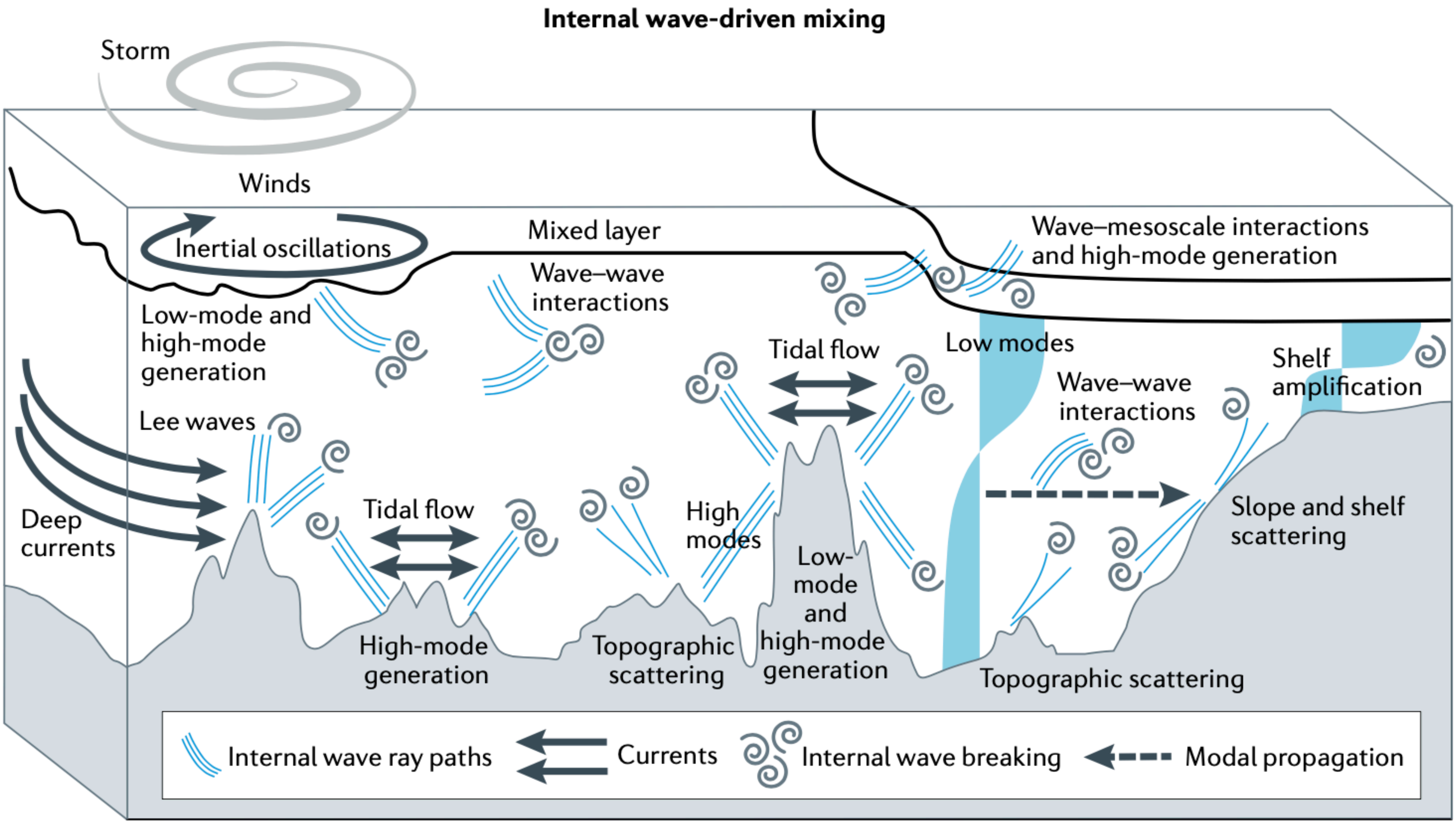
INTERNAL WAVES

3. GENERATION AND DISSIPATION

- **Today : Generation and propagation of Internal waves**
  - Internal tides
  - Lee waves
  - Near-Inertial waves

- **Next lesson : Propagation and dissipation of internal waves**

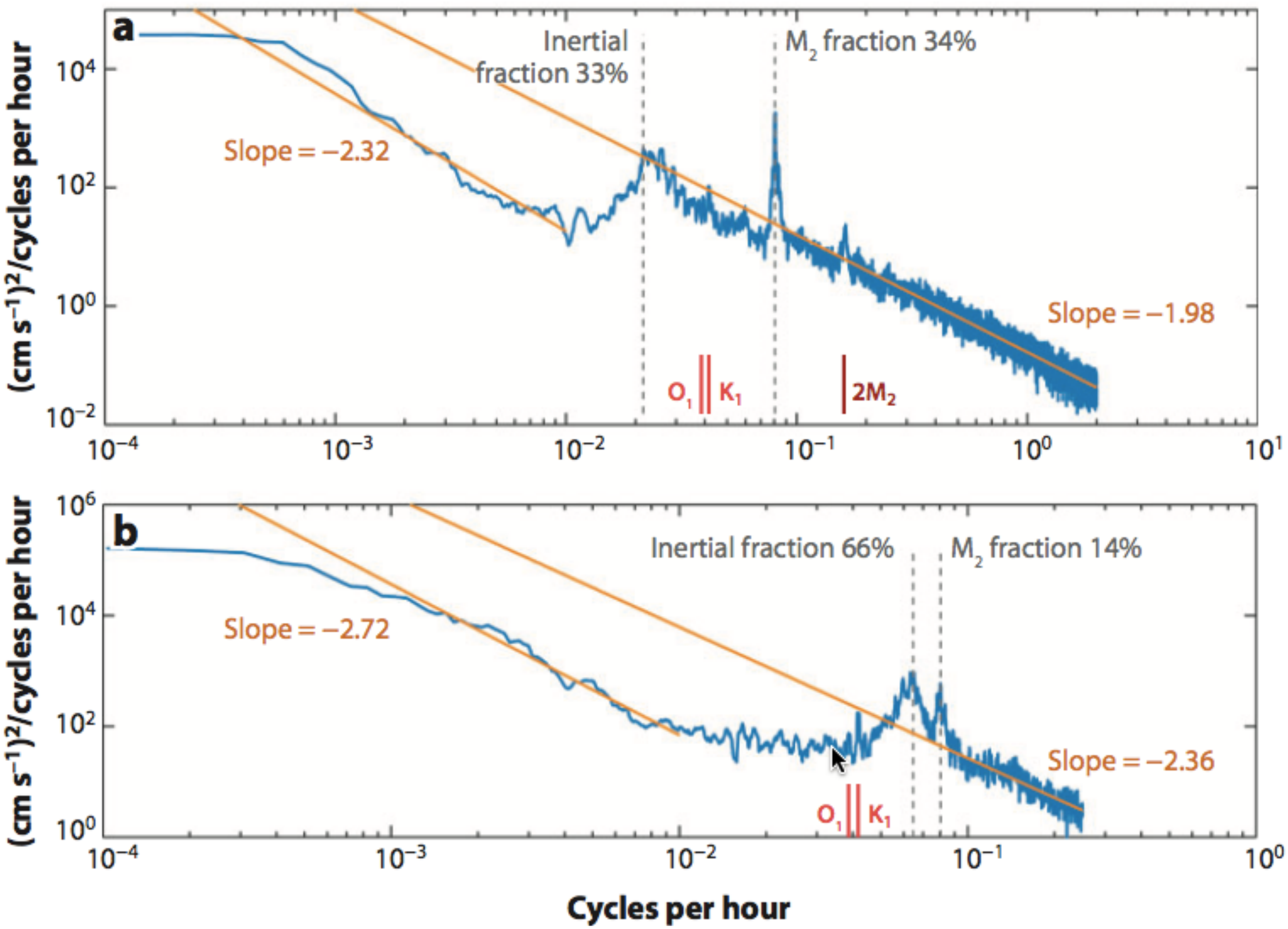
1. Internal waves generation



Whalen et al 2020

1. Internal waves generation

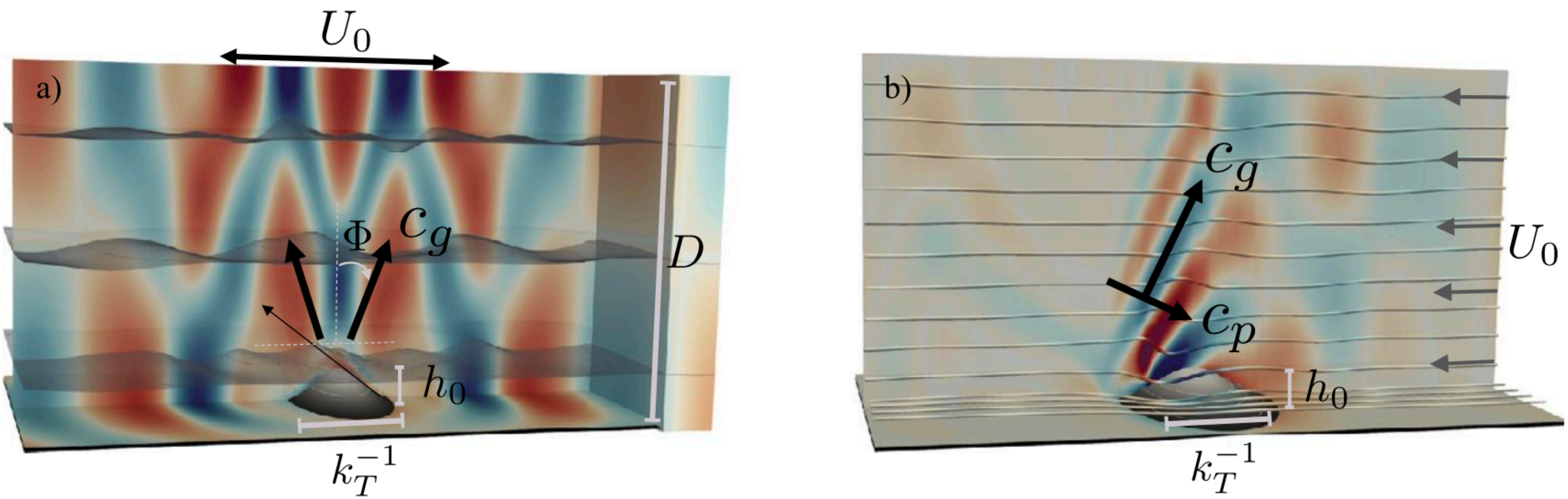
- Winds generate mostly near-inertial waves (frequency close to f)
- Barotropic tides generate internal waves at the frequency of tides that are called internal tides (or baroclinic tides)



(*a*) Kinetic energy estimate for an instrument in the western North Atlantic near 15◦N at 500 m. (*b*) Power density spectral estimate from a record at 1000 m at 50.7◦S, 143◦W, south of Tasmania in the Southern Ocean

1. Internal waves generation

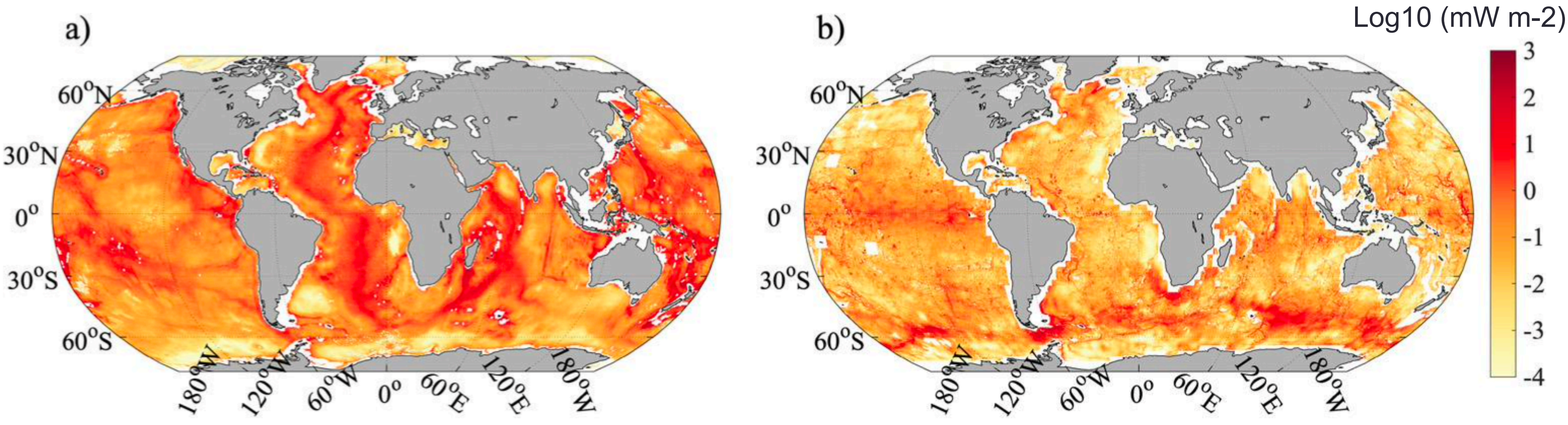
Idealised experiments of the generation of internal tides (left) and lee waves (right)



Musgrave et al — mixing book 2022

1. Internal waves generation

Geography of the generation of internal tides (left) and lee waves (right)



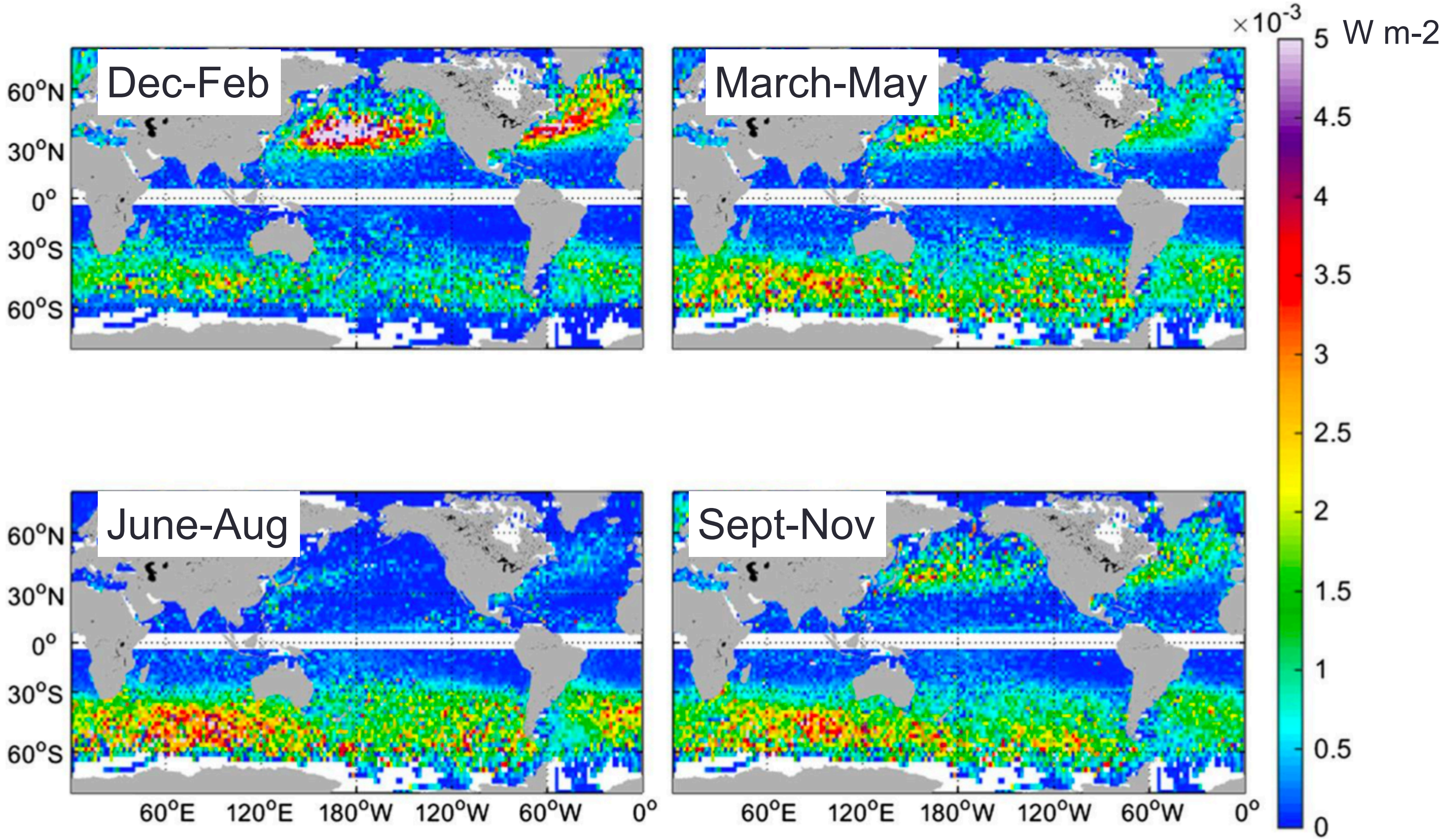
Global contribution ~ 1 TW

Global contribution ~ 0.15-0.75 TW

Musgrave et al — mixing book 2022

1. Internal waves generation

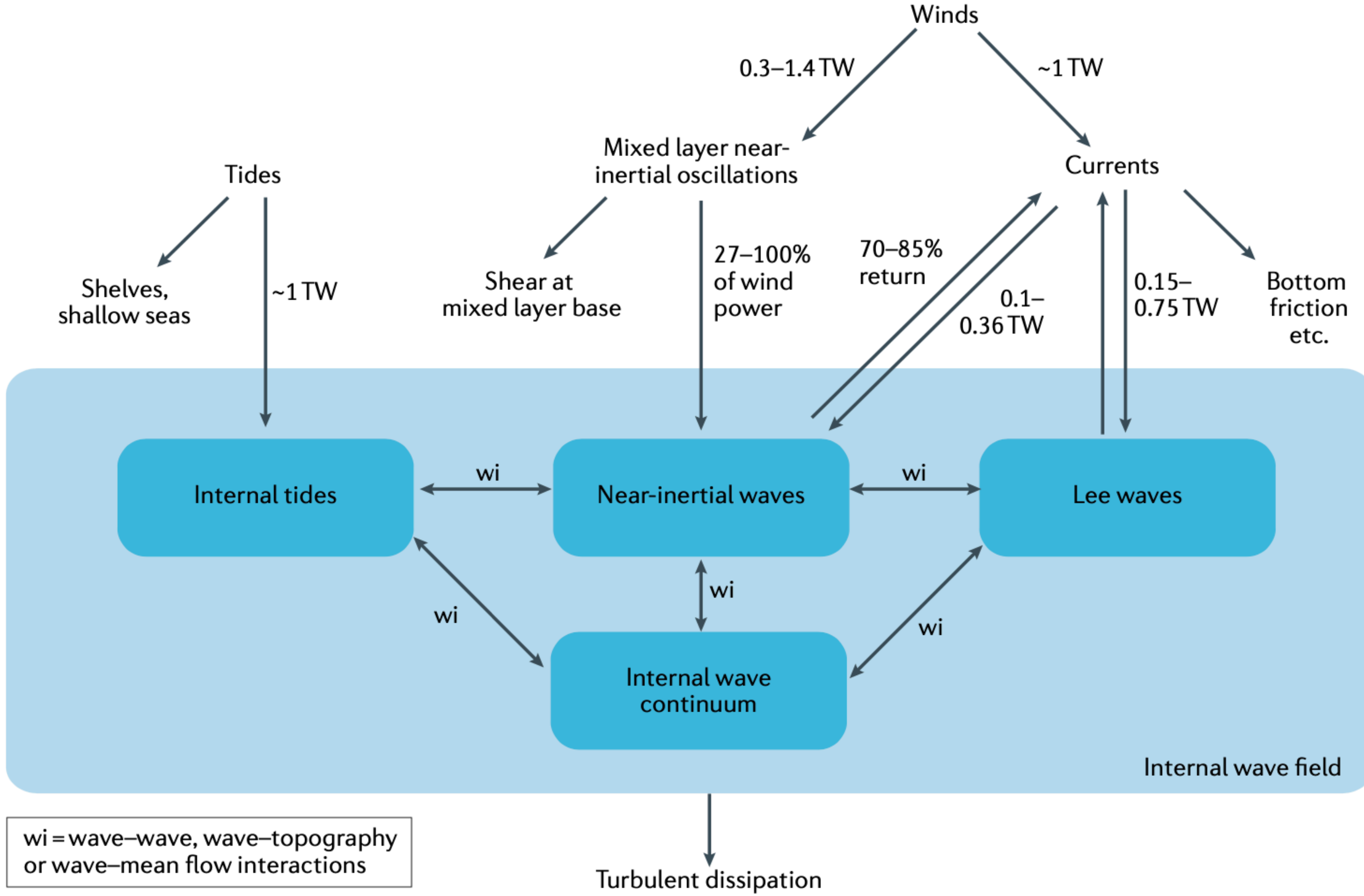
Geography of the generation of near-inertial waves by the wind



Global contribution ~ 0.3-1.5 TW

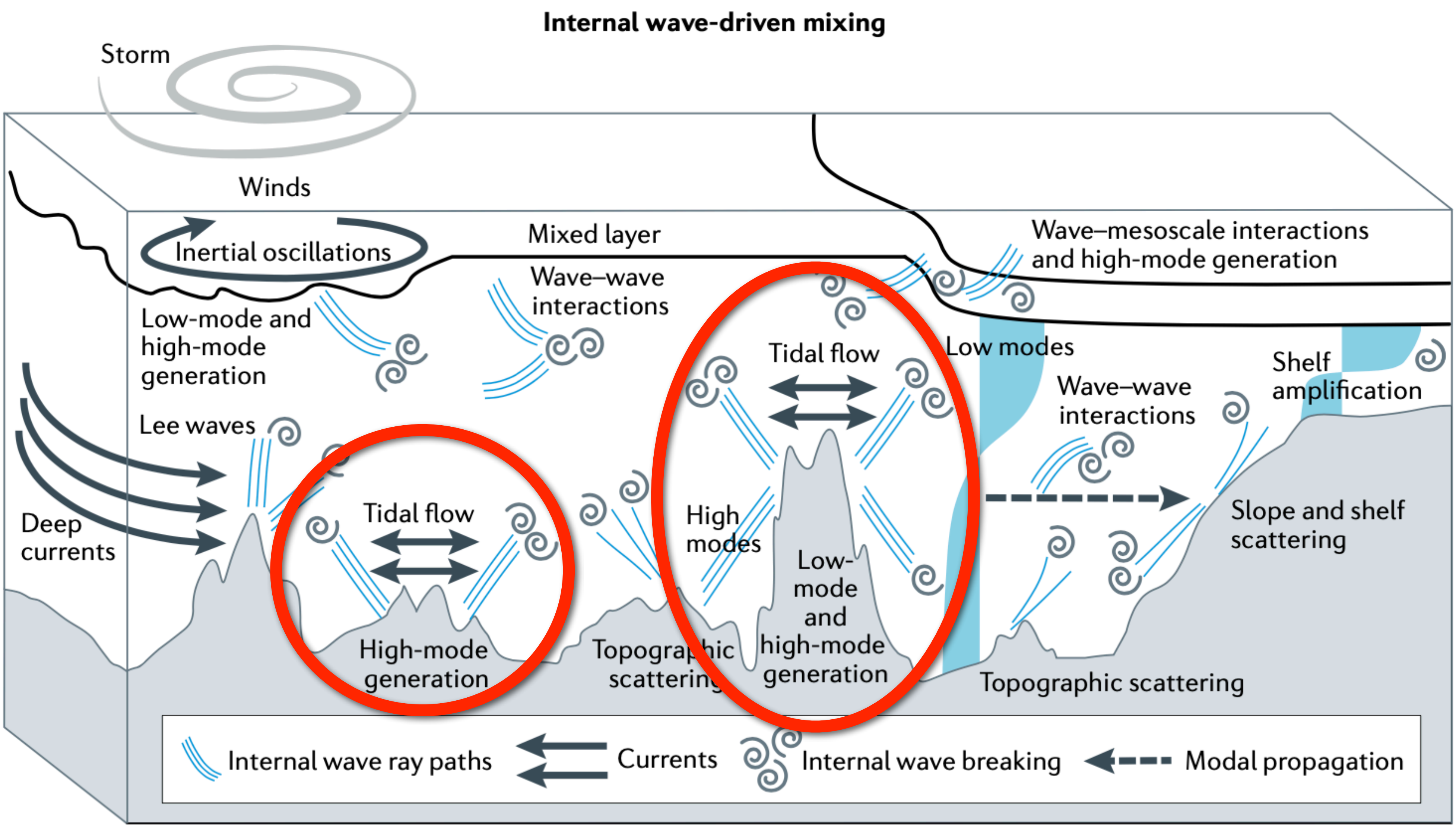
Thomas and Zhai — mixing book 2022

1. Internal waves generation



Whalen et al 2020

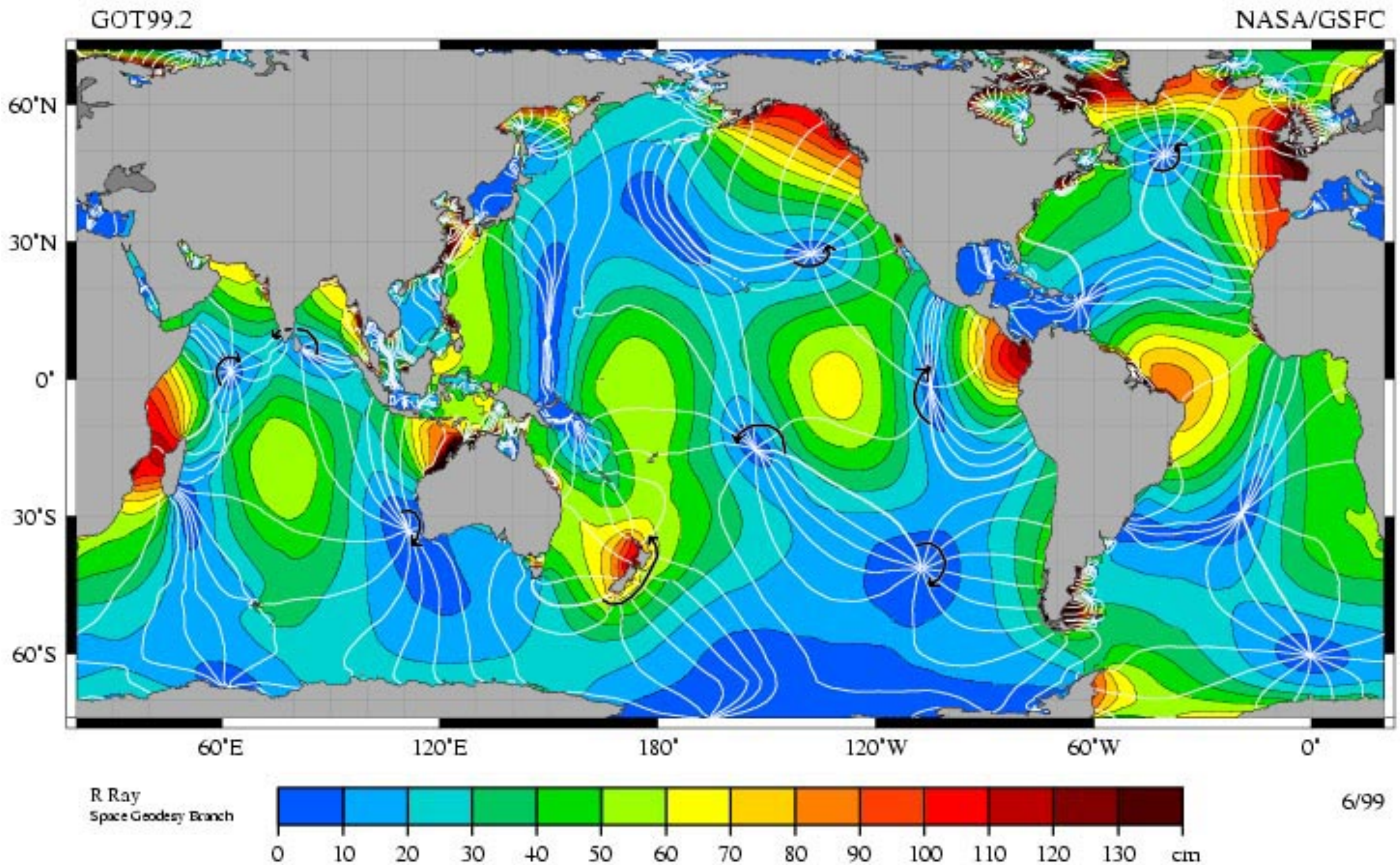
1.1 Generation of internal tides



Whalen et al 2020

1.1 Generation of internal tides

- Barotropic tides

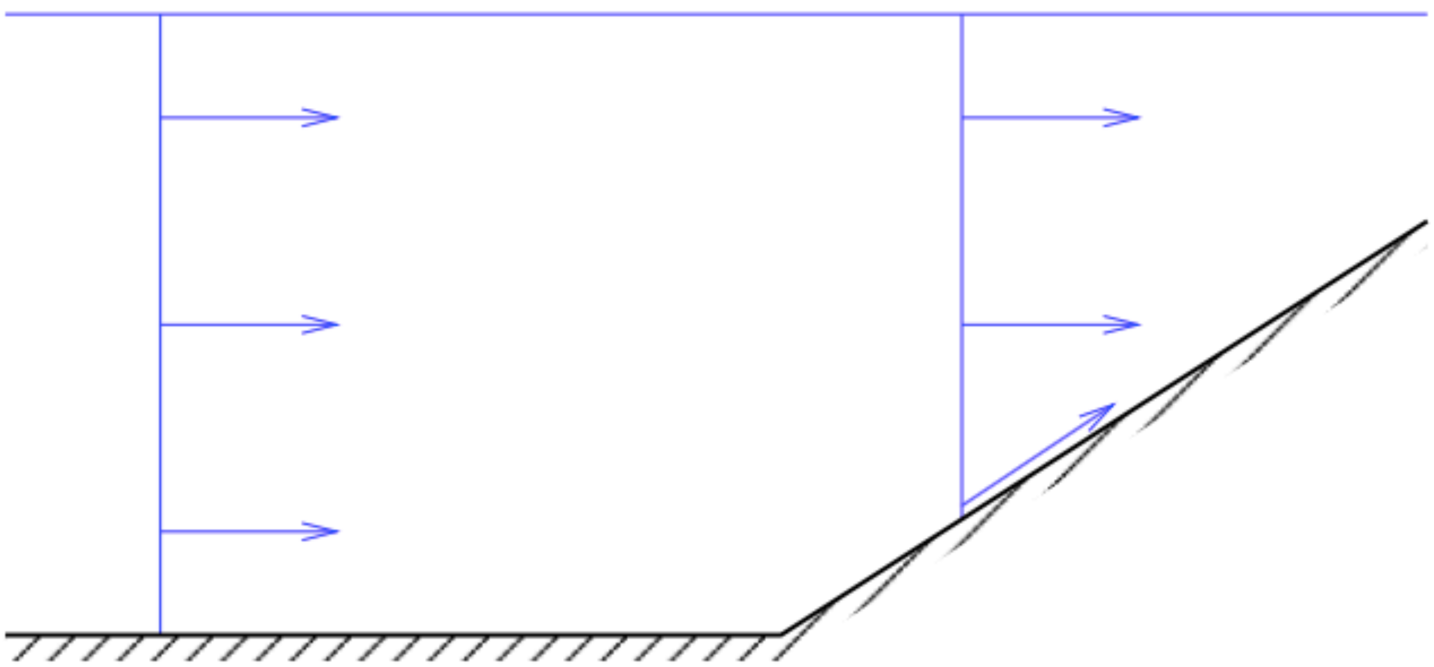


The *M2* tidal constituent. Amplitude is indicated by color, and the white lines are cotidal differing by 1 hour. The colors indicate where tides are most extreme (highest highs, lowest lows), with blues being least extreme.

1.1 Generation of internal tides

- Generation of Internal Tide on a Slope:

A barotropic velocity profile impinging on a sloping boundary. On the boundary, the velocity vector can only have a component tangential to it and hence over the slope, the velocity profile is no longer barotropic. Energy must go into generating internal waves, and propagate away along characteristics (WHOI course, Hendershott and Garrett)



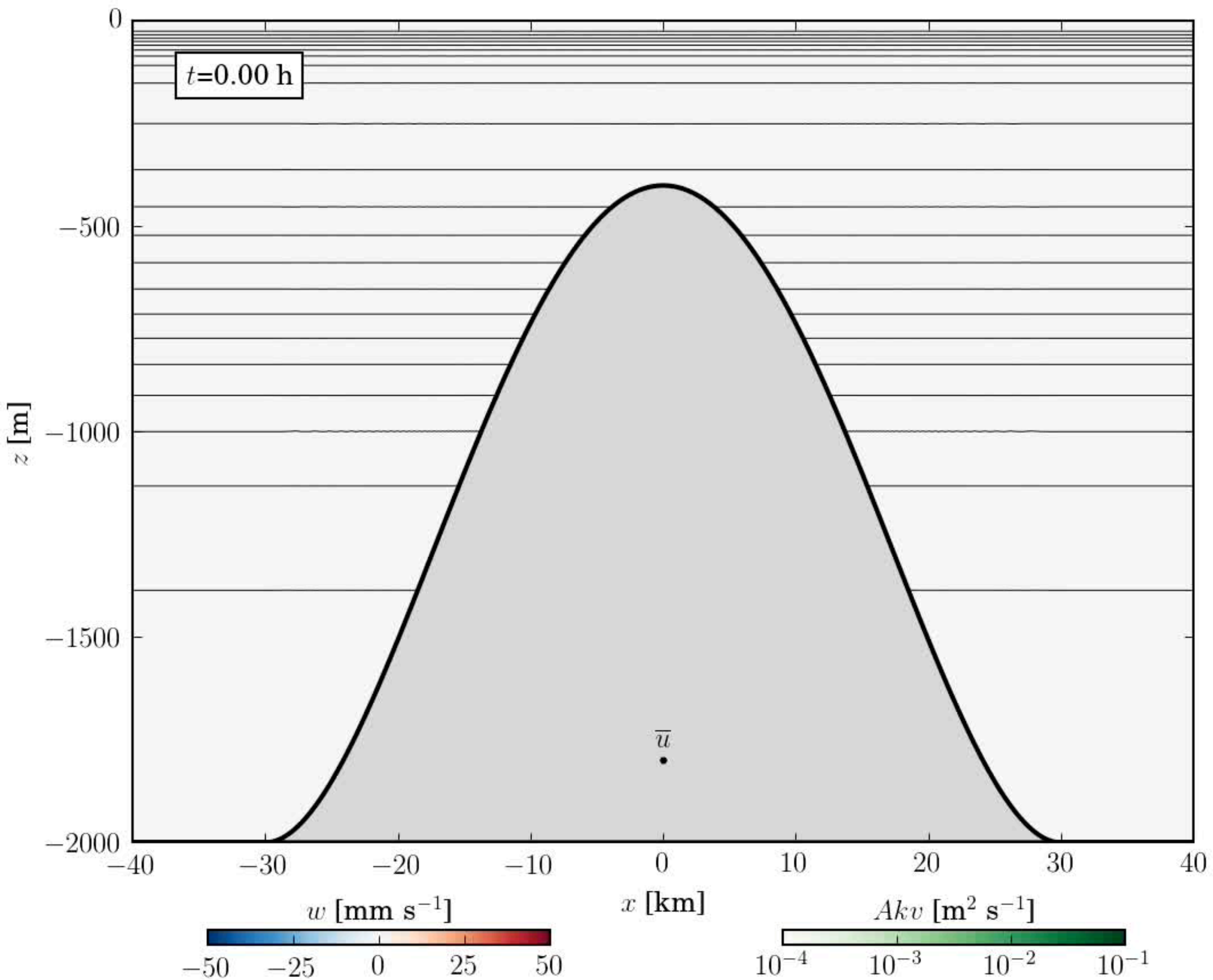
1.1 Generation of internal tides

Internal Tide Generation in the Deep Ocean

Chris Garrett and Eric Kunze

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8W 2Y2; Canada

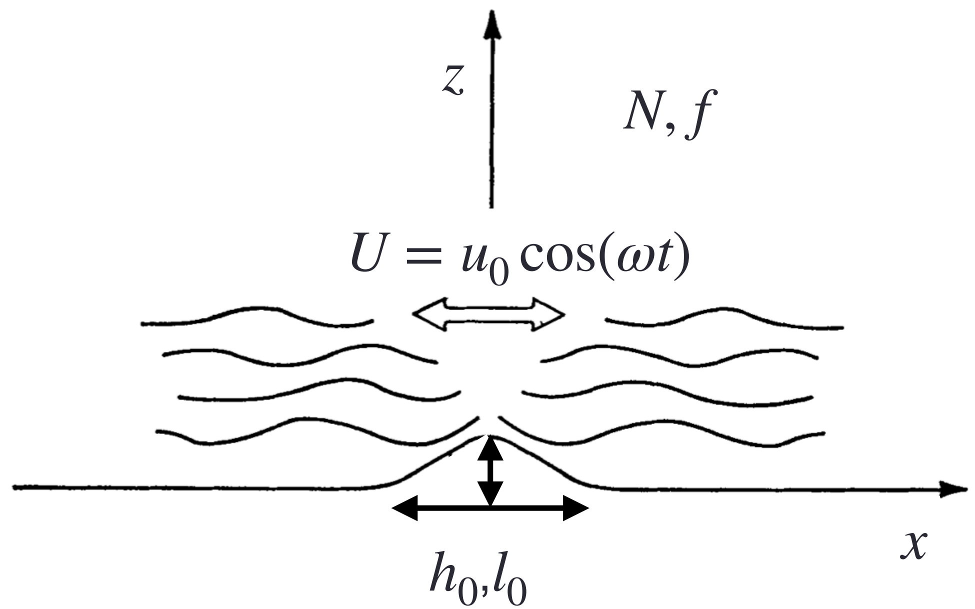
1.1 Generation of internal tides



1.1 Generation of internal tides

6 dimensional parameters :

- Coriolis frequency f
- Brunt-Vaisala frequency N
- Forcing (tidal) frequency ω
- Topographic height h_0
- Topographic wavenumber $k = 2\pi/l_0$
- Magnitude of the tidal current u_0



4 dimensionless parameters :

- ω/N
- ω/f
- ku_0/ω, ratio of the "tidal excursion" to the topographic length scale
- $\epsilon = \dfrac{kh_0}{\alpha} = \dfrac{\text{topographic slope}}{\text{beam slope}}$, with $\alpha = \sqrt{\dfrac{\omega^2 - f^2}{N^2 - \omega^2}}$

Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides

Assumptions to derive a linear expression for w :

(1) - $f < \omega < N$

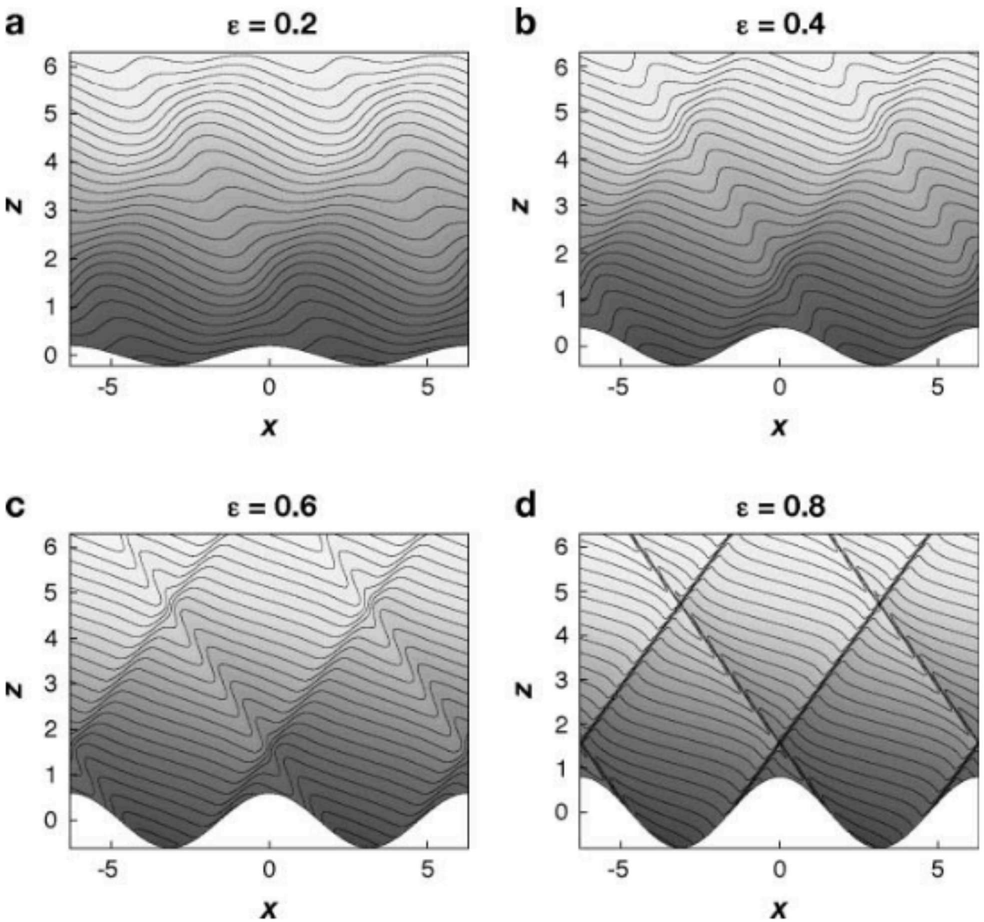
Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides

Assumptions to derive a linear expression for w :

(1) - $f < \omega < N$

(2) - The topographic slopes are subcritical : $\epsilon = \dfrac{kh_0}{\alpha} = \dfrac{\text{topographic slope}}{\text{beam slope}} < 1$



Beam slope in the deep ocean :
$N^2 = 10^{-6} - 10^{-7}$ (rad s^{-1})^2
$f = 10^{-4}$ rad s^{-1}
$\omega = 1.4 \times 10^{-4}$ rad s^{-1} (M2 tide)
Give
$\alpha = 0.09 - 0.34 = 9 - 34\ \%$ (steep !)

Vs typical topographic slopes are ~1-2%

Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides

Assumptions to derive a linear expression for w :

(1) - $f < \omega < N$

(2) - The topographic slopes are subcritical : $\epsilon = \dfrac{kh_0}{\alpha} = \dfrac{\text{topographic slope}}{\text{beam slope}} < 1$

(3) - The tidal excursion is small : $ku_0/\omega < 1$:

—> the distance traveled by a particle in half a tidal cycle = $u_0 \times \dfrac{1}{2} \times \dfrac{2\pi}{\omega} = \dfrac{\pi u_0}{\omega}$

should be smaller than half the topographic wavelength $\dfrac{1}{2} l_0 = \dfrac{\pi}{k}$

—> watch again the movie slide 11 !

For a semi-diurnal tide with $\omega = 1.4 \times 10^{-4}$ rad s^{-1} and $u_0 = 1 - 4$ cm s^{-1} ,

The theory is valid for $l_0 > \dfrac{2\pi u_0}{\omega} > 400 - 1800$ m,

—> OK for most topographic structures over mid-ocean ridges

Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides

For the 2D (x-z) problem with $h = h_0 \cos(kx)$ and a tidal current $u = u_0 \cos(\omega t)$, the response is:

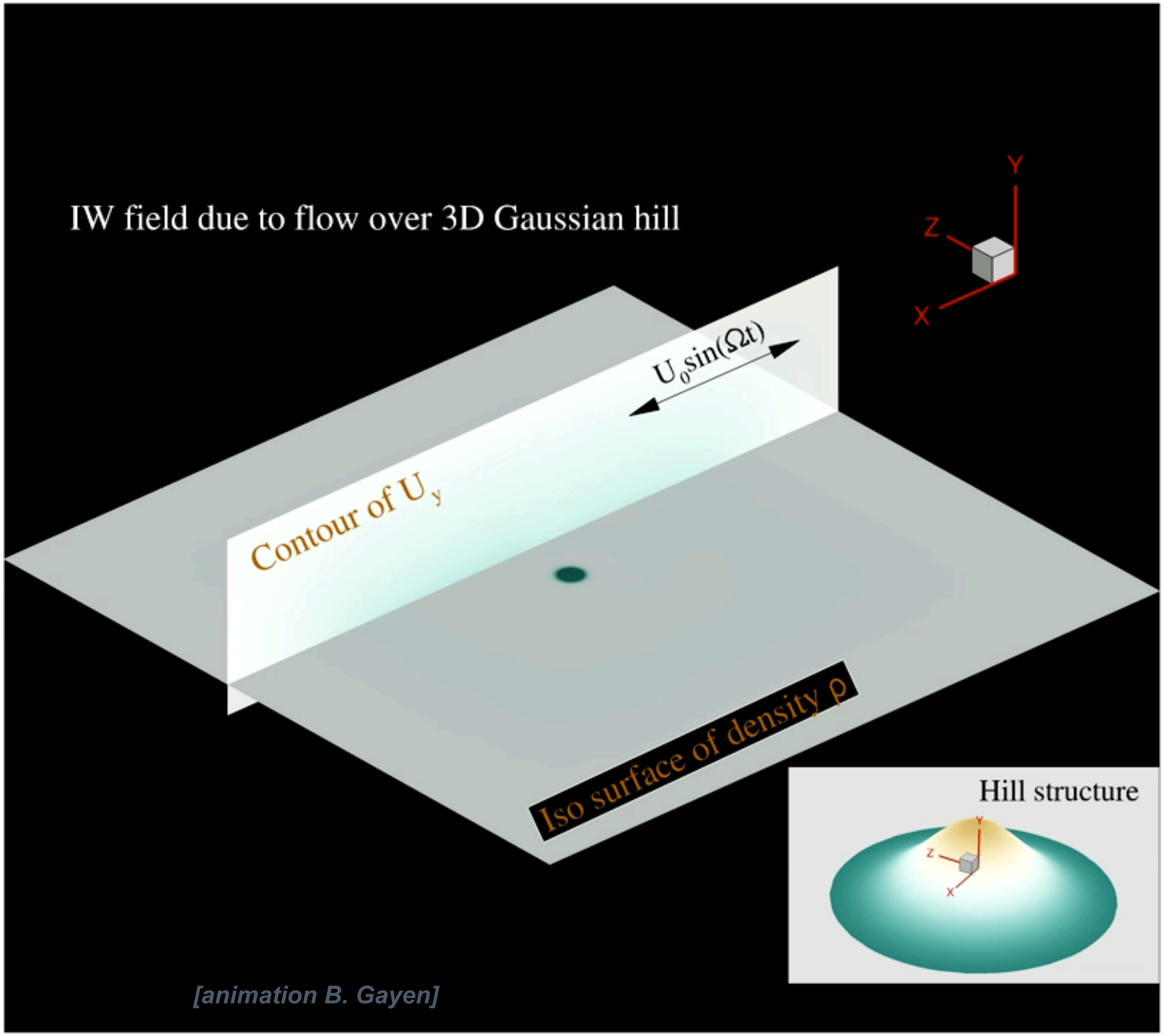
$u = m h_0 u_0 \cos(kx) \sin(mz + \omega t)$
$w = - k h_0 u_0 \sin(kx) \cos(mz + \omega t)$

The vertical energy flux is $F = \frac{1}{4} \rho_0 \omega^{-1} \left[(N^2 - \omega^2)(\omega^2 - f^2) \right]^{1/2} k u_0^2 h_0^2$

Take-home message : the energy flux (conversion) depends on :
- The shape of the seafloor topography k, h_0^2
- The frequencies of the systems ω, f, N
- The squared amplitude of the barotropic tide current u_0^2

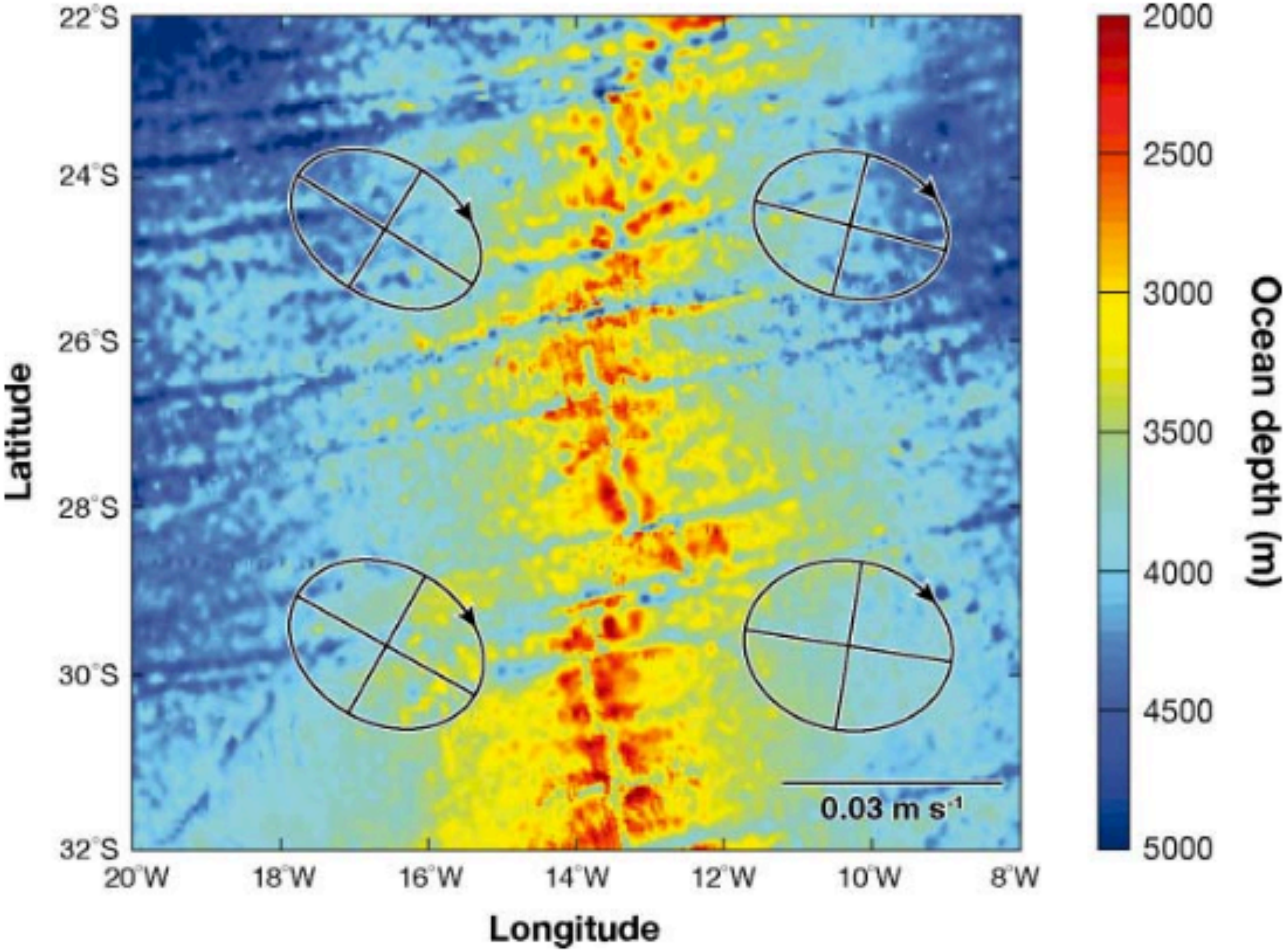
Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides



1.1 Generation of internal tides

This can be generalised to a 3D problem with random bathymetry

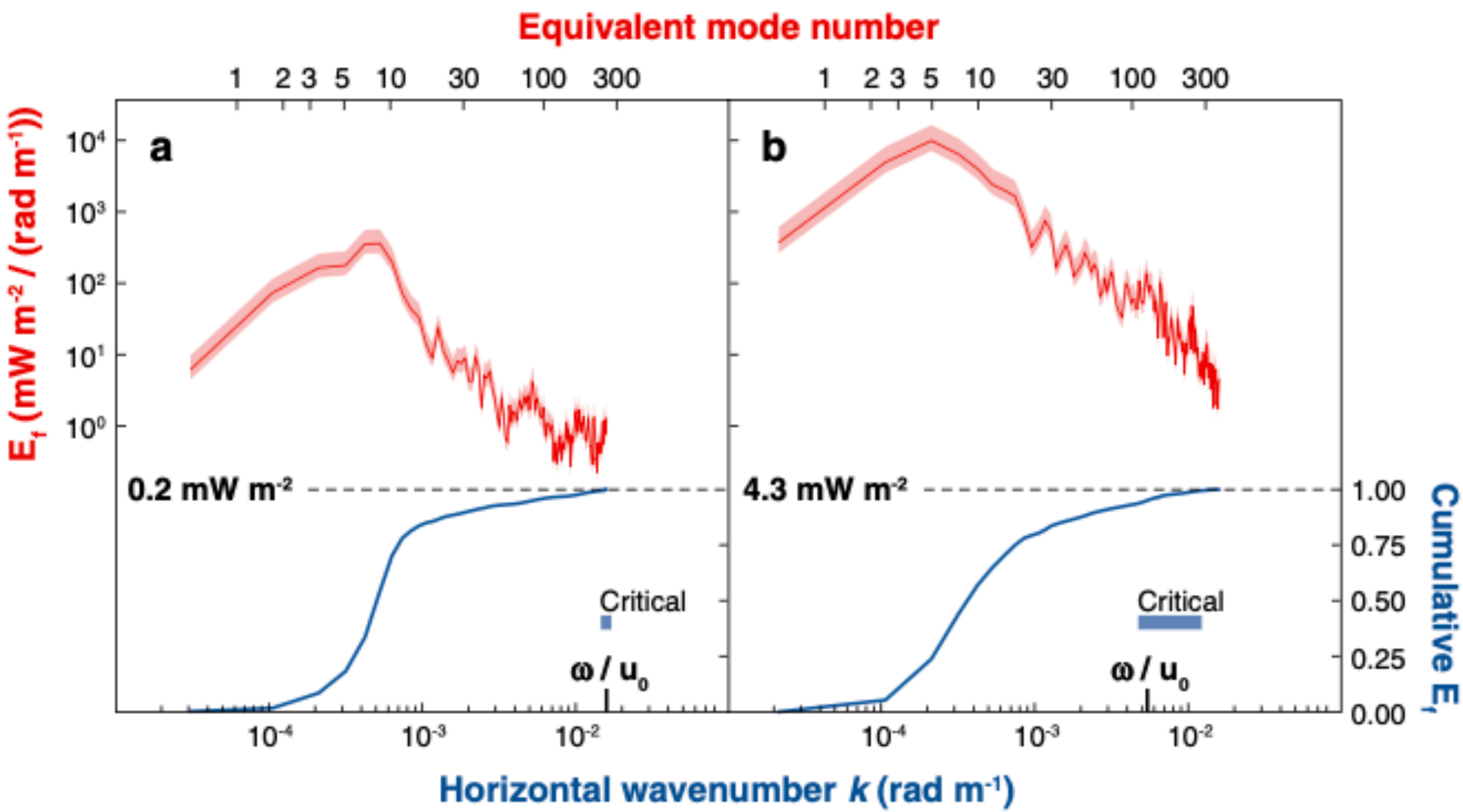


You must know :
- bathymetry properties (power density spectrum)
- tidal currents

Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides

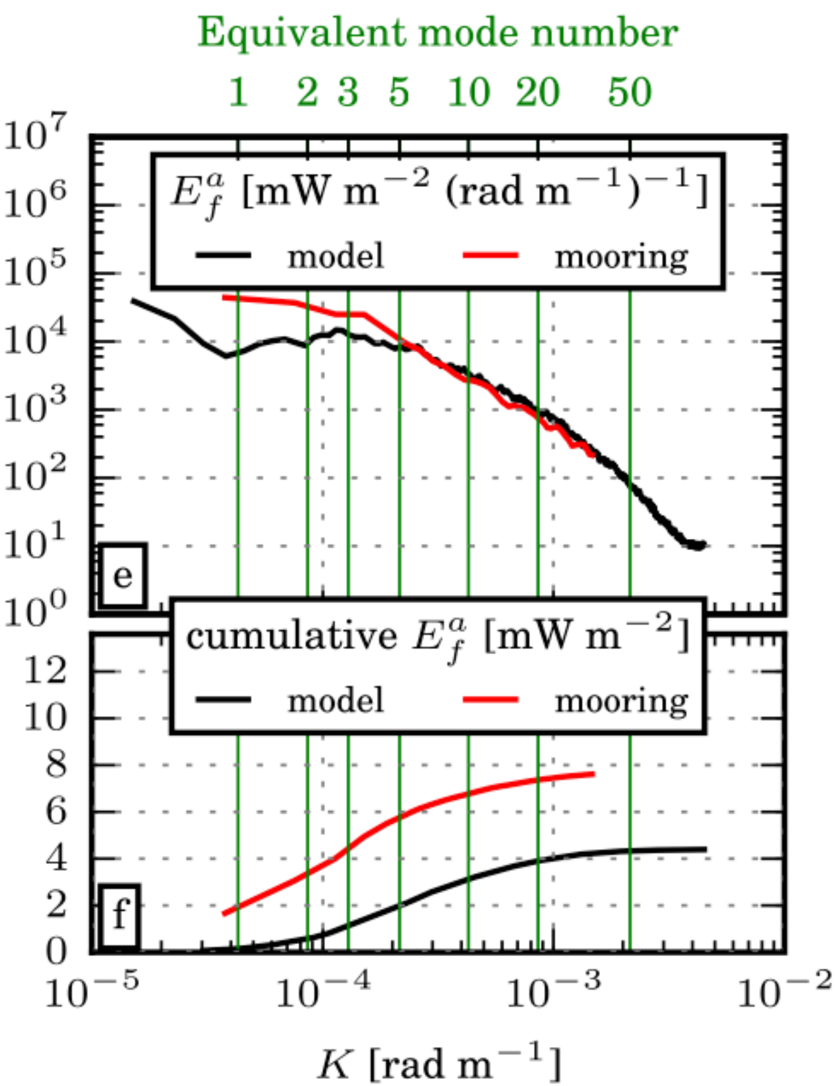
This can be generalised to a 3D problem with random bathymetry

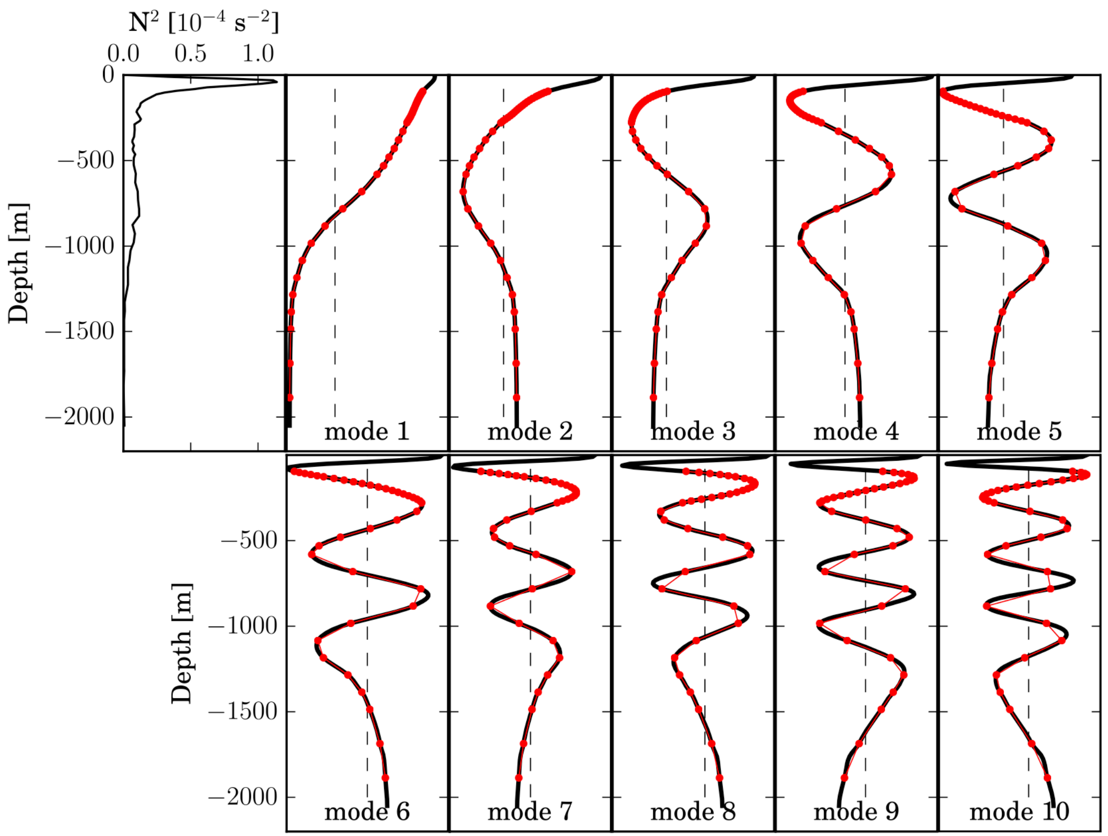


Bell 1975, Garrett and Kunze 2007

1.1 Generation of internal tides

This can be generalised to a 3D problem with random bathymetry



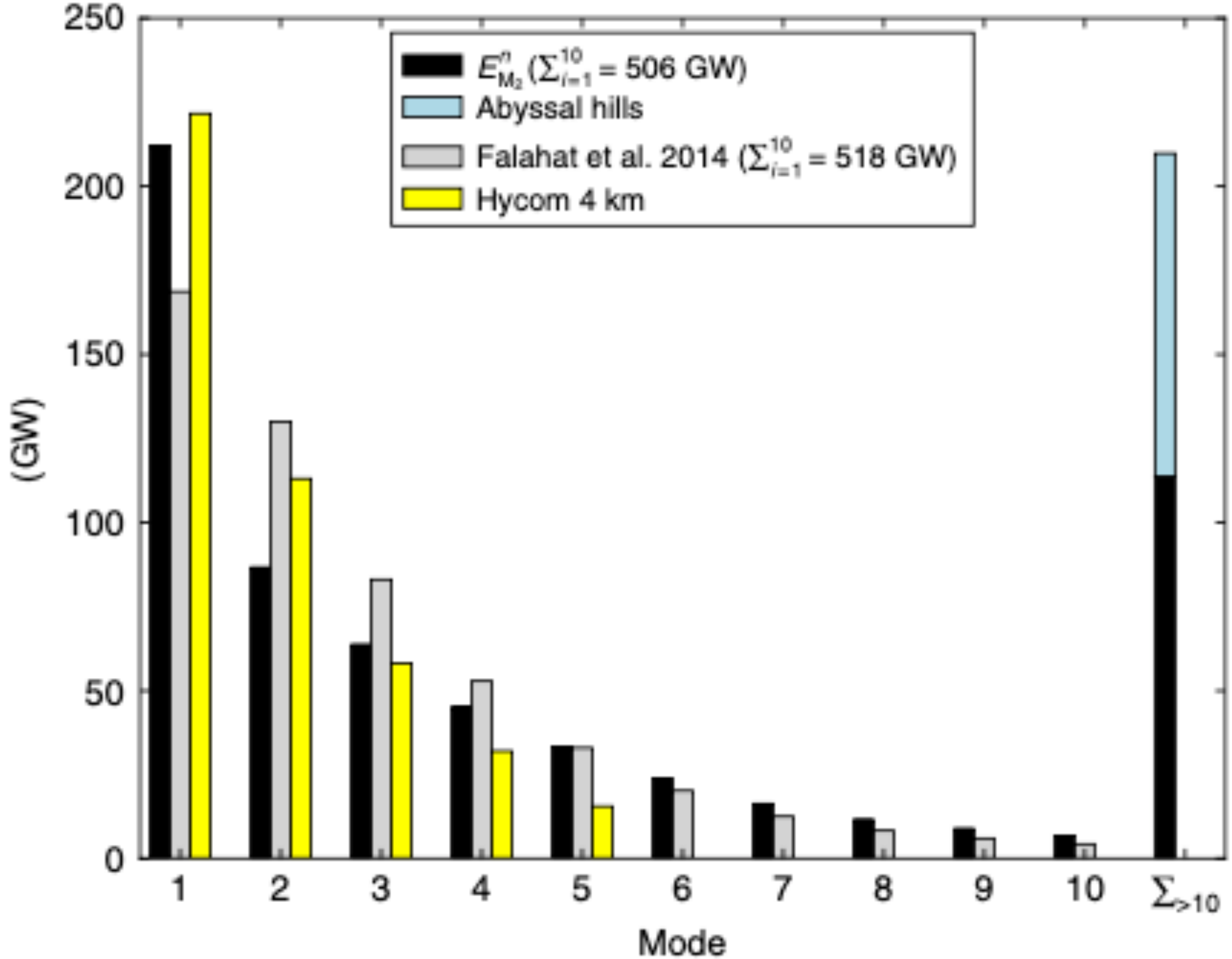


Vertical modes reconstructed with instruments on a mooring line

Vic et al 2018

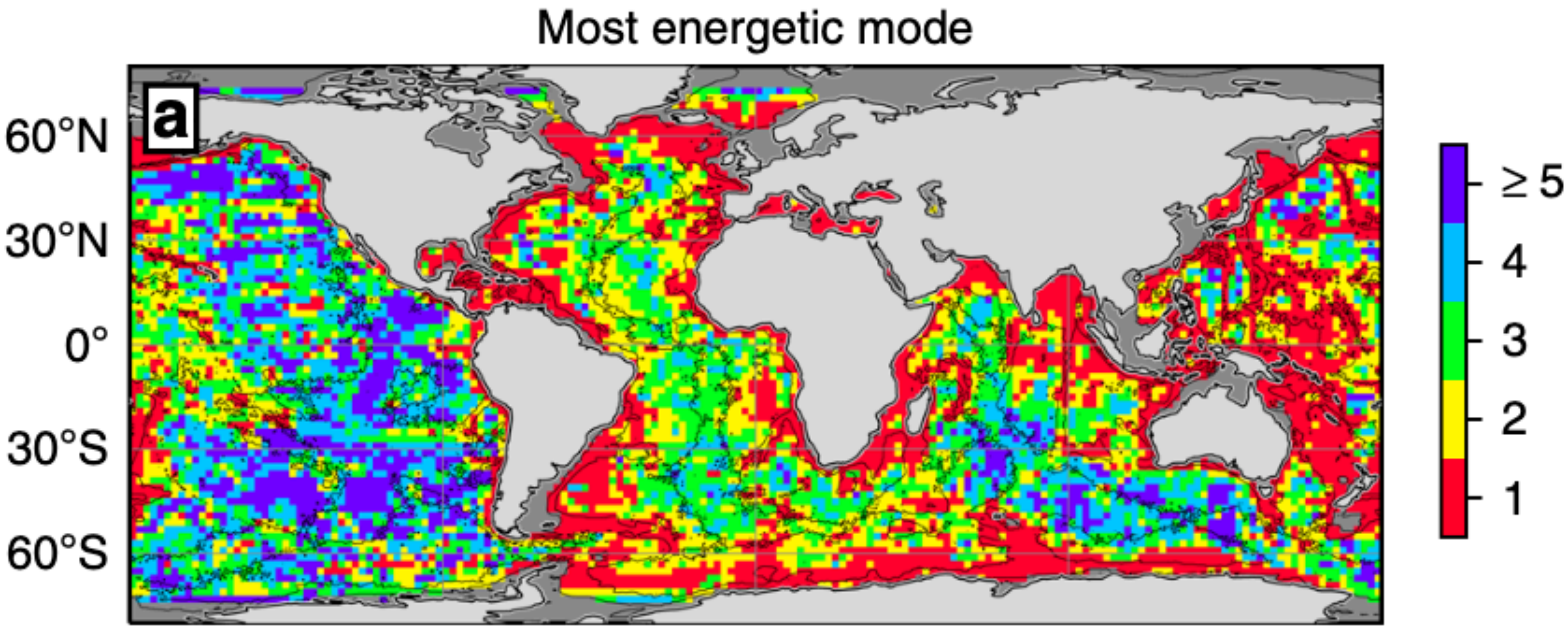
1.1 Generation of internal tides

Mapping the internal tide generation mode by mode



1.1 Generation of internal tides

Mapping the internal tide generation mode by mode



Interest : high modes are more unstable hence generate more mixing (next lesson)

1.1 Generation of internal tides

Internal Tide Generation in the ~~Deep Ocean~~

Chris Garrett and Eric Kunze

Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8W 2Y2; Canada

On continental shelf breaks : assumptions to derive a linear theory do not hold !

1.1 Generation of internal tides

On continental shelf breaks : assumptions to derive a linear theory do not hold ! Why ?

1.1 Generation of internal tides

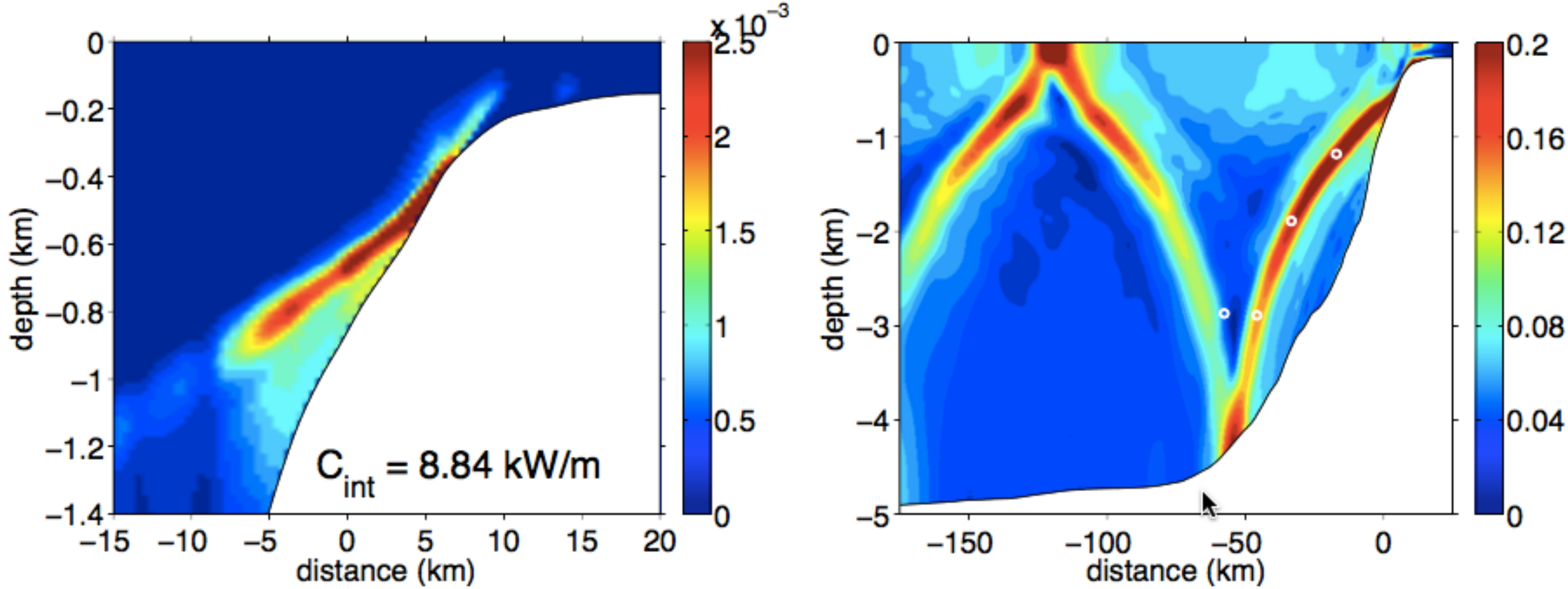
On continental shelf breaks : assumptions to derive a linear theory do not hold ! Why ?

- Shallower depths : N^2 is much larger —> beam is more horizontal
- Topographic slopes are steeper

—> $\epsilon = \dfrac{kh_0}{\alpha} = \dfrac{\text{topographic slope}}{\text{beam slope}}$ can be no longer <1

—> critical slopes $\epsilon = 1$ and supercritical slopes $\epsilon > 1$

1.1 Generation of internal tides



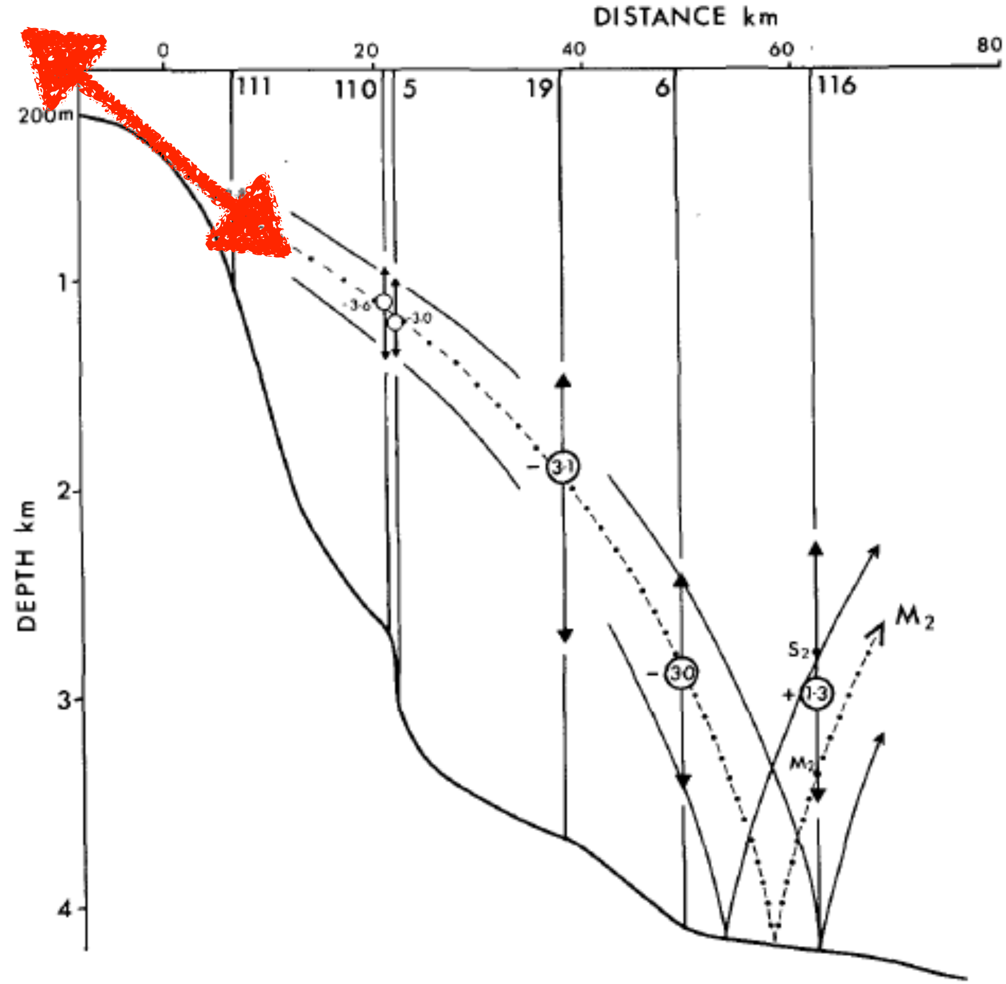
Results from a numerical model, here applied to the Bay of Biscay. Left: The spatial distribution tidally-averaged conversion rate, $C = -\rho_{*}\langle bW \rangle$, in W/m3; Right: The internal tide emanating from the continental slope, here depicted in terms of the amplitude of the cross-slope velocity u, in m/s.

1.1 Generation of internal tides

Internal beams are preferentially excited where the slope is critical

- One ray goes toward the coast (difficult to see because of mixing).

- A second ray goes downward, is reflected at the bottom,



New and Pingree 1991, 1992

1.1 Generation of internal tides

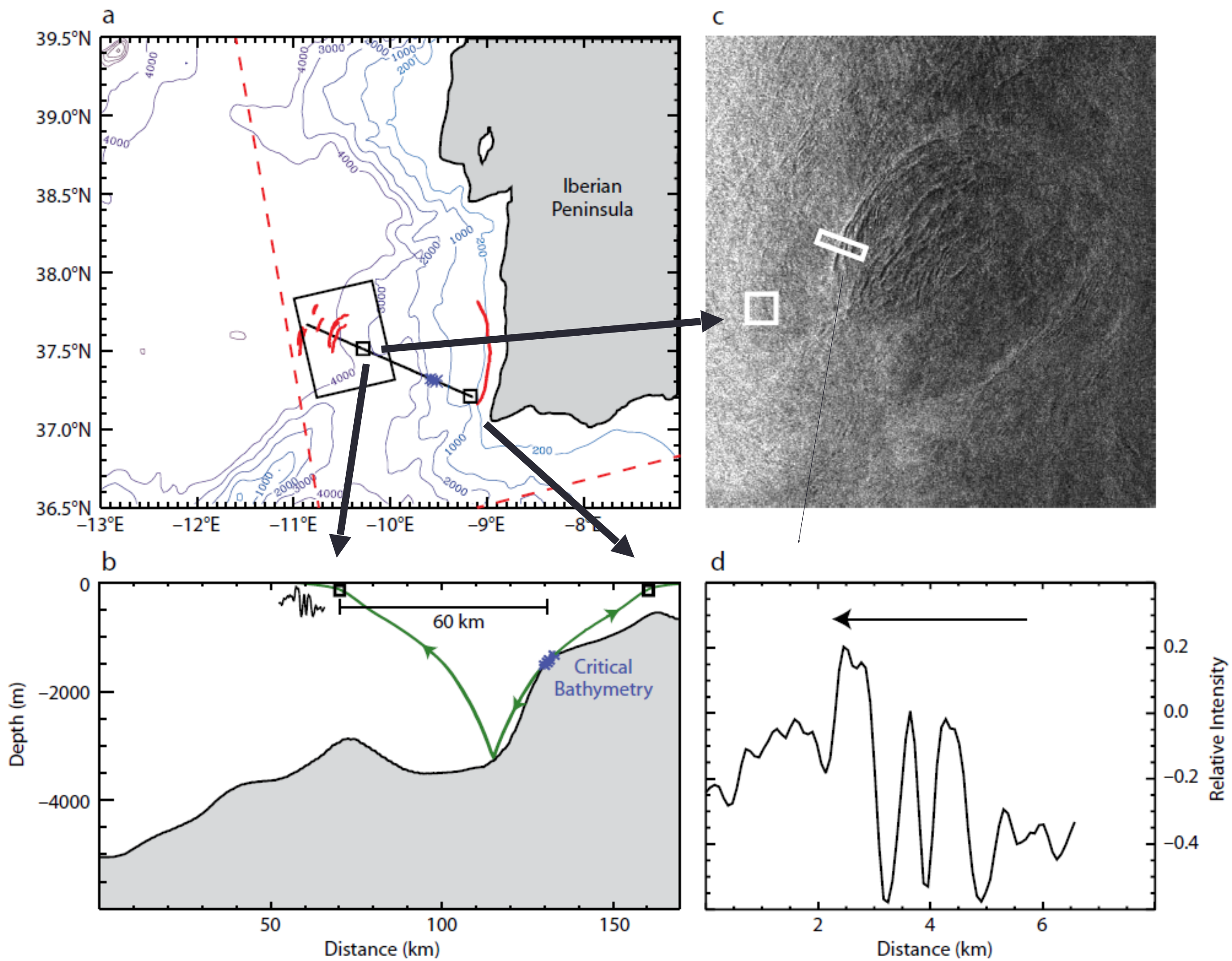
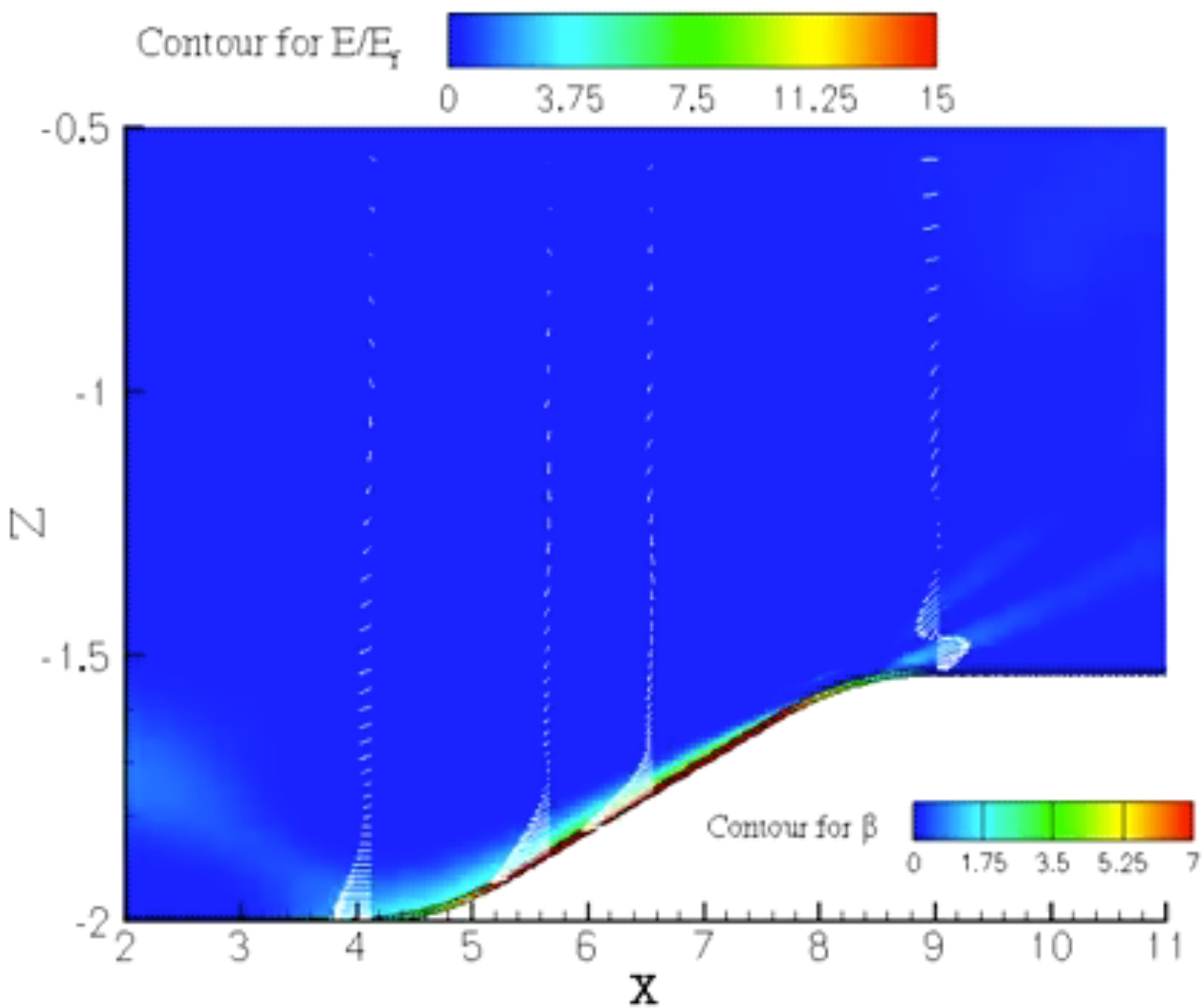


Figure 5. (a) Map of area southwest of the Iberian Peninsula with internal solitary wave crests marked in red based on one Envisat Advanced Synthetic Aperture Radar (ASAR) image in Wide-Swath Mode dated August 4, 2004 (22:27 UTC). (b) Ray-tracing diagram showing internal tide ray paths (in green; emanating from critical topography, in blue) along the black line in part (a). The small black squares in part (a) show where the ray path crosses the near-surface thermocline (taken at a depth of 50 m), and are also marked in part (b). (c) Full-resolution detail of a nonlinear internal wave train observed to propagate toward the west-northwest and believed to be generated by the tidal beam in part (b). (d) Radar backscatter profile showing the wavelength cross section of a nonlinear internal wave train generated by the tidal beam. The narrow rectangle in part (c) represents the cross section from which part (d) was obtained. The square in part (c) is a background backscatter reference used to normalize the radar profile in part (d). Zero in part (d) represents the average unperturbed backscatter of the SAR image in part (c).

1.1 Generation of internal tides

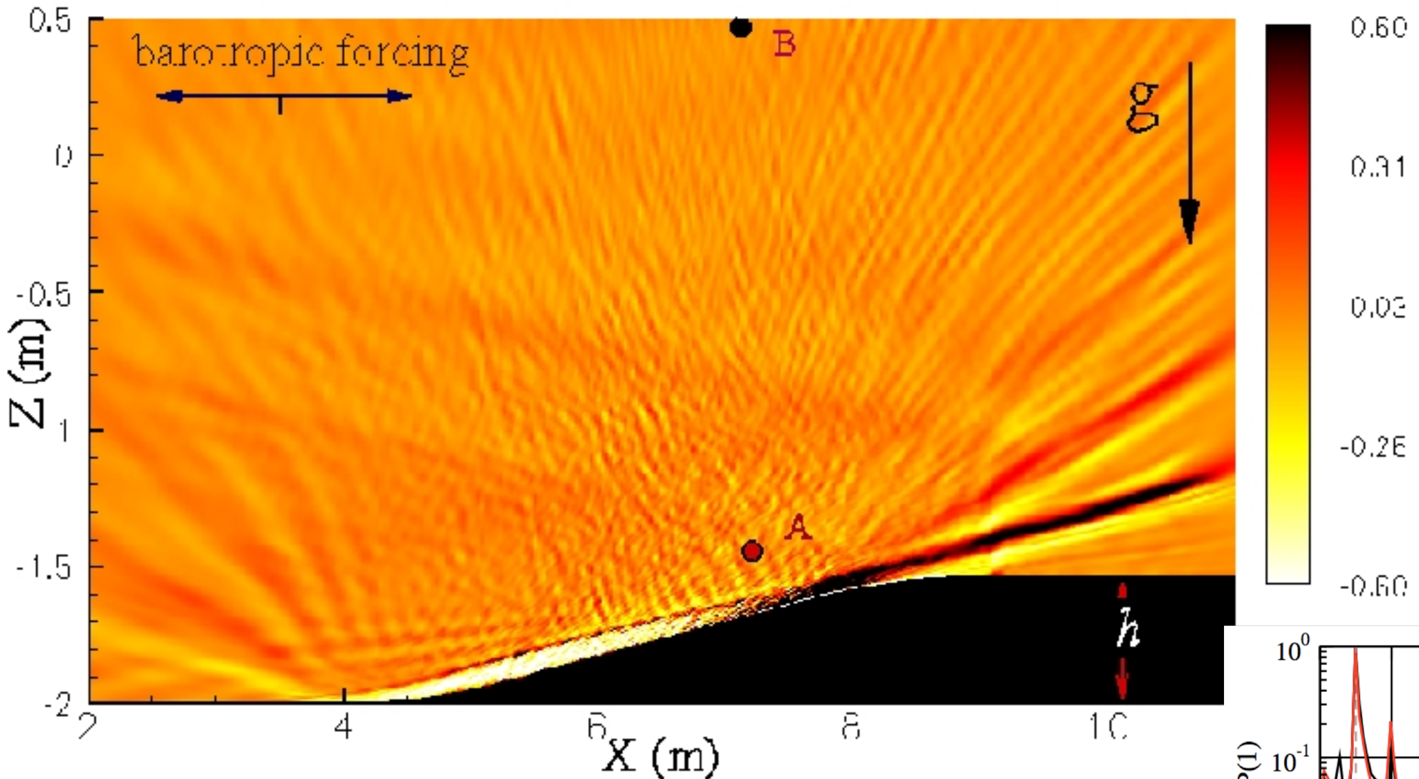
- Generation of Internal Tide on a Critical Slope:



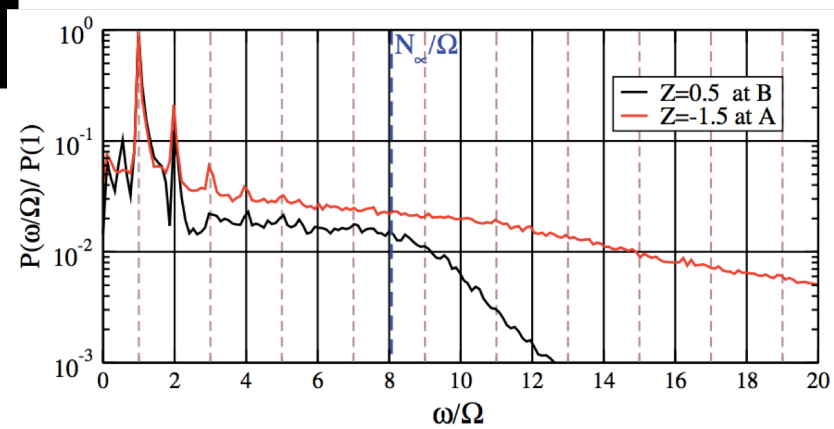
[Gayen & Sarkar, 10]

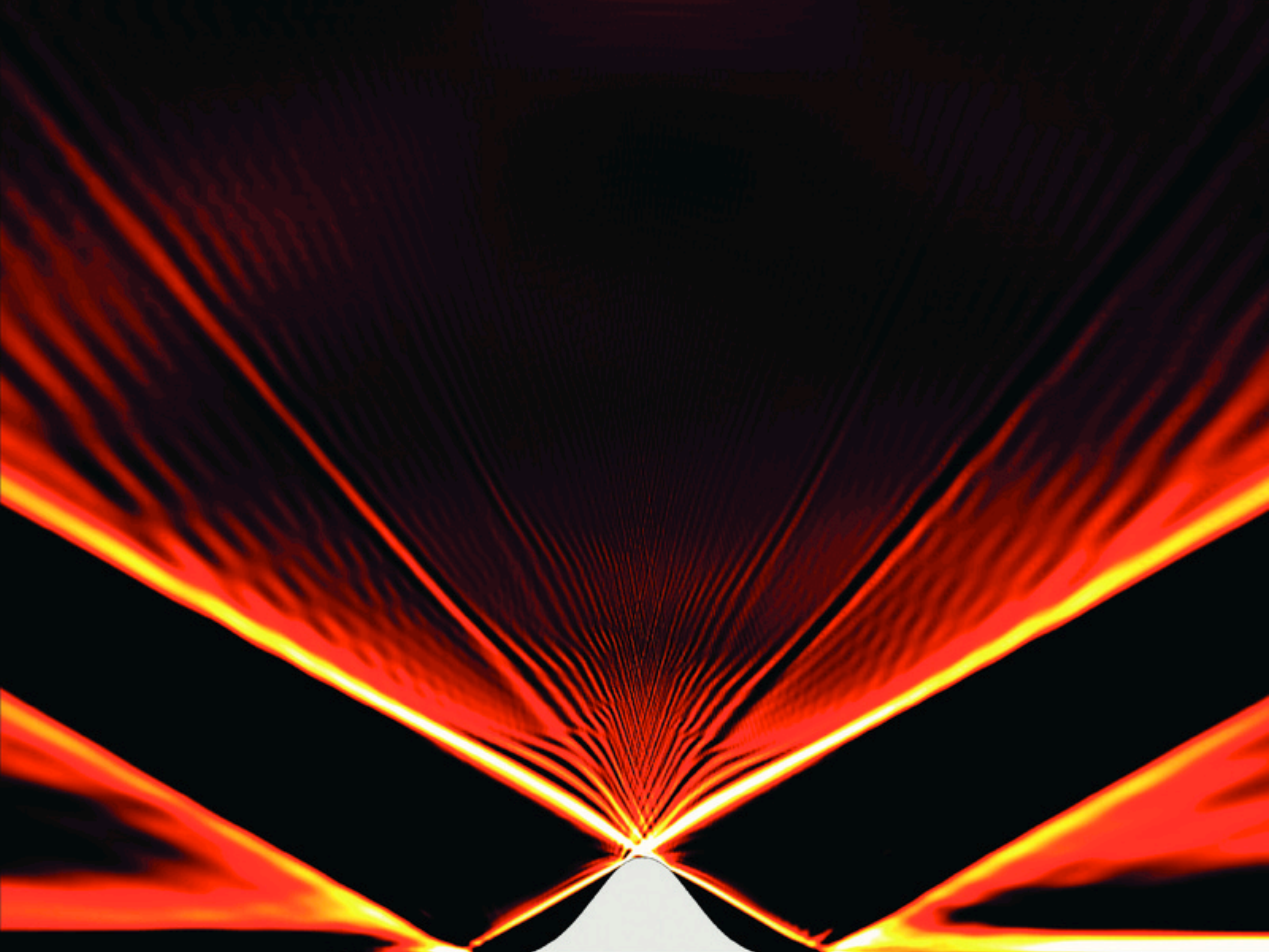
1.1 Generation of internal tides

- Generation of Internal Tide on a Critical Slope:

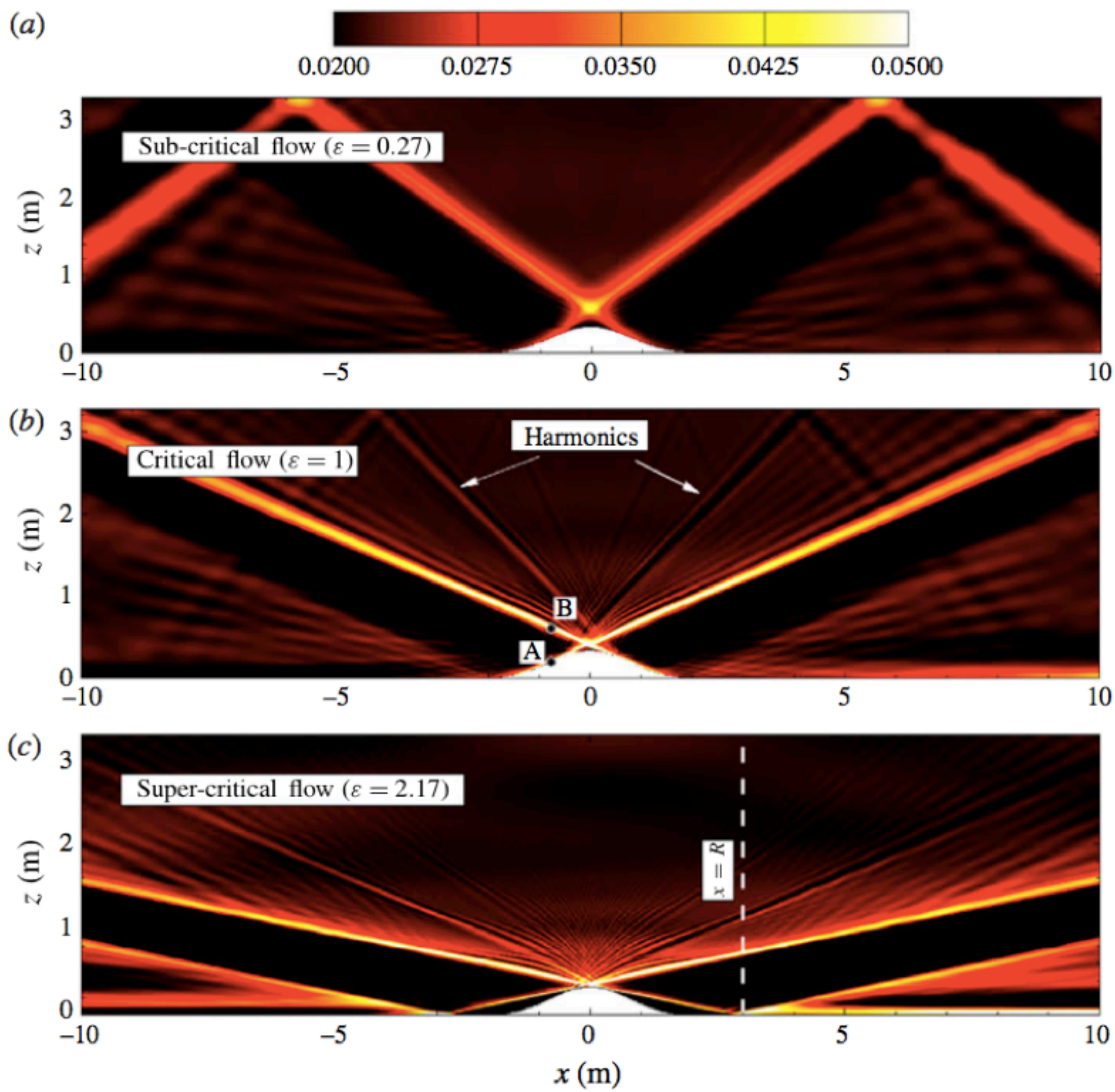


Internal wave field from DNS visualized by a slice of dw/dz field in x-z plane [Gayen & Sarkar, 10]





1.1 Generation of internal tides



Rapaka et al 2013

1.1 Generation of internal tides

Impact of tidally-driven mixing on erosion and sediment transport

The Shaping of Continental Slopes by Internal Tides

D. A. Cacchione,[1] L. F. Pratson,[2] A. S. Ogston[3]

The angles of energy propagation of semidiurnal internal tides may determine the average gradient of continental slopes in ocean basins (~2 to 4 degrees). Intensification of near-bottom water velocities and bottom shear stresses caused by reflection of semi-diurnal internal tides affects sedimentation patterns and bottom gradients, as indicated by recent studies of continental slopes off northern California and New Jersey. Estimates of bottom shear velocities caused by semi-diurnal internal tides are high enough to inhibit deposition of fine-grained sediment onto the slopes.

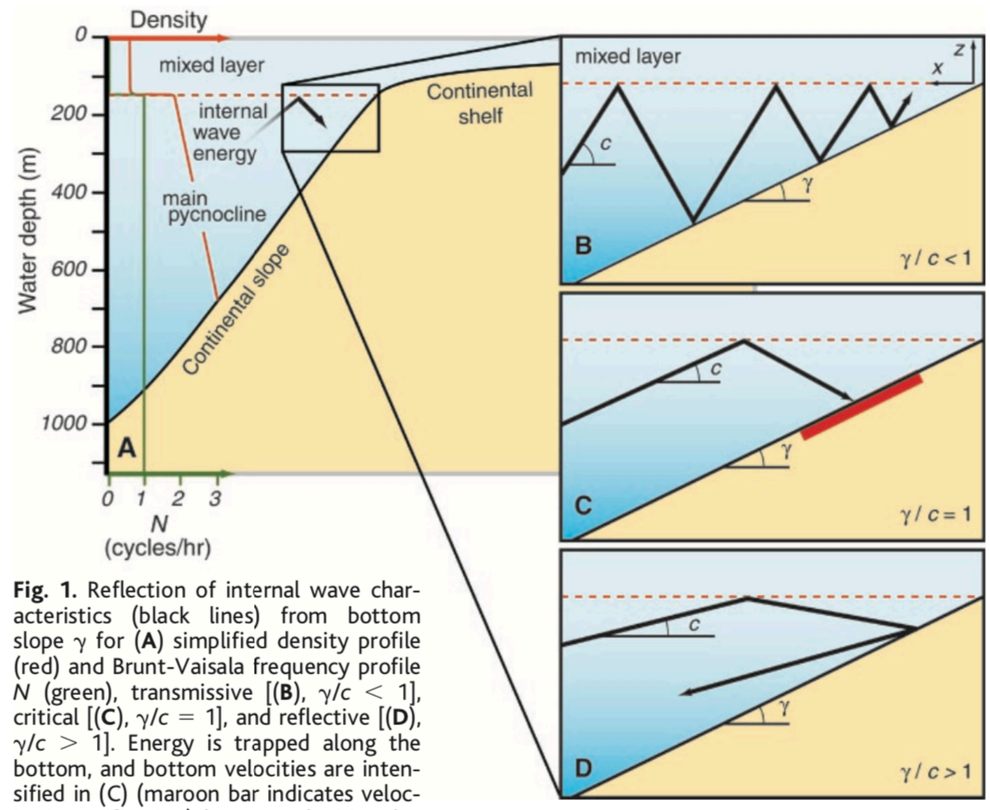
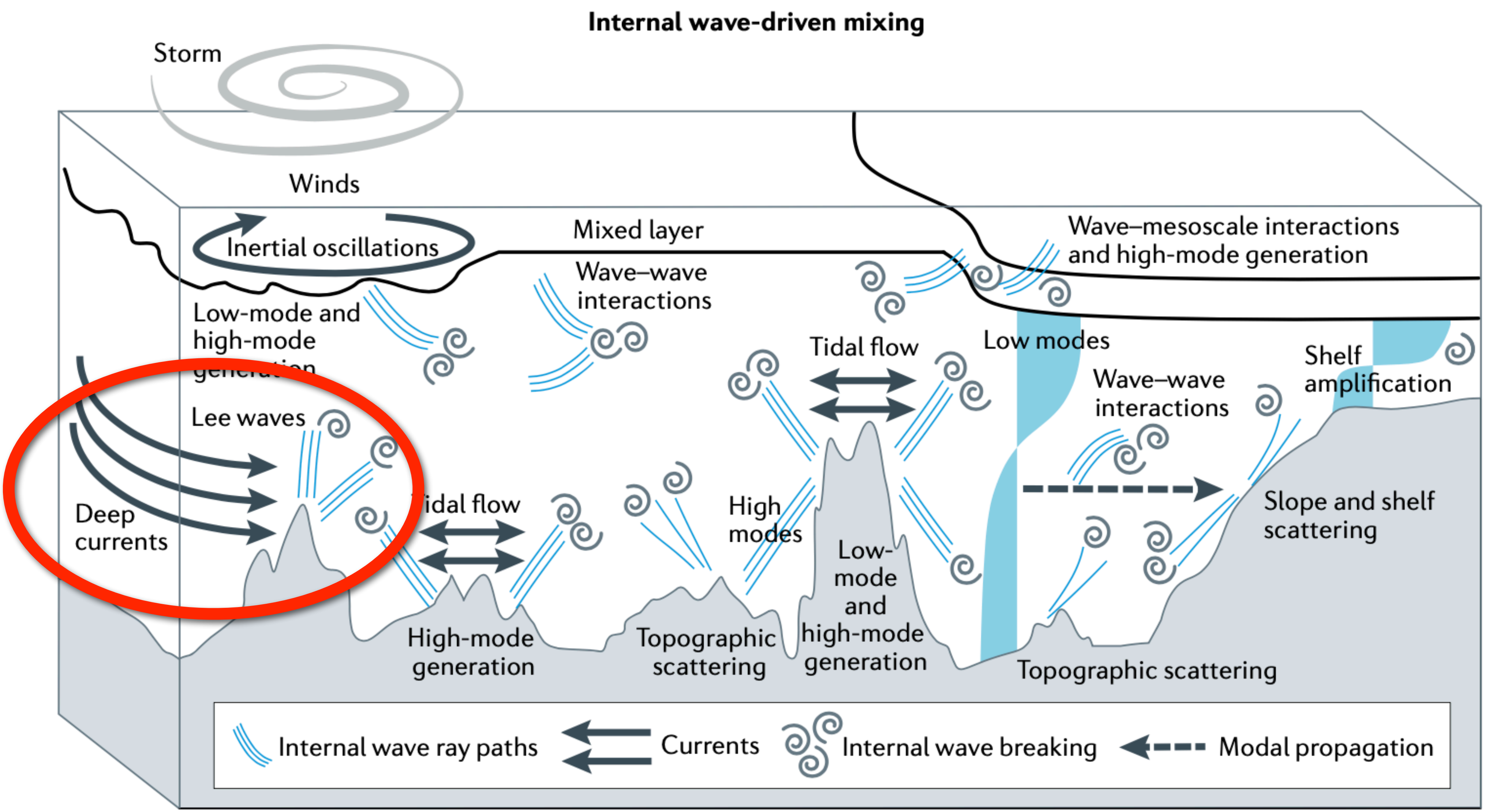


Fig. 1. Reflection of internal wave characteristics (black lines) from bottom slope γ for (**A**) simplified density profile (red) and Brunt-Vaisala frequency profile N (green), transmissive [(**B**), $\gamma/c < 1$], critical [(**C**), $\gamma/c = 1$], and reflective [(**D**), $\gamma/c > 1$]. Energy is trapped along the bottom, and bottom velocities are intensified in (C) (maroon bar indicates velocity intensification); bottom velocities also increase upslope in (B) (*10*).

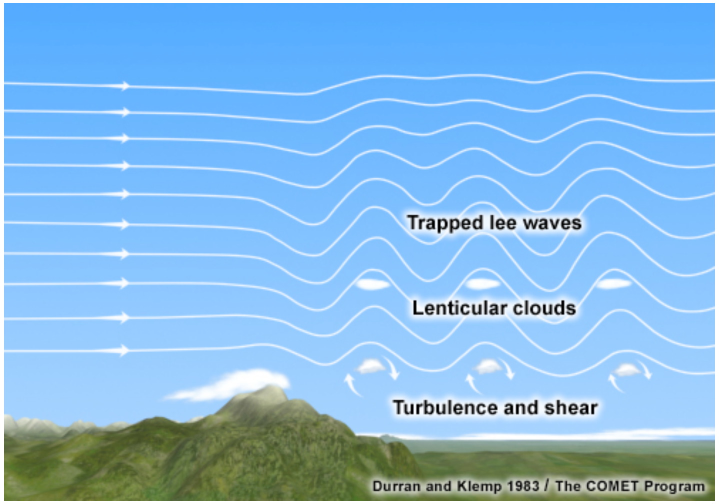
1.2 Generation of lee waves



Whalen et al 2020

1.2 Generation of Lee waves

- **Lee waves** (or mountain waves) can be seen in ocean and atmosphere



Modis, 23/11/2009 - South Atlantic – Sandwich Islands

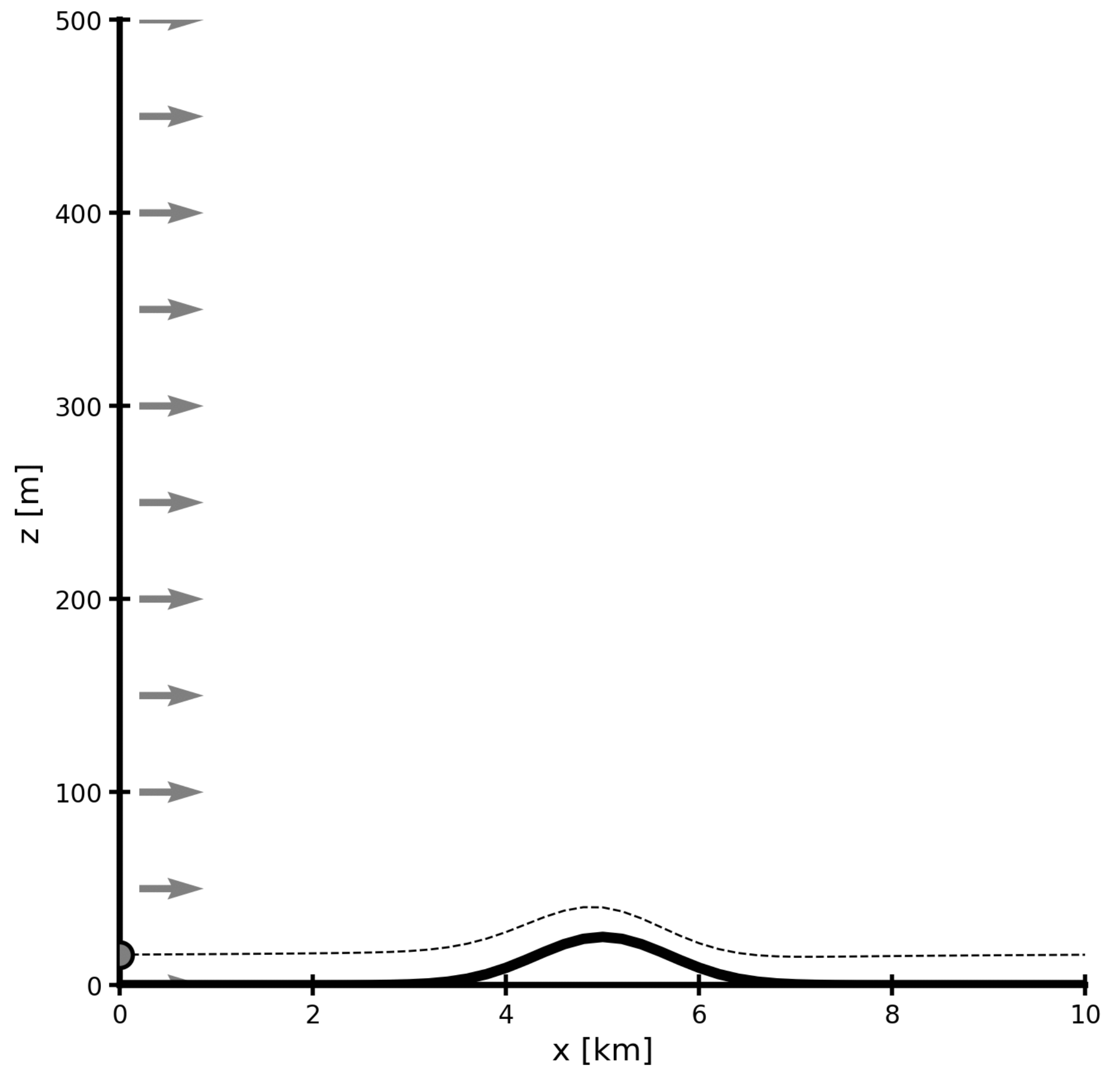
The lower atmosphere is drier – Downwind of the islands the waves are seen when the air goes up, condensate and form clouds

1.2 Generation of Lee waves

Ingredients for the propagation of a lee wave :

✓ A current…

✓ …flowing over a topography



de Marez et al 2020

1.2 Generation of Lee waves

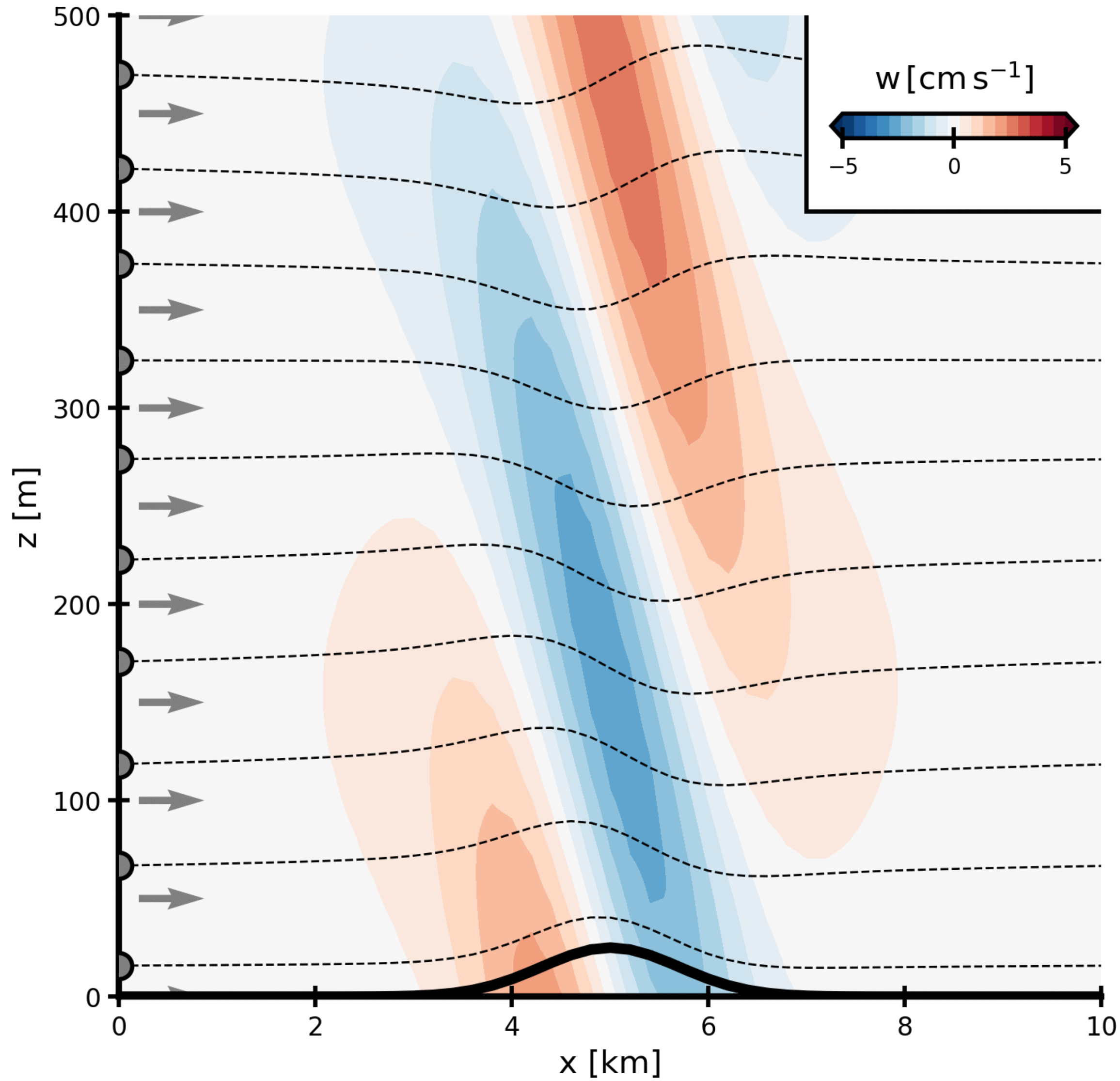
Ingredients for the propagation of a lee wave :

✓ A current…

✓ …flowing over a topography

✓ A stratification

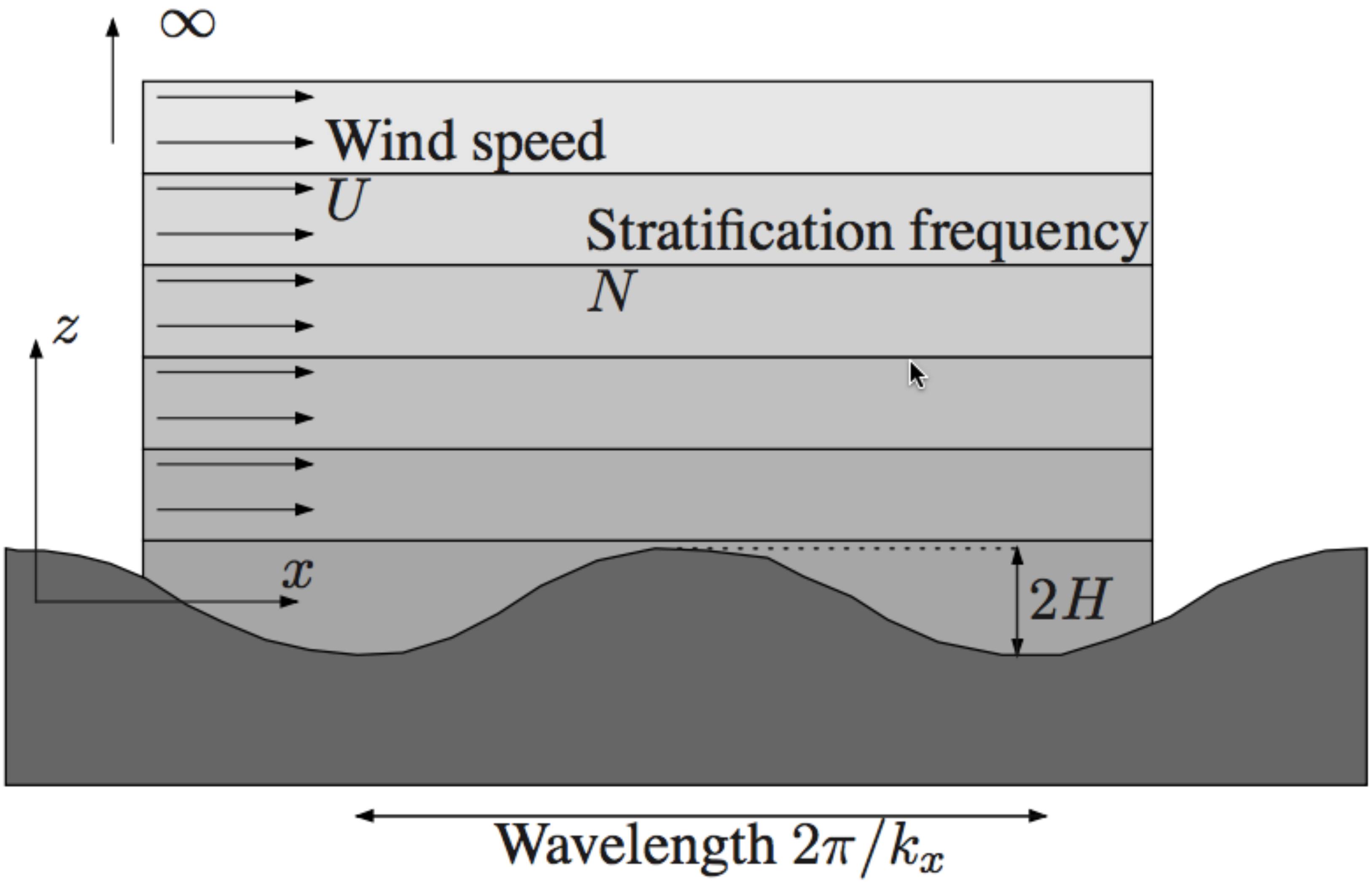
→ *Propagation of an internal wave forced by the topography*



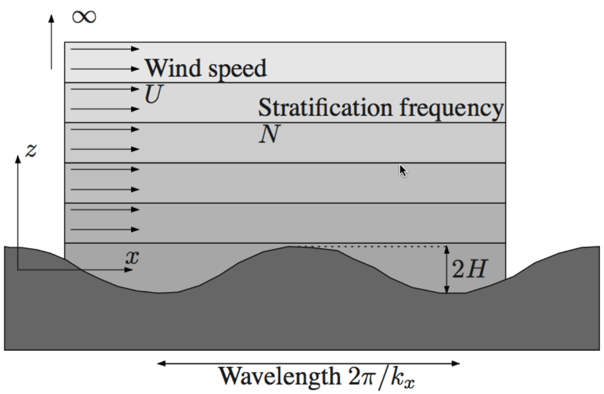
de Marez et al 2020

1.2 Generation of Lee waves

- Internal waves generated at horizontal boundary:



1.2 Generation of Lee waves



- Topography $z_b = H\sin(k_x x)$
- In the frame moving at constant speed U, $z_b = H\sin(k_x(x+Ut))$
- We can identify the frequency of the motion: $\omega = -k_x U$
- Recall the general equation for internal waves: $(w_{xx} + w_{yy} + w_{zz})_{tt} + f^2 w_{zz} + N^2(w_{xx} + w_{yy}) = 0$

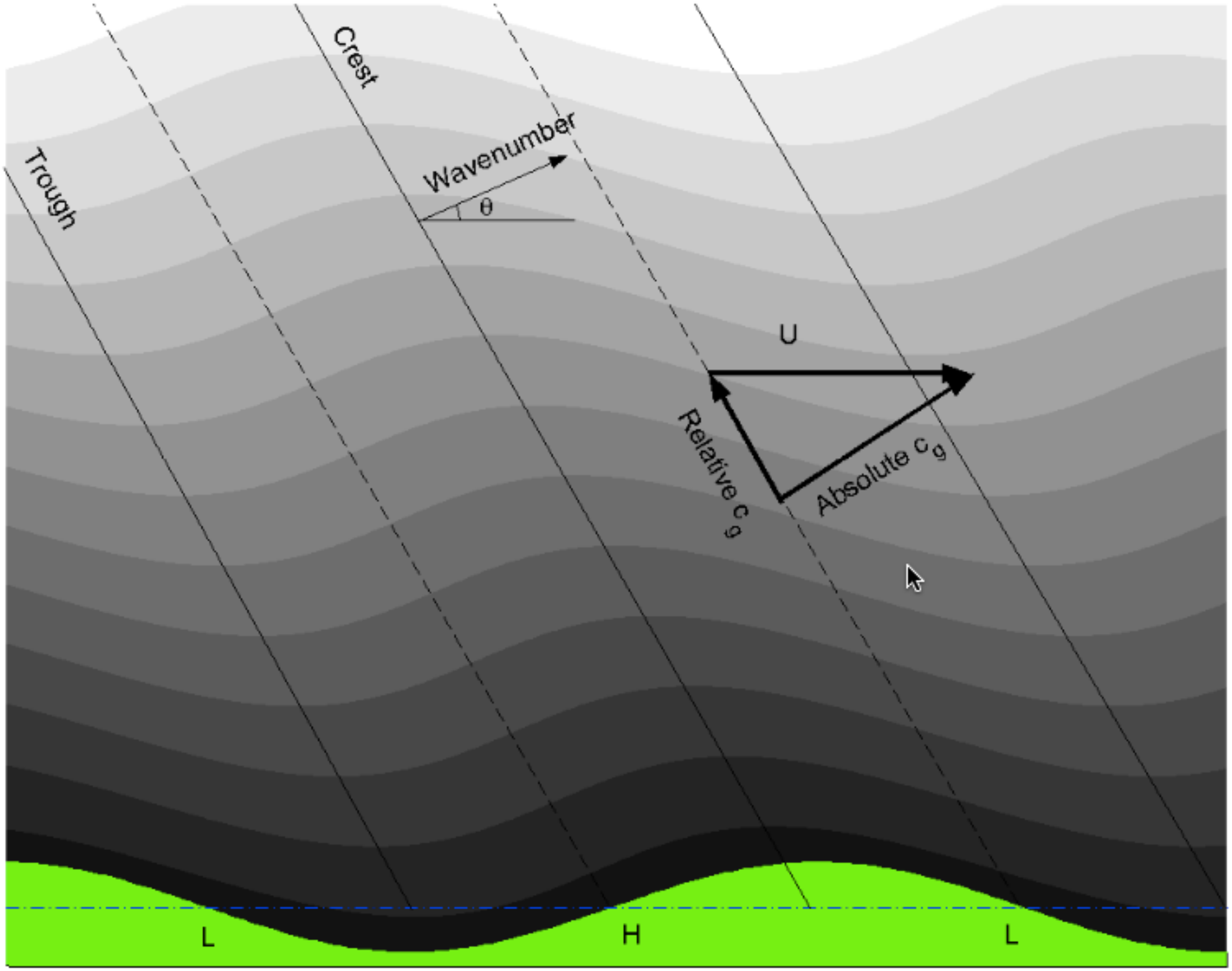
Activity: Solve the equation for linear internal waves in the $x - z$ plane assuming:

- Earth's rotation can be neglected $f = 0$
- The topography is small compared to typical scales of stratification $H \ll U/N$

1. Write the bottom boundary condition for the vertical velocity $w(z_b) \approx w(0)$
2. Solve for a solution in the form $w = w_0 \exp(i(k_x x + k_z z - \omega t))$

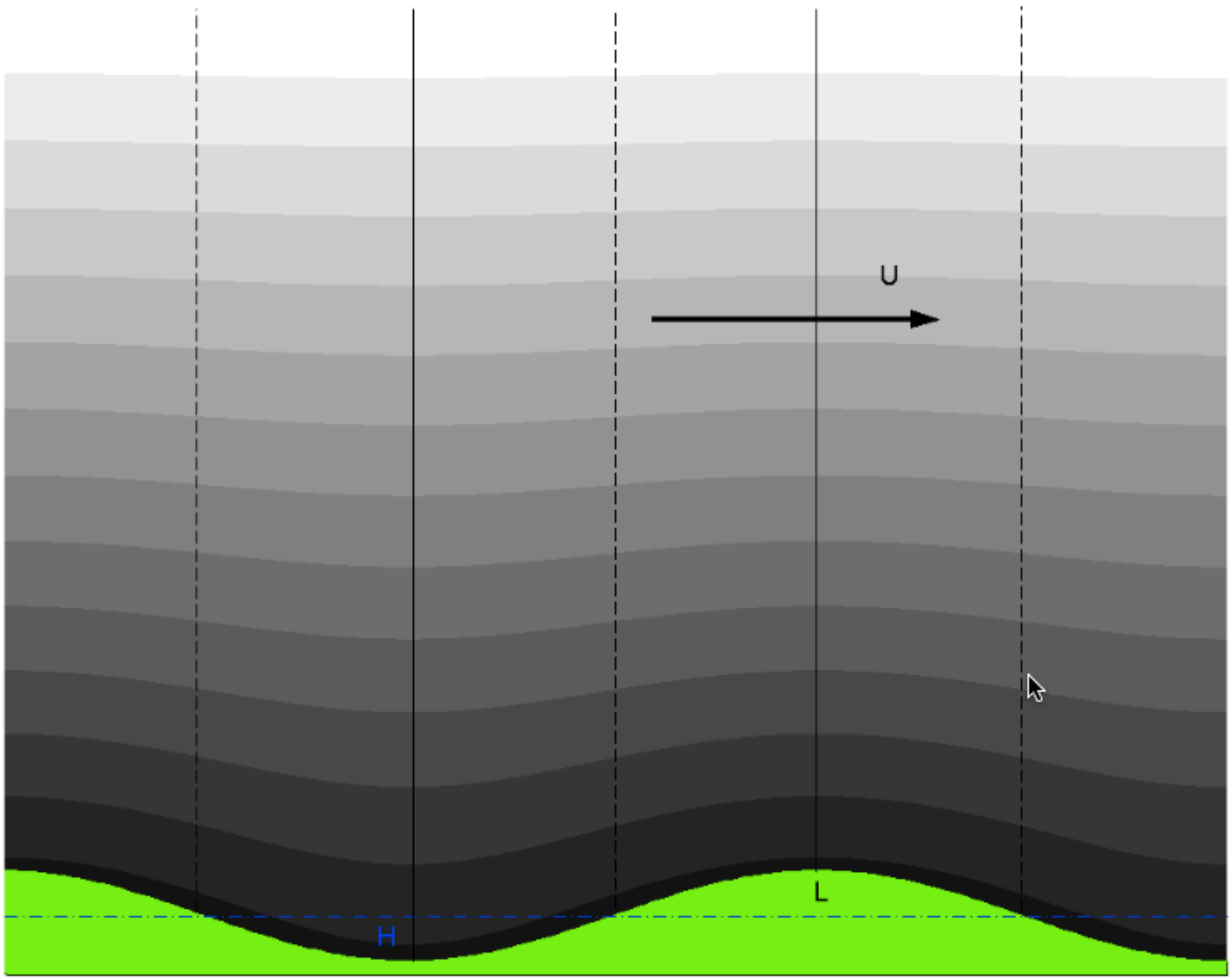
1.2 Generation of Lee waves

- Case 1 = **Radiating waves**



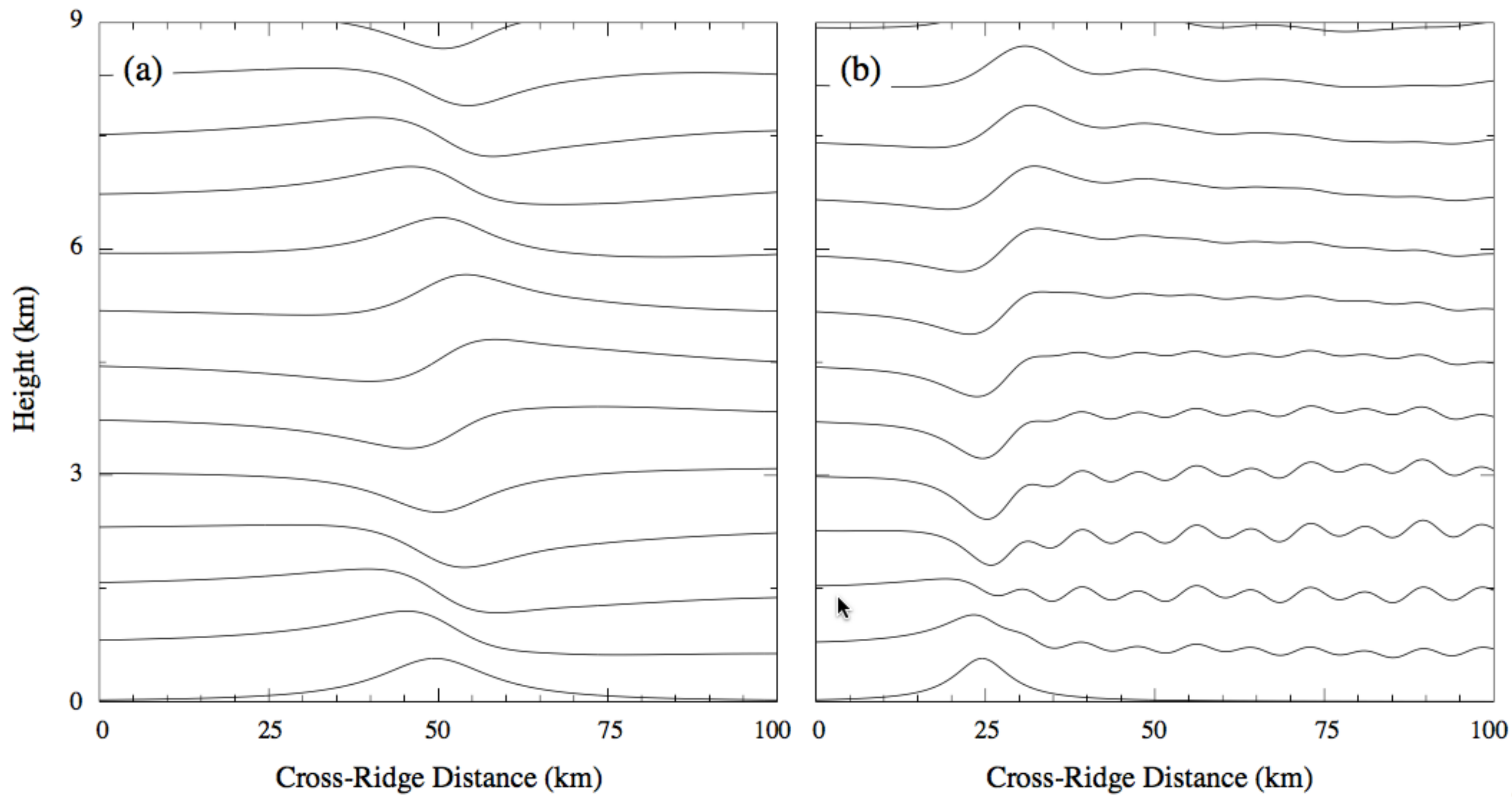
1.2 Generation of Lee waves

- Case 2 = **Trapped waves**



1.2 Generation of Lee waves

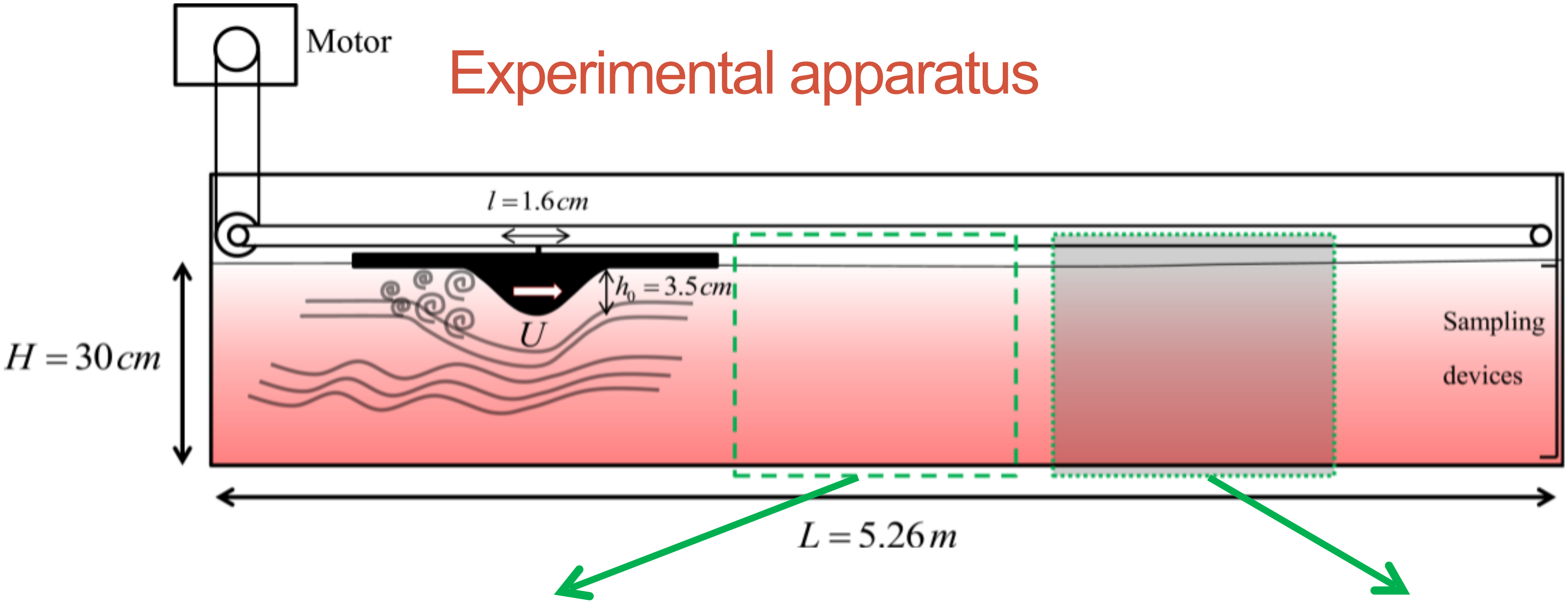
- **General topography**



Streamlines in steady airflow over an isolated ridge as predicted by linear theory

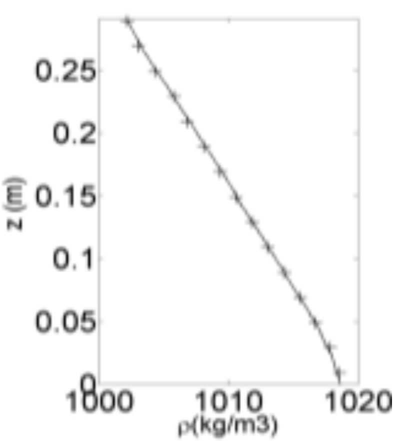
1.2 Generation of Lee waves - Experiments

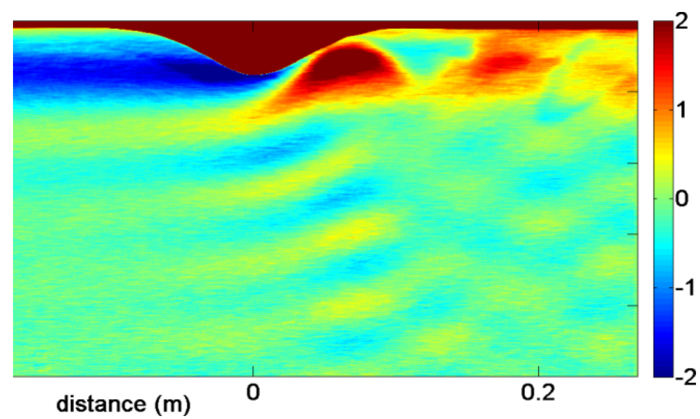
Experimental apparatus

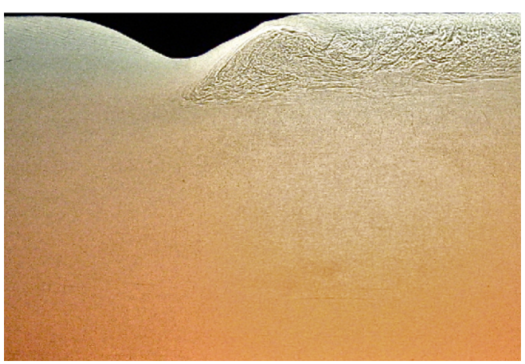


Light attenuation technique
High resolution density measurements

Shadowgraph pictures
Direct observation of mixing

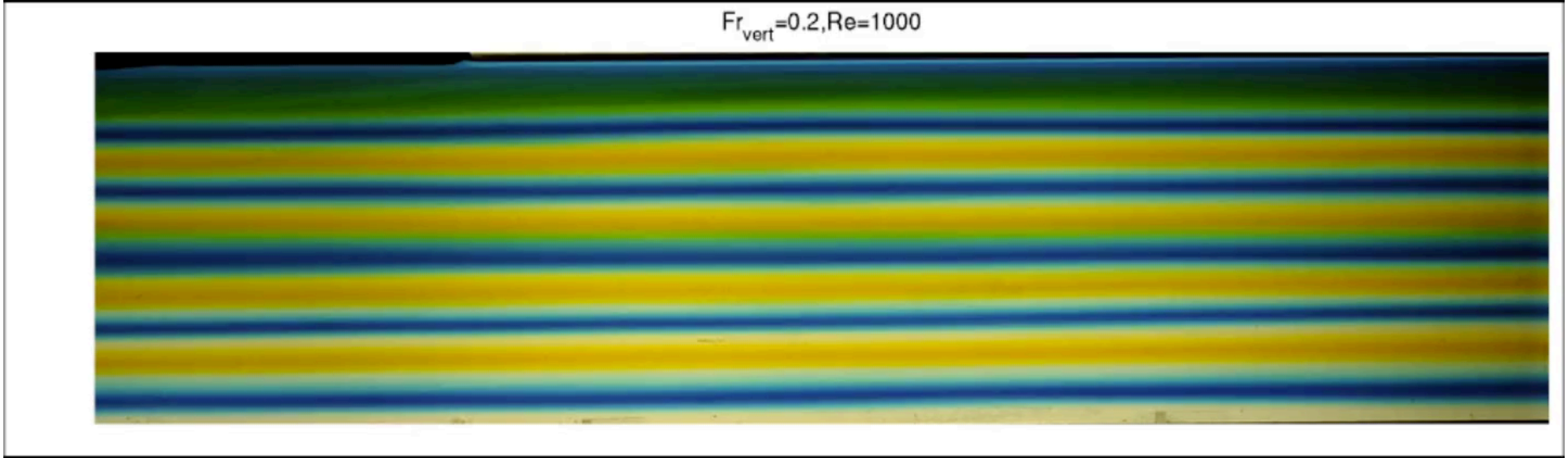






[Y. Dossmann]

1.2. Generation of Lee waves - Experiments



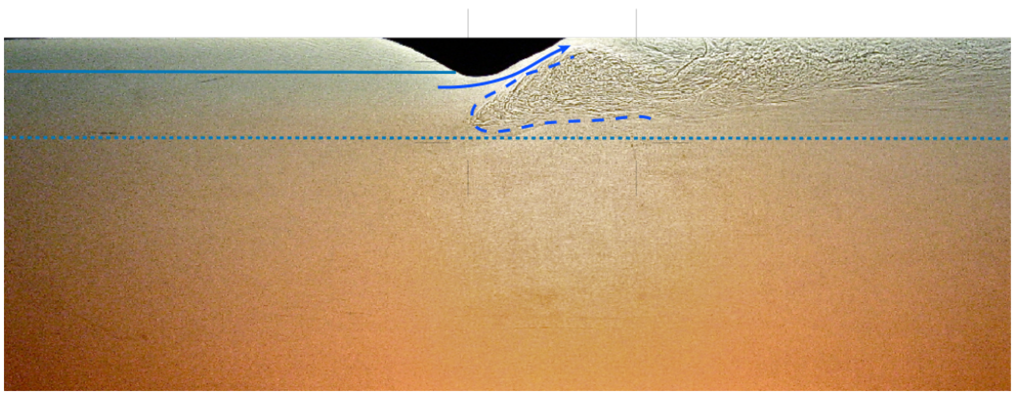
Froude number : Flow regime

Reynolds number : Turbulence regime

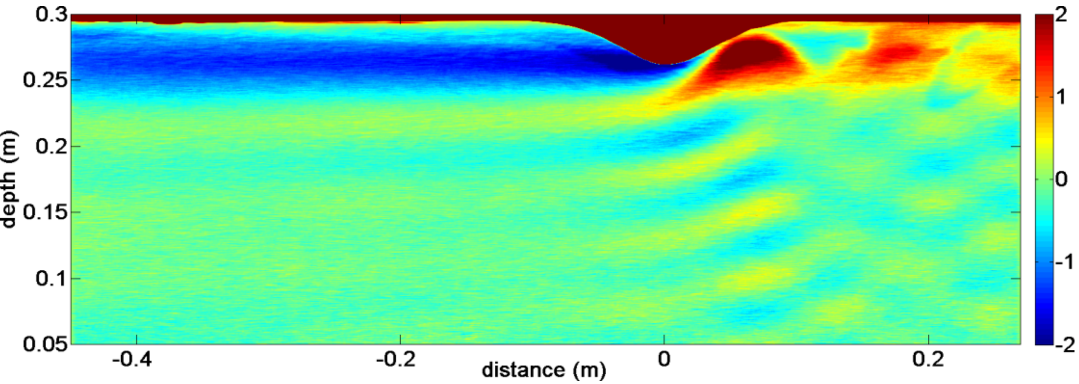
[Y. Dossmann]

1.2. Generation of Lee waves - Experiments

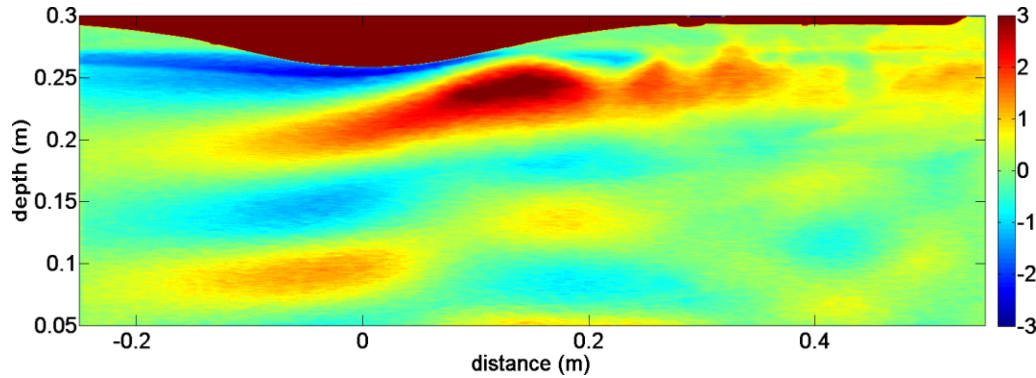
Fr=0.2; Re=500



Fr=0.4; Re=1700



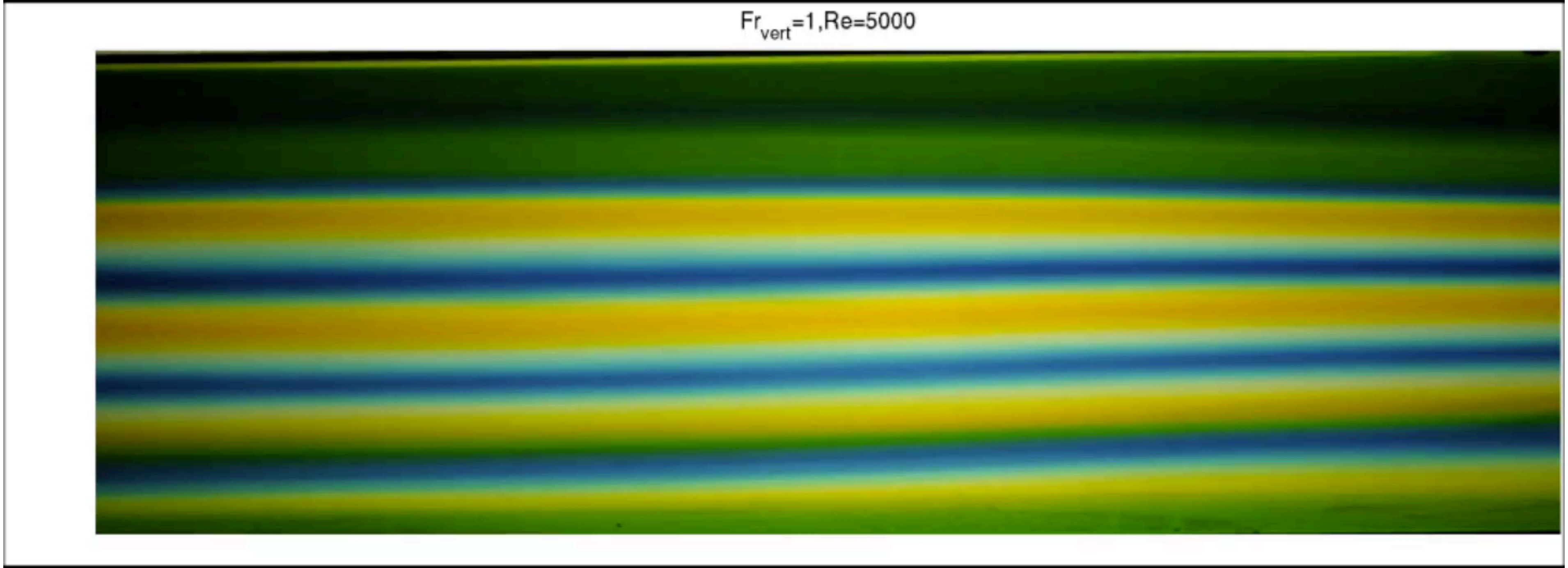
Density anomaly (kg/m3)



Density anomaly (kg/m3)

[Y. Dossmann]

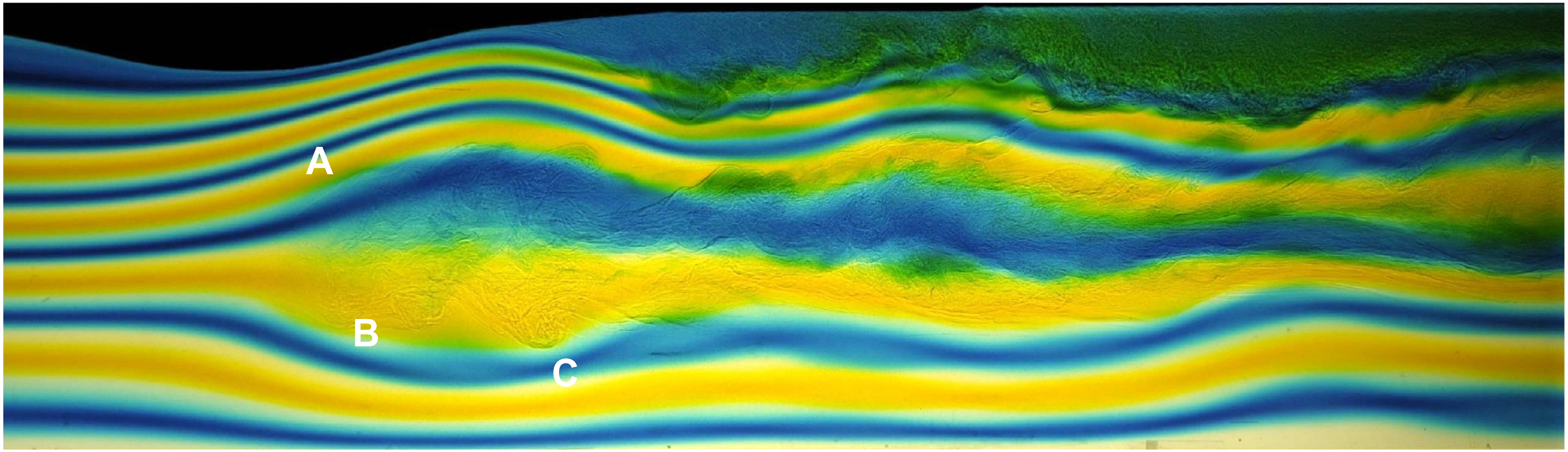
1.2. Generation of Lee waves - Experiments



[Y. Dossmann]

1.2. Generation of Lee waves - Experiments

Fr=1 ; Re=3500

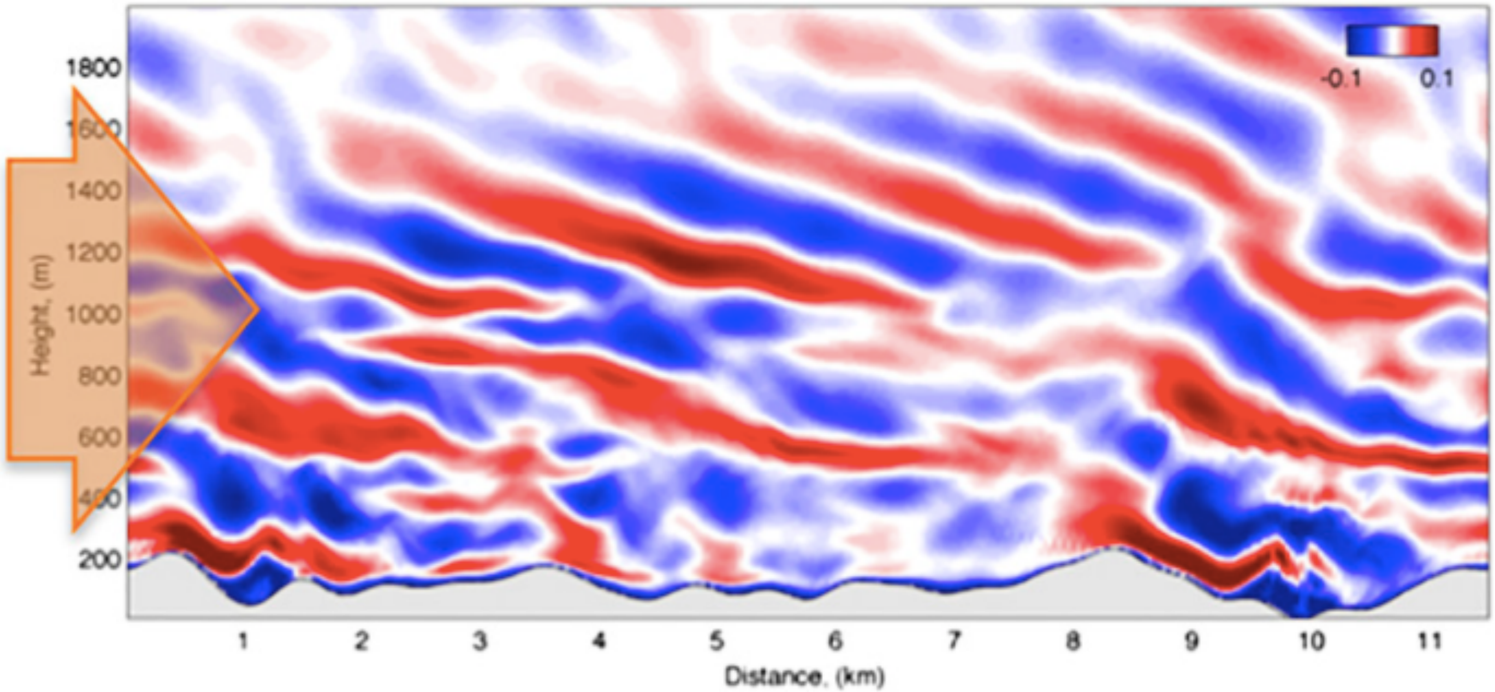


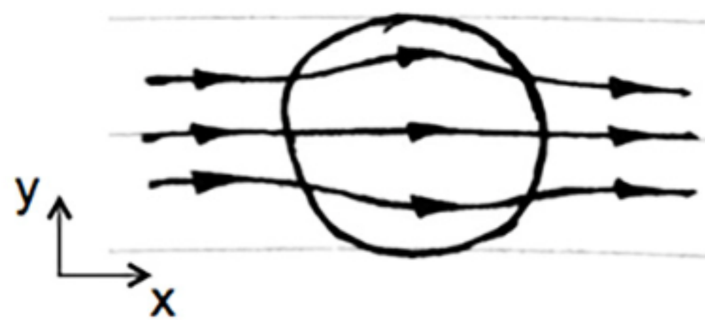
A: Unstable Lee waves
B: Narrow accelerating jet
C: Periodic turbulent patches

[Y. Dossmann]

1.2. Generation of Lee waves

Limitation of the 2d linear theory:

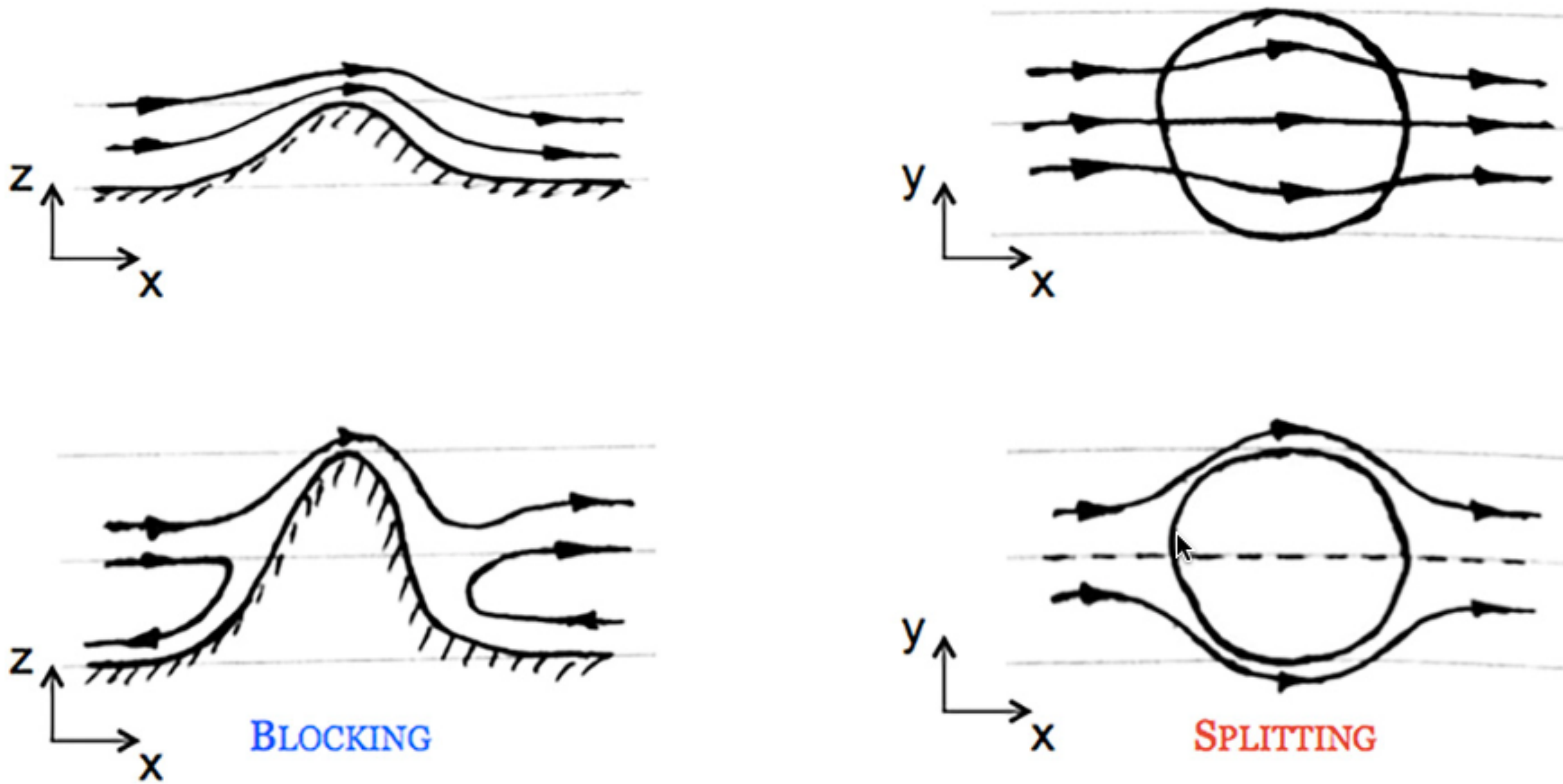




[Nikurashin et al., 2014]

1.2. Generation of Lee waves

Limitation of the 2d theory



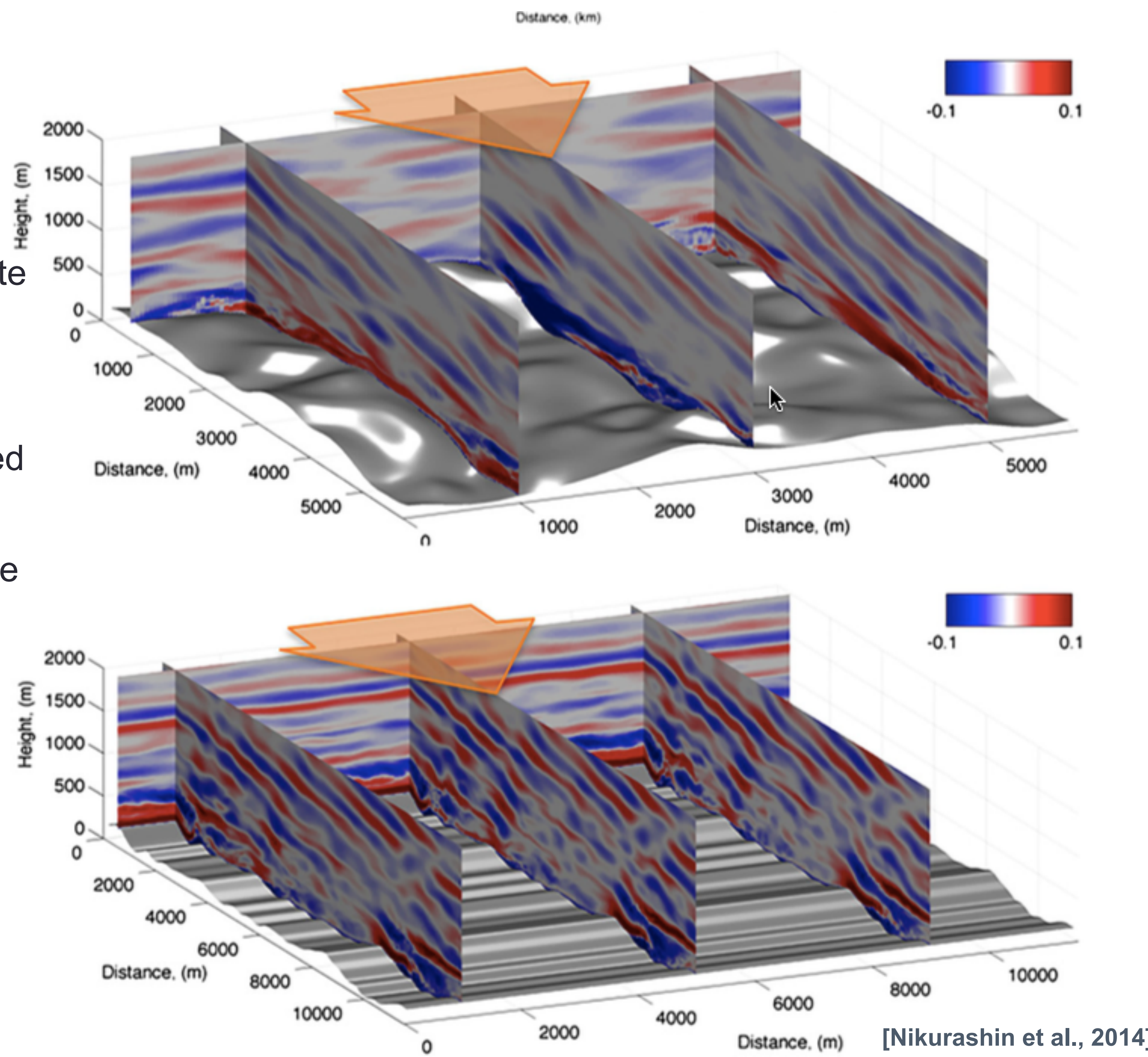
[Nikurashin et al., 2014]

1.2. Generation of Lee waves

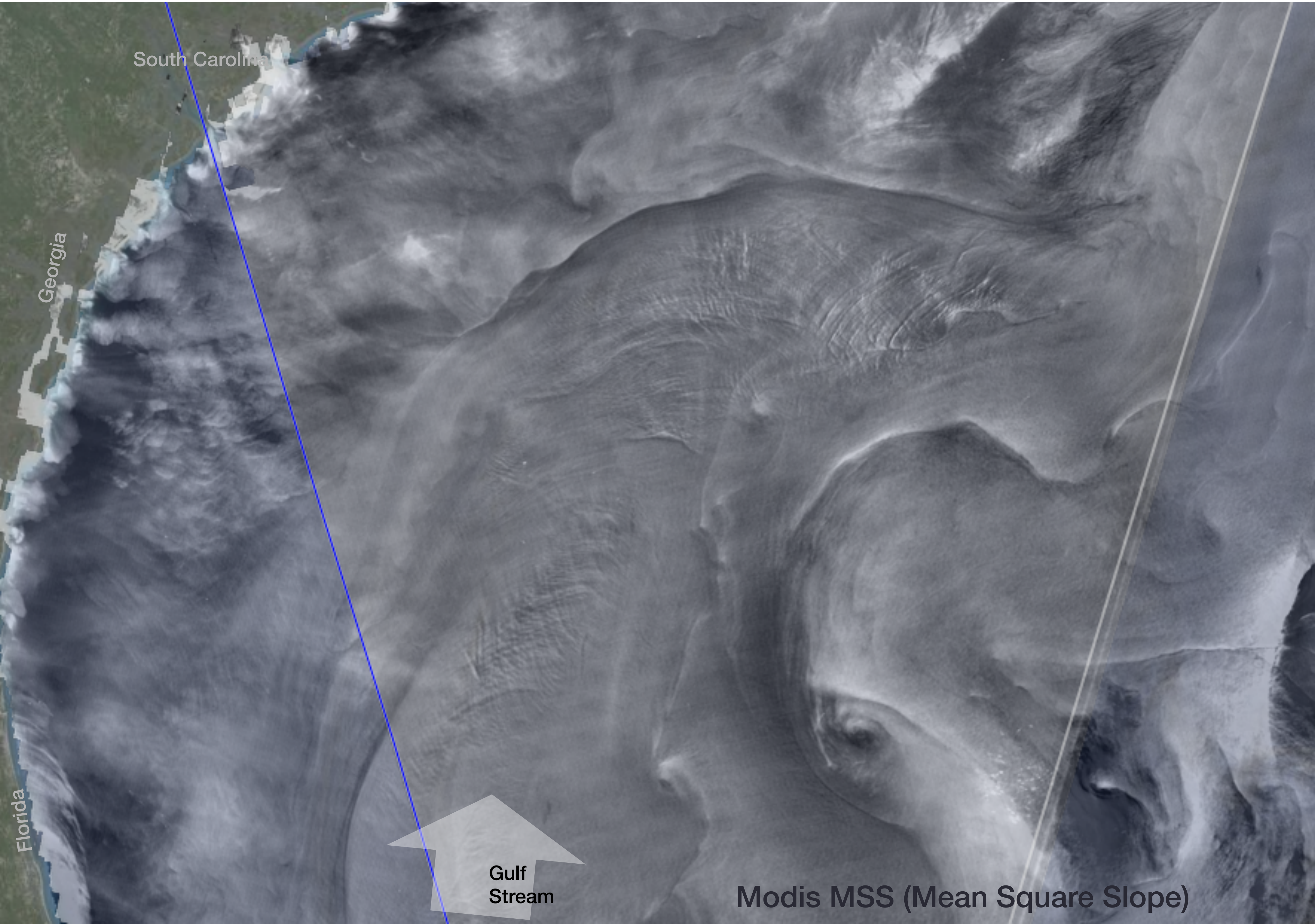
Limitation of the 2d theory

Internal wave generation at 3D, finite bottom topography is reduced compared to the two-dimensional case.

The reduction is primarily associated with finite-amplitude bottom topography effects that suppress vertical motions and thus reduce the amplitude of the internal waves radiated from topography.

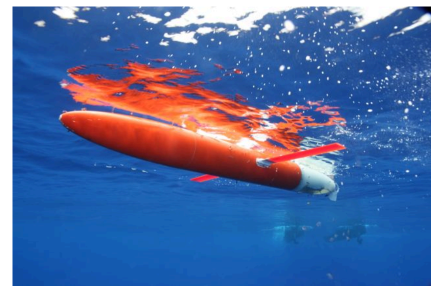


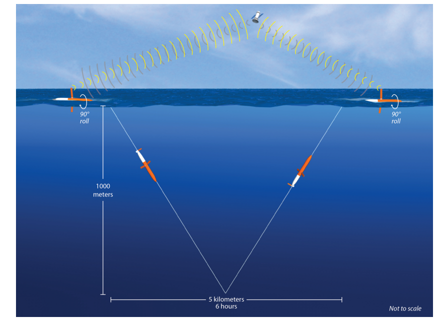
[Nikurashin et al., 2014]


South Carolina
Georgia
Florida
Gulf
Stream
Modis MSS (Mean Square Slope)

1.2. Generation of Lee waves - Real example

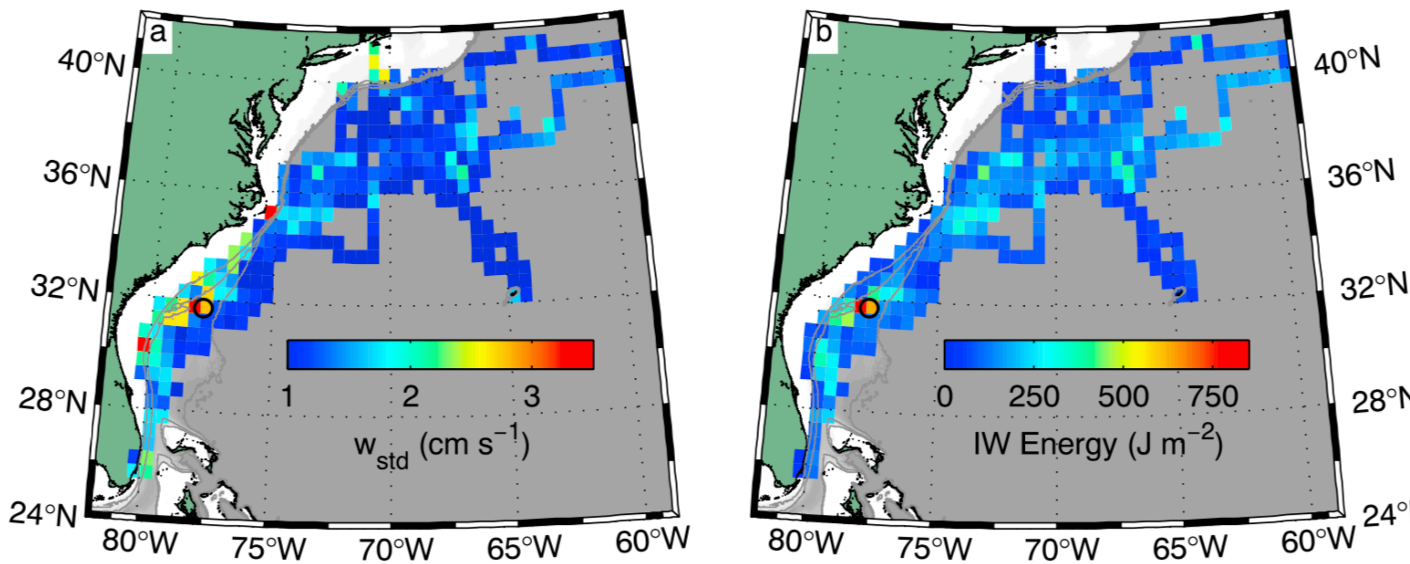
- Internal waves with vertical velocities exceeding 0.1 m s−1 are found over the Charleston Bump.





internal wave activity in the GS

Glider data

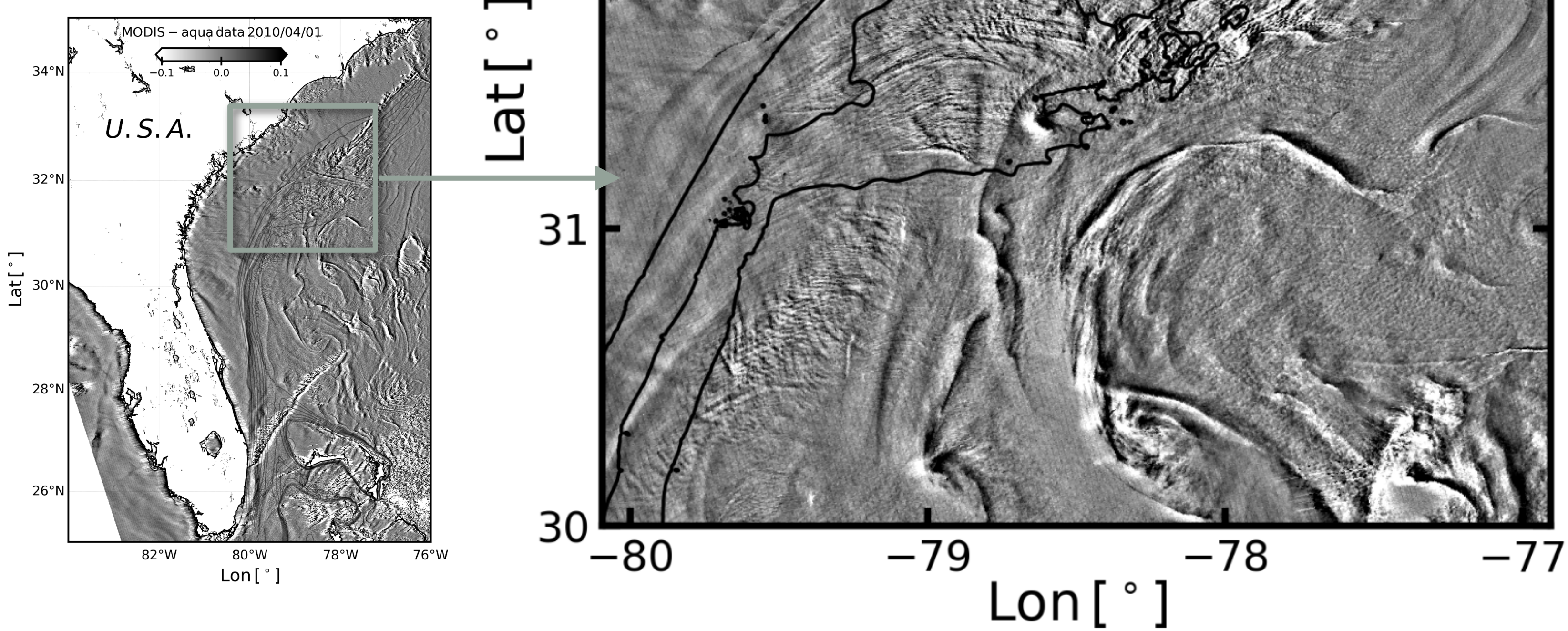


(a) Standard deviations of vertical velocities from individual glider dives averaged in 0.5◦ × 0.5◦ boxes. (b) Vertically integrated internal wave energy [Todd, 17]

1.2. Generation of Lee waves - Real example

- Internal waves can be observed using synthetic aperture radars (SAR) or Sun-glitter images through their surface roughness signature.

Observations of Lee Waves in the Gulf Stream



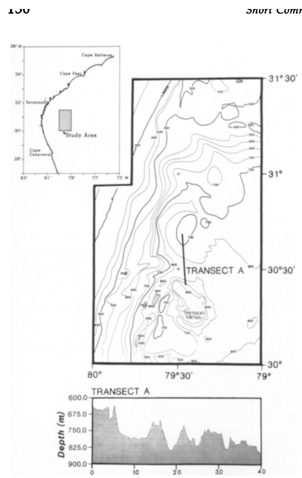
1.2. Generation of Lee waves - Real example

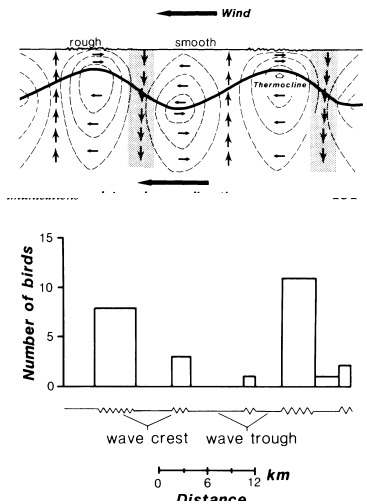
- They were also previously inferred from patchiness in sea-birds distribution:

Observations of Lee Waves in the Gulf Stream

The American Ornithologists' Union

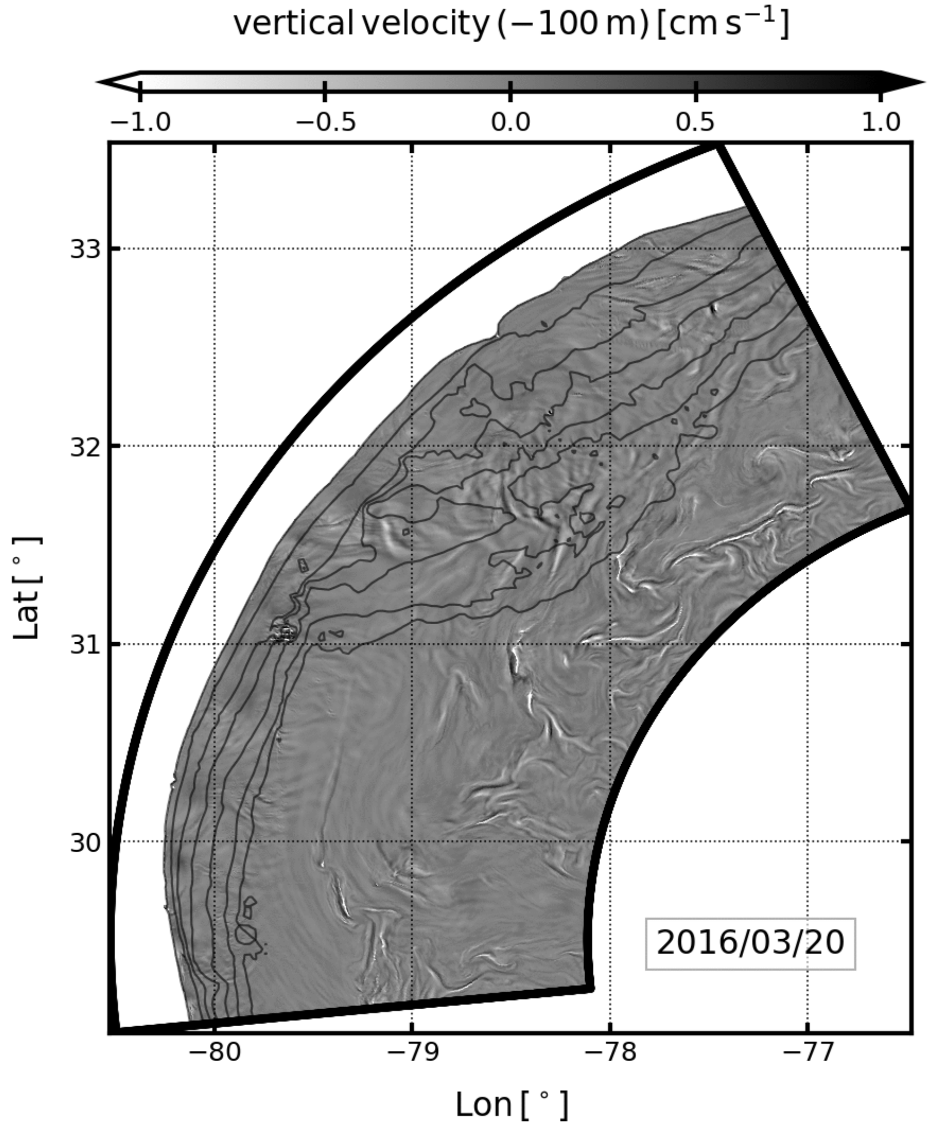
Haney, 1986: "Ocean Internal Waves as Sources of Small-Scale Patchiness in Seabird Distribution on the Blake Plateau".





1.2. Generation of Lee waves - Real example

- We performed a ROMS/CROCO nest dx = 200 m,
- Nx x Ny x Nz = 1024 x 2048 x 128
- Climatological forcings (monthly winds, no tides)
-

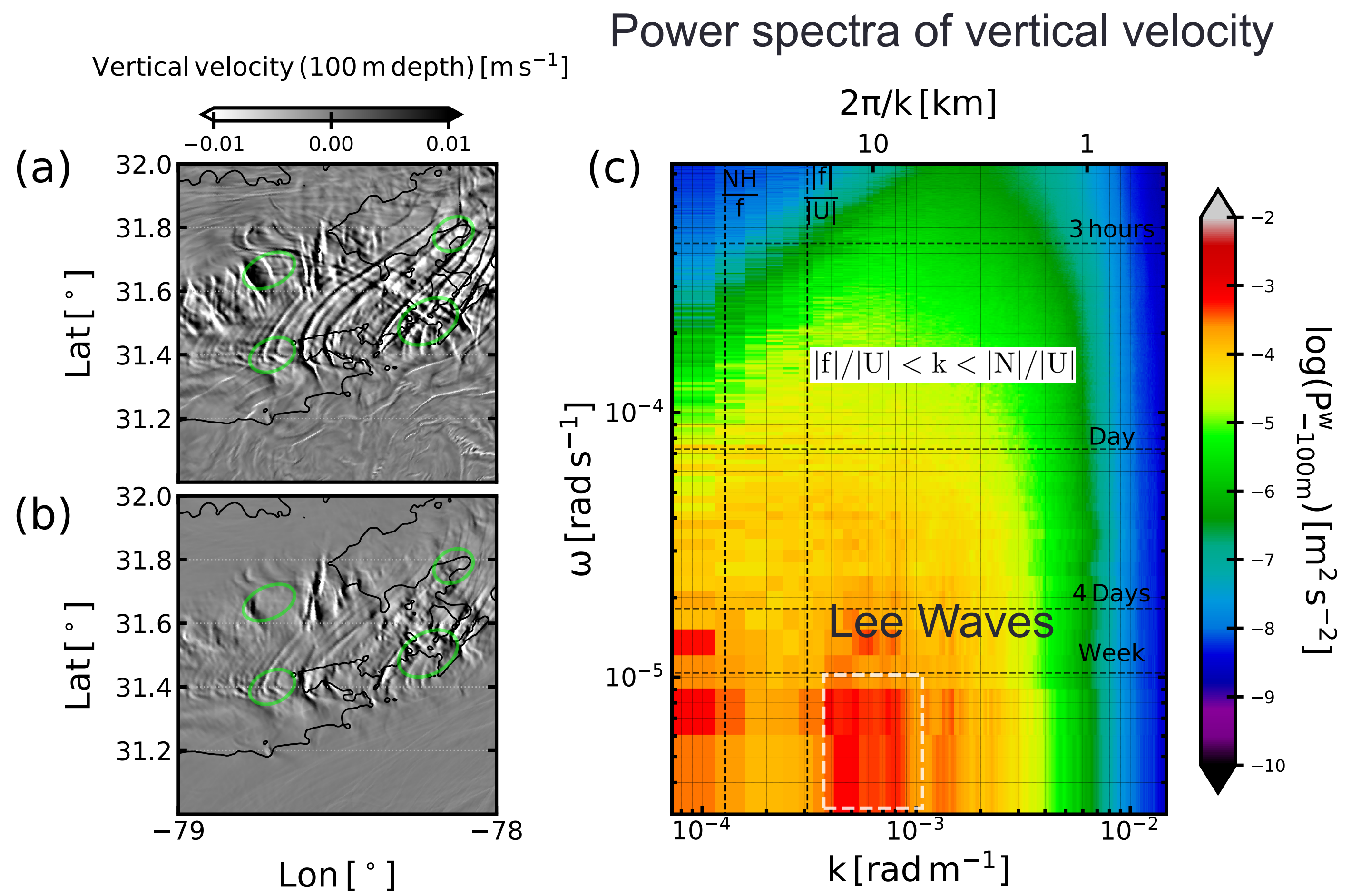


Simulation of the Gulf Stream

1.2. Generation of Lee waves - Real example

- We can isolate patterns related to Lee Waves by looking at time-low passed vertical velocities below the thermocline:

Lee Waves in the Gulf Stream



1.2. Generation of Lee waves - Real example

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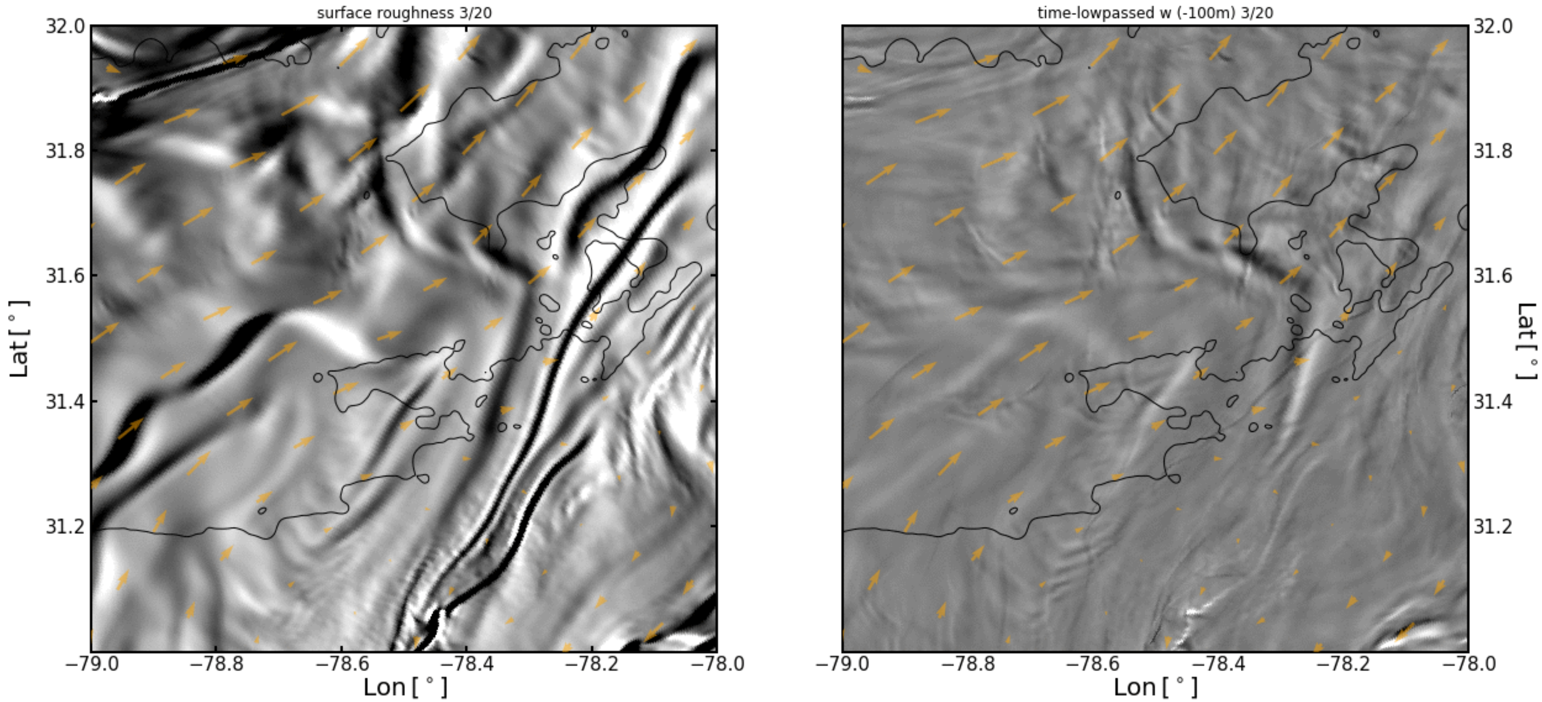


1.2. Generation of Lee waves - Real example

- 3D theoretical prediction of hydrostatic lee waves is obtained by numerically solving:

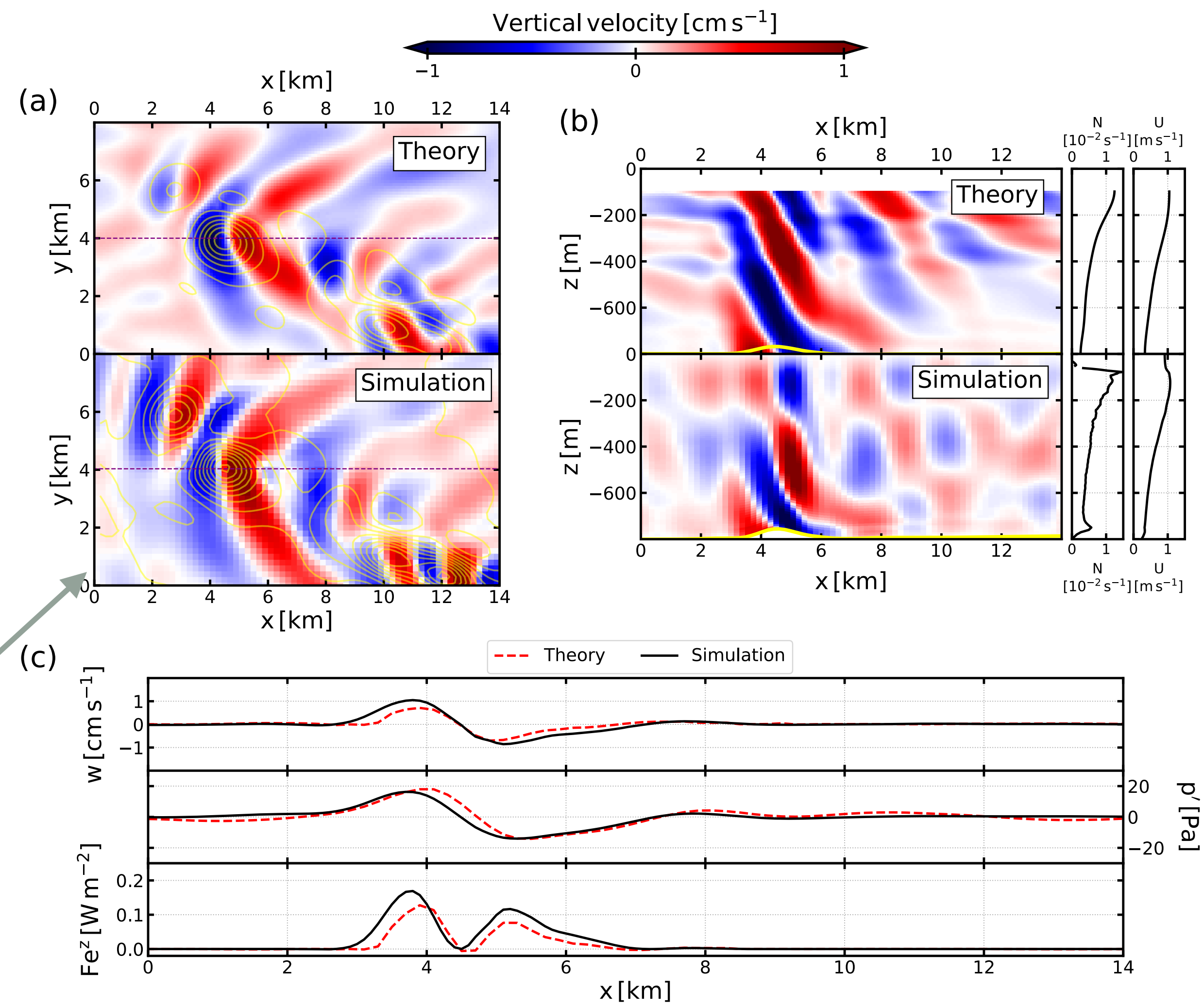
$$\partial_{zz}\,\tilde{\eta}(\mathrm{k},\mathrm{m},\mathrm{z}) + \mathrm{n}^2\,\tilde{\eta}(\mathrm{k},\mathrm{m},\mathrm{z}) = 0$$

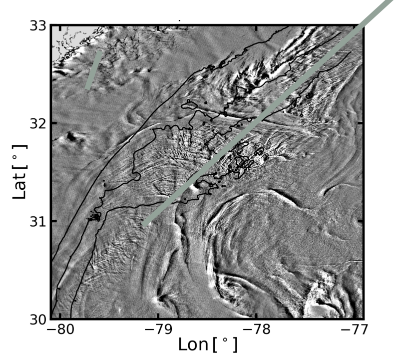
- under the WKBJ approximation with the dispersion relation:

$$\mathrm{n}^2(\mathrm{k},\mathrm{m},\mathrm{z}) = \mathrm{k}^{-2}(\mathrm{k}^2+\mathrm{m}^2)\left(\frac{\mathrm{N}^2}{\mathrm{U}^2} + \frac{\partial_{zz}\mathrm{U}}{\mathrm{U}}\right)$$

- and radiation condition at the top of the domain and a Dirichlet condition at the bottom.

Comparison of Lee Waves with linear theory





1.2. Generation of Lee waves - Real example

- A significant amount of energy (O(1) GW) is being dissipated in the interior of the fluid by the lee waves, including at locations where these waves may exhibit nonlinearities.

- The lee wave energy flux ($\mathrm{Fe^z} = \mathrm{p'w}$) computed using analytical formulation of Nikurashin and Ferrari (2011) yields a total conversion of O(0.3)GW.

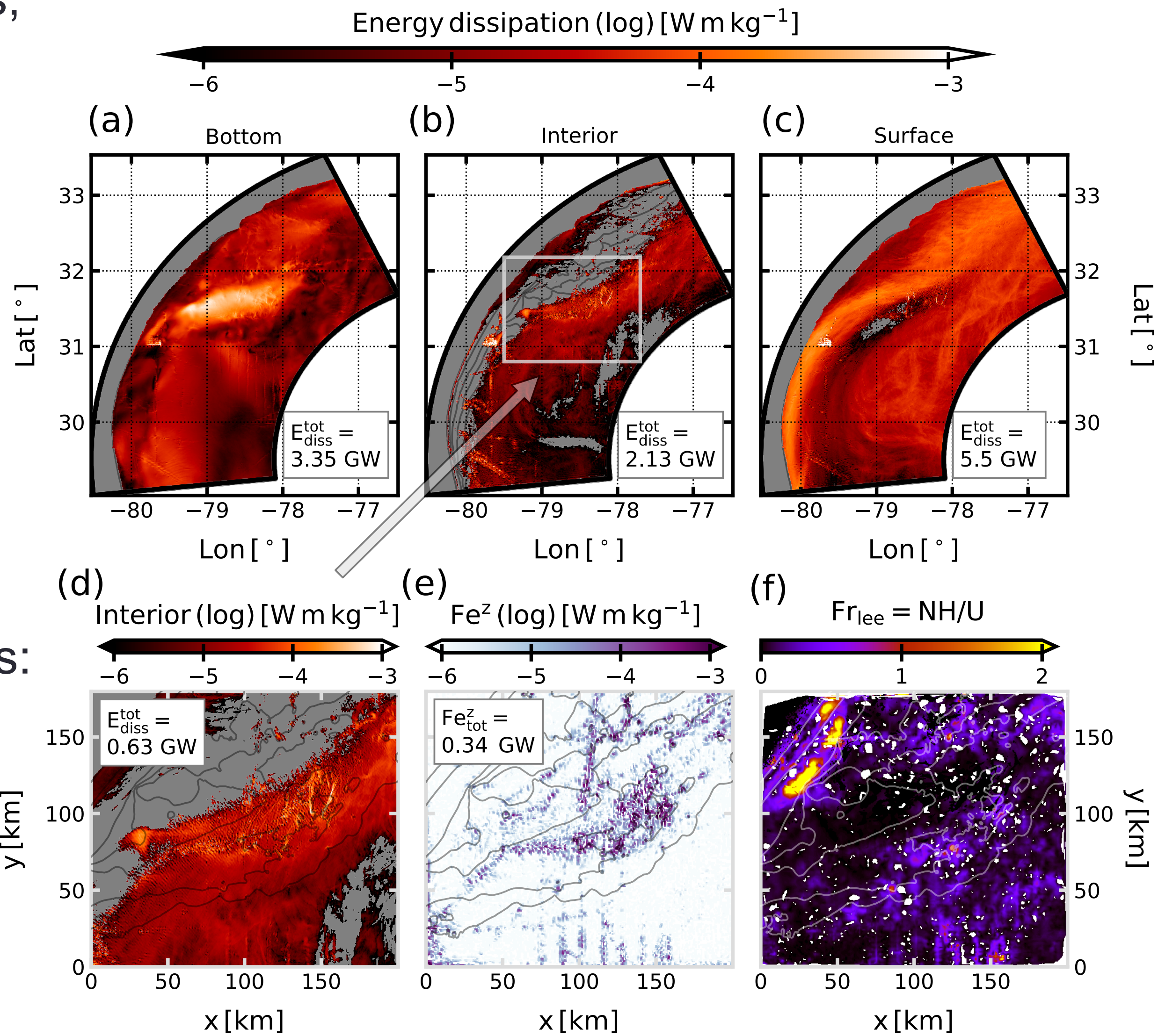
$$E = \frac{\rho_0|\mathbf{U}|}{2\pi}\int_{|f|/|\mathbf{U}|}^{N/|\mathbf{U}|} P_*(k)\sqrt{N^2-|\mathbf{U}|^2k^2}\sqrt{|\mathbf{U}|^2k^2-f^2}dk,$$

- The wave drag can be computed as:

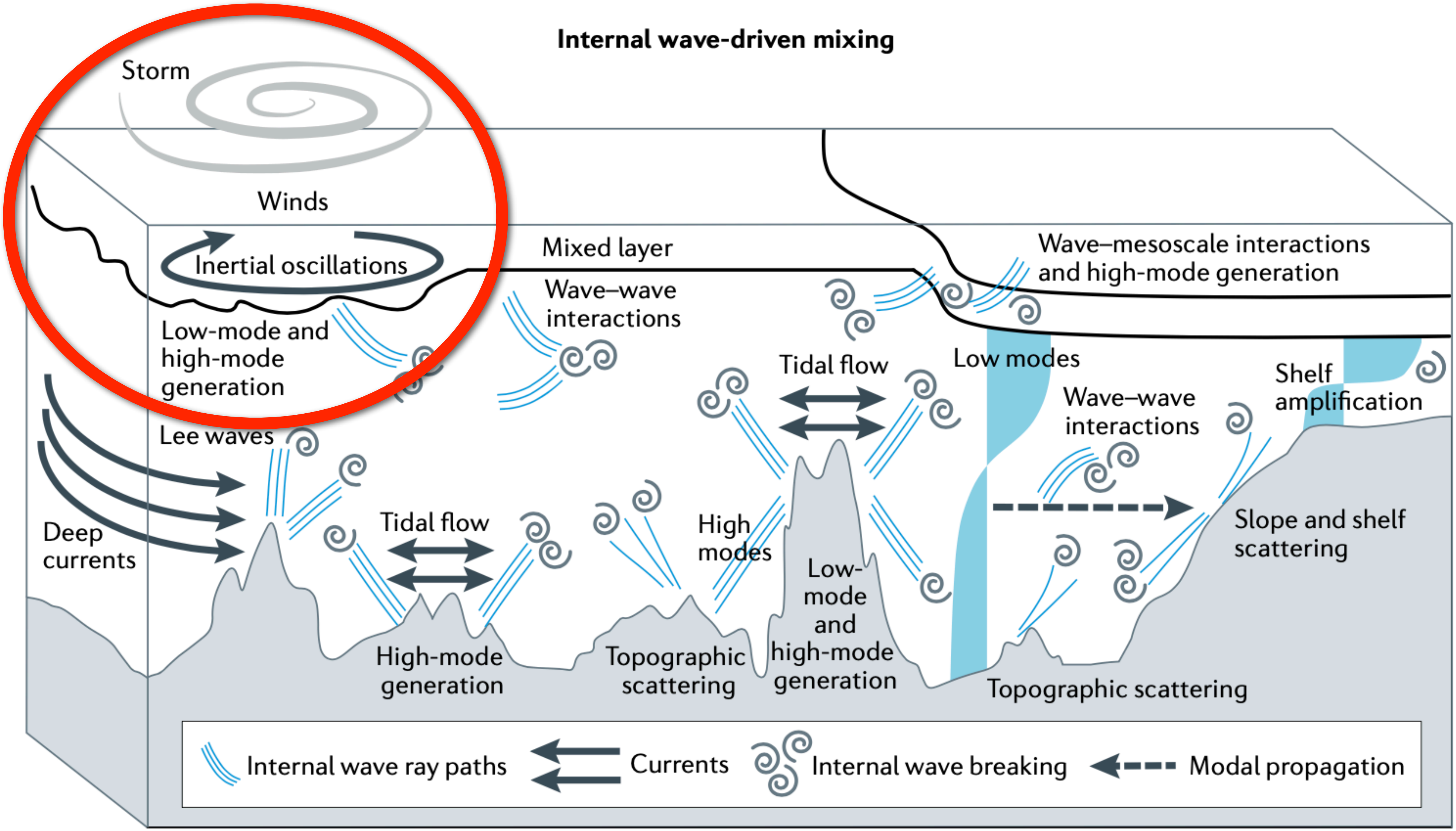
$$\text{Form Drag} = \rho_0\sqrt{(\mathrm{u'w})^2+(\mathrm{v'w})^2}$$

- It amounts to O(1) GN and represents about 20% of the form drag exerted by the whole Charleston Bump.

Energy dissipation due to Lee Waves



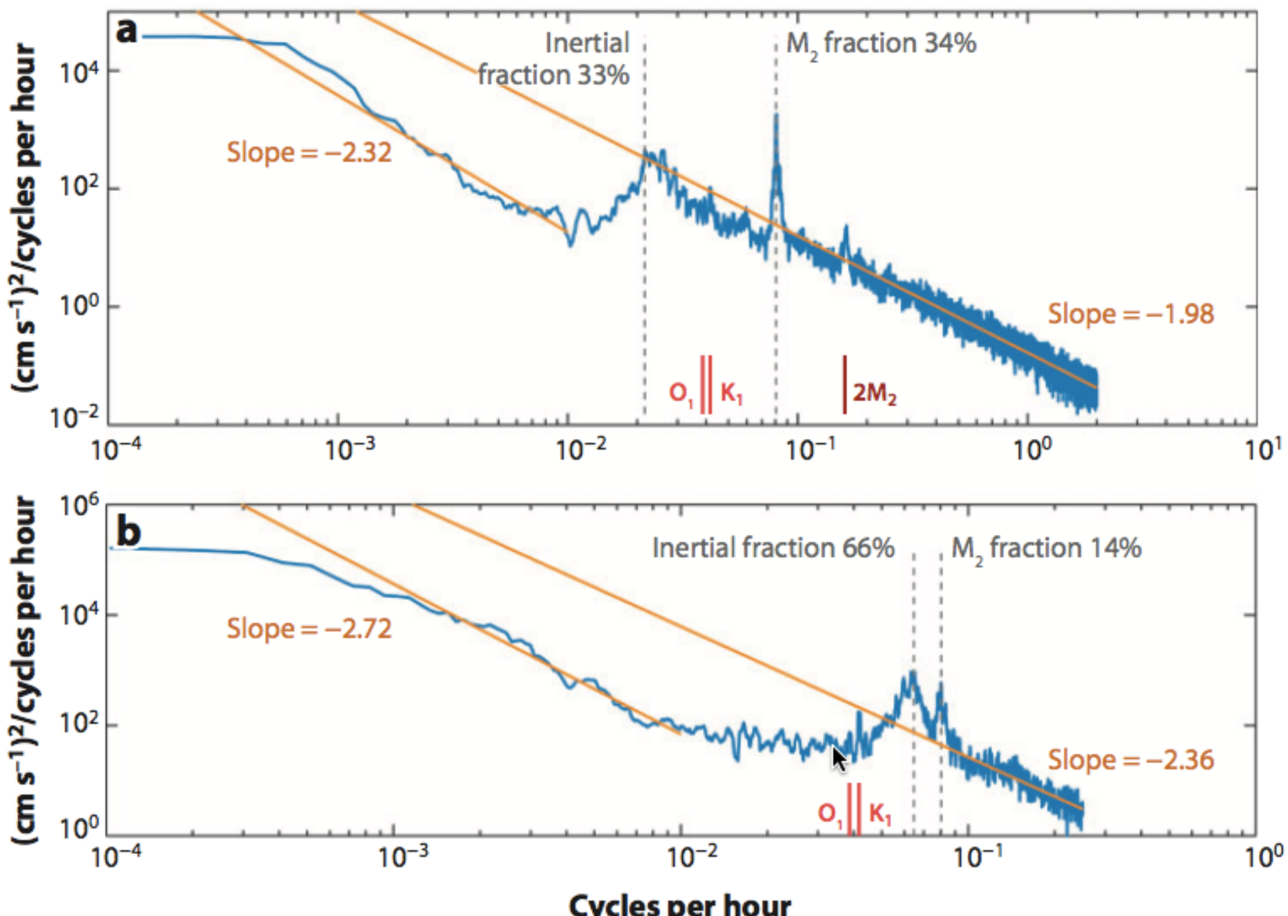
1.3 Generation of near-inertial waves



Whalen et al 2020

1. Internal waves generation

- Winds generate mostly near-inertial waves (frequency close to f)
  = The near-inertial peak contains about half the kinetic energy in the internal wave spectrum



(*a*) Kinetic energy estimate for an instrument in the western North Atlantic near 15◦N at 500 m. (*b*) Power density spectral estimate from a record at 1000 m at 50.7◦S, 143◦W, south of Tasmania in the Southern Ocean

1.3. Generation of Near-Inertial waves (NIW)

- Near-inertial frequencies are associated primarily with atmospheric forcing.

- The ocean selects near-inertial frequencies for amplification because the aspect ratio of the forcing is exceedingly small.
  - Storms tends to have horizontal scales of O(100-1000 km)
  - The ocean mixed layer is typically no deeper than 100 m
  - Storms move rapidly so that the ocean does not have time to adjust

1.3. Generation of Near-Inertial waves (NIW)

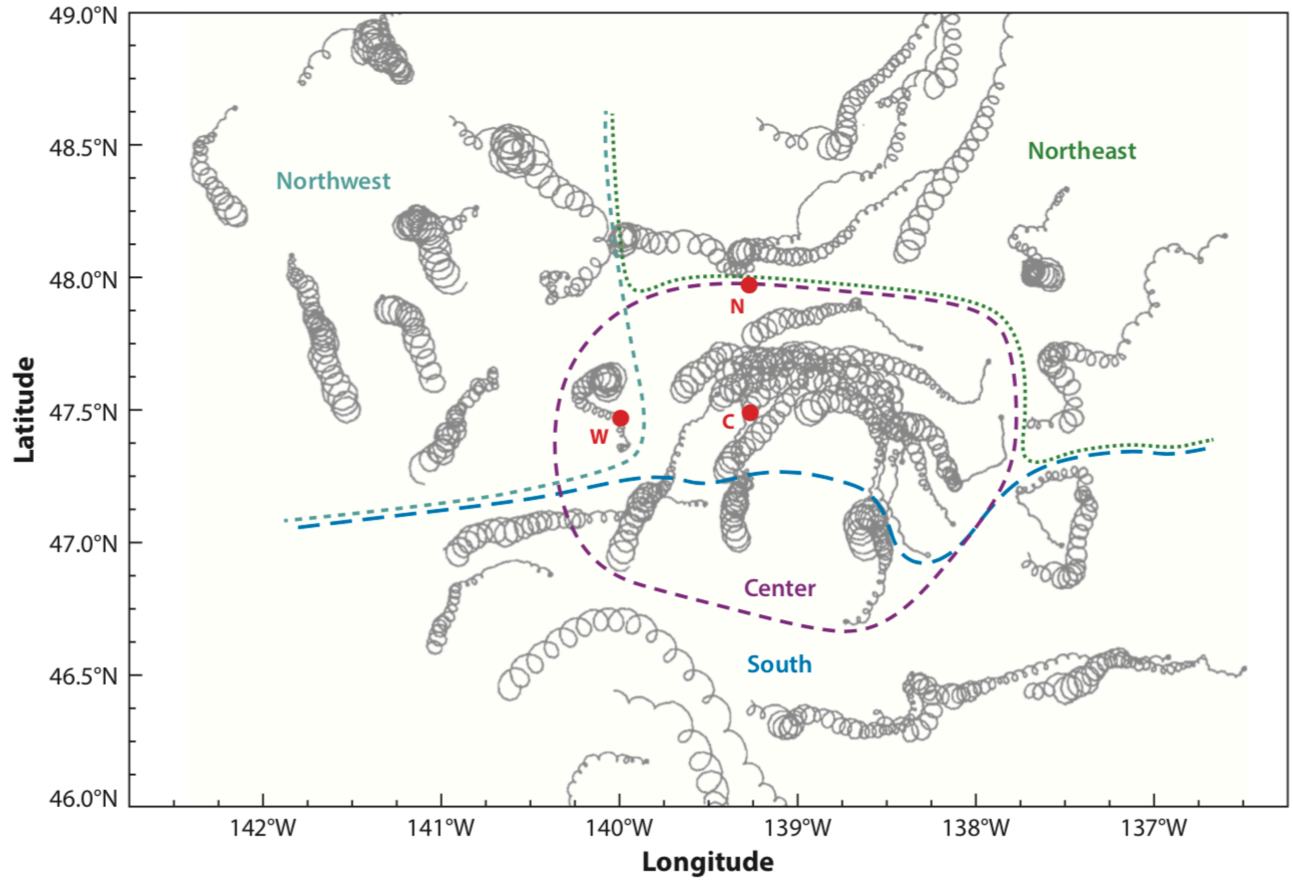
- We can integrate the linearized hydrostatic Boussinesq equations on the *f*-plane over the mixed layer (Horizontal gradients and vertical velocities can be neglected at the lowest order):

$$
\begin{aligned}
\frac{\partial u}{\partial t} &= -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + fv + \frac{1}{\rho_0}\frac{\partial}{\partial z}\tau_x, \\
\frac{\partial v}{\partial t} &= -\frac{1}{\rho_0}\frac{\partial p}{\partial y} - fu + \frac{1}{\rho_0}\frac{\partial}{\partial z}\tau_y, \\
\frac{\partial p}{\partial z} &= -g\rho', \\
\frac{\partial}{\partial z}\mathbf{u} &= 0, \\
\frac{\partial \rho'}{\partial t} &= \frac{\rho_0}{g}N^2 w,
\end{aligned}
\quad \longrightarrow \quad
\begin{aligned}
\frac{\partial U}{\partial t} &= +fV + \frac{1}{\rho_0}\frac{\partial}{\partial z}T_x, \\
\frac{\partial V}{\partial t} &= -fU + \frac{1}{\rho_0}\frac{\partial}{\partial z}T_y,
\end{aligned}
$$

- Solutions are the sum of a steady Ekman transport to the right of the wind and anticyclonic circular motions at the local inertial frequency, **f**

1.3. Generation of Near-Inertial waves (NIW)

- NIW are recognizable by their characteristic circularly polarized velocities



Twenty-five days of surface drifter trajectories after a storm in the eastern north Pacific. The drifters trajectories represent a combination of decaying inertial motions (circular oscillations) and weak geostrophic flow (the time-averaged drift). **[D'Asaro et al, 1995]**

1.3. Generation of Near-Inertial waves (NIW)

- Dispersion relation for internal waves:

$$\omega^2 = \frac{N^2 k^2 + f^2 m^2}{k^2 + m^2}$$

-

1.3. Generation of Near-Inertial waves (NIW)

- Dispersion relation for internal waves:

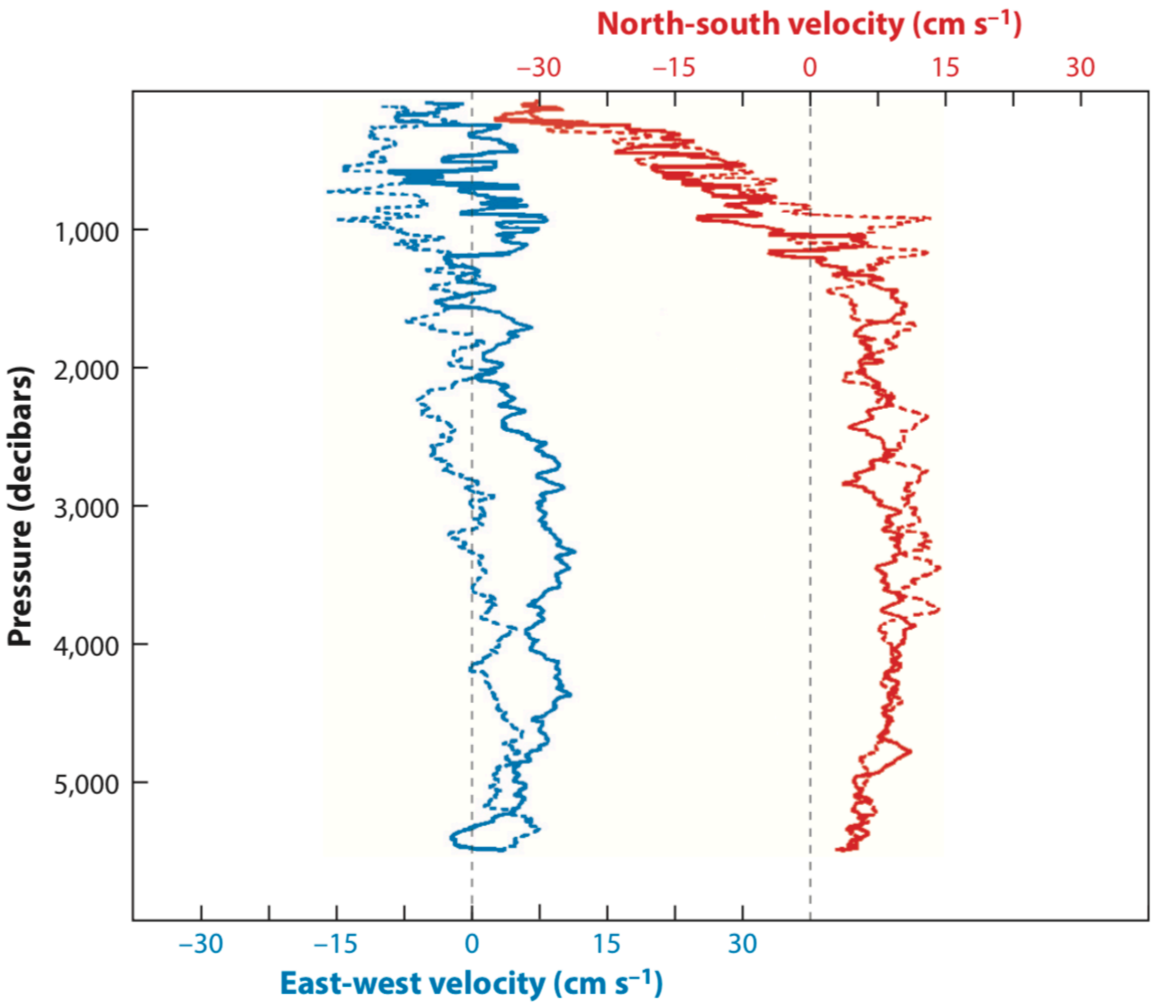
$$\omega^2 = \frac{N^2 k^2 + f^2 m^2}{\cancel{k^2} + m^2}$$

- For hydrostatic NIW:

$$\omega^2 = f^2 + \frac{N^2 k^2}{m^2} \qquad k << m$$

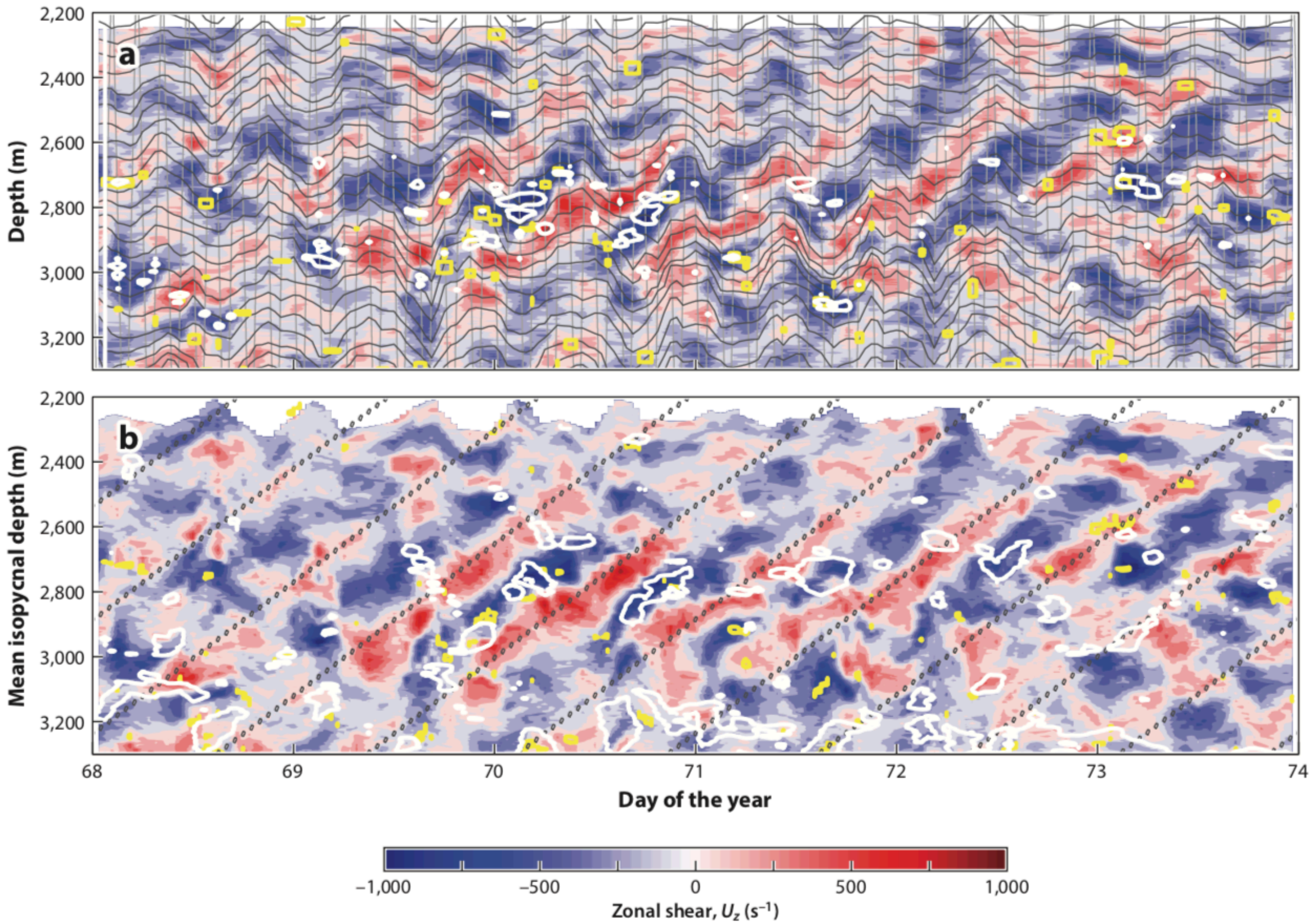
1.3. Generation of Near-Inertial waves (NIW)

- NIW are also recognizable by their a strong vertical shears



Two profiles (dashed and solid lines) of east-west (blue) and north-south (red) velocity taken at an interval of half an inertial period, showing high-wavenumber near-inertial motions. **[Leaman & Sanford, 1975]**

1.3. Generation of Near-Inertial waves (NIW)



For vertical wavelength of 350 m and ω = 1.03f, the horizontal wavelength would be 80 km and the vertical group velocity 10^{-3} m s^{-1}

Zonal shear plotted versus (a) depth and (b) density (expressed as the mean depth of each isopycnal), showing the upward phase propagation of near-inertial shear layers. Shear layers are aligned with isopycnals (dark gray lines in panel a), which are heaved vertically by internal waves of other frequencies (primarily tidal; light gray lines); this heaving is removed in the isopycnal-following frame (panel b). The dissipation rate from overturns is contoured in yellow (contour value 1.5 × 10−8 W kg−1); the Richardson number (white contours) drops below 0.8 once per wave period. In panel b, the dotted lines represent the wave phase for a signal with ω = 1.03 f and λ = 350 m.

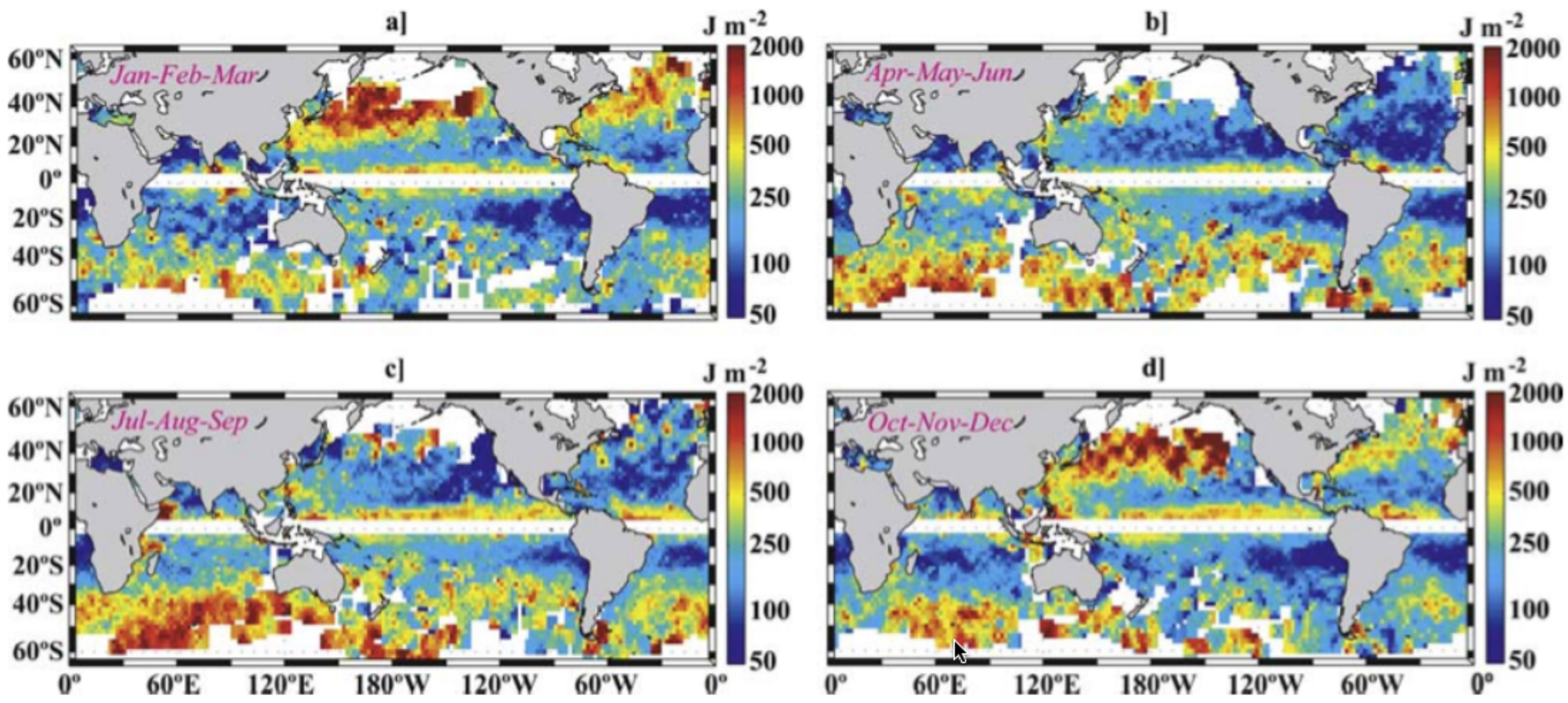
1.3. Generation of Near-Inertial waves (NIW)

The general characteristics of NIWs are as follows:

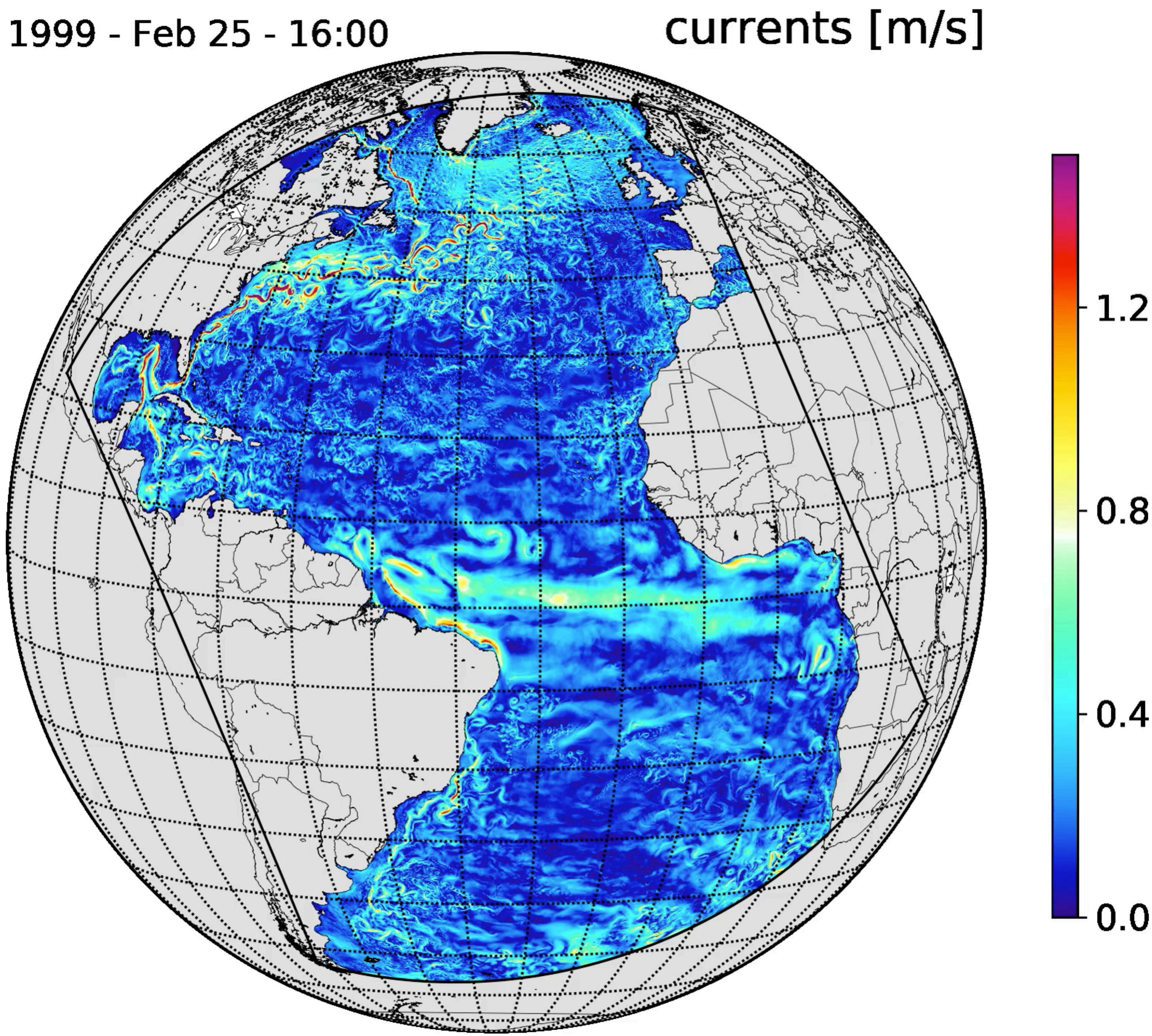
- Clockwise and counterclockwise polarization in the Northern and Southern Hemispheres, respectively
- Frequency of 1–1.2f
- Vertical wavelength of 100–400 m
- Lateral scale of 10–500 km

1.3. Generation of Near-Inertial waves (NIW)

Seasonal band-passed near-inertial energy density in the boundary layer is elevated under storm tracks. Results computed from surface drifter trajectories. **[Chaigneau et al., 2008]**

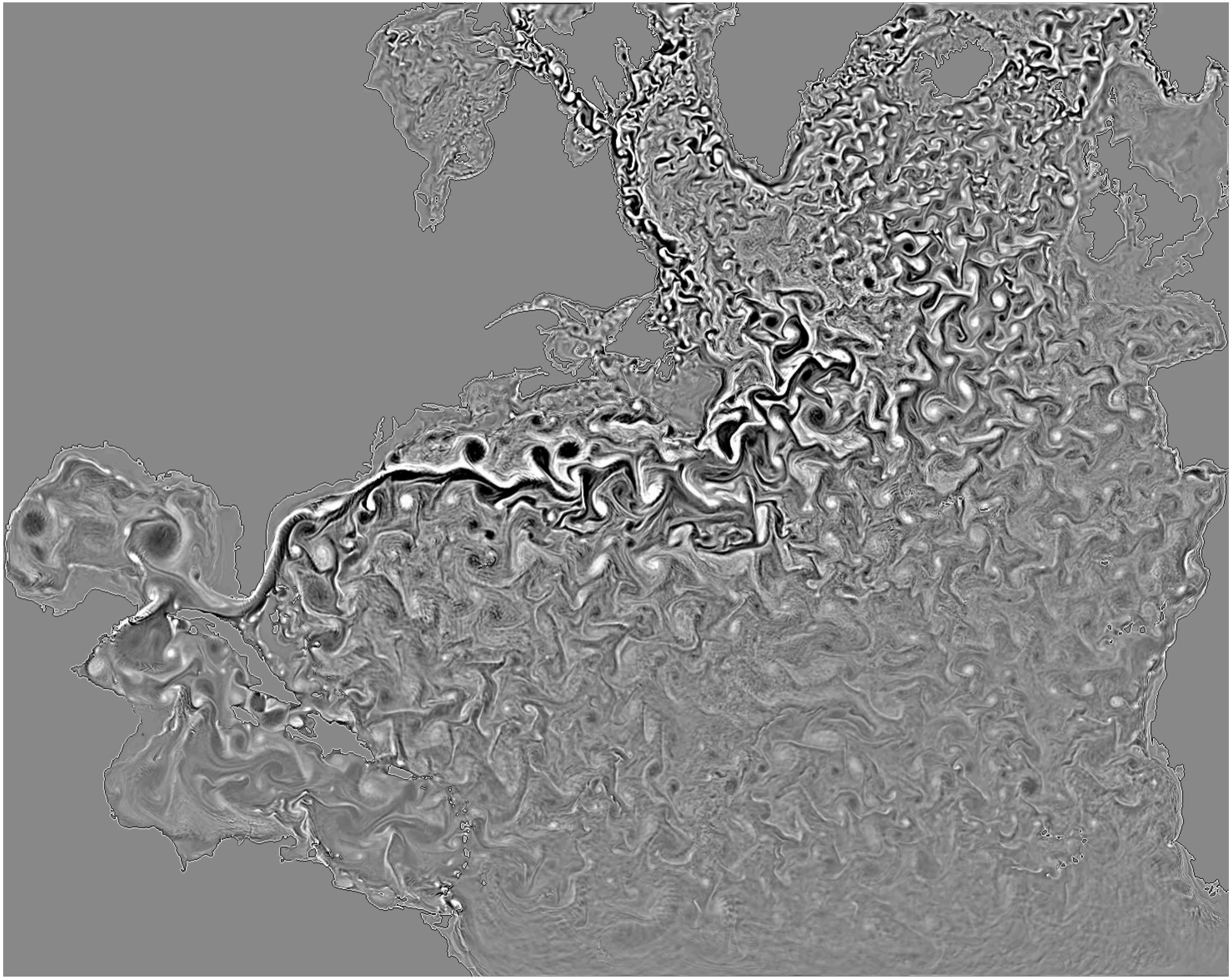


- **High-frequency surface forcings** (using hourly CFSR data and bulk flux formulae)
-

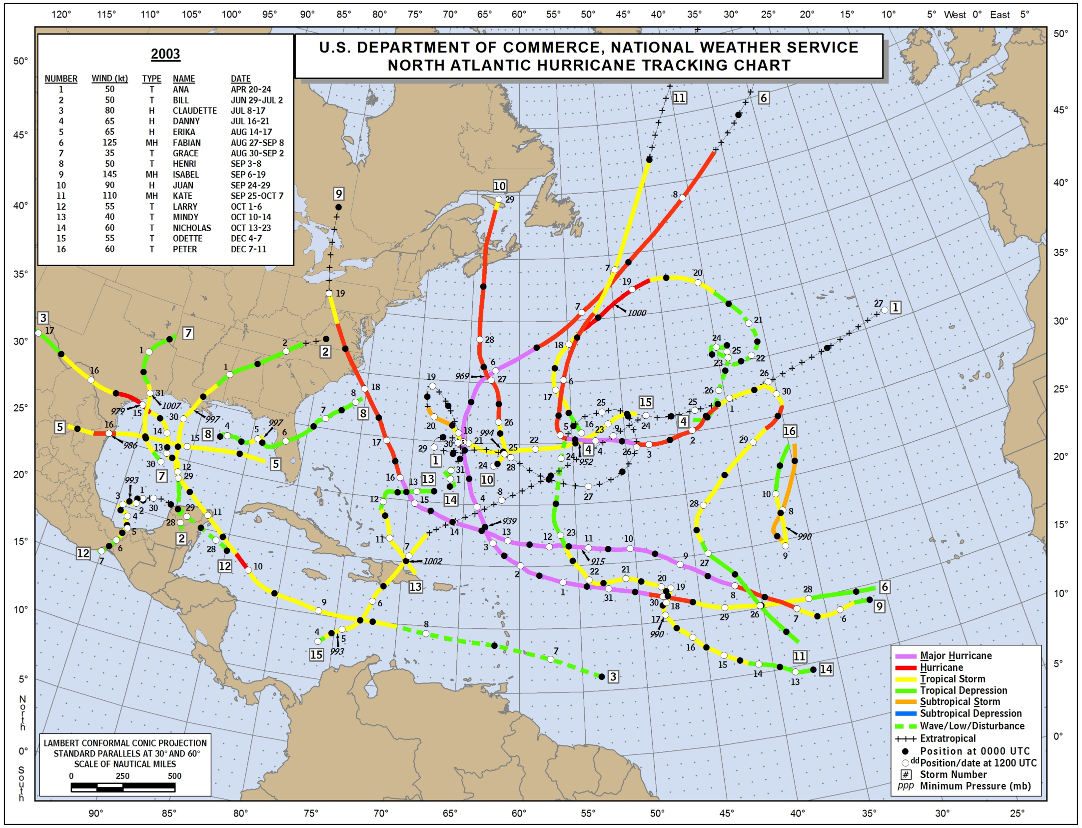


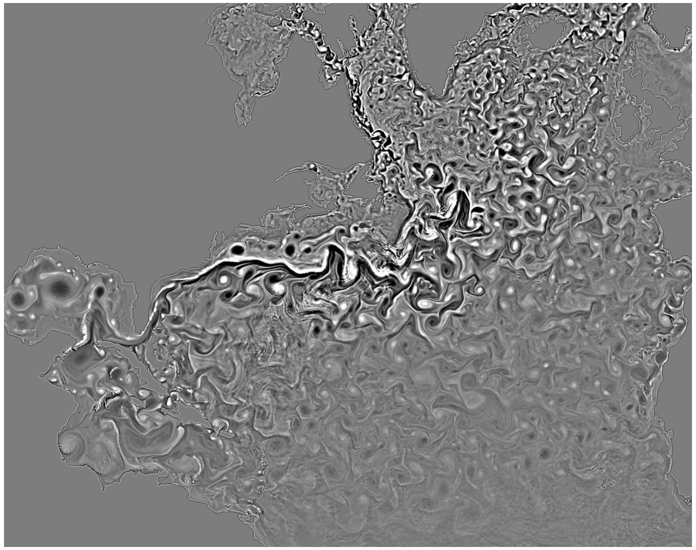
1.3. Generation of Near-Inertial waves (NIW)

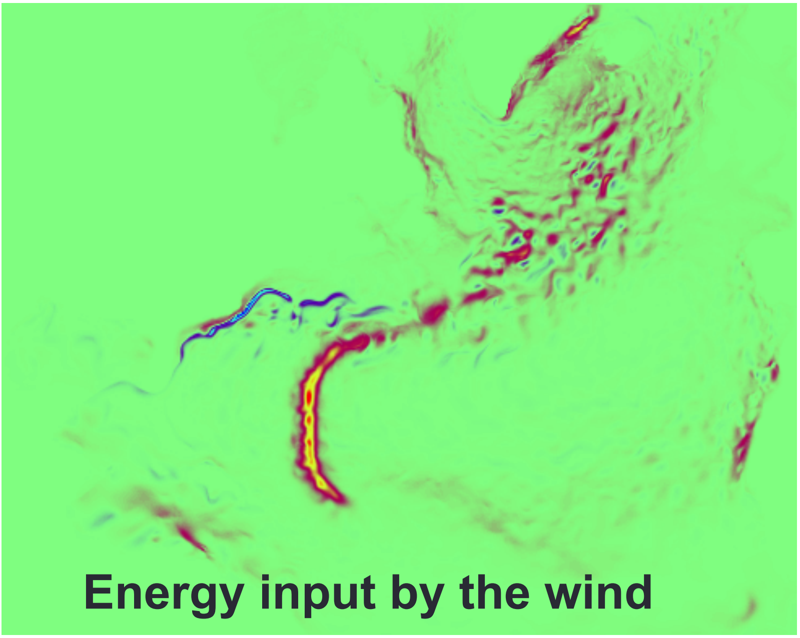
- **High-frequency surface forcings** (using hourly CFSR data and bulk flux formulae)
-



1.3. Generation of Near-Inertial waves (NIW)

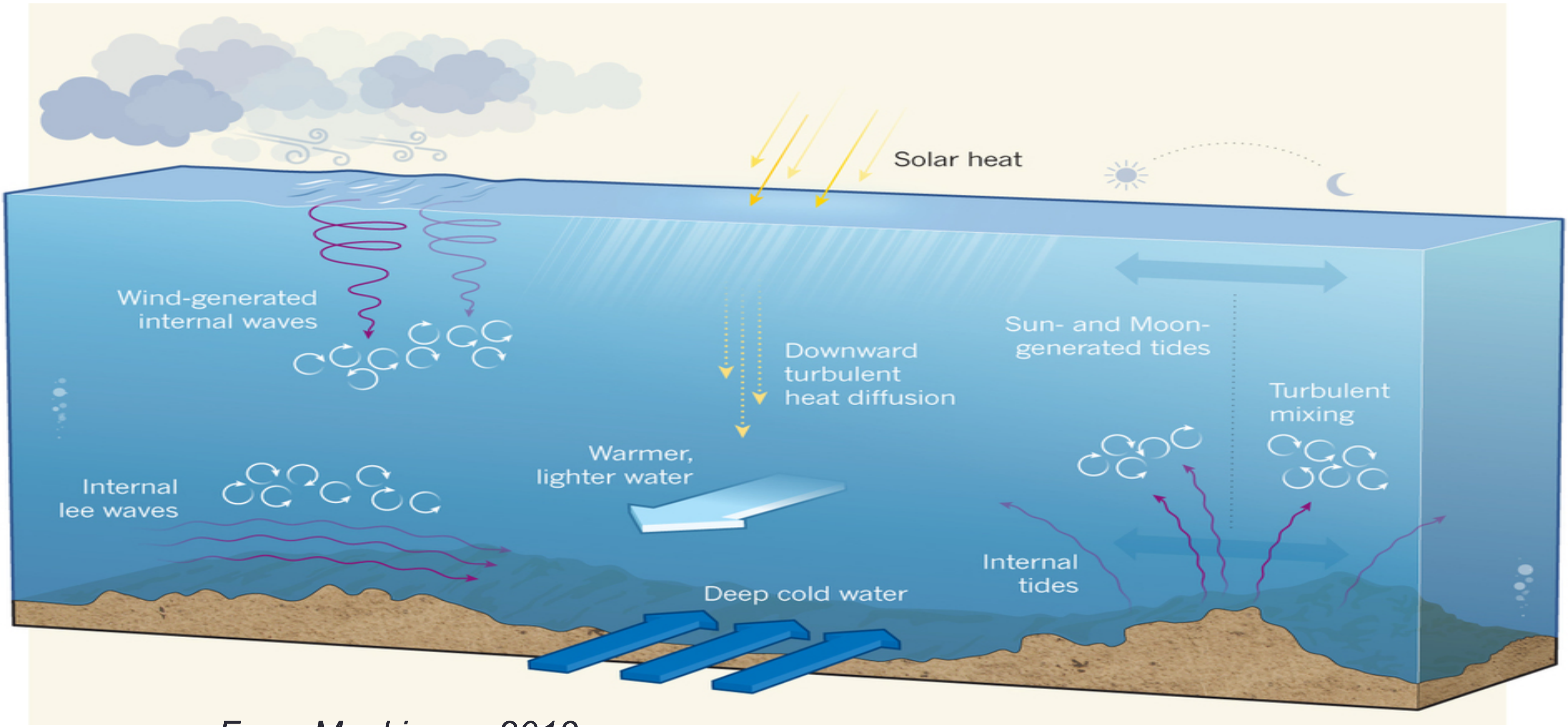






1. Internal waves generation

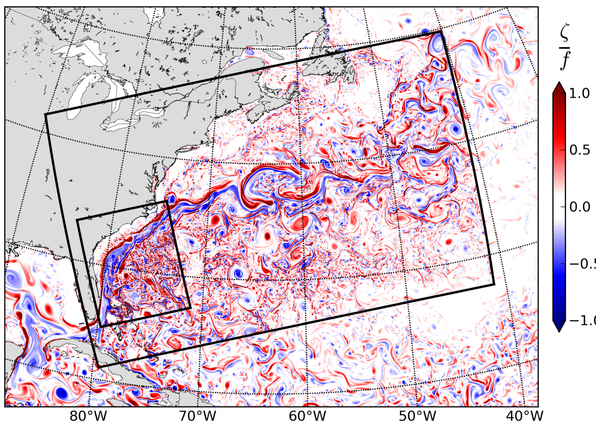
- Mechanisms:



From Mackinnon 2013

Realistic modelling including tides and NIW

- **Gulf Stream / Sargasso Sea**

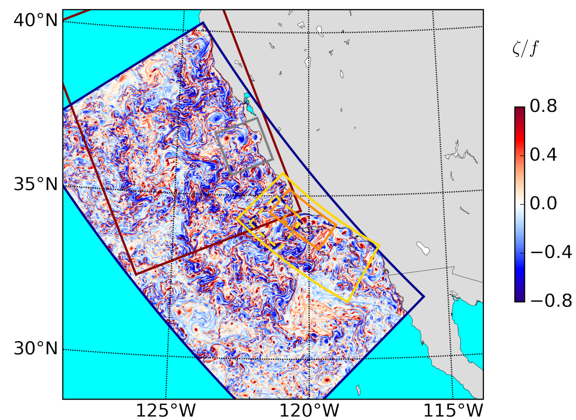


750 m res. forced with:

- Monthly winds
- Hourly winds
- Hourly winds + Tides

(+200 m with HF forcings)

- California Current

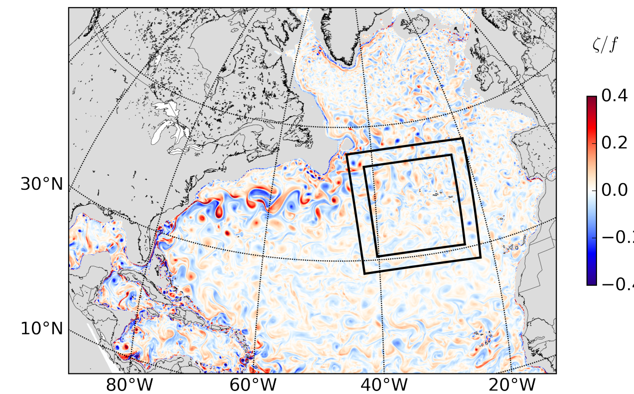


1 km res. forced with:

- Daily winds
- Hourly winds
- Hourly winds + Tides

(+300 m, 100 m with HF forcings and tides)

- Mid-Atlantic ridge

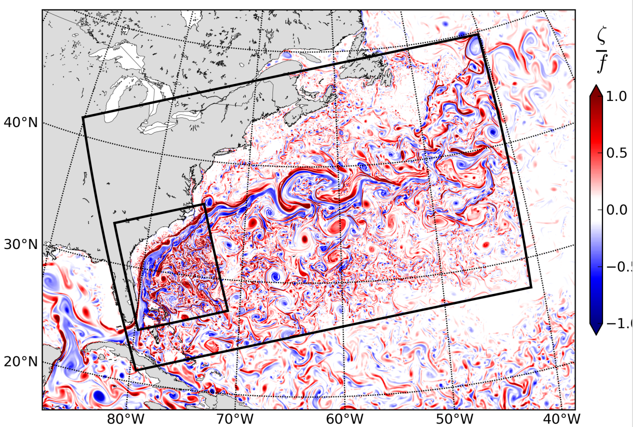


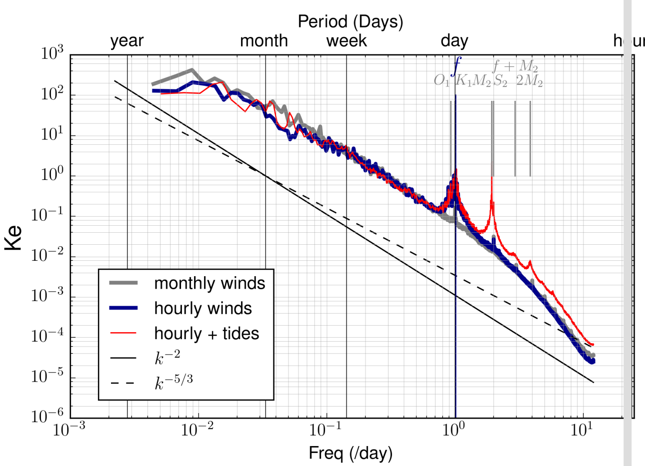
750 m res. forced with:

- daily winds
- daily winds + Tides
- Only tides

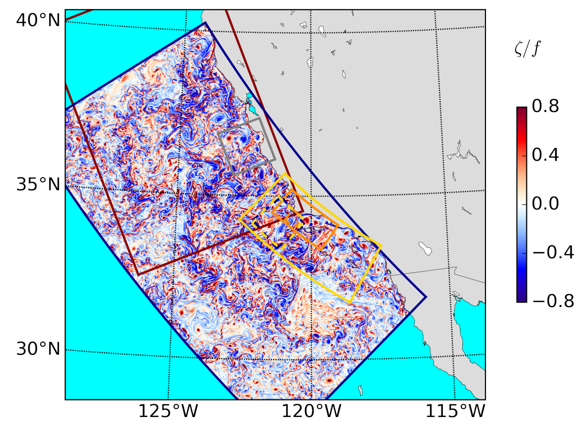
Realistic modelling including tides and NIW

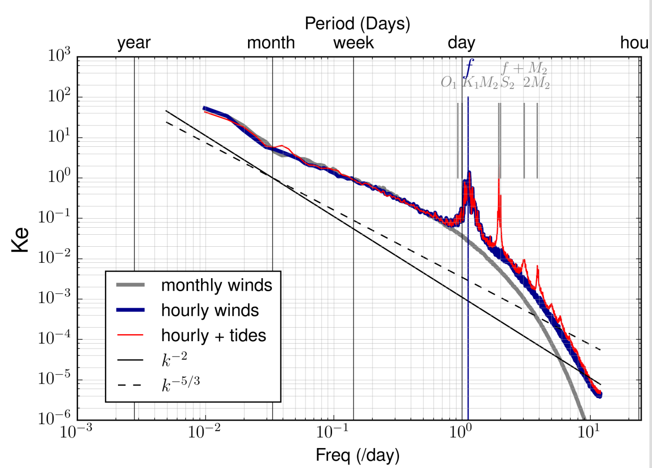
- **Gulf Stream / Sargasso Sea**



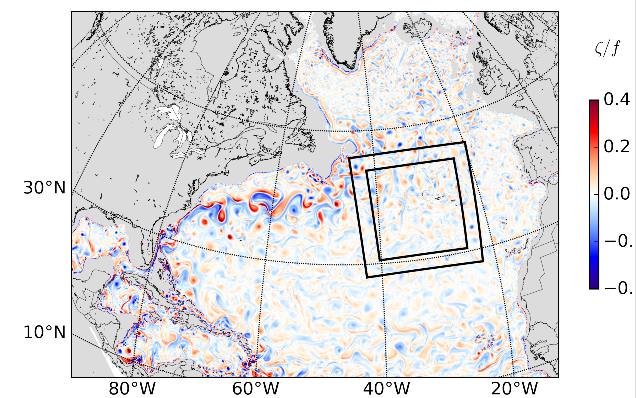


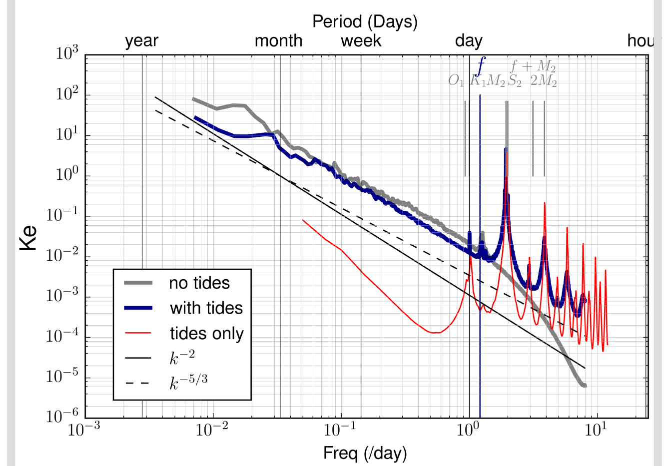
- California Current



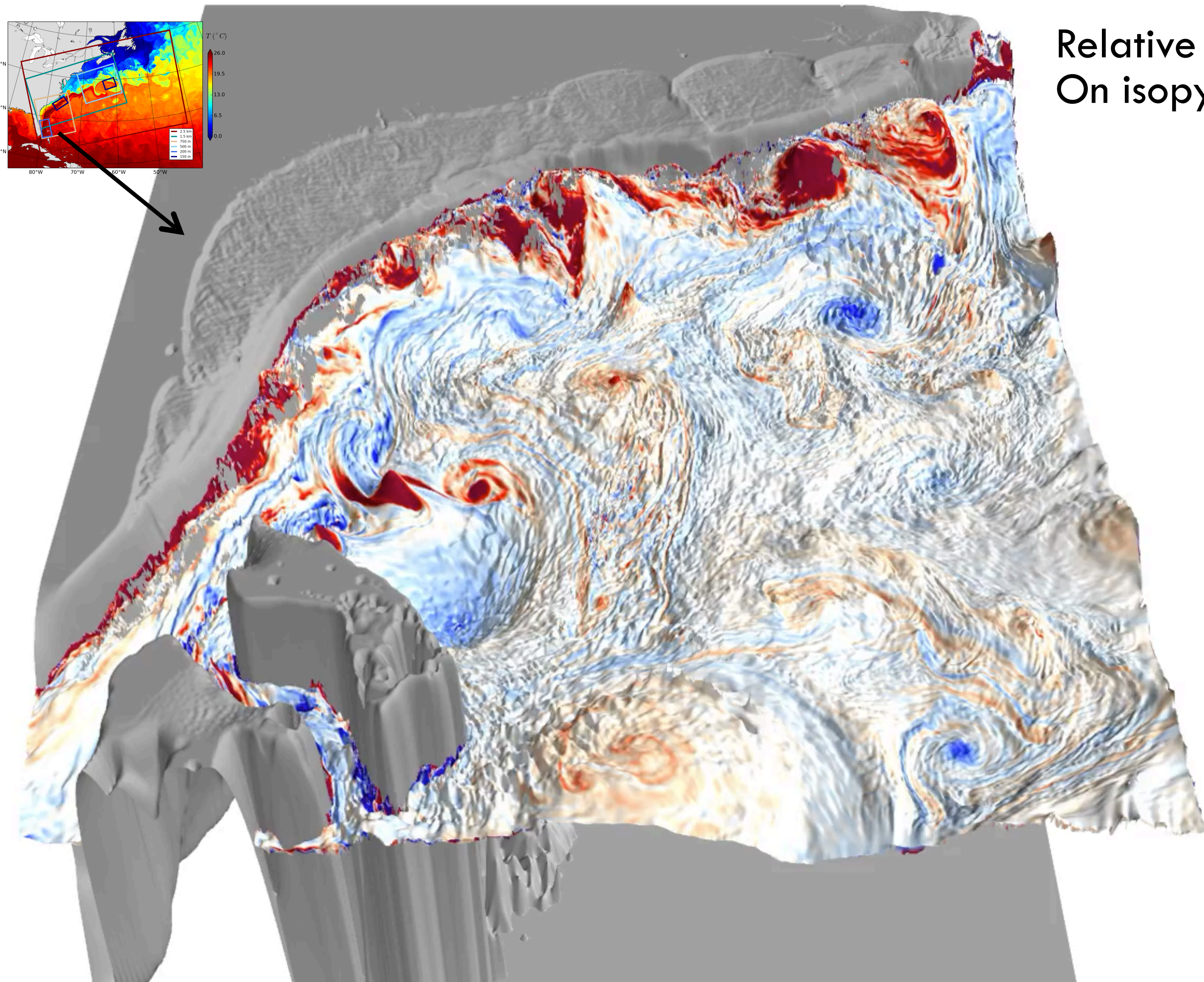


- Mid-Atlantic ridge





Method: Realistic modelling including tides



Relative vorticity $(\pm f)$

On isopycnal $\sigma = 27\,\mathrm{kg\,m^{-3}}$

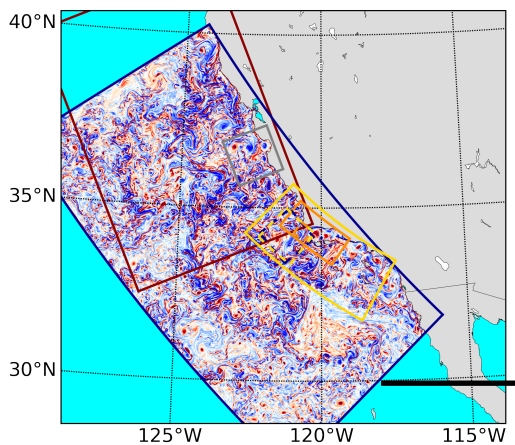
$$\Delta x = 750\,\mathrm{m}$$

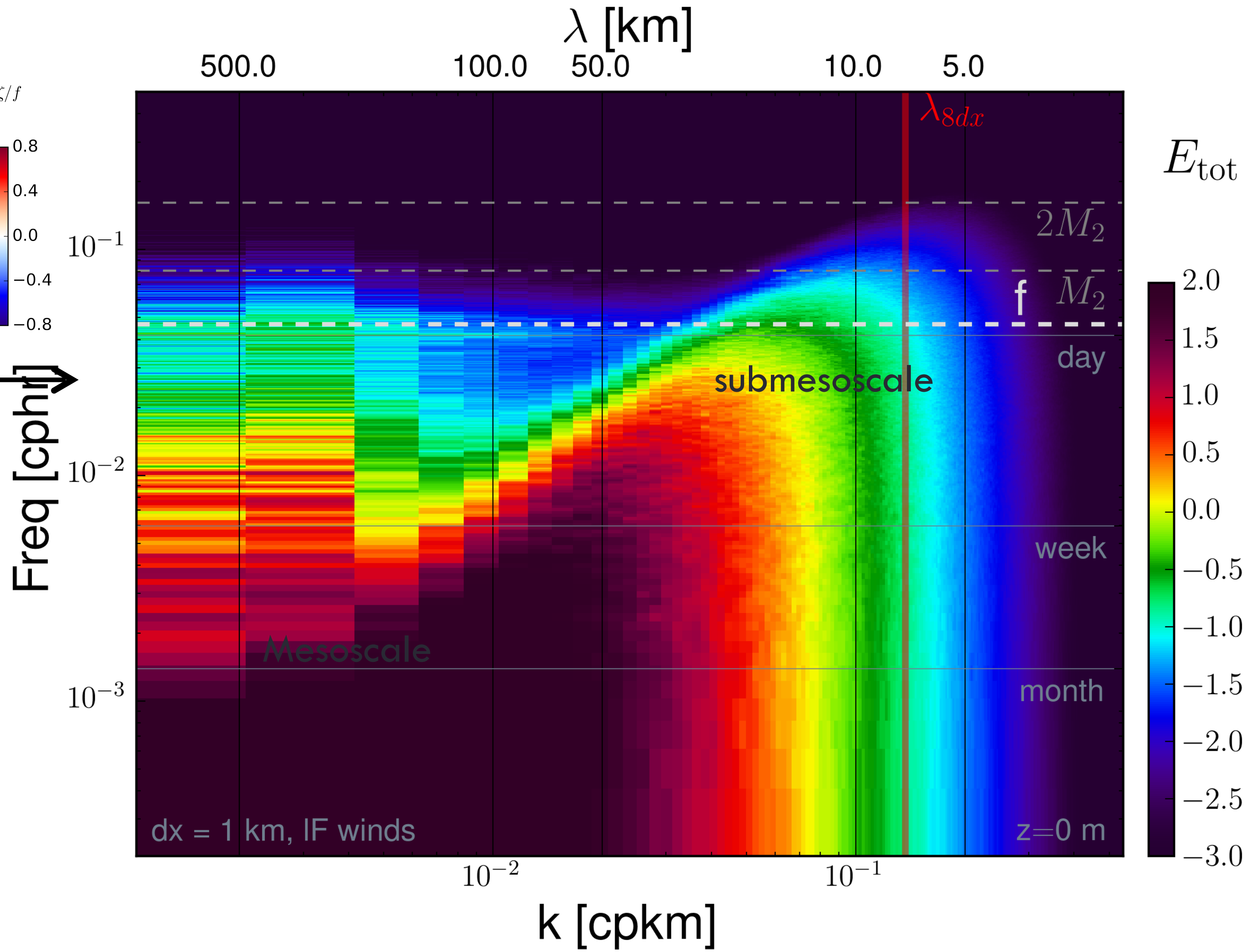
HF wind

+

Tides

Realistic modelling including tides and NIW



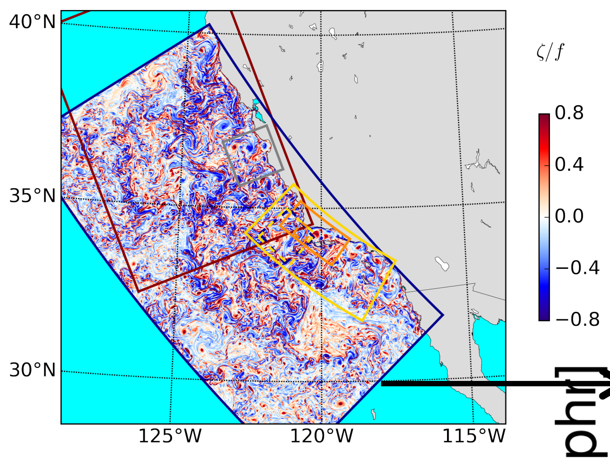


Daily winds No tides

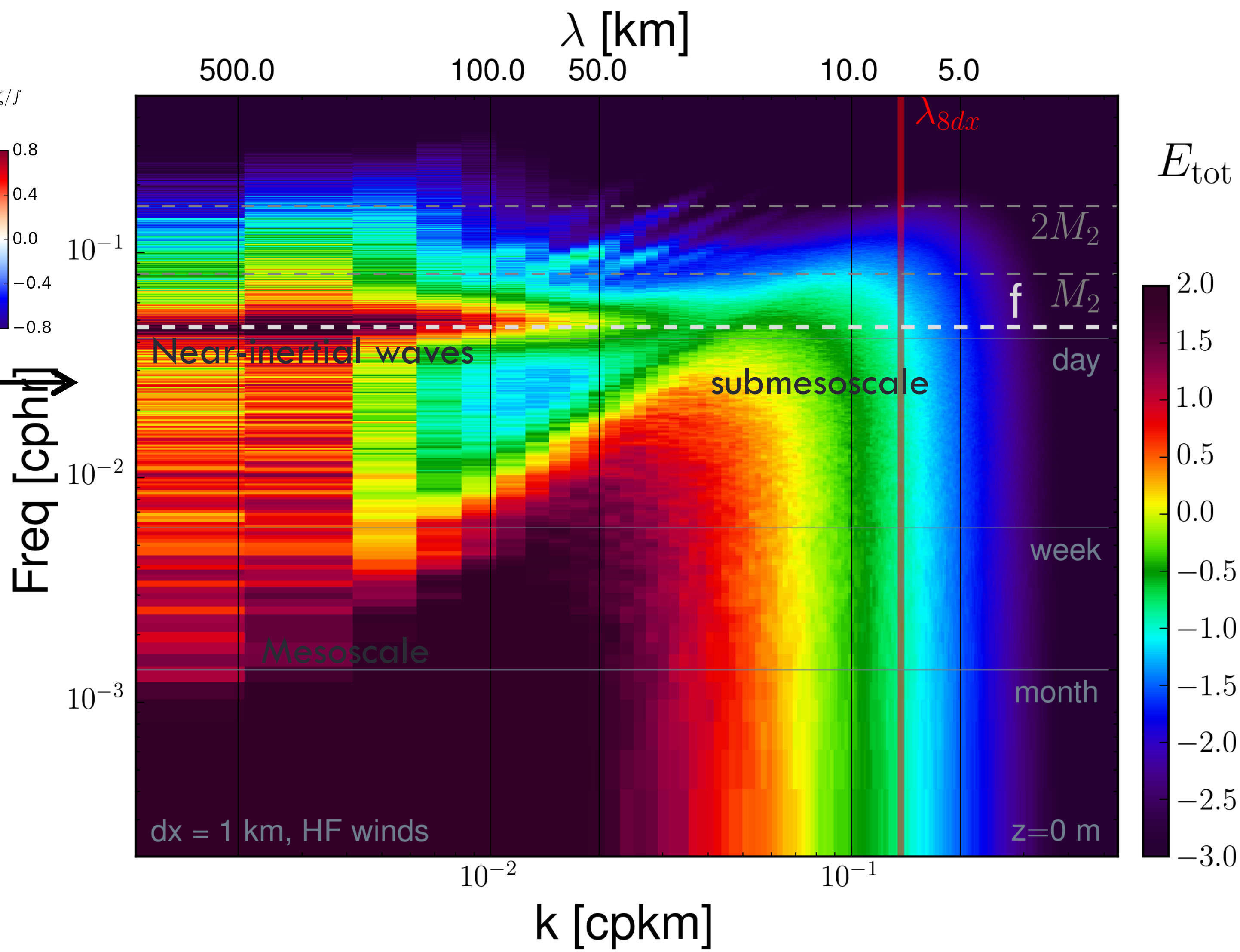
= deficient in internal waves

Azimuthally-averaged 2D frequency-wavenumber kinetic energy spectra in the California Current.

Realistic modelling including tides and NIW

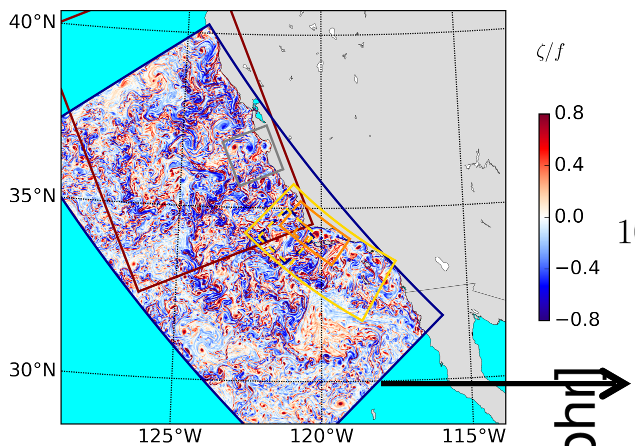


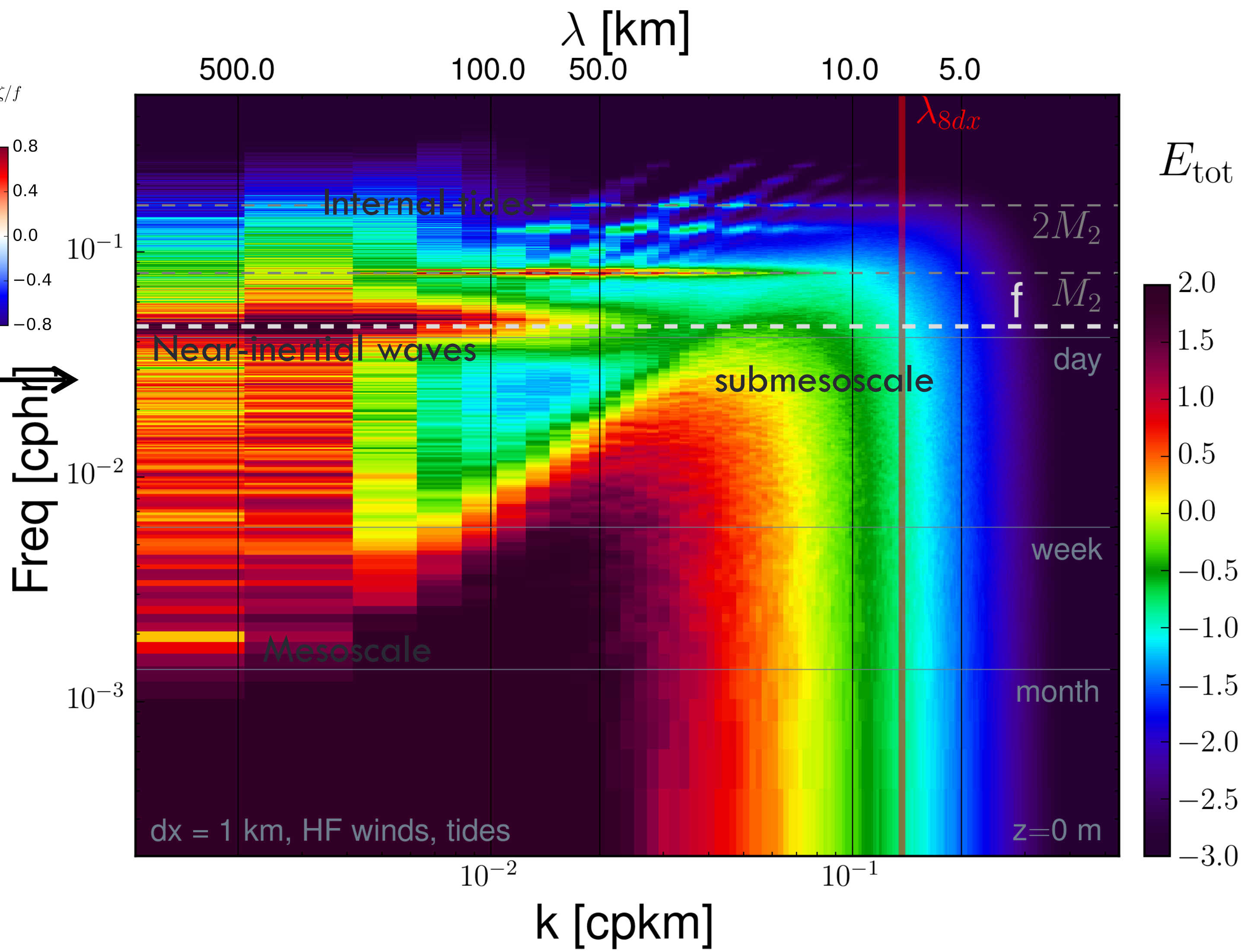
+ High frequency wind



Azimuthally-averaged 2D frequency-wavenumber kinetic energy spectra in the California Current.

Realistic modelling including tides and NIW

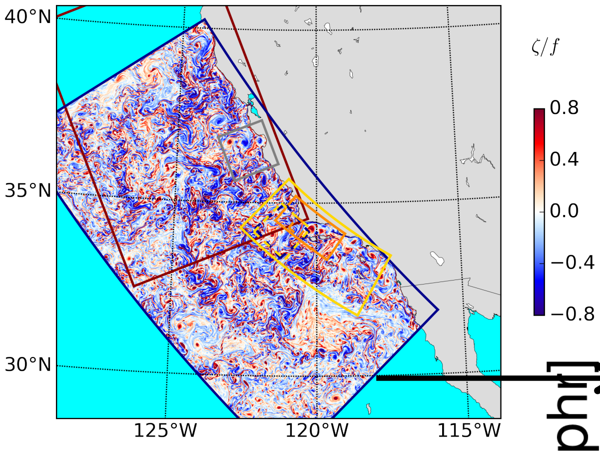


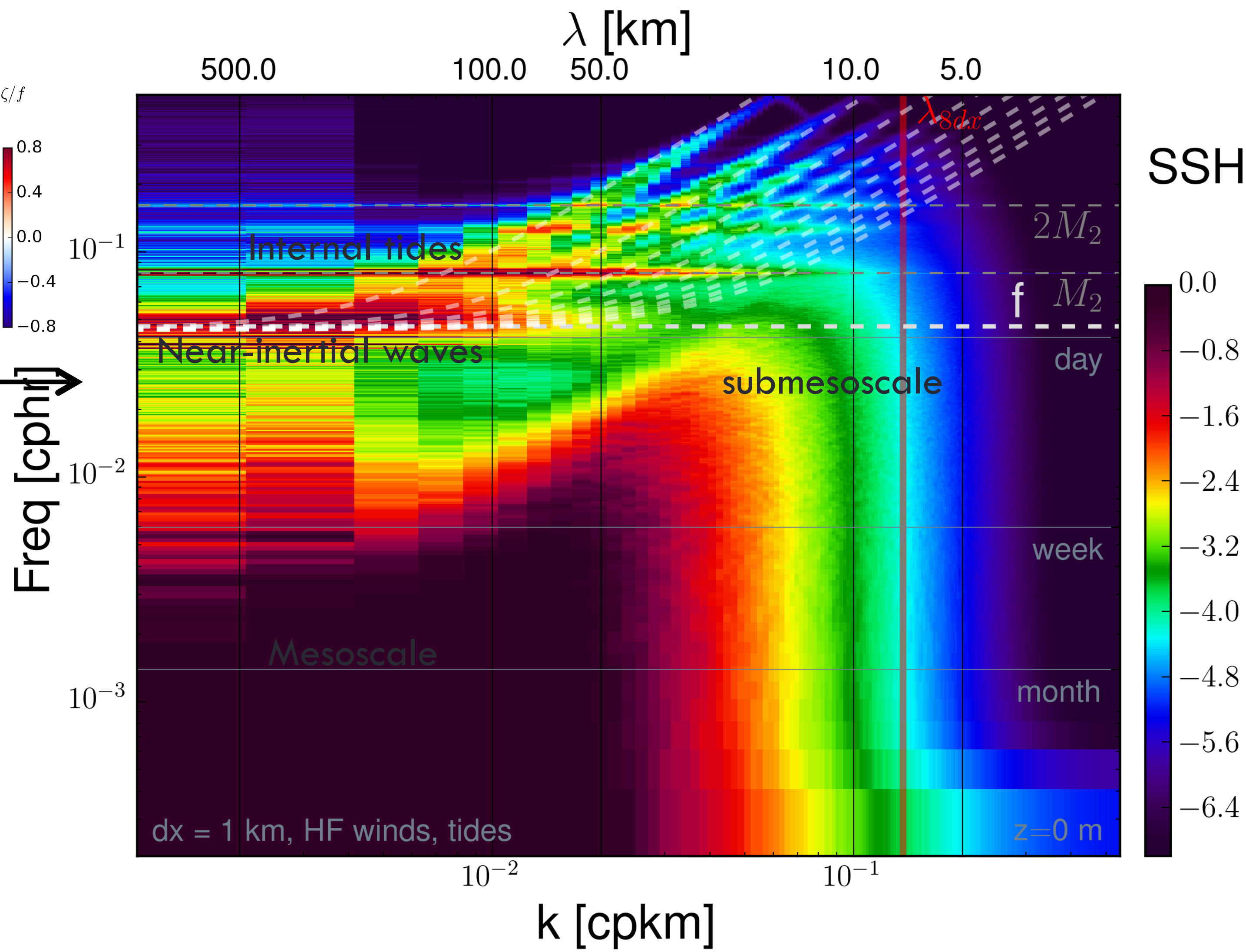


+ High frequency wind
+ Tidal forcings

Azimuthally-averaged 2D frequency-wavenumber kinetic energy spectra in the California Current.

Realistic modelling including tides and NIW



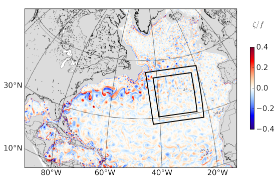


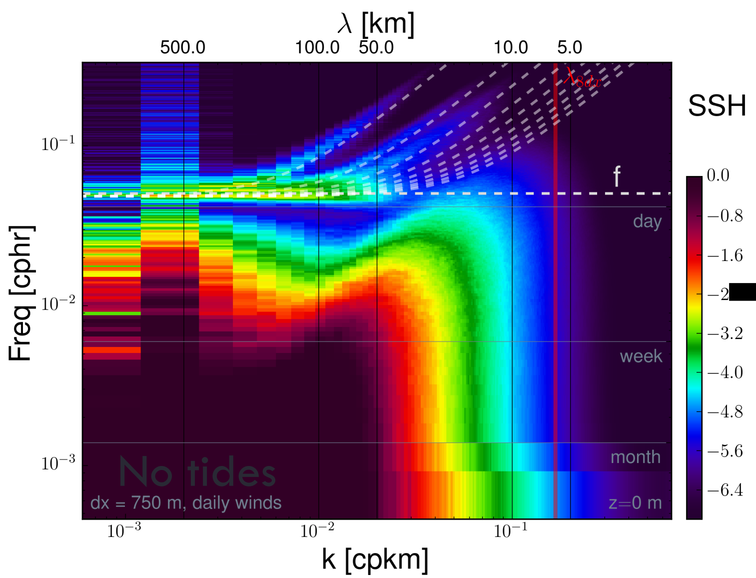
Signature of high-frequency internal waves are amplified on **Sea Surface Height.**

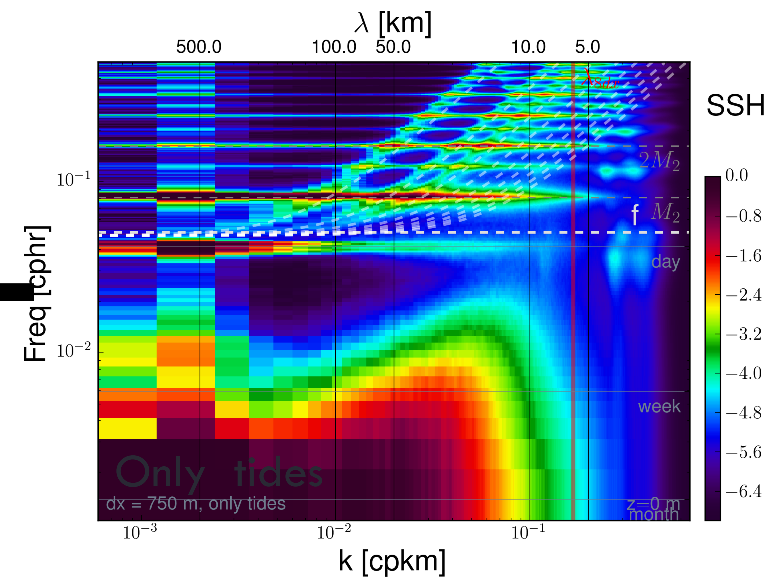
Azimuthally-averaged 2D frequency-wavenumber spectra for SSH in California Current

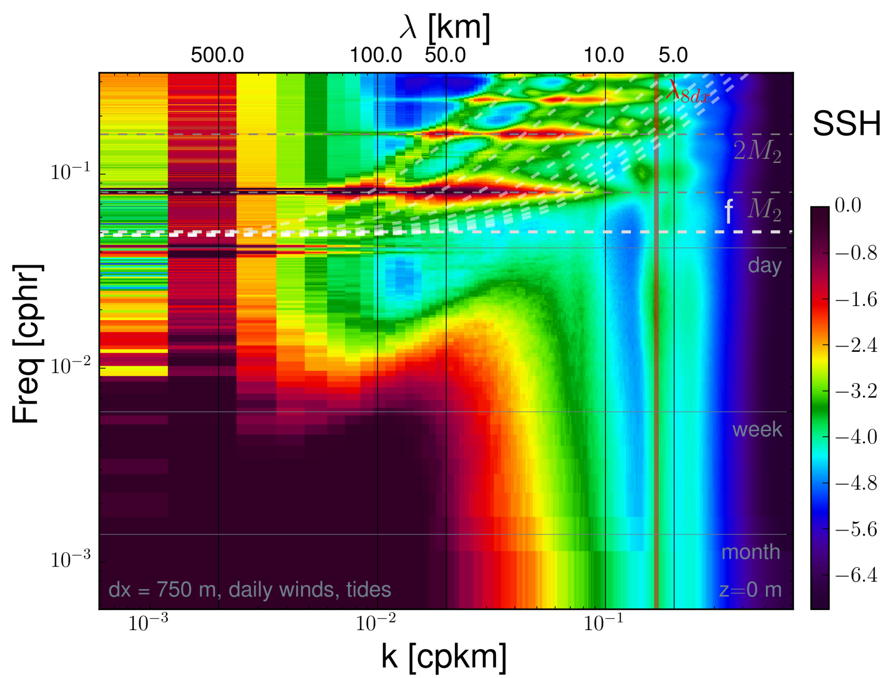
Realistic modelling including tides and NIW

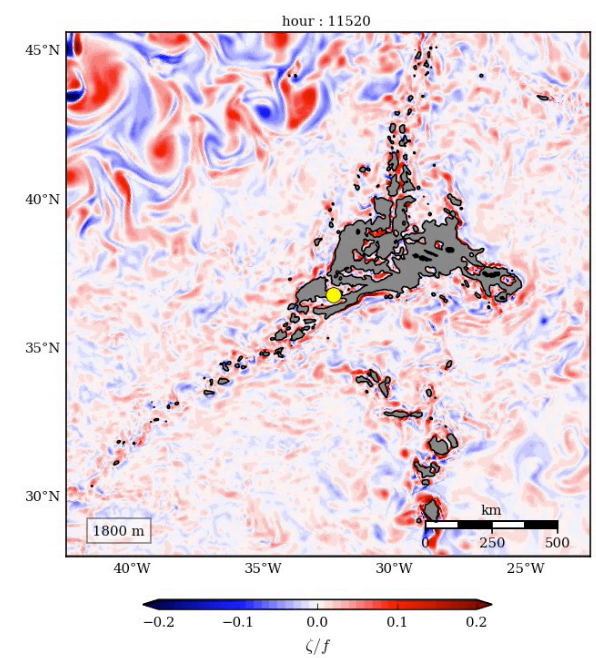
Mid-Atlantic ridge:



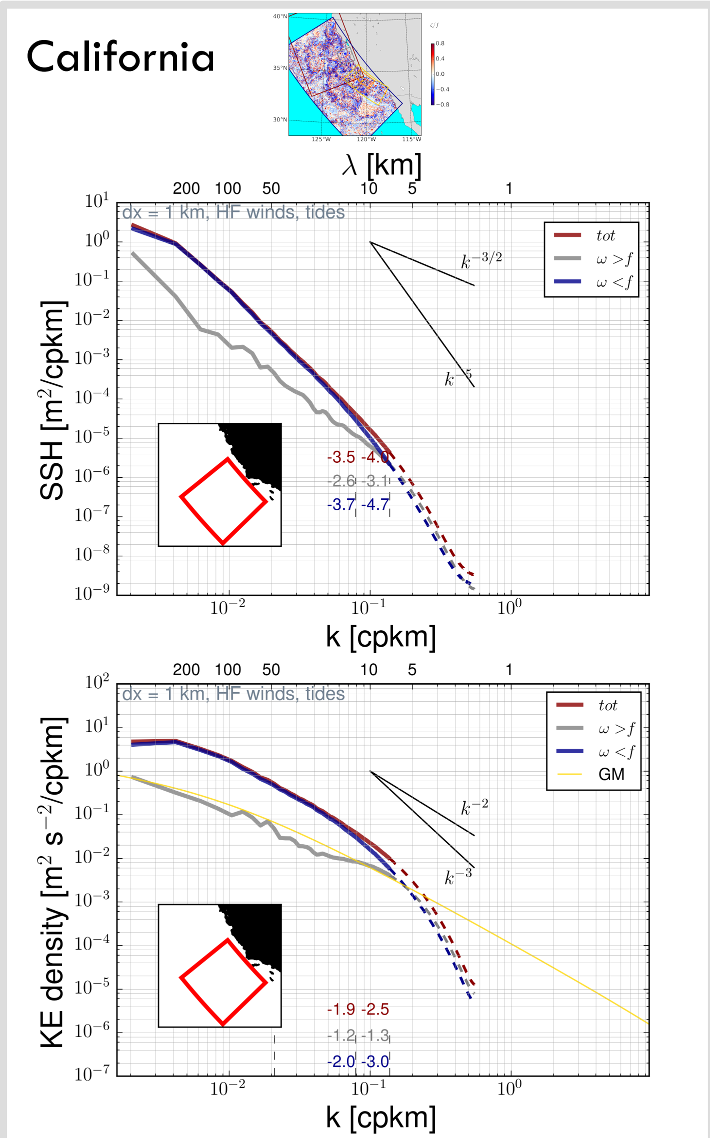


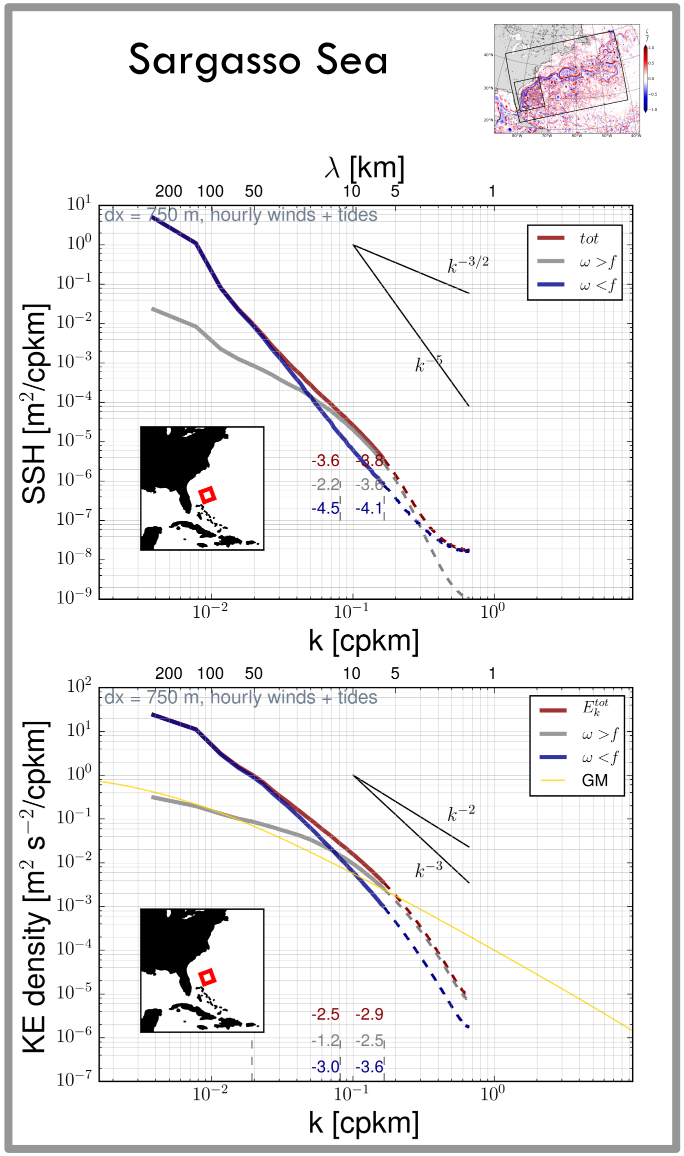


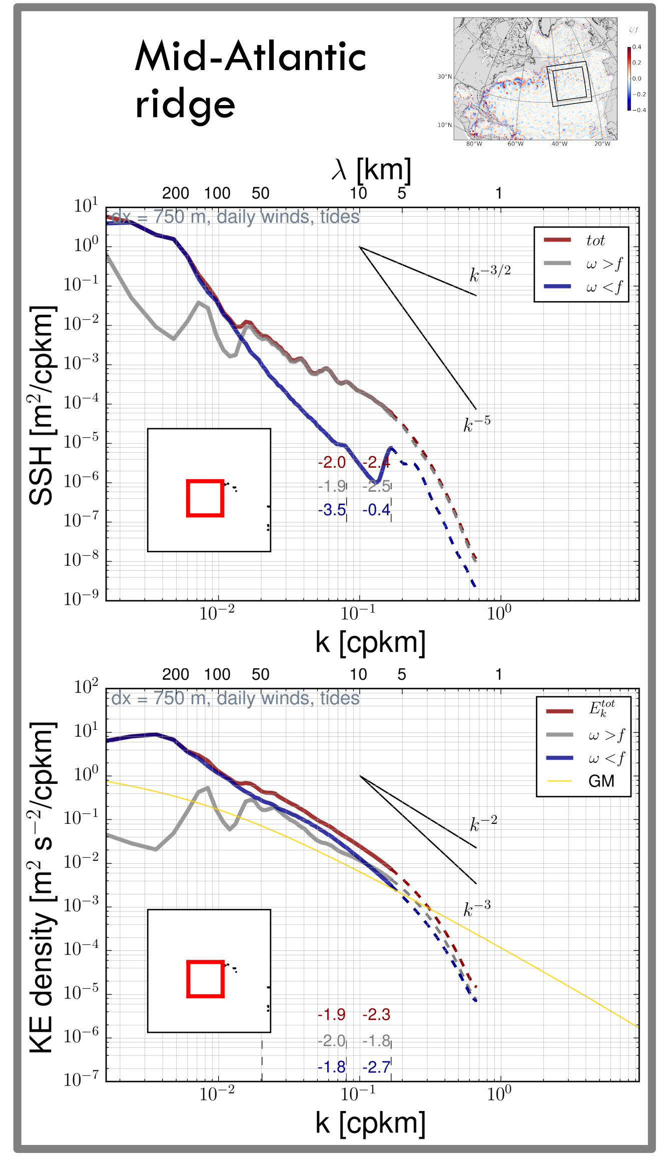




Where is the flow balanced?

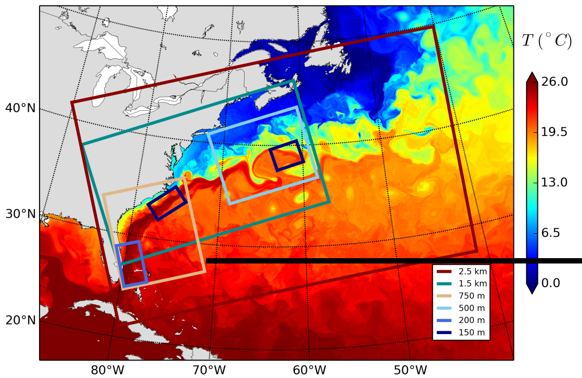


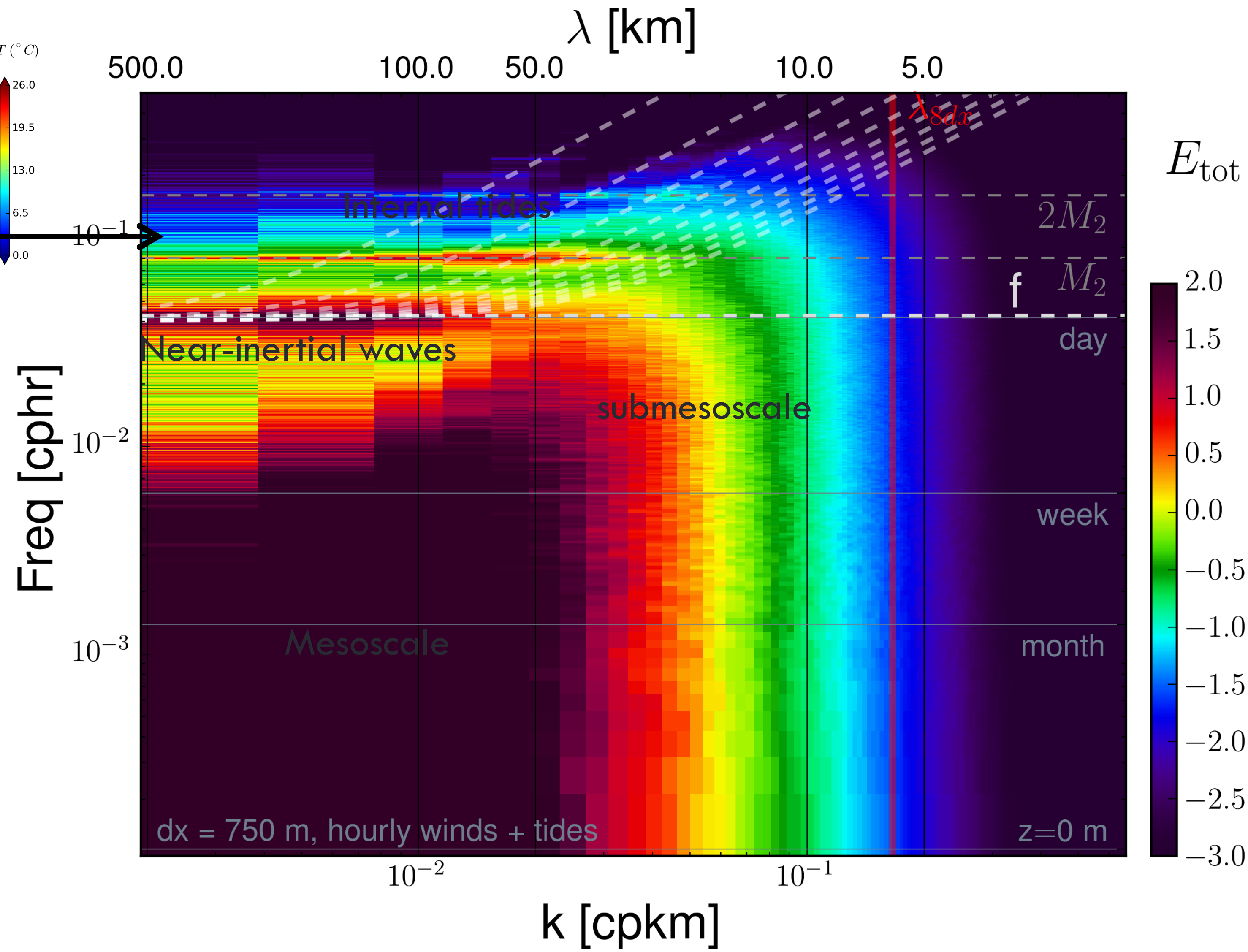




Signature of internal waves are amplified on **Sea Surface Height** – Leading to more dramatic breaks in slopes than in Kinetic energy.

Where is the flow balanced?





+ High frequency wind
+ Tidal forcings

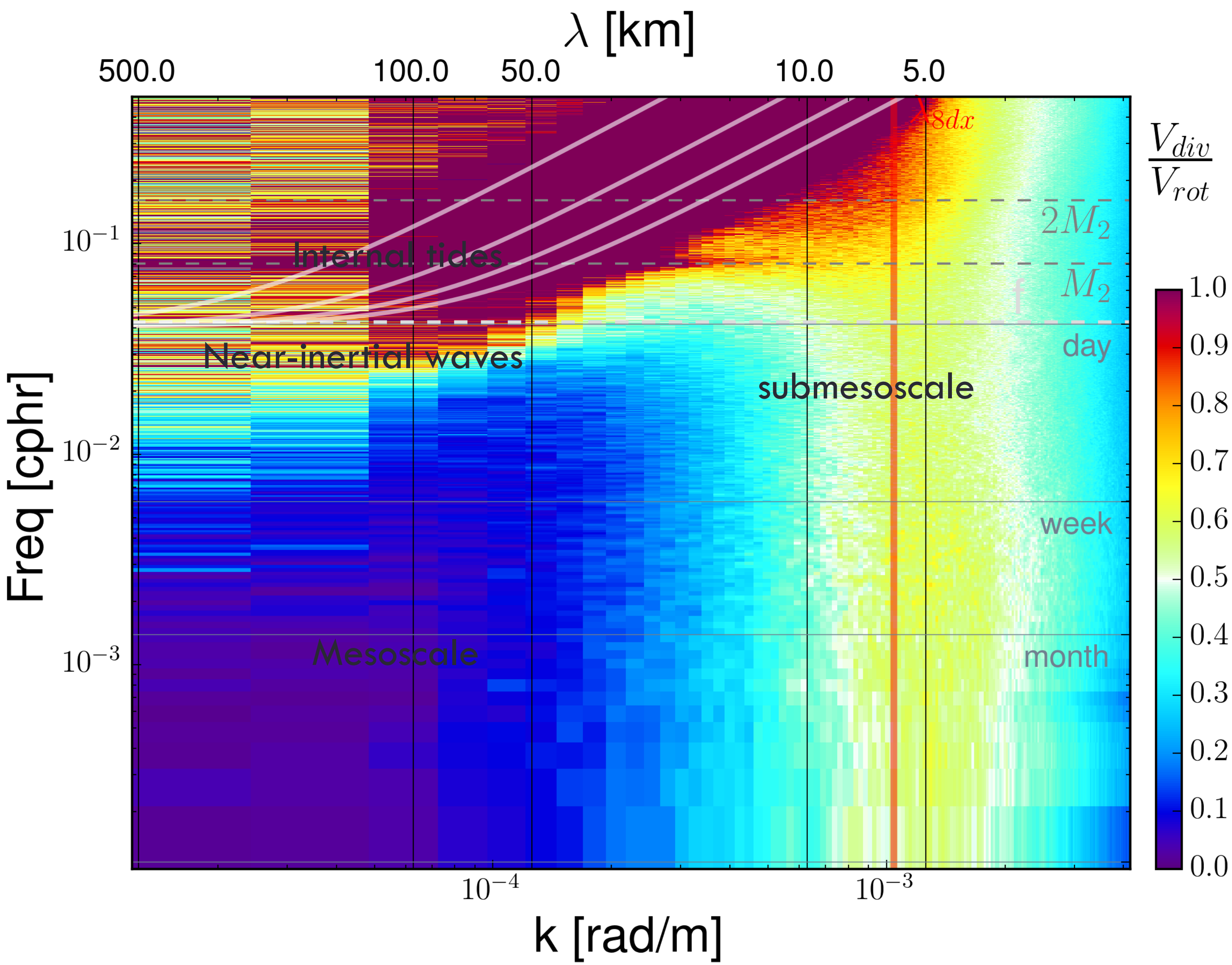
Azimuthally-averaged 2D frequency-wavenumber kinetic energy spectra in the Sargasso Sea.

Where is the flow balanced?

Ratio of divergent / rotational part of the kinetic energy

using Helmoltz decomposition of a 3d incompressible flow

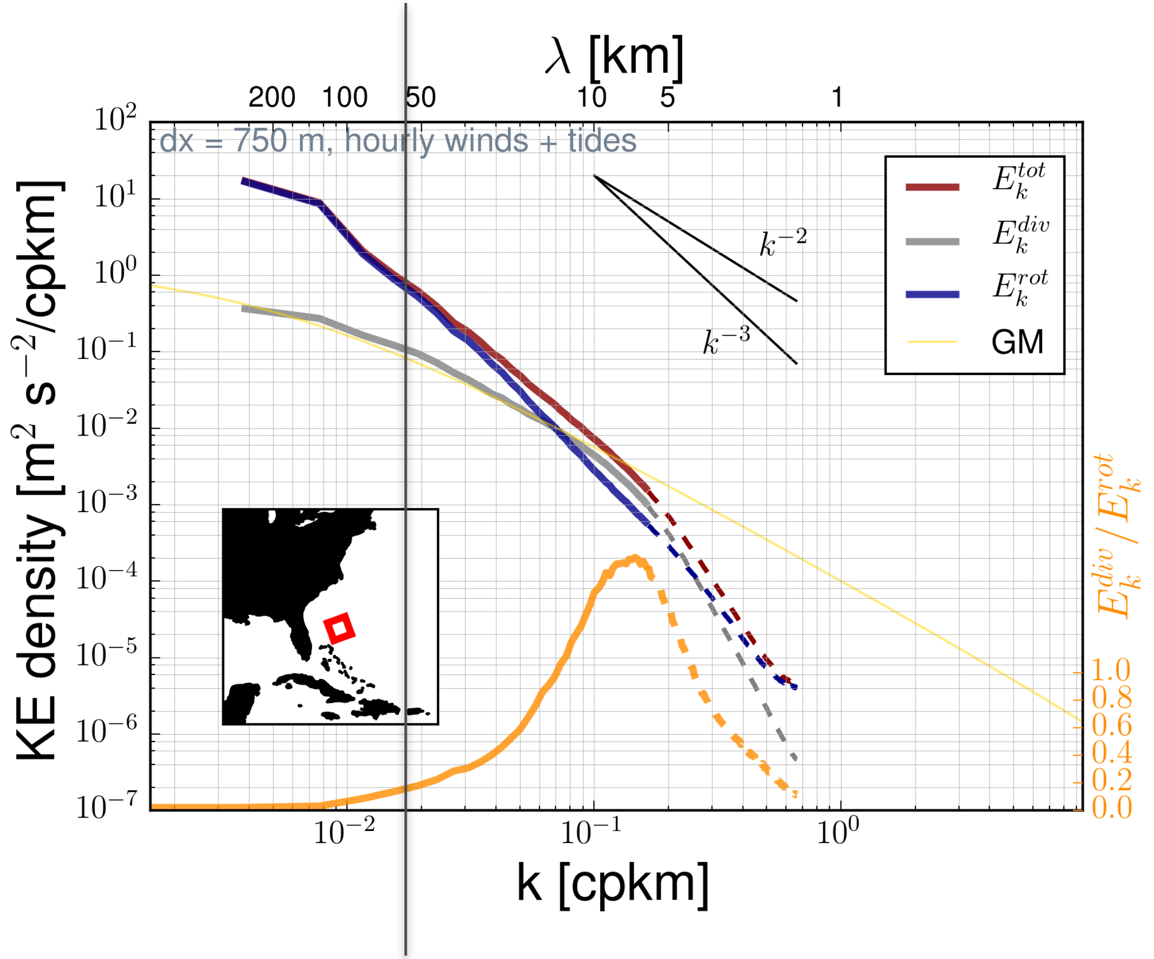
$$\mathbf{u}_h = \mathbf{u}_r + \mathbf{u}_d \,,$$
$$\nabla_h \cdot \mathbf{u}_r = 0$$
$$\hat{\mathbf{z}} \cdot \nabla_h \times \mathbf{u}_d = 0$$



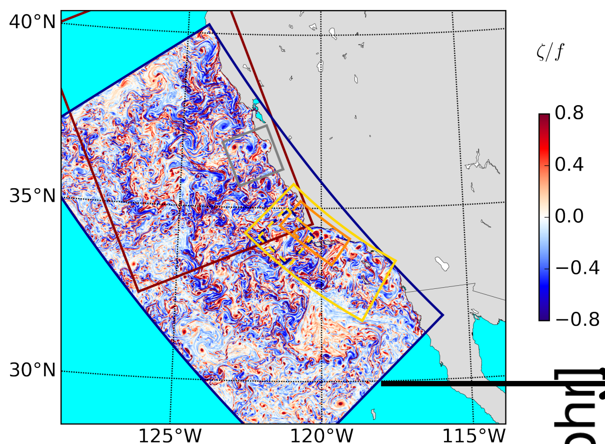
Where is the flow balanced?

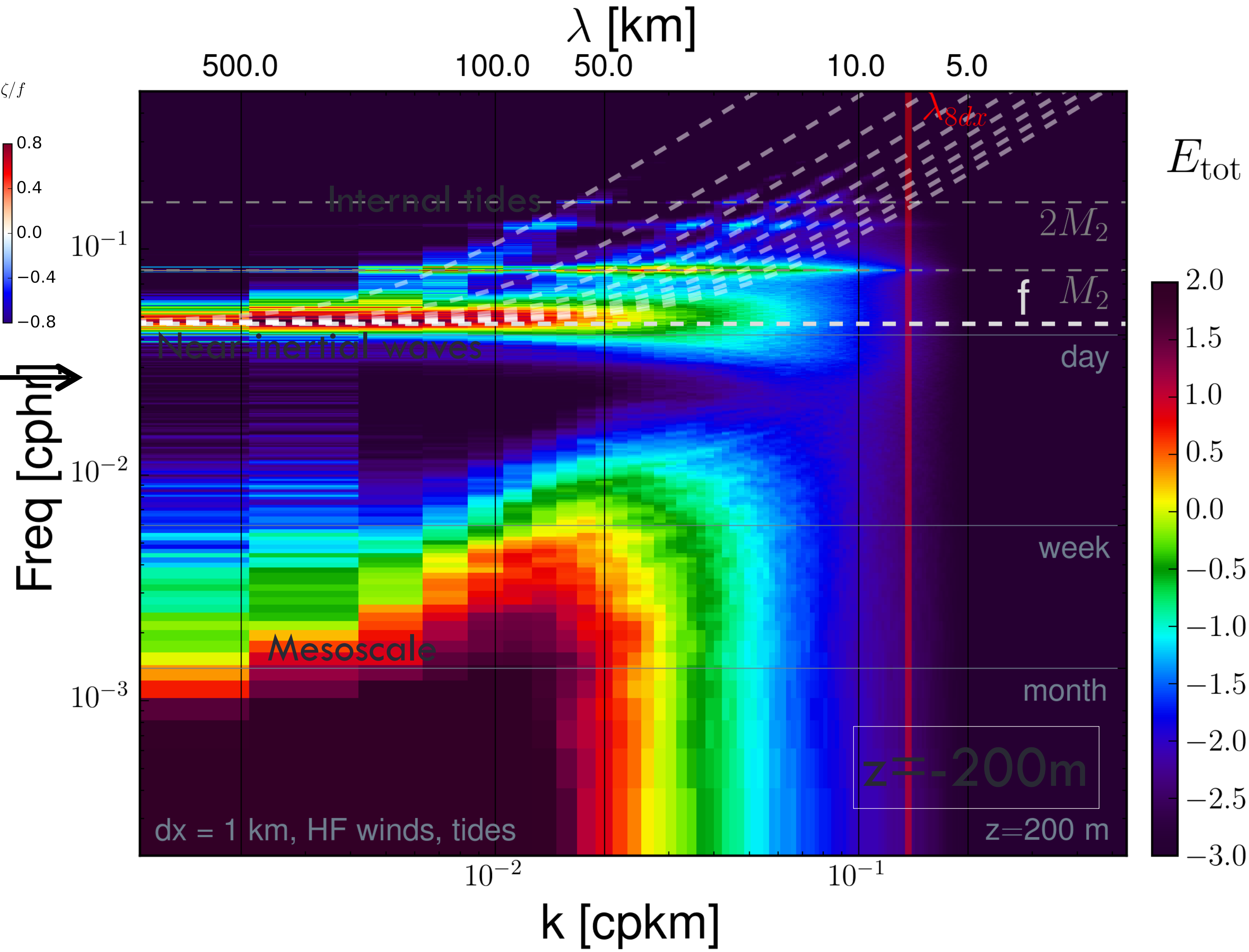
Transition between balanced and unbalanced at scales between 10 – 100 km depending on the dynamical regime (geographical region + season).

Qualitatively similar results for Northwestern Pacific [Rocha et al., 2016a; Qiu et al., 2017] or the Drake Passage [Rocha et al., 2016]. See global census in [Qiu et al., 2018].



Can we separate waves from submesoscales?

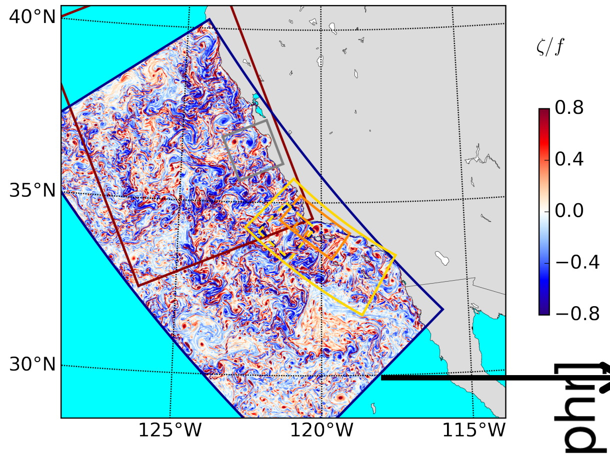


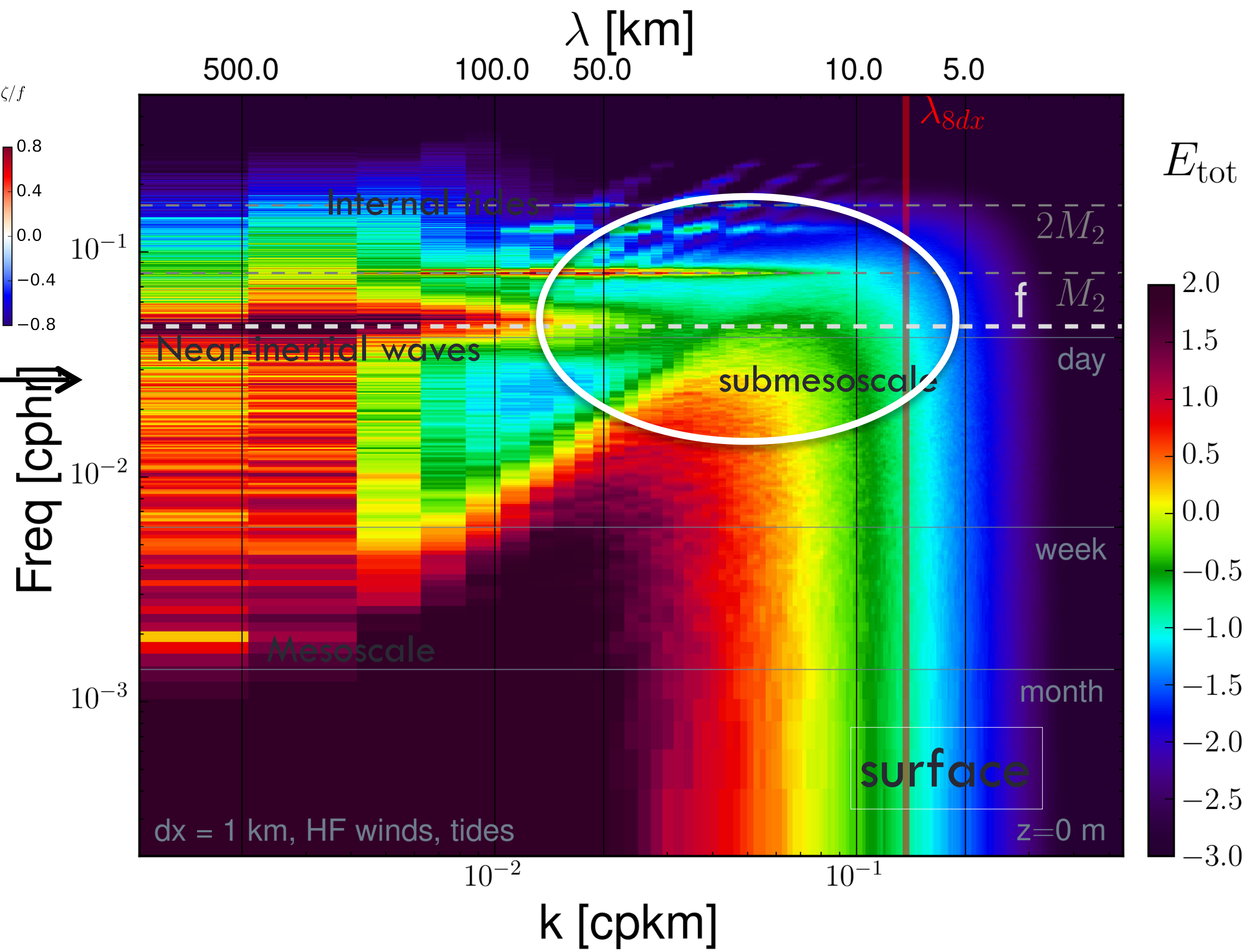


Azimuthally-averaged 2D frequency-wavenumber kinetic energy spectra in the California Current.

Below the mixed-layer, separation between internal waves and balanced dynamics is easy.

Can we separate waves from submesoscales?





In the mixed-layer it is much more complicated

Azimuthally-averaged 2D frequency-wavenumber kinetic energy spectra in the California Current.

Activity: Numerical simulation of Internal waves

- Download and unzip Fluid2d: jgula.fr/Ondes/fluid2d.tar.gz
- Install (see also http://mespages.univ-brest.fr/~roullet/fluid2d/docs/howto.html#download-and-install)

To have the code run you need to have the following python packages installed

numpy

matplotlib

netCDF4

mpi4py >= 2.0.0

```
tar -xf fluid2d.tar.gz
cd fluid2d

make
source activate.sh
```

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cd fluid2d

make
source activate.sh
```

Activity: Numerical simulation of Internal waves

Run the Interfacial wave case:

- cd nhom/Interfacial
- python interfacialwave.py

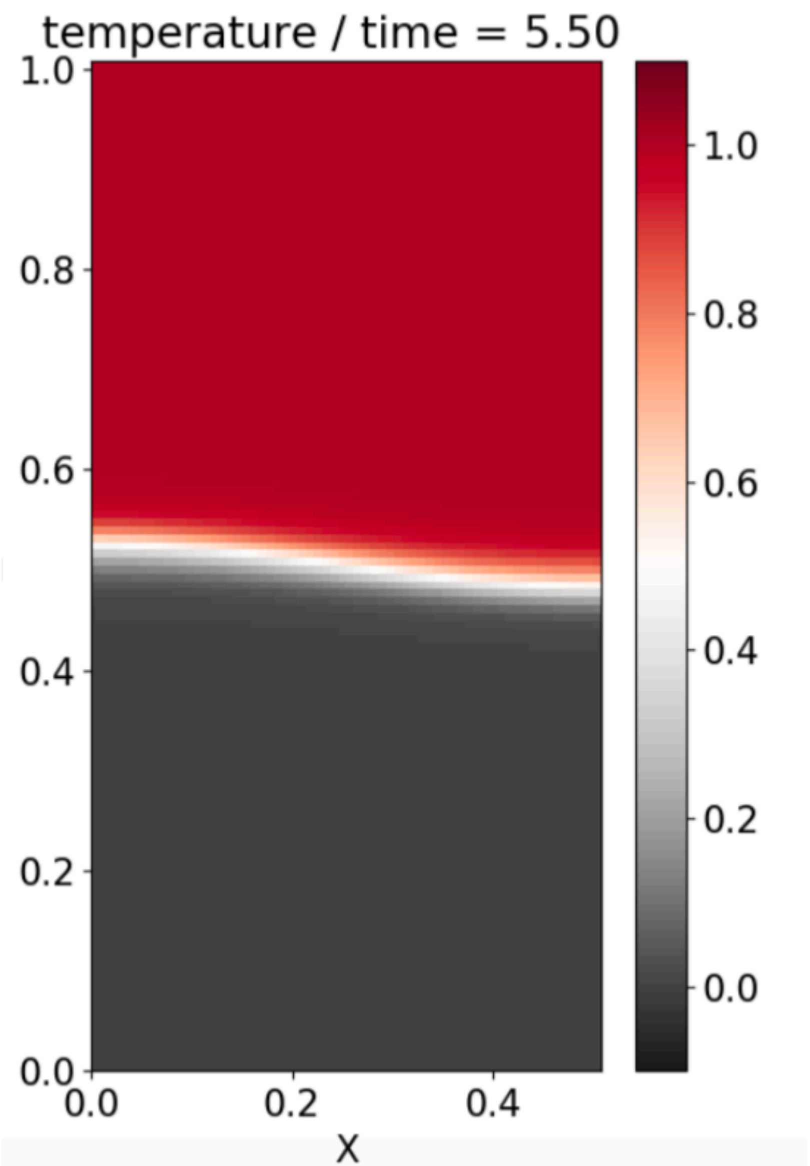
Either

- 1) a sine wave in a tank (stationary wave) or
  2) a localized perturbation on the left
  (propagating wave)

In 2) look at how the Stokes drift deforms the tracer field

In 1) play with hydroepsilon (not smaller than 0.2), look at the structure of the velocity field

In 1) increase the amplitude until you trigger KHI and wave breaking

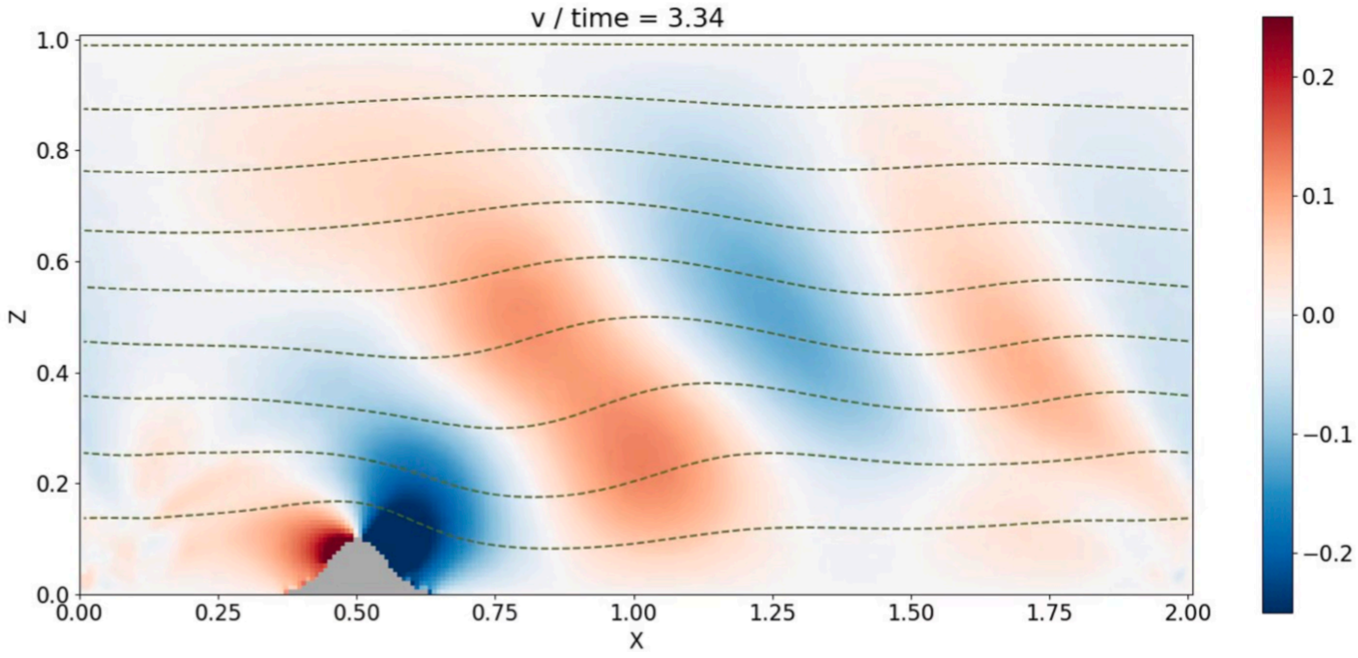


Activity: Numerical simulation of Internal waves

Run the Lee wave case:

- cd nhom/Leewave
- python leewave.py

- A flow past a seamount
- See the wave setting up
- Increase N and observe mixing downstream

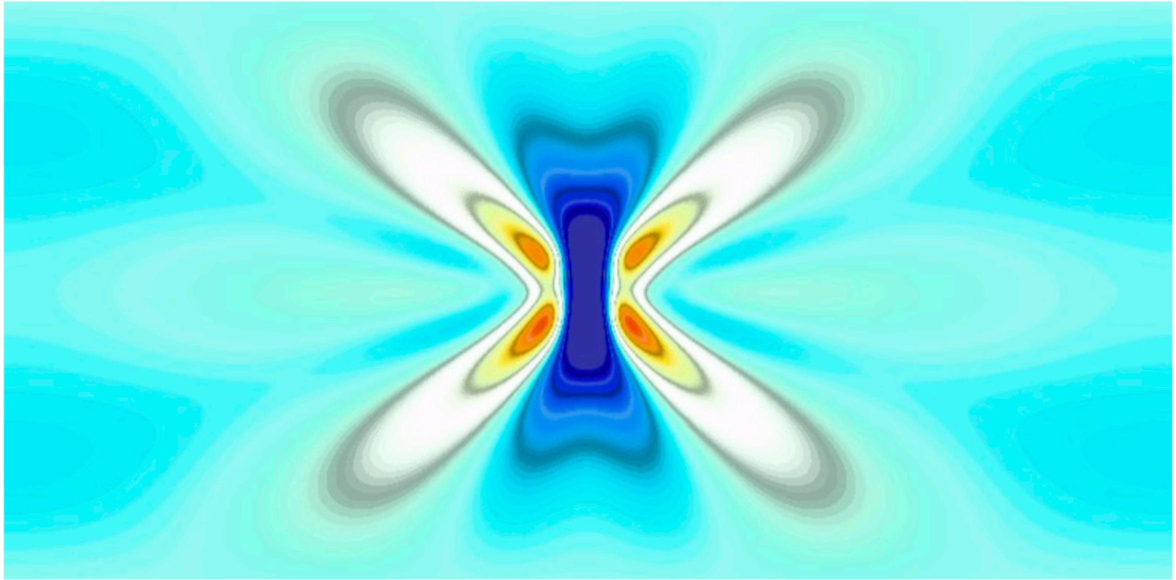


Activity: Numerical simulation of Internal waves

Run the Internal wave case:

- cd nhom/Internal_IVP
- python internalwave.py

- This is an initial value problem: gaussian perturbation of b’
- Play with the wave amplitude
- Play with the hydroepsilon (0.2 is the minimum)
- Play with the size of the initial perturbation



Activity: Numerical simulation of Internal waves

Run the Internal wave case:

- cd nhom/Internal_forced
- Python forcedinternal.py

- This is a localized periodic forcing
- Play with the forcing frequency (in forcedinternal.py)
- Generate evanescent waves