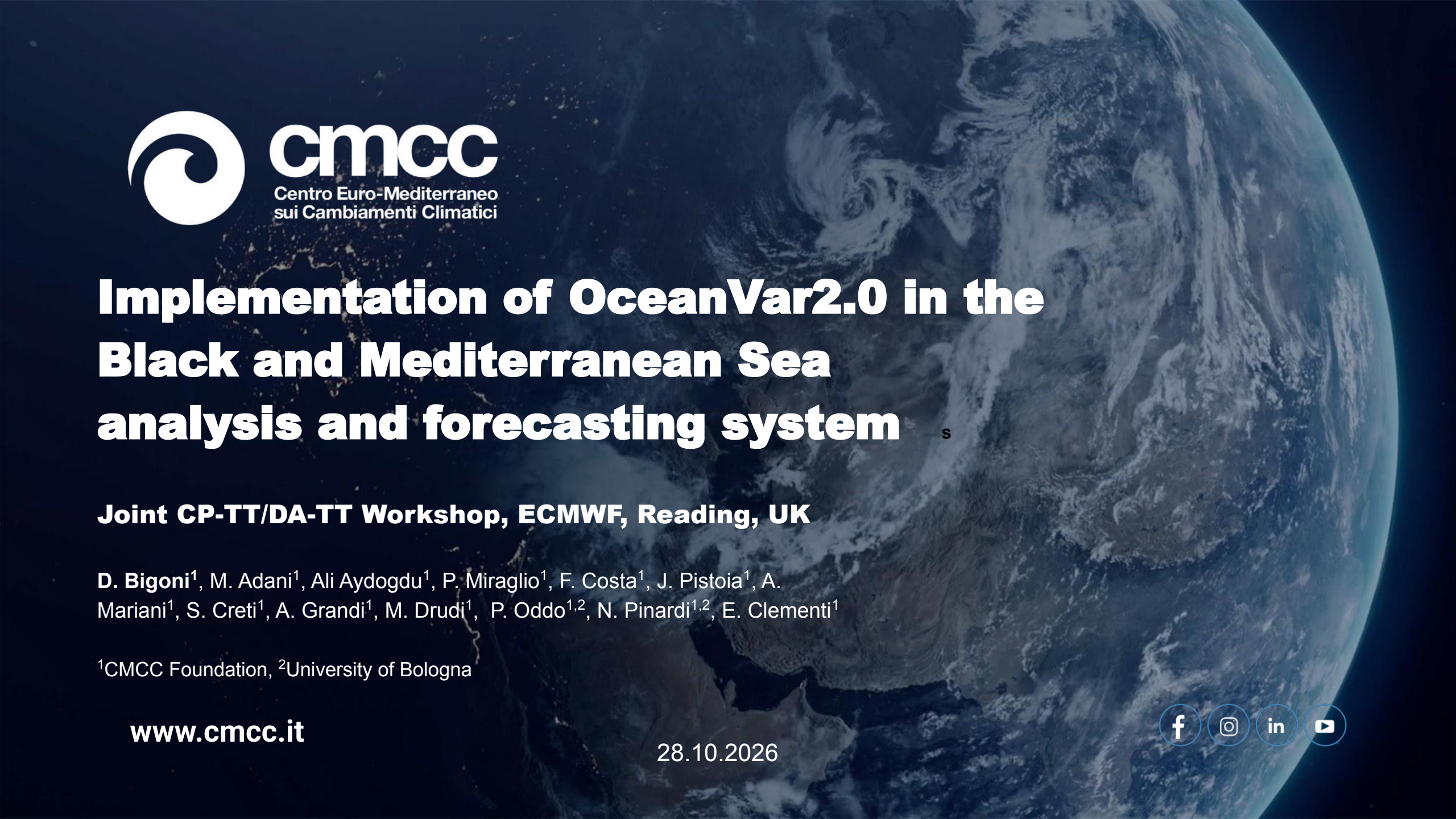


Implementation of OceanVar2.0 in the Black and Mediterranean Sea analysis and forecasting system s

Joint CP-TT/DA-TT Workshop, ECMWF, Reading, UK

D. Bigoni[1], M. Adani[1], Ali Aydogdu[1], P. Miraglio[1], F. Costa[1], J. Pistoia[1], A. Mariani[1], S. Creti[1], A. Grandi[1], M. Drudi[1], P. Oddo[1,2], N. Pinardi[1,2], E. Clementi[1]

[1]CMCC Foundation, [2]University of Bologna

www.cmcc.it

28.10.2026

The MedFS and BSFS forecasting systems

Initial condition:
01/01/2015
Regional Reanalysis

Atl. Boundary conditions:
GLO-MFC physics

Bosphorus-Dardanelles
From U-TSS unstructured mesh model

Land river runoff:
EFASv5

Atmospheric forcing:
IFS, 0.1°,1hr
(msl,u10m,v10m,T2m,d2m,precip)

NEMO v5
heat flux correction
with SST L4

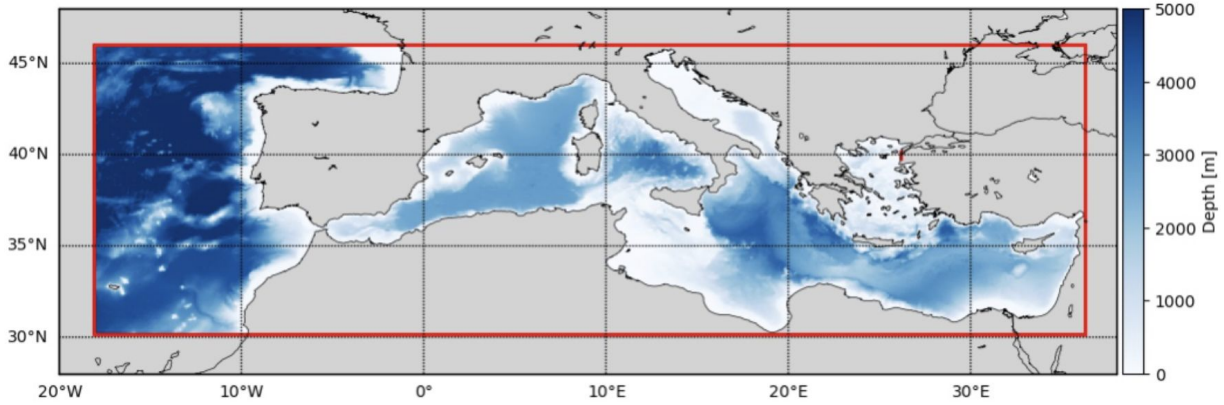
Products
Last two years
Daily and monthly:
- Temp, Sal, U,V, SSH, MLD, Tb

Hourly:
- SSH, SSU, SSV

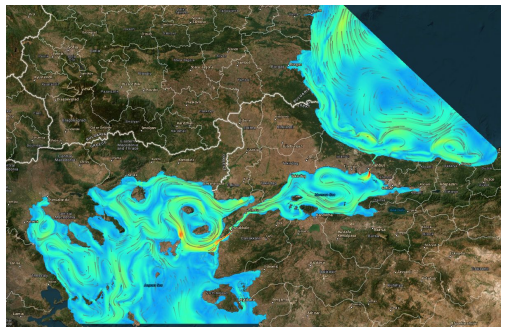
Data Assimilation: OceanVar2 (3DVar-FGAT)
T: INS-obs (XBT, MBT); T/S INS-pairs (CTD,ARGO); SLA
Gliders → in the Mediterranean Sea
SST → in the Black Sea

The MedFS and BSFS forecasting systems

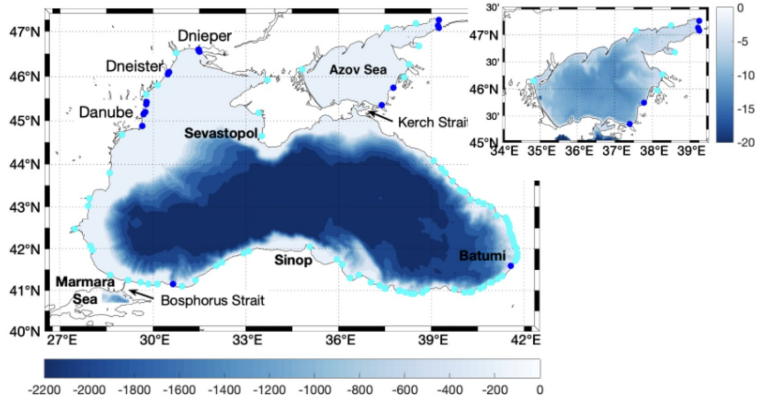
	Mediterranean Sea – EAS10	Black Sea (incl. Azov) – EAS8
Model	Nemo v4.2 + WaveWatchIII v6.07	Nemo v4.2 + WaveWatchIII v6.07
Resolution	Spatial: 1/24° x 141 vert. levels Temporal: Daily / 10 days forecasts	Spatial: 1/40° x 121 vert. levels Temporal: Daily / 10 days forecasts
Land forcing	39 rivers	90 rivers
Boundary Conditions	Atm: ECMWF IFS 1/10° Lat: CMEMS GLO-MFC @ Atlantic Lat: U-TSS @ Dardanells	Atm: ECMWF IFS 1/10° Lat: U-TSS @ Marmara Sea
Data Assimilation	OceanVar2.0 (3dVar - FGAT)	OceanVar2.0 (3dVar - FGAT)
Assimilated obs.	SLA satellite altimetry In-situ (XBT, ARGO, Gliders, CTD) SST L4 relaxation (heat fluxes)	SLA satellite altimetry In-situ (XBT, ARGO, CTD) SST L4 relaxation (heat fluxes) + L3 assimilation



https://medfs.cmcc.it



https://utss.cmcc.it



https://bsfs.cmcc.it

OceanVar 2.0 with FGAT

Incremental Formulation

Background Covariance

Observation Covariance

$$J(\delta\mathbf{x}) = \frac{1}{2}\|\delta\mathbf{x}\|_{\mathbf{B}^{-1}} + \frac{1}{2}\|\mathbf{H}\delta\mathbf{x} - \mathbf{d}\|_{\mathbf{R}^{-1}}$$

$$\mathbf{d} = \mathbf{y} - H(\mathbf{x}_b)$$

Misfits computed at Appropriate Time

Whitened Incremental Formulation

$$\mathbf{B} = \mathbf{V}\mathbf{V}^T \qquad \delta\mathbf{x} = \mathbf{V}\mathbf{v}$$

$$J(\mathbf{v}) = \frac{1}{2}\|\mathbf{v}\|_2 + \frac{1}{2}\|\mathbf{H}\mathbf{V}\mathbf{v} - \mathbf{d}\|_{\mathbf{R}^{-1}}$$

$$\mathbf{V} = \mathbf{V}_D\ \mathbf{V}_{uv}\ \mathbf{V}_\eta\ \mathbf{V}_H\ \mathbf{V}_V$$

Divergence Damping

Geostrophic balance

Free Surface

Dynamic Height

Barotropic Operator

Vertical EOFs

Horizontal Operator

Recursive Filter

Diffusive Filter

OceanVar 2.0 introduces the Barotropic Operator and the Diffusive Filter.

OceanVar 2.0: Barotropic operator

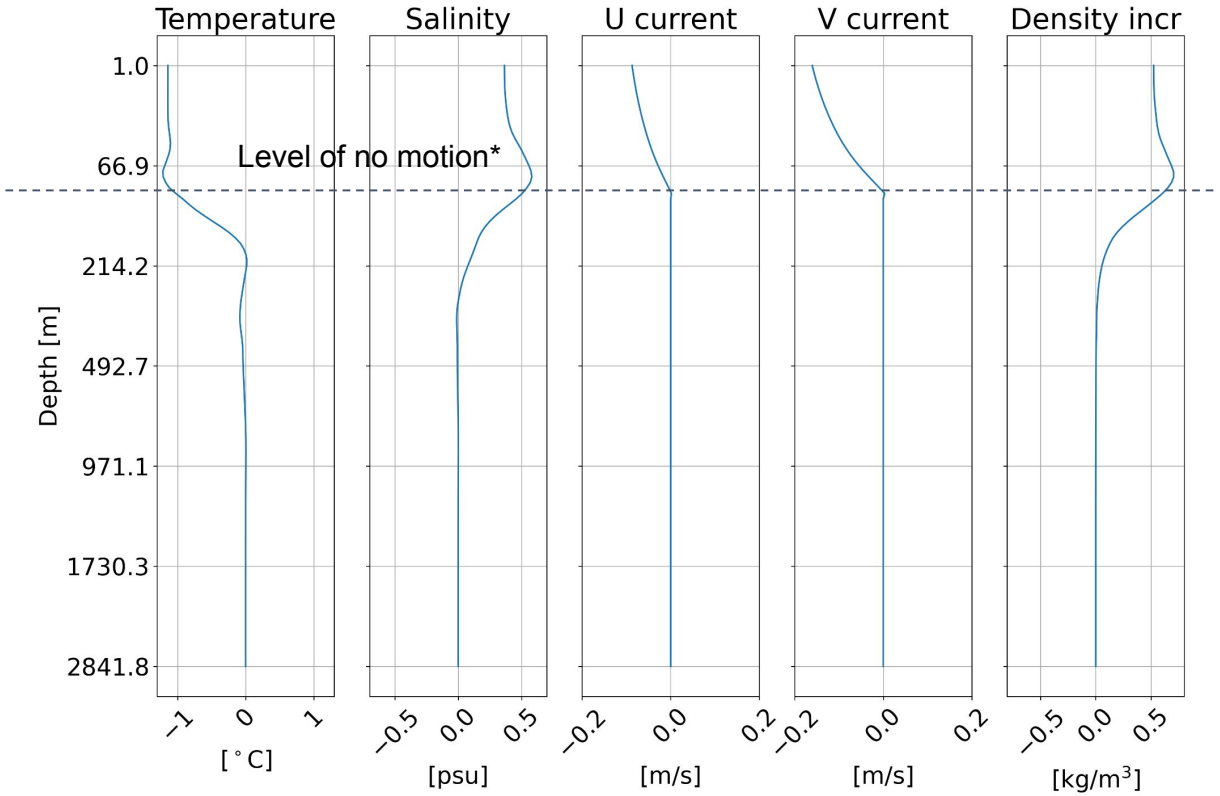
$$\delta\eta^{\mathrm{DH}} = -\frac{1}{\rho_0}\int_{-D}^{0}[-\alpha\delta T + \beta\delta S]\,\mathrm{d}z$$

$$\dot{U} = gH\partial_x\eta + fV - \int_{-H}^{0}\left[\int_{z}^{0}\partial_x\delta b\,\mathrm{d}z'\right]\mathrm{d}z + \gamma\nabla^2 U$$

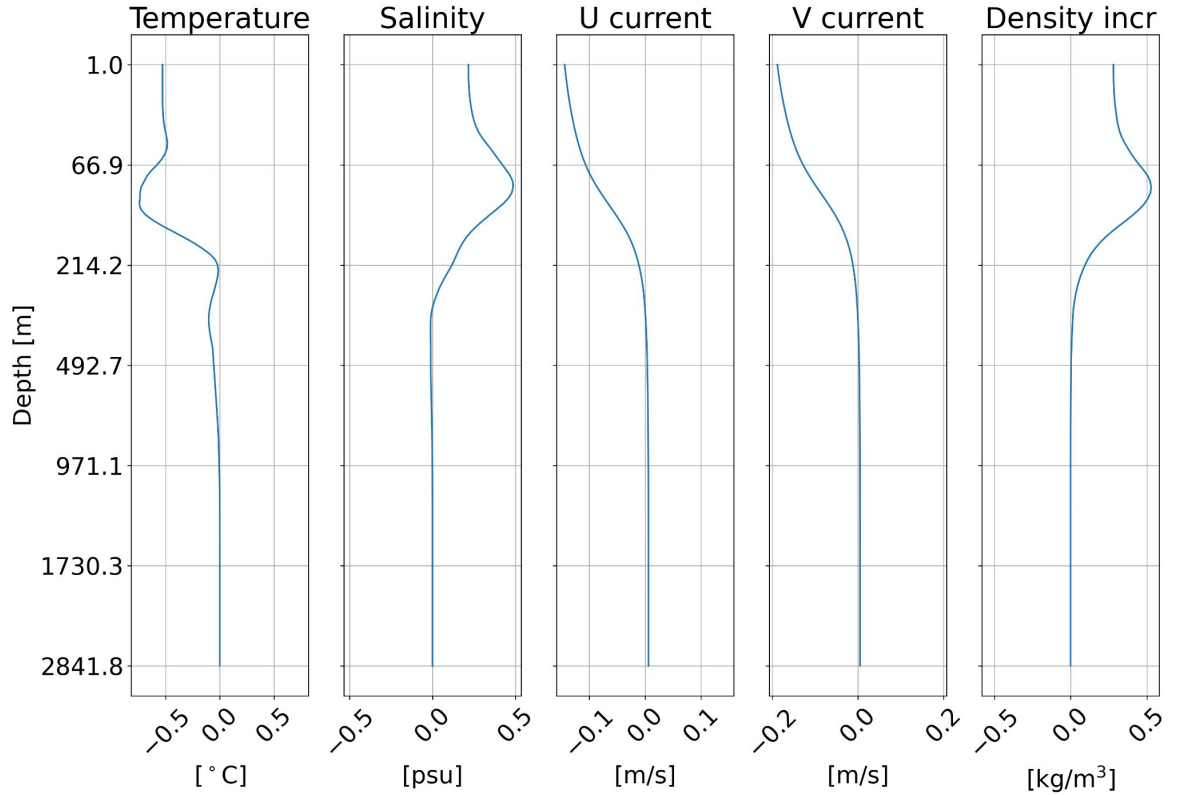
$$\dot{V} = gH\partial_y\eta - fU - \int_{-H}^{0}\left[\int_{z}^{0}\partial_y\delta b\,\mathrm{d}z'\right]\mathrm{d}z + \gamma\nabla^2 V$$

$$\dot{\eta} = -\nabla\cdot[U,V]^{\top}$$

Dynamic Height operator



Barotropic operator



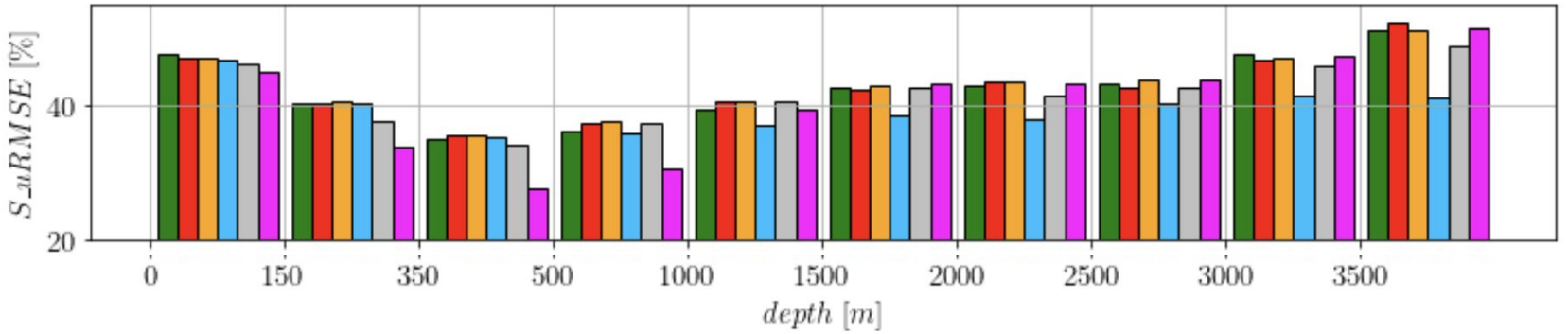
* Here the level of no motion for Dynamic Height is set to a level unrealistically shallow just to exacerbate its effects

OceanVar 2.0: Barotropic operator

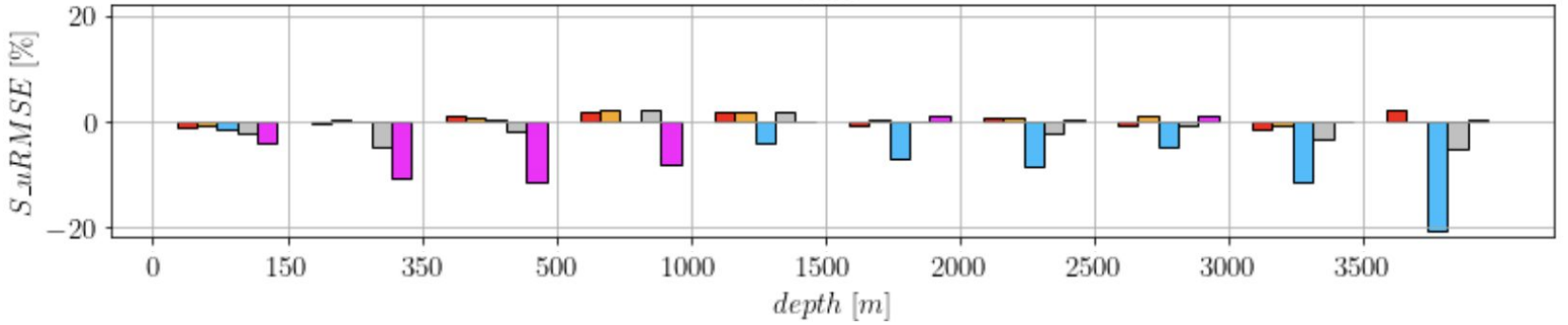
Basin	Mediterranean
Year	2021
Hor. Corr.	27km
In-situ	ARGO, XBT

	Exp-1	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6
Sea level operator	BM	BM	BM	DH	DH	DH
α/β	Const.	Const.	MC	Const.	Const.	Const.
Reference Level for DH (m)	n/a	n/a	n/a	150	350	1000
SLA Min depth rejection (m)	100	150	150	150	350	1000

Unbiased RMSE % improvement of SLA with respect to free run by bathymetry bins

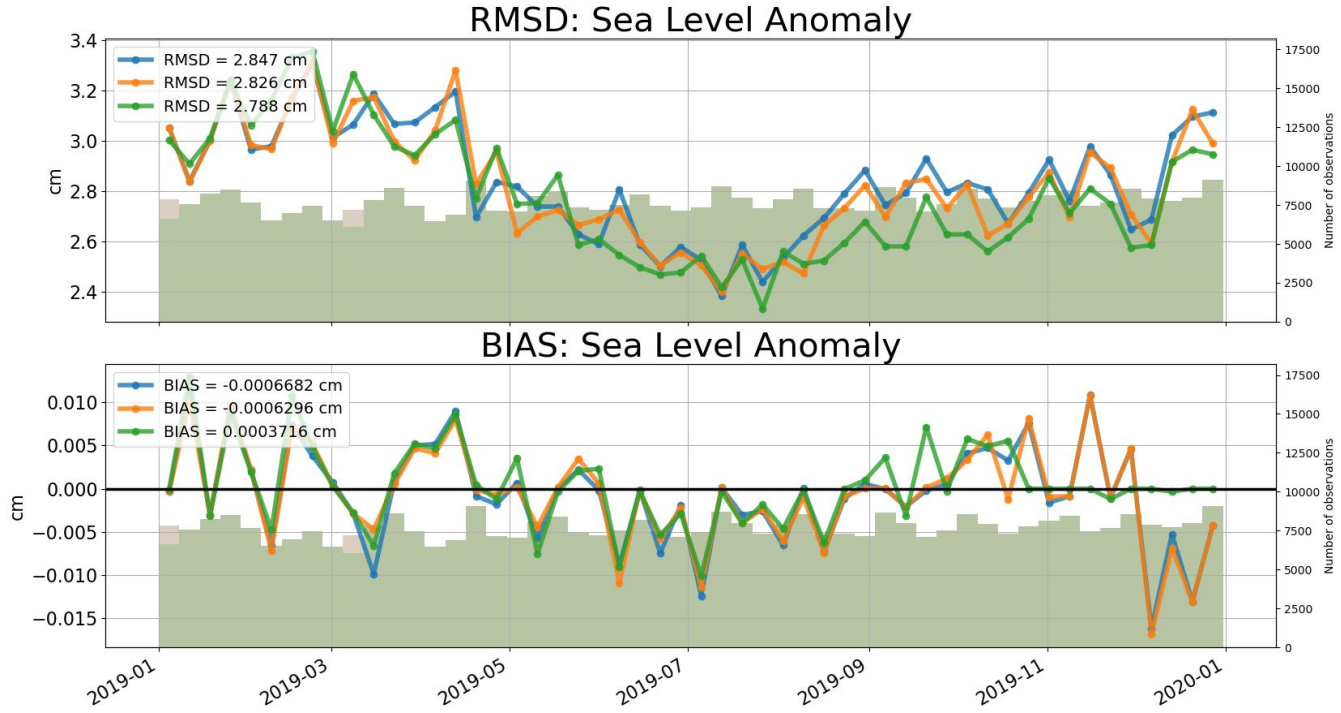


Unbiased RMSE % improvement or degradation of SLA with respect to Exp-1

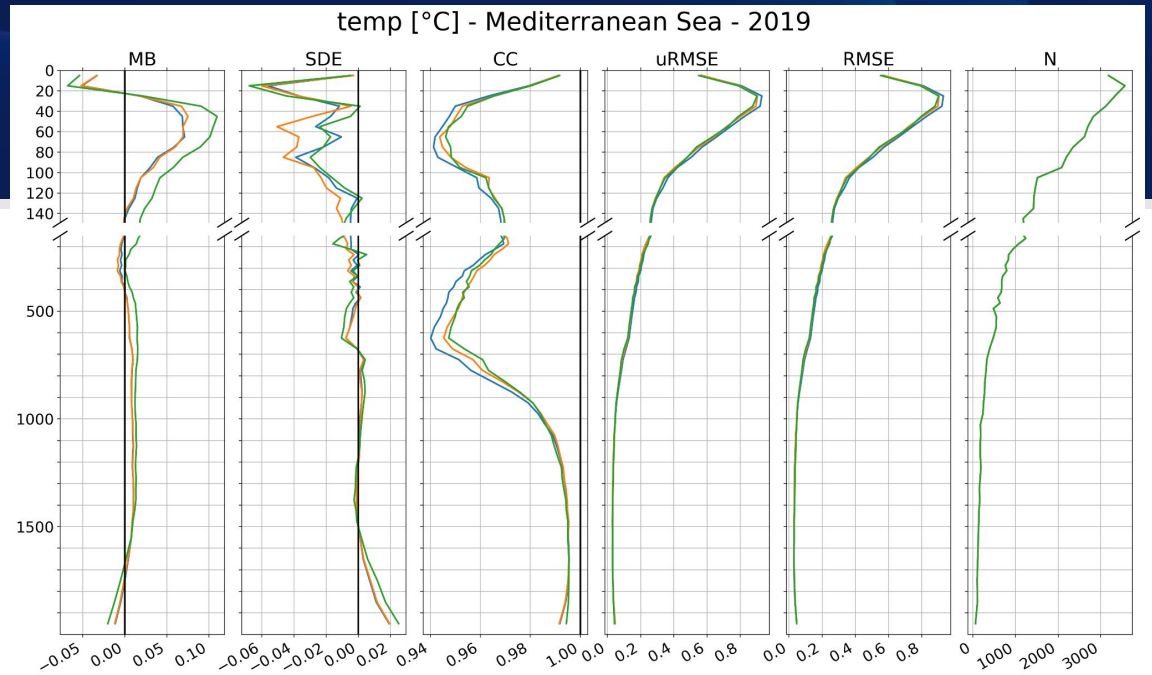


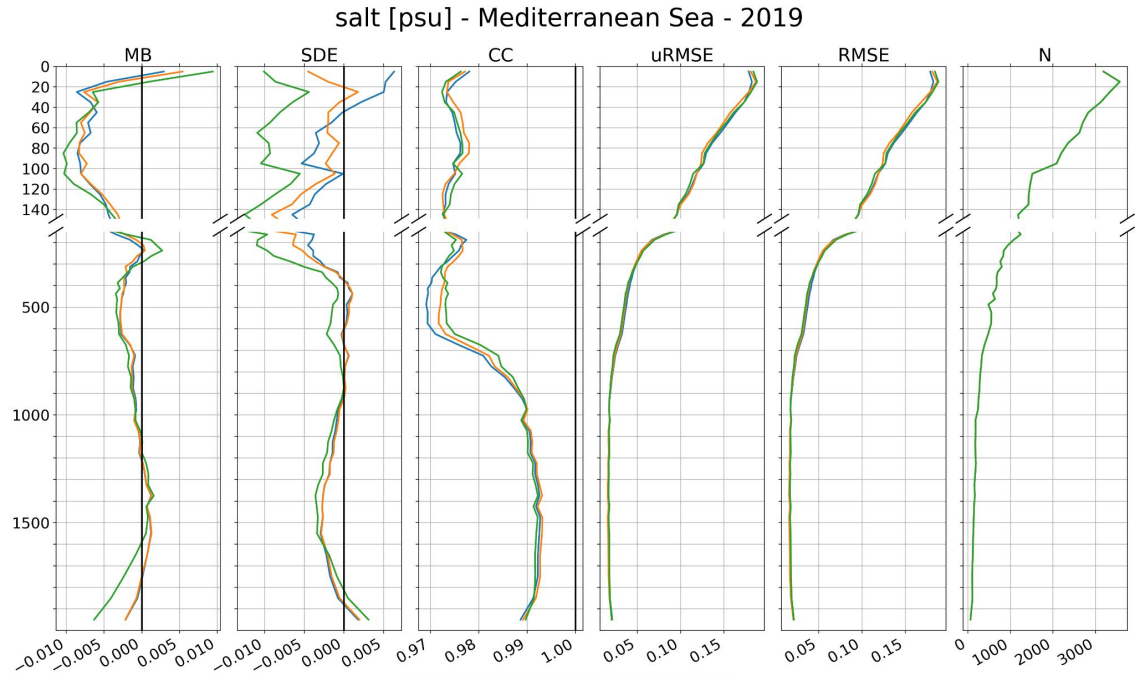
Oddo, P. *et al.* (2026) “Implementation and evaluation of sea level operators in OceanVar2.0: an open-source oceanographic three-dimensional variational data assimilation system,” *Geoscientific Model Development*, 19(1), pp. 423–445. Available at: https://doi.org/10.5194/gmd-19-423-2026.

MED OV1 vs OV2



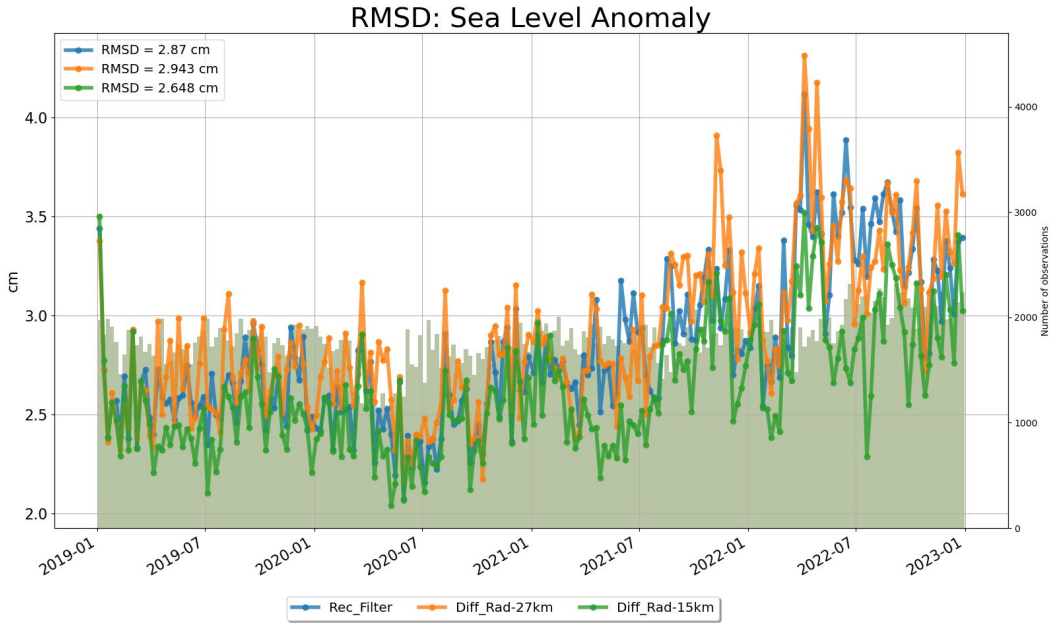






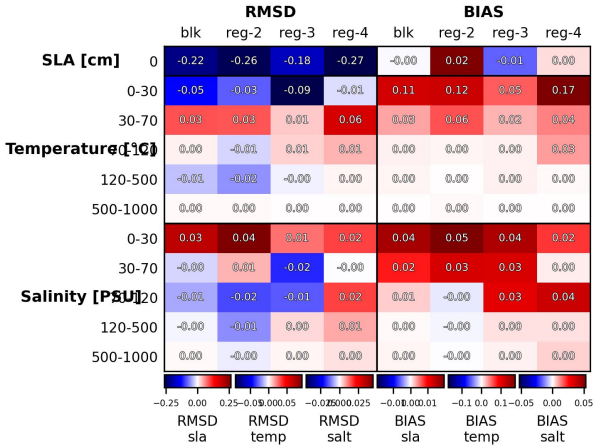
OV2 improves SLA RMSD in the MedSea. The bias for T,S is higher while RMSD of temperature is slightly better with slight degradation in salinity.

BSFS RF vs. DF



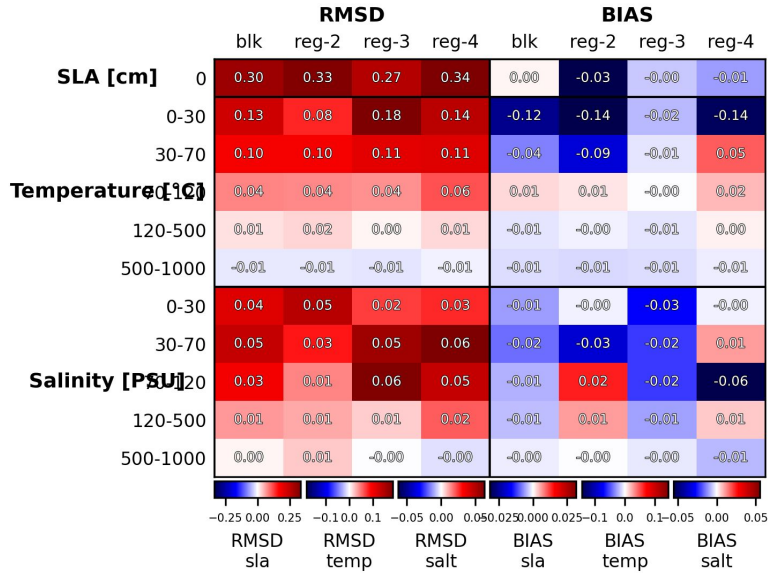
Exp Name	SLA	SST	IN-SITU	Filter Radius	Period
Diff_Rad-15km	L3	L3 NRT	ARGO	**15 km**	2019 - 2022
Diff_Rad-27km	L3	L3 NRT	ARGO	**27km**	2019 - 2022
Diff_Rad-10km	L3	L3 NRT	ARGO	**10km**	2019 - 2022

EAN comparison Diff_Rad-15km-Rec_Filter 2019-2022

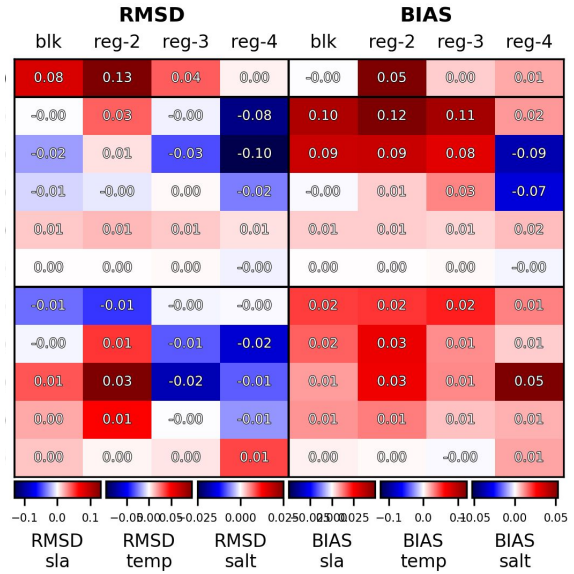


Blue if better Diffusive filter with radius 15 km. Bias is better with recursive filter. RMSD is better for SLA and surface temperature and sub-surface salinity for diffusive filter.

EAN comparison Diff_Rad-27km-Diff_Rad-15km



Diff_Rad-10km-Diff_Rad-15km 2019-2022



Red if better Diffusive filter with radius 15 km. For SLA, 15 km is better compared to 10 km and 27 km. For T,S better than 27 km comparable to 10 km.

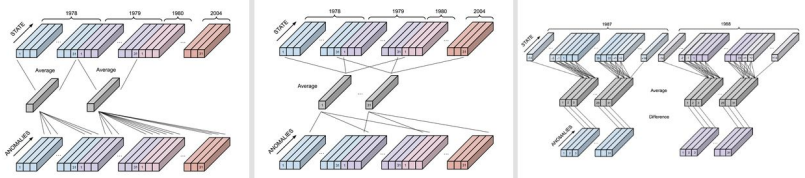
Vertical EOFs

Picking the Dataset

Dataset	Simulation / Reanalysis
Time span	Decadal / Multi-decadal
Partitioning	Monthly / Seasonal

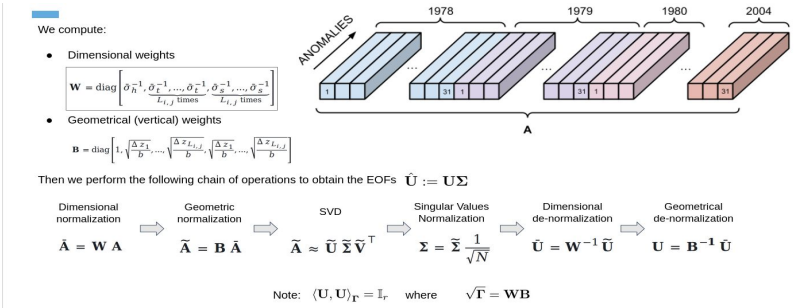
State Vector to Anomalies

Monthly Mean | **Daily Climatology** | **Daily Moving Average**



$$\mathbf{S} \longrightarrow \mathbf{A} = \mathbf{S} - \bar{\mathbf{S}} \longrightarrow \mathbf{B}_V = \frac{1}{N-1}\mathbf{A}\mathbf{A}^\top$$

Anomalies to EOFs

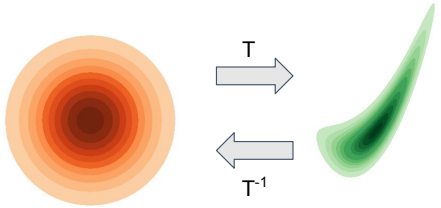


$$\mathbf{B}_V^{(r)} = \mathbf{U}\boldsymbol{\Sigma}^2\mathbf{U}^\top = \mathbf{V}_V\mathbf{V}_V^\top$$

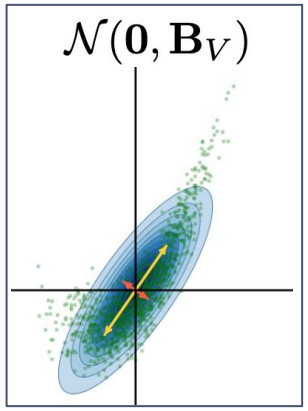
Definitions of the state vectors and methods of construction of the anomalies affect the **basic structure of the background covariance matrix**

Different weighting choices affect the **relative importance given to features of the background covariance matrix**

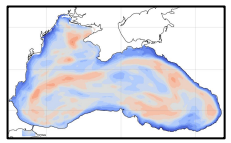
Anomalies are not necessarily Gaussian

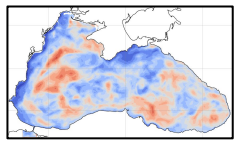


Represent true distribution:
- Normalizing flows
- Flow/score matching
- Auto-Encoders



Anomalies are not necessarily state independent


Static

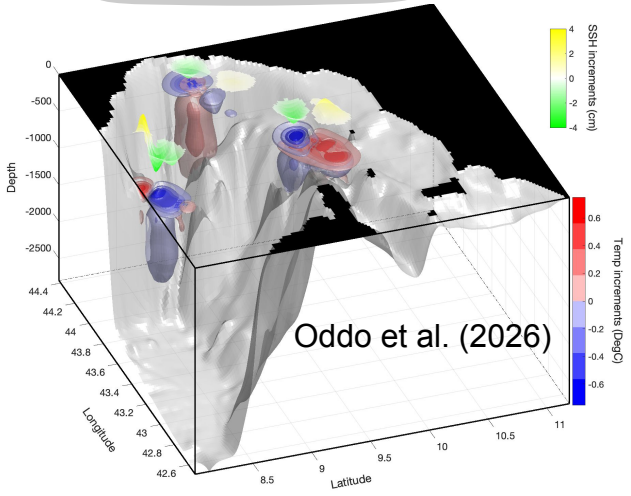

Ensemble

Flow dependent background
- Hybrid En3DVar
- Conditional flows

Copernicus Marine Service – Phase 2

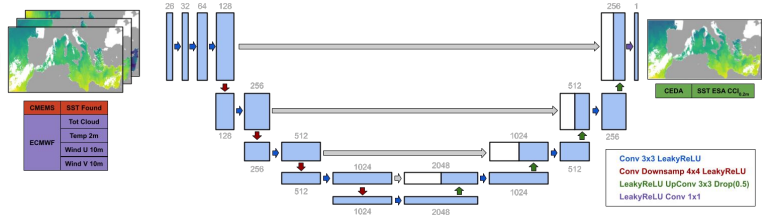
2025

OceanVar2

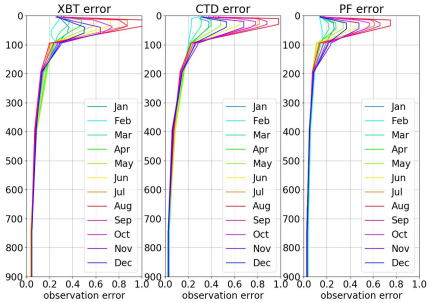


2026

SST assimilation using ML



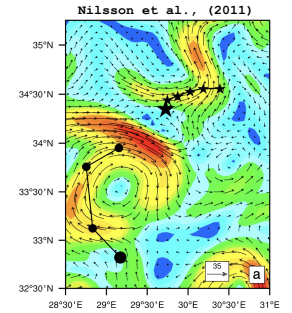
Updating OBS for NEMO5

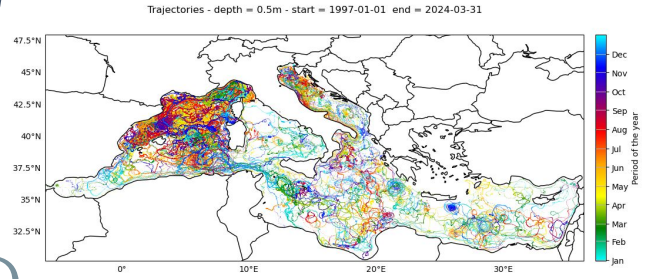


Update R, V_v

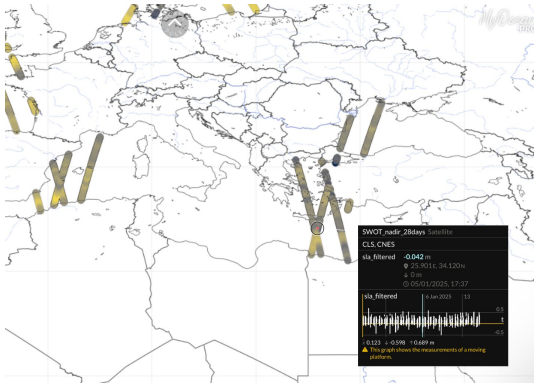
2027

Currents (Drifters, floats)





SWON / S6B



COMEDI - Overview

COPERNICUS MARINE SERVICE WITH ENHANCED DATA ASSIMILATION AND IMPROVED INTEROPERABILITY (COMEDI)

COMEDI

cmcc

COMEDI

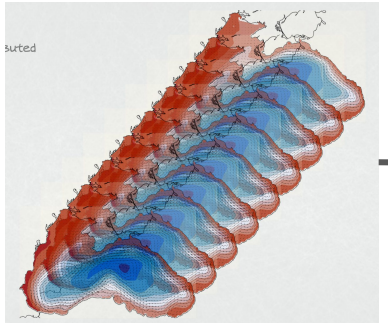
JuliaLang based preprcessing

NNEMO OBS module

Correlated R

Hybrid/Ensemble DA

$$B = \alpha B_c + (1-\alpha)\gamma B_{ens}$$

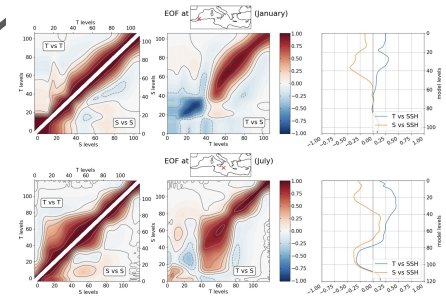


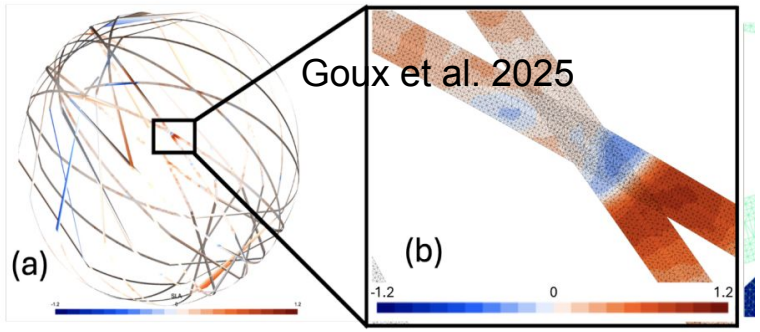
Oddo et al. (2016) ensemble of data assimilation

$$\delta \boldsymbol{x} = \left(V_D \boldsymbol{V}_{u,v} \boldsymbol{V}_\eta \boldsymbol{V}_H\right)\left(\alpha^{1/2} \boldsymbol{S}_c \boldsymbol{\Lambda}_c^{1/2} \boldsymbol{v}_c + (1-\alpha)^{1/2} \boldsymbol{S}_e \boldsymbol{\Lambda}_e^{1/2} \boldsymbol{v}_e\right)$$

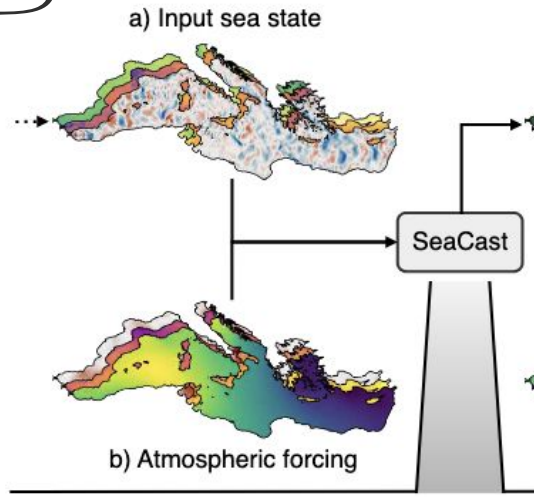
Generative DL for ensemble

EOF vs AE





Goux et al. 2025



Holmberg et al. (2025)


cmcc
Centro Euro-Mediterraneo
sui Cambiamenti Climatici
www.cmcc.it

Copernicus Marine Service – Phase 1

2022

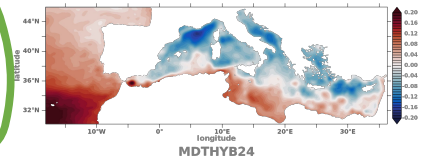
2023

2024

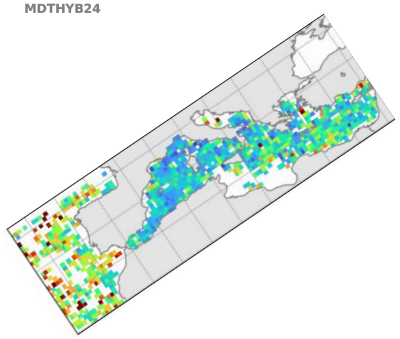
Post-2024

New MDT

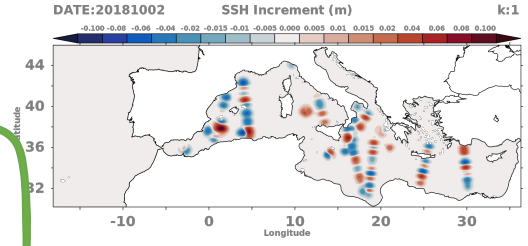
Jousset et al. (2025) In prep



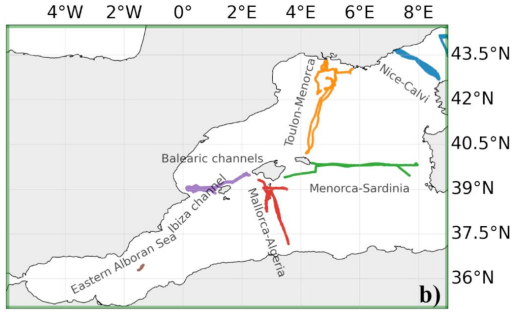
In-situ assimilation in the Atlantic-box



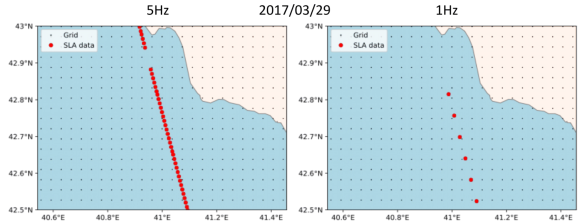
Filtered 7km SLA + HY-2B and S-6

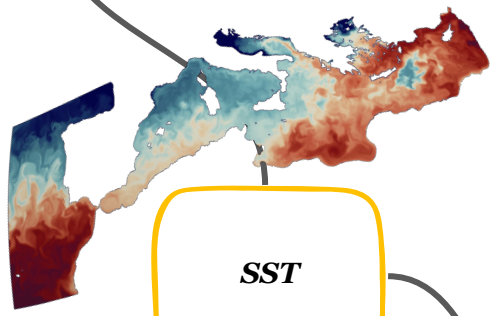


Gliders
Aydogdu et al. (2025)



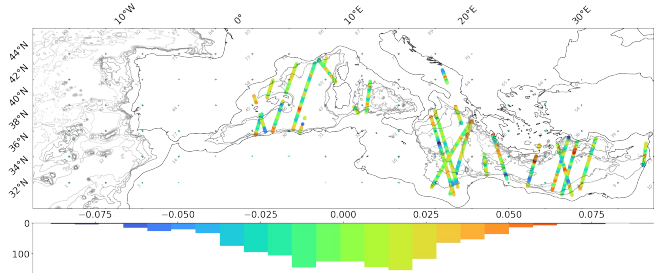
5Hz SLA





SST

ML/DA



SWOT and correlated obs

Currents

