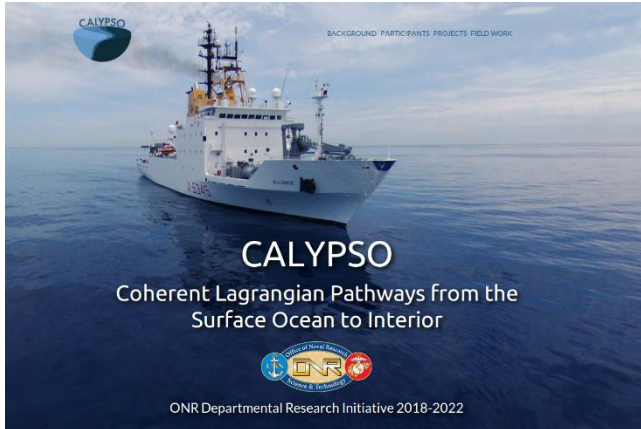


# High-resolution real-time forecasting systems and services in support of fine-scale field experiments in the Western Mediterranean Sea

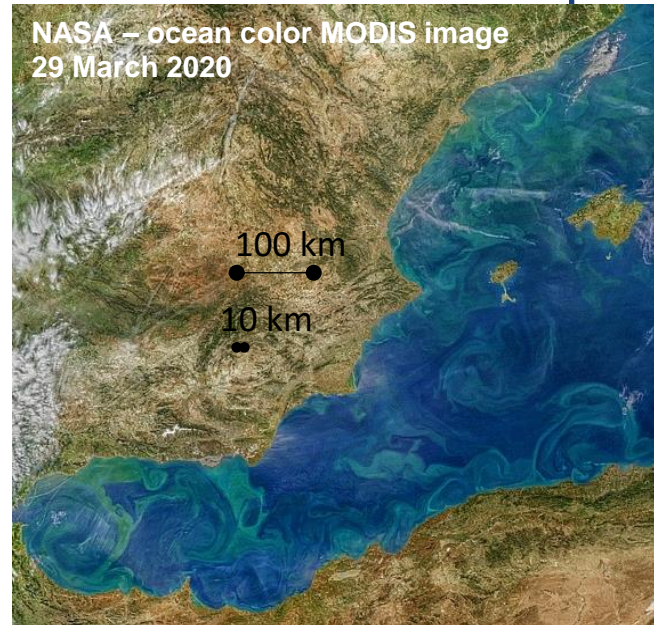
Baptiste Moure, Máximo Garcia-Jove, Nikolaos D. Zarokanellos,  
Alex Santana, Pierre Lermusiaux, Patrick J. Haley, Chris Mirabito,  
Helga Huntley, Irina Rypina, Daniel Rudnick, Joaquín Tintoré  
([bmoure@imedea.uib-csic.es](mailto:bmoure@imedea.uib-csic.es))

Paris, 18 November 2024

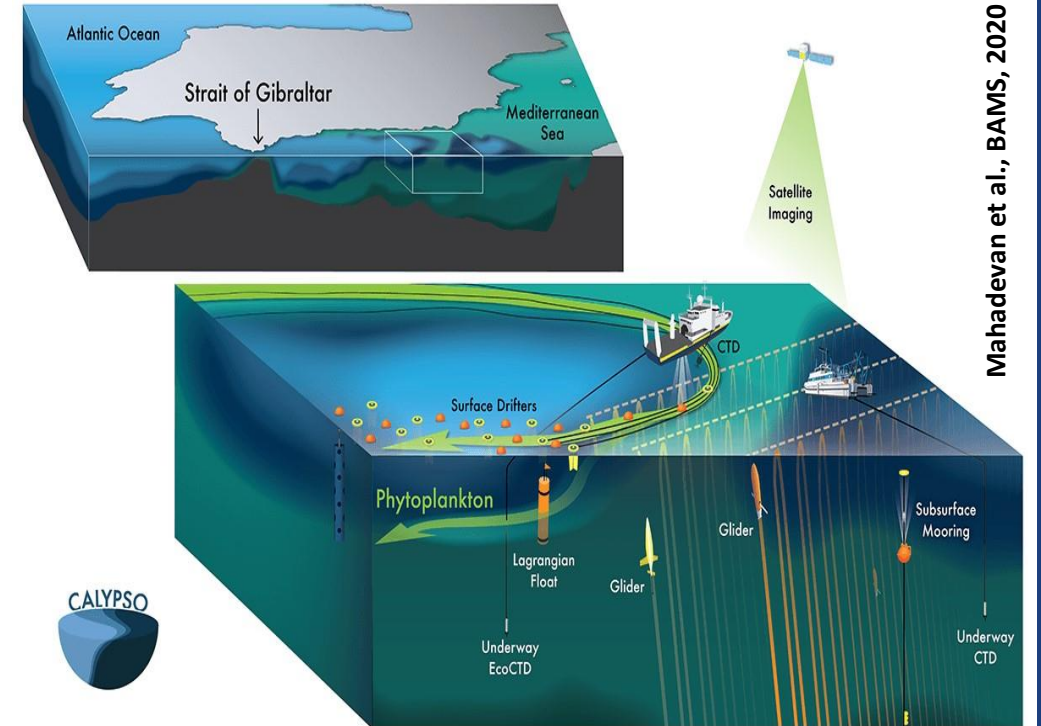
# CALYPSO: Coherent Lagrangian Pathways from the Surface Ocean to Interior



<https://calypsodri.whoj.edu/>



Objective: improve understanding of 3-dimensional water pathways in the surface ocean

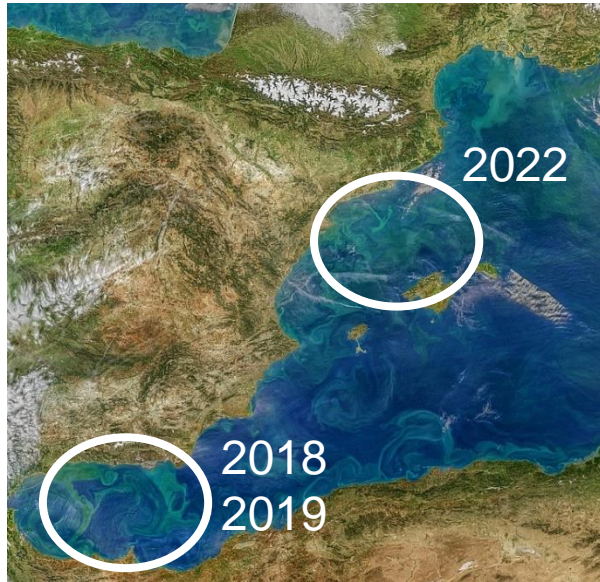


Mahadevan et al., BAMS, 2020

→ High-resolution observations and modelling of small-scale variability in the western Mediterranean Sea

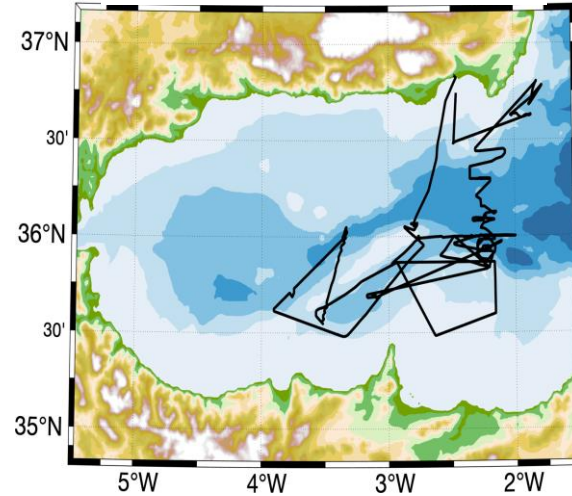


# CALYPSO: Coherent Lagrangian Pathways from the Surface Ocean to Interior



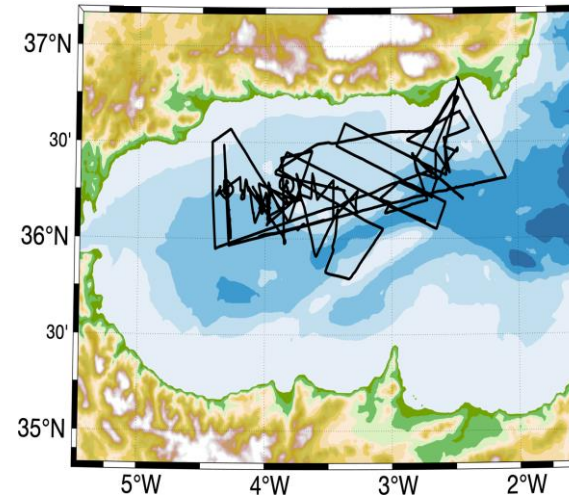
→ 3 intense observational campaigns

Alboran Sea  
May-June 2018



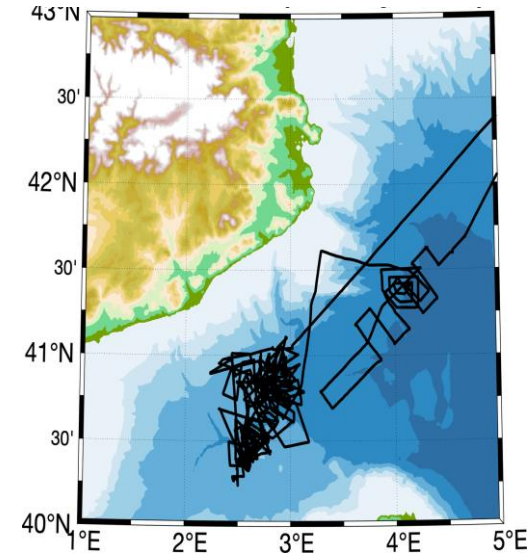
- 2 ships
- > 1600 uCTD profiles
- 3 gliders
- > 80 drifters

Alboran Sea  
Mar-Apr 2019



- 2 ships
- > 3500 uCTD profiles
- 8 gliders
- > 180 drifters

Balearic Sea  
Feb-Mar 2022





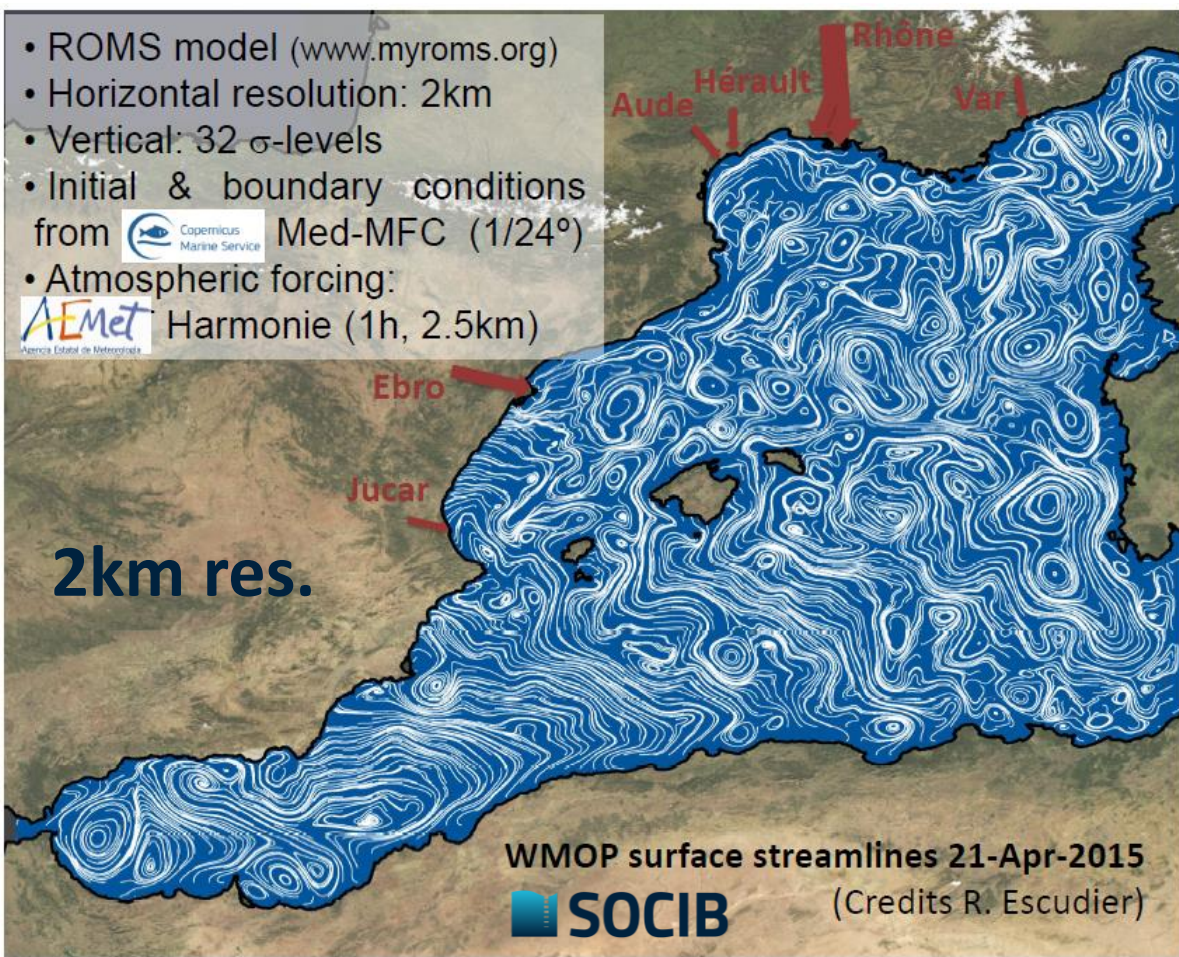
- 2 ships
- > 2400 EcoCTD profiles
- 8 gliders
- > 300 drifters

(Mathieu Dever, Amala Mahadevan)

# Real-time forecasting support

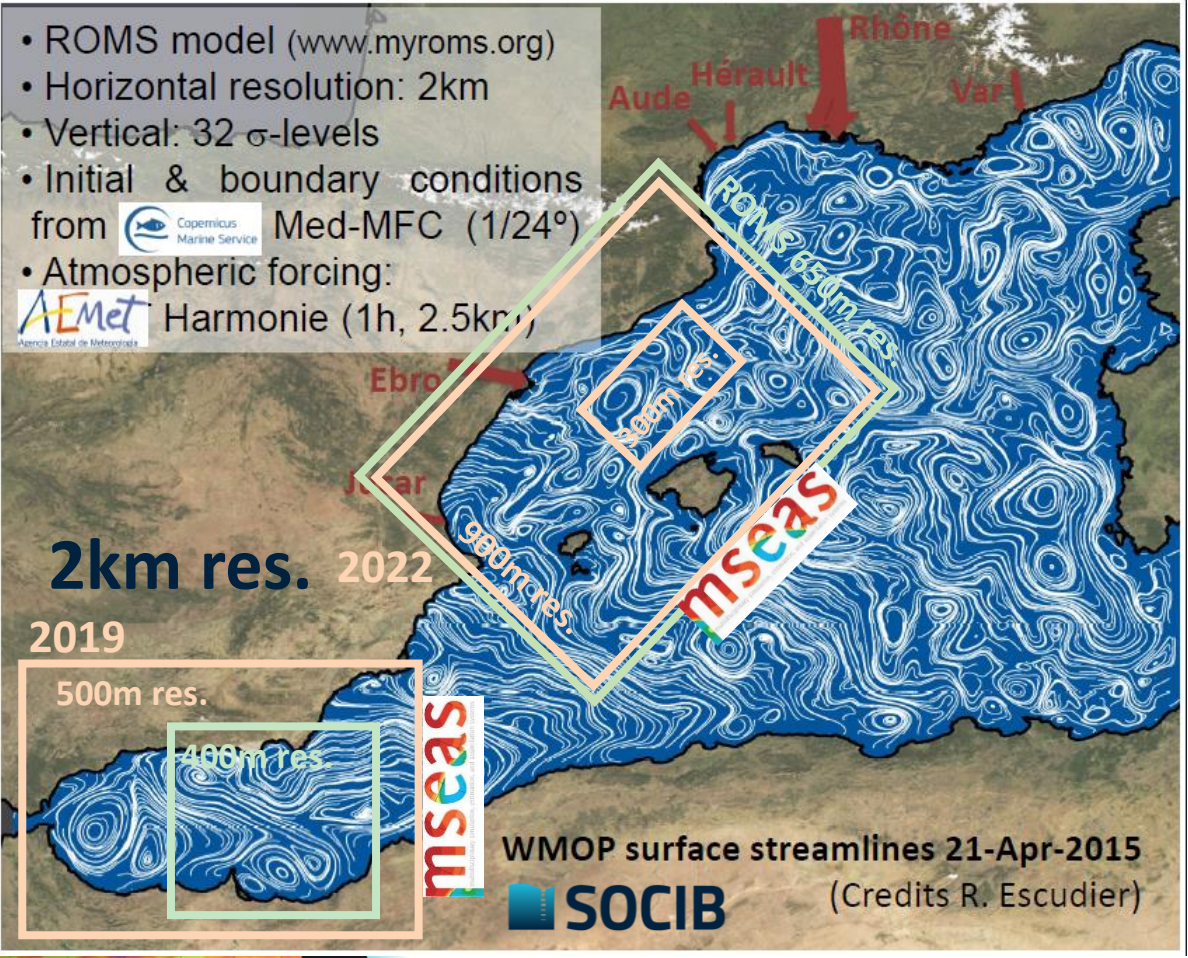
**WMOP** Western Mediterranean Operational modelling system

- ROMS model ([www.myroms.org](http://www.myroms.org))
- Horizontal resolution: 2km
- Vertical: 32  $\sigma$ -levels
- Initial & boundary conditions from  Med-MFC (1/24°)
- Atmospheric forcing:  Harmonie (1h, 2.5km)



# Real-time forecasting support

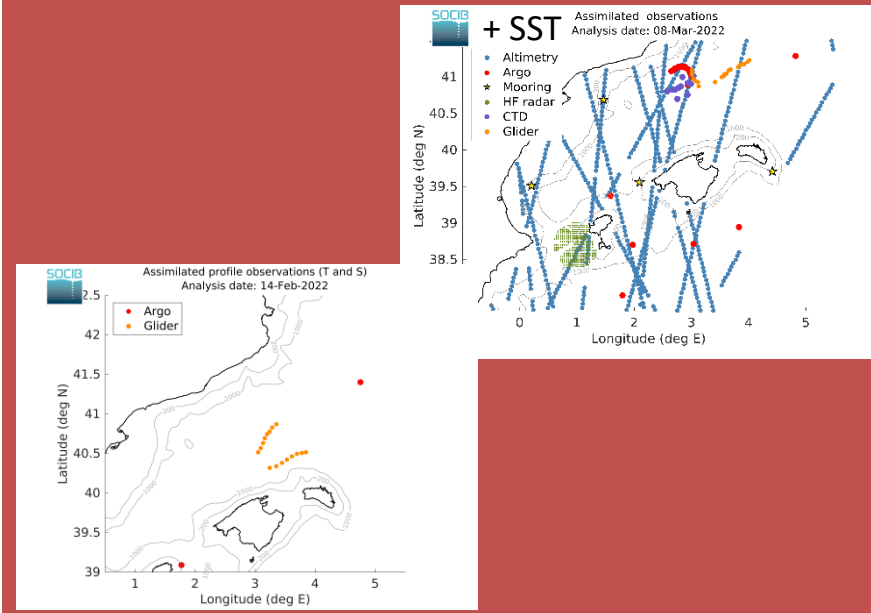
**WMOP** Western Mediterranean OPERational modelling system



- ROMS model ([www.myroms.org](http://www.myroms.org))
- Horizontal resolution: 2km
- Vertical: 32  $\sigma$ -levels
- Initial & boundary conditions from Capernicus Marine Service Med-MFC (1/24°)
- Atmospheric forcing: AEMet Harmonie (1h, 2.5km)

- 1-way nesting
- Delayed time – free run
- Reanalysis

**Data assimilation:**  
Multimodel Local Ensemble  
Optimal Interpolation



Daily analysis, including glider and underway CTD data during the 2022 campaign.

→ 72-hour forecast horizon

# Real-time forecasting support

Real-time model results, validation against observations and advanced Lagrangian diagnostics were made available through several web pages with the objective to help identifying frontal and subduction areas.

**SOCIB / CALYPSO CAMPAIGN**

WMOP forecasts 0-24h horizon  
 WMOP forecasts 24-48h horizon  
 WMOP forecasts 48-72h horizon  
 Satellite pictures and model evaluation  
 Latest assimilated data

« Previous date      **Wednesday 23rd February 2022**      Next date »

**WMOP forecasts 0-24h horizon**

WMOP ocean forecast  
 average from 23-Feb-2022 00:00 to 24-Feb-2022 00:00 UTC  
 Surface density anomaly ( $\text{kg m}^{-3}$ ) and currents

Surface density and currents

WMOP ocean forecast  
 average from 23-Feb-2022 00:00 to 24-Feb-2022 00:00 UTC  
 Surface density gradients ( $\text{kg m}^{-3} \text{ km}^{-1}$ ) and currents

Surface density gradients

**mseas**

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## CALYPSO Real-Time Sea Experiment 2019

### Alboran Sea – March-April 2019

P.F.J. Lermusiaux, P.J. Haley, C. Mirabito, M. Doshi, A. Gkirkgis, W.H. Ali, C. Kulkarni, A. Gupta  
**Massachusetts Institute of Technology**  
 Center for Ocean Engineering  
 Mechanical Engineering  
 Cambridge, Massachusetts

**MSEAS Deterministic Ocean Forecasts**  
**MSEAS Probabilistic Ocean Forecasts**  
**MSEAS Methods & Systems Forecasts**  
**MSEAS Atmos. Forecasts**  
**MSEAS Results From Partners**

Data sources

CALYPSO Project Main Page

The CALYPSO 2019 experiment occurs in the Alboran Sea from March 27 to April 11, 2019. Our specific objectives are to: (i) Utilize our new Lagrangian transport theory and methods to forecast, characterize and quantify ocean processes involved in the three-dimensional transports and transformation of water masses and subduction dynamics in the Alboran Sea; (ii) Apply and expand our multi-resolution submesoscale-to-regional-scale ocean modeling, 2-way nesting, and uncertainty predictions, for real-time forecasting and process studies; (iii) Help design field experiments and predict sampling strategies that maximize information on 4D pathways and dynamics in the region. We thank all of the CALYPSO team members for their inputs and collaboration. We also thank NCEP for their atmospheric forcing data.

This research is sponsored by the **Office of Naval Research**

**CALYPSO Field Experiment Support Mar/Apr 2019**

CURRENT

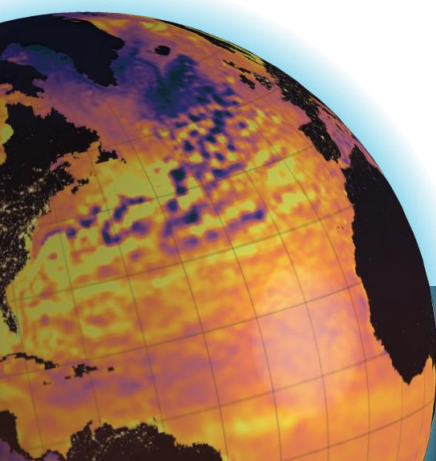
02 Mar 2019 - 03 Mar 2019 - 04 Mar 2019 - 05 Mar 2019 - 07 Mar 2019 - 08 Mar 2019 - 09 Mar 2019 - 10 Mar 2019 - 11 Mar 2019 - 12 Mar 2019 - 13 Mar 2019 - 14 Mar 2019 - 15 Mar 2019 - 16 Mar 2019 - 17 Mar 2019 - 18 Mar 2019 - 19 Mar 2019 - 20 Mar 2019 - 21 Mar 2019 - 22 Mar 2019 - 23 Mar 2019 - 24 Mar 2019 - 25 Mar 2019 - 26 Mar 2019 - 27 Mar 2019 - 28 Mar 2019 - 29 Mar 2019 - 30 Mar 2019 - 31 Mar 2019 - 01 Apr 2019 - 02 Apr 2019 - 03 Apr 2019 - 04 Apr 2019 - 05 Apr 2019 - 06 Apr 2019 - 07 Apr 2019 - 08 Apr 2019 - 09 Apr 2019 - 10 Apr 2019 - 11 Apr 2019

Model Products from the Latest 2-km SOCIB WMOP Forecasts Initialized

14 April 2019

SOCIB WMOP (2 km res)

1-day trajectories      Animated 3-day trajectories      DLE

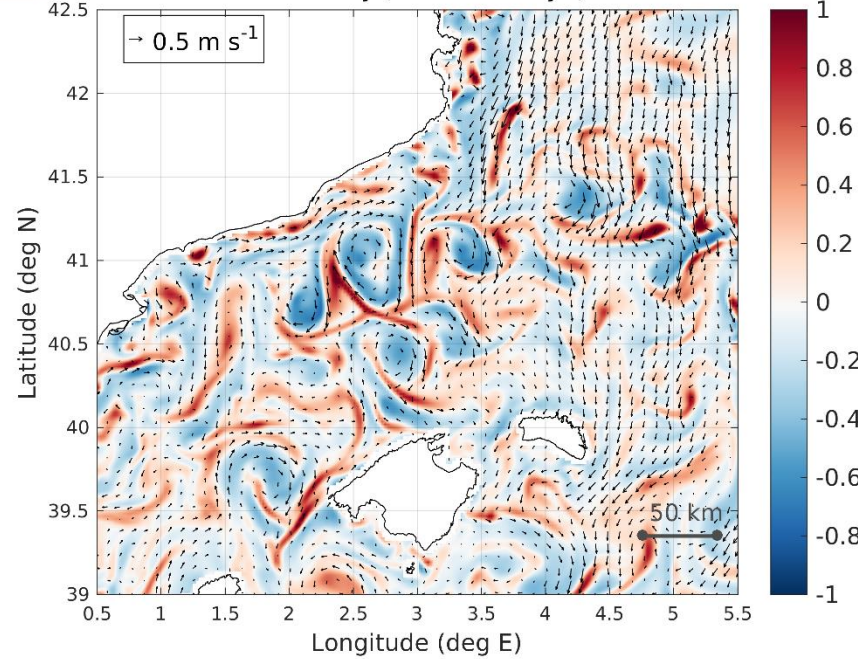


# Real-time

Real-time model re  
diagnostics were m  
identify frontal and



WMOP ocean forecast  
average from 22-Feb-2022 00:00 to 23-Feb-2022 00:00 UTC  
Surface relative vorticity (normalized by f) and currents



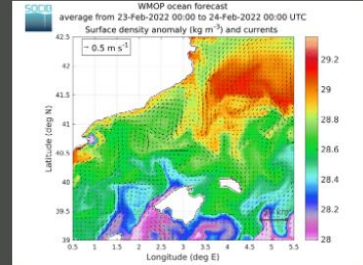
Advanced Lagrangian  
with the objective to help

## SOCIB / CALYPSO CAMPAIGN

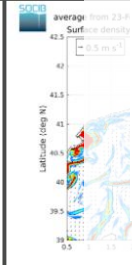
WMOP forecasts 0-24h horizon  
WMOP forecasts 24-48h horizon  
WMOP forecasts 48-72h horizon  
Satellite pictures and model evaluation  
Latest assimilated data

« Previous date **Wednesday 23rd February 2022**

## WMOP forecasts 0-24h horizon



Surface density and currents



Surface density gradients

subduction dynamics in the Alboran Sea; (ii) Apply and expand our multi-resolution submesoscale-to-regional-scale ocean modeling, 2-way nesting, and uncertainty predictions, for real-time forecasting and process studies; (iii) Help design field experiments and predict sampling strategies that maximize information on 4D pathways and dynamics in the region. We thank all of the CALYPSO team members for their inputs and collaboration. We also thank NCEP for their atmospheric forcing data.

This research is sponsored by the Office of Naval Research



CALYPSO Field Experiment Support Mar/Apr 2019

| Calendar    |             |
|-------------|-------------|
| 02 Mar 2019 | 03 Mar 2019 |
| 04 Mar 2019 | 05 Mar 2019 |
| 06 Mar 2019 | 07 Mar 2019 |
| 08 Mar 2019 | 09 Mar 2019 |
| 10 Mar 2019 | 11 Mar 2019 |
| 12 Mar 2019 | 13 Mar 2019 |
| 14 Mar 2019 | 15 Mar 2019 |
| 16 Mar 2019 | 17 Mar 2019 |
| 18 Mar 2019 | 19 Mar 2019 |
| 20 Mar 2019 | 21 Mar 2019 |
| 22 Mar 2019 | 23 Mar 2019 |
| 24 Mar 2019 | 25 Mar 2019 |
| 26 Mar 2019 | 27 Mar 2019 |
| 28 Mar 2019 | 29 Mar 2019 |
| 30 Mar 2019 | 31 Mar 2019 |

Model Products from the Latest 2-km SOCIB WMOP Forecasts Initialized

14 April 2019

SOCIB WMOP (2 km res)

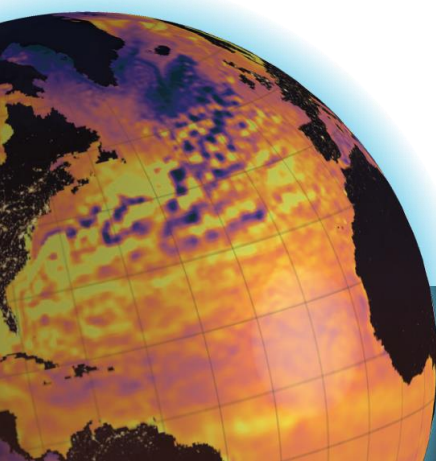
1-day trajectories

Animated 3-day trajectories

DLE

Utilize our new Lagrangian transport

information of water masses and

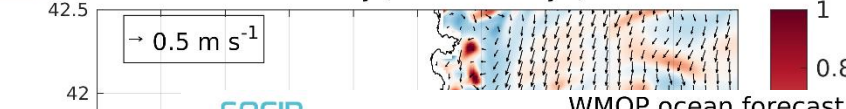


# Real-time

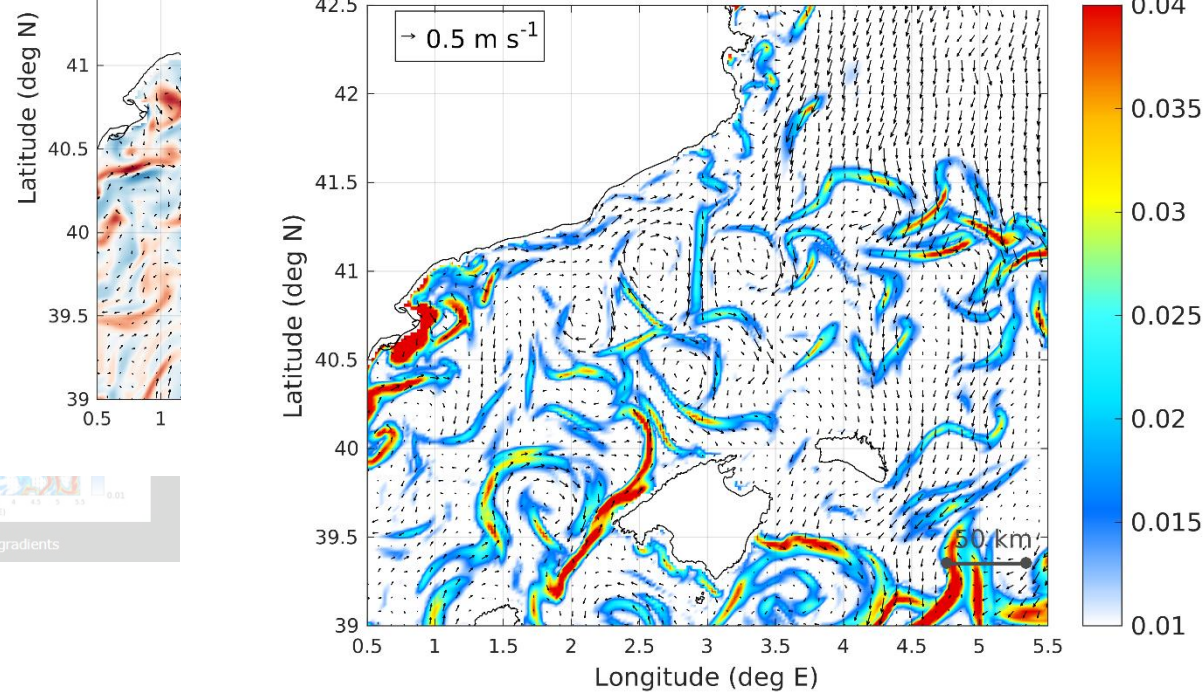
Real-time model re diagnostics were m identify frontal and



WMOP ocean forecast  
average from 22-Feb-2022 00:00 to 23-Feb-2022 00:00 UTC  
Surface relative vorticity (normalized by f) and currents



WMOP ocean forecast  
average from 22-Feb-2022 00:00 to 23-Feb-2022 00:00 UTC  
Surface density gradients ( $\text{kg m}^{-3} \text{ km}^{-1}$ ) and currents



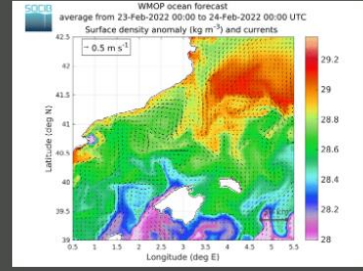
Advanced Lagrangian with the objective to help

## SOCIB / CALYPSO CAMPAIGN

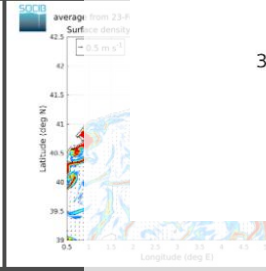
- WMOP forecasts 0-24h horizon
- WMOP forecasts 24-48h horizon
- WMOP forecasts 48-72h horizon
- Satellite pictures and model evaluation
- Latest assimilated data

« Previous date **Wednesday 23rd February 2022**

## WMOP forecasts 0-24h horizon



Surface density and currents



Surface density gradients

CALYPSO Field Experiment Support Mar/Apr 2019

| 2019        |             |             |             |             |             |
|-------------|-------------|-------------|-------------|-------------|-------------|
| 02 Mar 2019 | 03 Mar 2019 | 04 Mar 2019 | 05 Mar 2019 | 07 Mar 2019 | 08 Mar 2019 |
| 09 Mar 2019 | 11 Mar 2019 | 12 Mar 2019 | 13 Mar 2019 | 14 Mar 2019 | 15 Mar 2019 |
| 17 Mar 2019 | 18 Mar 2019 | 19 Mar 2019 | 20 Mar 2019 | 21 Mar 2019 | 22 Mar 2019 |
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| 07 Apr 2019 | 08 Apr 2019 | 09 Apr 2019 | 10 Apr 2019 | 11 Apr 2019 |             |

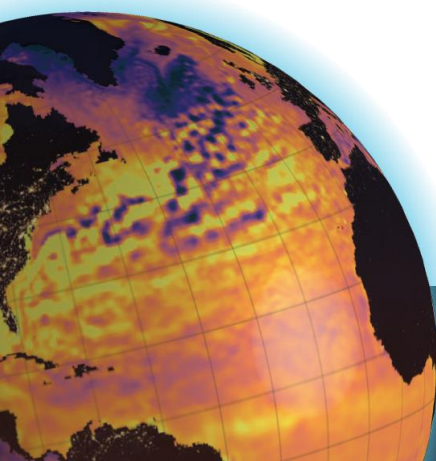
Model Products from the Latest 2-km SOCIB WMOP Forecasts Initialized

14 April 2019

SOCIB WMOP (2 km res)

Animated Salty Trajectories

DLE



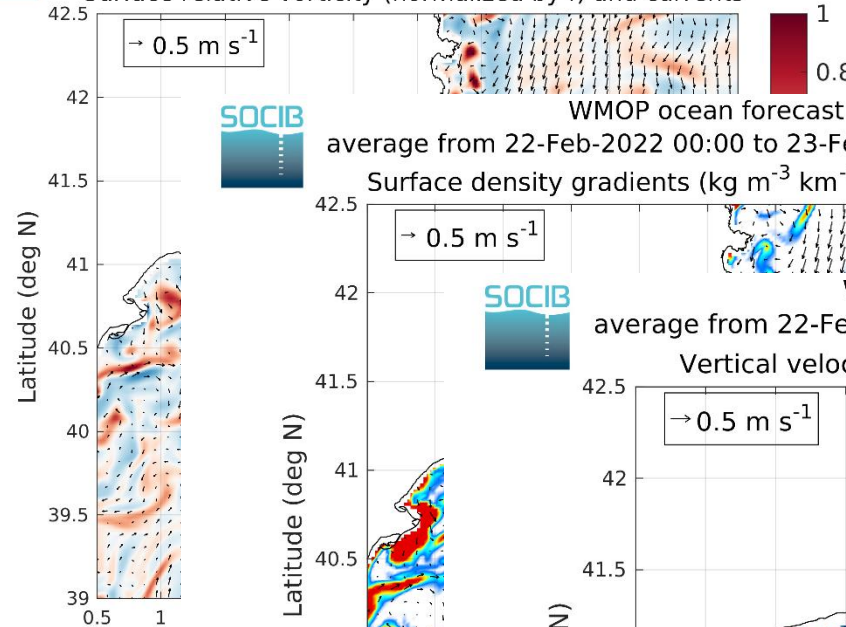


# Real-time

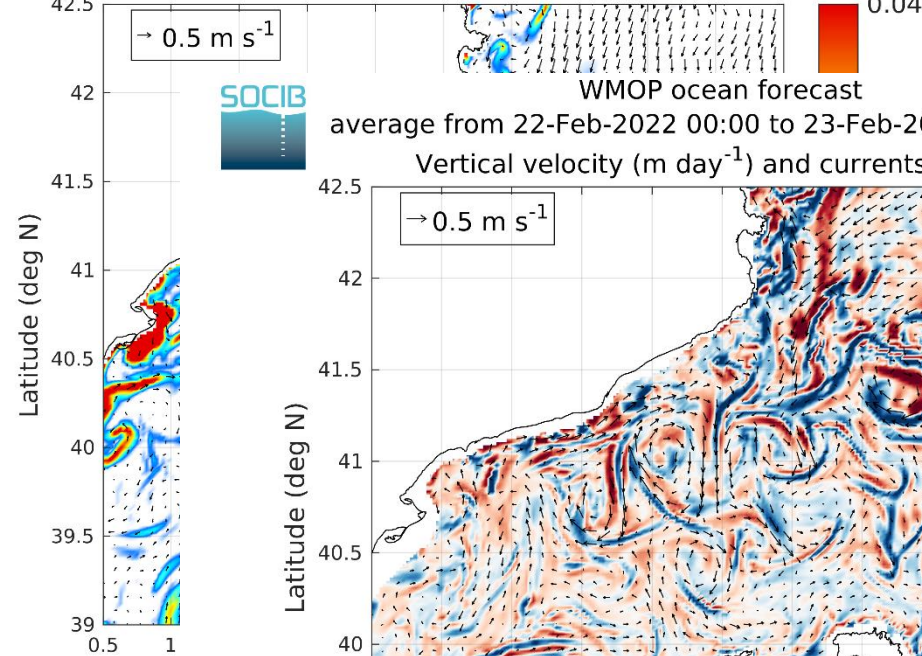
Real-time model re  
diagnostics were m  
identify frontal and



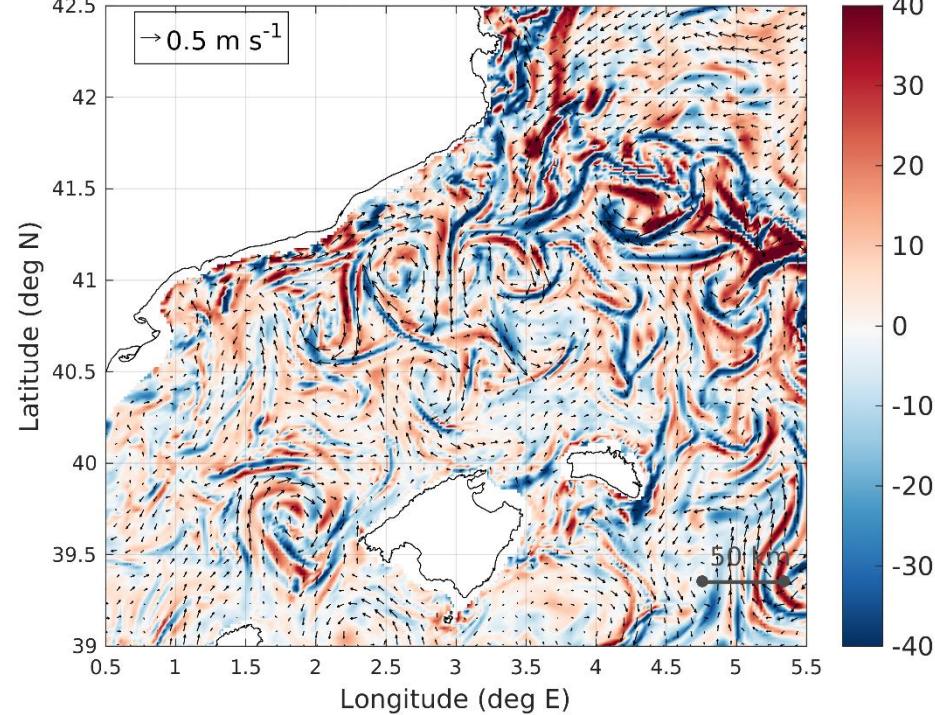
WMOP ocean forecast  
average from 22-Feb-2022 00:00 to 23-Feb-2022 00:00 UTC  
Surface relative vorticity (normalized by  $f$ ) and currents



WMOP ocean forecast  
average from 22-Feb-2022 00:00 to 23-Feb-2022 00:00 UTC  
Surface density gradients ( $\text{kg m}^{-3} \text{ km}^{-1}$ ) and currents



WMOP ocean forecast  
average from 22-Feb-2022 00:00 to 23-Feb-2022 00:00 UTC  
Vertical velocity ( $\text{m day}^{-1}$ ) and currents at 40m



Advanced Lagrangian  
with the objective to help

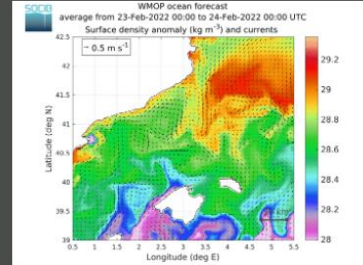
## SOCIB / CALYPSO CAMPAIGN

- WMOP forecasts 0-24h horizon
- WMOP forecasts 24-48h horizon
- WMOP forecasts 48-72h horizon
- Satellite pictures and model evaluation
- Latest assimilated data

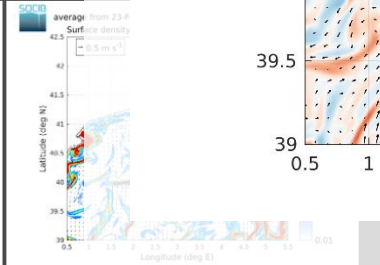
« Previous date

Wednesday 23rd February 2022

## WMOP forecasts 0-24h horizon

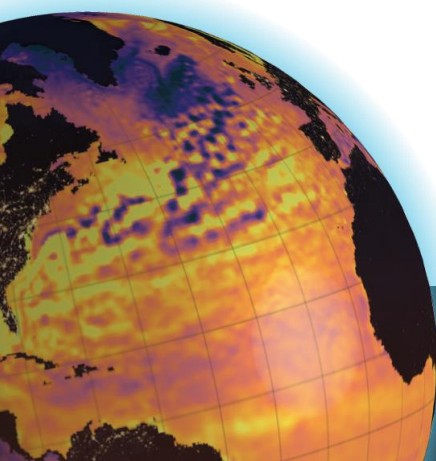


Surface density and currents



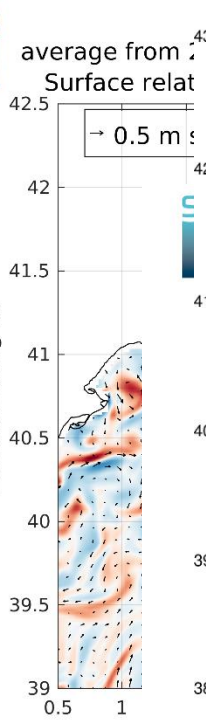
Surface density gradients

## CALYPSO Field Experiment Support Mar/Apr 2019

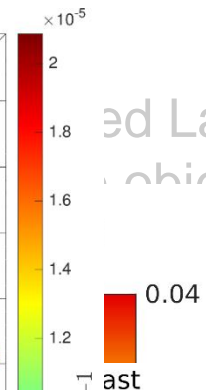
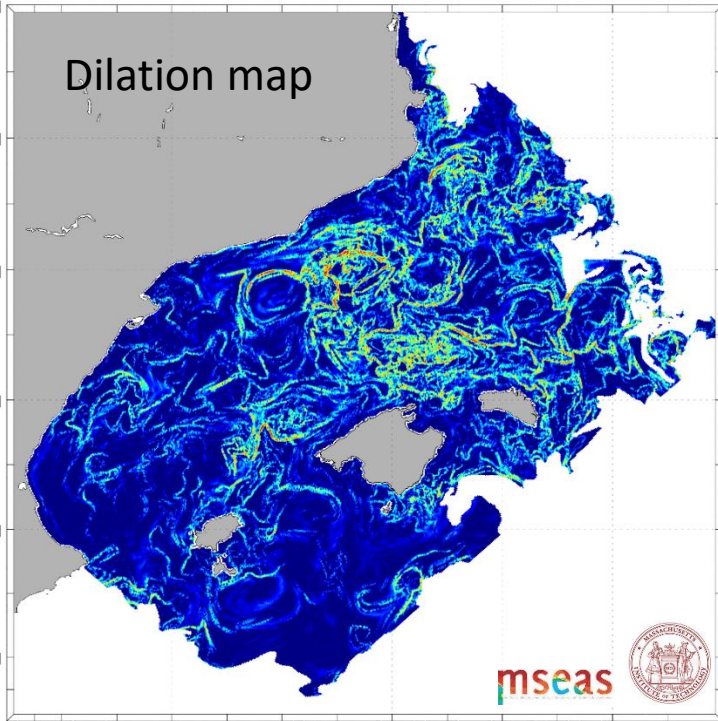


# Real-time

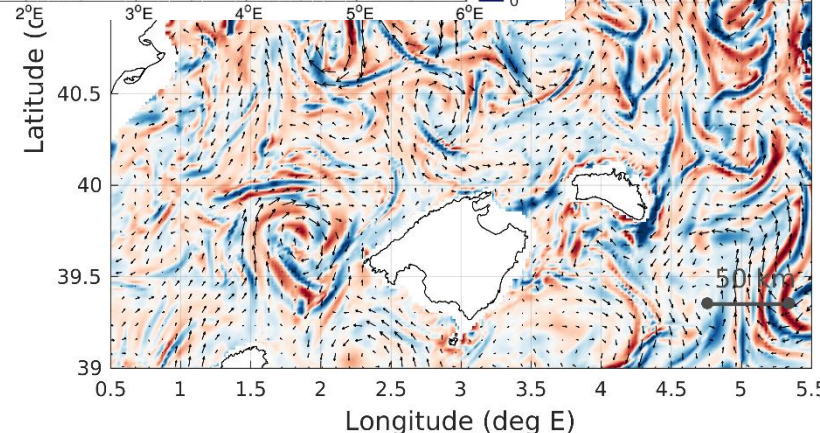
Real-time model re  
diagnostics were m  
identify frontal and



Forward Dilation (depth 000m) between 28-Feb-2022 00:00:00 and 04-Mar-2022 00:00:00 GMT



last  
3-Feb-2022 00:00 UTC  
currents at 40m



**SOCIB / CALYPSO CAMPAIGN**

- WMOP forecasts 0-24h horizon
- WMOP forecasts 24-48h horizon
- WMOP forecasts 48-72h horizon
- Satellite pictures and model evaluation
- Latest assimilated data

« Previous date      **Wednesday 23rd February 2022**

**WMOP forecasts 0-24h horizon**

Surface density and currents

Surface density gradients

ed Lagrangian  
objective to help

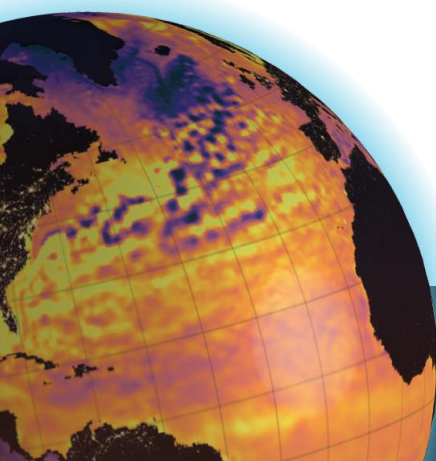
CALYPSO Field Experiment Support Mar/Apr 2019

last  
3-Feb-2022 00:00 UTC

SOCIB WMOP Forecasts Initialized

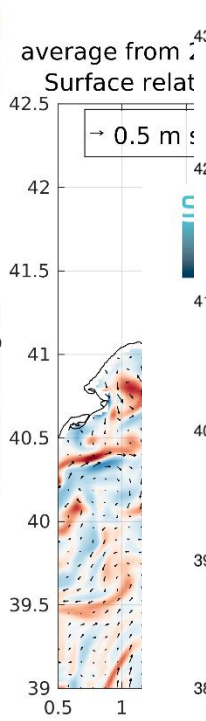
2019

8 WMOP (2 km res)

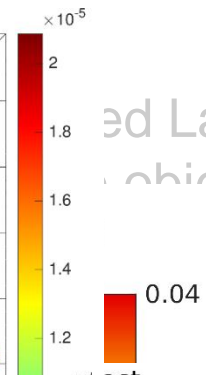
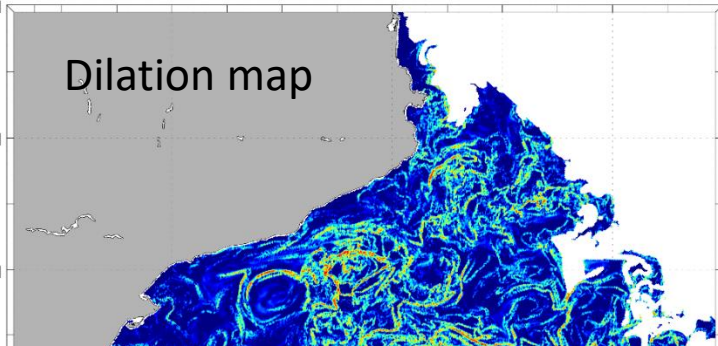


# Real-time

Real-time model re diagnostics were m identify frontal and



Forward Dilation (depth 000m) between 28-Feb-2022 00:00:00 and 04-Mar-2022 00:00:00 GMT



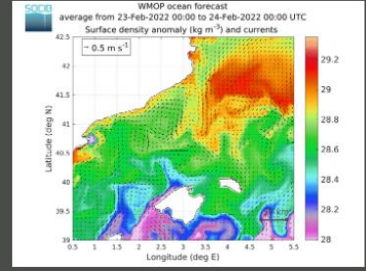
ed Lagrangian objective to help

## SOCIB / CALYPSO CAMPAIGN

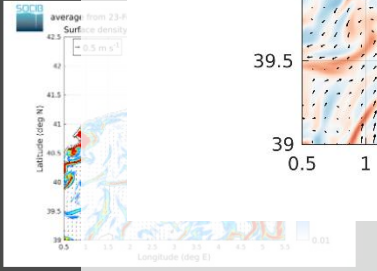
- WMOP forecasts 0-24h horizon
- WMOP forecasts 24-48h horizon
- WMOP forecasts 48-72h horizon
- Satellite pictures and model evaluation
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« Previous date **Wednesday 23rd February 2022**

## WMOP forecasts 0-24h horizon

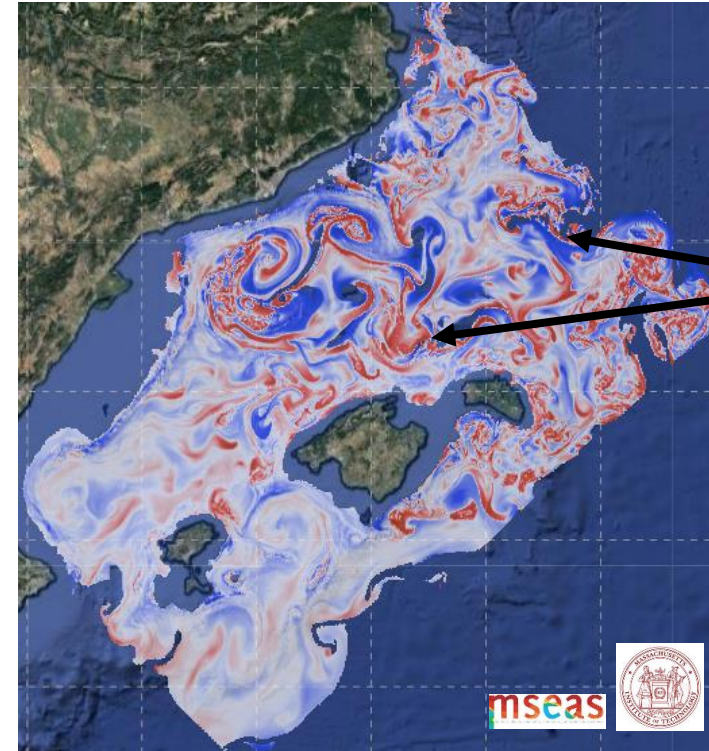


Surface density and currents



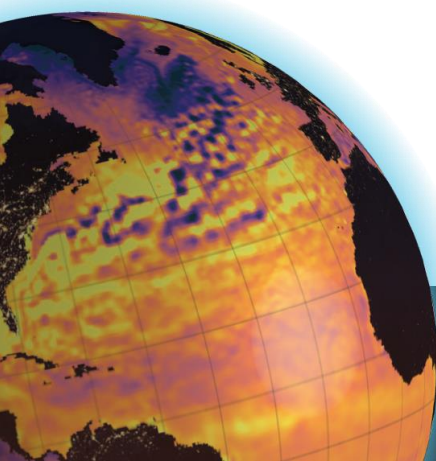
Surface density gradients

## Backward (Z) Flowmaps



Subducting water masses (red):  
28 Feb 2022 0 Z at 102m

Displays at final location of water parcel its initial position (z0) as it is advected over 4 days: helps find subduction regions



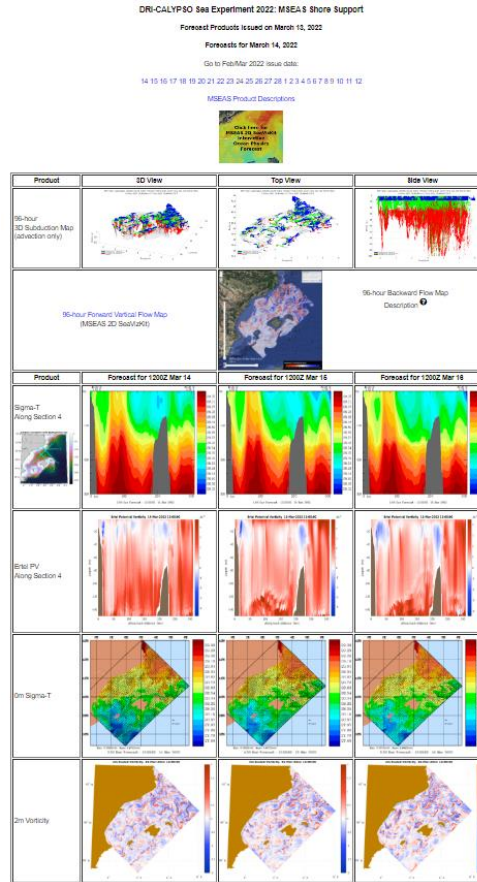
# Real-time forecasting support

Help for sampling design

Support during the campaigns

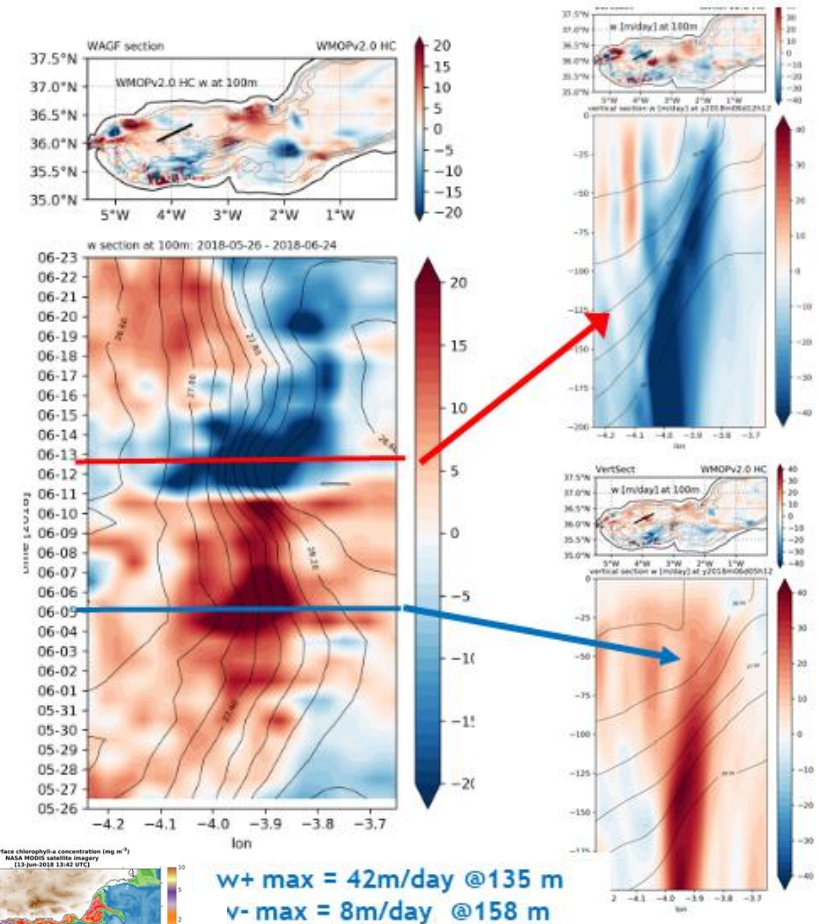
Analysis of small-scale dynamics and associated 3-dimensional pathways

2018

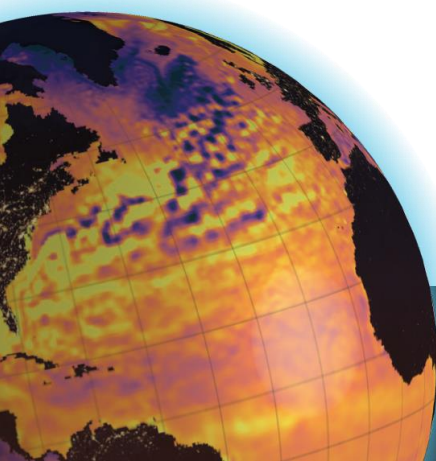


w@100m

w+ max = 18m/day @57 m  
w- max = 55m/day @156 m

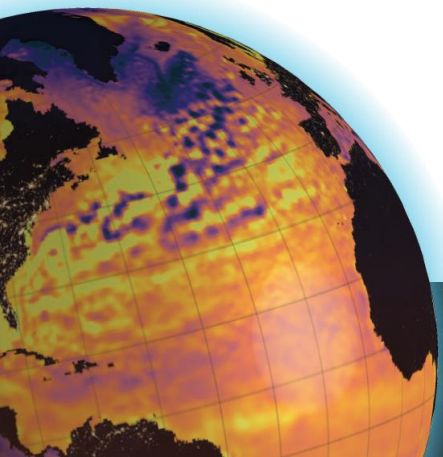
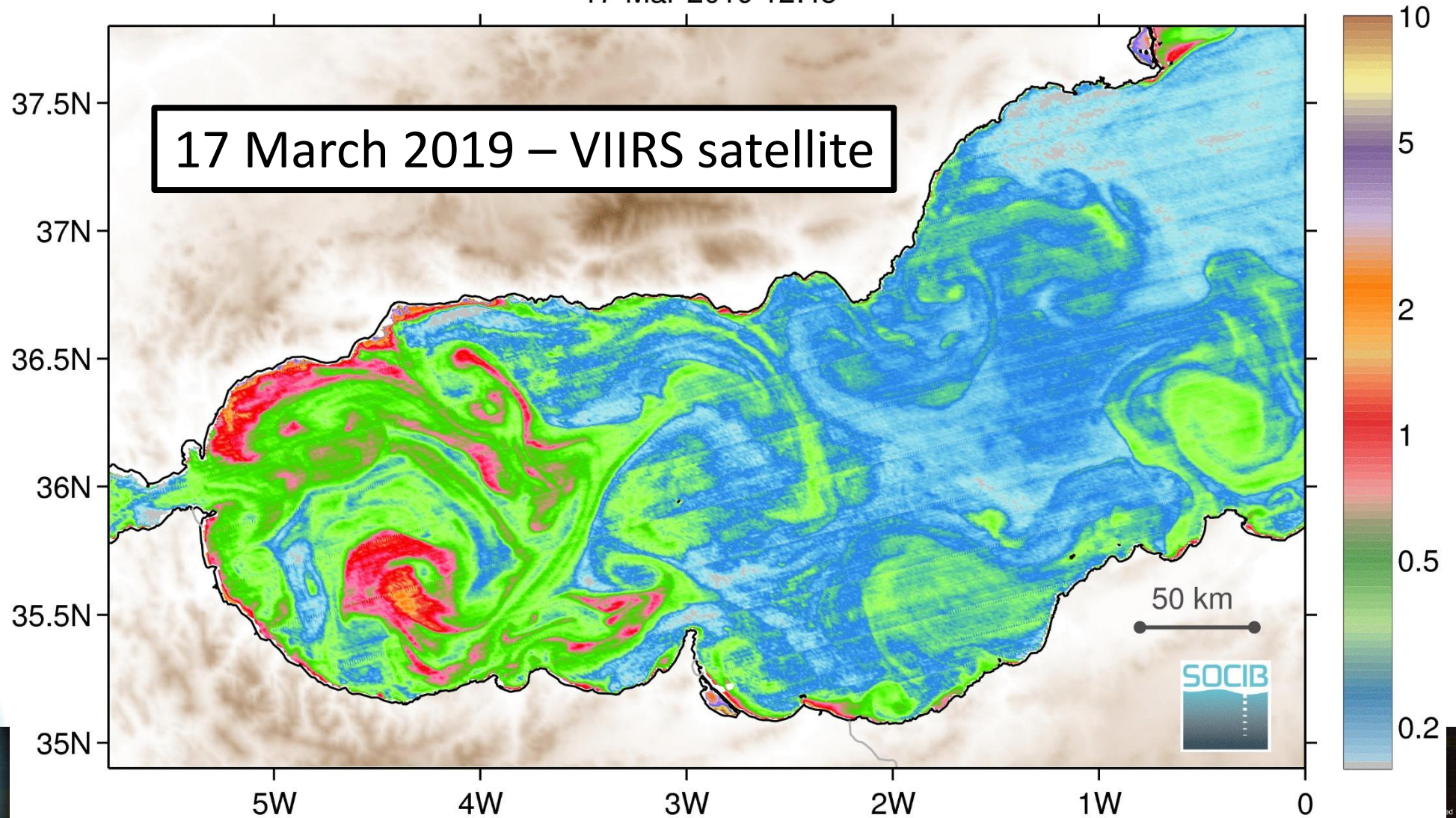


(Garcia-Jove et al., JGR-Oceans, 2022)



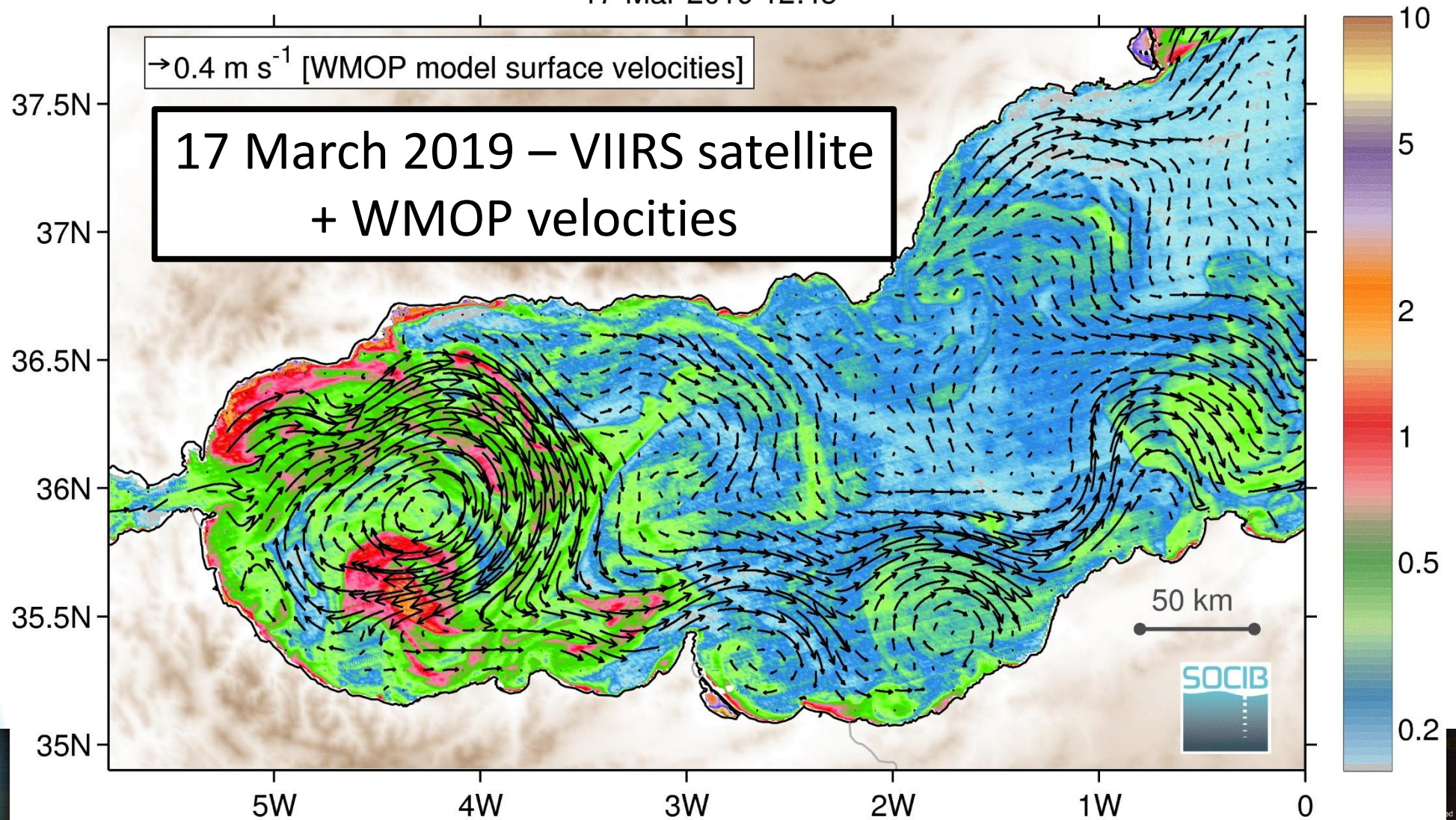
# Real-time forecasting support

Chlorophyll concentration from VIIRS satellite imagery ( $\text{mg m}^{-3}$ )  
17-Mar-2019 12:45



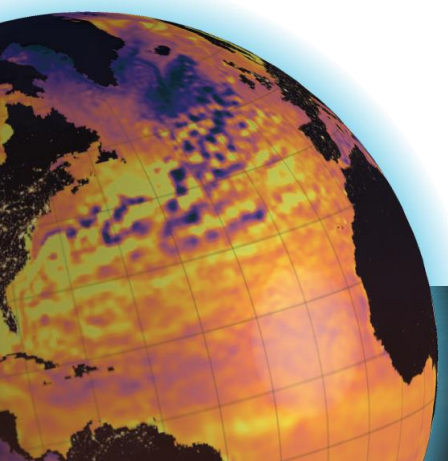
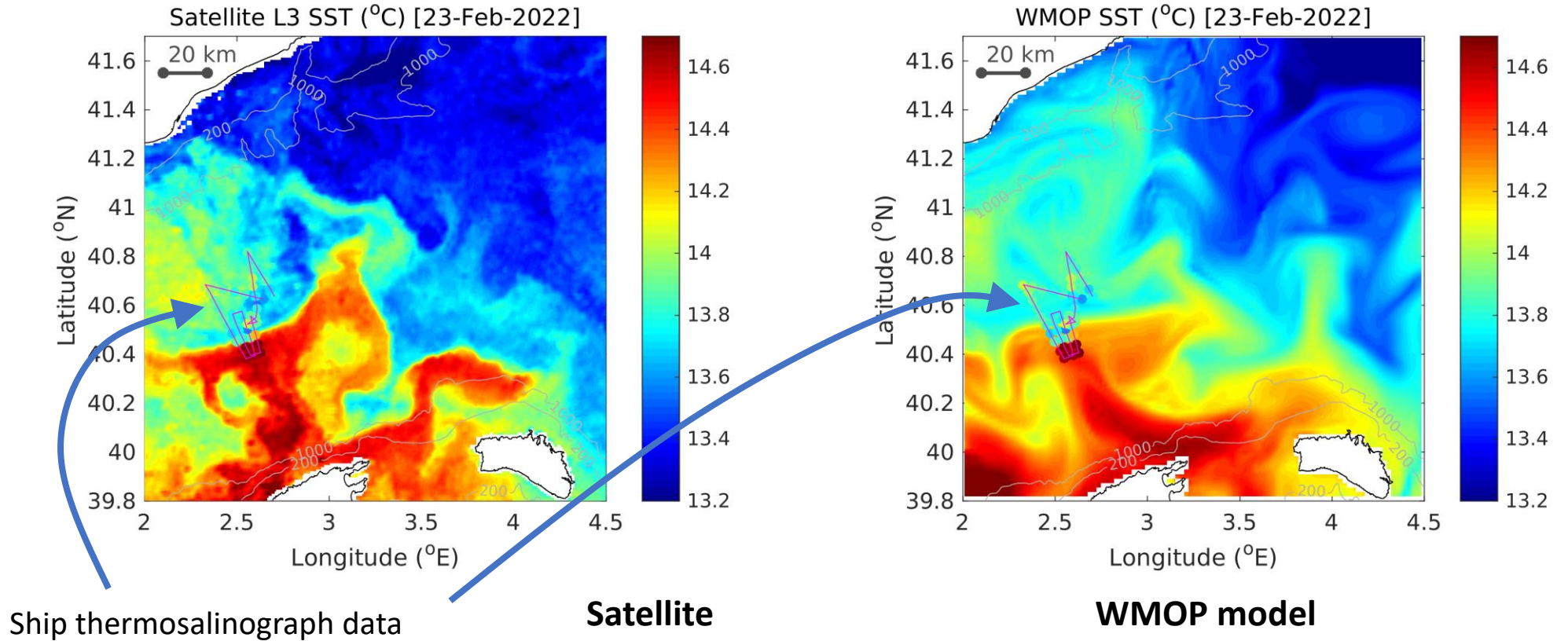
# Real-time forecasting support

Chlorophyll concentration from VIIRS satellite imagery ( $\text{mg m}^{-3}$ )  
17-Mar-2019 12:45



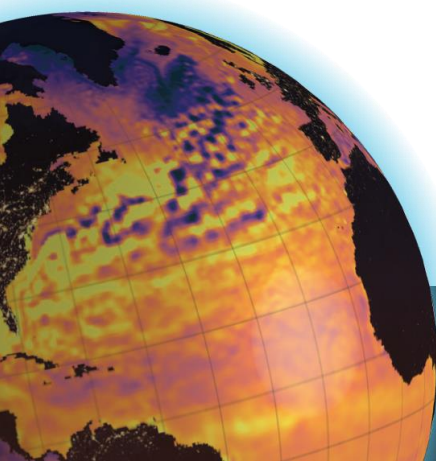
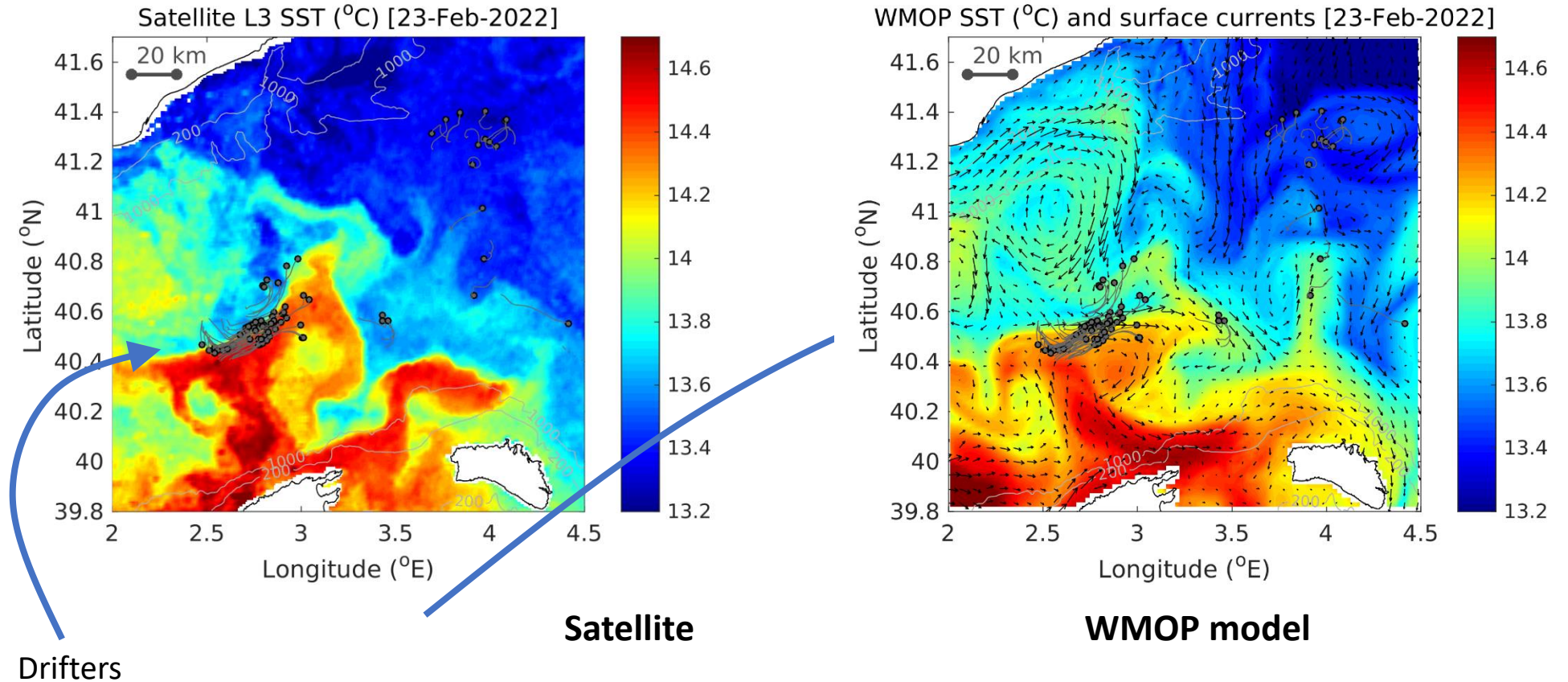
# Real-time forecasting support

## SST maps on 23-Feb-2022



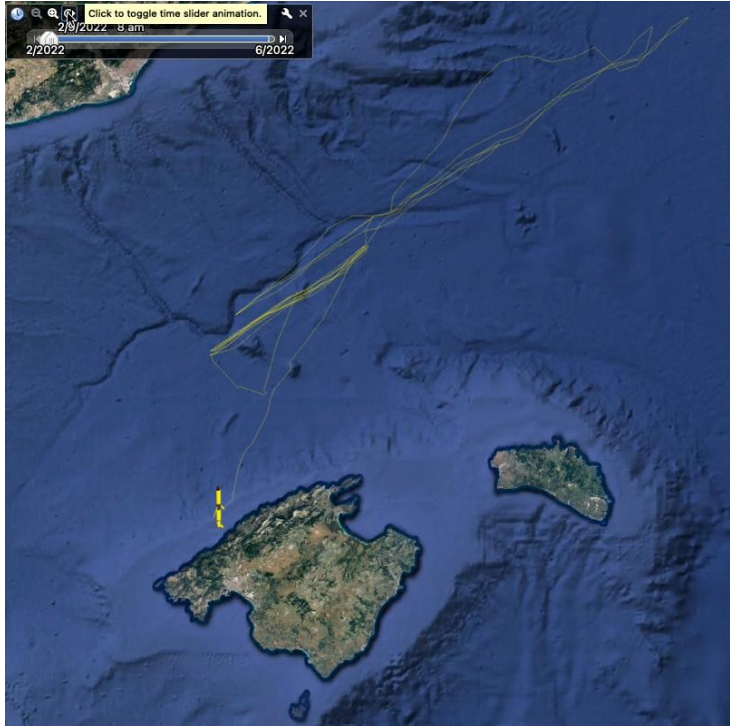
# Real-time forecasting support

## SST maps on 23-Feb-2022



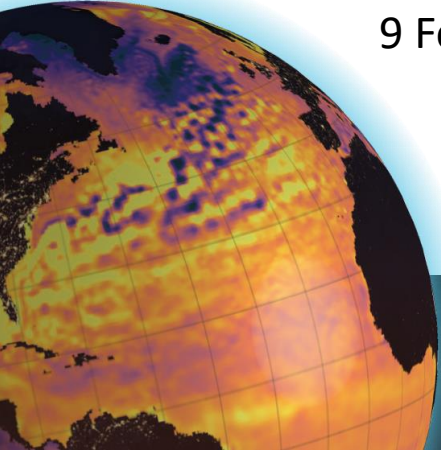


# Glider sampling design and data assimilation



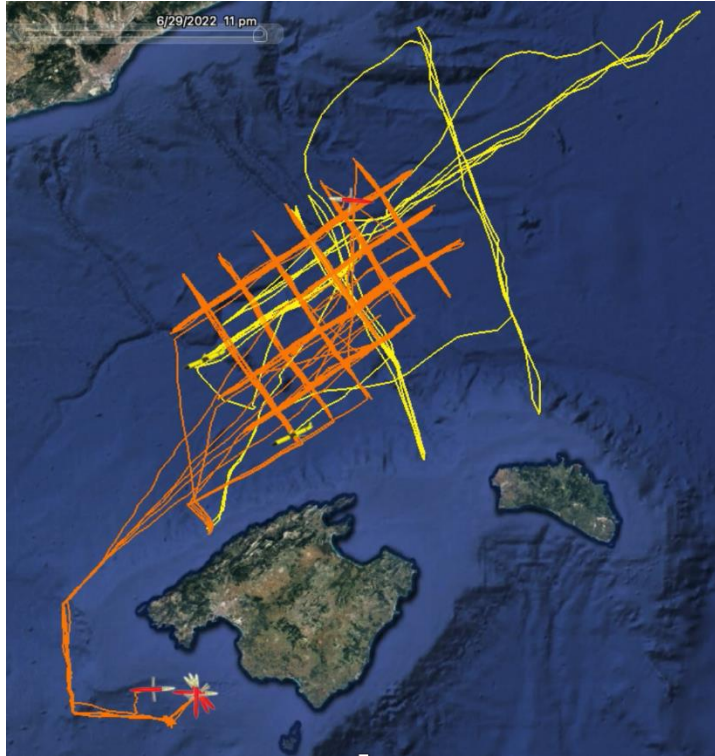
8 gliders

9 Feb – 29 June 2022

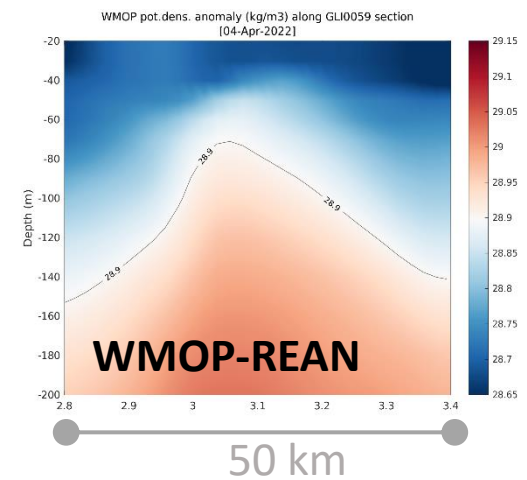
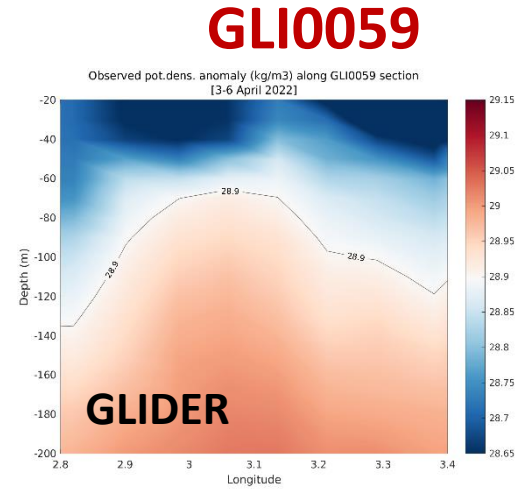
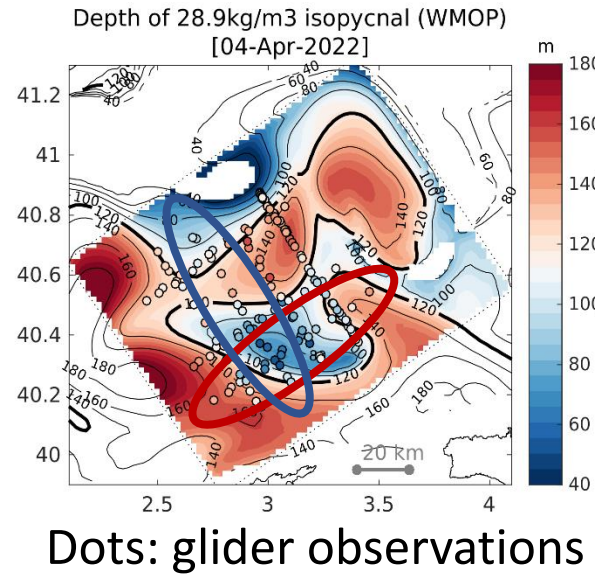
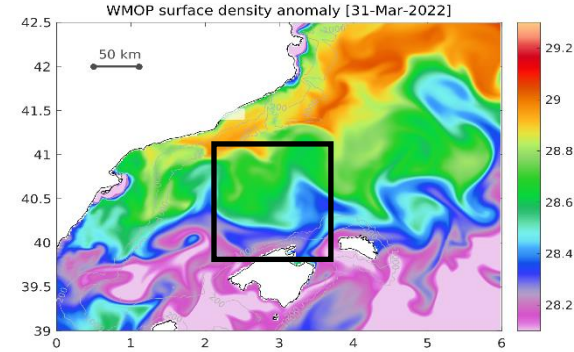
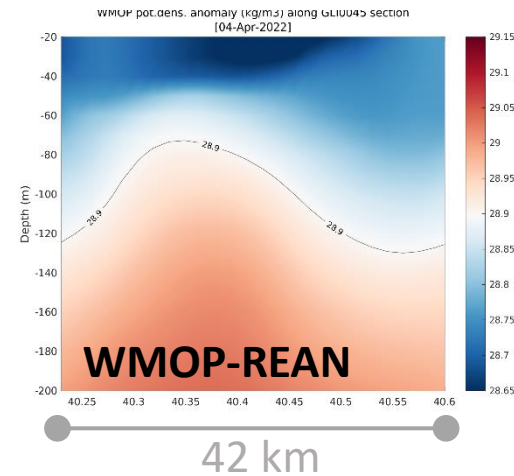
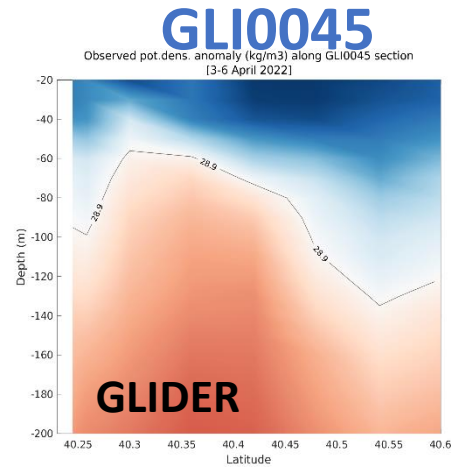


# Glider sampling design and data assimilation

Evaluation: depth of 28.9kg/m<sup>3</sup> isopycnal

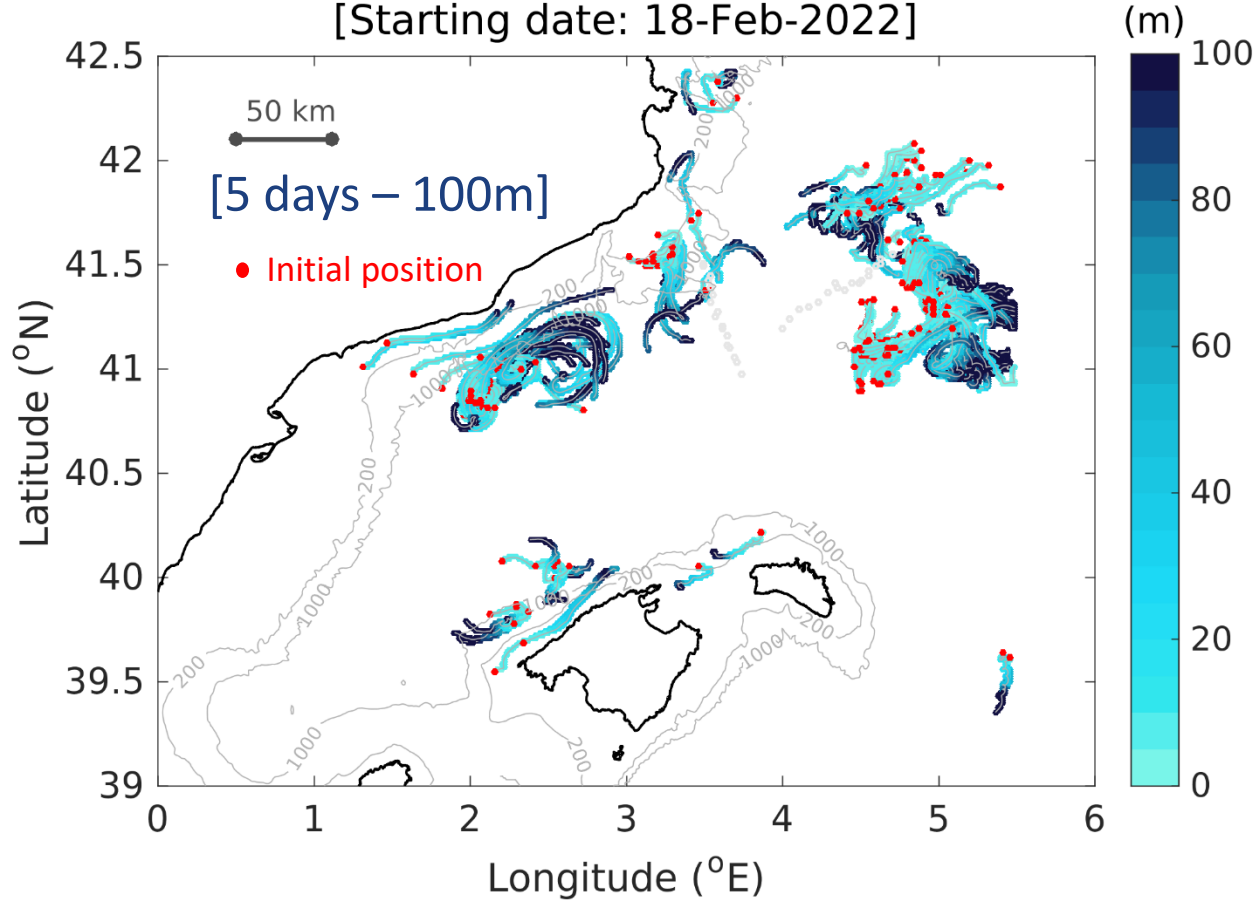


8 gliders  
9 Feb – 29 June 2022

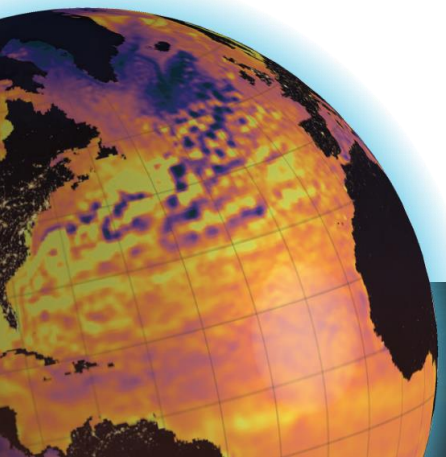


# 3D pathways

Trajectories of surface particles  
reaching at least 100m depth in 5 days  
[Starting date: 18-Feb-2022]

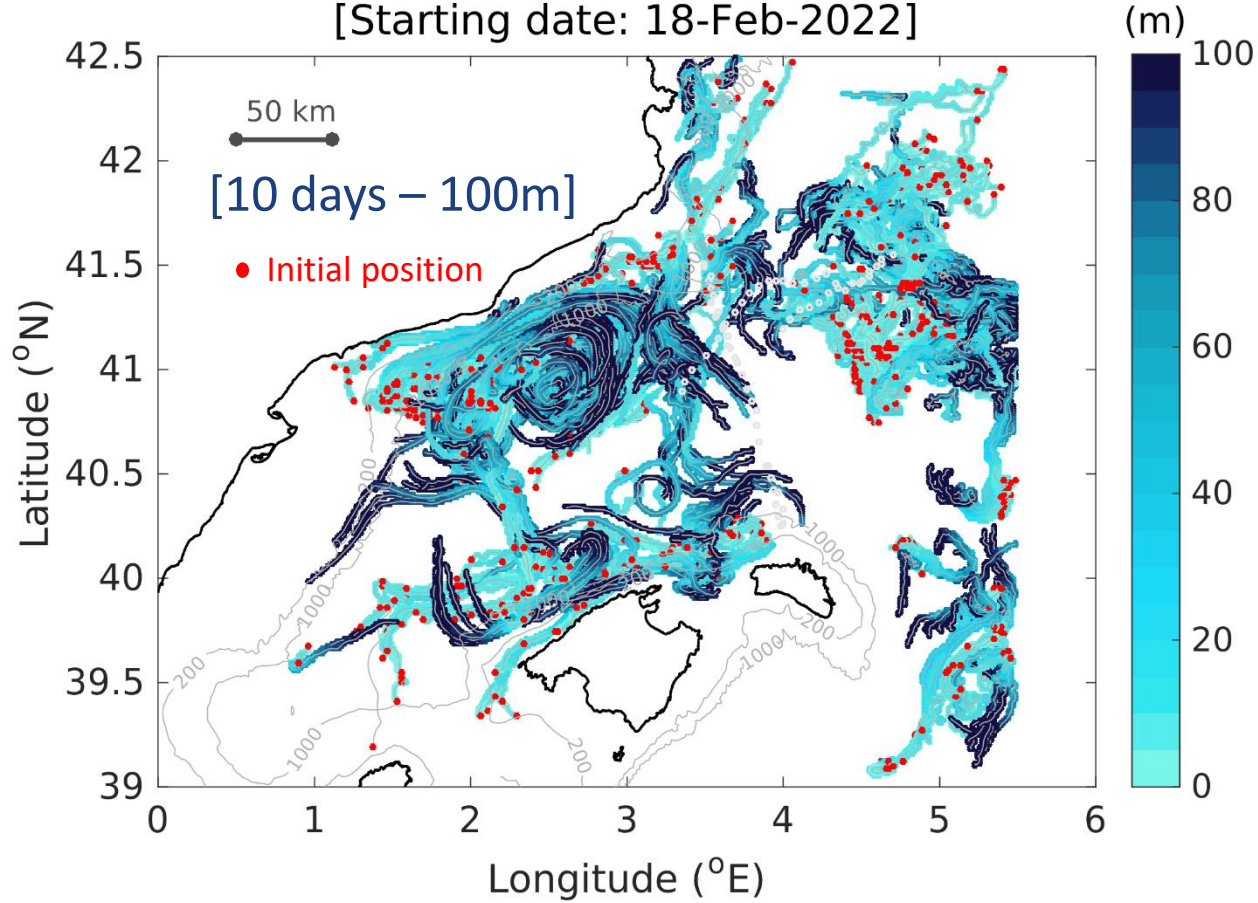


Parcels are seeded at every model gridpoint (2km-res) at 5m depth, and advected by model velocities ( $u$ ,  $v$ ,  $w$ ) during 15 days.

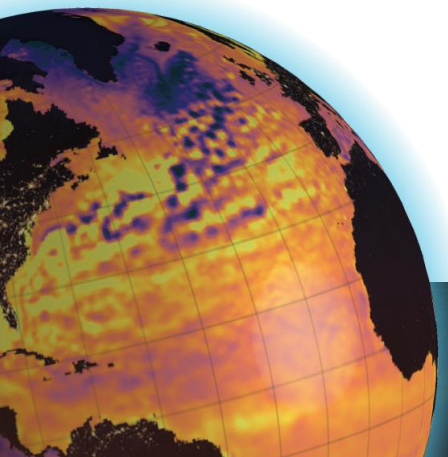


# 3D pathways

Trajectories of surface particles  
reaching at least 100m depth in 10 days  
[Starting date: 18-Feb-2022]

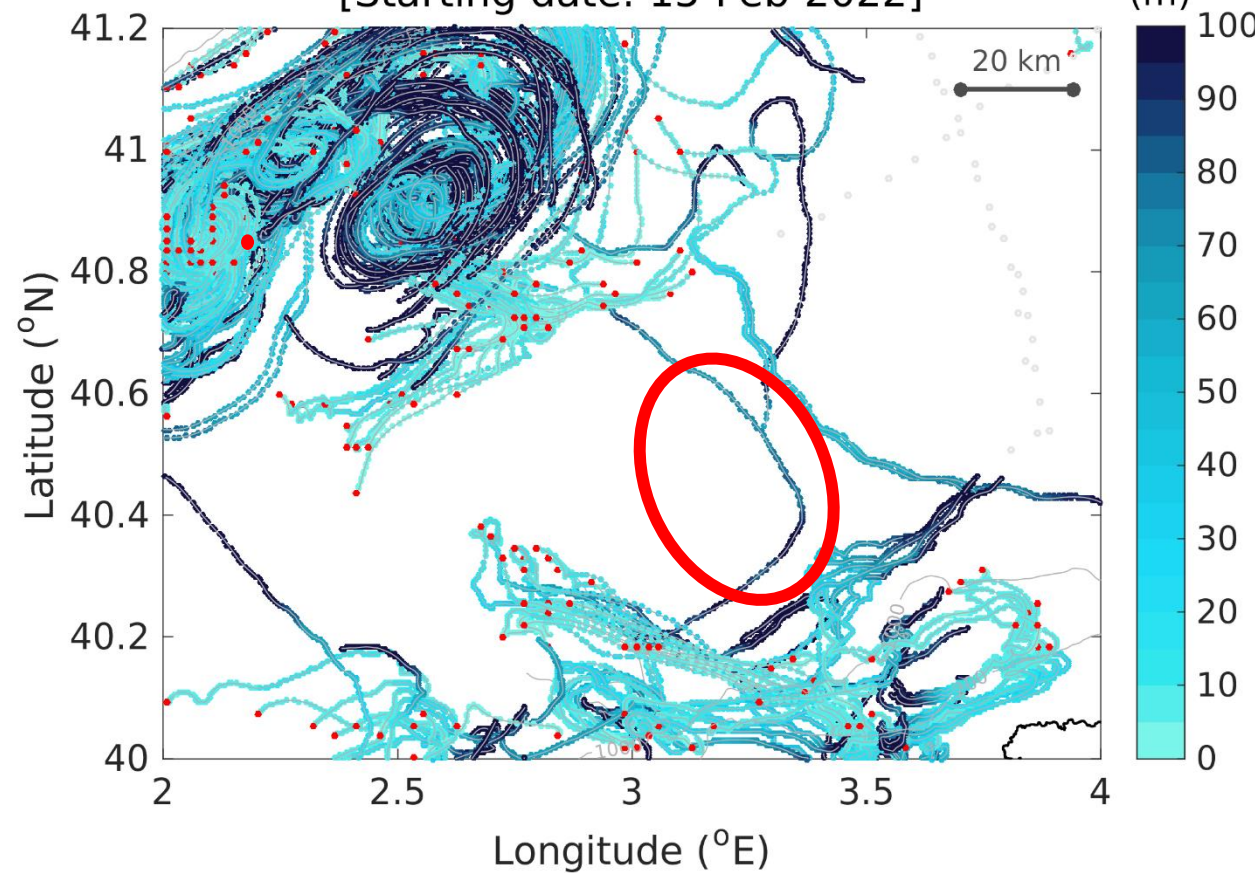


Parcels are seeded at every model gridpoint (2km-res) at 5m depth, and advected by model velocities ( $u$ ,  $v$ ,  $w$ ) during 15 days.

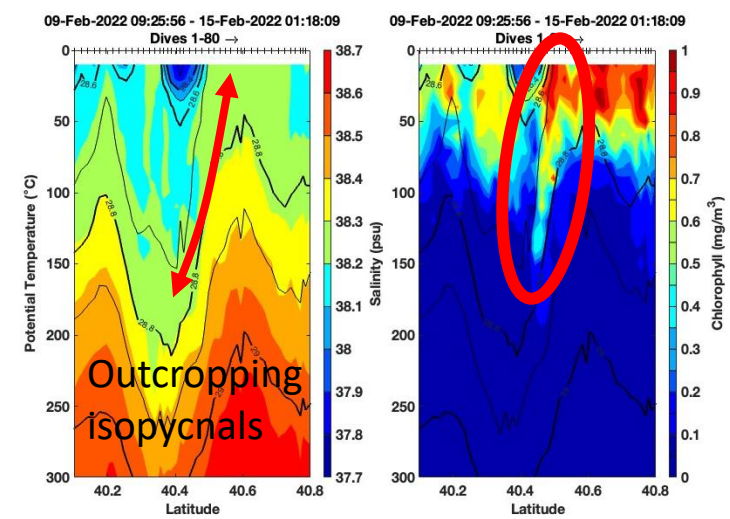
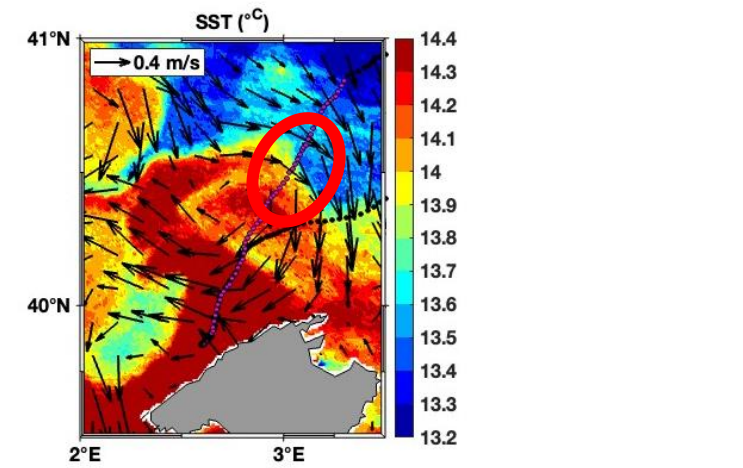
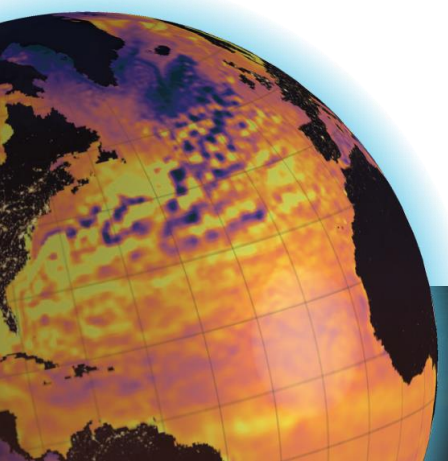


# 3D pathways

Trajectories of surface particles reaching at least 100m depth in 10 days [Starting date: 15-Feb-2022]



Parcels are seeded at every model gridpoint (2km-res) at 5m depth, and advected by model velocities (u, v, w) during 15 days.



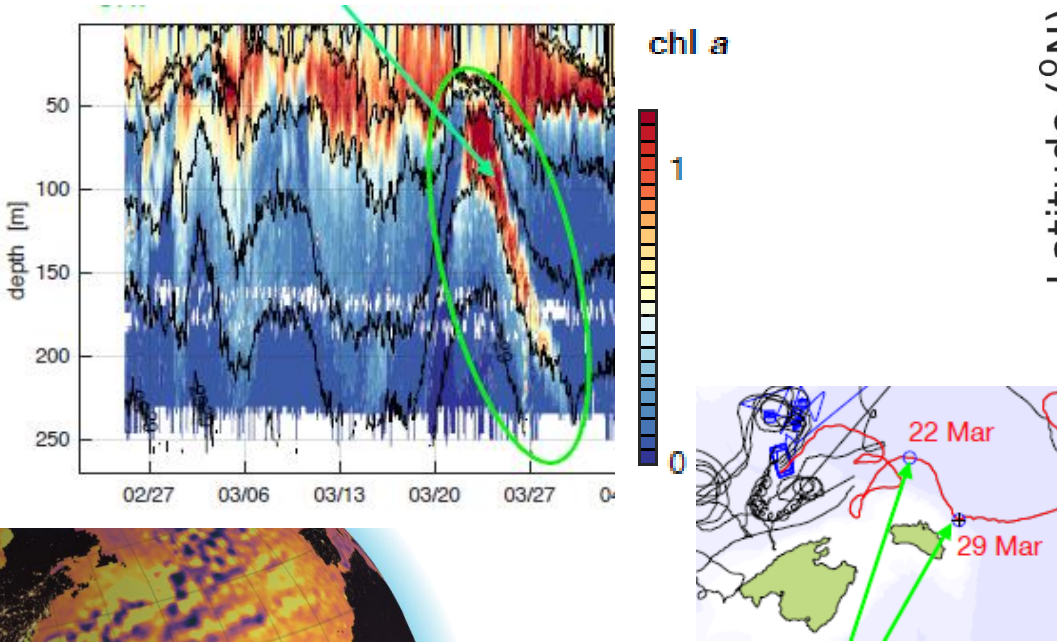
Glider data (from N. Zarokanellos)

→ Subduction from the surface to below 100m identified in the frontal area

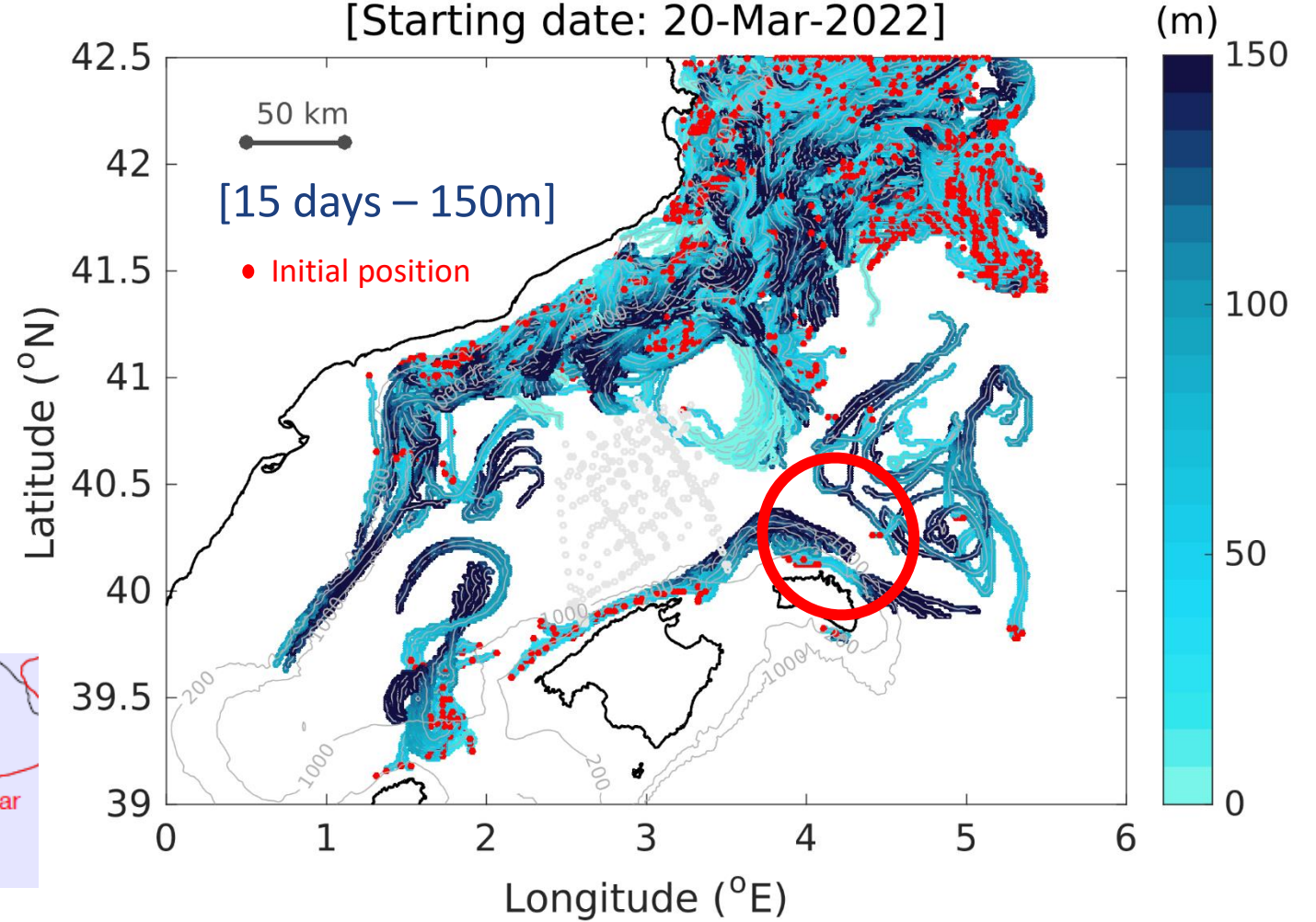
# 3D pathways

(Initial depth: 50m)

→ Subduction area north of Menorca identified in Chla observations from a profiling float.



Particles starting at 50 m depth  
reaching at least 150m depth in 15 days  
[Starting date: 20-Mar-2022]



(figure from Shaun Johnston)

# Conclusions

- Collaborative high-resolution real-time forecasting effort providing support to small-scale ocean observing experiments
  - Simulations and modelling products developed during three campaigns: opportunity for incremental improvements!
  - Modelling tools applied for predictions, nested free runs on refined grids and reanalysis, providing a satisfactory level of realism
- Used for sampling design, characterization of multivariate variability, understanding of dynamical processes, Lagrangian analysis and three-dimensional pathways at meso- and submesoscale

