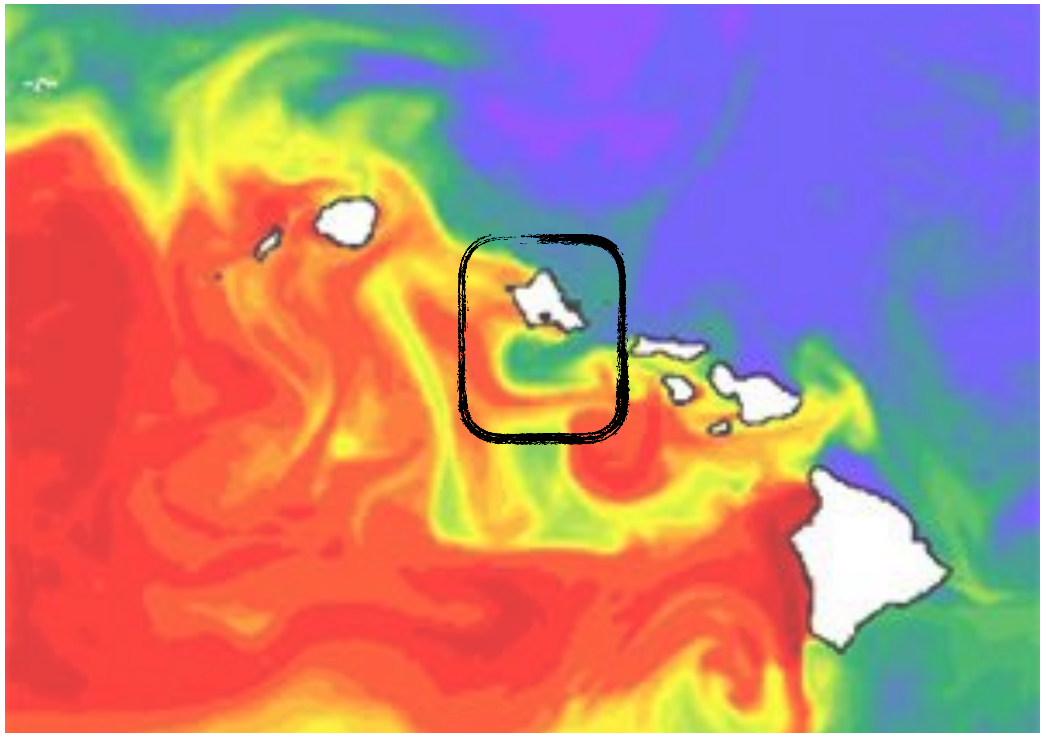
Ocean dynamics off the south shore of Oahu, Hawai’i. From mean circulation to near-inertial waves and submesoscale



Alma Carolina Castillo Trujillo
May 11, 2018

Dissertation committee
Pierre Flament
Brian Powell
Jim Potemra
Oceana Francis
Mark Merrifield

Thesis contents

1. Vorticity Balance south shore of Oahu, Hawaii derived by high-frequency radio Doppler current observations

2. Near-Inertial Oscillations off the south shore of Oahu, Hawaii

3. Interactions between submesoscale eddies and the background flow south shore of Oahu, Hawaii

4. High-frequency radio Doppler and ROMS comparison and validation south shore of Oahu, Hawaii

Outline

- Introduction
- Objectives
- Area of study and Data

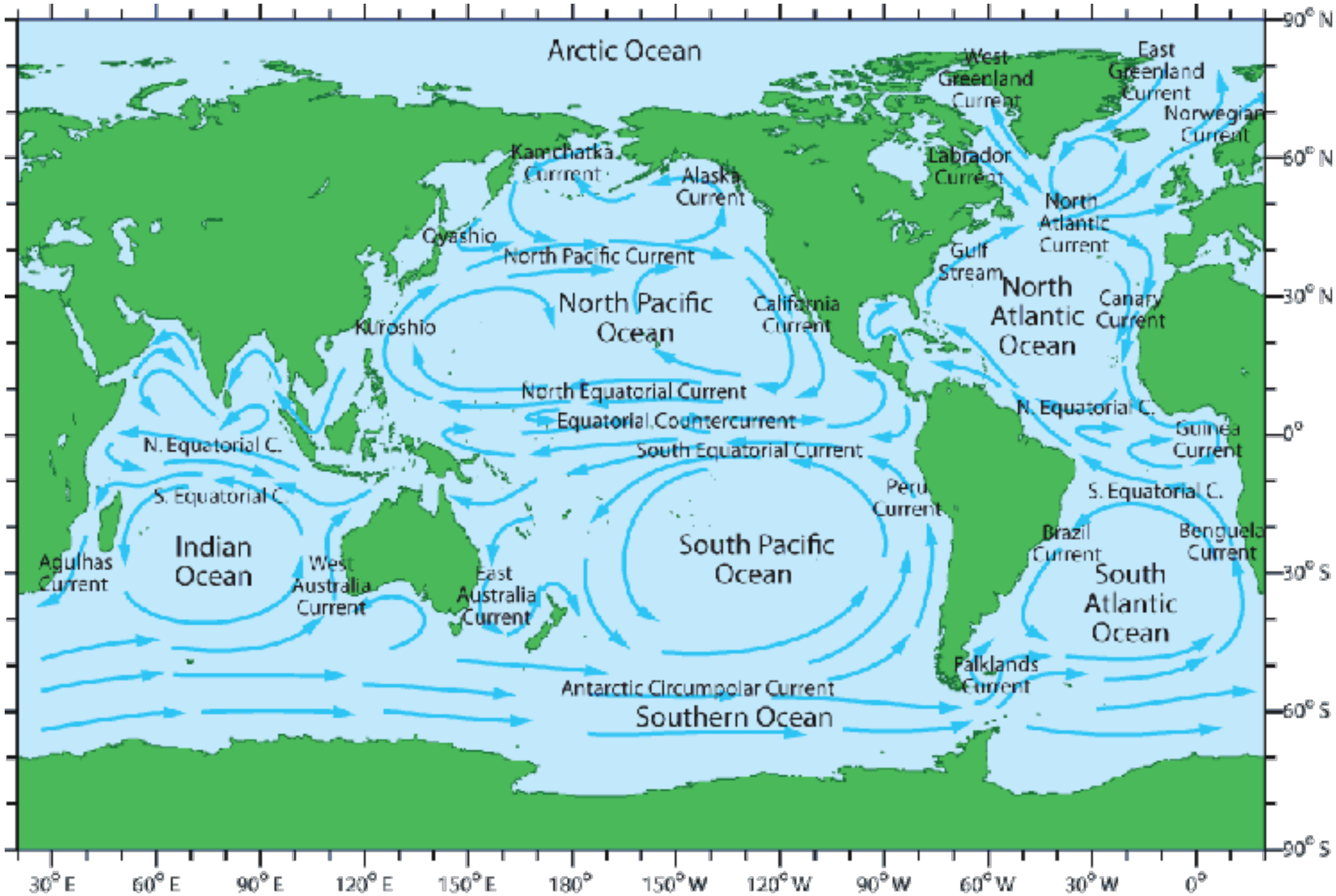
Results

  - **Near-Inertial Oscillations off the south shore of Oahu, Hawaii (observations)**
  - **Interactions between submesoscale eddies and the mean background flow south shore of Oahu, Hawaii (observations and model)**

- Final remarks and summary

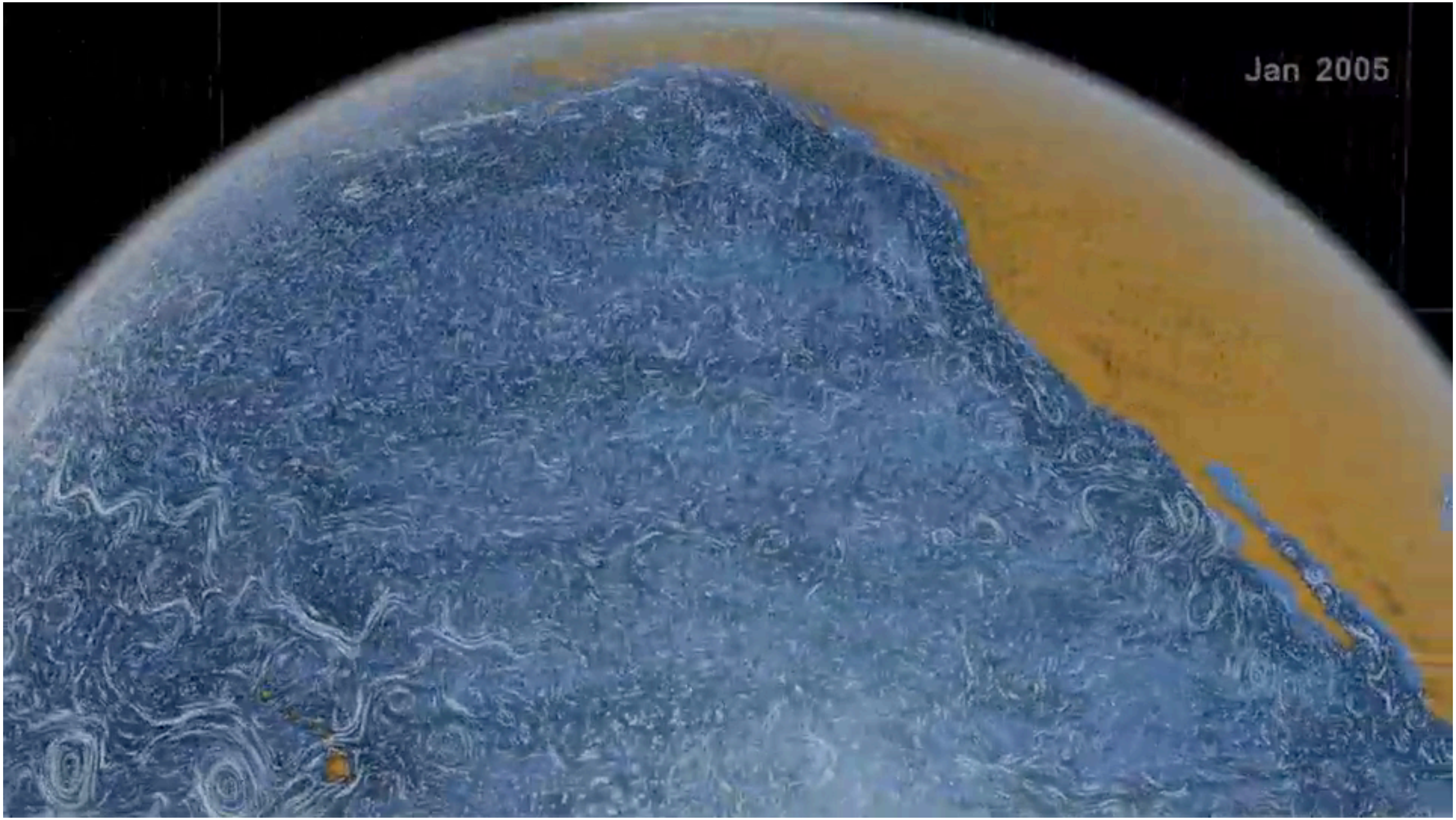
Introduction

Ocean circulation



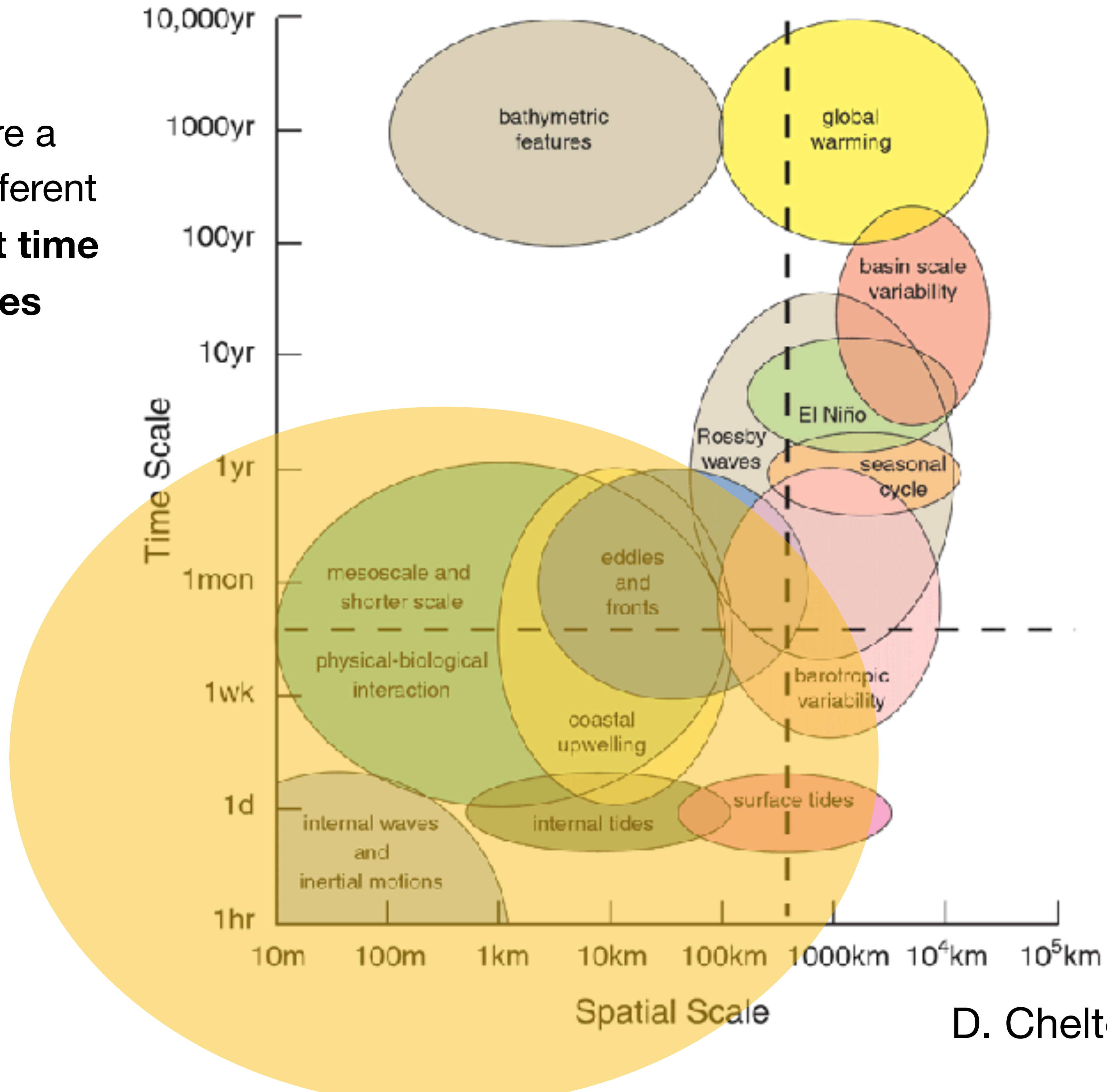
Most of the large (low-frequency currents) in the world are geostrophically balanced (effect of rotation and pressure).

Ocean circulation from satellite observations and model



Time and space scales of ocean processes

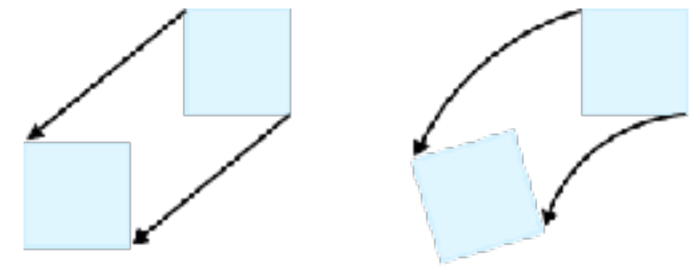
Ocean currents are a super position of different waves with **different time and spatial scales**



D. Chelton

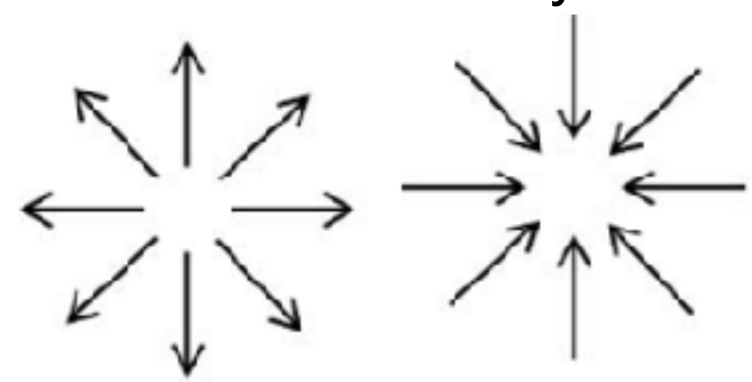
Vorticity conservation is a useful to understand dynamics of rotating flows

relative vorticity → $$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

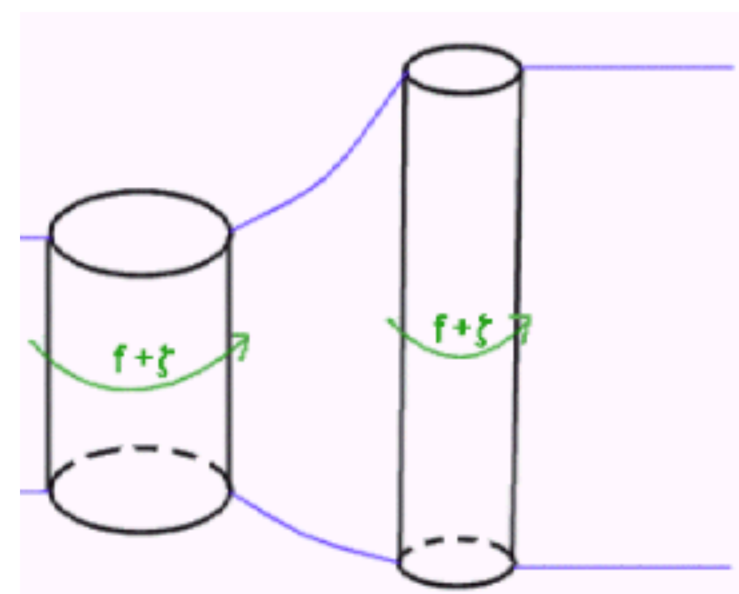


Rossby # = Relative vorticity / rotation $\frac{\zeta}{f}$

divergence → $$\delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

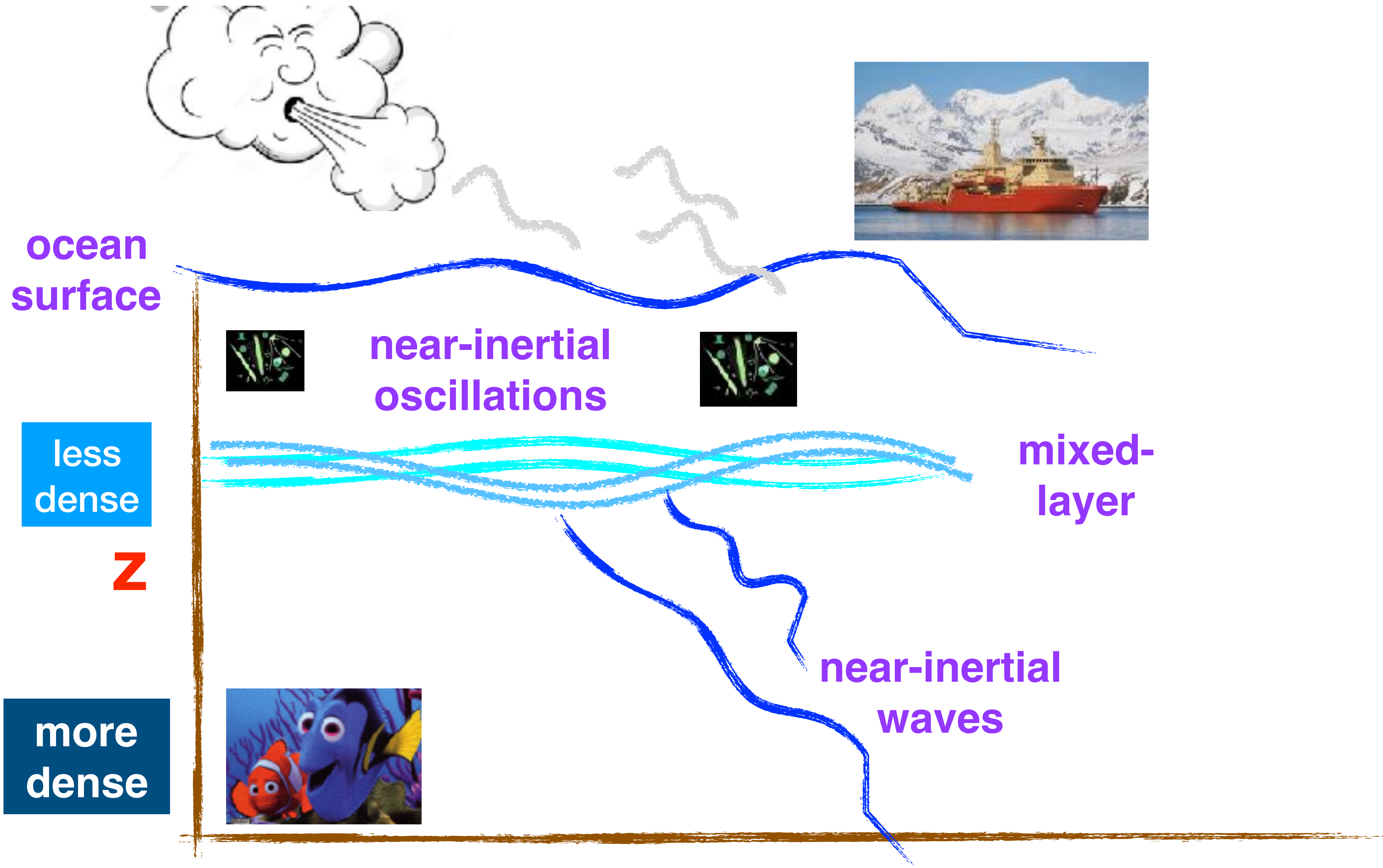


potential vorticity (PV) → $$q = \frac{f + \zeta}{H}$$



PV is conserved

Why inertial-oscillations?

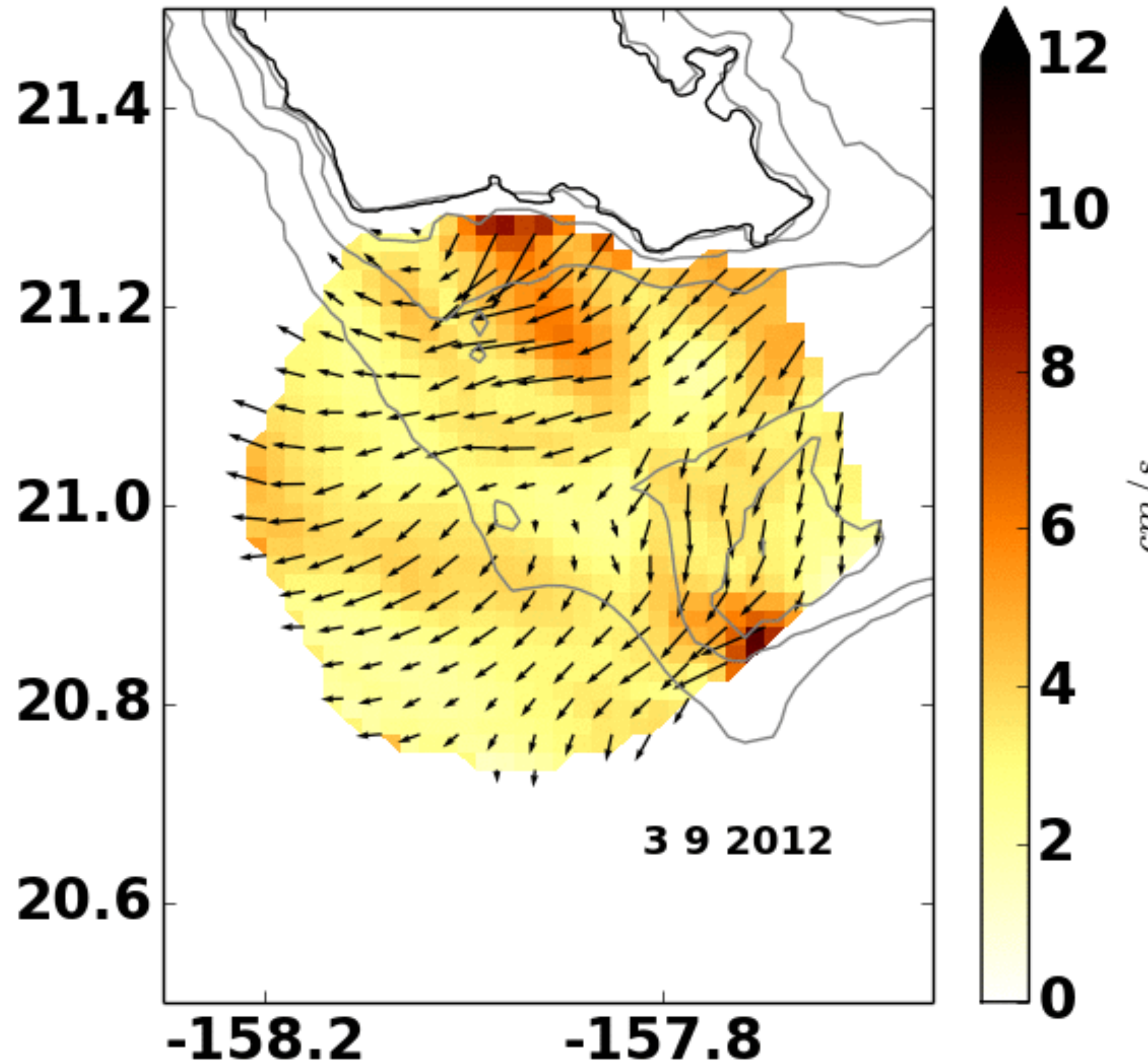


Why inertial-oscillations?

- Near Inertial Oscillations (NIOs) have **periods/frequencies** according to their latitude. Oahu: **0.71 cpd, 33.4 h.** They rotate CW in the NH and generate near-inertial waves.

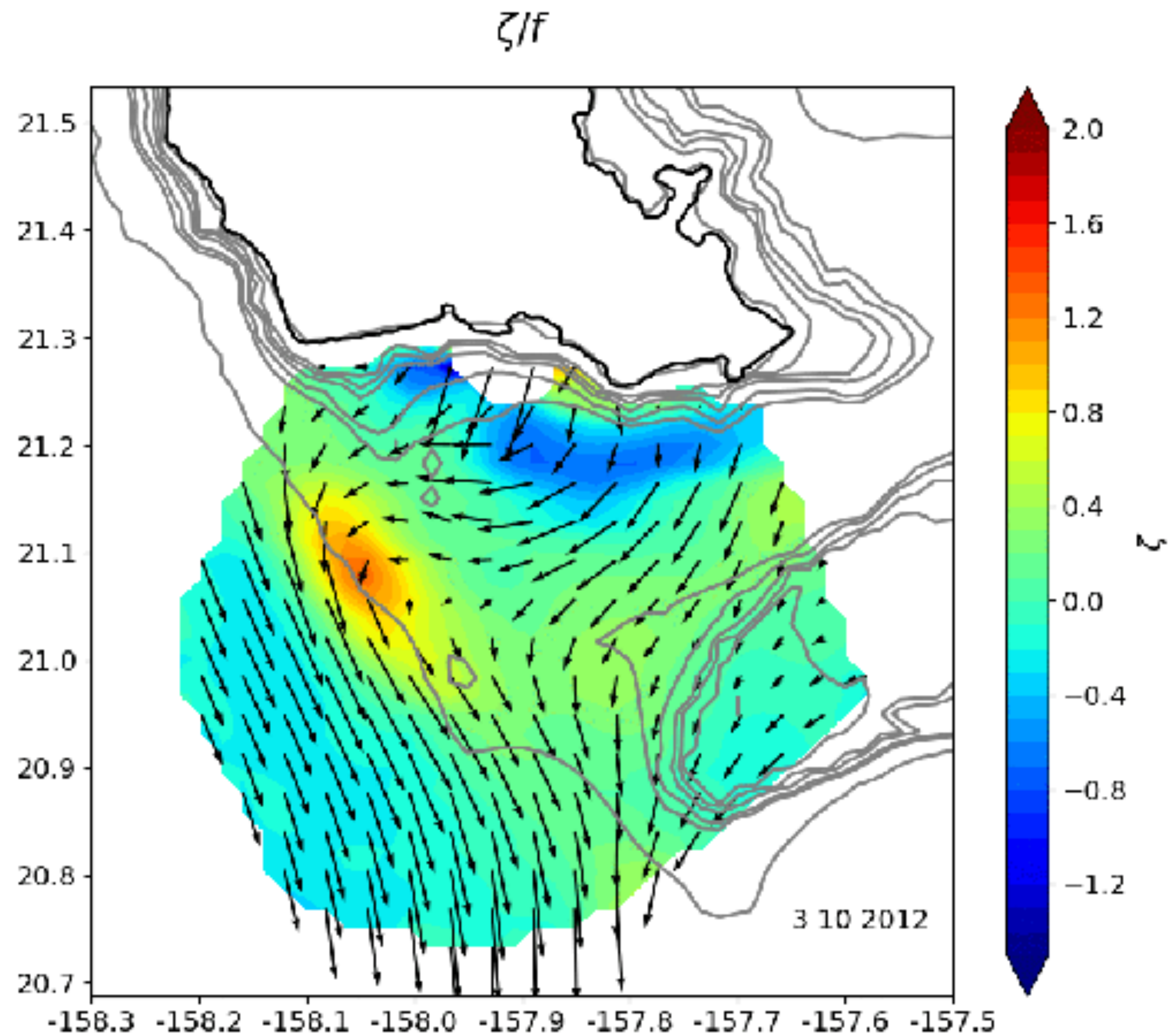
- NIO spatial **scales** are in the order of **1000** km consistent with wind storm scales (Pollard and Millard, 1970).

- Recent model and theoretical studies have shown **variability dependent on mean background flow and wind forcing** (Thomas, 2014).



Why submesoscale?

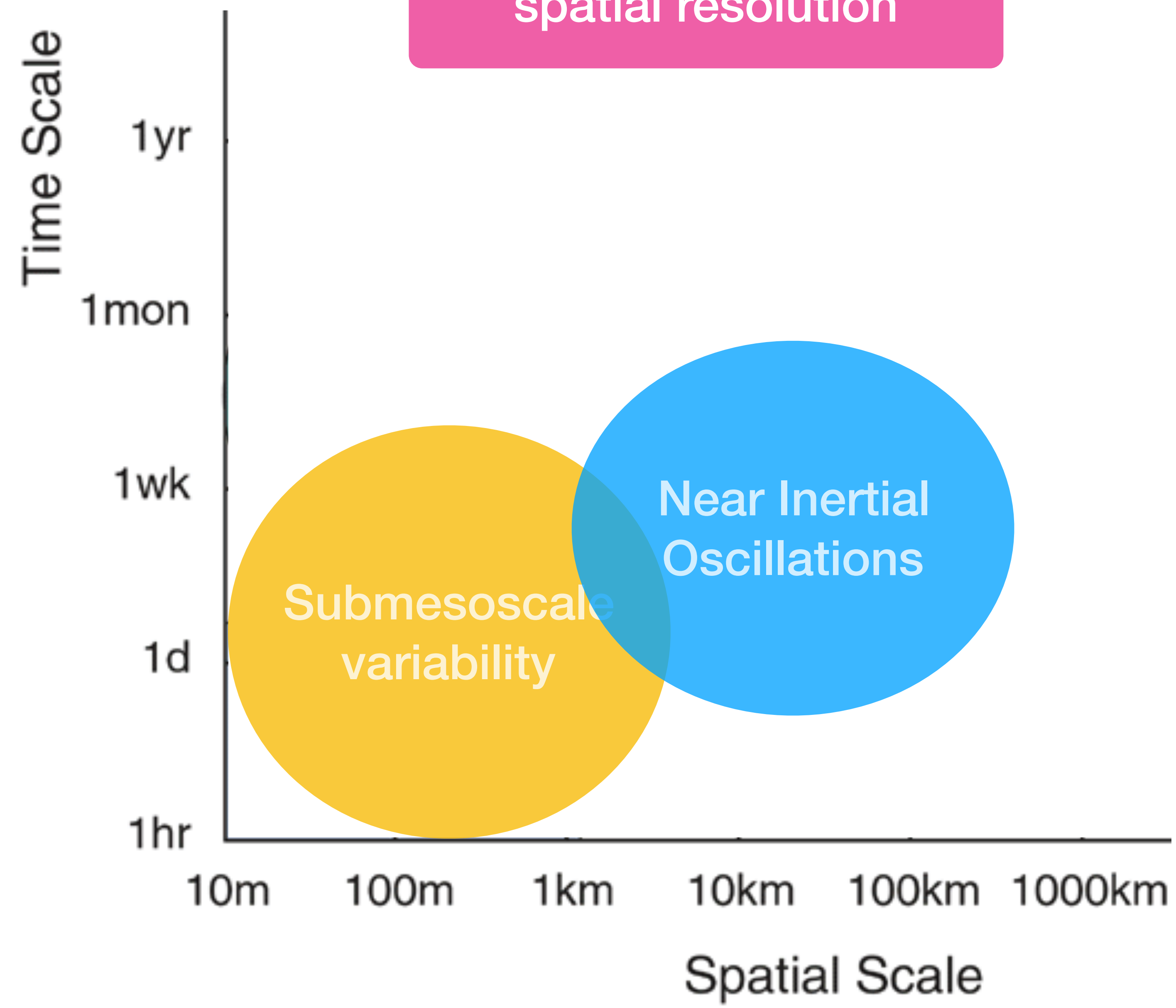
- Submesoscale **Circulation** around (**~10 km**) south of **Oahu** is unknown!
- It is important for lateral and vertical transport of tracers (**nutrients, phytoplankton**).
- **Vertical velocities** one order of **magnitude larger** than in the mesoscale.
- **Lack of observations** and computational power precludes the study of submesoscale regime.



Objectives

- How the wind and background flow contribute to the spatial and temporal variability of **Near-Inertial Oscillations?**
- What processes generate **submesoscale eddies** and what is their **temporal variability?**

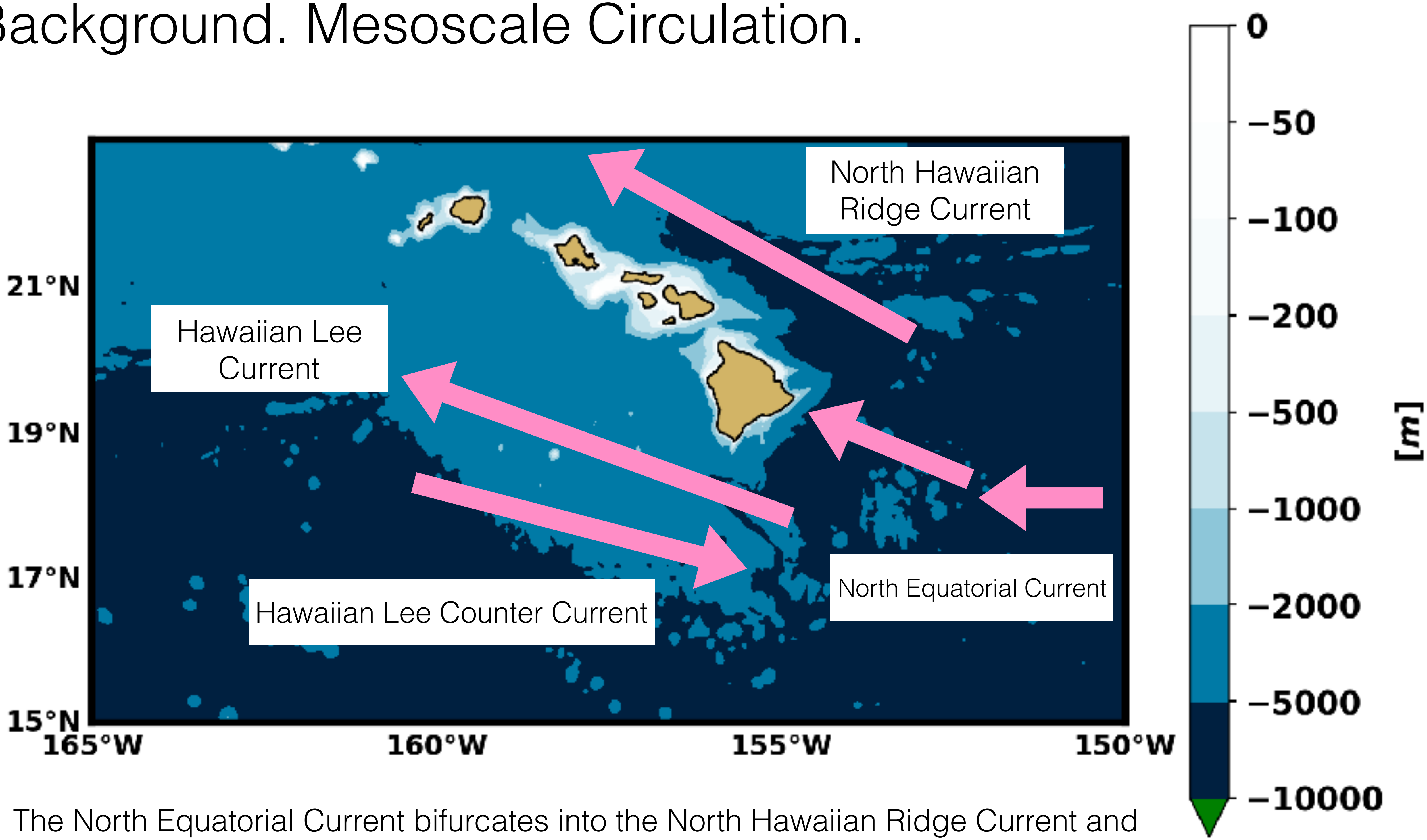
High-Frequency Doppler Radars south of Oahu Hawaii measure surface currents at a 1.5 km spatial resolution



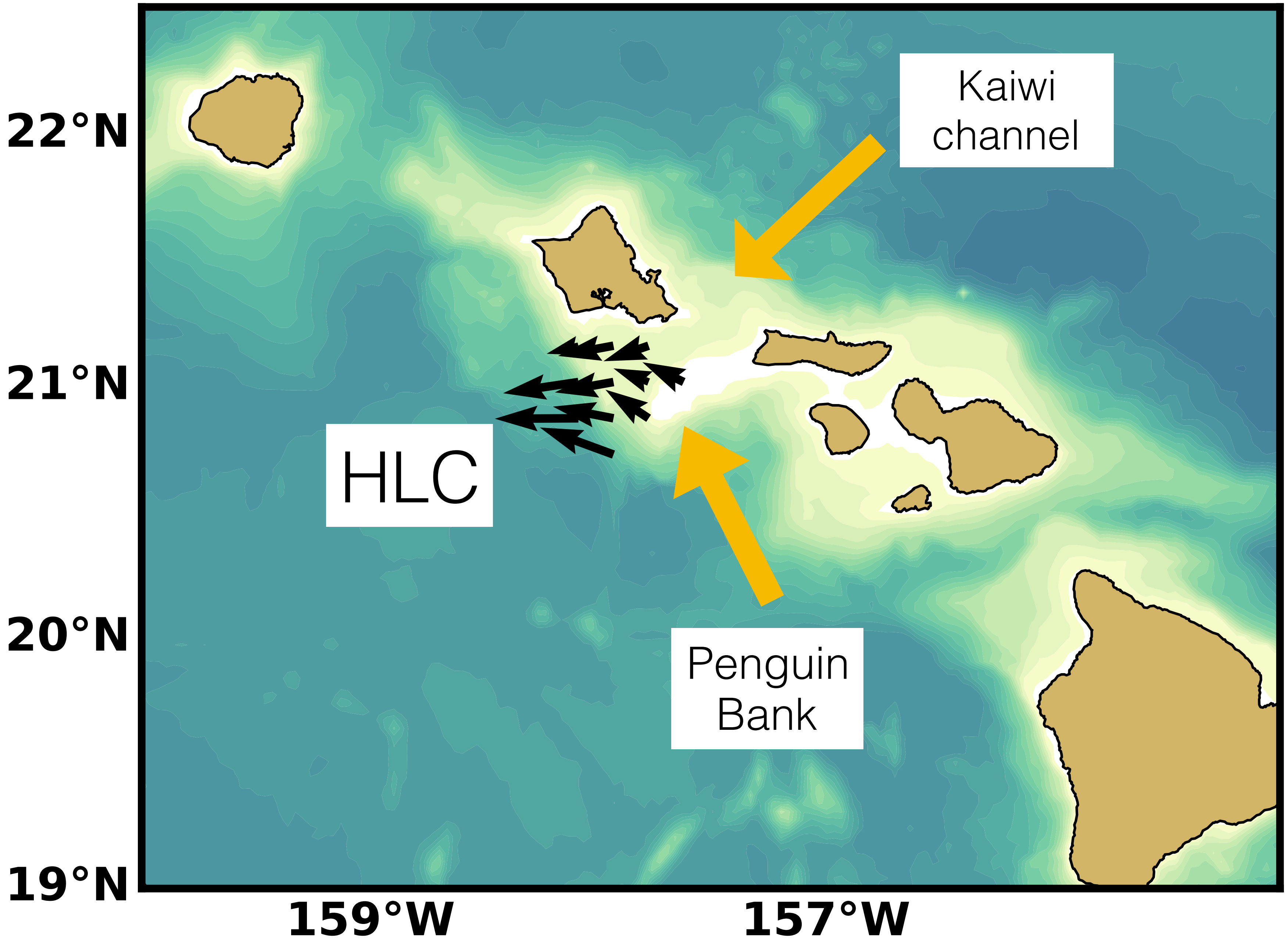
Area of study

Hawaiian Islands at the center of the North Pacific Current Gyre

Background. Mesoscale Circulation.



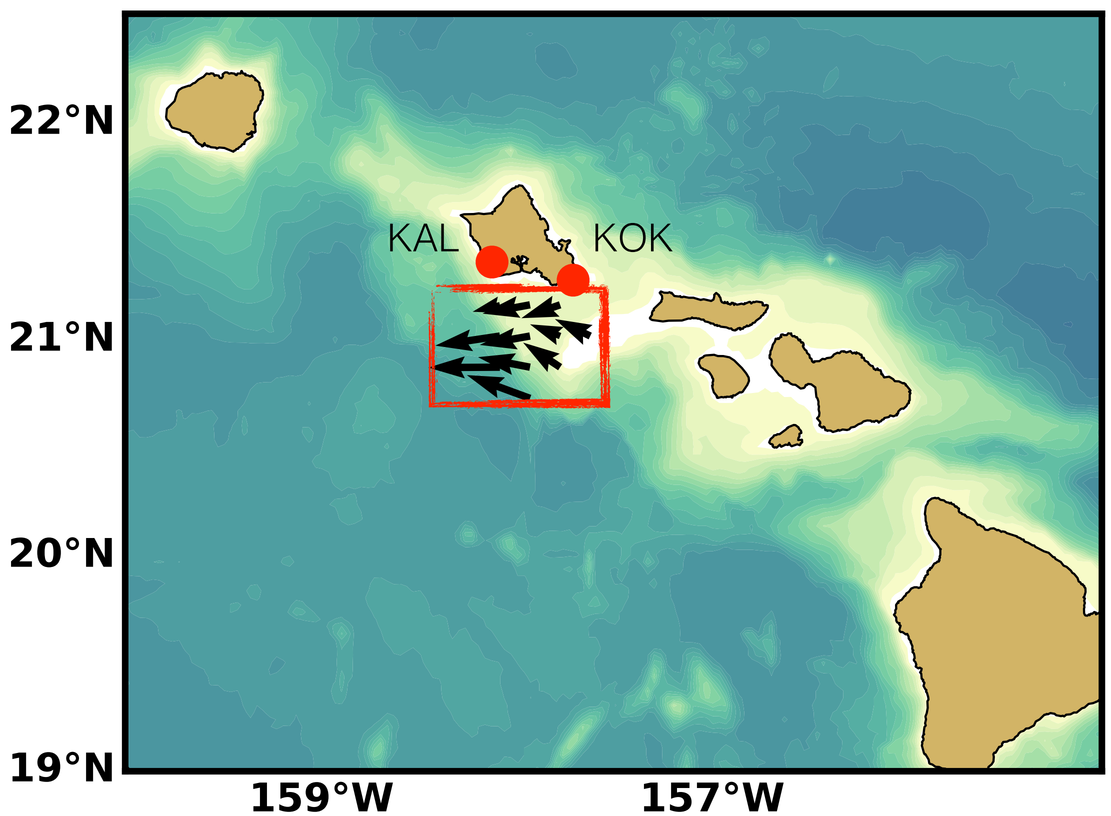
- The North Equatorial Current bifurcates into the North Hawaiian Ridge Current and Hawaiian Lee Current (Firing, 1996, Qiu, 1997, Flament, 1998, Lumpkin et al., 2013).
- Shear between Hawaiian Lee Counter Current and Hawaiian Lee Current generates instability (mesoscale eddies) (Yoshida et al., 2011).
- Big Island and wind stress curl from trade winds generates eddies. (Chavanne et al., 2002, Calil et al., 2008, Jia et al., 2011).



The 50 m deep Penguin Bank and the 1000-m deep Kaiwi Channel modify the low-frequency Hawaiian Lee Current (HLC).

(Chapter 2, PhD dissertation)

Data



- Two years of **High Frequency Doppler Radar** (HFR) **surface currents** from 2010 to 2012

- **1.5 km** and **1 hour** spatial and temporal resolution

- HFR map ocean currents from the coast by scattering radio waves from the surface.

- HFR measure radial currents. Two HFR are needed to calculate vector currents.

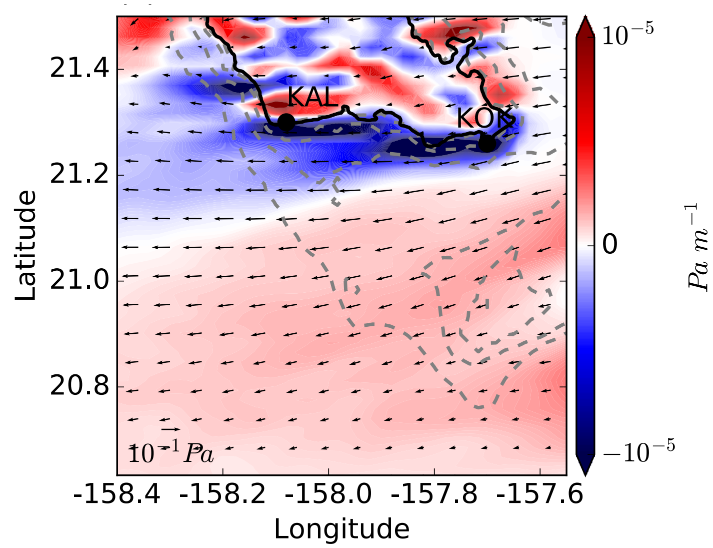
KAL HFR Tx antennas

HFR Power Amplifier and Rx

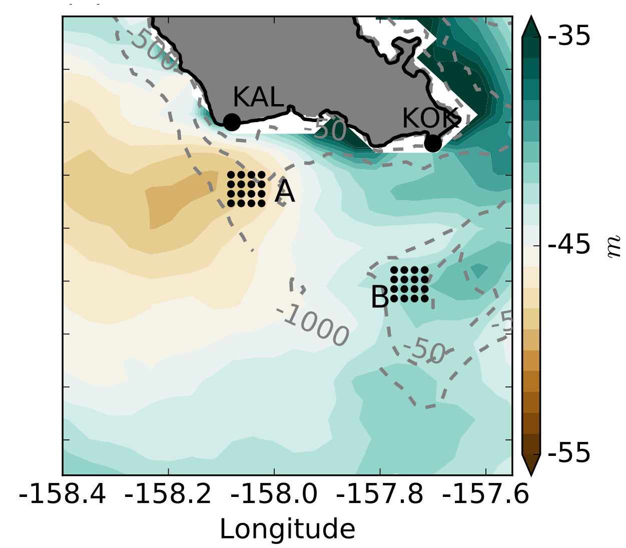
2 years of **WRF** wind model

- 1.5 km spatial resolution
- assimilates available wind observations

WRF Wind Stress Curl



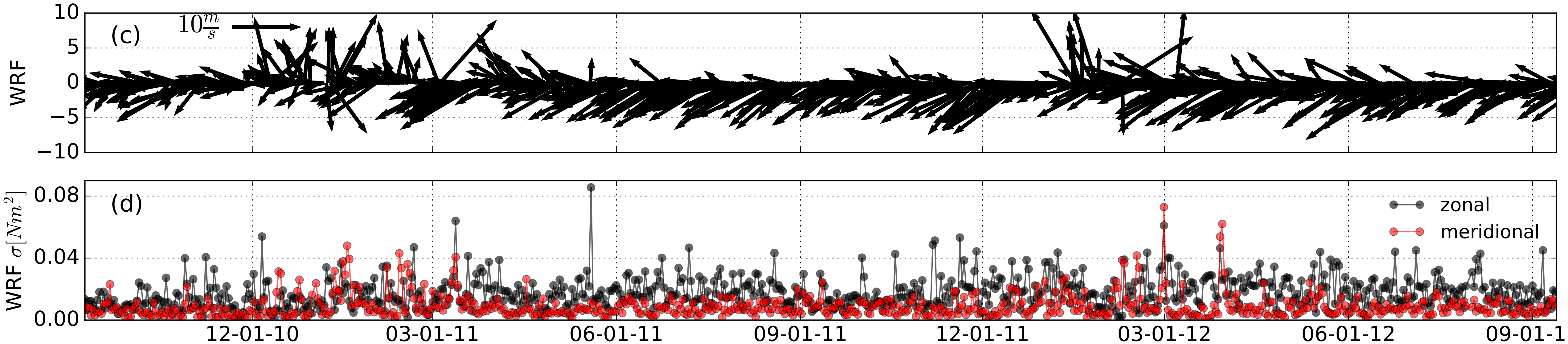
ROMS Mixed Layer Depth



2 years of **ROMS** model assimilating HFR radials (4D-VAR) and other available observations

- 32 vertical levels
- 4 km and 3 hour resolution
- forced by WRF wind model

Time series of WRF wind vectors and variability



Results

Near Inertial Oscillations

latitude

$$f = 2\Omega sin(\theta)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + f\mathbf{k} \times \mathbf{u} = \frac{1}{\rho} \nabla P + F$$

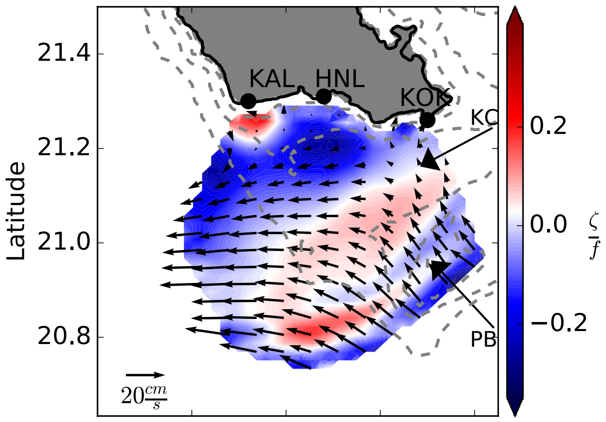
rate of change of motion

advection

earth rotation

pressure gradient

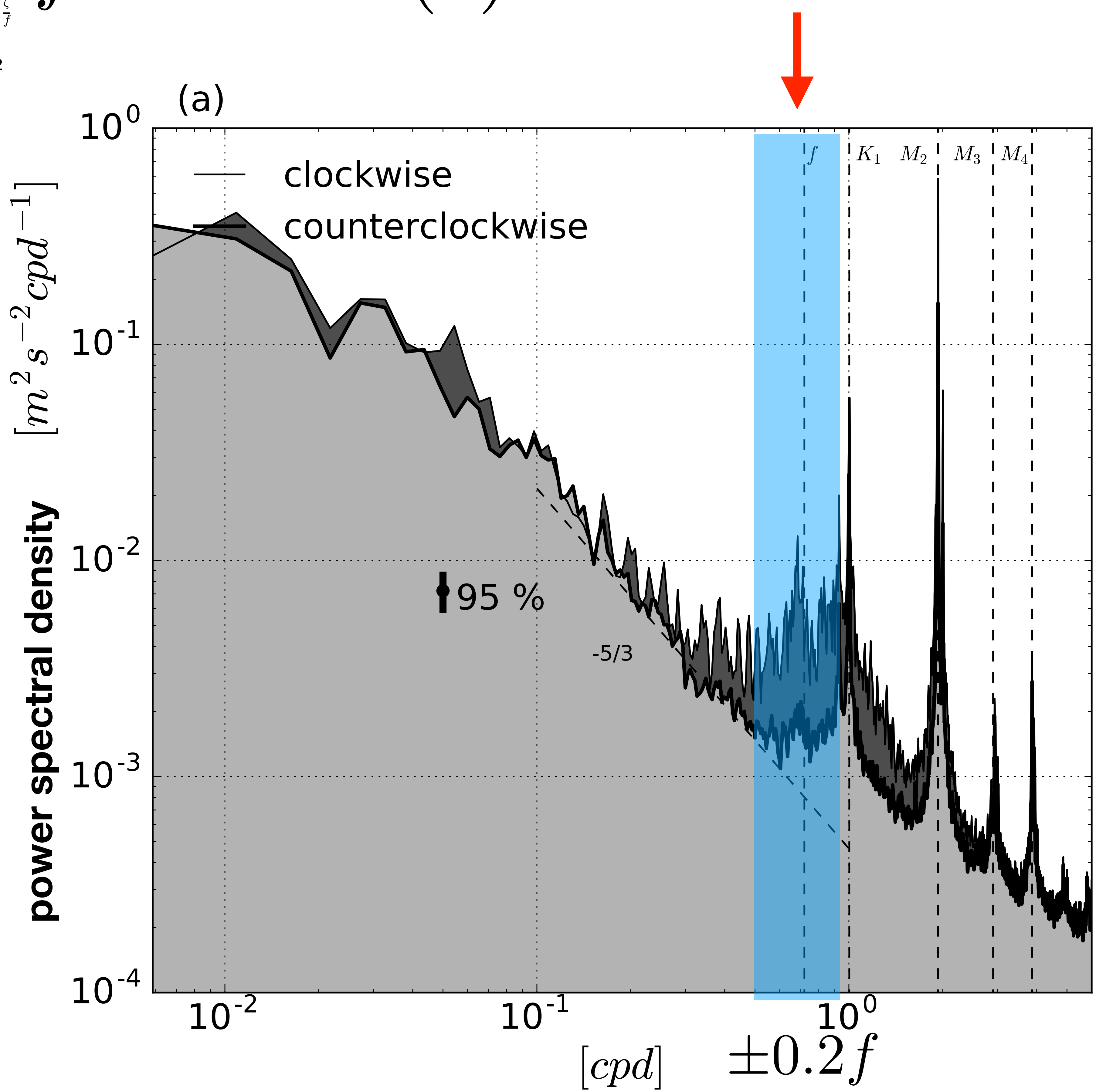
external forces



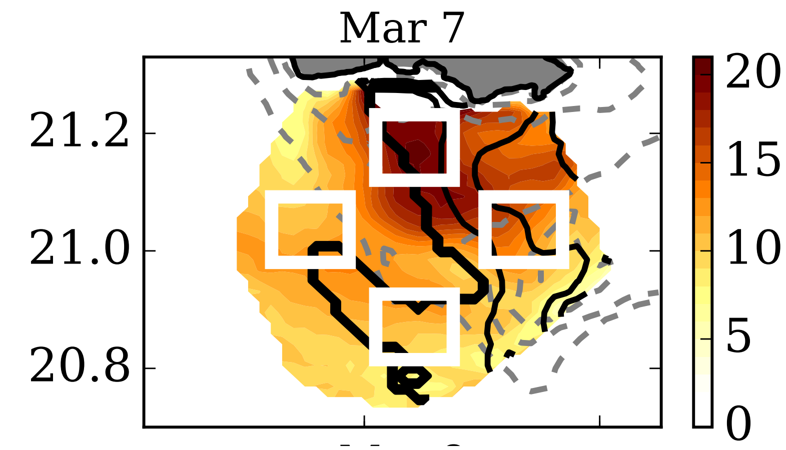
$$f = 2\Omega sin(\theta)$$

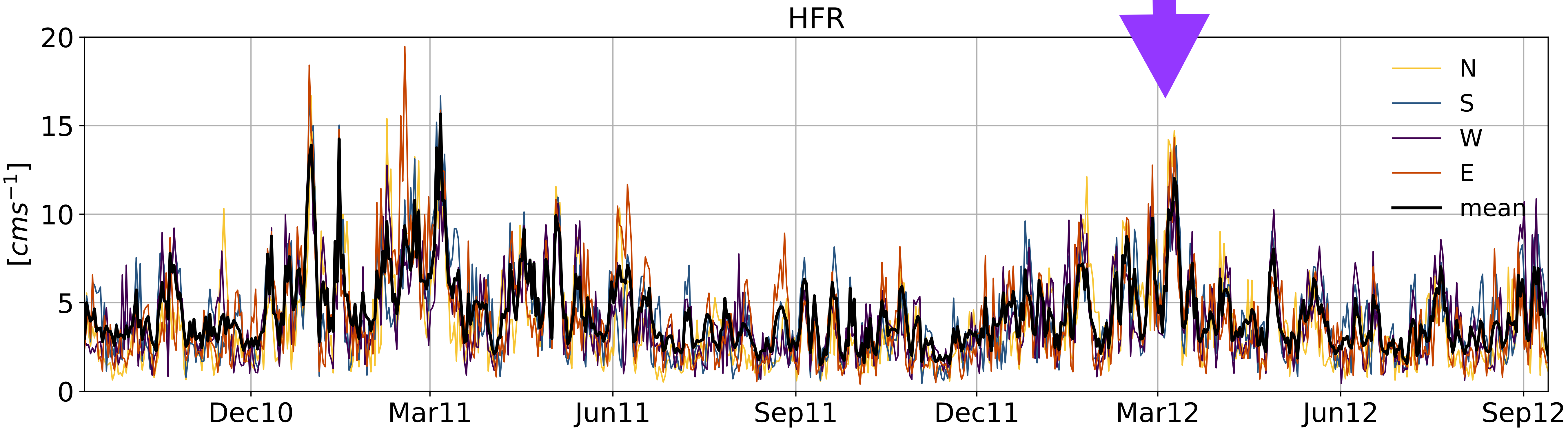
33.4 h

HFR surface current spectra averaged over spatial domain



Near Inertial Currents: Demodulated currents at 0.71 cpd (33.4 h)

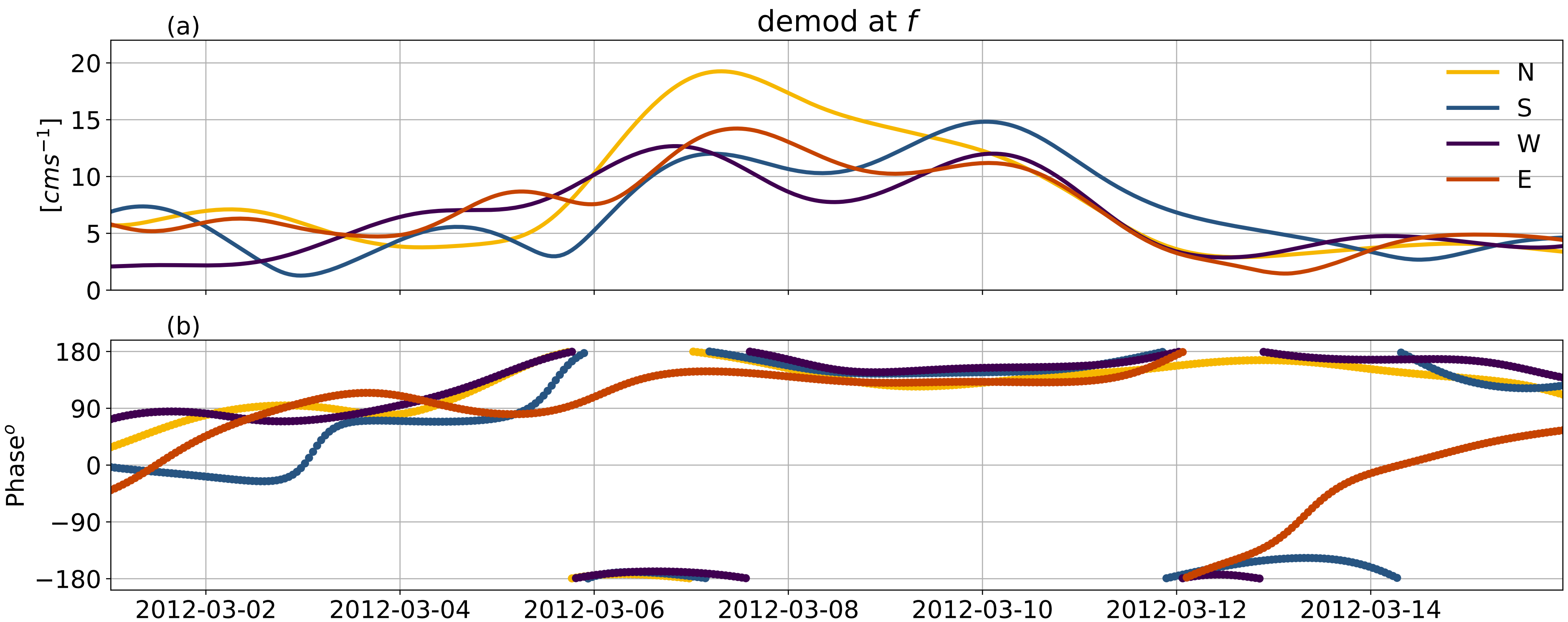




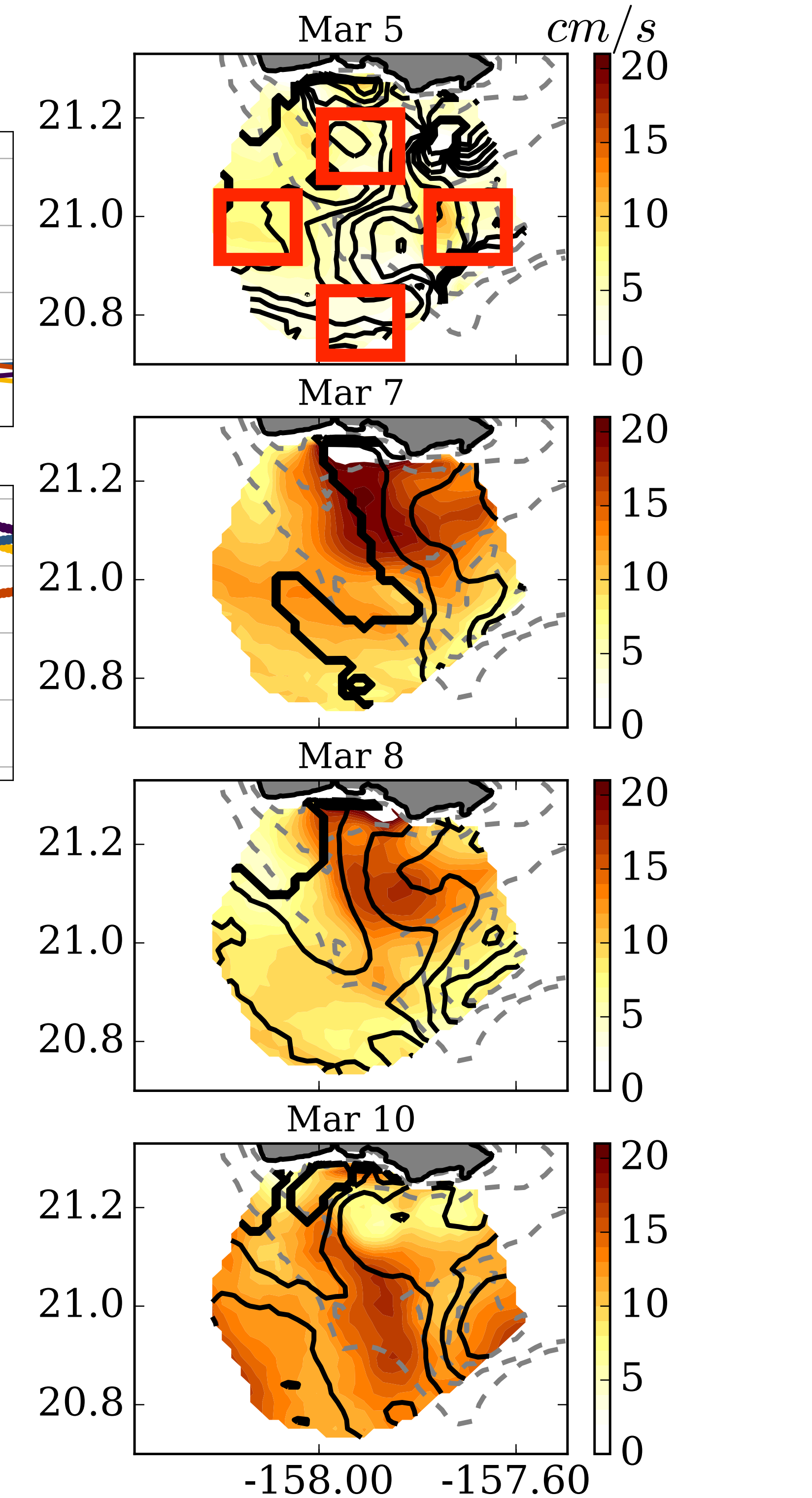
Seasonality with larger amplitudes in **winter and spring** months

One near-inertial event is analyzed in terms of the spatial and temporal variability.

Temporal and Spatial variability



Daily snapshots of near-inertial amplitude



Black lines indicate phase of NIO (estimated from complex demodulation)

- Amplitude and phase of near-inertial currents, spatial variability of ~25 km
- Maximum amplitudes at 20 cm/s
- NIO amplitude decays after 6 days
- Southward propagation of NI event

Slab Layer model

Pollard and Millard, 1970

If the NIO is generated purely by wind, then the demodulated currents should compare with slab-layer model currents

$$\frac{\partial u}{\partial t} - fv = \frac{\tau_x}{\rho H} - ru$$

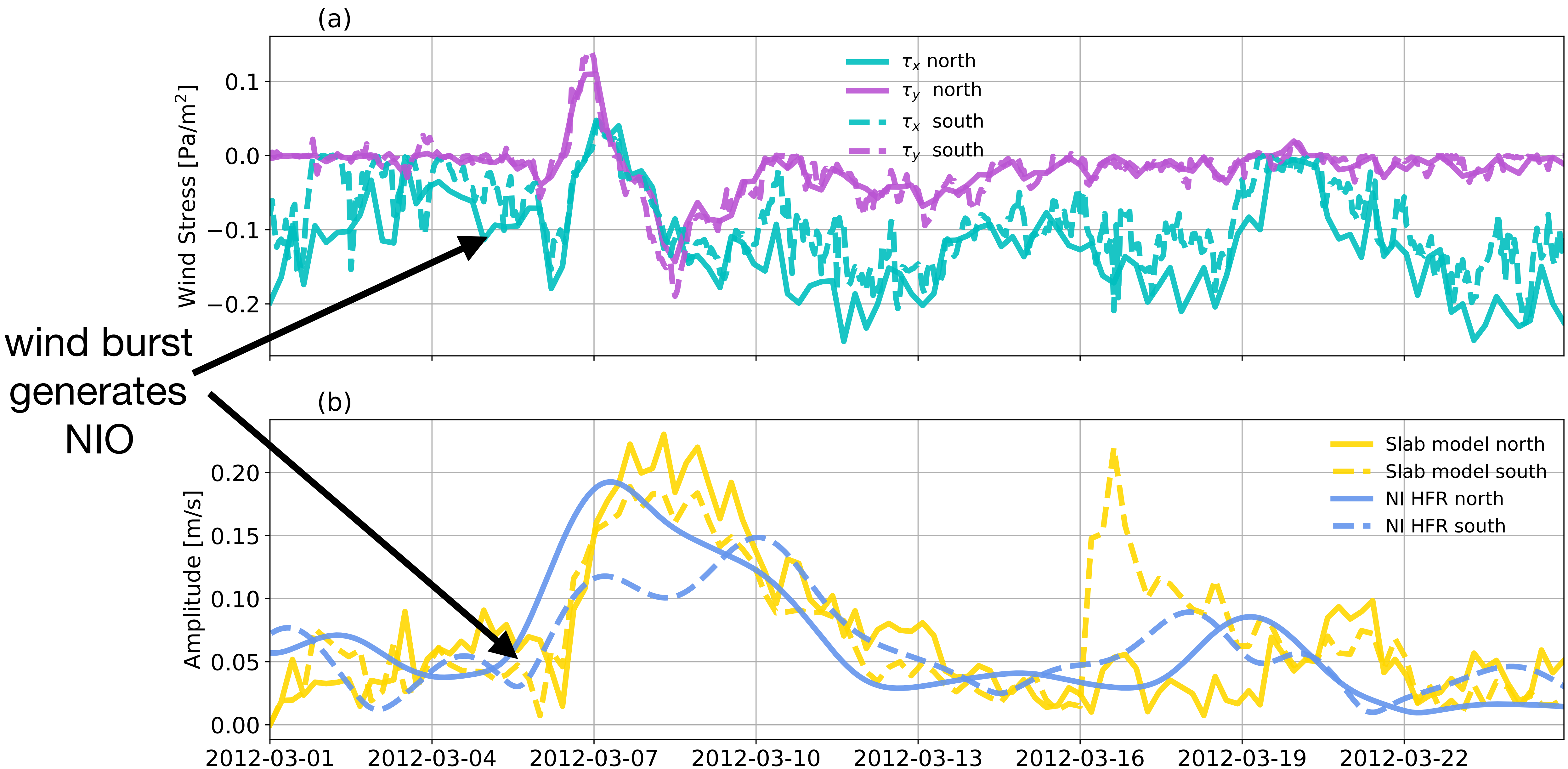
$$\frac{\partial v}{\partial t} + fu = \frac{\tau_y}{\rho H} - rv$$

near-inertial oscillation | **rotation** | **wind** | **damping**

The **slab layer model** equations are solved numerically (using WRF wind) and are compared to near-inertial currents from HFR.

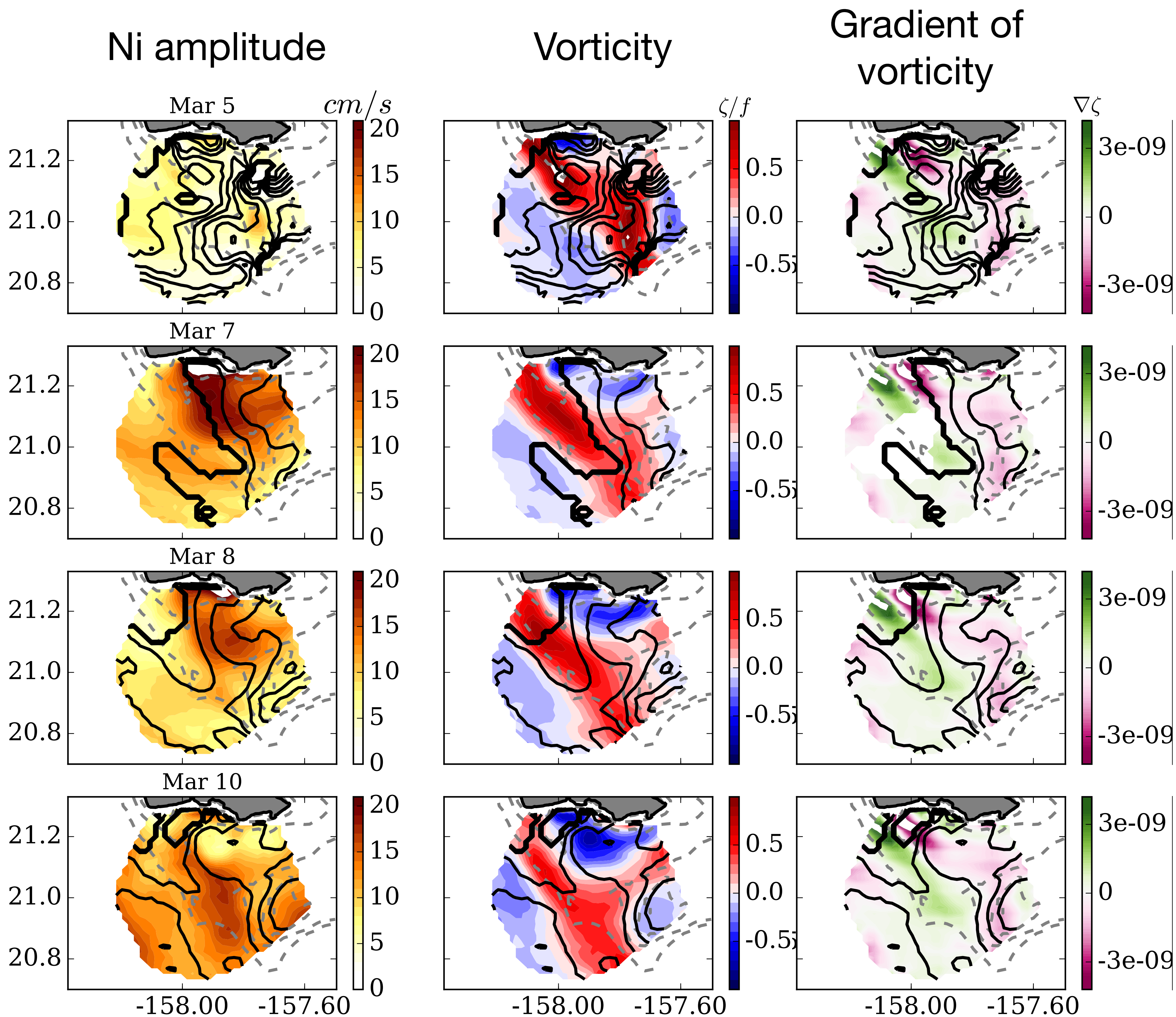
$$\frac{\partial u}{\partial t} - fv = \frac{\tau_x}{\rho H} - ru$$

$$\frac{\partial v}{\partial t} + fu = \frac{\tau_y}{\rho H} - rv$$



Interactions with the mean background flow

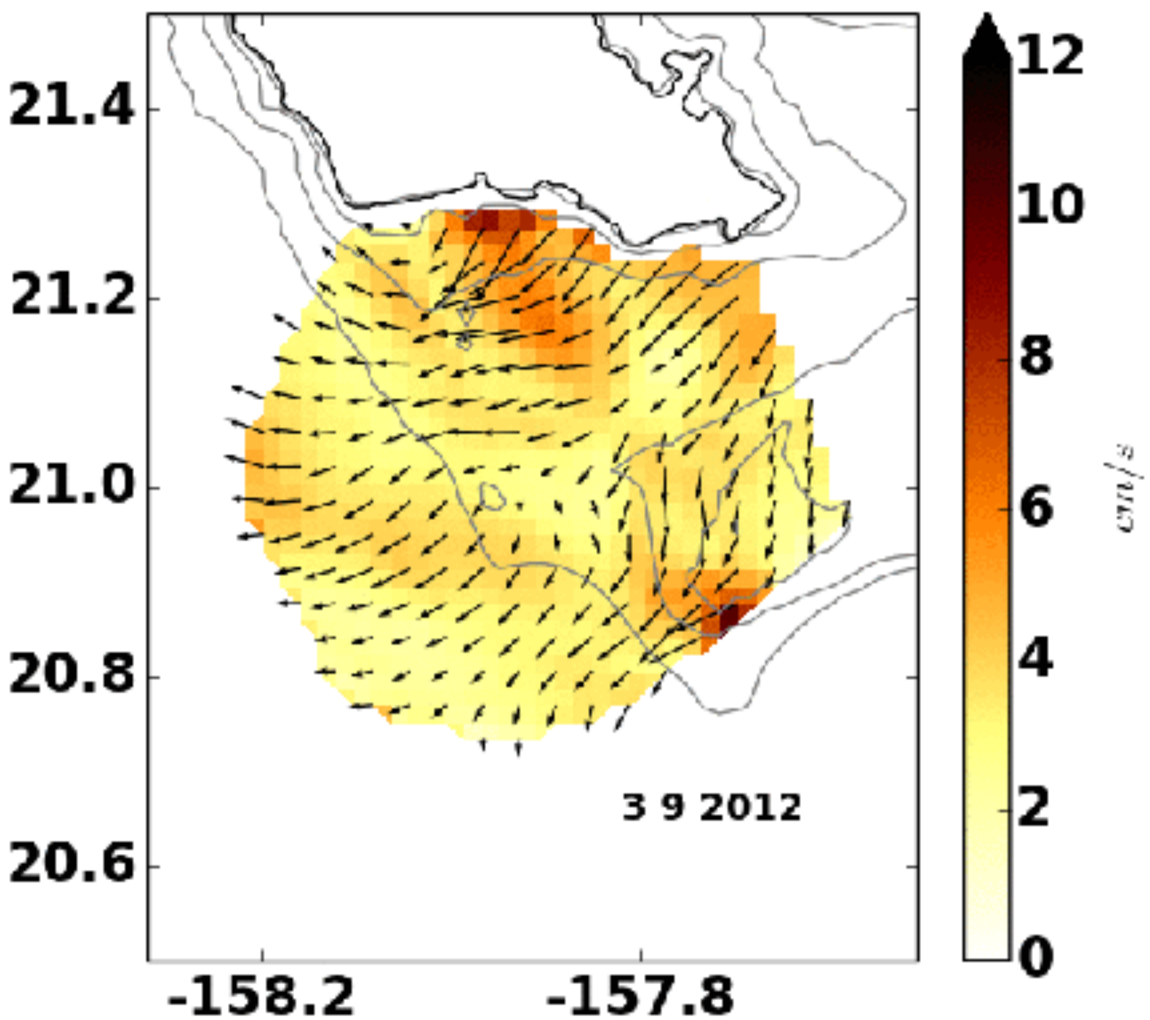
$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$



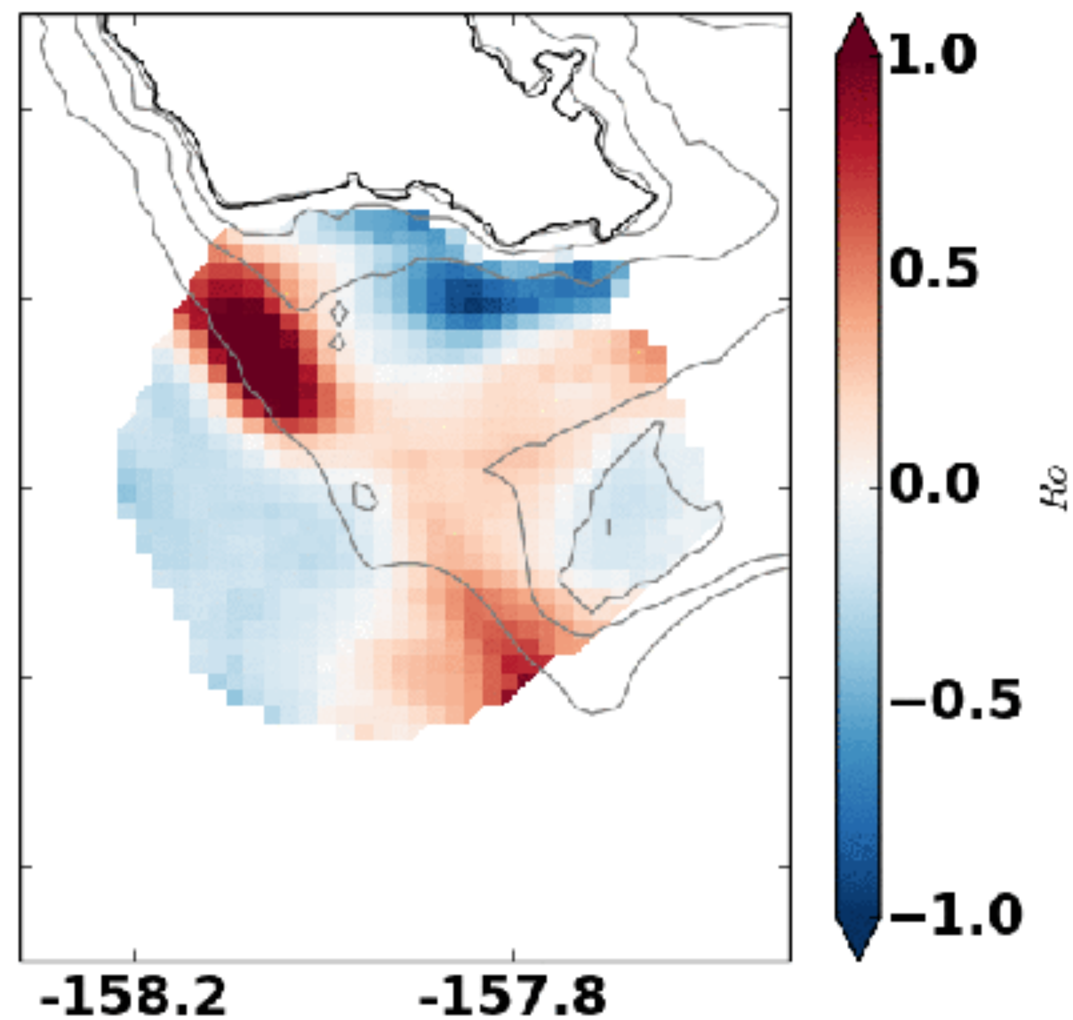
- **vorticity** calculated from **3-day low pass** surface currents has Rossby numbers O(1)
- **Phase** lines seem to **follow vorticity** and gradient of vorticity

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Near-inertial currents



Vorticity



Unforced NIO oscillation interacting with mean background flow

u = u + U

u = near-inertial oscillation
U = geostrophic flow

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{U} + f\mathbf{k} \times \mathbf{u} = 0$$

The dispersion-relation of an NIO in the presence of a two-dimensional geostrophic flow is dependent on divergence (growth or decay) and vorticity and strain (frequency of NIO) :

$$\omega = i\frac{\delta}{2} \pm \sqrt{(f + \frac{\zeta}{2})^2 - \frac{\sigma^2}{4}}$$

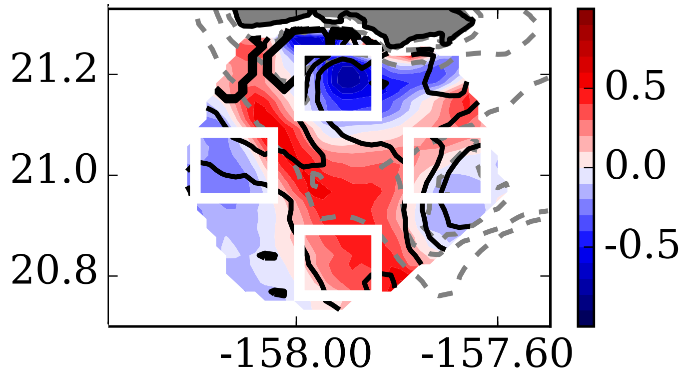
Chavanne et al., 2012

$$\omega \approx f_{eff}$$

The effective frequency **$\mathbf{f_{eff}}$** an NIO would have in the presence of a background flow

$$f_{eff} = \sqrt{f^2 + f(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}) - \frac{\partial V}{\partial x}\frac{\partial U}{\partial y} + \frac{\partial U}{\partial x}\frac{\partial V}{\partial y}}$$

(Chavanne et al., 2012, Kunze, 1984)

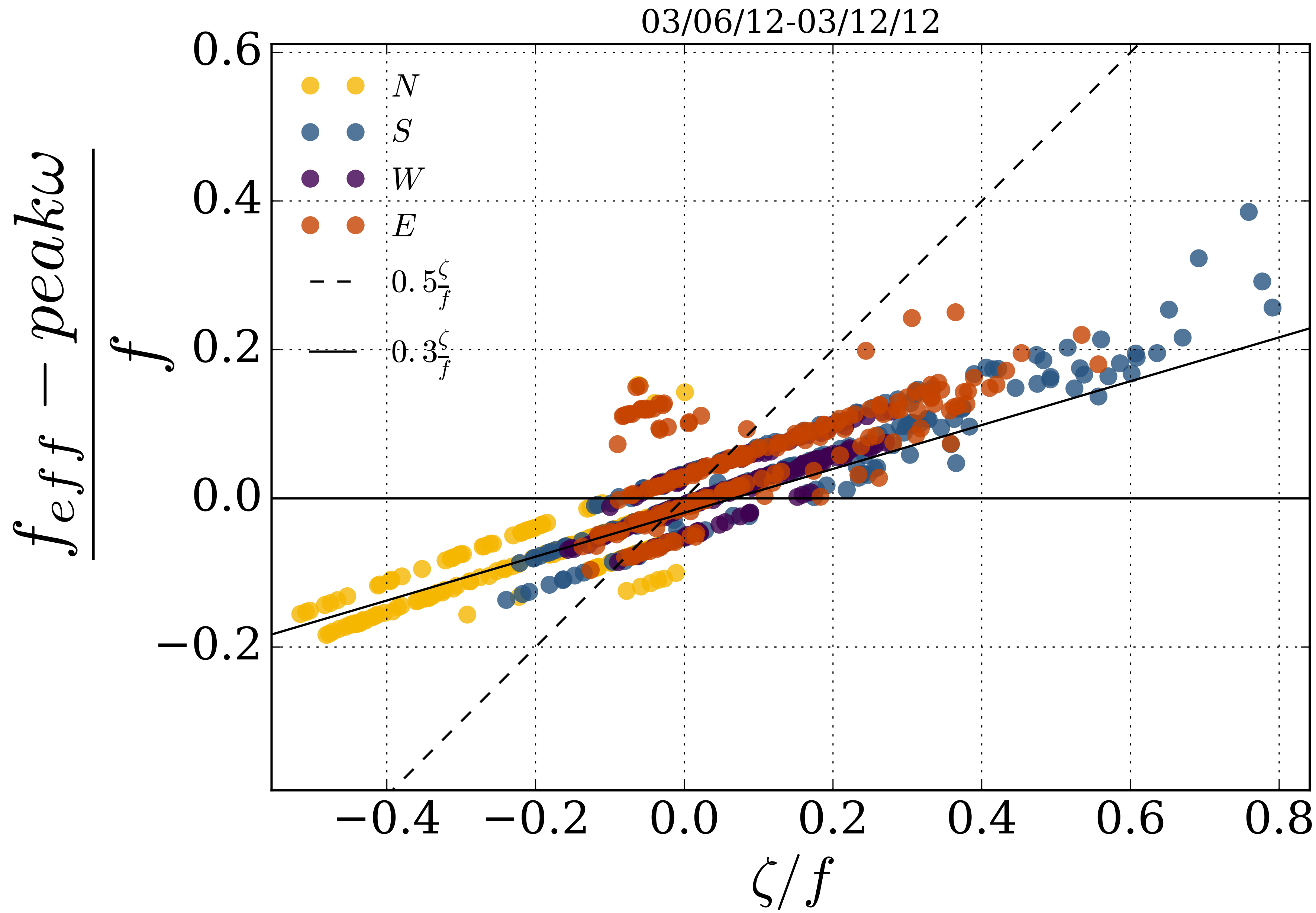


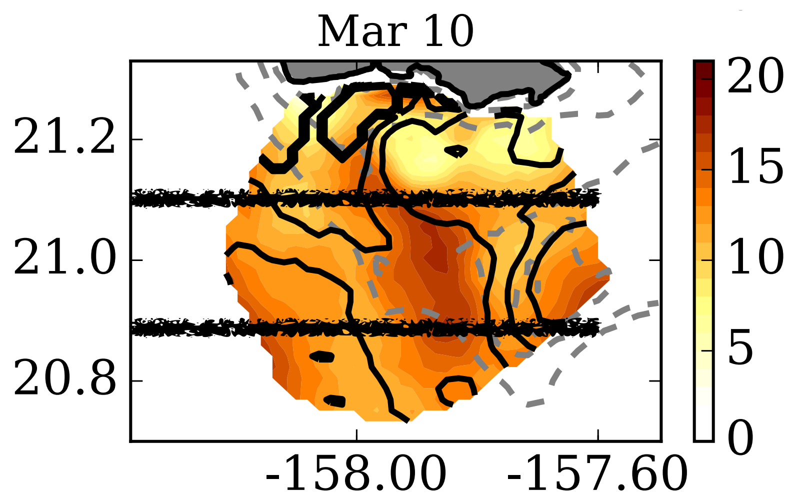
f_{eff} is estimated from the 3-day low pass surface currents (~geostrophic)

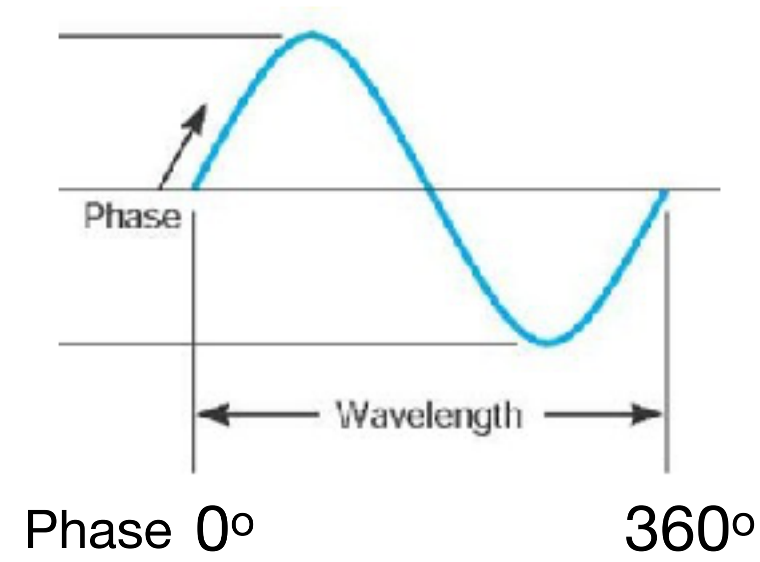
$$f_{eff} = \sqrt{f^2 + f\left(\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y}\right) - \frac{\partial V}{\partial x}\frac{\partial U}{\partial y} + \frac{\partial U}{\partial x}\frac{\partial V}{\partial y}}$$

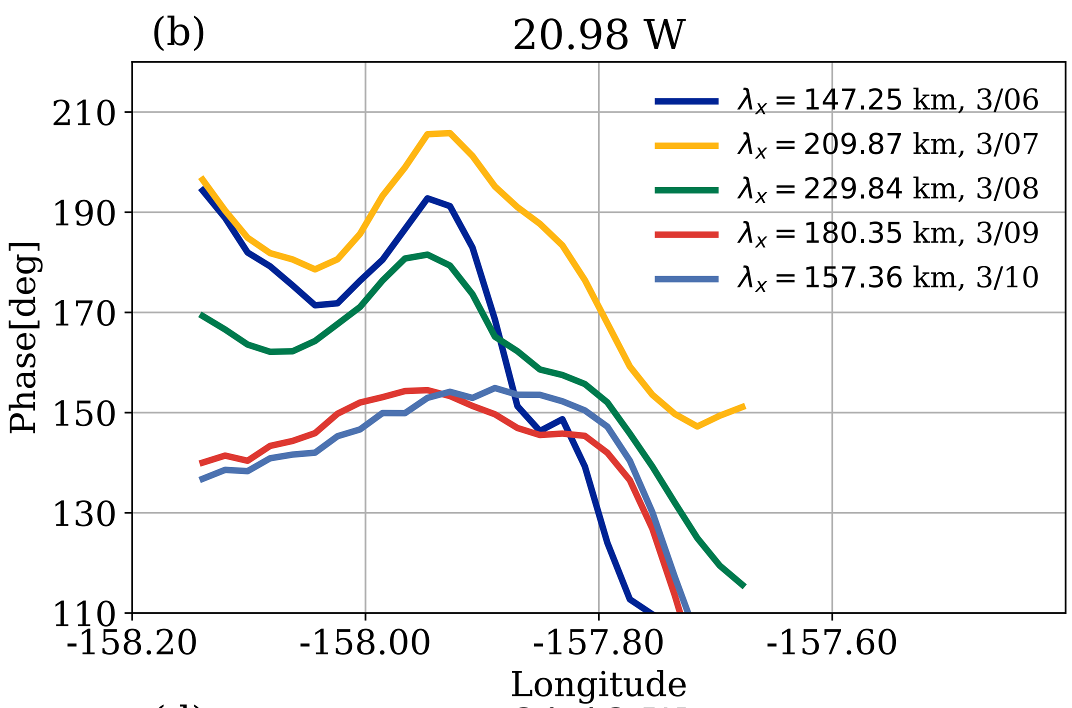
peak w (the “real" frequency of the NIO) is estimated from the near-inertial currents

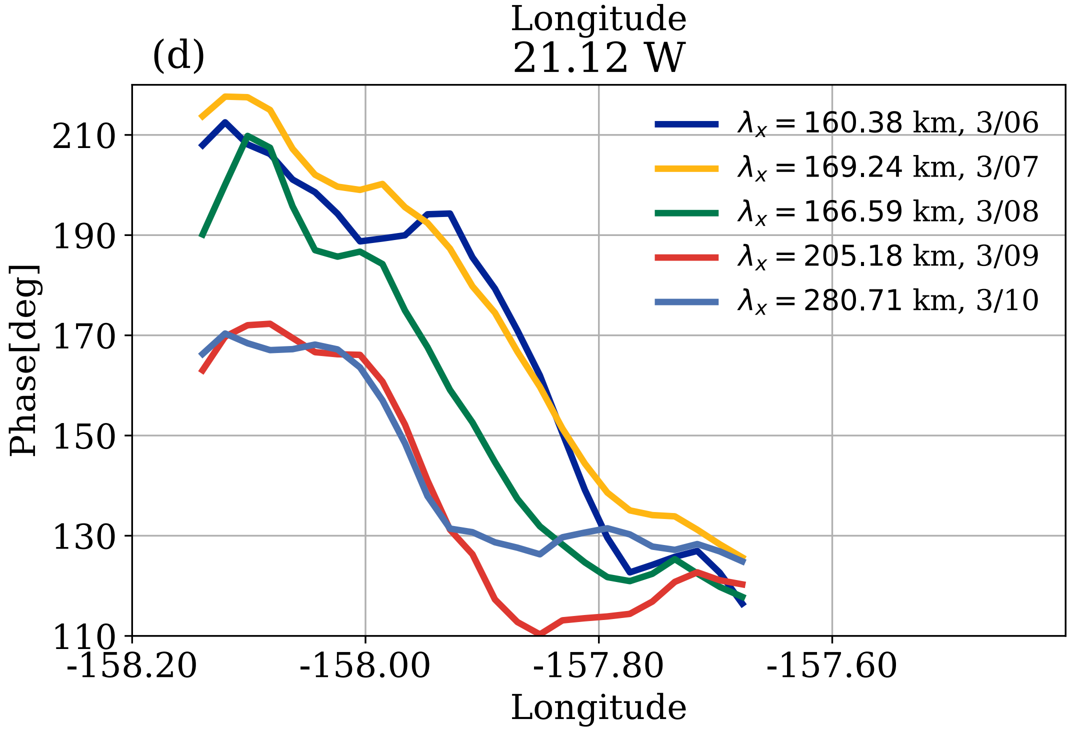
The difference between **f_{eff}** and **peak w** increases with Rossby number











Zonal wavelengths estimated from the least-square-fit of **longitude** vs **phase** of demodulated currents over NI event and selected zonal transects.

- Zonal **wavelengths** in the *O*(100 km)
- **Coast** and **background flow** could modify wavelength.

Energy Budget

$$E(t) - E(0) = -\int_0^t (2u^2U_x + 2v^2V_y + uvU_y + uvV_x + u^2V_y + v^2U_x)ds$$

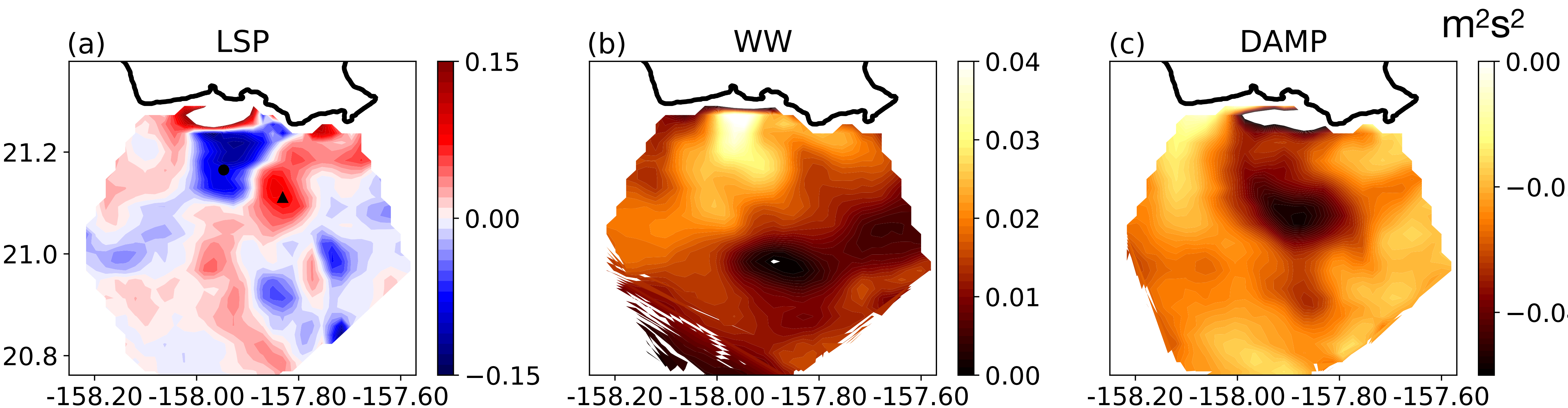
$$+ \int_0^t \frac{\tau_x u + \tau_y v}{\rho_o H} ds - \int_0^t r(u^2 + v^2)ds,$$

Rate of change of energy over (mixed layer)

Energy loss/gain to background flow (LSP)

Energy input from wind (WW)

Energy loss (DAMP)



- **NIOs "looses" and "gains" energy** to/from mean background flow
- Larger NIO amplitude where **WW** is **larger**

Conclusions

- The **frequency** is **modified** by the vorticity of the **background flow.** Previous theoretical framework not very accurate.

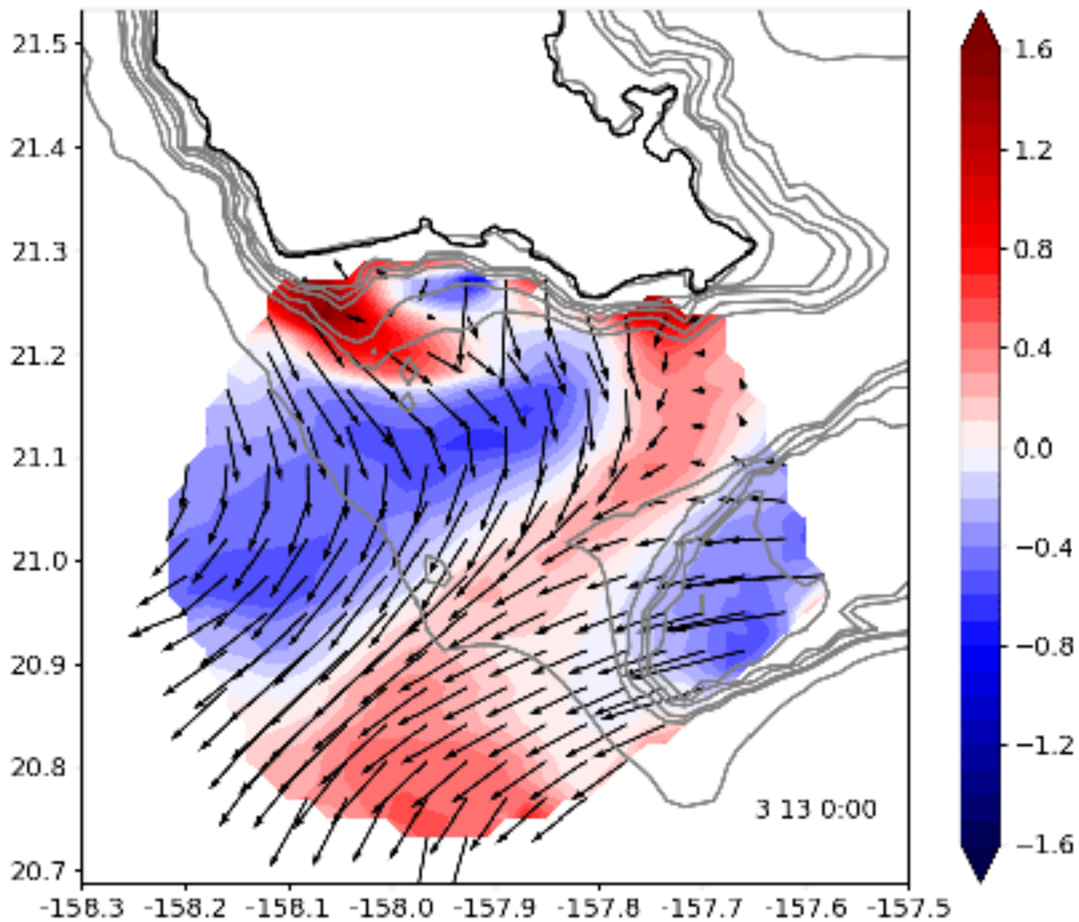
- **Amplitude** of NIO modified by the wind.

- The NIO **zonal wavelength** is in the ***O*(100 km)** Important for NIW propagation.

- The **NIO looses and gains energy** to the mean background flow.

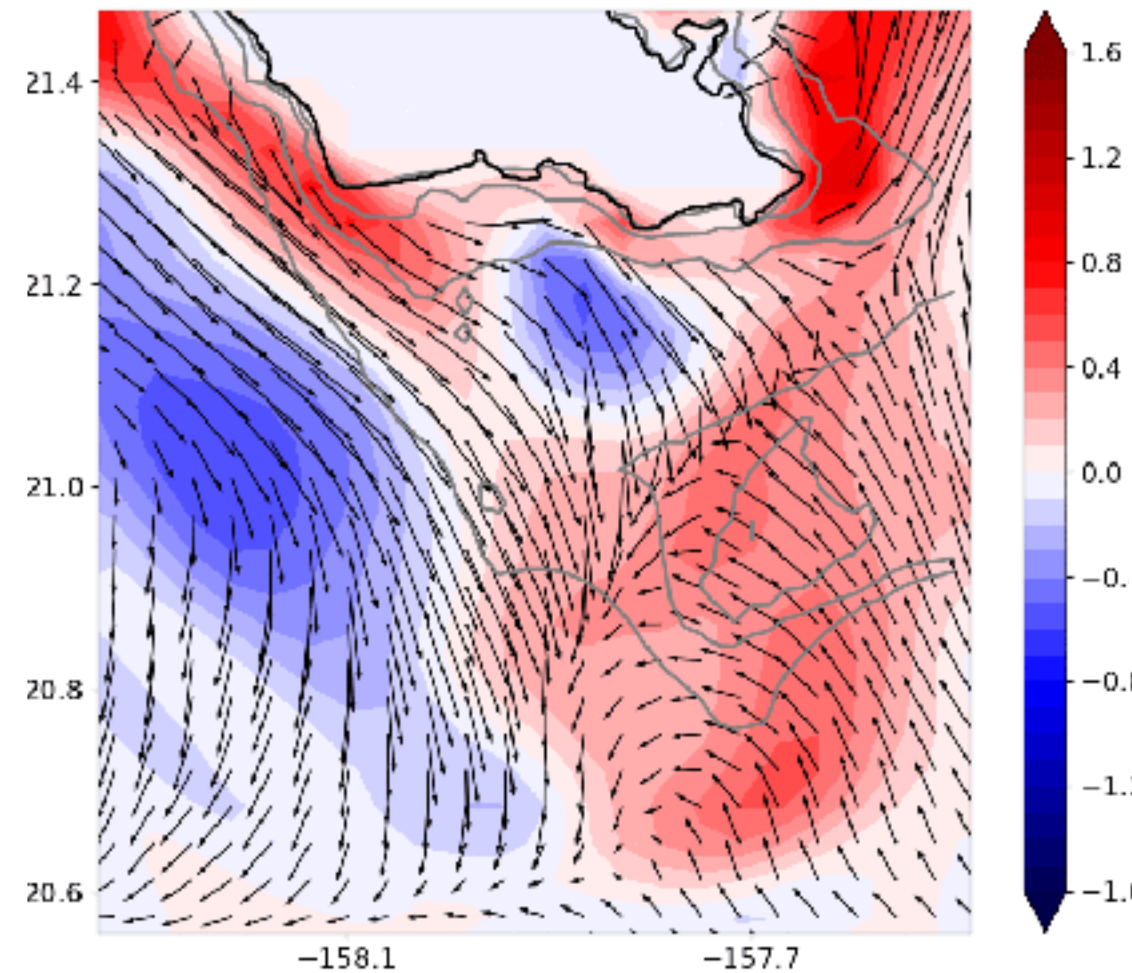
Results Submesoscale variability (~10 km)

observations (HFR)



$\frac{\zeta}{f}$

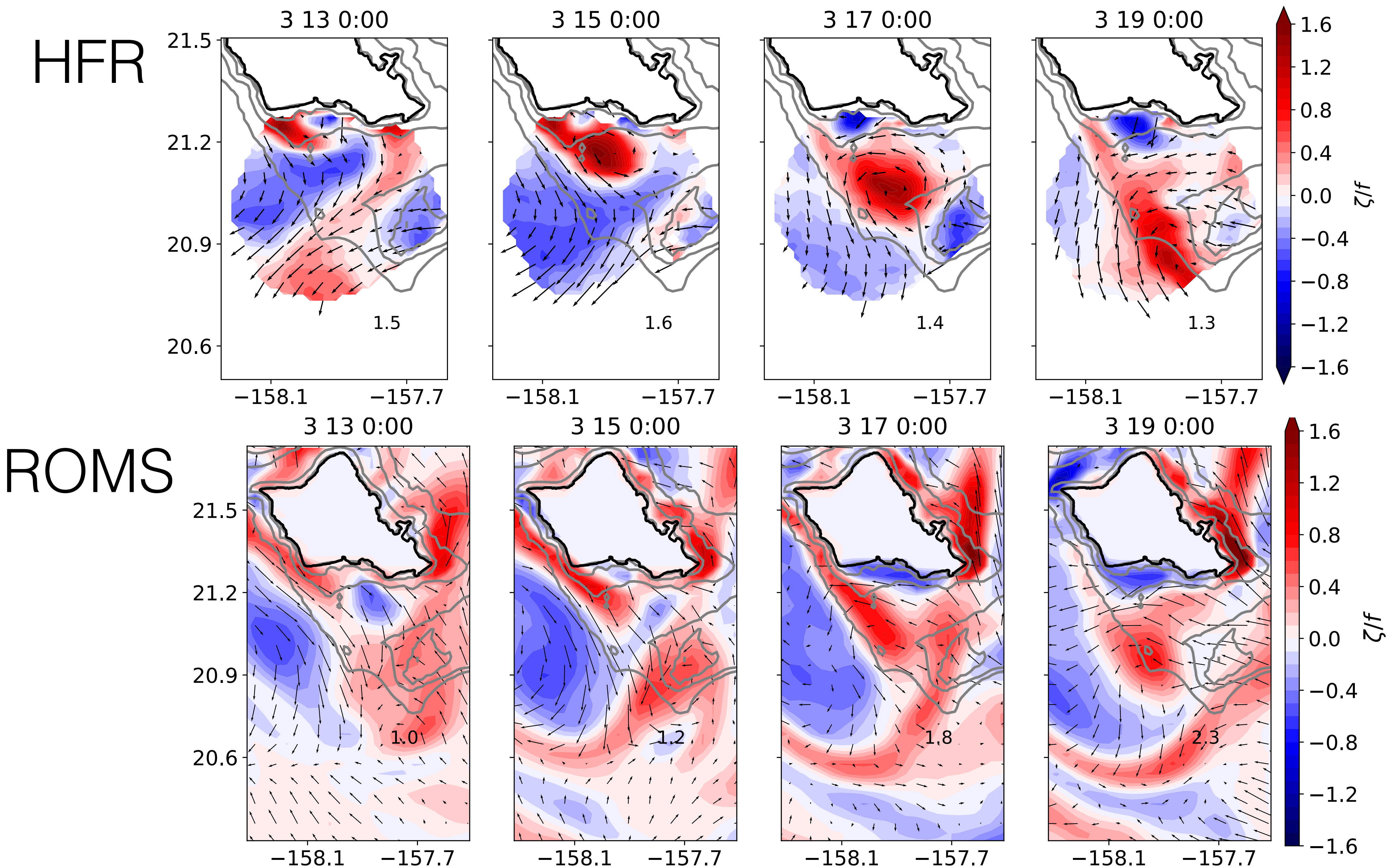
model (ROMS)



- Is it observed in ROMS?
- What are the **growth** and a**mplification** mechanisms?
- Is there a **seasonality** associated with it?

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

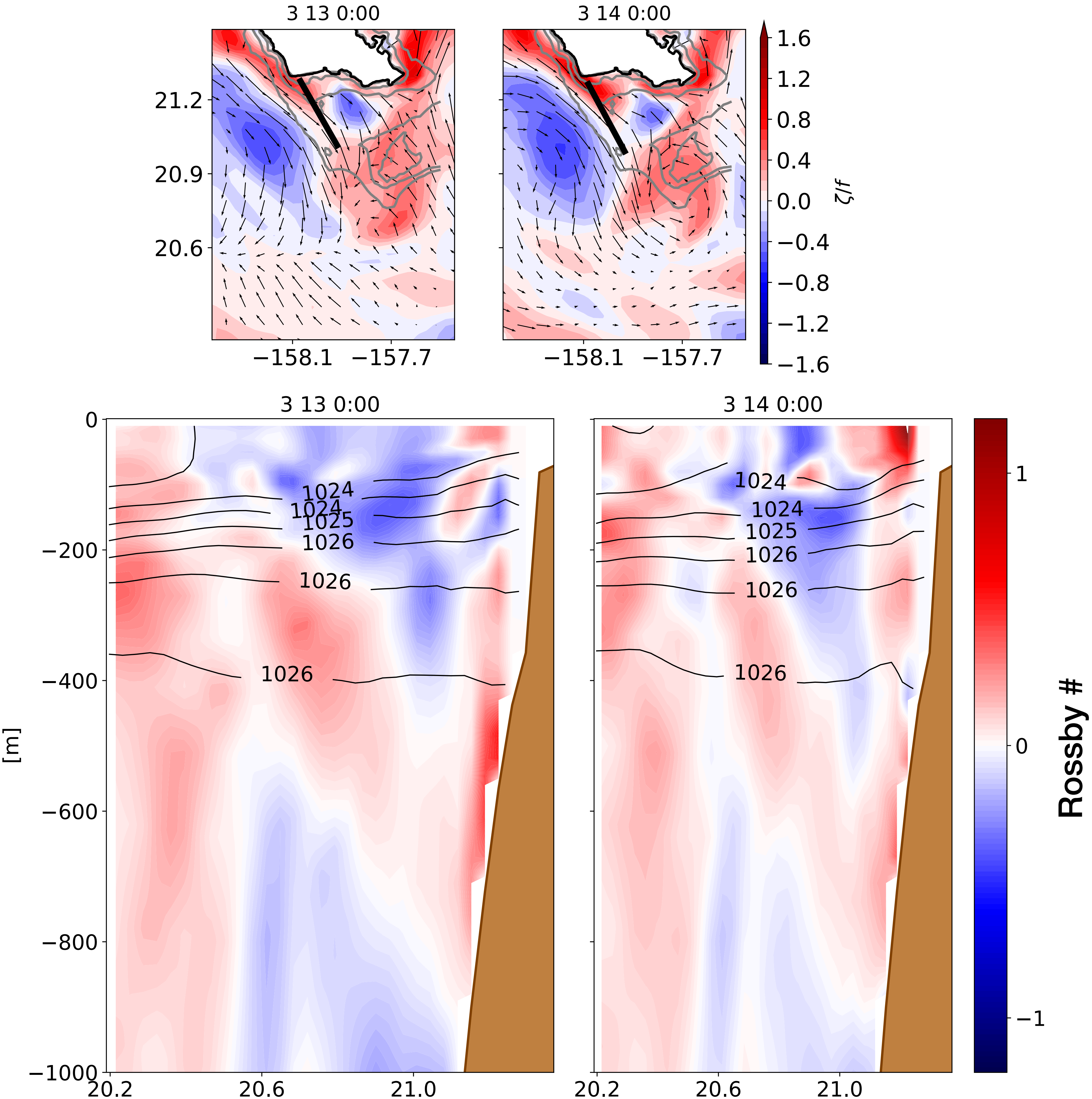
Eddy growth and propagation



The **filament** evolves into a **vortex** (30 km diameter)

The vortex **propagates towards Penguin Bank** and its squeezed by topography (5 km/day)

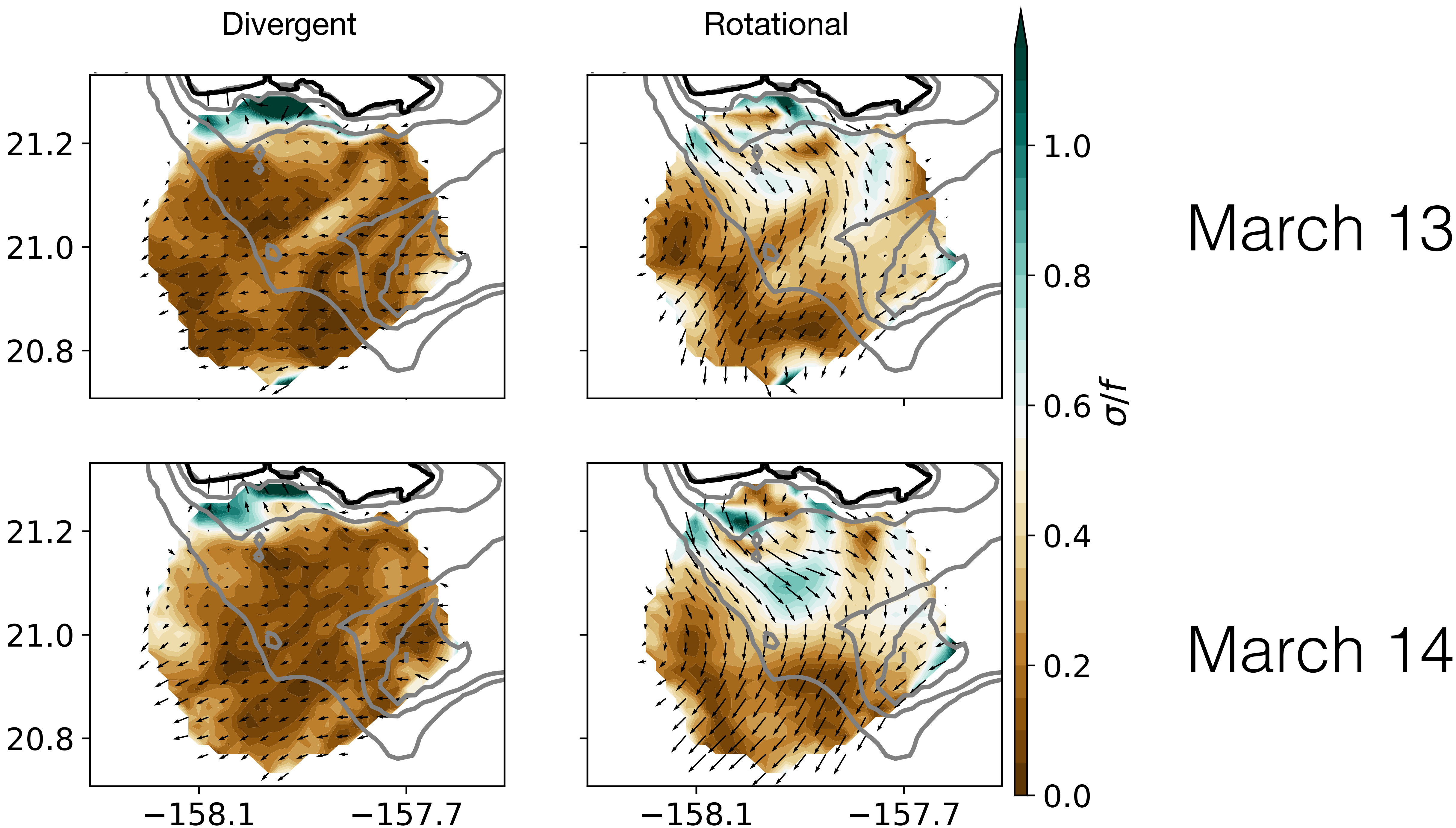
The vortex is weakly observed in model (ROMS)



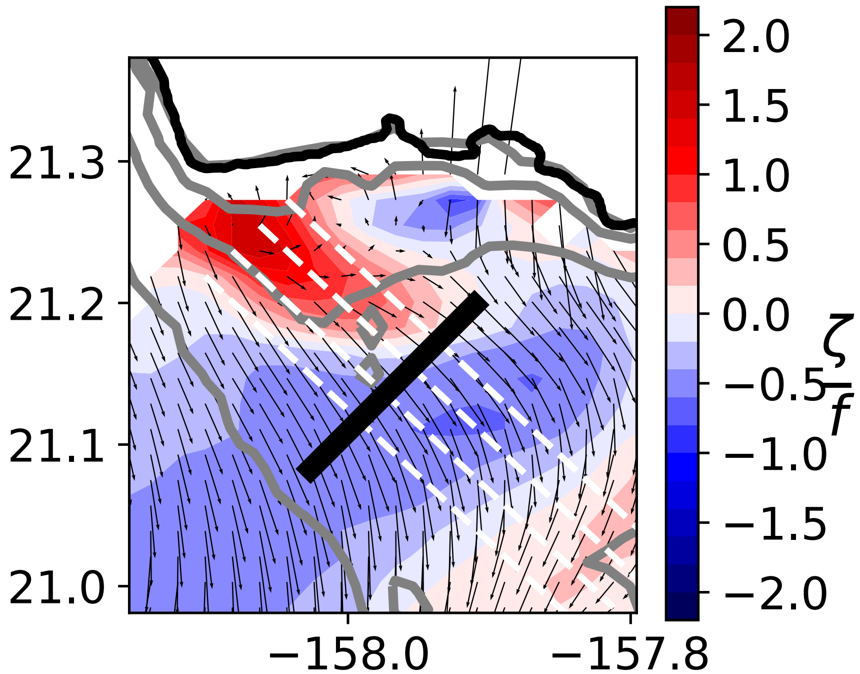
The filament is surface intensified

The filament could be generated by interaction with the coast and topography

Snapshots of decomposed HFR surface currents



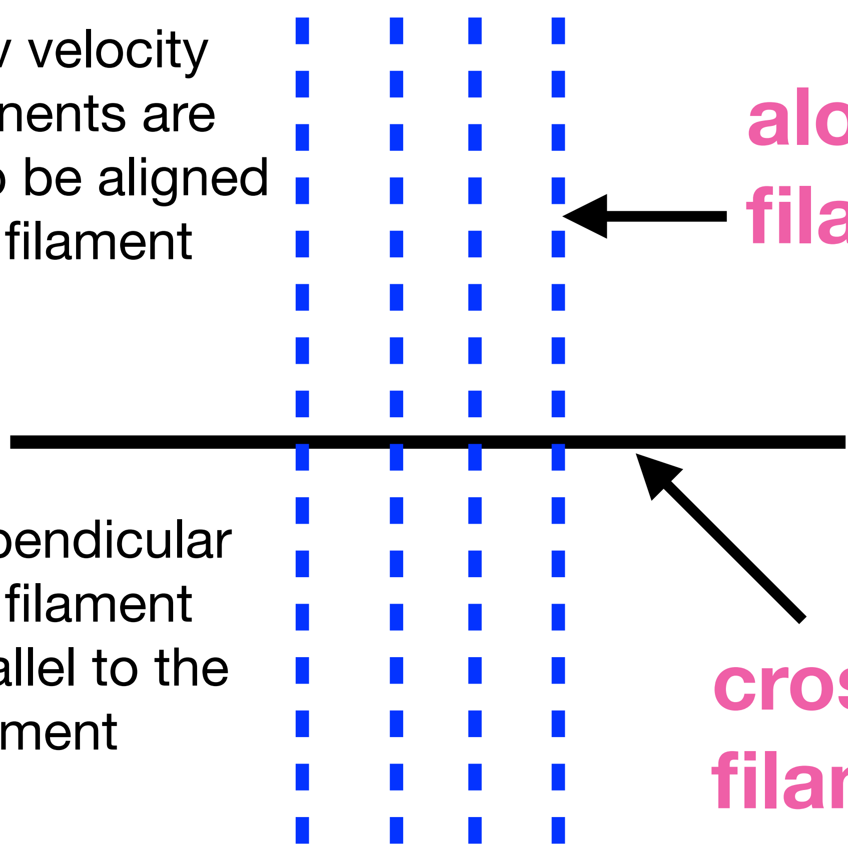
- Helmholtz decomposition following Smith, 2008.
- The filament is rotational. What generates this rotation?



Eddy Kinetic Energy of the filament/vortex

u = **U** + **u’**
U = along filament average
u’ = fluctuations relative to that mean

u and v velocity components are rotated to be aligned to the filament

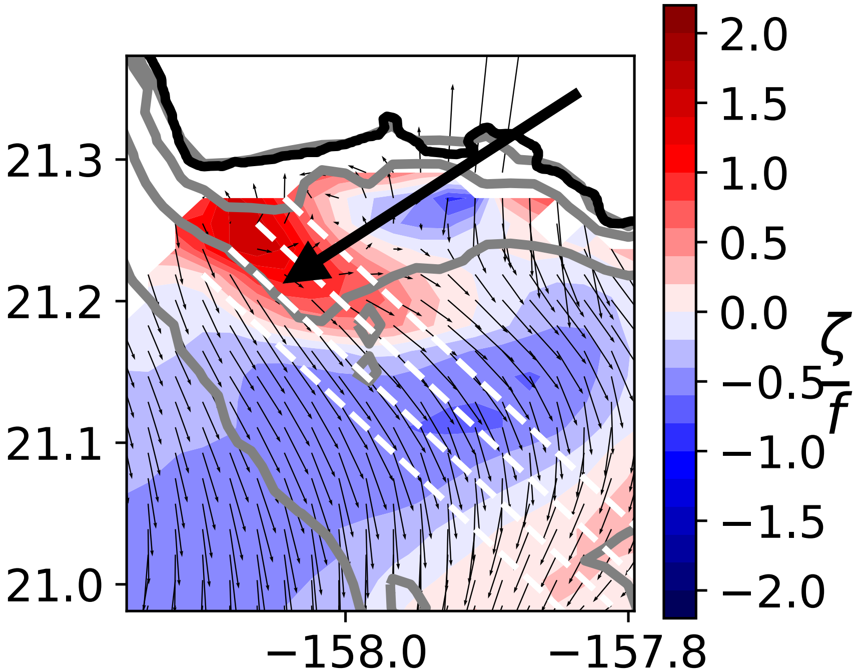


along filament

cross filament

u = perpendicular to the filament
v = parallel to the filament

$$EKE = \frac{1}{2}(\overline{u'}^2 + \overline{v'}^2)$$



Conversion terms from mean energy to EKE

$$\frac{\partial EKE}{\partial t} = HRS + VRS + VBF$$

horizontal shear stress

$$HRS = -\overline{u'^2}\frac{\partial \overline{U}}{\partial x} - \overline{u'v'}\frac{\partial \overline{U}}{\partial y} - \overline{v'^2}\frac{\partial \overline{V}}{\partial y} - \overline{u'v'}\frac{\partial \overline{V}}{\partial x}$$

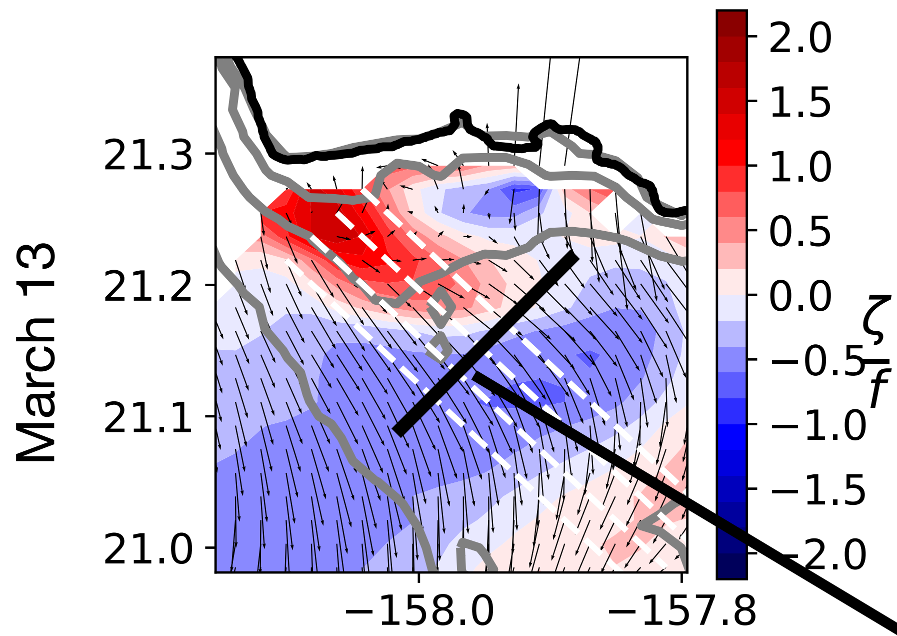
vertical shear stress

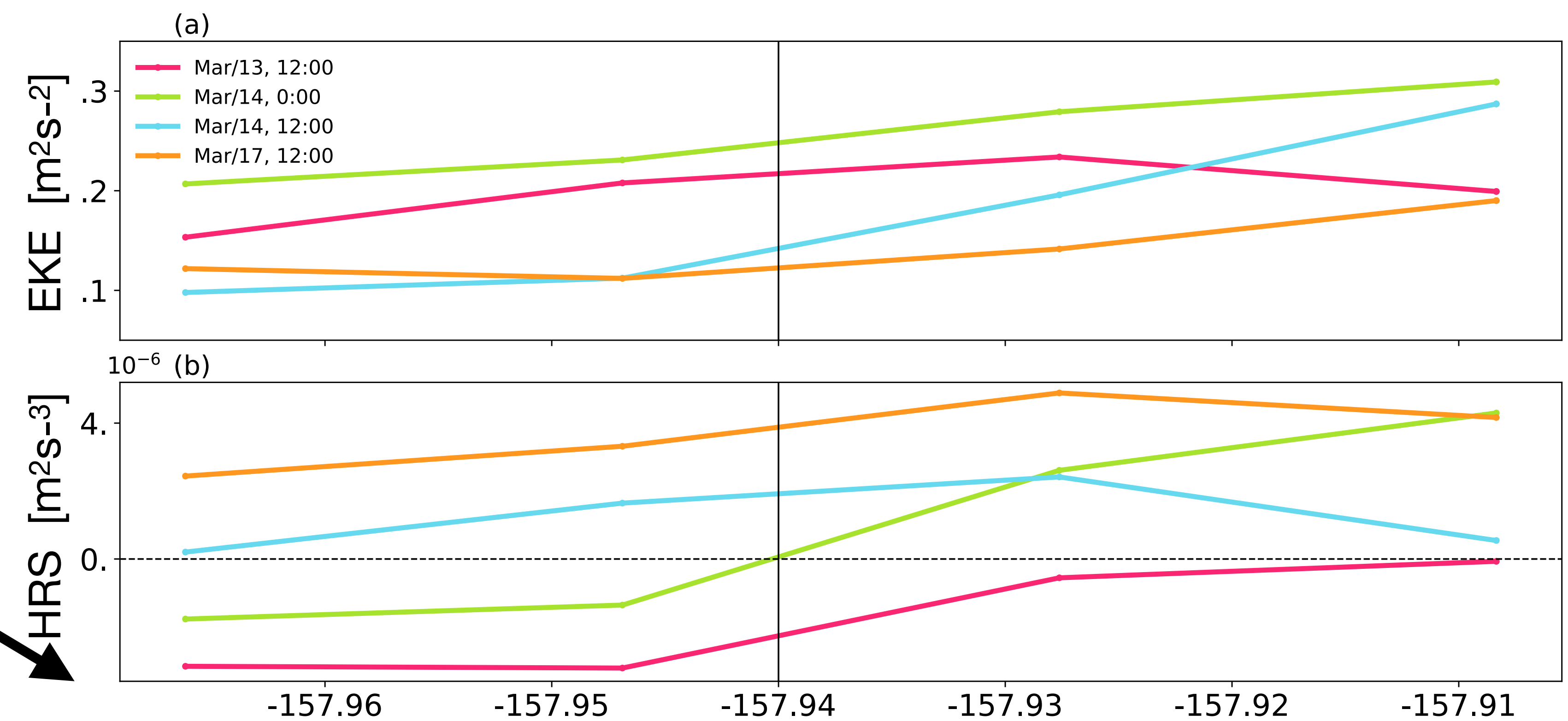
$$VRS = -\overline{u'w'}\frac{\partial \overline{U}}{\partial z} - \overline{u'w'}\frac{\partial \overline{V}}{\partial z}$$

eddy buoyancy flux, potential to eddy kinetic energy

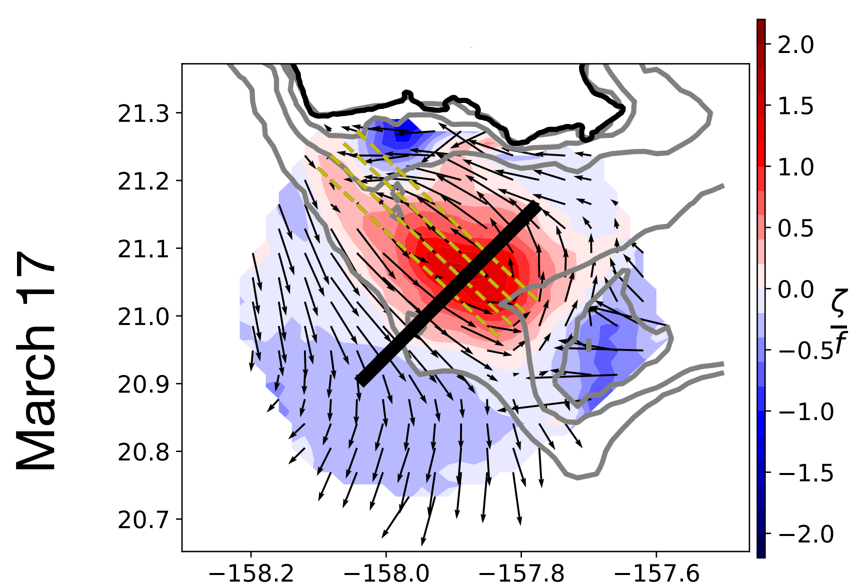
$$VBF = \overline{w'b'}$$

Along-filament surface Eddy Kinetic Energy budget (HFR)



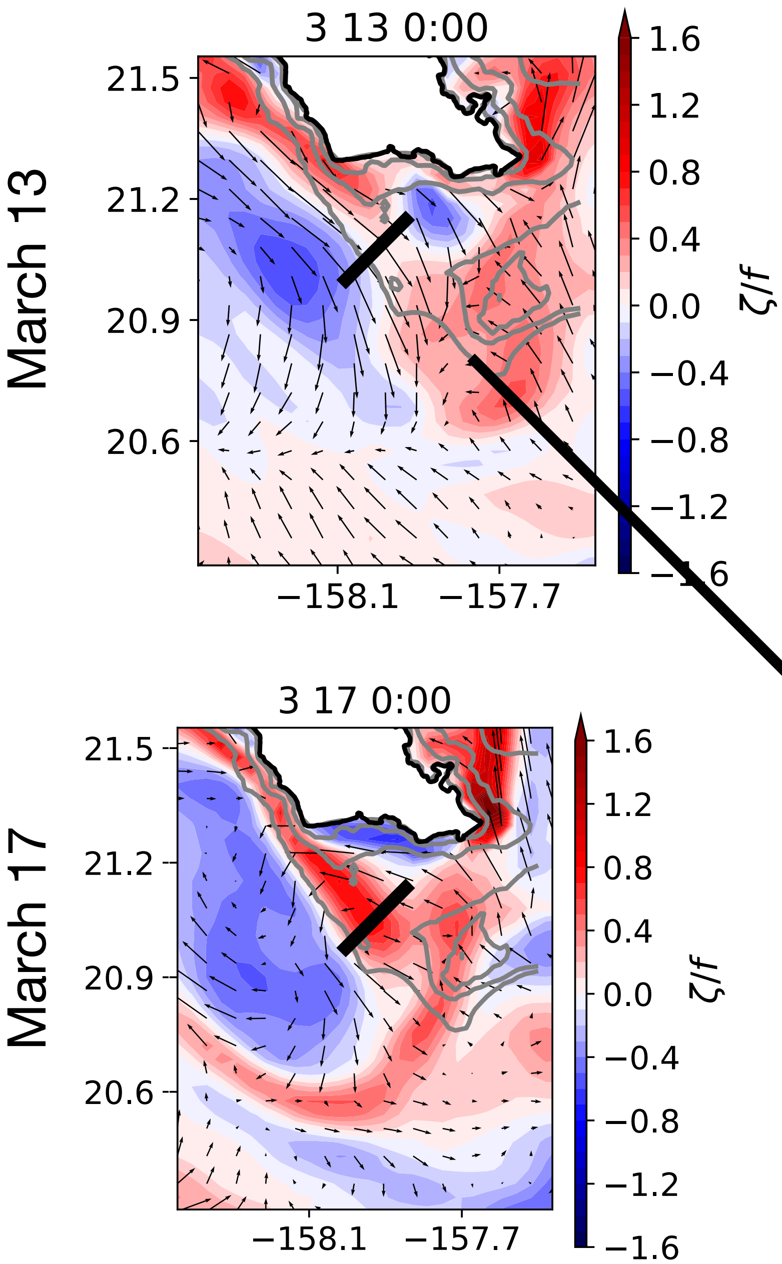


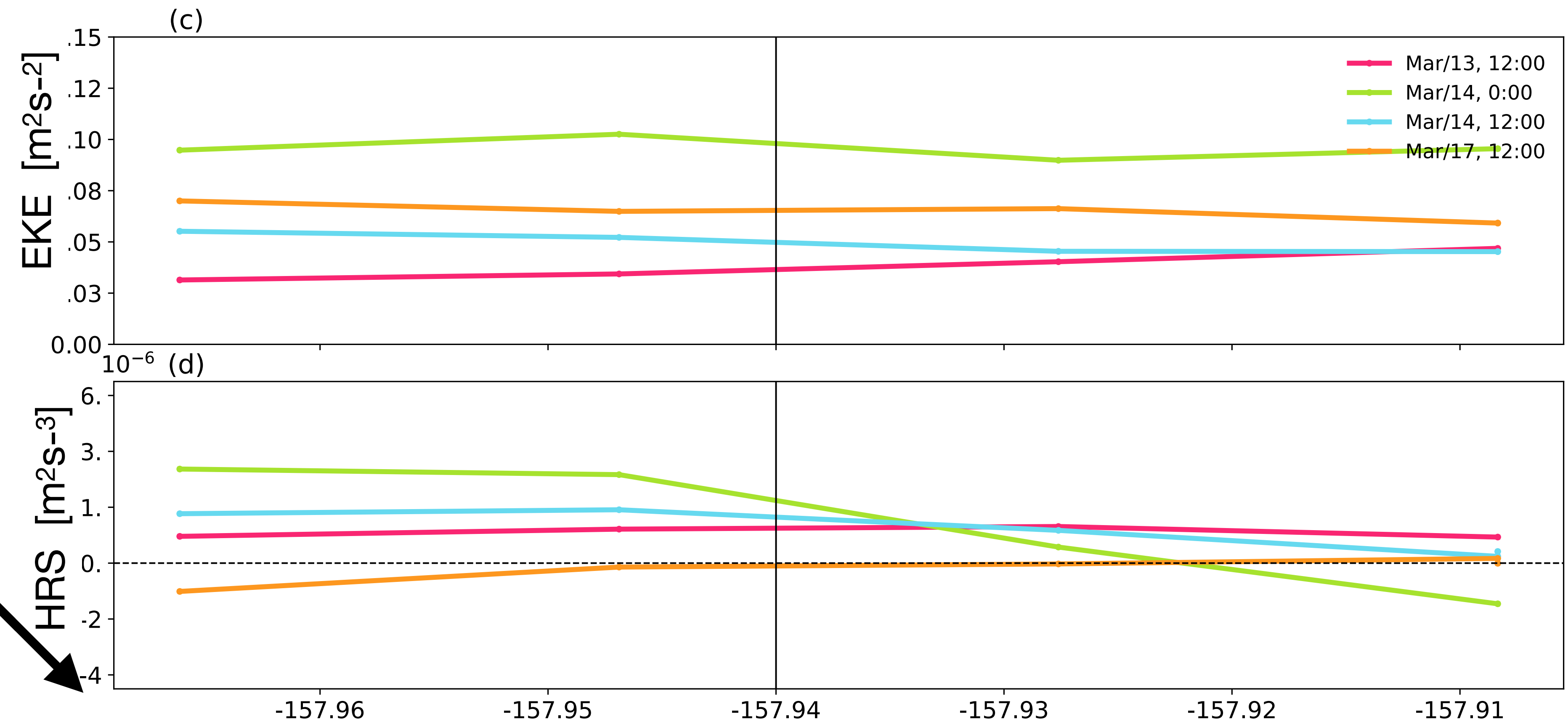
Cross filament direction



- After March 13 EKE increases and HRS>0. Indication of barotropic instability.
- HRS amplifies the vortex after March 14.

Along-filament integrated surface Eddy Kinetic Energy budget (ROMS)

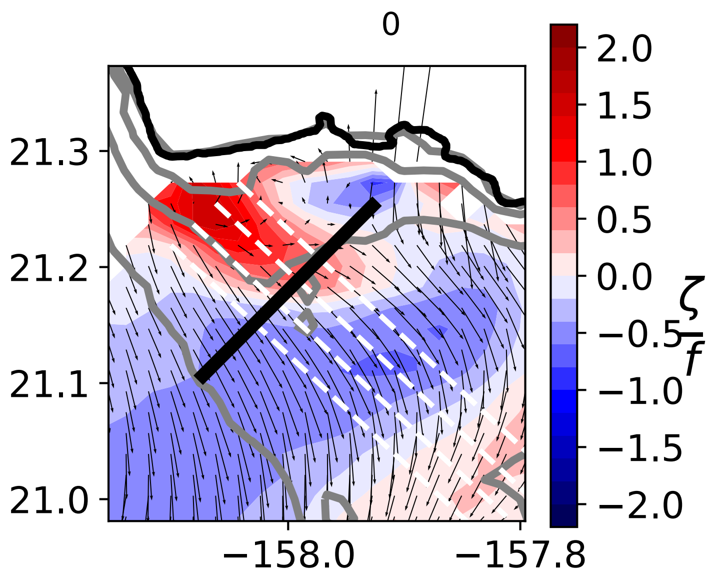


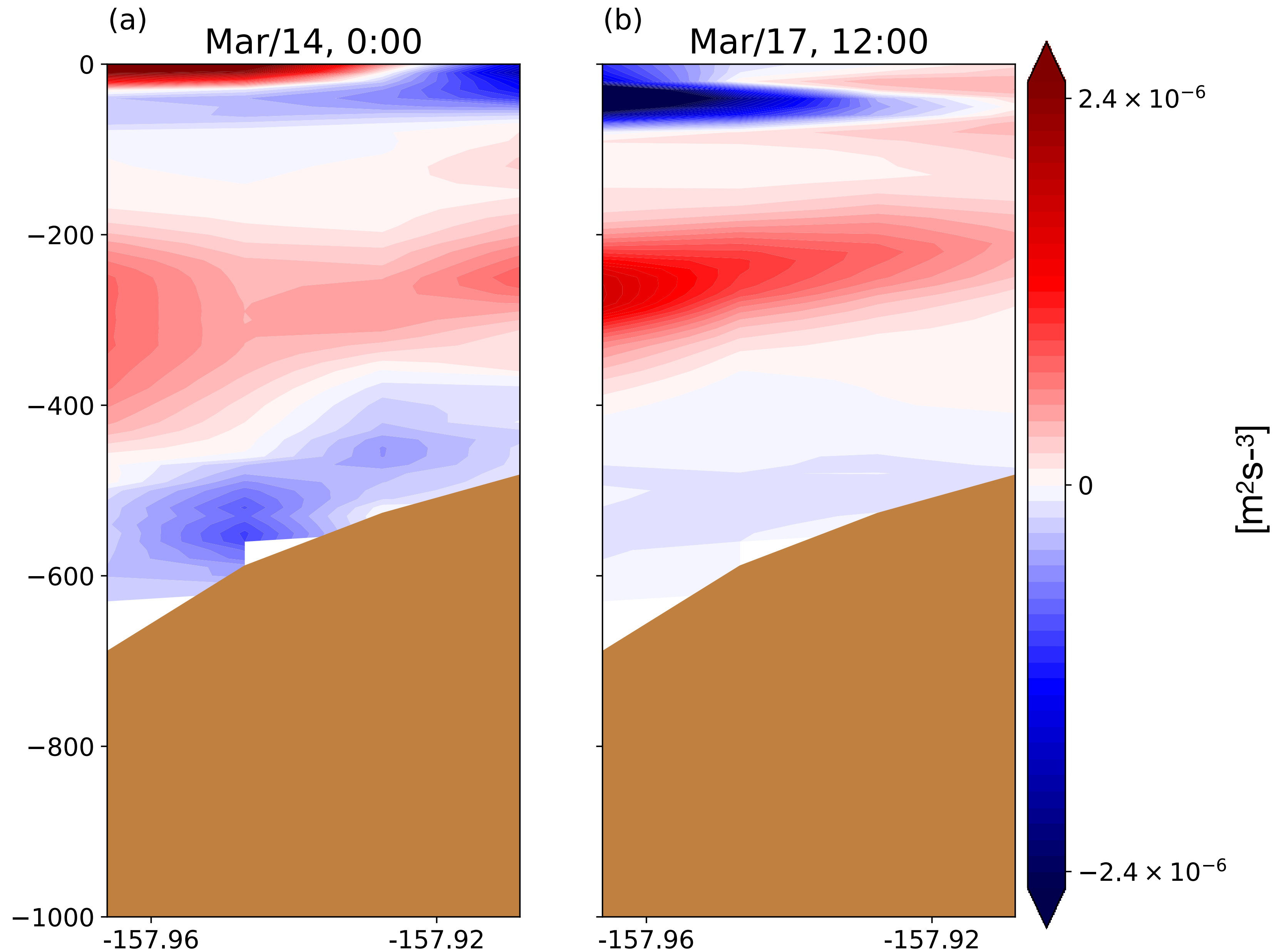


Cross filament direction

- HRS < 0 in March 14
- Other energy conversion terms negligible in model

Vertical distribution of along-filament HRS (ROMS)

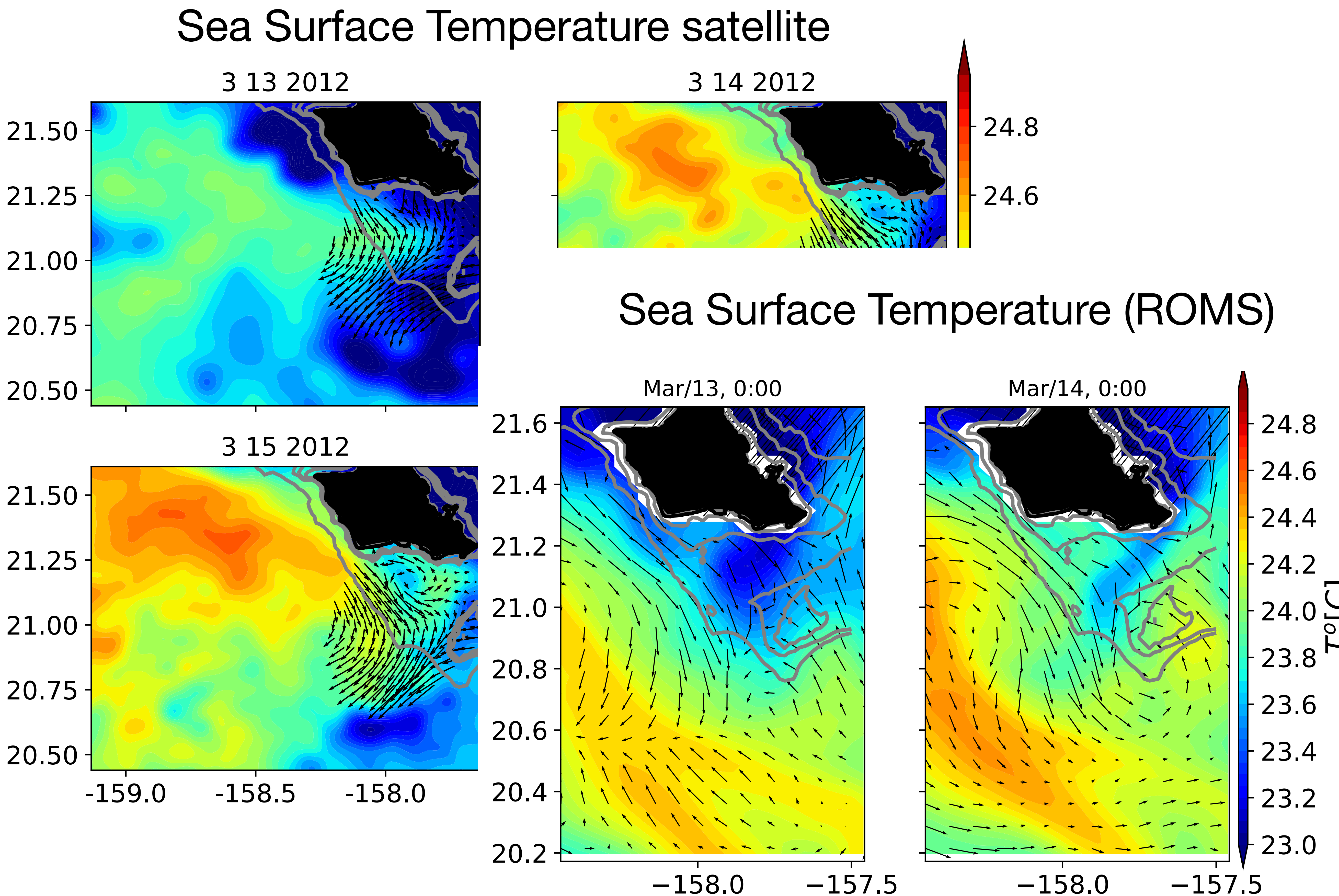




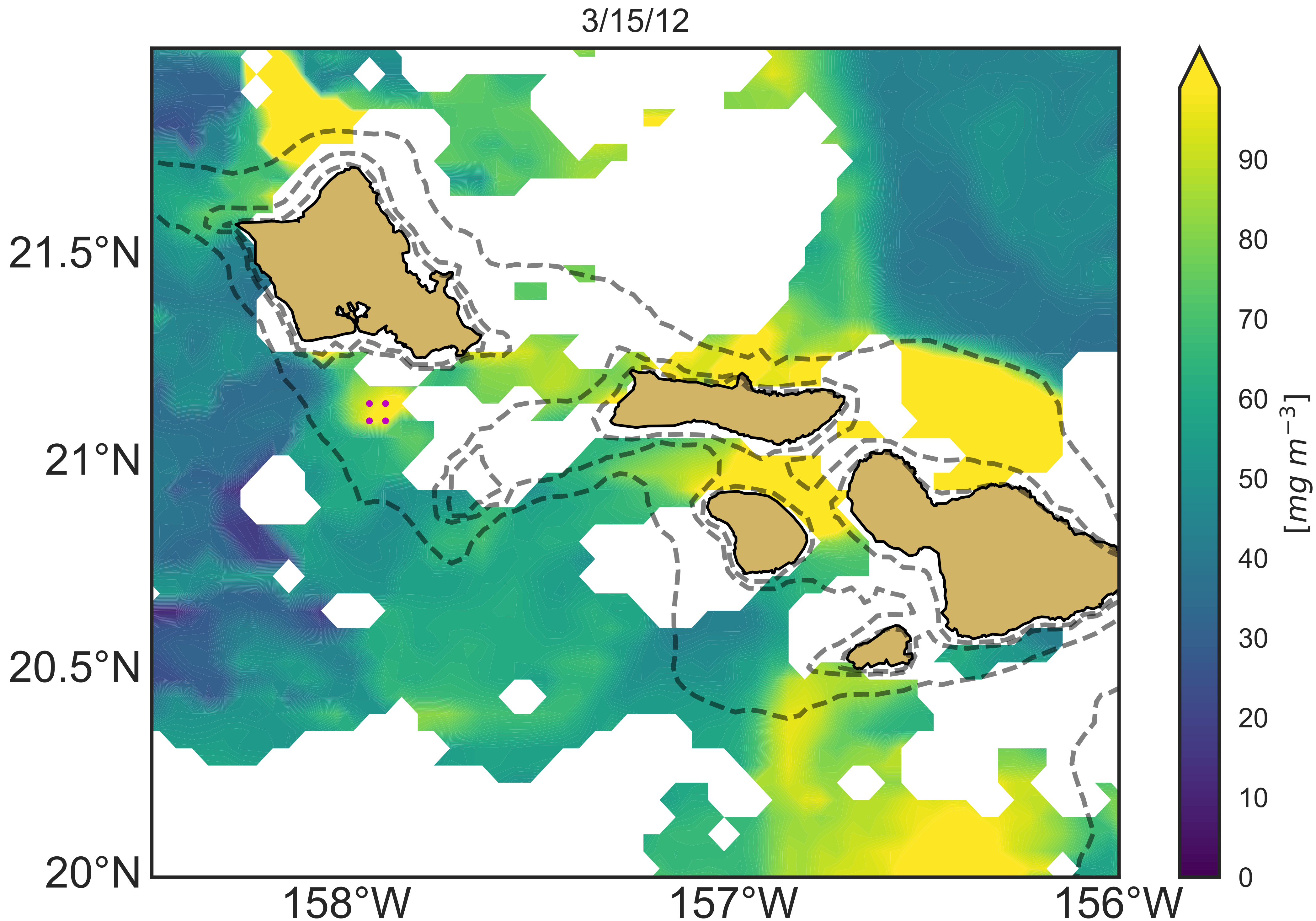
- HRS is surface intensified
- HRS <0 after March 14

$$HRS = -\overline{u'^2}\frac{\partial \overline{U}}{\partial x} - \overline{u'v'}\frac{\partial \overline{U}}{\partial y} - \overline{v'^2}\frac{\partial \overline{V}}{\partial y} - \overline{u'v'}\frac{\partial \overline{V}}{\partial x}$$

Horizontal Shear Stress



Sea Surface Temperature satellite
3 13 2012
3 14 2012
3 15 2012
21.50
21.25
21.00
20.75
20.50
-159.0
-158.5
-158.0
24.8
24.6
Sea Surface Temperature (ROMS)
Mar/13, 0:00
Mar/14, 0:00
21.6
21.4
21.2
21.0
20.8
20.6
20.4
20.2
−158.0
−157.5
24.8
24.6
24.4
24.2
24.0
23.8
23.6
23.4
23.2
23.0
$T^o[C]$

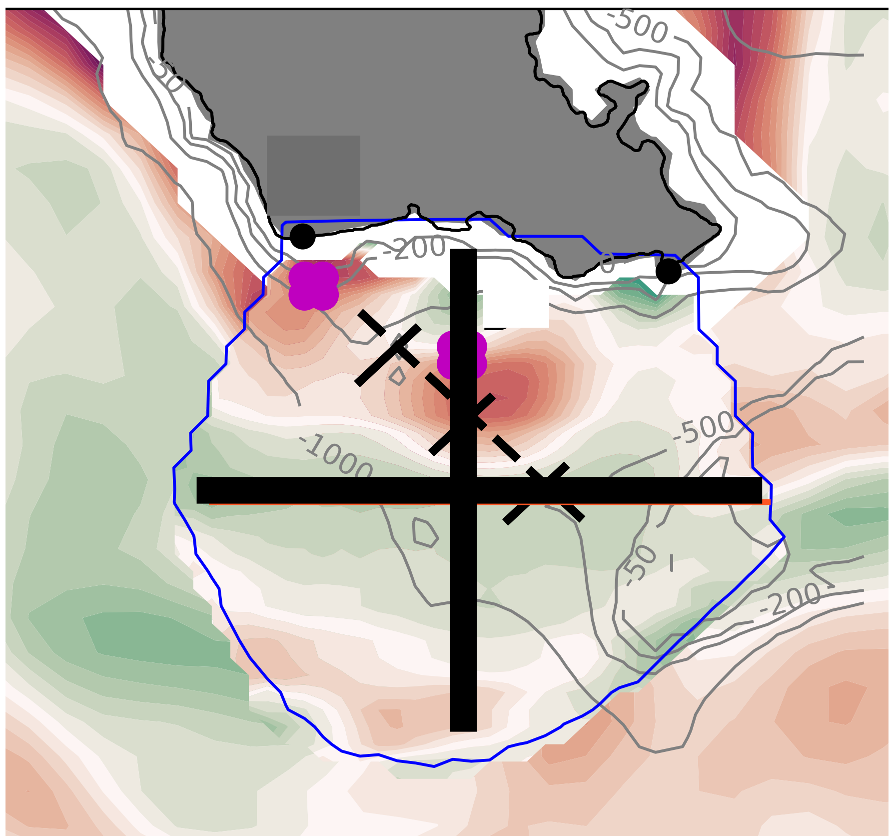


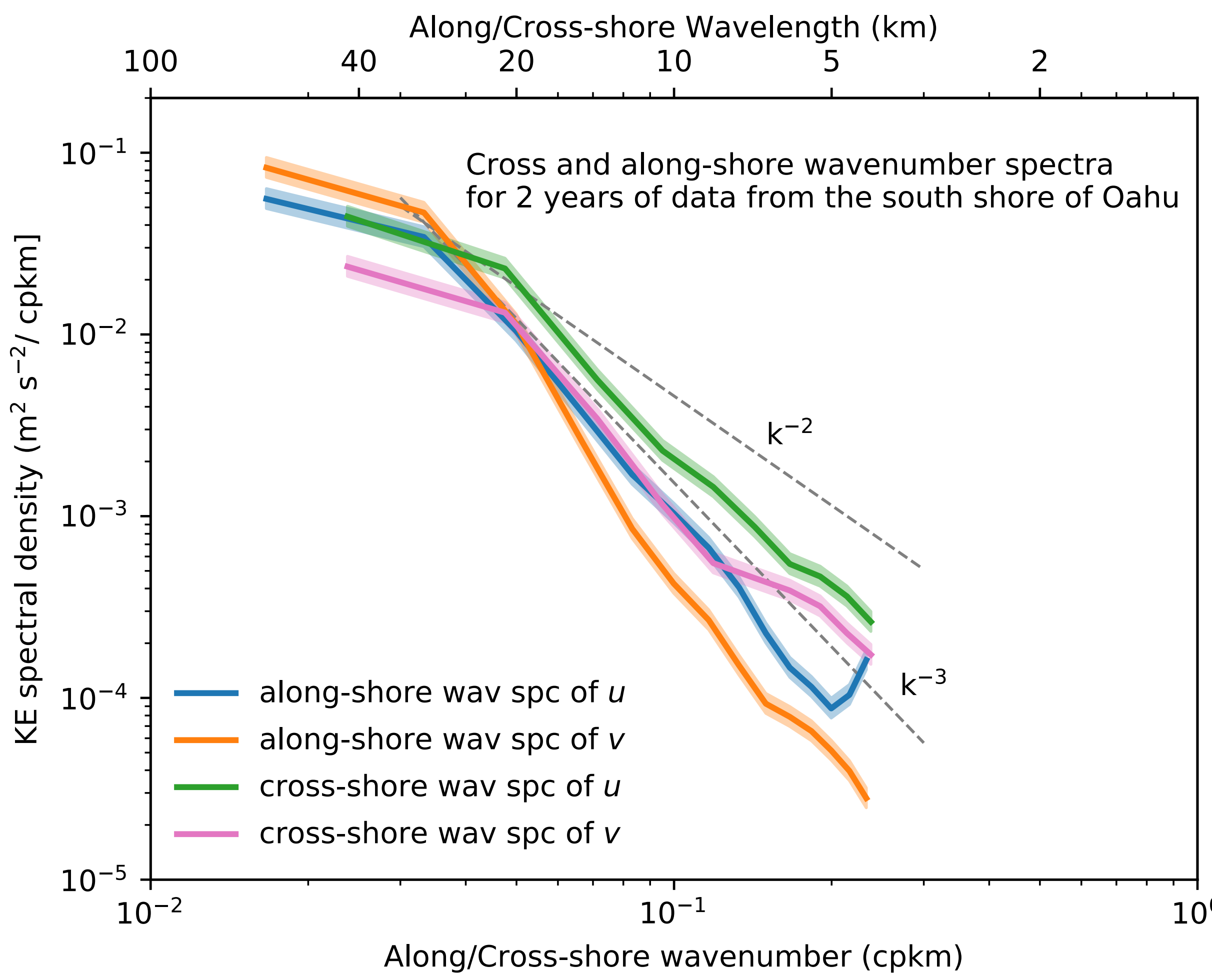
Surface chlorophyll increases when the submesoscale eddy is observed

Eddy seasonality

Horizontal wavenumber spectra explain:

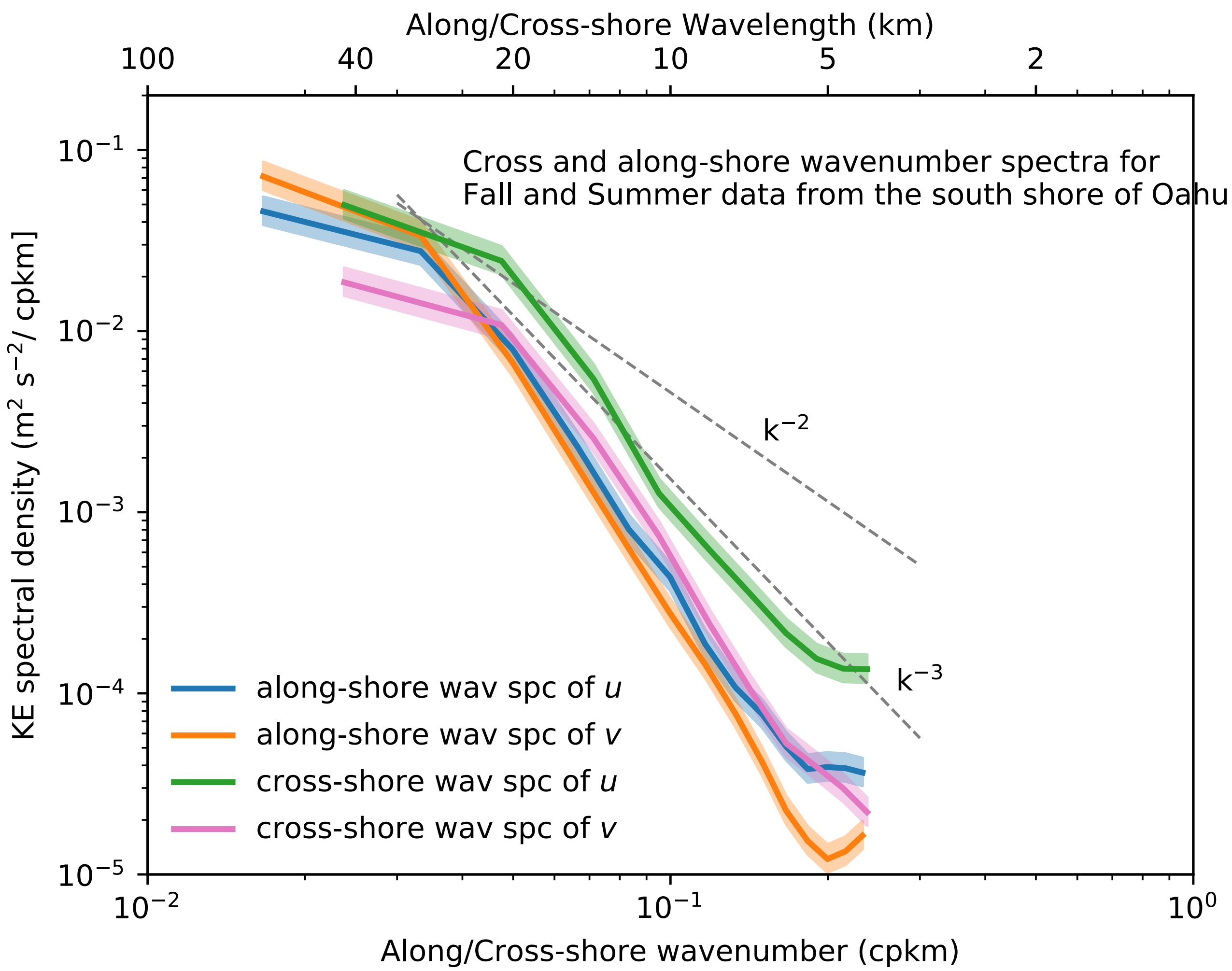
- forward (**large to small** scale) energy cascade
- inverse (**small to large** scale) energy cascade

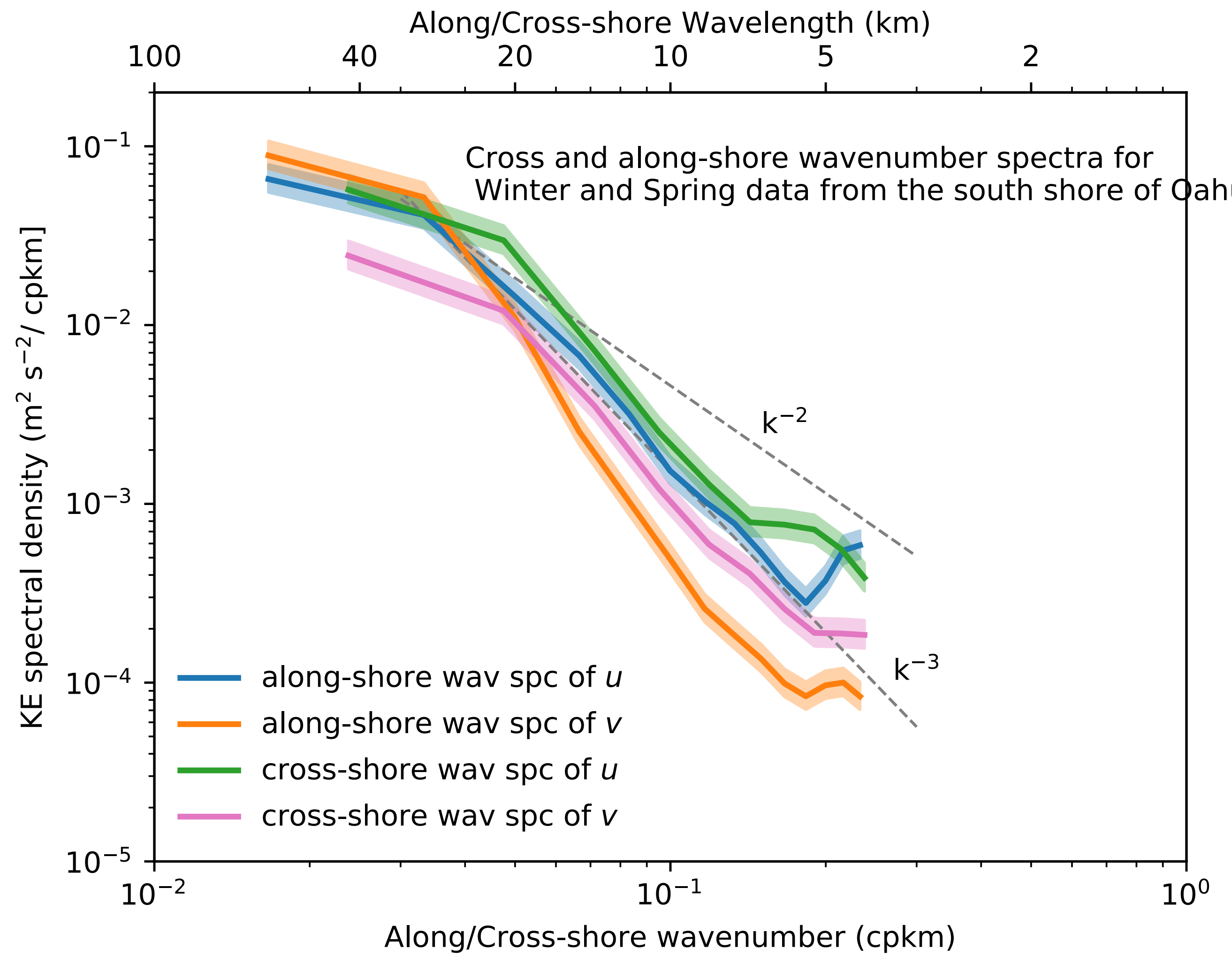




- QG turbulence theory predicts k^{-3} for forward and $k^{-5/3}$ for inverse energy cascade

Charney, 1971





- Follow a slope for **forward energy** cascade in QG theory (k^{-3}). Energy cascade from **large to small**.

- Flatter slopes at higher wavenumbers in **Winter and Spring** due to enhanced activity of submesoscale eddies. In contrast to steeper slopes in **Fall and Summer** indicative of weaker eddy activity.

"a power spectrum of some bars of Beethoven would be rather an oversimplification too; maybe just enough to decipher the key."

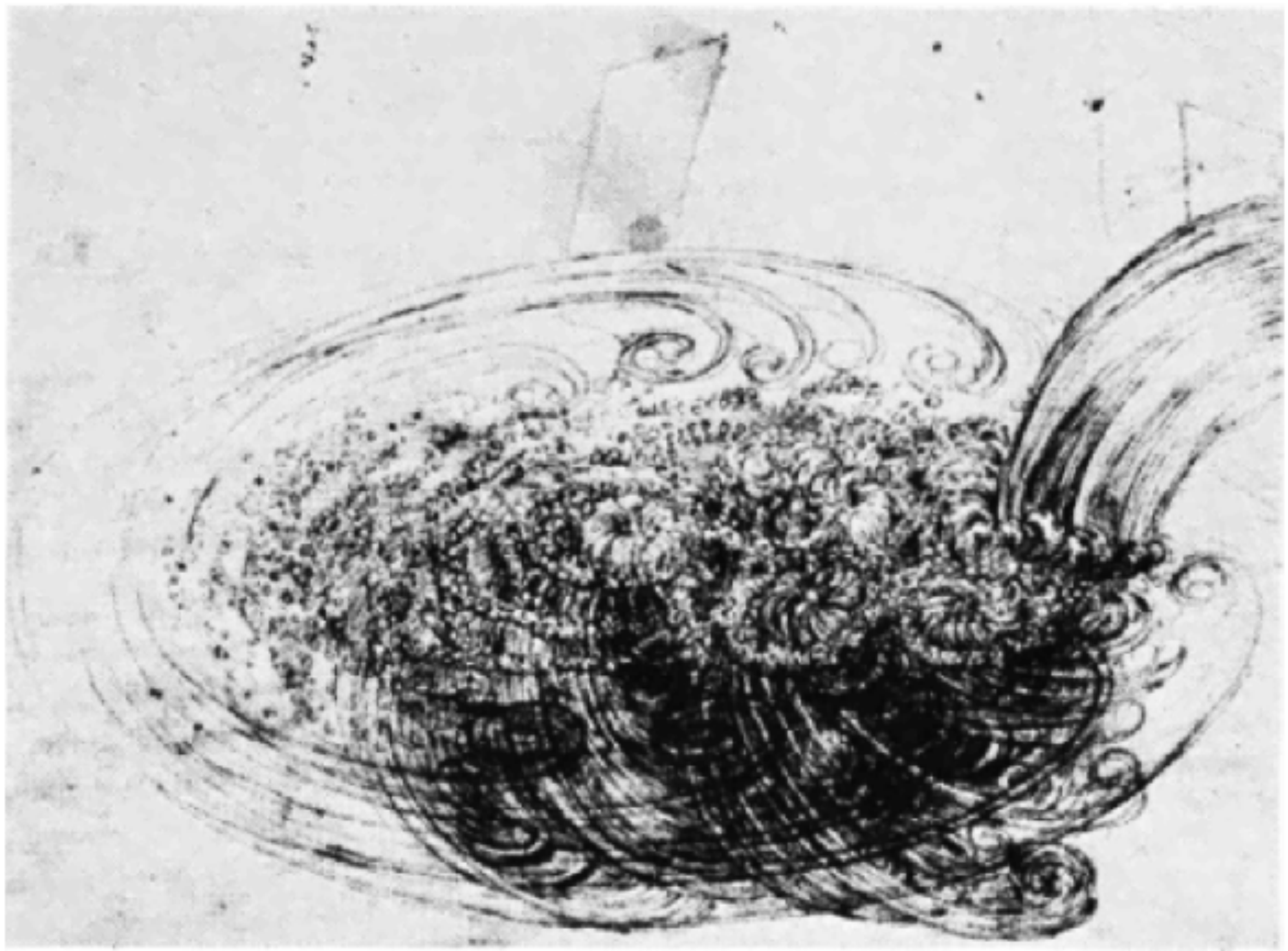


Fig. 4. Line drawing of a turbulent outfall by L. da Vinci (personal communication, 1508) containing no magnitude information.

(Armi and Flament, 1985)

Conclusions

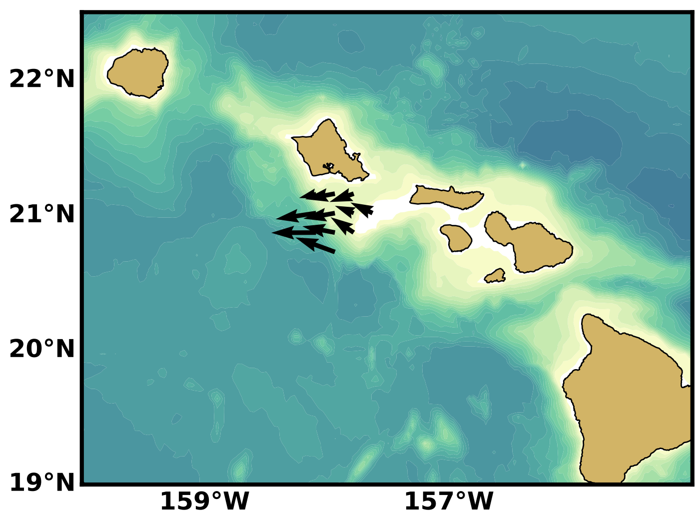
- A positive vorticity filament is observed in both HFR and ROMS associate with a coastal jet (**Spring and Winter**).

- The filament evolves into a **vortex** (only in observations).

- An eddy kinetic energy budget suggest shear from the **background flow** generates and **amplifies** the **vortex.**

- The **model** lower spatial resolution (4 km vs 1.5 km) does not allow for eddy generation and production of horizontal shear by the background flow.

Take home message



Hawaiian Lee Current

Mesoscale eddies

Coastal jets

Mean background flow (low-frequency)

Two-way energy transfer

Forward energy cascade

Larger in winter and spring months (wind generated)

Near-Inertial Oscillations

Wavelength *O*(100 km)

Amplitude and frequency spatial variability *O*(25 km)

Transport coastal nutrients to Penguin Bank

Submesoscale eddies (~10 km)

Mostly observed from March to May

Generated and amplified by shear from the background flow

Mahalo ...

- My advisor Pierre Flament.
- My committee members.
- My Mexican Ohana.
- My Hawaiian Ohana.
- Maile Ohana.
- Faculty and students at the Department of Oceanography.

University of Hawai'i

FULBRIGHT

PacIOOS
Pacific Islands Ocean Observing System

CONACYT
Consejo Nacional de Ciencia y Tecnología

Questions?