Report on the representation of vertical velocities in the Iberian Biscay Irish Ocean Analysis and Forecasting system using multi-platform observations

Master internship presentation

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This master internship has been led to review the **Iberian Biscay Irish Ocean Analysis and Forecasting System**, that predicts the sea state in the North-Atlantic and Western Mediterranean.

We investigate the performances of this model focusing on the **vertical velocities** variable, which play an important role in the exchange of nutrients between the surface and the ocean's interior. Measuring this variable turns out to be complicated still, as its intensity is **3-4 orders of magnitude smaller** than horizontal currents intensity. This review **uses the dataset of the Calypso 2018 experiment** including ADCP, CTD and surface drifters data.

Goal:

Identify the assets and the drawbacks of the IBI model in terms of vertical velocities.

Outline

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The **Alboran sea** is the Westernmost part of the Mediterranean. It is an adequate place to observe the **mesoscale mixing between fresh Atlantic waters salty Mediterranean waters**. This results in a very active area, where we can observe **two semi-permanent gyres**: the Eastern and Western Alboran gyres. [1]

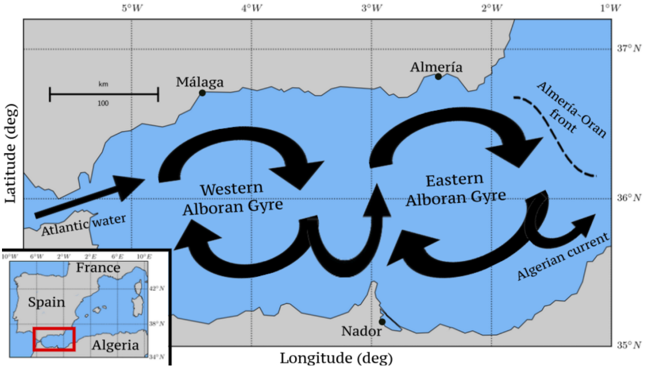
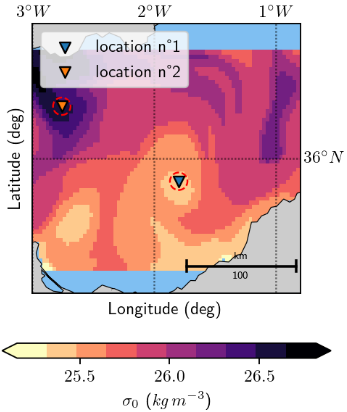


Figure: The Alboran sea global circulation.



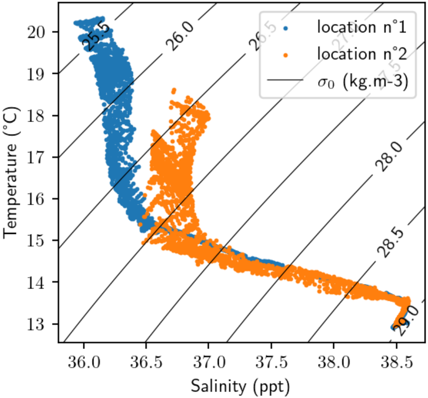


Figure: IBI model temperature and salinity profiles on June 1^{st}, 2018.

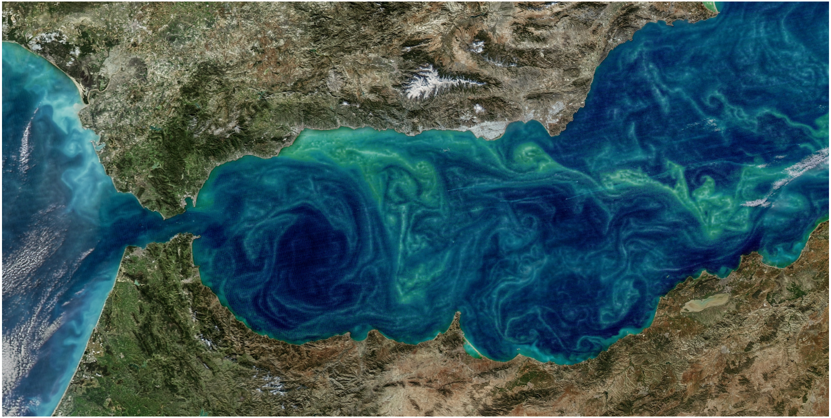


Figure: Surface chlorophyll spatial image in the Alboran sea (NASA).

The IBI model provides a **5-days hydrodynamical forecast** of various quantities in the **North-Atlantic** and in the **Western Mediterranean** [2].

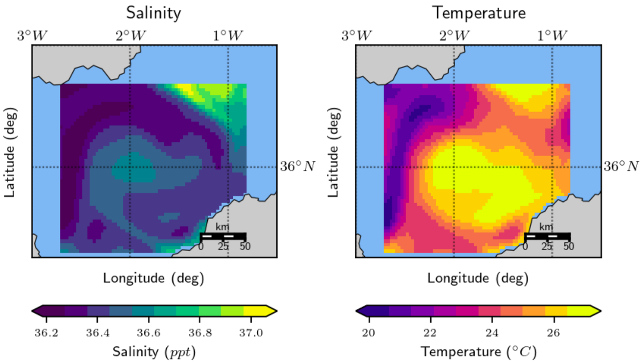


Figure: Model surface temperature and salinity on August 14^{th}, 2018.

Characteristics:

- Daily averaged
- Resolution of about $3km$ horizontally
- Irregular resolution vertically: from $1m$ at surface to $500m$ at $5000m$
- Daily assimilation of data: salinity profiles, SST and SSH
- Integrates tidal forcing, surges, fresh-water discharges...etc.

This **2017-2019** campaign aimed at the detection of 3D features involved in vertical motions. The 2018 expedition included the sampling of a front, North-West of the Eastern Alboran gyre with **surface drifters**, various **CTD sensors** and **ADCP** [3].

Figure: The NRV Alliance vessel (NATO CMRE website)

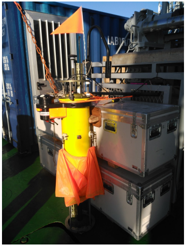


Figure: The Lagrangian float on the deck (picture: S. Ruiz).

Figure: A uCTD probe (Teledyne Marine website).

Figure: A CARTHE drifter (picture: S. Ruiz).

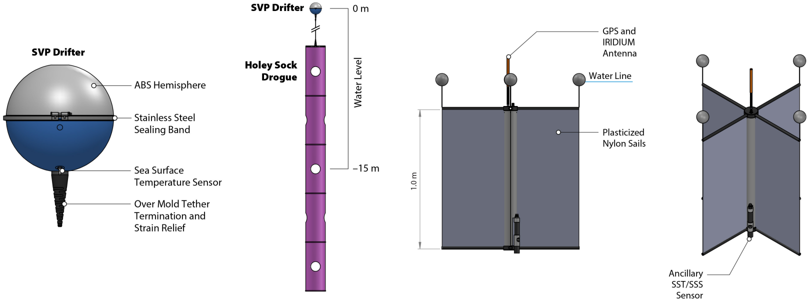


Figure: Schemes of SVP (left) and CODE (right) drifters (Scripps Institution of Oceanography website)

Outline

The processing line can be summed up as follows:

1. Raw variables smoothing: $5km$ radius bicubic filter
2. Integration of specific volume: dynamic height
3. Computation of geostrophic currents
4. Numerical integration of the quasi-geostrophic omega equation

Bicubic filter

The **bicubic filter** computes a weighted average of the variable nodes in a radius R using the following expression:

$$r \longmapsto \begin{cases} (1-(\frac{r}{R})^3)^3 & \text{if } r < R \\ 0 & \text{else.} \end{cases}$$

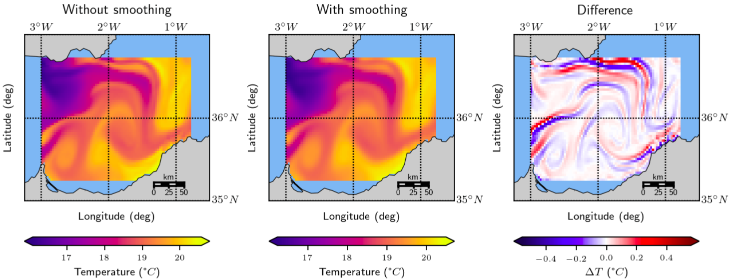


Figure: Original, smoothed model temperature and difference on June 1st, 2018

The inverse of potential density is the **specific volume**. It represents the space occupied by seawater of a particular density.

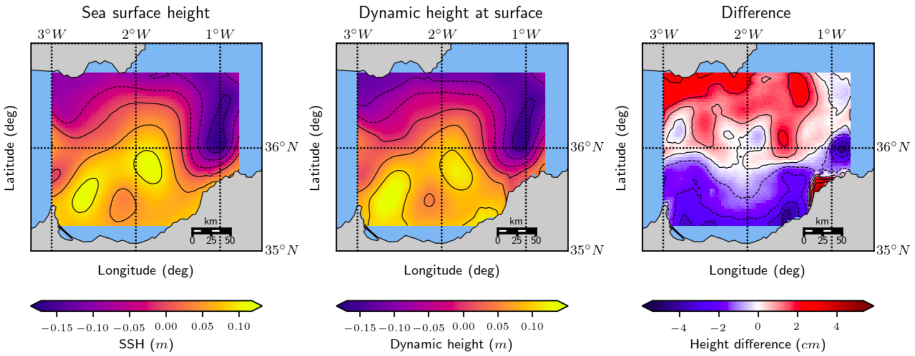


Figure: Satellite SSH, model surface dynamic height and difference on June 1st, 2018

Dynamic height can be considered a **potential** for geostrophic currents, as in the geostrophic approximation we have:

$$\begin{cases} f_0 u(x,y,z) = -\frac{1}{\rho_0}\frac{\partial p(x,y,z)}{\partial y} \implies u(x,y,z) = -\frac{g}{f_0}\frac{\partial H(x,y,z)}{\partial y} \\ f_0 v(x,y,z) = \frac{1}{\rho_0}\frac{\partial p(x,y,z)}{\partial x} \implies v(x,y,z) = \frac{g}{f_0}\frac{\partial H(x,y,z)}{\partial x} \end{cases}$$

with f_0 the Coriolis coefficient, ρ_0 the mean density, g the gravity acceleration, u and v respectively the geostrophic zonal and meridional water flow components, p the local pressure and H the dynamic height.

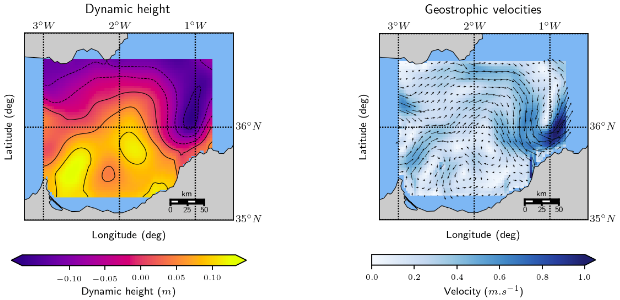


Figure: Model dynamic height and associated geostrophic currents on June 1st, 2018

From the uCTD sections, density transects have been deduced from the **thermodynamic equation of sea water**. At each level, the irregular sampling in the domain have been interpolated using a **kriging algorithm** with a range of about 4km.

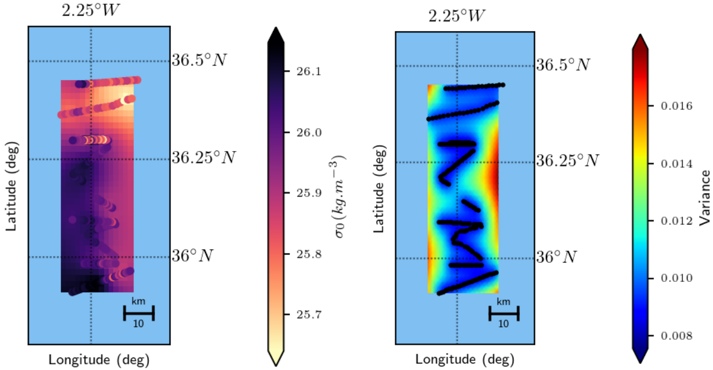


Figure: Surface kriged density from uCTD sections

From the model as from the in-situ dataset, we are in the need of a **method retrieving vertical velocities from raw variables**.

Quasi-geostrophic omega equation

It links the vertical velocities w to the geostrophic component of currents. It can be written as follows [4]:

$$N^2\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)w + f_0^2\frac{\partial^2 w}{\partial z^2} = 2\vec{\nabla}.\vec{Q}$$

with N the Brunt-Vassaila frequency, f_0 the Coriolis frequency, and a forcing involving:

$$\vec{Q} = \frac{g}{\rho_0}\left(\frac{\partial \vec{u}_g}{\partial x}.\vec{\nabla}\rho'; \frac{\partial \vec{v}_g}{\partial y}.\vec{\nabla}\rho'\right)$$

As first order finite differences, this equation becomes:

$$w_{i,j,k} = -\frac{1}{2}\left(\left(\frac{N_k}{\Delta x}\right)^2 + \left(\frac{N_k}{\Delta y}\right)^2 + \left(\frac{f_0}{\Delta z_k}\right)^2\right)^{-1}\Big(F_{i,j,k} - N_k^2\frac{w_{i-1,j,k} + w_{i+1,j,k}}{\Delta x^2}$$
$$- N_k^2\frac{w_{i,j-1,k} + w_{i,j+1,k}}{\Delta y^2} - f_0^2\frac{w_{i,j,k-1} + w_{i,j,k+1}}{\Delta z_k^2}\Big)$$

with $F = 2\vec{\nabla}.\vec{Q}$ the forcing scalar term, and i, j and k the indices on the x, y and z axes.

After computing the forcing term $2\vec{\nabla}.\vec{Q}$, the quasi-geostrophic omega equation as **finite differences** is **applied successively until convergence** to give an estimation of the vertical velocities. The boundary condition is chosen null.

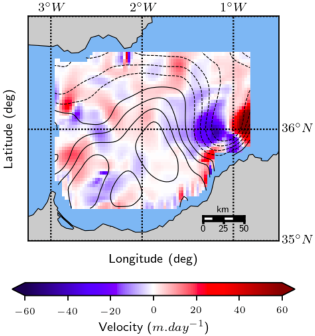


Figure: Vertical velocities numerically integrated from model data at 60m on June 1^{st}, 2018

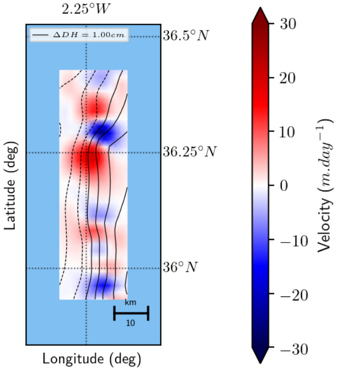


Figure: Vertical velocities numerically integrated from uCTD sections data at 60m on June 1^{st}, 2018

From the trajectories of the 82 drifters in our area of study, there is also a way to retrieve vertical velocities. **A polygon of drifter changes shape**, and hence allows us to **estimate via a least-square adjustment the divergence field**.

Taylor expansion of a drifter speed

$$u_i \approx \overline{u} + \frac{\partial u}{\partial x}(x_i - \overline{x}) + \frac{\partial u}{\partial y}(y_i - \overline{y})$$

with u_i the zonal component of the i drifter speed, u the zonal component of the velocity field, x_i its position in longitude, y_i its position in latitude, x the polygon barycentre position in longitude and y the polygon barycentre position in latitude.

In our case, **some drifters are drifting at surface** and **others along the 15m deep field**. Through the continuity equation then, it is possible to estimate vertical velocities at $15m$ integrating between the two horizontal divergence field.

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

u, v and w being the three components of the 3D velocity field.

Vertical velocities expression from the continuity equation

$$w(D) = \int_{z=0}^{D} [\frac{\partial u}{\partial x}(z) + \frac{\partial v}{\partial y}(z)] dz$$

considering a z-axis oriented down.

More detail about this method is given in *Tarry et al., 2021* [5].

Outline

The model outputs **maximum velocities at surface** of about $10\,m\,day^{-1}$ in module, and sometimes up to $50\,m\,day^{-1}$ in the interior. Maximum speeds are usually located between $50\,m$ and $150\,m$. The most intense patterns **surround the eddies**, and leave the interior more passive.

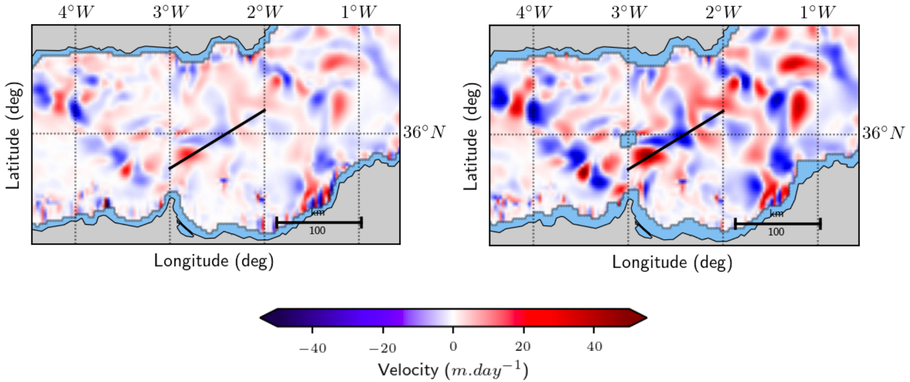


Figure: Vertical velocities from IBI model variables on April 7th, 2018 at $20\,m$ and $60\,m$

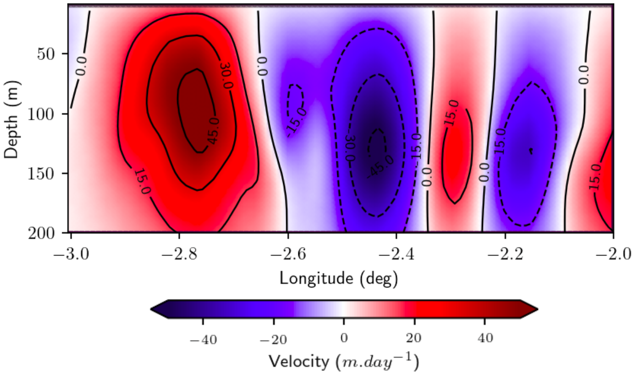


Figure: Vertical velocities section from IBI model variables on April 7^{th}, 2018

Even though the uCTD domain is small, it lets appear **high velocities** in spite of the close boundaries. At 10 m, velocities observed reach about 20 $m\,day^{-1}$ in module, and can go up to 90 $m\,day^{-1}$ around 100 m.

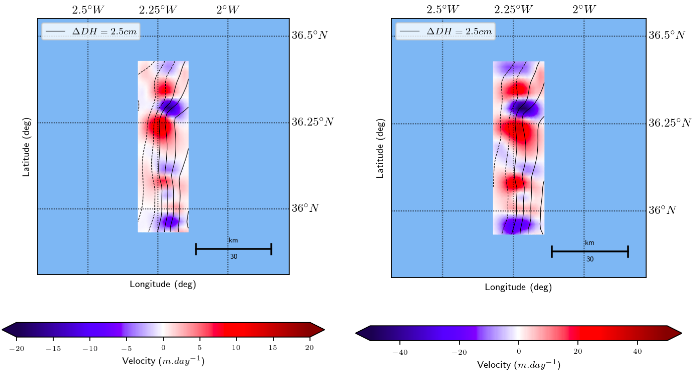


Figure: Vertical velocities from kriged uCTD sections at 10 m and 60 m on June 1st, 2018.

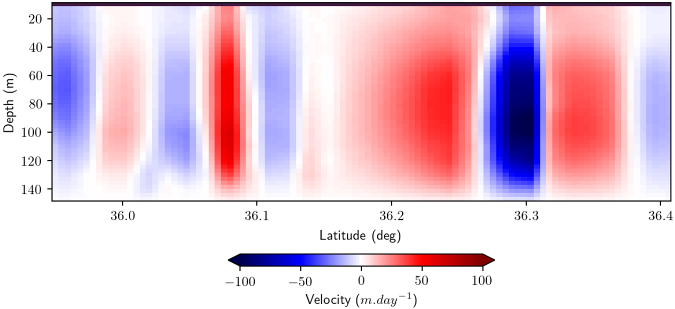


Figure: Vertical velocities section along latitude (2.25°W fixed) from uCTD variables.

The work of *Tarry et al. 2021* [5] leads to computing values that have a non-negligible temporal variability. The 15 m deep velocities reach about 30 $m\,day^{-1}$ in module. This method outputs **higher values because of the resolved scale that is smaller** than the other two methods. The **pattern sizes** — although not identifiable — are **compatible with previous uCTD results**.

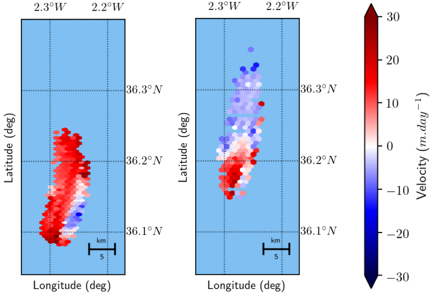


Figure: Vertical velocities from drifters on 1st June, 2018 at 0:20am and 3:30am.

Outline

Analysis

Model localisation of features

The model output sometimes **displaces, tilts, distorts or delays** some features. This lack of accuracy directly impacts the vertical velocities derived.

On June 1^{st}, we observe that the Eastern Alboran gyre is **tilted 45° to the right**, and that the **best fit for the density variable is visually the 2^{nd} of June**.

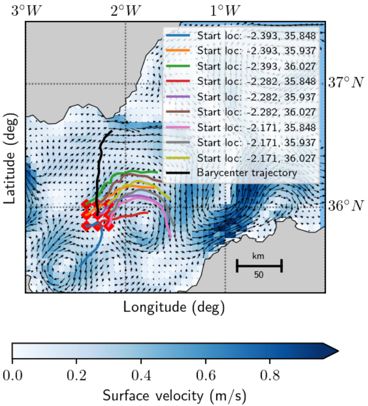


Figure: Barycentre 4 days trajectory of drifters number 16, 17 and 18 (black) and numerically simulated 4 days trajectories of lagrangian particles 10 km spaced at $t = 0$ in the 1^{st} of June, 2018 model field.

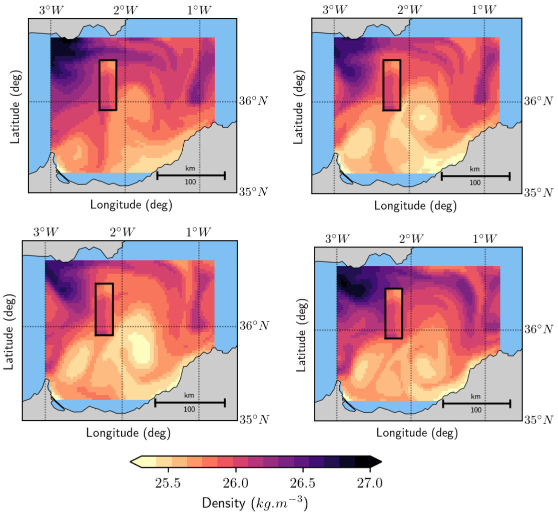


Figure: Model surface potential density and interpolated in-situ potential density (inside black rectangle) from May 31st to June 3rd (from left to right and top to bottom).

Looking at the uCTD sections results, **we expect maximum velocities up to a hundred meters per day** in absolute. At 10 m, maximum velocities should reach about 20 $m\,day^{-1}$ taking into consideration both surface drifter and uCTD estimations.

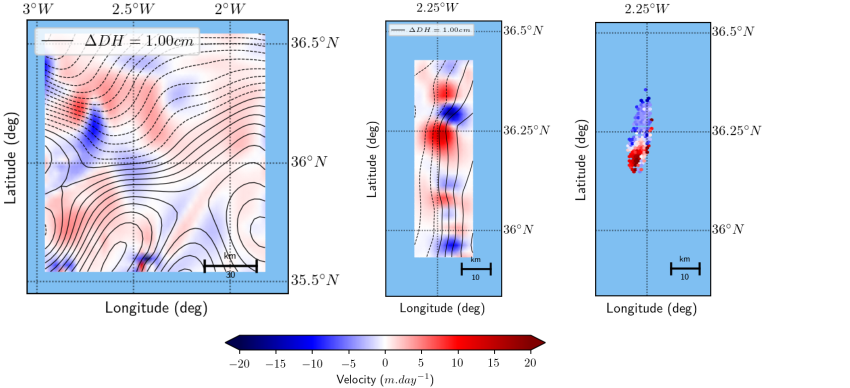


Figure: 10 m deep vertical velocities from model on June 2nd, 2018 with 1cm spaced dynamic height lines (left), from uCTD sections (middle) and from drifter float on June 1st at 3:30am (right).

Outline

Conclusion

- Model features are not accurate enough yet to allow prediction of vertical velocities: the same processing chain leads to very different outputs.
- Mesoscale features appear clearly. The model dynamics are realistic, and describe situations that look coherent.
- Features in early June, 2018 are at least tilted, underestimated and delayed.
- Apart from the deepness of maximum velocities, model and in-situ vertical speeds are not so correlated.
- The small size of the domains for in-situ variables makes the cross-check incomplete.

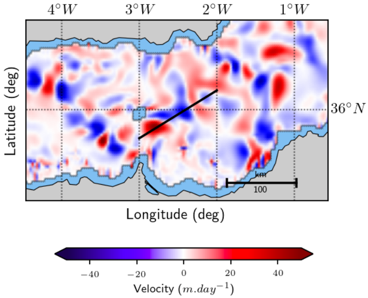


Figure: Vertical velocities from IBI model variables on April 7^{th}, 2018 at 60 m

References

[1] L. Renault, T. Oguz, A. Pascual, G. Vizoso, & J. Tintoré. *Surface circulation in the Alboran Sea inferred from remotely sensed data*. Journal of Geophysical Research. 2012.

[2] Copernicus Marine Service website. *Atlantic-Iberian Biscay Irish Ocean Physics Analysis and Forecast*. https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=IBI_ANALYSISFORECAST_PHY_005_001. 2021.

[3] A. Mahadevan, E. D'Asaro, J. Allen, P. Almaraz García, E. Alou-Font, *CALYPSO 2019 Cruise Report: Field Campaign in the Mediterranean*. Technical report. https://hdl.handle.net/1912/25266. 2020.

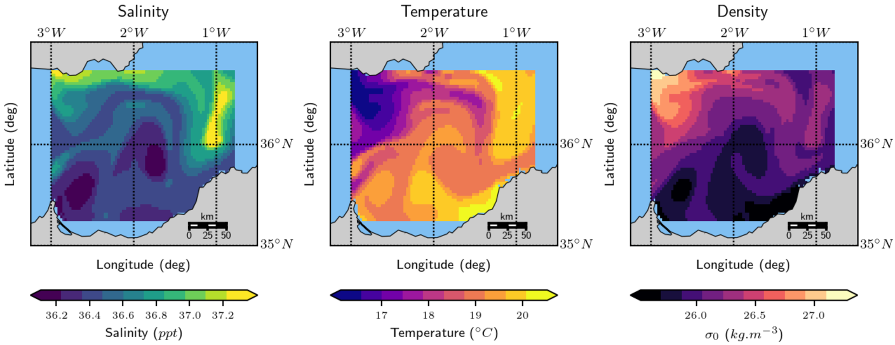
[4] B. J. Hoskins, I. Draghici & H. C. Davies. *A new look at the ω-equation*. Royal Meteorological Society. 1977.

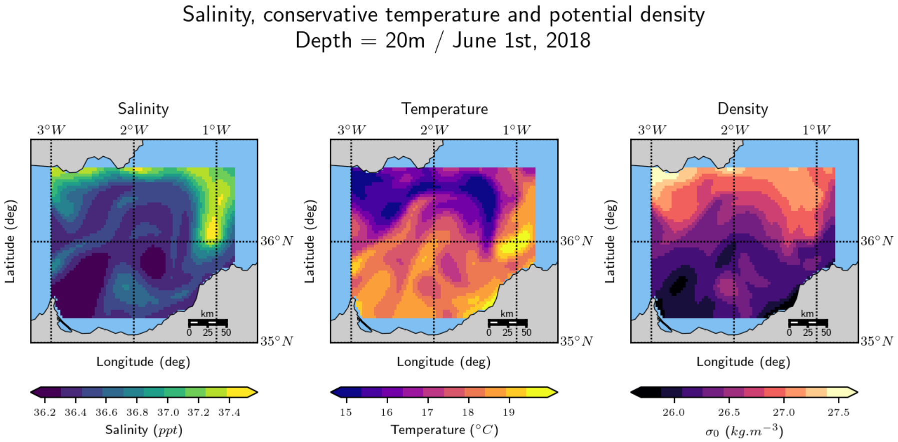
[5] D. R. Tarry, S. Essink, A. Pascual, S. Ruiz, P.-M. Poulain, T. Özgökmen, L. R. Centurioni, J. T. Farrar, A. Shcherbina, A. Mahadevan & E. D'Asaro. *Frontal convergence and vertical velocity measured by drifters in the Alboran Sea*. Journal of Geophysical Research. https://doi.org/10.1029/2020JC016614. 2021.

Github link to the open-source vertical velocities integration code:
https://github.com/hermilth/verticalvelocities

Thank you for your attention!

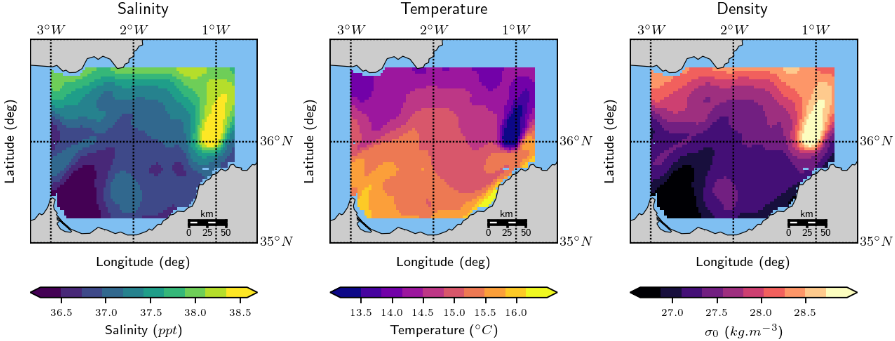
Salinity, conservative temperature and potential density
Depth = 10m / June 1st, 2018

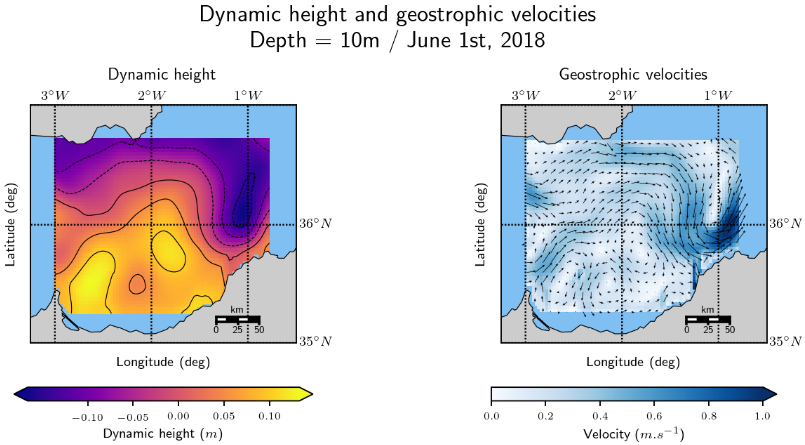


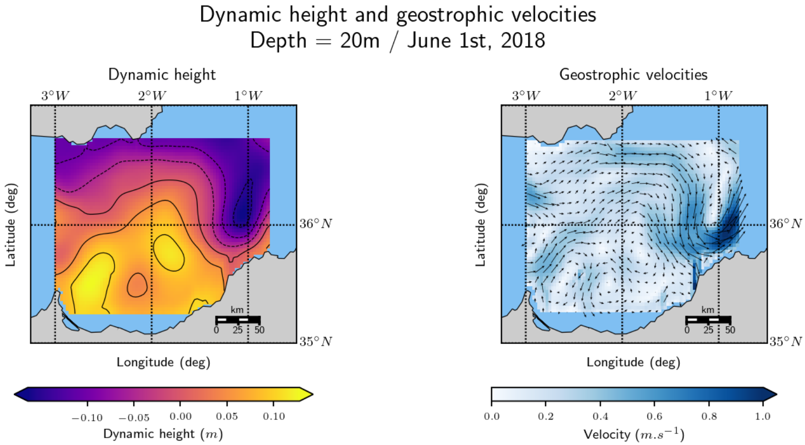


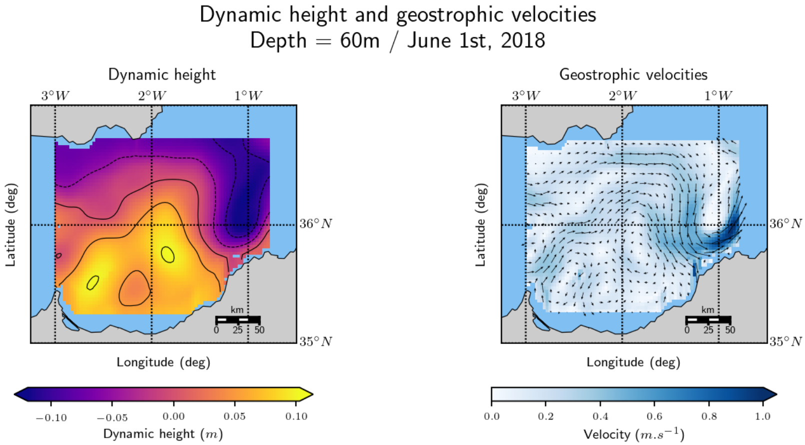
Salinity, conservative temperature and potential density
Depth = 20m / June 1st, 2018
Salinity
Temperature
Density
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0 25 50
36.2 36.4 36.6 36.8 37.0 37.2 37.4
Salinity (ppt)
15 16 17 18 19
Temperature (°C)
26.0 26.5 27.0 27.5
σ0 (kg.m−3)

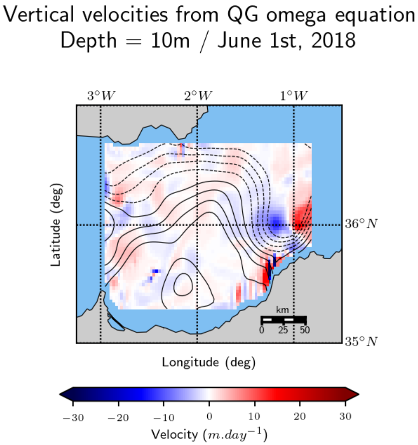
Salinity, conservative temperature and potential density
Depth = 60m / June 1st, 2018

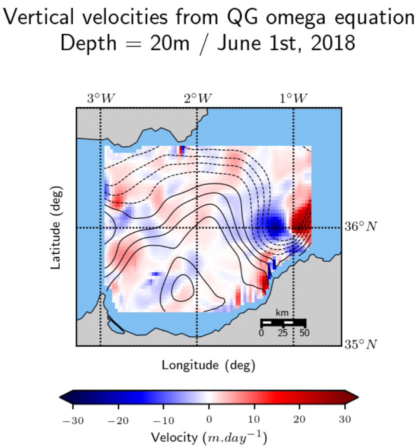


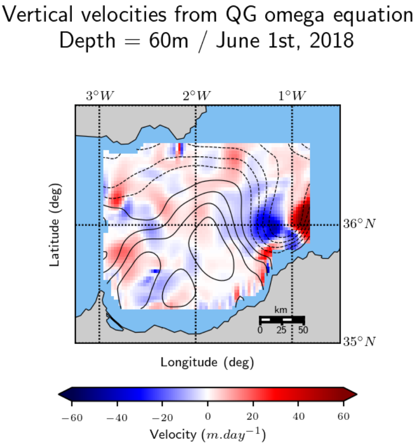

Dynamic height and geostrophic velocities
Depth = 10m / June 1st, 2018
Dynamic height
3°W
2°W
1°W
36°N
35°N
km
0 25 50
Latitude (deg)
Longitude (deg)
−0.10 −0.05 0.00 0.05 0.10
Dynamic height (m)
Geostrophic velocities
3°W
2°W
1°W
36°N
35°N
km
0 25 50
Latitude (deg)
Longitude (deg)
0.0 0.2 0.4 0.6 0.8 1.0
Velocity (m.s^-1)


Dynamic height and geostrophic velocities
Depth = 20m / June 1st, 2018
Dynamic height
Geostrophic velocities
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0 25 50
−0.10 −0.05 0.00 0.05 0.10
Dynamic height (m)
0.0 0.2 0.4 0.6 0.8 1.0
Velocity (m.s^−1)

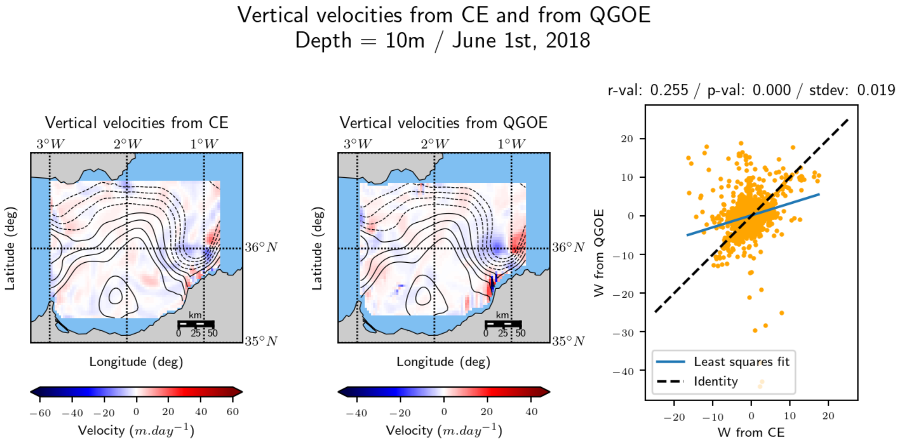

Dynamic height and geostrophic velocities
Depth = 60m / June 1st, 2018
Dynamic height
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0
25
50
−0.10
−0.05
0.00
0.05
0.10
Dynamic height (m)
Geostrophic velocities
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0
25
50
0.0
0.2
0.4
0.6
0.8
1.0
Velocity ($m.s^{-1}$)


Vertical velocities from QG omega equation
Depth = 10m / June 1st, 2018
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0 25 50
−30 −20 −10 0 10 20 30
Velocity ($m.day^{-1}$)

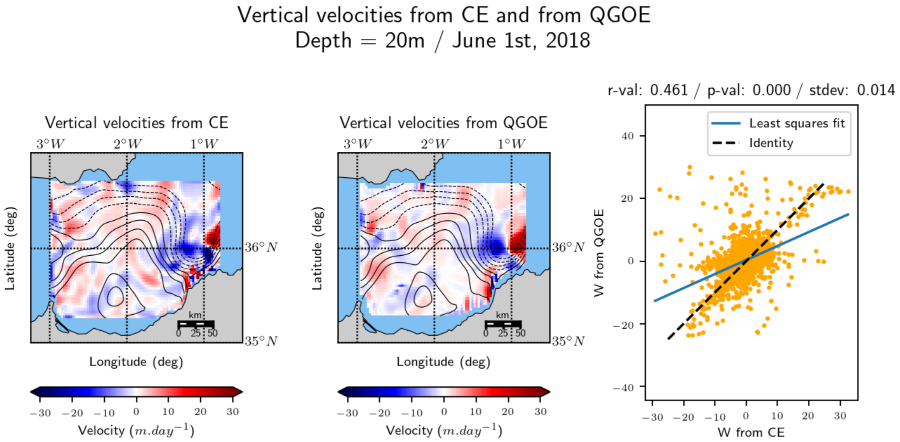

Vertical velocities from QG omega equation
Depth = 20m / June 1st, 2018
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0
25
50
−30
−20
−10
0
10
20
30
Velocity (m.day⁻¹)



Vertical velocities from QG omega equation
Depth = 60m / June 1st, 2018
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0
25
50
−60
−40
−20
0
20
40
60
Velocity (m.day−1)



Vertical velocities from CE and from QGOE
Depth = 10m / June 1st, 2018
Vertical velocities from CE
3°W 2°W 1°W
36°N
35°N
km
0 25 50
Latitude (deg)
Longitude (deg)
−60 −40 −20 0 20 40 60
Velocity (m.day−1)
Vertical velocities from QGOE
3°W 2°W 1°W
36°N
35°N
km
0 25 50
Latitude (deg)
Longitude (deg)
−40 −20 0 20 40
Velocity (m.day−1)
r-val: 0.255 / p-val: 0.000 / stdev: 0.019
20 10 0 −10 −20 −30 −40
W from QGOE
−20 −10 0 10 20
W from CE
Least squares fit
Identity


Vertical velocities from CE and from QGOE
Depth = 20m / June 1st, 2018
Vertical velocities from CE
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0 25 50
−30 −20 −10 0 10 20 30
Velocity ($m.day^{-1}$)
Vertical velocities from QGOE
3°W
2°W
1°W
36°N
35°N
Latitude (deg)
Longitude (deg)
km
0 25 50
−30 −20 −10 0 10 20 30
Velocity ($m.day^{-1}$)
r-val: 0.461 / p-val: 0.000 / stdev: 0.014
Least squares fit
Identity
40
20
0
−20
−40
W from QGOE
−30 −20 −10 0 10 20 30
W from CE

Vertical velocities from CE and from QGOE
Depth = 60m / June 1st, 2018