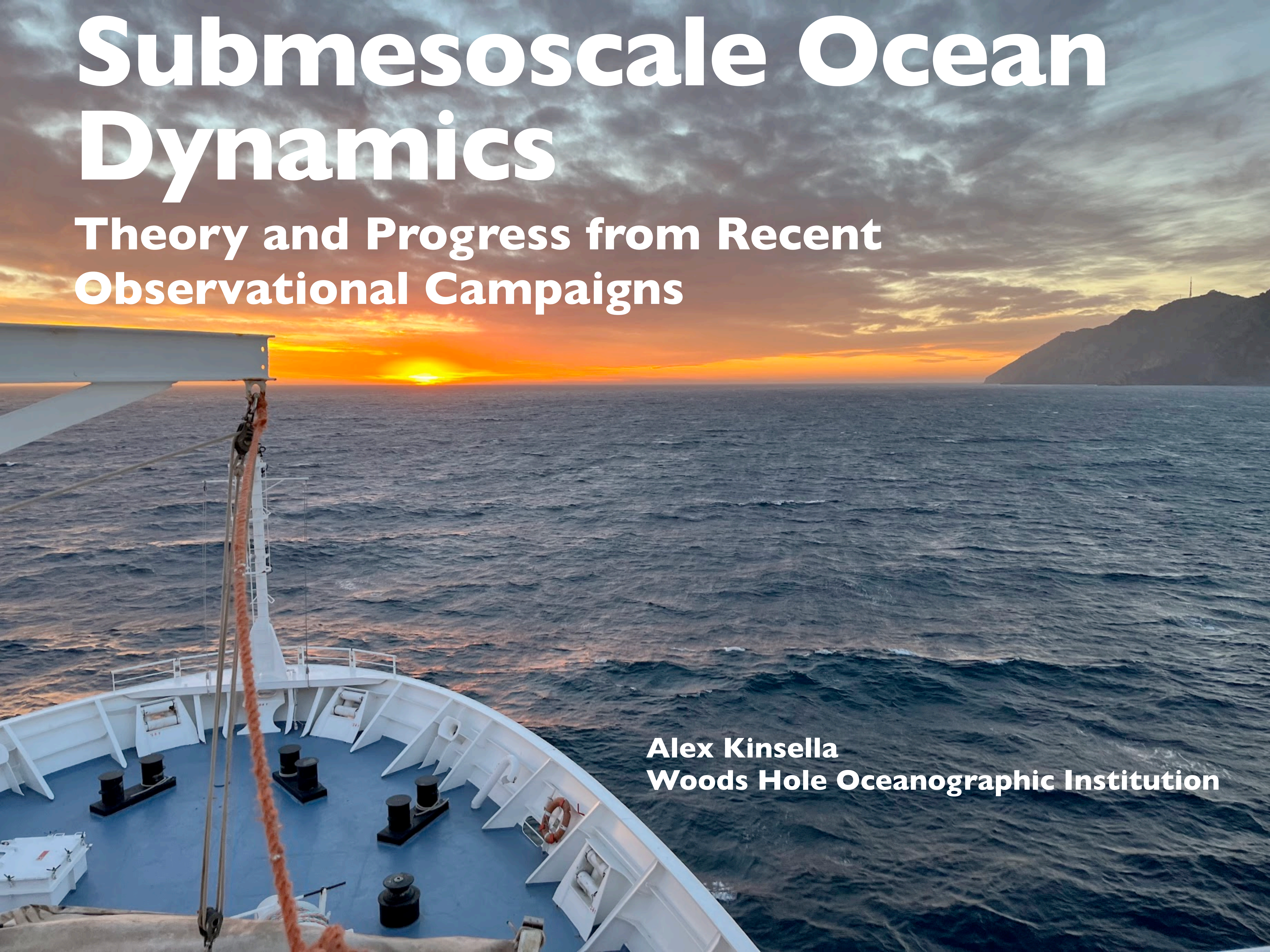
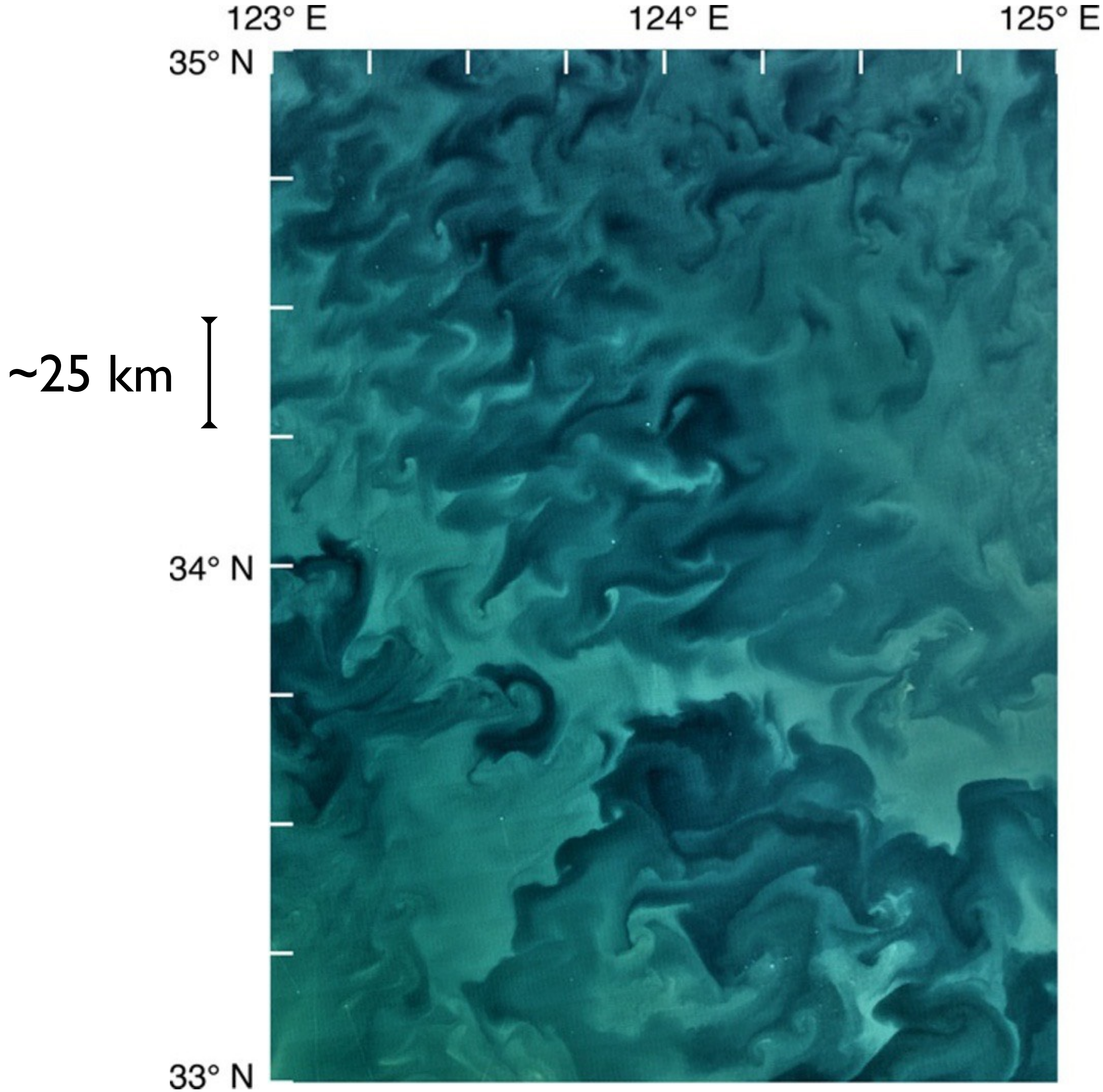


Submesoscale Ocean Dynamics

Theory and Progress from Recent Observational Campaigns

Alex Kinsella
Woods Hole Oceanographic Institution

The Oceanic Submesoscale



NASA MODIS imagery by Norman Kuring

The Oceanic Submesoscale

Scalings

How do energy and properties get fluxed downscale?

Non-dissipative 2-D				Dissipative 3-D
Mesoscales	→	Submesoscales	→	Small scales
Ro << 1, Ri >> 1		Ro and Ri are O(1)		Ro >> 1, Ri << 1
L ~ 10 - 100 km		L ~ 1 km		L < 100 m
D/L << 1, hydrostatic		D/L << 1, hydrostatic		D/L ~ 1, nonhydrostatic

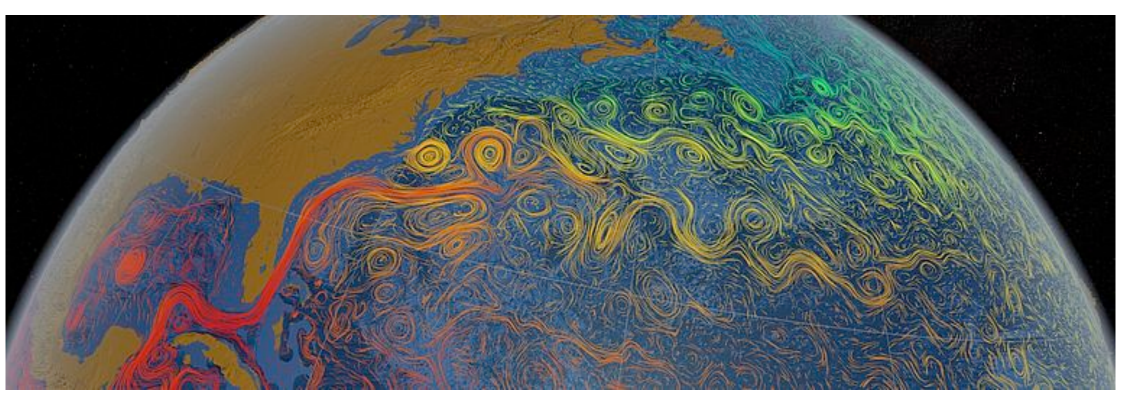


Image from NASA/GSFC Scientific Visualization Studio

Why Care About the Submesoscale?

Characteristics:
- Strong density fronts
- Strong vorticity
- Strong vertical velocities

Consequences
- Relevant for biology
  - Upwelling of nutrients
  - Similar timescale to phytoplankton
- Relevant for climate
  - Subduction of dissolved and particulate carbon
  - Subduction of heat
- Relevant to turbulent cascade

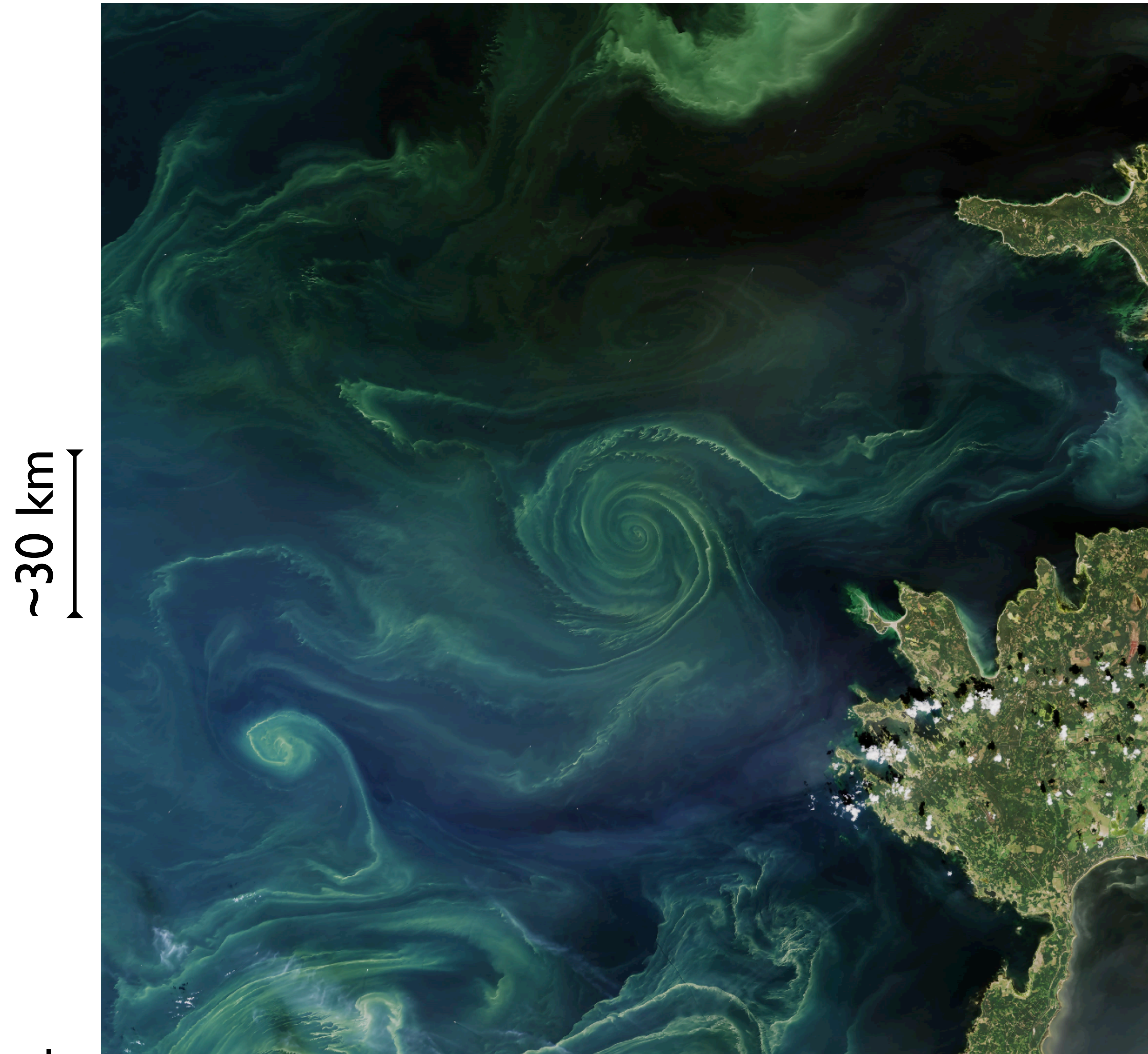
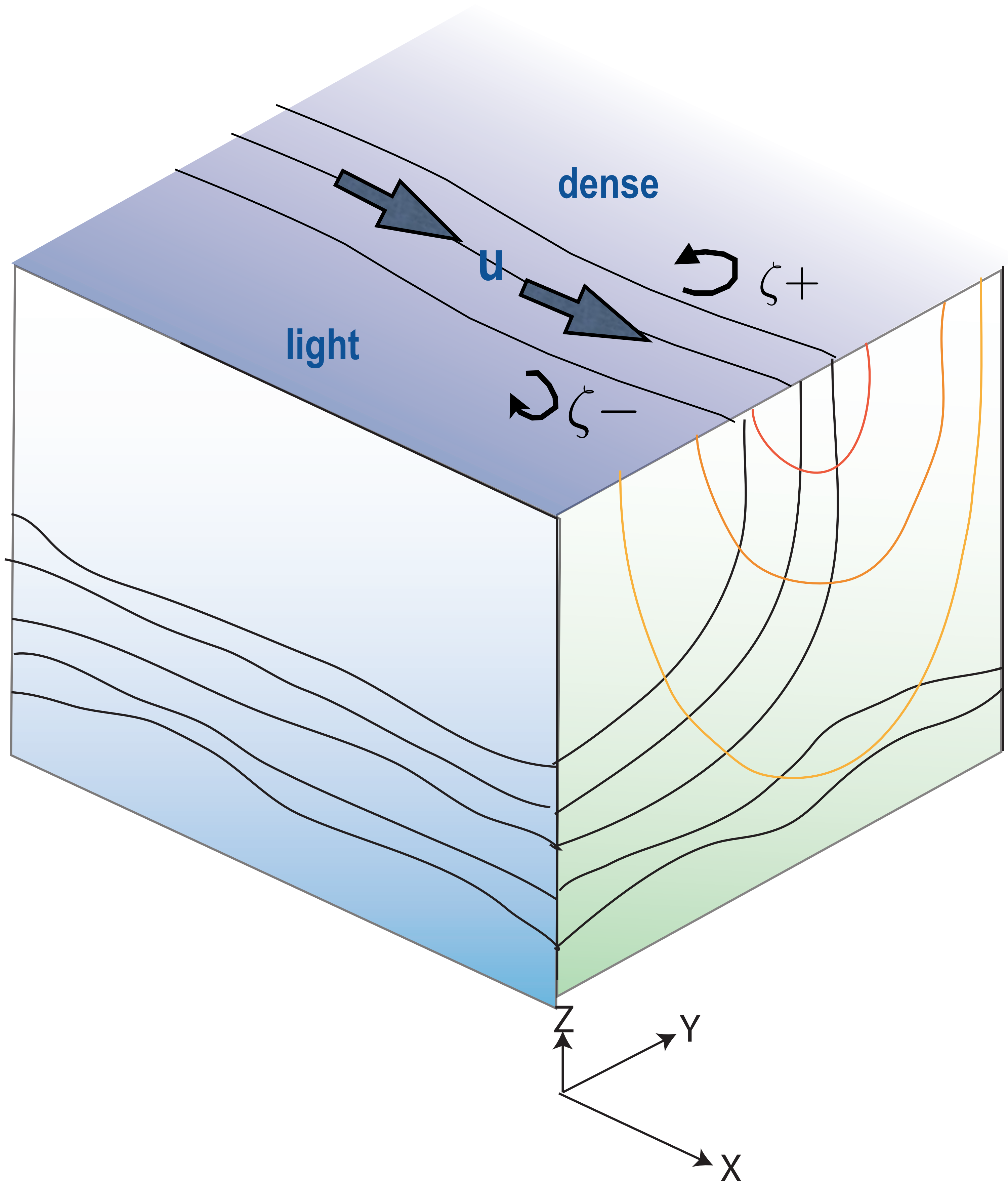


Image from NASA Earth Observatory

Submesoscale Fronts



Buoyancy

$$b = -\frac{g}{\rho_0}\rho'$$

$$\frac{Db}{Dt} = 0$$

Conserved in the absence of forcing.

Geostrophic & thermal wind balance, for small Ro

$$fu = -p_y \qquad fu_z = b_y$$

Slide from Amala Mahadevan

For intuition: The most famous thermal wind jet

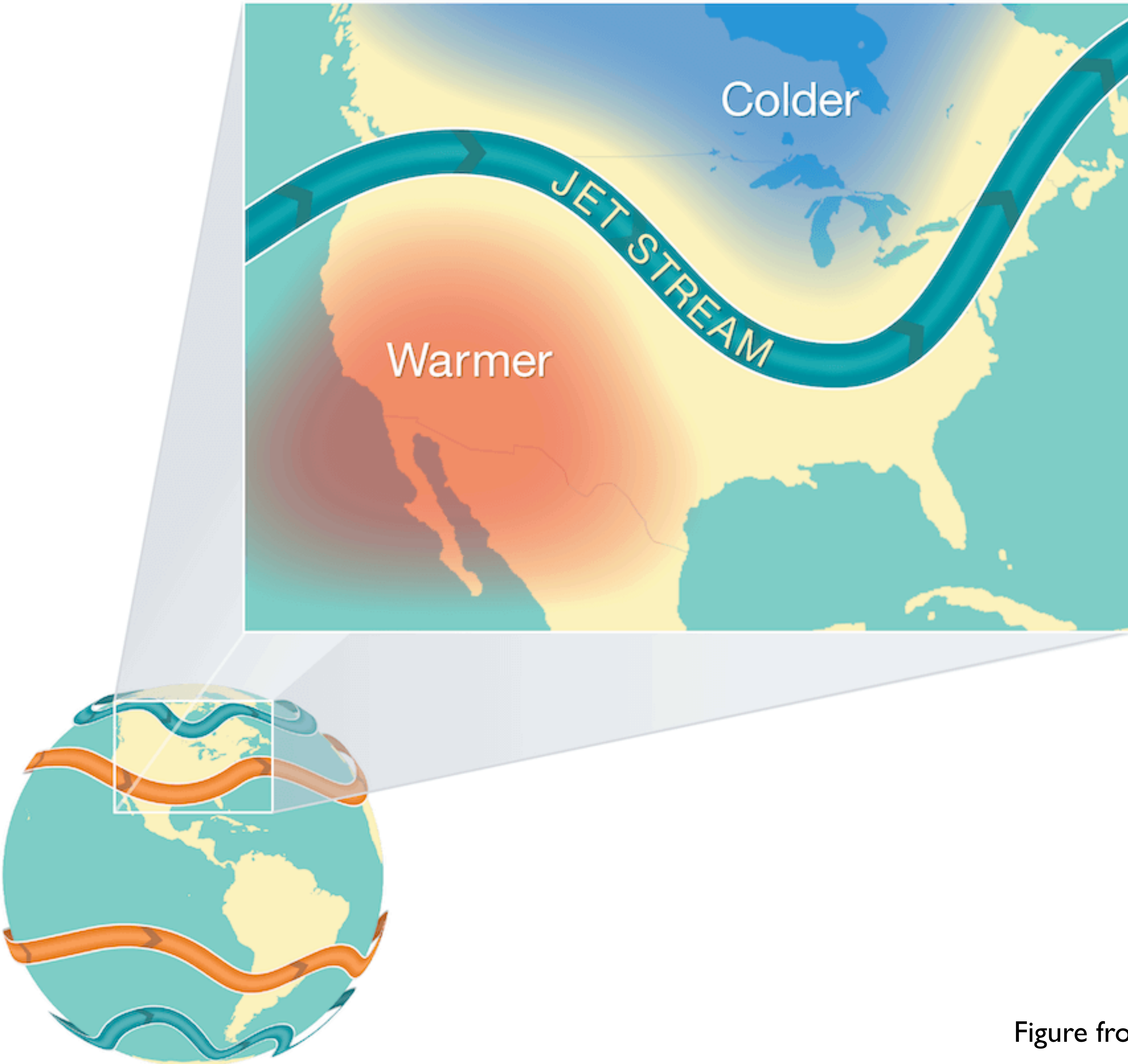
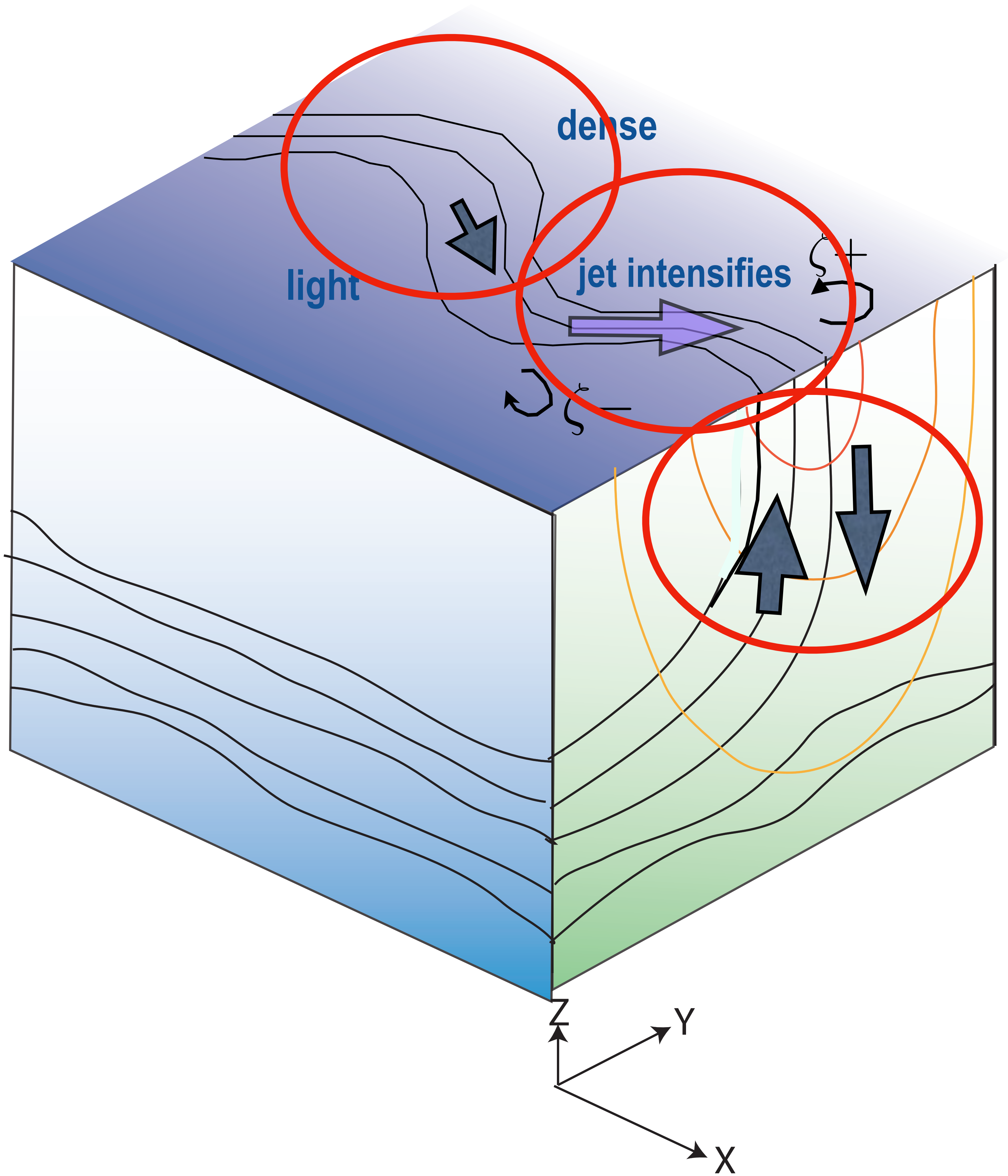


Figure from NOAA/JPL-Caltech

Frontogenesis and submesoscale dynamics



1. Thermal wind balance is disturbed
2. An ageostrophic secondary circulation develops to counteract the forcing
3. The front is strengthened as thermal wind balance is restored

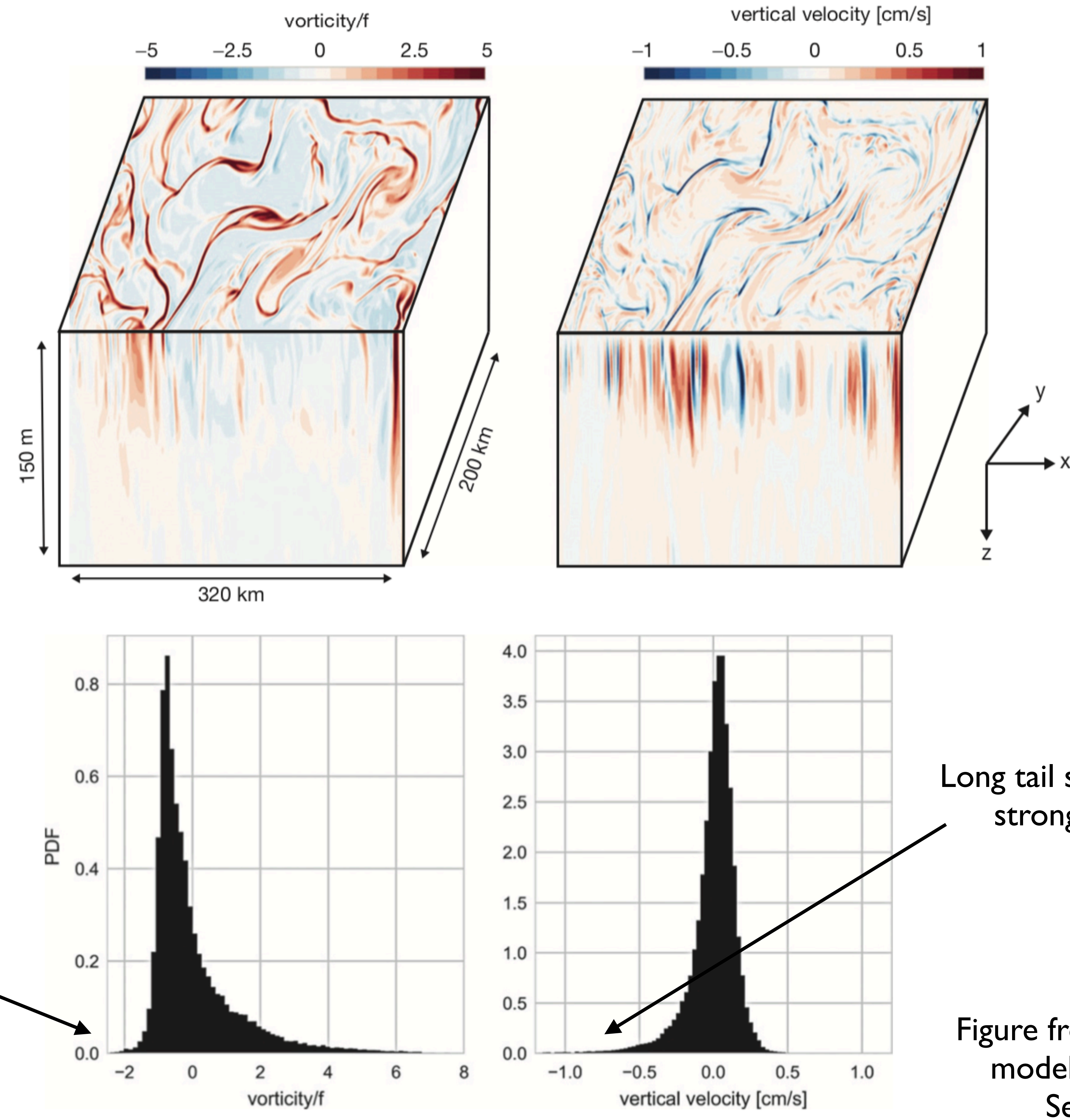
$$\boxed{\begin{array}{c} b_y \\ fu_z \sim -b_y \\ \zeta = v_x - u_y \end{array}}$$

increase due to frontogenesis

$$\boxed{\zeta / f = Ro = O(1)}$$

Slide from Amala Mahadevan

Submesoscale Dynamics Enhance Vertical Velocity

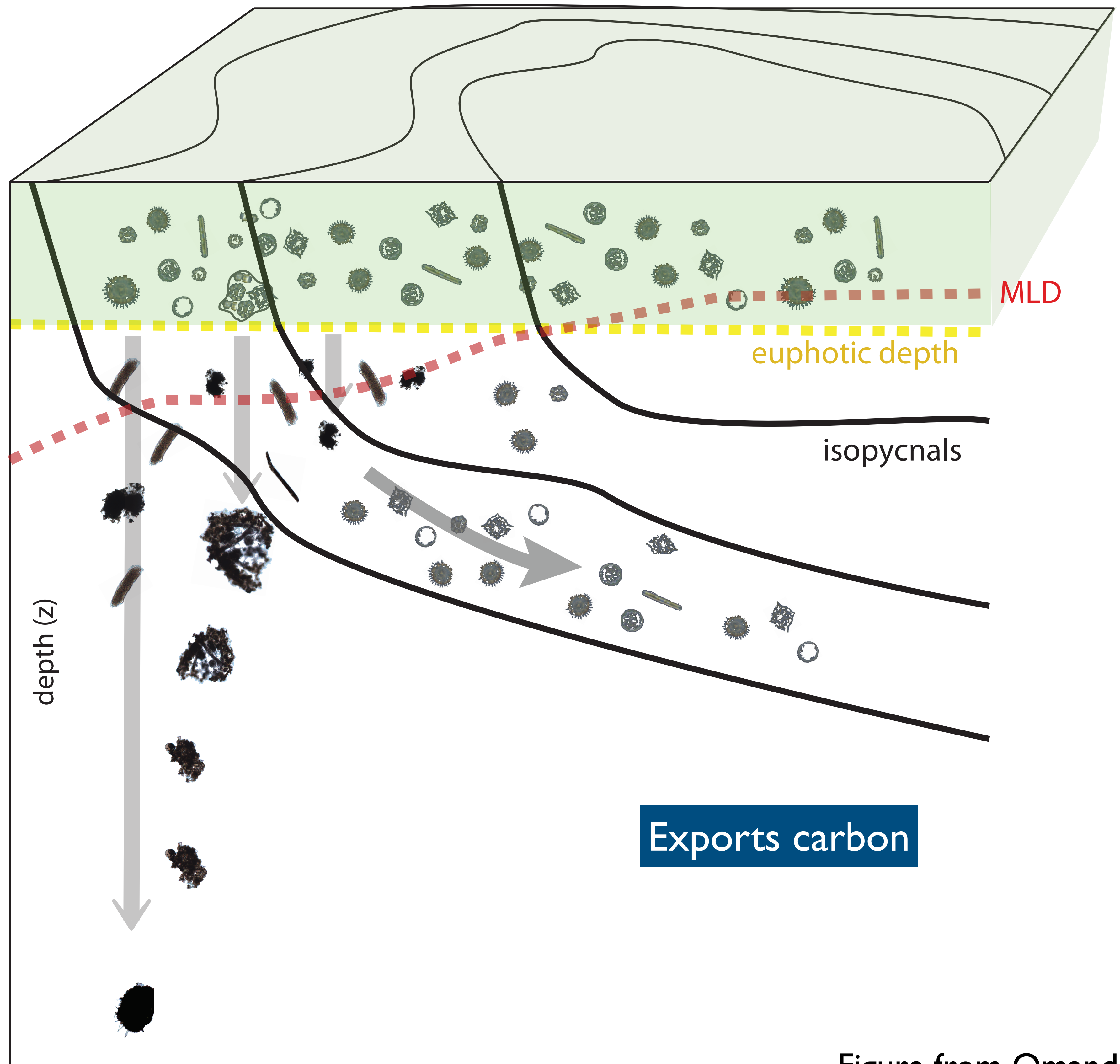


Instability for strong anticyclonic vorticity

Long tail shows episodes of strong downwelling

Figure from Mahadevan 2018, model & visualization by Sebastian Essink

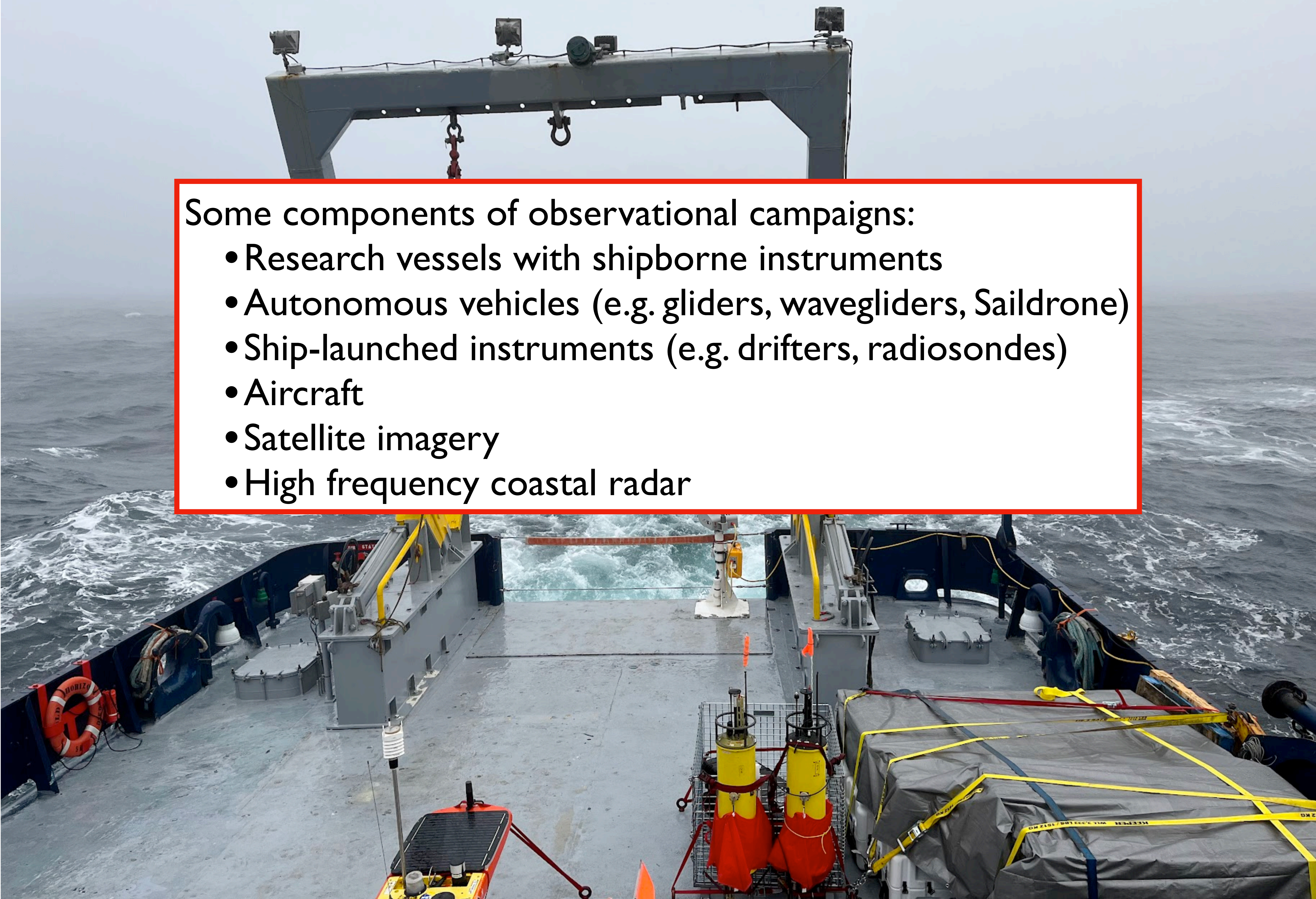
Submesoscale subduction at fronts



Exports carbon

Figure from Omand et al. (Science, 2015)

Observational Tools



Some components of observational campaigns:

- Research vessels with shipborne instruments
- Autonomous vehicles (e.g. gliders, wavegliders, Saildrone)
- Ship-launched instruments (e.g. drifters, radiosondes)
- Aircraft
- Satellite imagery
- High frequency coastal radar

Underway Profiling

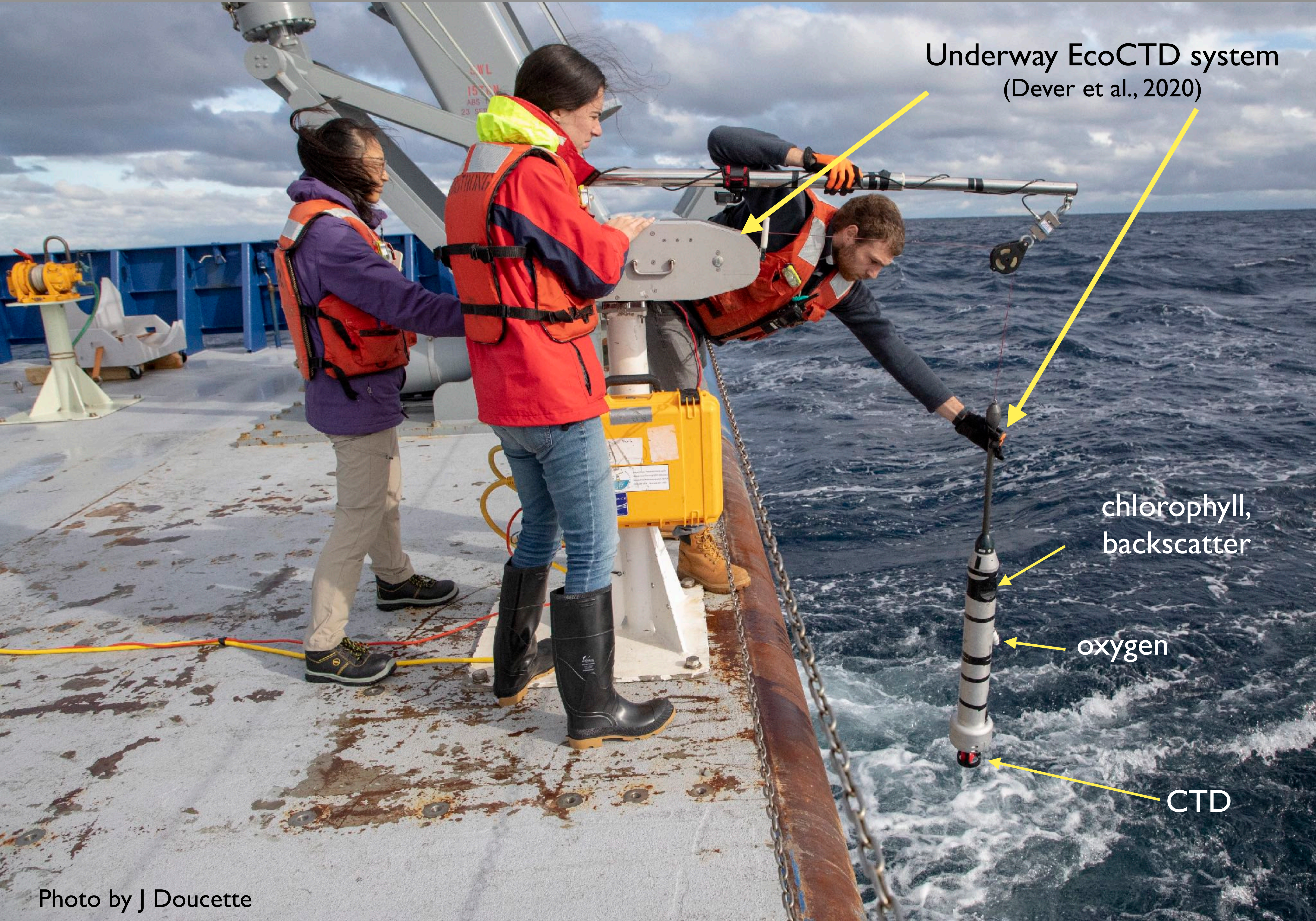
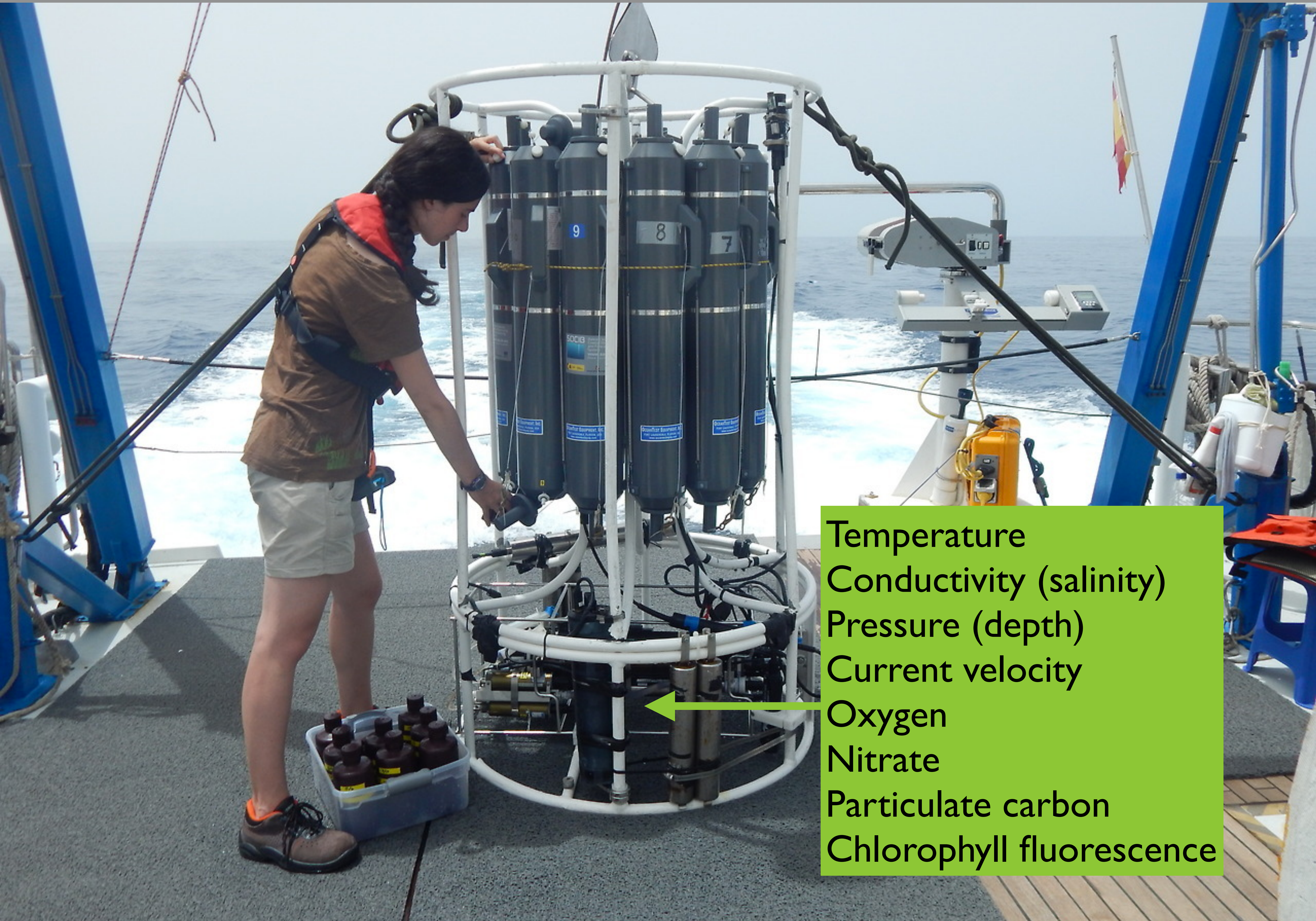


Photo by J Doucette

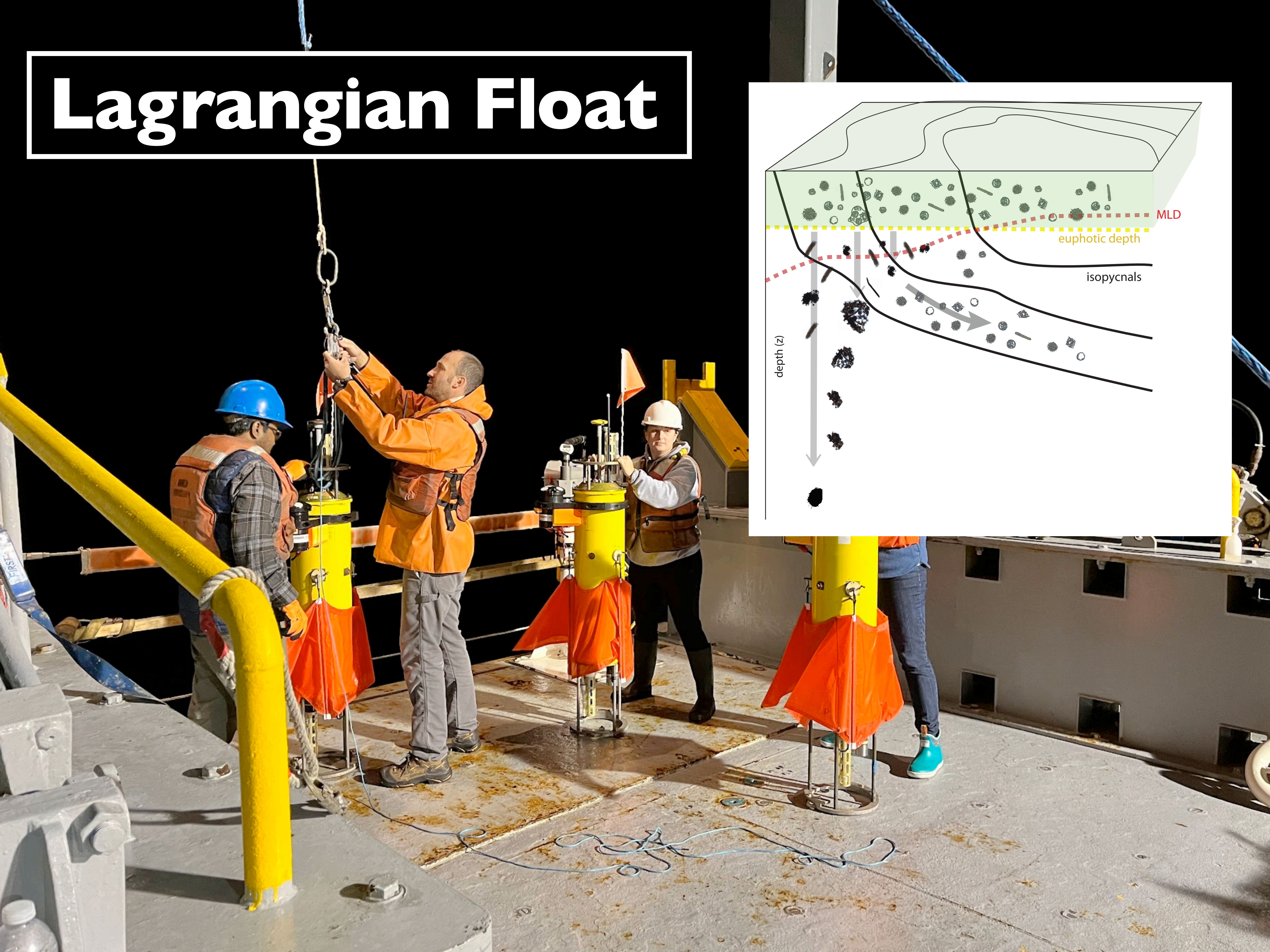
Water Sampling: CTD Rosette




CMU 250 KG
GENAVIR

Emergency eye wash

Lagrangian Float

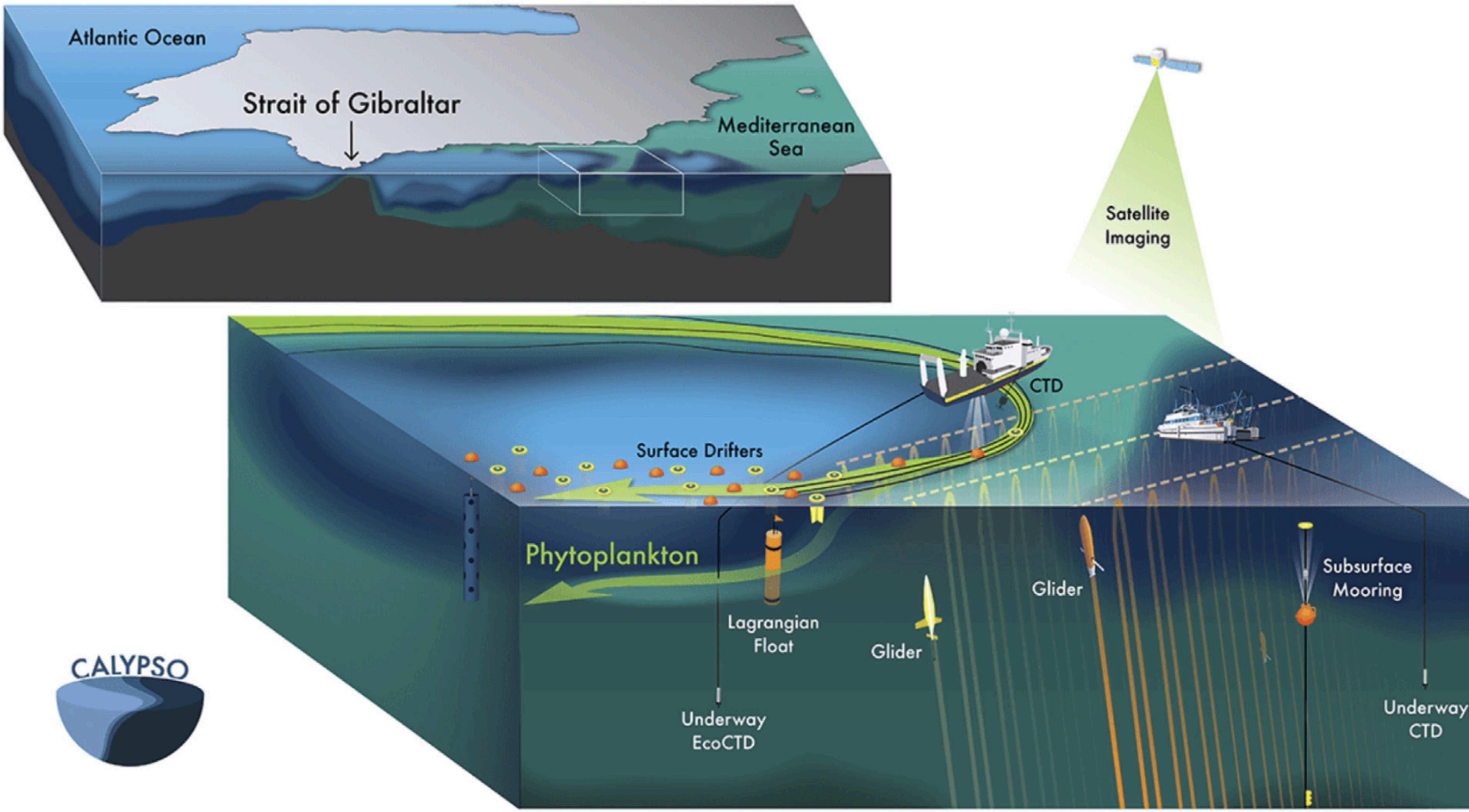


Saildrone

Photo from Saildrone website

CALYPSO

Coherent Lagrangian Pathways from the Surface Ocean to Interior



CALYPSO

Figure from Mahadevan et al (2020), BAMS

CALYPSO Campaign: Winter 2022

The CALYPSO 2022 Campaign

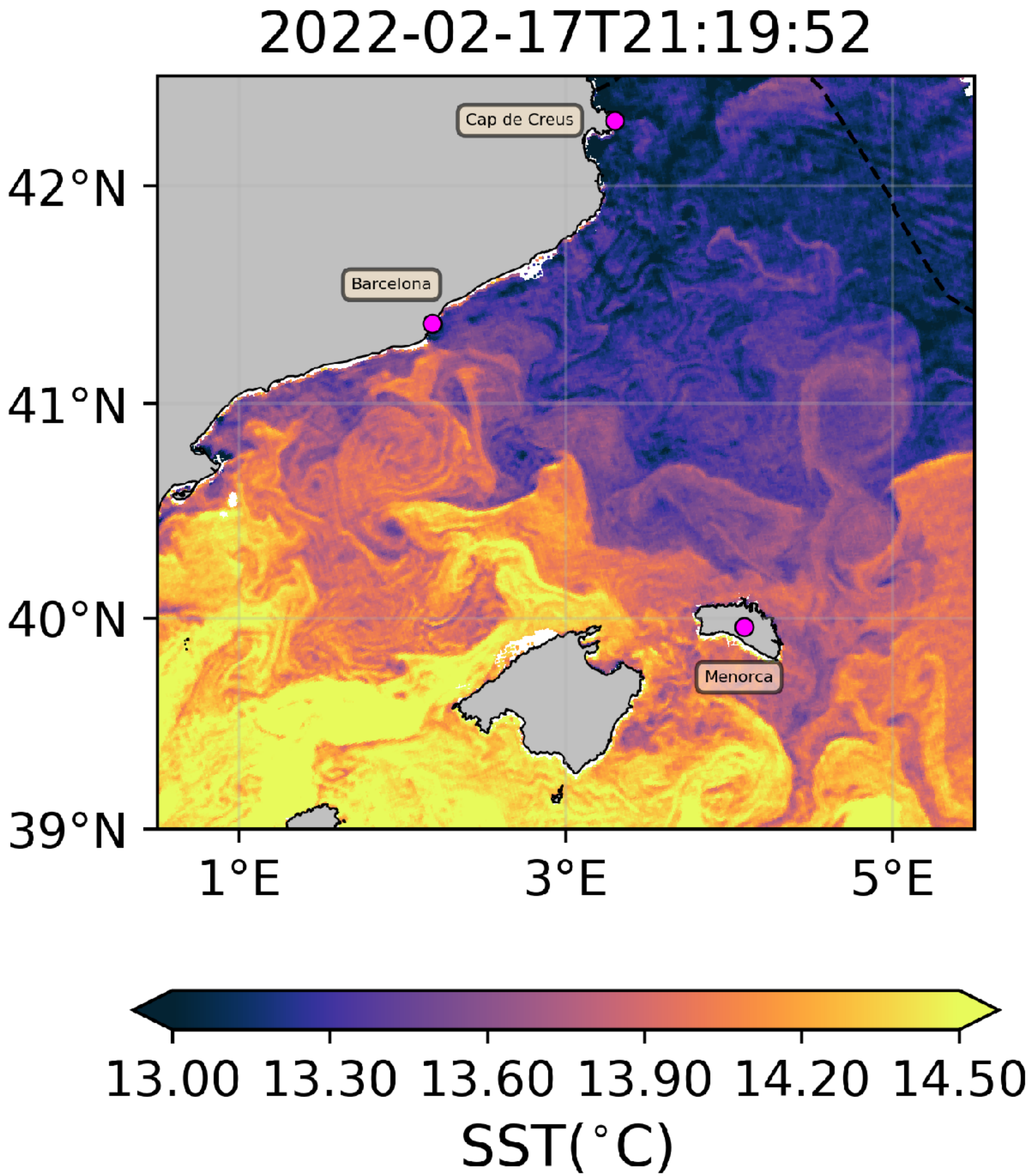
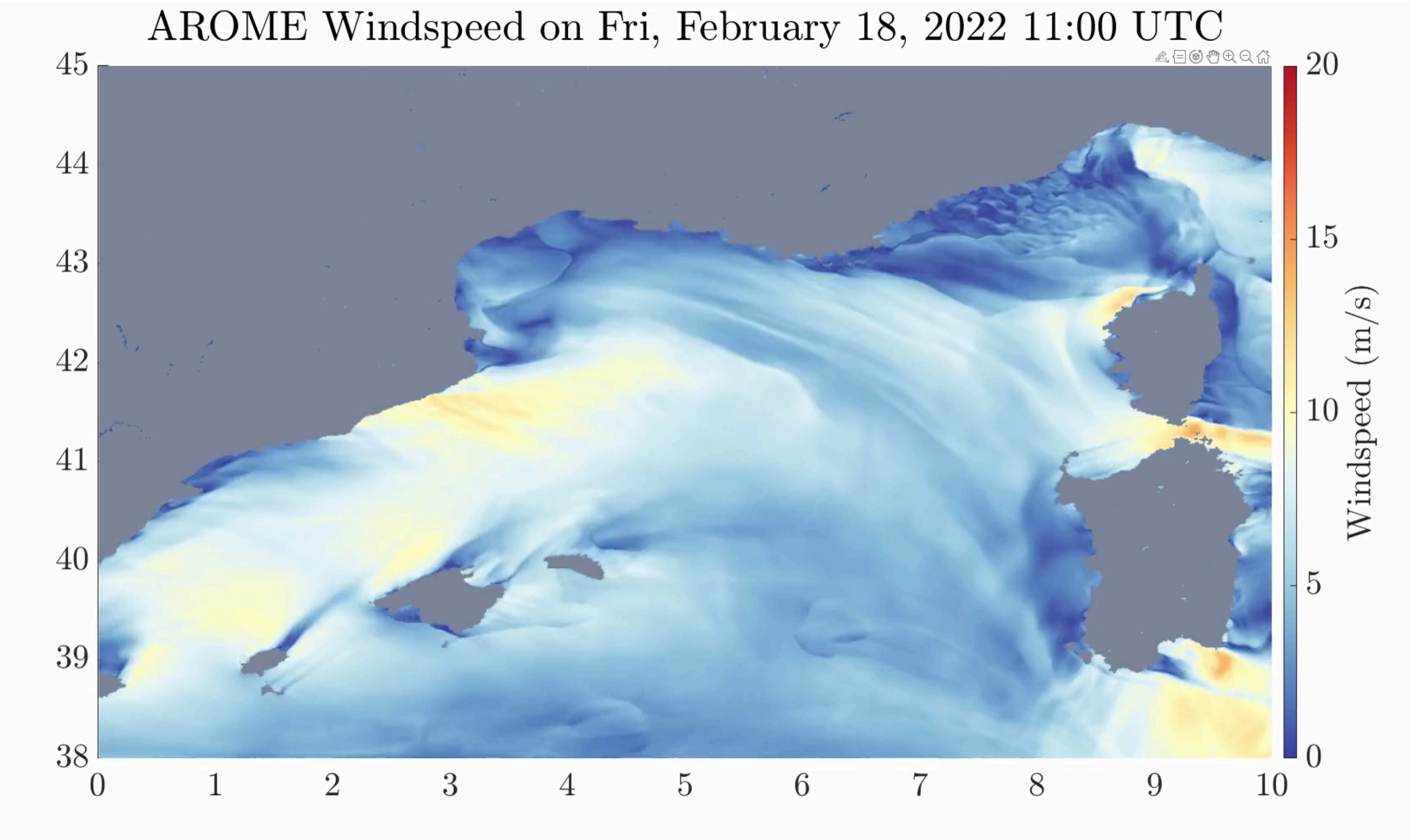


Figure by Daniel Tarry

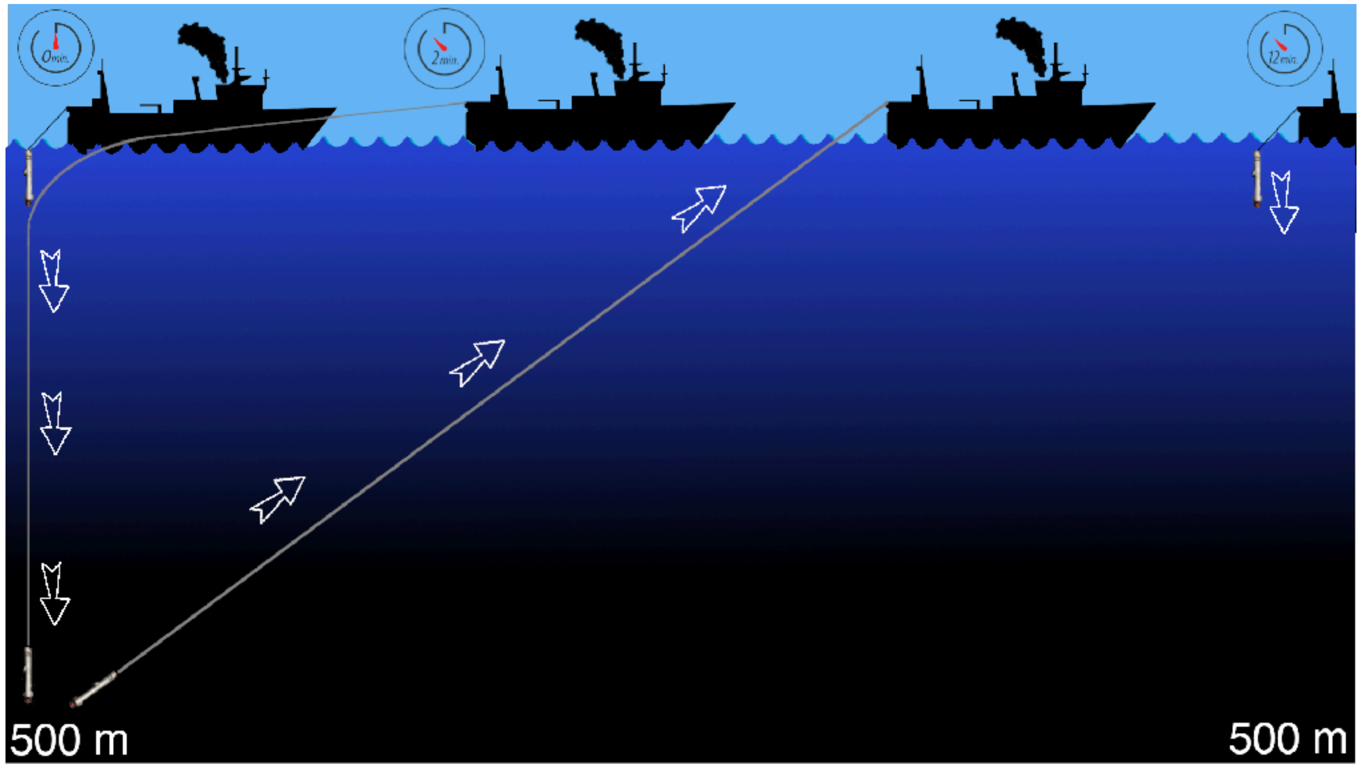
The Mistral

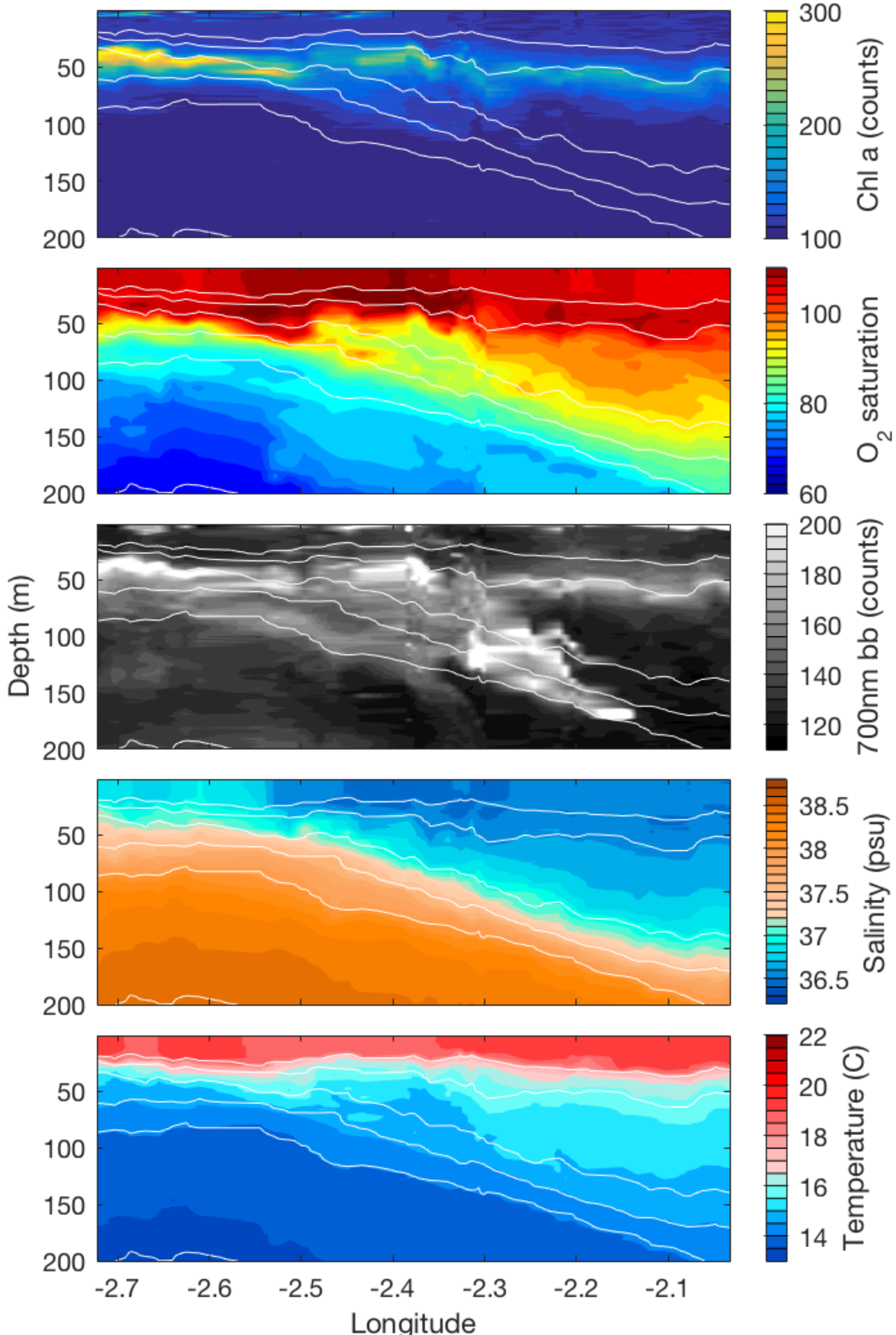


AROME Windspeed on Fri, February 18, 2022 11:00 UTC
45
44
43
42
41
40
39
38
0
1
2
3
4
5
6
7
8
9
10
20
15
10
5
0
Windspeed (m/s)

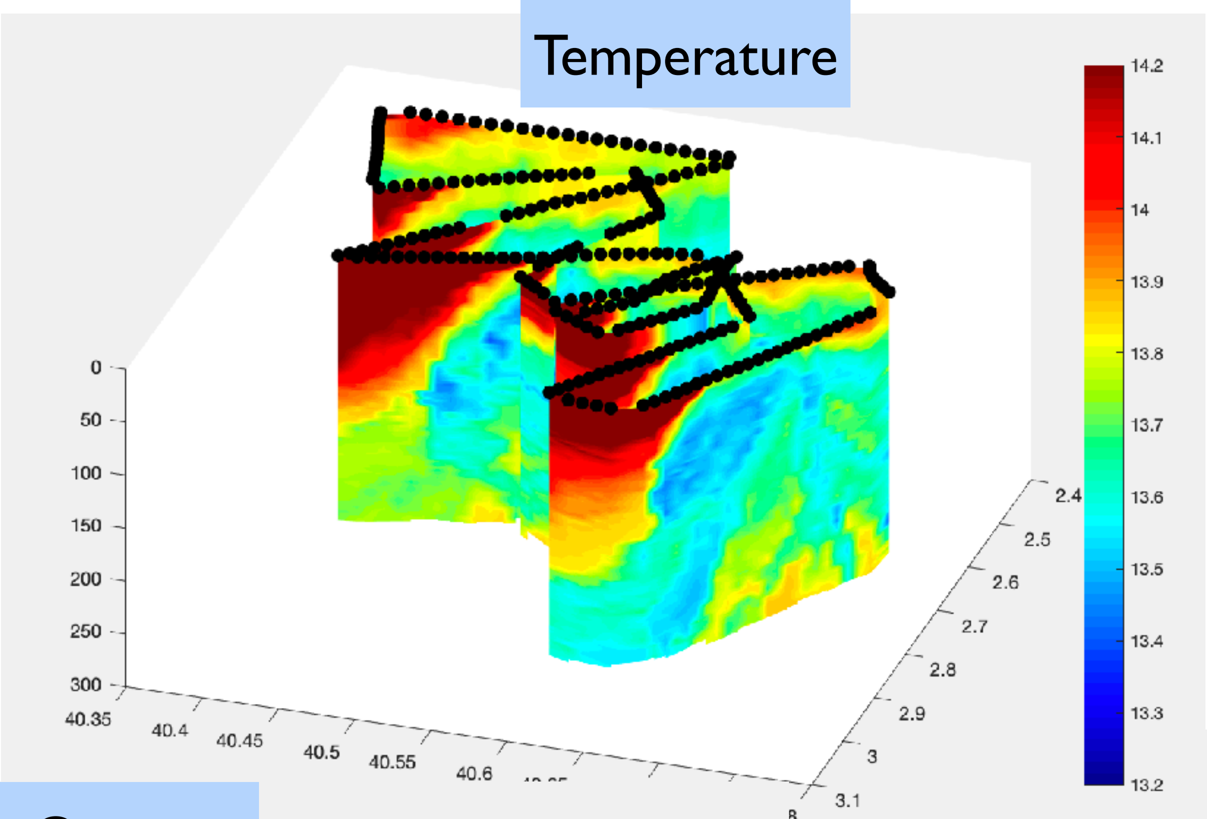
Simultaneous underway profiling: T,S+bio-optics

EcoCTD (Dever et al., 2020)

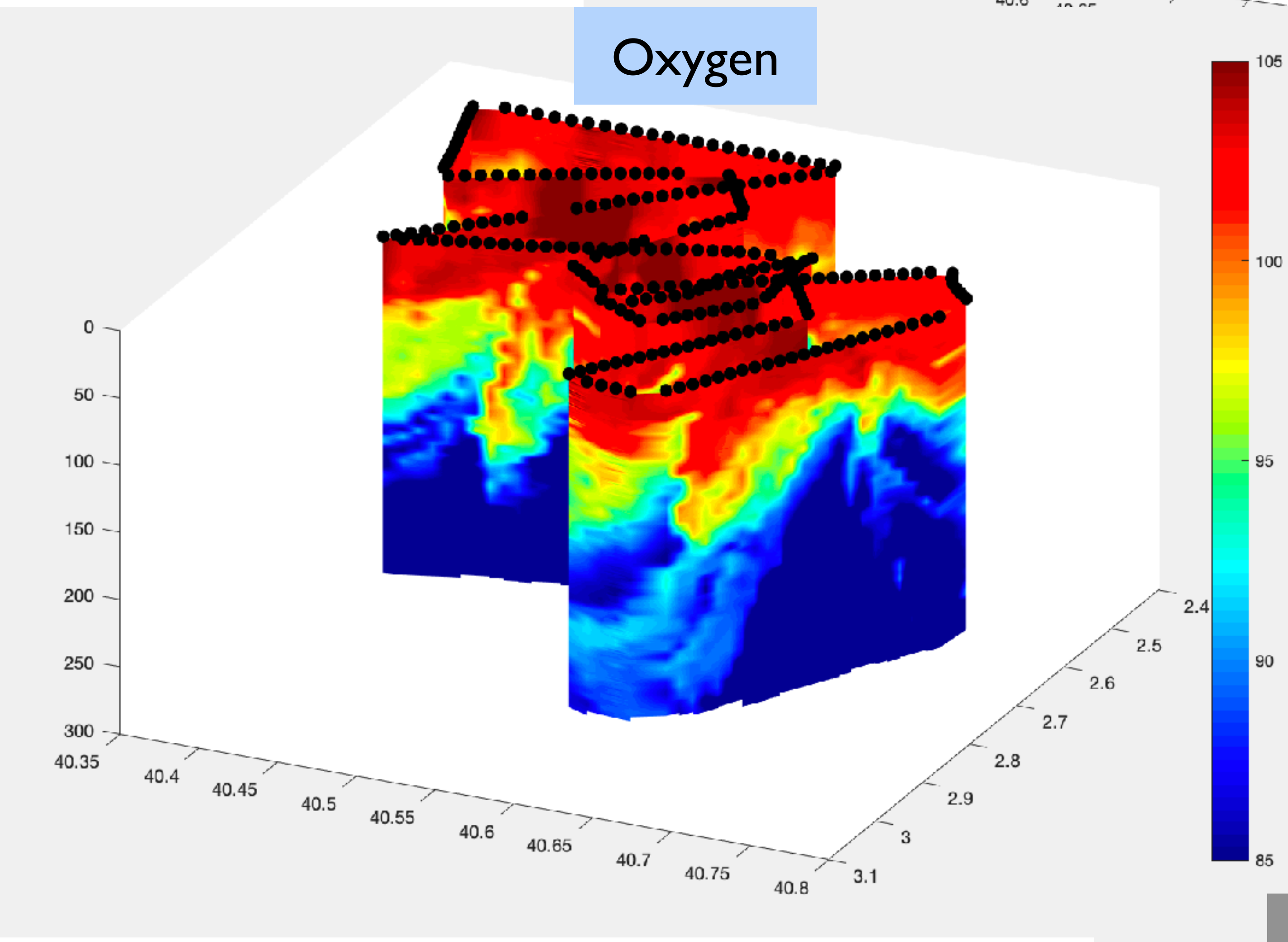


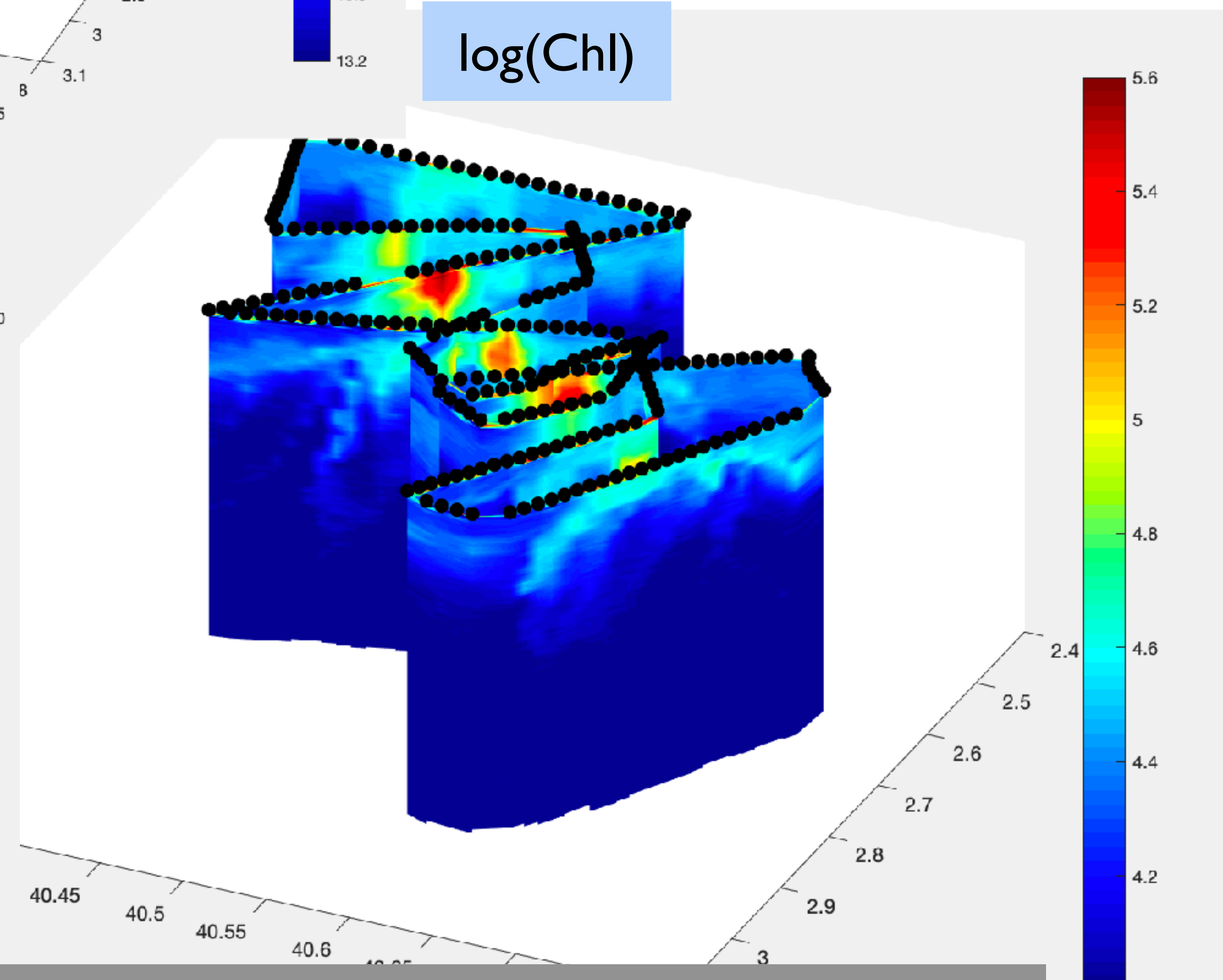


Slide from Amala Mahadevan



Multiple tracers with different time scales





EcoCTD profiles along ship track to 250 m

Slide from Amala Mahadevan

Submesoscale Ocean Dynamics Experiment

Intensive Observation Period 1, Fall 2022

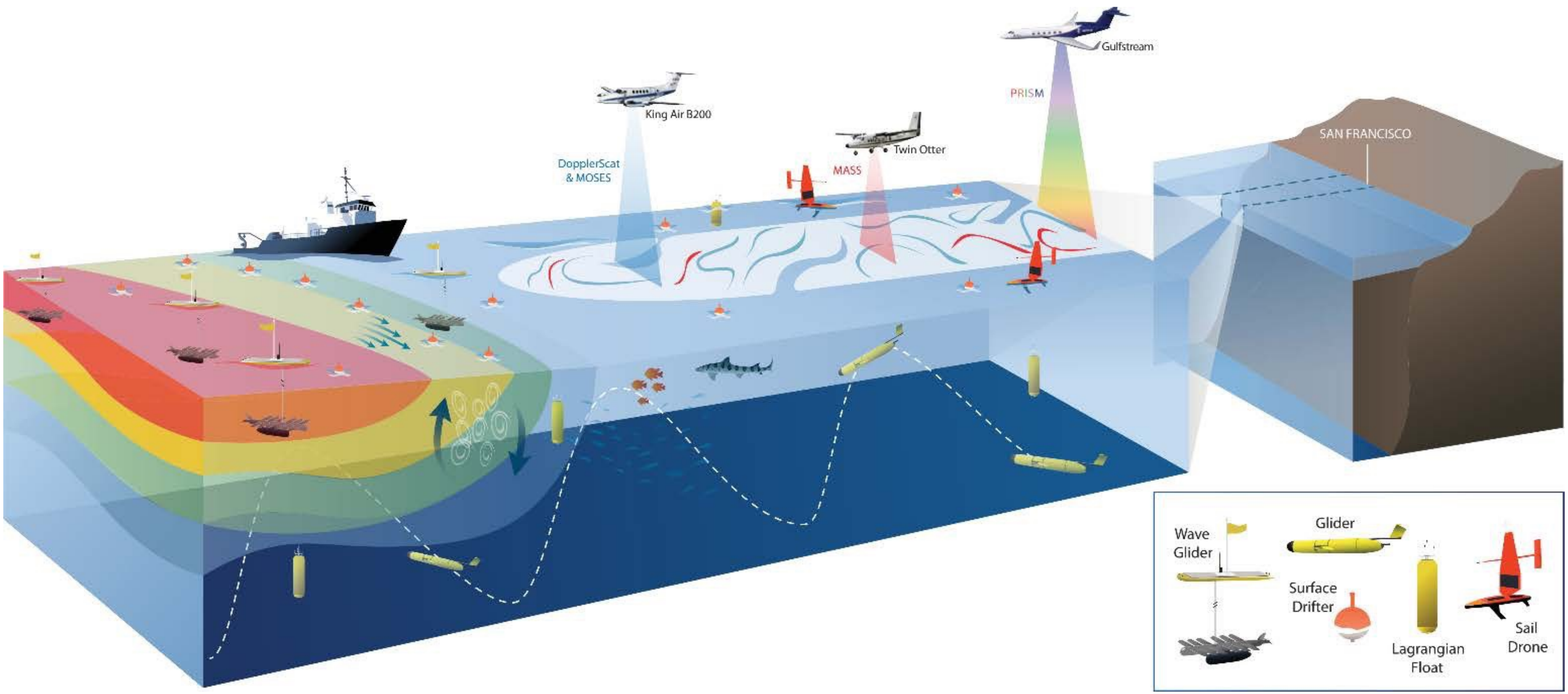
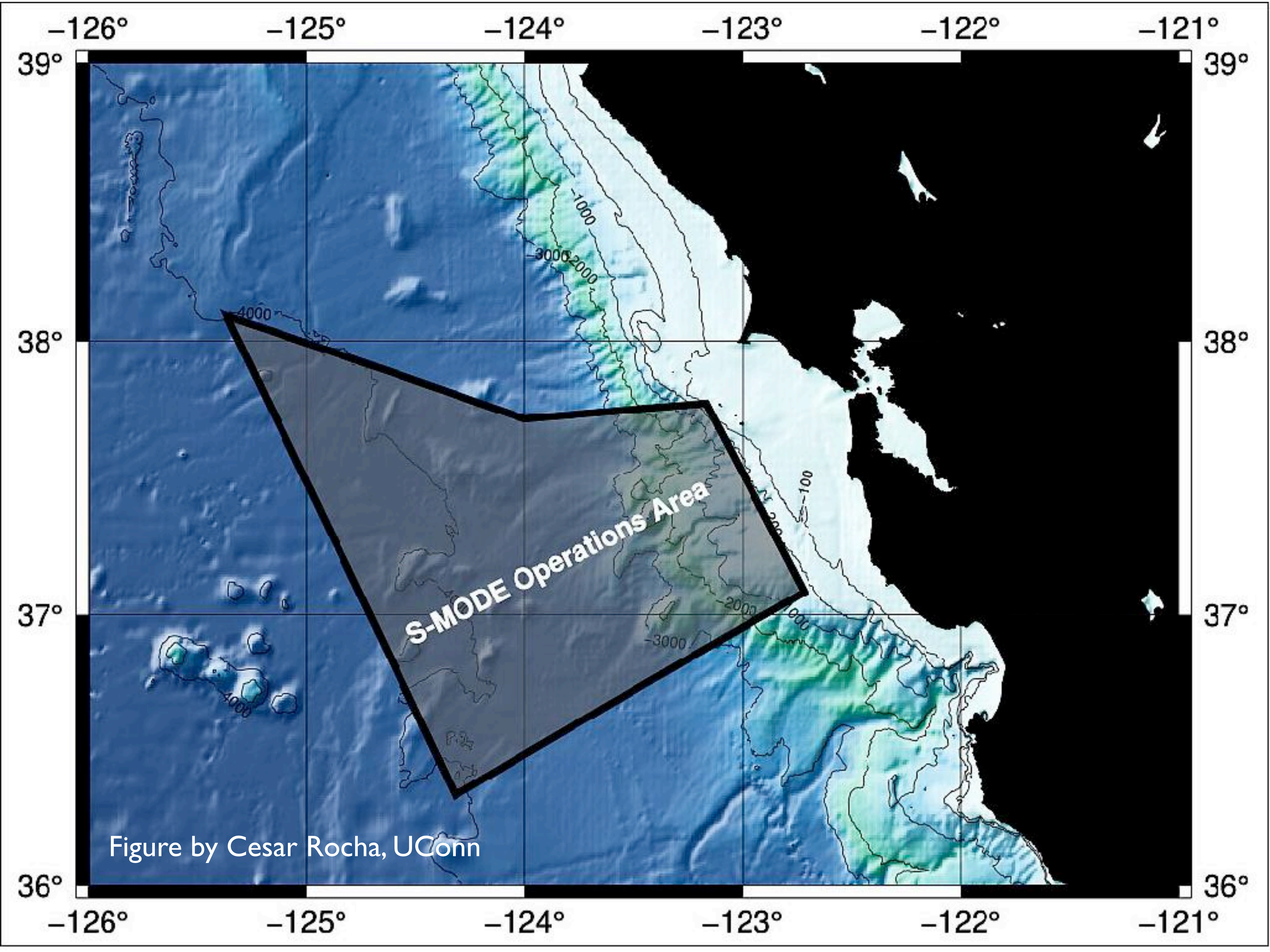
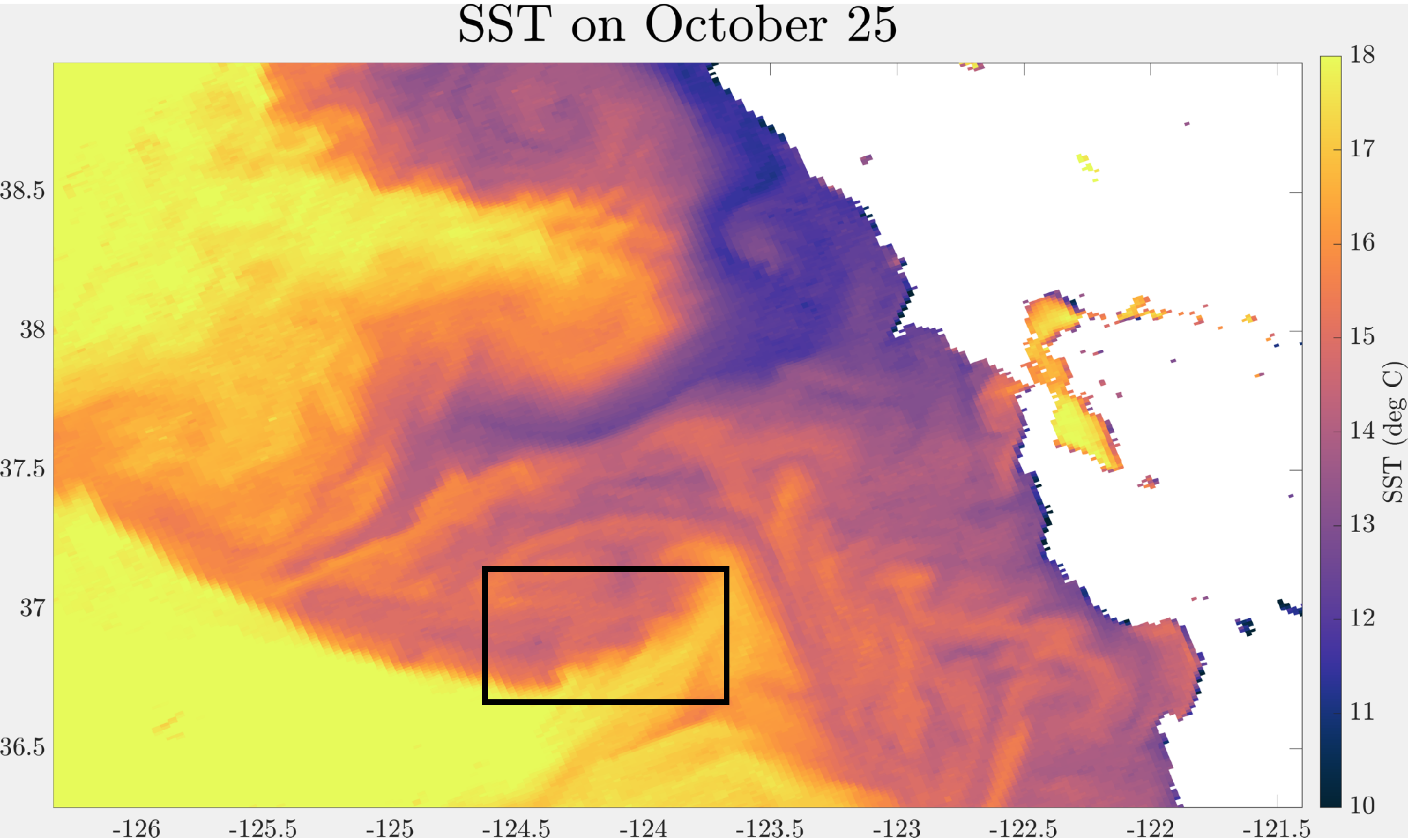


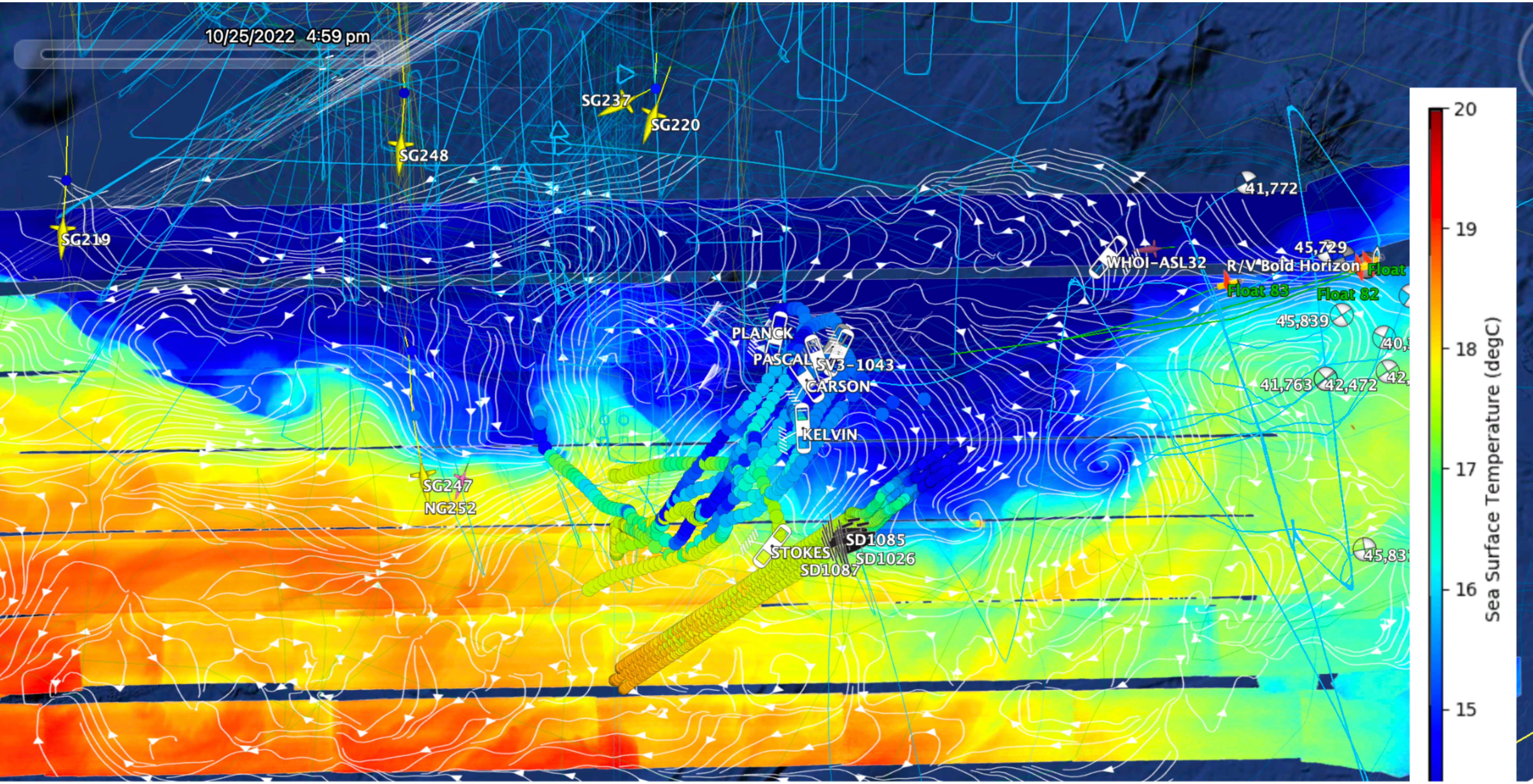
Illustration by Jennifer Matthews, SIO



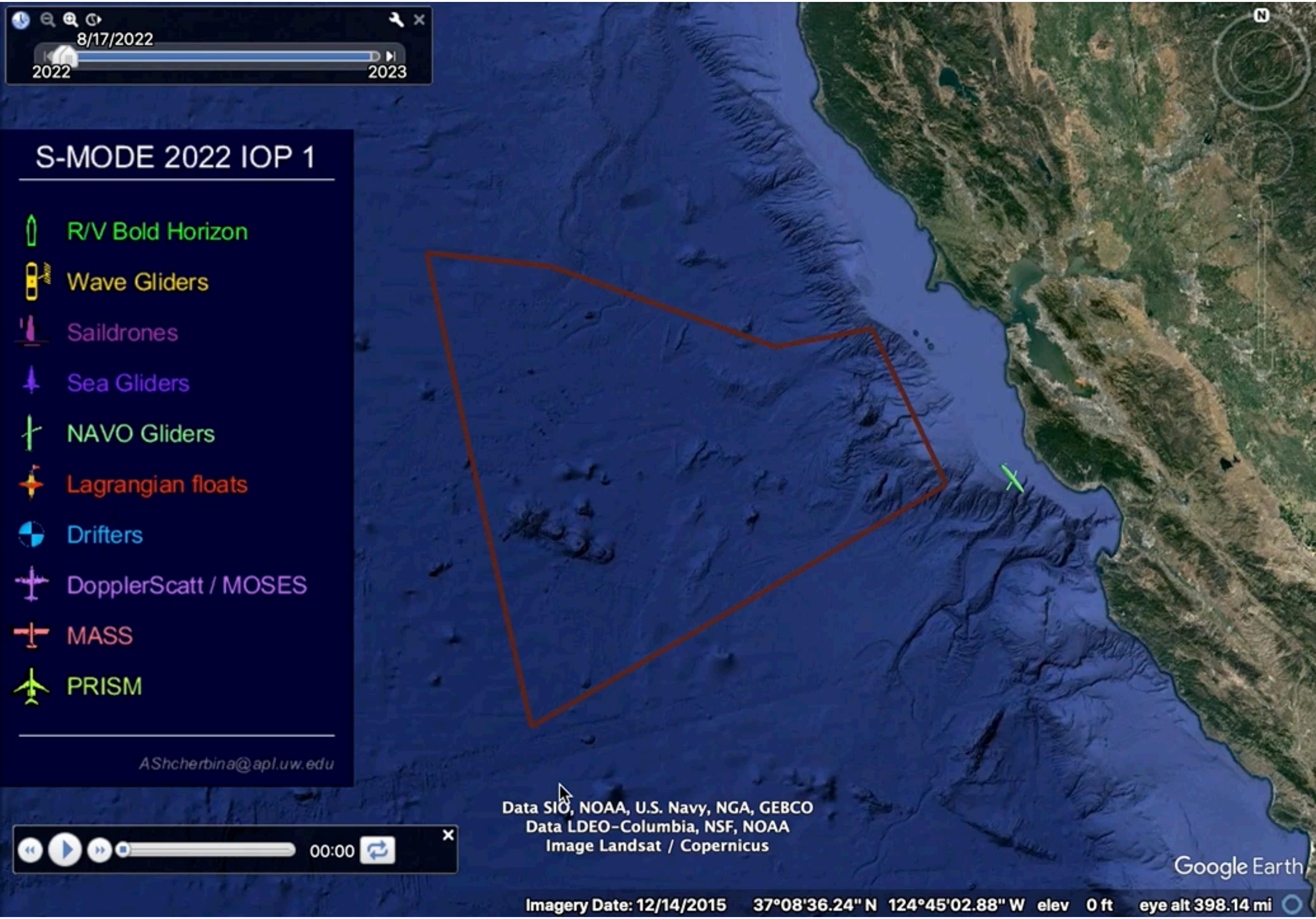
−126°
−125°
−124°
−123°
−122°
−121°
39°
38°
37°
36°
S-MODE Operations Area
-1000
-2000
-3000
-4000
-100
Figure by Cesar Rocha, UConn

Photo by Erin Czech, NASA


SST on October 25
38.5
38
37.5
37
36.5
-126
-125.5
-125
-124.5
-124
-123.5
-123
-122.5
-122
-121.5
18
17
16
15
14
13
12
11
10
SST (deg C)



10/25/2022 4:59 pm
SG237
SG220
SG248
SG219
41,772
45,729
WHOI-ASL32
R/V Bold Horizon
Float
Float 83
Float 82
45,839
PLANCK
PASCAL
SV3-1043
CARSON
41,763
42,472
KELVIN
SG247
NG252
SD1085
STOKES
SD1026
SD1087
Sea Surface Temperature (degC)
20
19
18
17
16
15



Animation by Andrey Shcherbina, UW-APL

Nature at Sea

Summary

- The submesoscale is where Rossby numbers become O(1), usually around 1 km in scale
- Submesoscale fronts feature large vertical velocities relevant to biology and climate
- Recent campaigns have gathered data to map the pathways of subducting water - stay tuned!