Internal Waves in the Ocean

Master 2 — Physique de l'Océan et du Climat

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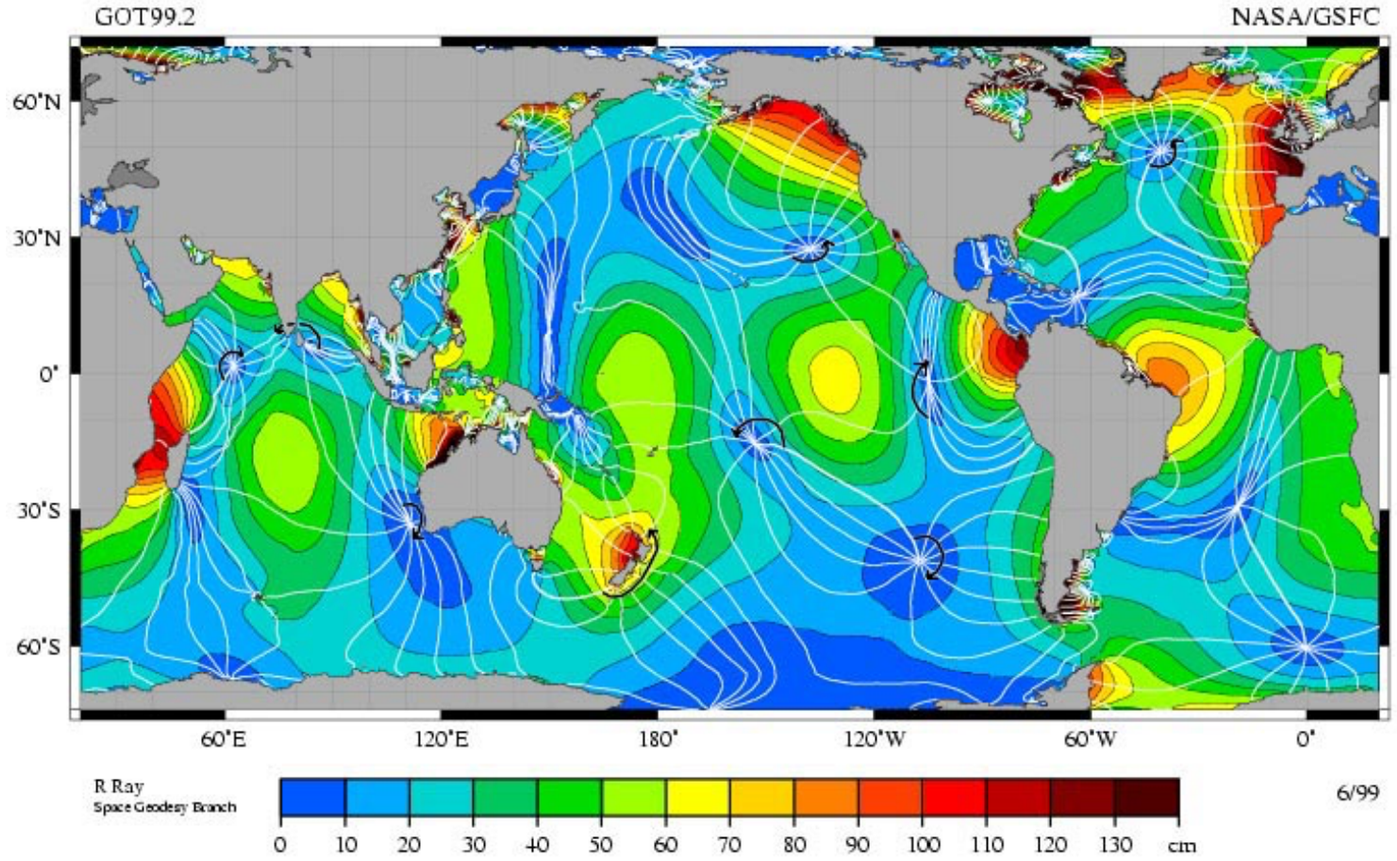
Outline

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

2. Internal waves: what ? why ?

External (barotropic) waves exist at the atmosphere-ocean interface,
they do not “feel” the stratification of the ocean interior.

wave breaking on the shore



amplitude of the semidiurnal M2 tide

2. Internal waves: what ? why ?

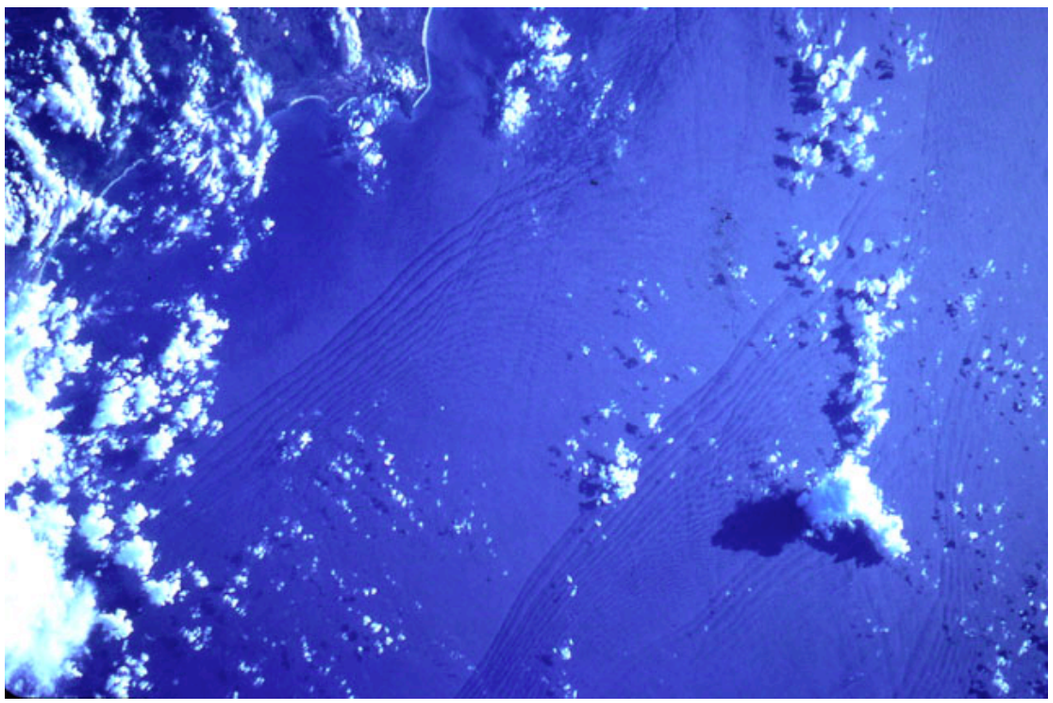
Internal (baroclinic) waves exist at the interface between density layers in the interior of the ocean. The ocean needs to be stratified.

2. Internal waves: what ? why ?

- **External waves** = surface gravity waves

- **Internal waves** = gravity waves that oscillate **in the interior of** a fluid
  - In a 2-layer stratification (density changes over a small vertical distance), they propagate horizontally
  - If the fluid is continuously stratified, they can also propagate vertically

Internal Waves in Rosario Strait North Puget Sound Washington



South China Sea Internal Waves as seen by NASA's Shuttle- June 1983

2. Internal waves: what ? why ?

Internal (baroclinic) waves exist at the interface between density layers in the interior of the ocean. The ocean needs to be stratified.

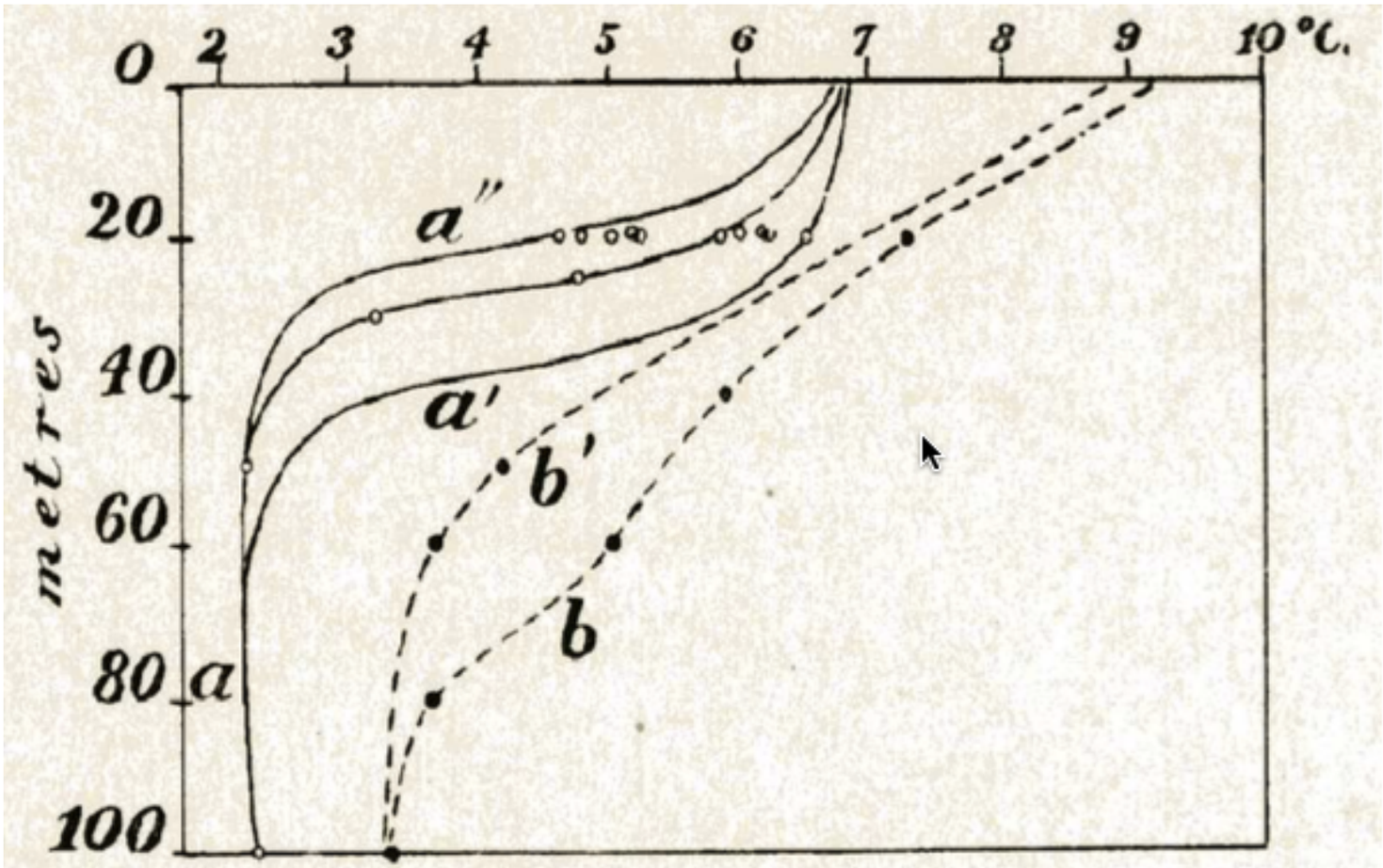


Fig. 14. Vertical Temperature-Curves at Stat. 15 (a) and Stat. 9 (b), 1900.

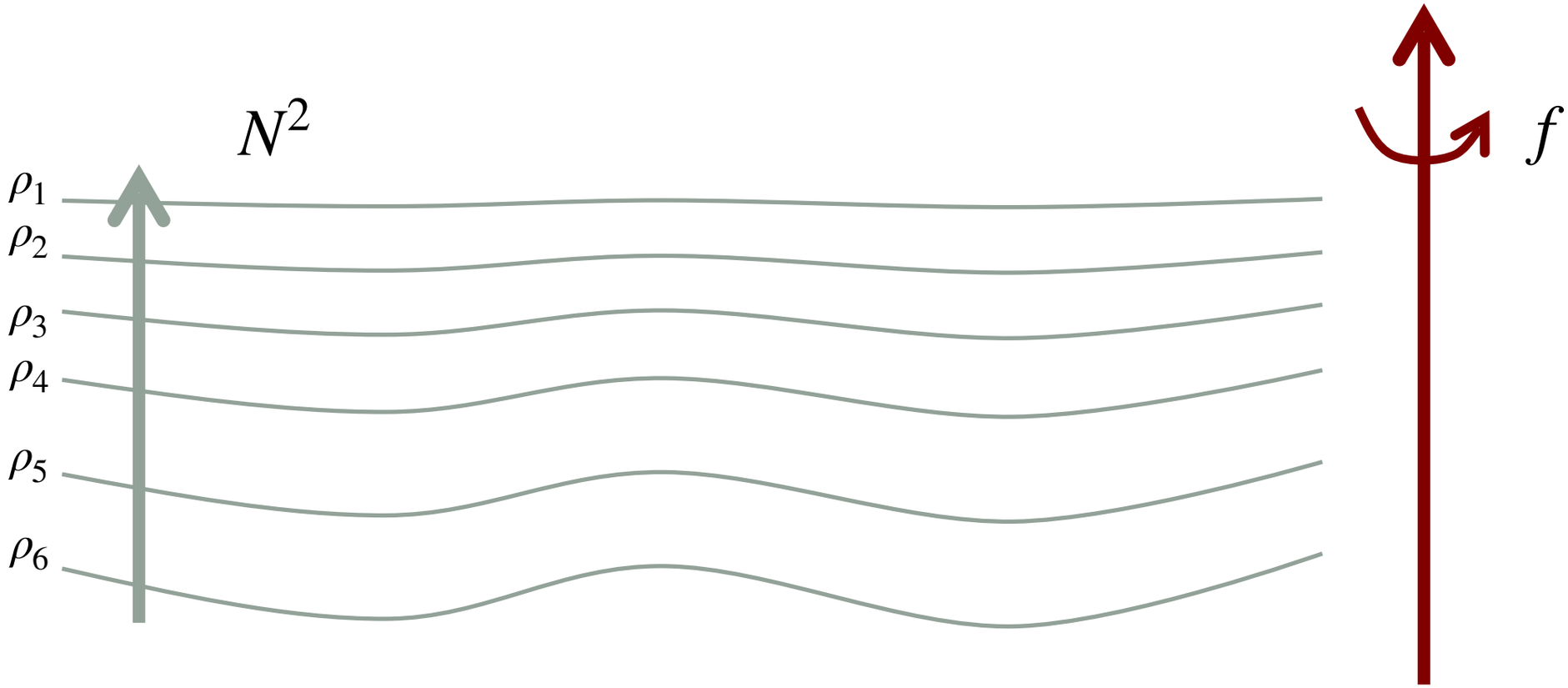
First observation by Helland-Hansen and Nansen (1909). Temperature profiles measured at 2.5 h interval reveal isotherms displacements.

2. Internal waves: what ? why ?

Internal (baroclinic) waves exist at the interface between density layers in the interior of the ocean. The ocean needs to be stratified.

Restoring forces:

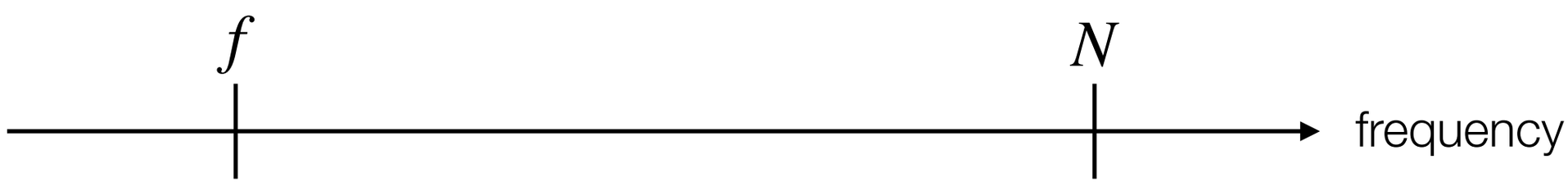
- buoyancy, due to the stable stratification, characterised by $N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}$
- Coriolis force due to Earth's rotation, characterised by $f = 2\Omega \sin(\text{latitude})$



2. Internal waves: what ? why ?

Internal (baroclinic) waves exist at the interface between density layers in the interior of the ocean. The ocean needs to be stratified.

Internal waves freely propagate with a frequency ω such that $f < \omega < N$

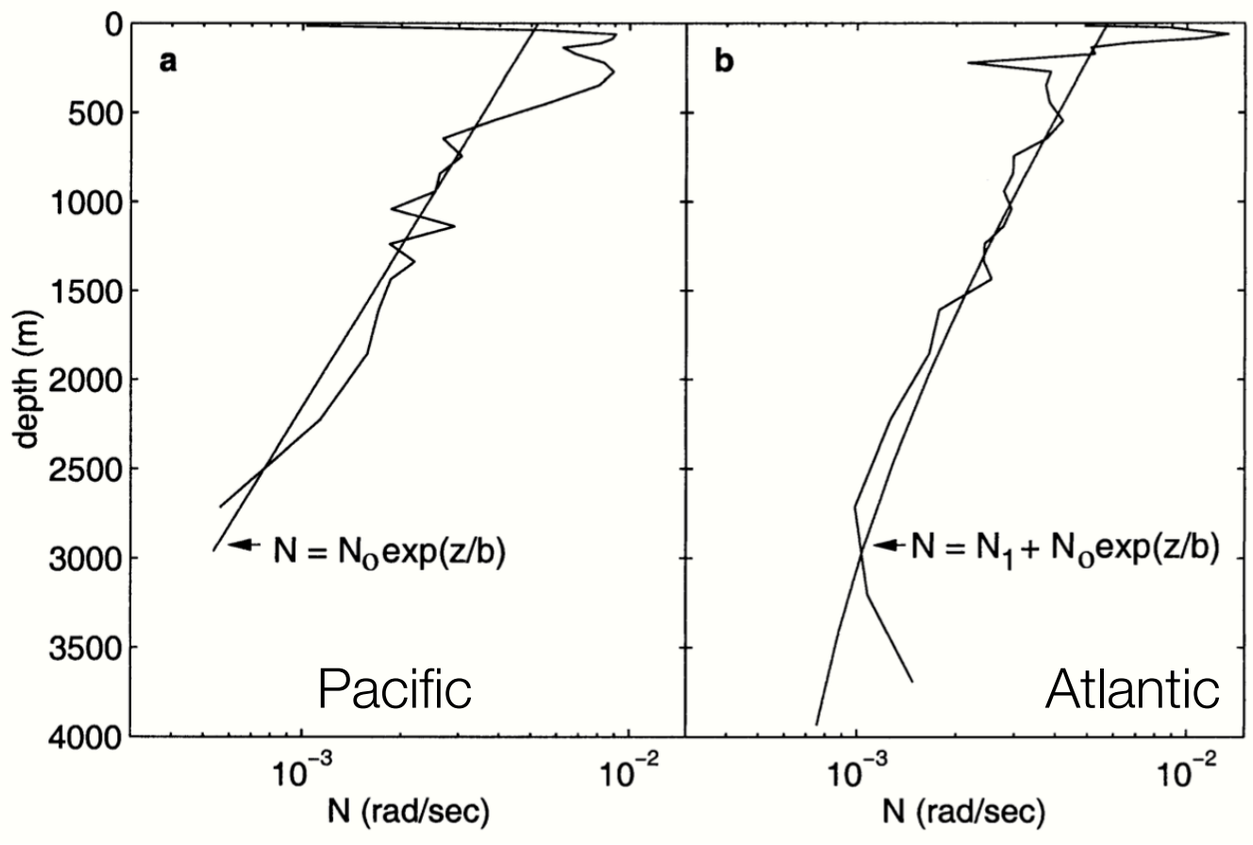


$2\pi/f = 12.1$ h at 80°N

$2\pi/f = 16.9$ h at 45°N

$2\pi/f = 68.9$ h at 10°N

$15\ \text{min} < 2\pi/N < 3$ h



St Laurent and Garrett 2002

2. Internal waves: what ? why ?

A few definitions:

- **gravity wave**: a wave that feels the stratification.

- **inertia-gravity wave**: a wave with a large-enough wavelength and long-enough period to feel the Earth's rotation.

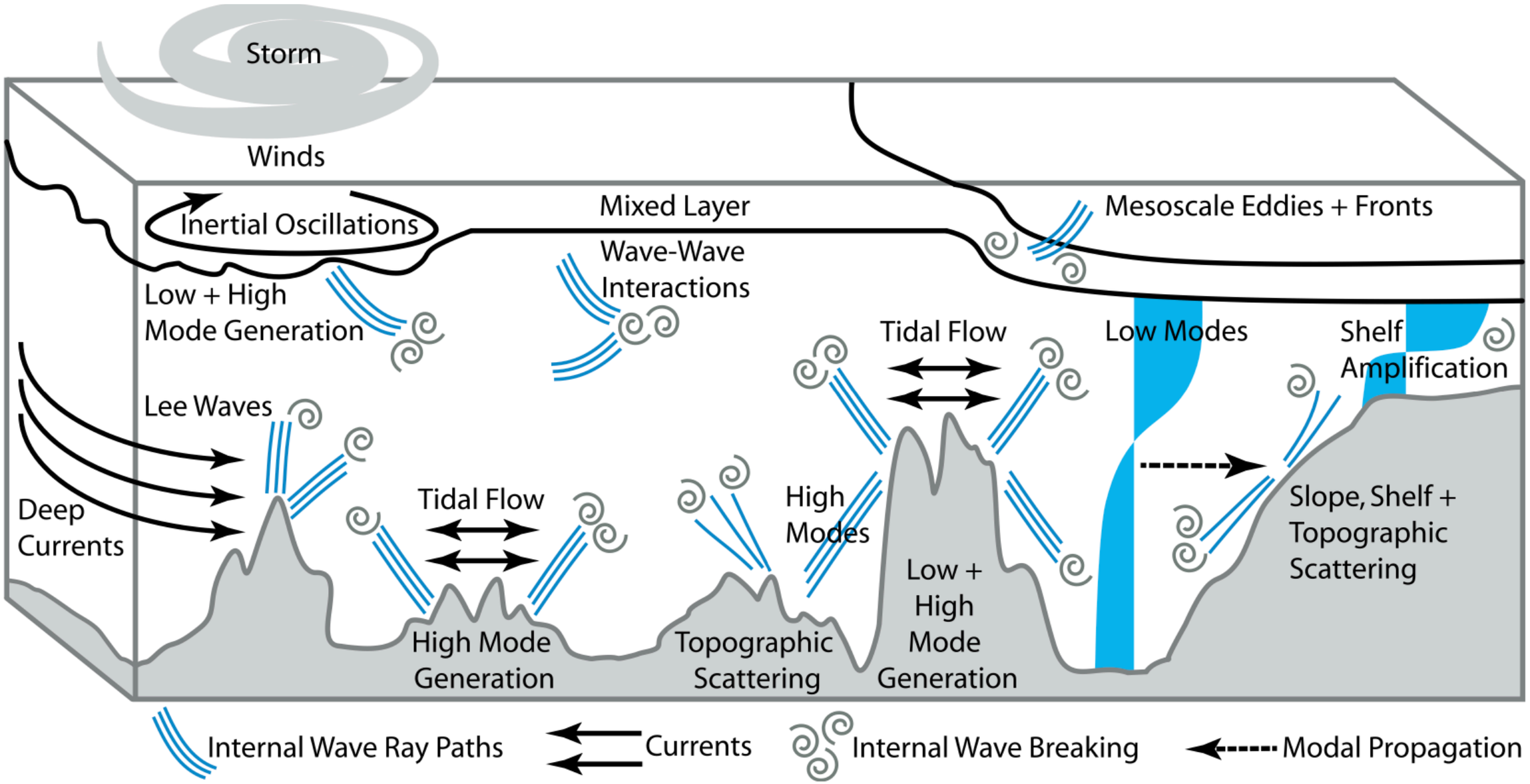
- **near-inertial wave**: an internal wave with a frequency close to the Coriolis frequency. Most near-inertial waves are generated by the wind.

- **internal tide** or **baroclinic tide**: an internal wave with a frequency equal to a tidal frequency (semidiurnal or diurnal). Internal tides are generated by the interaction of the barotropic tide with the seafloor topography.

- **lee wave**: an internal wave generated by the interaction of a low-frequency (non-oscillating) flow with the seafloor topography.

- **internal solitary wave**: a type of non-linear internal wave characterised by a short period and a large amplitude.

2. Internal waves: what ? why ?



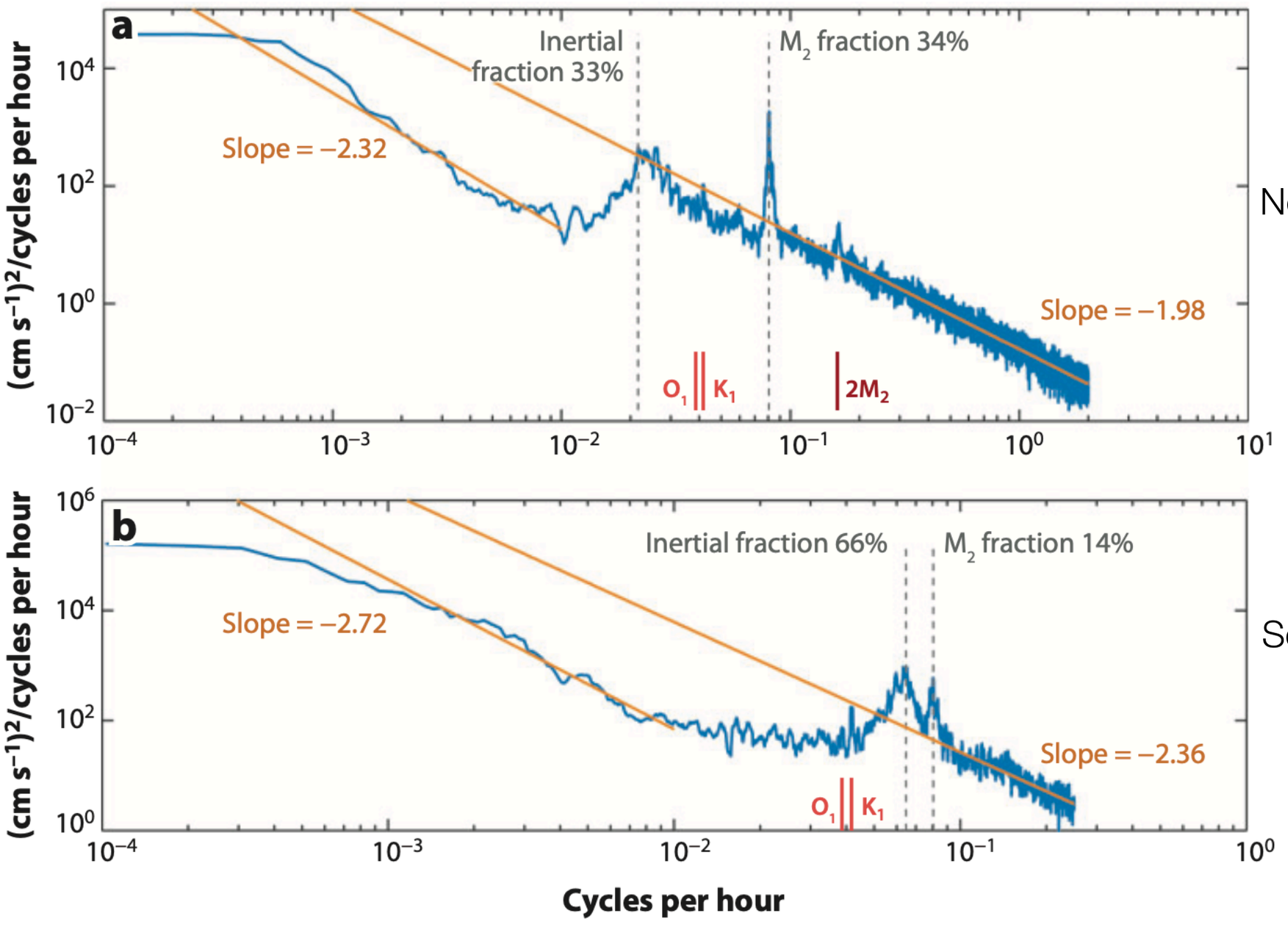
Two major mechanisms generate internal gravity waves :

- Generation of near-inertial waves by the wind
- Interactions of currents (tides + low-frequency) with the seafloor topography

NB: The generation of internal waves will be developed in part 5 of this course.

MacKinnon et al. 2017

2. Internal waves: what ? why ?

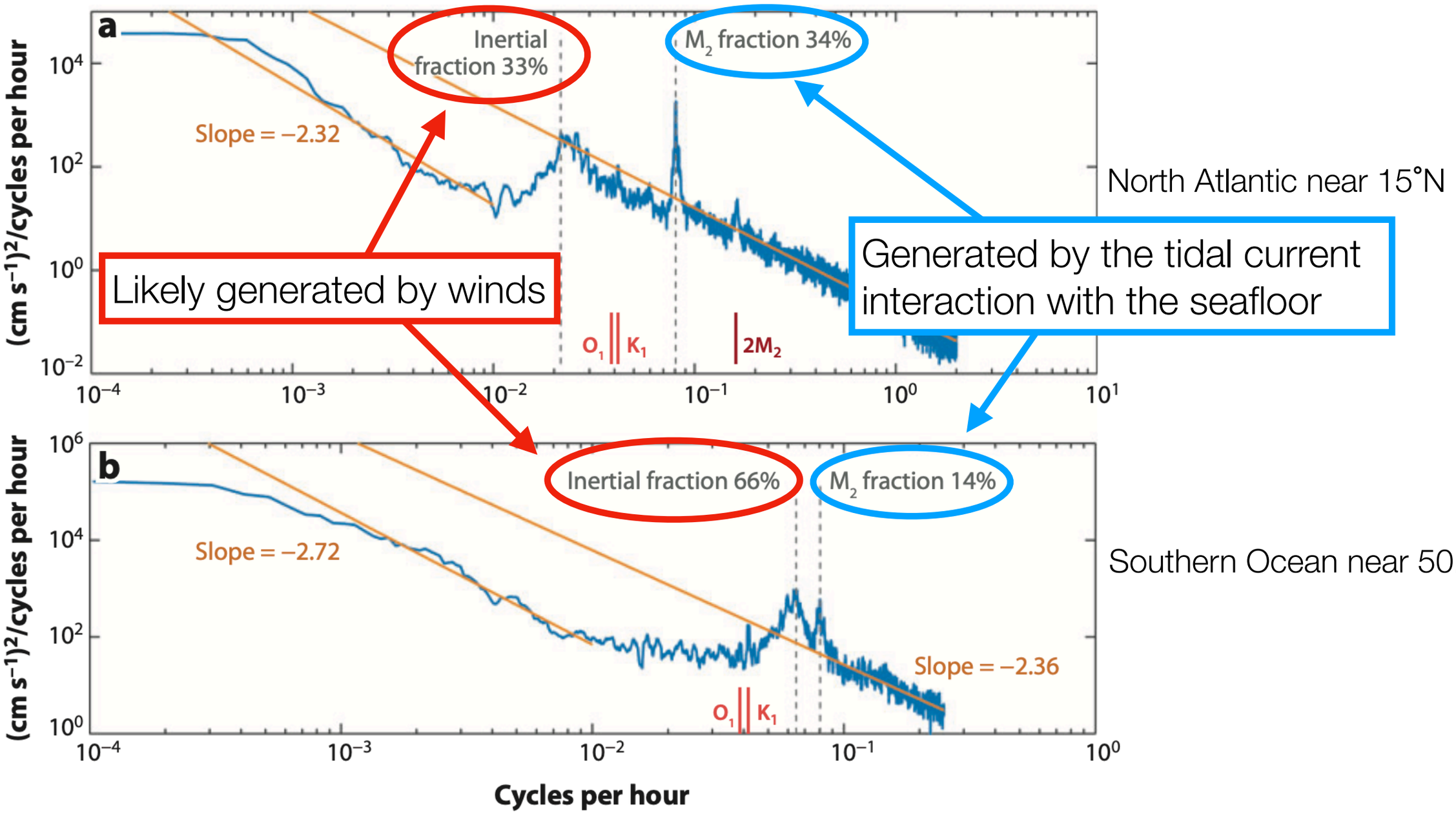


North Atlantic near 15°N

Southern Ocean near 50.7°S

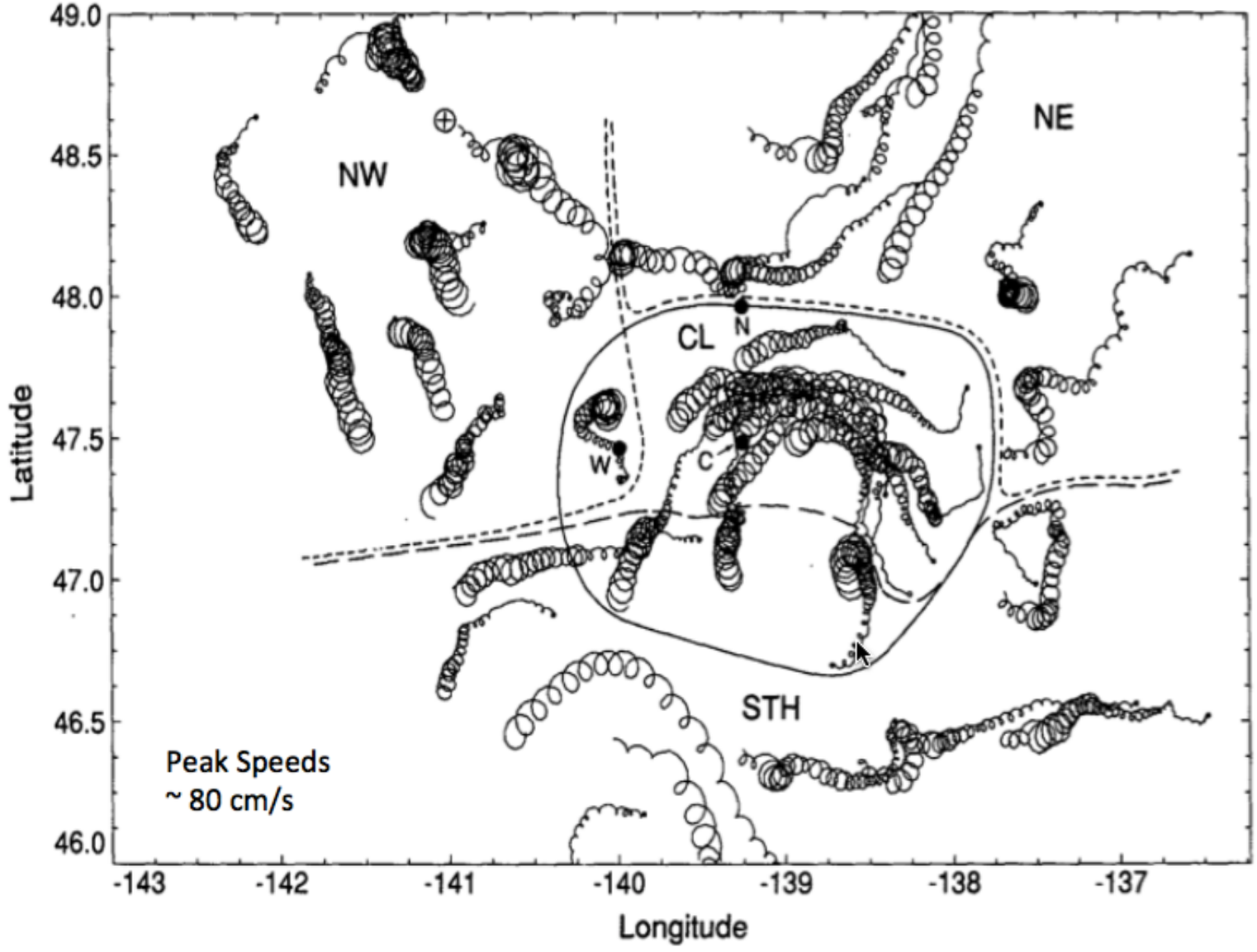
Ferrari and Wunsch 2009

2. Internal waves: what ? why ?



Ferrari and Wunsch 2009

- Winds generate mostly near-inertial waves (frequency close to f)

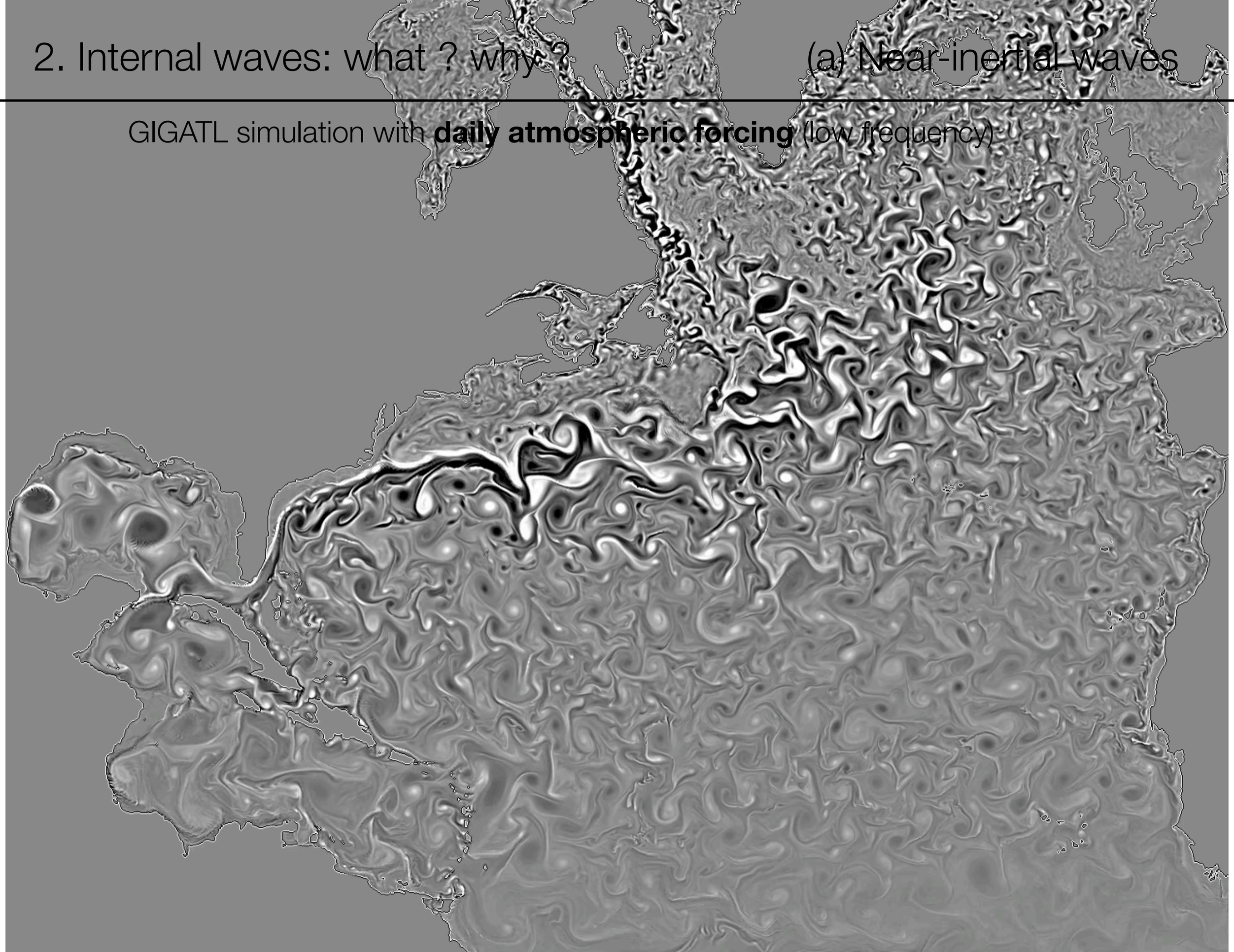


Twenty-five days of surface drifter trajectories after a storm in the eastern north Pacific. The drifters trajectories represent a combination of decaying inertial motions (circular oscillations) and weak geostrophic flow (the time-averaged drift). **[D'Asaro et al, 1995]**

2. Internal waves: what ? why ?

(a) Near-inertial waves

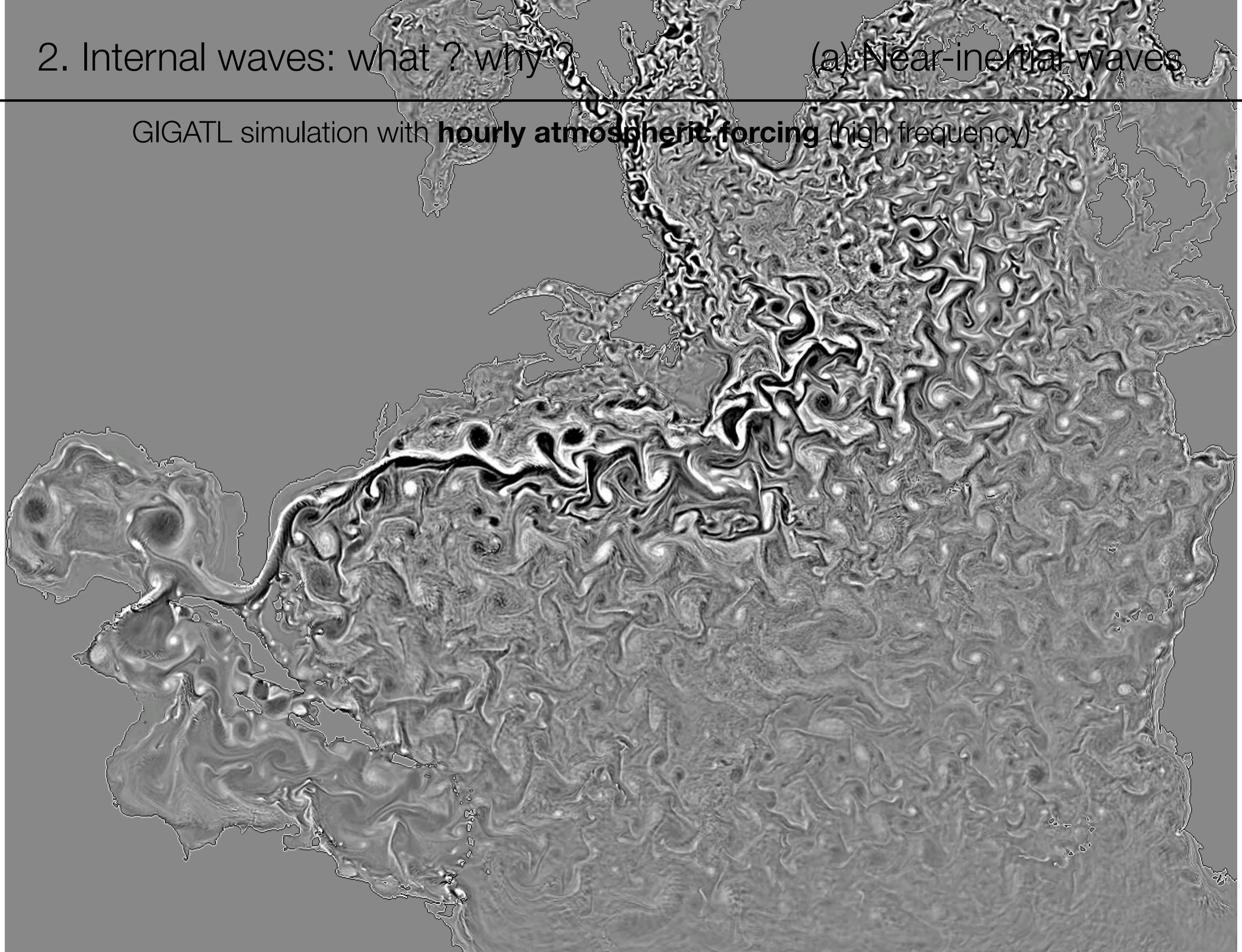
GIGATL simulation with **daily atmospheric forcing** (low frequency)



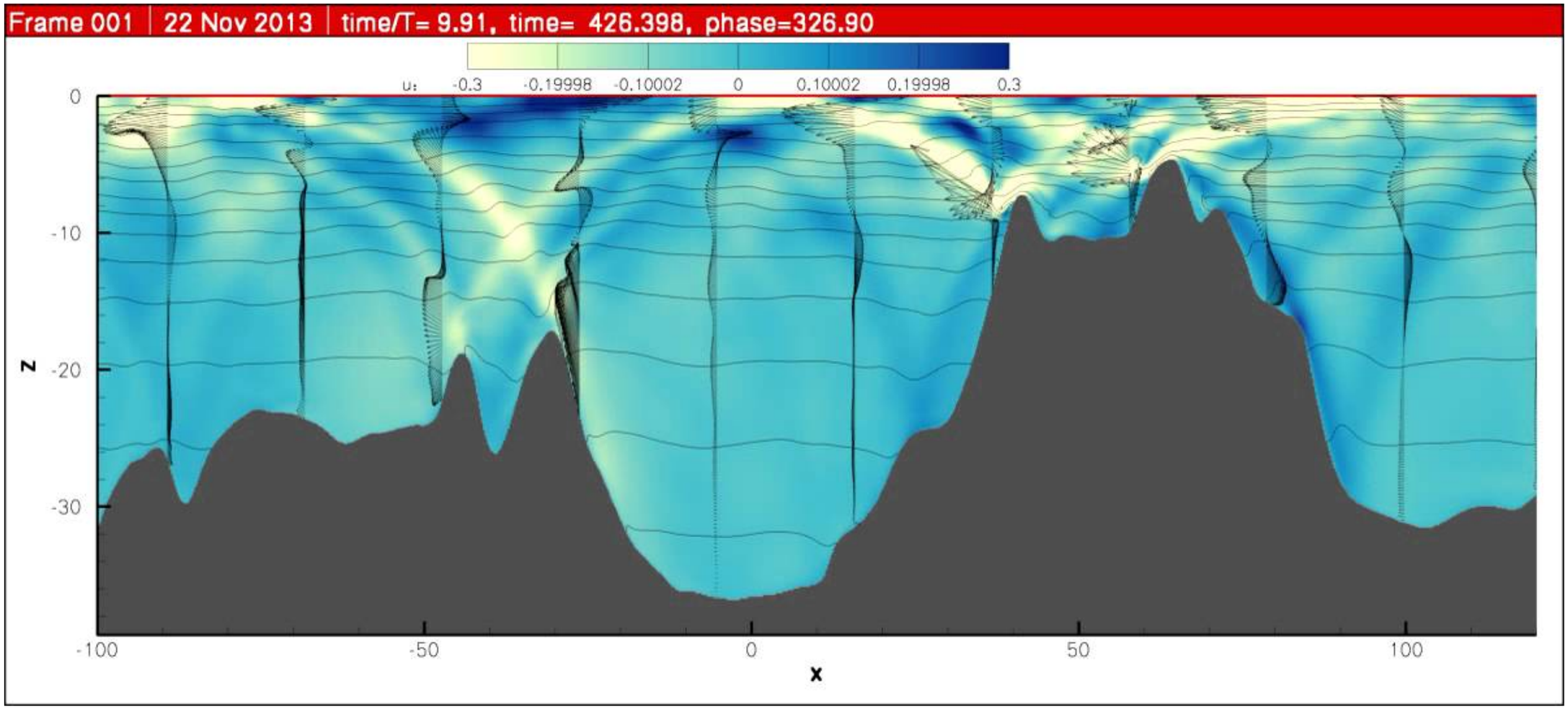
2. Internal waves: what ? why ?

(a) Near-inertial waves

GIGATL simulation with **hourly atmospheric forcing** (high frequency)

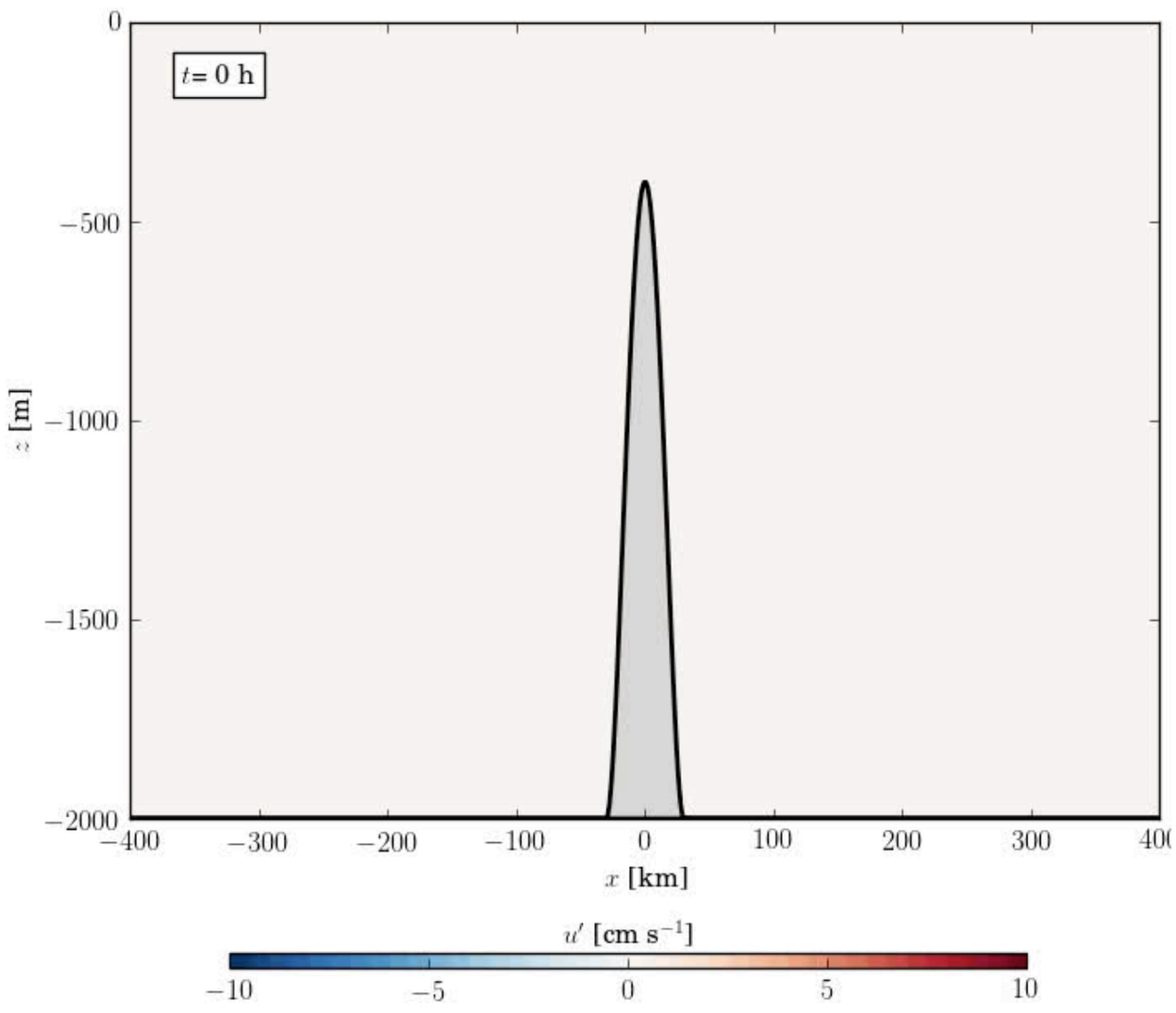


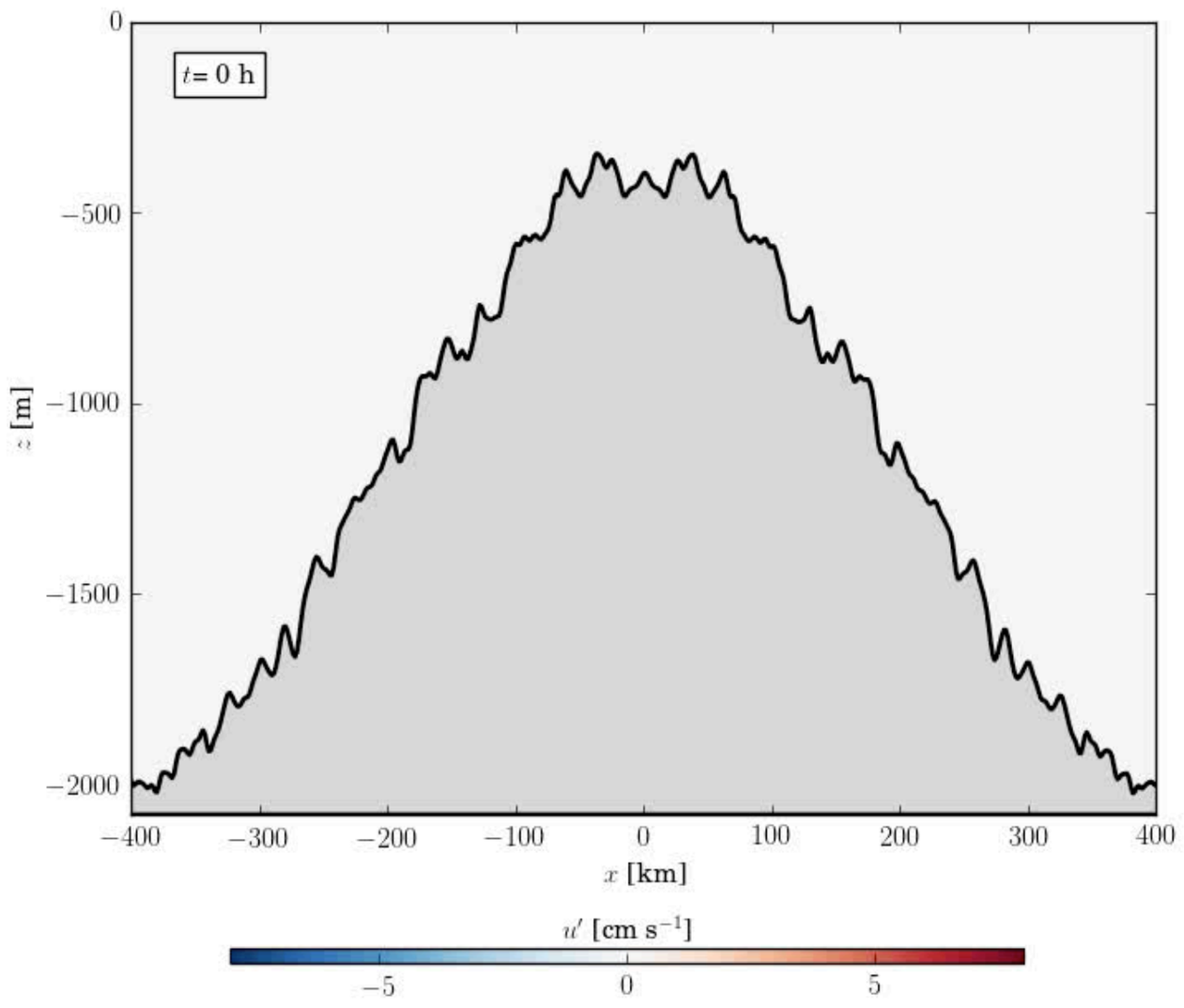
- Barotropic tides generate internal tides at the frequency of tides



2. Internal waves: what ? why ?

(b) internal tides

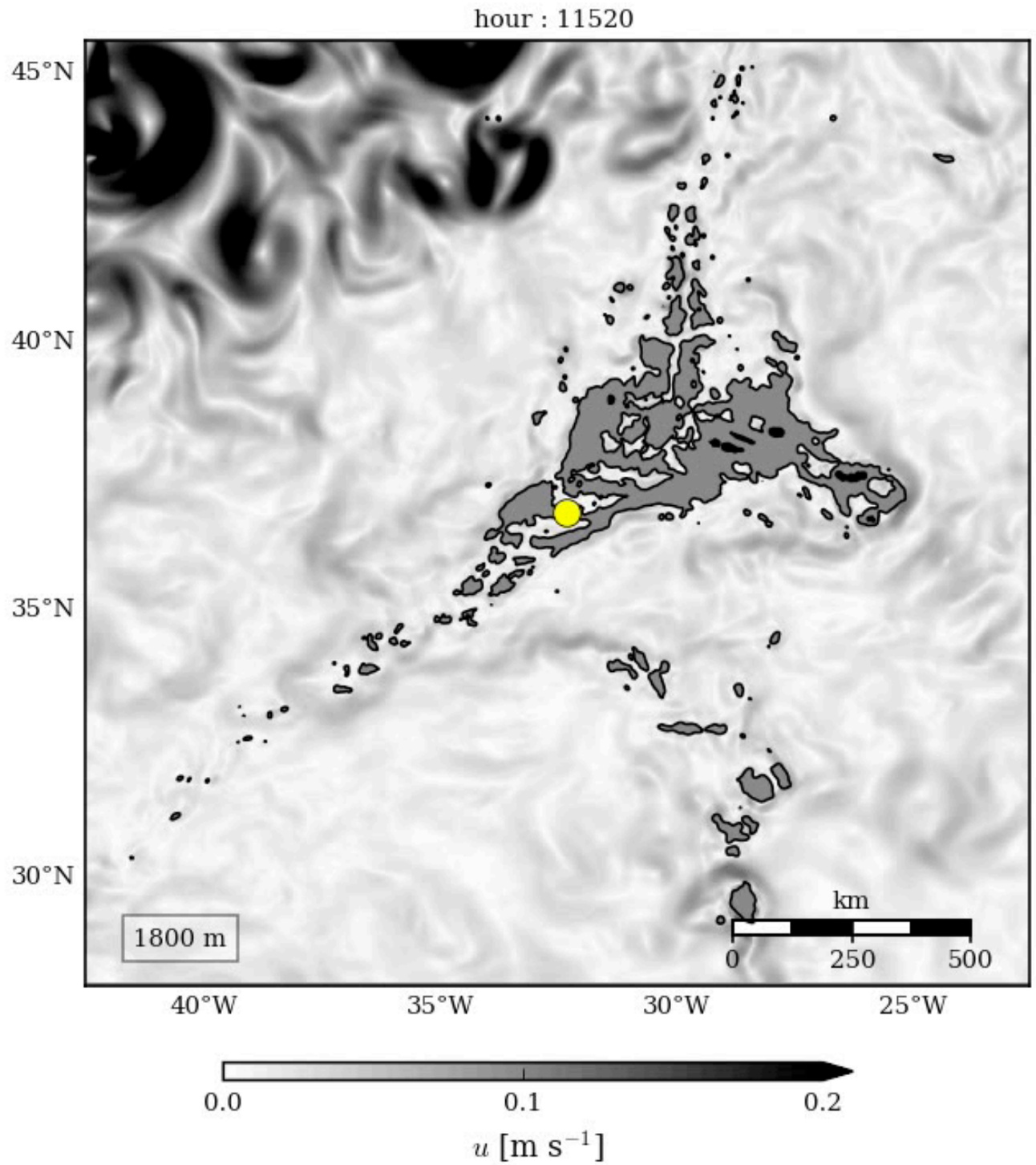




2. Internal waves: what ? why ? (b) internal tides

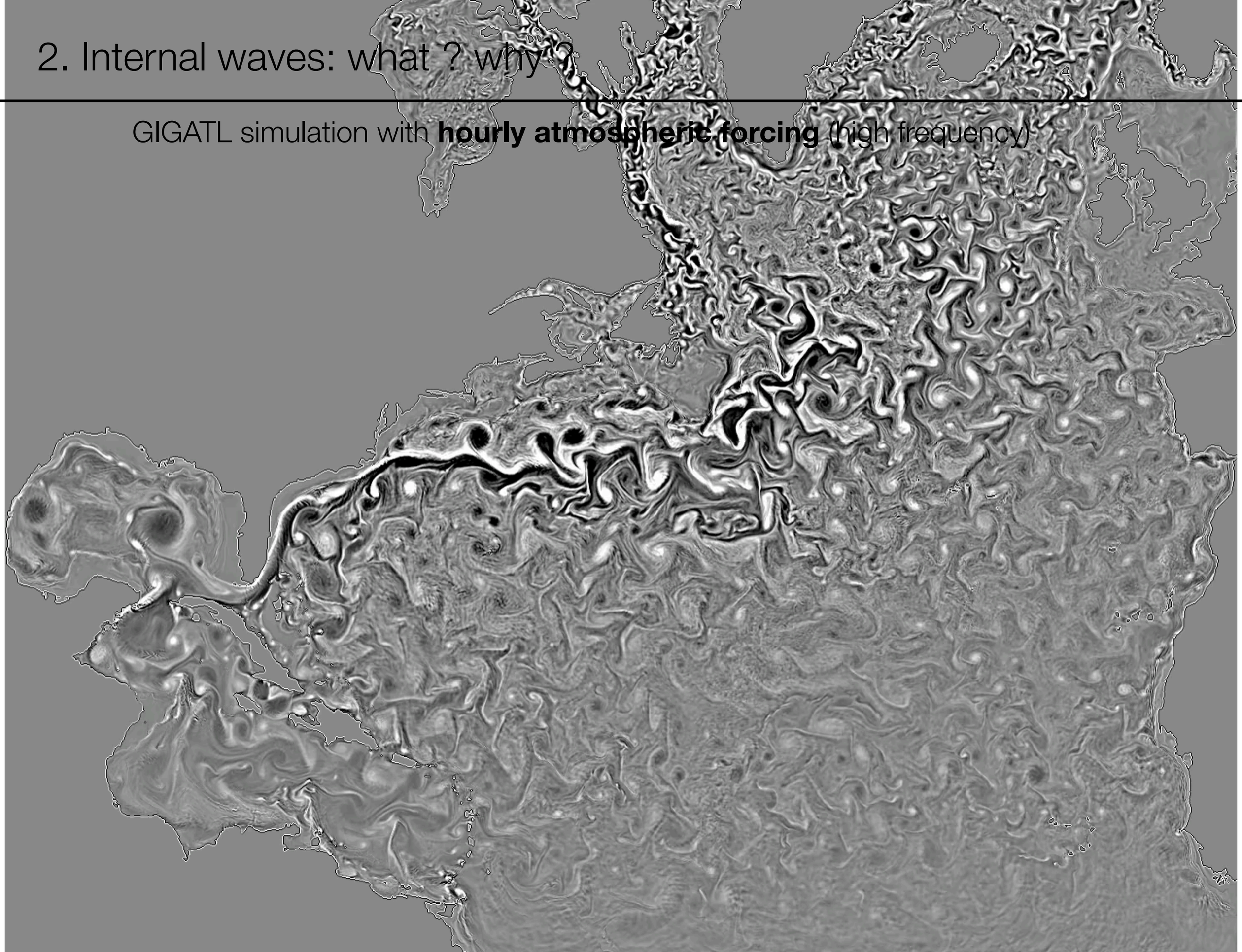
- Velocity amplitude at 1800m
- simulation ROMS (dx = 2km)

WITH TIDES:



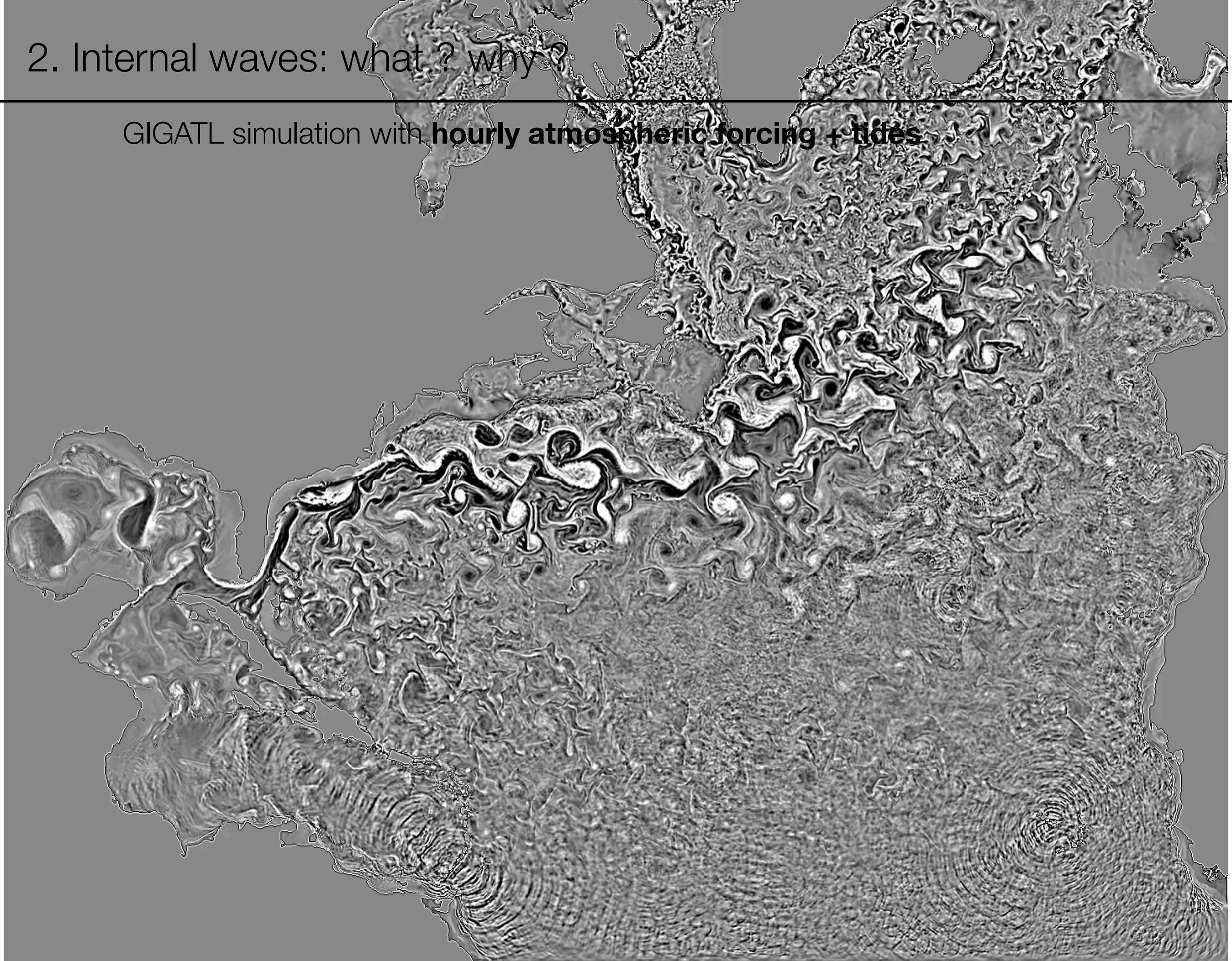
2. Internal waves: what ? why ?

GIGATL simulation with **hourly atmospheric forcing** (high frequency)

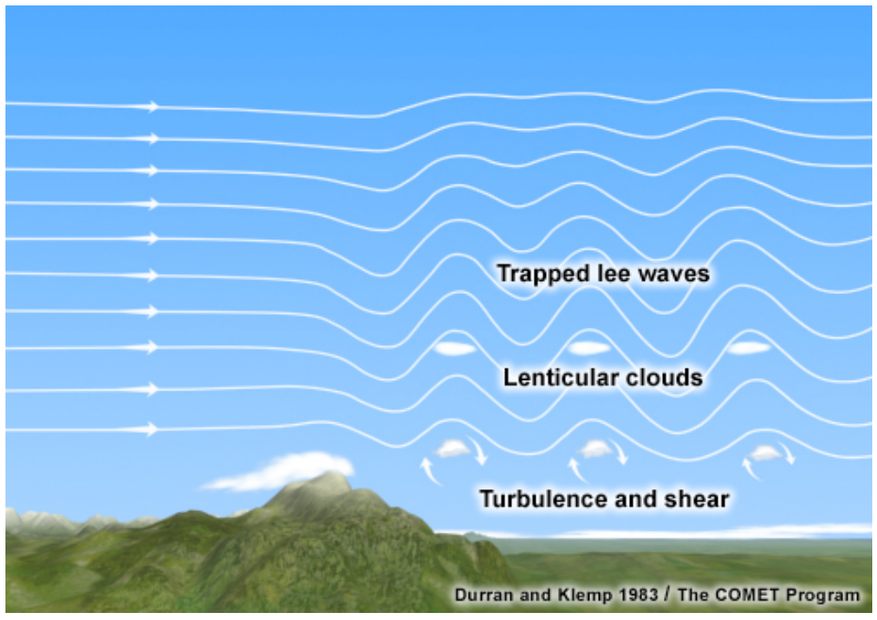


2. Internal waves: what ? why ?

GIGATL simulation with **hourly atmospheric forcing + tides**



- **Lee waves** are similar to mountain waves in the 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

MODIS sun-glitter of the Gulf Stream

(c) lee waves

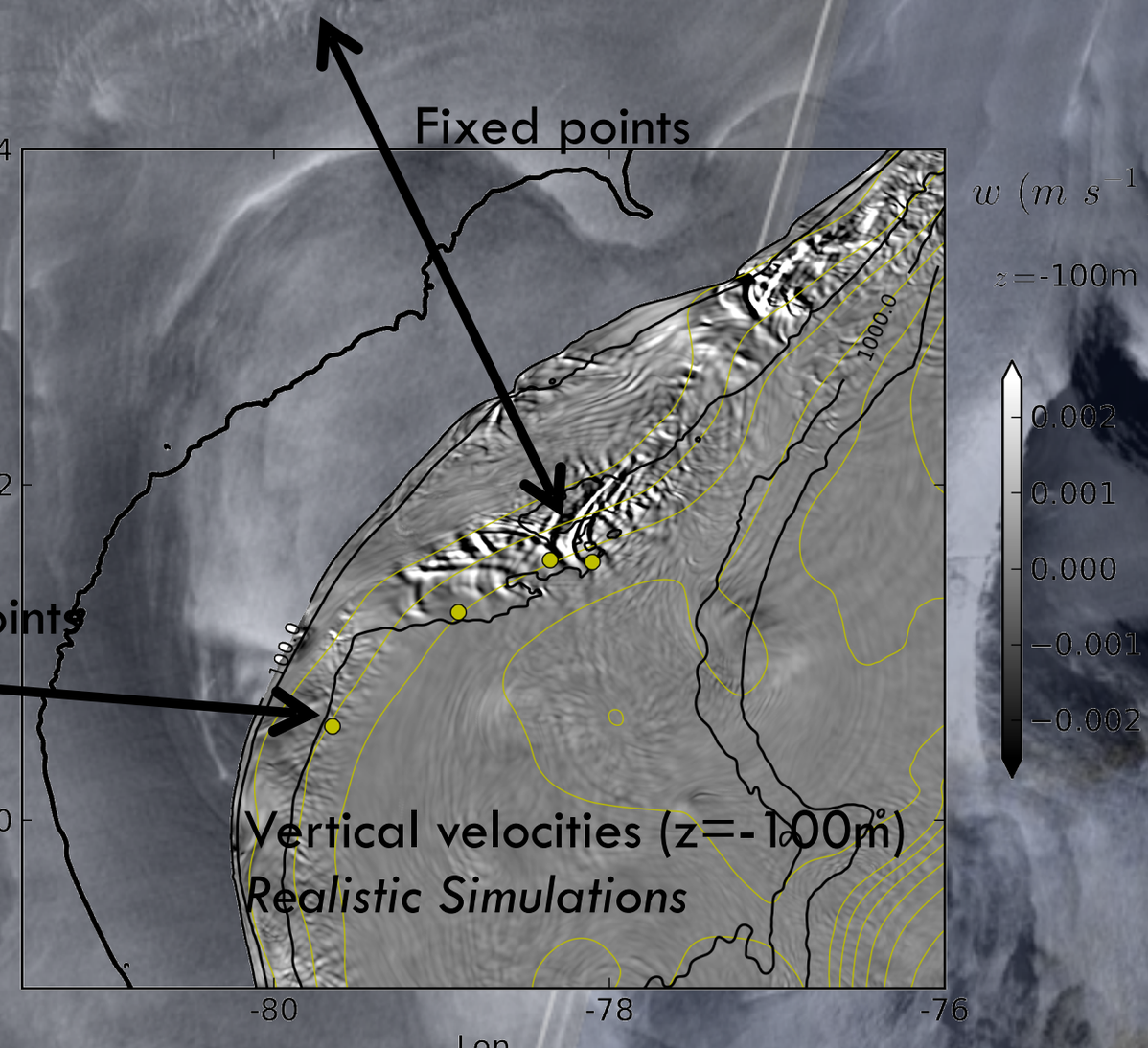
Fixed points

Fixed points

Gulf Stream

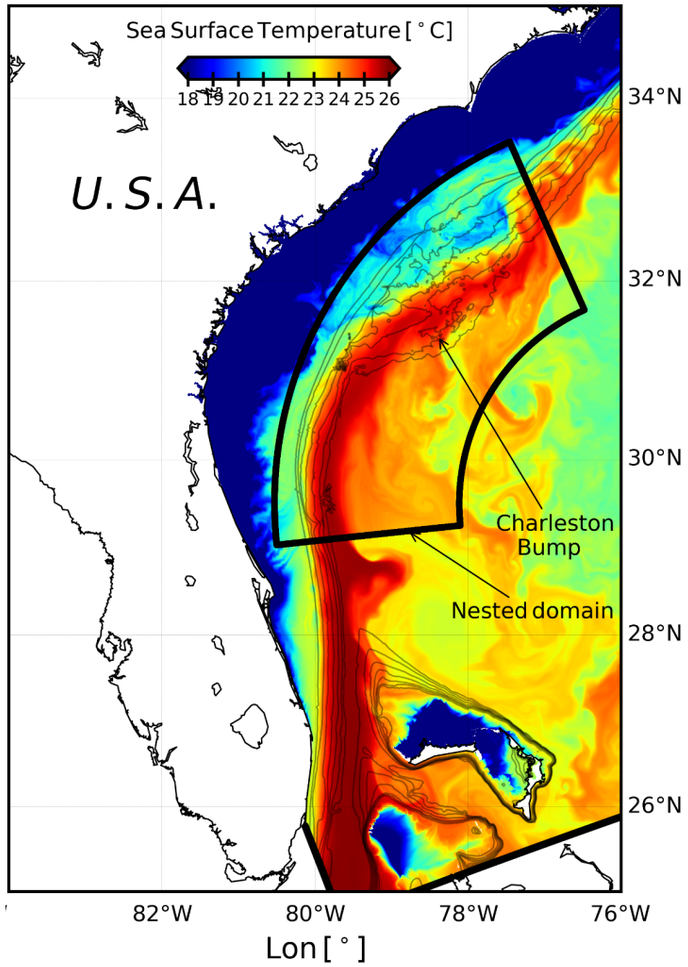
Vertical velocities (z=-100m)
Realistic Simulations

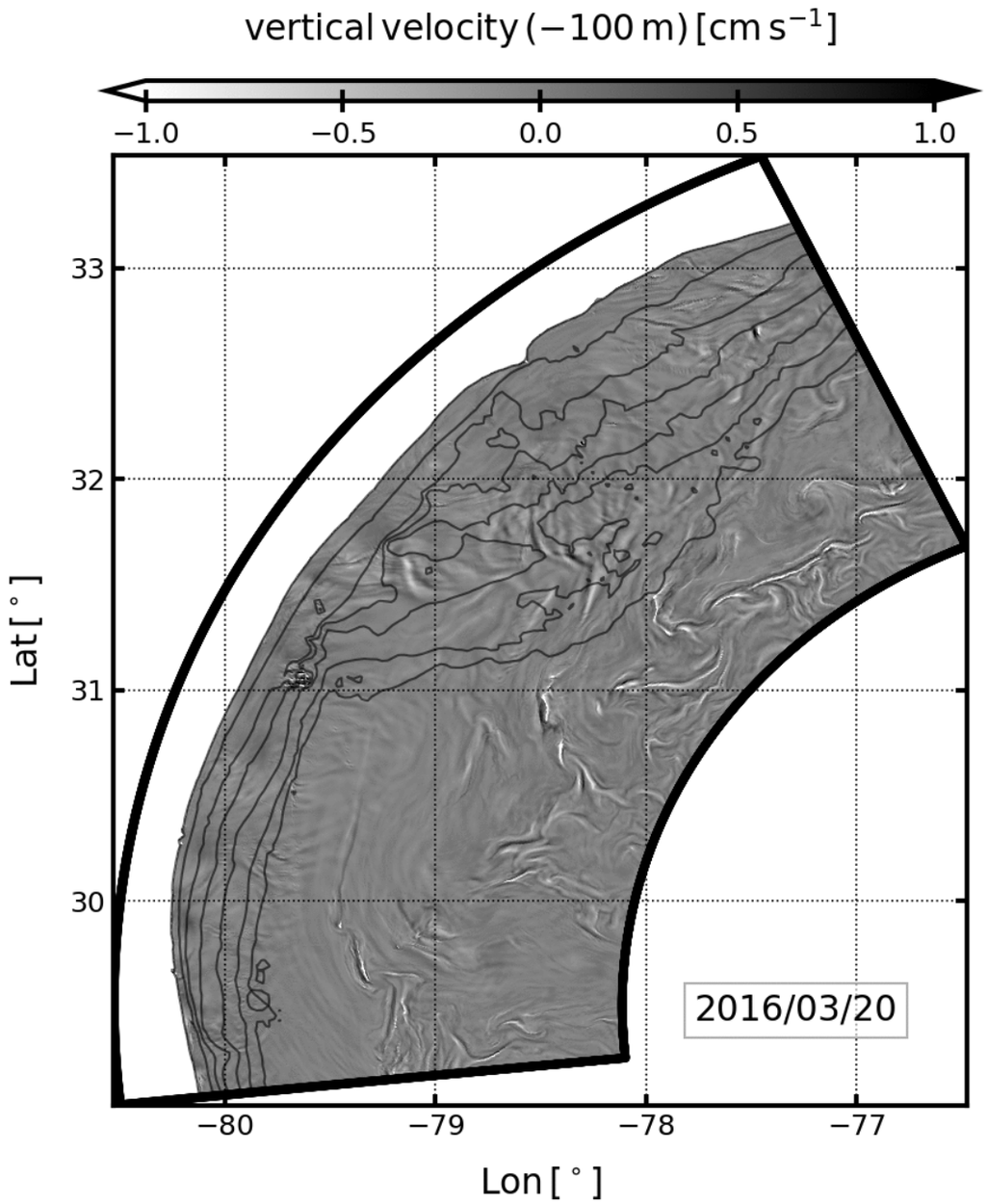
MODIS sun-glitter of the Gulf Stream



2. Internal waves: what ? why ?

(c) lee waves

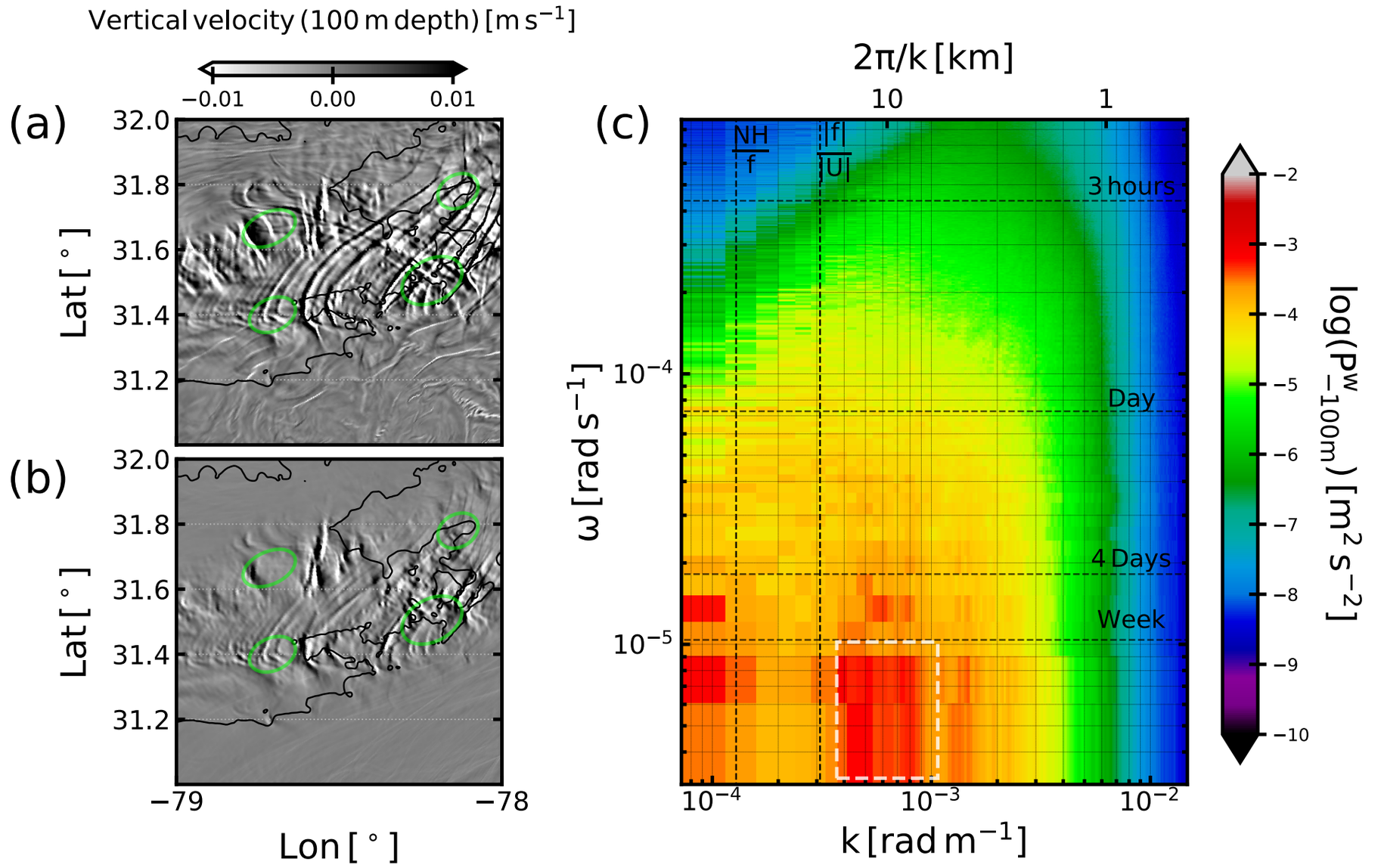




Simulation of the Gulf Stream

2. Internal waves: what ? why ? (c) lee waves

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

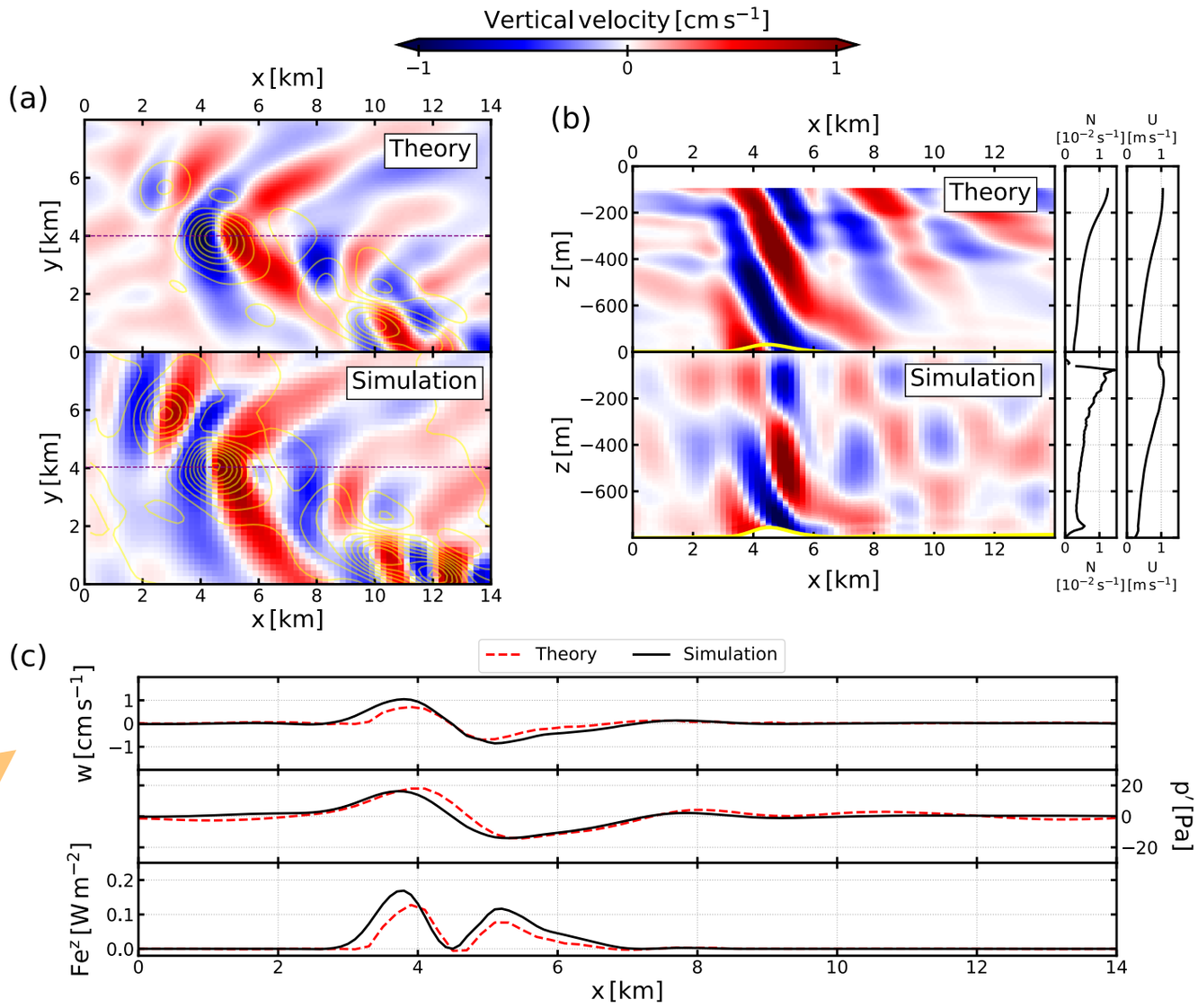


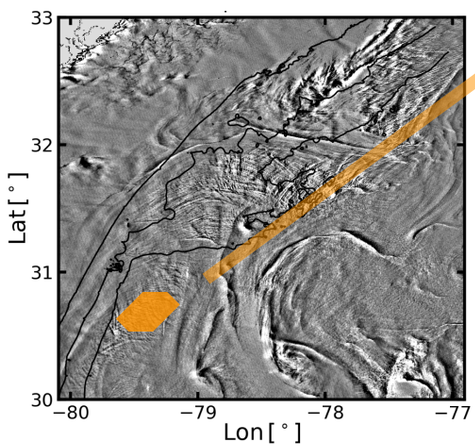
2. Internal waves: what ? why ?

(c) lee waves

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

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





nature geoscience

ARTICLES

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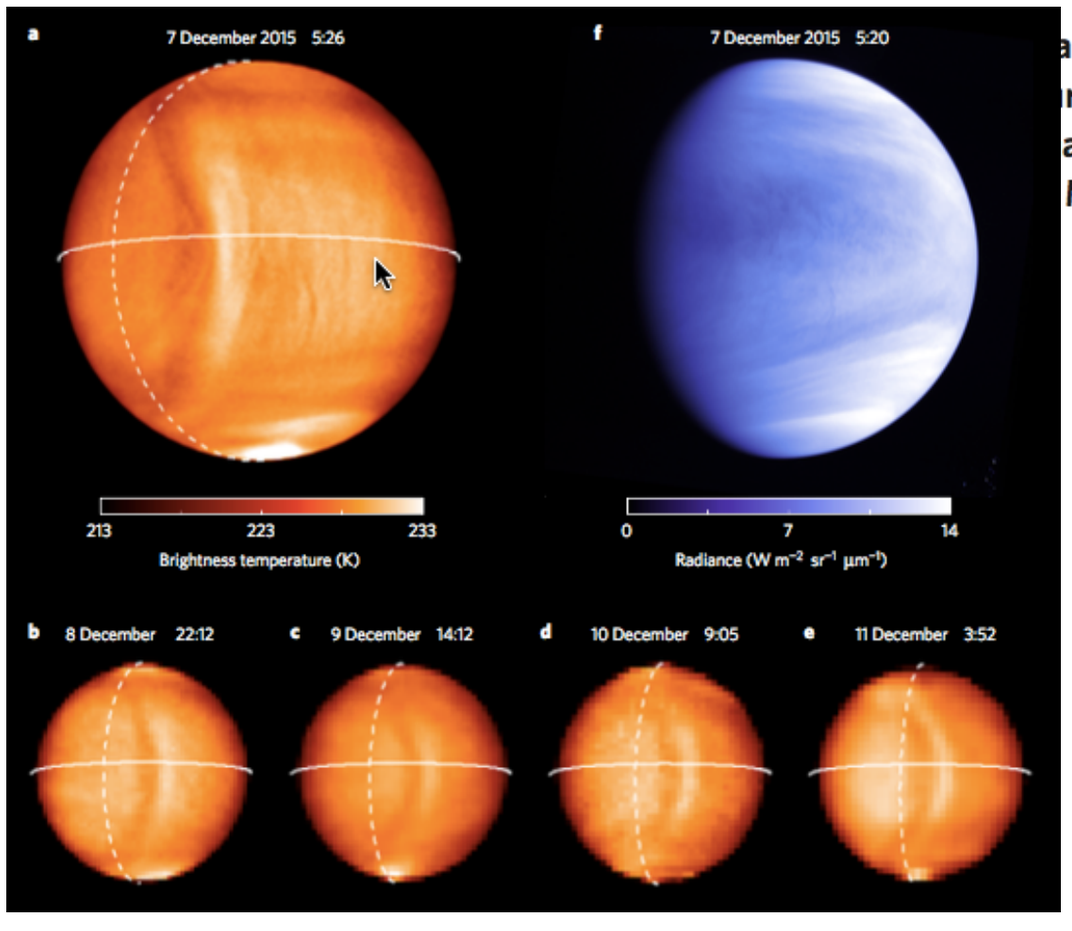
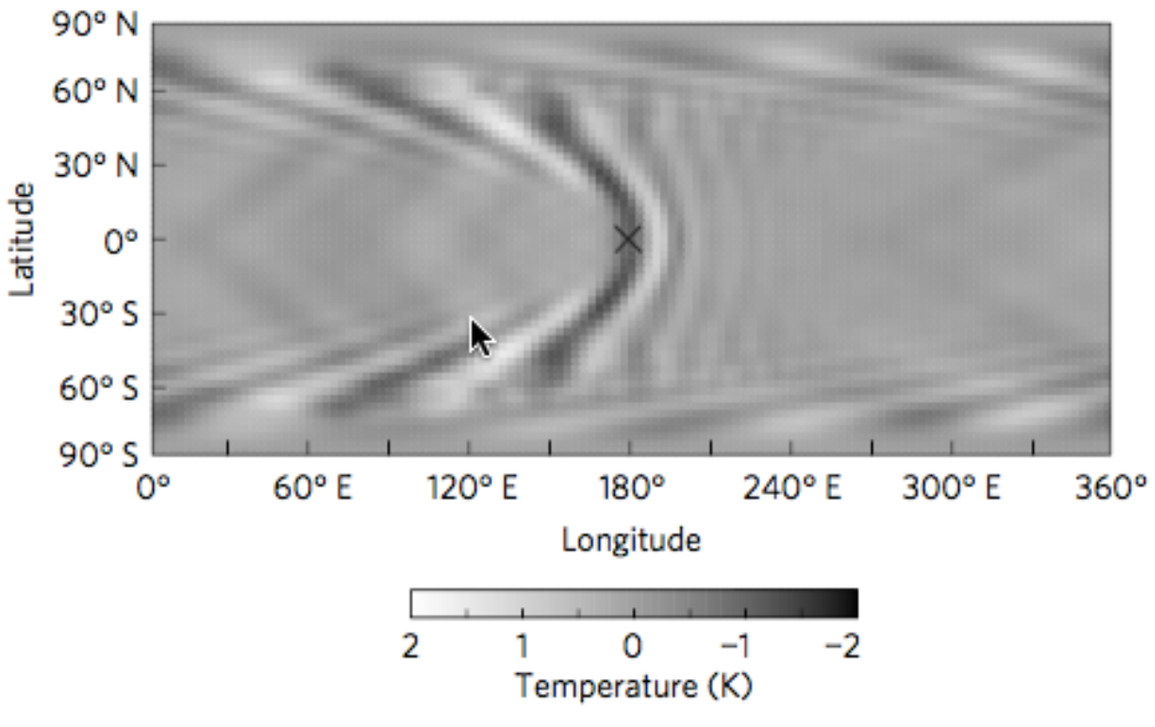
Large stationary gravity wave in the atmosphere of Venus

ara[1], Masahiko Futaguchi[2], George L. Hashimoto[3], Takeshi Horinouchi[4], ra[5], Naomoto Iwagaimi[6], Toru Kouyama[7], Shin-ya Murakami[8], Masato Nakamura[8], ara[9], Mitsuteru Sato[4], Takao M. Sato[8], Makoto Suzuki[8], Makoto Taguchi[1]*, Munetaka Ueno[11], Shigeto Watanabe[12], Manabu Yamada[13] and Atsushi Yamazaki[8]

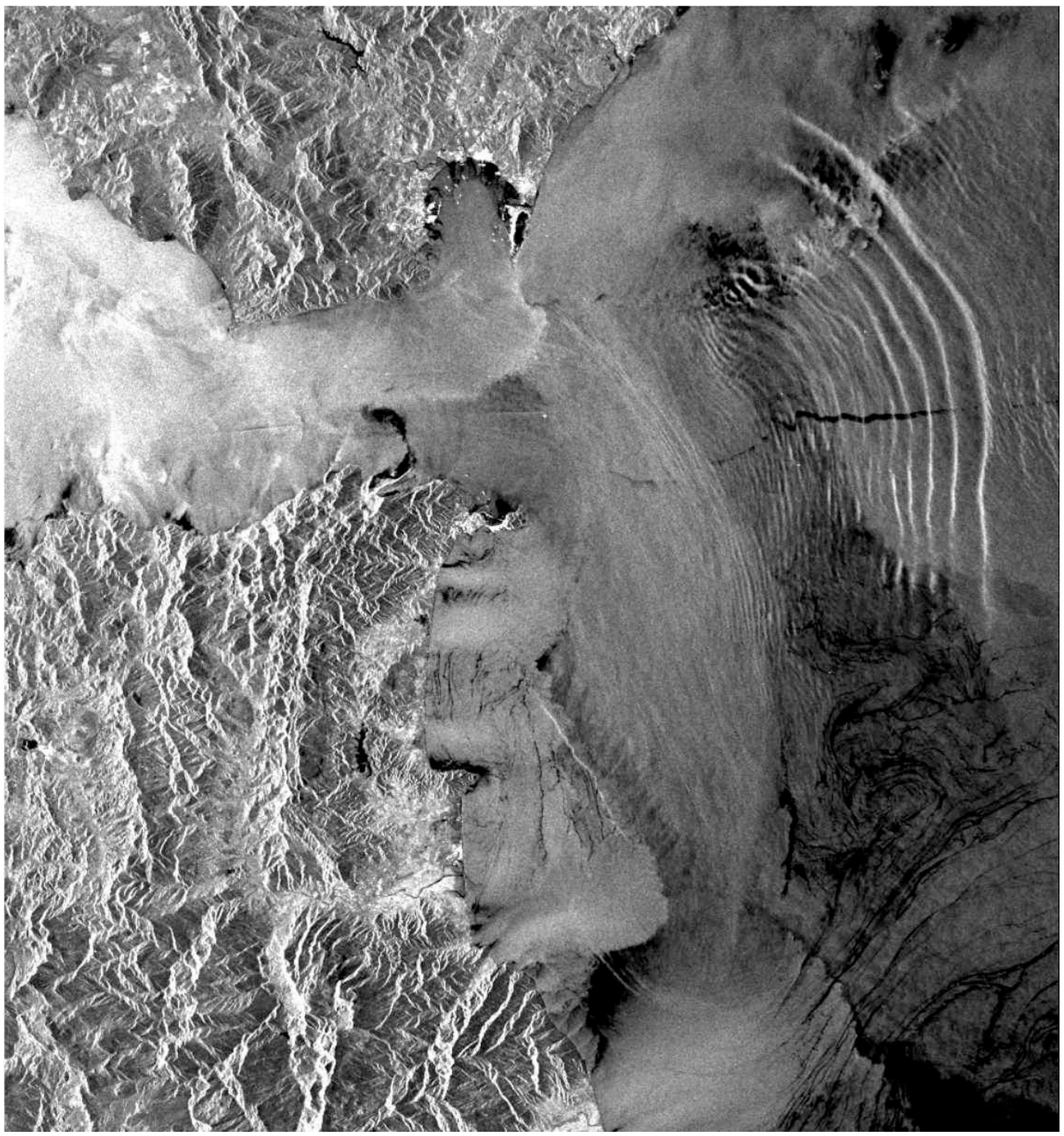




Example: Strait of Messina

- Solitary waves train in the Strait of Messina

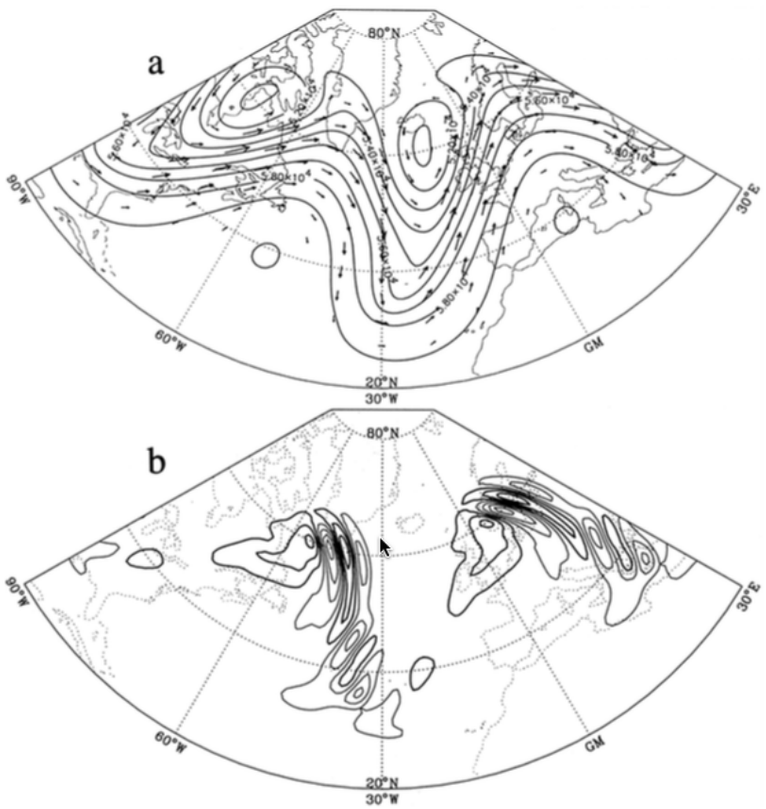
Picture from 11/08/2003 - Terra (NASA) ASTER radiometer - Sunglitter



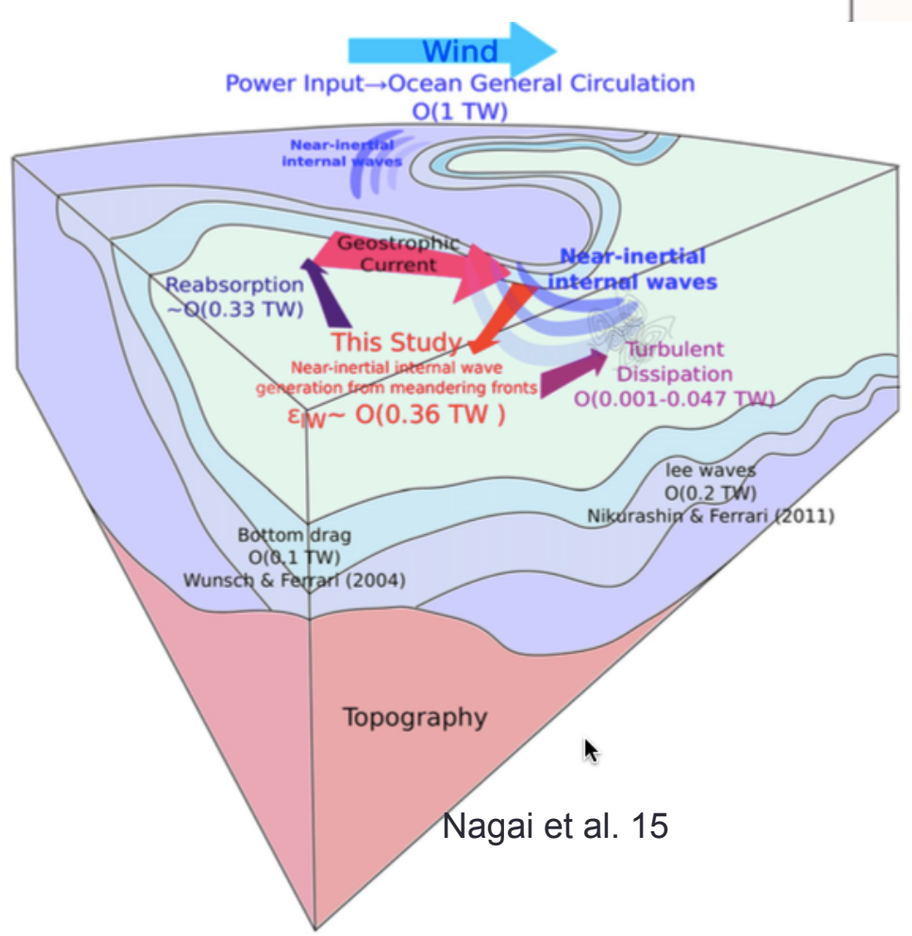
- Solitary waves train in the Strait of Gibraltar

Picture from 01/01/1993 – SAR image

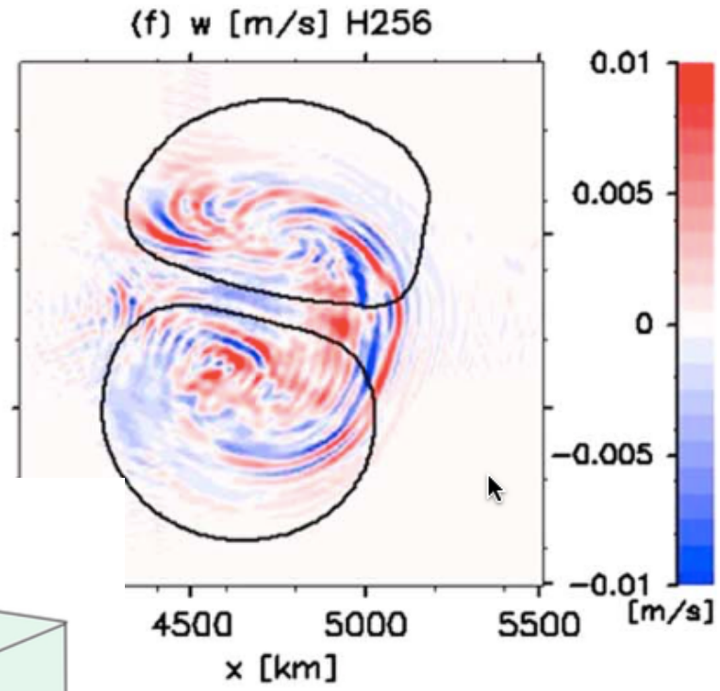
- **Spontaneous wave emission** from jets and fronts



Fritts & Alexander, 04

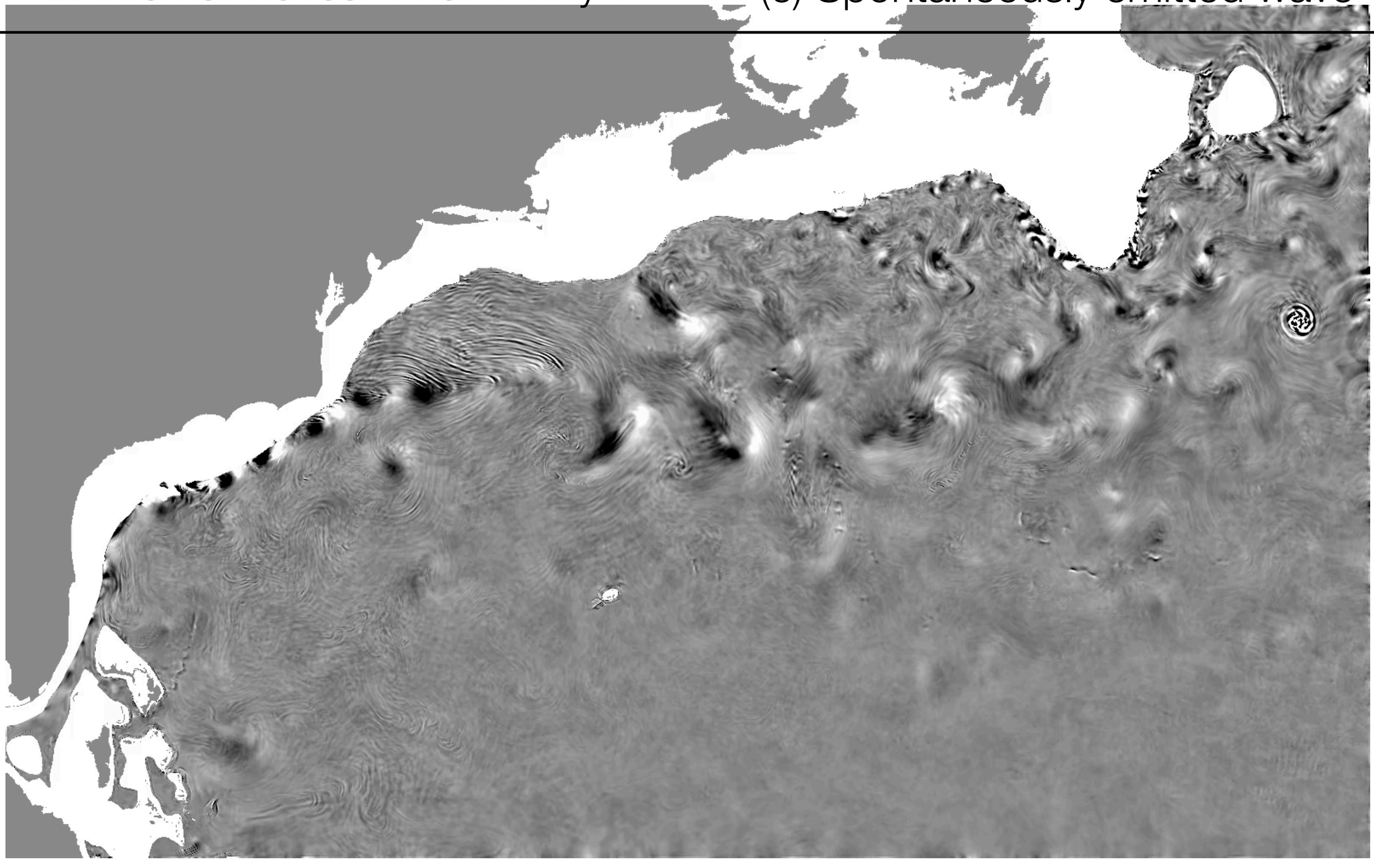


Nagai et al. 15



Sugimoto & Plougonven 16

(e) Spontaneously emitted wave



Vertical velocities at z = -500 m in the Gulf Stream

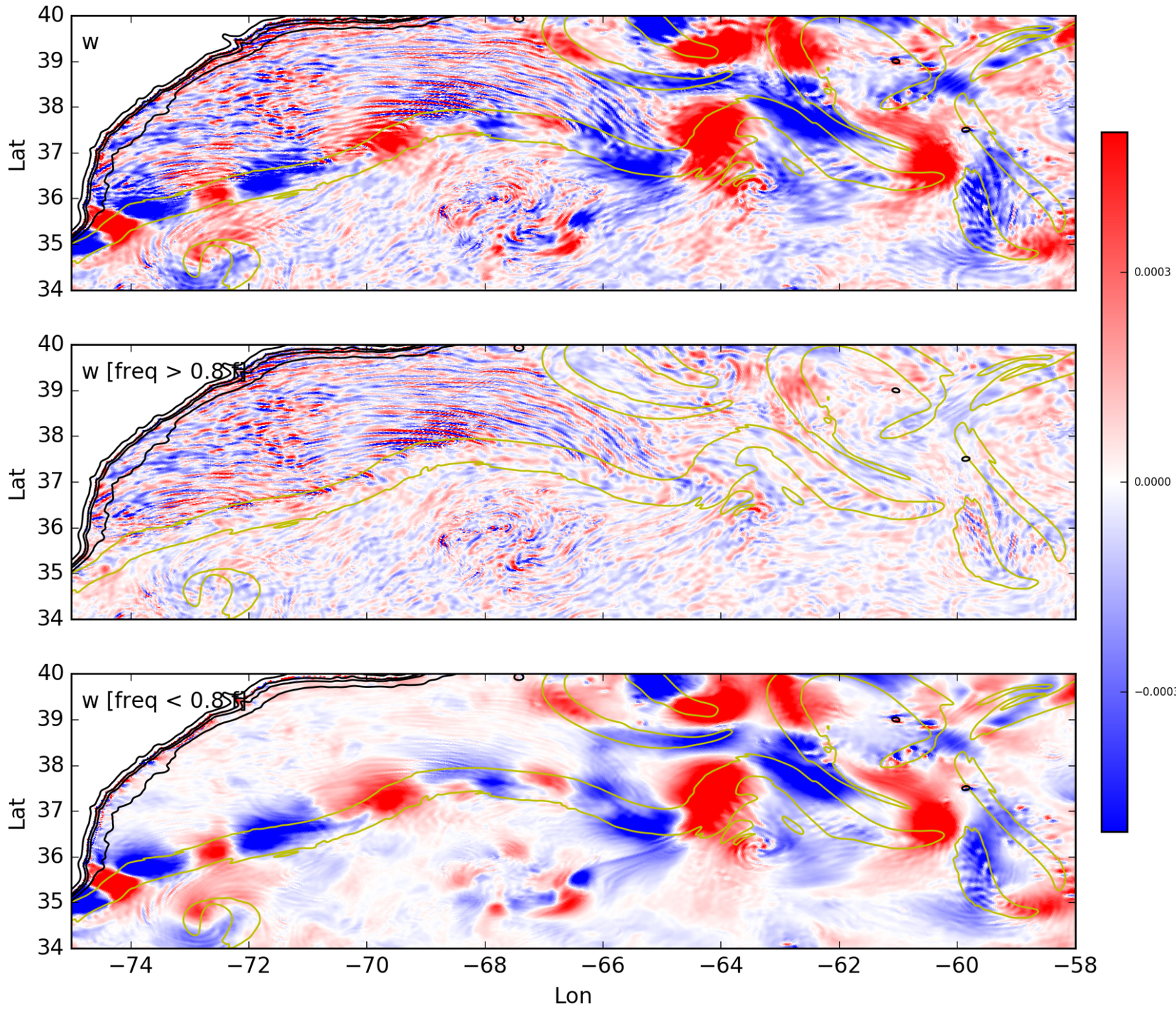
(e) Spontaneously emitted wave

Total w

w [freq > 0.8 f]]

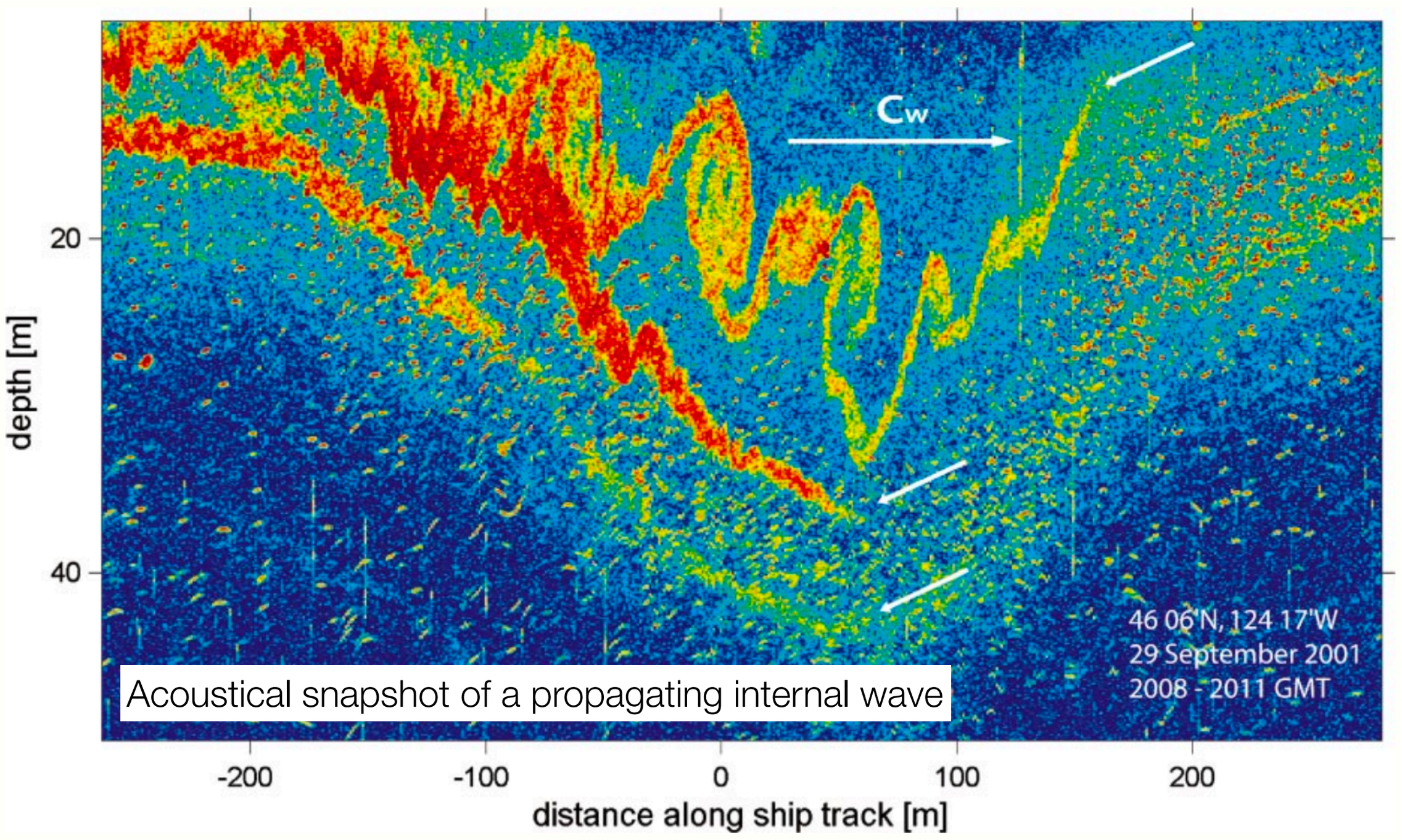
Vertical velocities at z = -500 m in the Gulf Stream

w [freq < 0.8 f]



2. Internal waves: what ? why ?

Why do we care about internal waves ?

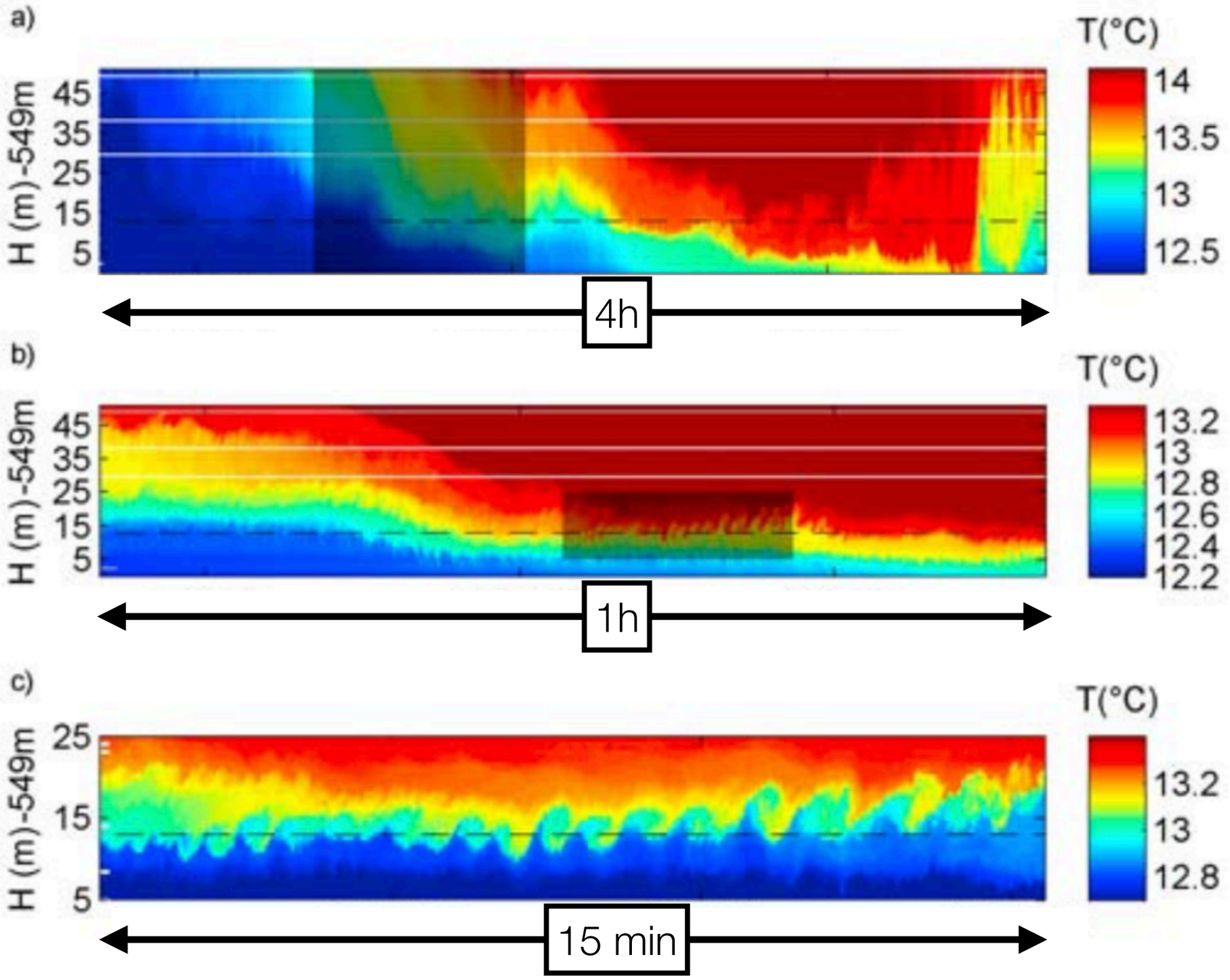


Acoustical snapshot of a propagating internal wave

Moum et al. 2003

2. Internal waves: what ? why ?

Why do we care about internal waves ?



van Haren and Gostiaux 2010

2. Internal waves: what ? why ?

Why do we care about internal waves ?

→ Because they break ! They generate **turbulence** and **mixing through density surfaces**.

Which is important for:

de Lavergne et al. 2022

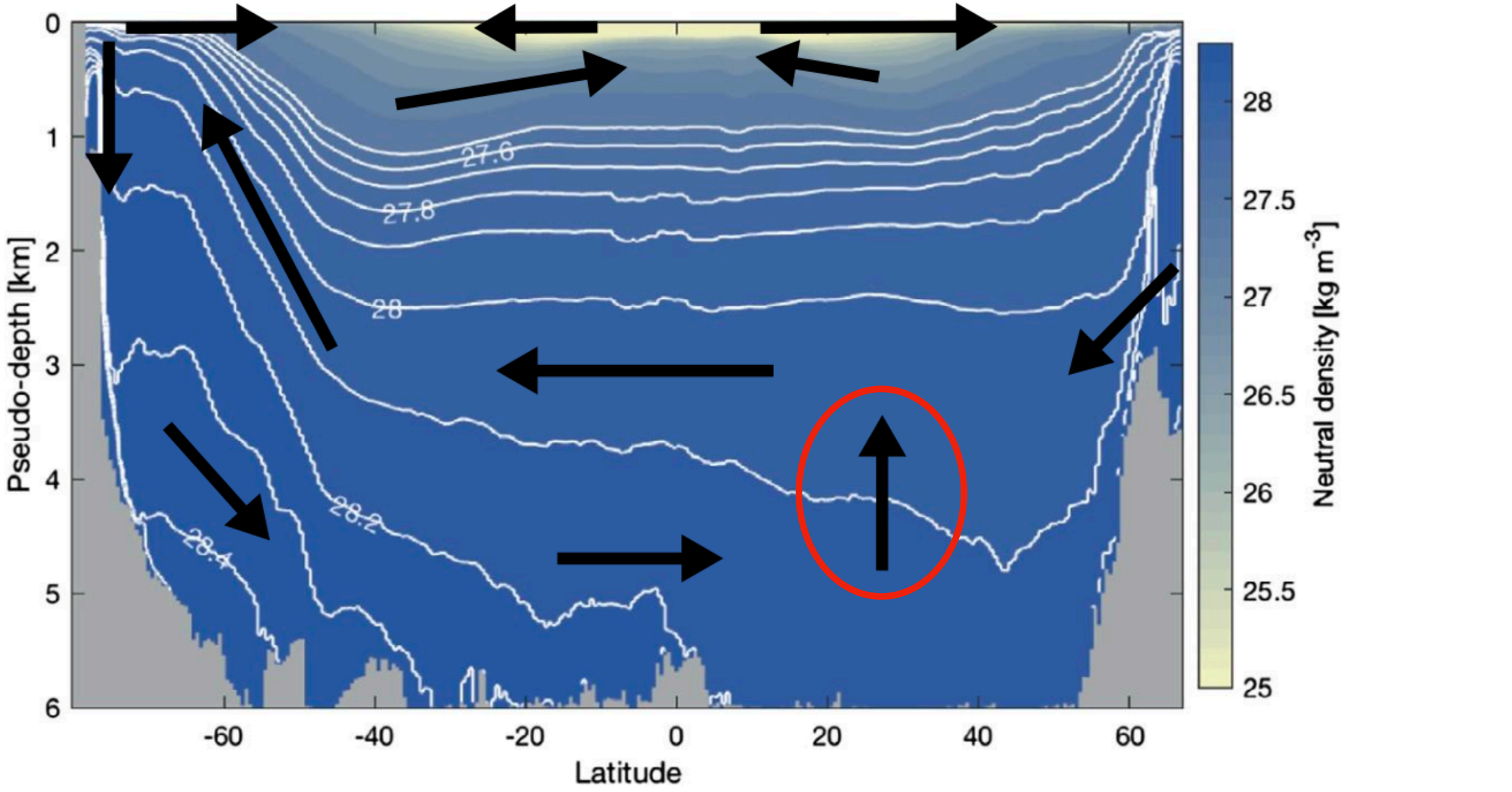
2. Internal waves: what ? why ?

Why do we care about internal waves ?

→ Because they break ! They generate **turbulence** and **mixing through density surfaces**.

Which is important for:

- The **meridional overturning circulation** (MOC)



de Lavergne et al. 2022

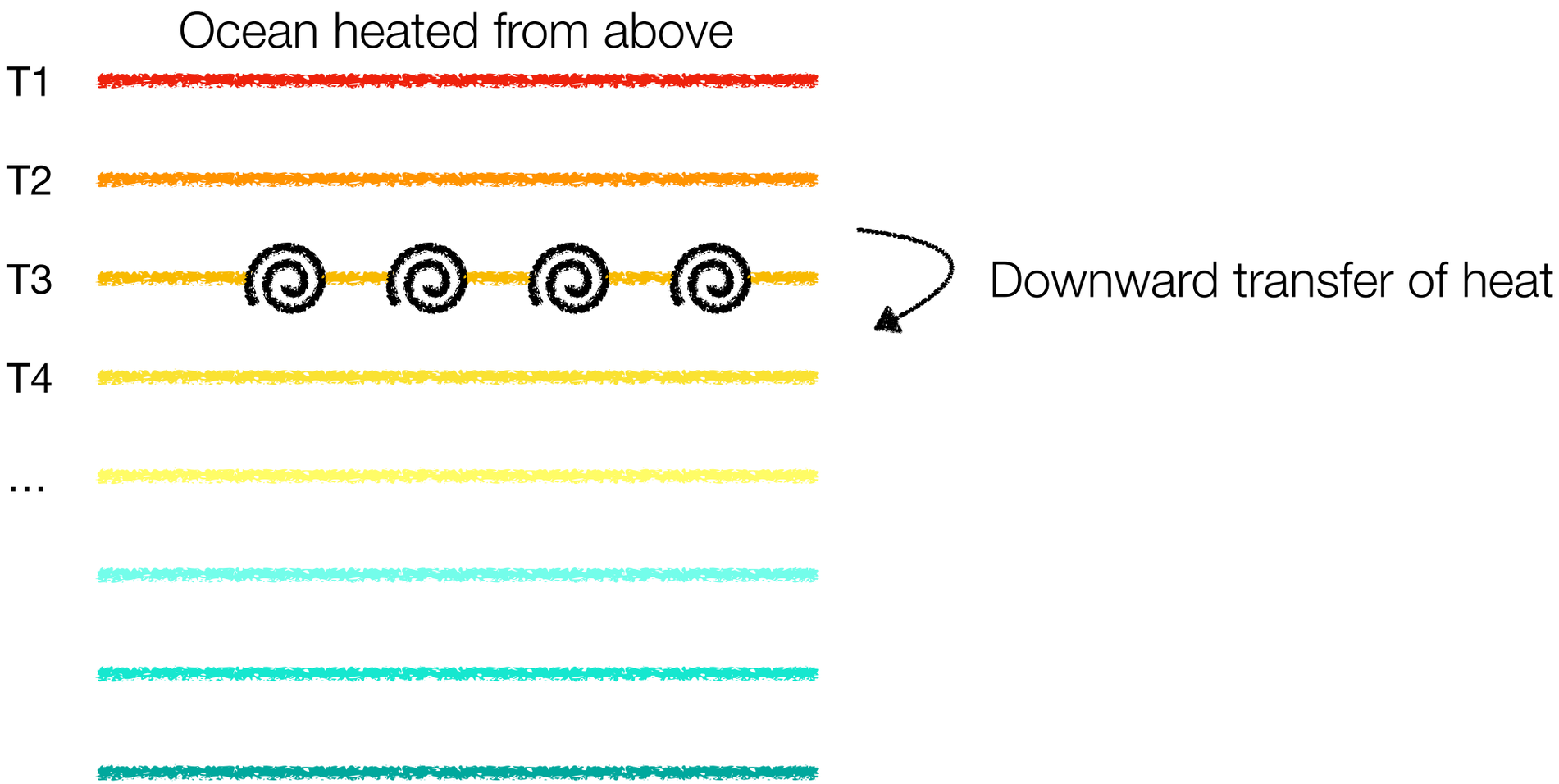
2. Internal waves: what ? why ?

Why do we care about internal waves ?

→ Because they break ! They generate **turbulence** and **mixing through density surfaces**.

Which is important for:

- **Heat exchange** between the surface and the interior



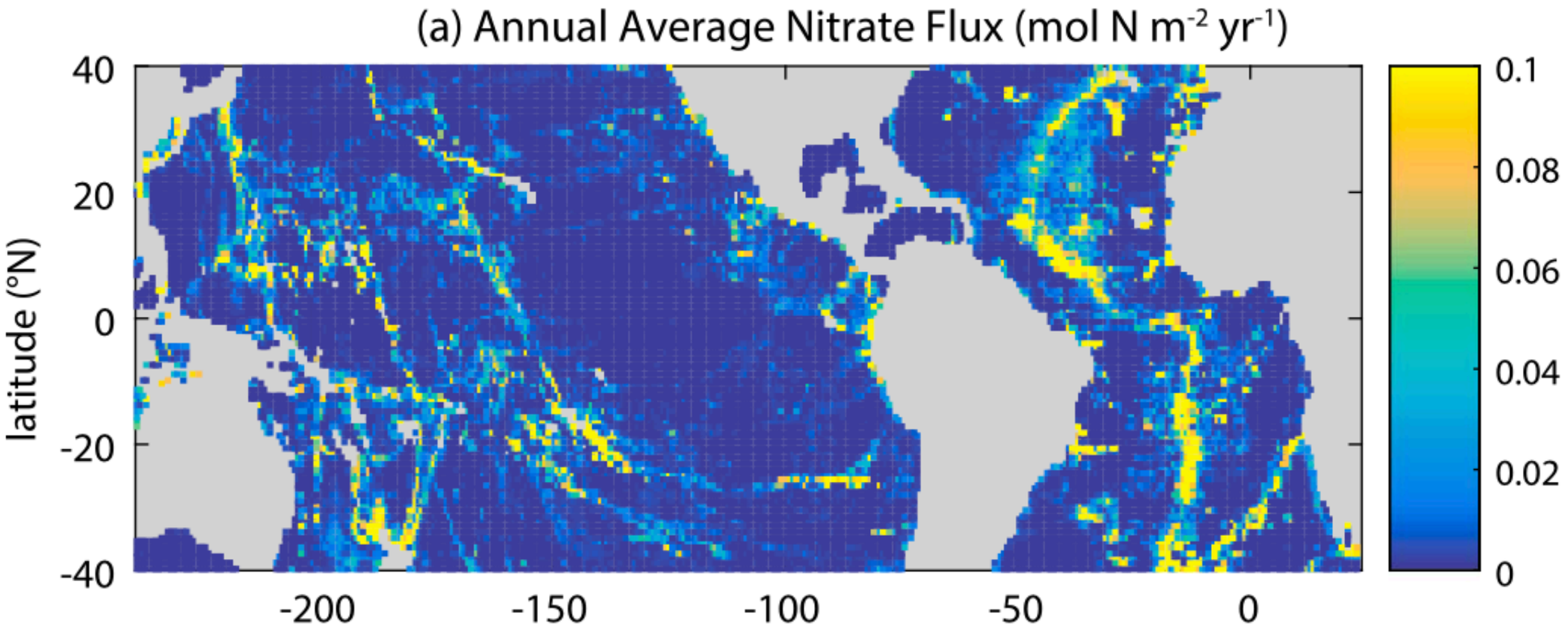
2. Internal waves: what ? why ?

Why do we care about internal waves ?

→ Because they break ! They generate **turbulence** and **mixing through density surfaces**.

Which is important for:

- The upward **flux of nutrients** in the euphotic layer



Nitrate flux into the euphotic zone powered by internal wave turbulence

Tuerena et al. 2019

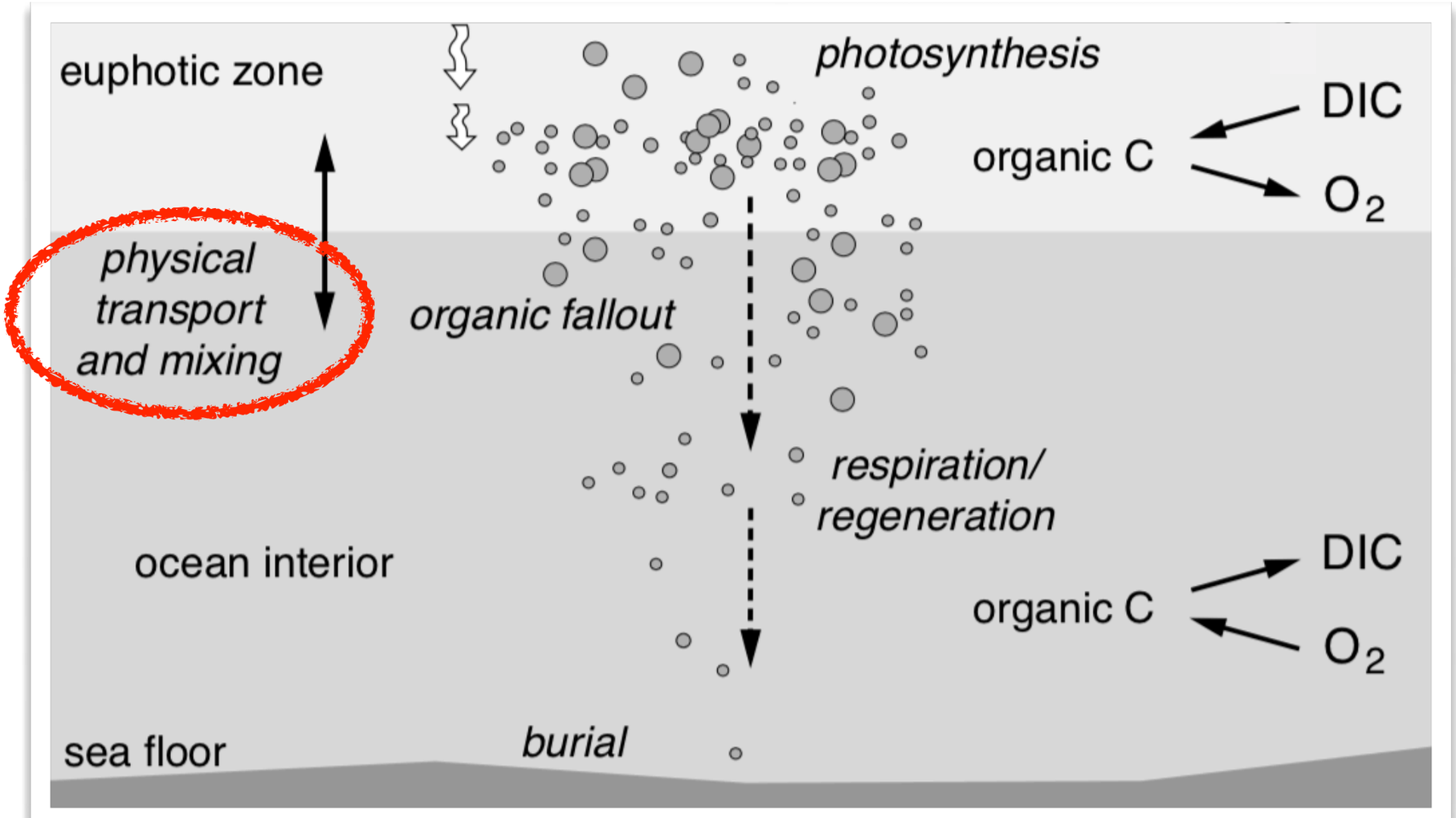
2. Internal waves: what ? why ?

Why do we care about internal waves ?

→ Because they break ! They generate **turbulence** and **mixing through density surfaces**.

Which is important for:

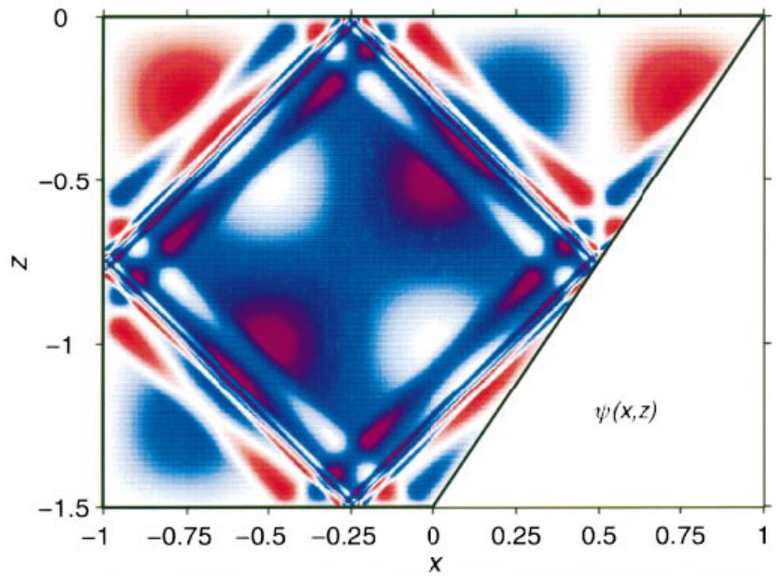
- The downward **flux of carbon** (product by primary production)



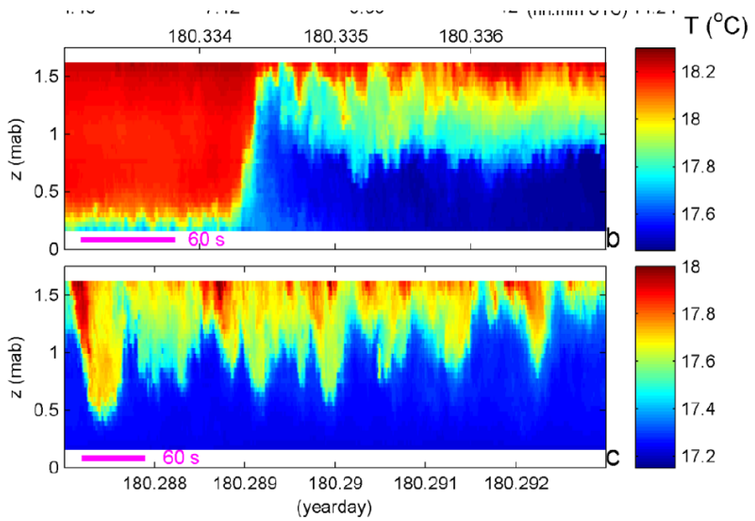
Williams and Follows 2011

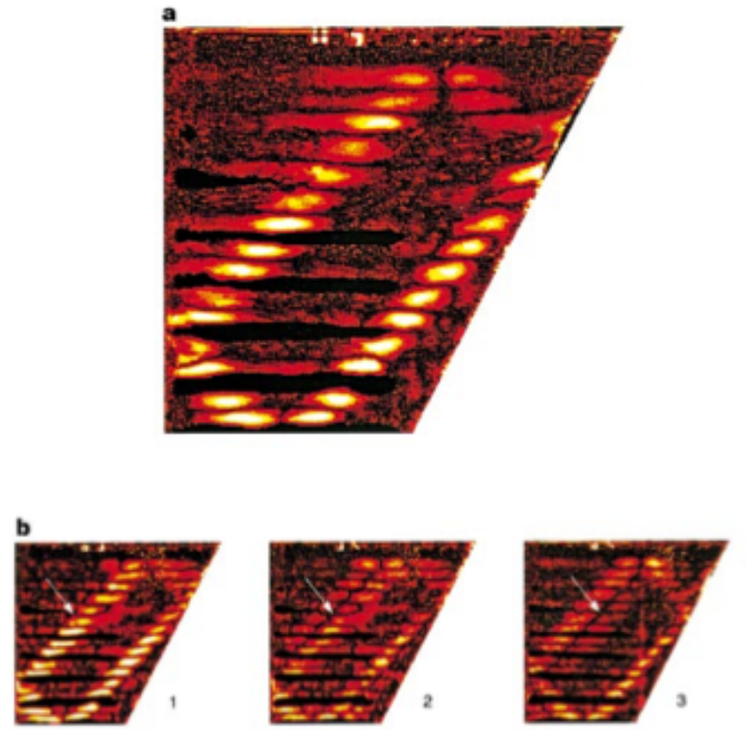
Observation of internal waves

- Satellite observations
- In-situ measurements
- Laboratory experiments



Maas et al, Nature, 1997





Satellite observations

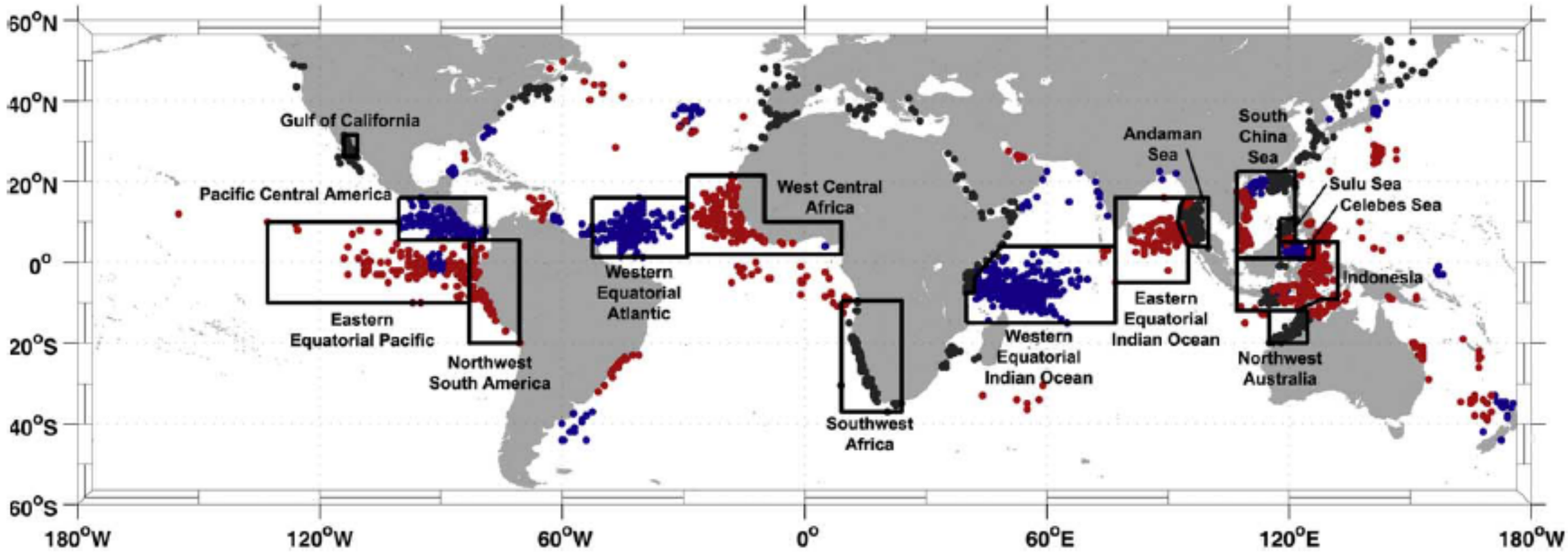
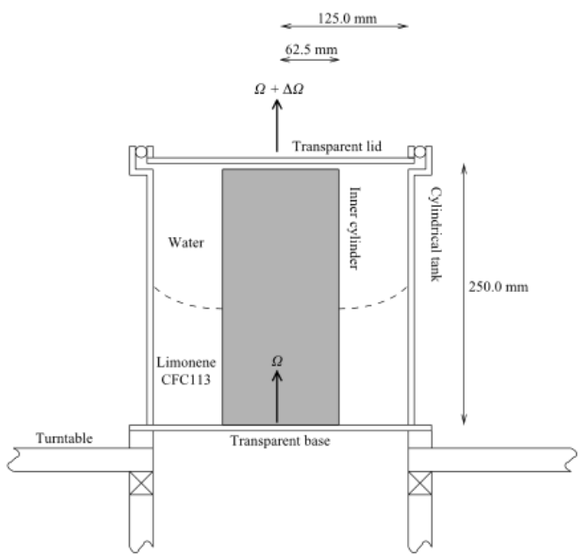
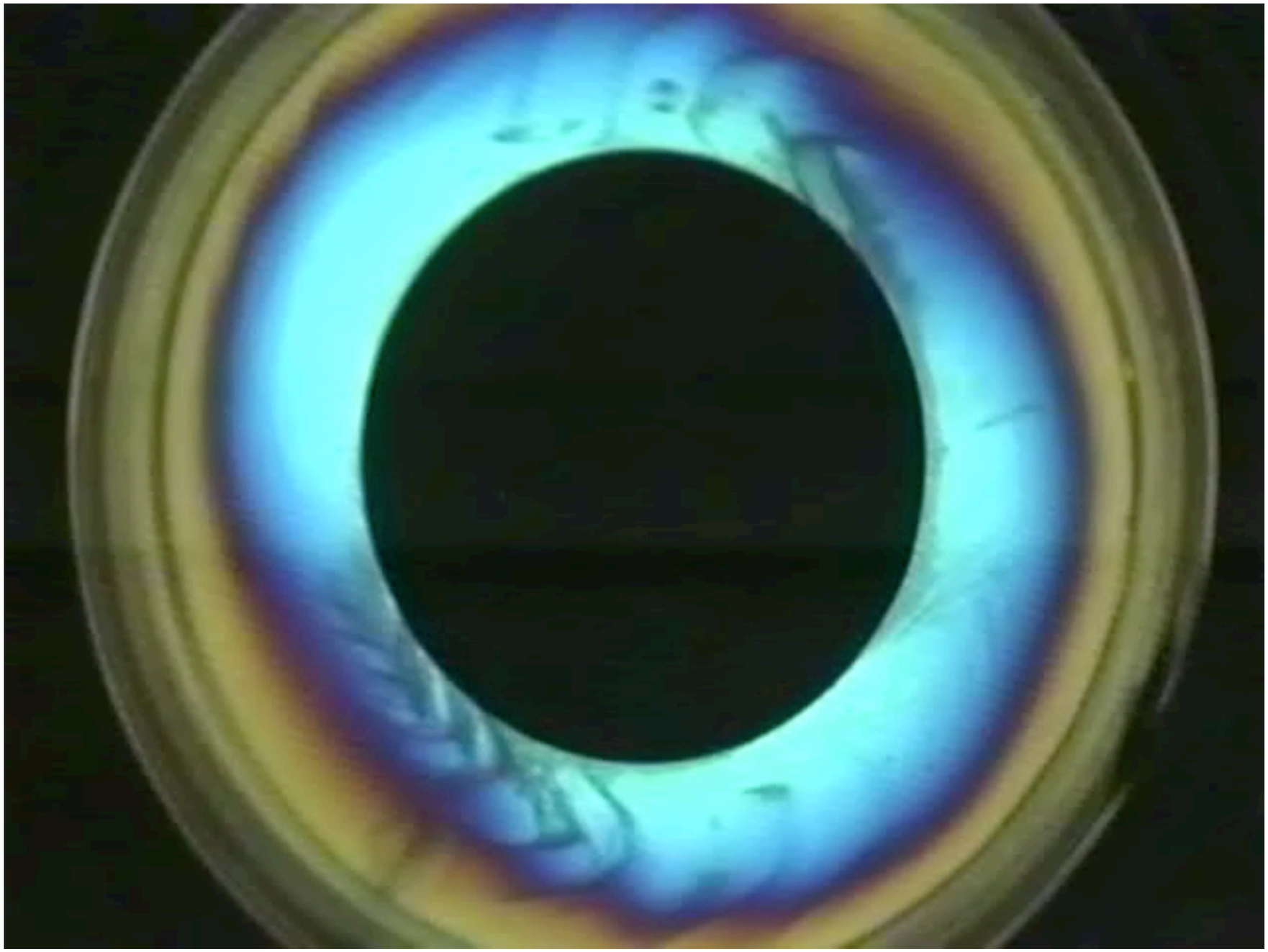


Figure 1. Location of internal waves observed in MODIS imagery from August 2002 through May 2004 along with the geographic boundary for the 15 regions listed in Table 1. The survey identified a total number of 3581 wave occurrences which combine to create 2774 distinct region, area, and date occurrences. Well-known occurrence sites are shown in gray, new areas of activity are shown in red, and areas of geographically expanded activity are shown in blue.

Lab experiment





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In-situ observations

Mooring for real-time observation of internal waves

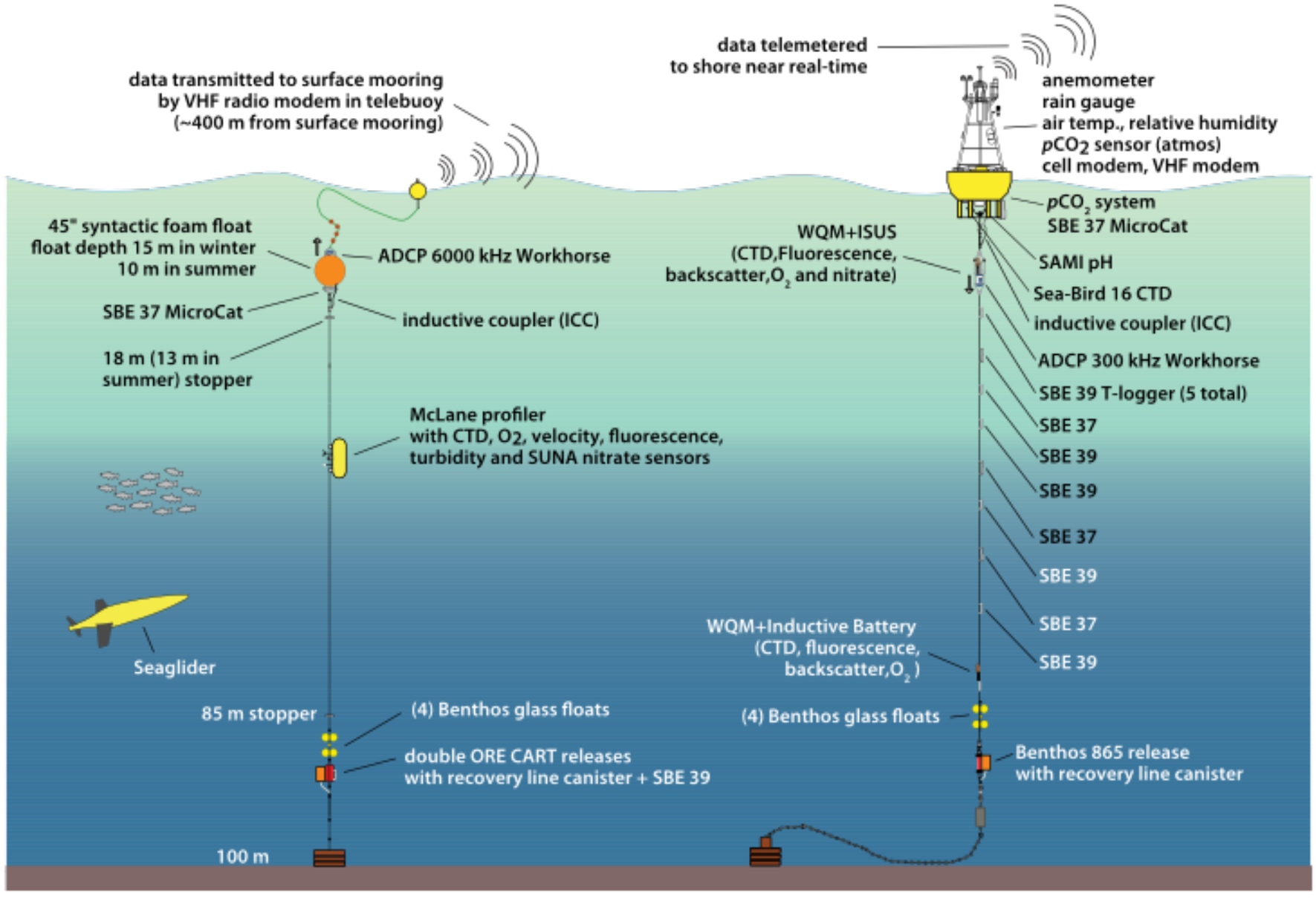


Figure 2. Schematic of the NEMO system showing the surface mooring (right), the subsurface profiling mooring (left), and the glider.

In-situ observations

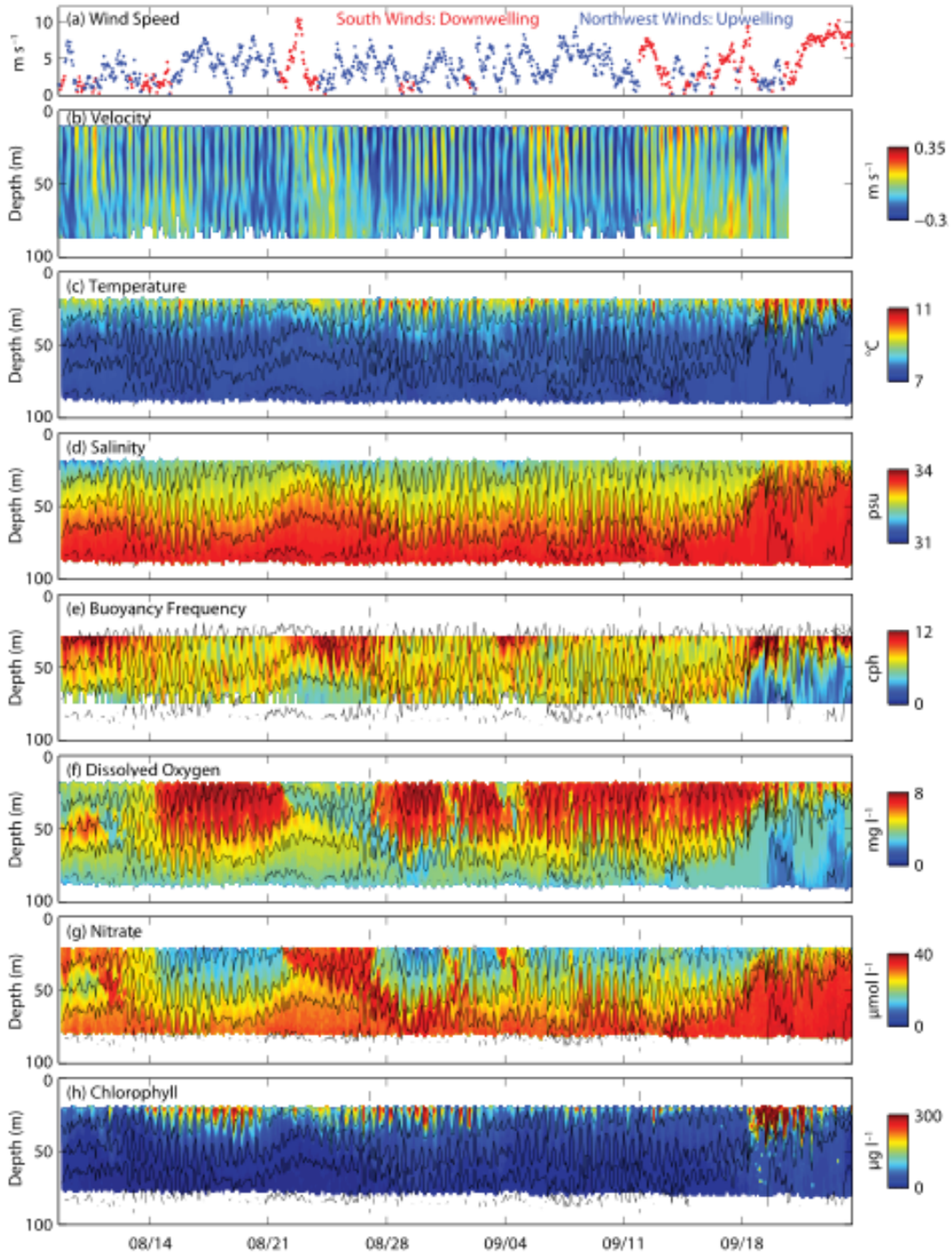


Figure 4. Time series of data from the subsurface mooring, corresponding to the last 46 days of the period plotted in the previous figure. Panels are wind speed colored by (a) direction as in Figure 3, (b) velocity toward 315° true, (c) temperature, (d) salinity, (e) buoyancy frequency, (f) dissolved oxygen, (g) nitrate, and (h) chlorophyll. Isopycnals whose mean spacing is 10 m are over-plotted in each panel in black.

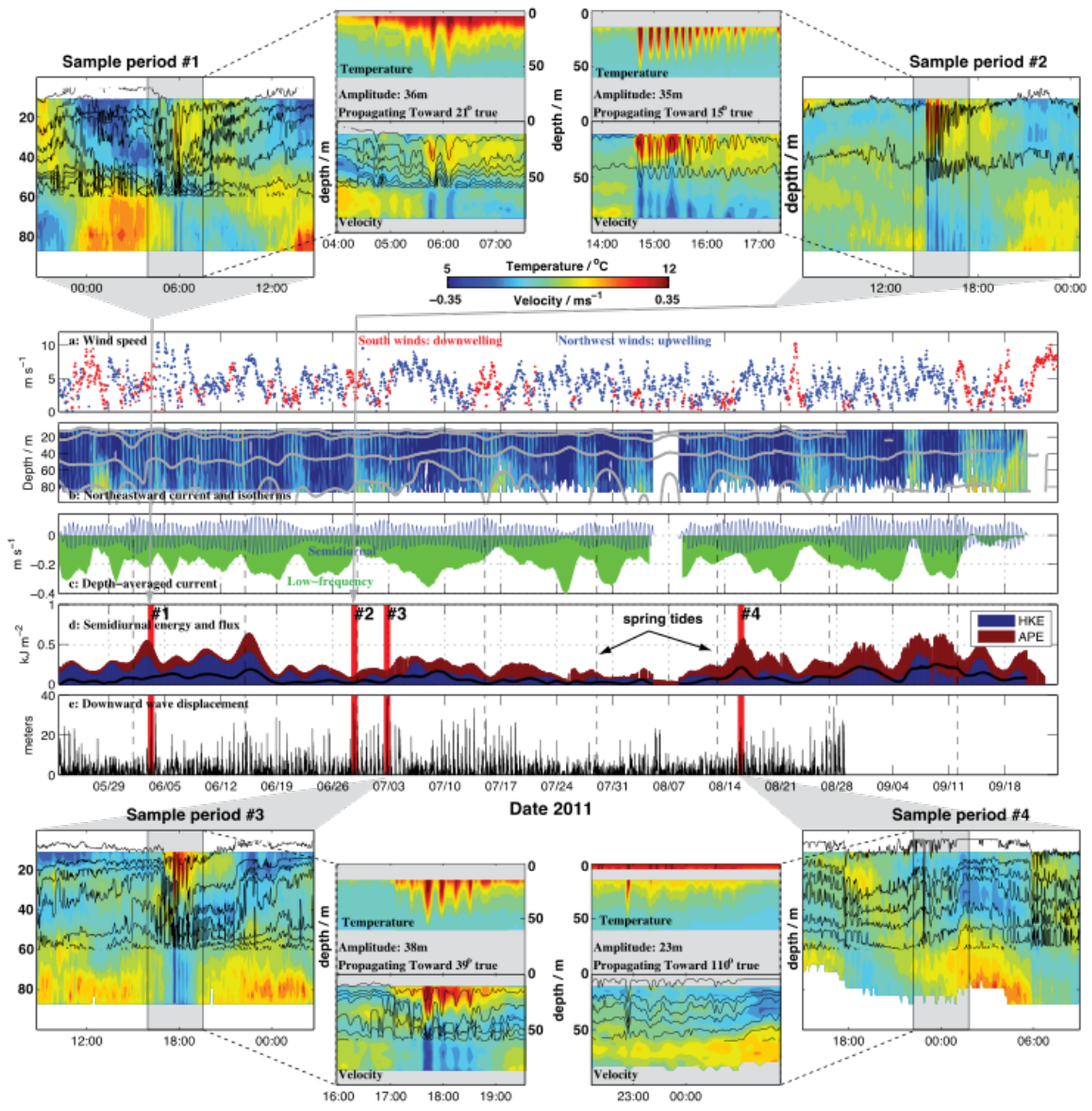
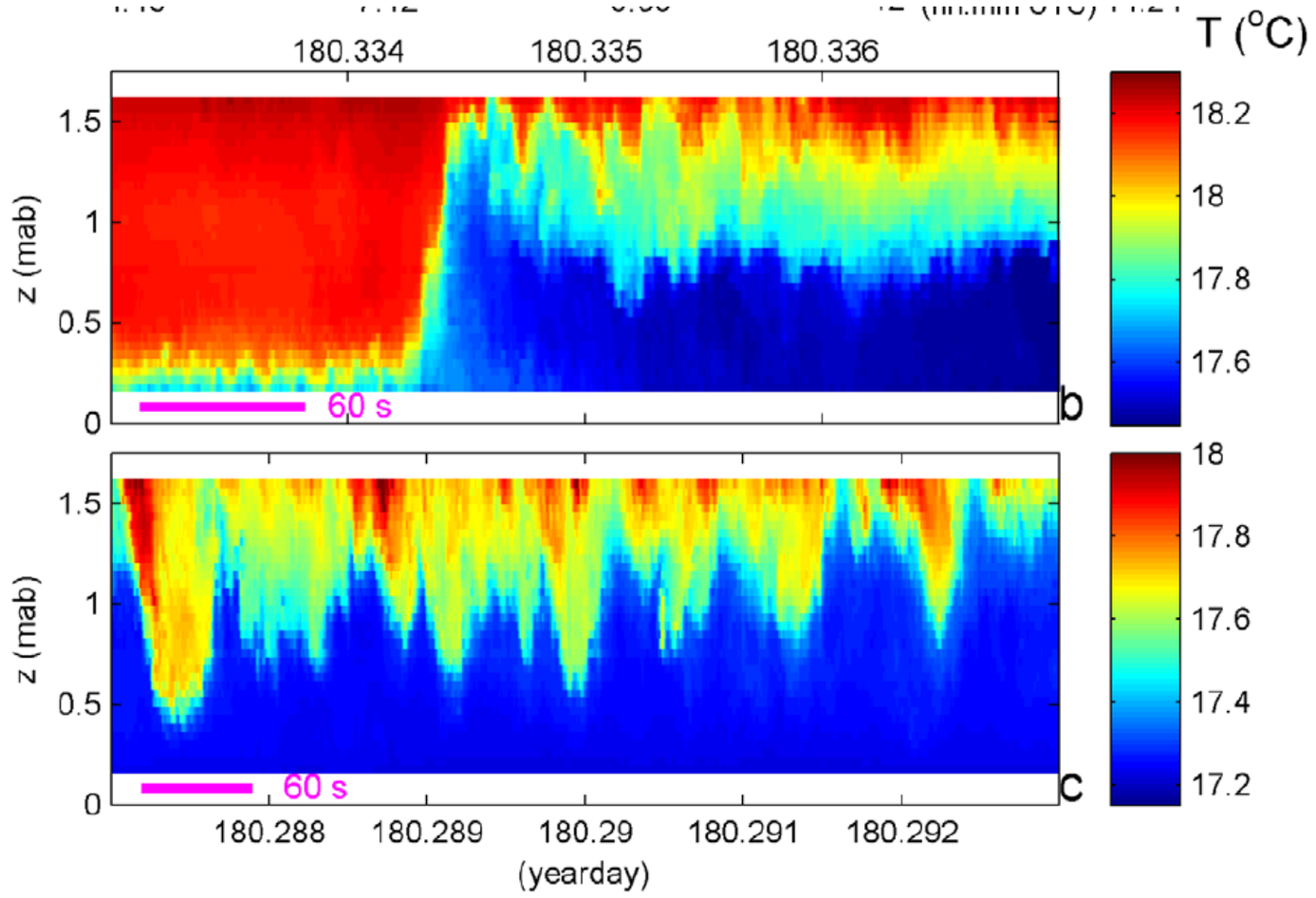


Figure 3. A 2011 time series from the surface mooring, with outer insets showing zoom-ins of 18-hour periods around the four times marked in (d) to demonstrate the variability in the internal tide. Inner insets are zoomed in further on the period indicated in each outer inset to illustrate the temperature (top) and baroclinic northward velocity (bottom) of the nonlinear internal waves. (a) Wind speed, colored by direction (south = red, northwest = blue). (b) Velocity toward 315° true (northwest), with blue colors indicating flow to the southeast. The 8°, 9°, and 10°C isotherms are contoured in gray. (c) Depth-averaged velocity towards 315° true (northwest) of the low-frequency flow (green) and the semidiurnal tidal band (blue). (d) Mode-1 semidiurnal tide: Horizontal kinetic energy (HKE) and available potential energy (APE) are plotted as stacked histograms, with their sum indicating total energy. Energy flux magnitude in kW m^{-1}, which is always toward the north-northeast, is plotted in black. The times of the insets are indicated in red in (d,e). Black dashed lines in (c–e) show full and new moons, which should correspond with spring tides or maximal semidiurnal tidal forcing. (e) Amplitude of the nonlinear internal waves computed by tracking the depth of the isotherm normally at 15 m depth.

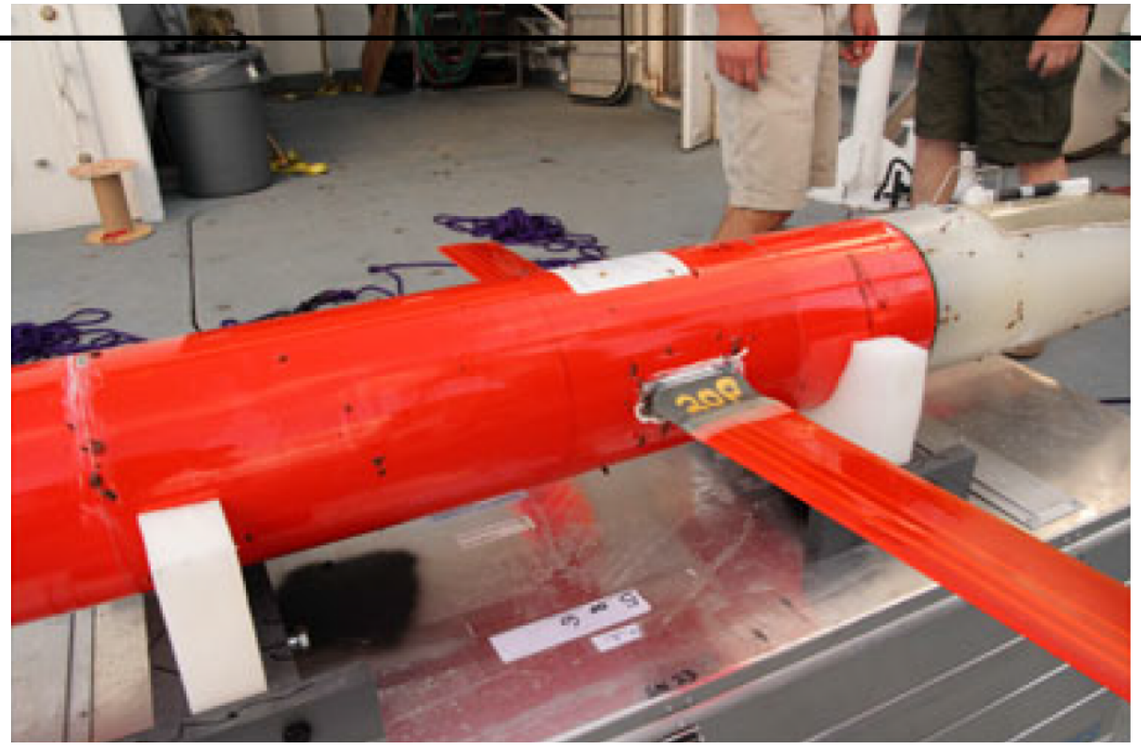
Alford, M.H., J.B. Mickett, S. Zhang, P. MacCready, Z. Zhao, and J. Newton. **2012** Internal waves on the Washington continental shelf. *Oceanography*. 25(2):66–79.

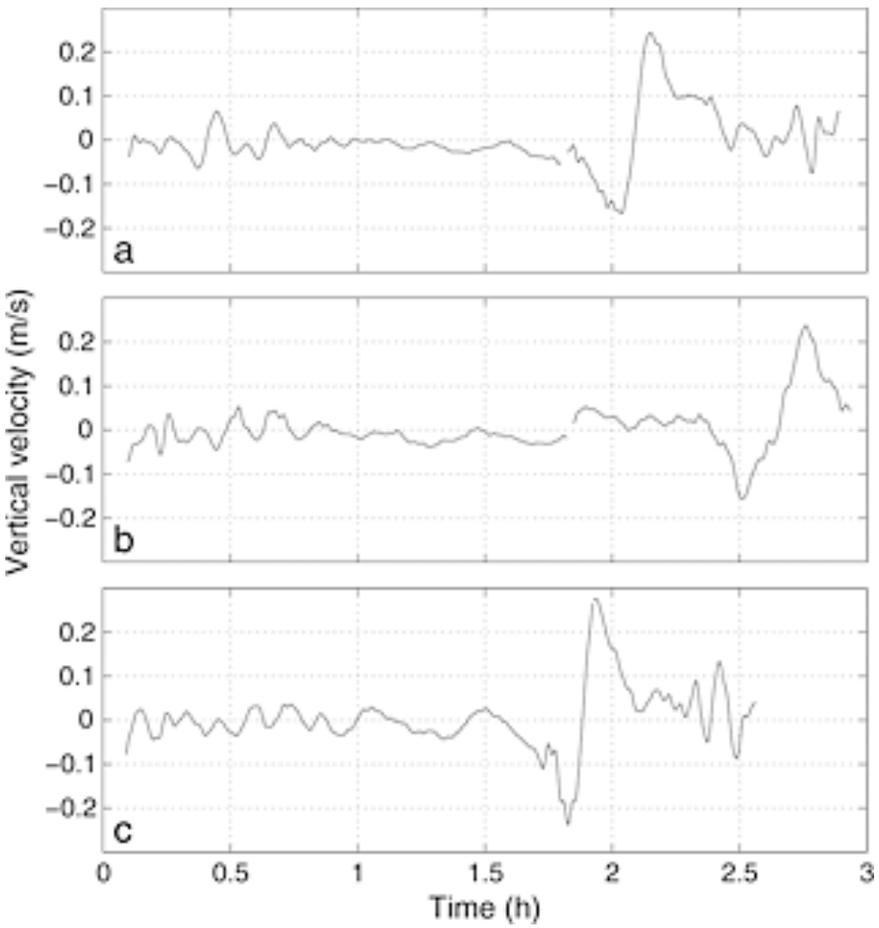
In-situ observations

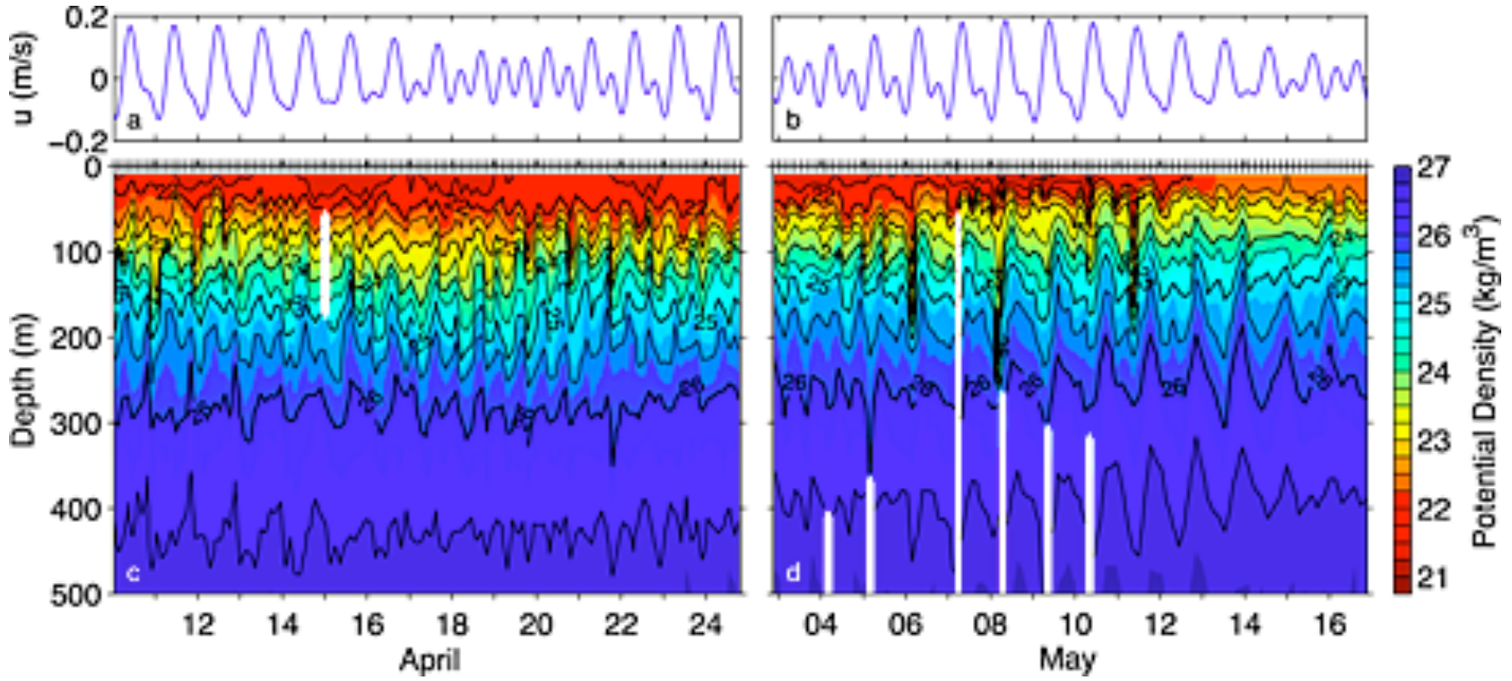


van Haren H, Gostiaux L, Laan M, van Haren M, van Haren E, Gerringa LJA (**2012**) Internal Wave Turbulence Near a Texel Beach. *PLoS ONE* 7(3): e32535. doi:10.1371/journal.pone.0032535

In-situ observations







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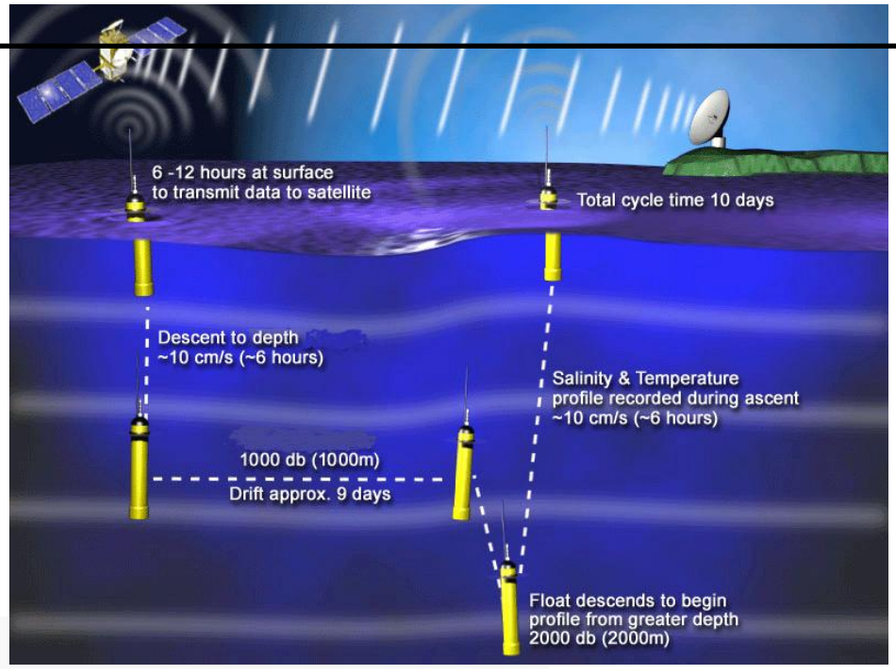
In-situ observations



Observations of Internal Gravity Waves by Argo Floats

By: Hennon, Tyler D.; Riser, Stephen C.; Alford, Matthew H.
JOURNAL OF PHYSICAL OCEANOGRAPHY Volume: 44 Issue: 9 Pages: 2370-2386 Published: SEP 2014

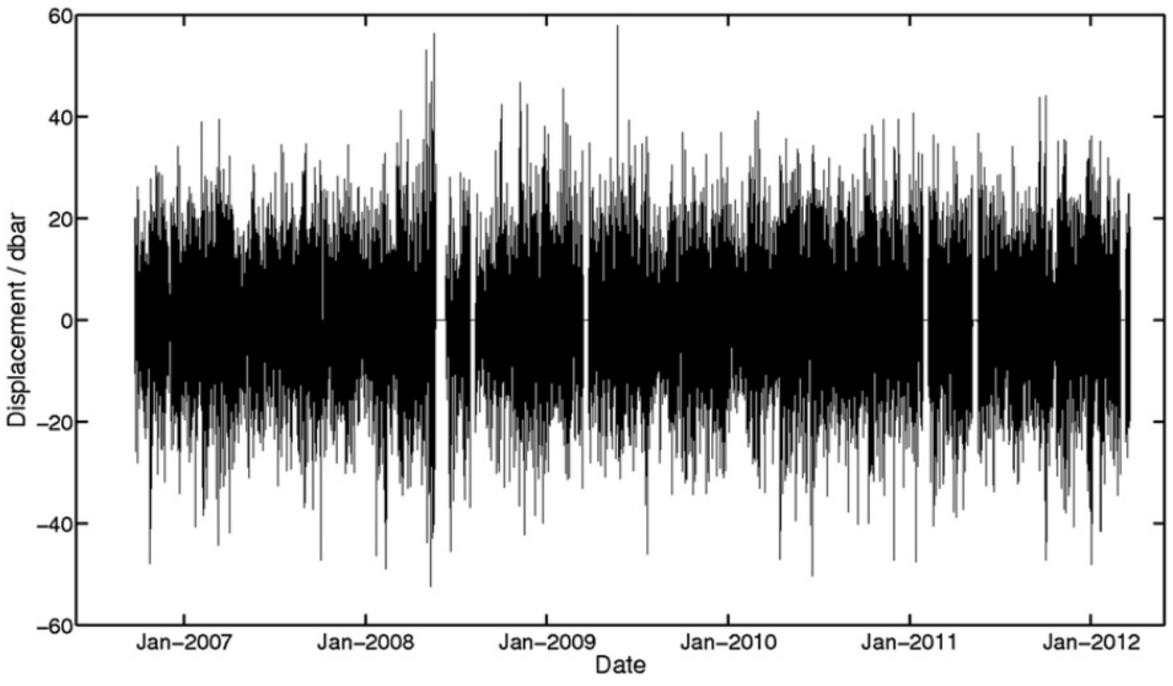


FIG. 4. The synthesized time series of vertical internal wave displacement for float 5135, located in the Indian Ocean. The small gaps of data (zeroes) correspond to park phases where the vertical temperature profile was not linear enough to meet quality control (see section 2c).

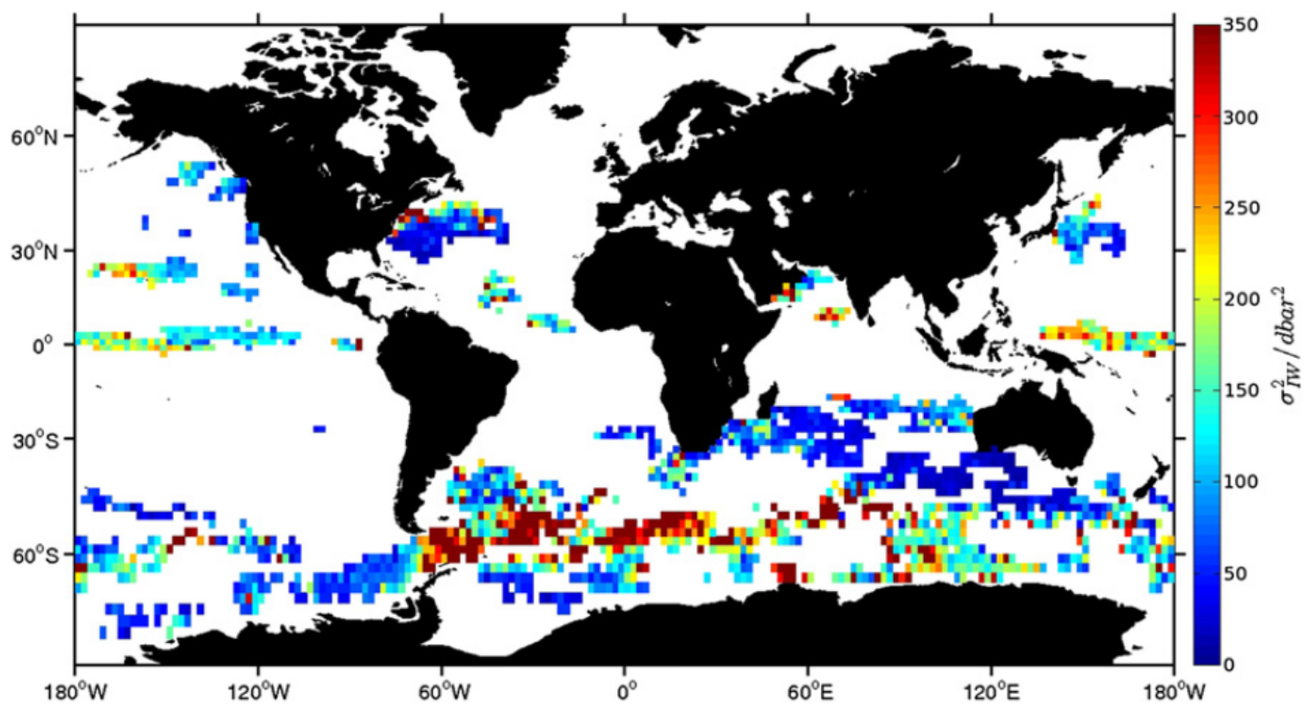


FIG. 11. Estimates of internal gravity wave vertical displacement variance from the 194 profiling floats used in this study. Values are averaged into 2° by 2° bins.

2. Internal waves: what ? why ?

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