Characterisation of internal waves in the Strait of Messina

Gaëlle Casagrande[1,2], Yann Stéphan[1], Alex Warn Varnas[3], and Thomas Folégot[2]

[1] Service Hydrographique et Océanographique de la Marine, BP 30316, 13, rue Le Chatellier, 29200 BREST, FRANCE (gaelle.casagrande@shom.fr)
[2] NATO Undersea Research Centre, MILOC, Viale San Bartolomeo, 400, 19126 La Spezia, ITALY
[3] Naval Research Laboratory, Stennis Space Center, MS 39529, USA

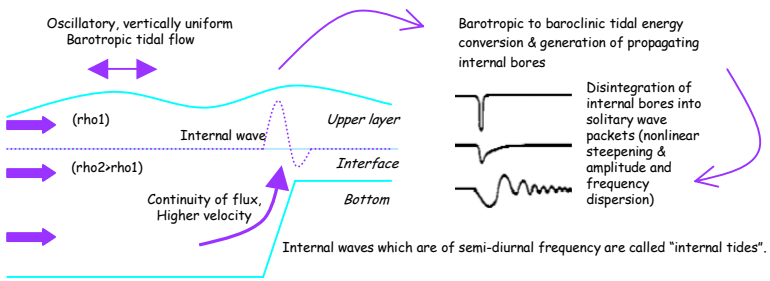
Abstract

The internal waves (IW) in the south of the Strait of Messina (Italy) are studied using observational data and numerical simulations. The observational data consisted in SAR images, XBT/CTD measurements and thermistor string measurements from the COACH06 cruise. The numerical model used was the Lamb model, which solves the fully nonlinear, nonhydrostatic Boussinesq equations on a f plane. The model is two-dimensional, with spatial variation in the vertical and cross-bank directions only.
Ten out of fourteen SAR images presented internal waves' events for the month of October 2006. From these images, we estimated some of the internal waves figures: a propagation speed of 1.00 m/s, a bore release time of 2 hours after maximum northward tidal flow at Punta Pezzo, a wavelength increase of 37m/km for the two first waves.
The in-situ data were then used to initialize and evaluate the Lamb model. An Empirical Orthogonal Function (EOF) analysis was applied to the data and the model outputs. The first two empirical functions' structure represent over 99% of the variability. The data and the model are in a very good qualitative and quantitative agreement, giving an IW propagation depth at 90m with a density gradient oscillating from 85 to 115m. Using these two first modes, an original method for detecting IW was carried out by looking at the hysteresis caused by the density anomaly projected on the first EOF versus the density anomaly projected on the second EOF. In the presence of IW, this hysteresis has a specific parabolic shape.

Internal waves recipe : "tide-topography interaction"

- Density stratified fluid (thermocline)
- Pronounced variation in depth (strait topography)
- Barotropic tidal flow (M2 – 12.4h)

} **Internal Tides Generation**



Internal waves which are of semi-diurnal frequency are called "internal tides".

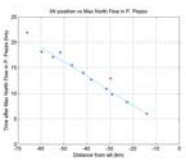
The Strait of Messina: data available

SAR Data Analysis

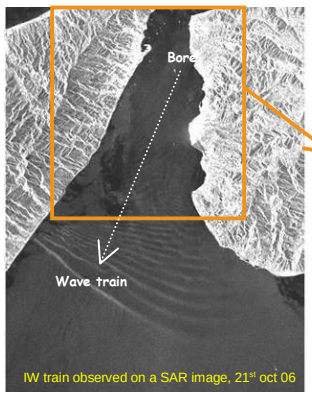
- 8 ASAR images
  Envisat Satellite (2002)
  European Space Agency
  12-13m resolution
- 7 RADARSAT images
  RadarSat I Satellite (1995)
  Canadian Space Agency
  8m resolution

→ *15 SAR images available*
- 11 IW occurrence in october

→ *15 SAR images available*
→ 11 IW occurrence in October



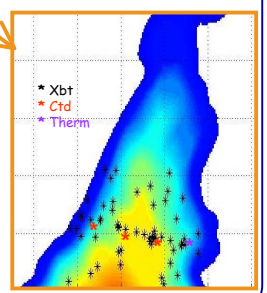
Velocity : 0.97m/s
Release time : 1.93 hrs
First wavelength increase:37m/km



IW train observed on a SAR image, 21st oct 06

In situ data

- XBT : 129 measurements
  → 58 in the south
- CTD : 35 measurements
- Thermistor strings :
  → 2 south (2.8 days)
  → 1 north



The LAMB model to describe the Strait of Messina

Description :

Solves fully nonlinear,nonhydrostatic Boussinesq equations on a f-plane :

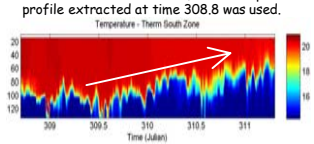
$$U_t + U.\nabla U - fv_i = -\nabla p - \rho g$$
$$v_t + U.\nabla v + fu = 0$$
$$\rho_t + U.\nabla \rho = 0$$
$$\nabla.U = 0$$

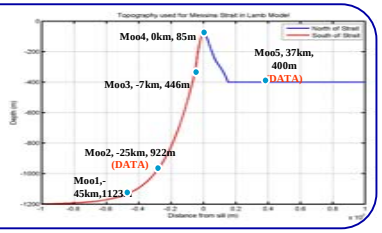
2D : vertical and cross-bank directions

Initialization :

- No meteorology,
- Rigid lid at the surface
- Outflow on right boundary,
- One tidal component (M2), initialization on left boundary,
- Smooth topography described as a function,
- Density profile at both boundaries, data inputs from measurements,
- 1350x150 grid points, 36 hours runs,
- Five implemented moorings.

For the initialization, the density profiles were computed from the temperature measured by the thermistor string (below). For the first simulation, the temperature profile extracted at time 308.8 was used.

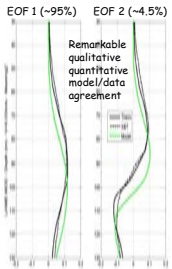


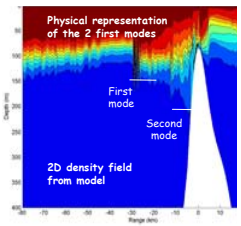


How internal waves events can be detected using EOF hysteresis curves ?

EOF analysis :

To study the data and the corresponding model outputs (mooring 2), an **empirical orthogonal function (EOF) analysis** of the time series of the potential density was carried out. The EOF procedure provides a compact description of the spatial and temporal variability of data series in terms of orthogonal functions. Only the two first modes (over 99.5% of the variability) are displayed. The amplitude of the first mode does not change sign over the water column and therefore, all the isopycnals oscillate in the same direction; the maximum displacement is around 95m. The 2nd EOF is changing sign around 105m indicating that isopycnals are moving in opposite directions above and below the thermocline.

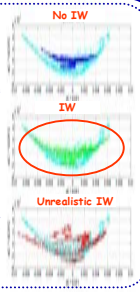




An original detection method:

In the presence of IW, it was noticed that the hysteresis formed by the projection on mode 2 versus projection on mode 1 of the data density anomaly had a parabolic shape (data in cyan).

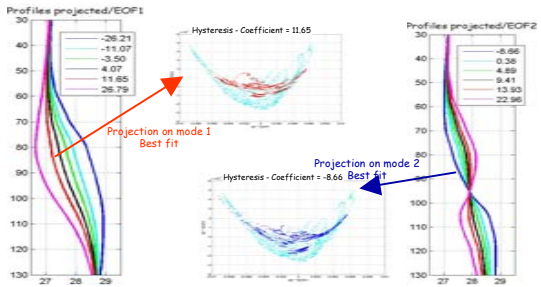
Applying this to several model outputs confirmed the detection property:
- no IW (blue): the hysteresis is small and concentrated,
- IW (green): the hysteresis takes a parabolic shape traducing the increasing amplitudes of modes 1 and 2,
- unrealistic IW (red): the hysteresis is too wide.



Sensitivity tests :

The density profiles were projected either on the 1st mode, either on the 2nd mode, with different projection coefficients ranging from the minimum value to the maximum value of the coefficients observed from data (profiles besides, the legend gives the coefficients' value).

Projecting the profiles on one mode was a way to see how the model behaved and what had to be tuned precisely (gradient ? thermocline depth ?) to get the best representation of the internal waves dynamics.



Looking at the hysteresis, the best density profile to get internal waves can be identified. It is the one representative of a well stratified water column, independently of the mode considered (red profile for the profiles projected on EOF1, blue profile for the profiles projected on EOF2).

Once a representative profile is chosen, the inflexion point's depth becomes the main factor impacting on the model outputs' quality.

Profiles presenting a gradient inversion annihilate the internal waves generation (mainly profiles projected on mode 2) because of instability and thus mixing in the water column.

What should you remember ?

➢ Very good fit data/model :

The model, initialized by two density profiles on each side of the strait, behaves very well for reproducing internal waves characteristics,

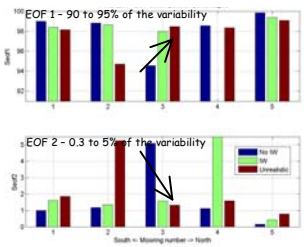
➢ EOF hysteresis, an original internal wave detection method :

The decomposition was used as a tool to detect the presence of internal waves by plotting the density anomaly projected on EOF2 versus the density anomaly projected on EOF1 :
- **➢ No internal waves : the hysteresis is small and centered, the projection on the second mode is less important than the one on the first mode,**
- **➢ Internal wave event : the value intervals of the projection coefficients on the two first modes become wider and leads to a parabolic shape of the hysteresis,**

➢ For an operational and tactical benefit :

➢This method can be easily implemented and used to detect the presence of internal waves and thus warn the users to use an appropriate modelling for acoustic propagation purposes,
➢ The study focused on the south of the strait but it was noticed that the variability of the modes in the south hardly impacts on the north of the strait (military scenario where armed forces are in possession of one side of the strait),
➢ The modelling effort must be focused on the first mode, thus the thermocline depth.

Percentages of the two first EOFs for several runs with or without IW



Increase of first mode at the expense of mode 2 close to the bore formation location in the presence of internal waves events. This location appears to be the tactical position for measurement and characterisation

Very weak impact of the dynamics of the south of the Strait onto the North of the Strait

Mode 2 very present at the strait (tidal dynamics)