Internal Waves in the Ocean

Master 2 — Physique de l'Océan et du Climat

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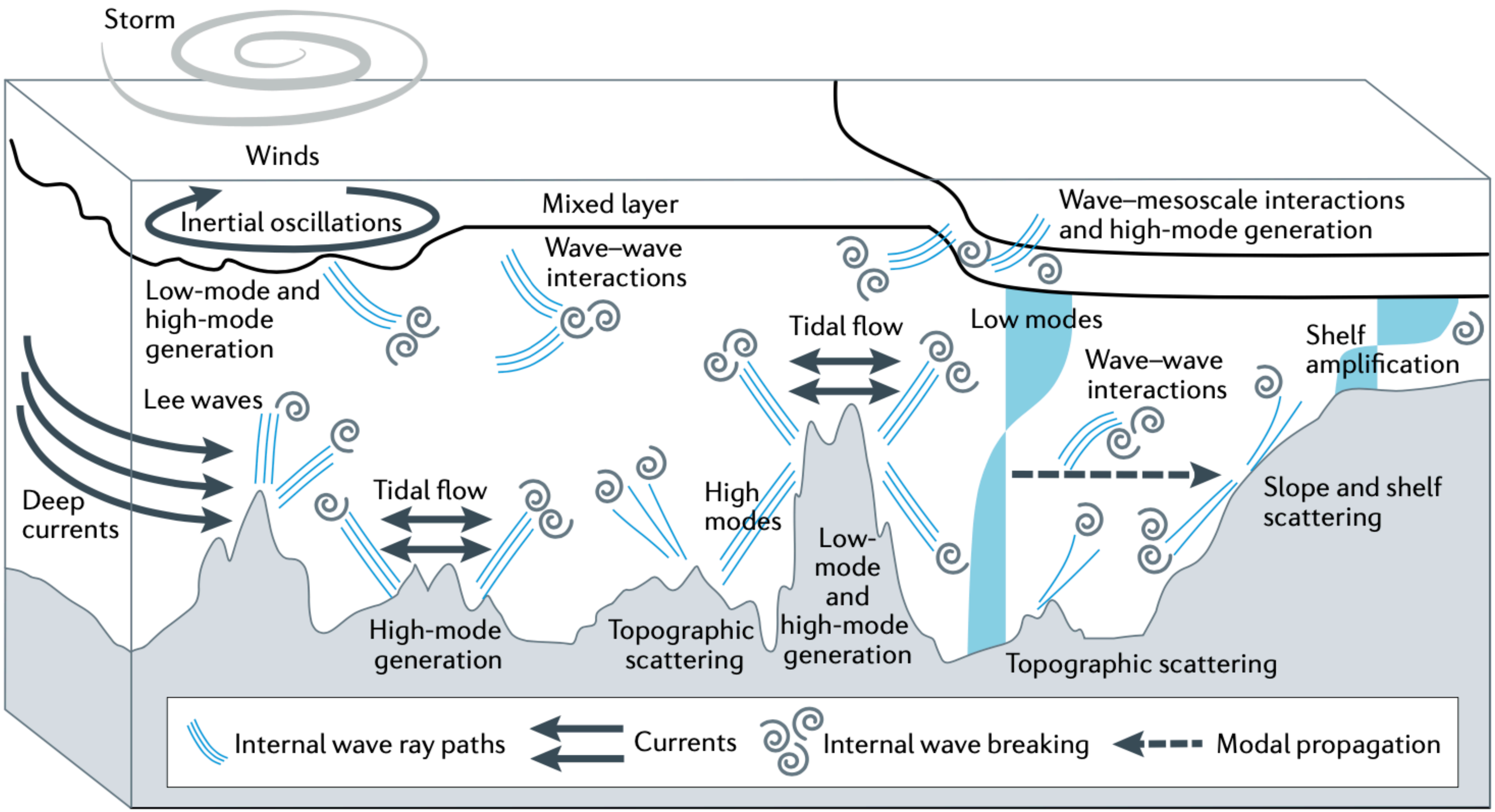
Outline

1. A general introduction to ocean waves
2. What are internal waves ? Why do we study internal waves ?
3. Internal waves in the two-layer shallow-water model
4. Internal waves in the continuously-stratified model
5. **Generation of internal waves**
6. Propagation of internal waves
7. Dissipation of internal waves and impacts

5. Generation of internal waves



Three main classes of waves:

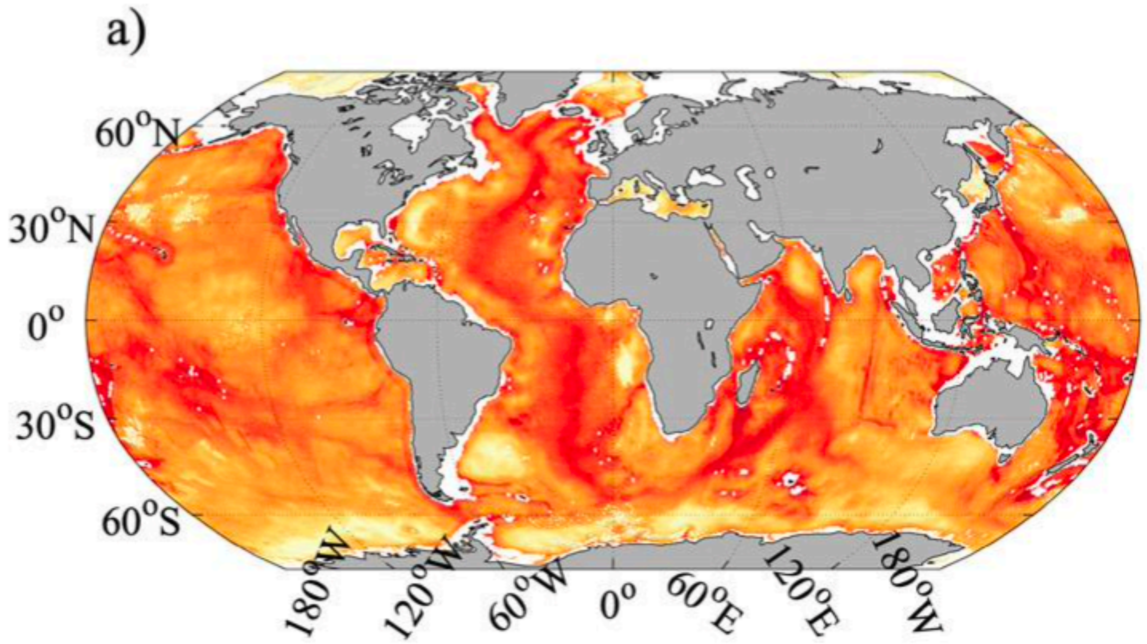
- **near-inertial waves**, mostly generated by winds
- **internal tides = baroclinic tides**, generated by the interaction of the barotropic tide with the seafloor topography
- **lee waves**, generated by low-frequency currents interacting with the seafloor topography

MacKinnon et al. (2017), Whalen et al. (2020)

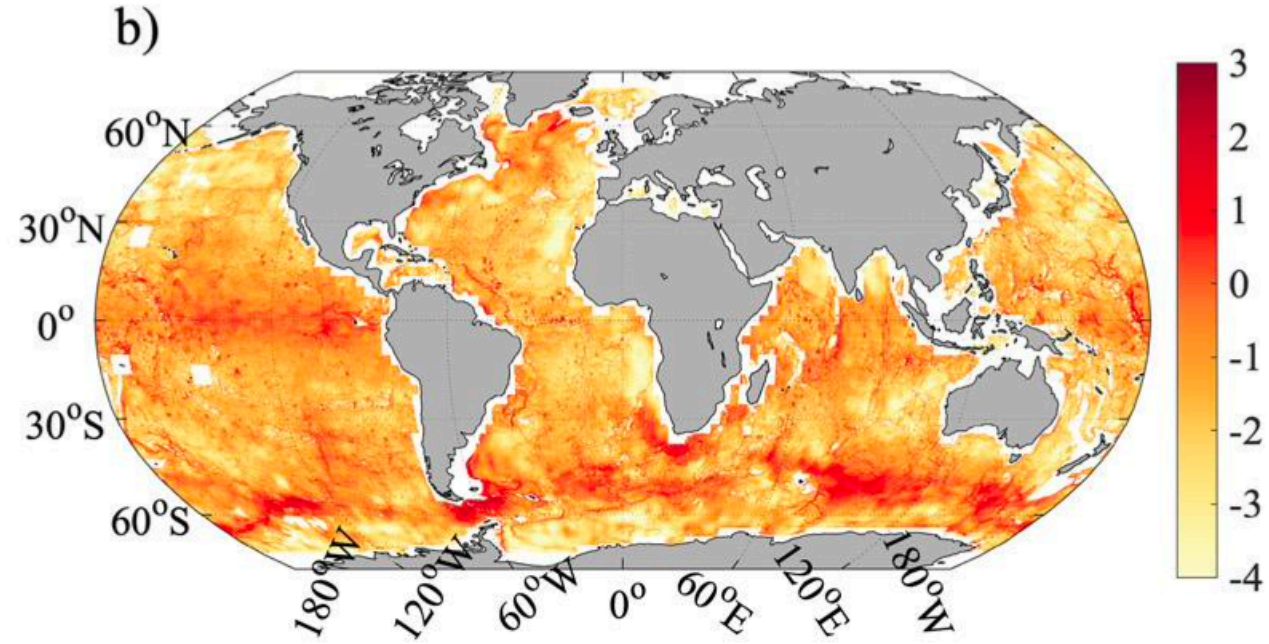
5. Generation of internal waves

Global energetics of internal waves:

- internal tides: 1 TW (10^{12} W)
- lee waves: 0.15-0.75 TW



Generation of internal tides



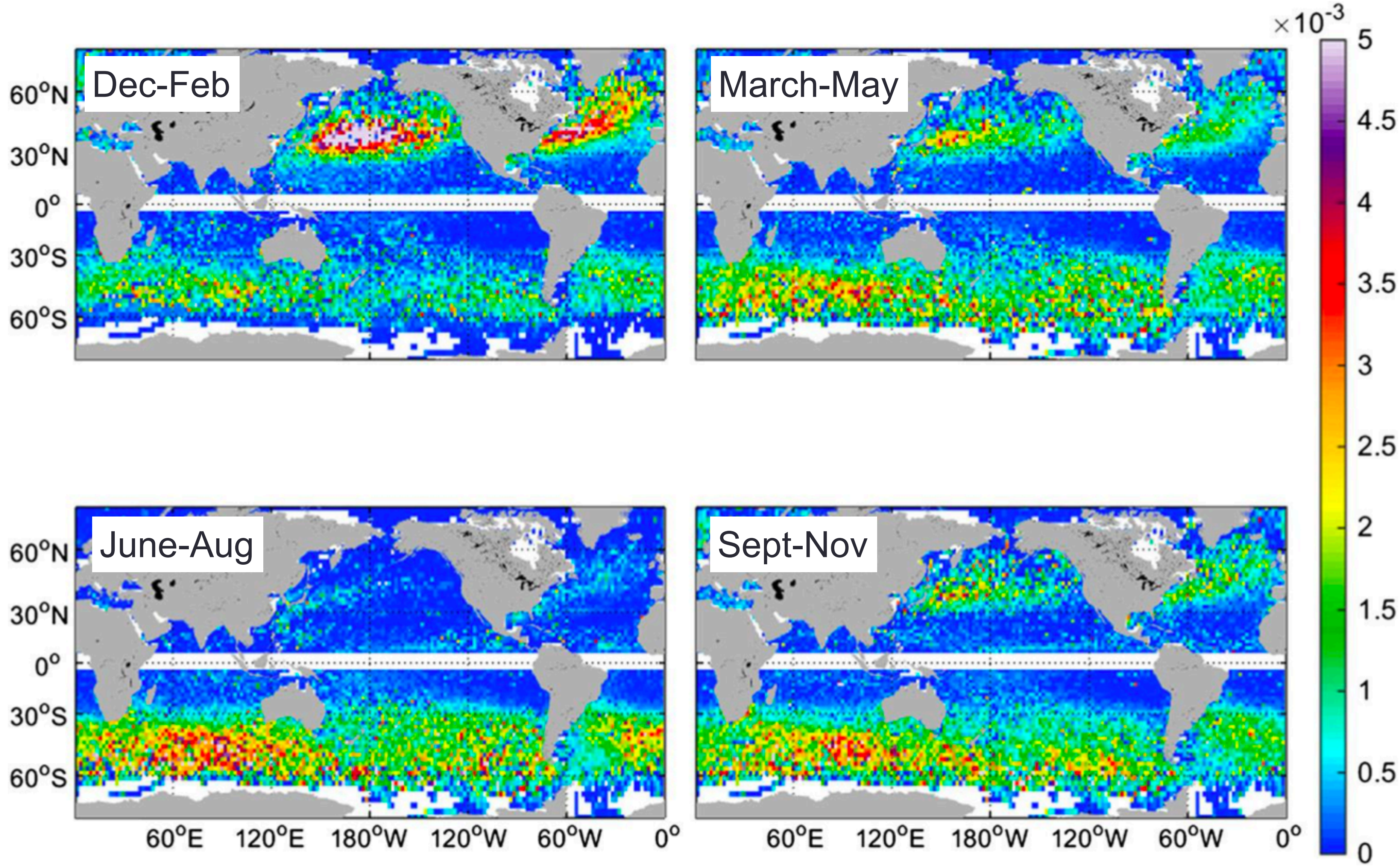
Generation of lee waves

Musgrave et al. (2022), Vic et al. (2019)

5. Generation of internal waves

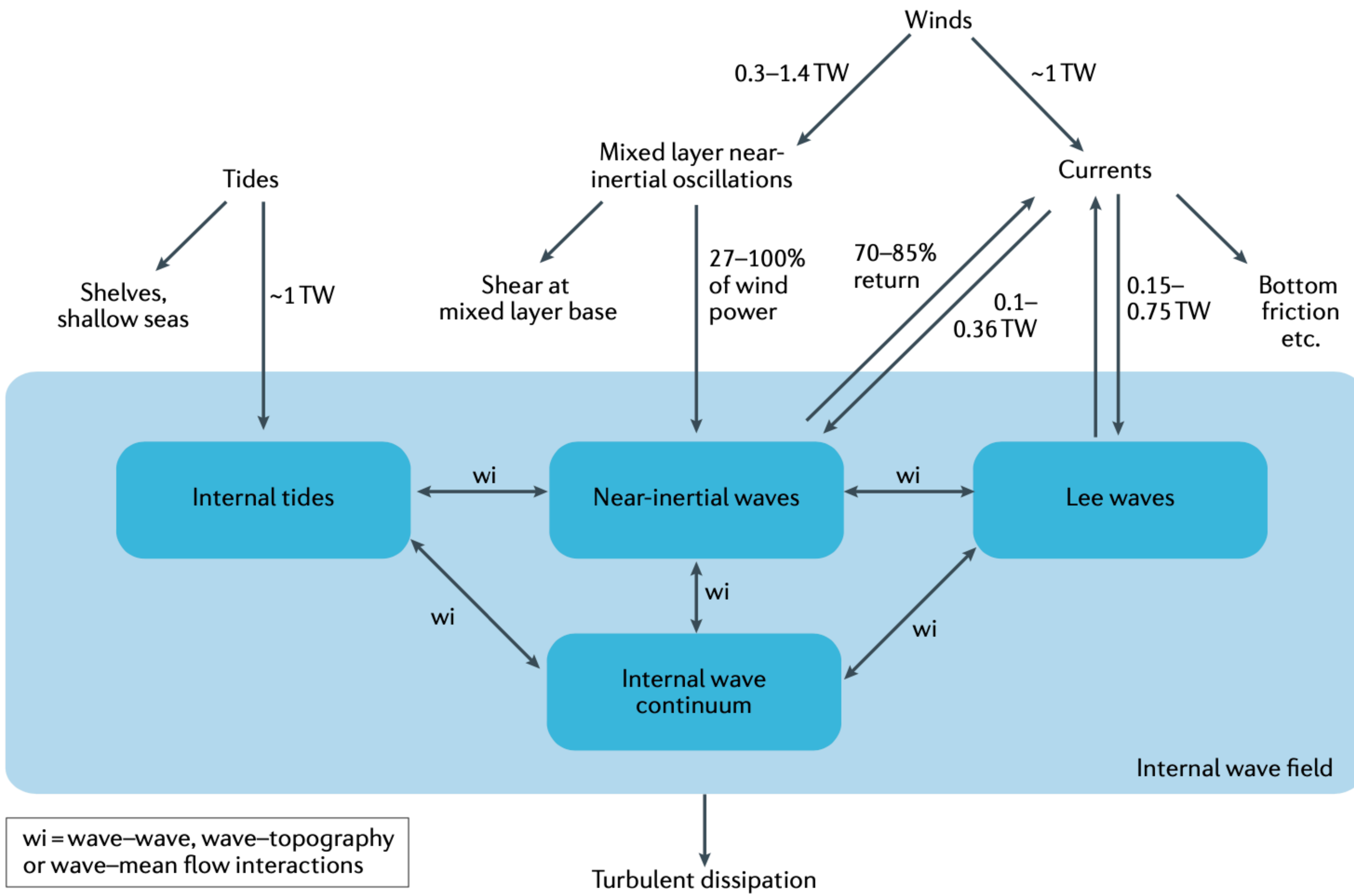
Global energetics of internal waves:

- internal tides: 1 TW (10^{12} W)
- lee waves: 0.15-0.75 TW
- near-inertial waves: 0.3-1.5 TW



Thomas & Zhai (2022)

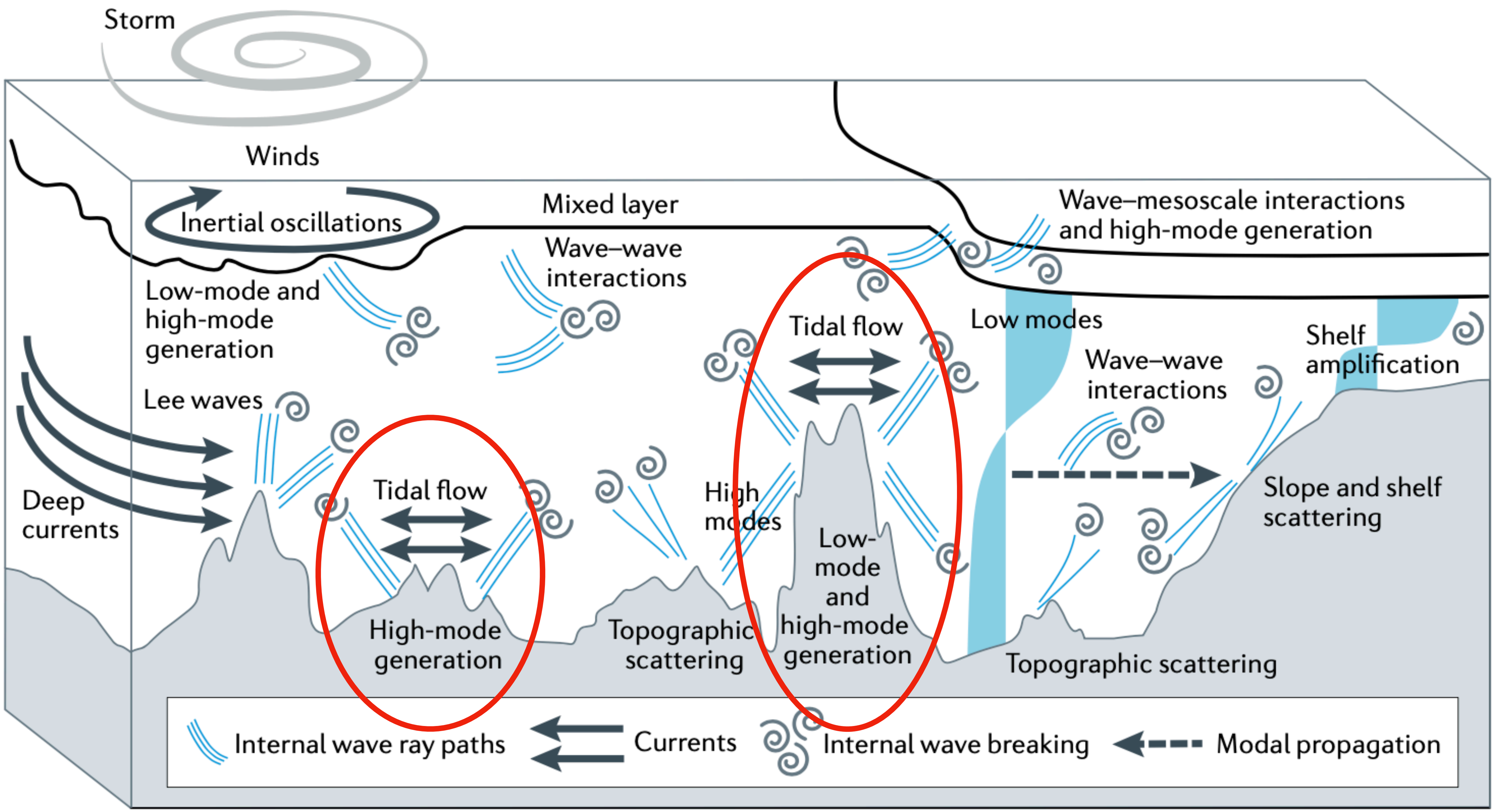
5. Generation of internal waves



Whalen et al. (2020)

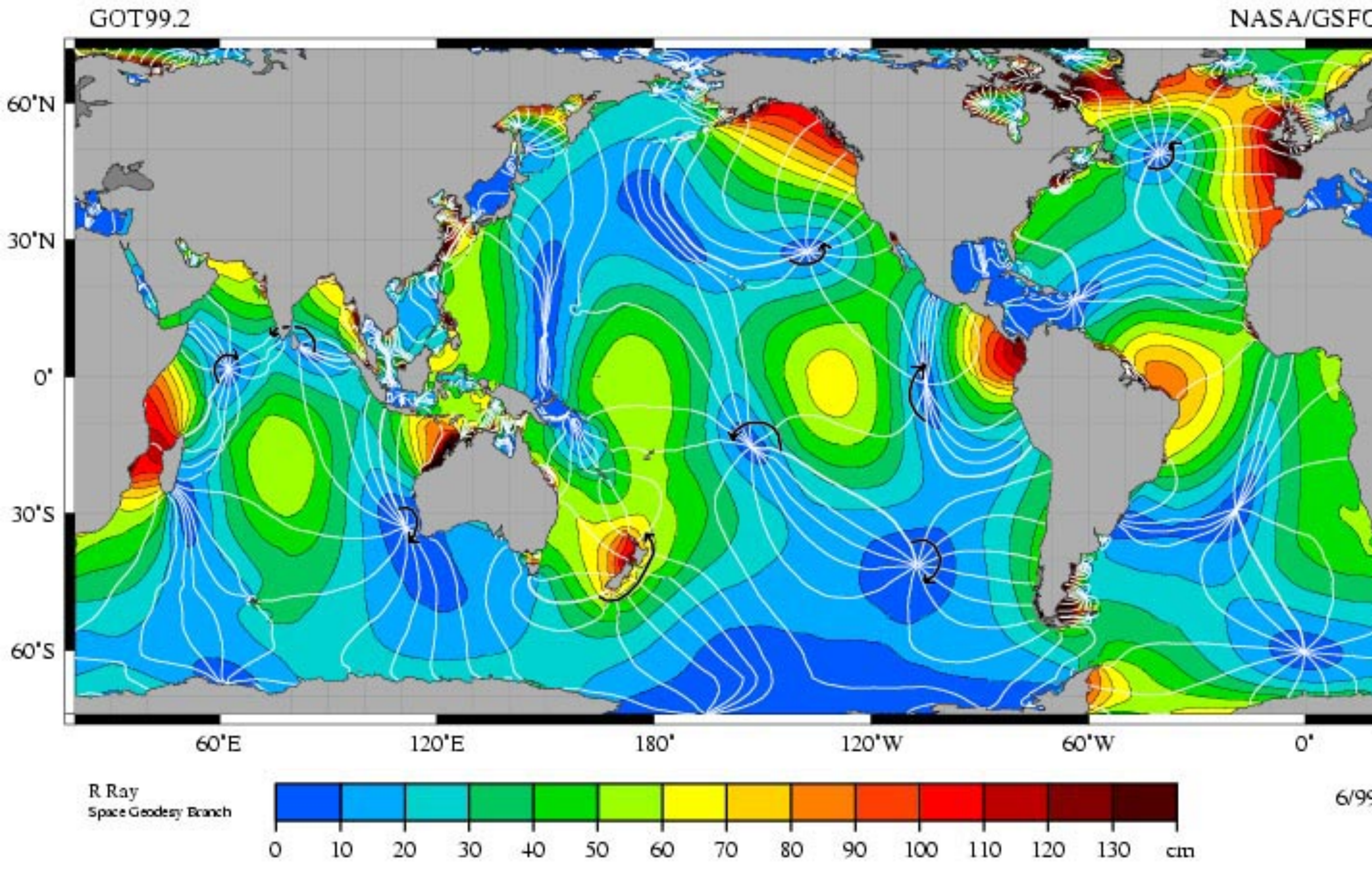
5. Generation of internal waves

Generation of internal tides



5. Generation of internal waves

Generation of internal tides. We first need to know the barotropic tidal currents.

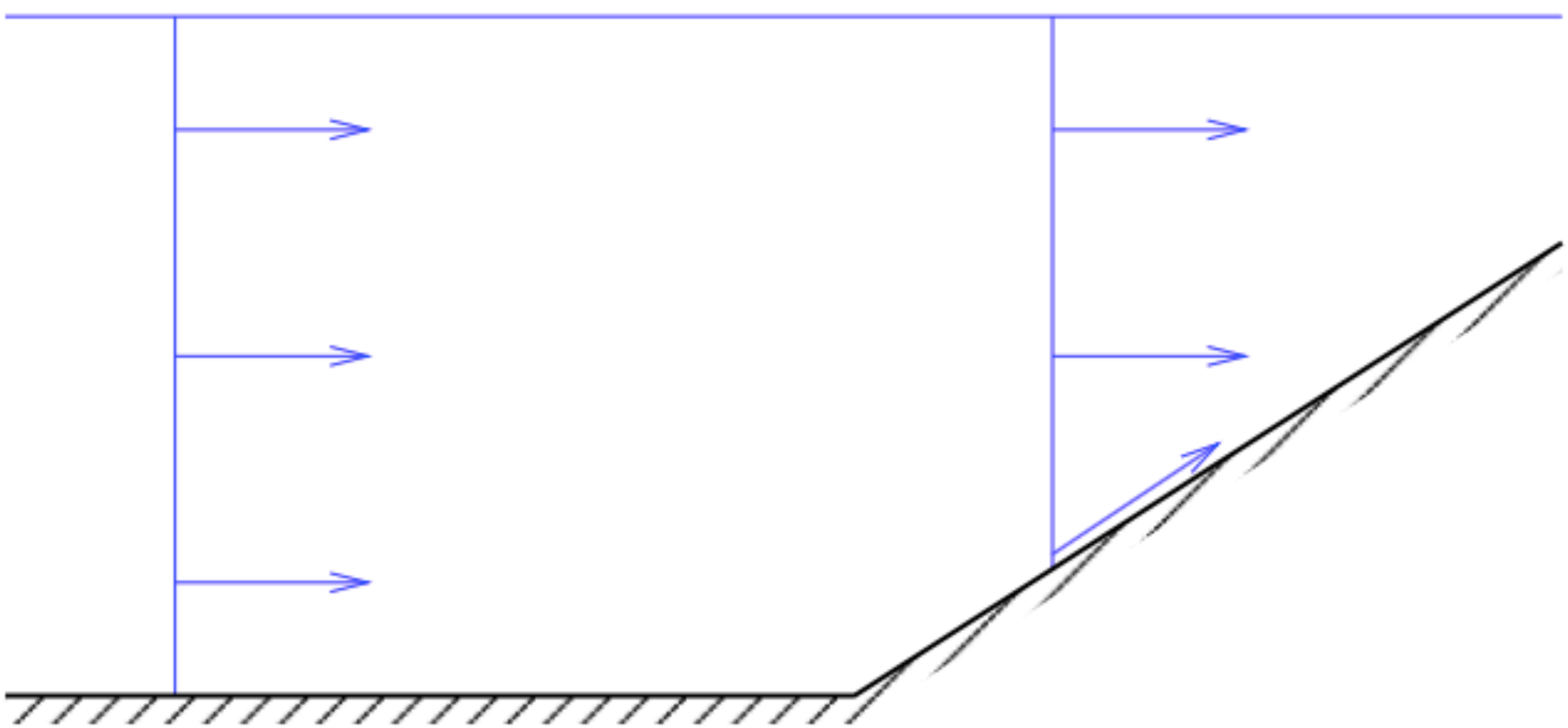


amplitude of the M2 tide

5. Generation of internal waves

Generation of internal tides.

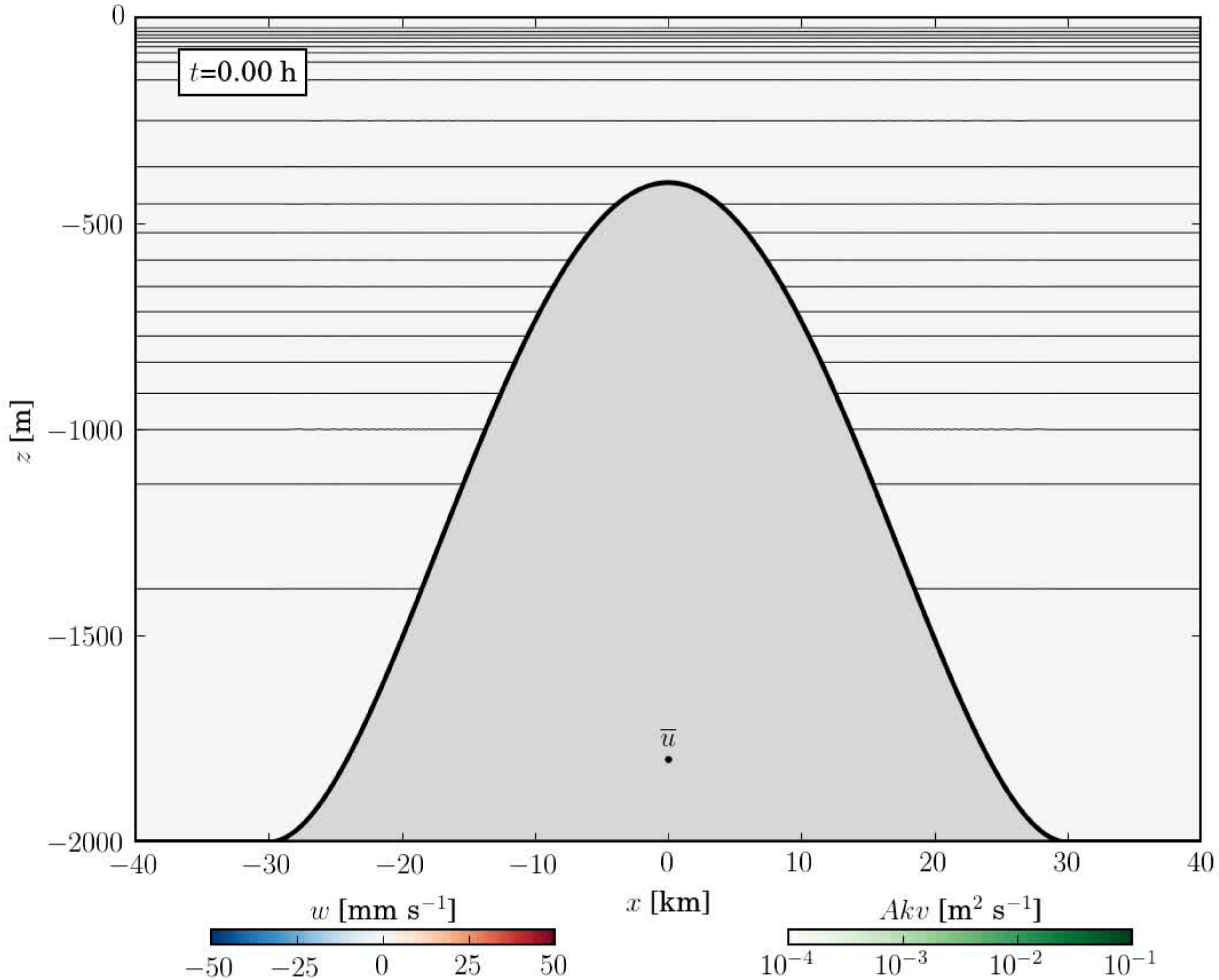
A barotropic velocity profile impinging on a sloping boundary. On the boundary, the velocity vector can only have a component tangential to it and hence over the slope, the velocity profile is no longer barotropic. Energy must go into generating internal waves, and propagate away along characteristics.



(WHOI course, Hendershott and Garrett)

5. Generation of internal waves

Generation of internal tides.



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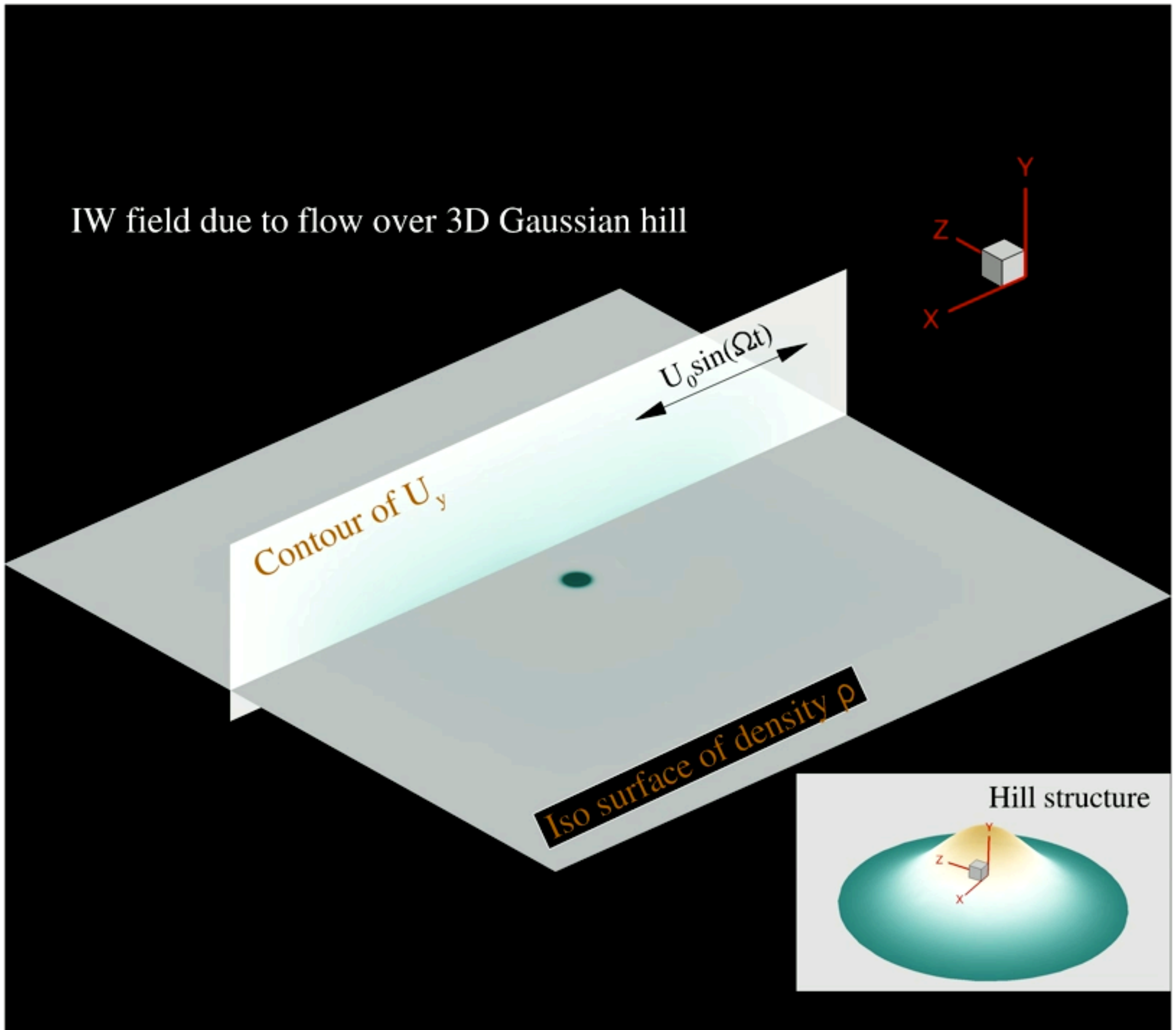
Generation of internal tides.

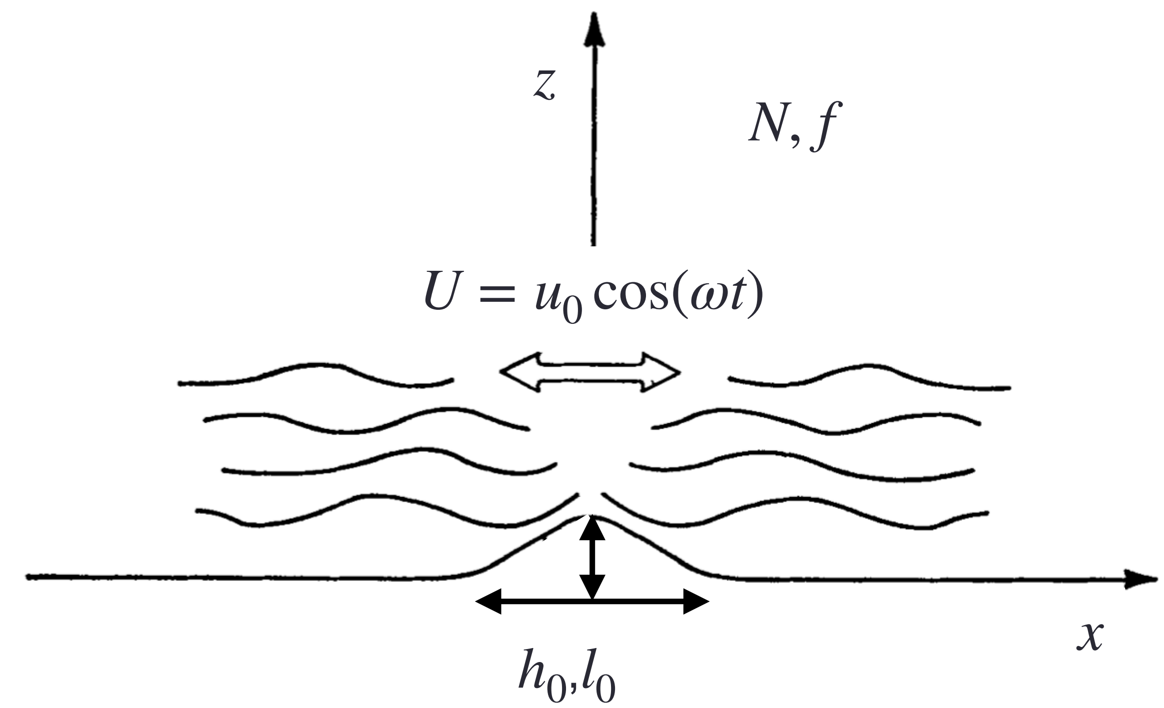


5. Generation of internal waves

Generation of internal tides in the deep ocean.

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 $\alpha = \sqrt{\dfrac{\omega^2 - f^2}{N^2 - \omega^2}}$

Garrett and Kunze (2007)

5. Generation of internal waves

Generation of internal tides in the deep ocean.

Assumptions to derive a linear expression for w :

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

Garrett and Kunze (2007)

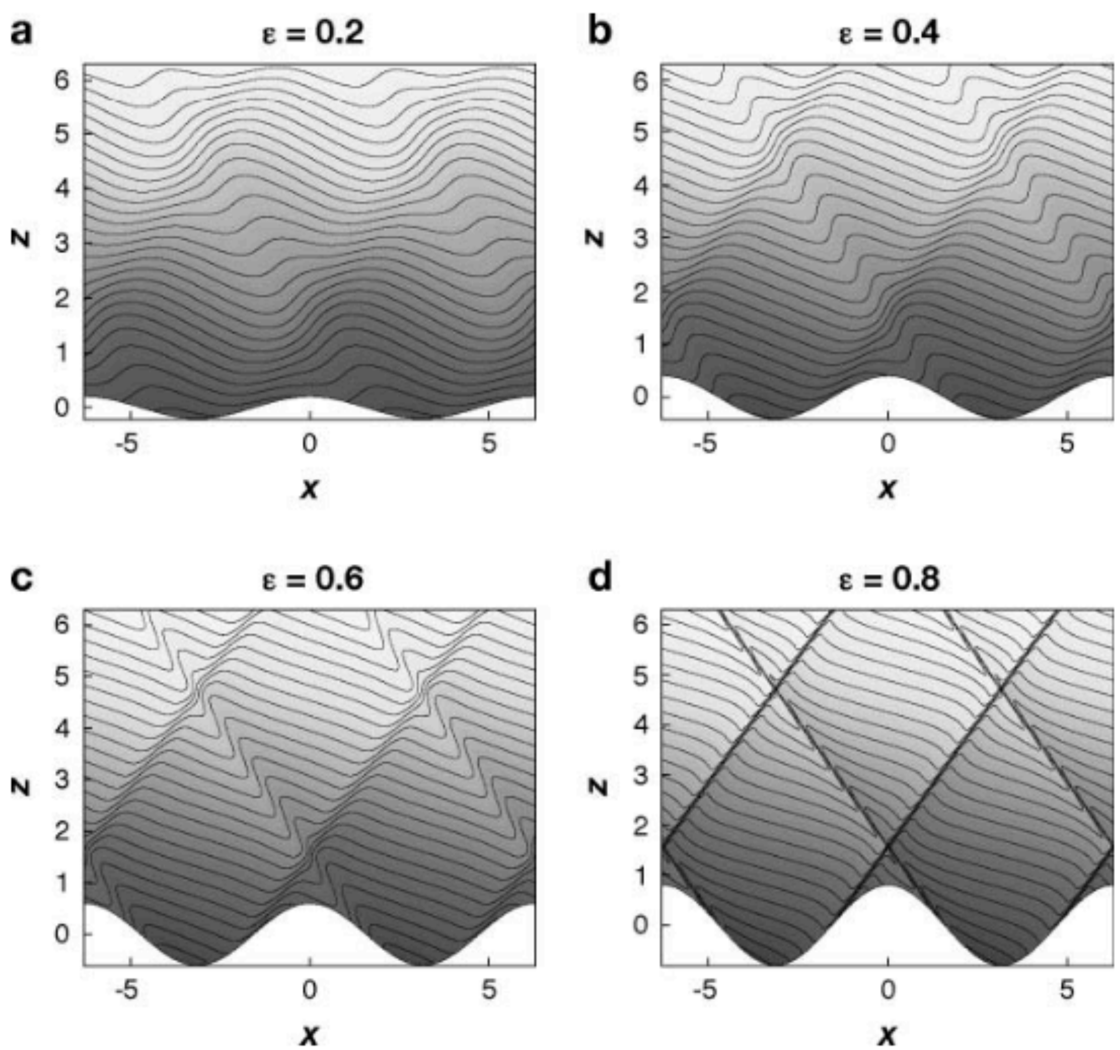
5. Generation of internal waves

Generation of internal tides in the deep ocean.

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%

Garrett and Kunze (2007)

Generation of internal tides in the deep ocean.

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 : :

→ 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 $\dfrac{1}{2} l_0 = \dfrac{\pi}{k}$

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.

Garrett and Kunze (2007)

Generation of internal tides in the deep ocean.

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 :

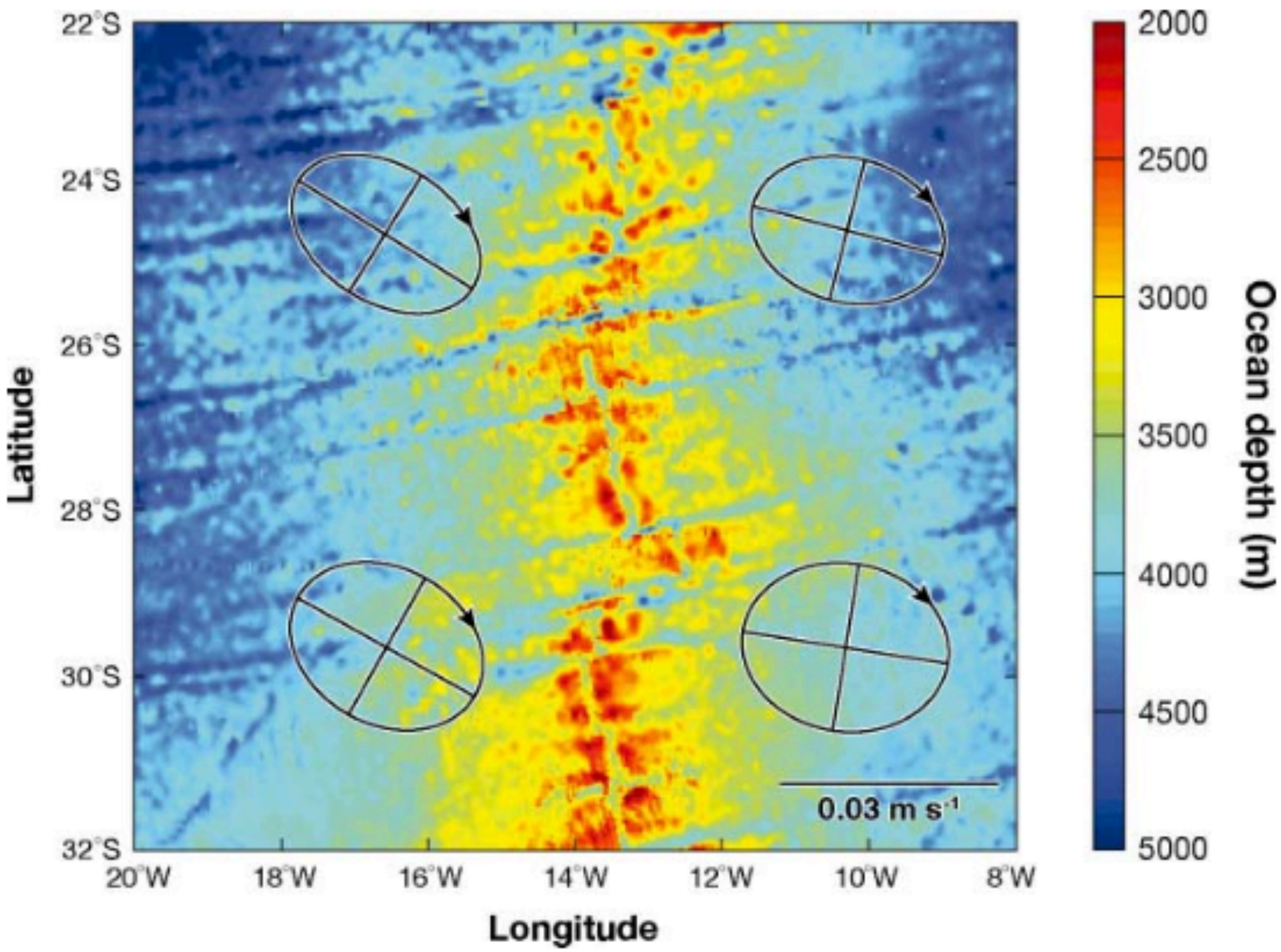
- The shape of the seafloor topography k, h_0^2
- The frequencies of the systems ω, f, N
- The squared amplitude of the barotropic tide current u_0^2

Garrett and Kunze (2007)

5. Generation of internal waves

Generation of internal tides in the deep ocean.

Generalisation to a 3-D problem with random bathymetry.



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

Garrett and Kunze (2007)

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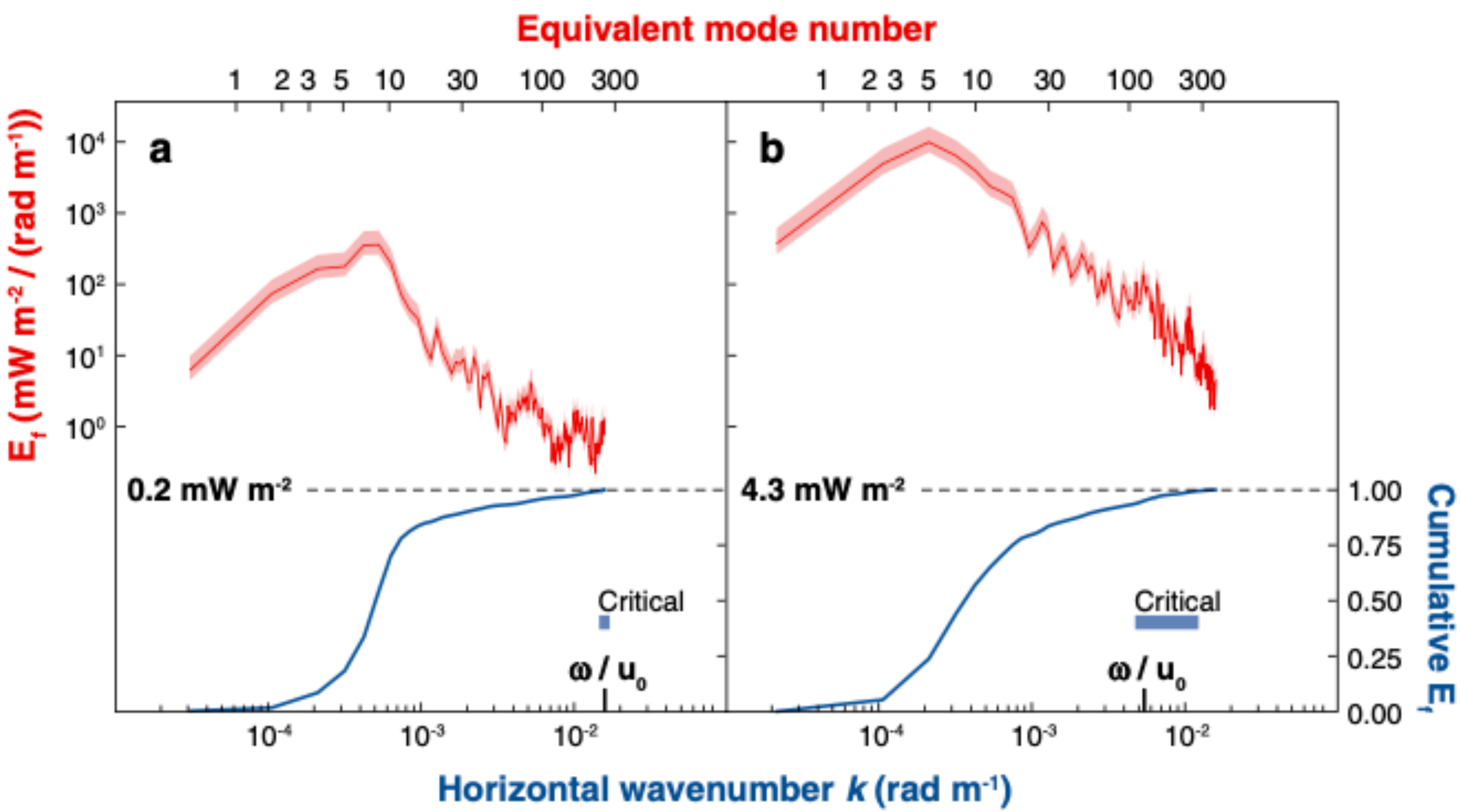
Generation of internal tides in the deep ocean.

Generalisation to a 3-D problem with random bathymetry.



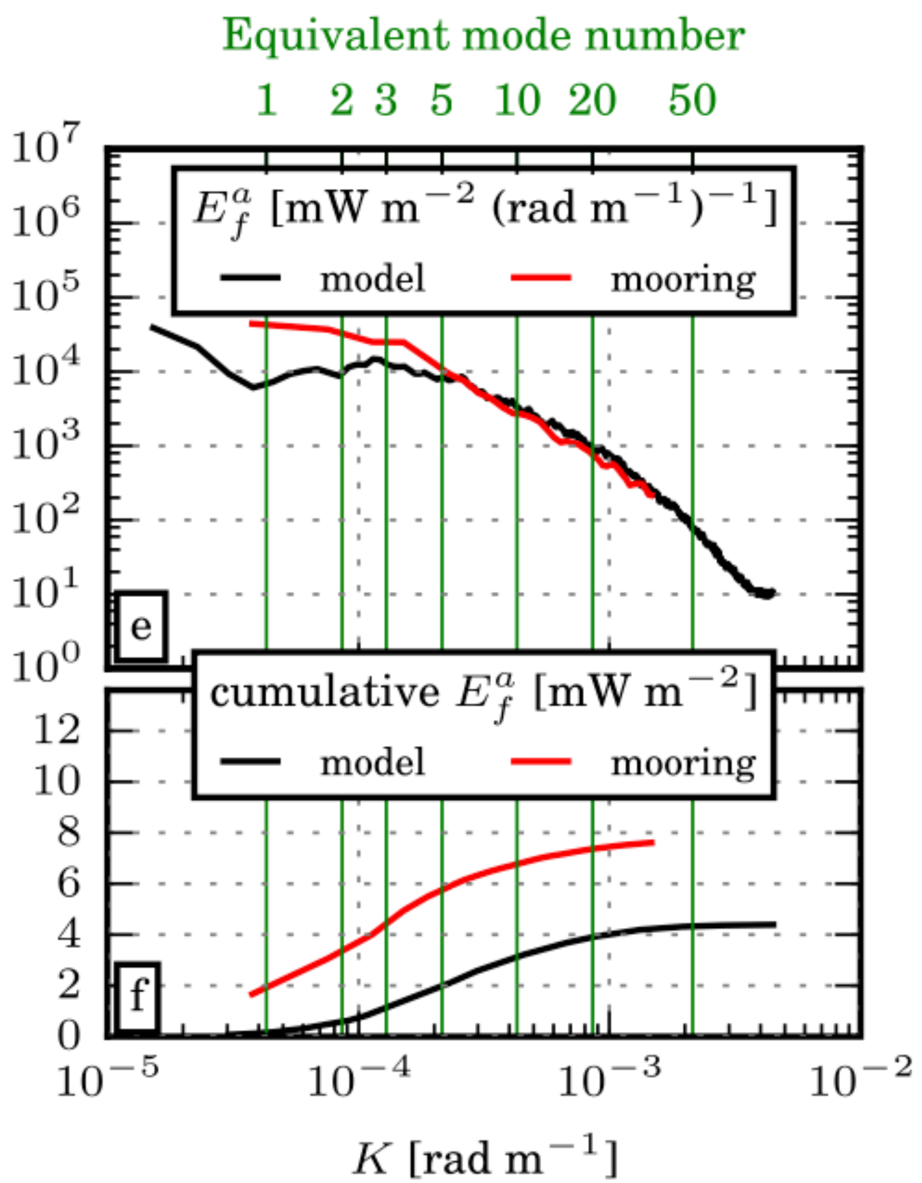
The generation can be cast into vertical modes (cf section 4 of this course).

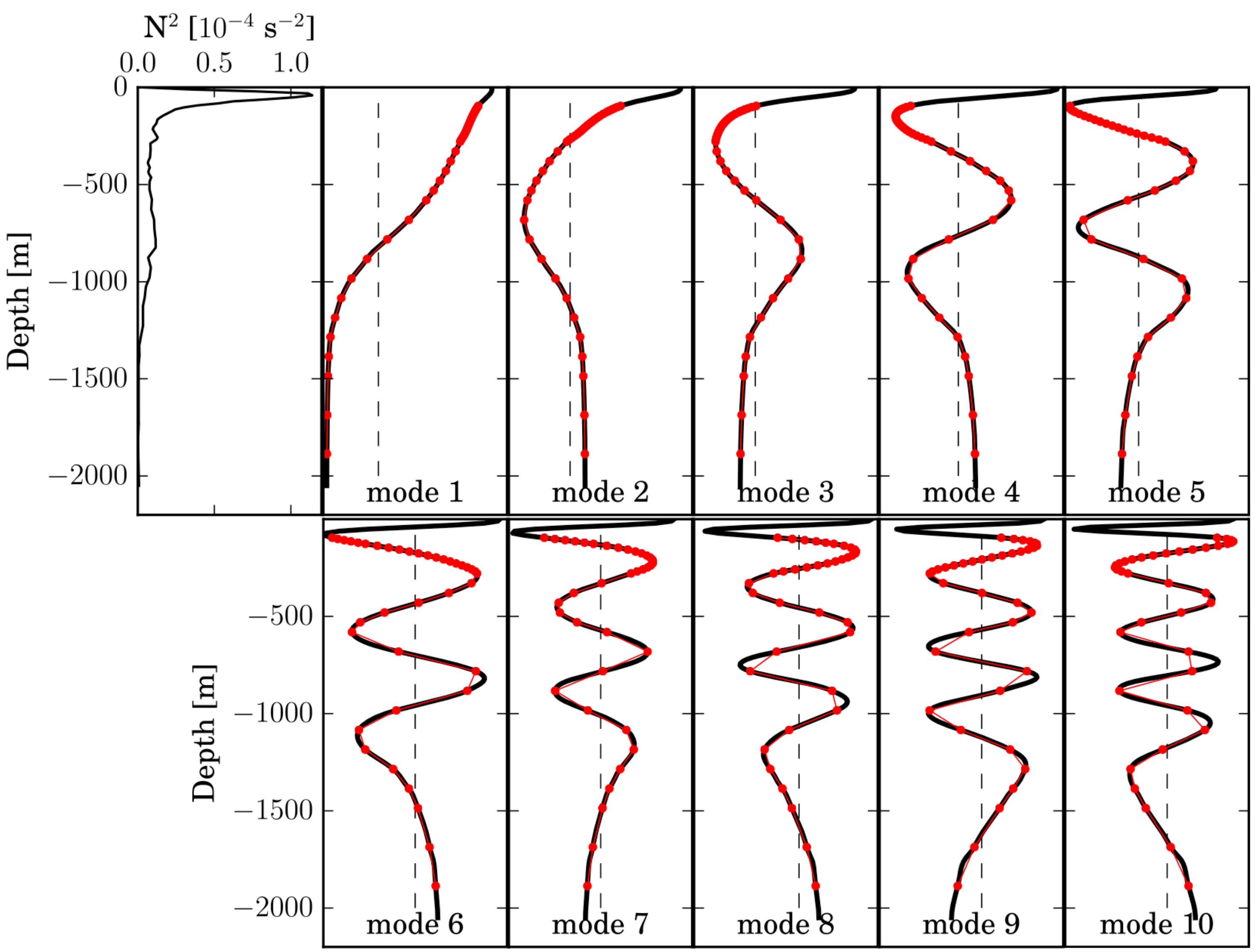
Garrett and Kunze (2007)

5. Generation of internal waves

Generation of internal tides in the deep ocean.

Generalisation to a 3-D problem with random bathymetry.

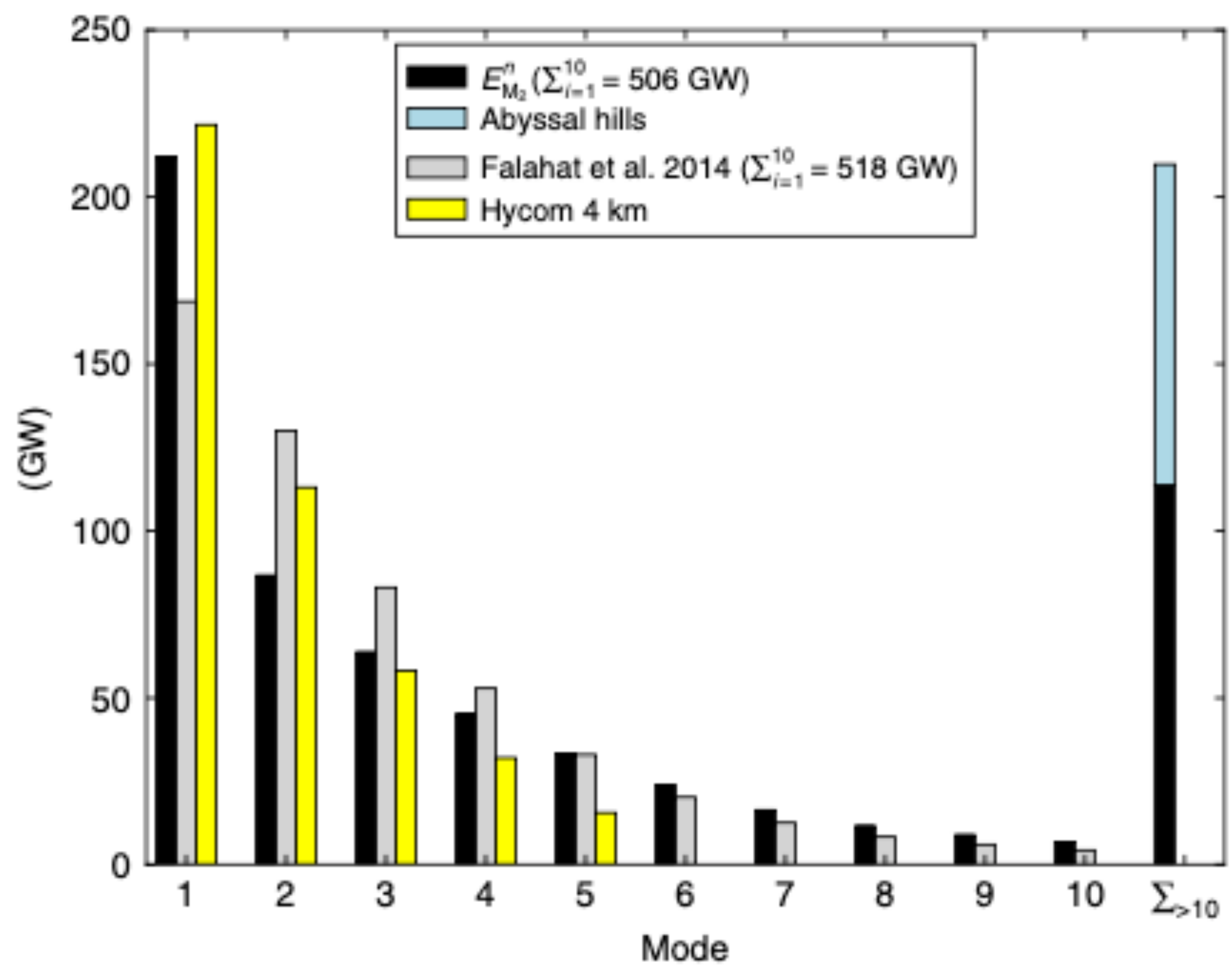




Vic et al. (2018)

Generation of internal tides in the deep ocean.

Global prediction of the generation into vertical modes.

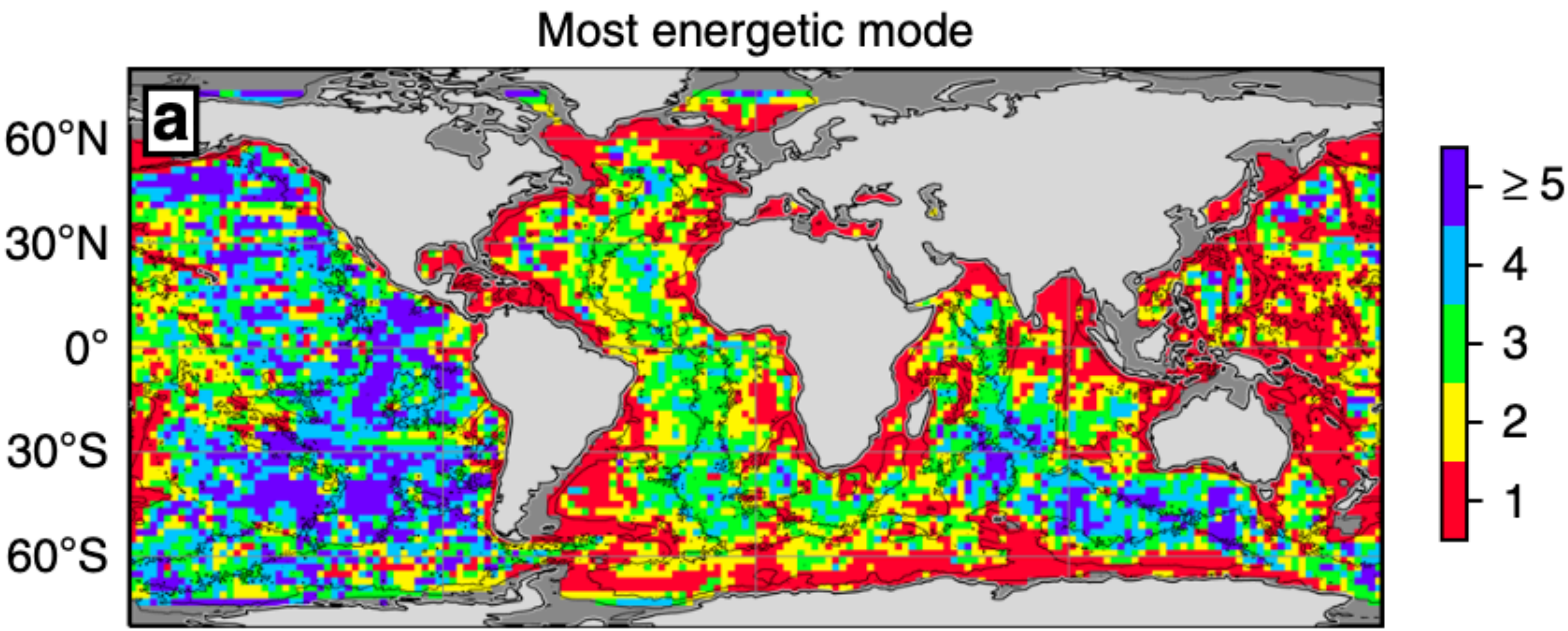


Vic et al. (2019)

5. Generation of internal waves

Generation of internal tides in the deep ocean.

Global prediction of the generation into vertical modes.



Interest of the method: link the generation to local and remote mixing. High modes are unstable and break locally vs low modes are stable and propagate long distances.

Vic et al. (2019), de Lavergne et al. (2019, 2020)

5. Generation of internal waves

Generation of internal tides ~~in the deep ocean.~~ in shallow seas.

On continental shelves / shelf breaks, the assumptions to derive a linear theory do not hold. Why ?

Vic et al. (2019), de Lavergne et al. (2019, 2020)

5. Generation of internal waves

Generation of internal tides ~~in the deep ocean.~~ in shallow seas.

On continental shelves / shelf breaks, the assumptions to derive a linear theory do not hold. Why ?

- Shallower depths : N is much larger (stratification ++) → beams are more horizontal

- Topographic slopes are steeper

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

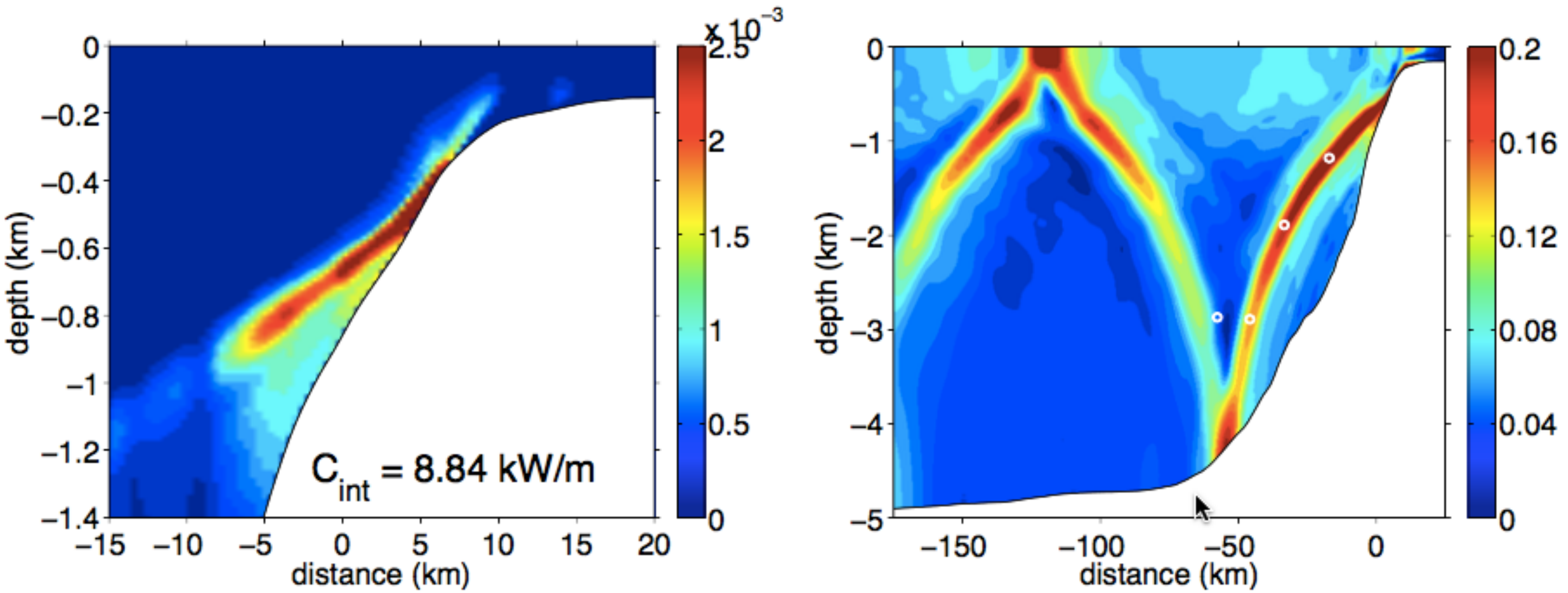
→ critical slopes $\epsilon = 1$ and supercritical slopes $\epsilon > 1$

Vic et al. (2019), de Lavergne et al. (2019, 2020)

5. Generation of internal waves

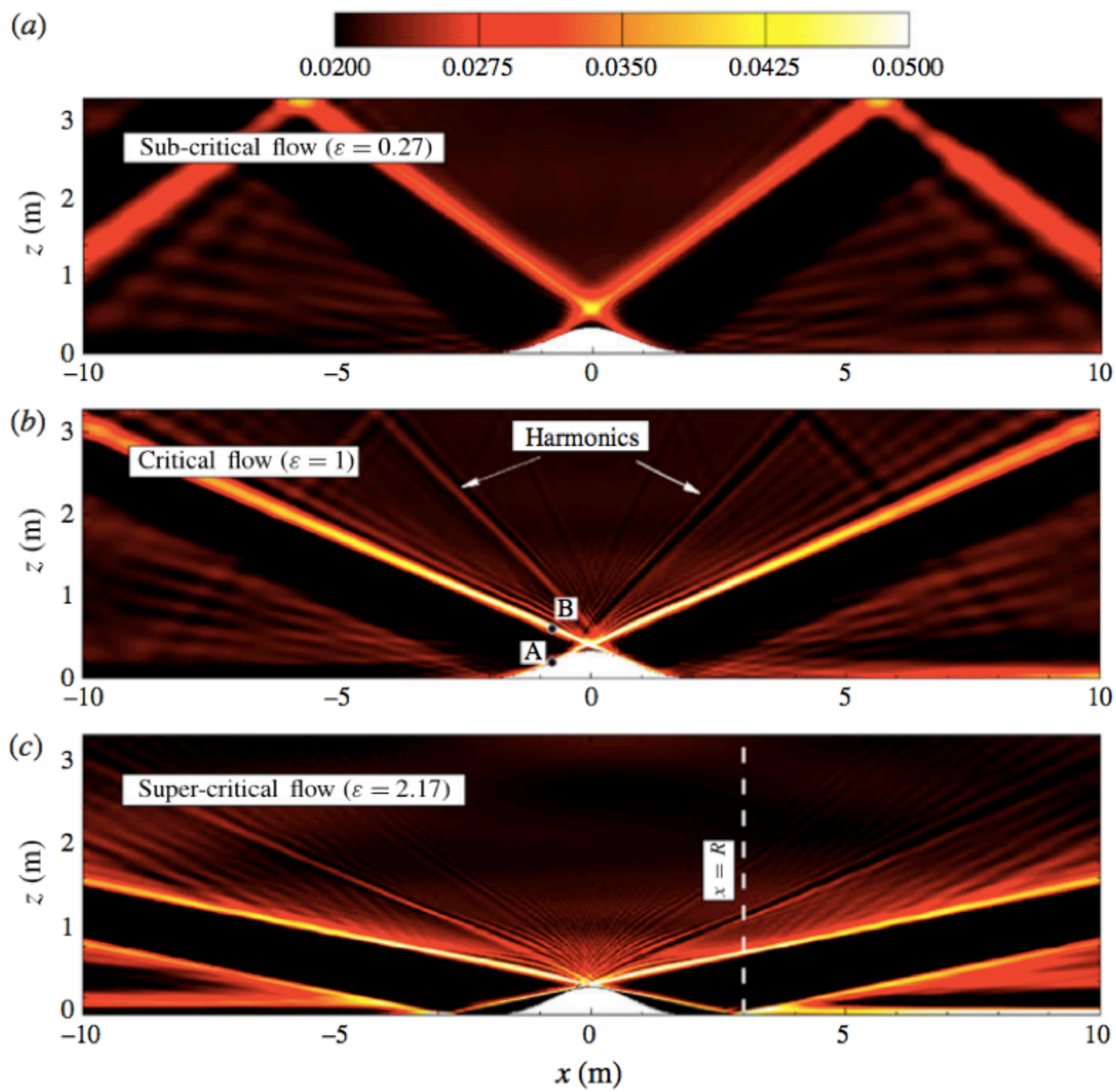
Generation of internal tides ~~in the deep ocean.~~ in shallow seas.

- Internal tides are preferentially generated where the topographic slope equals the beam slope (critical slopes).
- The wave field is more organised in beams (vs individual modes in the deep ocean).



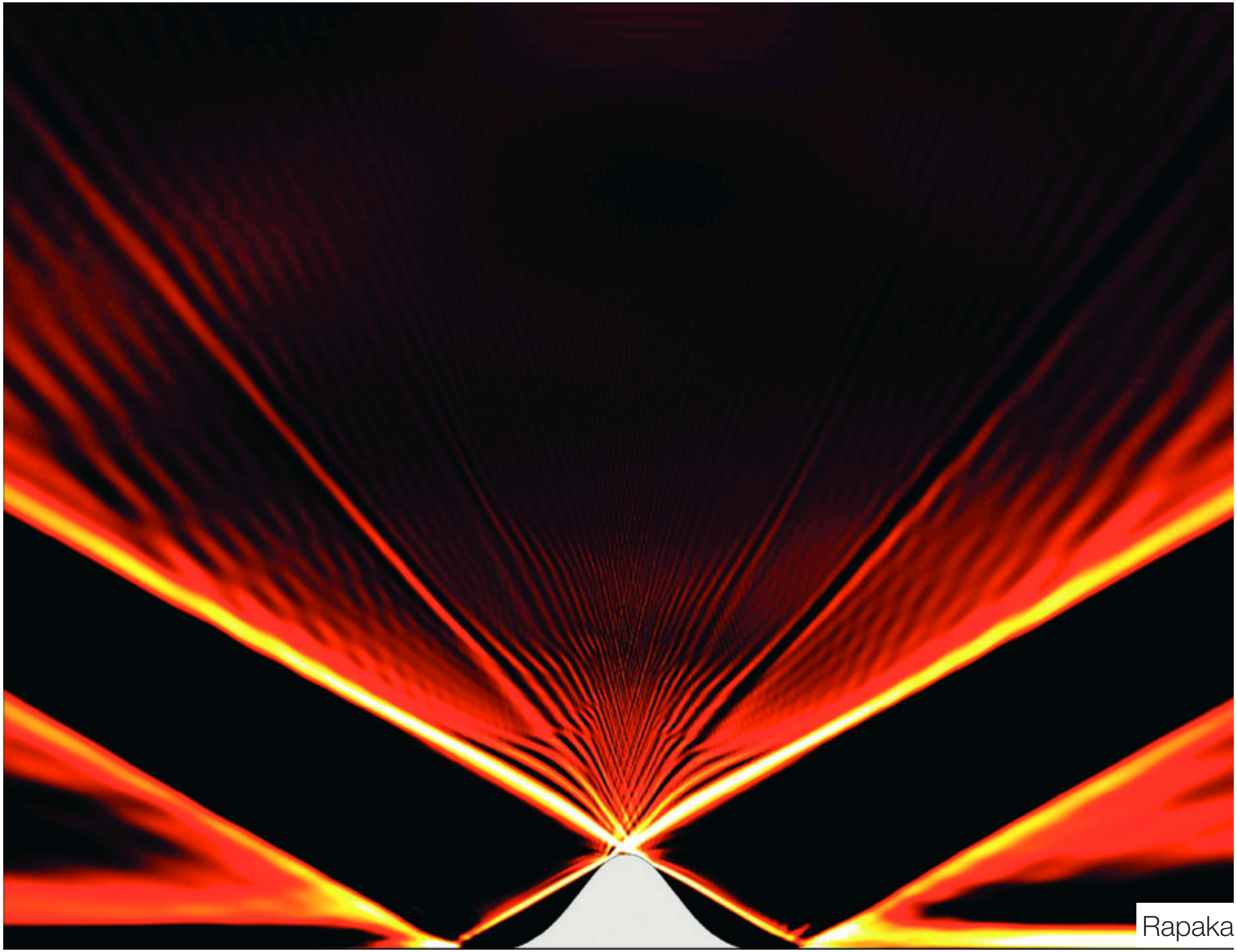
Gerkema et al. (2004)

Generation of internal tides (different slopes).



Rapaka et al. (2013)

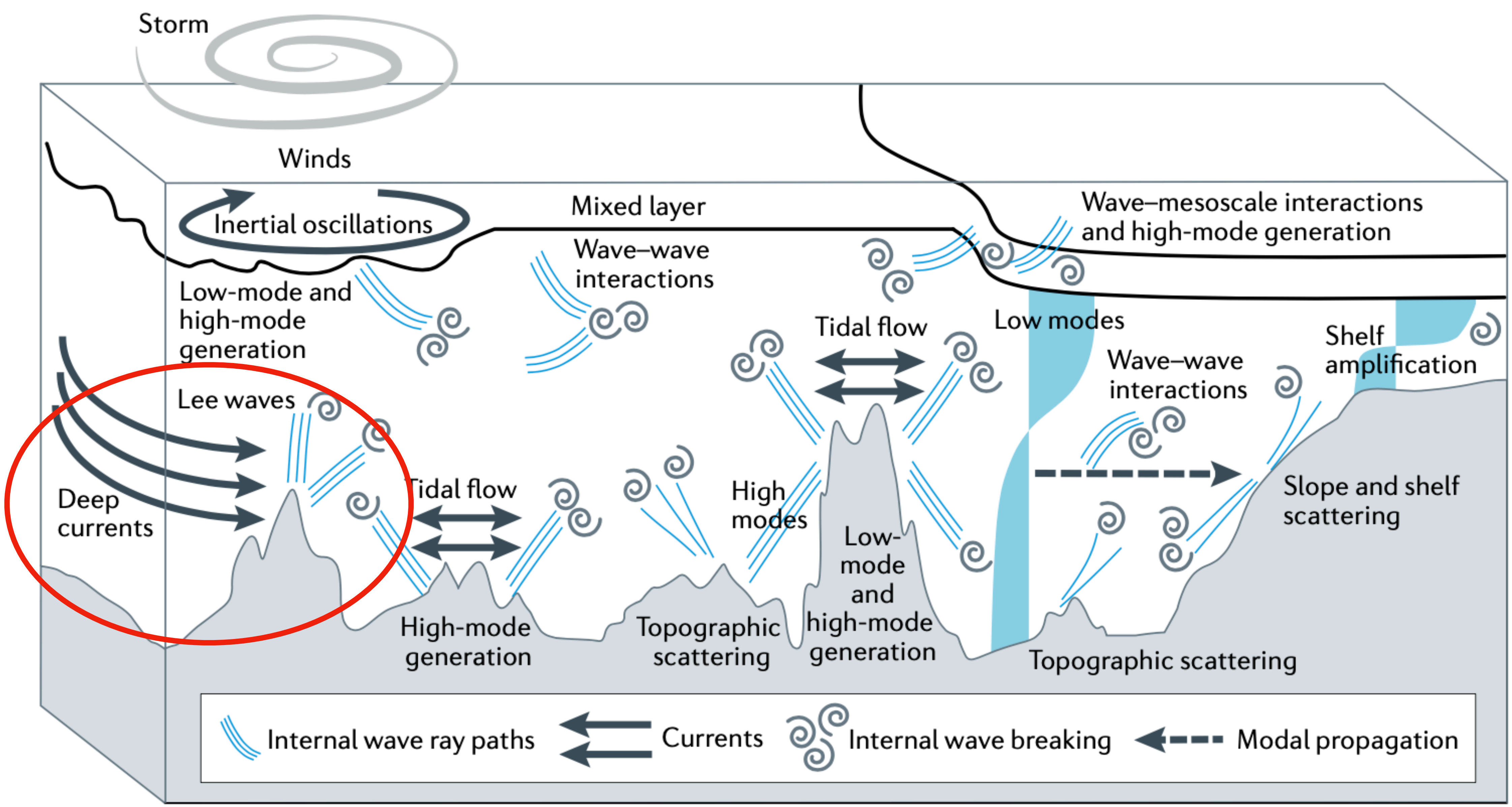
Generation of internal tides (different slopes).



Rapaka et al. (2013)

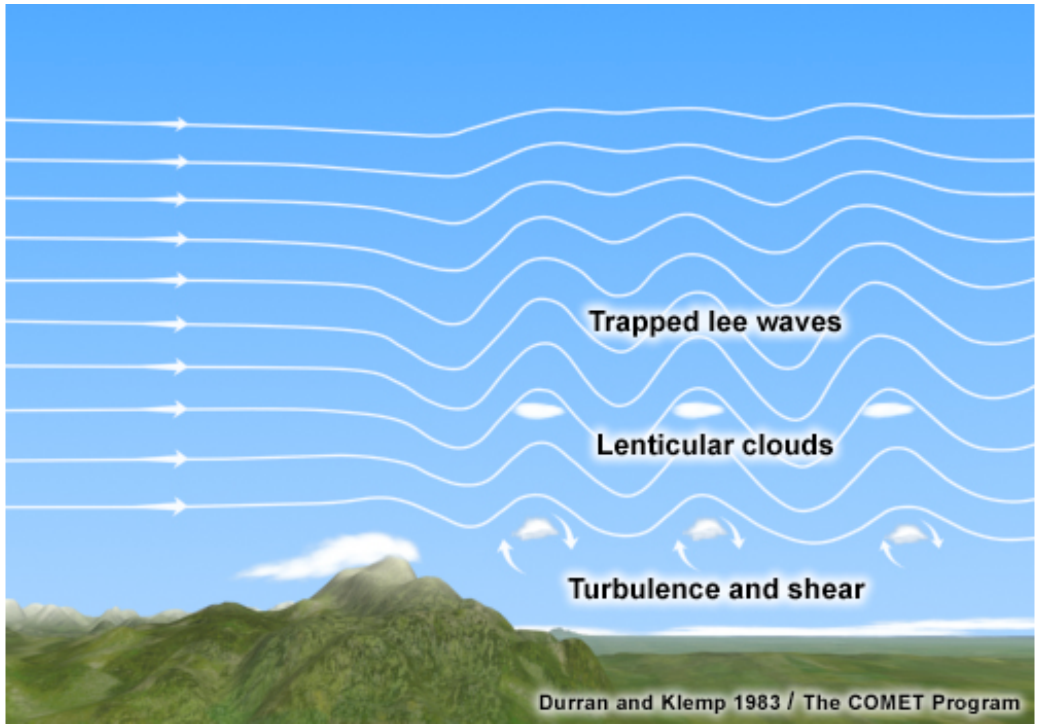
5. Generation of internal waves

Generation of lee waves



5. Generation of internal waves

Generation of lee waves

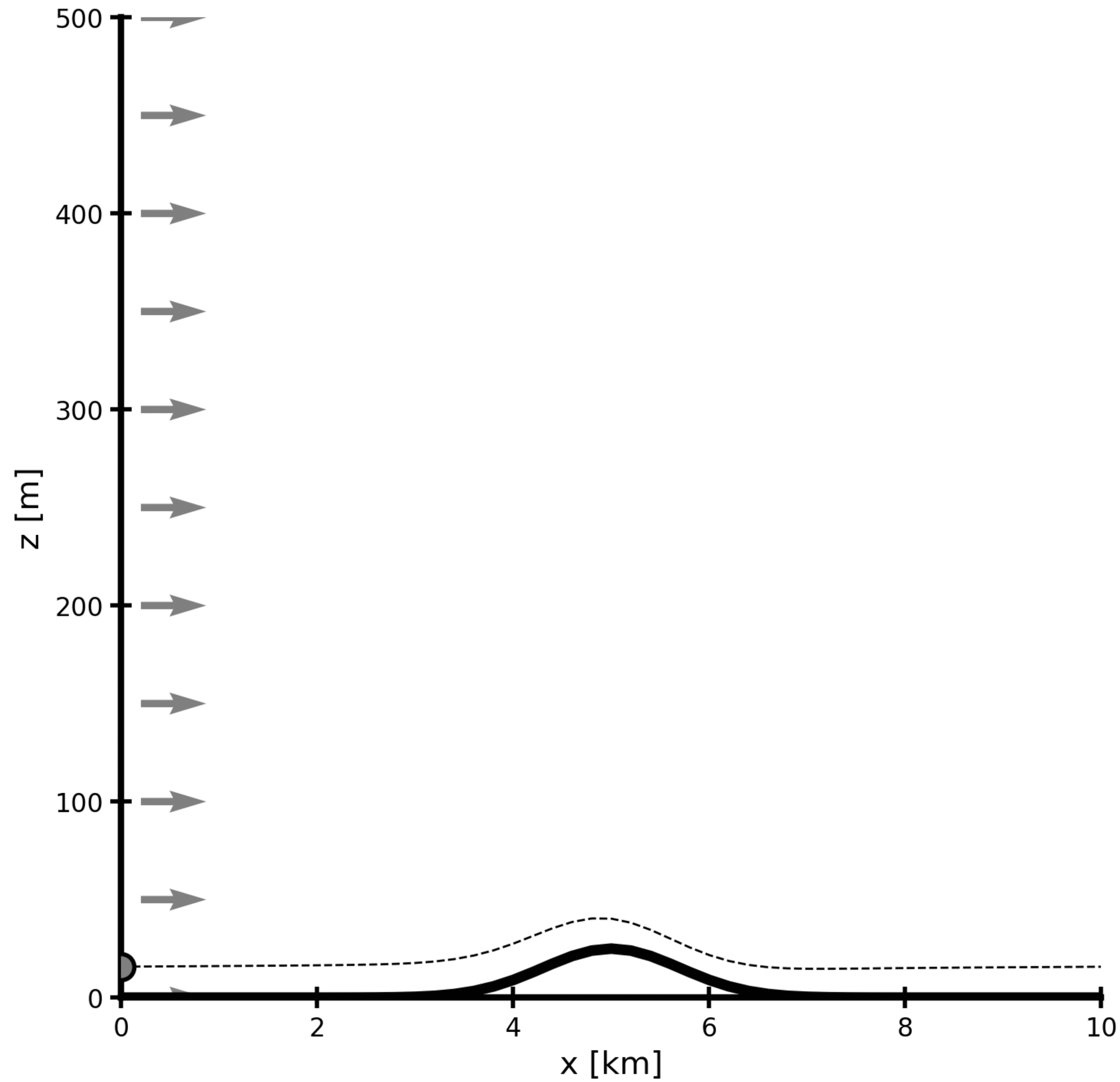


Modis, 23/11/2009 - South Atlantic – Sandwich Islands

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

5. Generation of internal waves

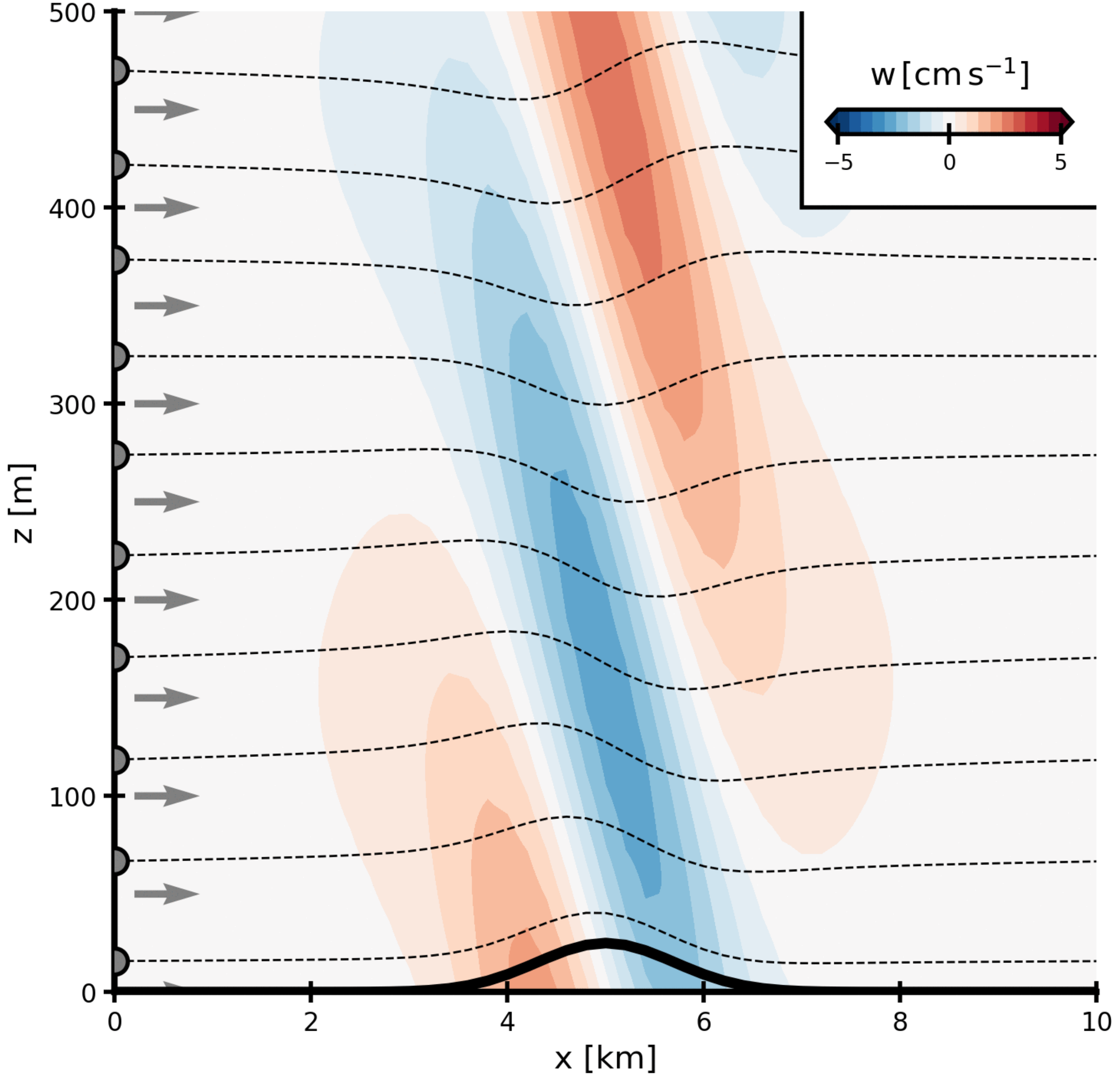
Generation of lee waves



de Marez et al. (2020)

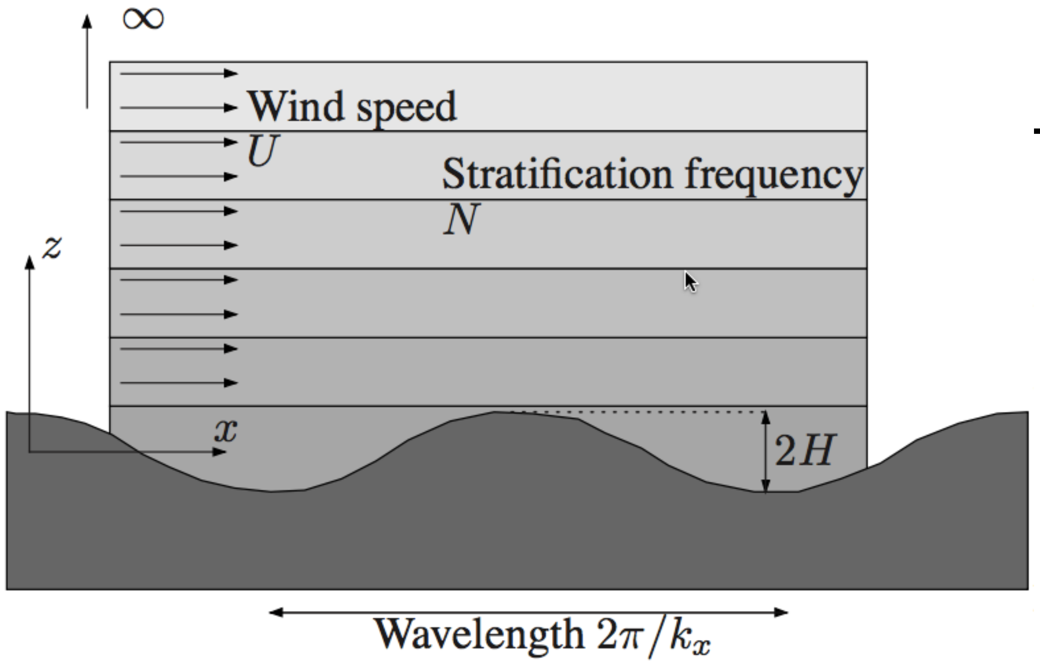
5. Generation of internal waves

Generation of lee waves



de Marez et al. (2020)

5. Generation of internal waves



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 motion: $\omega = -k_x U$
- Recall the general equation for internal waves:
  $(w_{xx} + w_{yy} + w_{zz})_{tt} + f^2 w_{zz} + N^2(w_{xx} + w_{yy}) = 0$

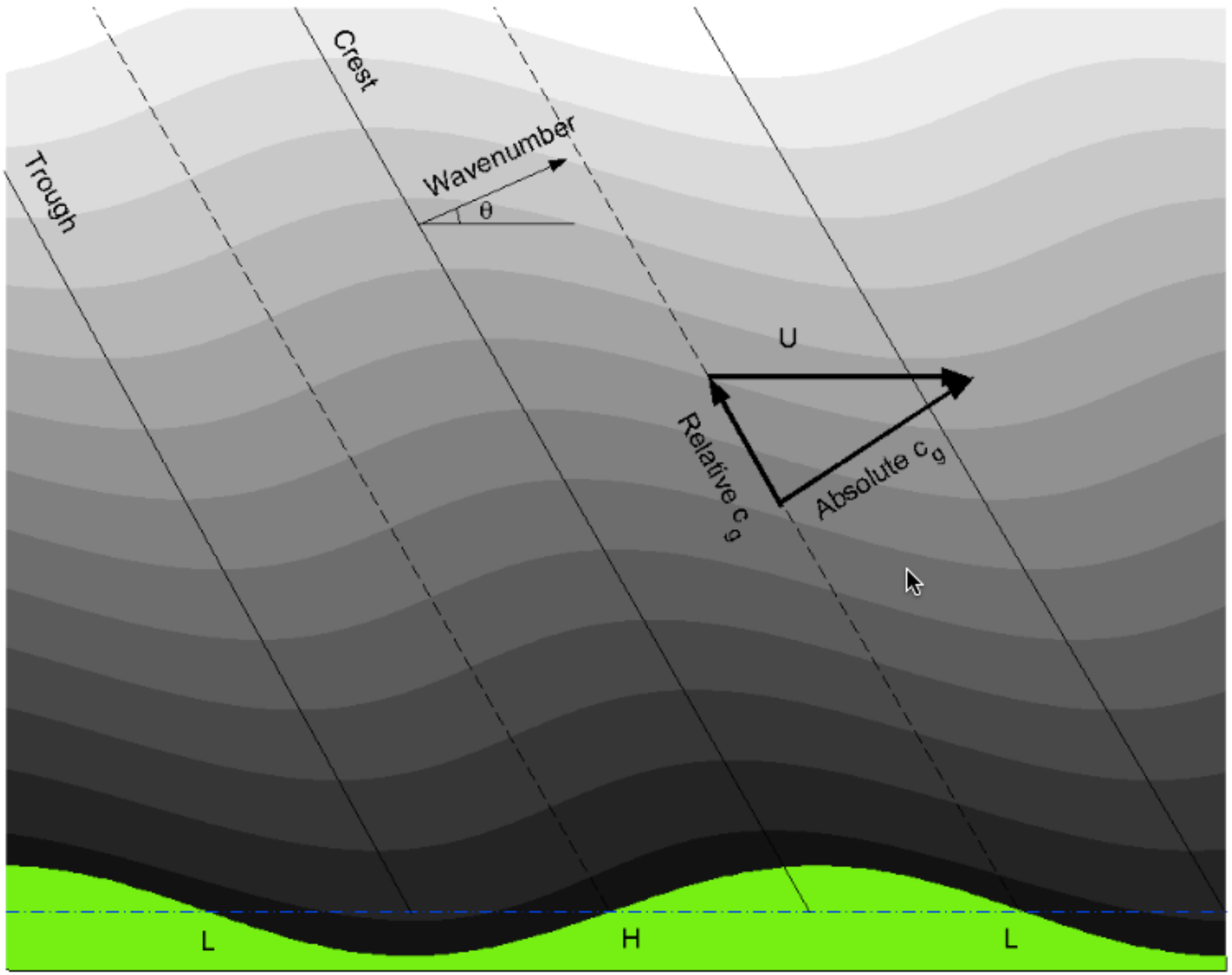
→ with a boundary condition, and some assumptions ($f = 0$, $H \ll U/N$),

we can solve the equation assuming a wave form $w = w_0 \exp(i(k_x x + k_z z - \omega t))$

5. Generation of internal waves

Generation of lee waves

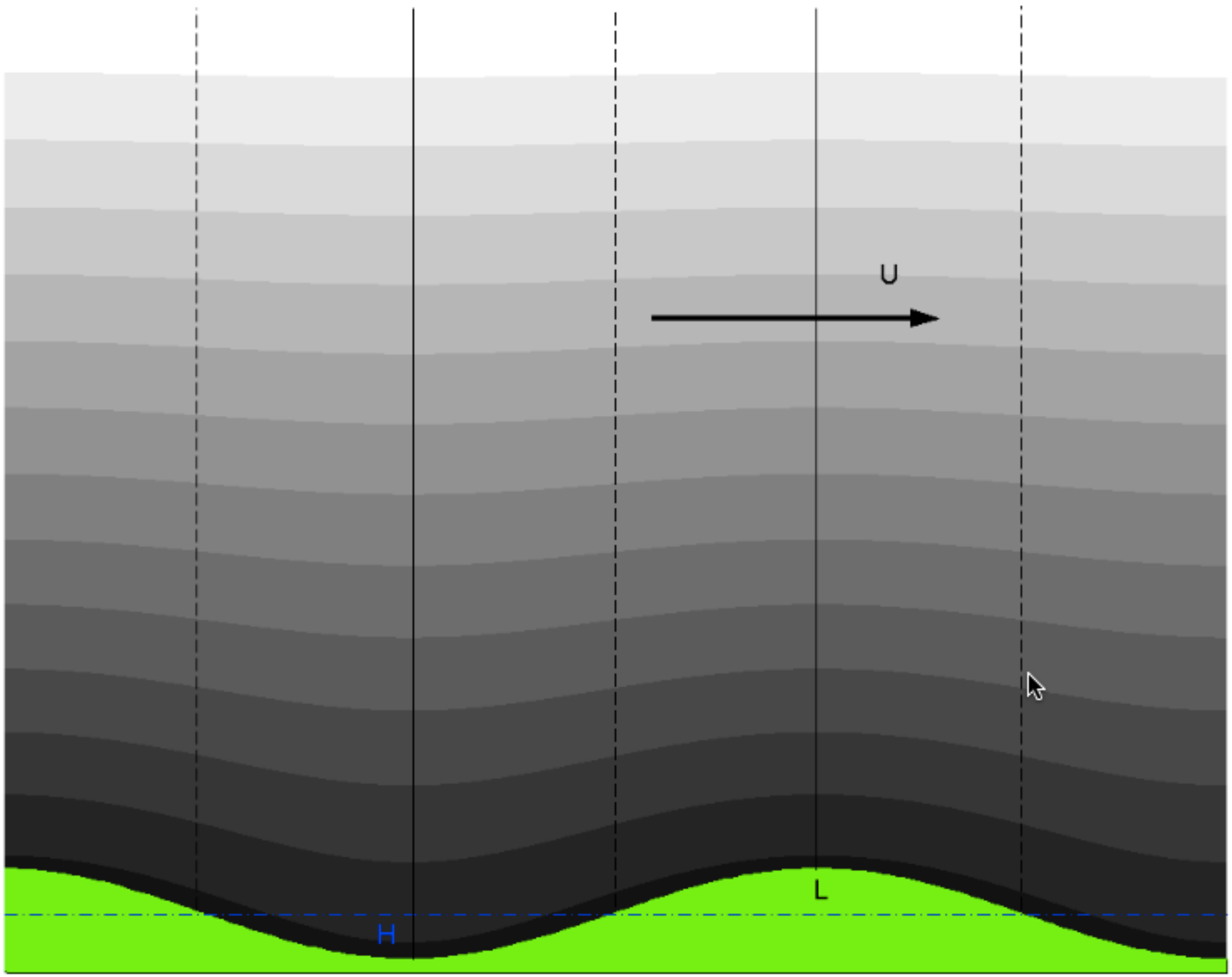
- if $N > Uk_x = \omega$, the wave radiates



5. Generation of internal waves

Generation of lee waves

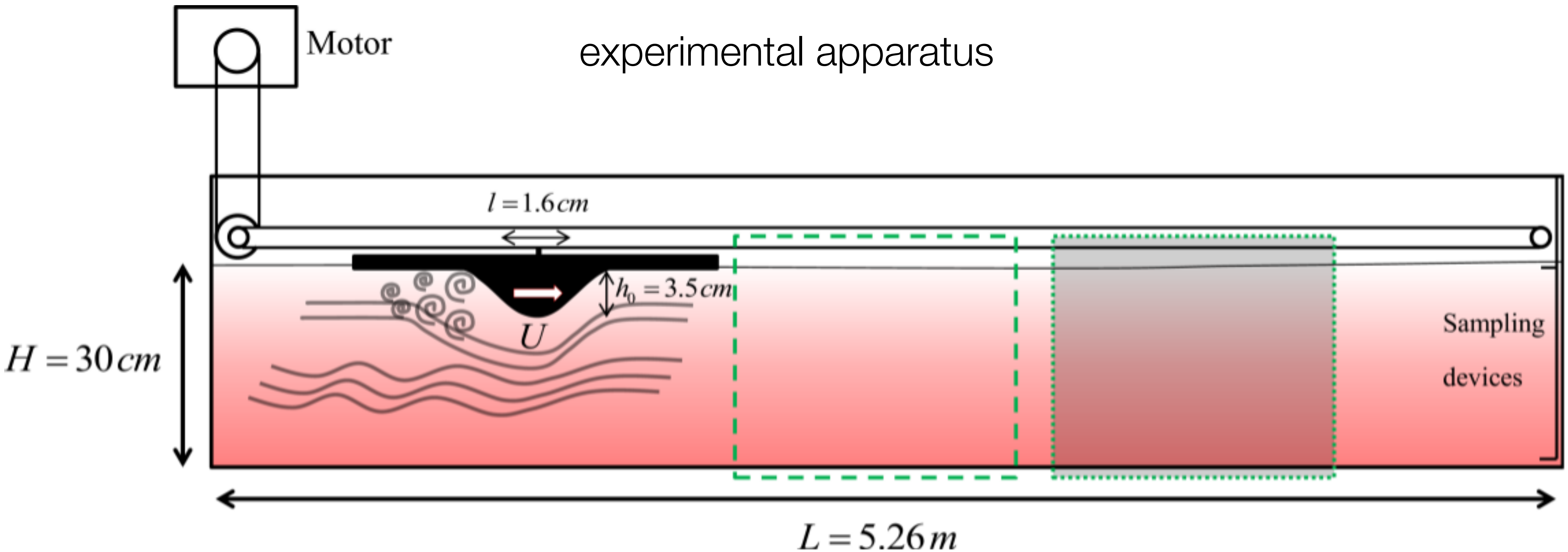
- if $N < Uk_x = \omega$, the wave is trapped



5. Generation of internal waves

Generation of lee waves

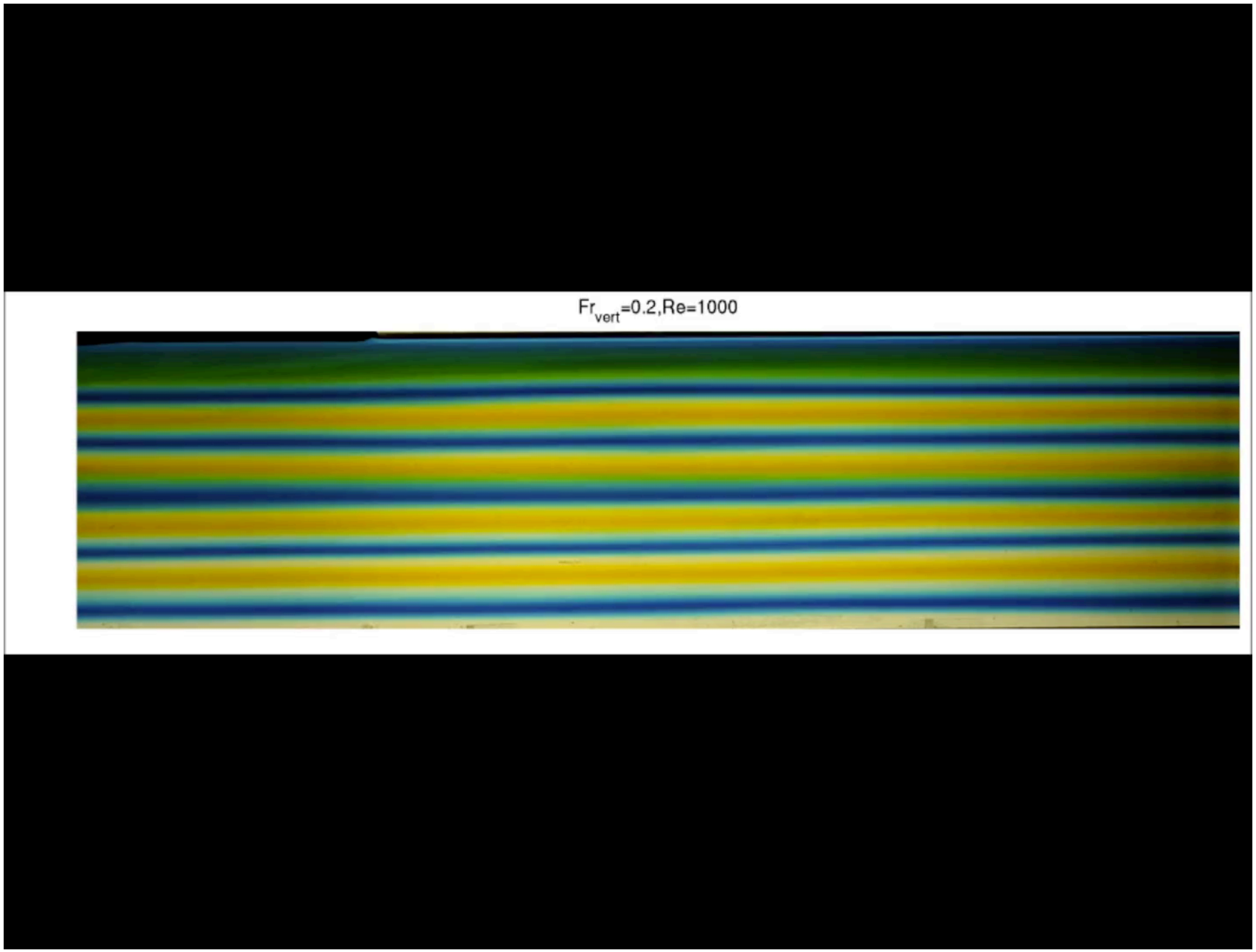
experimental apparatus



Dossmann et al. (2016)

5. Generation of internal waves

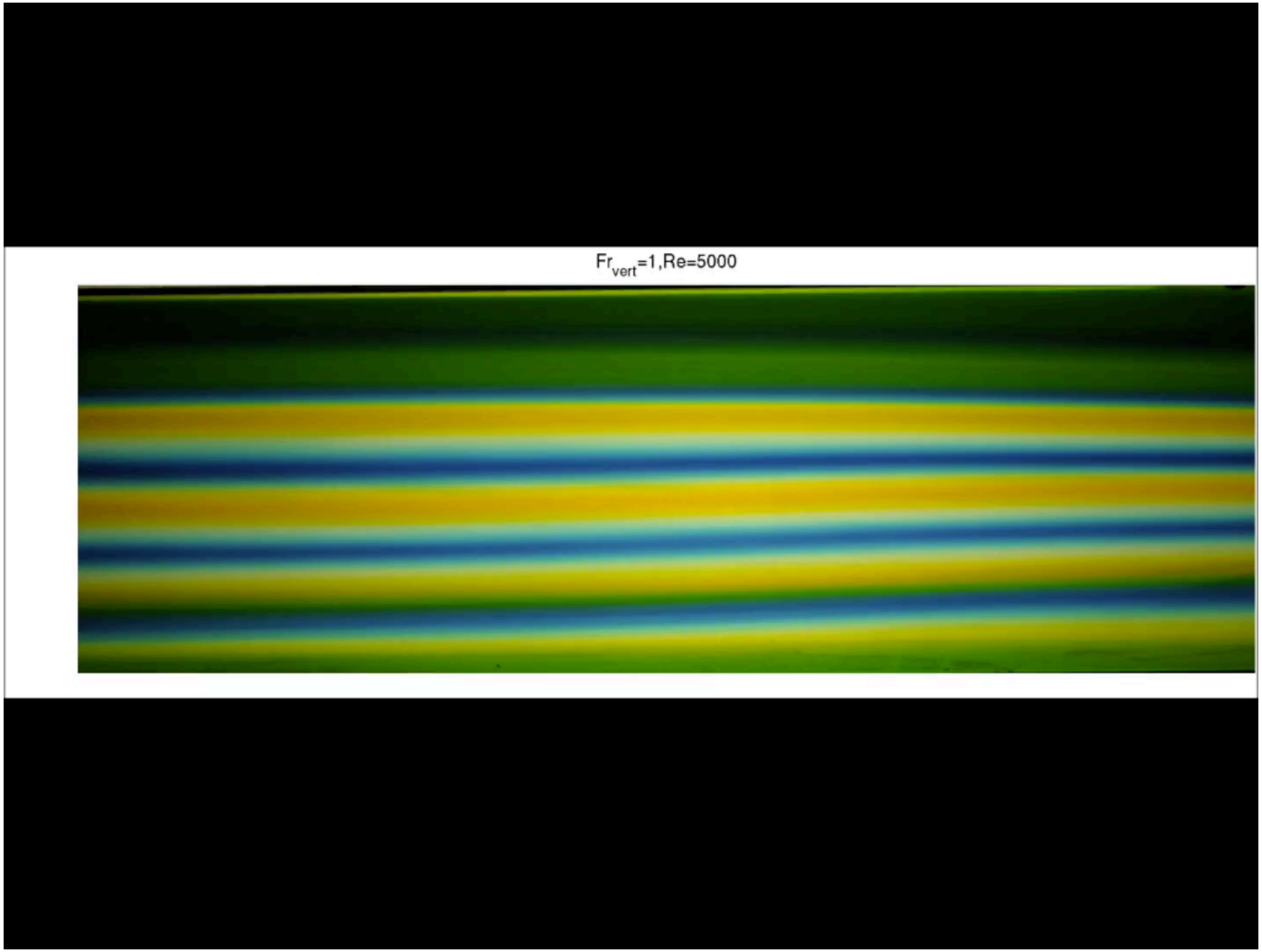
Generation of lee waves



Dossmann et al. (2016)

5. Generation of internal waves

Generation of lee waves

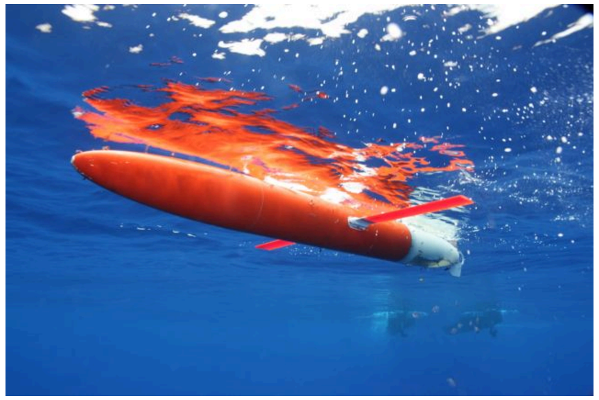


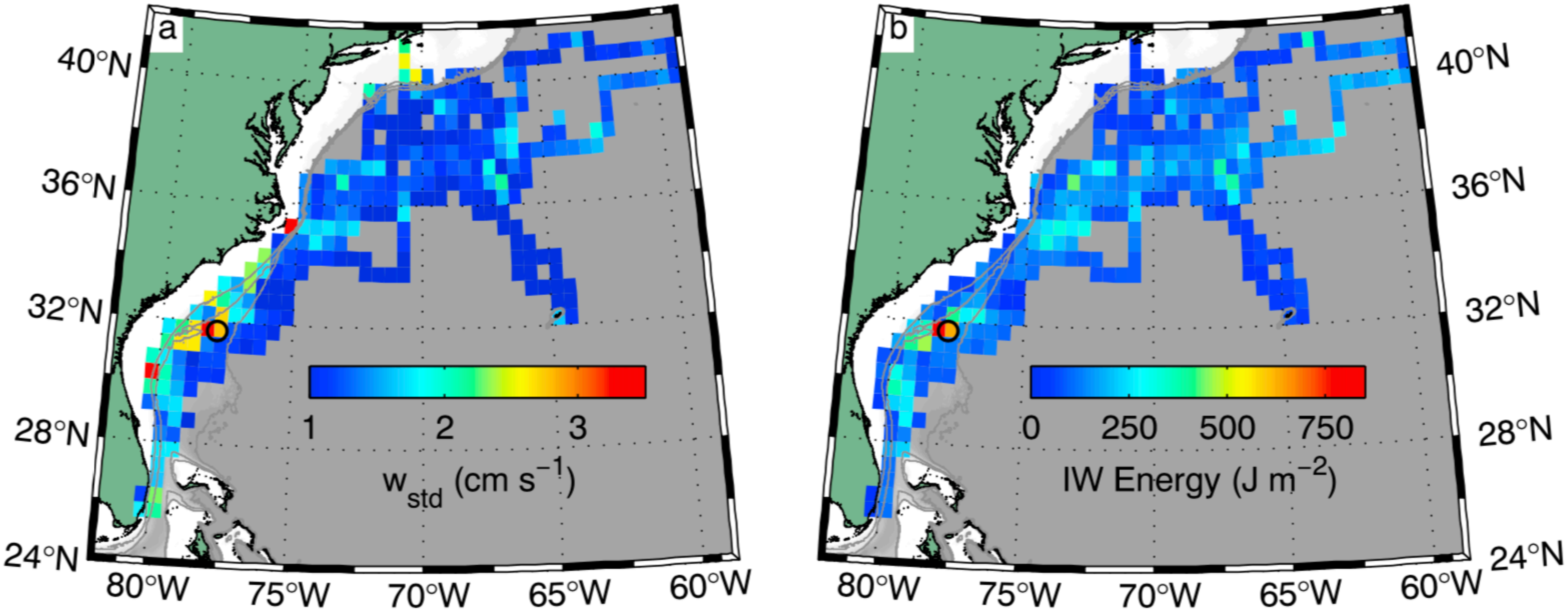
Dossmann et al. (2016)

5. Generation of internal waves

Generation of lee waves

Observation of lee waves by gliders in the Gulf Stream

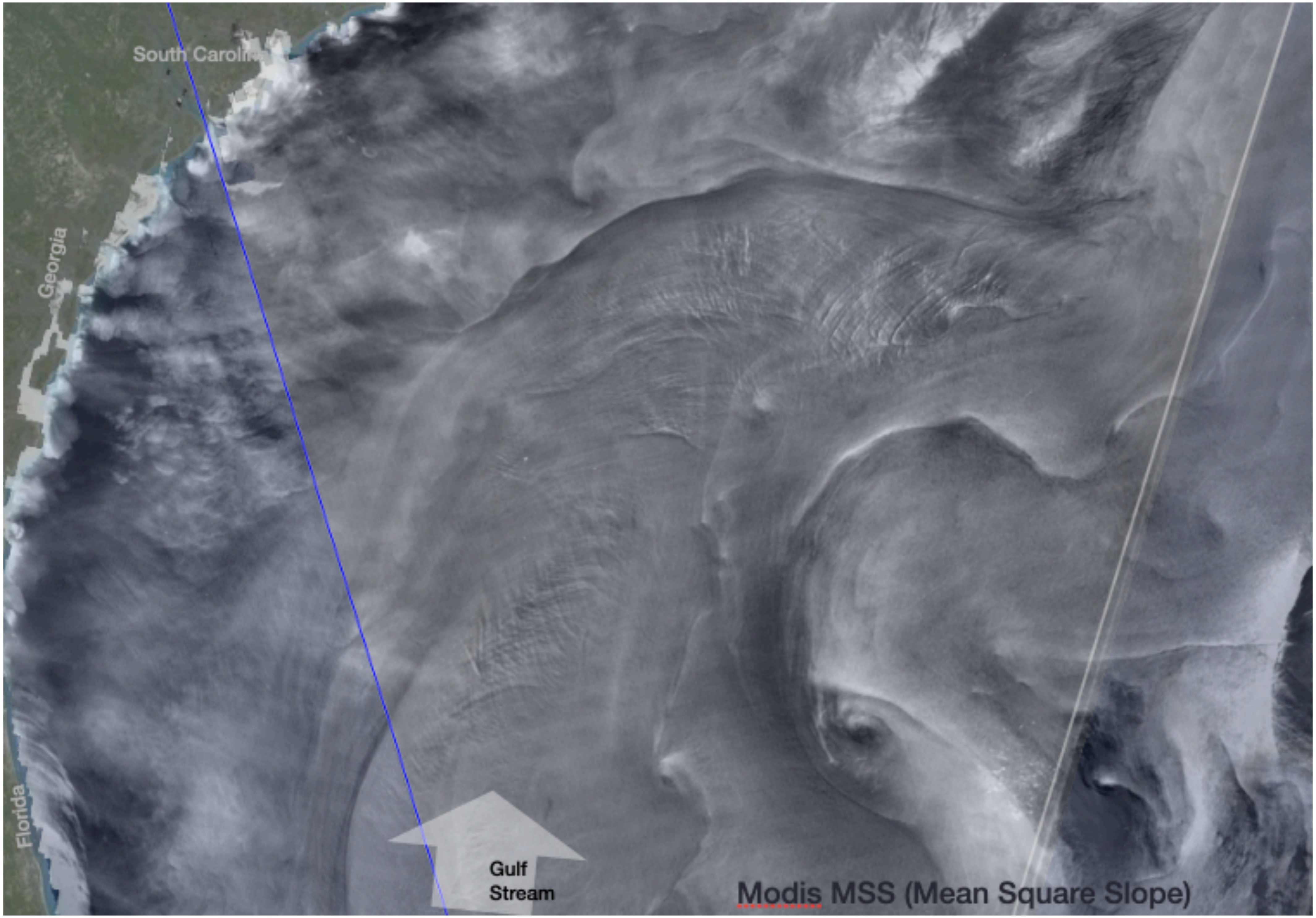




Todd (2017)

Generation of lee waves

Surface signature of lee waves

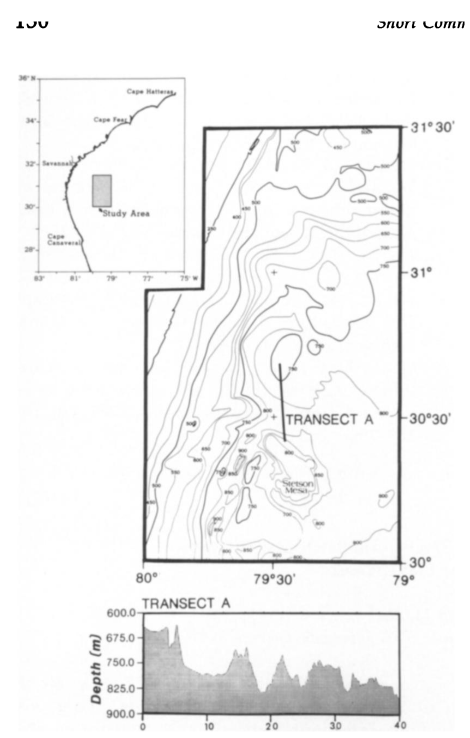


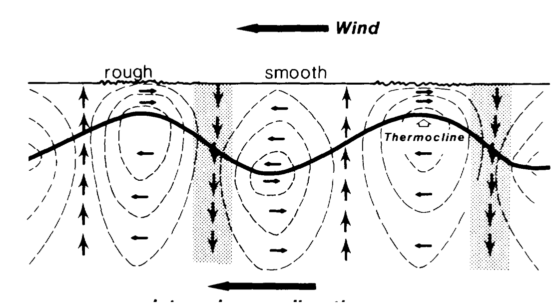
Generation of lee waves

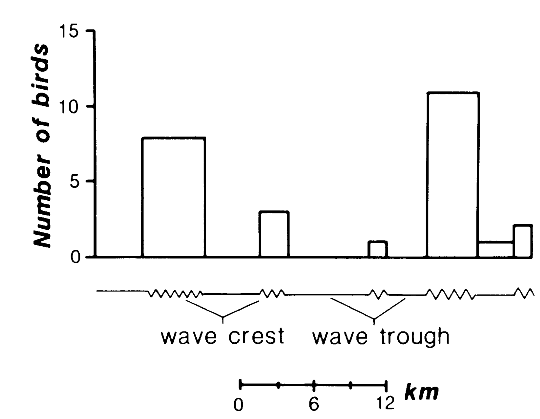
Surface signature of lee waves

The American Ornithologists' Union

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



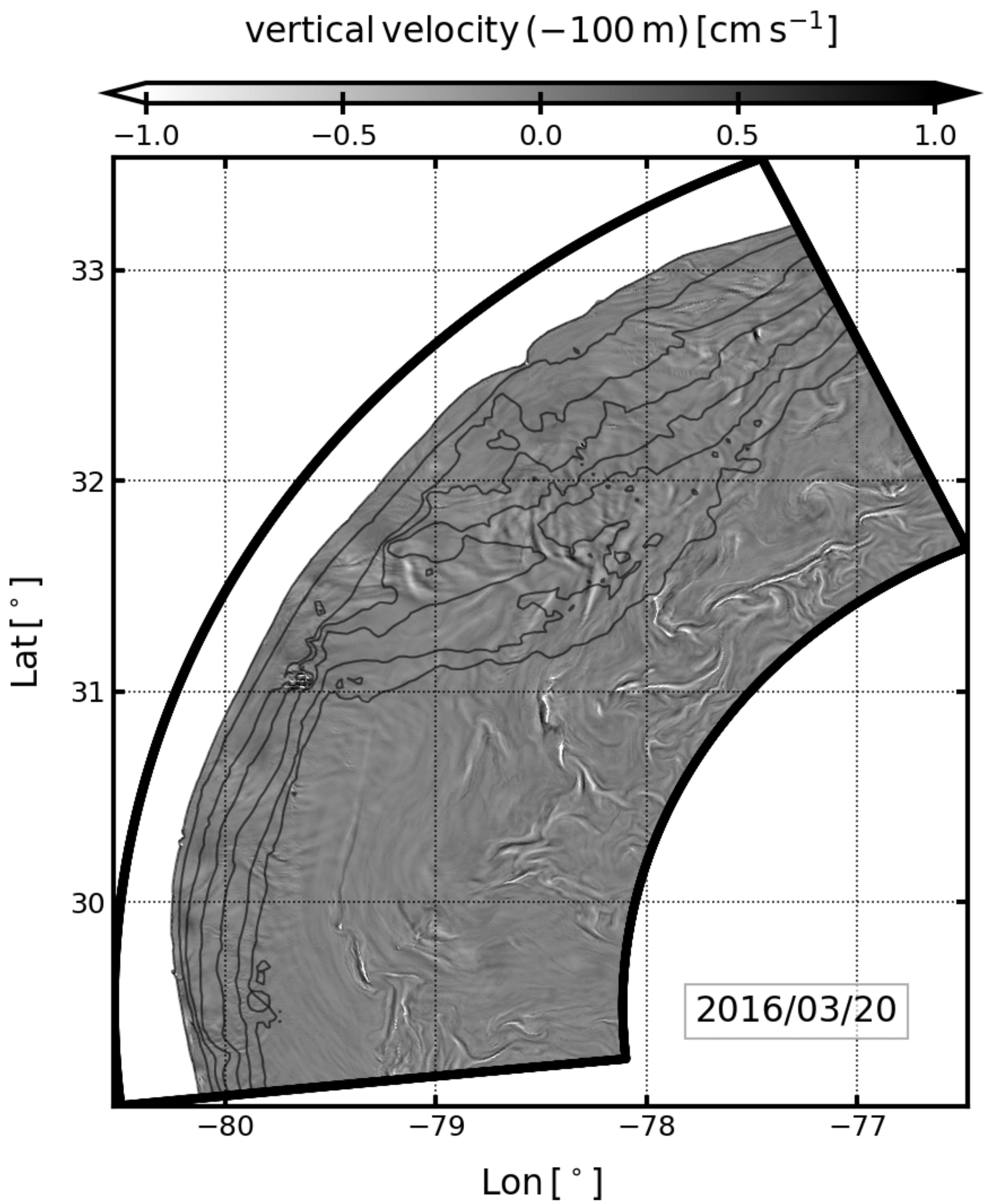




5. Generation of internal waves

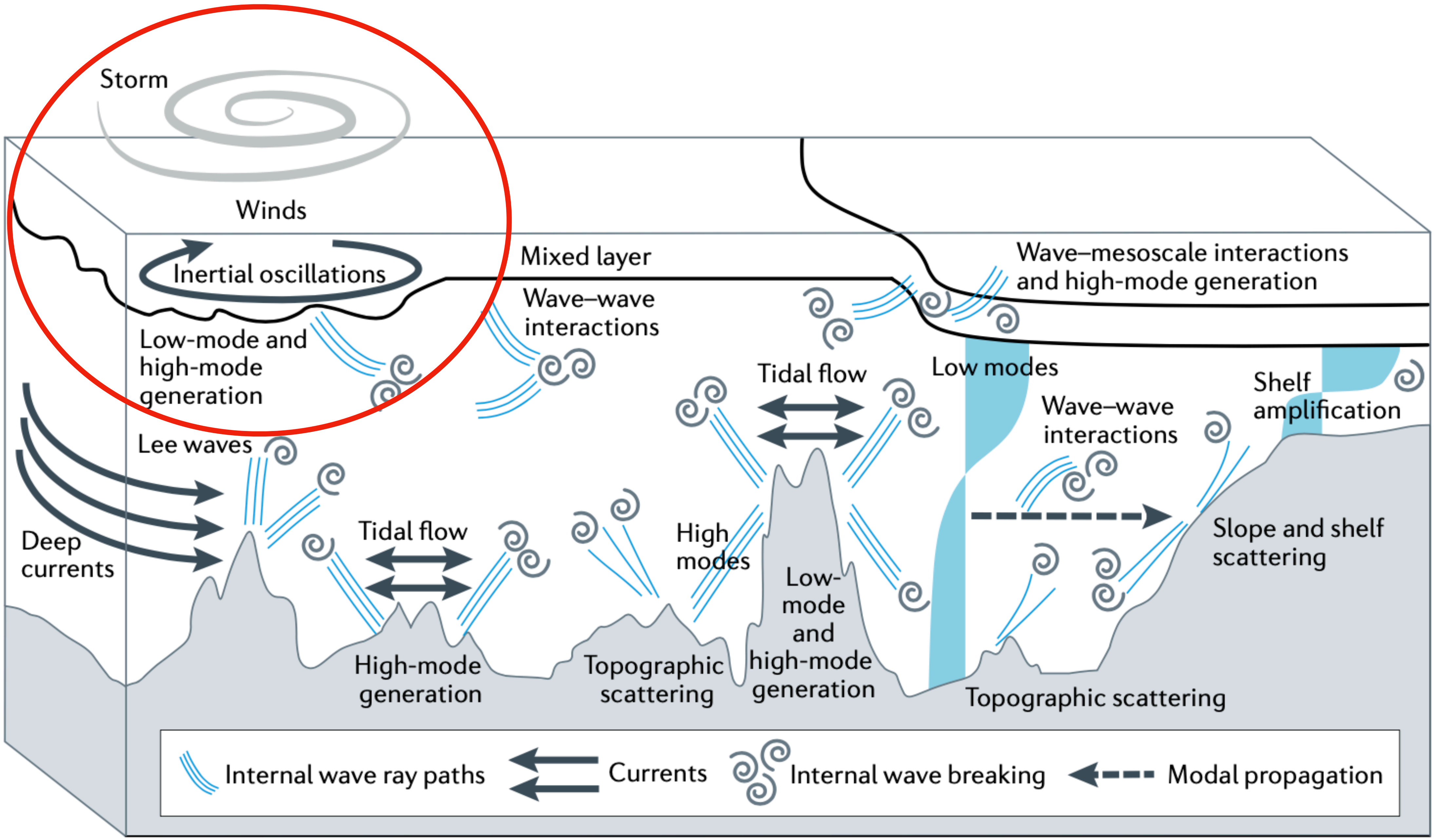
Generation of lee waves

Numerical model at high resolution (Δx=200 m, J. Gula)



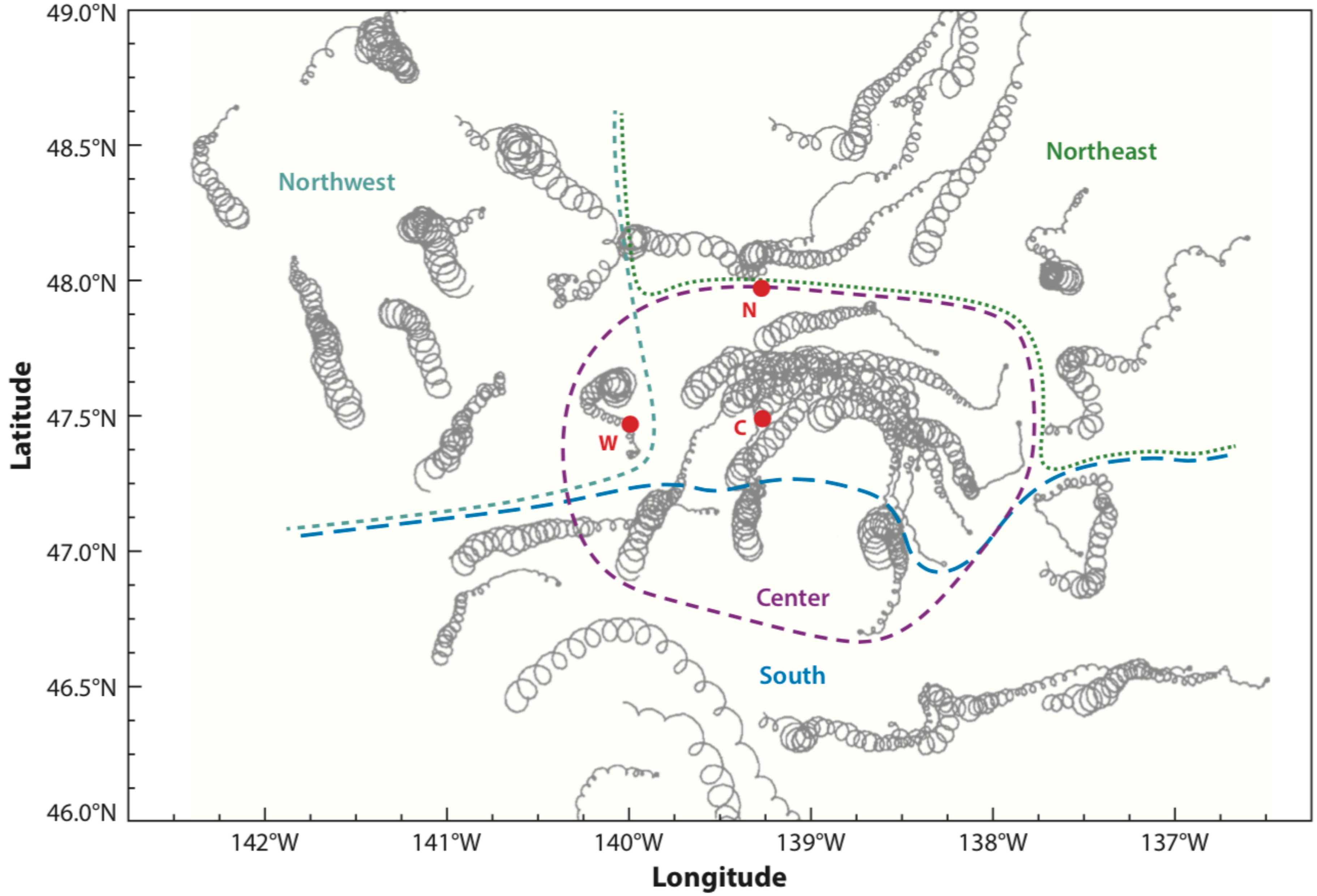
5. Generation of internal waves

Generation of near-inertial waves by winds



5. Generation of internal waves

Generation of near-inertial waves by winds



Near-inertial oscillations of surface drifters after the passage of a storm.
The velocity field is polarised in the clockwise direction (northern hemisphere)

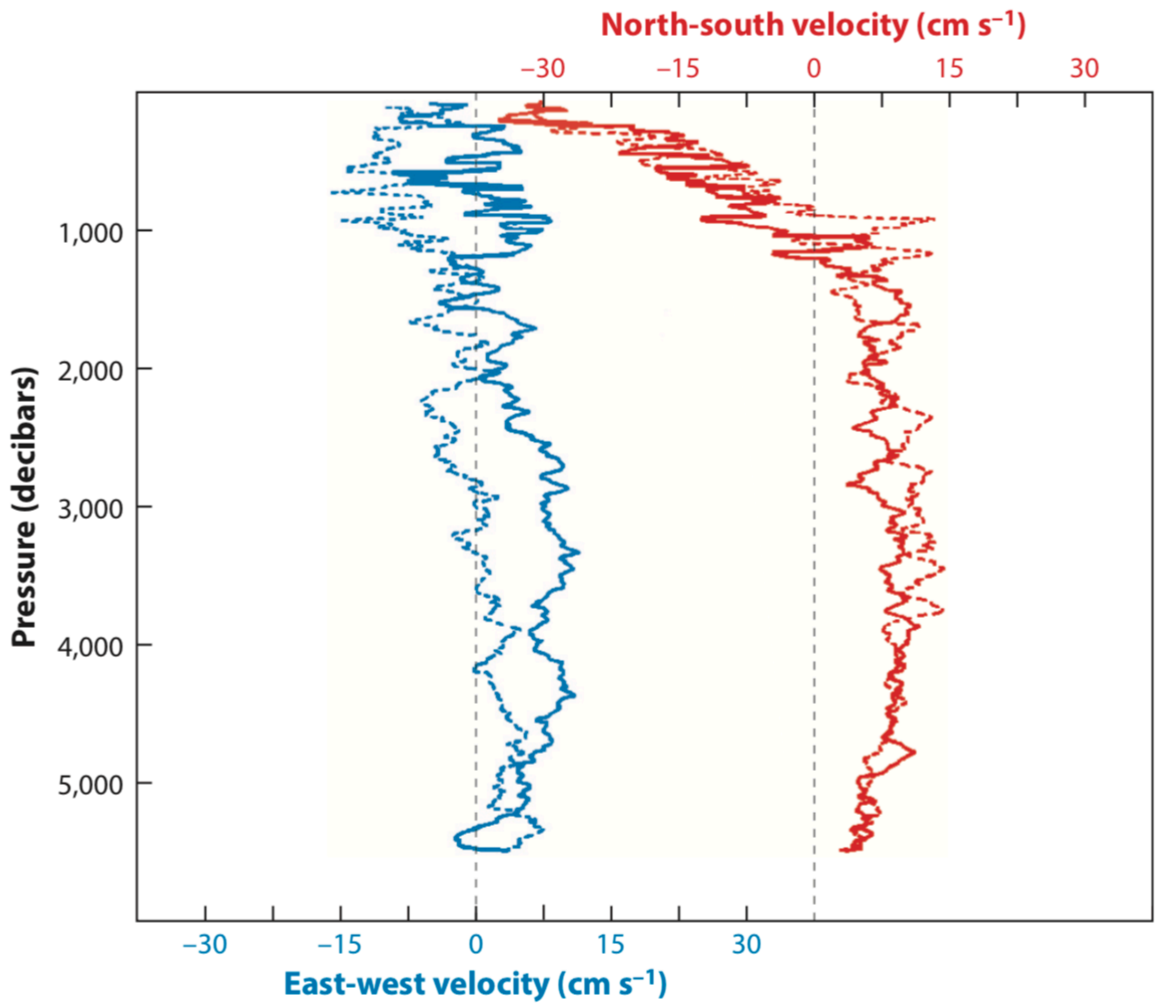
5. Generation of internal waves

Generation of near-inertial waves by winds

Near-inertial oscillation in the surface mixed layer (not stratified, so does not allow internal waves) create a pressure perturbation at the mixed-layer base that then propagates in the ocean interior (stratified), becoming **near-inertial waves**.

Near-inertial waves have very large horizontal wavelengths (>100 km) and short vertical wavelengths (~100 m).

They are characterised by strong vertical shear.



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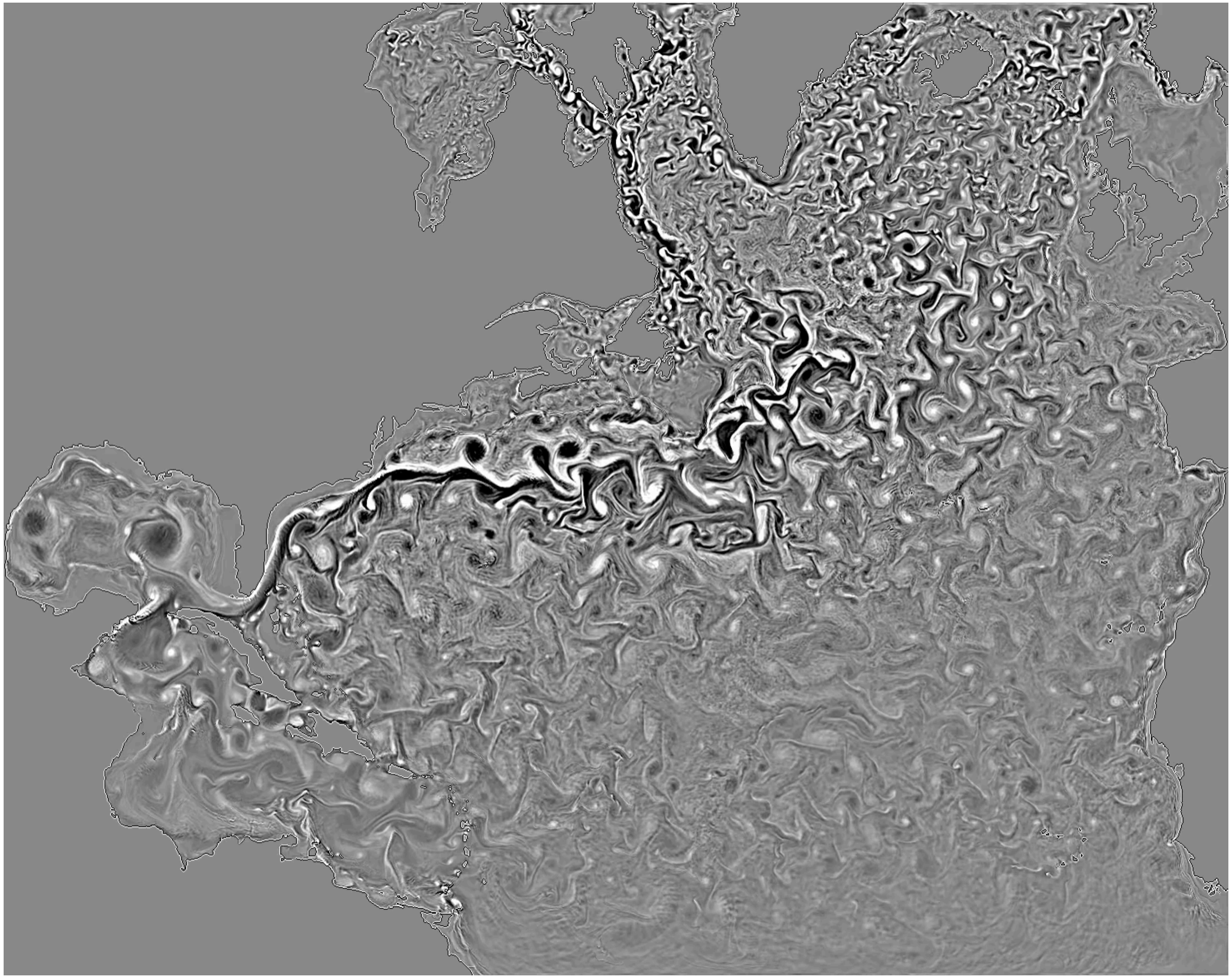
Generation of near-inertial waves by winds



5. Generation of internal waves

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- Whalen et al., Nature Reviews 2020, *Internal wave-driven mixing: governing processes and consequences for climate*
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- Rapaka et al., JFM 2013, *Tidal conversion and turbulence at a model ridge: direct and large eddy simulations*
- de Marez et al., SR 2020*, Interaction of the Gulf Stream with small scale topography: a focus on lee waves*
- Dossmann et al. JGR 2016*, Experiments with mixing in stratified flow over a topographic ridge*

5. Generation of internal waves

References used in this document:

- Todd, GRL 2017, *High-frequency internal waves and thick bottom mixed layers observed by gliders in the Gulf Stream*
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