Submesoscale Eddies and Internal Waves: from the base of the mixed layer to the sea surface microlayer

José da Silva,

With contributions from: Jorge Magalhaes &
Maarten Buijsman

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Outline of this presentation

- Submesoscale Eddies;

Frontogenesis; surface convergence; surface films; review of modelling achievements; satellite remote sensing off the Amazon shelf break; role of surface drifters to understand submesoscale;

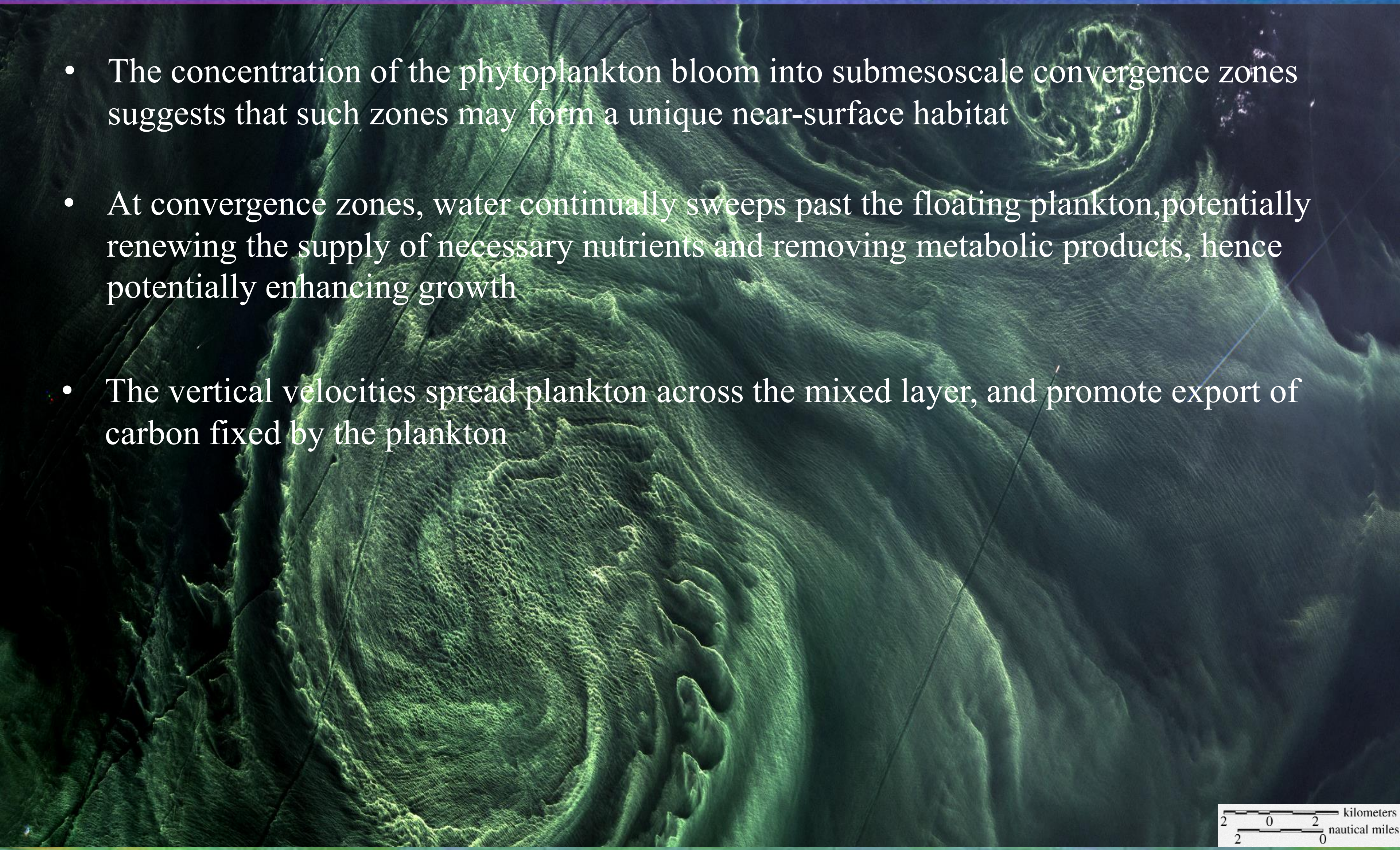
- Internal Waves;

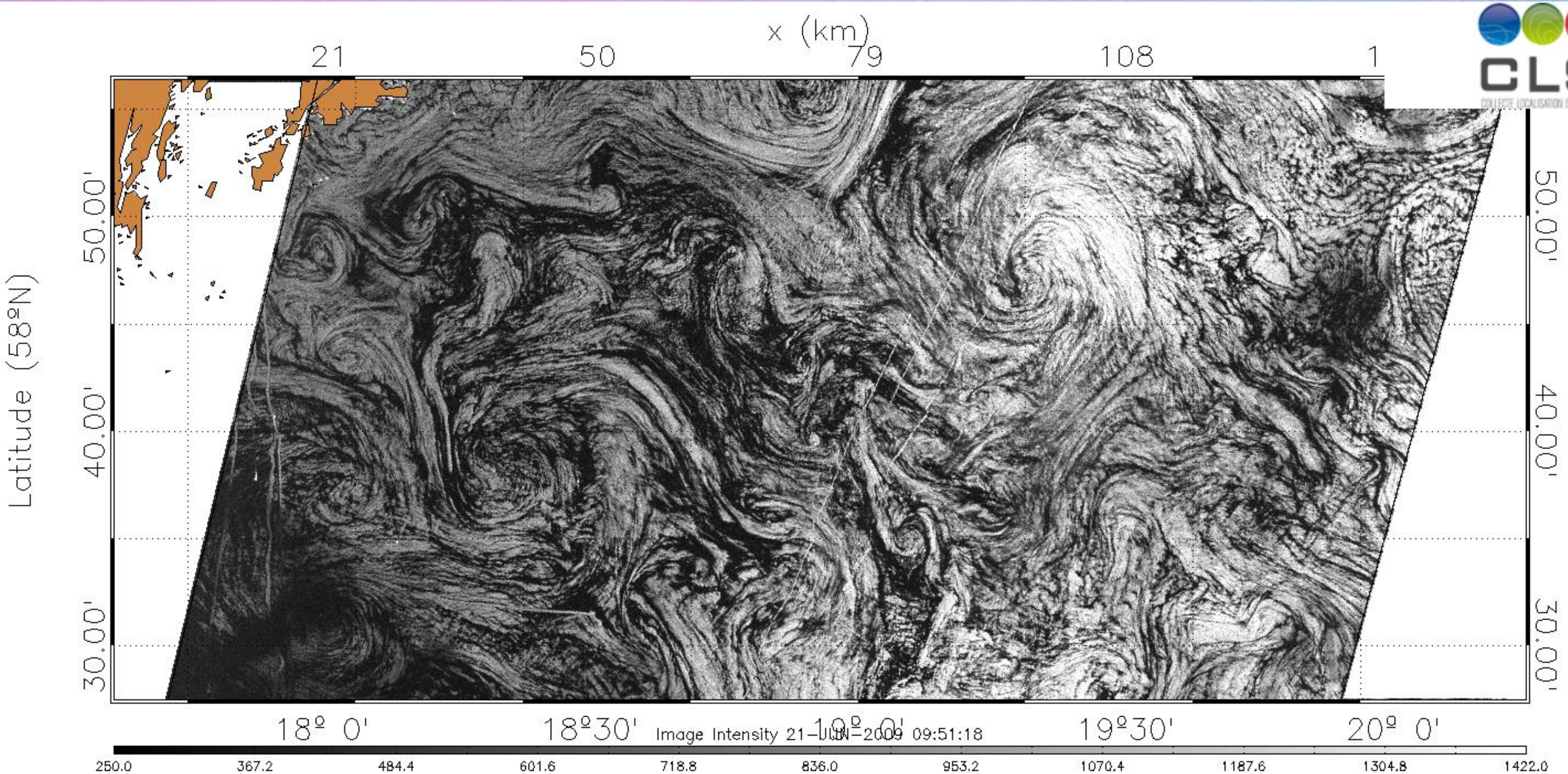
Motivations; role of satellite remote sensing; numerical modelling; generation mechanisms of solitons off the Amazon shelf break

- The concentration of the phytoplankton bloom into submesoscale convergence zones suggests that such zones may form a unique near-surface habitat

- At convergence zones, water continually sweeps past the floating plankton,potentially renewing the supply of necessary nutrients and removing metabolic products, hence potentially enhancing growth

- The vertical velocities spread plankton across the mixed layer, and promote export of carbon fixed by the plankton





SAR measurements suggest that surface convergence can dramatically concentrate floating surfactant materials in the ocean. These surface active organic materials are effective in damping short-scale wind (ripple) generated waves and readily show up in the SAR which is very sensitive to surface roughness. These are Baltic Sea observations, all cyclonic (anti-clockwise).

Submesoscale Dynamics are dominated by MLI and frontogenesis

- The depth of the mixed layer provides the energy that drives the submesoscale (hence seasonal cycle)
- Organization of the submesoscale along fronts
- Strong correlation between positive surface relative vorticity values and negative divergence $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$; $\delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$

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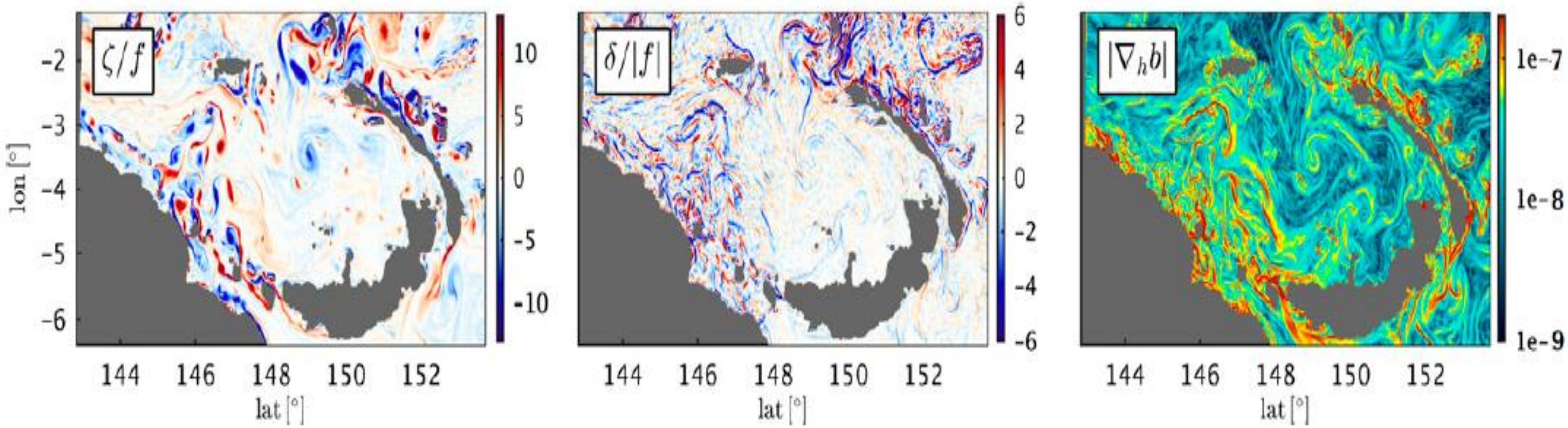
Srinivasan et al., 2017



A *Small Scale Summary* of model results (Molemaker, 2018)

$$R_o = \frac{\zeta}{f}$$

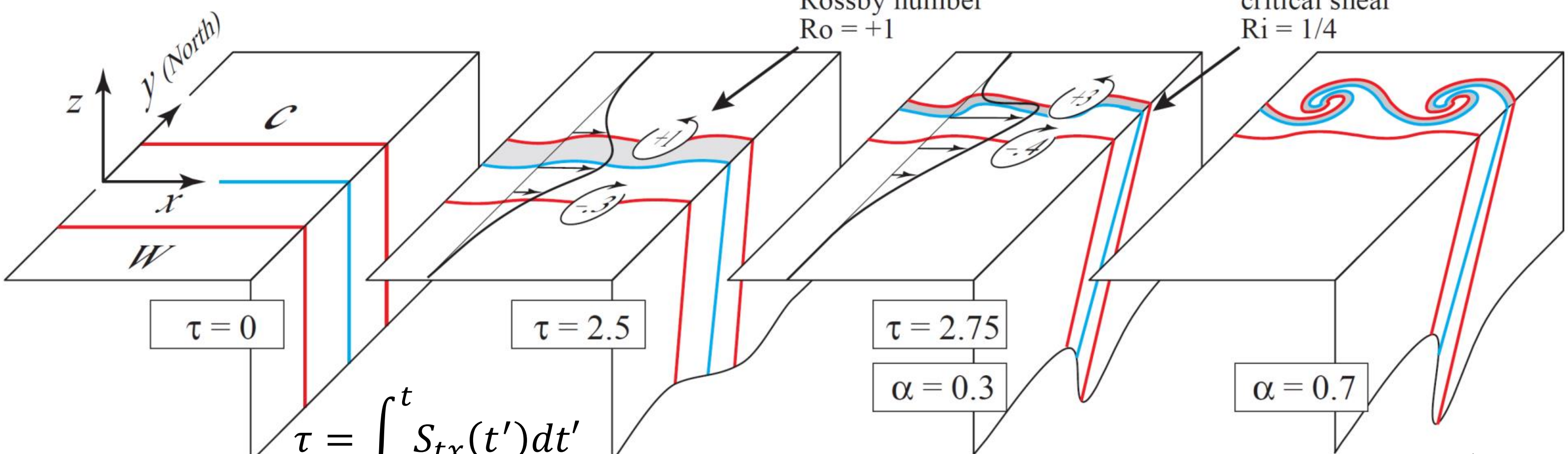
- Departures from geostrophic balance; Ro = O(1)
- Emergence of submesoscale phenomena fueled by mixed layer Available Potential Energy (APE); the amount of APE is a result of horizontal buoyancy gradients and a deeper mixed layer
- Asymetry between cyclonic and anti-cyclonic vorticity
- Significant surface convergence , organized in frontal lines and eddies
- Frontogenesis (the grouth in amplitude of gradients of the front) through:

1) Straining and resulting secondary circulation; (classic view)
2) Turbulent Thermal Wind (TTW); interaction between the mixed layer turbulence and horizontal buoyancy gradient
3) self-evolution of divergence (once we have $\delta = O(1)$)

- Important things happen at small scales, but models are currently poorly constrained for assimilation (need of measurements close in time to the evolution time scale)

Frontogenesis through straining

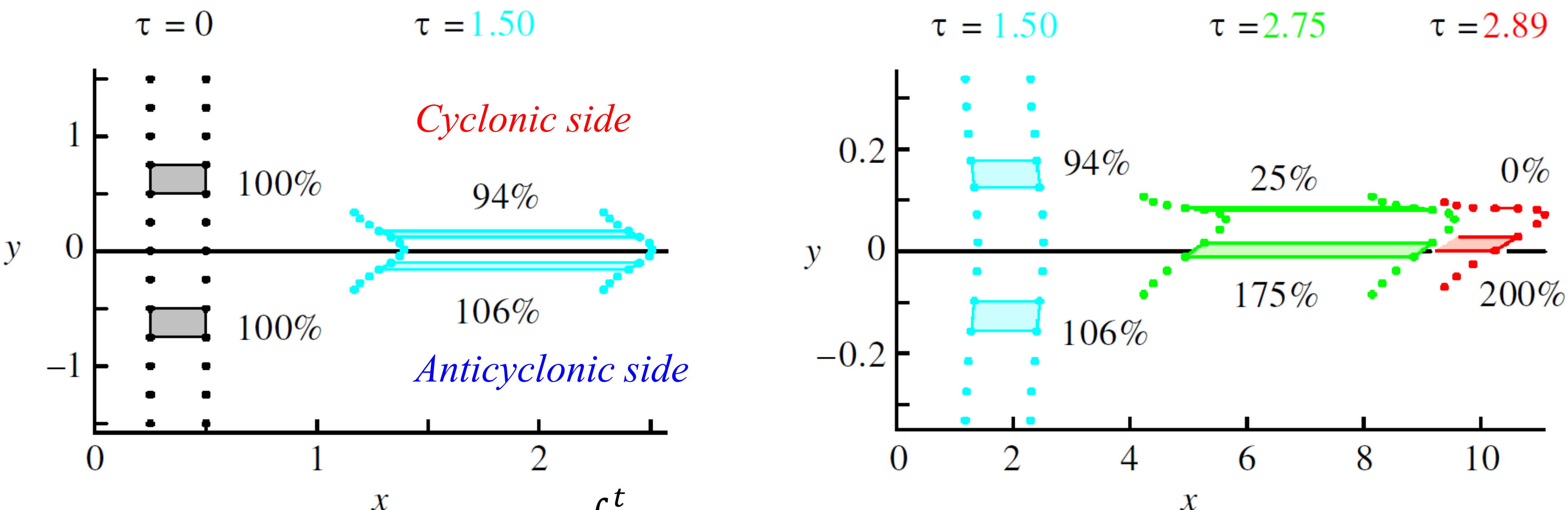
- Hoskins & Bretherton (1972): frontogenesis with conservation of density and potential vorticity (purely barotropic)
- 1) Initial density gradient develops into an eastward “thermal wind”
- 2) A deformation field (*Straining* S_{tx}) is superposed, causing the initially vertical isopycnals to tilt northward; $S_{tx} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$
- 3) The northern tilting of isopycnals is not uniform: the northern isopycnals converge at the surface, while the southern isopycnals diverge
- 4) The eastward thermal jet has a strong cyclonic shear at its northern flank, while the “southern” anticyclonic shear is weak (asymetry between cyclonic and anti-cyclonic vorticity)



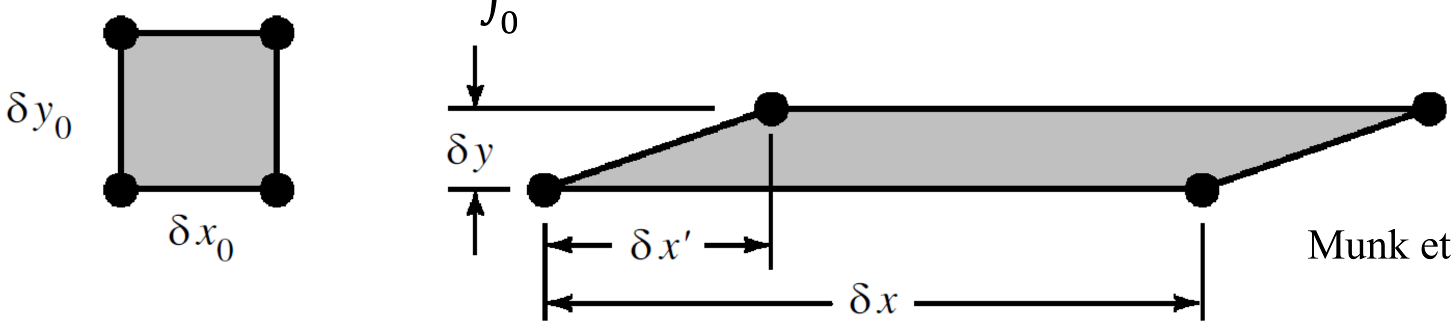
$$\tau = \int_0^t S_{tx}(t')dt'$$

(dimensionless time in units of roughly one day)

Munk, 2001



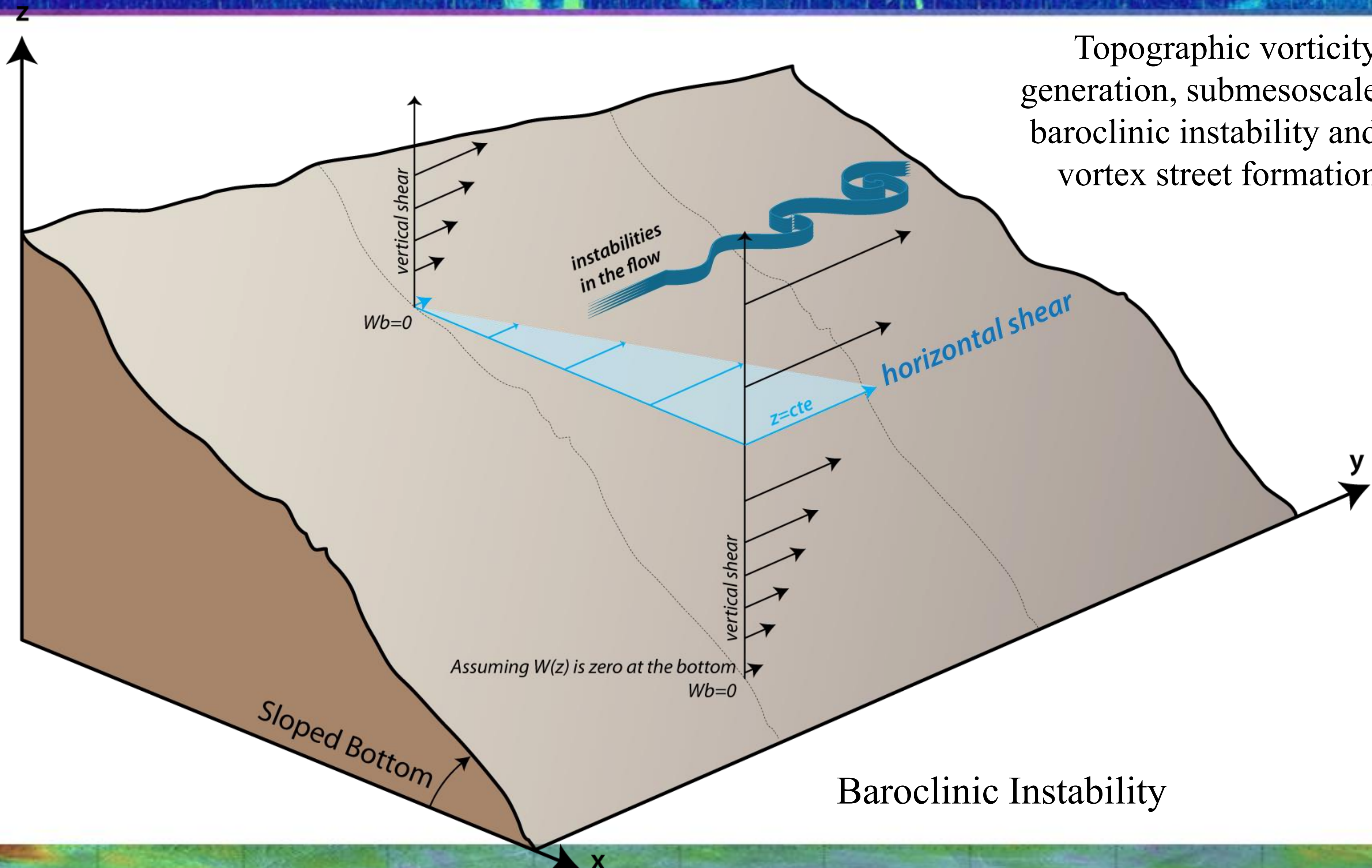
$$\tau = \int_0^t S_{tx}(t')dt'$$ (dimensionless time in units of roughly one day)



Munk et al., 2000

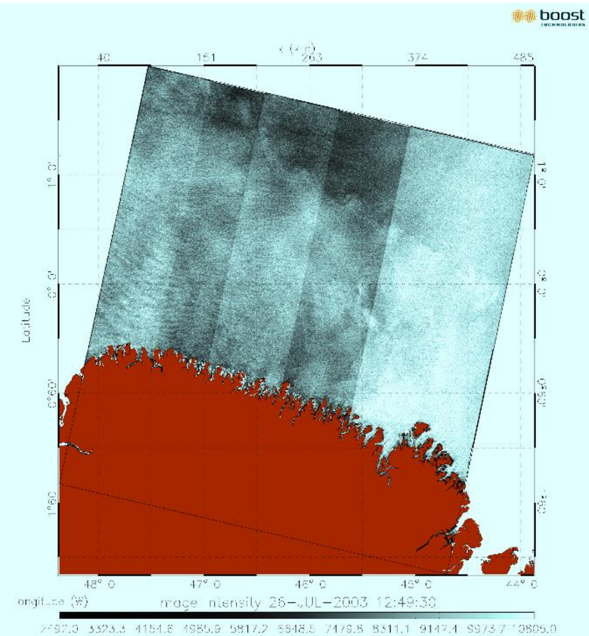
For the cyclonic front the square thins and stretches, with a 4:1 areal compression; while the overall area expands by a factor of 2 in the anticyclonic side (for τ = 2.75).

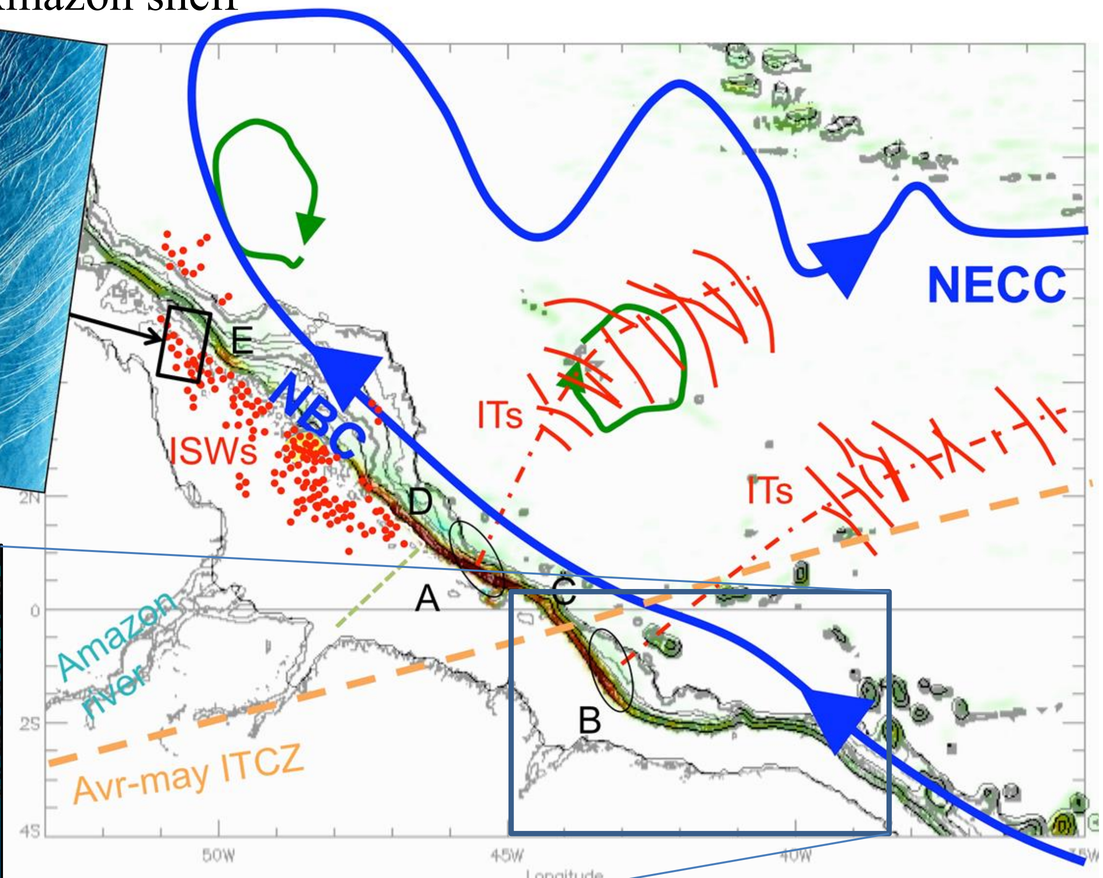
Topographic vorticity generation, submesoscale baroclinic instability and vortex street formation

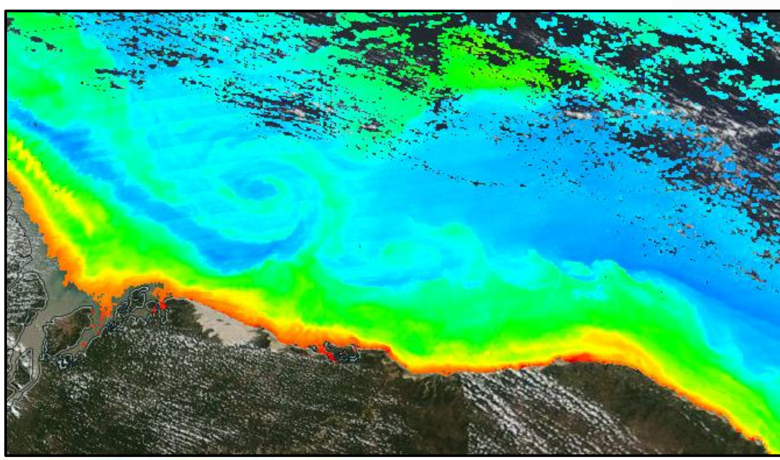


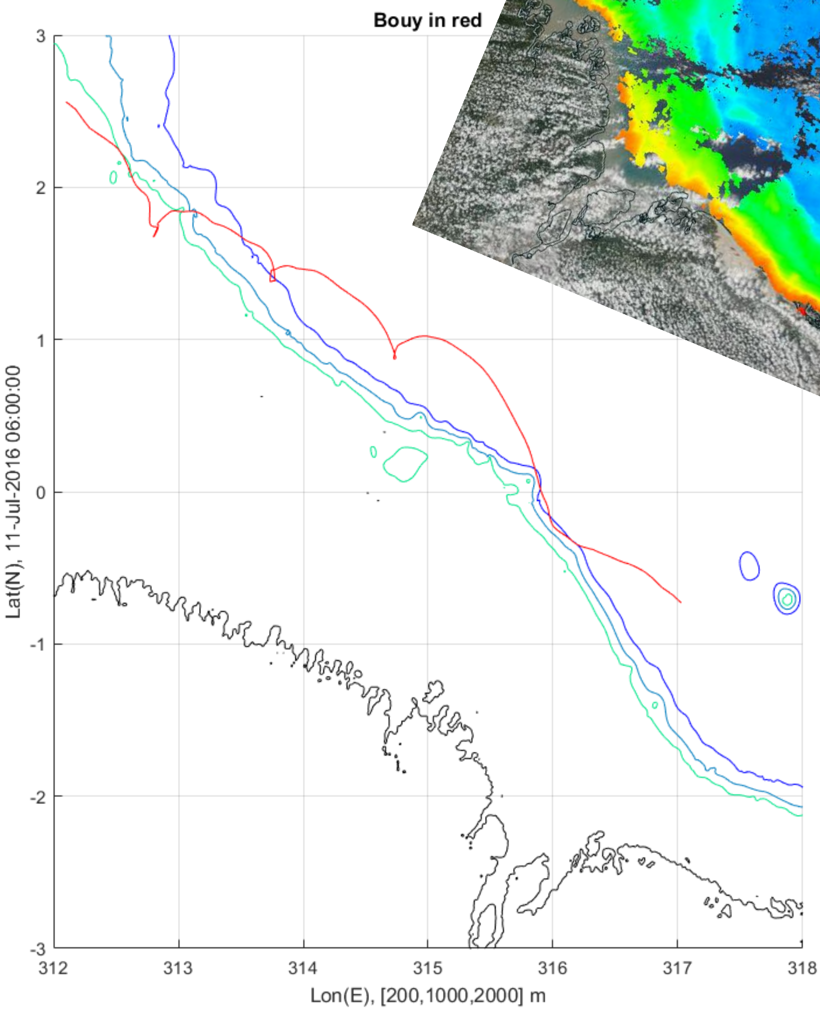
Baroclinic Instability

Study region: the tropical Atlantic deep ocean off the Amazon shelf

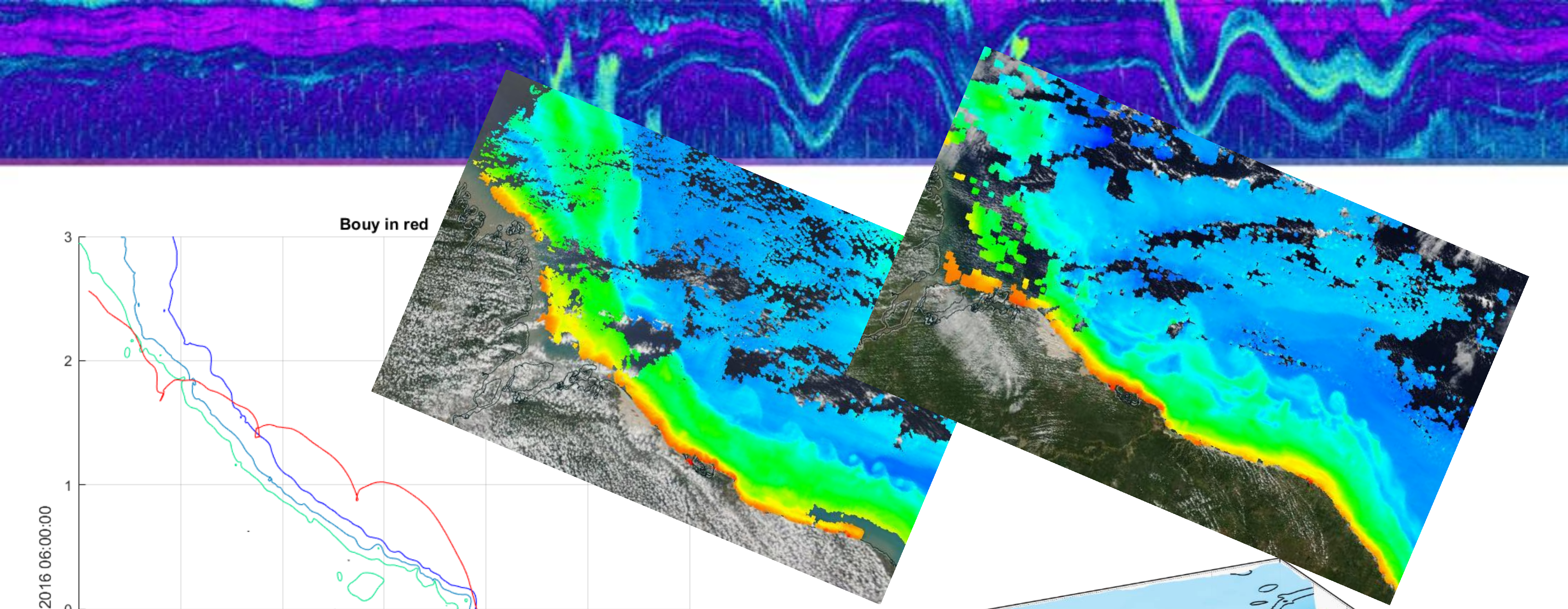


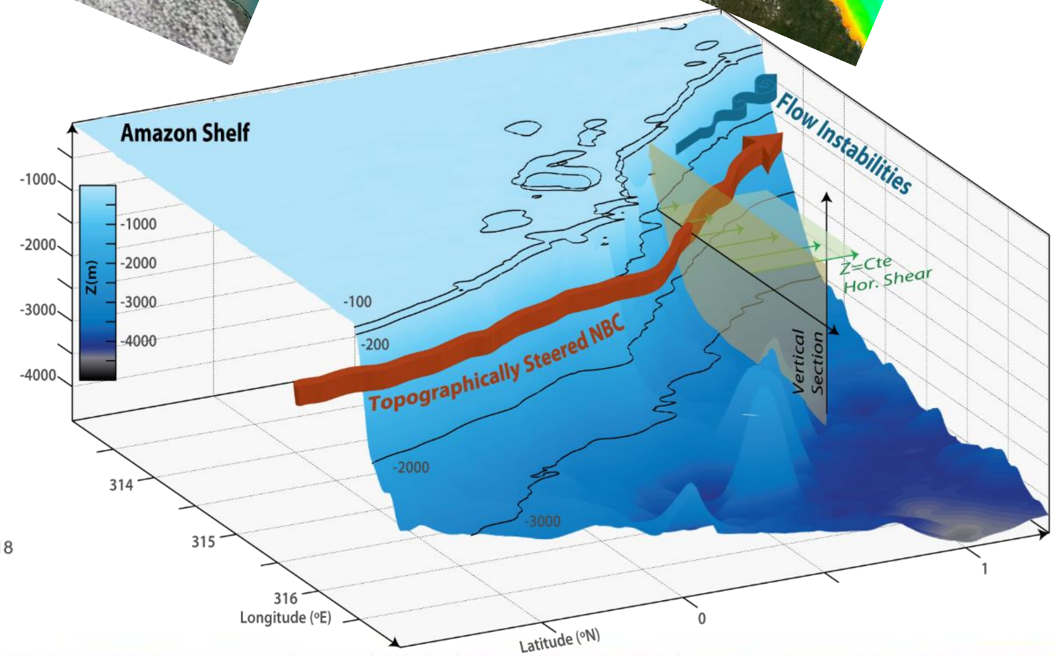




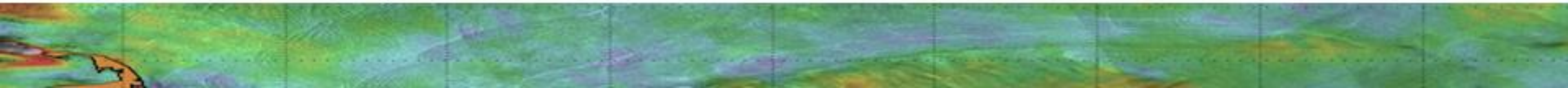


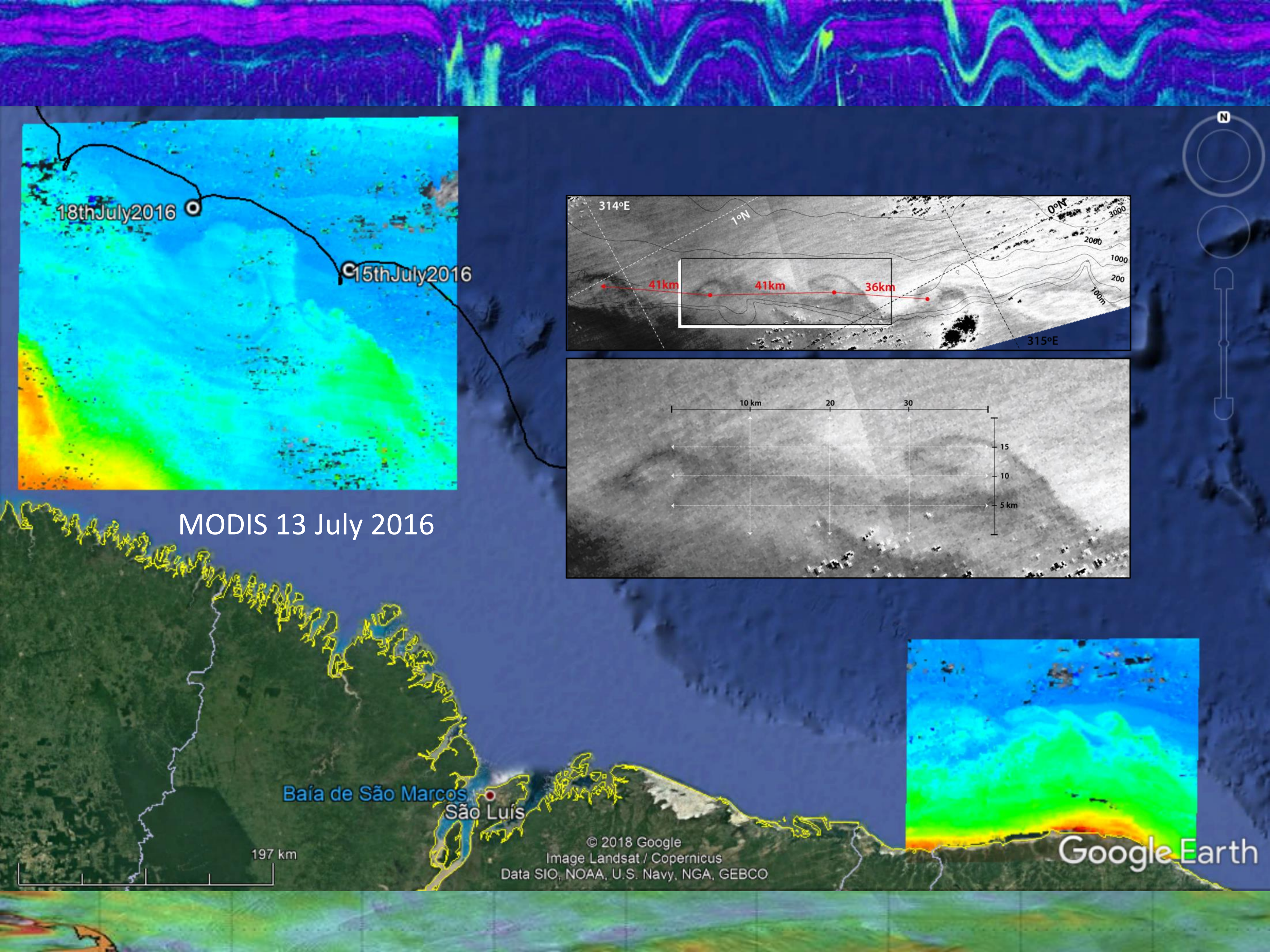
Bouy in red
Lat(N), 11-Jul-2016 06:00:00
Lon(E), [200,1000,2000] m
3
2
1
0
-1
-2
-3
312
313
314
315
316
317
318





Amazon Shelf
Flow Instabilities
Topographically Steered NBC
Z=Cte
Hor. Shear
Vertical Section
Z(m)
-1000
-2000
-3000
-4000
-100
-200
-2000
-3000
314
315
316
Longitude (ºE)
Latitude (ºN)
0
1



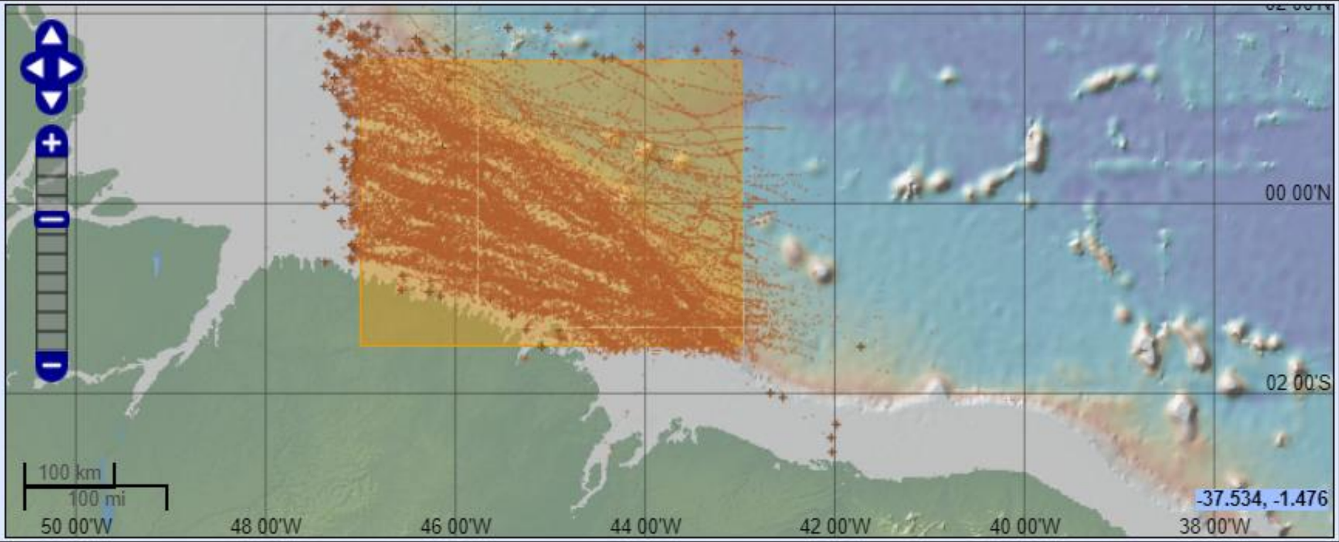

18thJuly2016
15thJuly2016
MODIS 13 July 2016
314°E
1°N
0°N
3000
2000
1000
200
100m
41km
41km
36km
315°E
10 km
20
30
15
10
5 km
Baía de São Marcos
São Luís
197 km
© 2018 Google
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google Earth

Hypothesis: is there in situ evidenve that the NBC looses 'energy' as it is topographically driven north-westwards?

Data selection

Tips: click "Download" to ... download data, click "Refresh" if "Download" is not active, click "Hide observations" to save some time.

Refresh
Download
NetCDF Argo
Data display
Map display
PNG
Hide observations
Help



Start date	End date
01/01/2000	20/11/2018

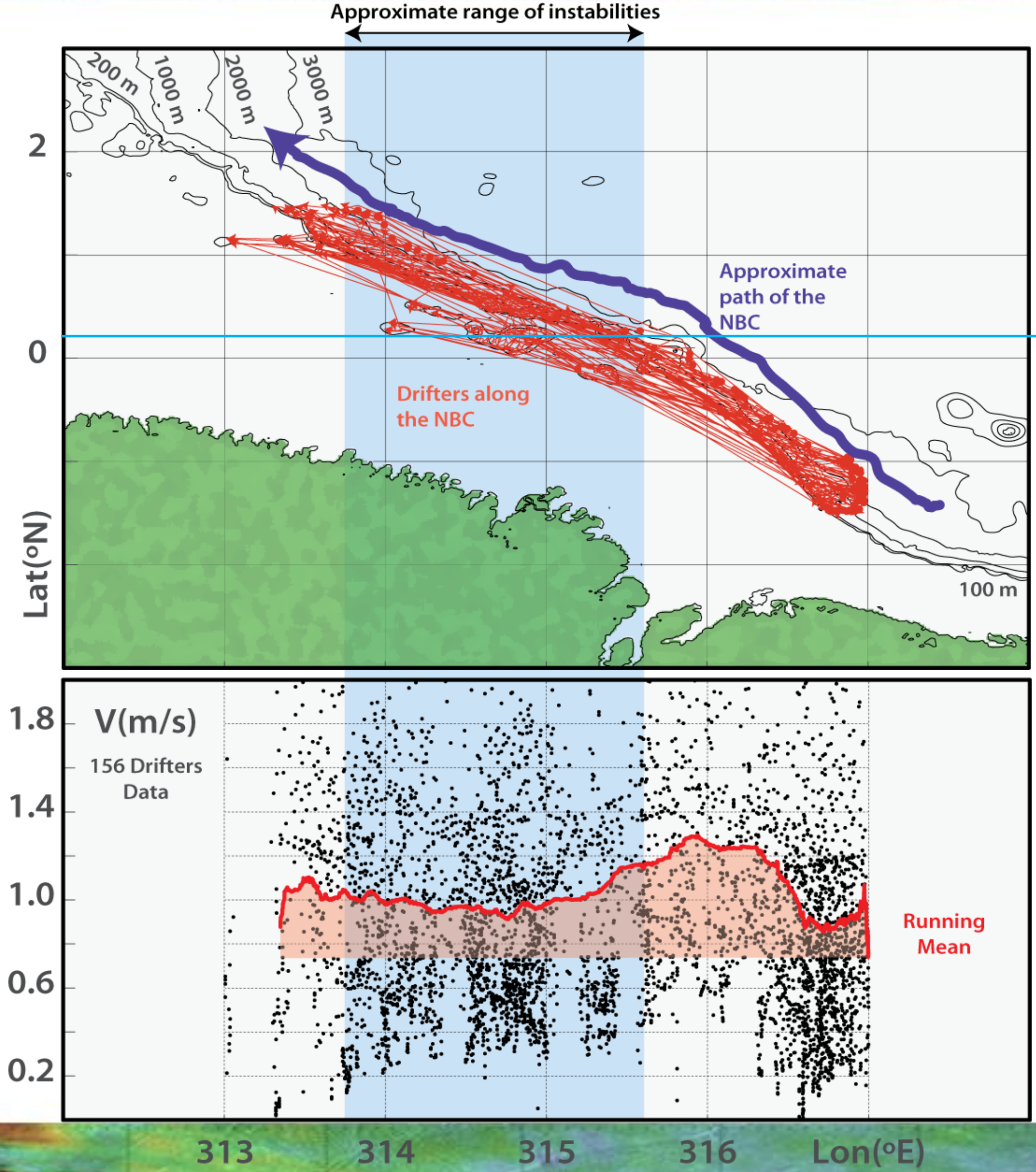
1.5 N
47 W — 43 W
1.5 S

	Vertical profiles	Stations (0)	Platforms (0)
	Argo profiles	0	0
	XBT profiles	0	0
	CTD profiles	0	0
	Glider profiles	0	0
	Sea mammal or Animal profiles	0	0
	Fixed buoys and mooring profiles	0	0
	Other profiles	0	0

	Times series	Platforms (171)
	Argo trajectories	0
✔	Drifting buoy	171
	TSG	0
	Bottles	0
	Fixed buoys & Mooring time series	0
	Other time series & trajectories	0

Drifting buoys along the NBC data from:
http://www.coriolis.eu.org/Data-Products/Data-Delivery/Data-selection

A proxy of KE may be obtained via surface drifters (running along-shelf between 100 and 2500 m deep)

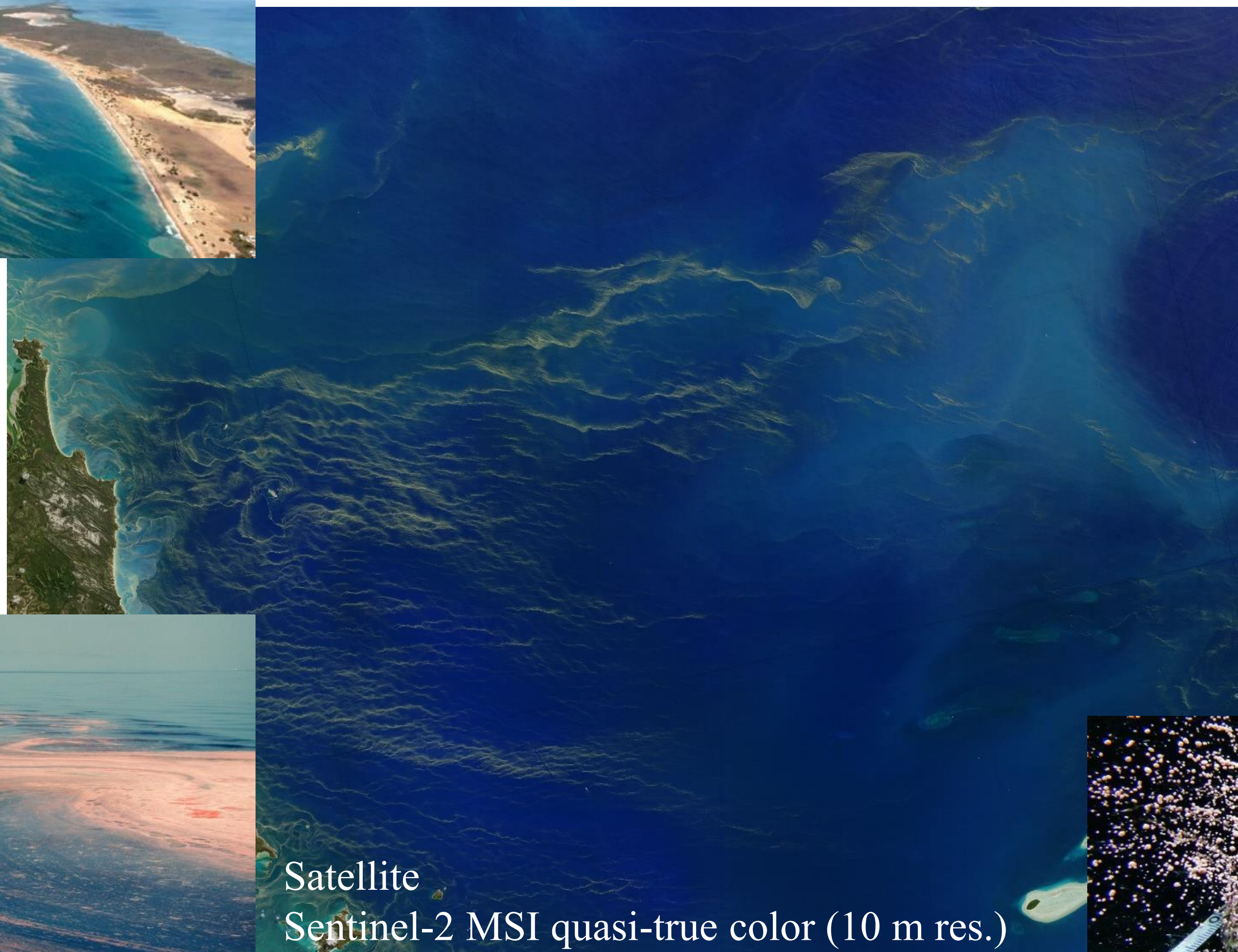


On average the NBC strength decreases around 40% just before the vortices observations.

***f* changes sign, meaning *f* is very small (conventional models may fail to reproduce these features at the equator)**

Accounts only for surface values. Deep currents need dedicated measurements/modelling.

Accumulation of Surface material



Satellite
Sentinel-2 MSI quasi-true color (10 m res.)

Great barrier reef, Eastern Australia, coral reef spawning grounds.

Conclusions about submesoscale vorticity measurements

Two very distinct roles for "small scale" observations:

- Process Studies: to help advance models and to validate models (where they exist); Aiming for finding statistical truths, e.g. Statistics of surface kinematics; (note that satellite remote sensing needs to be very high spatial resolution; complimented with drone type measurements at regular and high temporal resolution)

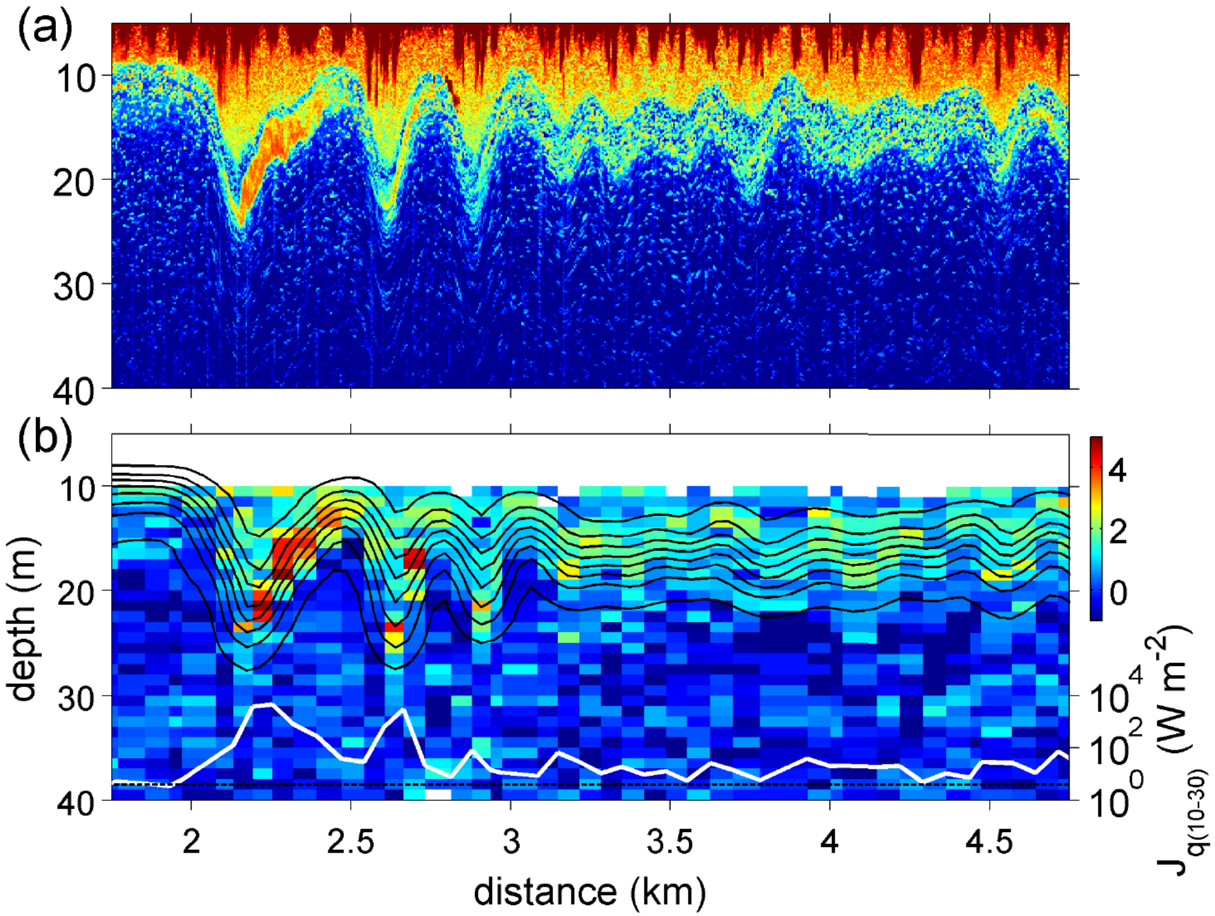
- Data assimilation for Ocean Forecast: provide data products for forecast models; e.g. Rescue Services, or oil spill prediction; predictability requires data availability at small scales and up to a day time scales

Internal solitary waves: why should we care?

Vertical heat fluxes peaked at over **1000 times** greater in the leading wave than in the background shelf waters (E. Shroyer, 2009).

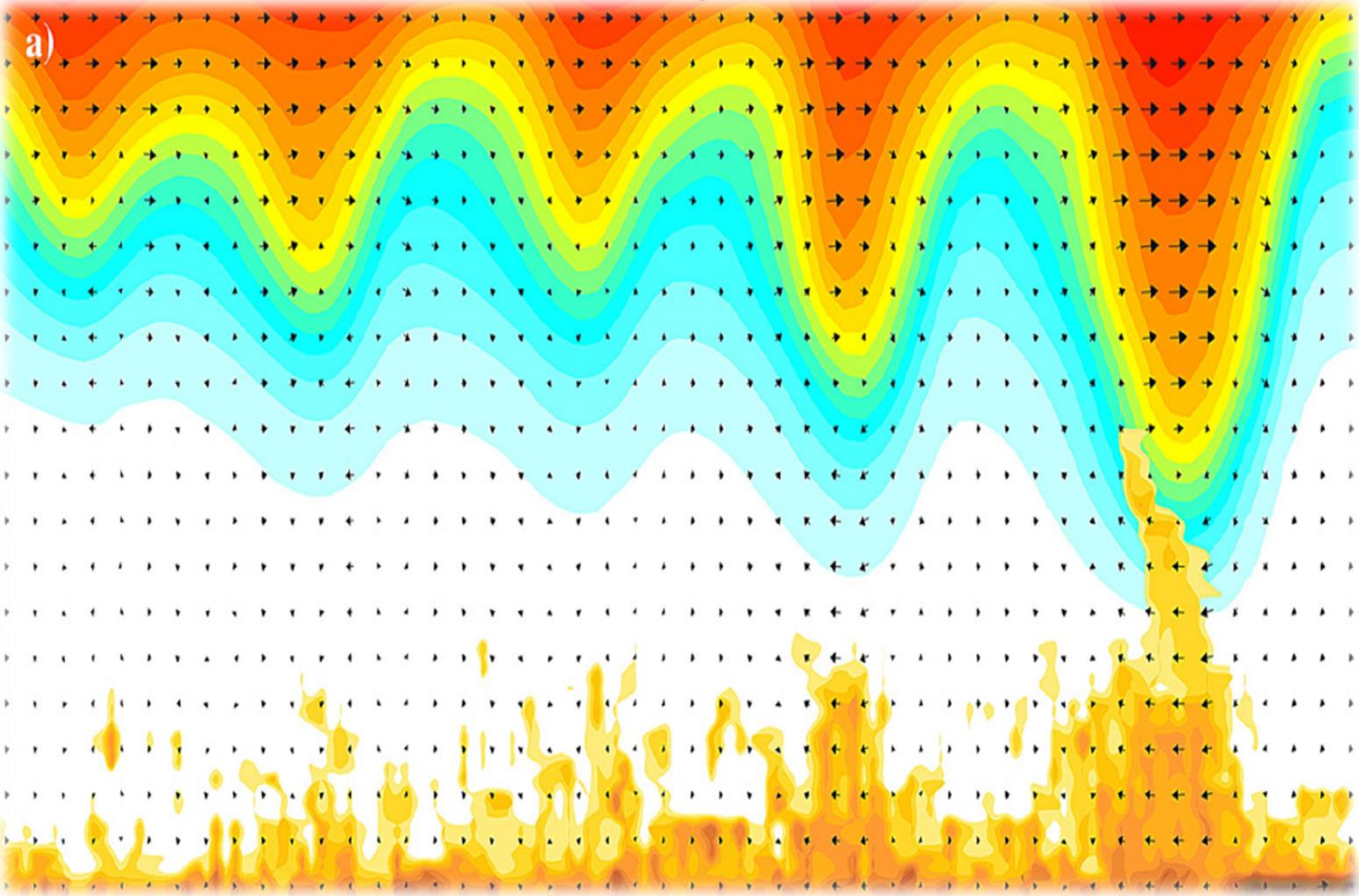
Acoustic backscatter

Vertical heat flux (log scale)



Internal solitary waves (ISWs) and motivation to study them

Sediment re-suspension in the nepheloid layer measured in the Nazareth Canyon, Portugal

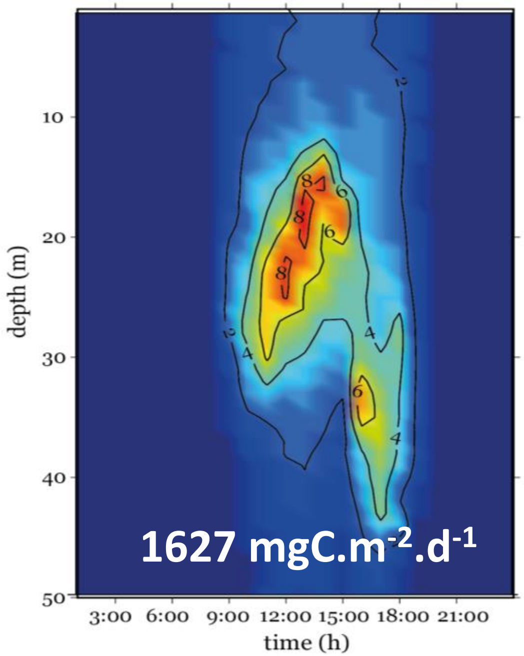


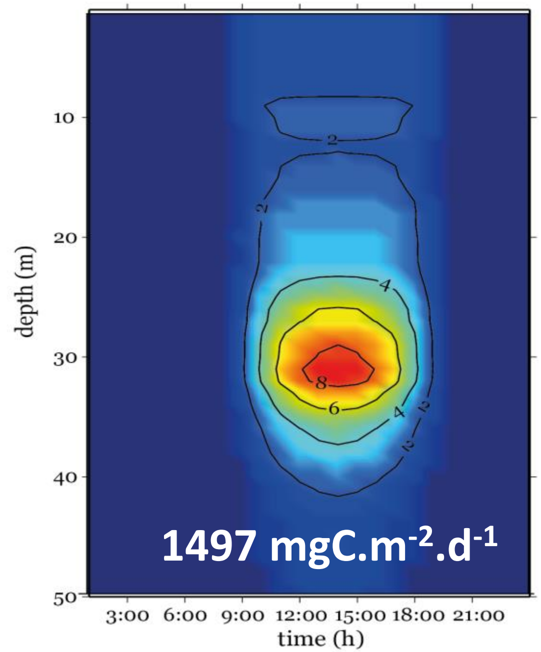
Sediment re-suspension

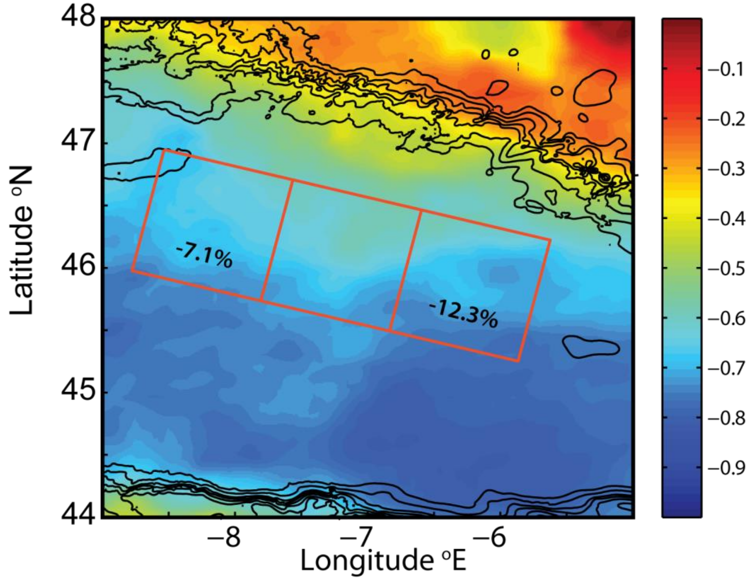
Adapted from Quaresma et al. (2007)

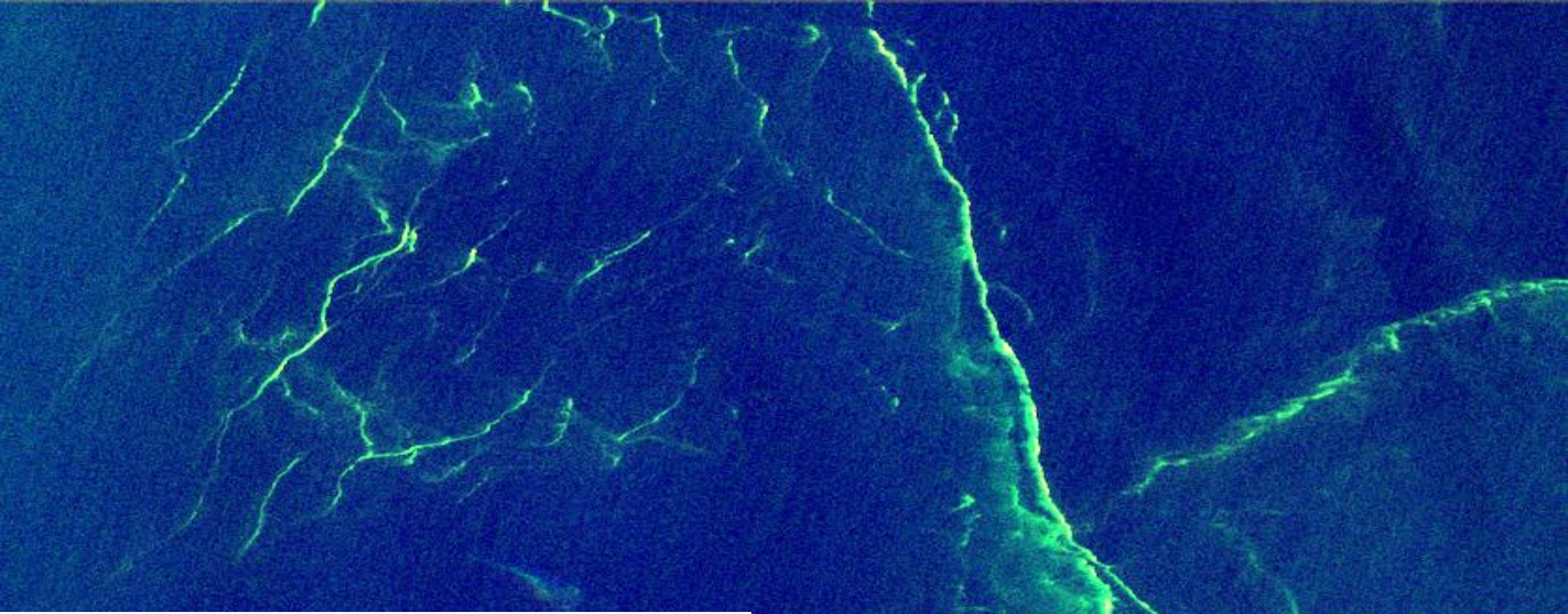
a) PP can increase up to 8% due to the presence of IT crests;
b) strong IT activity also presents ocean colour signatures on climatology satellite data.

Internal (Tidal) Waves can play an important role in the regional ecology in some coastal or oceanic regions, such as the Nazaré Canyon (Portugal) and the central region of the Bay of Biscay (France).





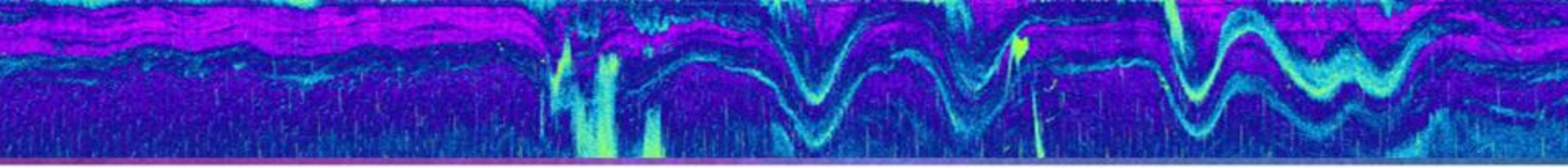




Phytoplankton Blooms and Physical Environement

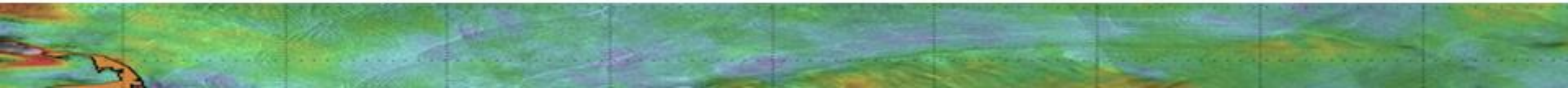
Noctiluca scintillans that has accumulated at a front formed by a nonlinear internal wave off the coast of San Diego CA, USA.

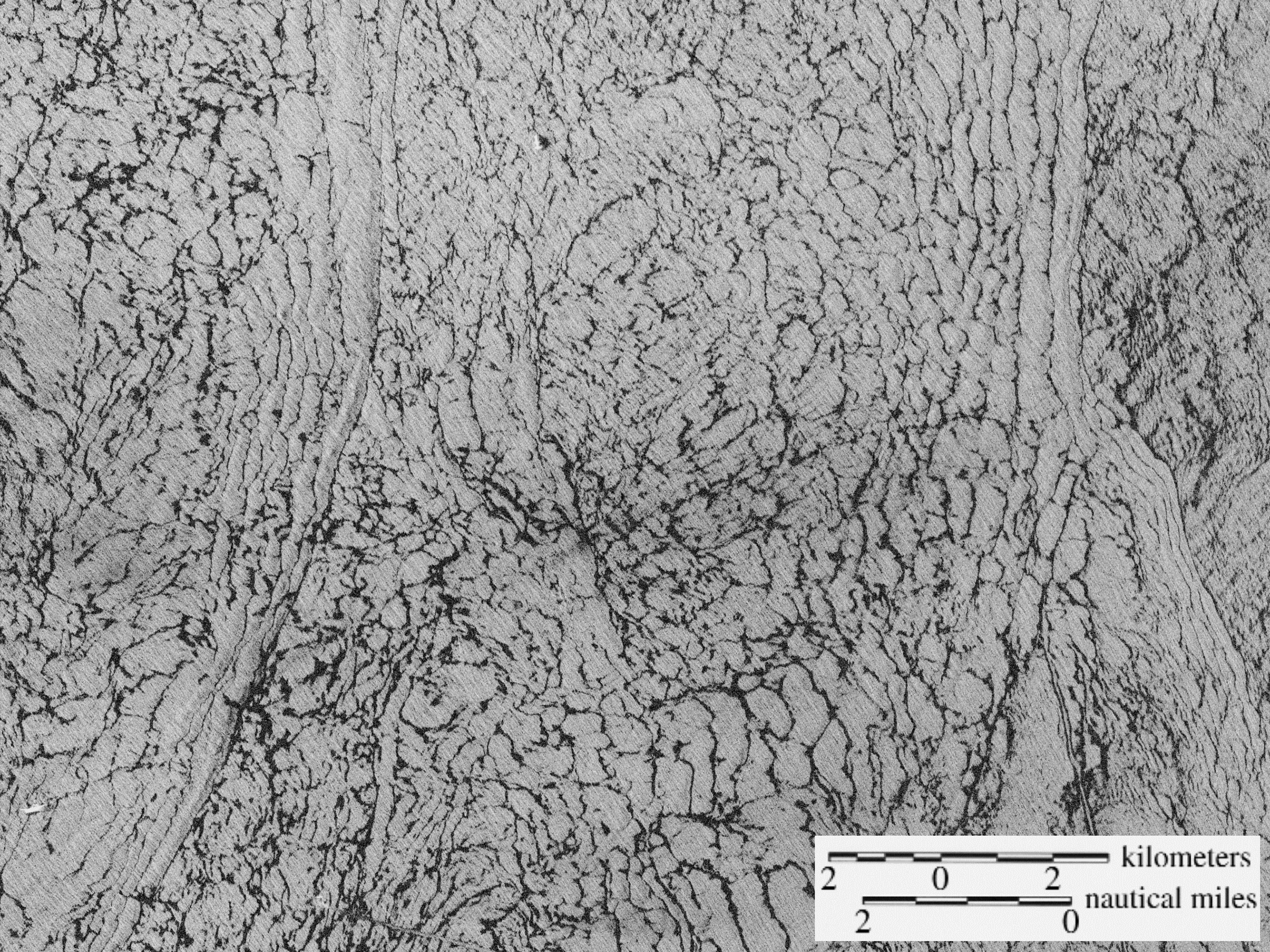
Bands of the dionflagellate *Lingulodinium polyedrum* moving onshore over the troughs of a series of internal waves

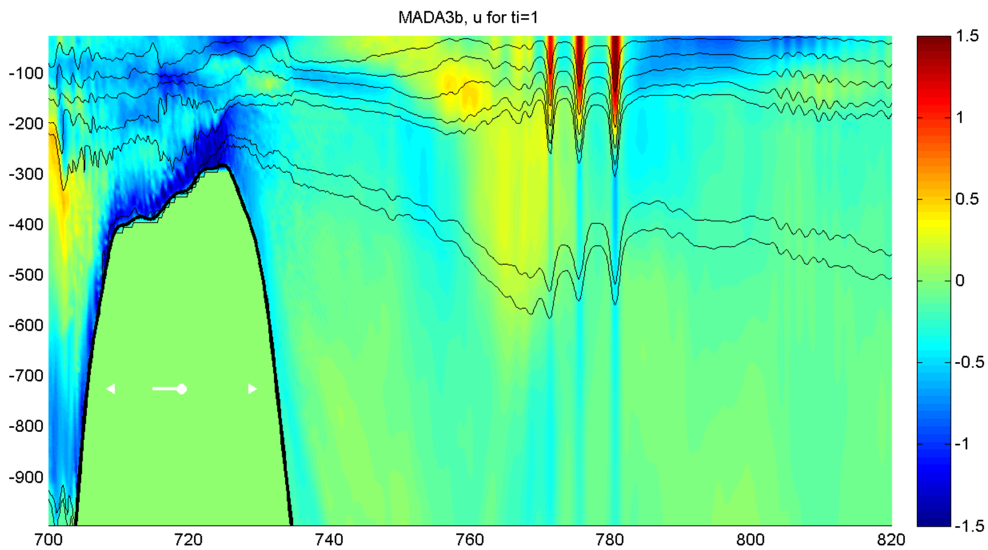


TYPICAL LARGE SOLITON CHARACTERISTICS

Vertical Amplitude	50m to 150m
Horizontal velocity	0.5m/s to 2.0m/s
Vertical velocity	about 1/3 horizontal velocities
Length scale	few hundred m to a few km
Duration	15 to 45 minutes




kilometers
2 0 2
nautical miles
2 0



MITgcm nonhydrostatic, fully nonlinear

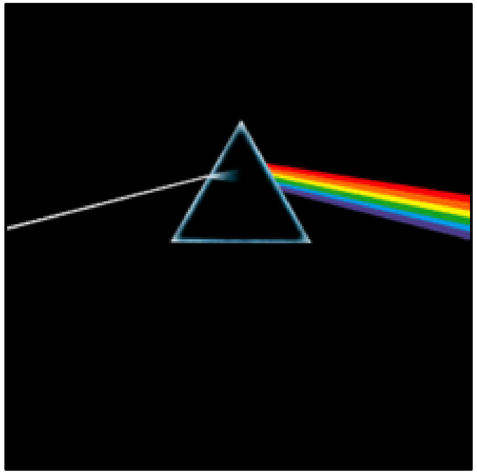
da Silva et al. (2015)

$$\frac{\partial\eta}{\partial t}+c_0\frac{\partial\eta}{\partial x}+\alpha\eta\frac{\partial\eta}{\partial x}+\beta\frac{\partial^3\eta}{\partial x^3}=0$$

Nonlinear steepening

or, *amplitude dispersion*

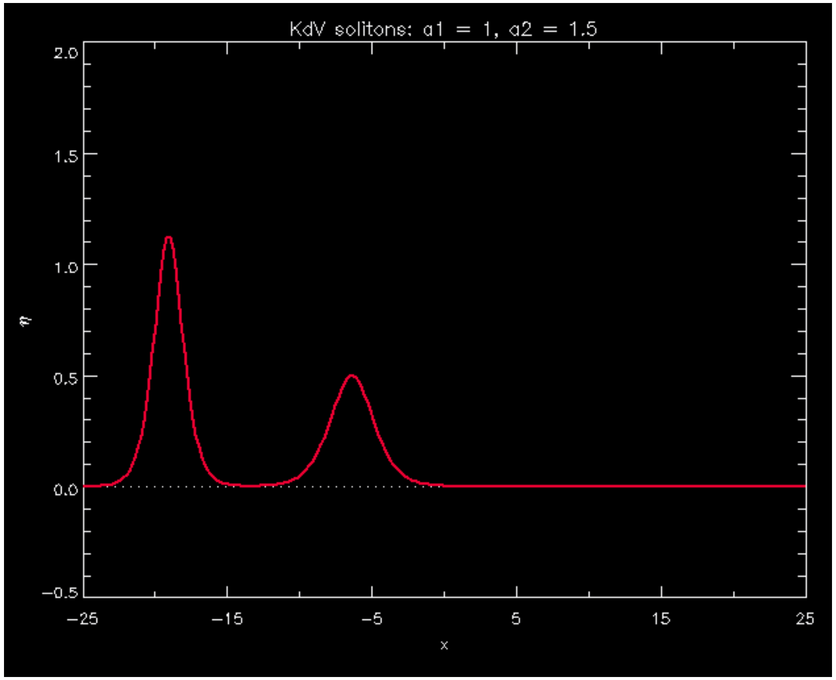
linear dispersion

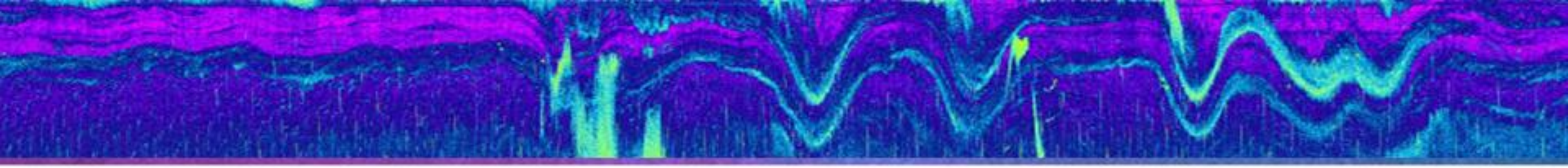


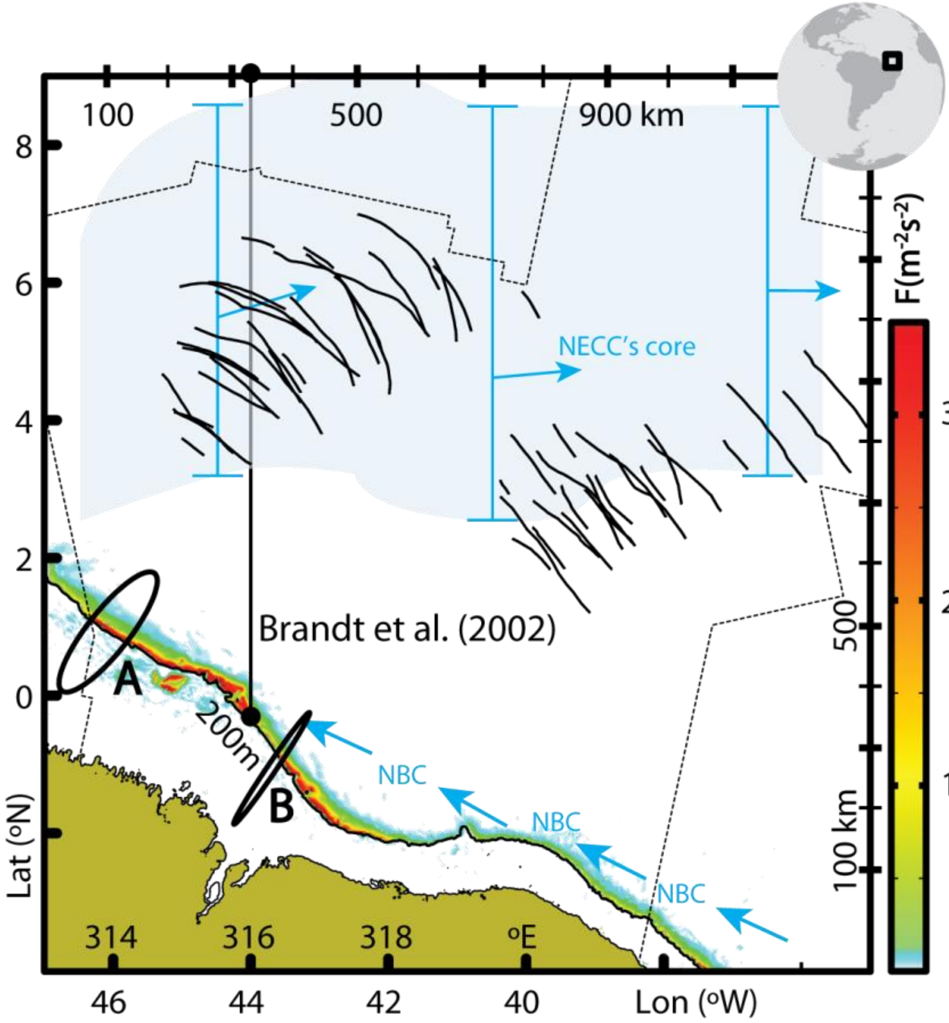
or*, frequency dispersion*

- During many decades solitary waves and the KdV solution were consider mere curiosities of nonlinear wave theory.

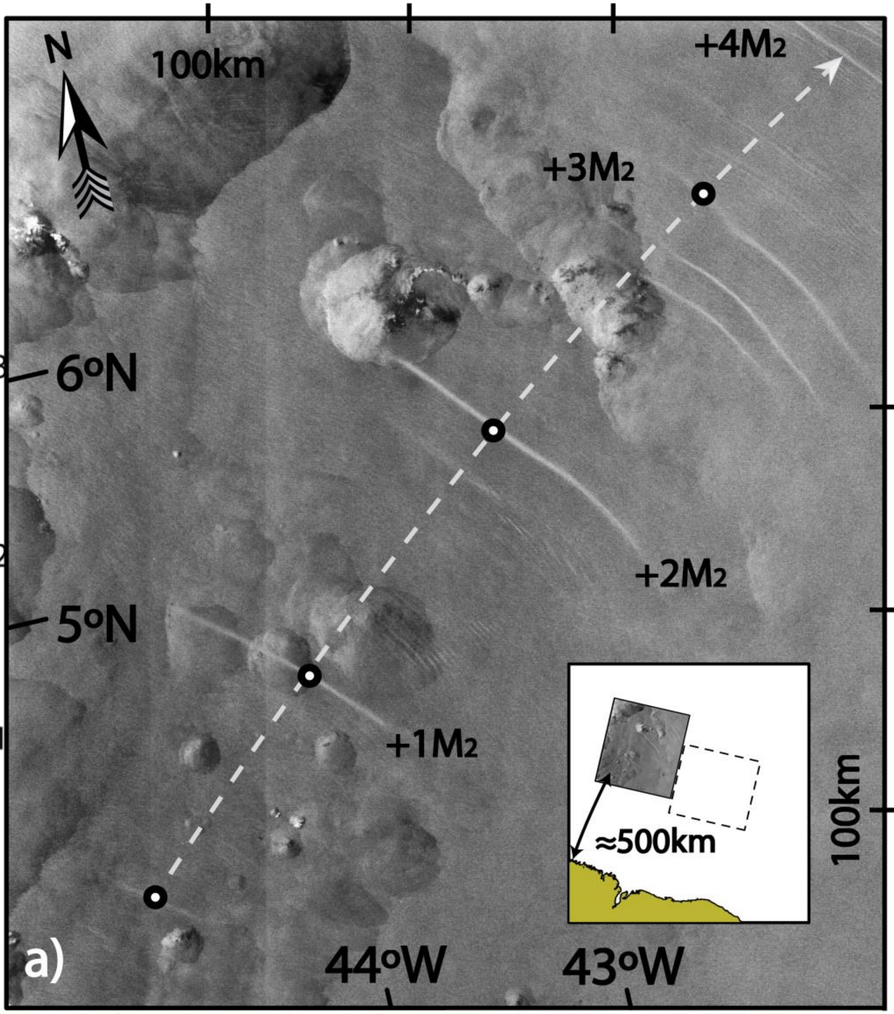
- But in 1965 *Zabusky & Kruskal* discovered, through numerical simulations, that those waves preserved their shape and speed after collision and interaction with each other!



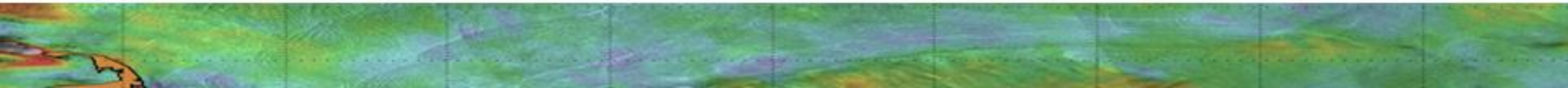


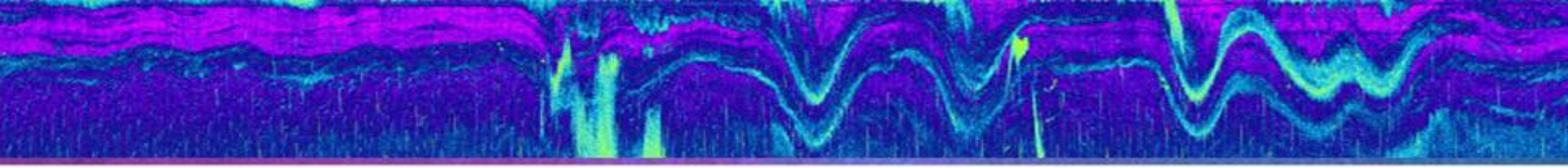


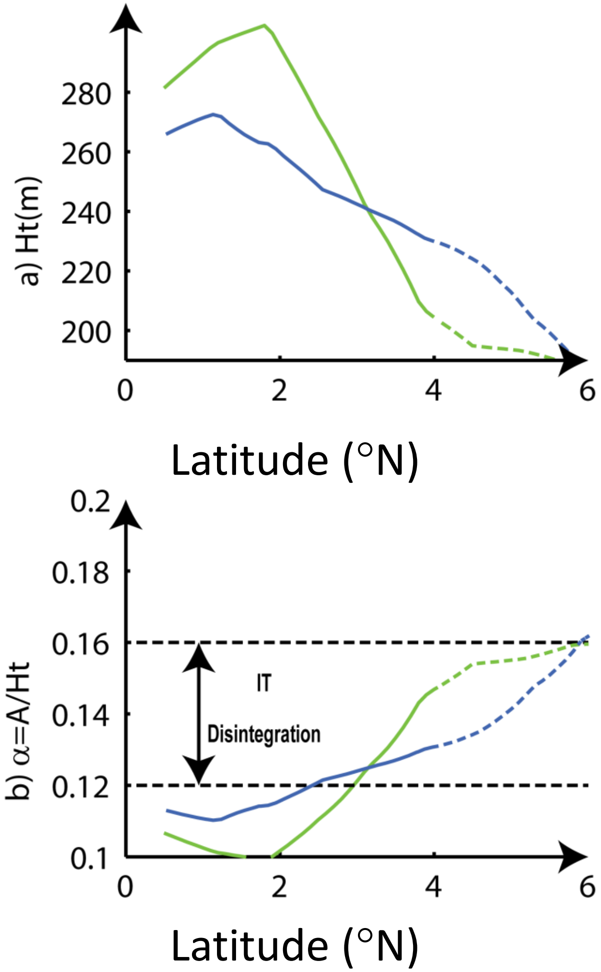
100
500
900 km
8
6
4
2
0
NECC's core
Brandt et al. (2002)
A
B
200m
NBC
NBC
NBC
314
316
318
°E
46
44
42
40
Lon (°W)
Lat (°N)
500
100 km
F(m⁻²s⁻²)



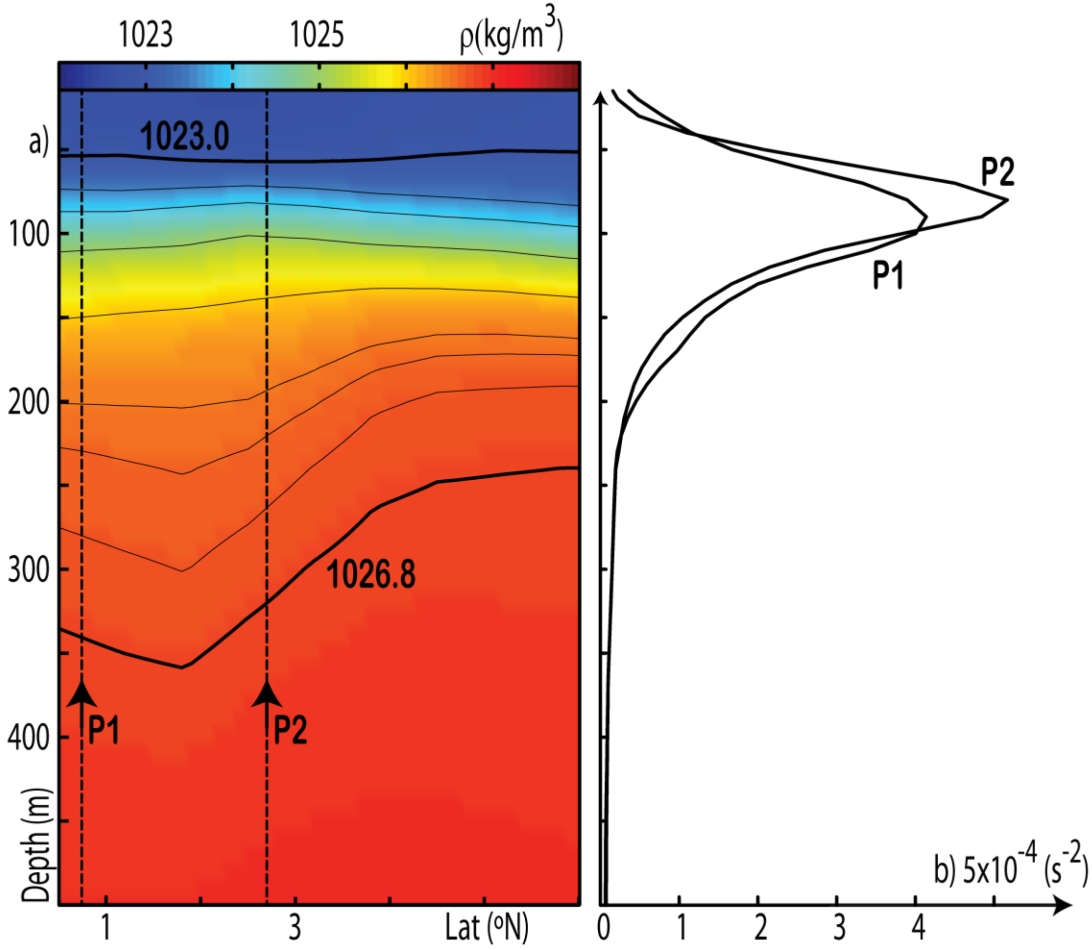
N
100km
+4M2
+3M2
+2M2
+1M2
6°N
5°N
≈500km
100km
a)
44°W
43°W



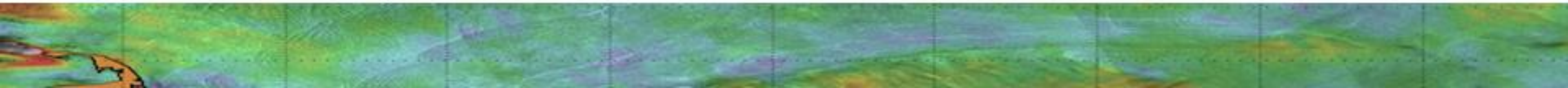




a) Ht(m)
280
260
240
220
200
0
2
4
6
Latitude (°N)
b) α=A/Ht
0.2
0.18
0.16
0.14
0.12
0.1
IT
Disintegration
0
2
4
6
Latitude (°N)

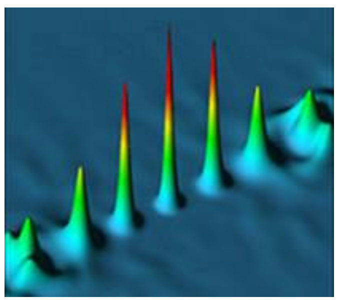


1023
1025
ρ(kg/m3)
a)
1023.0
100
200
300
400
1026.8
P1
P2
Depth (m)
1
3
Lat (ºN)
P2
P1
b) 5x10-4 (s-2)
0
1
2
3
4



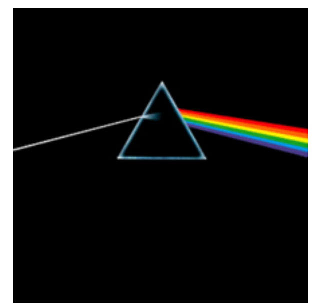
Nonlinear parameter

$$\alpha = \frac{A}{H_t}$$



Frequency dispersion term

$$\delta = \left(\frac{H_t}{L}\right)^2$$



$H_t \searrow$ $\alpha \nearrow$

$L \searrow$ $\delta \nearrow$

Conclusions for ISWs in the Tropical Atlantic Ocean:

- The increase of nonlinearity (inicially not compensated by dispersion) produces an increase of wave steepening (of the internal tide wave), which later reaches equilibrium in the form of shorter (high frequency) waves.

- During the desintegration of the internal (tide) wave, dispersion in frequency also increases substantially, due to the decrease of L of at least one order of magnitude. But eventually, balance between nonlinearity (dispersion with amplitude) and frequency dispersion is restored through the generation of short-period solitary waves.

Thank you!