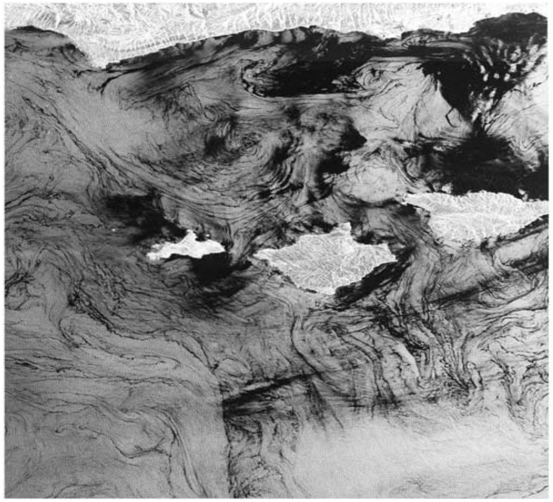
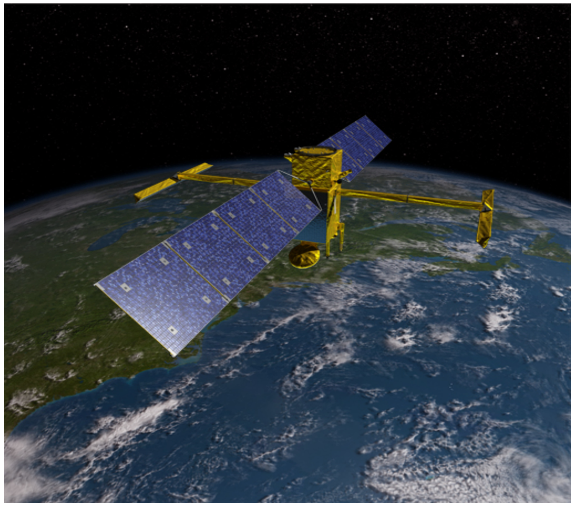
“Wave-Turbulence Interactions in the Oceans”

Patrice Klein (Caltech/JPL/Ifremer)

(I) Introduction (a)





Waves (near-inertial, tidal, internal gravity waves):

- Fast motions (high frequency: $f < \omega < N$)
- assumed to explain **most of the mixing** (at small-scale) **in the ocean interior**
- strong signature in in-situ (moorings, gliders, ADCP, surface drifters) and satellite observations [SAR] at high-resolution.

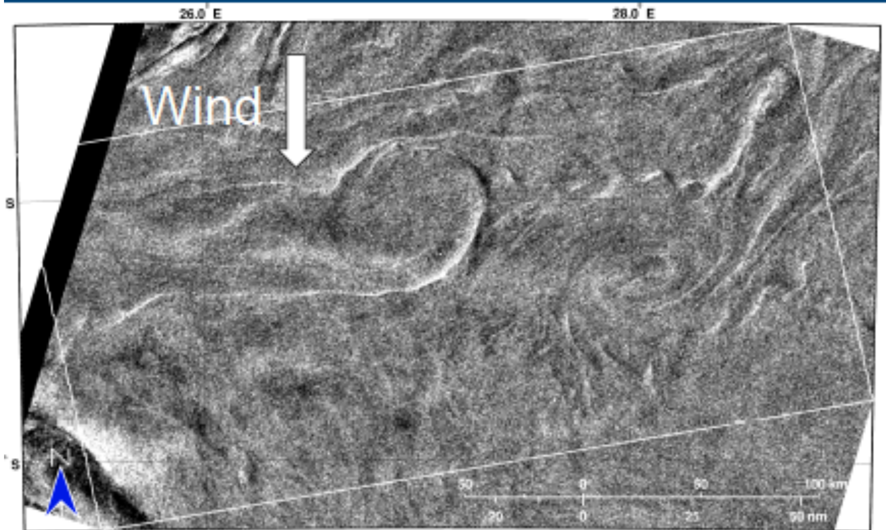
Geostrophic turbulence [1-500 km]:

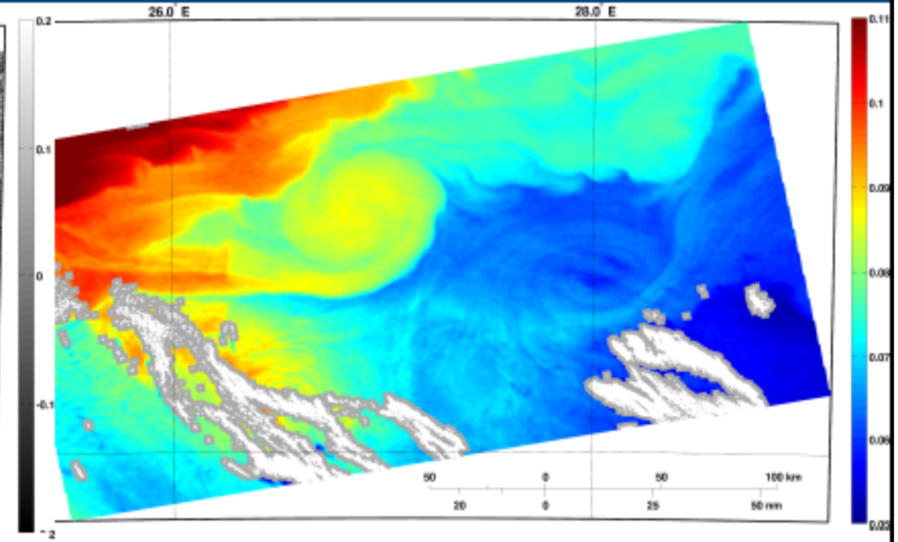
- Slow motions (low frequency: $\omega < f$)
- explains **most of the kinetic energy in the oceans,** well captured by satellite observations on a global scale [SSH (> 100 km), SST, Ocean Color, …]

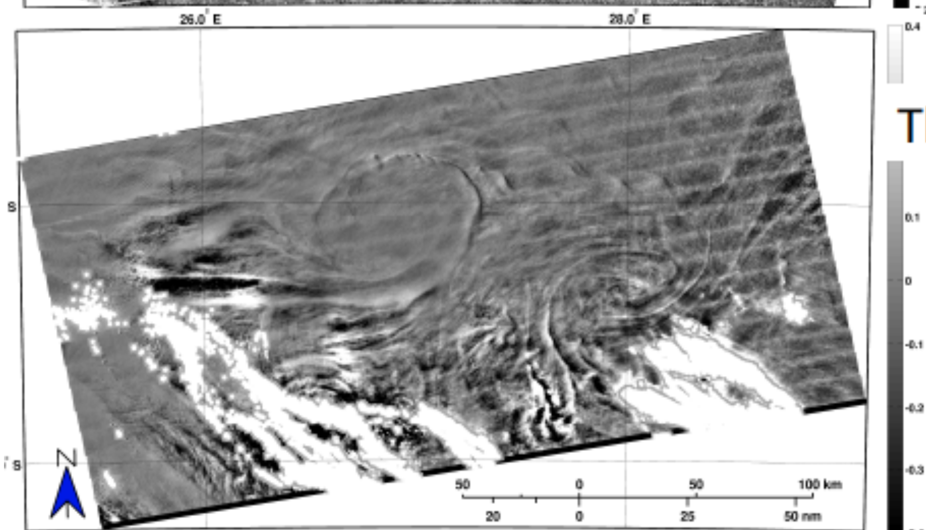
However it is usually difficult to discriminate these two classes of motions in high-resolution observations, since these observations have high resolution either in space or in time, BUT NOT both.

An example: SAR images …

Synergies with surface roughness







$$V = U + \overline{u} + \tilde{u}$$

The divergence of the total flow, $\nabla \cdot V$

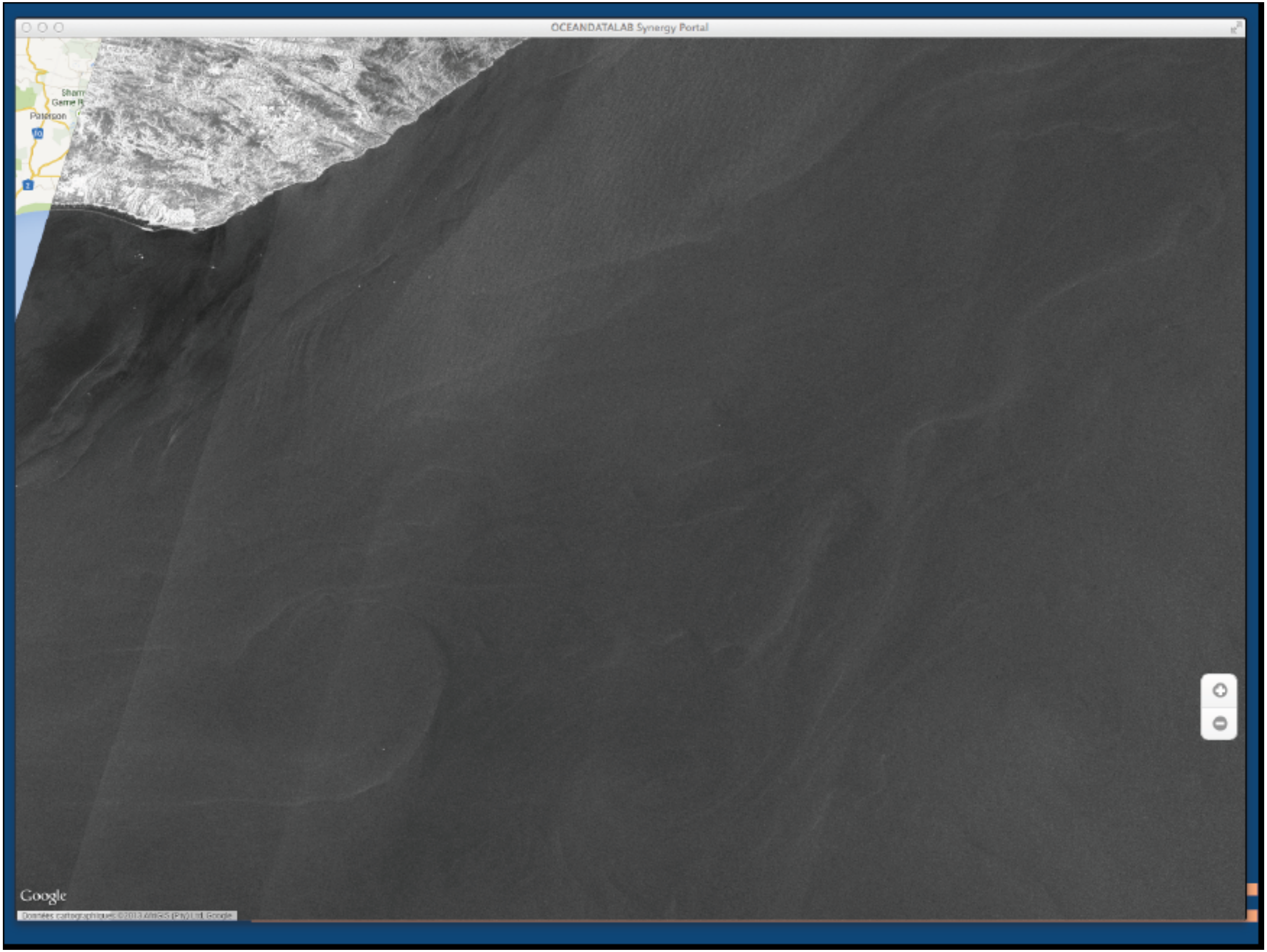
is governed by the secondary ageostrophic flow $\tilde{u}$

and reads $\nabla \cdot V = -f^{-1}\overline{u}_j \dfrac{\partial}{\partial x_j}\Omega_z$

where

$$\Omega_z = \partial U_1 / \partial x_2 - \partial U_2 / \partial x_1 \equiv \Delta \psi$$

is the vorticity of the QG currents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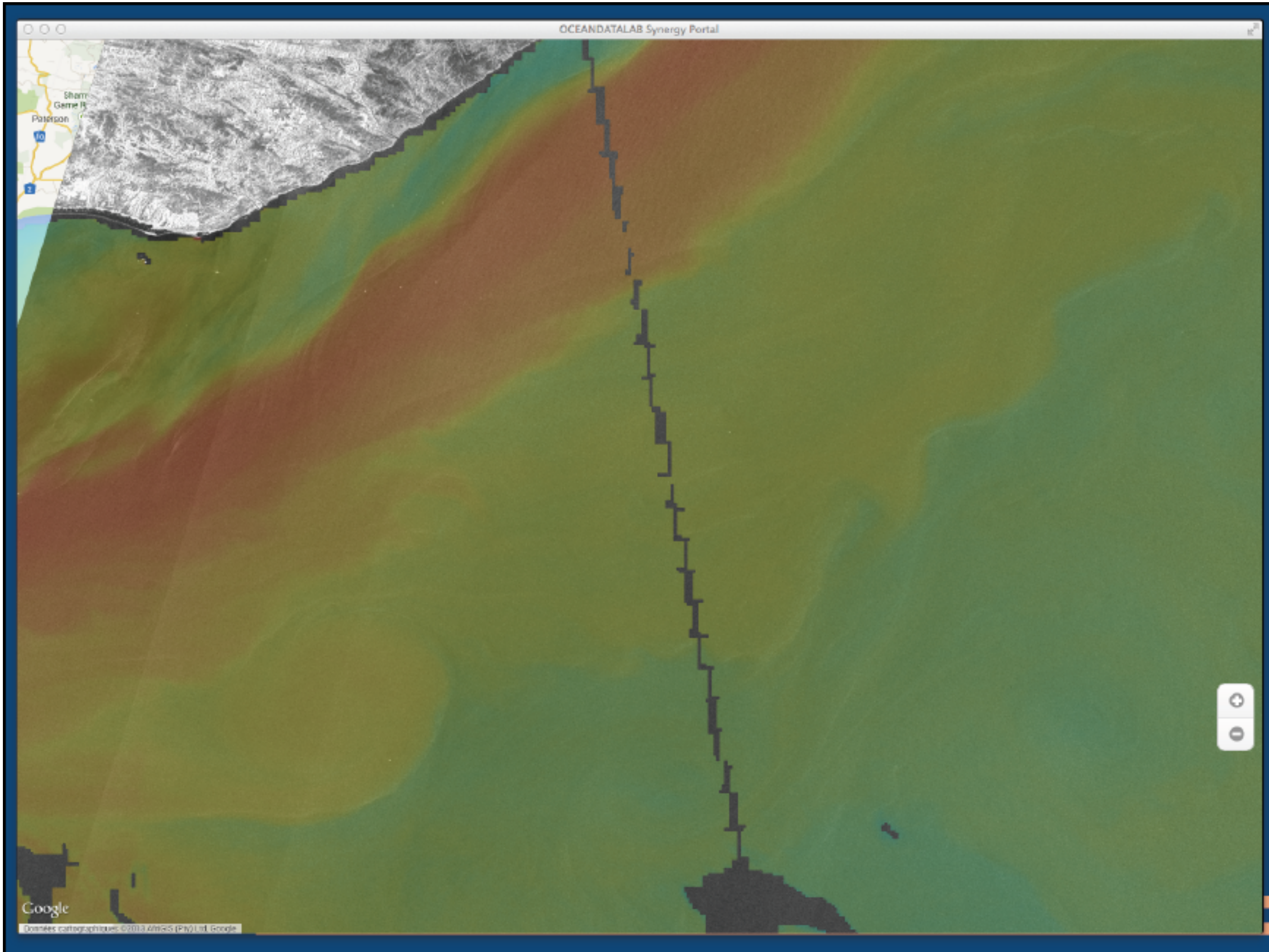
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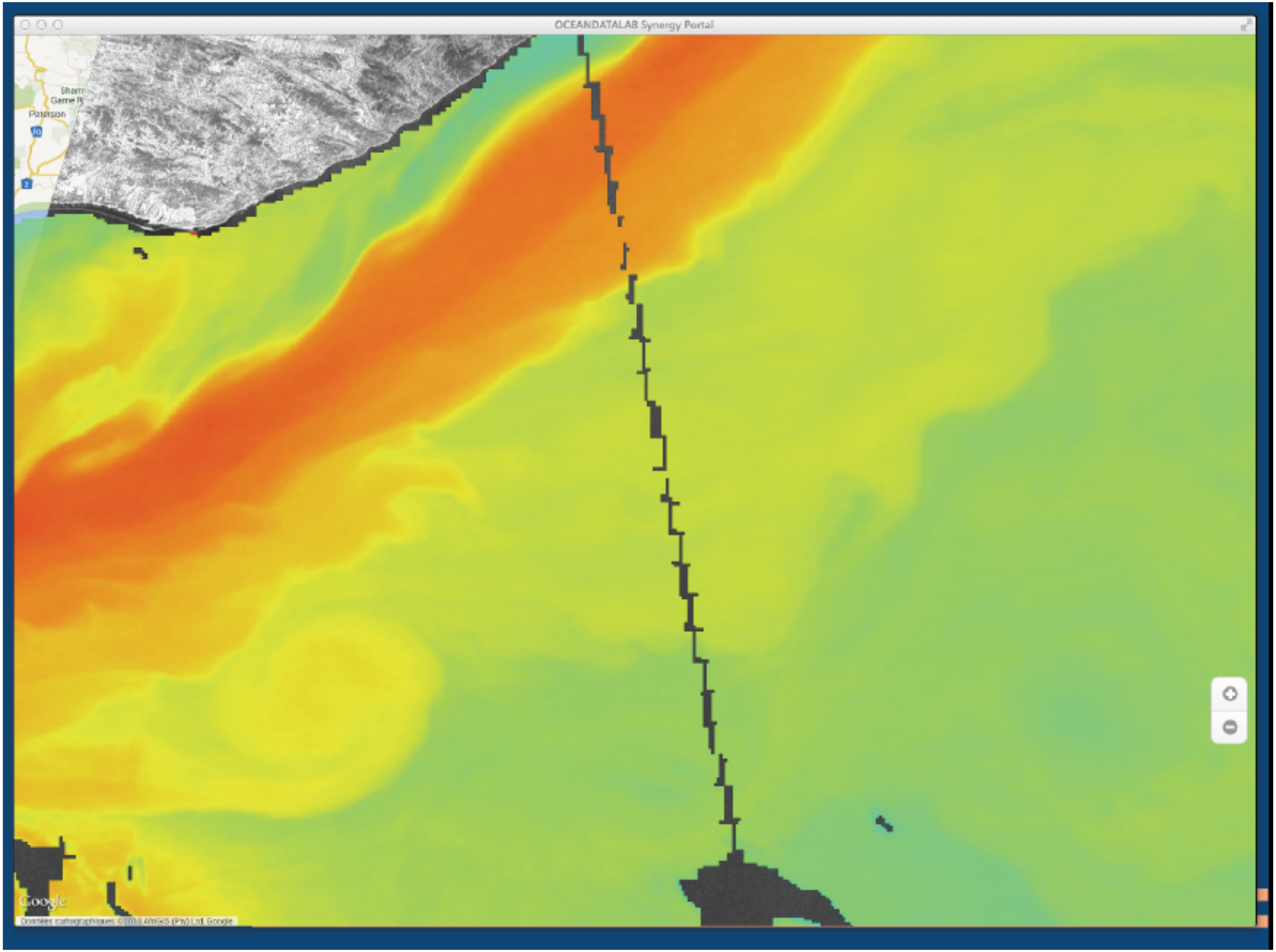
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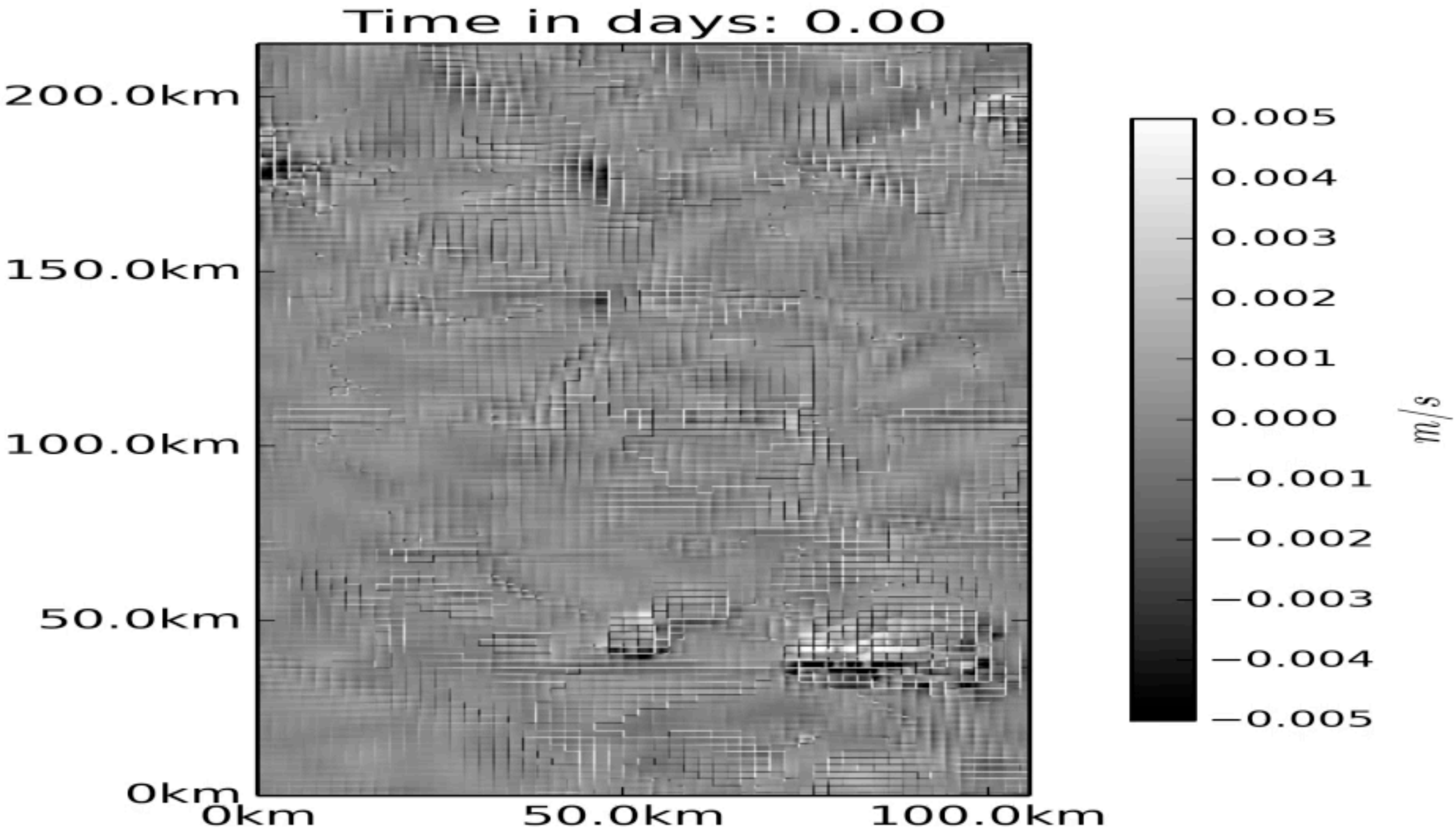

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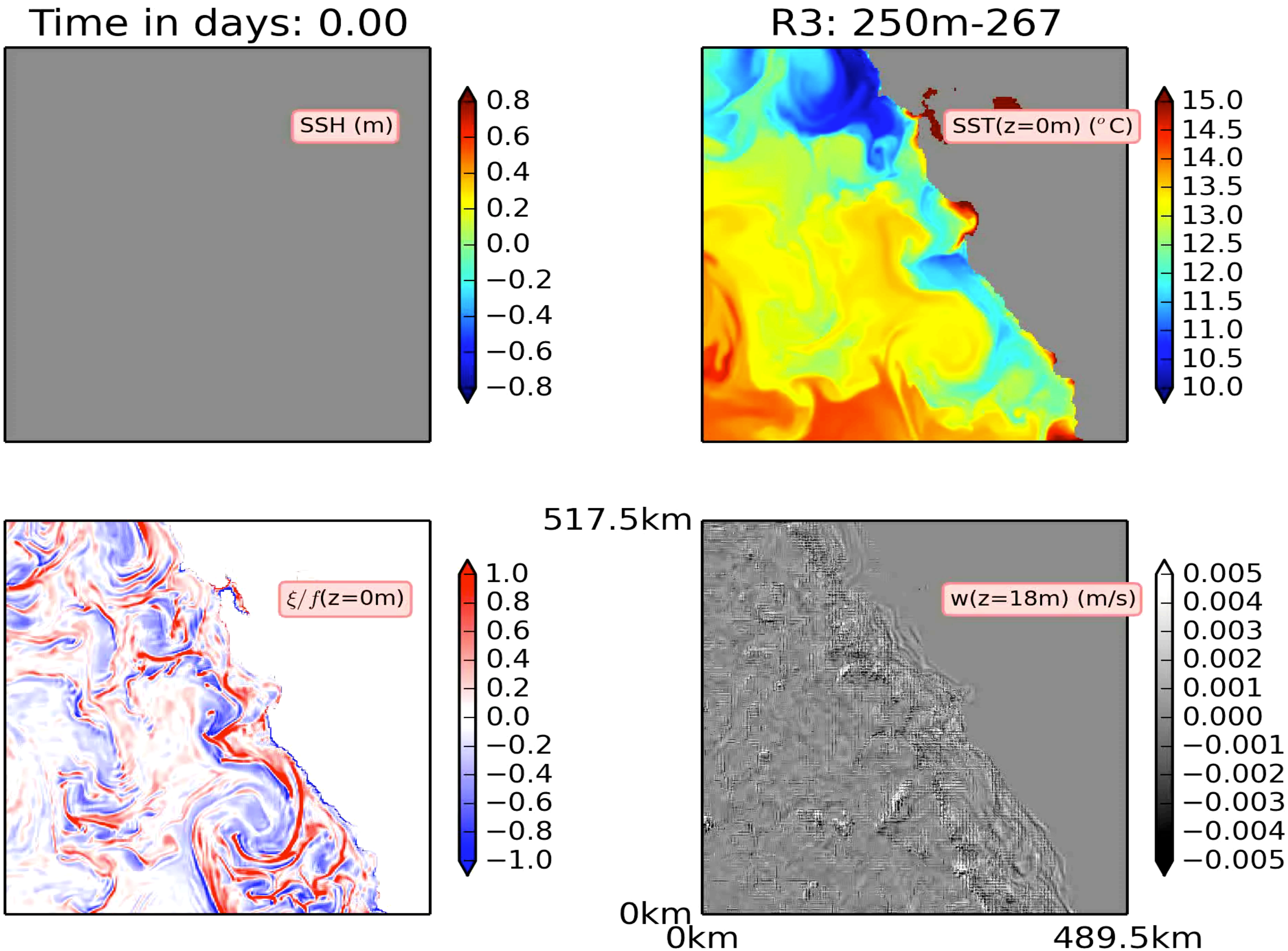

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Why waves and geostrophic turbulence have different signatures on SSH, SST, … ?

What is the motivation of this course ?

Waves (near-inertial, tidal, internal gravity waves):

- Fast motions
- assumed to explain **most of the mixing** (at small-scale) **in the ocean interior**
- strong signature in in-situ (moorings, gliders, ADCP, surface drifters) and satellite observations [SAR] at high-resolution.

Geostrophic turbulence [10-500 km]:

- Slow motions
- explains **most of the kinetic energy in the oceans,** well captured by satellite observations on a global scale [SSH (> 100 km), SST, Ocean Color, …]

How to discriminate these two classes of motions in high-resolution observations?

We need to better understand the specific dynamics of these two classes of motions and how they interact.

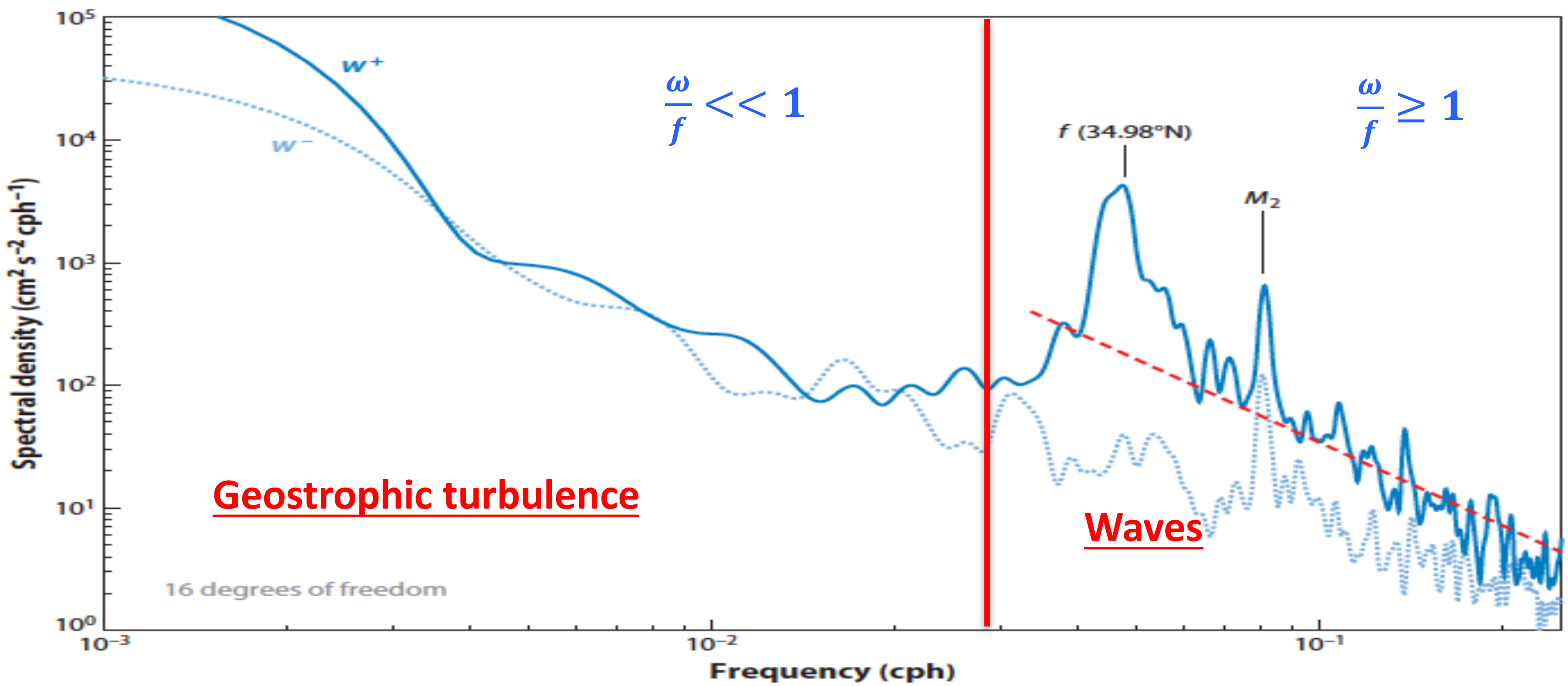


Figure 1

Rotary velocity spectrum at 261-m depth from current-meter data from the WHOI699 mooring gathered during the WESTPAC1 experiment (mooring at 6,149-m depth.) The solid blue line (w^+) is clockwise motion, and the dashed blue line (w^-) is counterclockwise motion; the differences between these emphasize the downward energy propagation that often dominates the near-inertial band. The dashed red line is the line $E_0 N \omega^{-p}$ with $N = 2.0$ cycles per hour (cph), $E_0 = 0.096$ cm^2 s^{-2} cph^{-2}, and $p = 2.25$, which is quantitatively similar to levels in the Cartesian spectra presented by Fu (1981) for station 5 of the Polygon Mid-Ocean Experiment (POLYMODE) II array.

SPECTRAL GAP AT FREQUENCIES (ω) LARGER (BUT CLOSE TO) f

Momentum equations

Rossby number: U/fL < 1

Slow motions: $\boldsymbol{\frac{\omega}{f} << 1}$

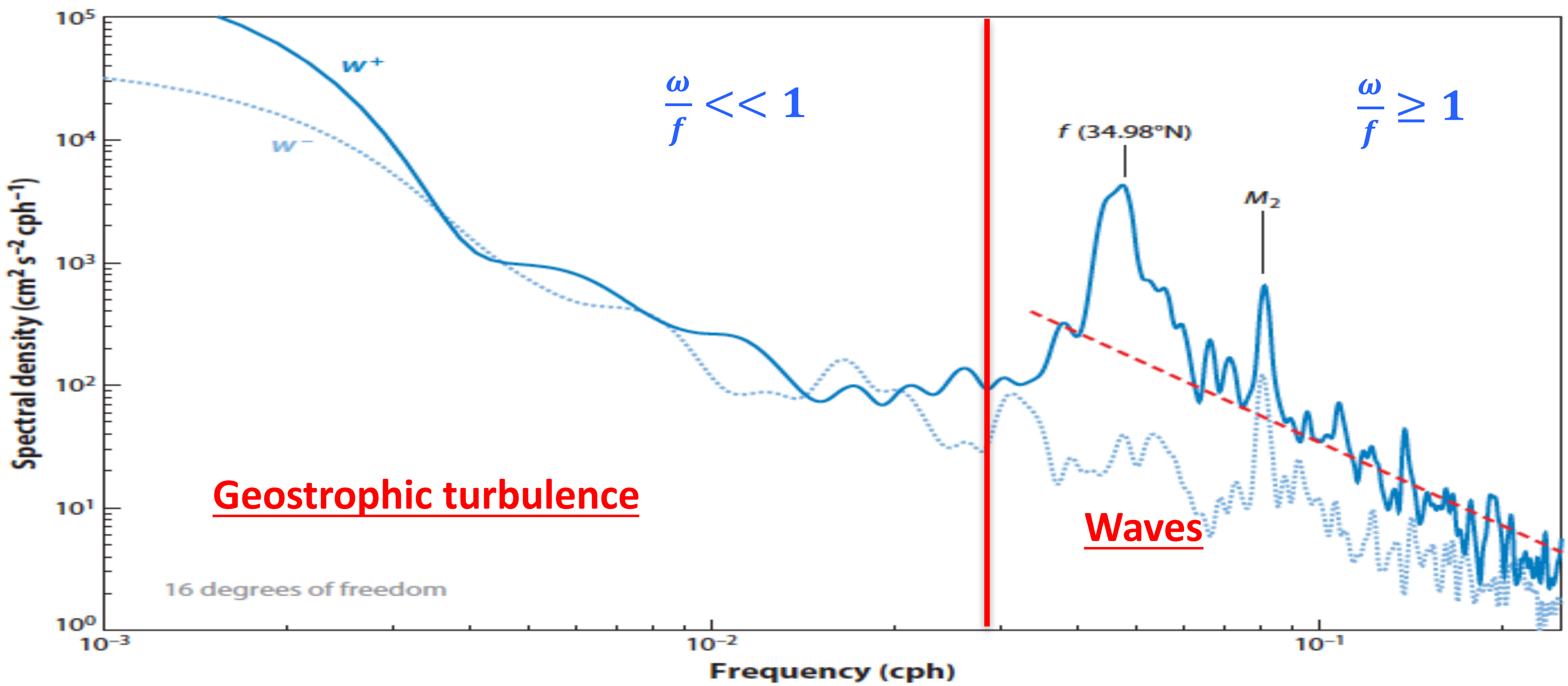
$$\cancel{\frac{\partial U}{\partial t}} + \cancel{\mathrm{U}.\nabla U} \; - f k \times U = -\frac{\nabla p}{\rho_o}$$

$\Rightarrow$ **Geostrophic balance at zero order** $[\boldsymbol{c} = \frac{\boldsymbol{\omega}}{\boldsymbol{k}} \ll \boldsymbol{U}]$

Fast motions: $\boldsymbol{\frac{\omega}{f} \geq 1}$

$$\frac{\partial U}{\partial t} + \cancel{\mathrm{U}.\nabla U} \; - f k \times U = -\frac{\nabla p}{\rho_o}$$

=> Wave equations $[\boldsymbol{c} = \frac{\boldsymbol{\omega}}{\boldsymbol{k}} >> \boldsymbol{U}]$



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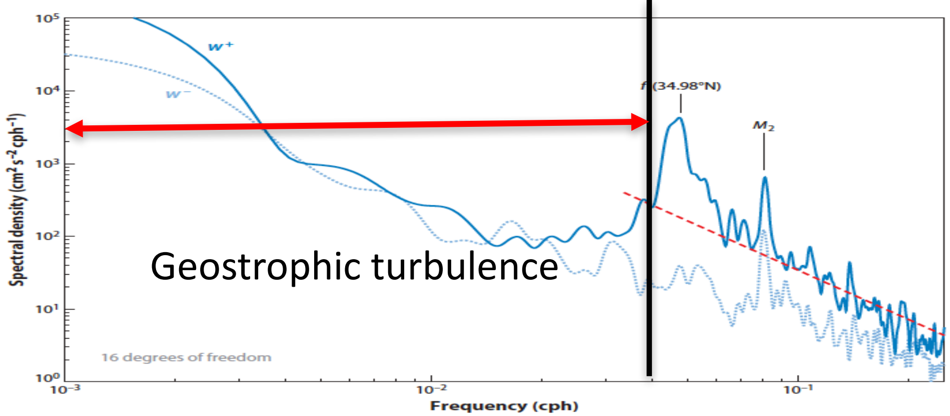
A frequency spectrum displays different properties between fast and slow motions

WAVES AND TURBULENCE:

A BRIEF REVIEW OF THE MAIN PROPERTIES FROM OBSERVATIONS

GEOSTROPHIC TURBULENCE:

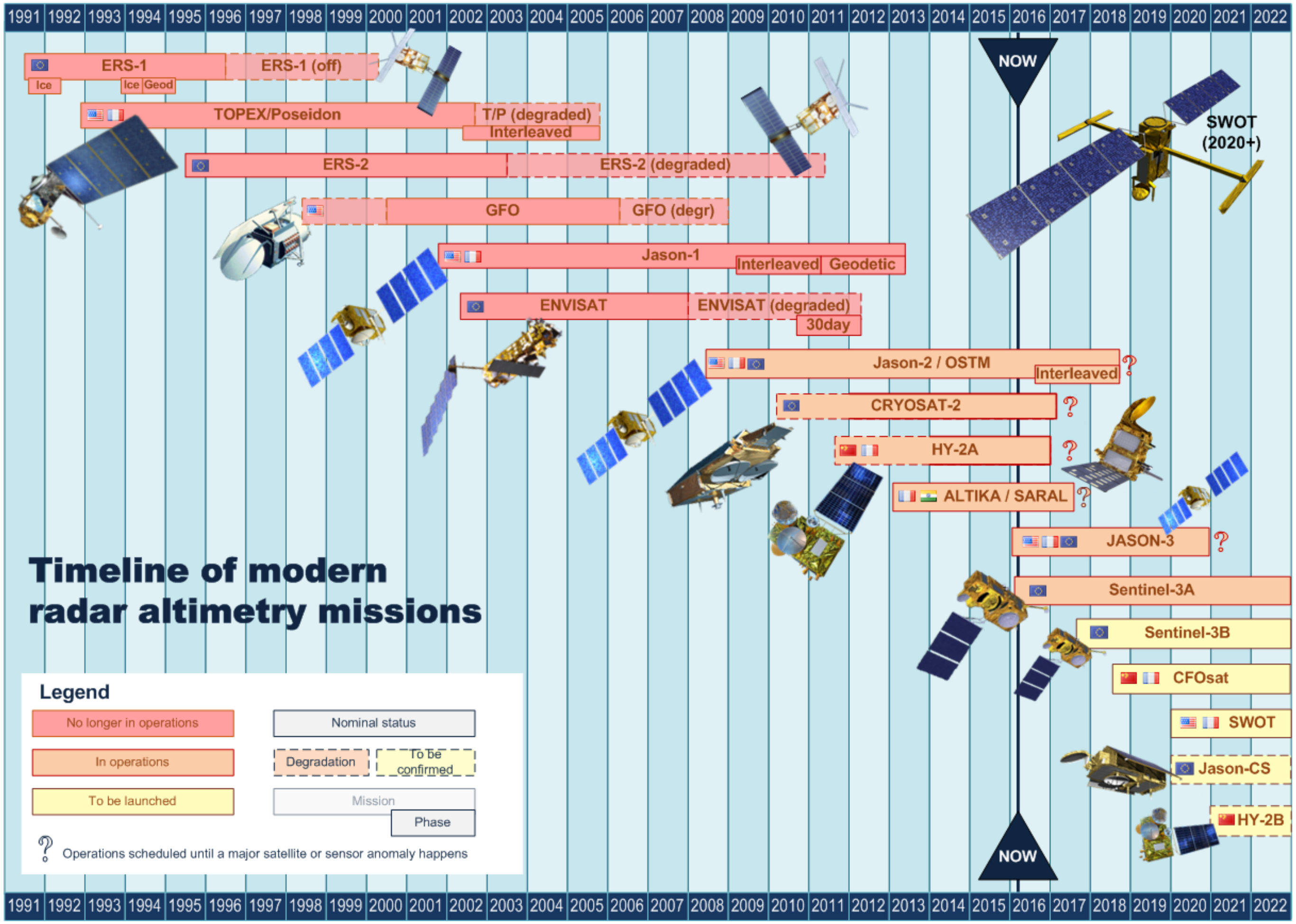
A BRIEF SUMMARY OF THE MAIN PROPERTIES



PROPERTIES OF GEOSTROPHIC TURBULENCE

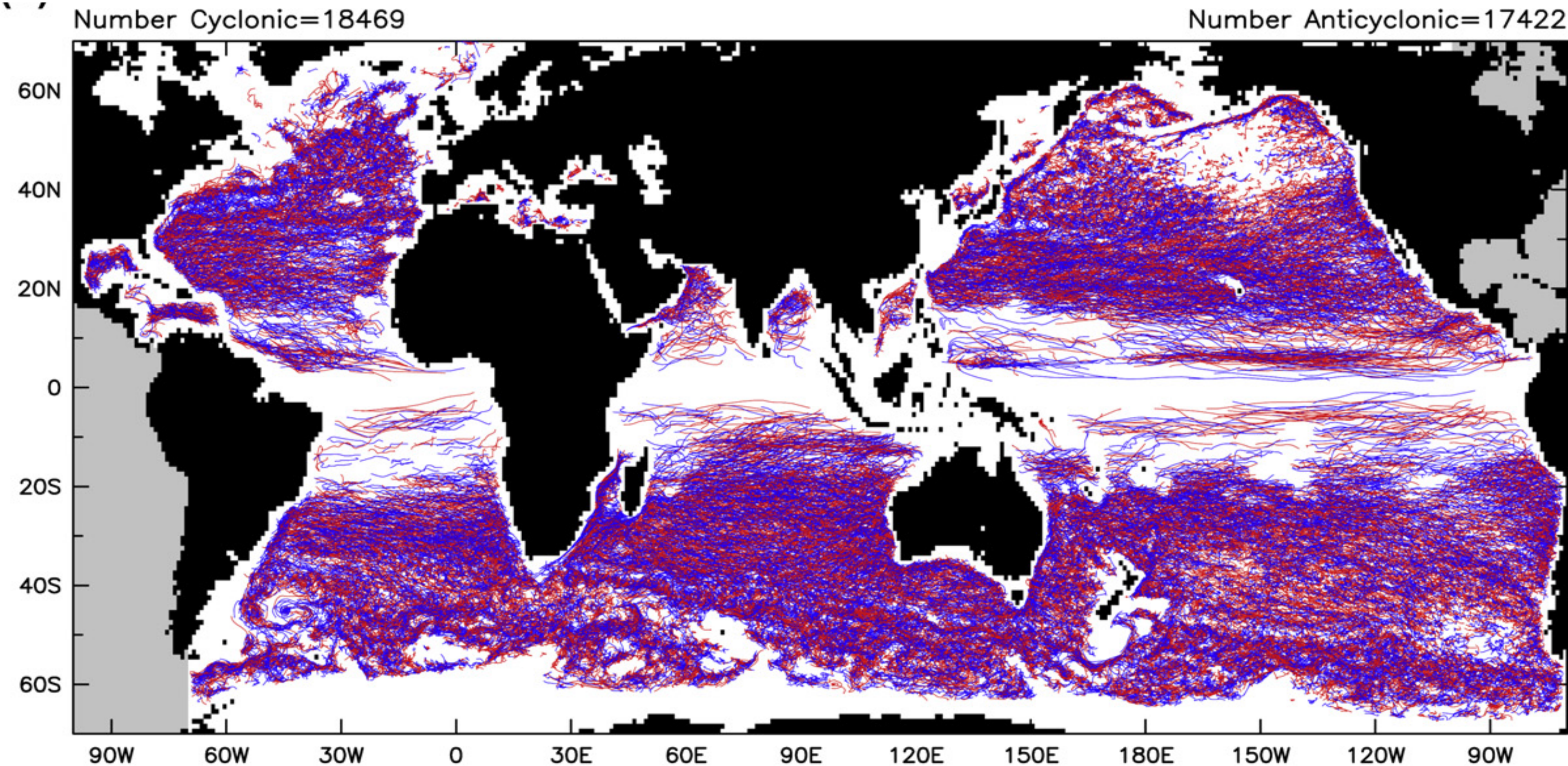
- Concern mesoscale eddies (100 - 400 km) and sub-mesoscale filaments and eddies (1-50km)
- Mesoscales (100-400km) better known on a global scale from >25 years of satellite altimeter observations (of SSH)
- Geostrophic balance at zero order: $-f.k\times U=-g.\nabla SSH$
- Capture most of the kinetic energy in the ocean

SATELLITE ALTIMETRY

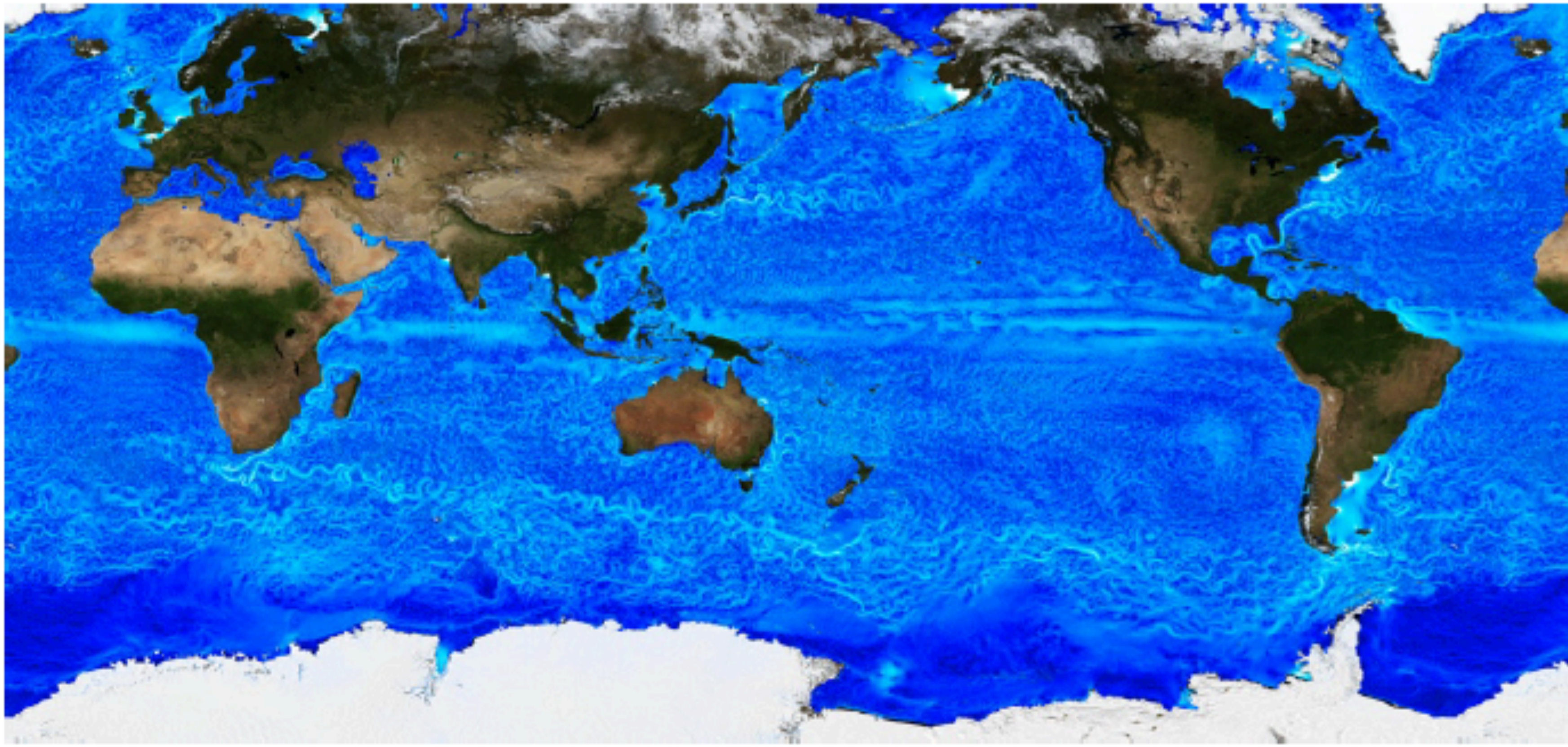


25 years of altimeter data have revealed the ubiquitous existence of mesoscale eddies (100 km – 300 km), assuming the geostrophic balance

20 years of altimeter data have revealed the ubiquituous existence of mesoscale eddies (100 km – 400 km). They are estimated to represent about 80% of the total kinetic energy of the oceans !

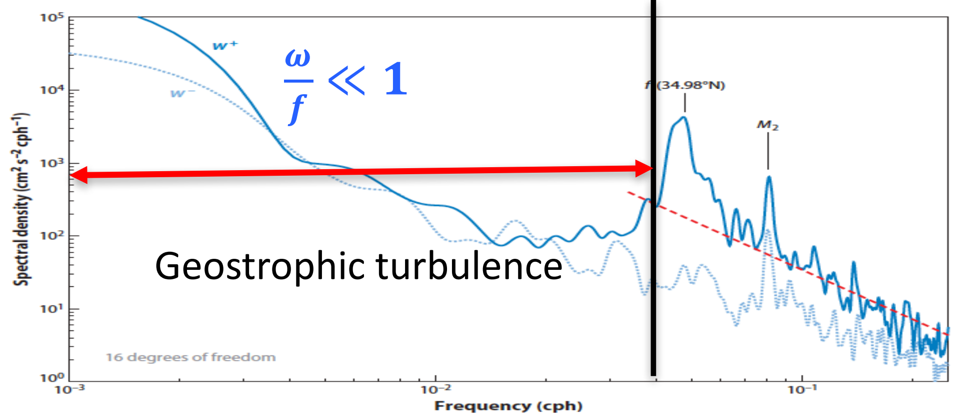


The trajectories of cyclonic (blue lines) and anticyclonic (red lines) eddies over the 16-year period October 1992–December 2008 for (a) lifetimes >16 weeks. The numbers of eddies of each polarity are labeled at the top of each panel. From D. Chelton et al., Prog. Ocean. 2011



MITGCM (1/48°, 90 VERTICAL LEVELS)

Turbulent nature of the ocean dynamics well confirmed by high resolution simulations



PROPERTIES OF GEOSTROPHIC TURBULENCE

- Concern eddies (100-400km) and submesoscale filaments and eddies (1-50km)
- Better known on a global scale from >25 years of satellite altimeter observations
- Capture most of the kinetic energy in the ocean
- **Geostrophic balance at zero order: $-f.k \times U = -g.\nabla SSH$**
- **At first order, their time evolution is driven by nonlinear interactions (leading to 3D direct tracer cascade and 3D inverse KE cascade)**

Assume a 2-D field:

$$\frac{\partial U}{\partial t} + U.\nabla U - fk \times U = -\frac{\nabla p}{\rho_o}$$

- Zero order: $-fk \times U = -\frac{\nabla p}{\rho_o}$
- First order:

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \qquad f = f(y).$$

$$\frac{\partial \zeta}{\partial t} + \underbrace{u \cdot \nabla \zeta}_{\text{NL term}} + \underbrace{\beta v}_{\beta\text{-effect}} = 0 \qquad (\text{2D version}).$$

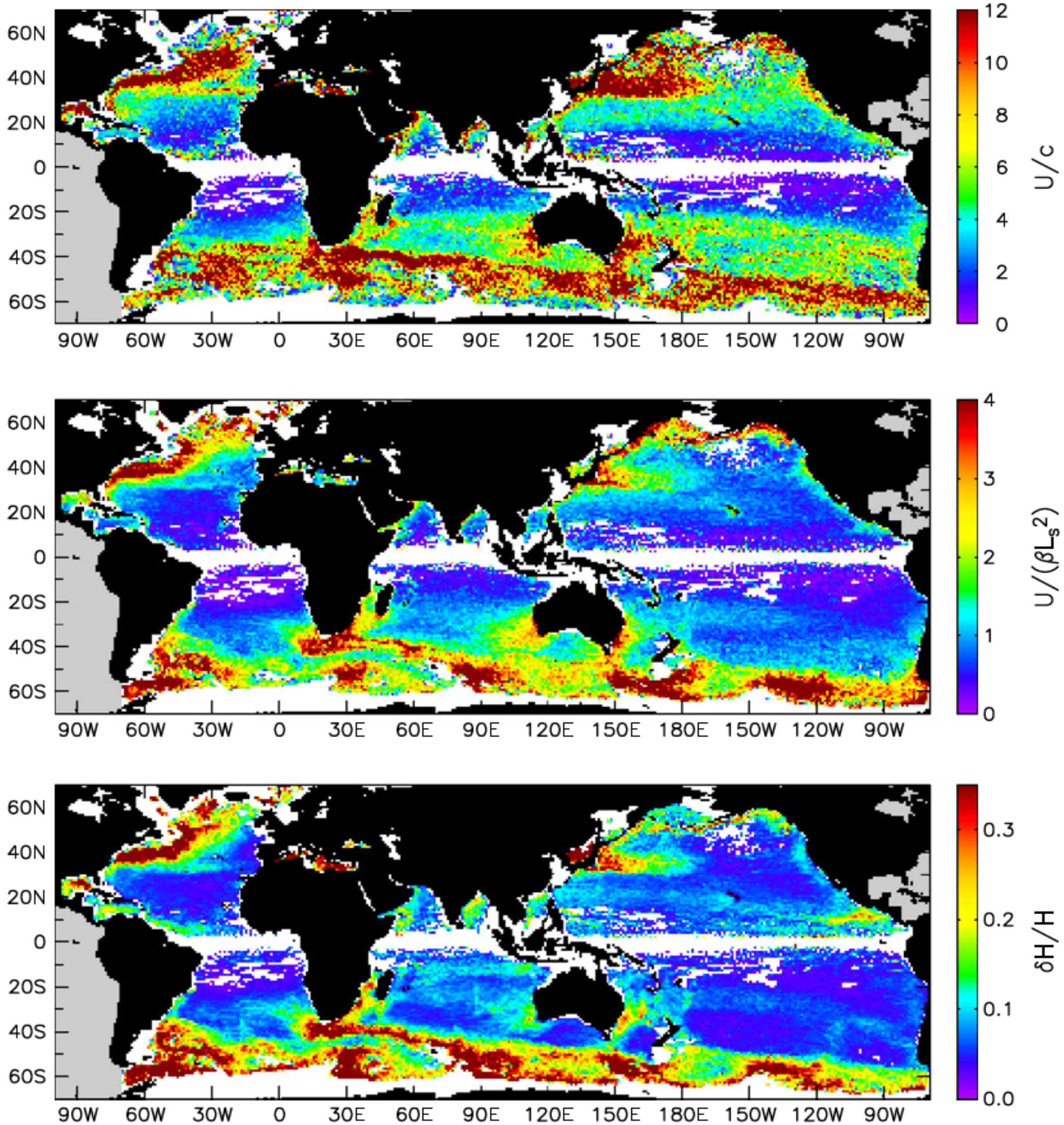
$$\boxed{\text{NL param.} = \frac{\text{NL term}}{\beta \text{ effect}} = \frac{U}{\beta L^2} \gg 1}$$

$$L_\beta = \left(\frac{U}{\beta}\right)^{1/2} \quad \text{Rhines scale.}$$

$$\text{NL param.} = \left(\frac{L_\beta}{L}\right)^2.$$

NL parameter is an index of the relative importance of the nonlinear terms, versus the linear terms (Rossby waves propagation)

Nonlinearities of the eddies (Chelton et al. PO 2011)



ig. 17. Maps of the average values of the three nonlinearity parameters in Fig. 16 for each $1° \times 1°$ region. Top to bottom: the advective nonlinearity parameter U/c; the quasi-eostrophic nonlinearity parameter $U/\left(\beta L_s^2\right)$; and the upper-layer thickness nonlinearity parameter $\delta H/H$.

At first order, time evolution of the geostrophic turbulence is driven by the nonlinear interactions (leading to 3D direct tracer cascace and 3D inverse KE cascade)

- **INVERSE KE CASCADE**: EDDY MERGING TWO SMALL-SCALE EDDIES WITH A SMALL DEPTH SCALE MERGE TO PRODUCE ONE EDDY WITH A LARGER HORIZONTAL AND VERTICAL SCALES
  => TRIAD INTERACTIONS

- **DIRECT TRACER CASCADE**: A LARGE-SCALE TRACER ANOMALY IS STIRRING BOTH, HORIZONTALLY AND VERTICALLY LEADING TO SMALL-SCALE ANOMALIES
  => HORIZONTAL + VERTICAL SHEARS

The Okubo-Weiss quantity allows to understand the inverse KE cascade and direct tracer cascade

$$\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} - f\,\vec{k}\times\vec{v} = -\frac{\nabla p}{\rho_0}$$

$$\rightarrow \boxed{\nabla\cdot(\vec{v}\cdot\nabla\vec{v}) - f\zeta = -\frac{\Delta p}{\rho_0}}$$

$O(R_0)$ $O(1)$ $O(1)$.

$\nabla\cdot(\vec{v}\cdot\nabla\vec{v})$ is the Okubo-Weiss quantity

$$\rightarrow \boxed{\nabla\cdot(\vec{v}\cdot\nabla\vec{v}) = \frac{1}{2}\left[S_1^2 + S_2^2 - \zeta^2\right]}$$

$$S_1 = \left[\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right],\quad S_2 = \left[\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right],\quad \zeta = \left[\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right]$$

O.W. < 0 in vorticity regions. → Eddy tracking

O.W. > 0 in strain regions. → **Dispersion of tracers** (Lyapounov exponents)

Strong underestimation of the nonlinear interactions using altimeter data:

Scales smaller than 100 km (sub-mesoscales) have to be taken into account !

Gradient wind balance (includes nonlinear terms)

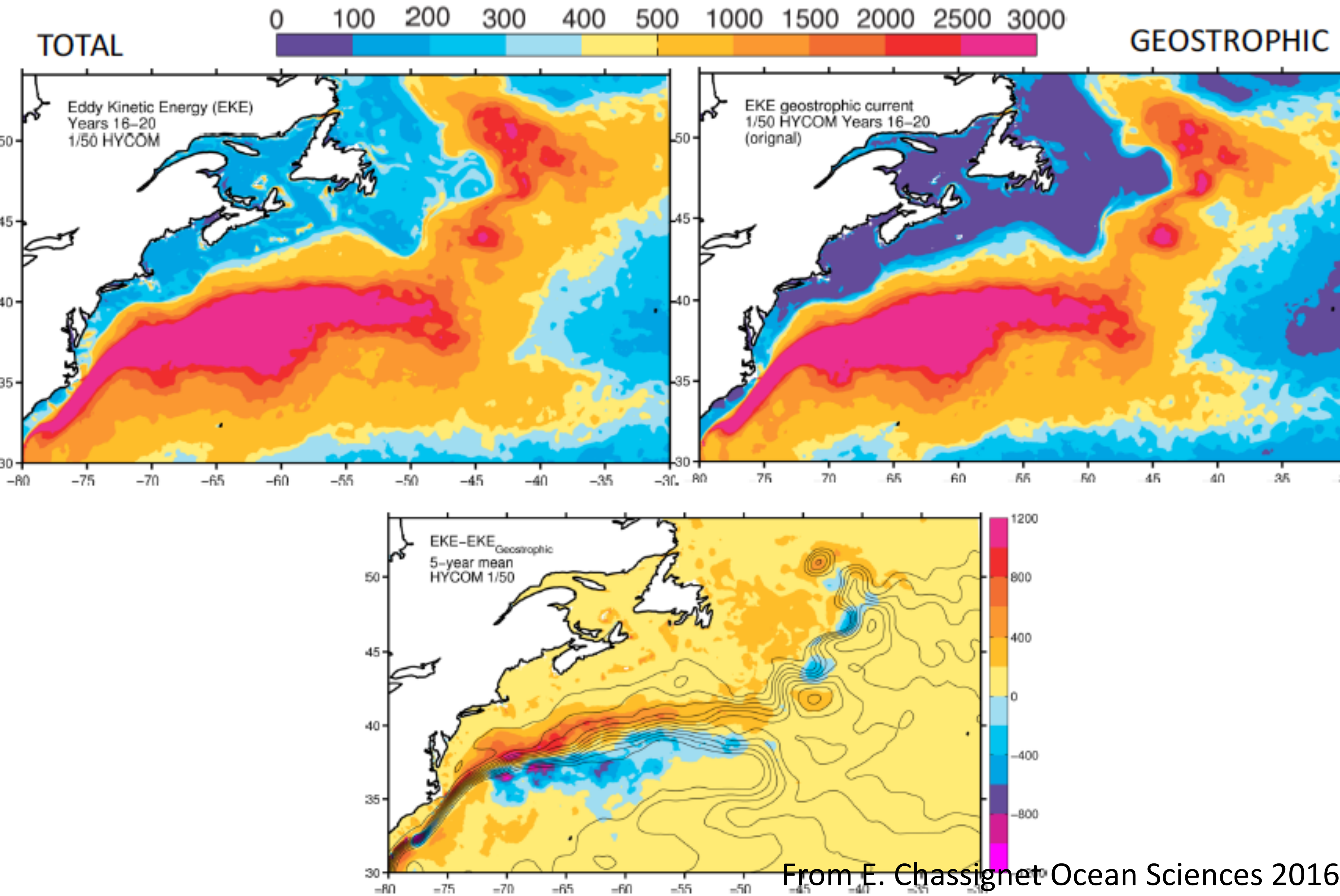
$$\boldsymbol{u}.\nabla\boldsymbol{u}+f\boldsymbol{k}\times\boldsymbol{u}=-g\nabla\eta$$

cyclogeostrophic motions [O(Ro)]

Coriolis term [O(1)]

pressure term [O(1)]

EKE geostrophic difference (1/50°)



From E. Chassignet Ocean Sciences 2016

The Okubo-Weiss quantity allows to understand the inverse KE cascade and direct tracer cascade

$\nabla \cdot (\mathbf{u} \cdot \nabla \mathbf{u})$ is the Okubo-Weiss quantity

$$\Rightarrow \boxed{\nabla \cdot (\mathbf{u} \cdot \nabla \mathbf{u}) = \frac{1}{2}\left[s_1^2 + s_2^2 - \zeta^2 \right]}$$

$$s_1 = \left[\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right], \quad s_2 = \left[\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right], \quad \zeta = \left[\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right]$$

O.W. < 0 in vorticity regions. Weak dispersion of tracers and particles

O.W. > 0 in strain regions. Strong dispersion of tracers and particles

→ **Dispersion of tracers** (Lyapounov exponents)

Rossby number in numerical models is LARGER than that from altimetry data

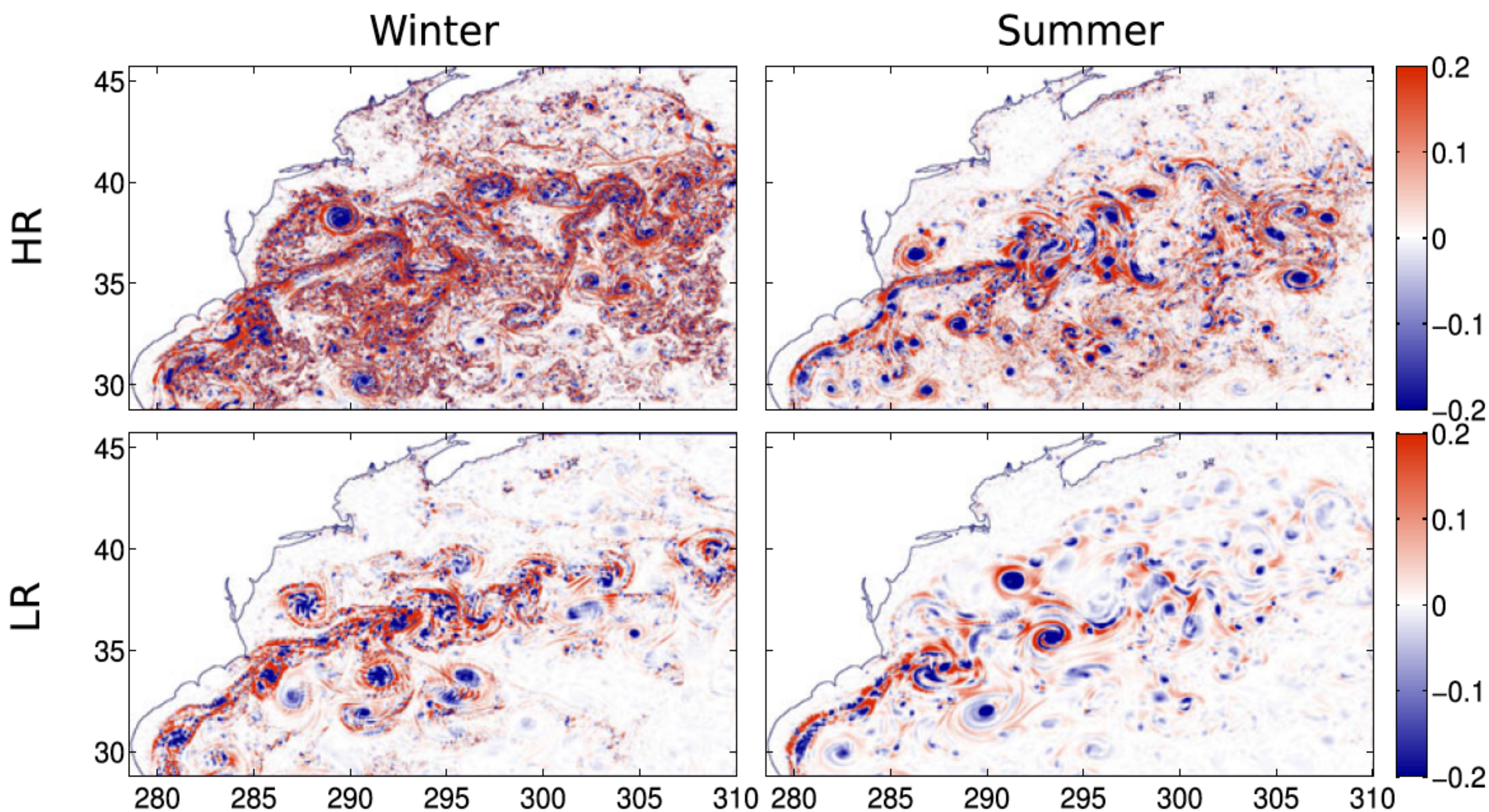


Fig. 14 Okubo–Weiss parameter normalized by f_0^2 computed at the surface (5 m) for winter (*left column*), summer (*right column*), HR (*top row*), and LR (*bottom row*)

From numerical simulations [Mensa et al., OD 2013]

Impact of scales < 100 km in terms of the dispersion of pollutants or floats by the surface currents (Finite Size Lyapunov Exponents) [Haza et al. '12]

No submesoscale

With submesoscales

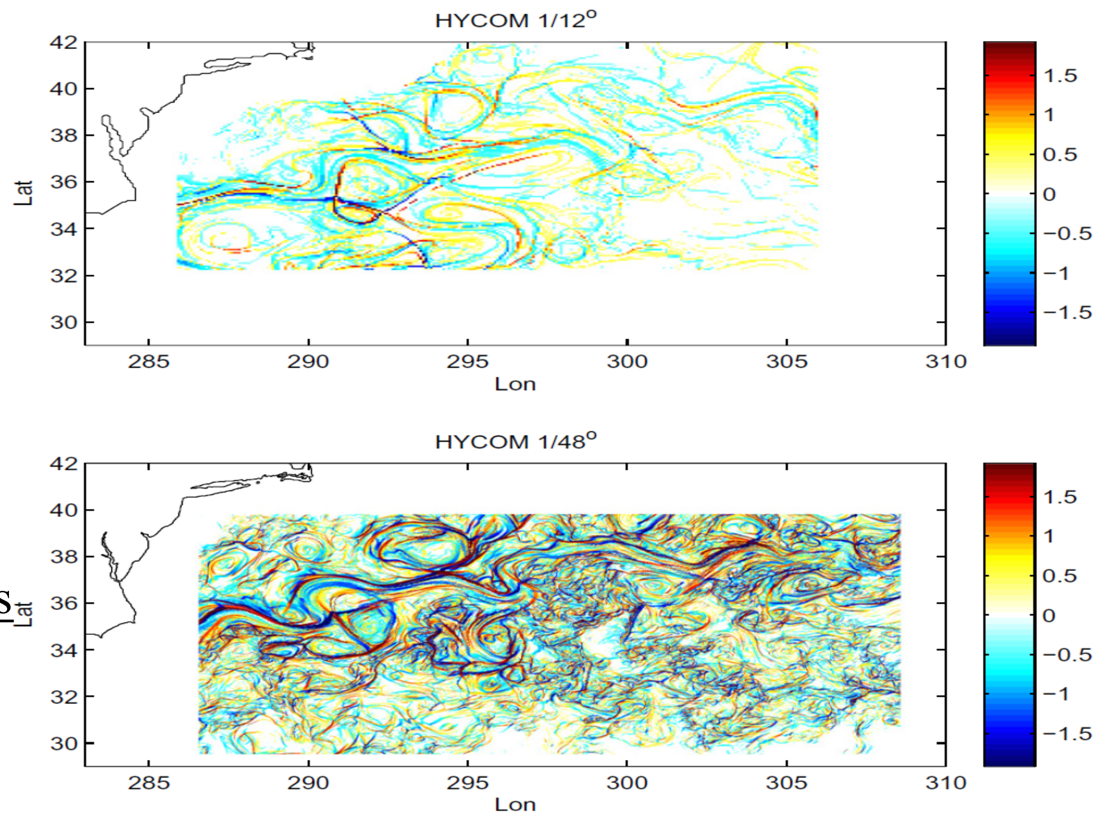
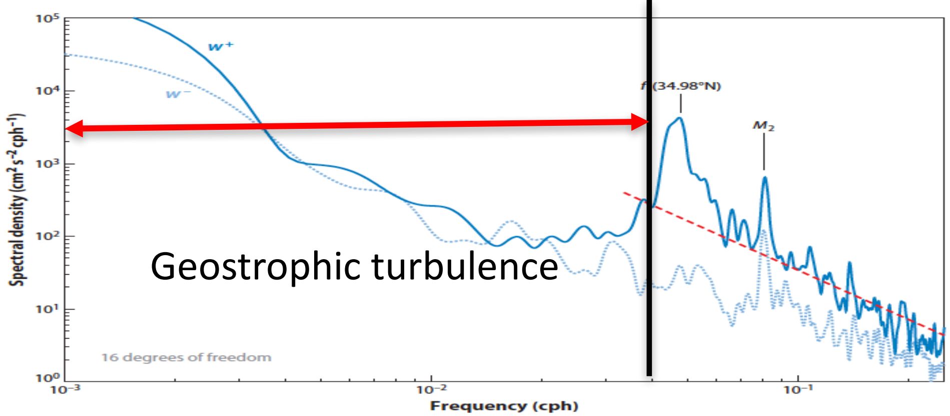


Fig. 1. FSLE branches from 1/12° (upper panel) and 1/48° (lower panel) HYCOM simulations in the Gulf Stream region. Note the rich submesoscale field in the higher resolution case. The color panels indicate FSLE in 1/days. Blue colors show inflowing/stable LCS from forward in time, and red colors out-flowing/unstable LCS from backward in time particle advection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

When scales < 100 km are present FSLE have a larger magnitude and involve smaller scales

=> Dispersion by scales < 100 km is significant.

These ideas are presently tested in the Gulf of Mexico where a very large number of surface drifters have been deployed.



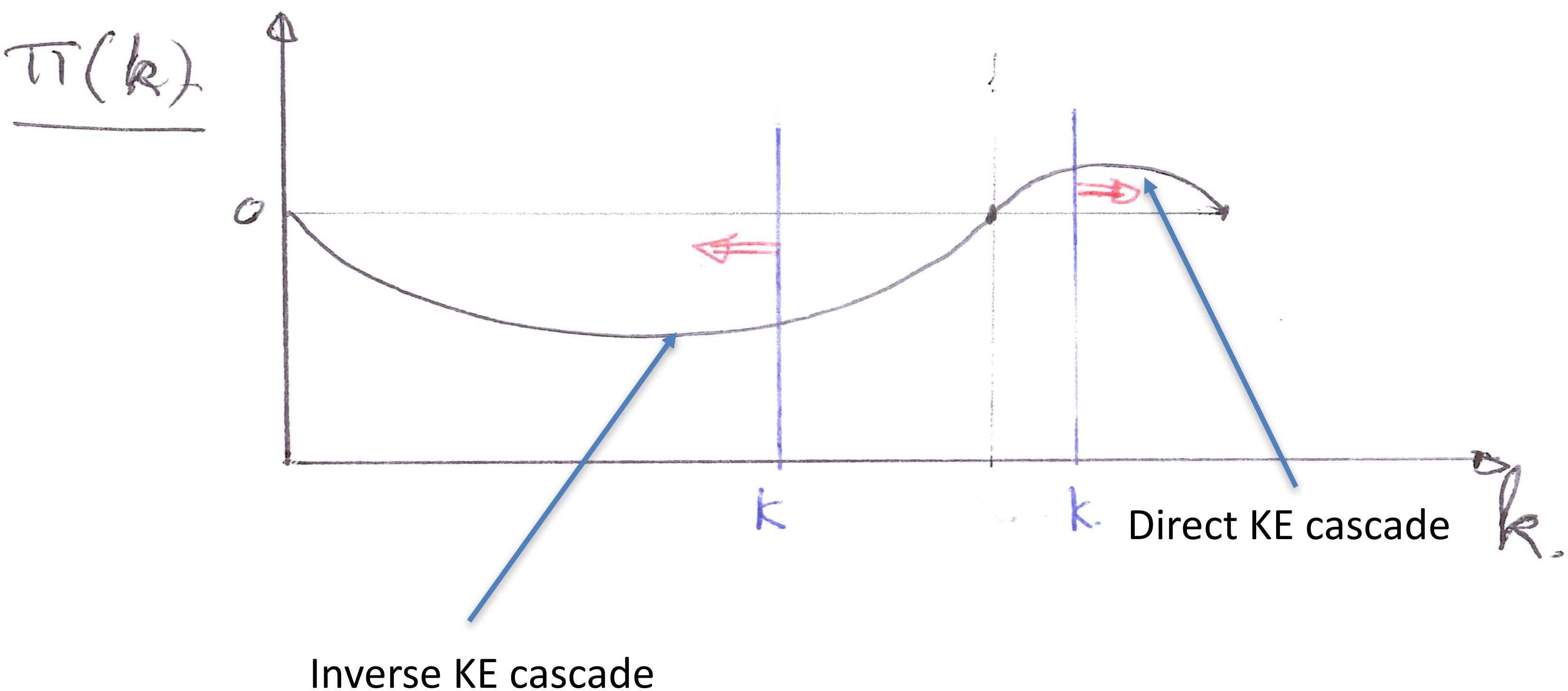
PROPERTIES OF GEOSTROPHIC TURBULENCE

- Concern eddies (100-400km) and submesoscale filaments and eddies (1-50km)
- Better known on a global scale from >25 years of satellite altimeter observations
- Capture most of the kinetic energy in the ocean
- Characterized by strong nonlinear interactions (leading to direct tracer cascace and inverse KE cascade)
- Driven by the PV equation

Spectral kinetic energy flux: $\Pi(k)$: Transfer of kinetic energy between wavenumbers(k)

$$\int_k^{\infty} \frac{\partial E(k)}{\partial t} = \Pi(k)$$

with E(k) the KE at wavenumber k and $\Pi(k)$ the spectral KE flux due to the nonlinear terms



Strong underestimation of the inverse KE cascade by satellite altimeter data !

(Arbic JPO'13)

Two-layer QG turbulence model

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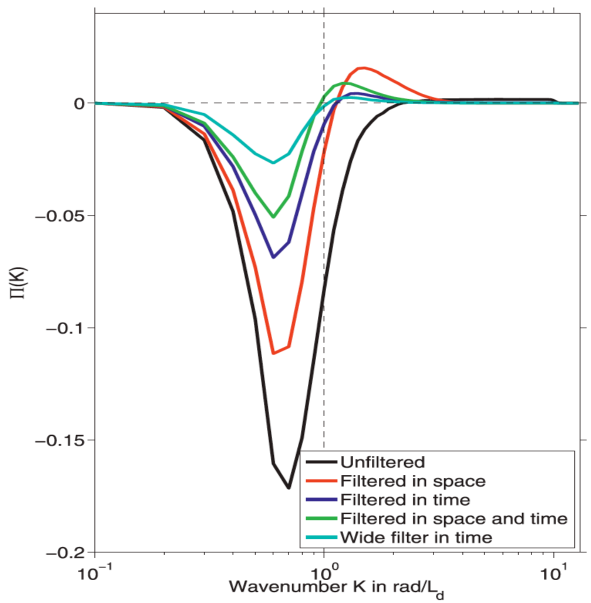
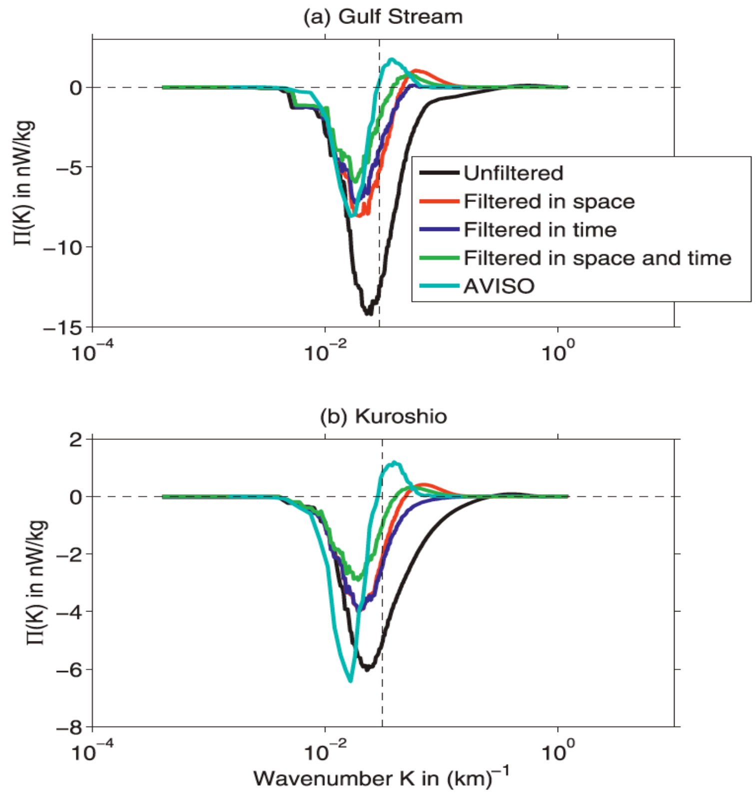


FIG. 6. Spectral flux $\Pi_{KE,1}(K)$ of upper-layer kinetic energy computed from the $\nu = 0$, $F_L = 0.4$ two-layer QG simulation ("unfiltered") and from filtered versions of this simulation. See text for descriptions of filters used. All fluxes normalized by $(\overline{u}_1 - \overline{u}_2)^3/L_d$.

NLOM

FEBRUARY 2013 ARBIC



Small scales (time and space) significantly impact the inverse KE cascade

3-D CASCADES

- INVERSE: EDDY MERGING TWO SMALL-SCALE EDDIES WITH A SMALL DEPTH SCALE MERGE TO PRODUCE ONE EDDY WITH A LARGER HORIZONTAL AND VERTICAL SCALES
  => TRIAD INTERACTIONS

- DIRECT: A TRACER IS STIRRING BOTH, HORIZONTALLY AND VERTICALLY
  => HORIZONTAL (OW QUANTITY)+ VERTICAL SHEARS (THERMAL WIND BALANCE)

THE AGEOSTROPHIC CIRCULATION (DIRECTLY RELATED TO THE NON-LINEAR TERMS) DRIVES THESE CASCADES

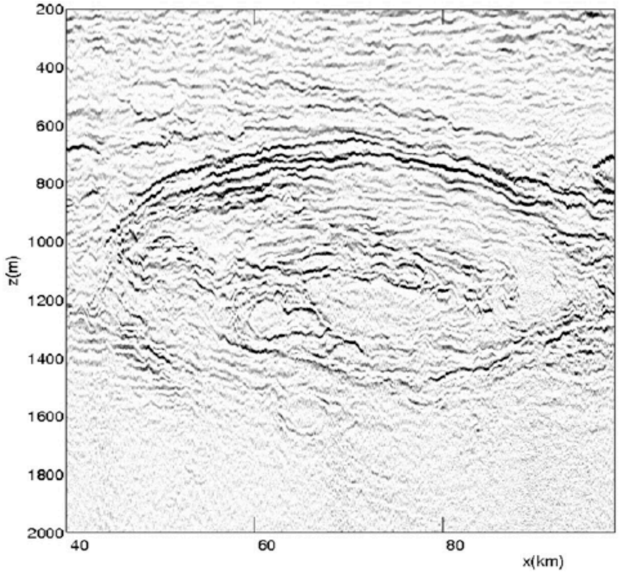


FIG. 1. Seismic reflectivity of the Meddy GO, adapted from Hua et al. (2013). The reflectors are doming all around the meddy, similar to Biescas et al. (2014).

Meunier et al. (JPO 2015)

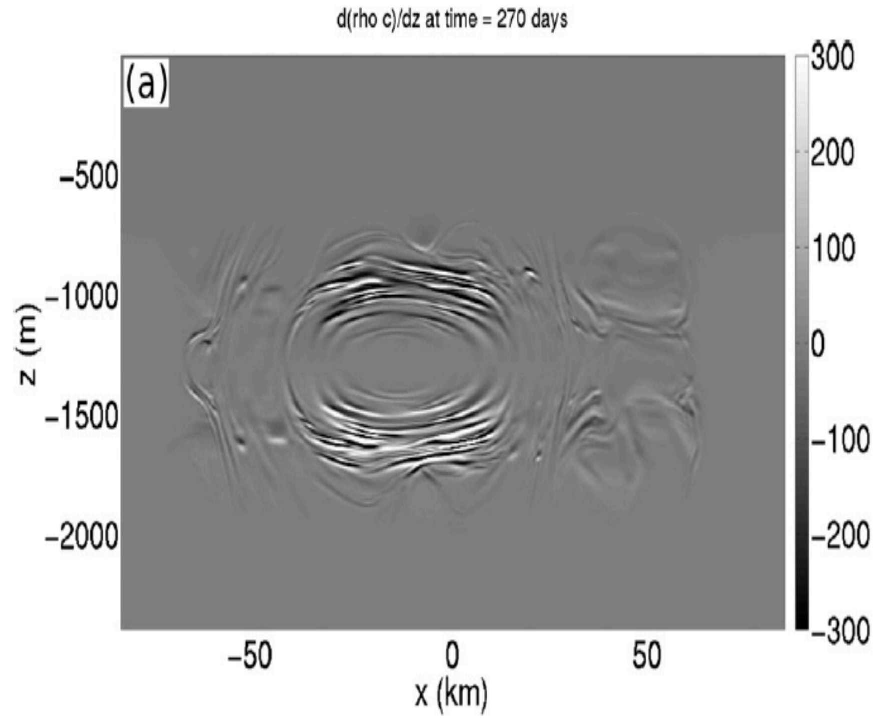
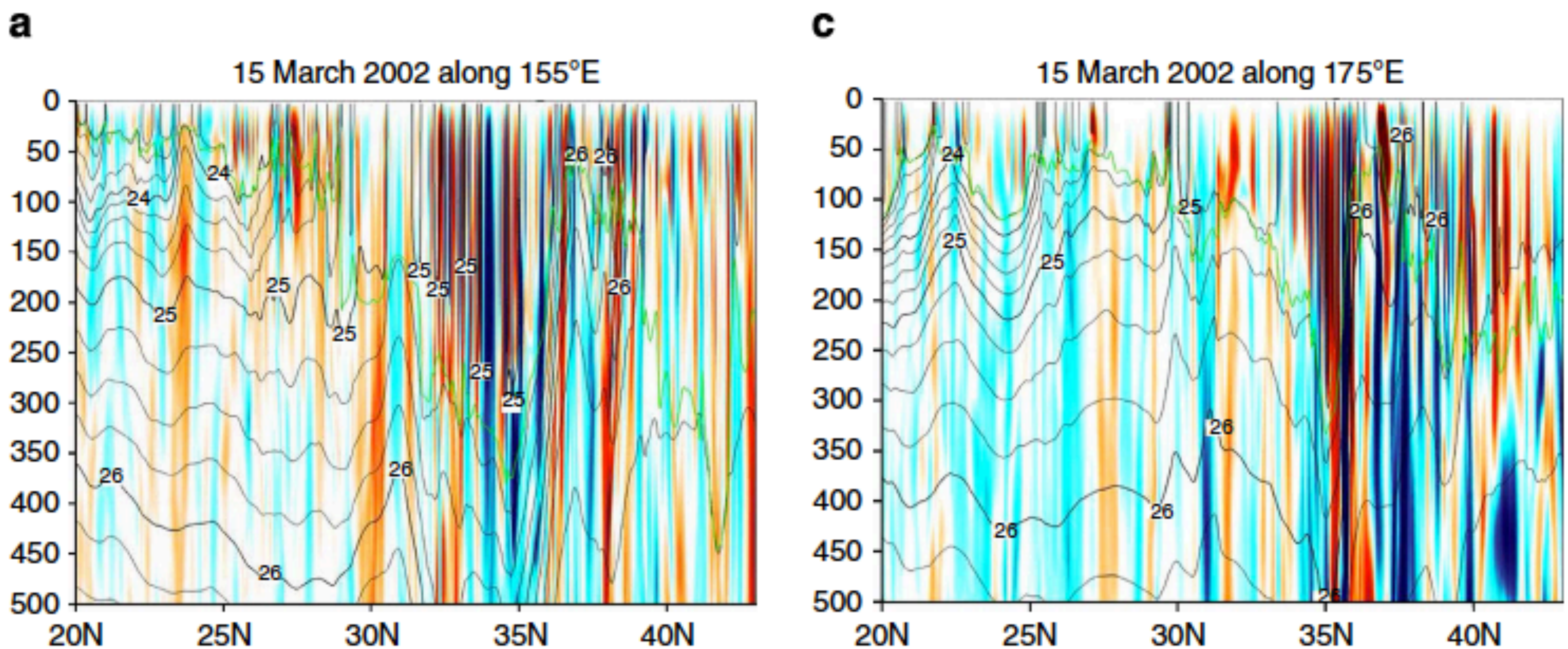


FIG. 4. (a) Vertical section of acoustic reflectivity in the central part of the vortex after 270 days of PE model integration.

Sub-mesoscales impact the transformation of PE in to KE

VERTICAL SECTIONS OF SIGMA AND W

Sasaki et al. 2014



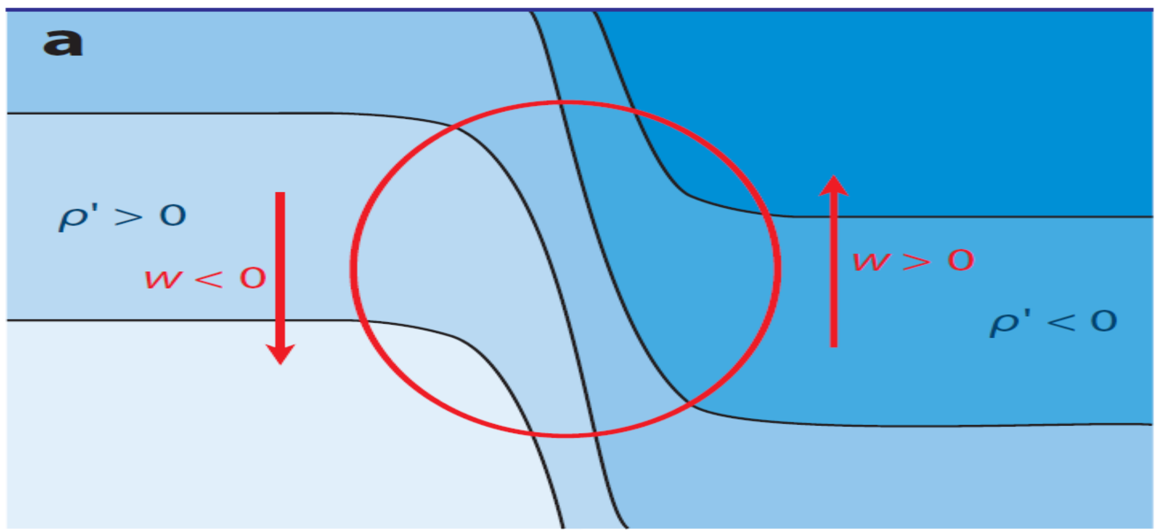
Sub-mesoscales lead to a net transformation of PE in to KE:

$$\overline{\rho'.w} < 0$$

One way to understand the impact of submesoscales on the transformation of PE into KE is to focus on SST ...

SST (or density) gradients are affected by FRONTOGENESIS !

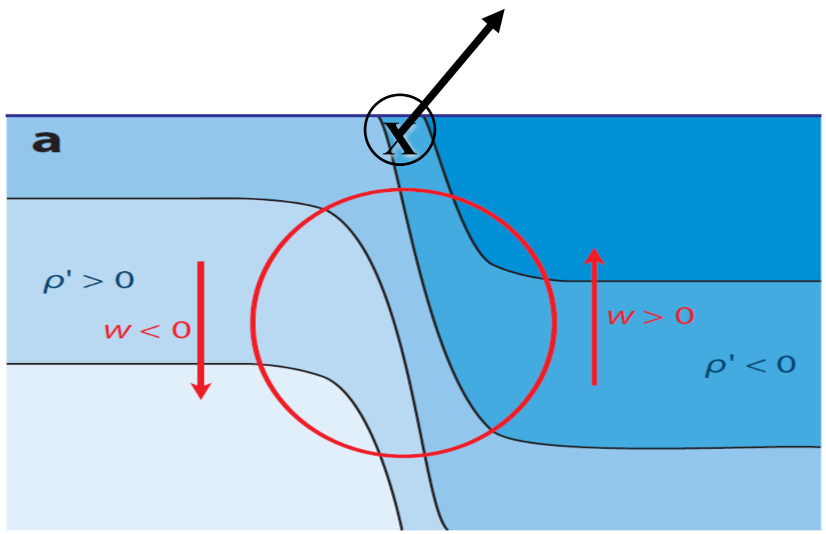
Then, because of frontogenesis, an ageost. circulation, including a W field, develops for the SST front to be in thermal wind balance, involving **|W| ~ |ΔSST|**



⇒ Since SST spectrum slope is in k^{-2} (=> **ΔSST ~ k^2**), this explains that the W-field is mostly significant within submesoscales (~ 20 km)

What are the consequences of this frontogenesis and associated W field on the larger oceanic scales ?

Frontogenesis corresponds to a transformation of Potential Energy (PE) into Kinetic Energy (KE)

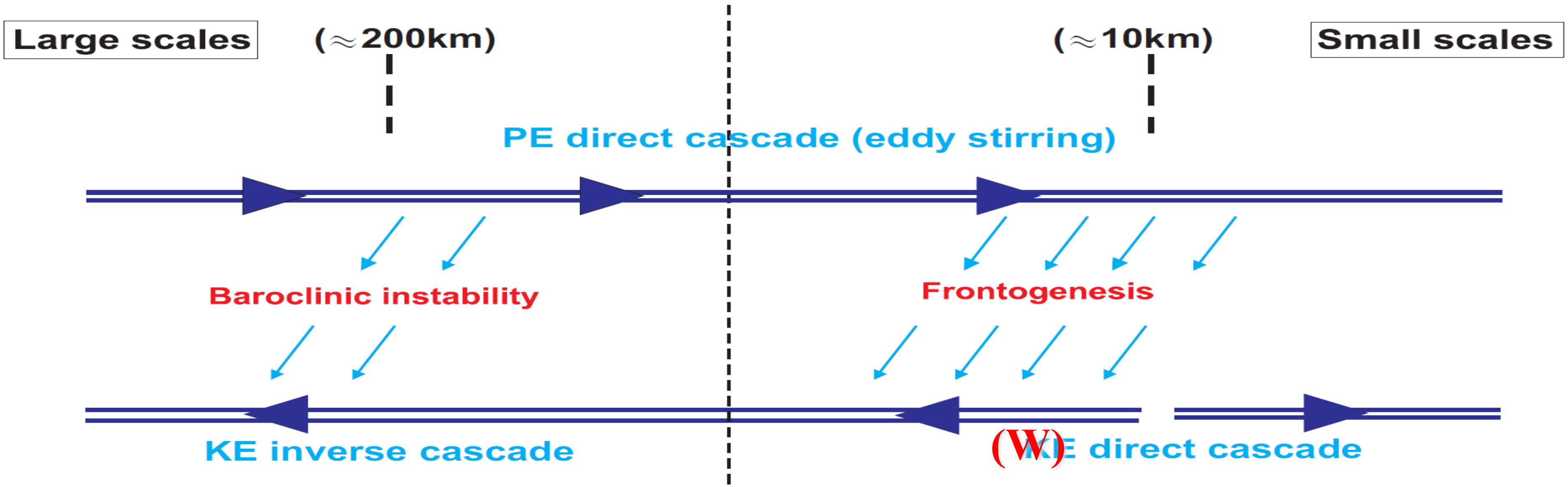


$$\overline{w'\rho'} < 0$$

PE => KE:

This energy transformation mostly occurs at submesoscale (~ 20 km)

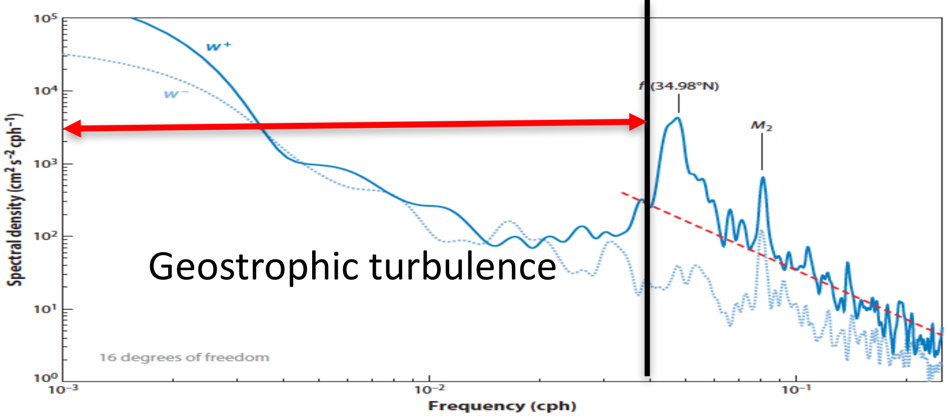
... the unstable frontal dynamics at small scale modifies the nonlinear interactions over a large spectral range



Submesoscales efficiently feed up the KE of mesoscale eddies through a transformation of PE into KE at small scales the acceleration of the inverse KE cascade.

=> **Velocity spectrum has a slope in $k^{-5/3}$** and NOT a slope in k^{-3} ;

=> **Total EKE is larger (by a factor 1.5 – 2)**; submesoscale impact is **not dissipative** ;



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- Better known on a global scale from >25 years of satellite altimeter observations
- Capture most of the kinetic energy in the ocean
- Characterized by strong nonlinear interactions (leading to direct tracer cascace and inverse KE cascade)
- Drive the dispersion of any ocean tracer
- **Driven by the PV equation**

PV EQUATION

Summarize the important quantities related to geostrophic turbulence:

AGEOSTROPHIC CIRCULATION AT MESOSCALE AND SUBMESOSCALE [RELATED TO NON-LINEAR TERMS INVOLVING RV, STRAIN, VERTICAL SHEAR]

Textbooks:

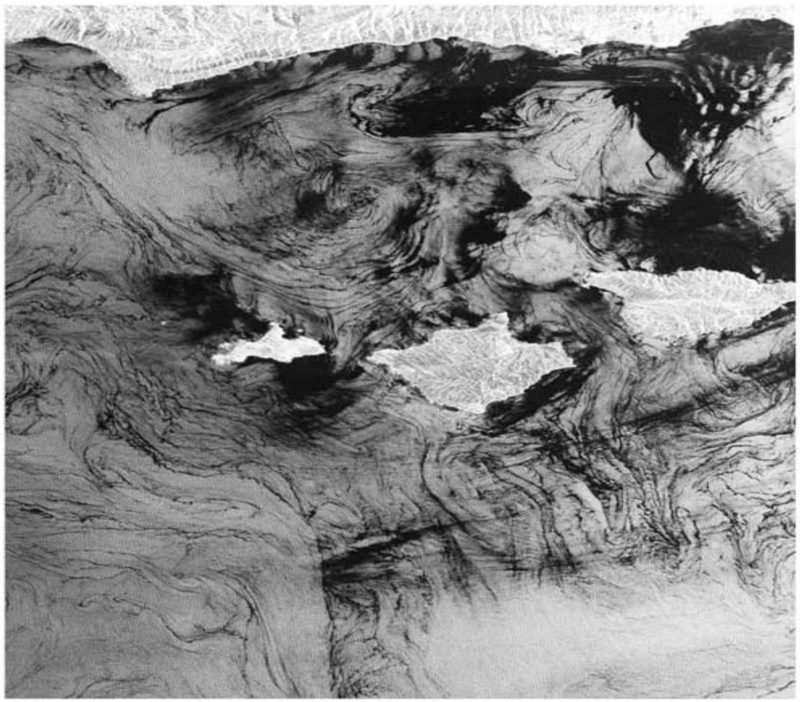
Cushman-Roisin B. & J.M. Beckers (2011): Introduction to Geophysical Fluid Dynamics. Academic Press.

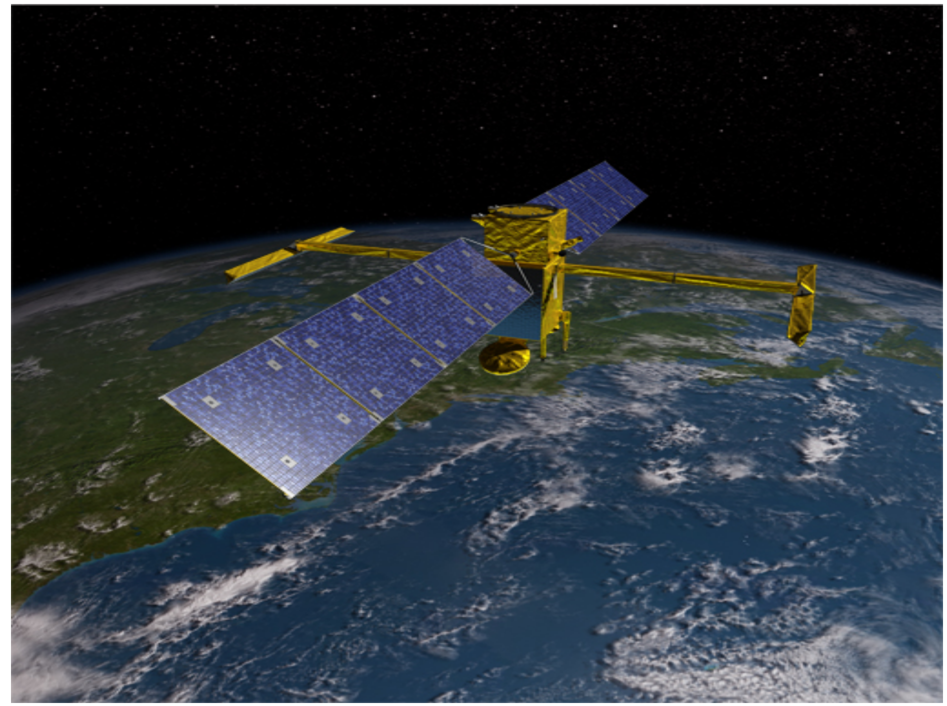
Gill A.E. (1982): Atmosphere-Ocean Dynamics. Academic Press.

Pedlosky J. (2003): Waves in the Ocean and Atmosphere: Introduction to Waves Dynamics.

Kundu P. (2015): Fluid Mechanics, Academic press

“Impact of internal waves on SSH: a challenge for SWOT”





HF internal gravity waves (not only internal tides) have an impact on SSH !

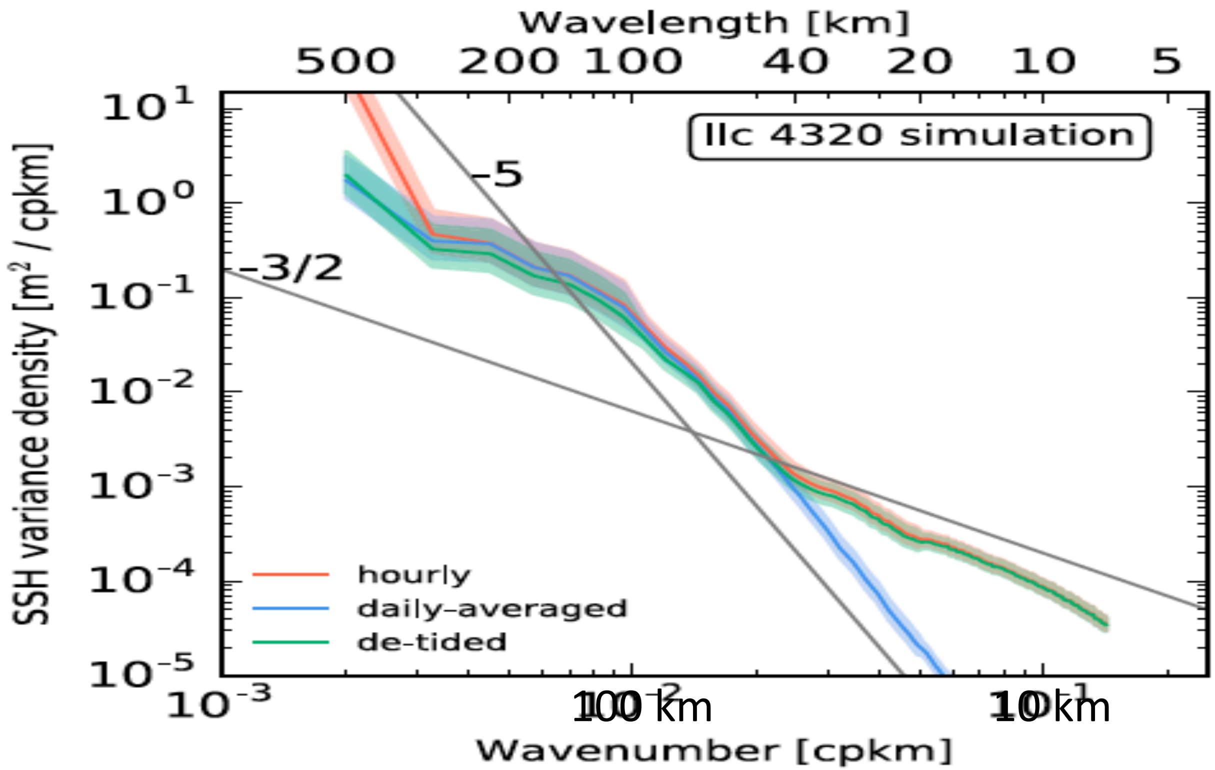


FIG. 9. Isotropic wavenumber SSH variance spectrum. Shades represent 95% confidence limits. For reference, $k^{-3/2}$ and k^{-5} curves are plotted (gray lines).

Rocha et al. JPO 2016: **in the Drake passage …**

Strong seasonality in western boundary currents due to submesoscales:

Results have been confirmed in the Gulf Stream by experimental data [Oleander, LatMix] (Callies et al., NC'15)

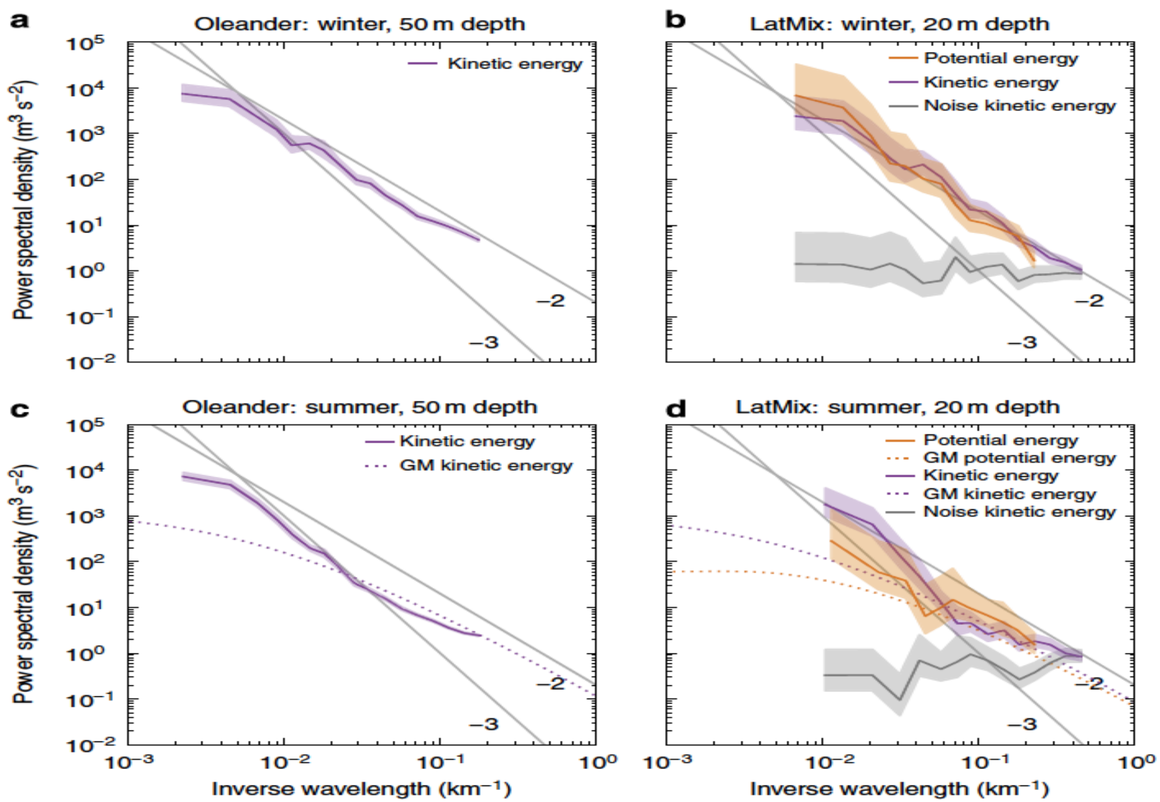


Figure 3 | Seasonality in observations. (**a**) Kinetic energy spectrum at 50 m depth for the Oleander winter data. (**b**) Potential and kinetic energy spectra at 20 m depth for the LatMix winter experiment. (**c**) Kinetic energy spectrum at 50 m depth for the Oleander summer data. (**d**) Potential and kinetic energy spectra at 20 m depth for the LatMix summer experiment. The light shadings are 95% confidence intervals. Also shown are the GM model spectra for internal waves in the seasonal thermocline (with parameters from ref. 30), estimates for the noise level of the LatMix velocity data and reference lines with slopes −2 and −3.

Internal waves affect the velocity spectrum at scales < 50-100 km in summer

See also Callies et al. JPO 2013, Qiu et al. 2016 in press