



Physical Oceanography  
NIOZ, Texel NL

# Processes near continental slopes, internal waves and mixing

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## *a tradition of internal wave studies...*

### **Start:**

~ thesis Leo Maas (1987)

- *theory*

- *modeling*

(-*observations North Sea*)

*...gradually expanding to (multidisciplinary) studies  
above sloping bottoms*

**..Laboratory modeling: internal wave focusing**

**..Observational projects**

(collaboration with biologists, sedimentologists ) e.g.:

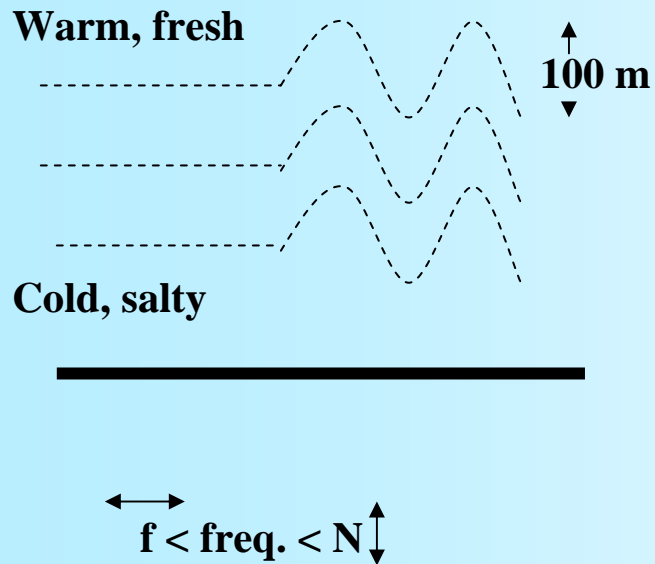
- *BBB (Bay of Biscay)*

- *PROCS (Faeroe-Shetland Channel)*

- *LOCO (Canary Basin, Irminger Sea, Mozambique Channel)*

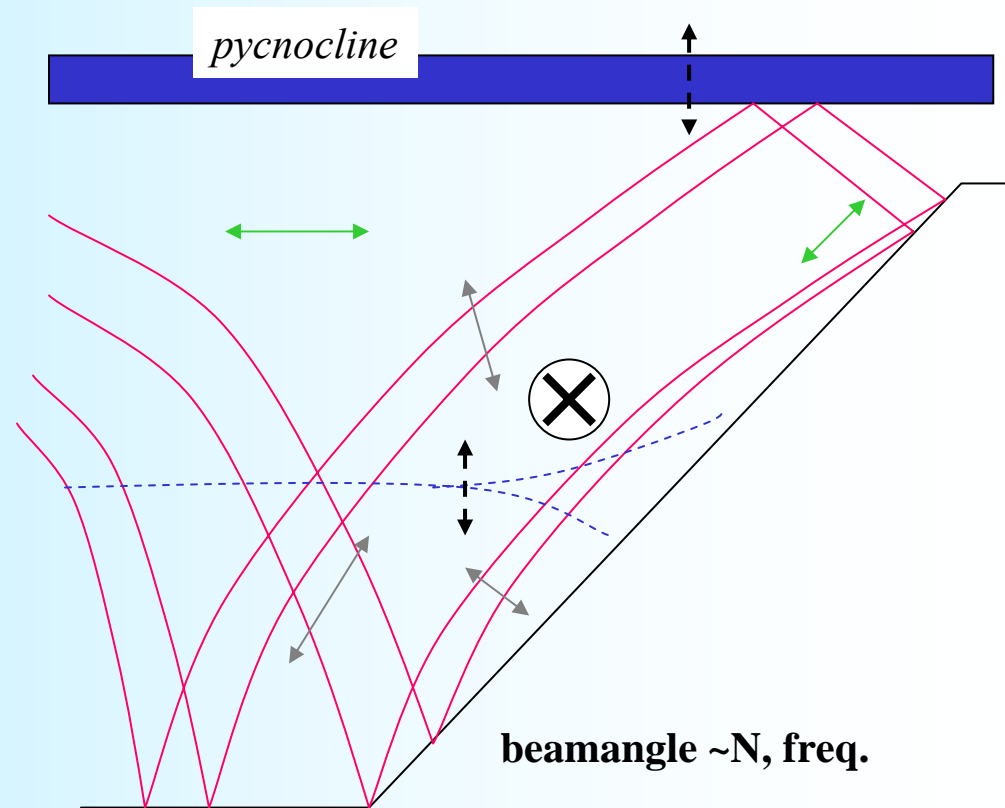
# What are internal waves?

**Vertical stratification  
in density support:  
internal gravity waves**



**Due to rotation of the Earth:  
inertial (gyroscopic) waves**

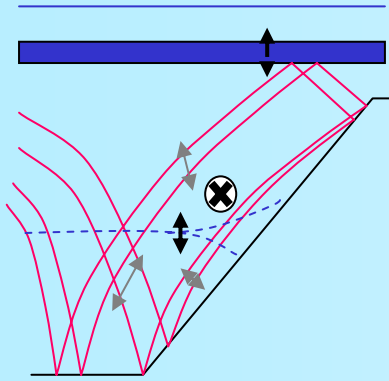
**3-D:  
'beam' generation above sloping bottoms**



## Impact of internal waves ---> mixing?

- affects sediment transport (generating ‘nepheloid layers’)
- affects biology (- plankton moving in/out the photic zone
  - supply of nutrients in photic zone)
- affects the large-scale meridional overturning circulation,  
(the ocean is very different from the (convective) atmosphere).  
(Munk & Wunsch, DSR 1998; MW);
  - Proposed required diapycnal diffusivity,  $K_\rho = 10^{-4} \text{ m}^2 \text{ s}^{-1}$
- ∴ mixing induced half by wind; half by tides (MW)
- ∴ mixing induced by breaking internal waves (MW)
  - Observed open ocean values  $K_\rho = 10^{-5} \text{ m}^2 \text{ s}^{-1}$ ;
- ∴ buoyancy flux achieved by a small number of concentrated sources, i.e. at sloping bottoms (Armi, JGR, 1978; Garrett, JGR 1990)

# internal waves and sloping bottoms



Internal tide generation

Critical reflection

Wave steepening + front formation

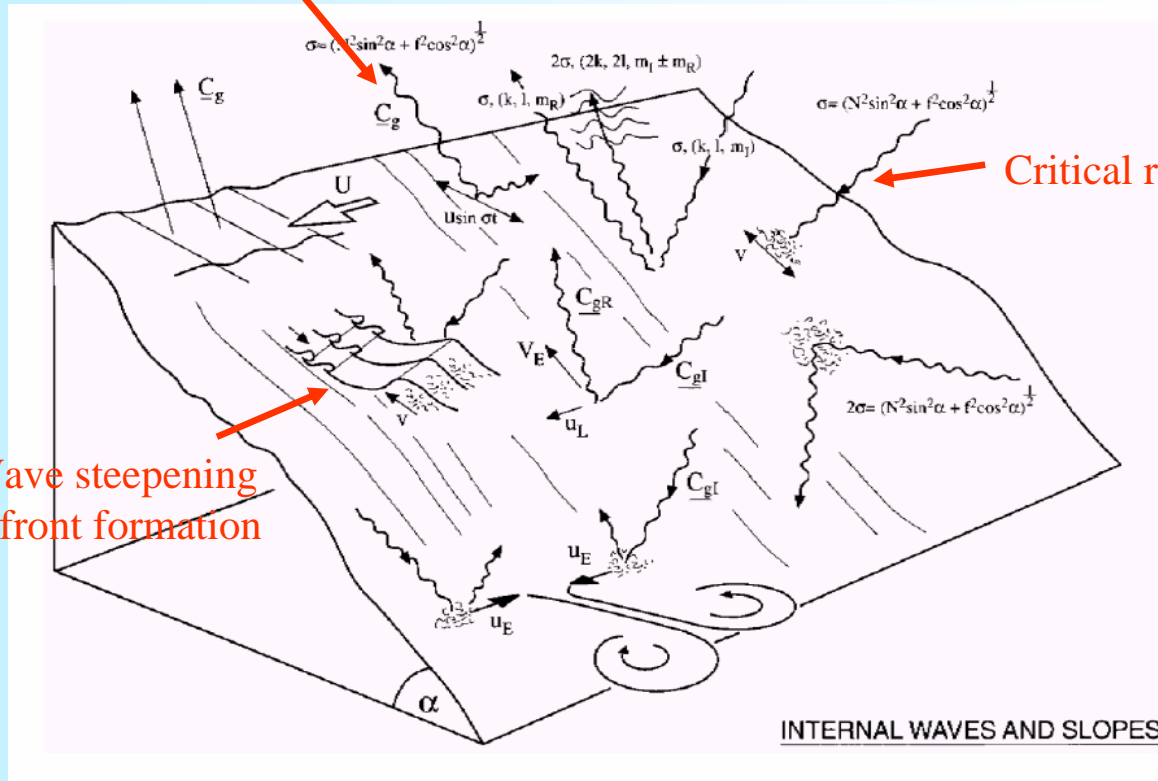
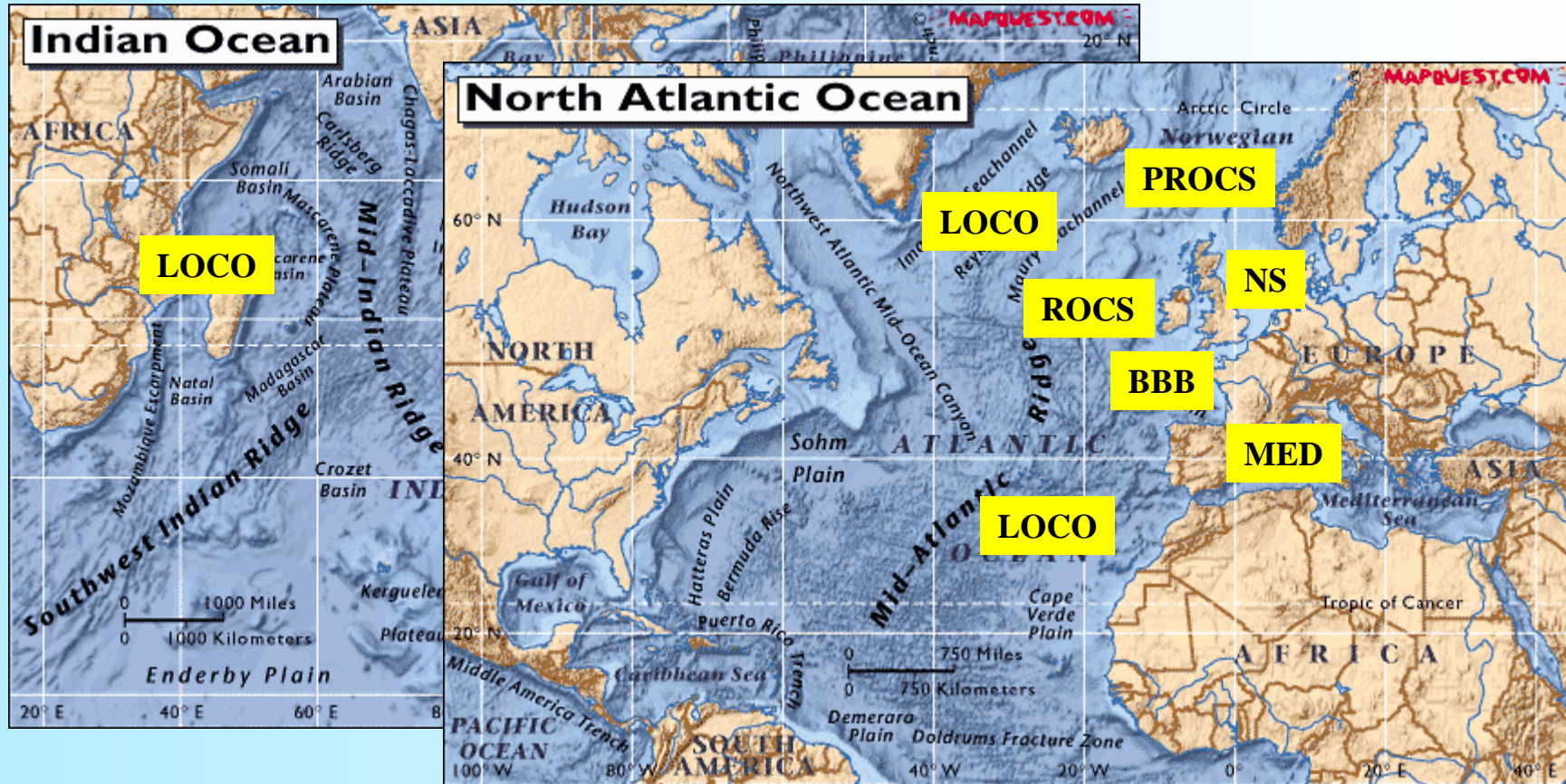


Figure: Thorpe, 1999

*As a result, we continue working on internal waves above sloping bottoms  
observational programs...*

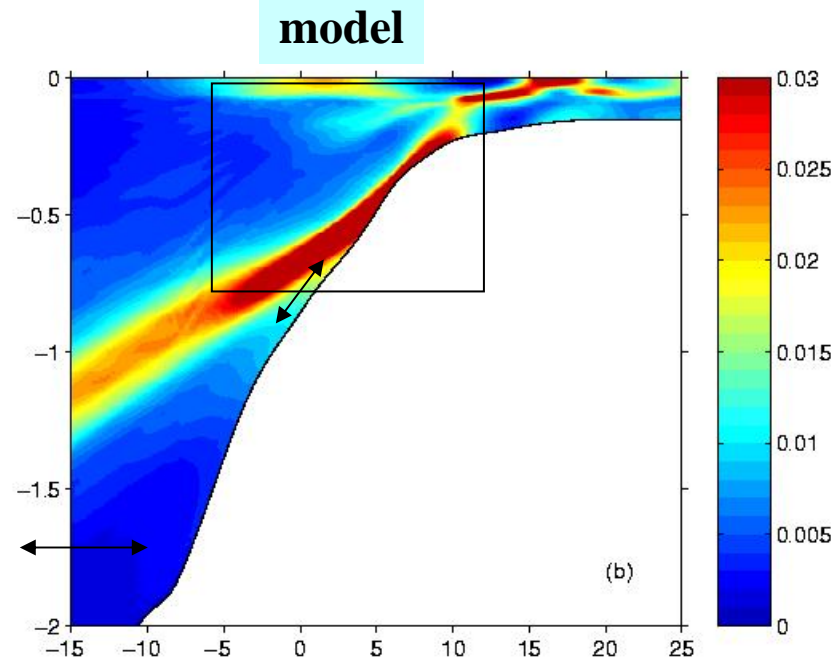


**NS:** 1981-1998  
**BBB:** 1994-1997  
**PROCS:** 1997-1999  
**ROCS:** 2002  
**MED:** 2002-2004?  
**LOCO:** 2003-2007?

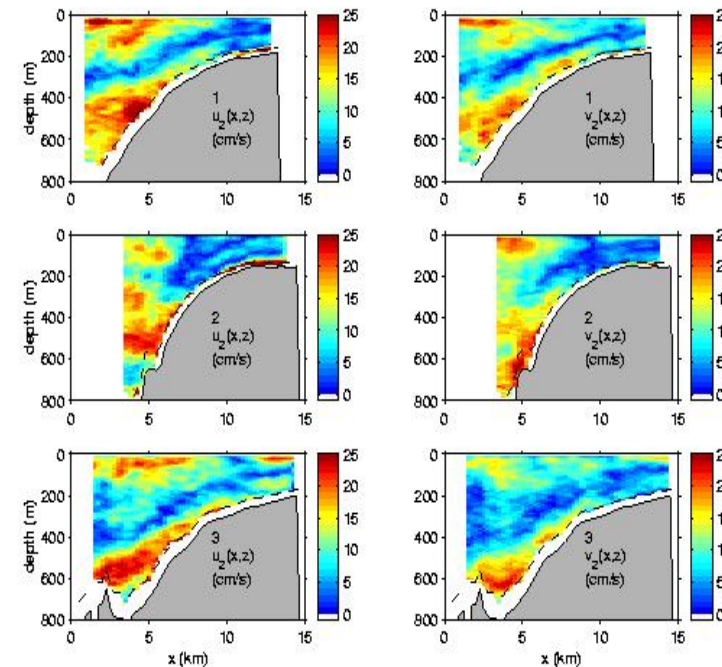
**...and modeling**

## An overview of the poster presentations/results

### Internal tide generation: BBB (F.-P. Lam, L. Maas, Th. Gerkema)

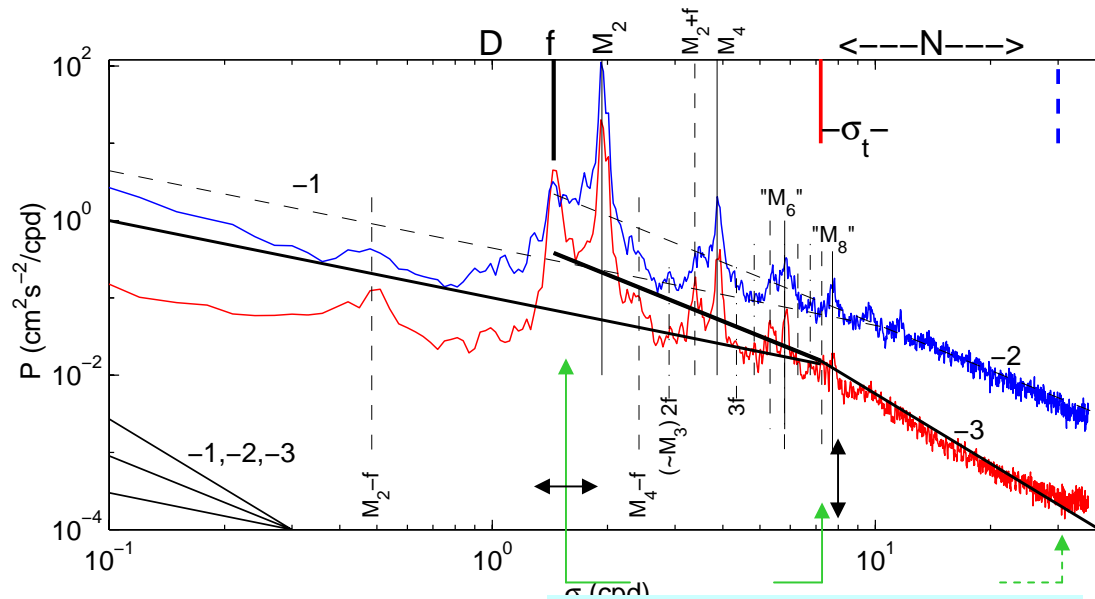


### ADCP transect observations



*Also: varying spring-neap cycles upon varying beams M2, S2 (Th. Gerkema)*

## Long-term monitoring: BBB (H. van Haren, L. Maas, H. van Aken)



(moored obs; 1 yr)  
1000 m above the bottom

1450 m

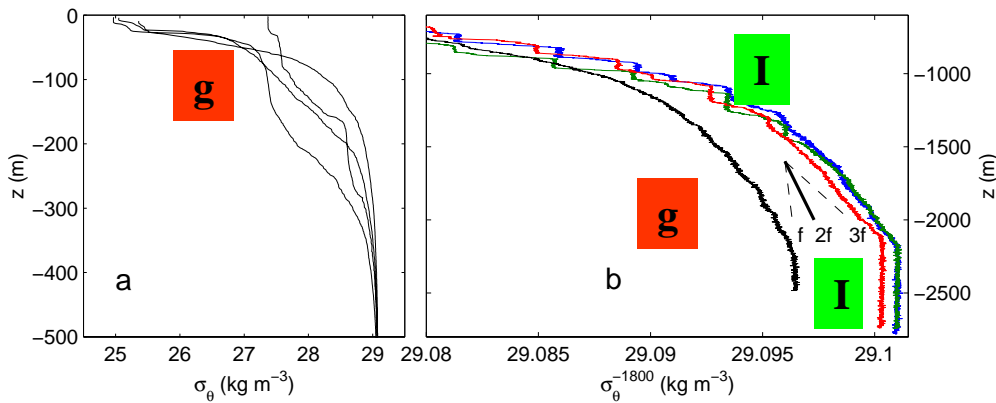
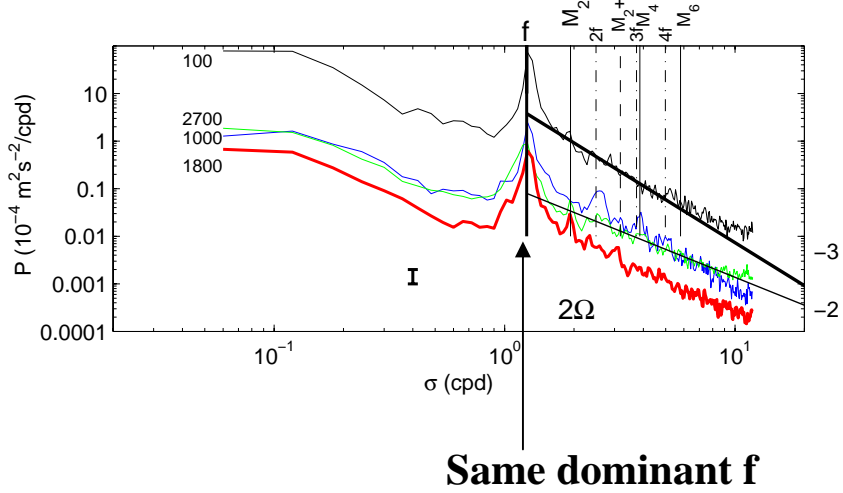
3810 m

Internal gravity wave band

**Inertial-tidal internal gravity wave  
non-linear interactions**

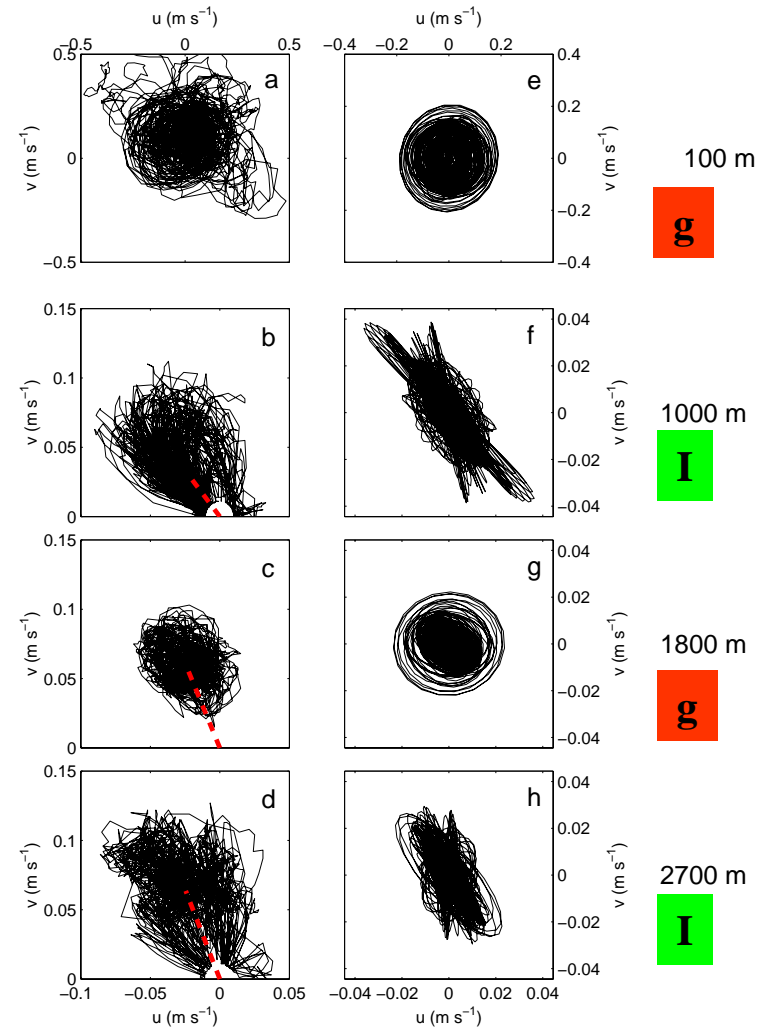
- largest energy
- largest shear
- “internal mixing”
- $f$  ‘indirect’ induced by atmosphere
- no direct wind-tide interaction

# MED (H. van Haren, C. Millot (Ifremer))



van Haren and Millot Figure 2

## Gravity (g) vs Inertial (I)



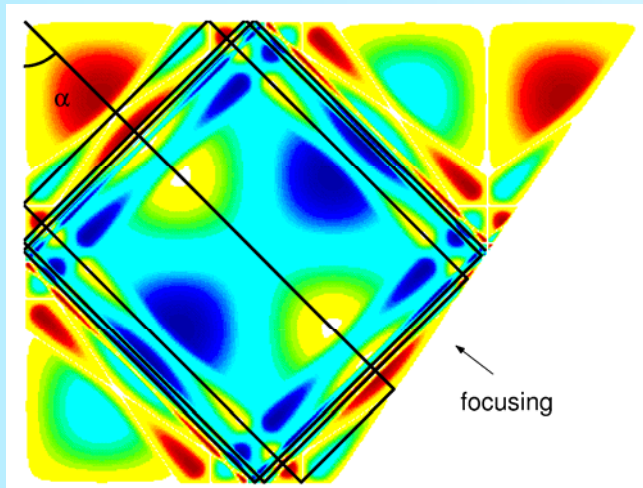
van Haren and Millot Figure 6

**Inertial (gyroscopic) waves:  
- strong vertical current**

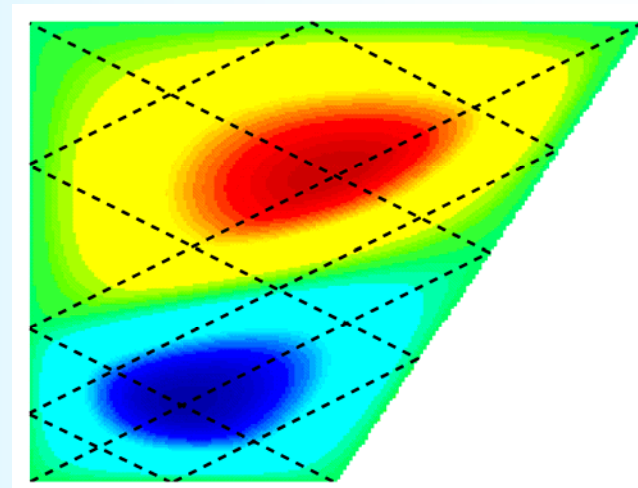
# Modeling Inertial (gyroscopic) waves (A. Manders, L. Maas;Grenoble, Eindhoven)

## Inertial wave focusing and attraction

Dispersion relation:  $\omega(\alpha)$ .  $\longrightarrow$  Angle  $\alpha$  conserved upon reflection  
sloping walls  $\longrightarrow$  focusing or defocusing of wave rays  
repeated reflection in enclosed basin  $\longrightarrow$  **wave attractor**



- net focusing
- attractors
- frequency intervals



- balance focusing-defocusing
- standing waves
- isolated frequencies

## Internal gravity wave Modeling (F.-P. Lam, L. Maas;E.N.S.L. LYON)

**Generation by a vertical oscillating cylinder above a sloping bottom**



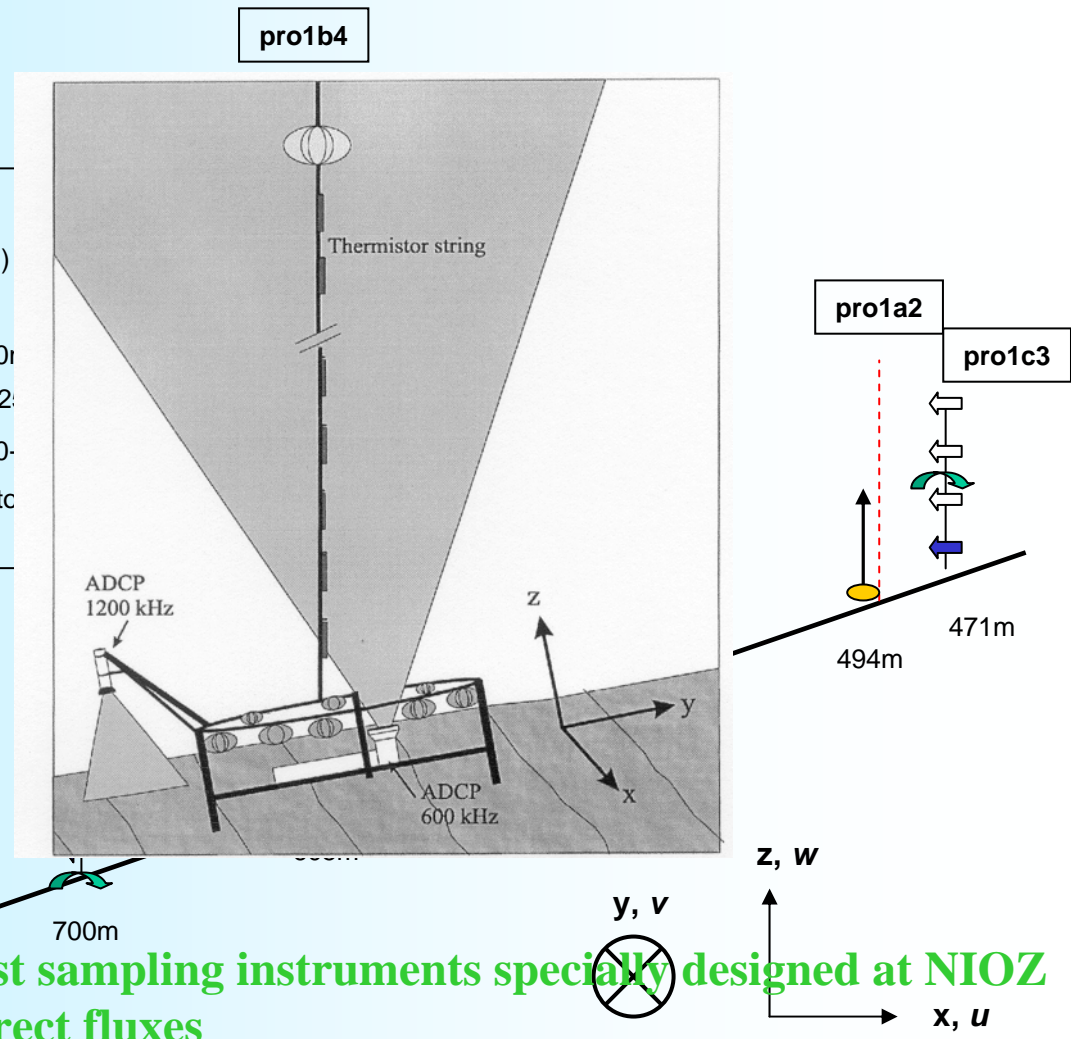
# Observations at sloping bottoms: PROCS

(Ph. Hosegood, H. van Haren, J. Zimmerman, C. Veth; H. Ridderinkhof; NIOZ Dept. MCG)

## Experimental set-up

### PROCS 99-1

- ← RCM-9 ( $z = 8\text{ m}$ )
- ↔ RCM-8 ( $z = 21, 34, 47\text{ m}$ )
- ★ No data available
- ↻ OBS, sed. trap ( $z = 2, 30\text{ m}$ )
- 75 kHz LR-ADCP (578-2000 m)
- 600 MHz BB-ADCP (440-578 m)
- - - NIOZ/Aanderaa thermistor ( $z = 2 - 57\text{ m}$ )



-fast sampling instruments specially designed at NIOZ  
-direct fluxes

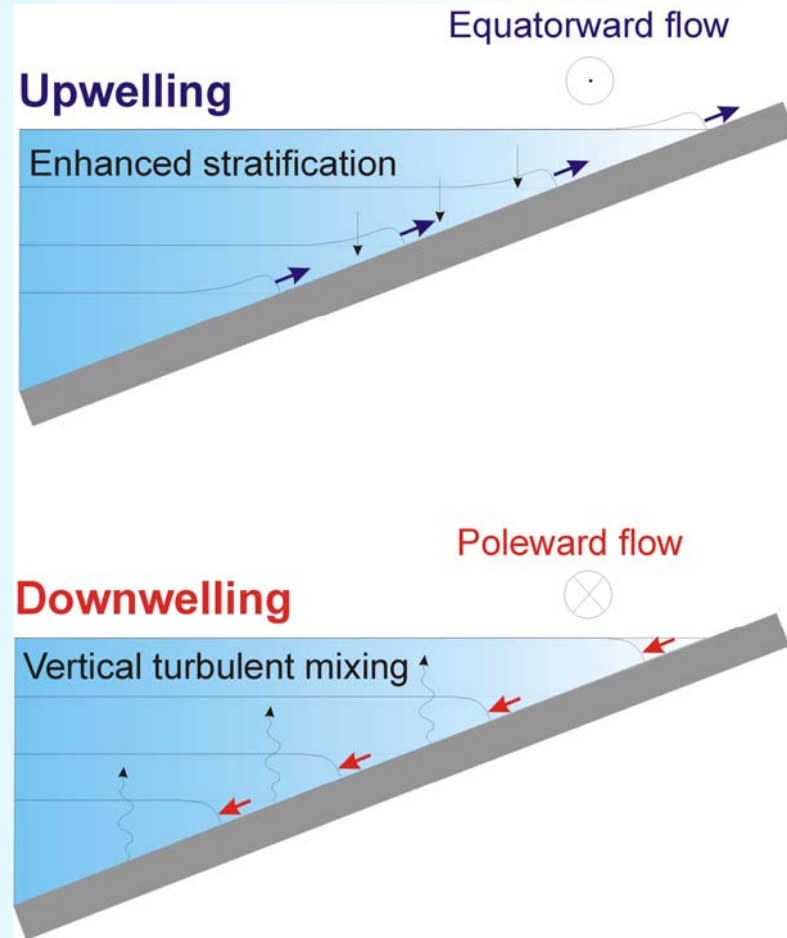
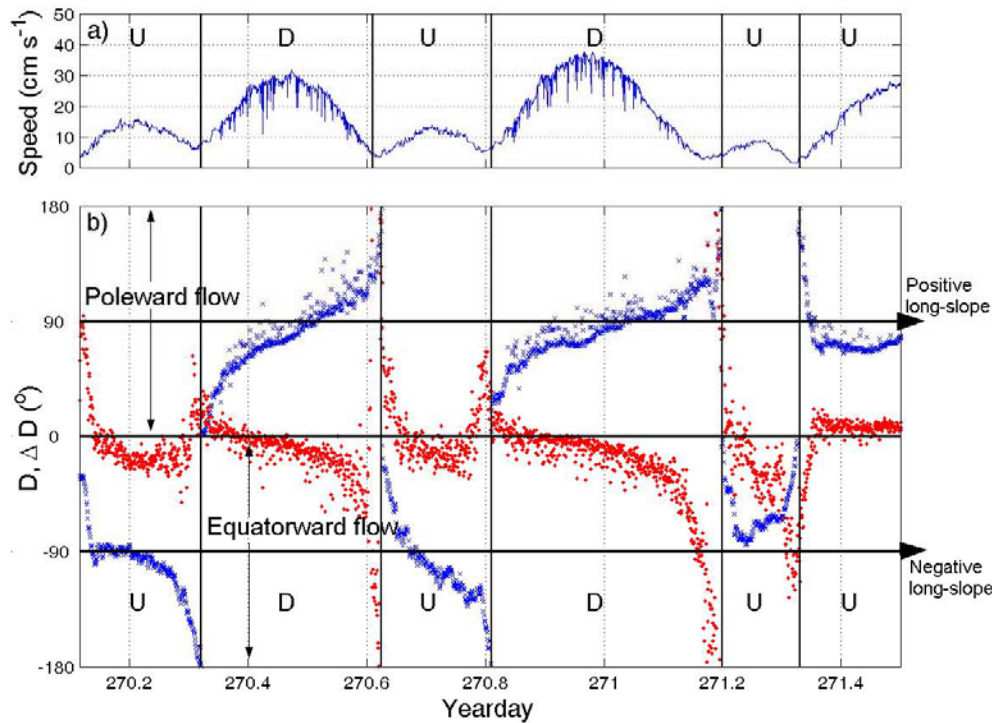
# 'Turbulence' from CM records

(Ph. Hosegood, H. van Haren)

Other turbulent motions over the slope:

- Ekman dynamics
- solibores

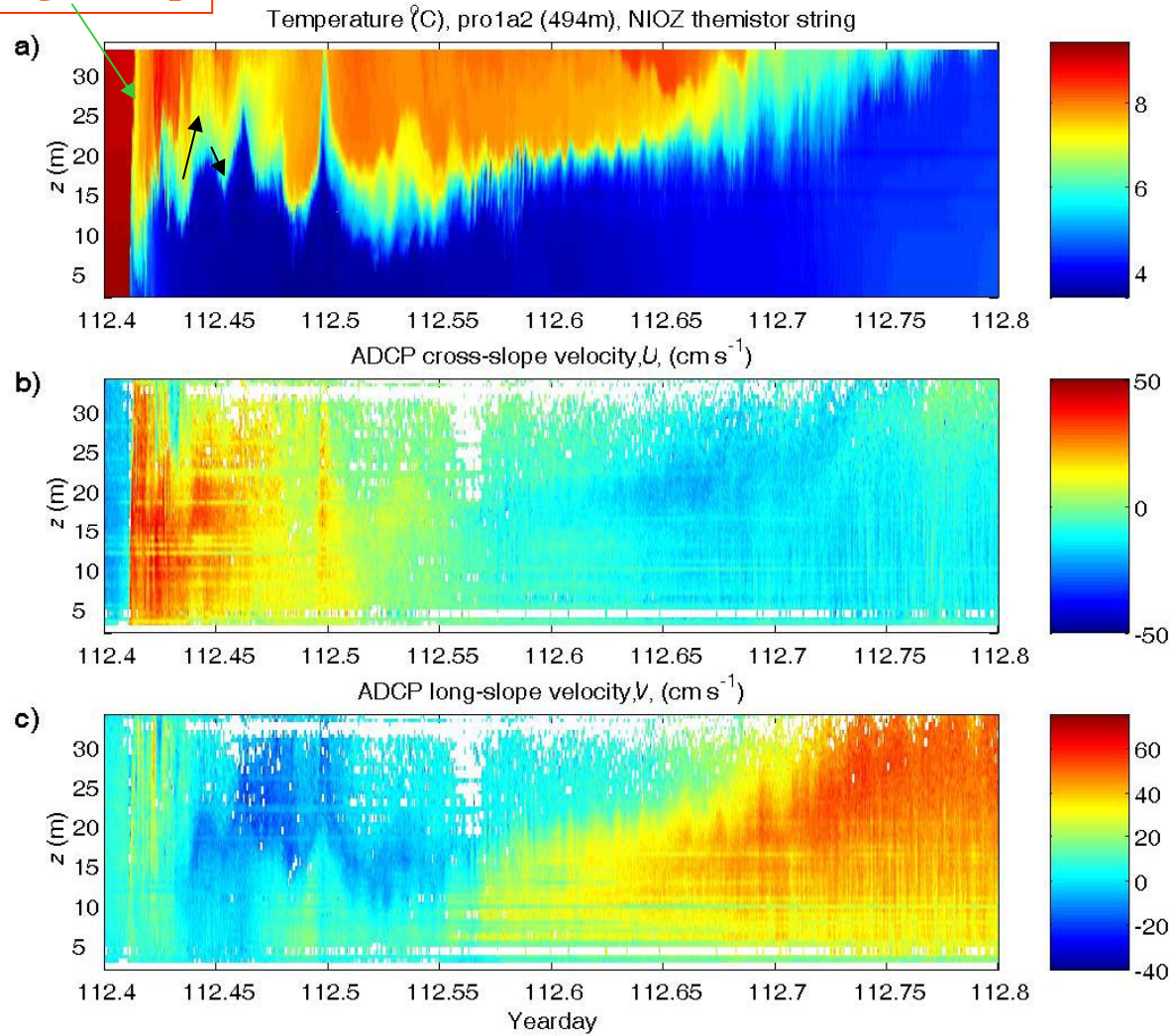
Ekman dynamics: asymmetric response



# Observations of vigorous turbulent event: solibore

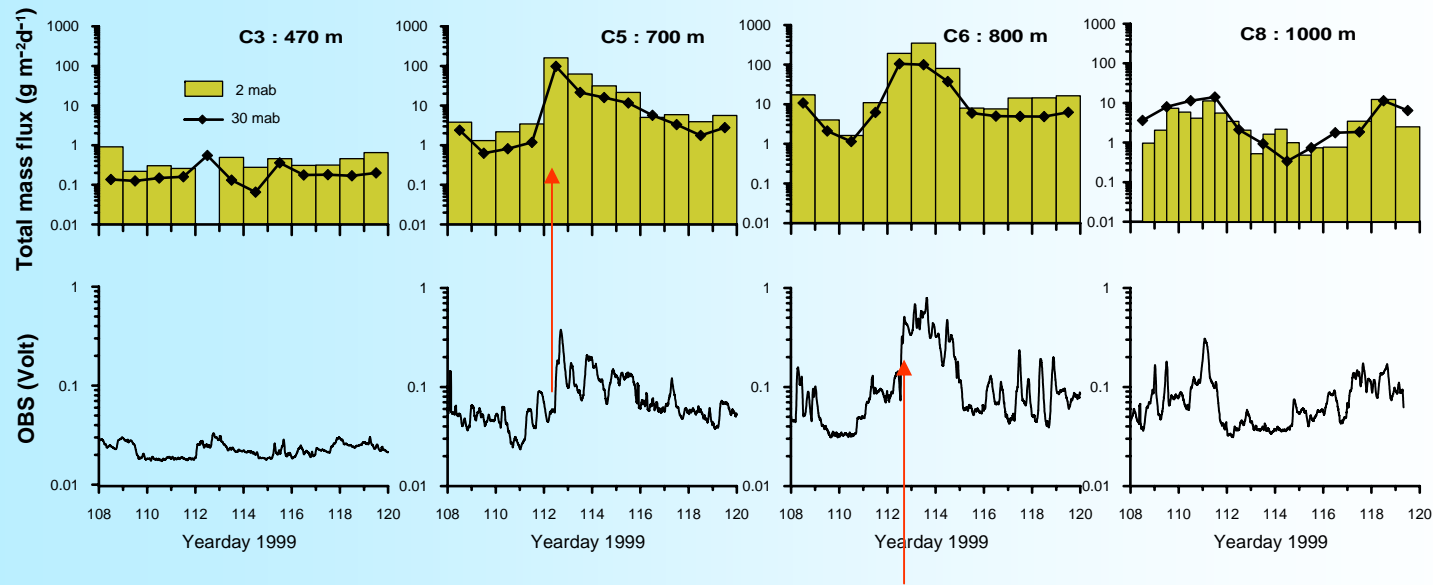
(Ph. Hosegood, J. Bonnin, H. van Haren)

**Strong T drop**



# Enhanced sediment transport during passage of the bore

- Sediment fluxes during period following event  $O(10^2)$  larger than prior to passage of bore;
- Fluxes largest at 777m and 700m  $>100 \text{ g m}^{-2} \text{ d}^{-1}$
- Fluxes at 471m  $<1 \text{ g m}^{-2} \text{ d}^{-1}$
- OBS at 1000m minimum during and after event



## **Future**

- 1) Observational programs: LOCO (just started), MED, collaboration POL in Faeroe-Shetland Channel
- 2) Continuation theoretical/modeling work (just funded NWO-ALW)
- 3) Continued collaboration with NIOZ-MCG department
- 5) We will apply for additional funds for Post-Doc, PhD positions within LOCO