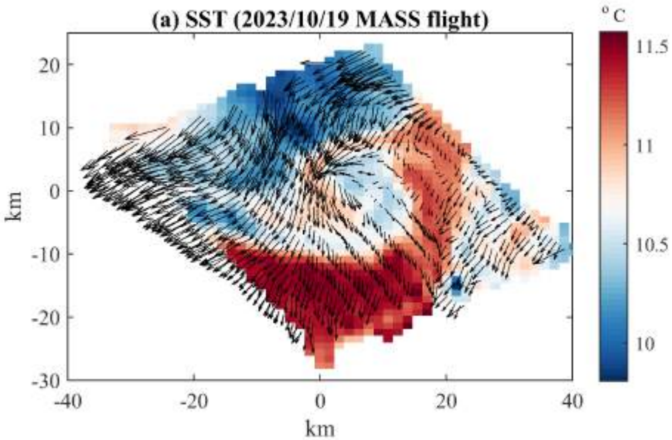
S-MODE IOP2 - April 19th 2023 MASS/DoppVis flight



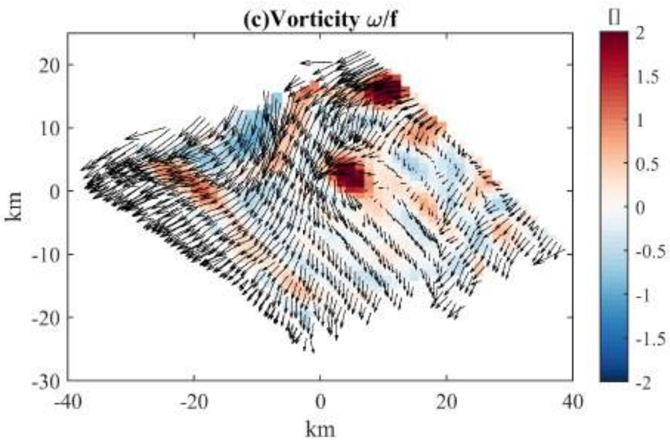
Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)

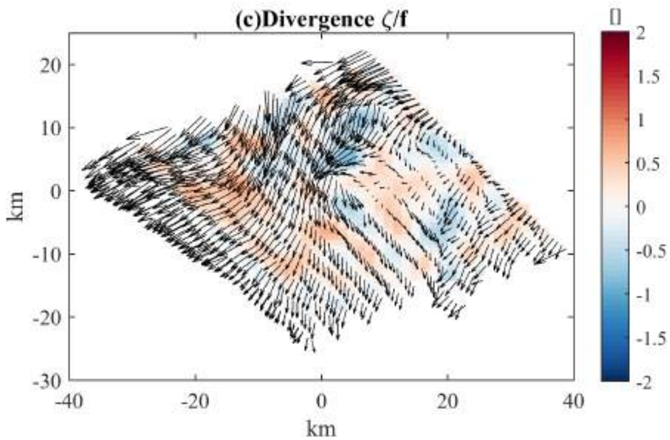


S-MODE IOP2 - April 19th 2023 MASS/DoppVis flight

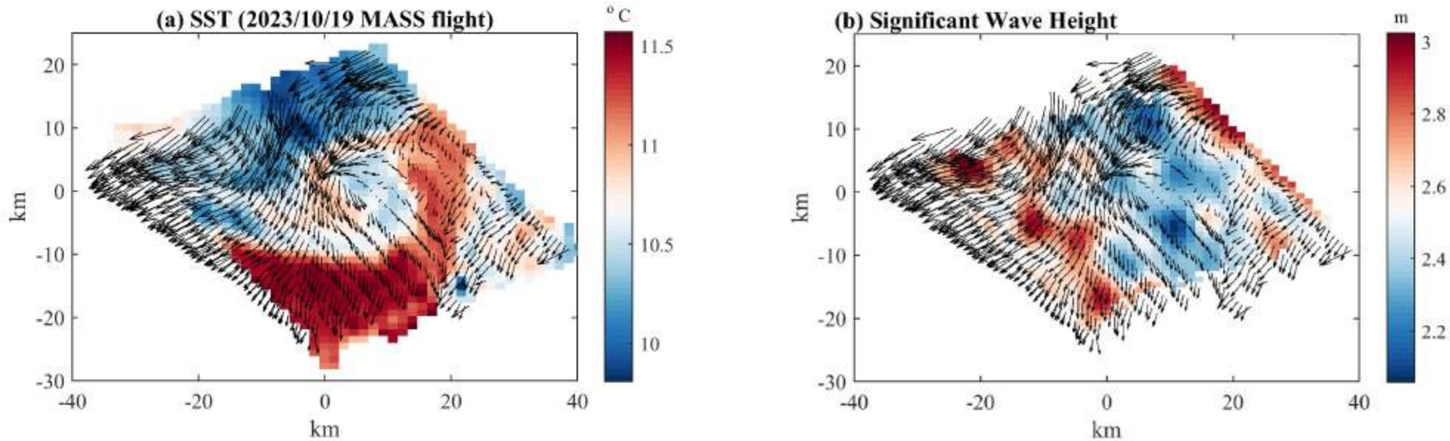


Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)

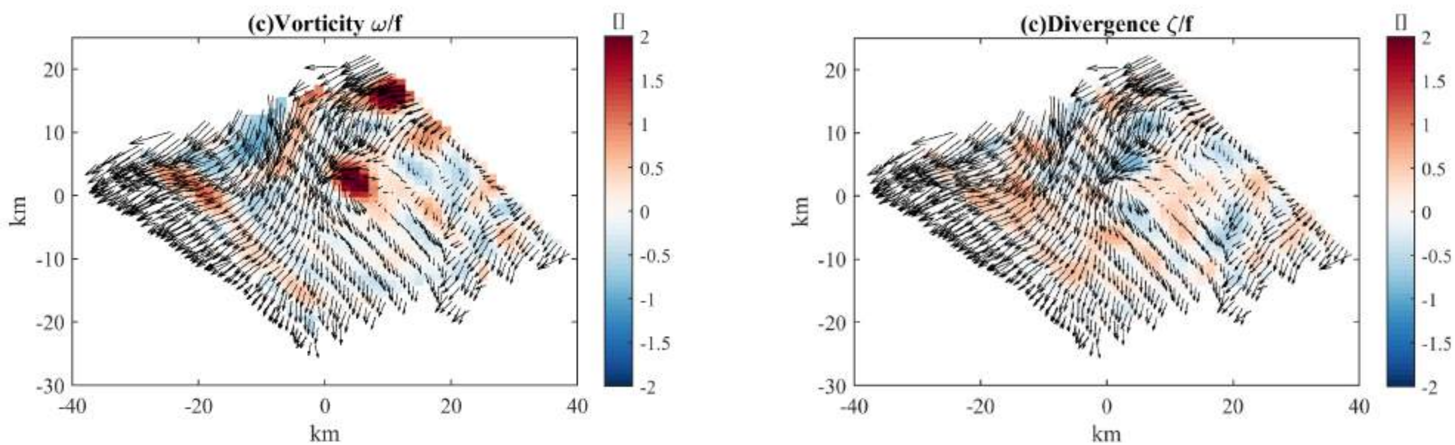




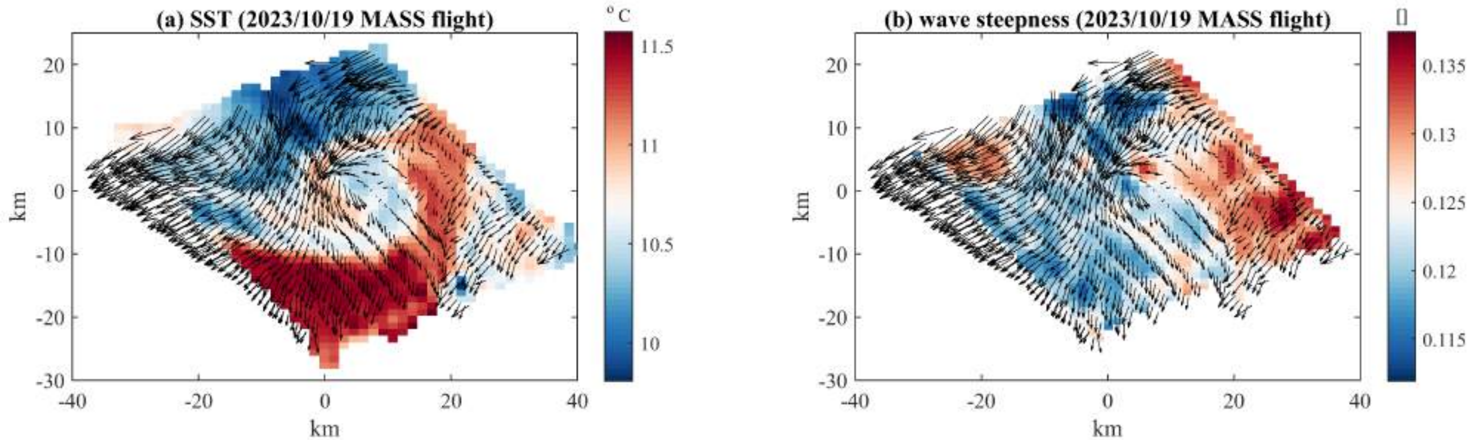
S-MODE IOP2 - April 19th 2023 MASS/DoppVis flight



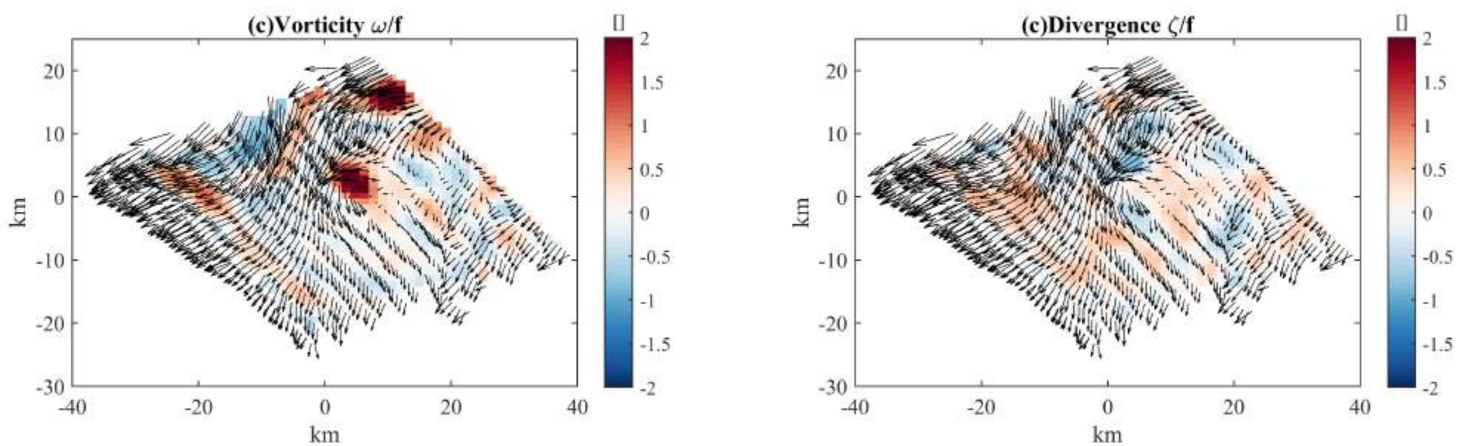
Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)



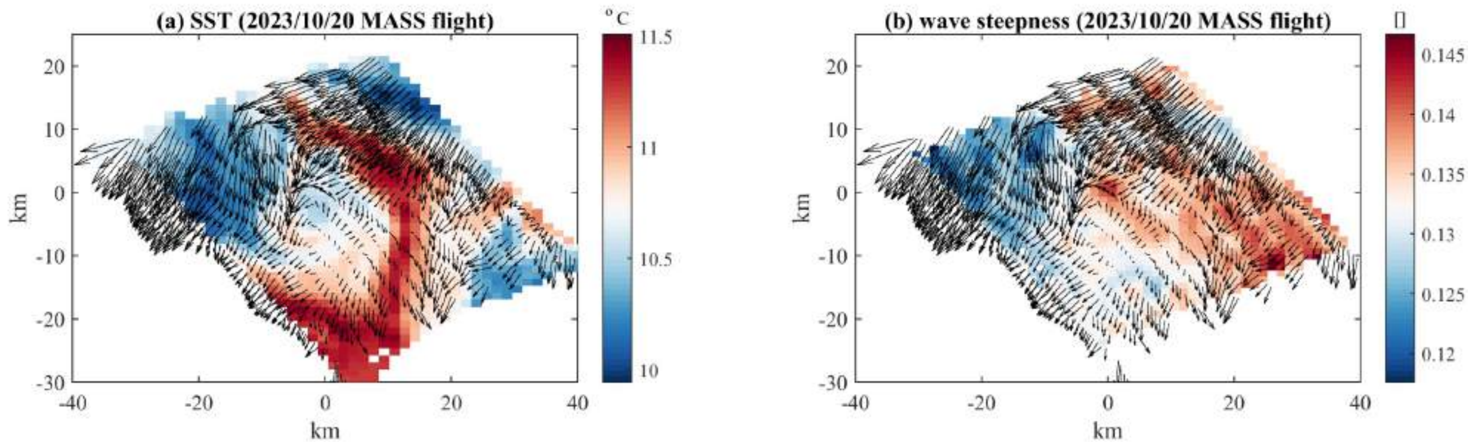
S-MODE IOP2 - April 19th 2023 MASS/DoppVis flight



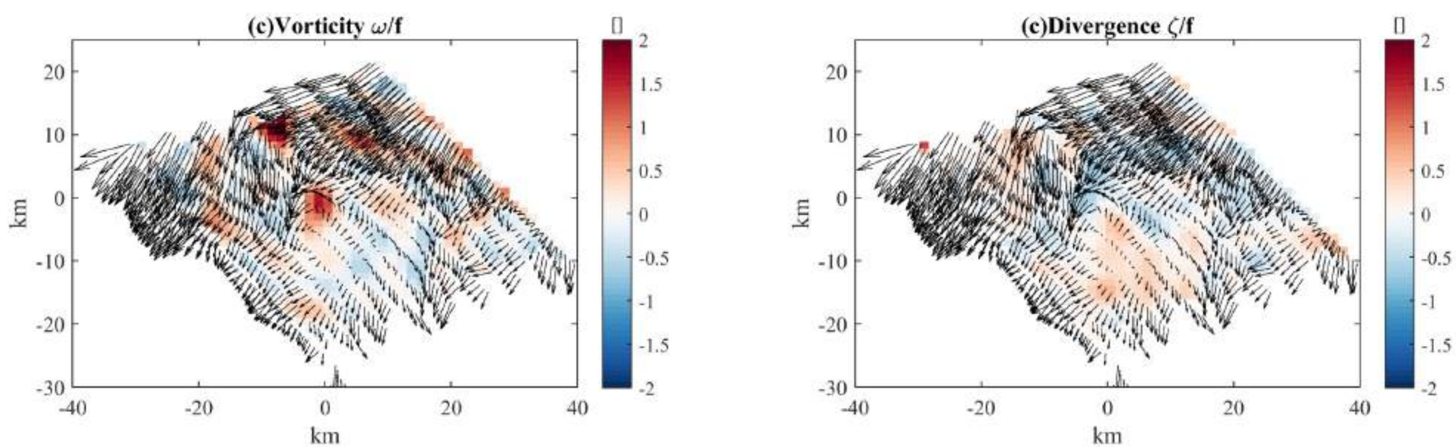
Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)



S-MODE IOP2 - April 20th 2023 MASS/DoppVis flight

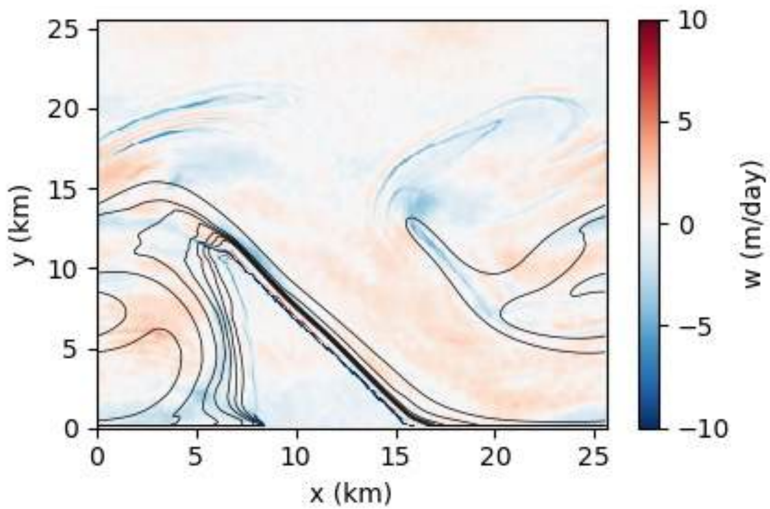


Objectively mapped products from along-track aircraft observations
(Lx = Ly = 3km)



Summary

- MASS & DoppVis offer coincident and co-located measurements of properties of the air-sea boundary layer.
- The waves and currents (and the wind) are strongly coupled, particularly at the submesoscale.
- Submesoscale velocity gradients generate hotspots of cross-scale kinetic energy flux.
- Wave-current interactions generate gradients in wave properties at submesoscale.



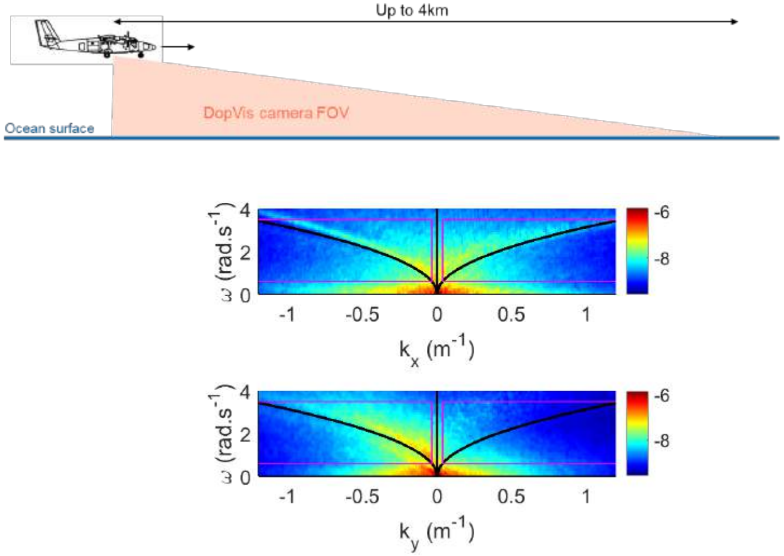
Summary

Thank you!!

EXTRA SLIDES

How well does DoppVis surface currents agree with in-situ observations?

Comparing DoppVis near surface current profiles to upward and downward ADCPs installed on the wave glider using coincident (within 5min), collocated (within 500m) observations.



+

Summary

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

- We report a unique set of coincident and collocated observations of high-resolution surface currents and directional properties of surface waves collected from an airborne instrument, the Modular Aerial Sensing System (MASS), off the coast of Southern California in May 2021, across two small counter-rotating eddies separated by approximately 100 km.

- We presented a novel instrument, DoppVis, capable of measuring surface currents down to 250m (and less!) horizontal resolution.

- This data set provides a unique opportunity to examine how currents at scales ranging from 1-100 km modulate surface gravity waves, i.e. bulk (e.g. significant wave height), directional and spectral properties through wave refraction and local wave-current interaction processes.

Summary

- We report a unique set of coincident and collocated observations of high-resolution surface currents and directional properties of surface waves collected from an airborne instrument, the Modular Aerial Sensing System (MASS), off the coast of Southern California in May 2021, across two small counter-rotating eddies separated by approximately 100 km.

- We presented a novel instrument, DoppVis, capable of measuring surface currents down to 250m (and less!) horizontal resolution.

- This data set provides a unique opportunity to examine how currents at scales ranging from 1-100 km modulate surface gravity waves, i.e. bulk (e.g. significant wave height), directional and spectral properties through wave refraction and local wave-current interaction processes.

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL102468

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

Luc Lenain[1], Benjamin K. Smeltzer[2,3], Nick Pizzo[1], Mara Freilich[1,4], Luke Colosi[1], Simen Å. Ellingsen[2], Laurent Grare[1], Hugo Peyriere[1], and Nick Statom[1]

[1]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA, [2]Department of Energy Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway, [3]Marinteknisk senter, SINTEF Ocean, Trondheim, Norway, [4]Department of Earth, Environmental and Planetary Science, Division of Applied Mathematics, Brown University, Providence, RI, USA

Key Points:

- Unique coincident and collocated airborne observations of Sea Surface Temperature, surface currents and properties of surface waves across submesoscales features
- A new airborne instrument enables observations of surface currents, vertical and horizontal shear to capture quickly evolving ocean features
- Such observations are crucial to develop better understanding of the physics of submesoscale processes and wave-current interaction

Correspondence to:
L. Lenain,
llenain@ucsd.edu

Citation:
Lenain, L., Smeltzer, B. K., Pizzo, N.,

Abstract In this work we present a unique set of coincident and collocated high-resolution observations of surface currents and directional properties of surface waves collected from an airborne instrument, the Modular Aerial Sensing System, collected off the coast of Southern California. High-resolution observations of near surface current profiles and shear are obtained using a new instrument, "DoppVis", capable of capturing horizontal spatial current variability down to 128 m resolution. This data set provides a unique opportunity to examine how currents at scales ranging from 1 to 100 km modulate bulk (e.g., significant wave height), directional and spectral properties of surface gravity waves. Such observations are a step toward developing better understanding of the underlying physics of submesoscale processes (e.g., frontogenesis and frontal arrest) and the nature of transitions between mesoscale and submesoscale dynamics.

Geophysical Research Letters

RESEARCH LETTER
10.1029/2023GL103745

Characterizing the Role of Non-Linear Interactions in the Transition to Submesoscale Dynamics at a Dense Filament

Mara Freilich[1], Luc Lenain[1], and Sarah T. Gille[1]

[1]Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

Key Points:

- Remote sensing observations reveal a kinetic energy spectrum with a continuous slope from 100 to 1 km in an eastern boundary region
- Between 1 and 10 km, ageostrophic non-linear interactions become dynamically important
- Cross-scale kinetic energy transfers computed from 2D velocity observations are associated with shear strain in the observed front

Supporting Information:
Supporting Information may be found in the online version of this article.

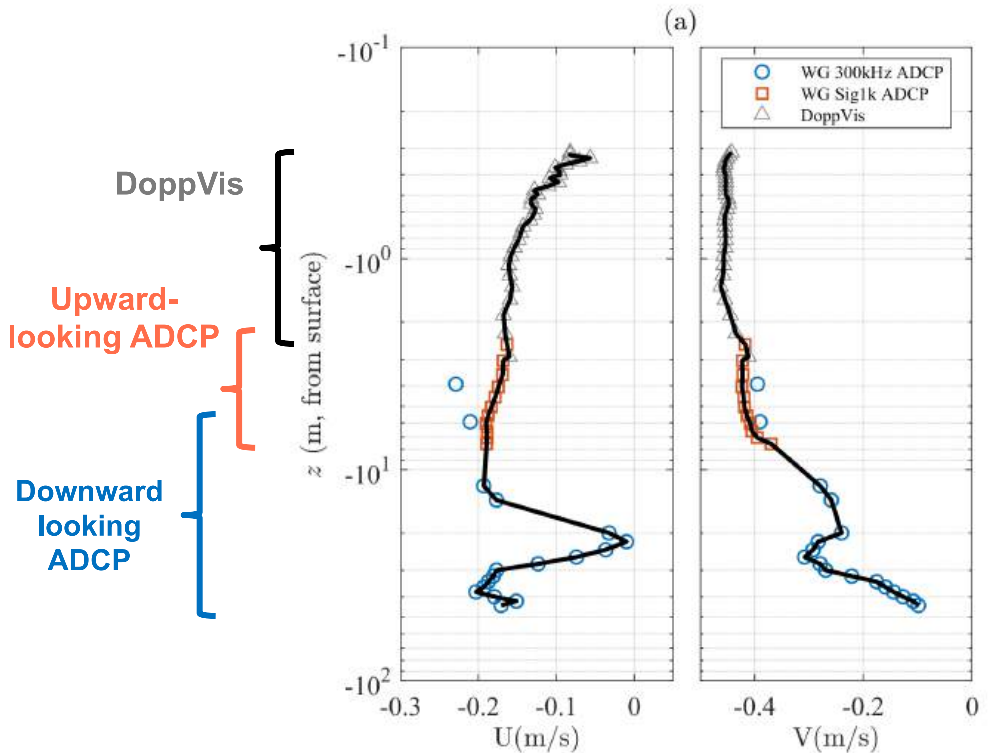
Abstract Ocean dynamics at the submesoscale play a key role in mediating upper-ocean energy dissipation and dispersion of tracers. Observations of ocean currents from synoptic mesoscale surveys at submesoscale resolution (250 m–100 km) from a novel airborne instrument (MASS DoppVis) reveal that the kinetic energy spectrum in the California Current System is nearly continuous from 100 km to sub-kilometer scales, with a k^{-2} spectral slope. Although there is not a transition in the kinetic energy spectral slope, there is a transition in the dynamics to non-linear ageostrophic interactions at scales of $\mathcal{O}(1\ \text{km})$. Kinetic energy transfer across spatial scales is enabled by interactions between the rotational and divergent components of the flow field at the submesoscale. Kinetic energy flux is patchy and localized at submesoscale fronts. Kinetic energy is transferred both downscale and upscale from 1 km in the observations of a cold filament.

Mara Freilich's talk on Wednesday!
PS33A-04

How well does DoppVis surface currents agree with in-situ observations?

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

Comparing DoppVis near surface current profiles to upward and downward ADCPs installed on the wave glider using coincident (within 5min), collocated (within 500m) observations.



Lenain, L., Smeltzer, B. K., Pizzo, N., Freilich, M., Colosi, L., Ellingsen, S. Å., et al. (2023). Airborne remote sensing of upper-ocean and surface properties, currents and their gradients from meso to submesoscales.

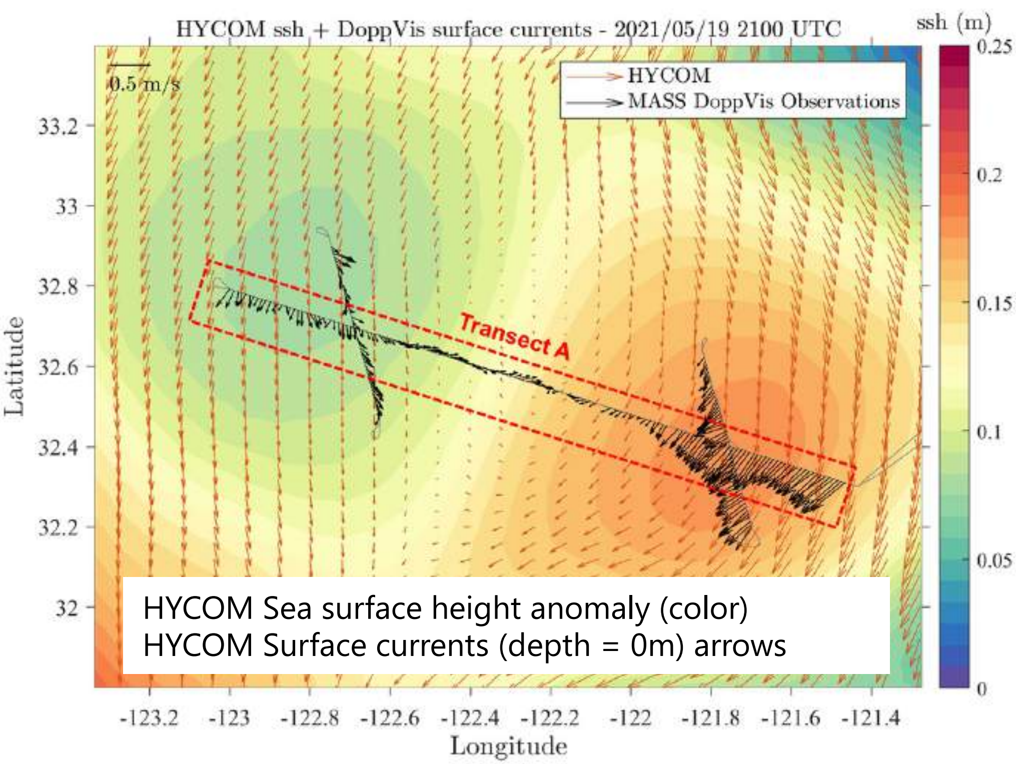
Comparing HYCOM and DoppVis observed currents

MASS DoppVis observations:

- Depth-averaged (0.5-3m) currents, 1km horizontal resolution are presented for all passes on May 19th flight.
- One pass, starting at 21:55 UTC (50min leg)

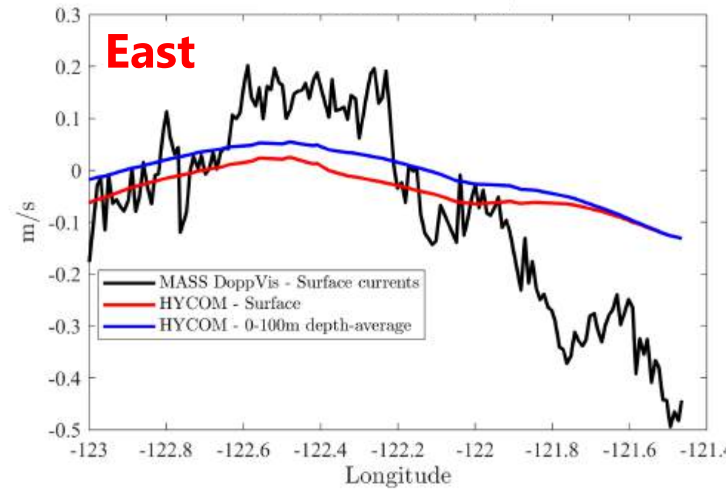
HYCOM products:

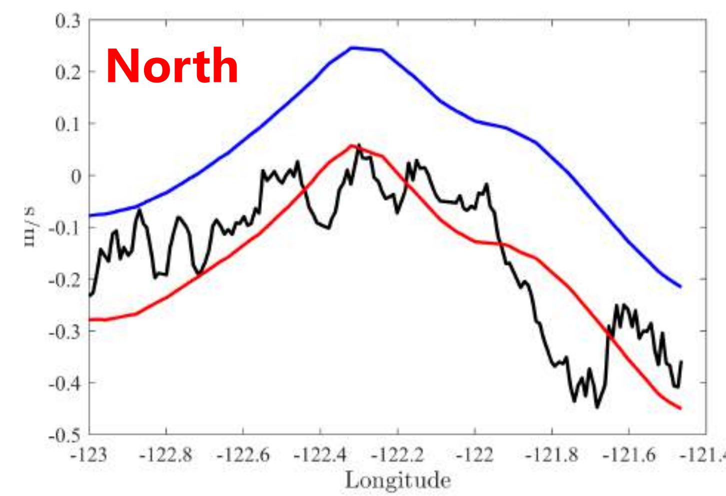
- Surface currents (depth = 0m) in red
- Depth-averaged currents (0-100m) in blue
- Interpolated product in **space and time** at the same location where MASS DoppVis currents are measured



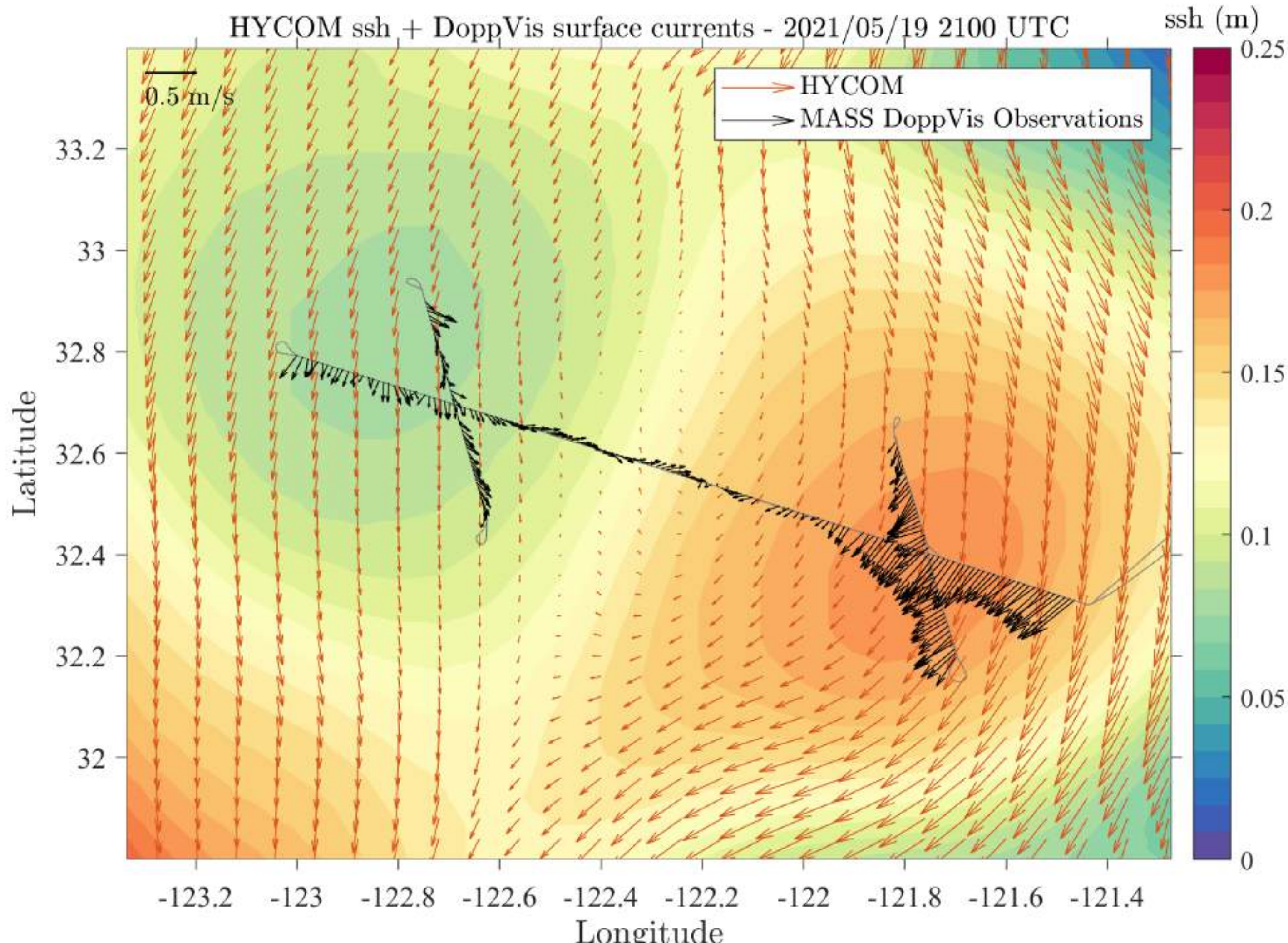
HYCOM Sea surface height anomaly (color)
HYCOM Surface currents (depth = 0m) arrows

Transect A





Comparing HYCOM and DoppVis observed currents



MASS DoppVis observations:

- Depth-averaged (~0.5-3m) currents, 1km horizontal
- Showing non-reciprocal passes for clarity

HYCOM products:

- Sea surface height anomaly (ssh)
- Surface currents (depth = 0m) plotted here