Modelling the barotropic sea level in the Mediterranean Sea by assimilating data from coastal stations

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Why the barotropic sea level?

- Floodings in Venice are due to a sum of **storm surges, tides and seiches**. Baroclinic oscillations are slowly varying in the five-day forecast;
- 2D barotropic simulations are **much faster** (about 30 times) than 3D full baroclinic simulations (less variables, simpler equations, higher timestep, …);
- 2D barotropic simulations need only wind and pressure forcing (**no heat fluxes**);
- Data assimilation much simpler, **no need to assimilate temperature and salinity** data. SLA is usually not assimilated (does not include the barotropic signal).

Issues:

- Fast oscillations (hours) need **hourly steps** and an advanced DA method (no 3DVar…);
- Not possible to remove the **baroclinic part in the sea-level** observations.

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Summary

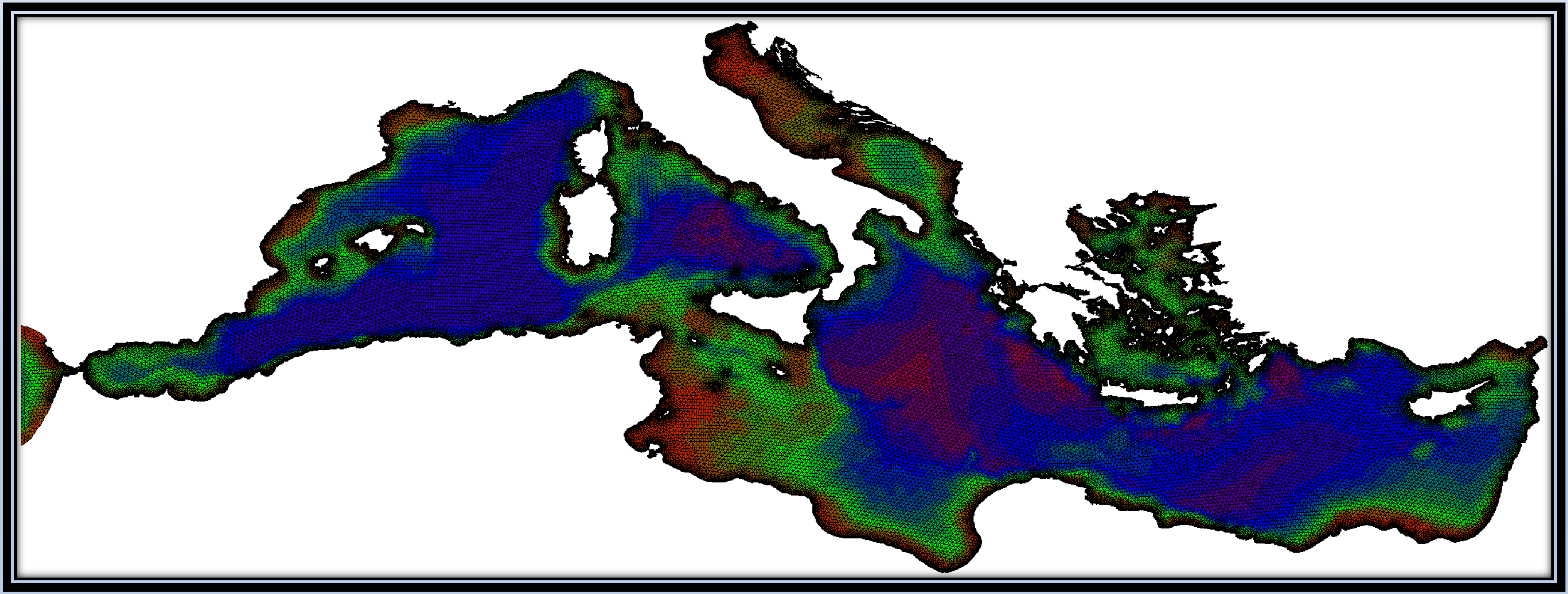
- The SHYFEM model in the Mediterranean Sea;
- The Ensemble Kalman Filter;
- Sea level in-situ observations;
- Hindcast vs Reanalysis of surges, total sea level and tides (work 1);
- Forecast of surges and seiches (work 1);
- Reanalysis of sea level (work 2);
- Conclusions.

The work 1 is published in:

Bajo, M., Ferrarin, C., Umgiesser, G., Bonometto, A., and Coraci, E.: *Modelling the barotropic sea level in the Mediterranean Sea using data assimilation*, Ocean Sci., 19, 559–579, https://doi.org/10.5194/os-19-559-2023, 2023.

The SHYFEM model

- **Model:** Finite element shallow water model, 2D barotropic, hydrostatic configuration;
- **Grid:** *163,153* elements with variable resolution;
- **Lateral Boundary Condition:** Total/residual/tidal sea level (Copernicus):
- **Surface Boundary Condition:** 10-m wind and MSL pressure.



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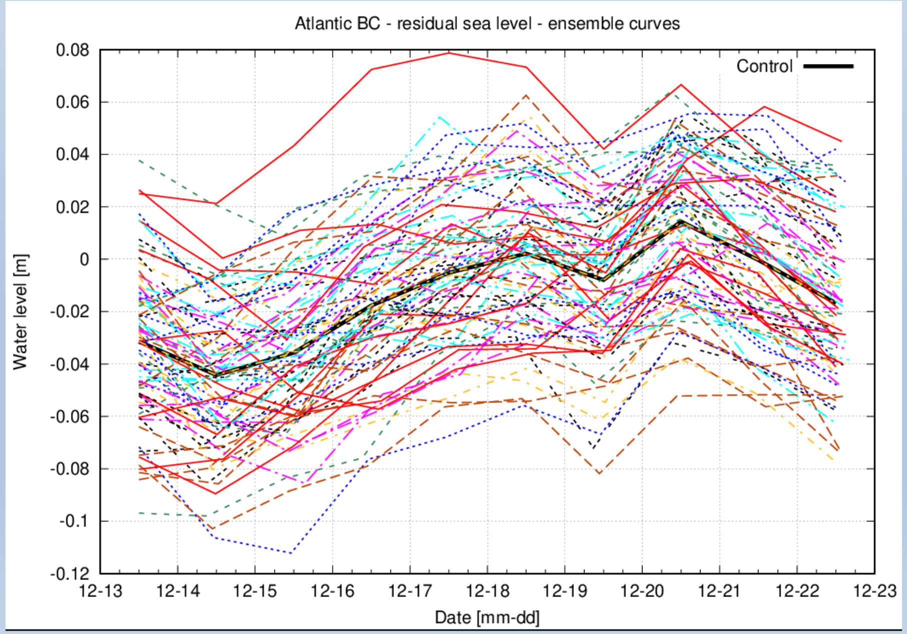
EnKF: settings

- Adaptation of Evensen's Github code to SHYFEM (https://github.com/marcobj/shyfem), to use different assimilation schemes (EnKF, EnSRF);
- BC (not initial state) problem. Forcing are more important than the initial state. Making gaussian perturbations of lateral and surface boundary conditions to create an ensemble of states and maintain the spread over time;
- Perturbations also for the bottom stress and the tidal loading coefficient (not in surge sims).



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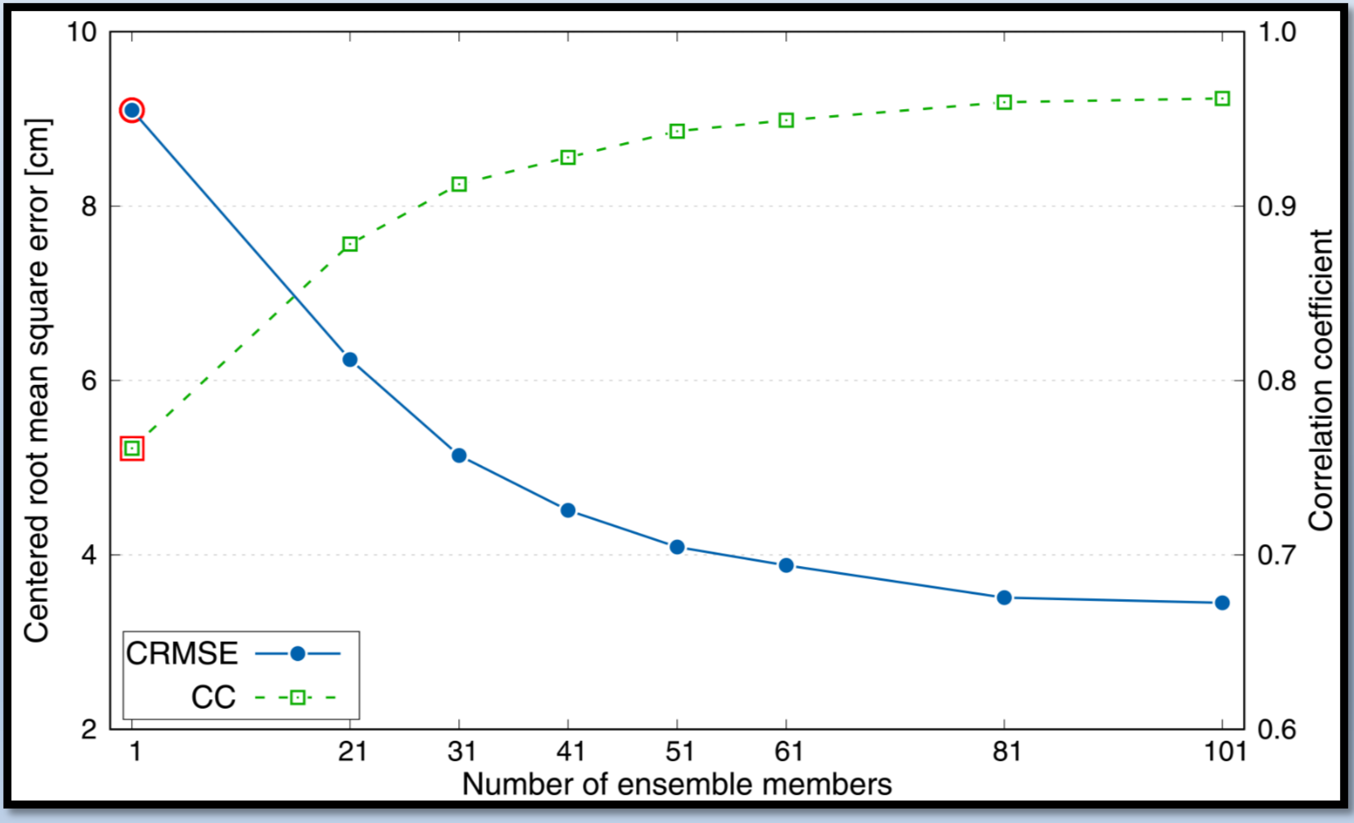
Work 1: calibration

Simulations of 2 months (November, December 2019), exceptional as storminess in the Adriatic Sea.

We run several tests changing DA method, localization radius (0-400km) and number of ensemble members.

- EnKF;
- No localization;
- 81 ensemble members.



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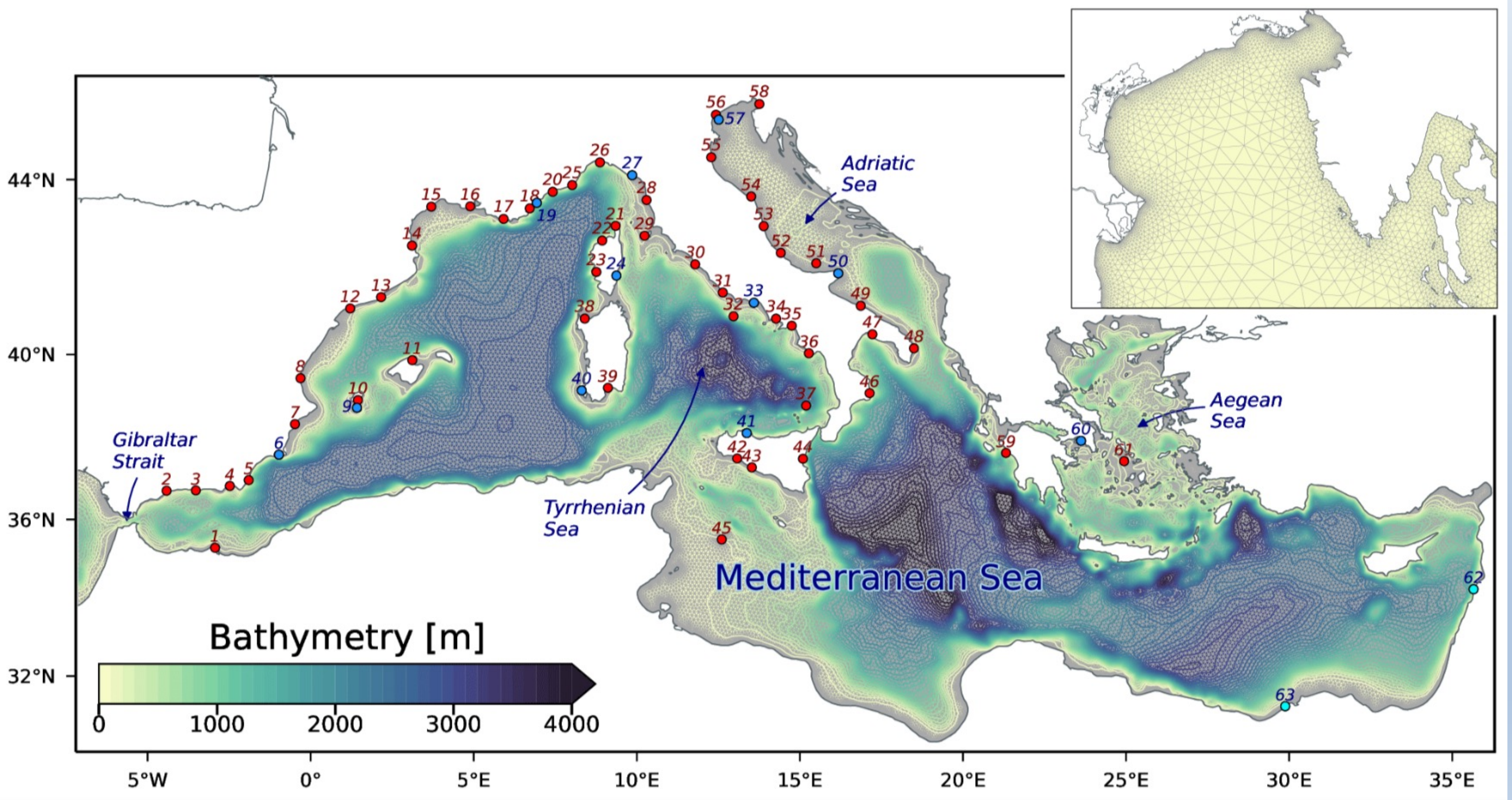
Work 1: observations

50 assimilated stations (red);
13 not-assimilated stations for validation (blue).



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Work 1: observations

Few stations in the **African coast** and in the **eastern part** of the Mediterranean Sea.

Observations are checked, de-tided (for storm surge simulations).

The **MSL** is modified to the model one (deterministic run).

ID	Long	Lat	Station	ID	Long	Lat	Station
1	−2.930	35.290	Melilla	35	14.750	40.676	Salerno
2	−4.417	36.711	Málaga	36	15.275	40.029	Palinuro
3	−3.520	36.720	Motril	37	15.190	38.785	Ginostra
4	−2.478	36.830	Almeria	38	8.403	40.842	Porto-Torres
5	−1.899	36.974	Carboneras	39	9.114	39.210	Cagliari
6*	−0.973	37.596	Murcia	40*	8.309	39.147	Carloforte
7	−0.481	38.338	Alicante	41*	13.371	38.121	Palermo
8	−0.310	39.440	Valencia	42	13.076	37.504	Sciacca
9*	1.419	38.734	Formentera	43	13.526	37.285	Porto-Empedocle
10	1.450	38.917	Ibiza	44	15.093	37.498	Catania
11	3.117	39.867	Alcúdia	45	12.604	35.499	Lampedusa
12	1.213	41.078	Tarragona	46	17.137	39.083	Crotone
13	2.160	41.340	Barcelona	47	17.223	40.475	Taranto
14	3.107	42.520	Port-Vendres	48	18.497	40.147	Otranto
15	3.699	43.397	Sète	49	16.866	41.140	Bari
16	4.893	43.405	Fos-sur-Mer	50*	16.177	41.888	Vieste
17	5.914	43.122	Toulon	51	15.501	42.119	Tremiti
18	6.717	43.359	Port Ferréol	52	14.414	42.355	Ortona
19*	6.933	43.483	La Figueirette	53	13.890	42.960	San Benedetto del Tronto
20	7.421	43.728	Monaco	54	13.506	43.624	Ancona
21	9.350	42.967	Centuri	55	12.282	44.492	Ravenna
22	8.938	42.635	L'Île-Rousse	56	12.426	45.418	Venice
23	8.760	41.920	Ajaccio	57*	12.511	45.313	AAOT
24*	9.374	41.836	Solenzara	58	13.757	45.649	Trieste
25	8.018	43.878	Imperia	59	21.319	37.640	Katakolo
26	8.870	44.380	Genova	60*	23.621	37.935	Peiraias
27*	9.857	44.096	La-Spezia	61	24.941	37.438	Syros
28	10.299	43.546	Livorno	62*	35.653	34.242	Batroun
29	10.238	42.742	Marina-di-Campo	63*	29.879	31.209	Alexandria
30	11.789	42.093	Civitavecchia				
31	12.634	41.446	Anzio				
32	12.965	40.895	Ponza				
33*	13.589	41.209	Gaeta				
34	14.269	40.841	Napoli				

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Work 1: simulations

We run several types of simulations:

- Sea level component (tide, surge, total sea level);
- With/without data assimilation;
- Hindcast/reanalysis or forecast.

BC and forcing as well as the observations vary according to the simulation.

ID	Variable	Type	DA
TH	Tide	Hindcast	No
TR_A	Tide	Reanalysis	Yes
SH	Surge	Hindcast	No
SR_A	Surge	Reanalysis	Yes
ZH	Total sea level	Hindcast	No
ZR_A	Total sea level	Reanalysis	Yes
SF	Surge	Forecast	No
SF_A	Surge	Forecast	Yes
ZF	Total sea level	Forecast	No
ZF_A	Total sea level	Forecast	Yes

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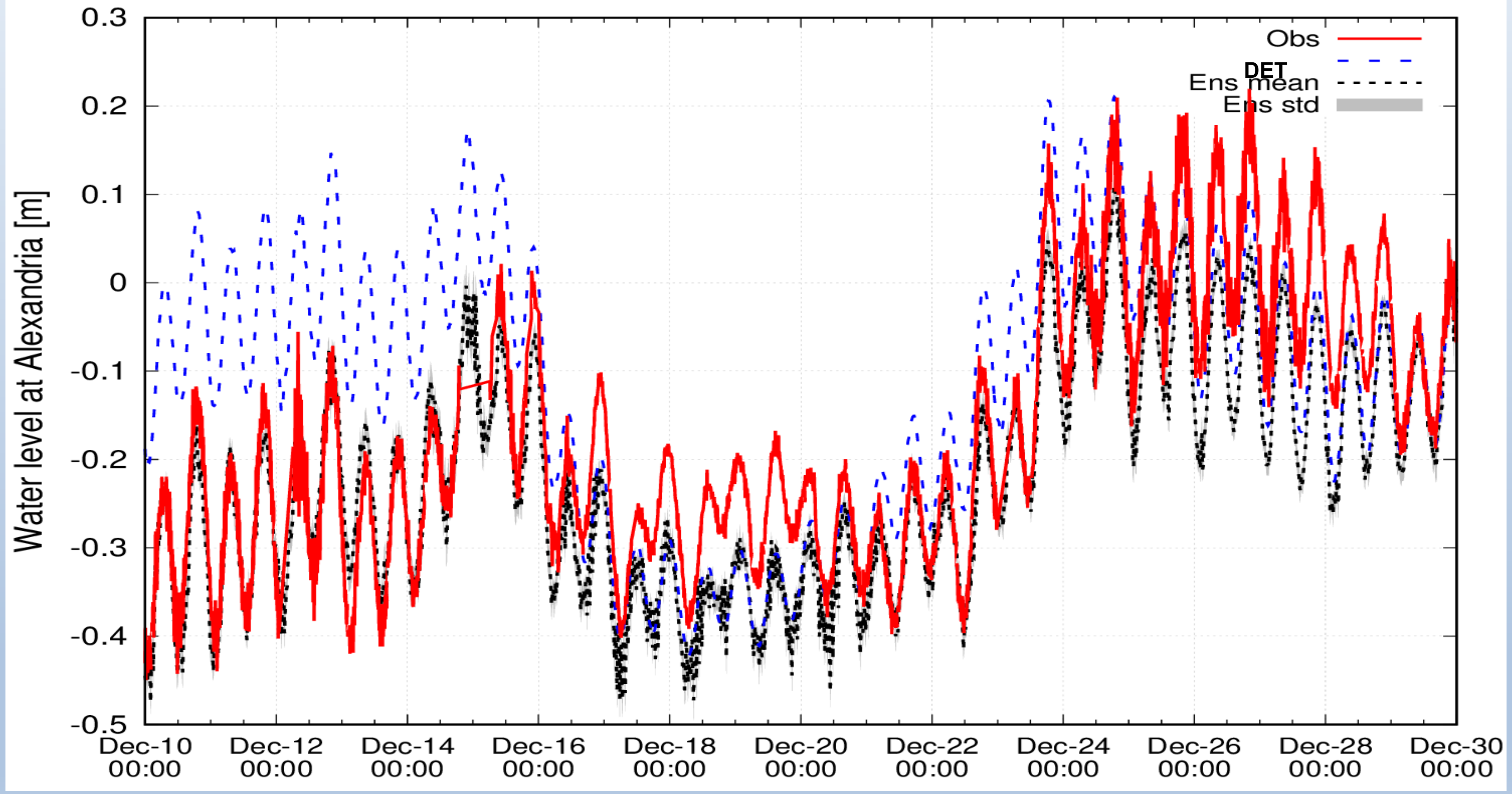
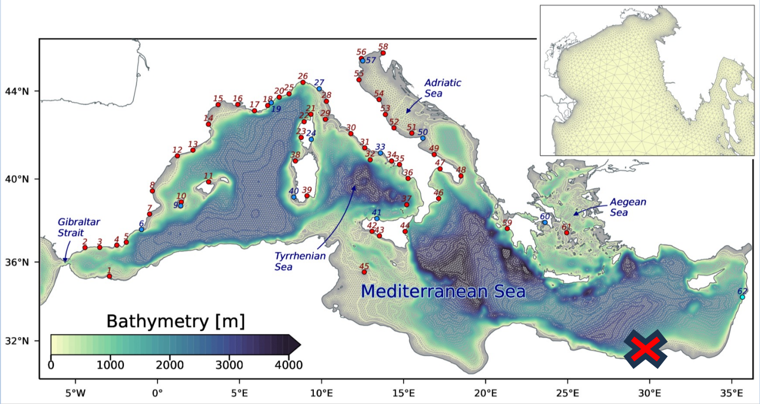
Work 1: sea-level reanalysis

Validation stations (**not assimilated**).
Total sea level reanalysis (**ensemble mean**) compared to the deterministic (det) run.
Alexandria is very far from the assimilated stations!





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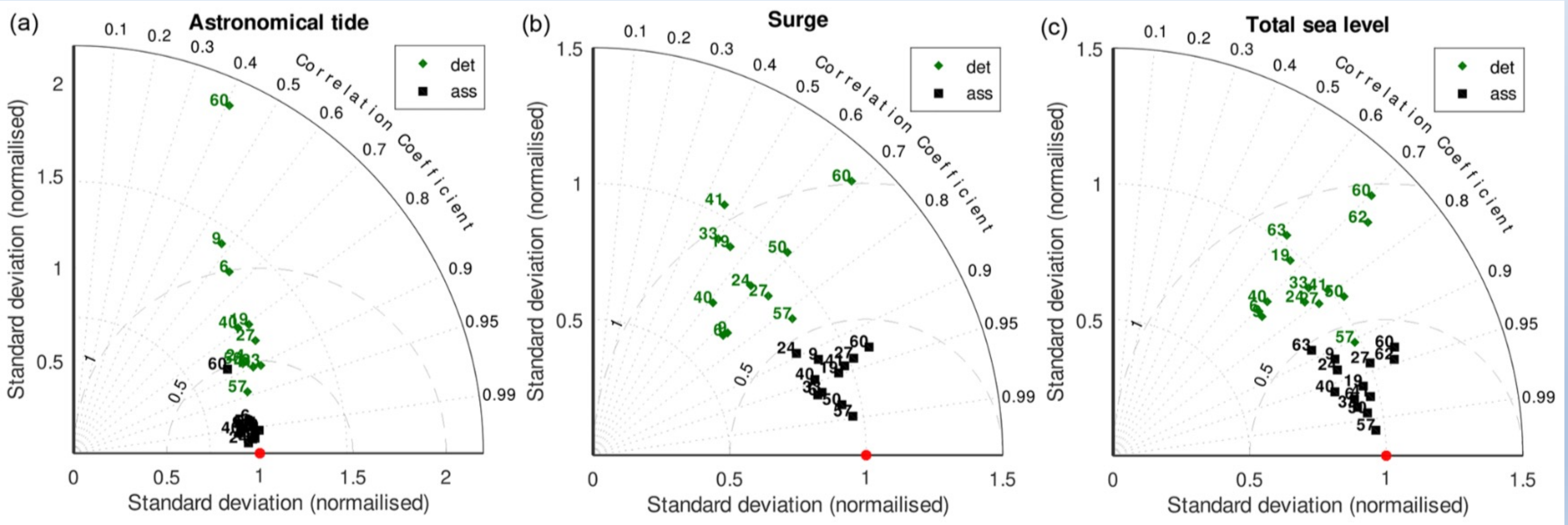
Work 1: reanalysis vs hindcast

Validation stations (not assimilated)

- Excellent DA results with all the components;
- Best performances reproducing only the **tide** (which is bias-free).



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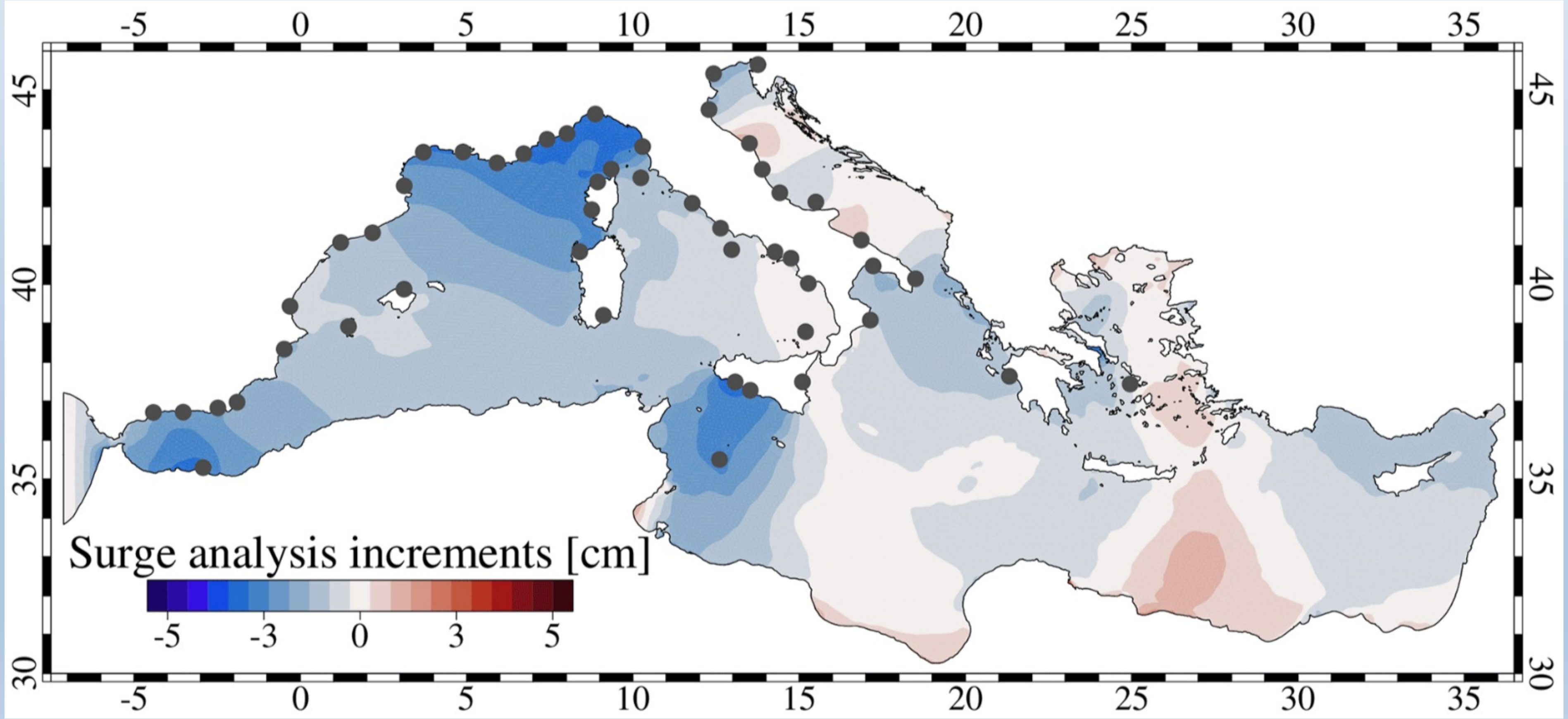
Work 1: example of surge increments

To check the correctness of the increments we looked at their spatial distribution. No local effect, resemble barotropic sea-level shapes.



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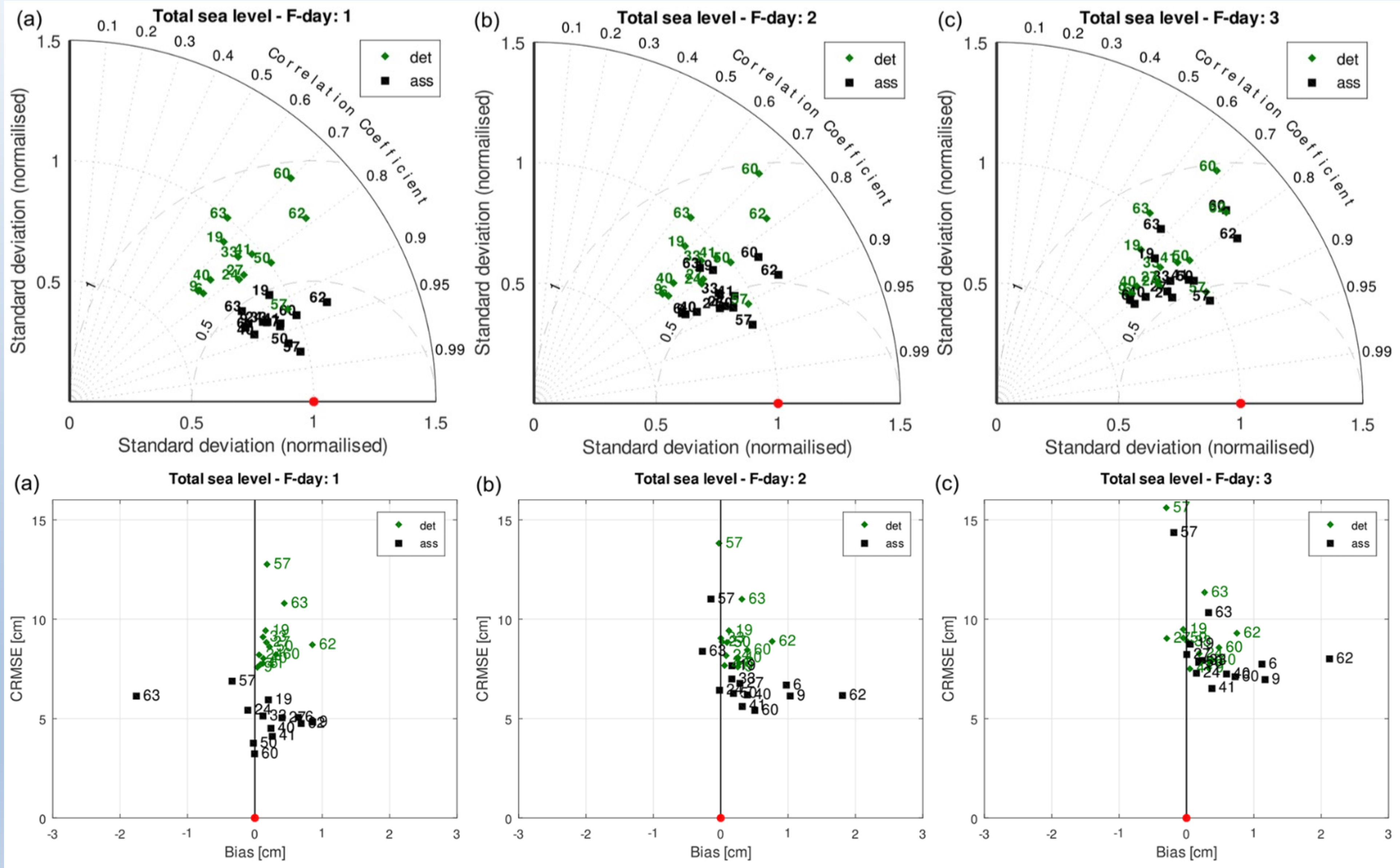
Work 1: Forecast

- Three days of forecast;
- DA simulations **start from the analysis ensemble mean**;

- Improvements especially the first day, due mainly to the **correction of the seiche signal.**



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Work 1: Reproduction of seiches

Seiches are free oscillations, triggered by an initial perturbation (e.g., a storm surge), following the barotropic modes of a basin. They are especially strong in the Adriatic sub-basin.

Spectral analysis of the observations revealed:

- Five modes in the Mediterranean Sea (M5 never detected);
- Four modes in the Adriatic Sea;

Papers are mostly focused on A1 and A2, the most energetic.

Mode ID	$T_{ol}[h]$	$T_s[h]$	$T_{op}[h]$
A_1	21.2	20.1	21.3
A_2	10.7	9.3	10.7
A_3	6.7	6.8	–
A_4	5.3	–	5.2
M_1	–	38.5	–
M_2	–	11.4	12.8
M_3	–	8.4	8.3
M_4	–	7.4	–
$M5$	–	–	6.2

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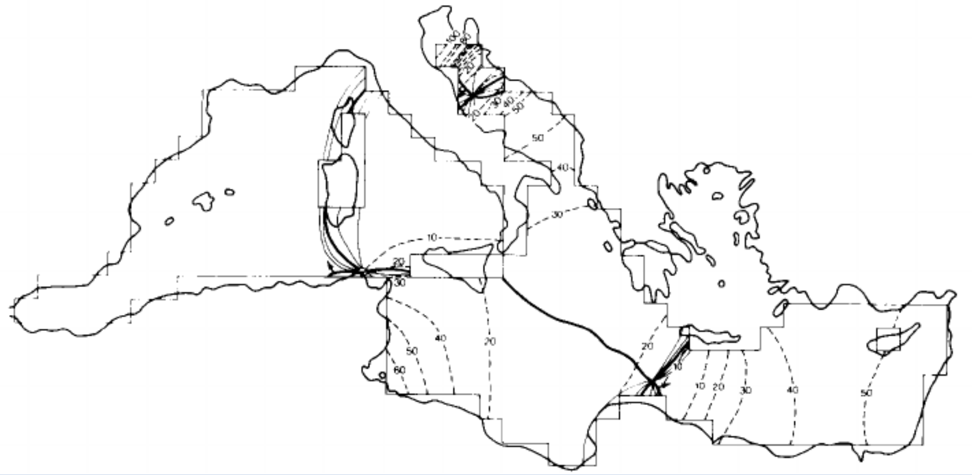
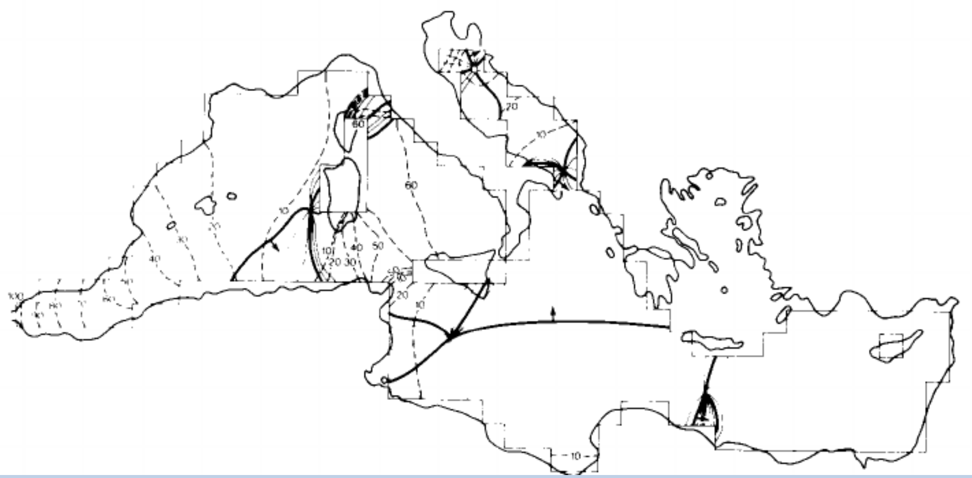
Work 1: shapes of barotropic modes

2nd Mediterranean mode (M2)

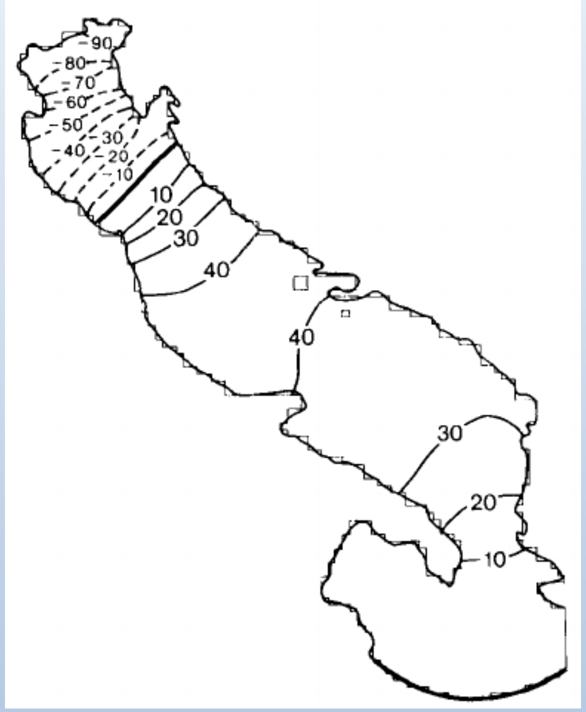


3rd Mediterranean mode (M3)



1st Adriatic mode (A1)

2nd Adriatic mode (A2)



Amphidromic node lines from modelling

From:
Schwab, D. and Rao, D.: Barotropic oscillations of the Mediterranean and Adriatic seas, Tellus A, 35, 417–427, 1983.

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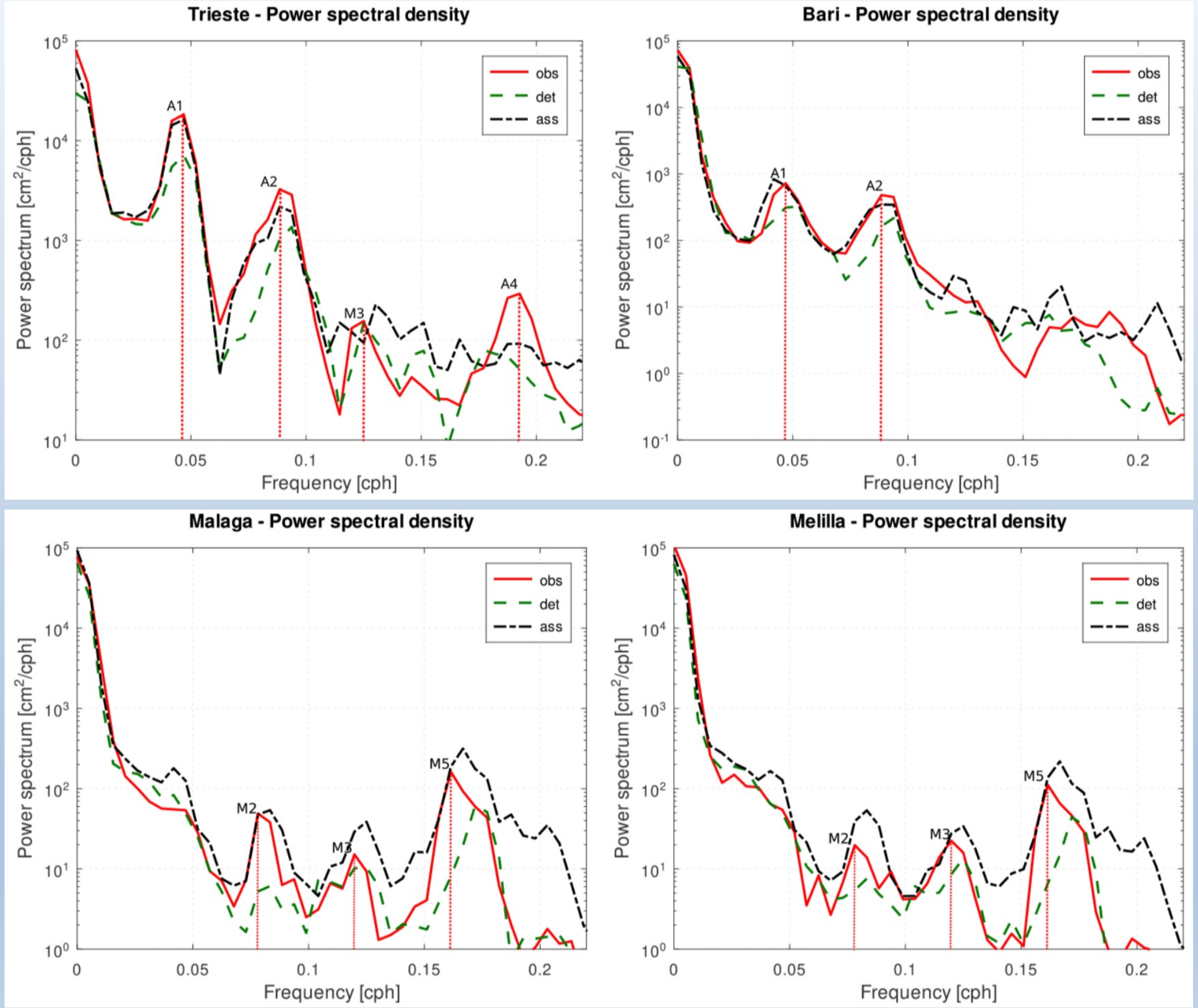
Work 1: power spectra comparison

Comparison of the power spectra in four stations from:

- Observations
- 1st day forecast from deterministic simulation
- 1st day forecast starting from the ensemble mean (DA)



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Work 1: conclusions

- **Excellent** EnKF performances for the astronomical **tide**. Probably due to the periodicity and to the zero-mean of the tidal signal;
- **Very good** EnKF performances in **reanalysis**. Able to correct bias errors and errors caused by bad forcing;
- **Good** EnKF performances in forecast. The correction is limited to the initial state. Error reduction especially with pre-existing seiches;

In 2023 an operational system based on this work was set up at the Italian Center for Environmental Protection (ISPRA), to forecast the sea level along all the Italian coasts.

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Work 2: Coast-Clim project

On April 2025 we started a project (PNRR-Return) called Coast-clim. Objective: To provide a hindcast of wind wave and a **reanalysis of the sea level** over the **Mediterranean Sea**, from **1994 to 2020**.

- CERRA (Copernicus reanalysis) wind and pressure forcing;
- IBI reanalysis (CMEMS) at the Atlantic boundary;
- Assimilation of all the available sea-level in-situ data over the Mediterranean Sea.

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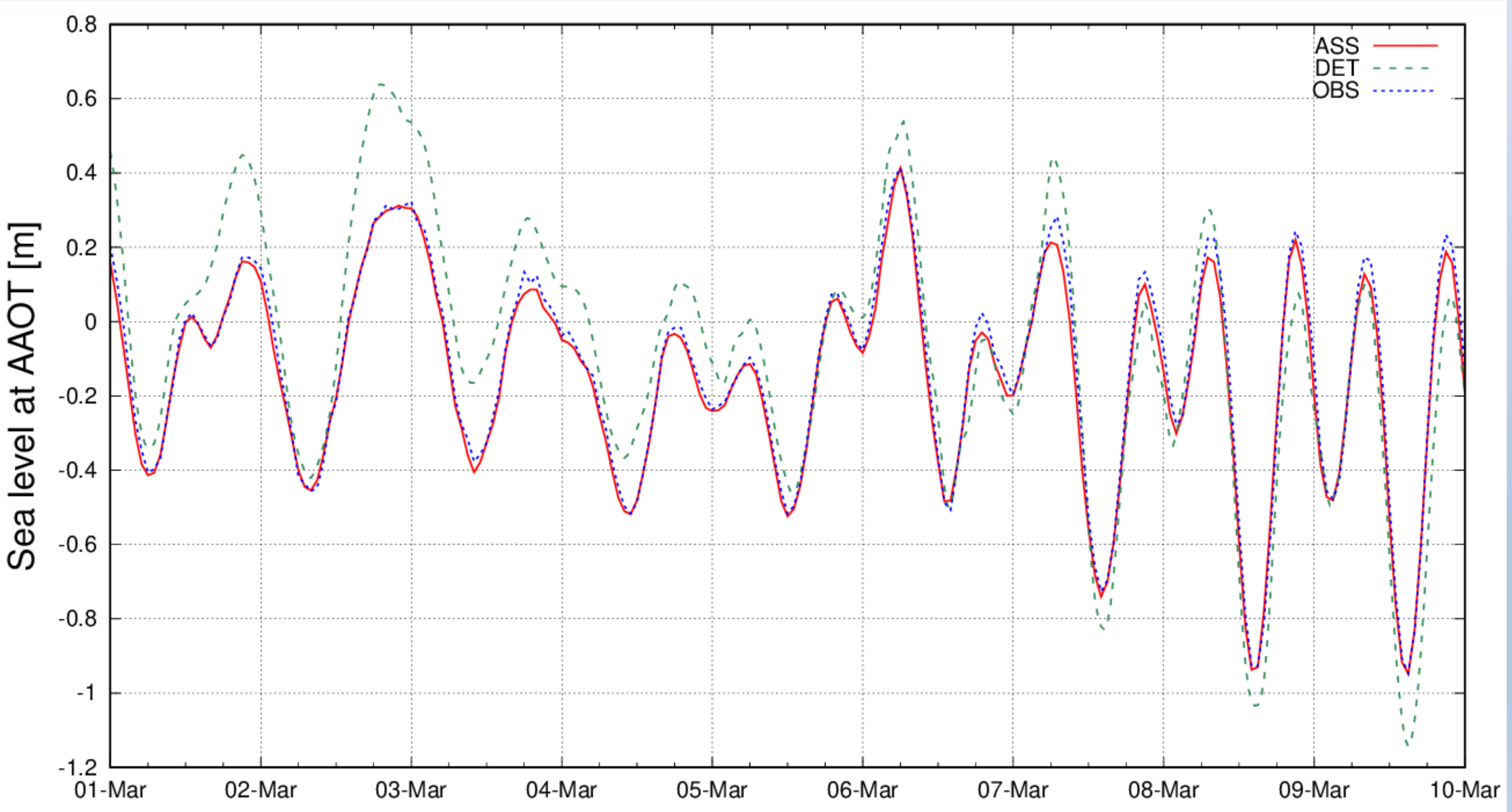
Work 2: simulation set-up

Spin-up every year (10 day deterministic run, initial ensemble creation, 3 day DA run, monthly runs). Each monthly run start from the final analysis state of the previous month).



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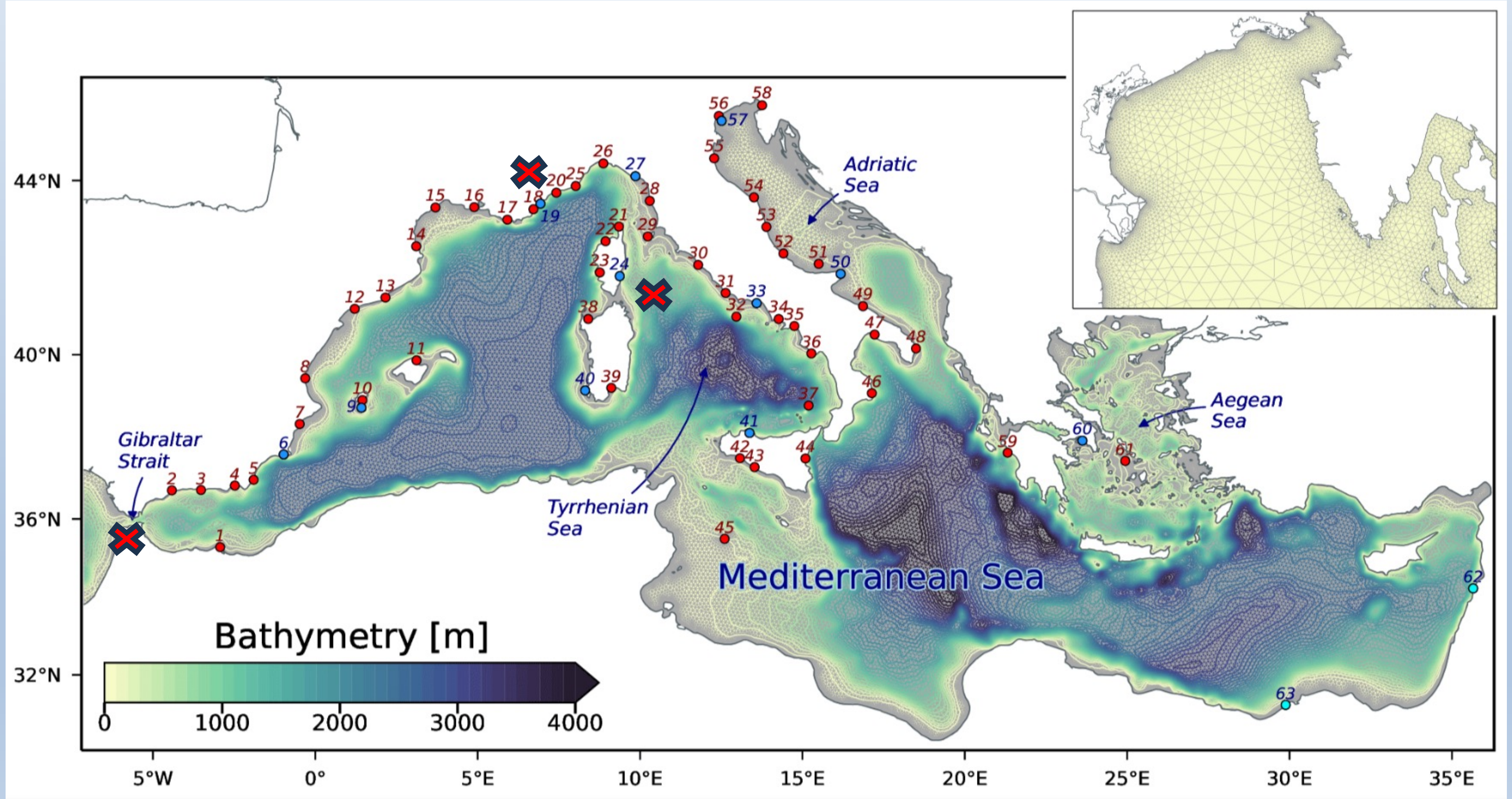
Work 2: issues

Some simulations diverges… Sea-level too high in some locations.



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Work 2: issues

Implementations that improved the results:

- Switch from 81 members to 41 but with **localization** (covariance loc., about 200km radius);
- The solution near the BC is a **weighted mean** between analysis (41 members) and background (non-perturbed), G-C function from the boundary (200km);
- Creation of **super observations**. Observations are merged if the distance is 4 times lower than the loc. radius;

Simulations with very few stations are stable. Simulations with many stations are sometimes unstable.

Still some simulations diverges… Any idea?

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Thank you!

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