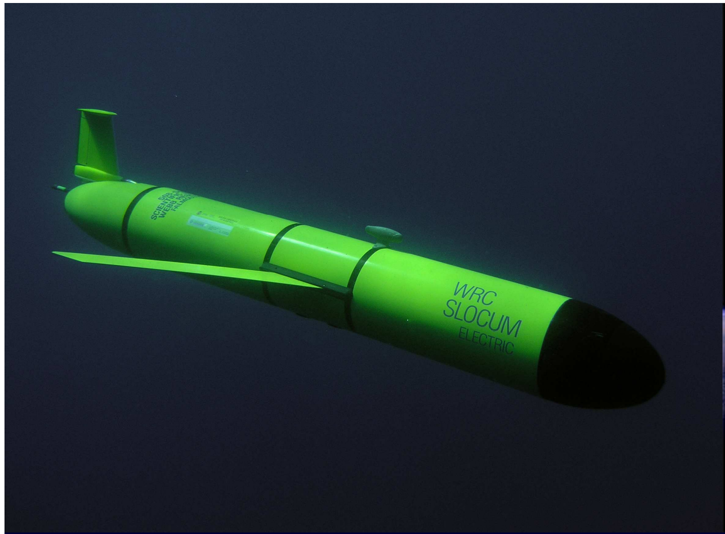


High resolution multi-sensor experiments to diagnose vertical motion in the upper ocean

A. Pascual, IMEDEA(CSIC-UIB), Spain
S. Ruiz, IMEDEA (CSIC-UIB), Spain
J. Bouffard, IMEDEA (CSIC-UIB), Spain
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Towards High-Resolution of Ocean Dynamics and Terrestrial Surface Waters from Space Workshop, Lisbon 2010

CSIC
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Universitat de les Illes Balears
IMEDEA
ISAC
CLS
COLLECTE LOCALISATION SATELLITES
Ifremer
SOCIB Balearic Islands Coastal Observing and Forecasting System

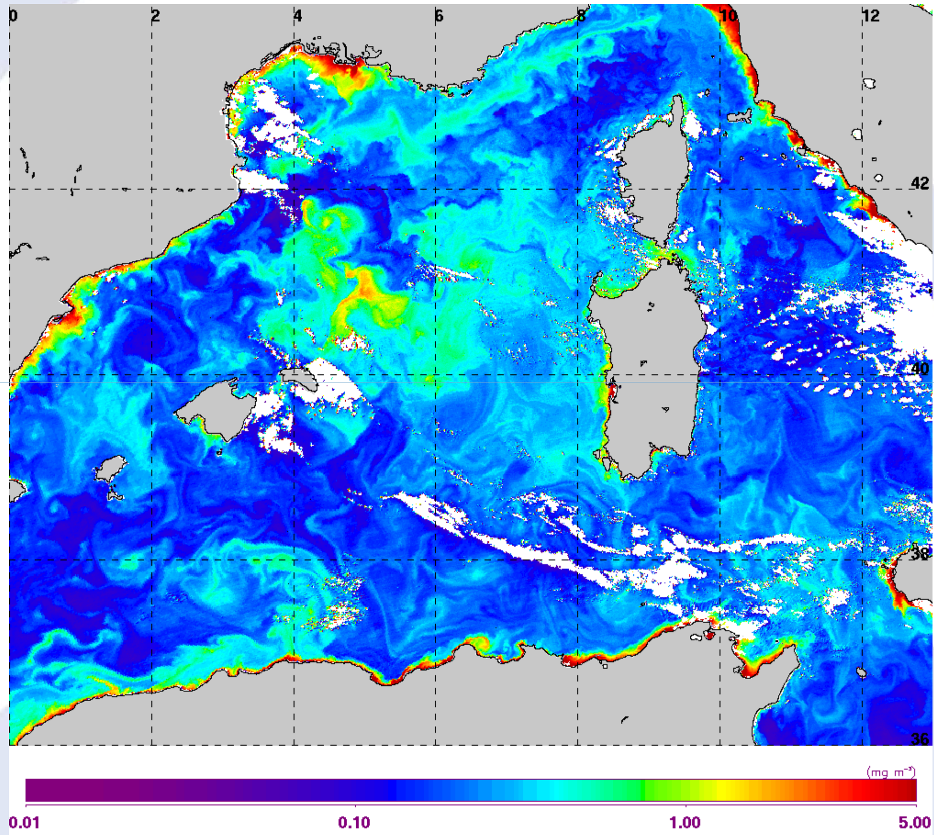
Outline

- Scientific motivation
- Past in situ experiments: limitations and challenges
- Recent multi-sensor experiments: use of new technologies
- Summary
- Perspectives

Scientific motivation

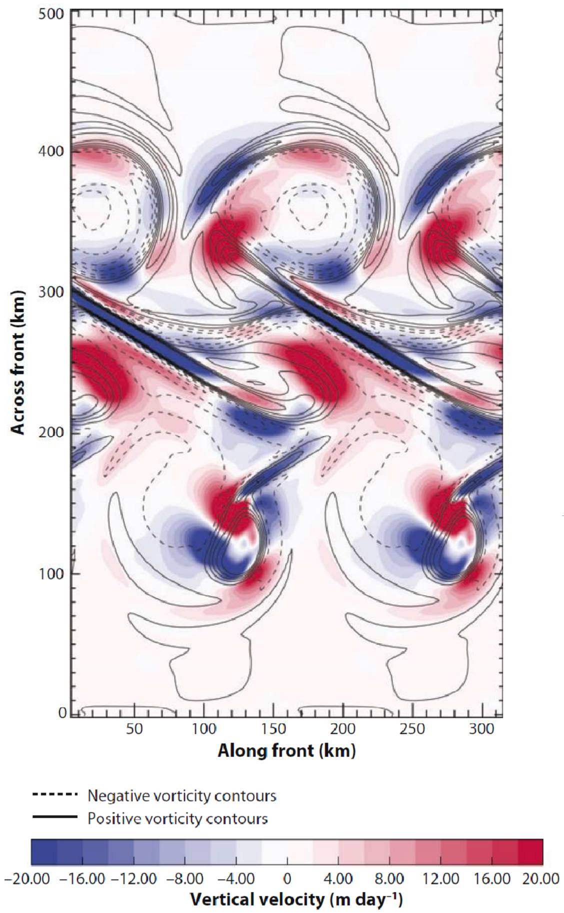
- Understanding the relationship between the physical and biological processes is crucial for predicting the marine ecosystems response to changes in the climate system (Siedler et al 2001; McGillicuddy et al 2007) .

- Vertical motion associated with mesoscale and sub-mesoscale features is plays a major role in the exchanges of properties between the surface and the ocean interior (Klein-Lapeyre 2008).



SeaWiFS chlorophyll image. Unites are mg m^{-3} .
Mesoscale dynamics modulates biological responses.

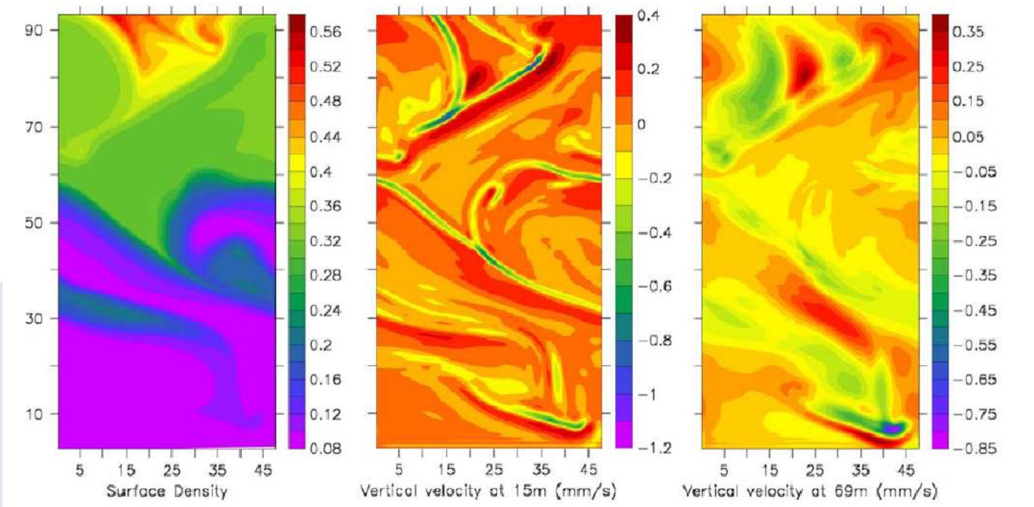
Scientific motivation



Vertical velocities at 90 m from primitive equation simulations. Lévy et al 2001, Klein & Lapeyre 2008

- Modelling studies of frontal regions (Lévy et al 2001; Mahadevan 2006; Capet et al 2006; Klein & Lapeyre 2008) suggest that vertical exchange is enhanced at density fronts.

- Unfortunately, it is not yet possible to make direct measurements of vertical velocities of values less than 1000 m/day. Instead, it can be inferred from a 3D field of the density field in the QG formulation (Hoskins et al. 1978).



Surface density, vertical velocitiy at 15 m and 69 m from primitive equation simulations. Mahadevan 2006.

Scientific motivation

QG Dynamics. Vertical velocity: Omega Equation. Vector-Q formulation

$$f^2 \frac{\partial^2 \omega}{\partial z^2} + \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \left(N^2 \omega \right) = \nabla_h Q$$

$$Q = \left[2f \left(\frac{\partial V}{\partial x} \frac{\partial U}{\partial z} + \frac{\partial V}{\partial y} \frac{\partial V}{\partial z} \right), -2f \left(\frac{\partial U}{\partial x} \frac{\partial U}{\partial z} + \frac{\partial U}{\partial y} \frac{\partial V}{\partial z} \right) \right]$$

Hoskins et al (1978)
Holton (1979)

$$\frac{|\mathbf{u}_a|}{|\mathbf{U}|} = O(\varepsilon) \qquad \varepsilon \ll 1$$

where (U,V) are the geostrophic velocity components, *N* Brunt-Vaisala frequency and *f* the Coriolis parameter.

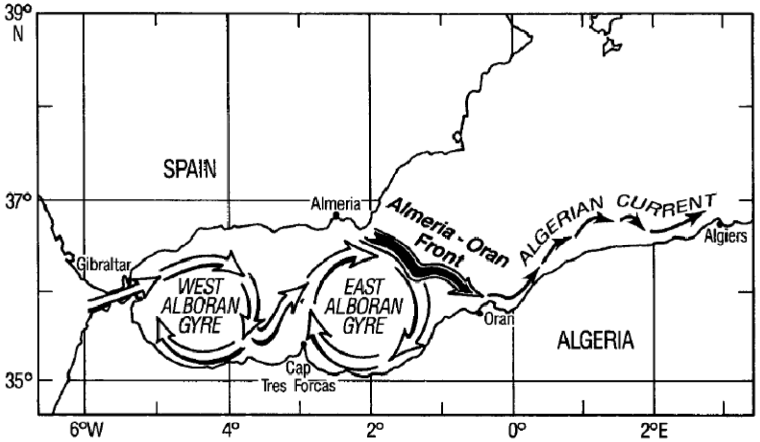
By assuming a BC for ω and from a 3D snapshot of the density field, the vertical velocity can be inferred. We set w = 0 at the upper and lower boundaries and Neumann conditions (normal derivative to zero) at the lateral boundaries (Pinot et al., 1996).

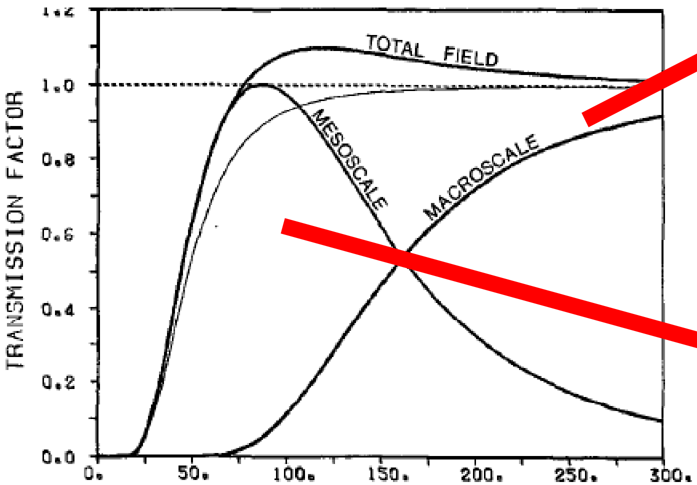
Past in situ experiments

JOURNAL OF PHYSICAL OCEANOGRAPHY

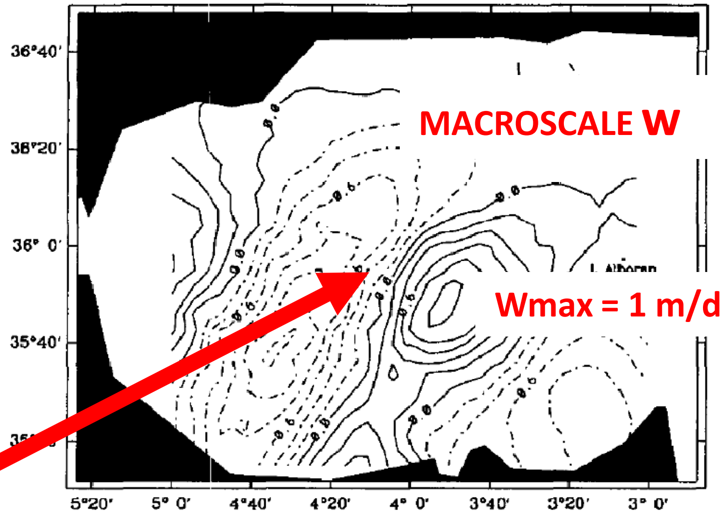
Mesoscale Dynamics and Vertical Motion in the Alborán Sea

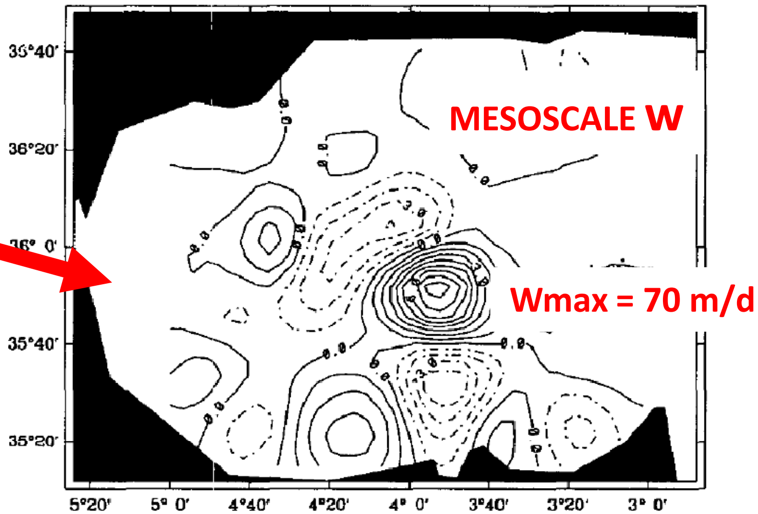
JOAQUÍN TINTORÉ, DAMIÀ GOMIS AND SERGIO ALONSO
Departament de Física, Universitat de les Illes Balears, Palma de Mallorca, Spain
GREGORIO PARRILLA





Mesoscale field separated from macroscale.





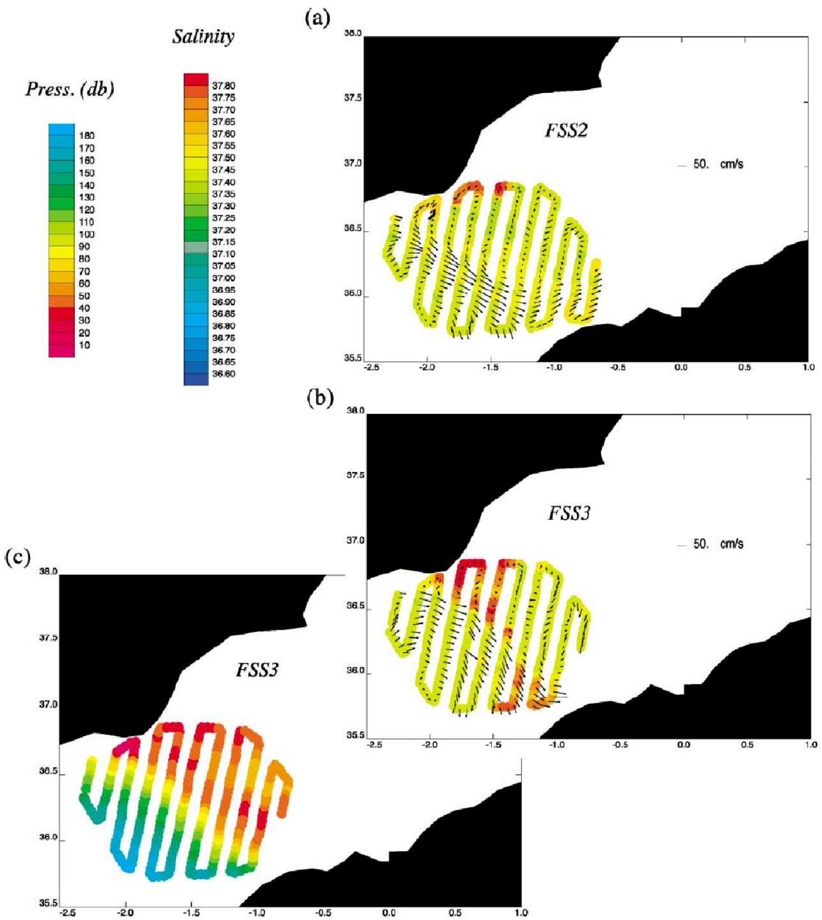
Vertical motion associated with mesoscale is one order of magnitude higher than the large scale vertical motion.

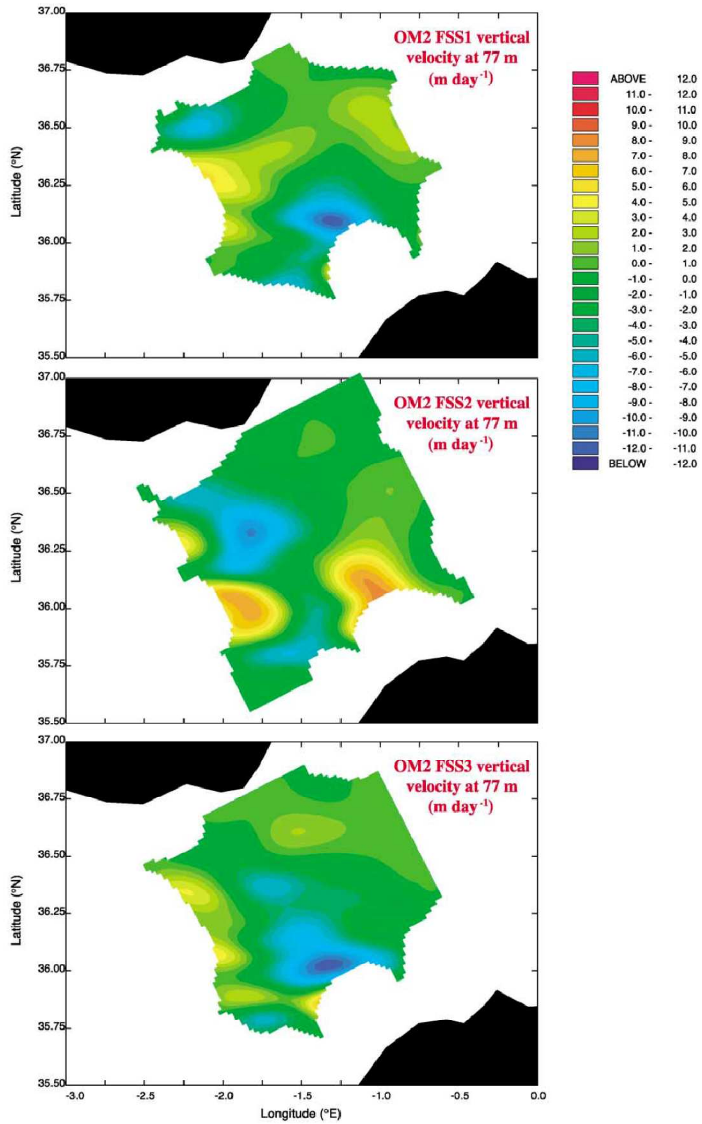
Past in situ experiments

Journal of Marine Systems 30 (2001) 263–285

Mesoscale subduction at the Almeria–Oran front Part 1: Ageostrophic flow

J.T. Allen [a,*], D.A. Smeed [a], J. Tintoré [b], S. Ruiz [c]





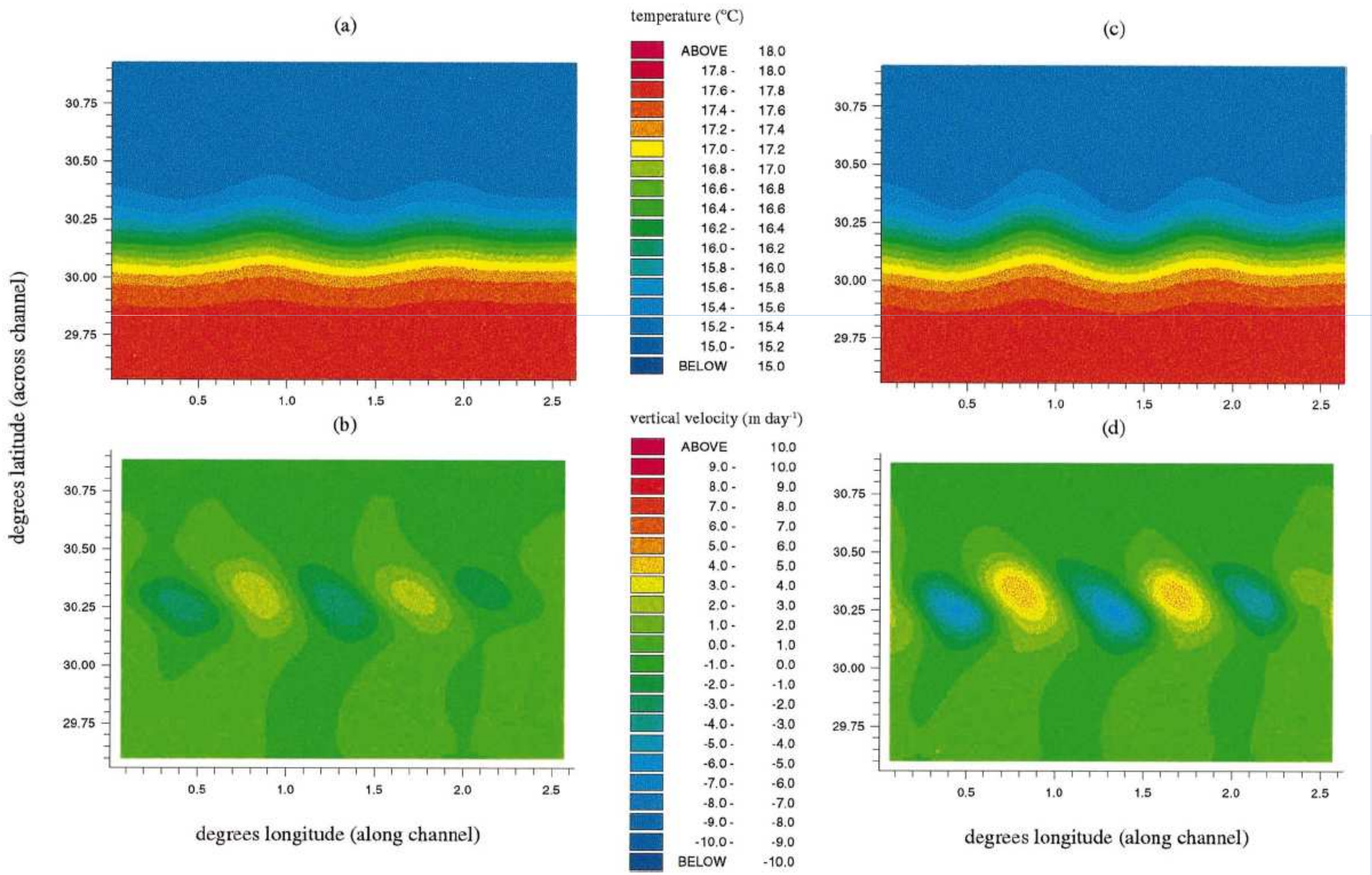
- Five repeated fine-scale surveys in the Alboran Sea in the region of the Almeria–Oran.
- The variability in the position and shape of the Almeria–Oran front and the strongly sheared velocity field indicate the presence of significant ageostrophic flow.

Limitations: resolution and synopticity

Deep-Sea Research I 48 (2001) 315–346

Diagnosis of vertical velocities with the QG omega equation: an examination of the errors due to sampling strategy

J.T. Allen[a,*], D.A. Smeed[a], A.J.G. Nurser[a], J.W. Zhang[a], M. Rixen[b]



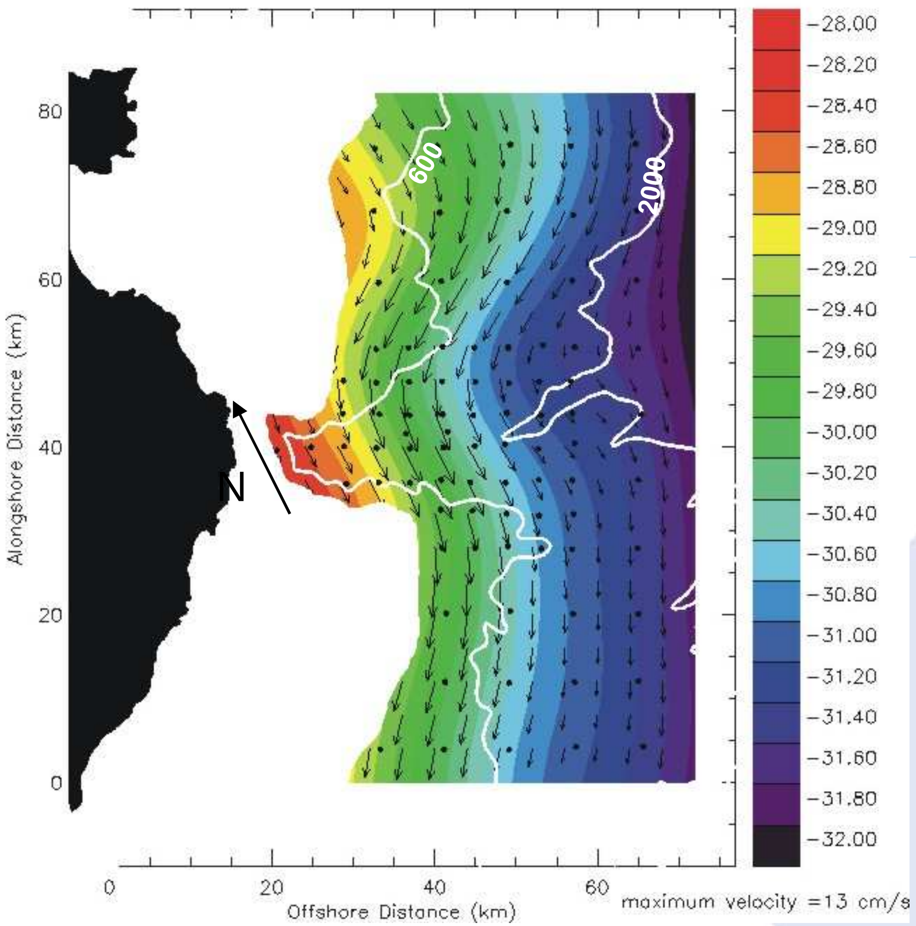
A combination of effects (lack of spatial resolution and synopticity) can typically lead to errors of 85% in the estimation of net vertical heat flux.

Mitigating the lack of synopticity

JOURNAL OF PHYSICAL OCEANOGRAPHY

A Quasigeostrophic Analysis of a Meander in the Palamós Canyon: Vertical Velocity, Geopotential Tendency, and a Relocation Technique

ANANDA PASCUAL DAMIÀ GOMIS ROBERT L. HANEY SIMÓN RUIZ



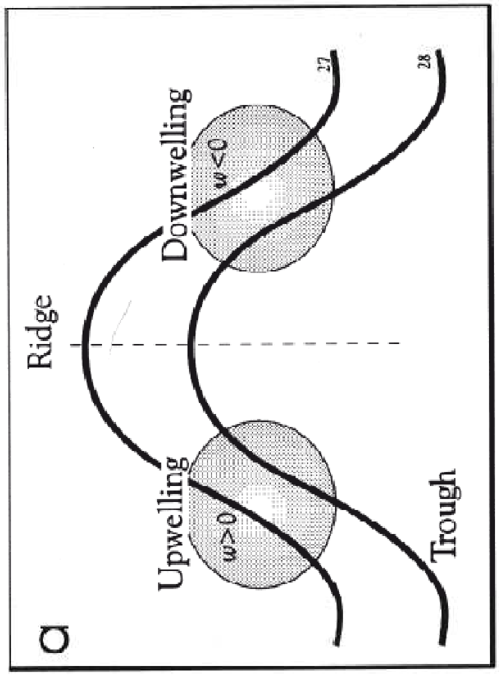
- 139 CTD stations during 24-31 May 2001.
- Stations were 4 km apart within the canyon and 8 km on the shelf.
- Maximum depth of the CTD casts: 600 m
- The survey was carried out in the upstream direction.
- Additional ADCP transects were sampled between CTD sections.

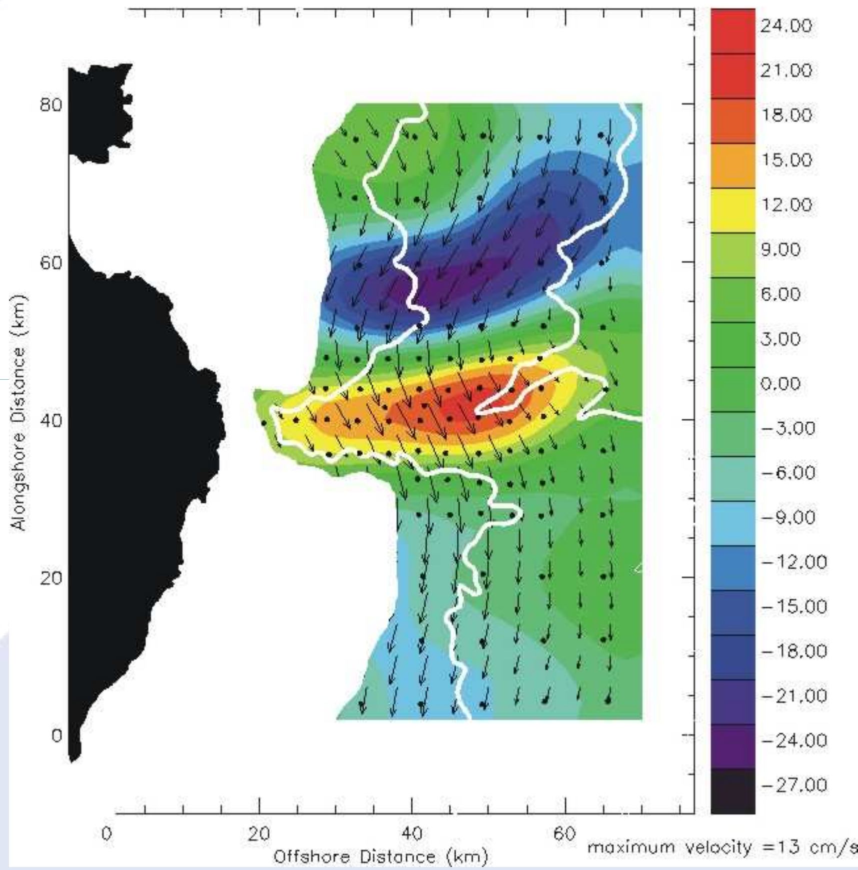
$$Ro = \frac{U}{f\ L} \approx \frac{13\,\mathrm{cm/s}}{10^{-4}\,s^{-1}13\,km} = 0.1$$

Dynamic Height and Geostrophic velocity at 200 m

QG vertical velocity

Downwelling upstream of the meander trough and upwelling downstream of the meander crest (Cushman-Roisin, 1994).





Vertical velocity (m/day) and geostrophic velocities (cm/s) at 200 m.

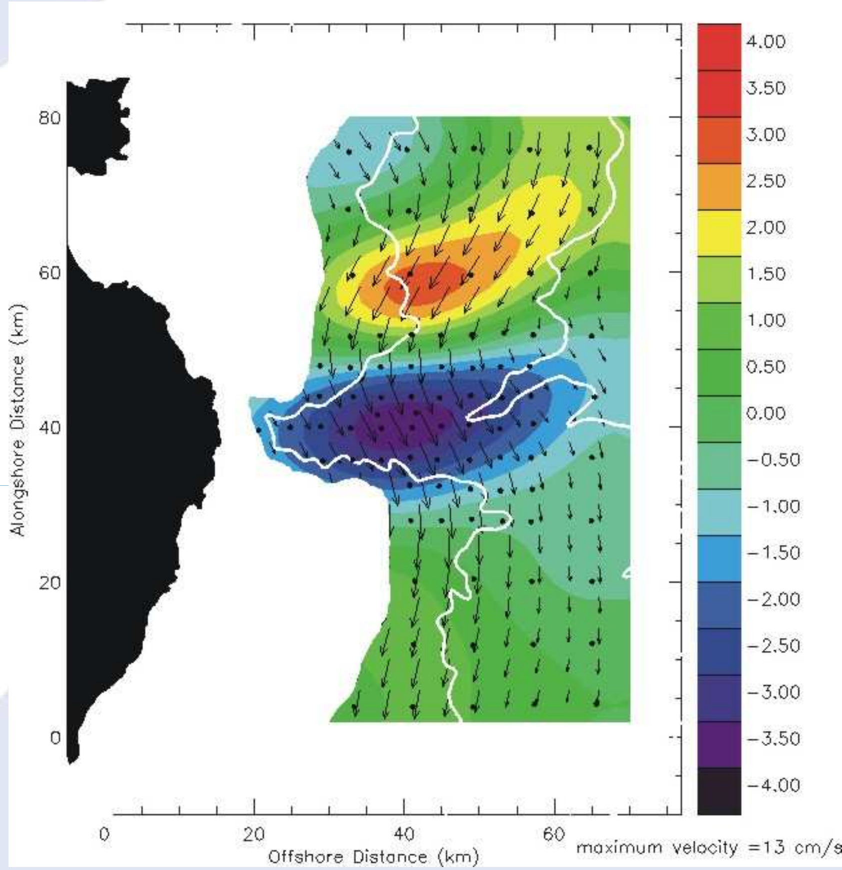
Pascual et al JPO 2004

QG geopotential tendency equation

$$\left[\nabla^2 + \frac{\partial}{\partial p}\left(\frac{f_0{}^2\rho^2 g^2}{N^2}\frac{\partial}{\partial p}\right)\right]\frac{\partial \Phi}{\partial t} = - f_0 v_g \cdot \nabla\left(\frac{1}{f_0}\nabla^2\Phi + f\right) - \frac{\partial}{\partial p}\left[\frac{f_0{}^2 g^2}{N^2} v_g \cdot \nabla\rho\right]$$

χ

The positive and negative patches are located upstream and downstream of the ridges and troughs and not on the ridges and troughs. This indicates that it is a propagating wave and not a growing/decaying wave.



QG geopotential tendency (1e-6 dyn cm/s) at 200 m.

Pascual et al JPO 2004

Problem of synopticity:
phase speed and relocation method

Fix frame of reference

$$\frac{D\Phi}{Dt} = \frac{\partial\Phi}{\partial t} + \vec{v}\cdot\nabla\Phi$$

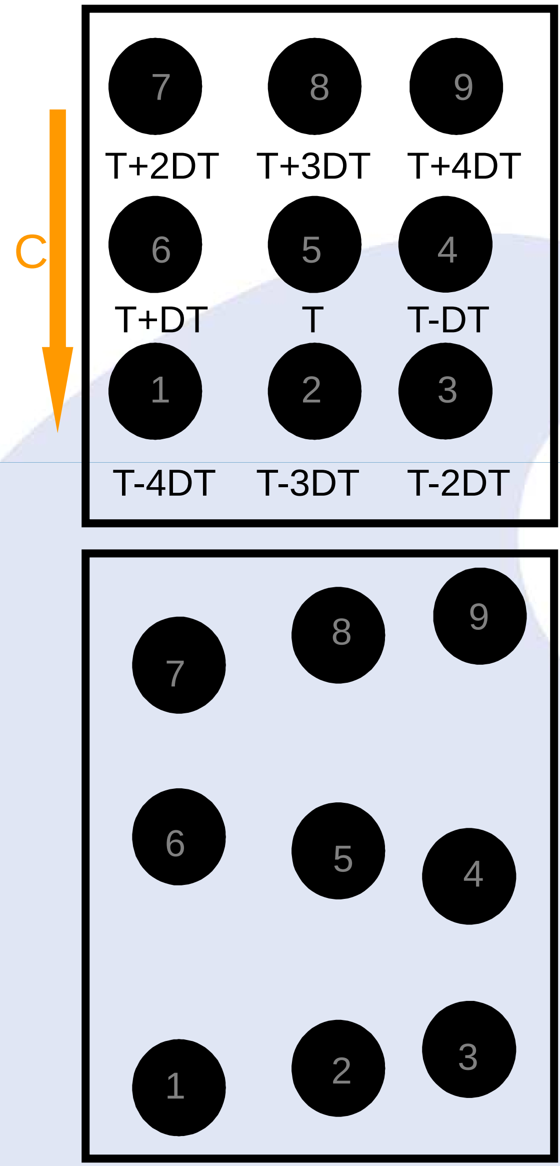
Moving frame of reference

$$\frac{D\Phi}{Dt} = \left.\frac{\partial\Phi}{\partial t}\right|_c + (\vec{v}-\vec{c})\cdot\nabla\Phi$$

$$\frac{\partial\Phi}{\partial t} = \left.\frac{\partial\Phi}{\partial t}\right|_c - \vec{c}\cdot\nabla\Phi$$

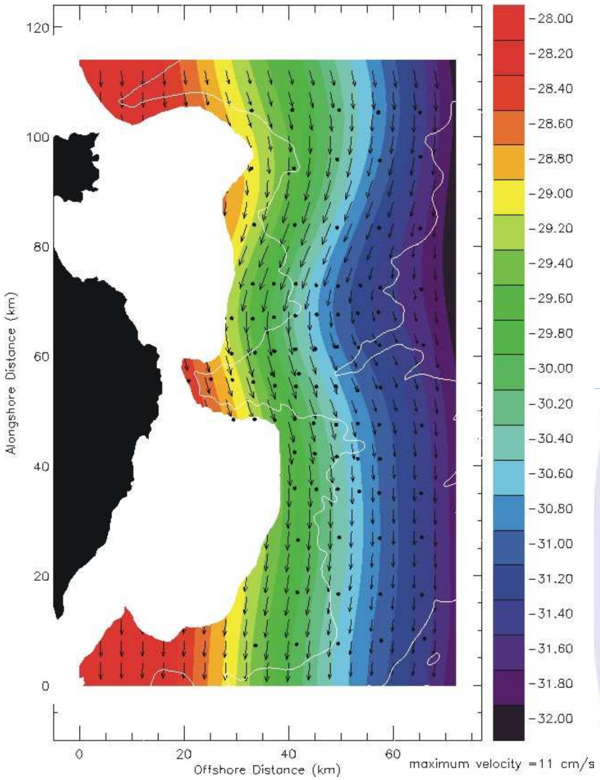
Find a frame of reference that minimizes the tendency

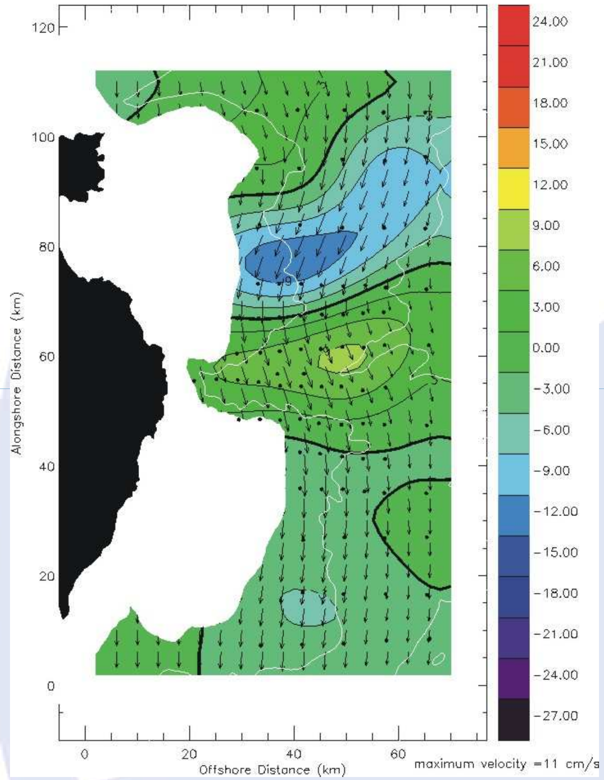
$$J(\vec{c}) = \int\left(\frac{\partial\Phi}{\partial t} + \vec{c}\cdot\nabla\Phi\right)^2 dV$$



Results of the iterative relocation method

c_y=-4 km/day, c_x=0 km/day





Dynamic Height at 200 m (dyn cm)

Vertical velocity at 200 m (m/day)

The results of the relocation scheme show that the actual wavelength of the meander after the relocation is 70 km. Vertical velocities are significantly reduced.

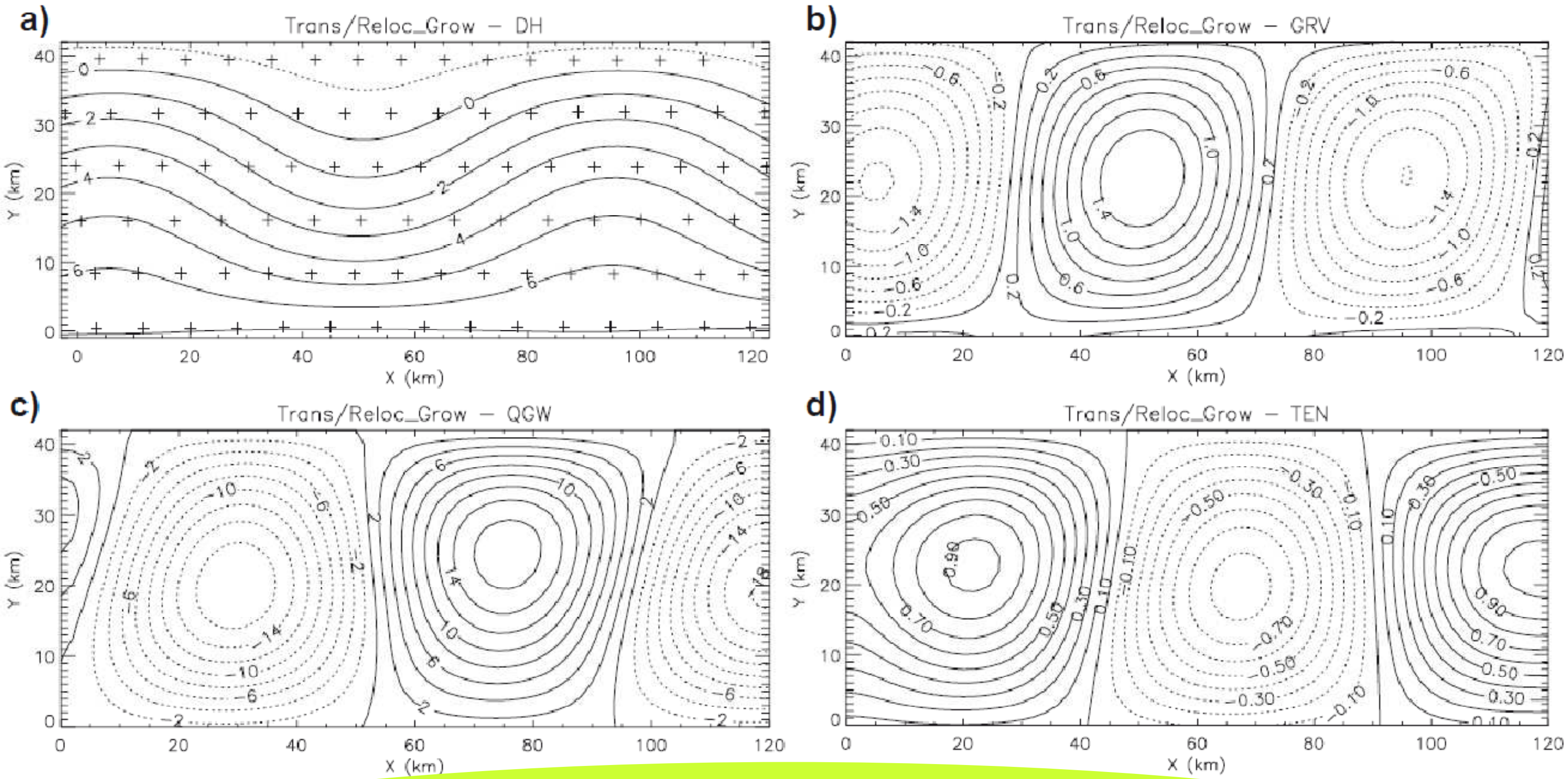
Pascual et al JPO 2004

Evaluation and mitigation of synopticity errors

Journal of Marine Systems 56 (2005) 334–351

Errors in dynamical fields inferred from oceanographic cruise data

Damià Gomis[a,*], Ananda Pascual[a,b], Mike A. Pedder[c]



• As suggested in Allen et al. 2001 and Rixen et al 2001, downstream and upstream cross-front samplings produce larger errors than along-front samplings. Synopticity errors lead to errors in vertical velocities of about 50%.

• A method aimed at reducing the impact of the lack of synopticity is proposed and tested, being able to eliminate practically all synopticity errors in the case of the along-front sampling.

Outline

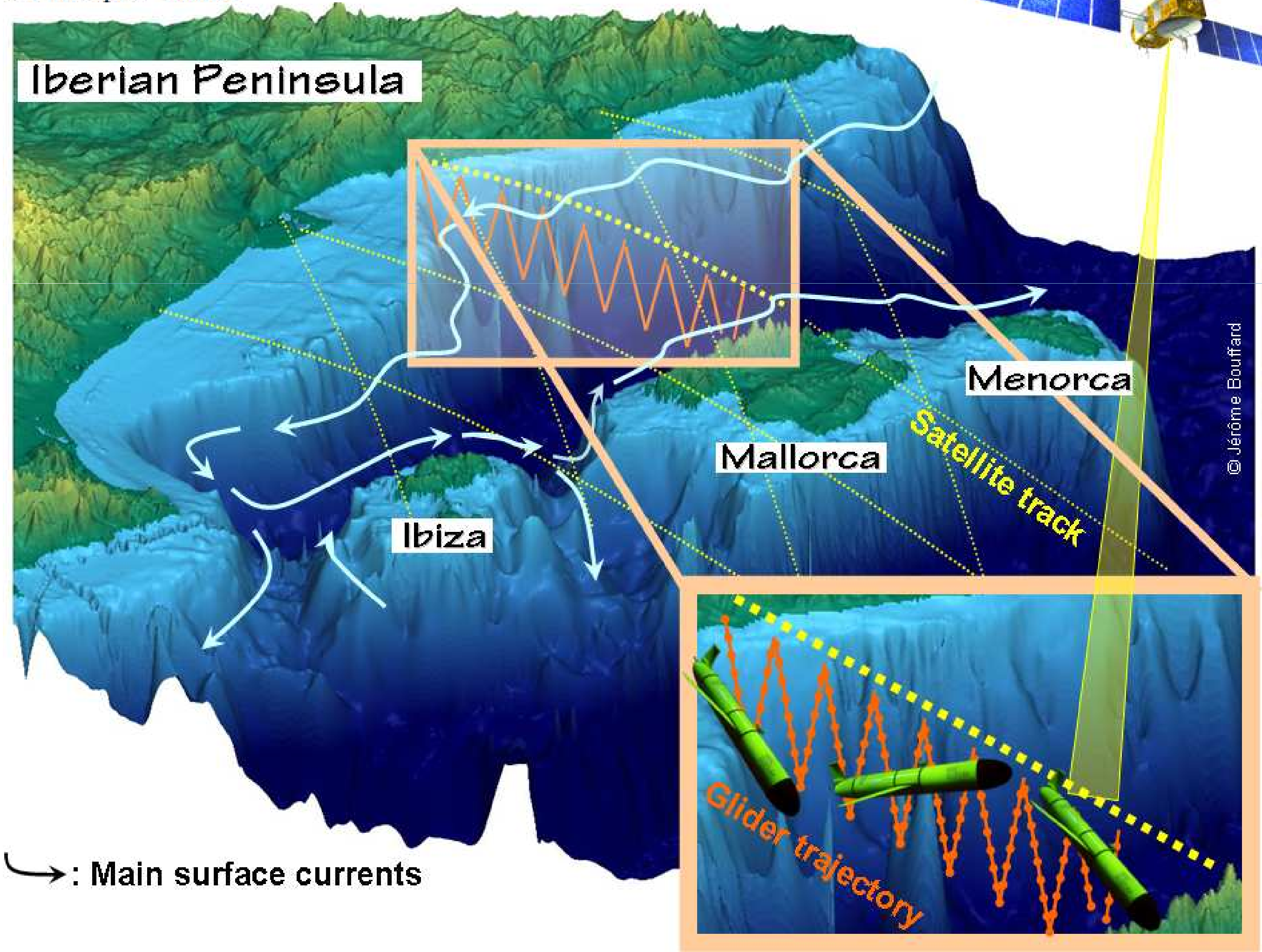
- Scientific motivation
- Past in situ experiments: limitations and challenges
- **Recent multi-sensor experiments: use of new technologies**
- Summary
- Perspectives

Multi-sensor experiments: use of new technologies

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, C10029, doi:10.1029/2009JC006087, 2010

Coastal and mesoscale dynamics characterization using altimetry and gliders: A case study in the Balearic Sea

Jérôme Bouffard,[1] Ananda Pascual,[1] Simón Ruiz,[1] Yannice Faugère,[2] and Joaquín Tintoré[1,3]



Altimetry

Variable:

* (M)SLA and along track SLA (1Hz / 20Hz)
* MDT: Rio et al. 2007 (ADT = SLA + MDT)

Horizontal resolution

* Gridded: 1/8°, 1Hz ~ 7km, 20Hz ~ 350m

Vertical resolution

* **NO** (only surface information)

Glider

Variables:

* P, T, S, oxig., chl., turb.
* Depth averaged absolute current (GPS)

Horizontal resolution:

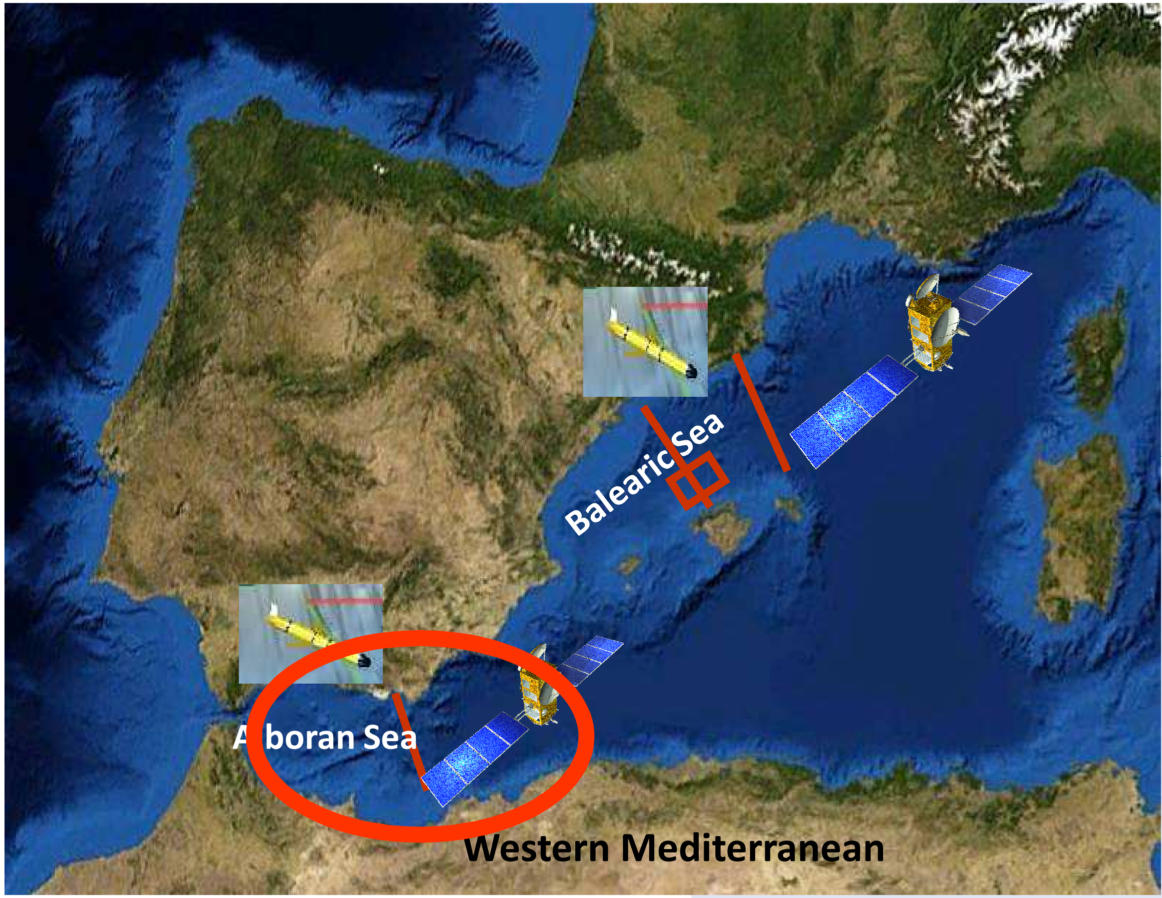
* 300 m / 1.1 km

Vertical extension:

* **10-180 m /600 m**

Altimetry vs glider

Missions background



ENVISAT:

- Balearic Sea**: T-773. 6 missions (every 70 days)**

JASON-1/2:

- Balearic Sea**: T-70 (August 2008).**
- Alboran Sea**: T-172 (July 2008).**

JASON-1 (new orbit):

- Balearic Sea: **T-70 (May, Oct 2009, Dec 2009 & Apr 2010).**

14 glider missions
From 2007 to 2010 in the WMed
along altimeter tracks

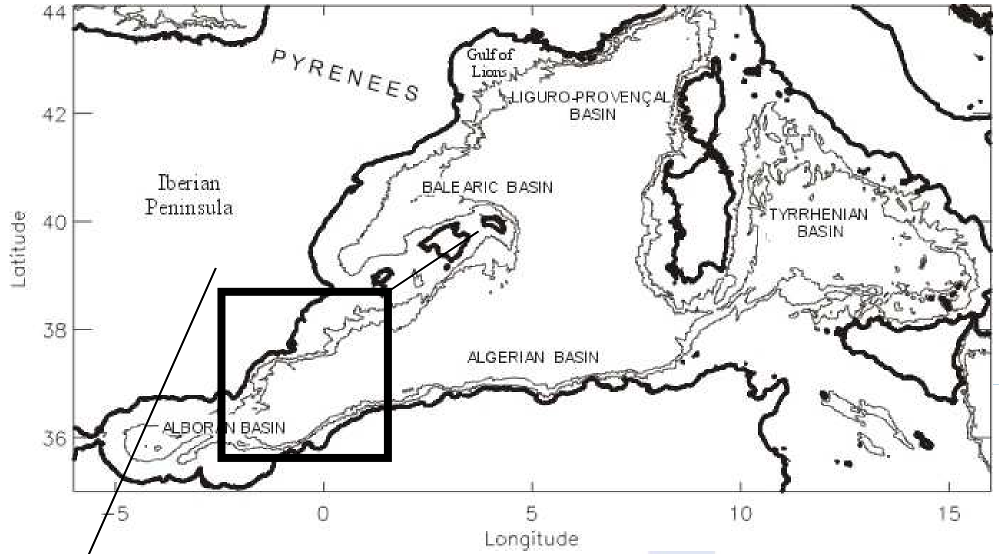
→ **7300 full CTD casts**
+ oxigen, chlorophyll, turbidity

Alboran Sea experiment

GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L14607, doi:10.1029/2009GL038569, 2009

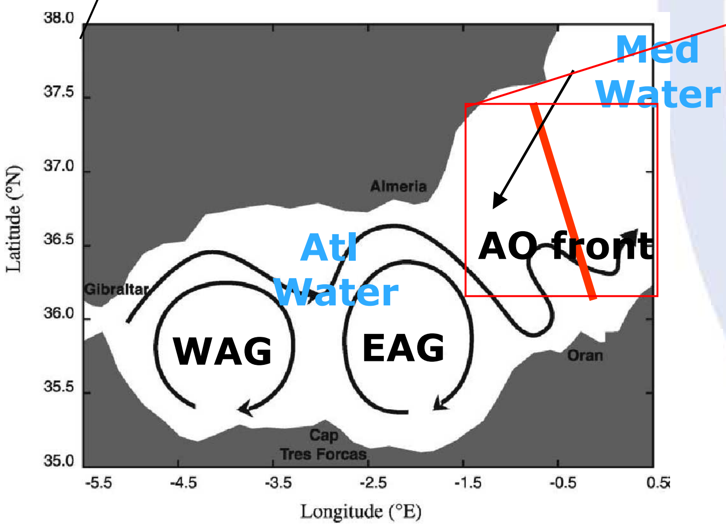
Vertical motion in the upper ocean from glider and altimetry data

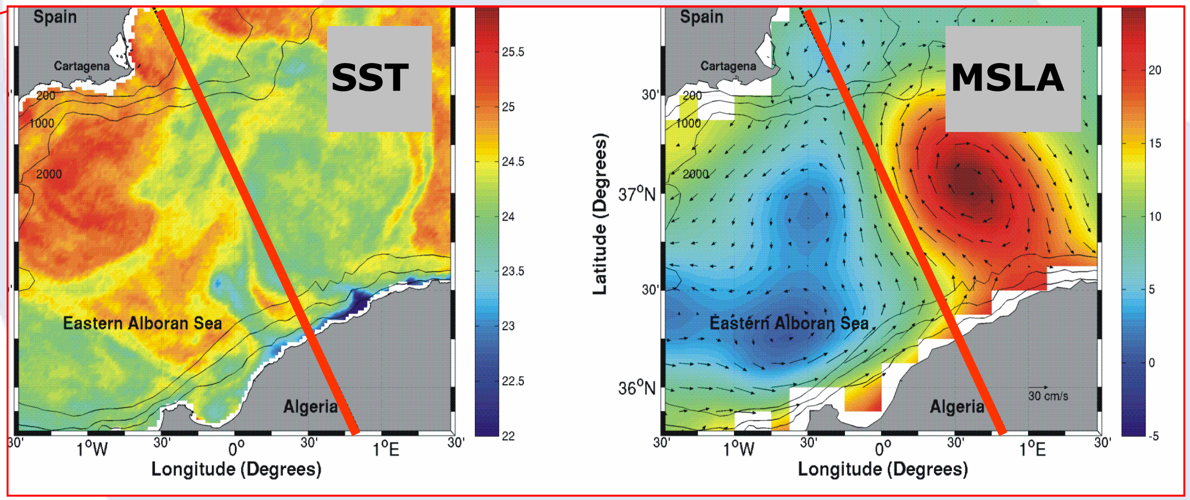
Simón Ruiz,[1] Ananda Pascual,[1] Bartolomé Garau,[1] Isabelle Pujol,[2] and Joaquín Tintoré[1]



Context

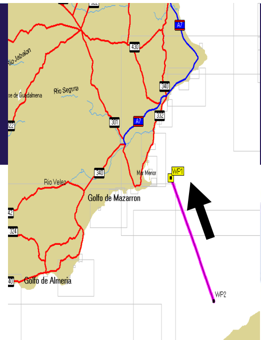
- Deployment of a glider in a very energetic area.
- To improve our knowledge on the driving mechanism in the area: Mesoscale structures (filaments, eddies,etc).
- Altimetry Cal/val Jason1/2 just two weeks after Jason 2 launch.



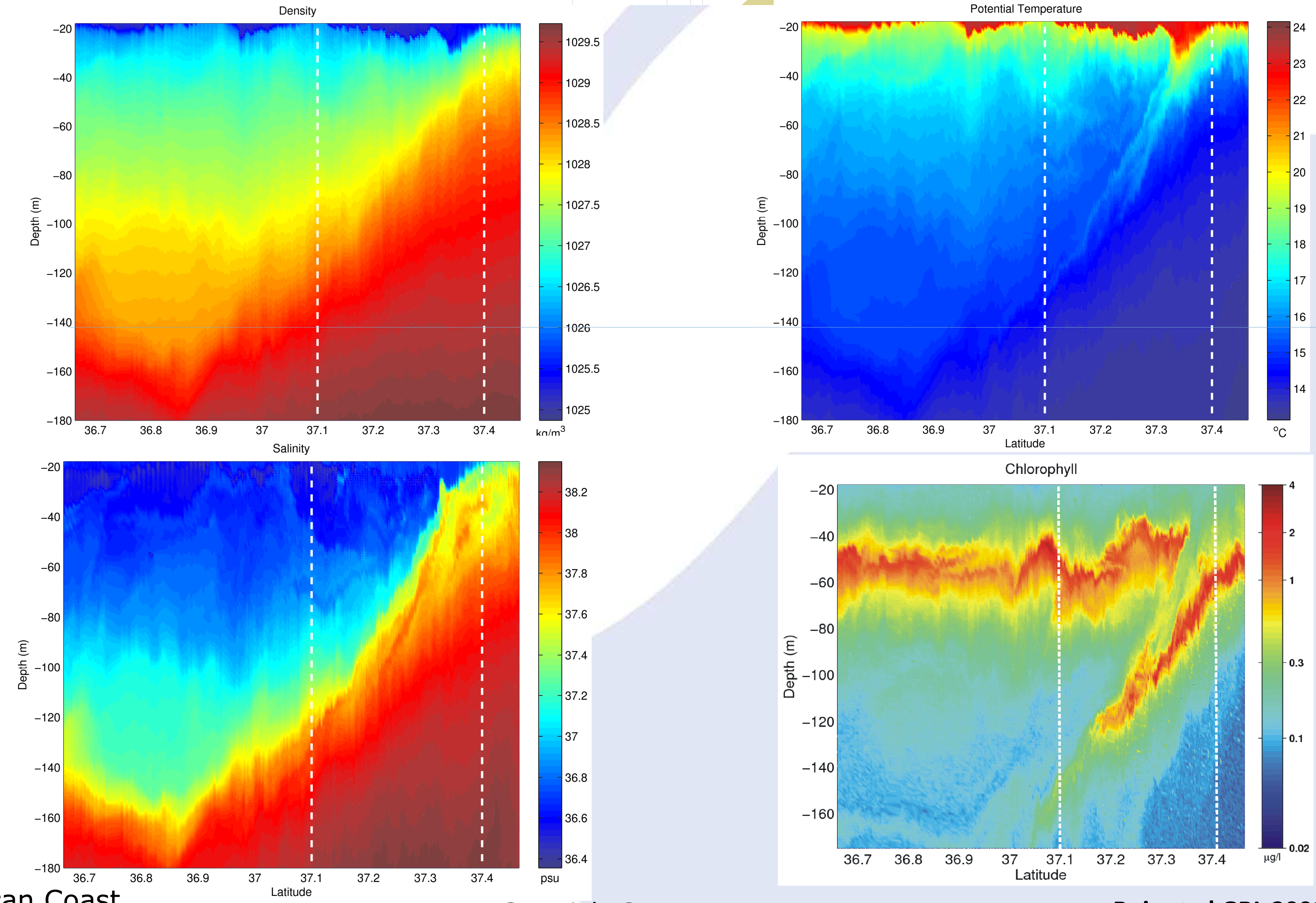


Alboran

Vertical sections



Return trip performed in 3 days



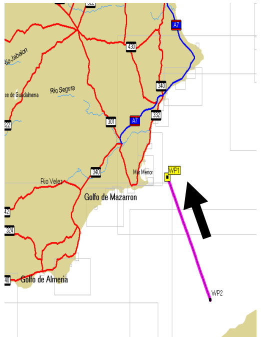
African Coast

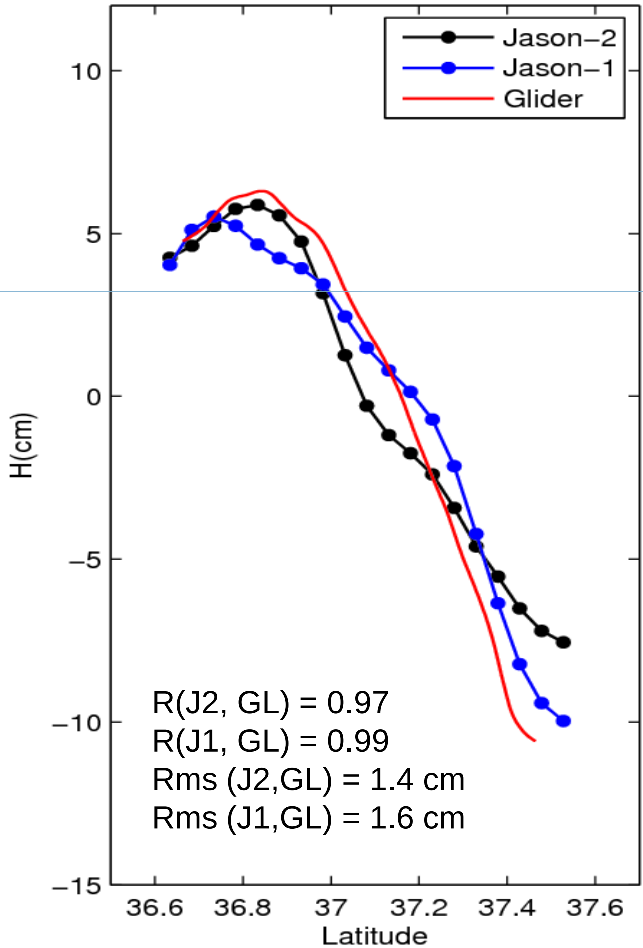
Spanish Coast

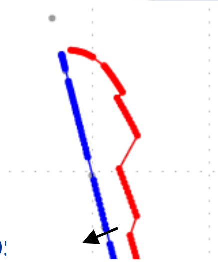
Ruiz et al GRL 2009

Alboran

Glider vs Altimeter data







- **Glider data:**
  - Projection of the glider ob position onto the closest track point.
  - Observation values are not modified.
  - Dynamic height referred to 180 m.
  - Along track Lanczos filter.
- **Altimetry data:**
  - Altimetry data: along-track SLA + MDT(Rio et al JMS 2007).
  - Along track Lanczos filter.

Remarkably good agreement between altimetry and glider data

Ruiz et al GRL 2009

Vertical velocity

Methodology

Step 1: build a 3D density field

Approach 1: **From OI of in situ data (see previous examples)**

Approach 2: **EOF decomposition to merge vertical profiles with standard gridded altimetry, inferring the 3D density and dynamic height fields**

In the case of a single dominant mode, the modelled profile can be expressed as (Pascual and Gomis, 2003):

$$\Phi_{x,y}(p) = A_1(x,y)EOF_1(p)$$

Thus, obtaining the single amplitude $A_1(x,y)$ corresponding to each profile would be straightforward given the surface altimetry data $[\Phi_{x,y}(p_0)]$ and the surface component of the leading EOF $[EOF_1(p_0)]$ from vertical profiles

Step 2: Use QG Omega Equation to examine vertical velocity

$$f^2 \frac{\partial^2 \omega}{\partial z^2} + \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\left(N^2 \omega\right) = \nabla_h Q \qquad Q = \left[2f\left(\frac{\partial V}{\partial x}\frac{\partial U}{\partial z} + \frac{\partial V}{\partial y}\frac{\partial V}{\partial z}\right), -2f\left(\frac{\partial U}{\partial x}\frac{\partial U}{\partial z} + \frac{\partial U}{\partial y}\frac{\partial V}{\partial z}\right)\right]$$

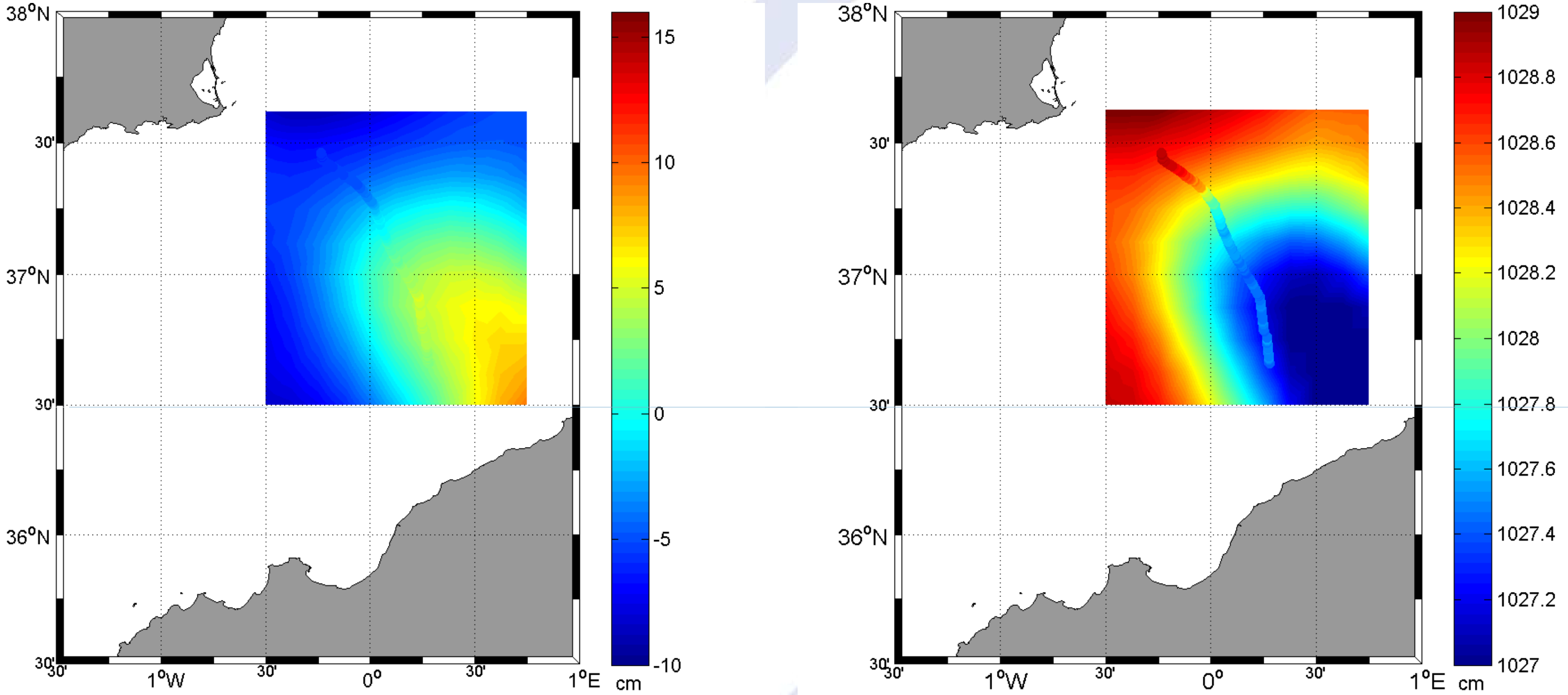
where (U,V) are the geostrophic velocity components

By assuming a BC for ω and from a 3D snapshot of the density field, the vertical velocity can be inferred. We set w = 0 at the upper and lower boundaries and Neumann conditions at the lateral boundaries (Pinot et al., 1996)

Alboran

3D reconstruction

First vertical EOF explains 98% of the total Dynamic Height

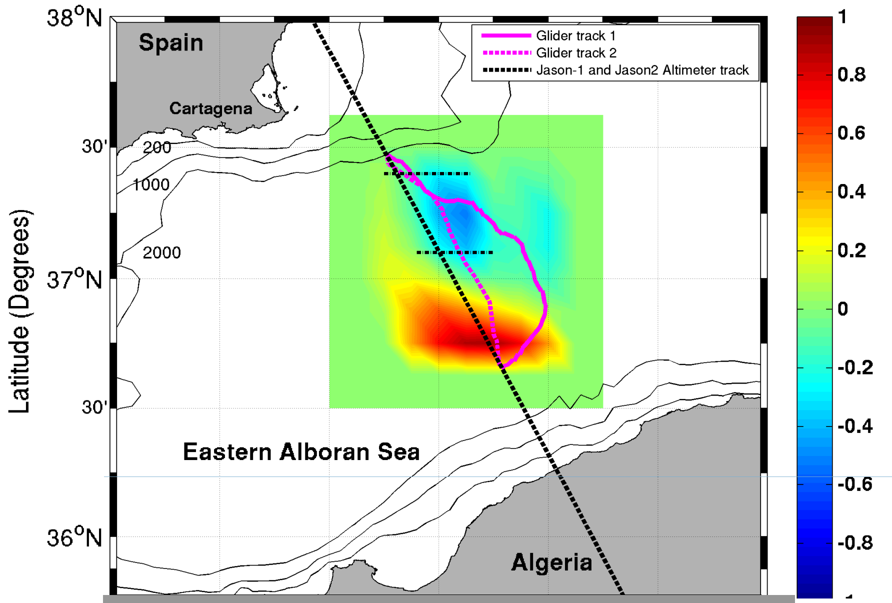


Reconstructed dynamic height field at 75 m depth. Colour dots correspond to dynamic height from glider at the same depth. b) as in a) but for density.

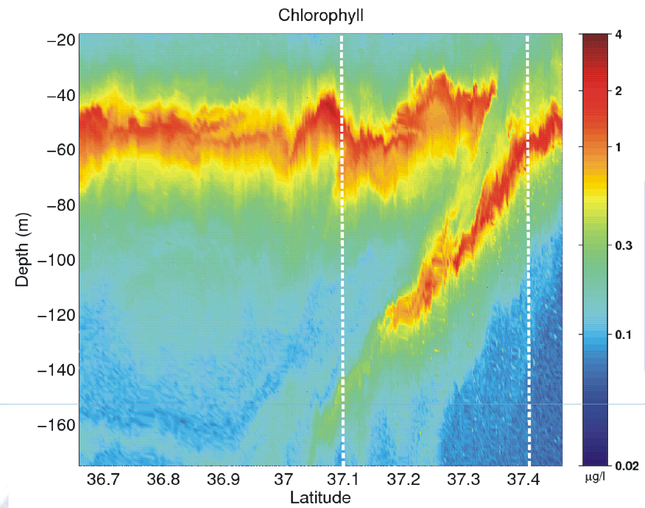
	Error variance (%)	**Correlation**
Dyn. Height	**2.80**	**0.98**
Density	**4.12**	**0.98**

Performance assessment of the reconstruction method.

Alboran Vertical velocity results



Quasi-geostrophic vertical velocity at 75 m.Units are m day-1.



- This study represents a first attempt on the combination of glider technology data with altimetry to **diagnose vertical velocities**.

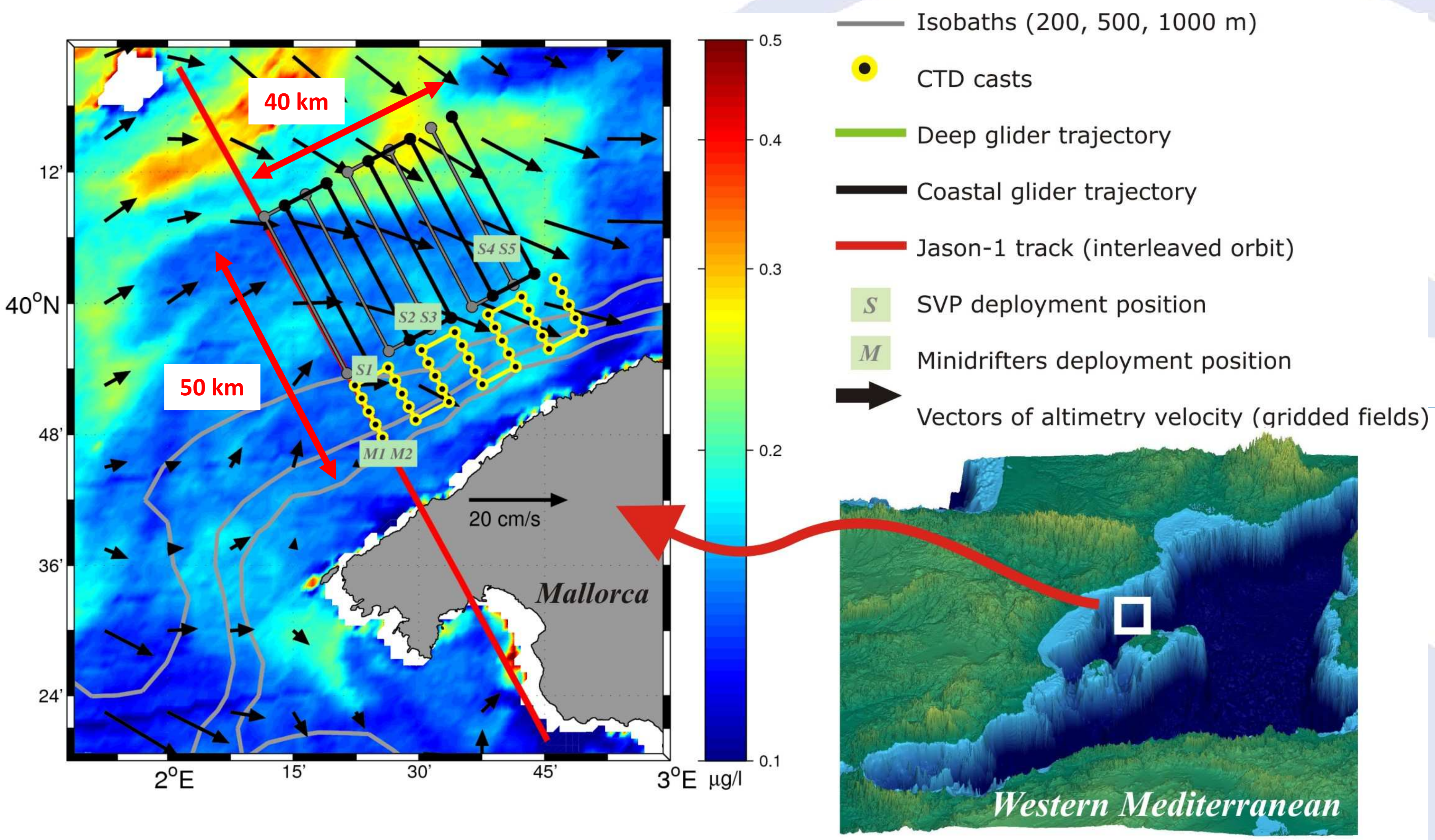
- The **vertical motion** diagnosed is **consistent** (magnitude is smaller) with previous studies (Tintoré et al., 1991; Allen et al., 2001b).

- The magnitude is very sensitive to the scales included in the analysis. (**100 km correlation** scale in gridded altimetry is too large).

Ruiz et al GRL 2009

SINOCOP

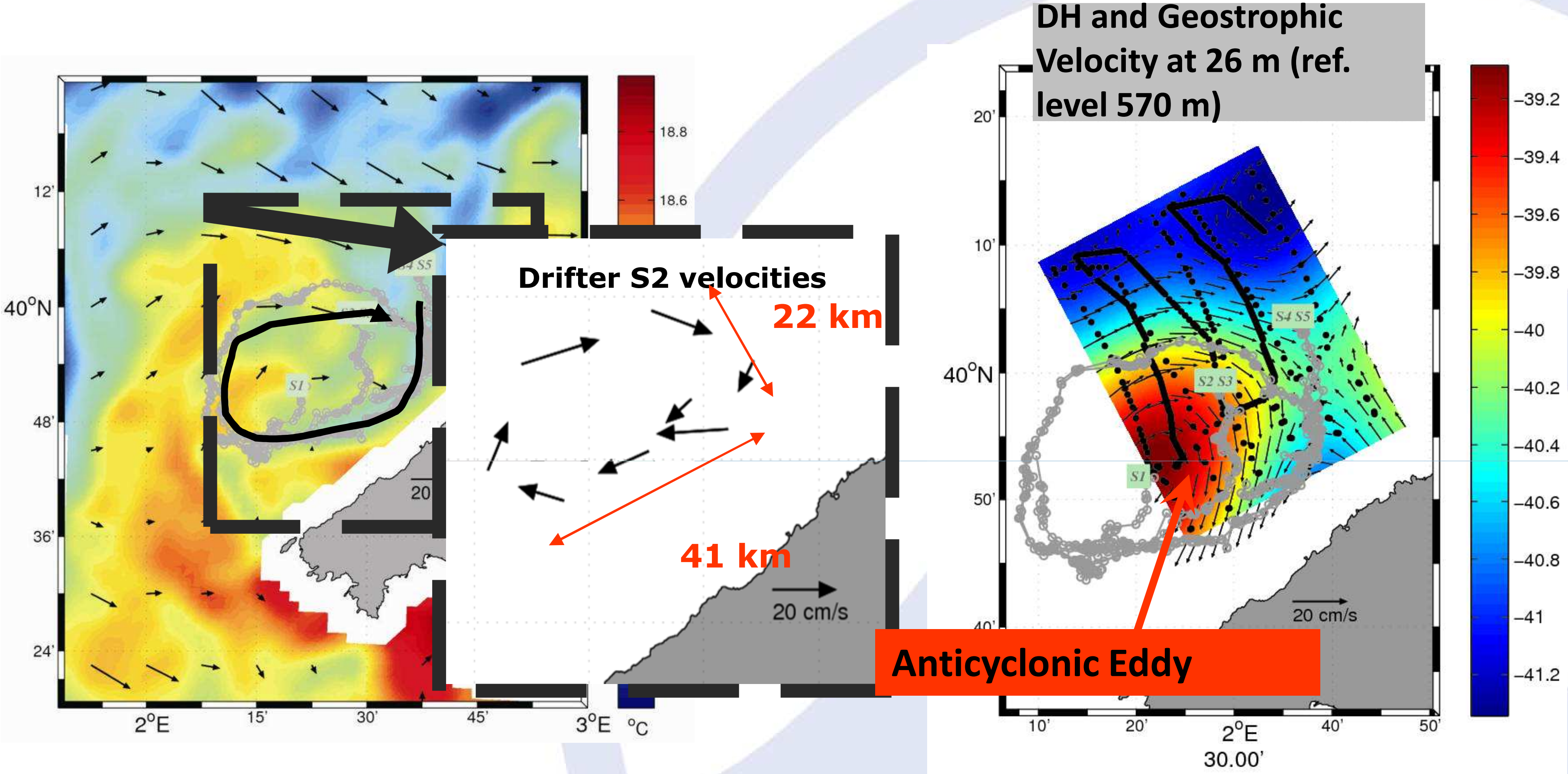
A HR multi-sensor experiment in May 2009



Pascual al Sea Tech 2010

Sampling performed in 6 days

SINOCOP Velocity calculations



Velocity from drifters:

- Filtering of HF signals (cut off at 36h)
- Reinterpolation every 6 hours + Velocity computation by finite differences
- Reinterpolation for daily values

Velocity from CTD and gliders:

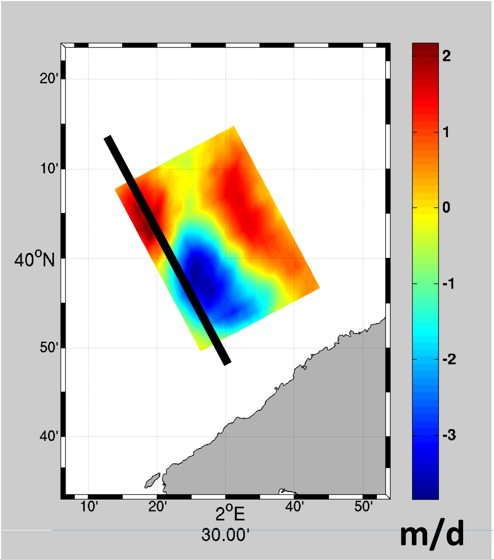
-Individual T & S Profiles: Removal of spikes, Vertical smoothing, Computation of DH through thickness (ref. level 180/570 m)

- Objective analysis: several correlation scales...

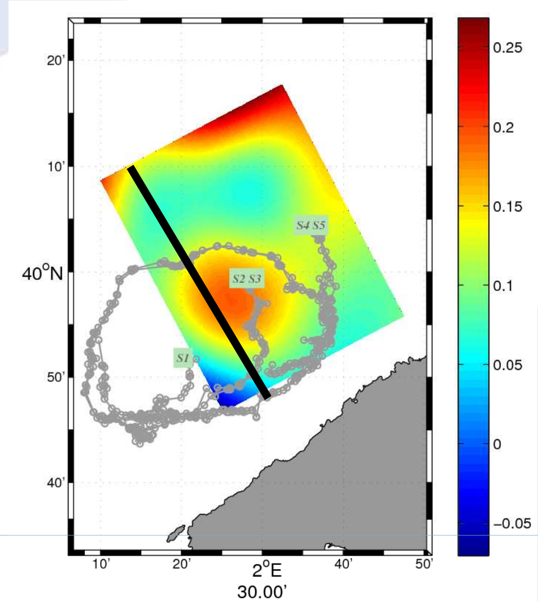
-Geostrophic velocities by finite differences

SINOCOP

Vertical velocity estimates

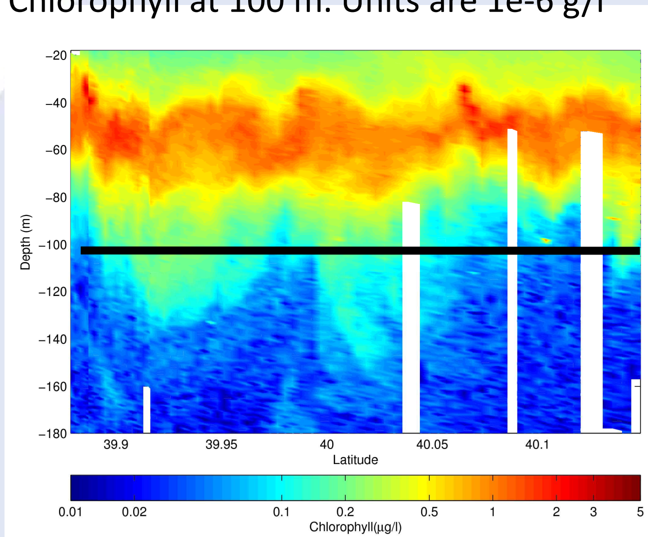


QG vertical velocity at 100 m. Units are m d-1.



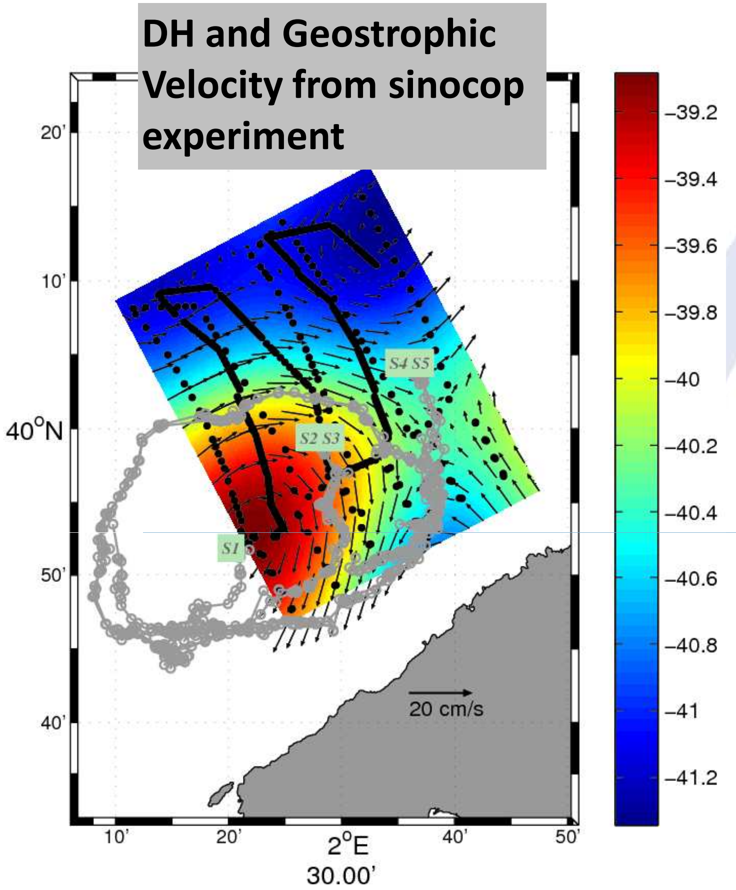
Chlorophyll at 100 m. Units are 1e-6 g/l

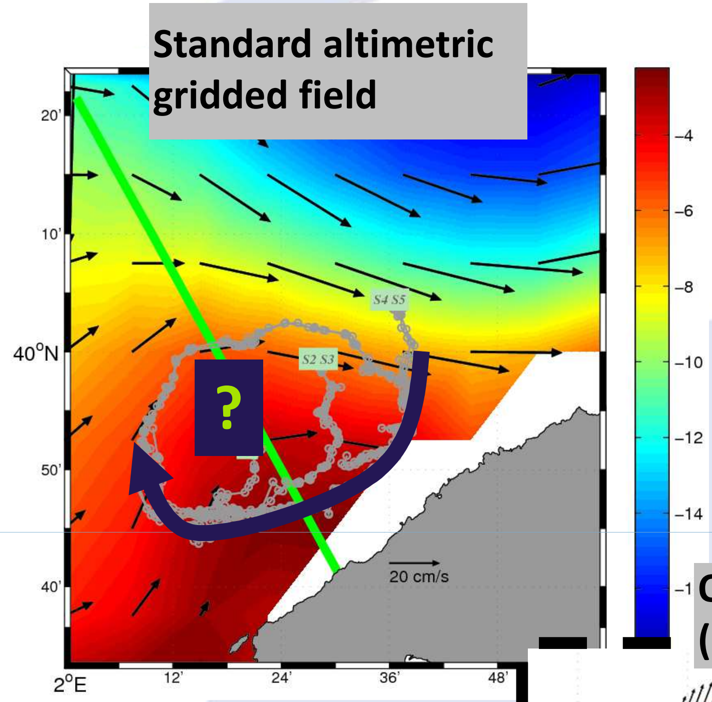
Preliminary estimates show sinking motion in the center of the eddy that may indicate an acceleration of the anticyclonic motion (deepening of isopycnals).

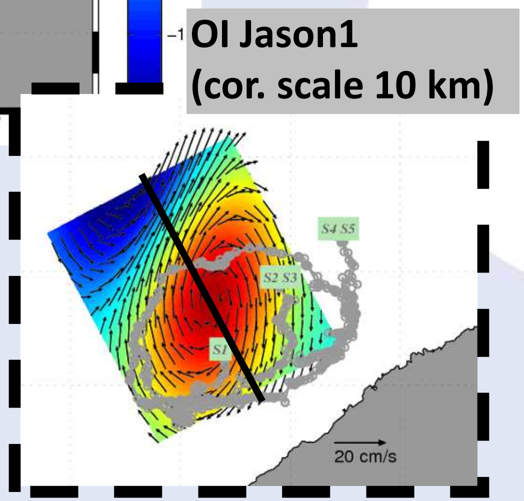


Vertical section of Chlorophyll. Units are 1e-6 g/l. Log scale.

Detecting submesoscale structures with altimetric fields ?





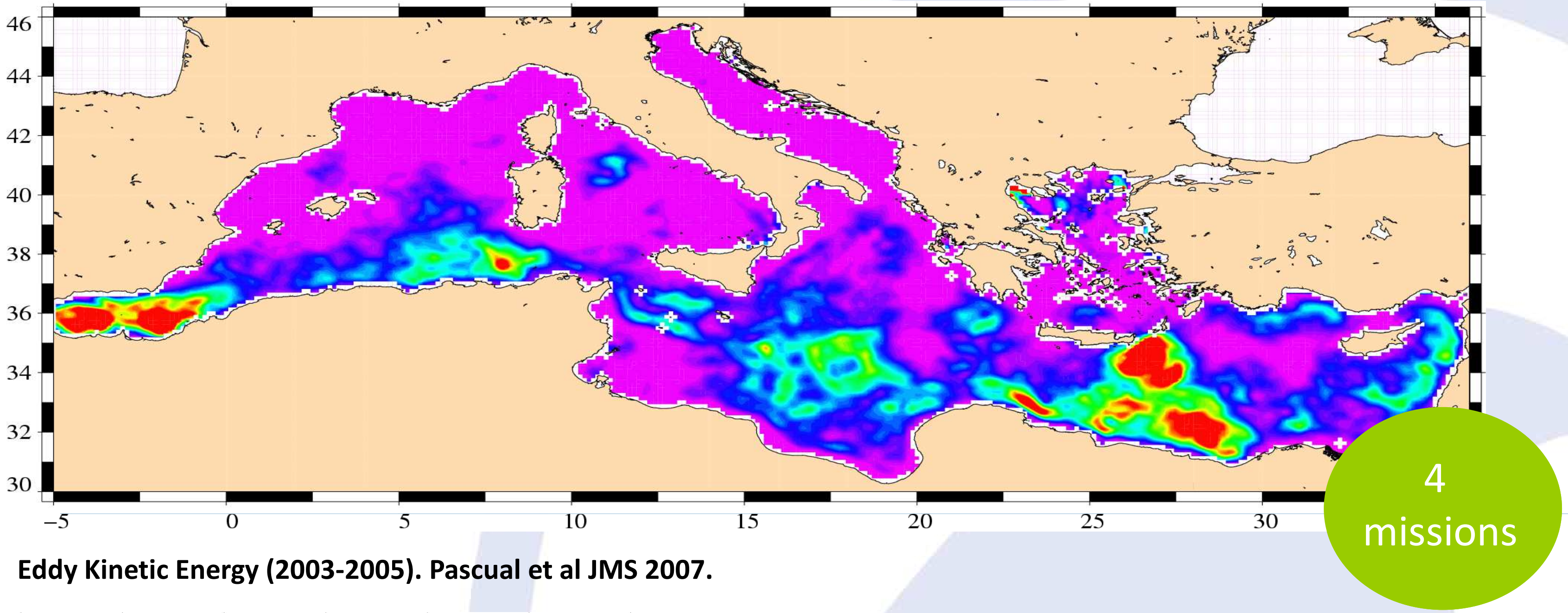


Very nice BUT…

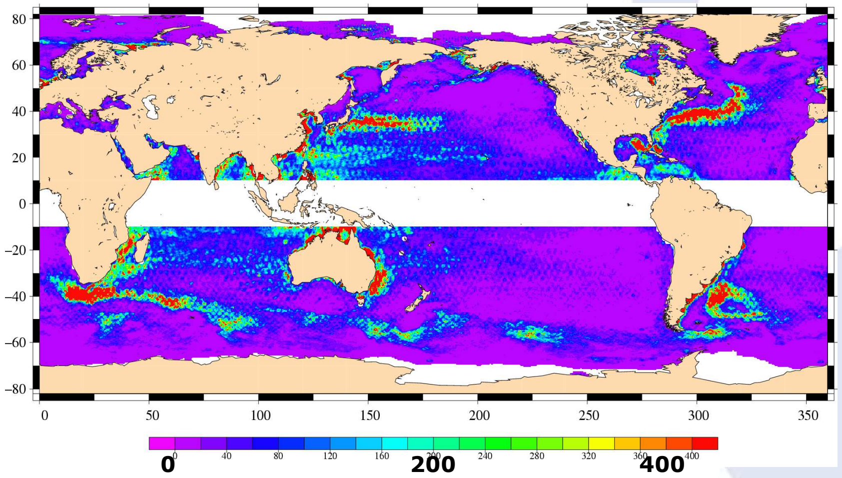
if the eddy's center is not located on a nadir track, we will miss the structure!

See Morrow's presentation, for similar methodology.

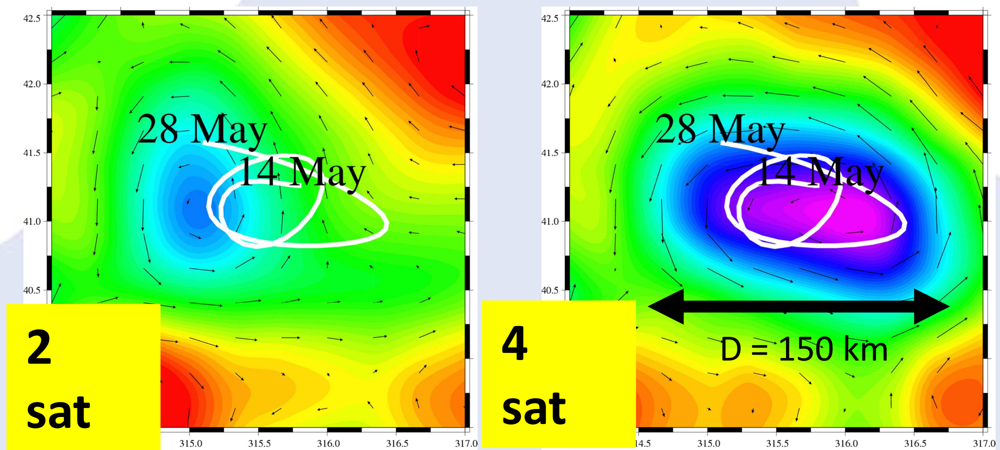
Increasing altimetric resolution with 4 altimeters?



Eddy Kinetic Energy (2003-2005). Pascual et al JMS 2007.



EKE differences between 4 and 2 satellite missions. Units are in cm2/s2.

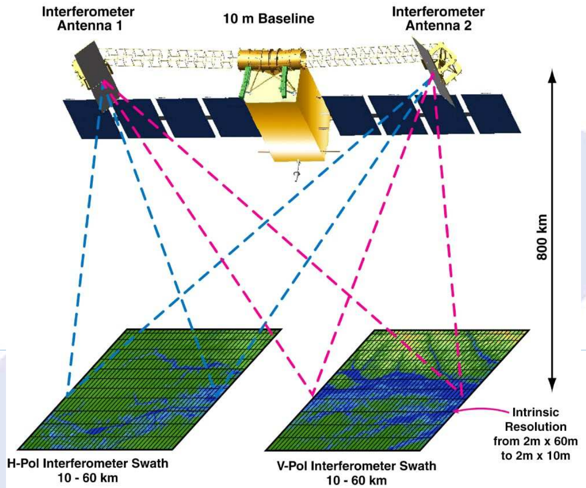


Trajectory of a drifting buoy in the Gulf Stream super-imposed over velocity vectors and ADT from altimetry.

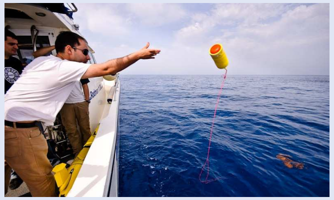
Pascual et al GRL 2006

Summary

- High resolution experiments are useful approaches for studying mesoscale and submesoscale dynamics (i.e. vertical velocities). The lack of synopticitiy can be partially mitigated with ad hoc methodologies.
- The alternative would be a fleet of gliders to circumvent the main limitations of traditional in situ experiments (resolution & synopticity).
- Altimeter gridded products do not have sufficient resolution for the detection of small mesoscale (~ 10-100 km) and submesoscale (< 10 km) features.
- This highlights the need of synergetic approaches through the combined use of models and observing systems including the SWOT mission!

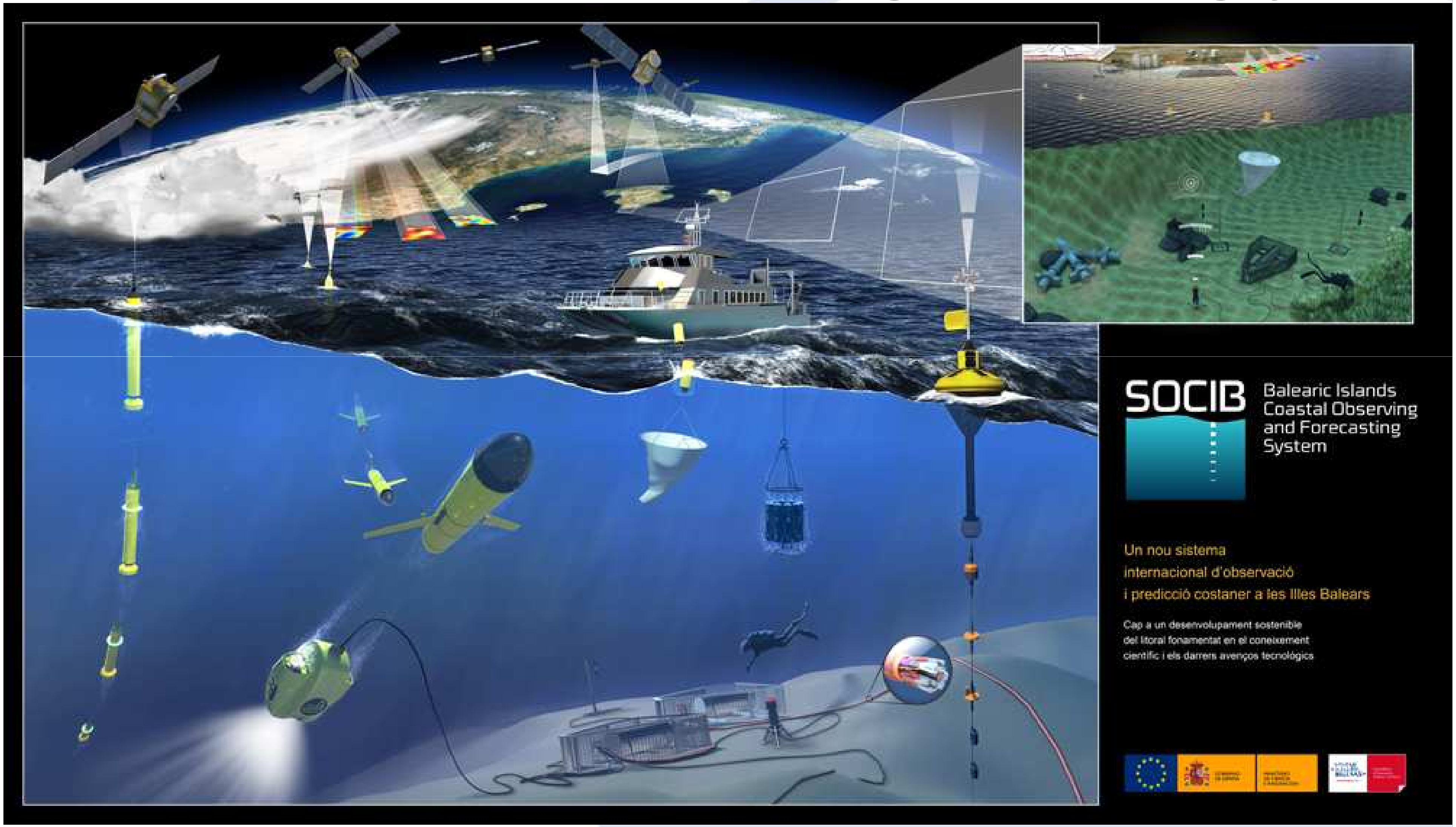







Perspectives

SOCIB –Balearic Islands Coastal Observing and Forecasting System



www.socib.eu

Perspectives

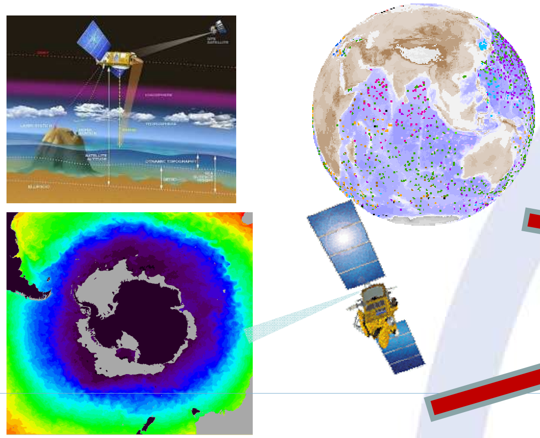
MEsoSCale dynamical Analysis through combined model, satellite and in situ data

2009 CALL FOR R&D PROPOSALS MyOcean

PI: Bruno Buongiorno Nardelli (ISAC, CNR)
Co-PI: Marie-Hélène Rio (CLS) & Ananda Pascual (IMEDEA, CSIC)

Objectives MESCLA

1. Improve existing observational 3D fields (ARMOR) testing other multivariate techniques, merging in situ and satellite data and improving resolution



EMPIRICAL/STATISTICAL TECHNIQUES → **High resolution 3D fields**
Temperature
Salinity
Density

2. High resolution 3D velocity fields will be estimated from synthetic fields and model output through a diagnostic numerical model

High resolution 3D fields
Temperature
Salinity
Density

$$\nabla^2\left(N^2 w\right) + f^2 \frac{\partial^2 w}{\partial z^2} = 2\nabla \cdot \vec{Q}$$

High resolution 3D velocity fields

$$\vec{Q} = \left[f\left(\frac{\partial V}{\partial x}\frac{\partial U}{\partial z} + \frac{\partial V}{\partial y}\frac{\partial V}{\partial z}\right), -f\left(\frac{\partial U}{\partial x}\frac{\partial U}{\partial z} + \frac{\partial U}{\partial y}\frac{\partial V}{\partial z}\right)\right]$$

3. High resolution 3D fields will be compared with estimates from MyOcean numerical model output

OS3.2

From physical to biogeochemical processes: ocean mesoscale and sub-mesoscale impact on marine ecosystem and climate variability

Convener: Ananda Pascual

Co-Conveners: John Allen, Bruno Buongiorno Nardelli, Marina Lévy

…This session will provide a forum to properly address the new scientific challenges associated with mesoscale and sub-mesoscale variability (between 1 km and 300 km), based on observations (both in situ and satellite and multi-sensor approaches), theory, and numerical simulations. ….

IMPORTANT DATES:

Call for papers: 20 October 2010

Deadline for receipt of abstracts: 10 January 2011