# Internal tides/lee waves coupling: dynamics and impact on the ocean budgets

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# Internal wave generation

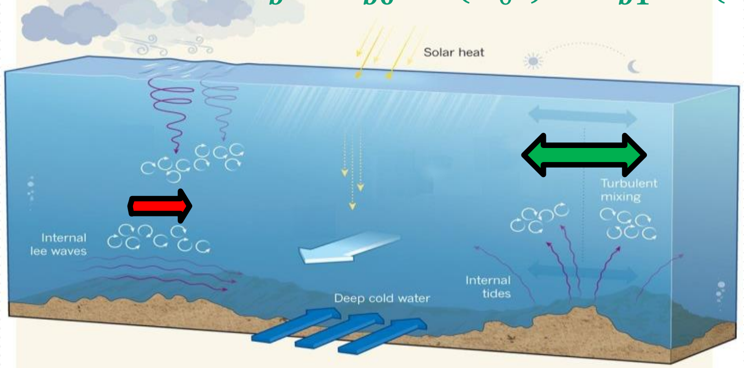
- Internal waves (IWs) are finescale processes involved in the **water masses transformation** in the stratified ocean.

- In the usual approach, topographic internal waves are separated in two classes: **Internal tides** and **Lee waves** that are respectively generated where **barotropic tides** and **geostrophic eddies** interact with oceanic topographies.

- Water-masses transformations by IT and LW have been **assessed independently** using linear theory (Bell 1975) and semi-empirical parameterizations (St-Laurent et al. 2002).

Barotropic forcing

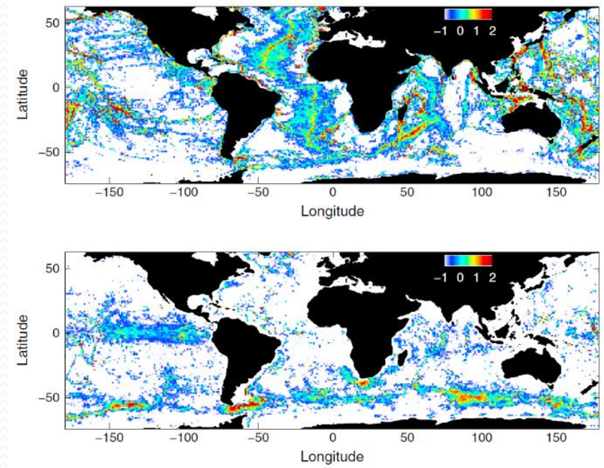
$\boldsymbol{U_b} = \boldsymbol{U_{b0}} \cos(\omega_0 t) + \boldsymbol{U_{b1}} \cos(\omega_1 t) + \cdots$




Quasi steady flow $\boldsymbol{U_g}$

*Adapted from Mackinnon, Nature 2013*

***log(mW/m2)***




*Nikurashin and Ferrari, JPO 2013*

# Internal lee / tides coupling

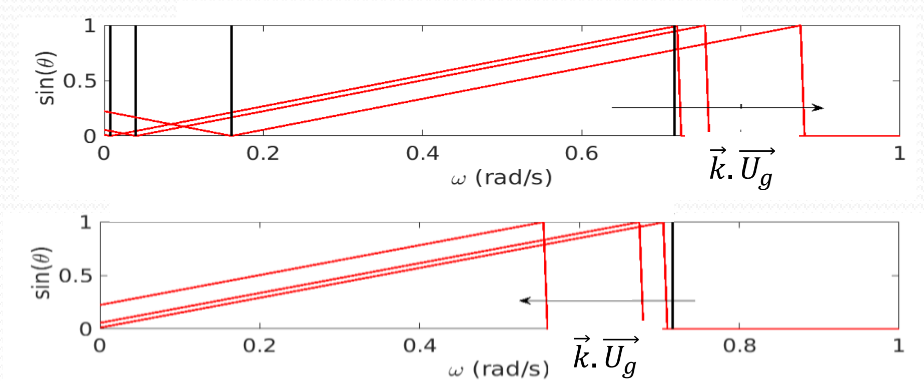
- **Multi-tidal** and **geostrophic** forcings are often both present in internal wave generation sites on abyssal hills.

- The **multiple forcing processes** introduce a linear coupling between internal tides and lee waves.

- The dispersion relation for linear internal tides is modified by the geostrophic flow:

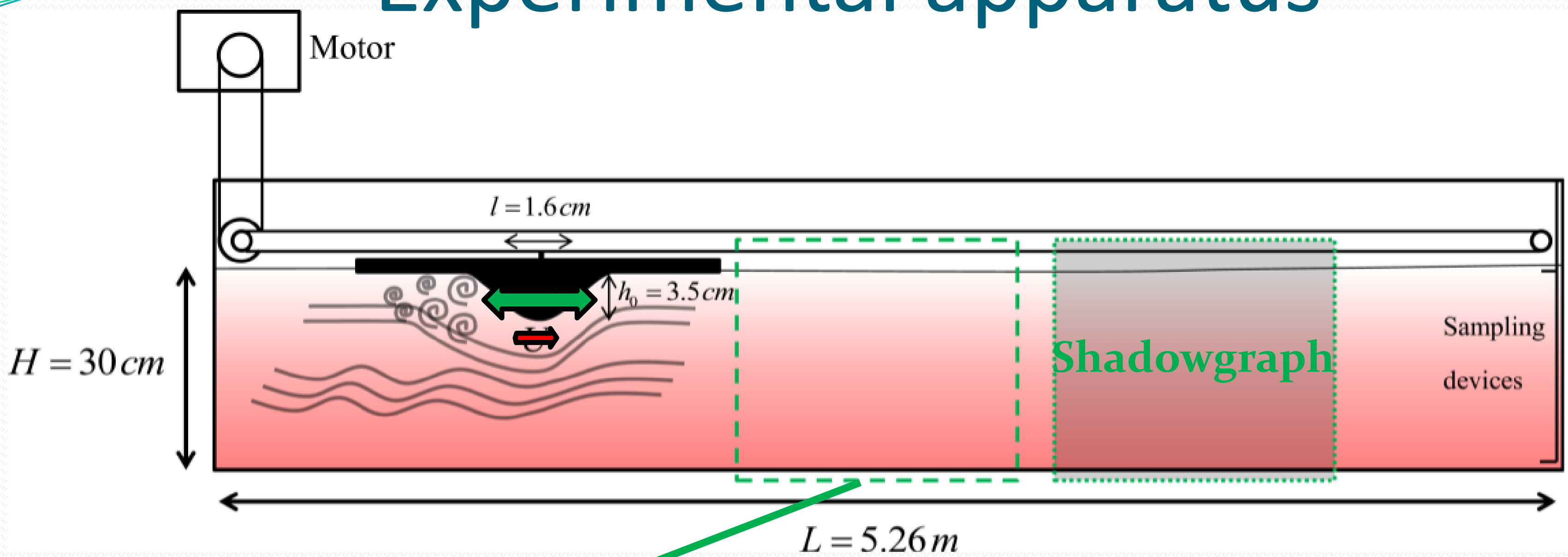
$$\omega = N\sin\theta \Rightarrow \omega - \vec{k}.\overrightarrow{U_g} = N\sin\theta$$ (Coriolis parameter $f = 0$)

- **Expect asymmetry** between downstream ($\vec{k}.\overrightarrow{U_g} > 0$) and upstream ($\vec{k}.\overrightarrow{U_g} < 0$) beams.



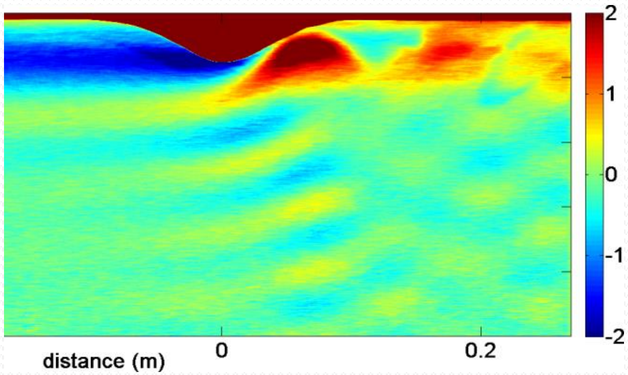

*Linear dispersion for the downstream (top) and upstream (bottom) IW beams of horizontal wavelength $\vec{k}$ in the presence of a constant flow $\overrightarrow{U_g}$ and a background buoyancy frequency $N = 0{,}7$ rad/s. he beam angle to the horizontal is $\theta$.*

# Experimental apparatus



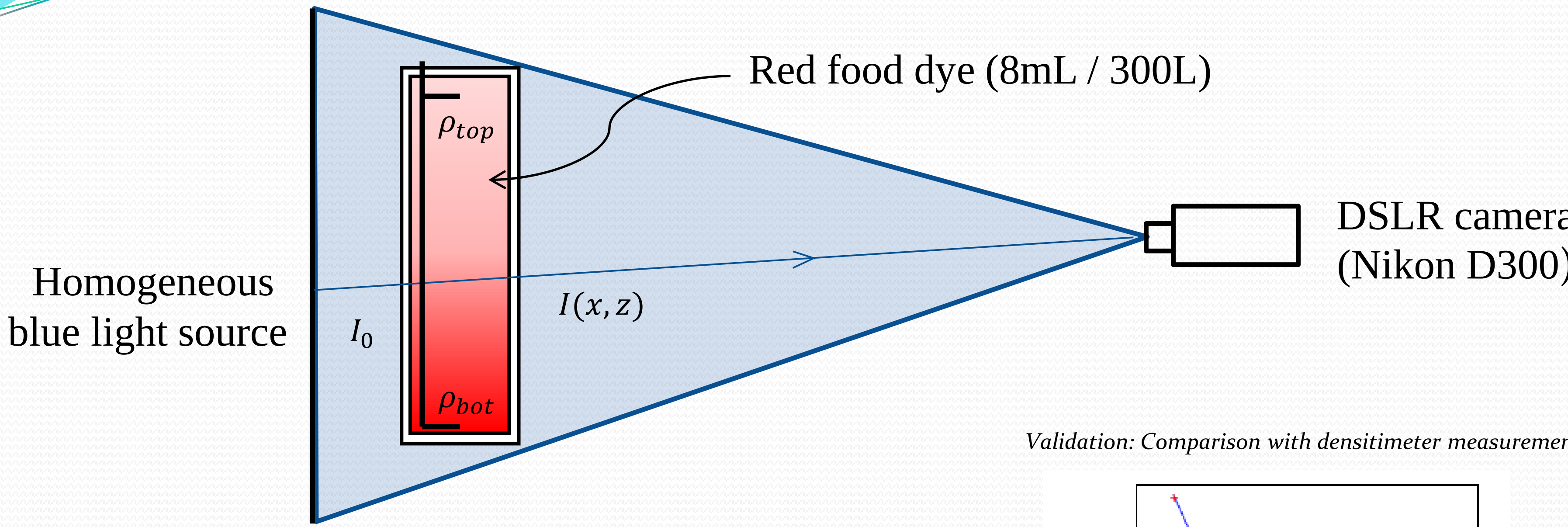

**Light attenuation technique**

High resolution density measurements

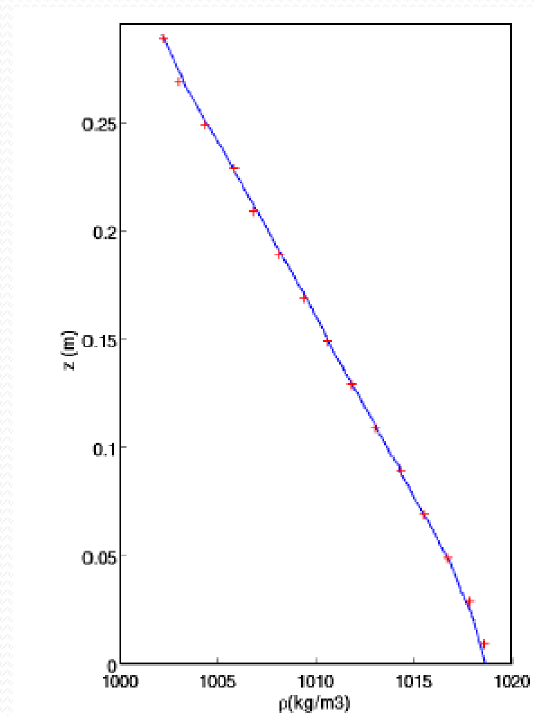



- Experiments were carried at the GFD lab of the Research School for Earth Sciences (ANU Canberra).
- The internal wave field is generated by the ridge motion at the free surface of the flow, in an initially linear stratification.
- The flow dynamics is captured by the light attenuation technique giving access to high resolution density (anomalies) fields.

# Light attenuation technique




*Validation: Comparison with densitimeter measurements*




**Protocol**

- Current and reference picture: $A(x,z) = -\log\left(\frac{I(x,z)}{I_0}\right)$
- Calibration and Beer-Lambert law:

$$\boldsymbol{\rho(x,z) = \rho_{top} + \alpha(A(x,z) - A_{top})}$$

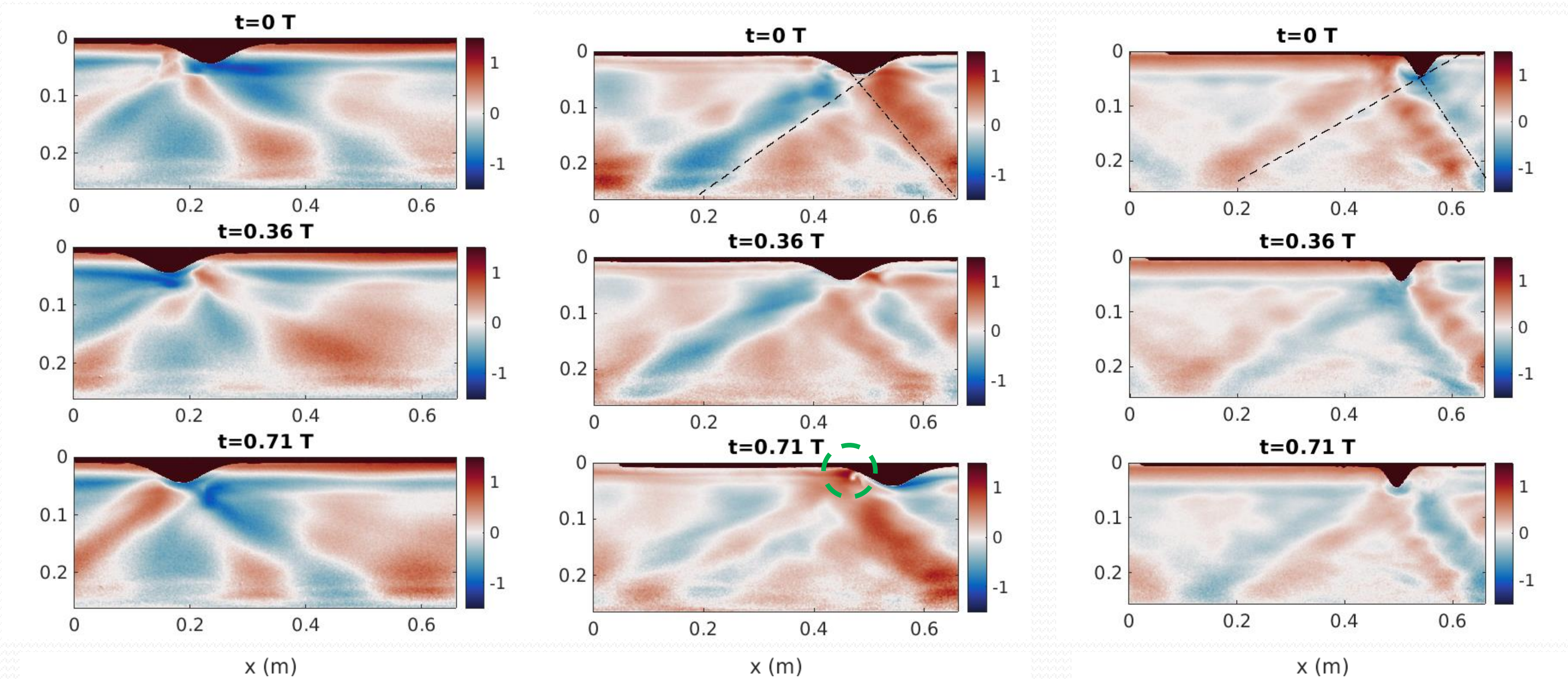
with $\alpha = \frac{\rho_{bot} - \rho_{top}}{A_{bot} - A_{top}}$. $\Delta x = \Delta z = 0{,}1\ mm$

# Density anomalies (kg/m3)

it17: $U_b = 2\ cm/s$, $\boldsymbol{U_g = 0}$, $\frac{\omega}{N} = 0{,}65$, $k * \frac{U_g}{N} = 0$

it16: $U_b = 2\ cm/s$, $\boldsymbol{U_g = 0.2\ cm/s}$, $\frac{\omega}{N} = 0{,}65$, $k * \frac{U_g}{N} = 0{,}05$

it15: $U_b = 2\ cm/s$, $U_g = 0.2\ cm/s$, $\frac{\omega}{N} = 0{,}65$, $\boldsymbol{k * \frac{U_g}{N} = 0{,}20}$




*Density anomaly fields are shown for three experiments,*
*in which the constant velocity $U_g$* ***is increased****, then the* ***ridge width is decreased****, from left to right.*

- Internal wave beams are observed in the three experiments it17 (no mean flow), it 16 (mean flow, large ridge) and it15 (mean flow, narrow ridge), with the beam angle matching the dispersion relation prediction for the upstream and downstream beams shown by the dashed lines.

- The periodic generation of vertical vortices (dashed circle) is observed for the wide ridge only when the two forcing flows are combined, showing that not only the linear IW propagation, but also the intense nonlinear activity in the vicinity of the ridge are controlled by the combined forcings.

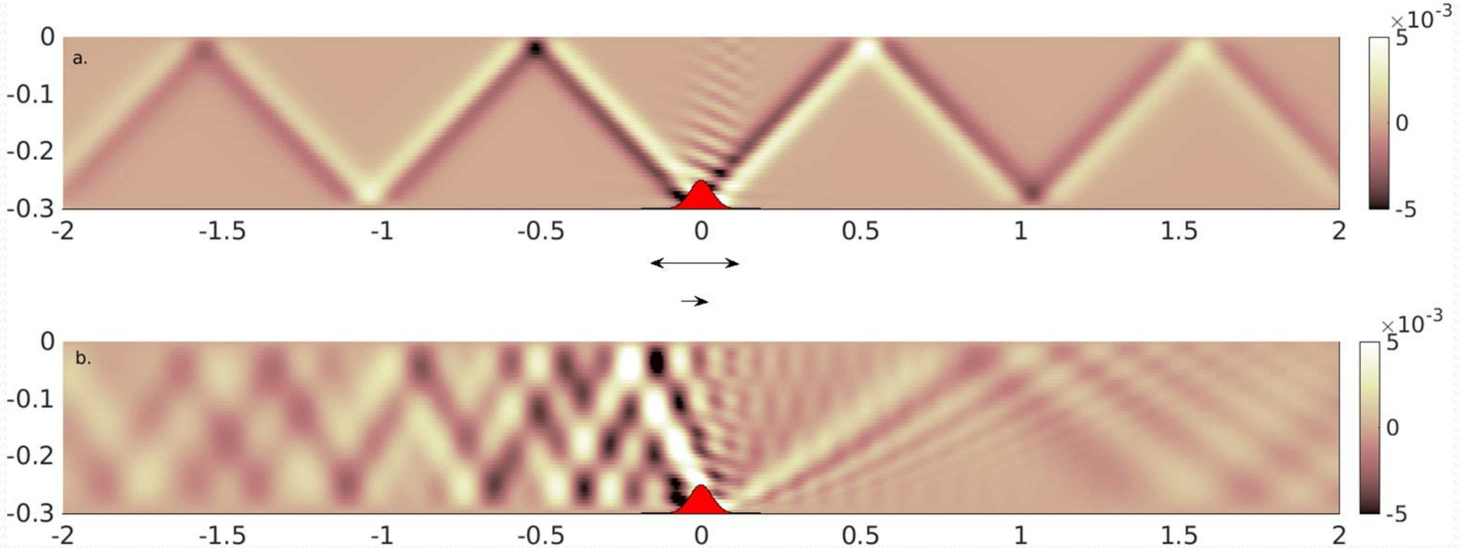
# Linear internal wave model

- The linear model of Bell (1975) is revisited by Shakespeare (2020) to investigate the **combined effects of a barotropic and a steady flow** on internal wave generation. Density, velocity, pressure and energy fluxes are obtained for the linear generation of internal waves over abyssal hills.

In panel a, the two **generation processes are decoupled**, leading to two **symmetrical internal wave beams** and **steady lee waves**.

In panel b, **the linear coupling is accounted for** using the generalized model introduced in Shakespeare (2020).
**A strong asymmetry** appears between the upstream (left) and downstream (right) beams.
The **generation of lee waves is damped** by the coupling mechanism.

- **How does the linear prediction compare to actual measurements of the energy fluxes transported away by internal waves ?**



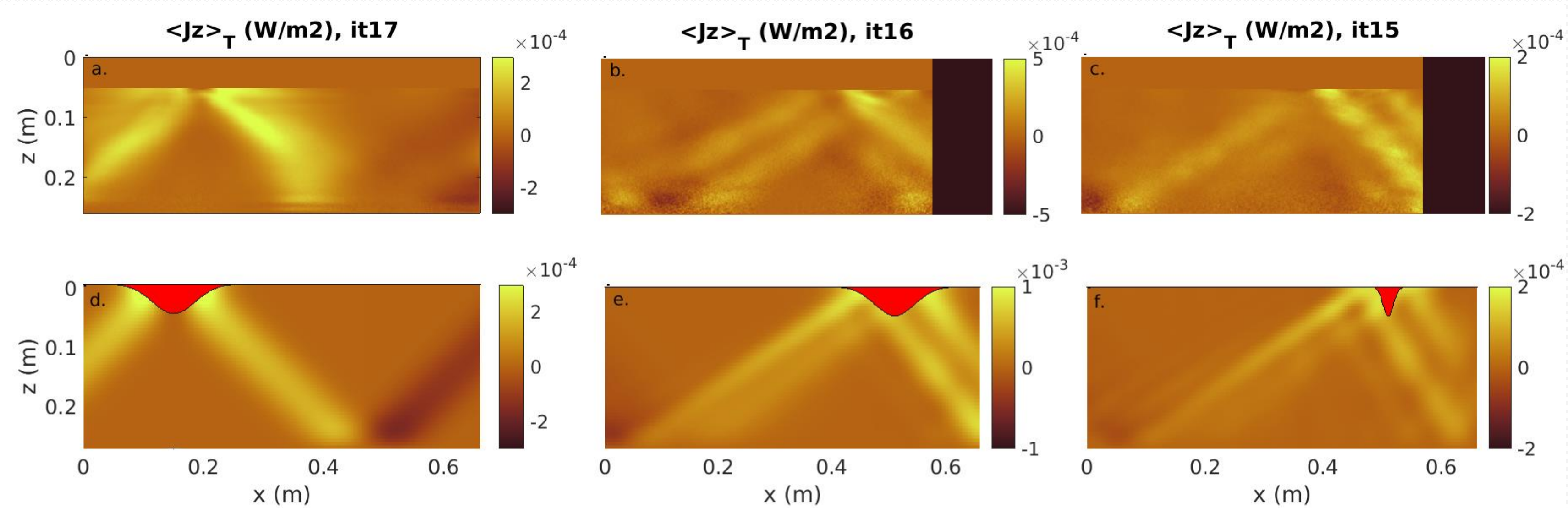

*Vertical velocity (m/s) field for internal wave generation over a Gaussian ridge using the model of Shakespeare (2020) for independent (a.) and coupled (b.) forcings. The arrows show the relative magnitude of the barotropic (2 cm/s) and geostrophic (0,4 cm/s) flows.*

# Energy fluxes: experiments vs linear prediction

it17: $U_b = 2\ cm/s$, $\boldsymbol{U_g = 0}$, $\frac{\omega}{N} = 0{,}65$, $k * \frac{U_g}{N} = 0$

it16: $U_b = 2\ cm/s$, $\boldsymbol{U_g = 0.2\ cm/s}$, $\frac{\omega}{N} = 0{,}65$, $k * \frac{U_g}{N} = 0{,}05$

it15: $U_b = 2\ cm/s$, $U_g = 0.2\ cm/s$, $\frac{\omega}{N} = 0{,}65$, $\boldsymbol{k * \frac{U_g}{N} = 0{,}20}$




*Linear Energy fluxes* $< J_z(x,z) >_T$ *are assessed from density anomalies using a Green's function technique described by Allshouse et al., PRF, 2016 (top panels), and compared against the analytical solution of the generalized linear IW model introduced by Shakespeare, JPO, 2020 (bottom panels).*

- Energy fluxes **have similar amplitudes** in the two beams when $U_g = 0$, while the **energy flux is larger** in the **upstream beam** for the two experiments including a constant flow.
- The beam structure and amplitude **are well captured** by the extended linear model, which motivates an application to **realistic configurations**. The energy flux amplitude **is overestimated** in the linear prediction for it16 plausibly owing to the **intense nonlinear** activity measured close to the ridge.

Dossmann, Y.; Shakespeare, C.; Steward, K.; McC. Hogg, A.: Asymmetric internal tide generation in the presence of a geostrophic flow, *submitted to JGR-Oceans*.

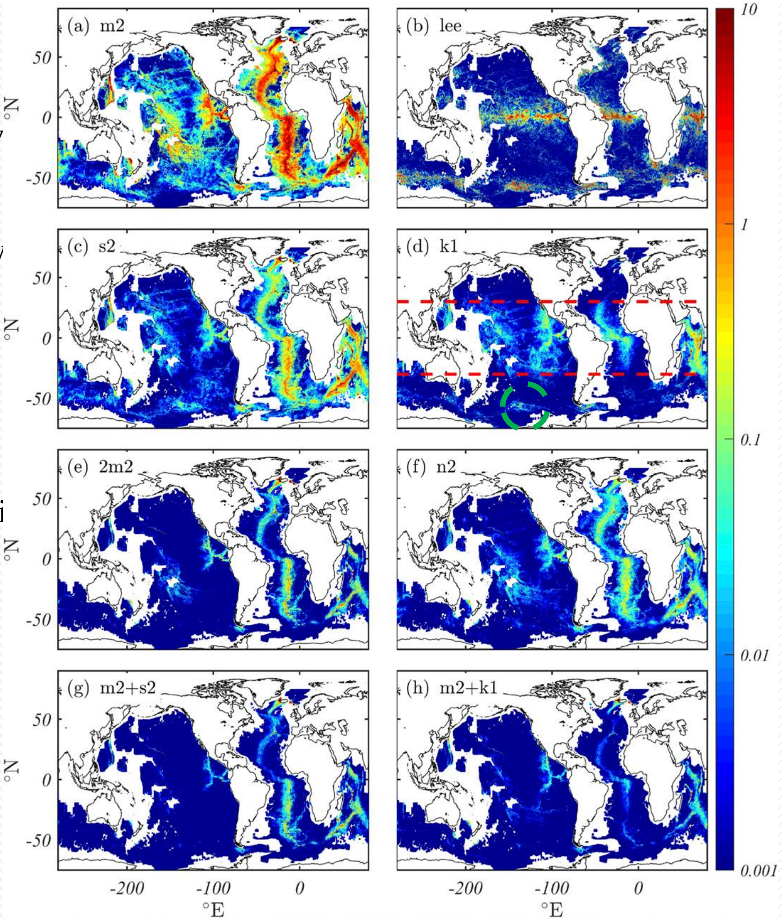
# Effects of IW coupling on oceanic budgets

- **Coupling** occurs between any single barotropic and geostrophic flow but also **between all possible combinations of barotropic flows**.

- Internal waves are classified either as « **free beams** » propagating away from their generation zone, or « **trapped waves** » that dissipates within the flow that generate them.

- **Doppler-shifted internal wave beams** can propagate in regions where they would dissipate in the absence of a steady flow, hence modifying the spatical distribution of internal waves and subsequent mixi

- The linear coupling causes an asymmetry betweem the upstream and downstream internal tide beams generated over hills, which in turn induces a **net wave stress of 0.1-1 N/m$^2$** comparable to the local wind stress.

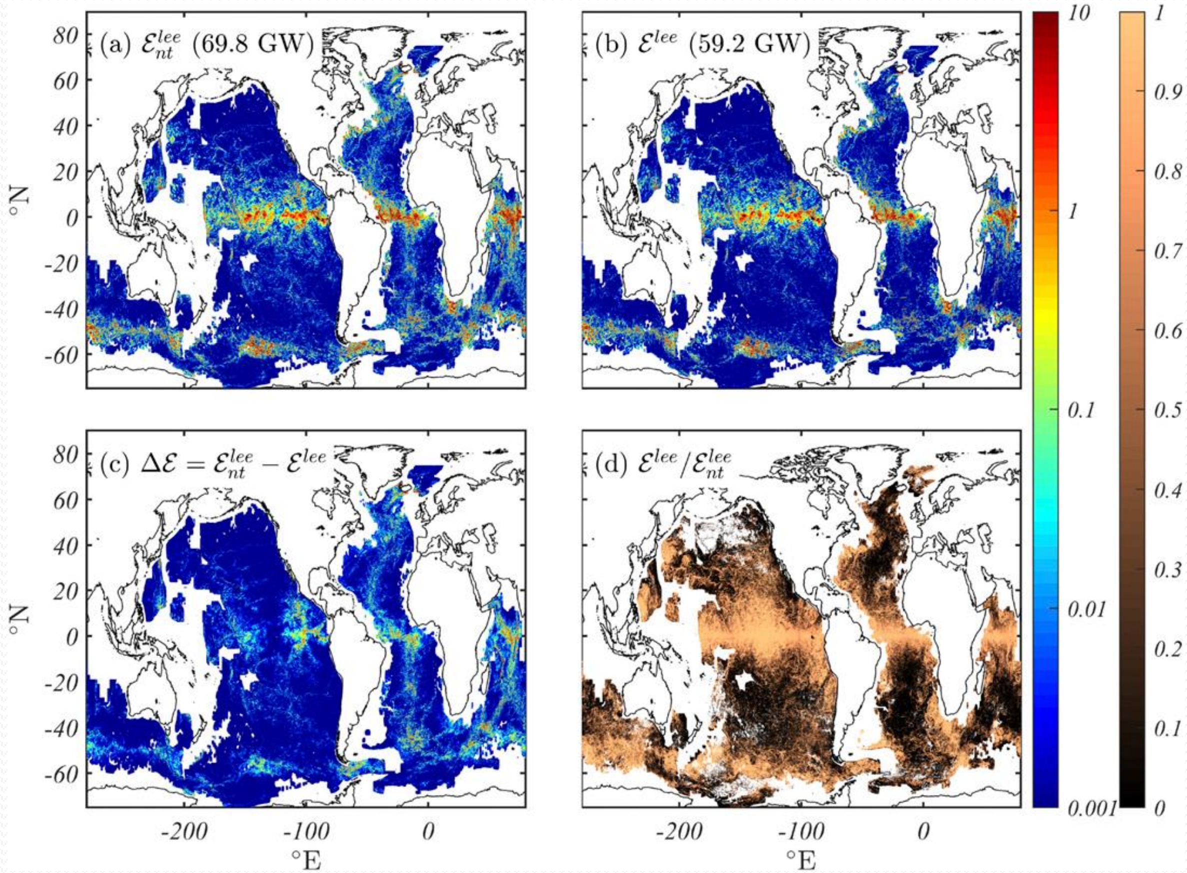



Shakespeare, C. J. (2020): Interdependence of internal tide and lee wave generation at abyssal hills: global calculations. *Journal of Physical Oceanography*, 50(3), 655-677.

*Wave energy flux (mW/m2) radiated from abyssal hills for the eight largest frequency contributors, accounting for 95% of the total flux, ranked from largest [(a) M2] to eighth largest [(h) M2 + K1]. The K1 critical latitudes are shown by dashed red lines on (d). Subinertial internal tides are shown by the dashed green circle. From Shakespeare, JPO, 2020.*

# Effects of IW coupling on oceanic budgets

**Lee wave** generation and induced mixing are **largely cancelled** – up to 90 %- in some key areas of the MOC such as the Drake Passage and is overestimated **by 10-19 %** on a global scale if the linear coupling **is not accounted for**.




*Lee wave energy flux (mWm22) radiated from abyssal hills: (a) energy flux at zero frequency (lee waves), ignoring the presence tides, as per previous calculations, (b) energy flux at zero frequency (lee waves), including the impact of the eight major tidal constituents, (c) the difference between (a) and (b), and (d) the lee wave suppression factor—i.e., the ratio of (b) to (a). The globally integrated energy flux in gigawatts is shown above (a) and (b). From Shakespeare, JPO, 2020.*

Shakespeare, C. J. (2020): Interdependence of internal tide and lee wave generation at abyssal hills: global calculations. *Journal of Physical Oceanography*, 50(3), 655-677.

# Conclusions

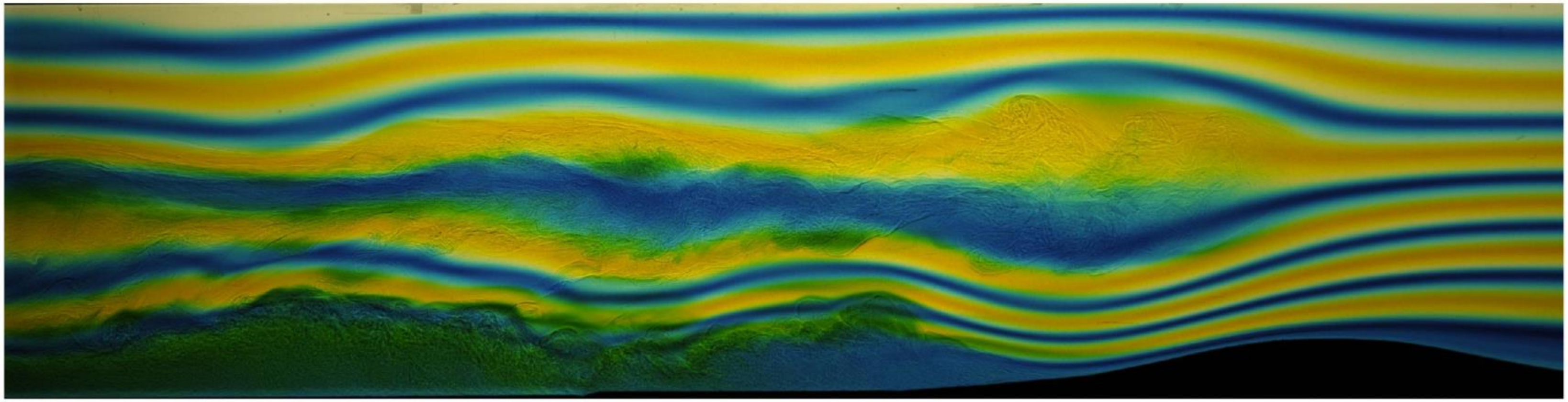
- **Internal tides and lee waves** dynamics and energy/momentum budgets are strongly affected by the existence of the **geostrophic/barotropic coupling**.

- The **symmetry breaking** induces an **impact on momentum/energy** fluxes Whose impact on the MOC is yet to quantify.

*What's next ?*

- **Describe the mixing induced by nonlinear processes close to the topography relative to internal wave mixing.**

Thank you ! Questions are welcome.



*From Dossmann et al., JGR-Oceans, 2016*