Ocean predictions: from descriptive to quantitative science

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Outline

- First part: an historical account of the science of ocean predictions
- Second part: operational oceanography and the operational ocean services
- Third part: Global, regional and coastal seas forecasting systems
- Fourth part: societal benefit applications
- Lessons learned

Background material

- Pinardi, N. and J. Woods (Eds), 2002. Ocean Forecasting: conceptual basis and applications, Springer
- Chassignet, E. and J.Verron (Eds), 2006. Ocean weather forecasting, Springer
- Schiller, A. and G. Brassington (Eds), 2011. Operational Oceanography in the 21st century, Springer
- Pinardi, Lermusiaux, Brink and Preller (Eds), 2017. The Science of Ocean Predictions, The Sea Vol. 17, Sears Foundation for Marine Research, https://doi.org/10.1357/002224017821836833

Third part: Global, regional and coastal seas forecasting systems

1. Global CMCC system and relocatable nested systems
2. Mediterranean Sea Copernicus system
3. The new coastal and harbor forecasting systems

Global and relocatable forecasting models: the incremental approach

Global Ocean-Ice model

Iovino et al., 2014, Iovino et al., 2016

Ocean/Sea Ice code

NEMO / LIM: OPA is a finite difference, hydrostatic, primitive equation ocean general circulation model coupled to Louvain-la-Neuve sea Ice Model. Z-coordinates and linear free surface

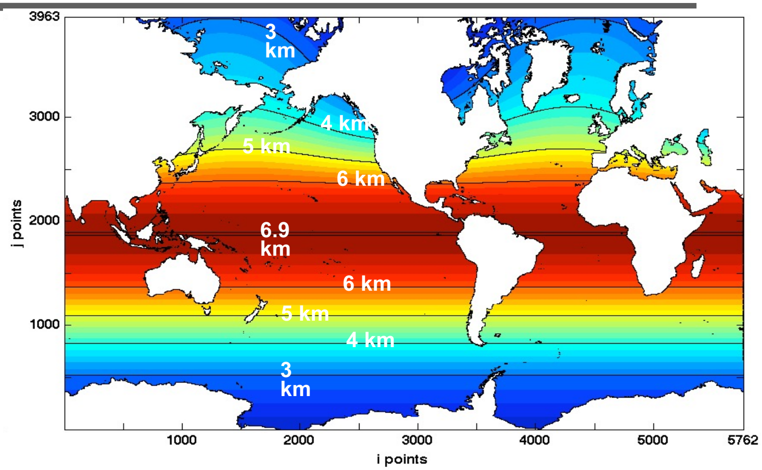
Mesh
Global tri-polar grid: horizontal resolution spacing from 6.9km at the equator to ~2km at high latitudes with 98 vertical levels (5762 x 3963 x 98 points)

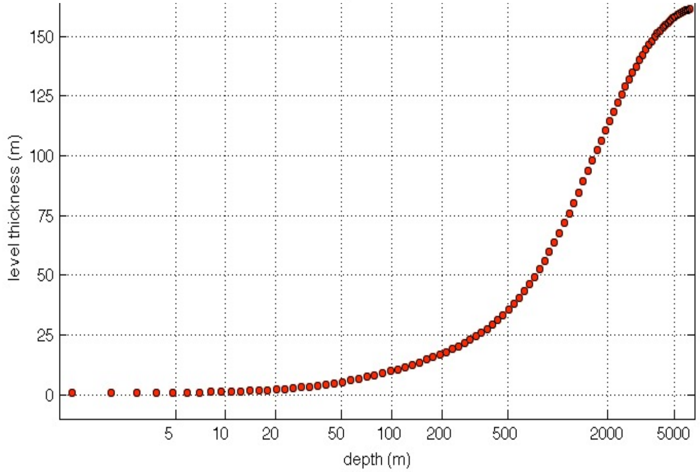
Bathymetry Etopo2 (deep ocean) + GEBCO (continental shelves) + Bedmap2 (Antarctic region) + hand editing
Bottom topography represented as partial steps

Initialization
Temperature and Salinity from WOA 2013
Sea ice properties from 1/4° ocean reanalysis

Atmospheric forcing
Bulk CORE-II formulation
2003-2013: Era-Interim atmospheric forcing (1/4°)
2014-2016: ECMWF operational system (1/8°)
River run-off from Dai et al. (2009) - global annual discharge of ~1.32 Sv

Output (ocean and sea ice): 3D variable = 10Gb for a time record

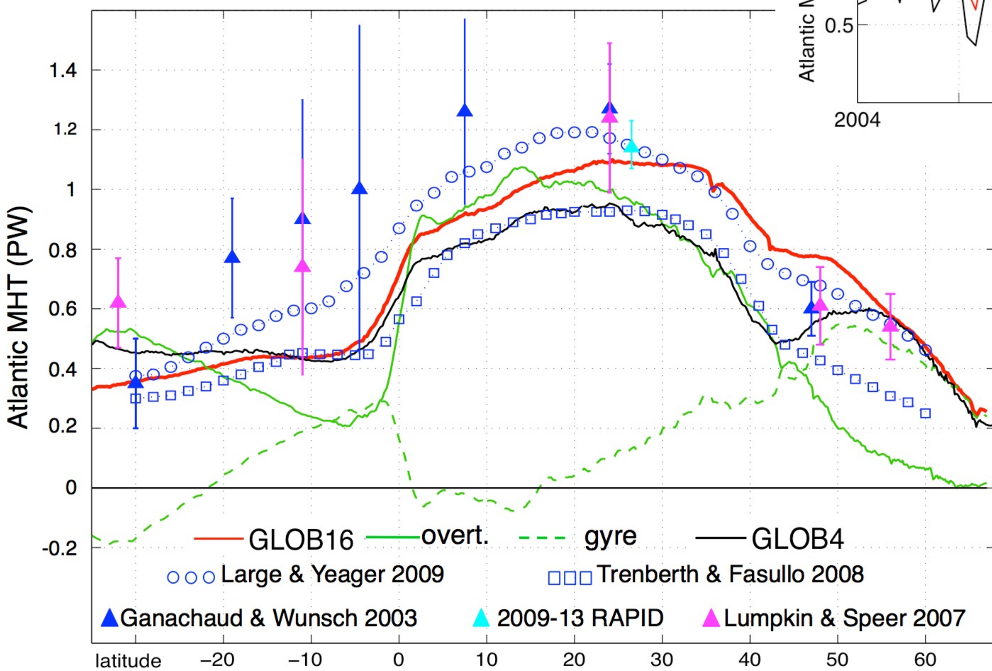


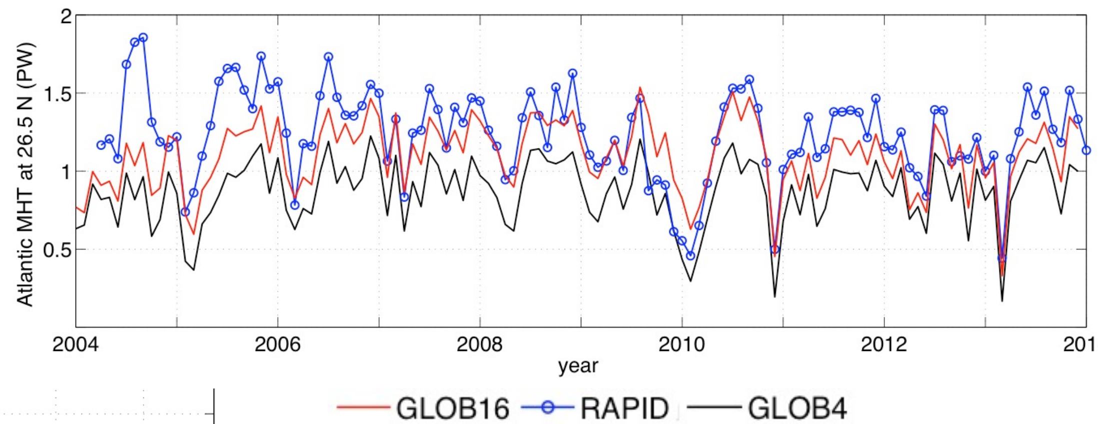


Global Ocean-Ice model

Iovino et al., 2014, Iovino et al., 2016

Extensive Model validation
With observational data





GLOB4 => ¼ degree model

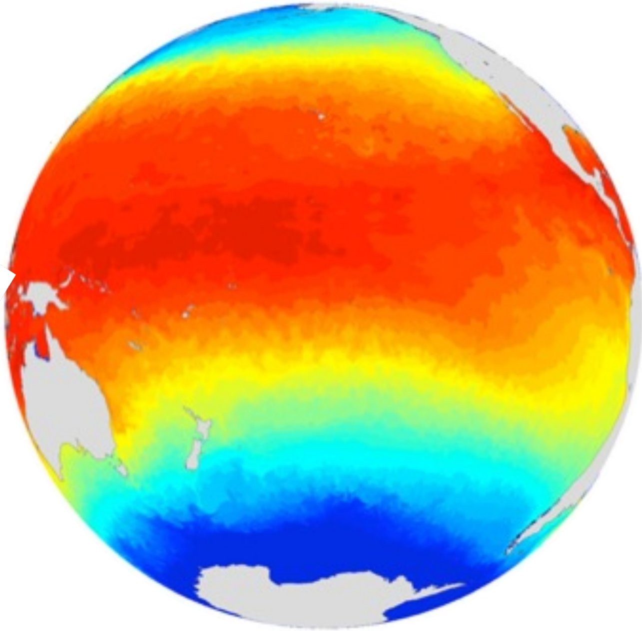
GLOB16 => 1/16 degree model

(Iovino et al. 2016)

Global Ocean Forecasting system: assimilation scheme

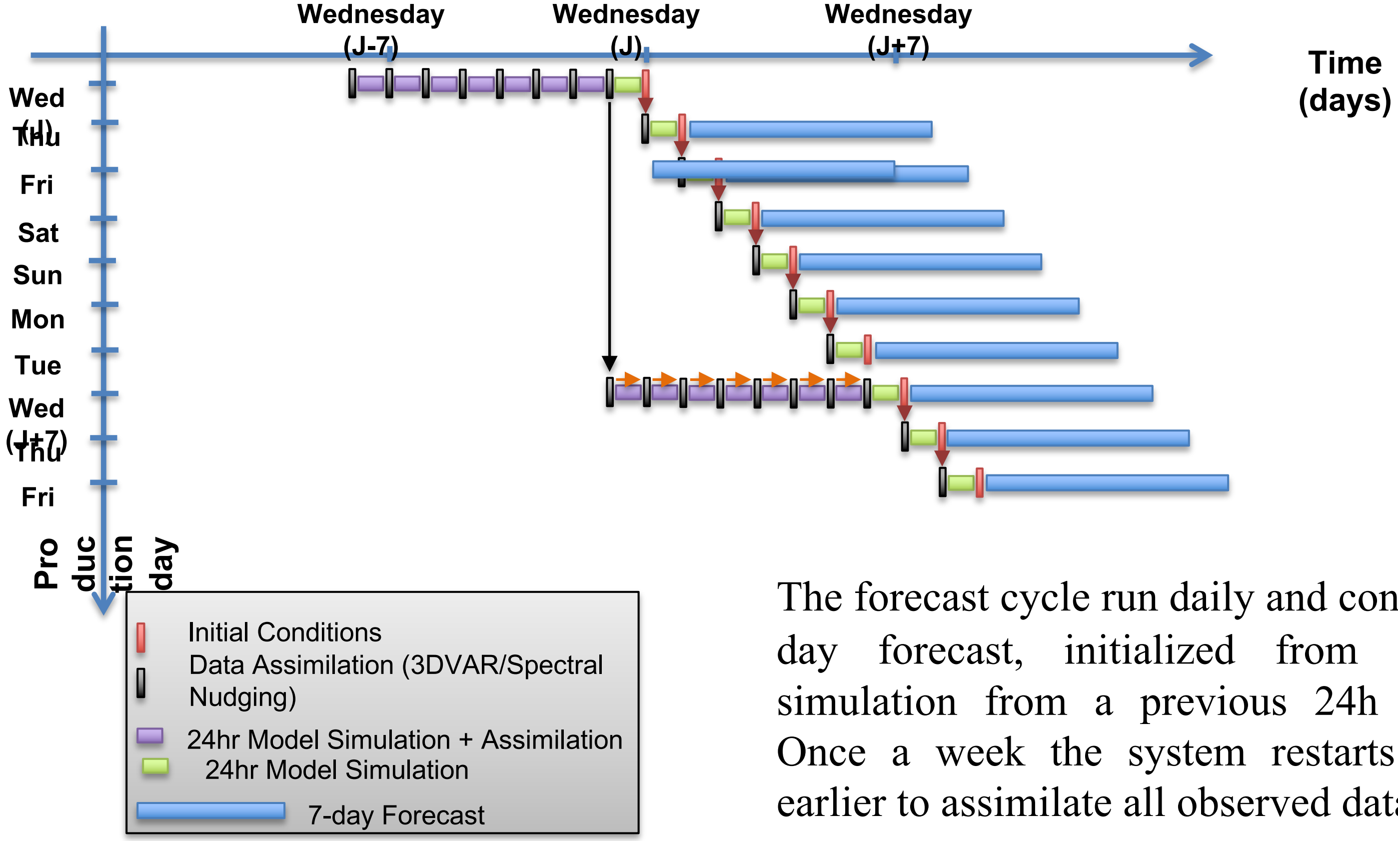
- 3Dvar assimilation scheme with daily updates from multiple data sources (Storto et al., 2014)
- Nudging of sea surface temperature and sea ice concentration)

- XBT, CTD, Argo, moorings, marine mammals
- along-track satellite altimetry observations (Jason-2, Altika and CryoSat2)



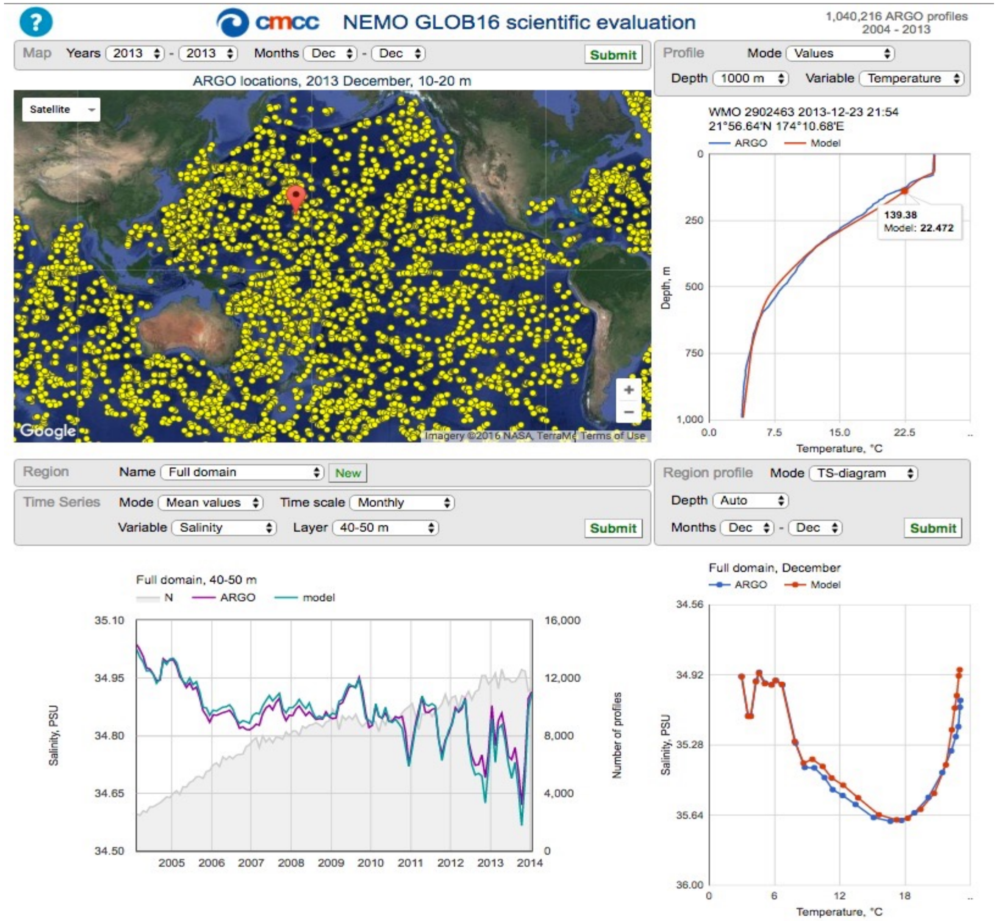
- SST relaxation toward NOAA 1/4° Analyses (15 days)
- SSS relaxation toward monthly objective analysis of MetOffice EN4

Global Ocean Forecasting system: The operational chain



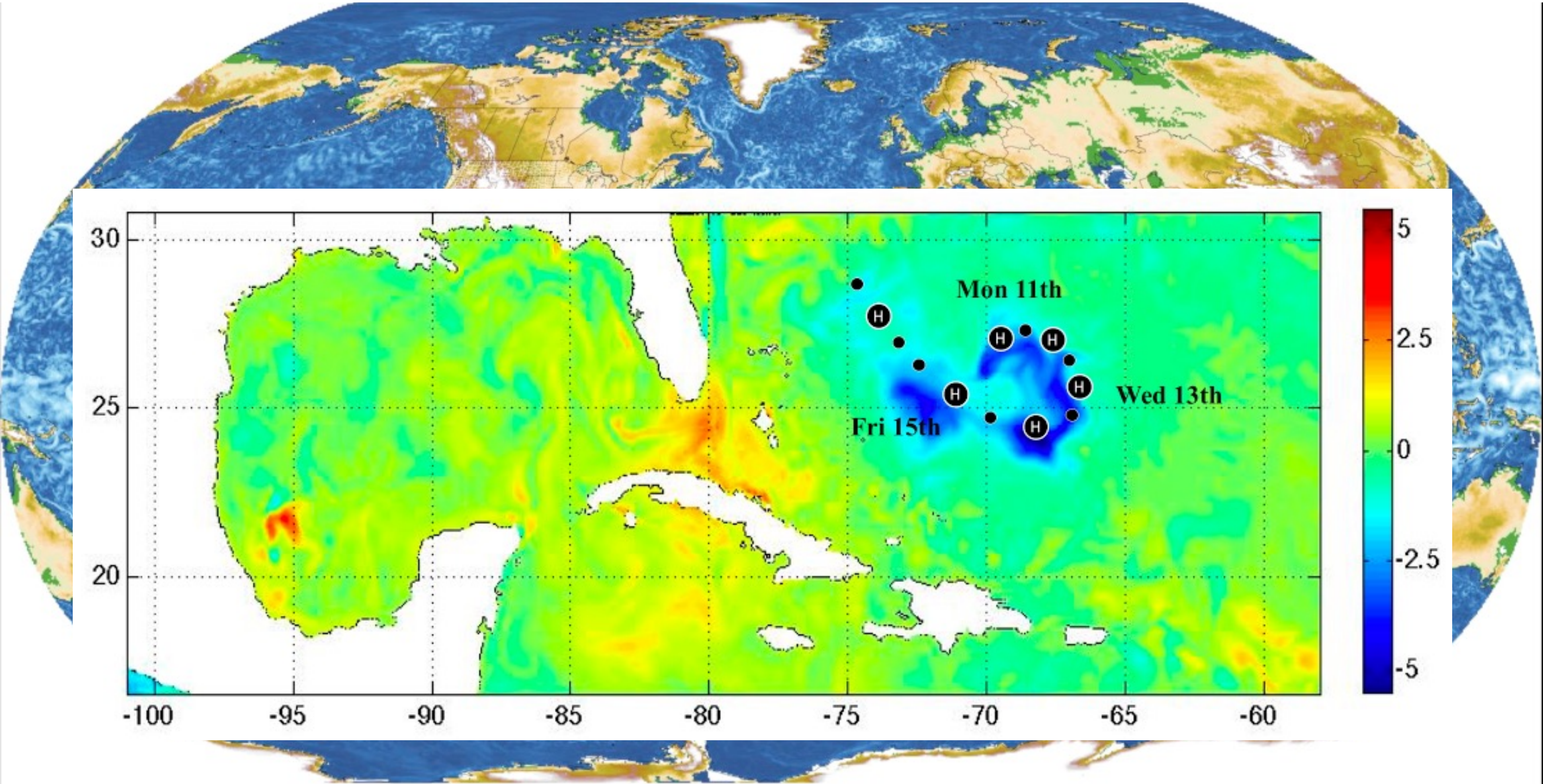
The forecast cycle run daily and consists of a 7-day forecast, initialized from the model simulation from a previous 24h simulation. Once a week the system restarts one week earlier to assimilate all observed data.

CMCC Global Forecasting System: Quality assessment tool



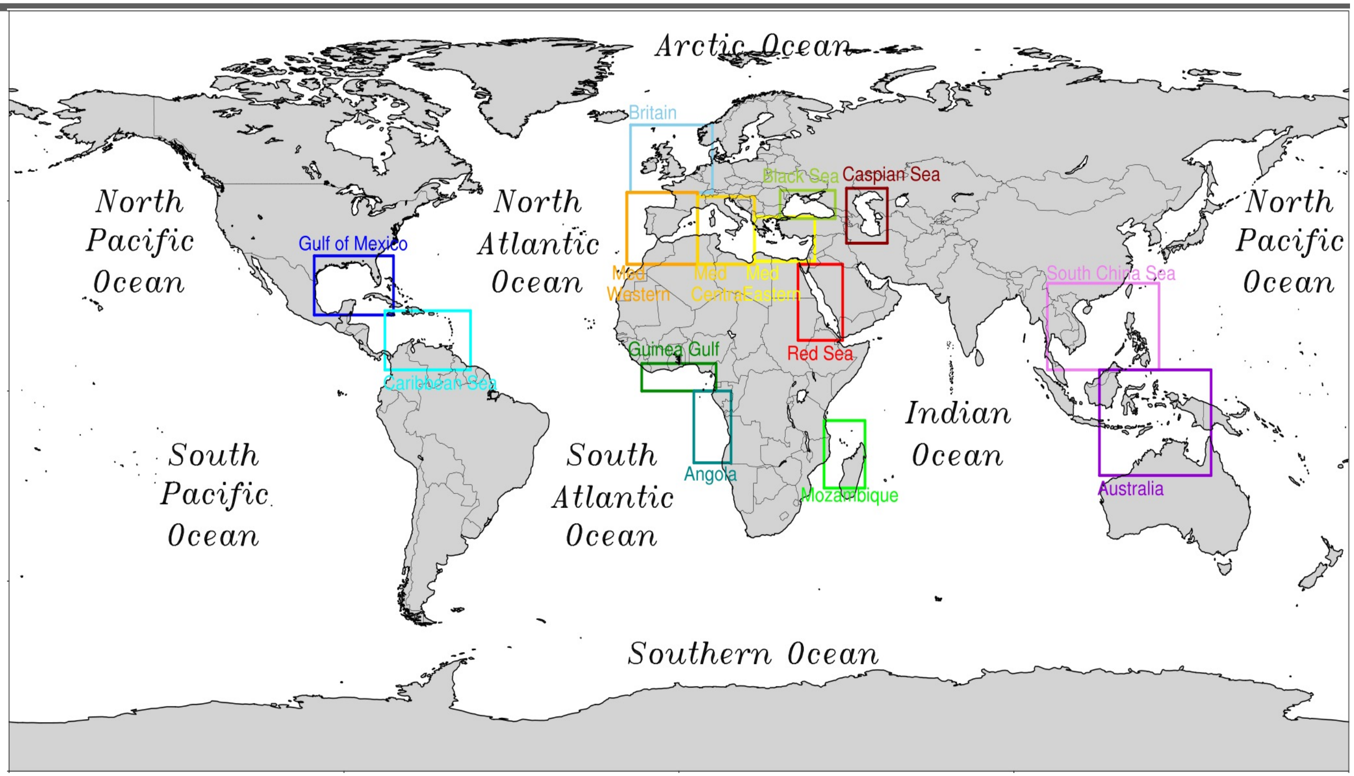
Every day the forecast or analysis is Compared with the Near real time observations, especially ARGO

Global Ocean Forecasting system: SST signature of a hurricane



Rilocatable forecasting: limited area modelling to zoom in areas of interest

Aim is to go to 1/64 degree resolution In all these areas. But strategy can be different for each of them



Need to define: grid refinement technique, the spin-up time, now many nestings to reach the required resolution, the lateral open boundary conditions

Rilocatable forecasting: limited area modelling to zoom in areas of interest

- The question is: can limited area ocean models increase coarse resolution forecast accuracy?
- Limited area forecasting requires to consider:
  - Coastal geometry details
  - High resolution bathymetry
  - Estuarine forcings
  - Shelf break dynamics
  - **The initialization problem**
  - **The lateral boundary condition problem**
  - Surface atmospheric forcing of adequate resolution

Need to focus on that, very special problem

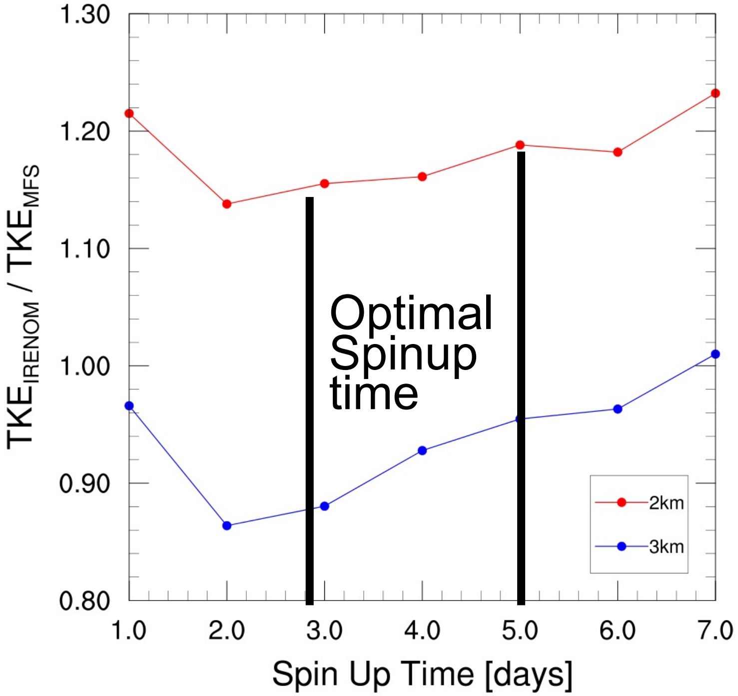
Initialization problem: the spin up time

- Determination of spin-up time for the nested model (Simoncelli et al., DAO, 2013, De Dominicis et al., 2014)

From a 6 km model

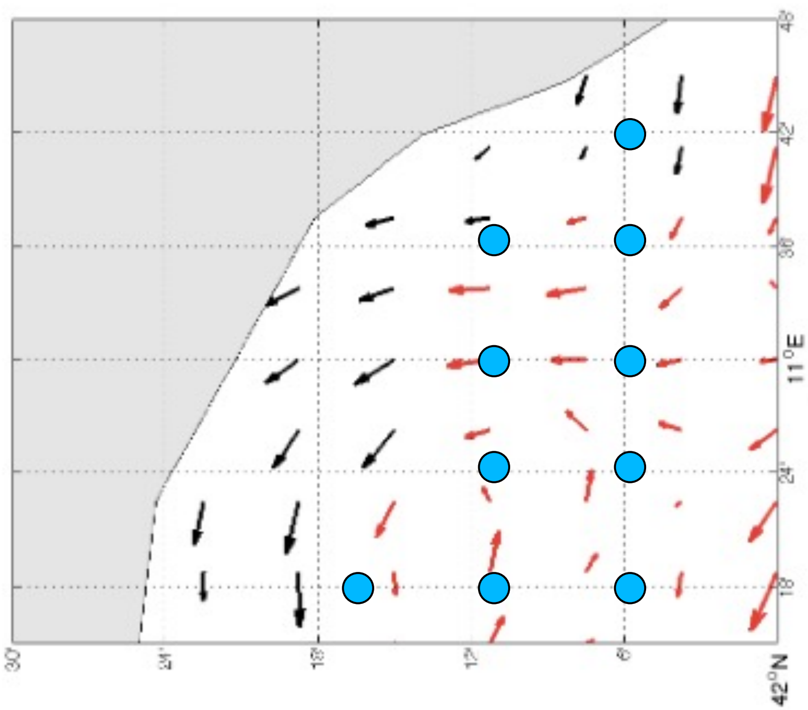
Red-> nested 2 km model
Blue-> nested 3 km model

Spin up time depends on the model domain and circulation regime but it is approx. **3-5 days**



Initialization problem: the interpolation from coarser resolution models

- Re-gridding of coarser fields in the finer grid (De Dominicis et al. OCDYN, 2013)



coarse grid

Red: velocity interpolated from coarse grid

Black: extrapolated from coarse grid with viscous boundary layer assumption so that velocities are parallel to the coasts

Lateral boundary condition problem

A For the tracers and total velocities at outflow/inflow:

$$\frac{\partial \theta}{\partial t} + u_{n\,coarse}\frac{\partial \theta}{\partial n} = \lambda(\theta - \theta_{coarse}) \quad ;\theta = (T, S, U_{total})$$

B For the barotropic component of velocity field, new GENERALIZED FLATHER BOUNDARY CONDITION has been developed (Oddo and Pinardi, 2008)

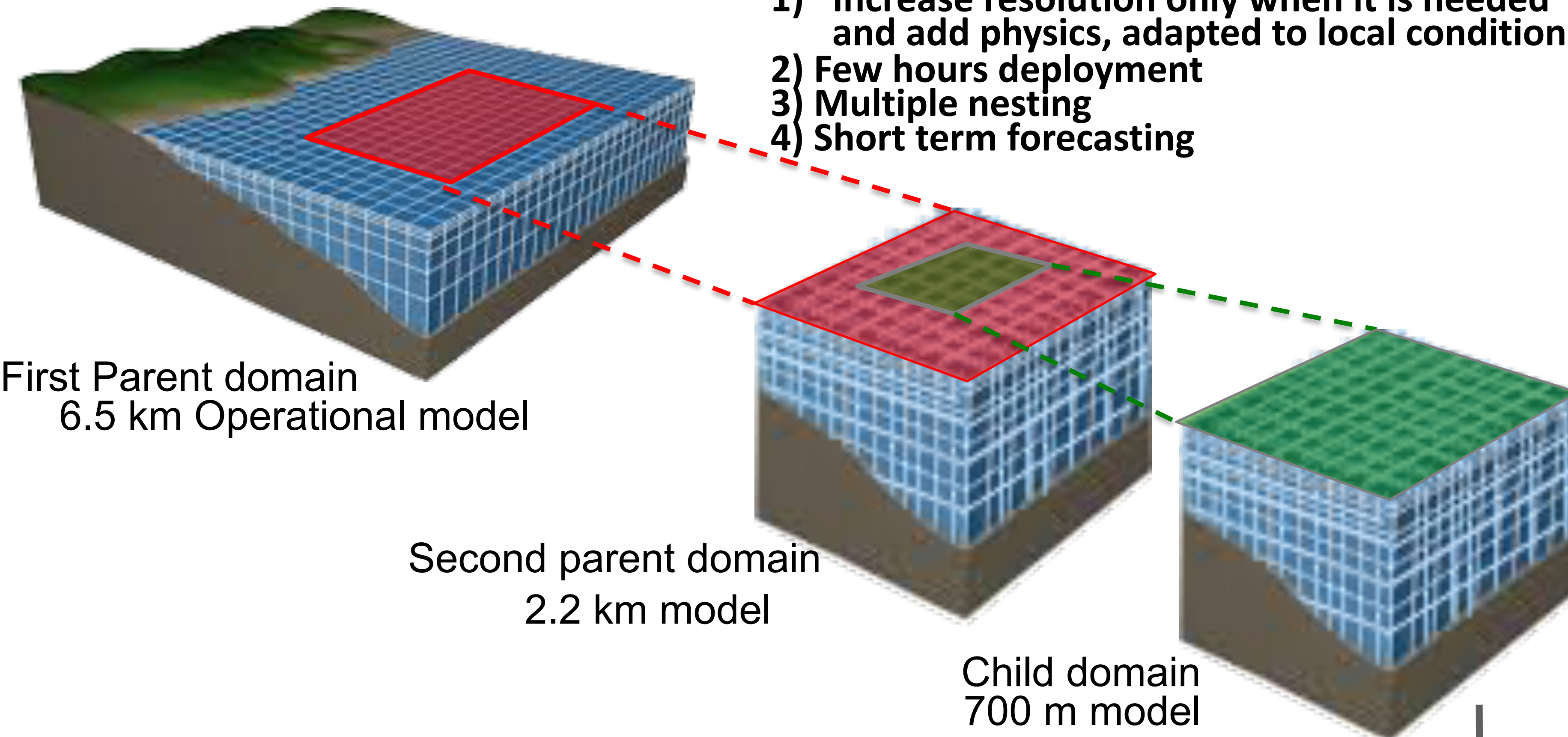
$$U_N^F = \frac{H_C + \eta_C}{H_F + \eta_F} U_N^C - \frac{C_N}{H_F + \eta_F}\left(\eta_C - \eta_F\right) \quad (!!!)$$

C For different topography at the open boundaries INTERPOLATION CONSTRAINT (Pinardi et al., 2003)

Relocatable structured and unstructured model (SURF, Trotta et al., 2015)

Main characteristics:

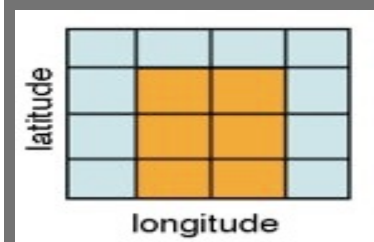
1) **Increase resolution only when it is needed and add physics, adapted to local conditions**
2) **Few hours deployment**
3) **Multiple nesting**
4) **Short term forecasting**



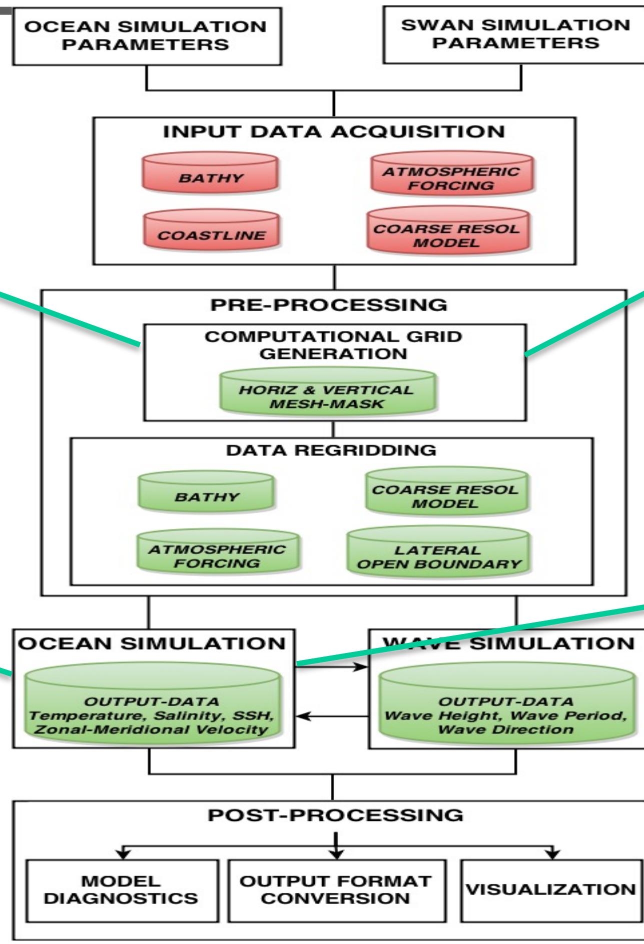
Relocatable structured and unstructured model (SURF, Trotta et al., 2015)

SURF_S

STRUCTURED D GRID



FINITE DIFFERENCE (NEMO)

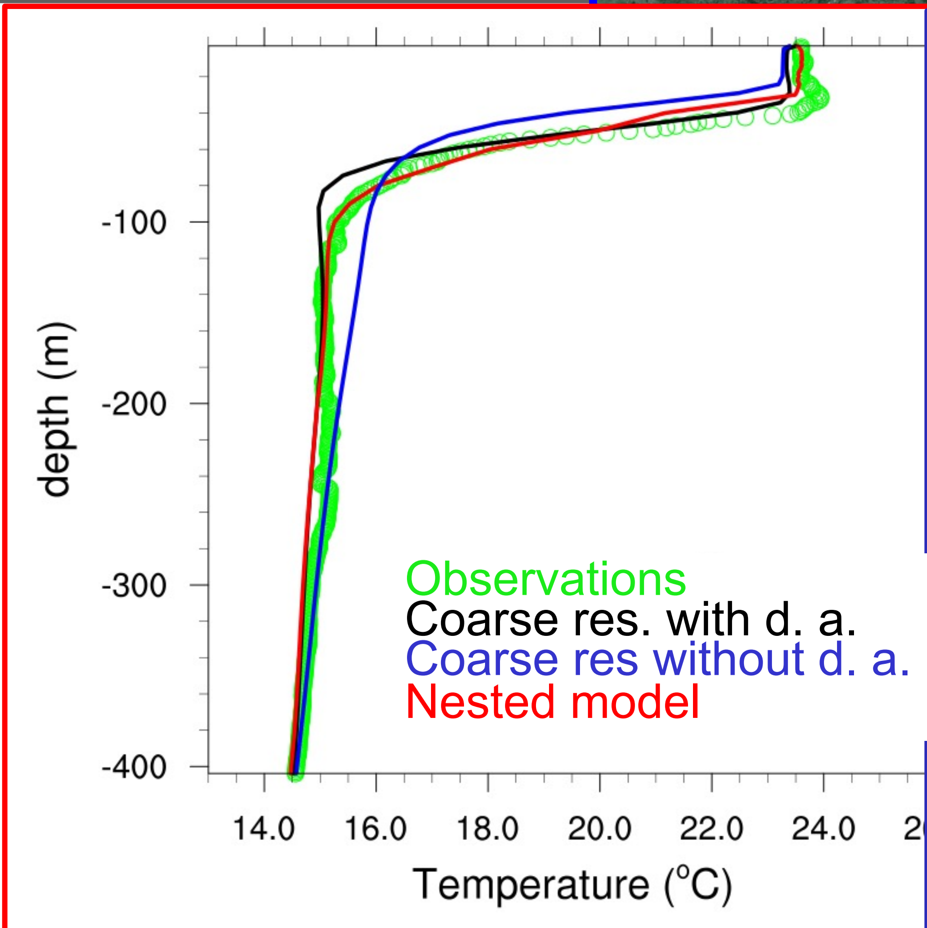


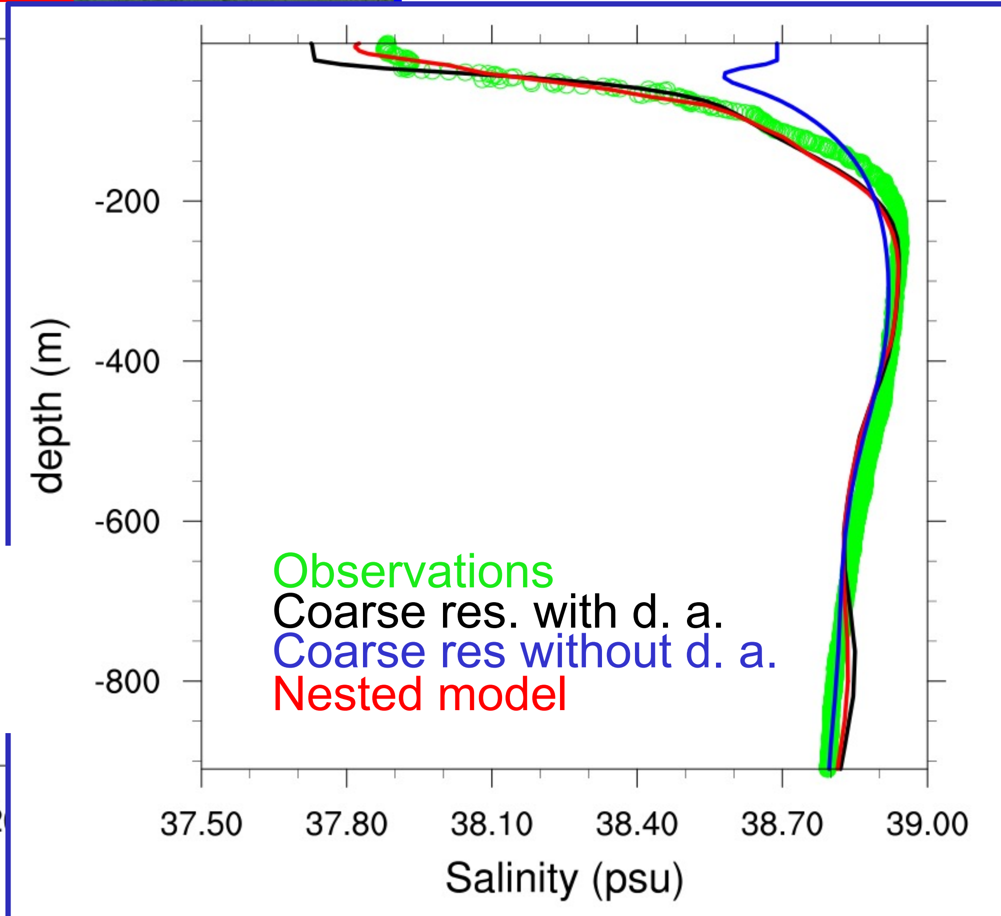
SURF_U

UNSTRUCTURED GRID

FINITE ELEMENTs (SHYFEM)

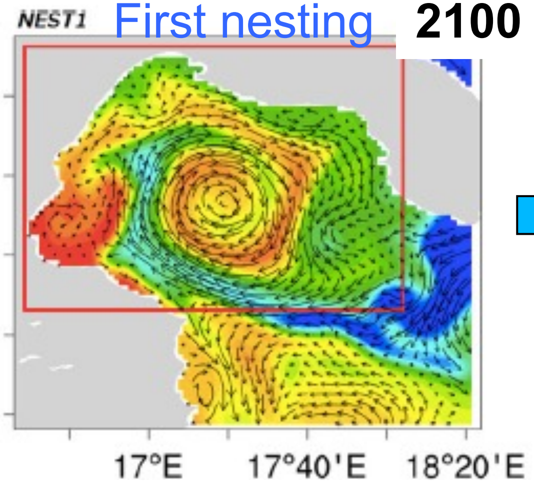
Relocatable modelling with unstructured grid models (Federico et al., 2015)



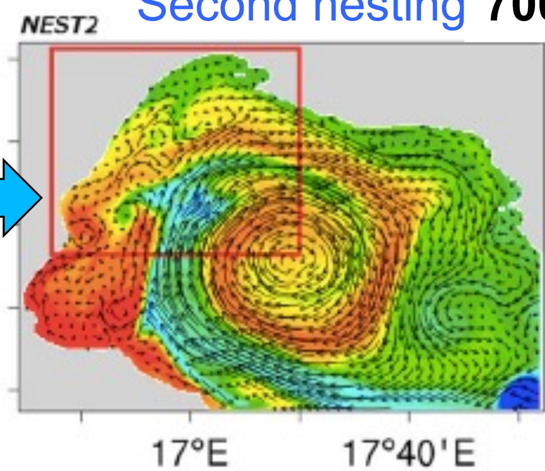


Relocatable modelling: multiple nesting to reach the submesoscales

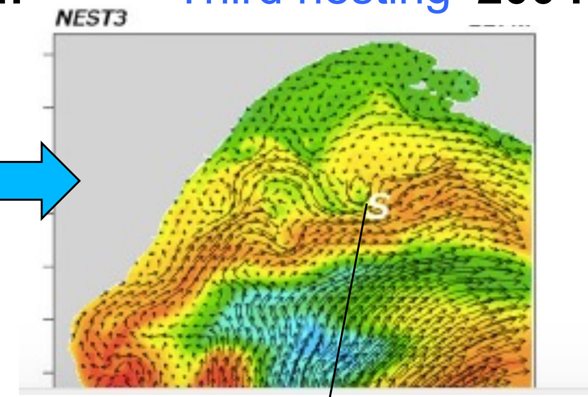
First nesting **2100 m**



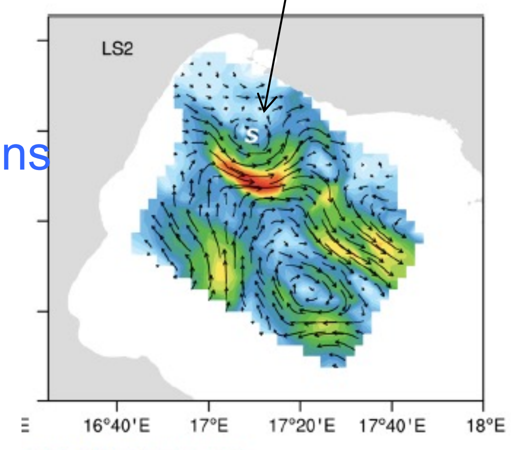
Second nesting **700 m**



Third nesting **200 m**



Observations

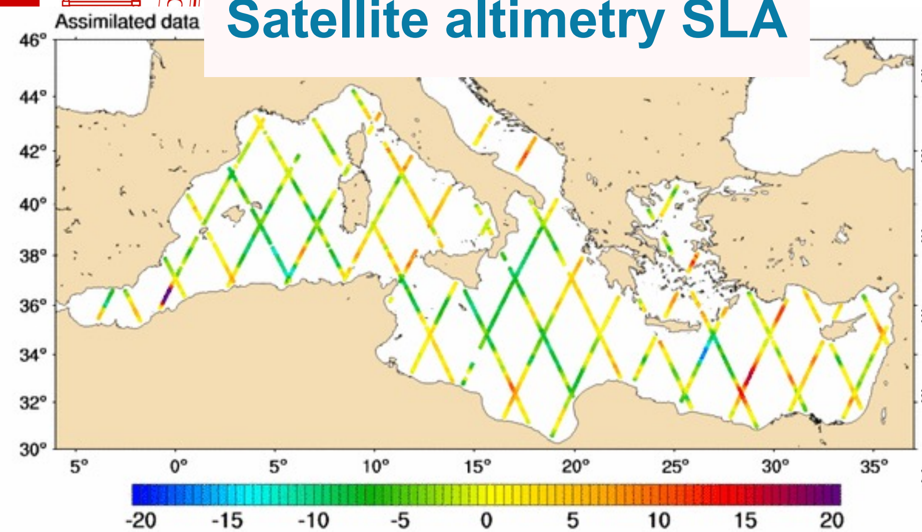


We do three nesting to go from the regional Forecasting model to the resolution which reproduces that data which has a submesoscale feature

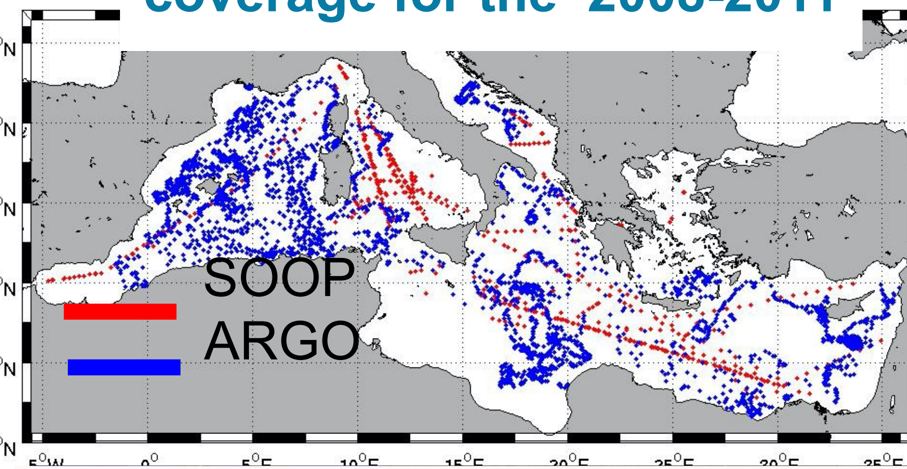
Mediterranean subsystem: the observational component

The European Earth Observation Programme

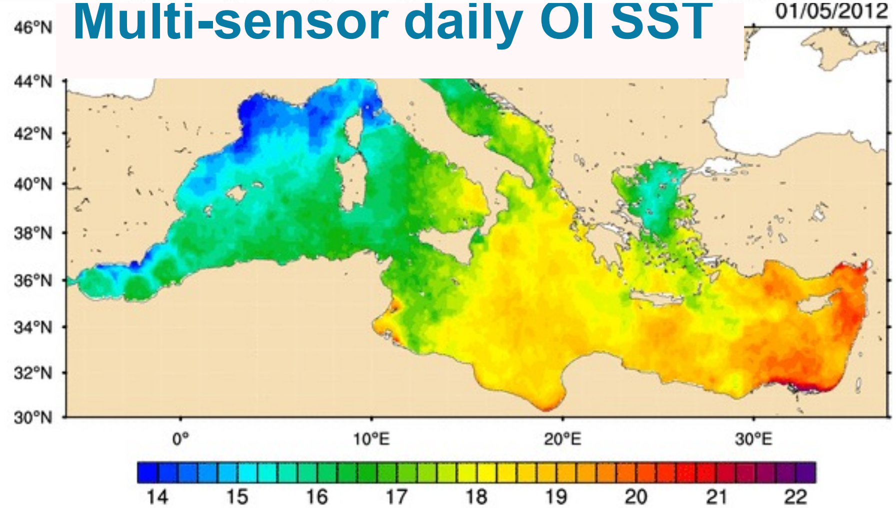
Satellite altimetry SLA



coverage for the 2008-2011



Multi-sensor daily OI SST

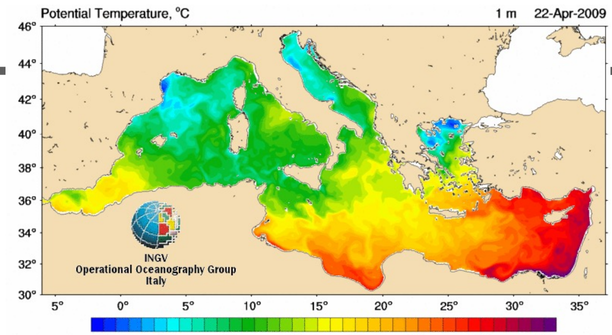


Real Time multidisciplinary coastal Buoys (sea level, T,S V, etc.)

Regional forecasting: the Mediterranean Sea

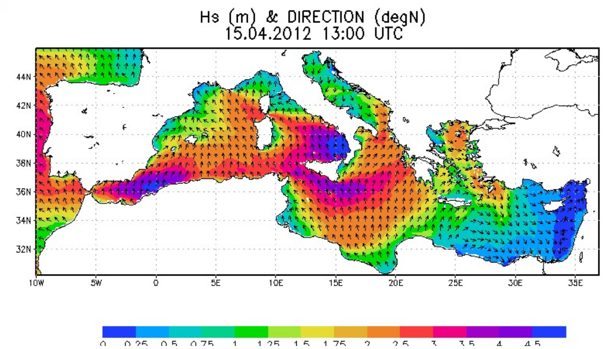
A) hydrodynamics

(1/16 x 1/16 x 72)



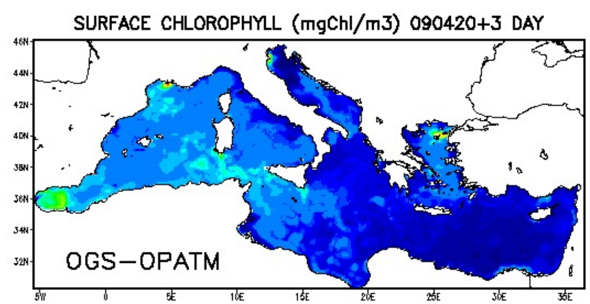
B) Waves

(1/16 x 1/16 x 30)



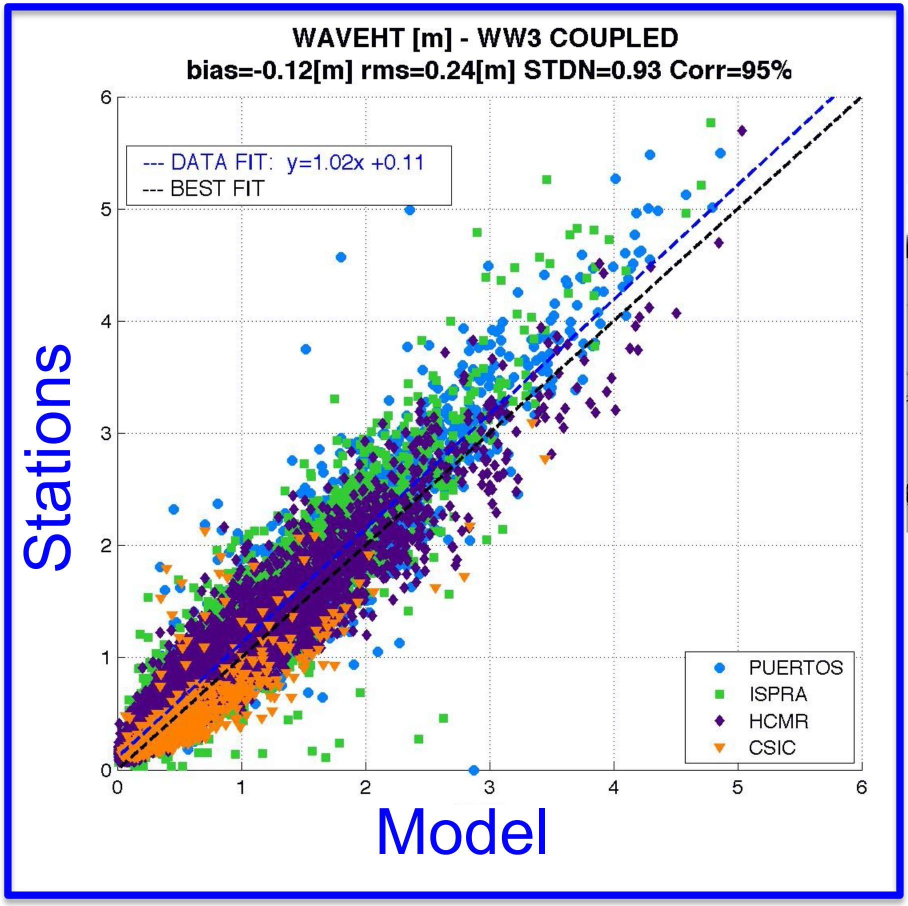
C) Pelagic biochemistry

(1/16 x 1/16 x 72)

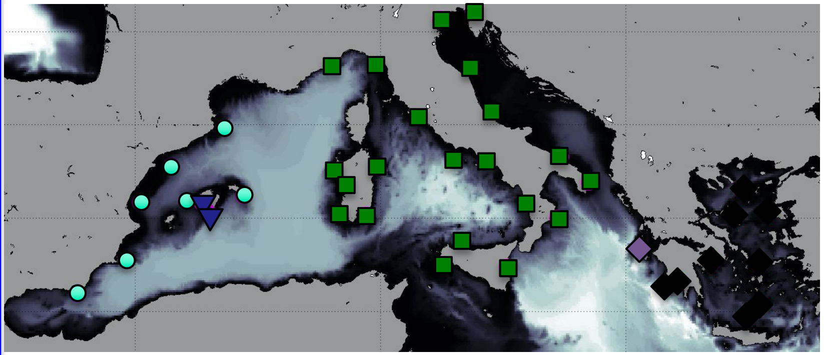


coupled

Regional forecasting: the Mediterranean Sea



Stations for validation

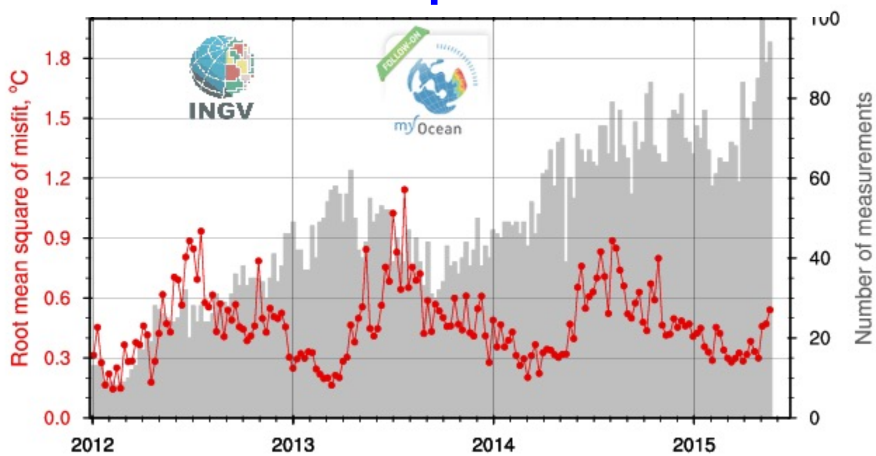


Mediterranean subsystem: the quality component

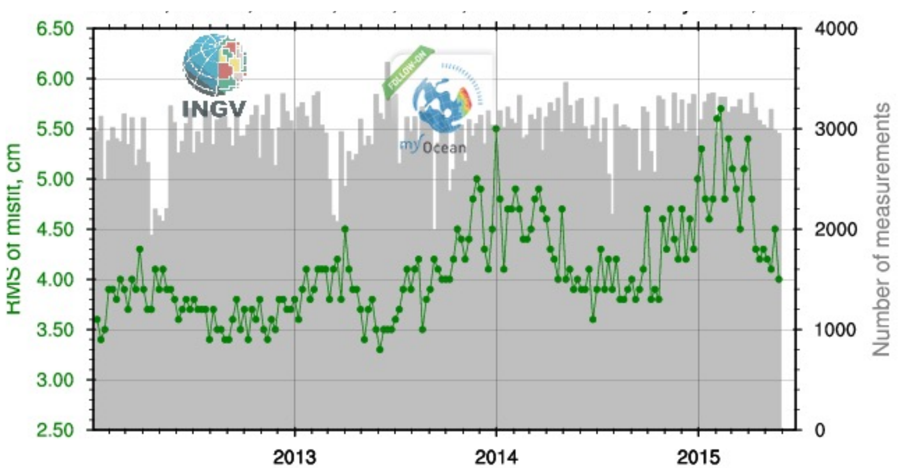
$$m = H(x_M) - y$$

Model - observations

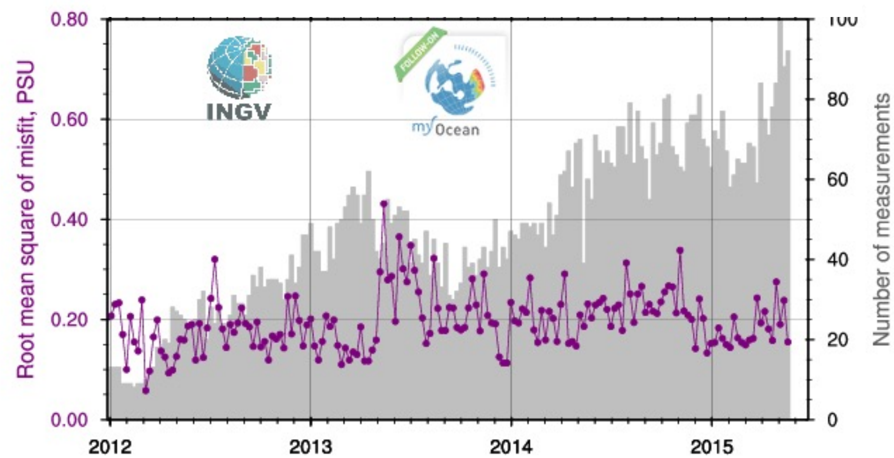
RMS of Temp misfit at 8 m



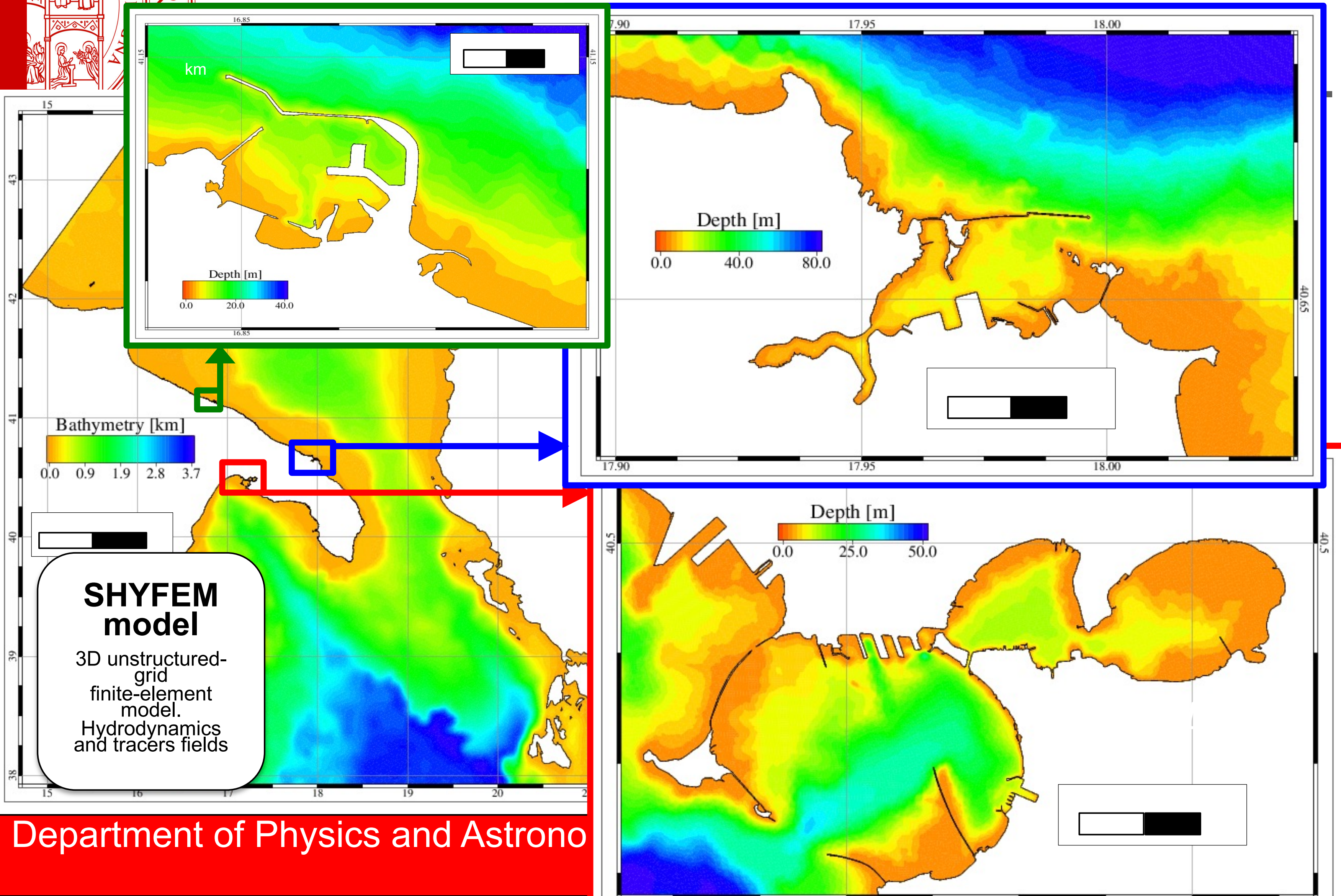
RMS of SLA misfit



RMS of Sal misfit at 8 m

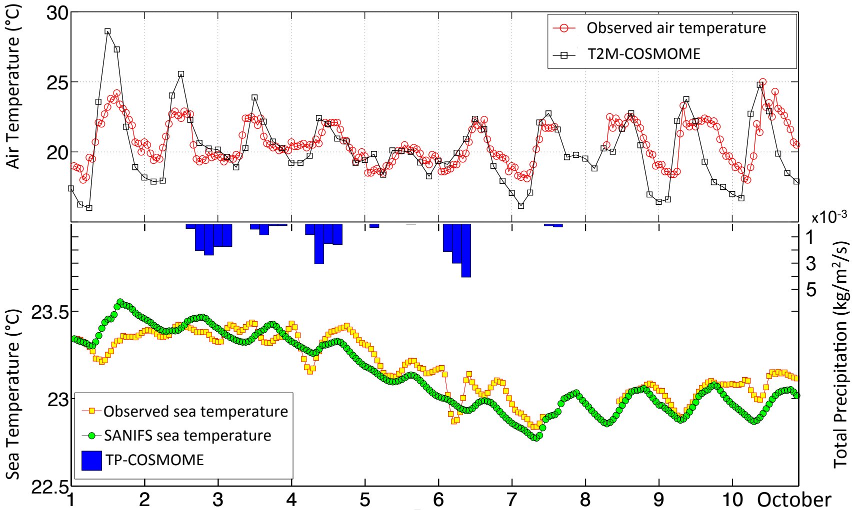


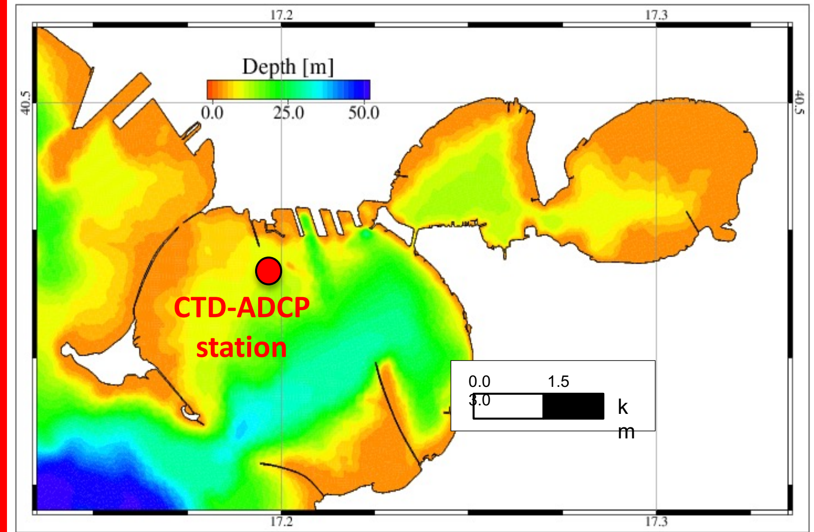
The new coastal and harbor forecasting systems



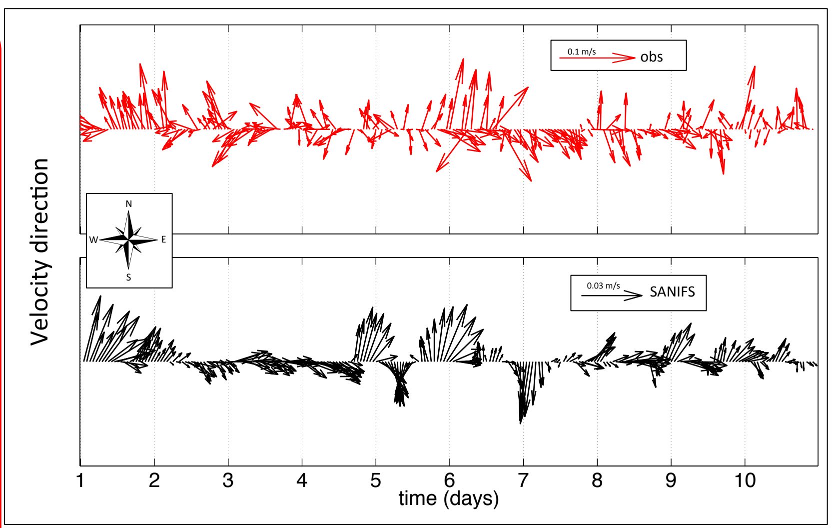
Forecasting at the harbor scale

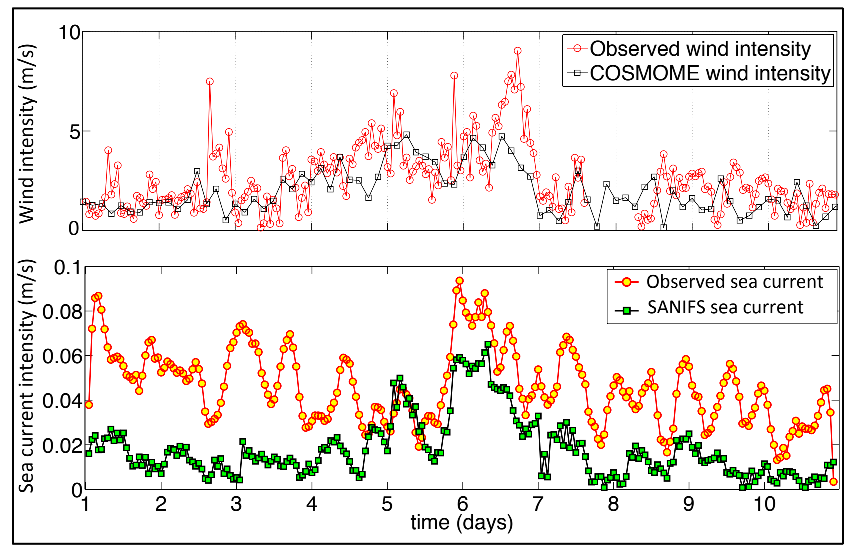
Comparison with **CTD** data





Comparison with **ADCP** data





- Satisfactory model agreement with observations in terms of sea **velocity direction**.
- Underestimation of ocean **velocity intensity**.

- Modelled sea velocity intensity closer to observations in period when the **intensity of wind is higher**.

Conclusions – Part III

- Global ocean forecasting systems are becoming accurate but:
  - bathymetry is not accurate enough
  - River runoff still parametrized (new intermediate estuarine models are coming!)
  - Tides not always included
  - Observations are still in near real time, should improve the timeliness also for satellite data post-processing, river inputs
- Relocatable ocean modelling, starting from the global or regional forecasts, with structured and unstructured grid models, can seamlessly connect the open ocean with the harbor scale