The science of ocean predictions and downscaling to the coastal areas

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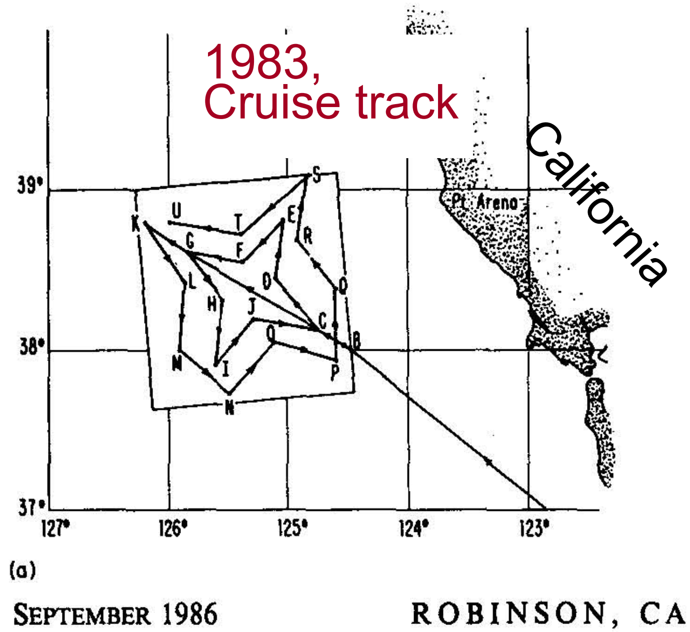
Outline

- The science of ocean predictions: an historical viewpoint
- The Copernicus Marine Environment Service, analysis and forecasts at regional scales and forecast uncertainty estimation
- The downscaling conundrum: can we forecast better with limited area, nested models?
- Conclusions and Outlook

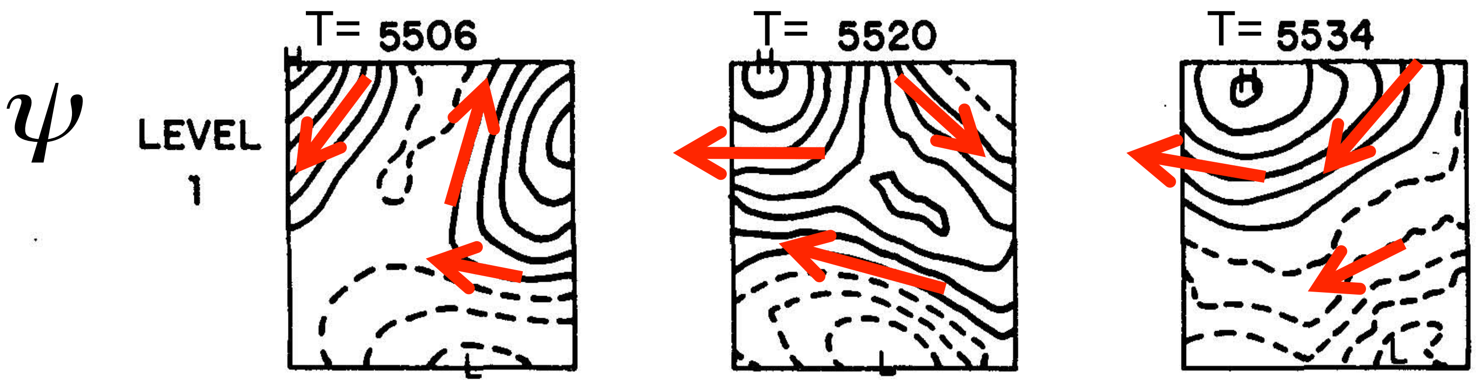
The science of ocean predictions: historical viewpoint

- Bjerknes (1904, 1914) defined for the first time the 'rational method for weather predictions'
- Two conditions should be fulfilled in order to solve the prediction problem in atmosphere and oceans
  - I- Know the present state of the system as accurately as possible
  - II- Know the laws of physics that regulate the time evolution of the basic field state variables, i.e. have predictive models for atmosphere and oceans
- These concepts are at the basis of ocean prediction science also today

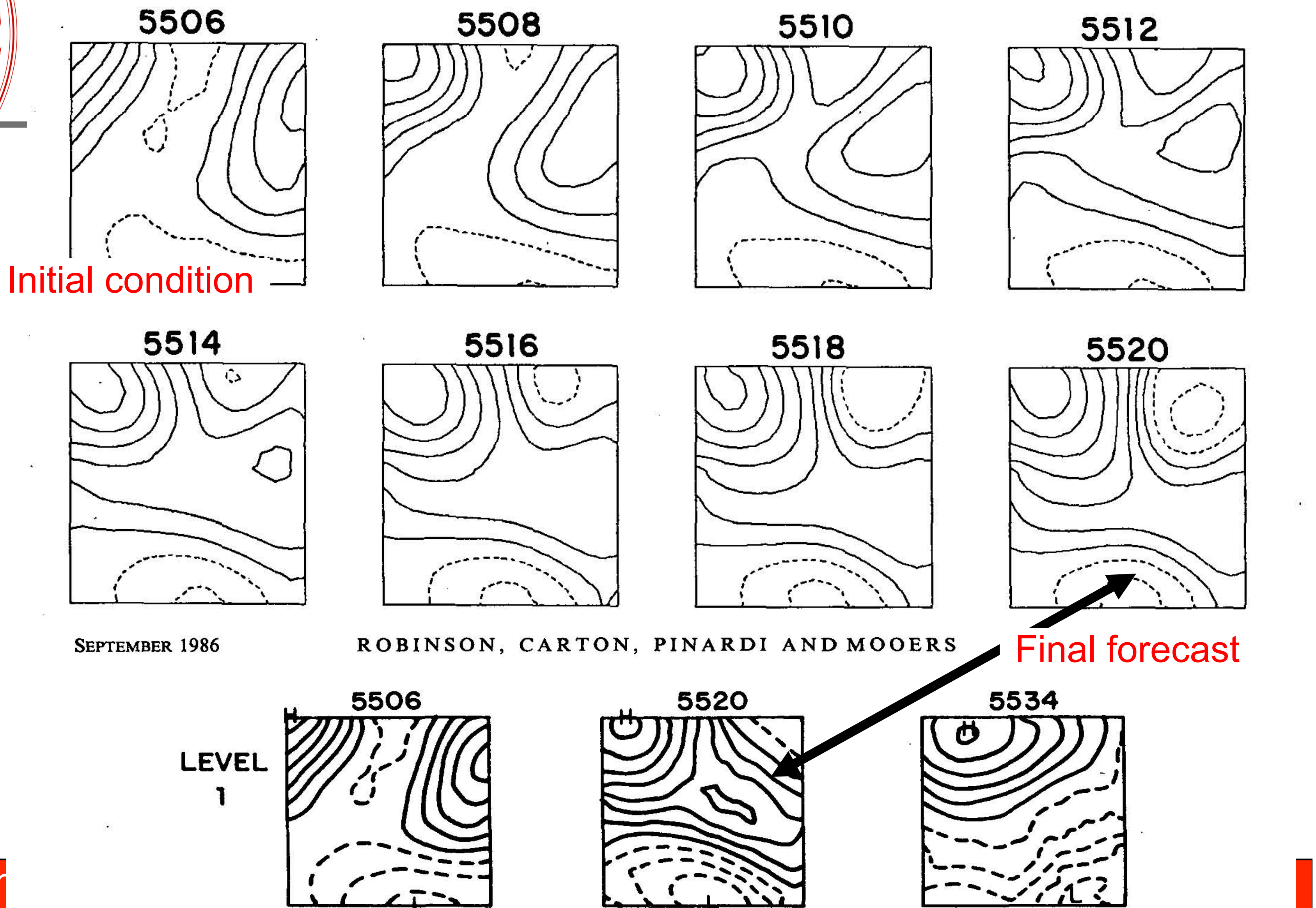
The first ocean prediction: Harvard and Monterey 1983



Robinson (1983) defined the correct sampling scheme for Initialization (condition I) and selected the correct mesoscale model (condition II)



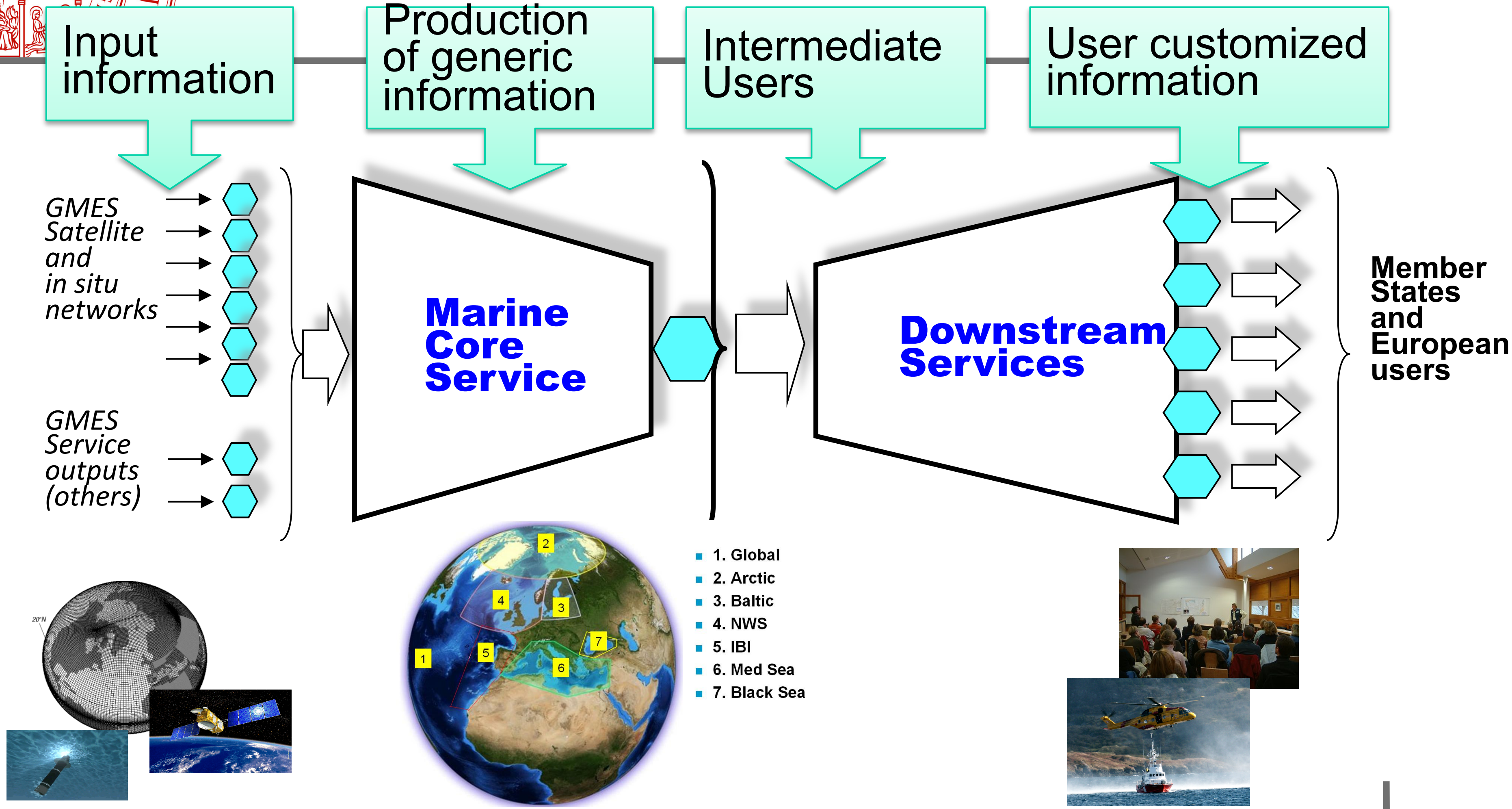
The first ocean prediction: Harvard and Monterey 1983



GOOS:operational oceanography starts in the 90s

Old, historical Web site

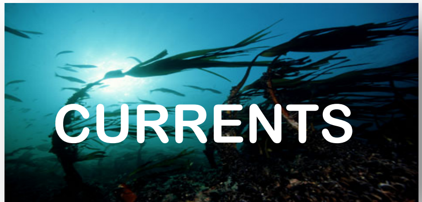
Operational oceanography and ocean prediction science today

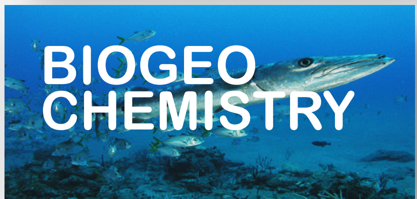


The European Marine Environment service: Copernicus

The European Earth Observation Programme

QC OBSERVATIONS in real time and 10-20 years t.s. → **ANALYSES** Daily/weekly → **FORECASTS** 2 to 10 days → **REANALYSES** 10 to 45 years





http://marine.copernicus.eu/

DISCOVER

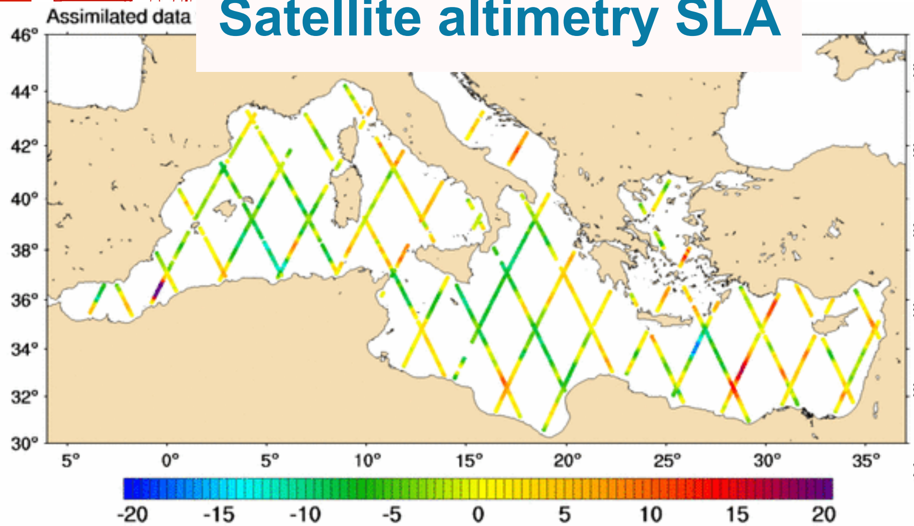
VIEW

DOWNLOAD

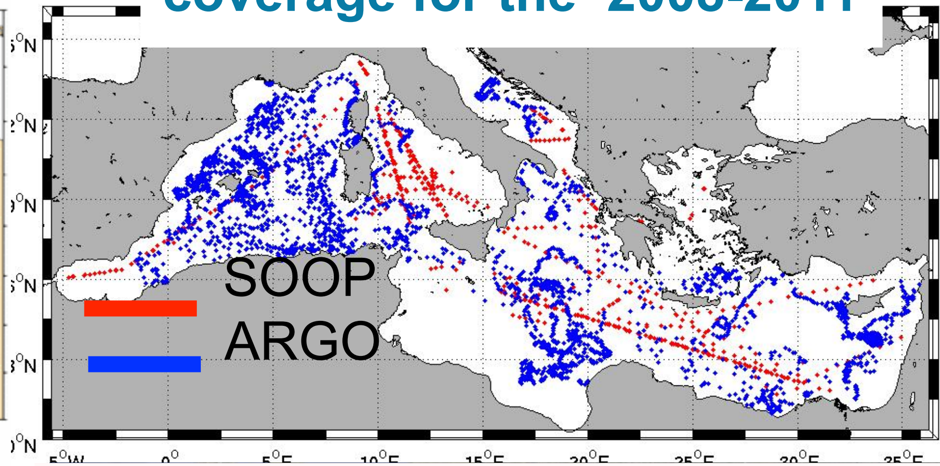
Open & Free

Mediterranean subsystem: the observational component

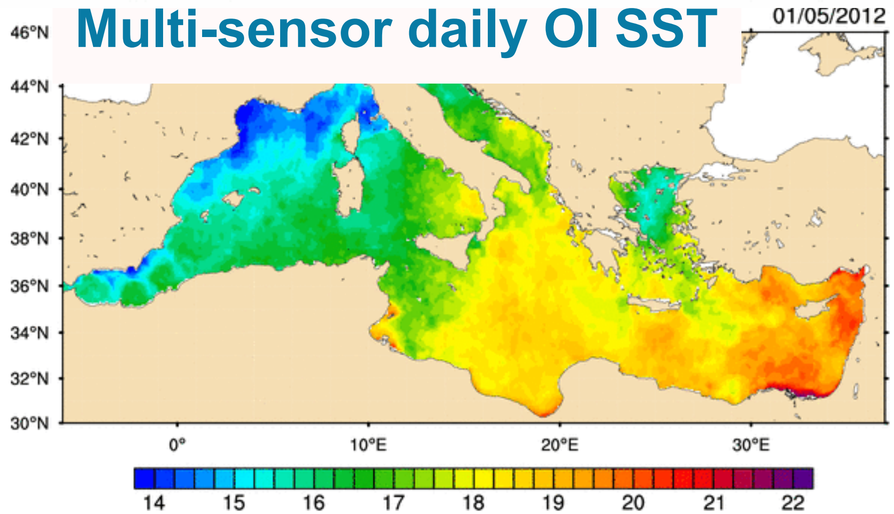
Satellite altimetry SLA



coverage for the 2008-2011



Multi-sensor daily OI SST

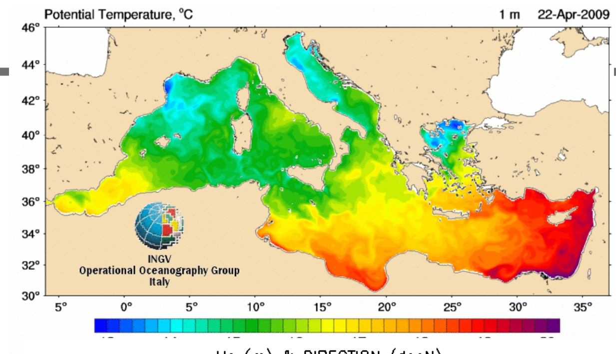


Real Time multidisciplinary coastal Buoys (sea level, T,S V, etc.)

Mediterranean subsystem: the modelling component

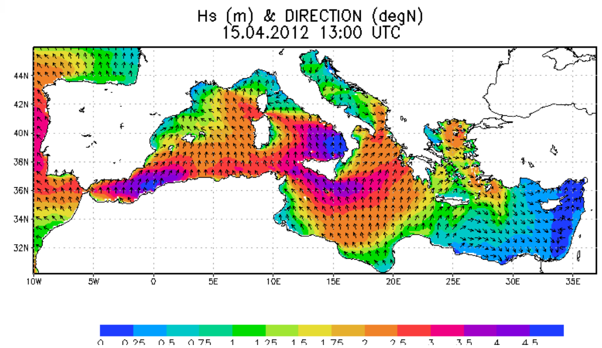
A) hydrodynamics

(1/16 x 1/16 x 72)



B) Waves

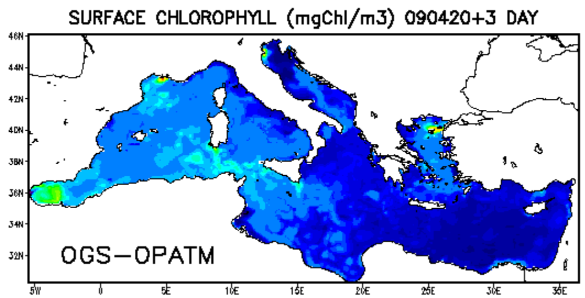
(1/16 x 1/16 x 30)



coupled

C) Pelagic biochemistry

(1/16 x 1/16 x 72)

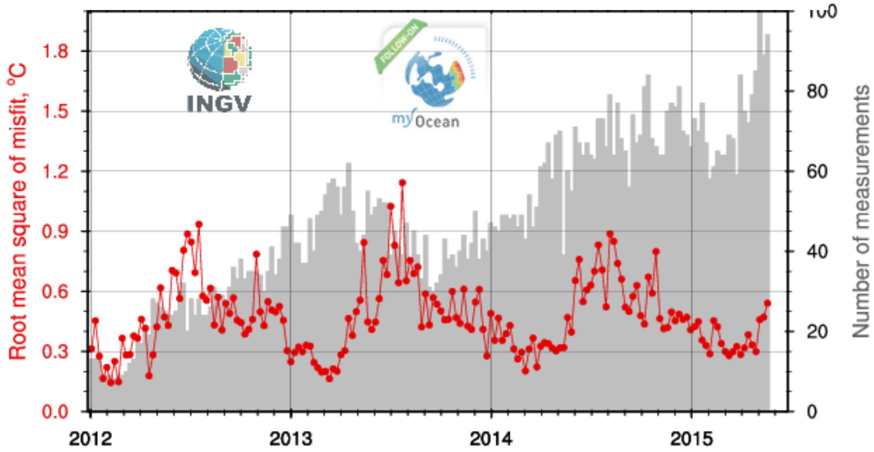


Mediterranean subsystem: the quality component

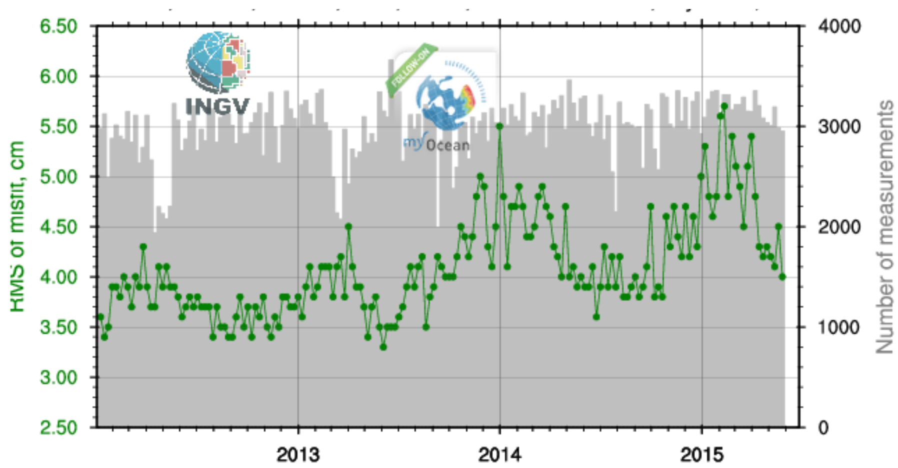
$$m = H(x_M) - y$$

Model - observations

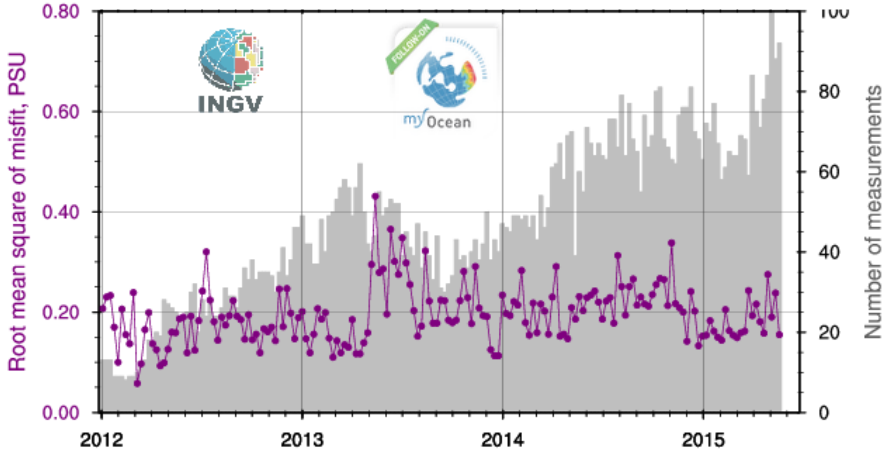
RMS of Temp misfit at 8 m



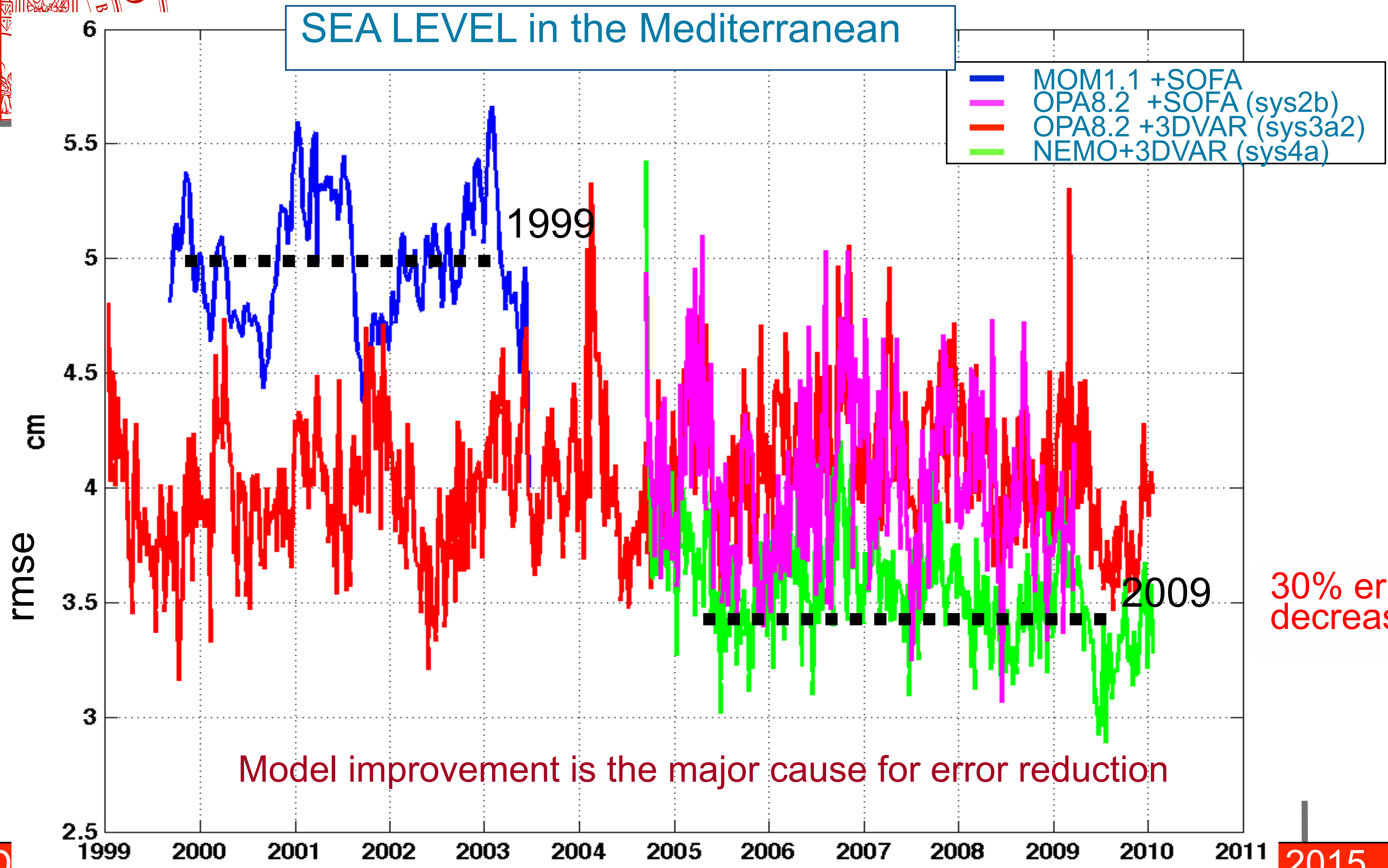
RMS of SLA misfit



RMS of Sal misfit at 8 m

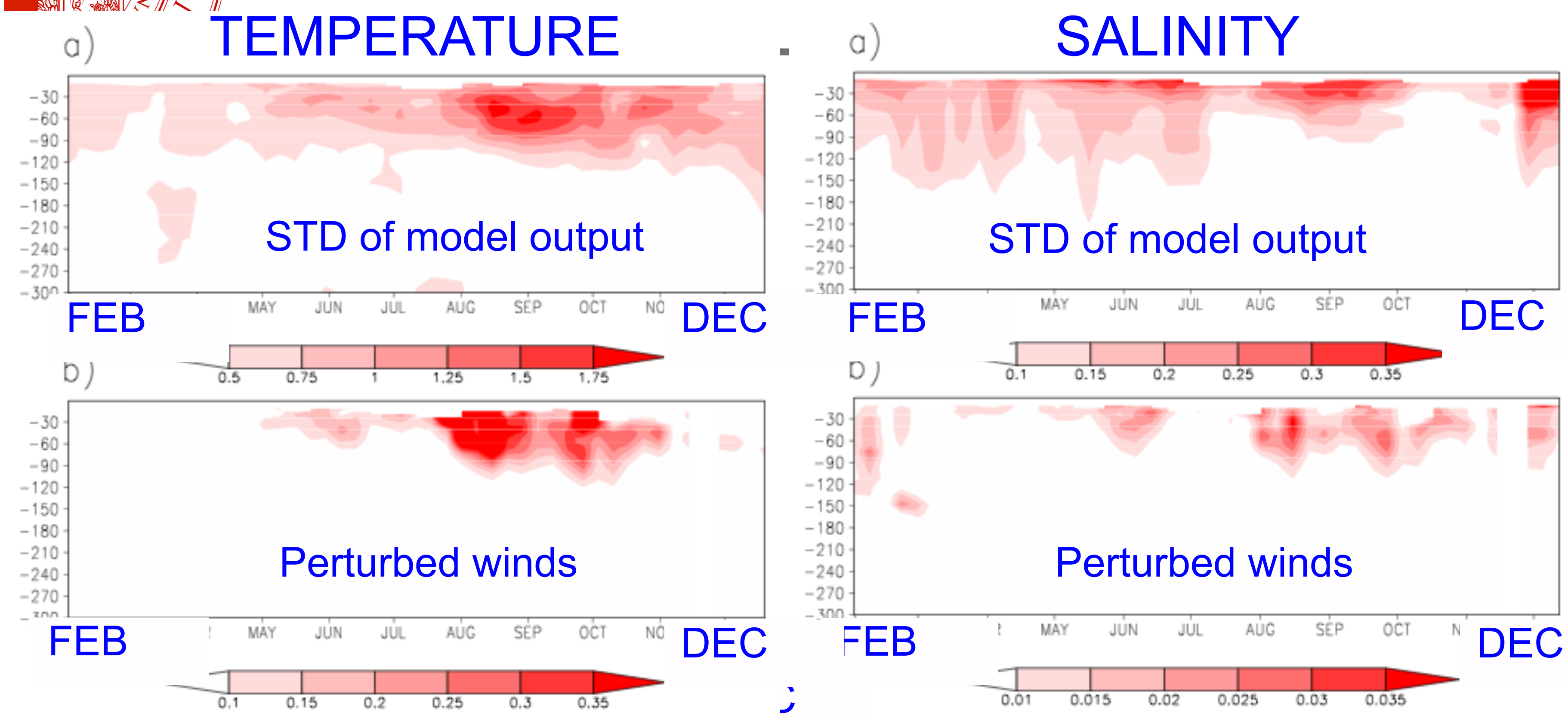


How did the error decrease in the first 10 years of operations?



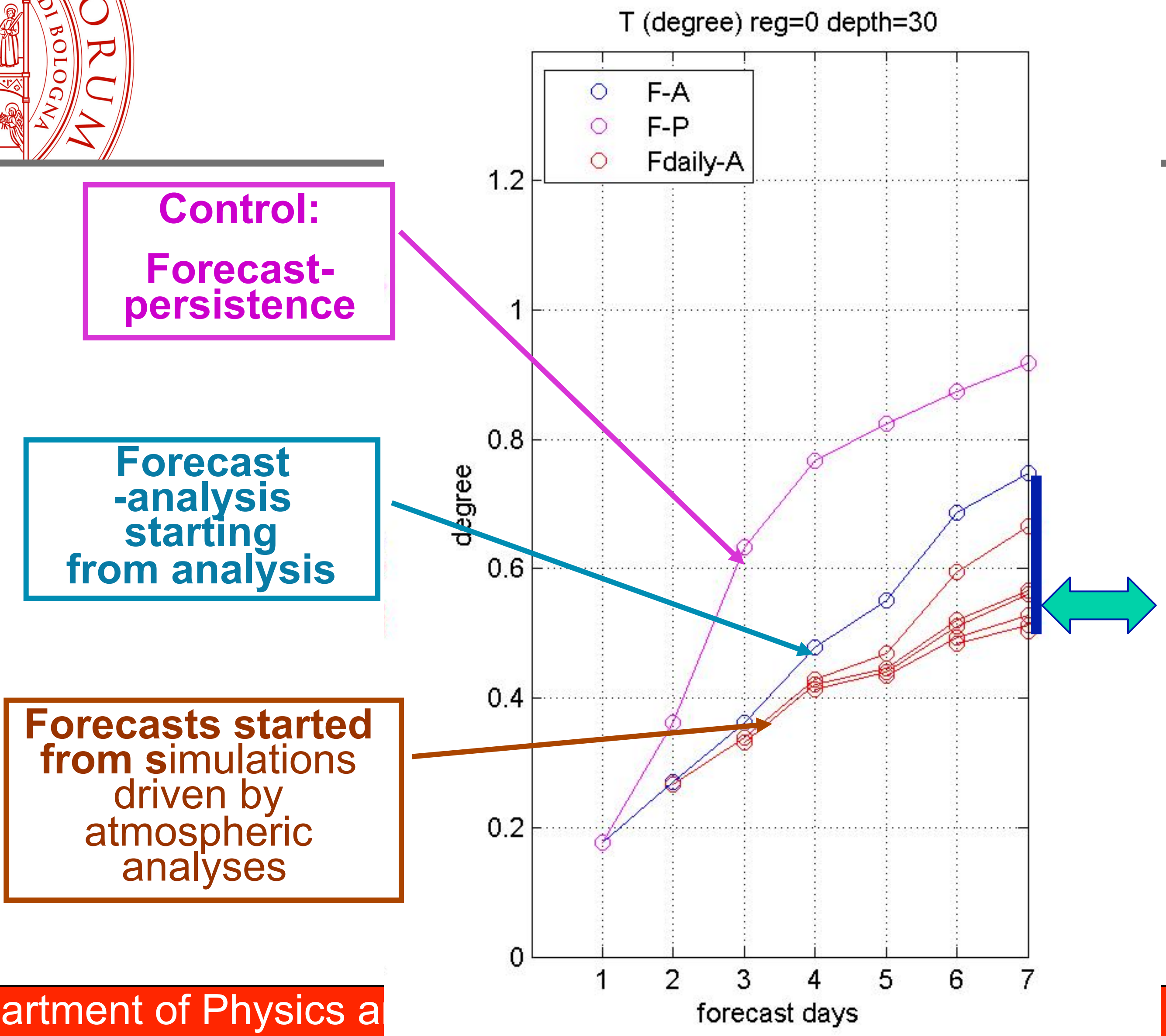
30% error decrease

Vertical analysis error standard deviation for temperature and salinity



Errors in atmospheric forcing are projecting on the vertical structure of the temperature & salinity errors

Forecast skill: the effect of atmospheric forcing errors



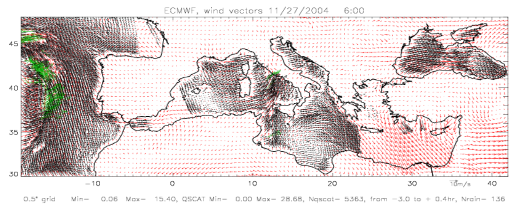
Forecast error at day 7 decreased by 30% due to use of higher accuracy atmospheric Forcings

Forecast Uncertainty estimation

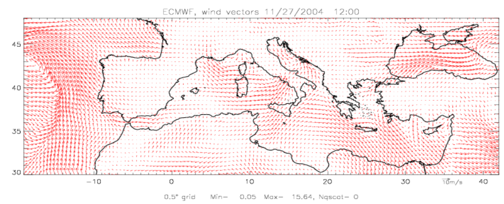
- Shukla (2005): ‘The largest obstacles in realizing the potential predictability of weather and climate are inaccurate models and insufficient observations, rather than an intrinsic limit of predictability’
- Uncertainty of ocean forecasts depends on:
  - Ocean Initial condition errors
  - Atmospheric forcing errors
  - Model errors (Physics, numerics)
- Hypothesis:
  - We use ensemble forecasting as a means to test ocean predictability issues
  - We concentrate on atmospheric wind forcing errors and how they affect the initial condition and forecast errors
  - We estimate realistic distribution of wind perturbations

Building the wind distributions using Bayesian Hierarchical Modelling (BHM-SVW)

Conceptual and implementation blocks:



QSCAT



ECMWF

Data Stage:
2 types of data, scatterometer winds and ECMWF analyses/forecasts

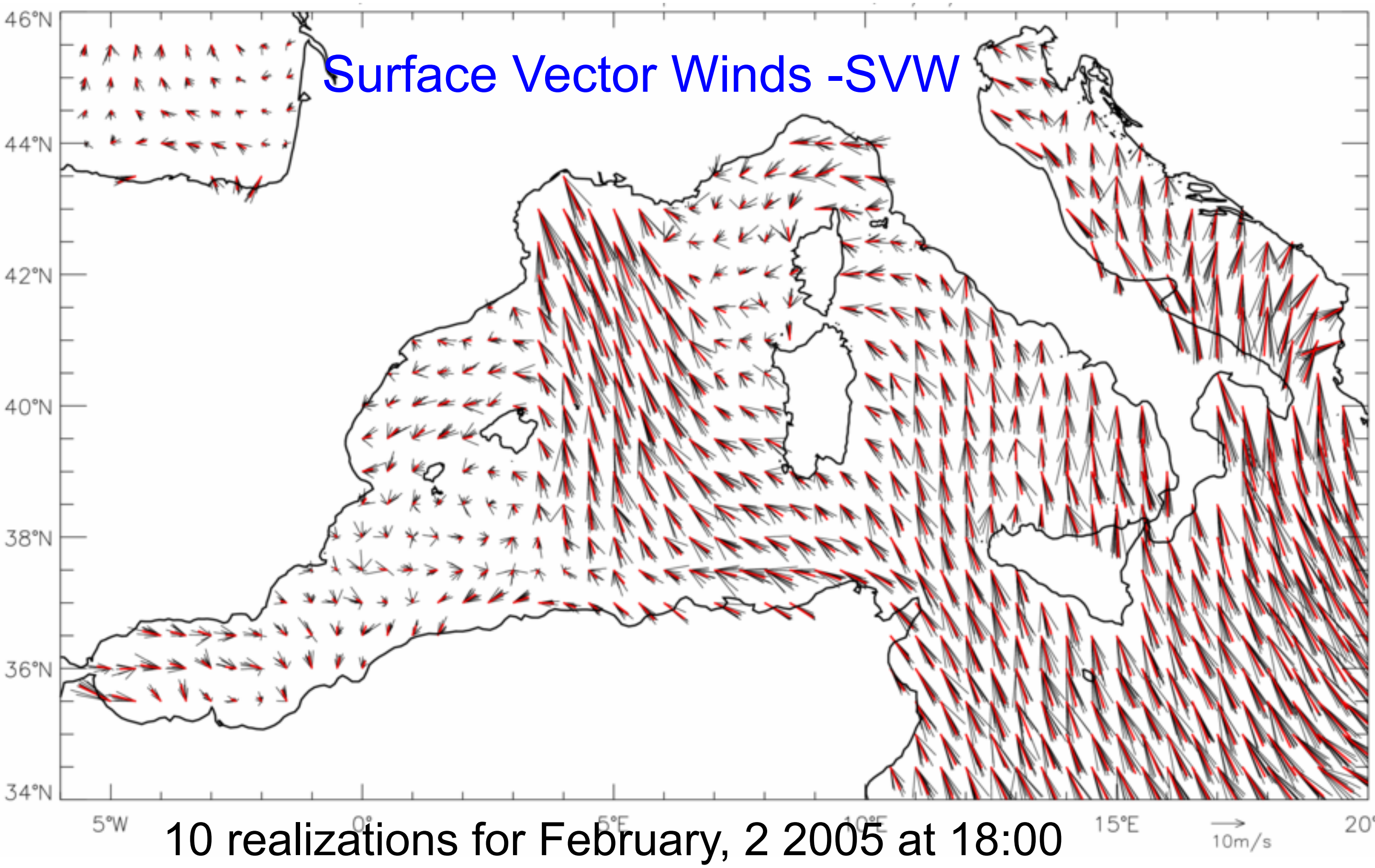
Process model stage:
Raylegh friction surface model translated into a stochastic finite difference equation

$$u = -\frac{f}{\rho_0\left(f^2+\gamma^2\right)}\frac{\partial p}{\partial y} - \frac{\gamma}{\rho_0\left(f^2+\gamma^2\right)}\frac{\partial p}{\partial x}$$

$$v = \frac{f}{\rho_0\left(f^2+\gamma^2\right)}\frac{\partial p}{\partial x} - \frac{\gamma}{\rho_0\left(f^2+\gamma^2\right)}\frac{\partial p}{\partial y}$$

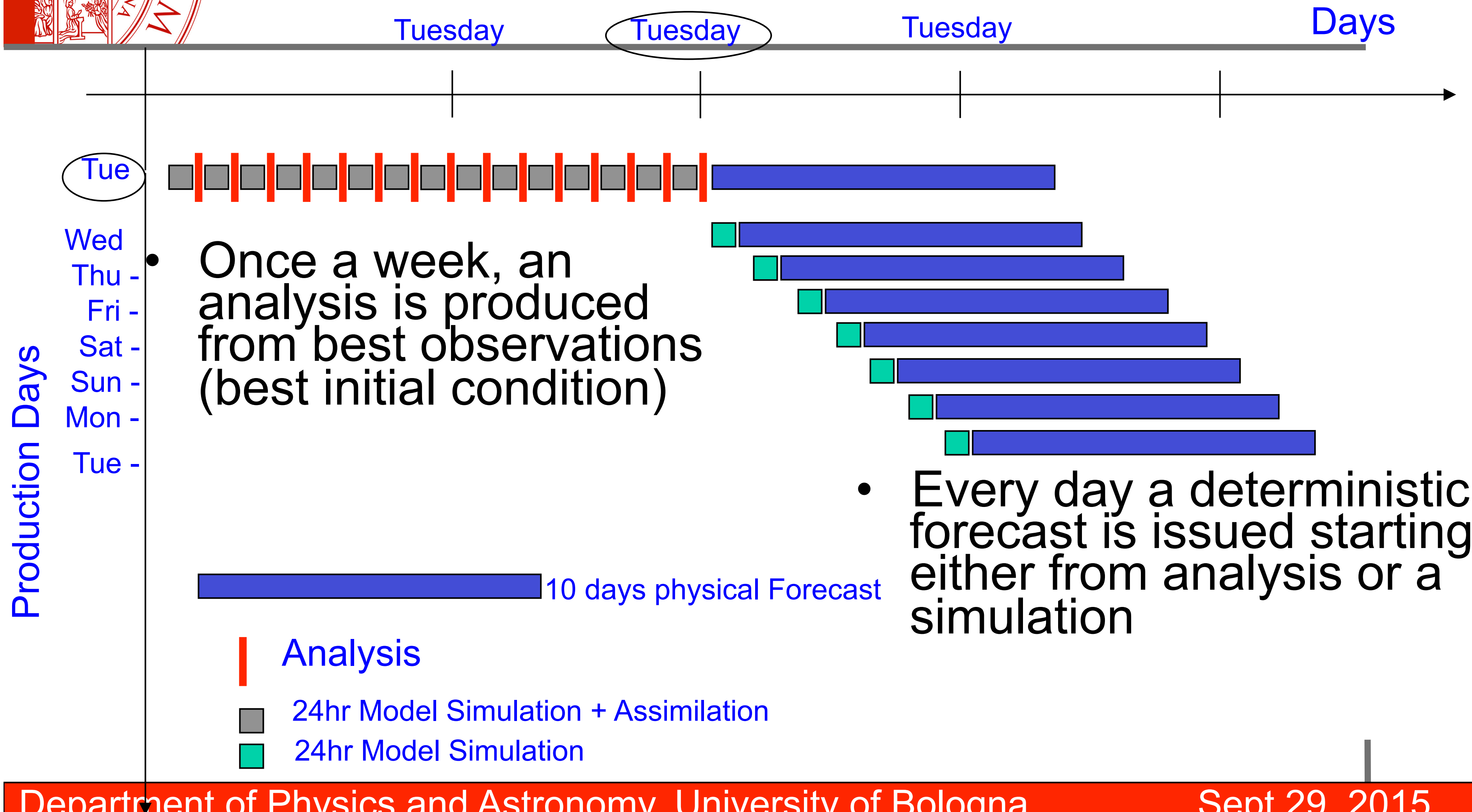
$$\begin{aligned} U_t &= \theta_{uy} D_y P_t + \theta_{ux} D_x P_t + \epsilon_u \\ V_t &= \theta_{vx} D_x P_t + \theta_{vy} D_y P_t + \epsilon_v \end{aligned}$$

Posterior distributions of BHM-SVW (Milliff et al., 2011)



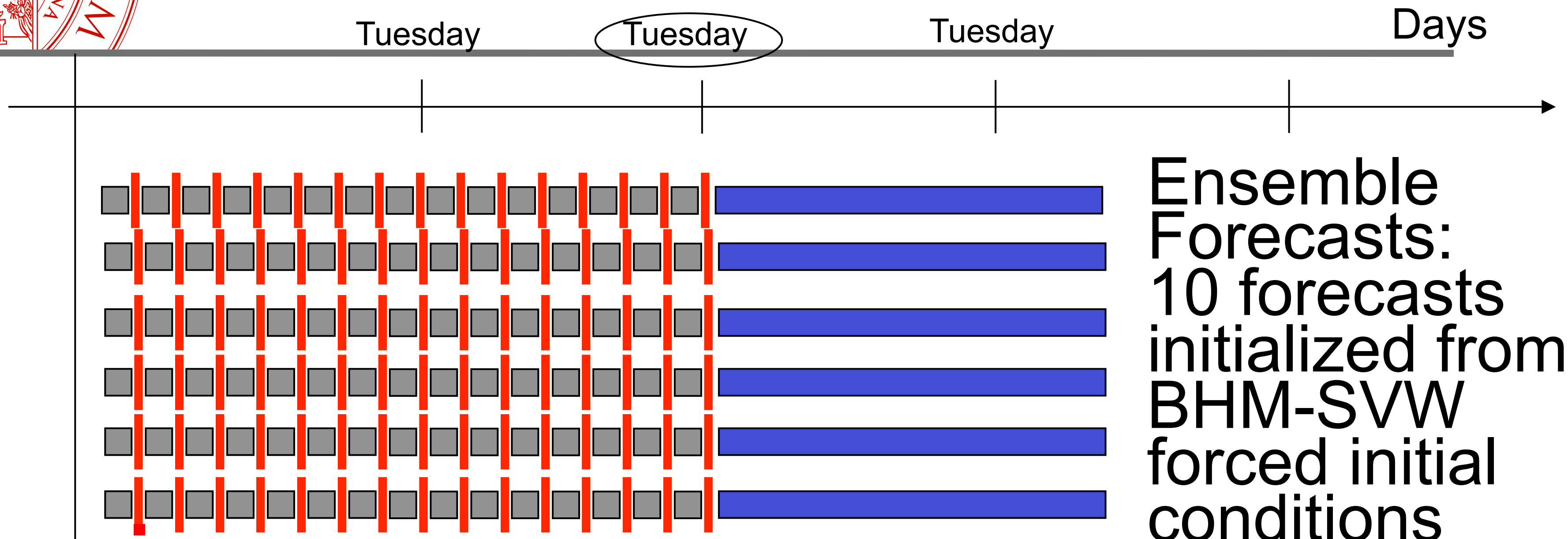
10 realizations for February, 2 2005 at 18:00

The MFS deterministic forecast and analysis system



- Once a week, an analysis is produced from best observations (best initial condition)
- Every day a deterministic forecast is issued starting either from analysis or a simulation

The BHM-SVW Ocean Ensemble Forecast method (Pinardi et al., 2011)



Ensemble Forecasts: 10 forecasts initialized from BHM-SVW forced initial conditions

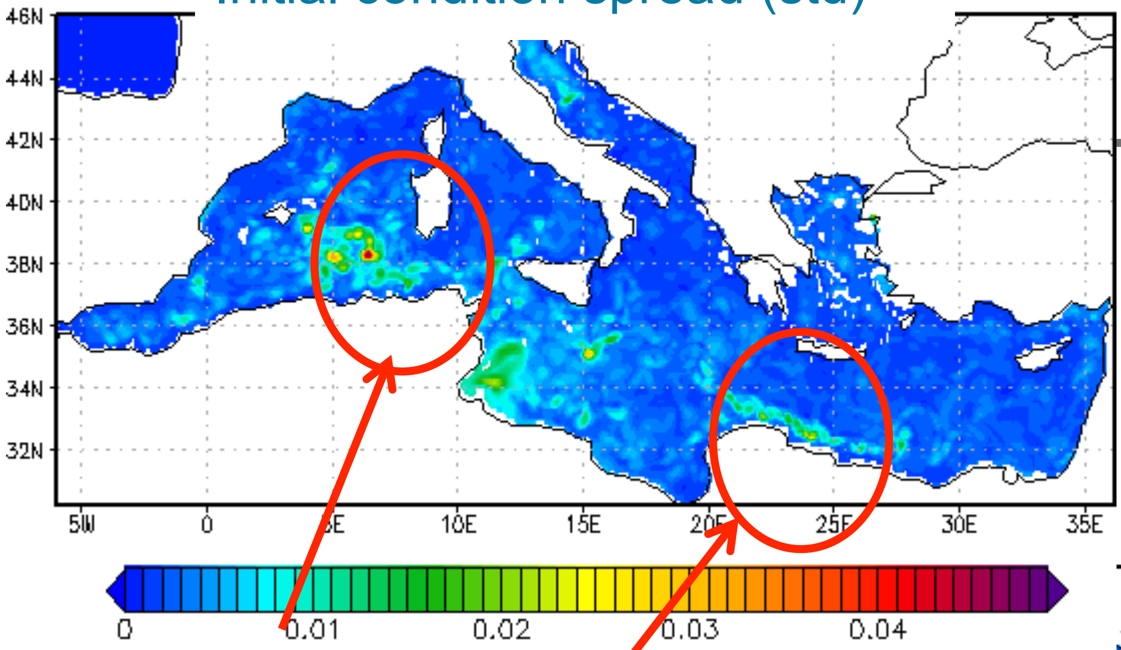
- Each ensemble member initial
- condition is produced by
- assimilating data and forcing with
- BHM-SVW realizations

10 days Forecast

Analysis

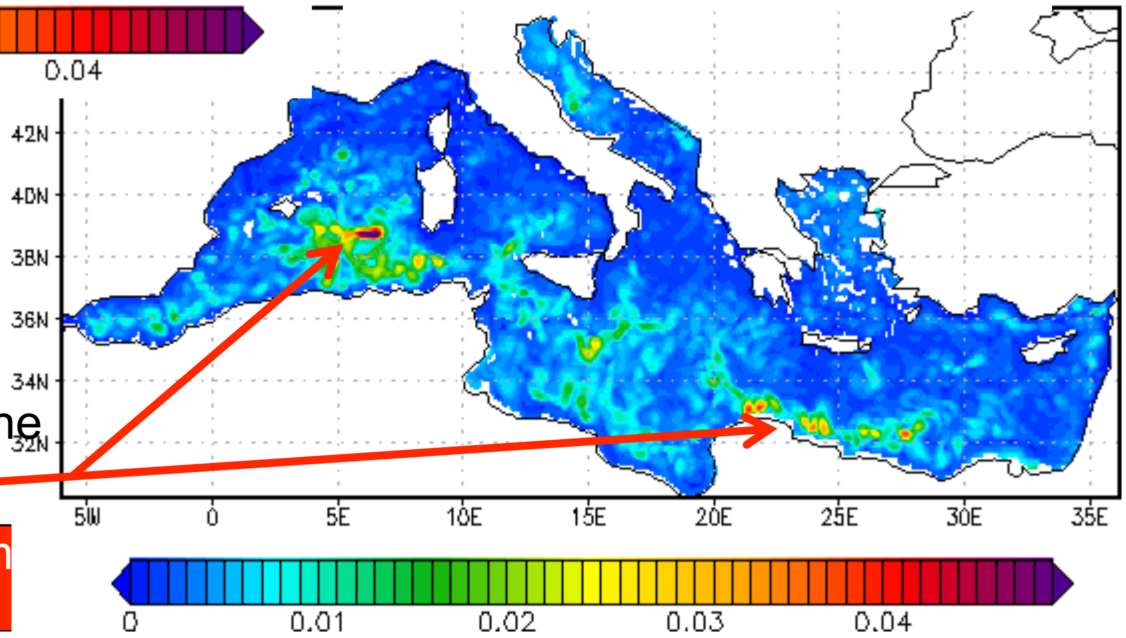
BHM-SVW-OEF initial condition and last forecast day spread

Initial condition spread (std)



Sea Surface Height

10-th fcst day spread (std)

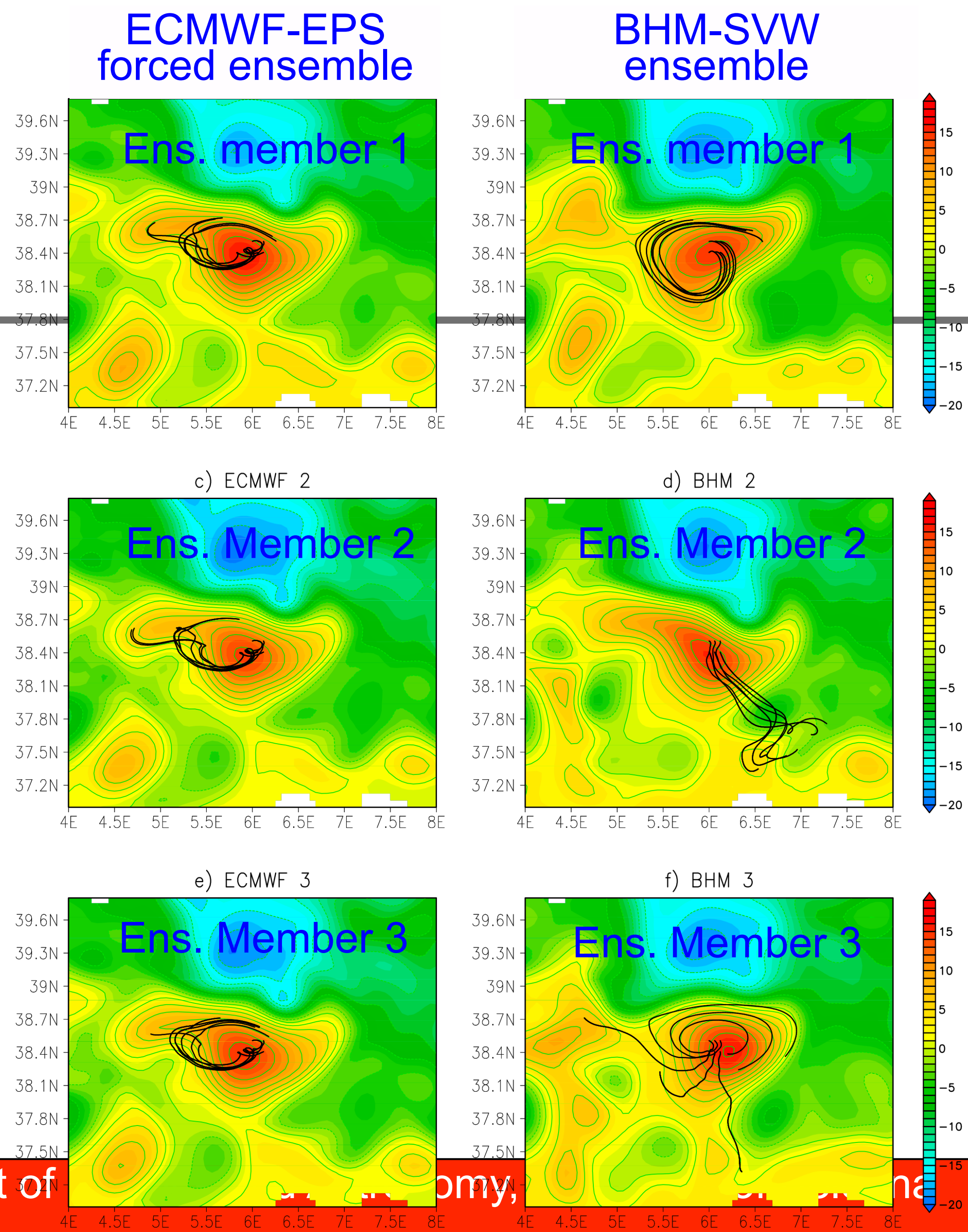


Uncertainty is concentrated at the mesoscales. Sea level spread is comparable to observed sea level error

Uncertainty is amplified during the 10 days of forecast

Department of Physics and Astronom

The forecast spread at 10F

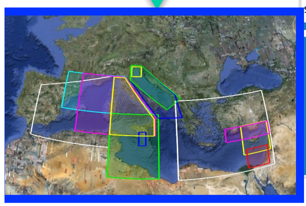


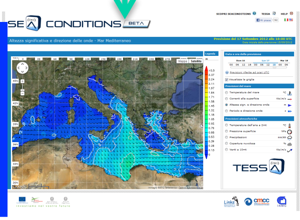
ECMWF Ensemble Prediction System forcing is not effective to produce flow field changes at the mesoscales while BHM-SVW is

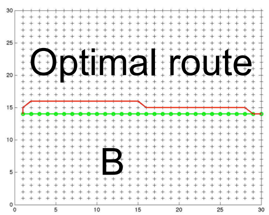
The Copernicus service: coastal forecasting and new applications

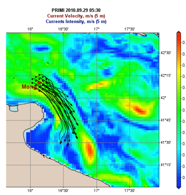
OPEN AND FREE DATA WAREHOUSE

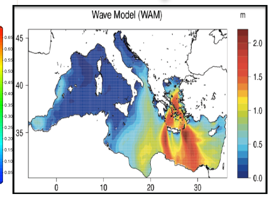
- Nested FCST models
- Sea-Conditions
- DSS Oil spill
- DSS Ship routing
- DSS search and rescue
- DSS early warning
- DSS env. quality

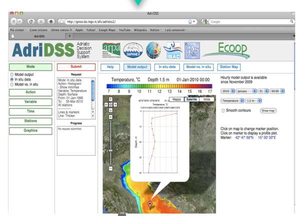












The limited area forecasting conundrum

- The question is: can limited area ocean models increase coarse resolution forecast accuracy?
- Limited area forecasting requires to consider:
  - Coastlines at high resolution
  - High resolution bathymetry
  - Estuary forcings
  - Shelf break dynamics
  - **The initialization problem**
  - **The lateral boundary condition problem**
  - Surface atmospheric forcing of adequate resolution and extrapolated to minimize land contamination

Need to focus on that, very special problem

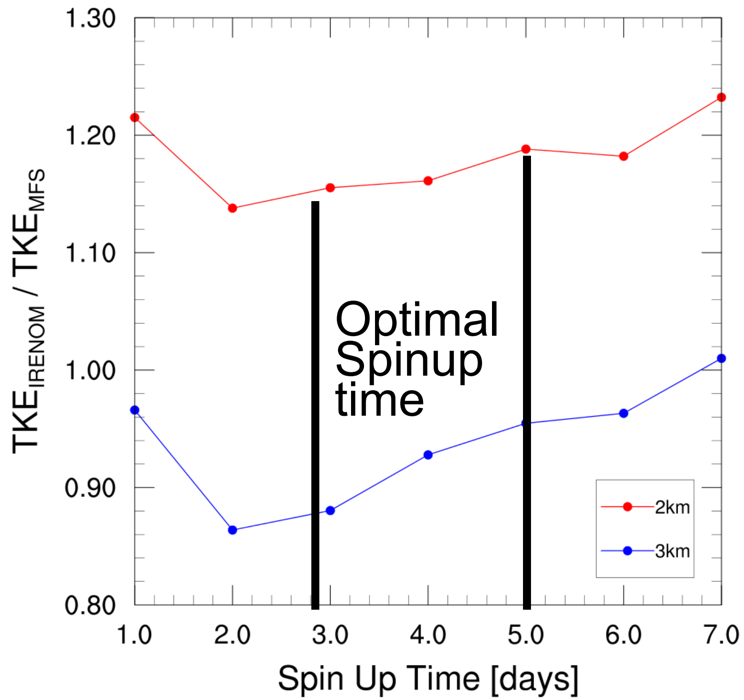
Initialization problem: the spin up time

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

From a 6 km model

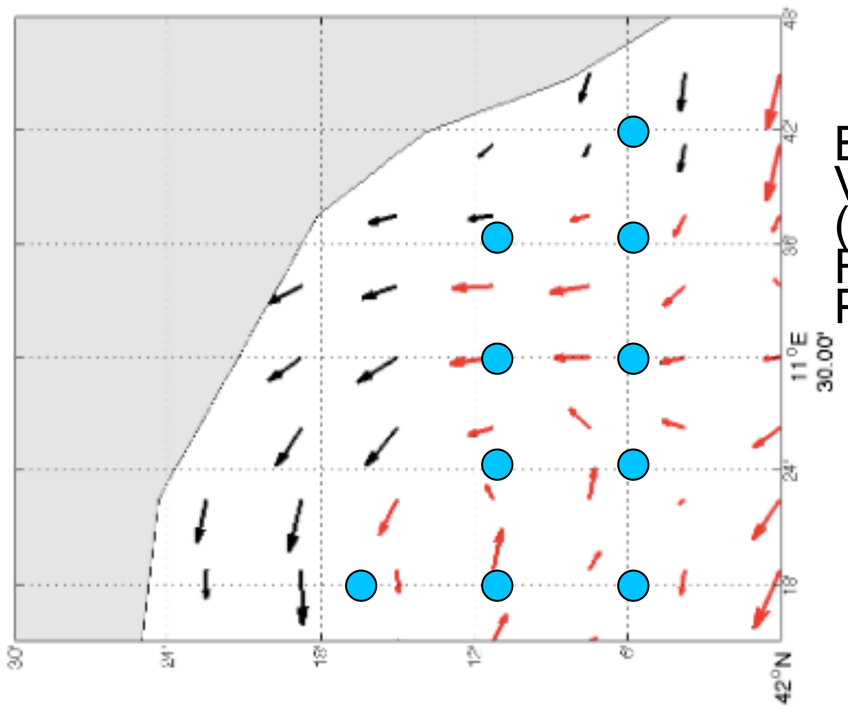
Red-> nested 2 km model
Blue-> nested 3 km model

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 and velocity interpolated from coarse grid

Black: extrapolated from coarse grid with Viscous boundary layer assumption (AVERAGE OF NINE COARSE RESOLUTION GRID POINTS)

Variational methods can also be used to enforce no-slip boundary conditions at the wall after extrapolation

Lateral boundary condition problem

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

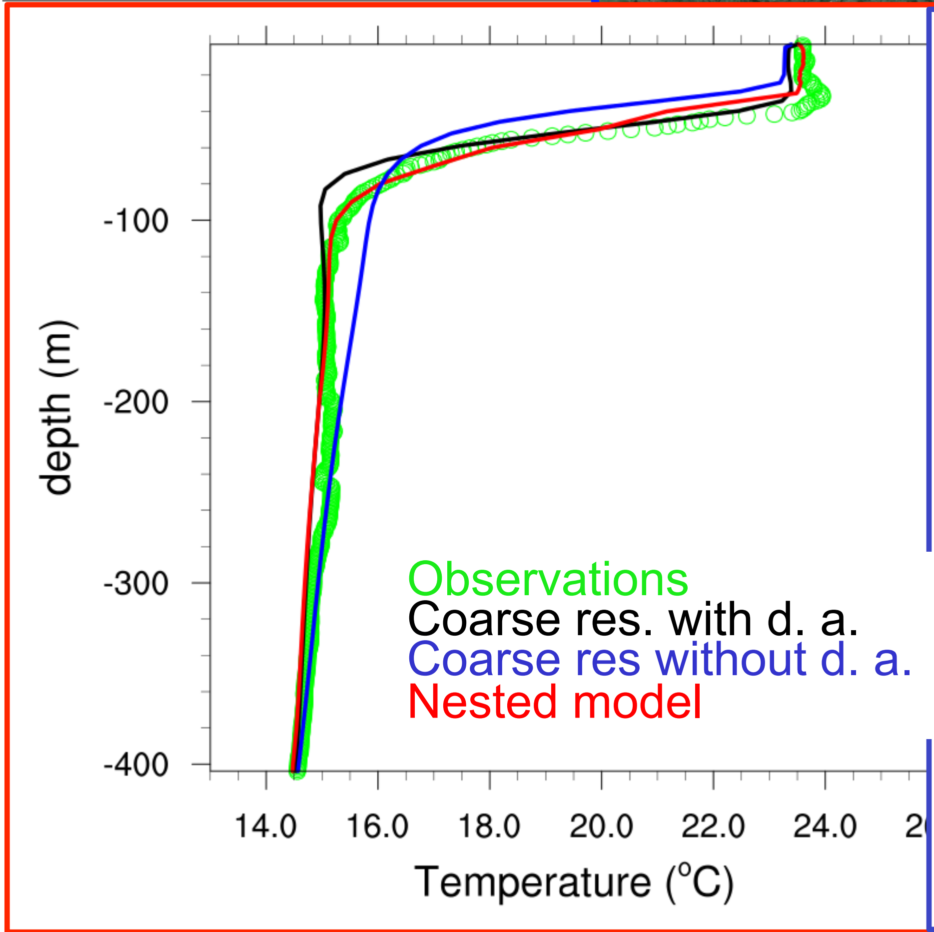
$$\frac{\partial \theta}{\partial t} + u_{n\,coarse}\frac{\partial \theta}{\partial n} = \lambda(\theta - \theta_{coarse}) \quad ; \theta = (T, S, U_{total})$$

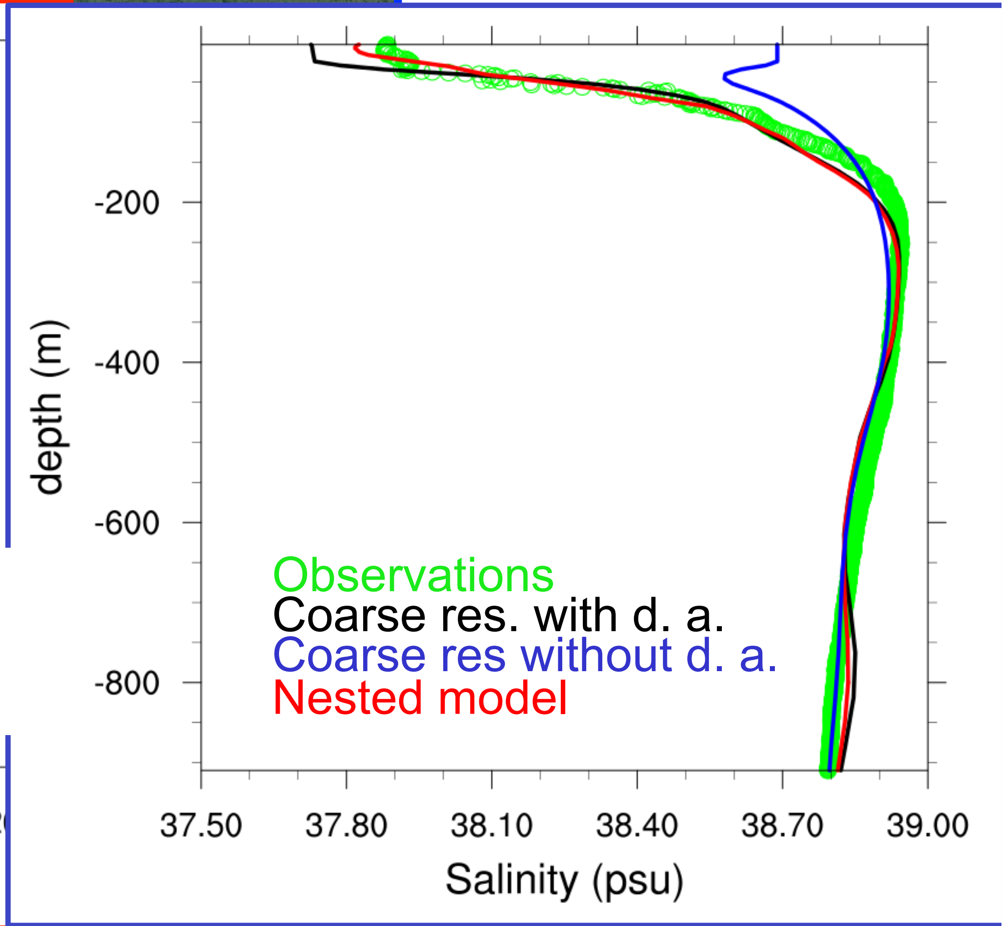
B For the barotropic component of velocity field, new GENERALIZED FLATHER BOUNDARY CONDITION has been developed (Oddo and Pinardi, 2008)

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

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

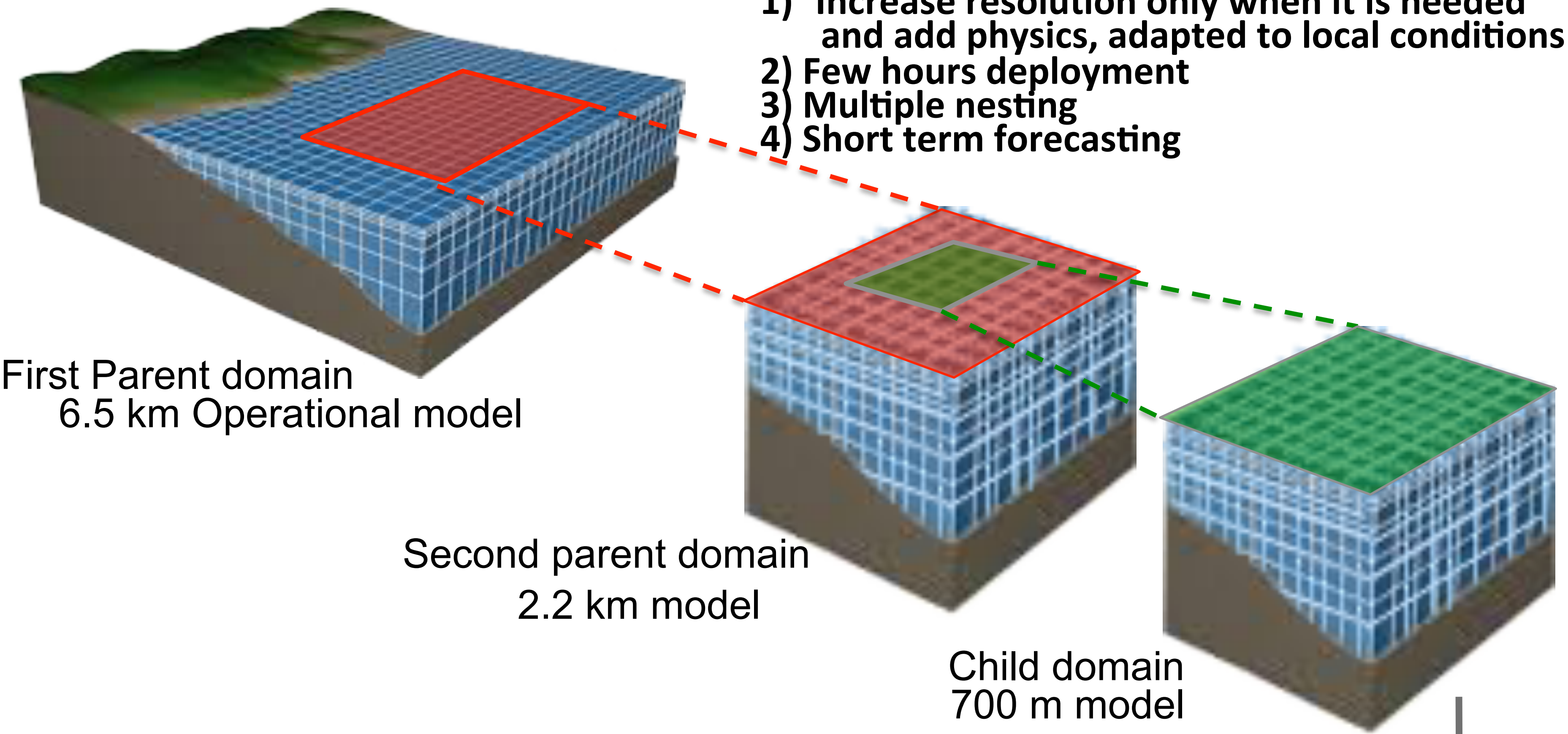
Case 1: coastal forecasting with unstructured grid models (Federico et al., 2015)





Case 2: 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**



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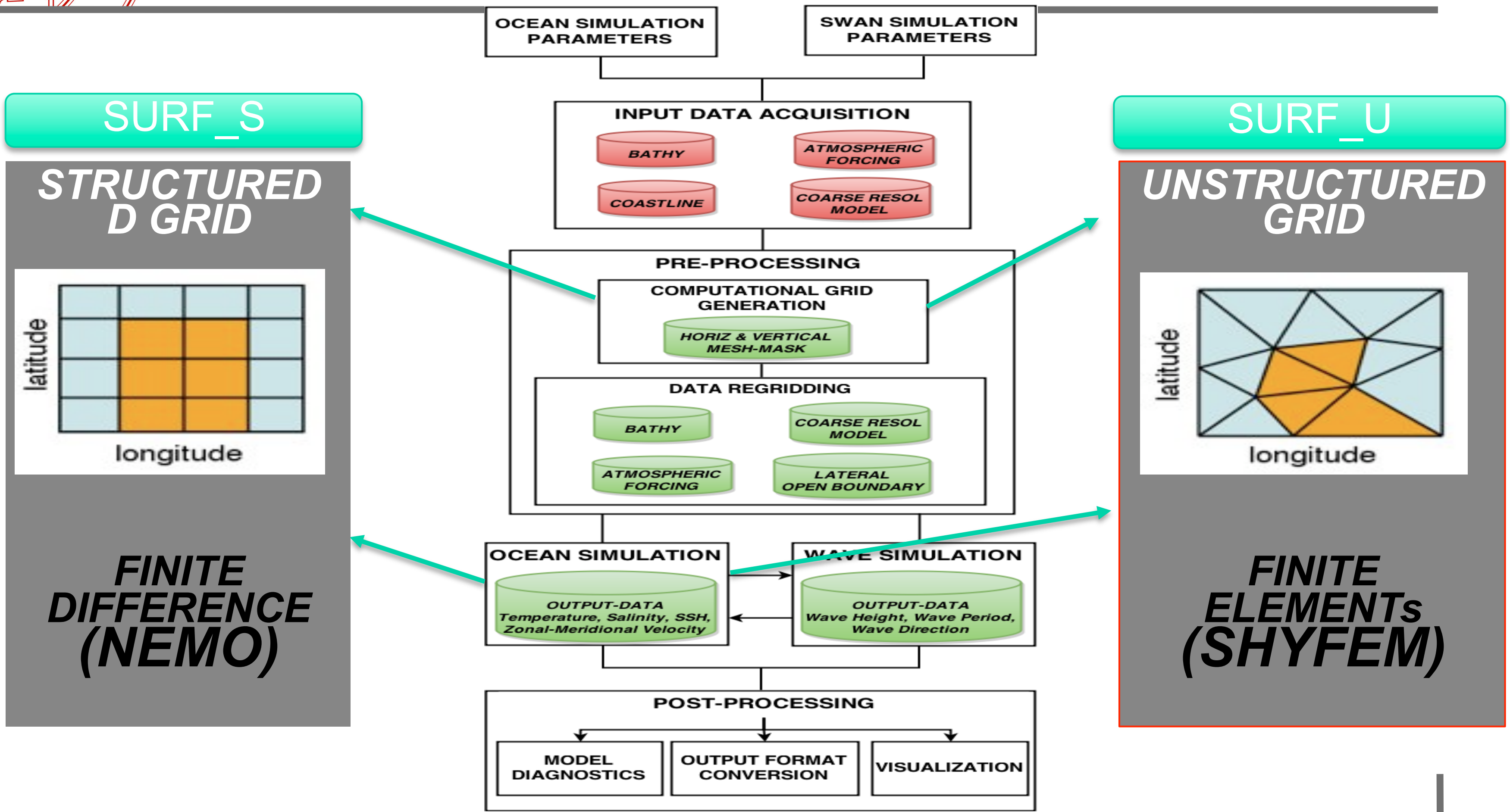
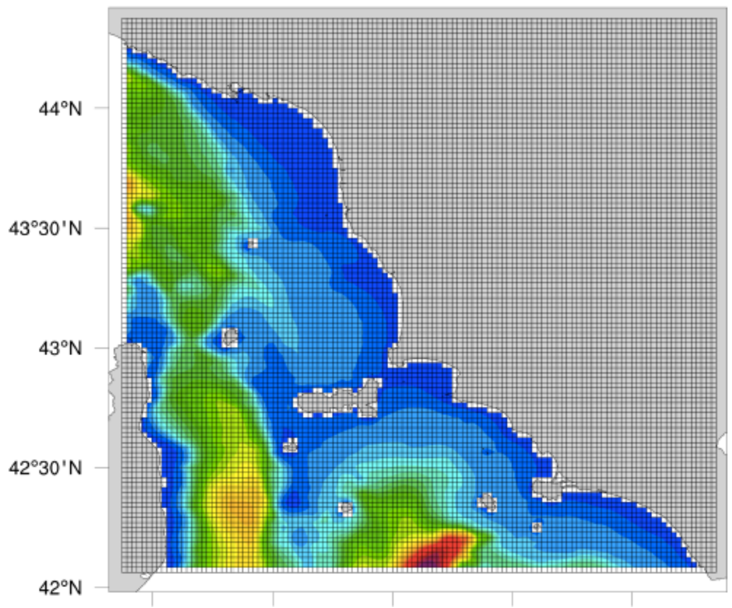
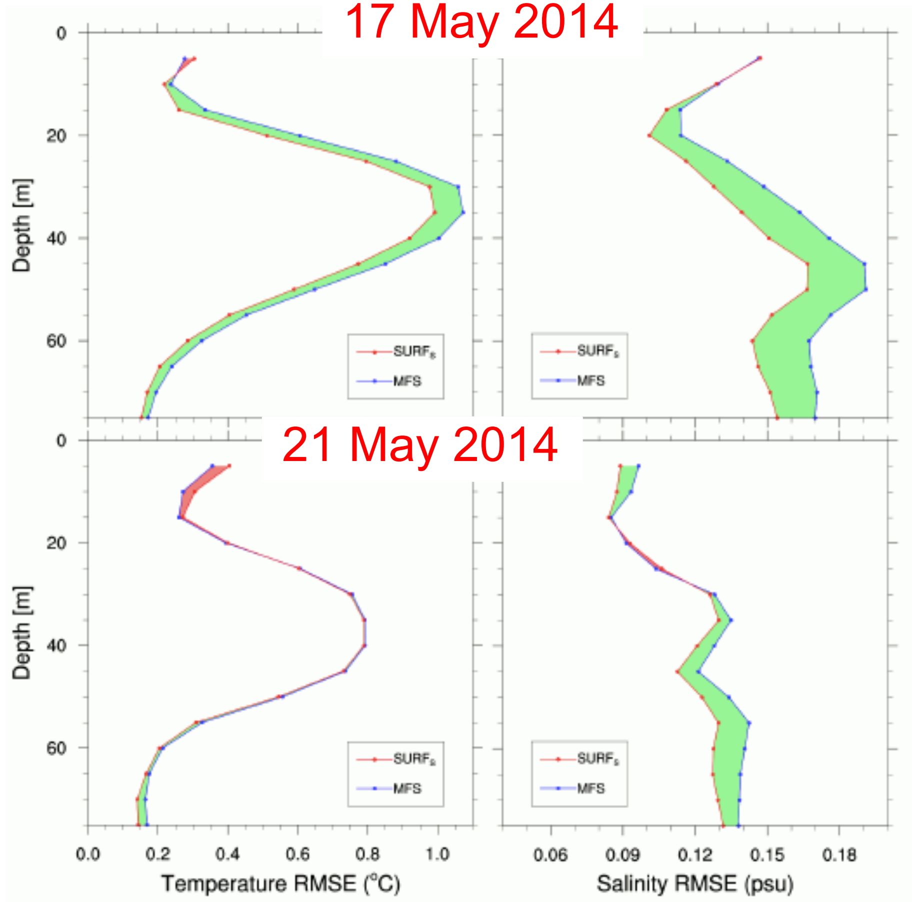


Case 2: **SURF** model error reduction

Area of donscaling



Green: nested model better in RMSE than the father model
Red: the contrary



Case 2: using SURF for Decision Support Systems

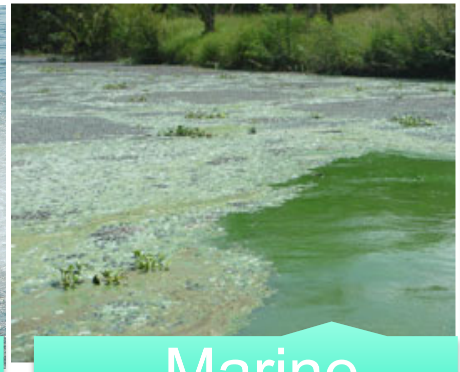
SURF

Decision Support Systems

Oil Spill

Ship routing

Search&Rescue



Marine Ecosystem

SHIP ROUTING

WWIII large scale prediction

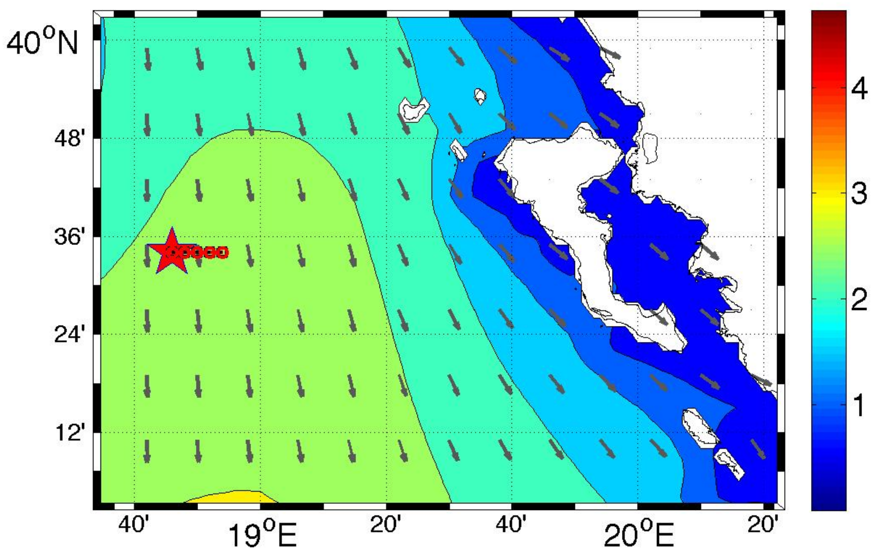
ECMWF Wind (Interpolated)

SURF_SWAN prediction

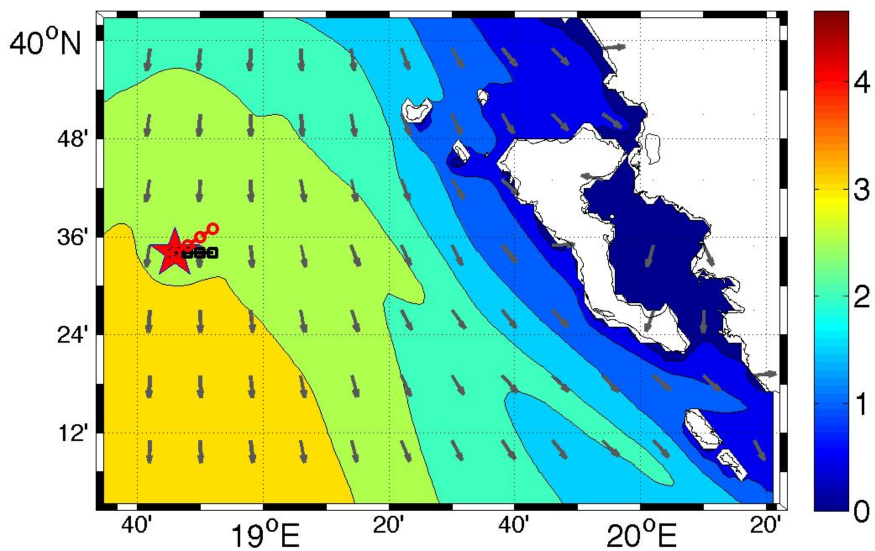
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

Starting point



Starting point



SHIP ROUTING

WWIII large scale prediction

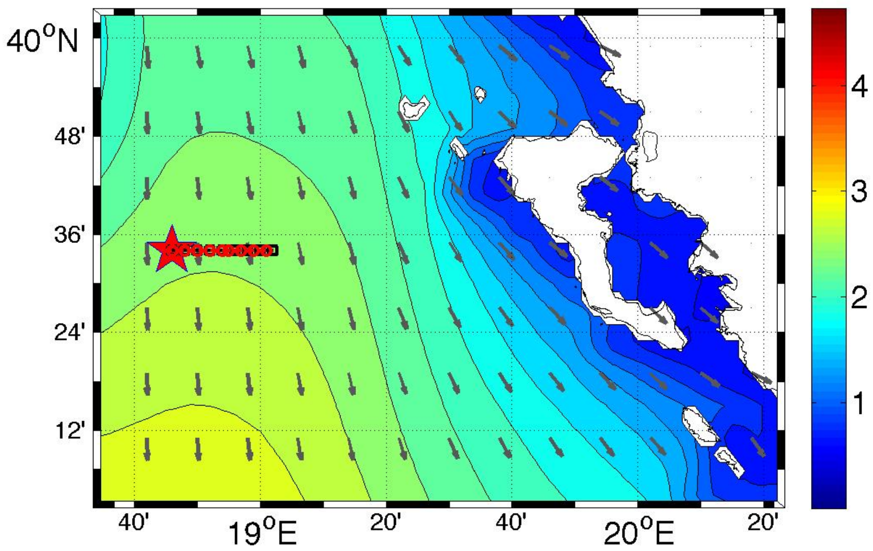
ECMWF Wind (Interpolated)

SURF_SWAN prediction

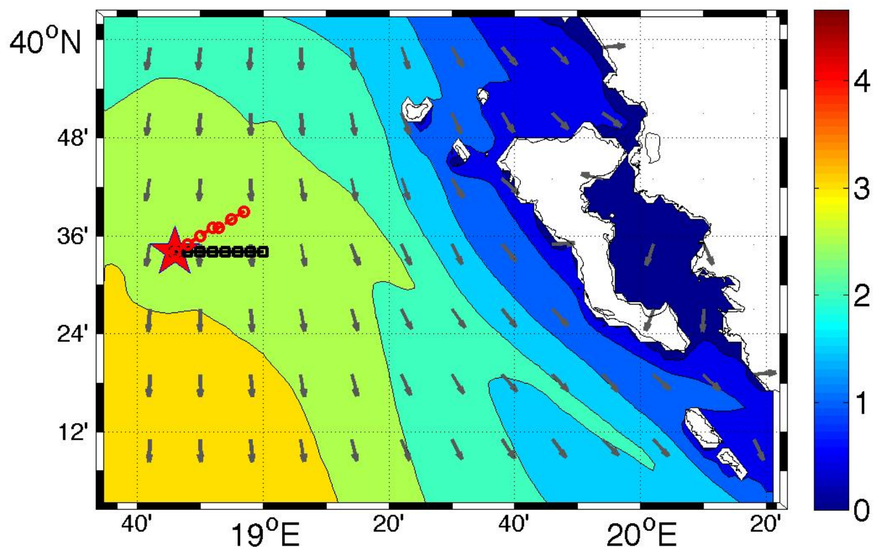
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

After 1 hour



After 1 hour



SHIP ROUTING

WWIII large scale prediction

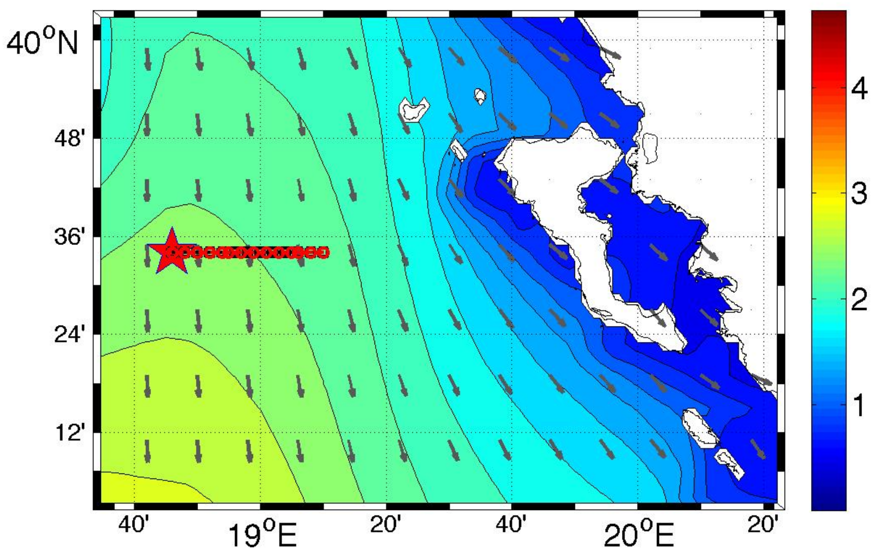
ECMWF Wind (Interpolated)

SURF_SWAN prediction

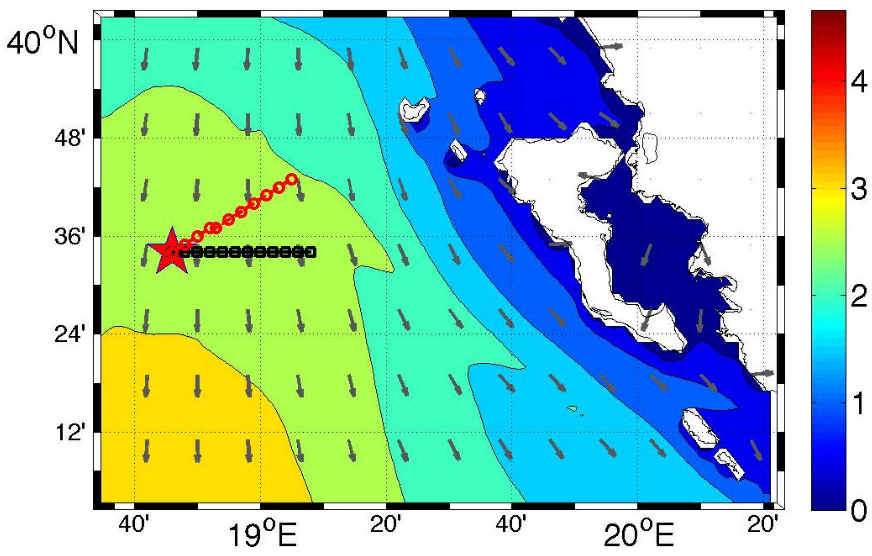
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

After 2 hours



After 2 hours



SHIP ROUTING

WWIII large scale prediction

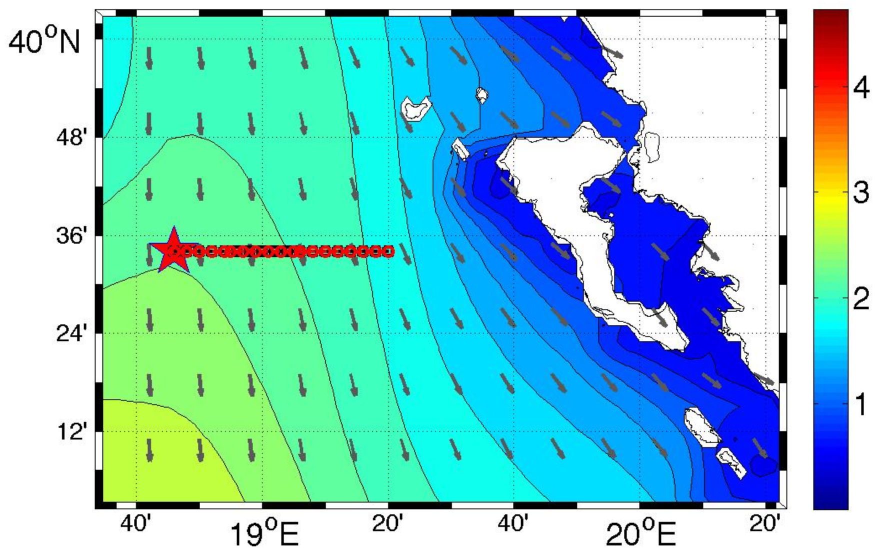
ECMWF Wind (Interpolated)

SURF_SWAN prediction

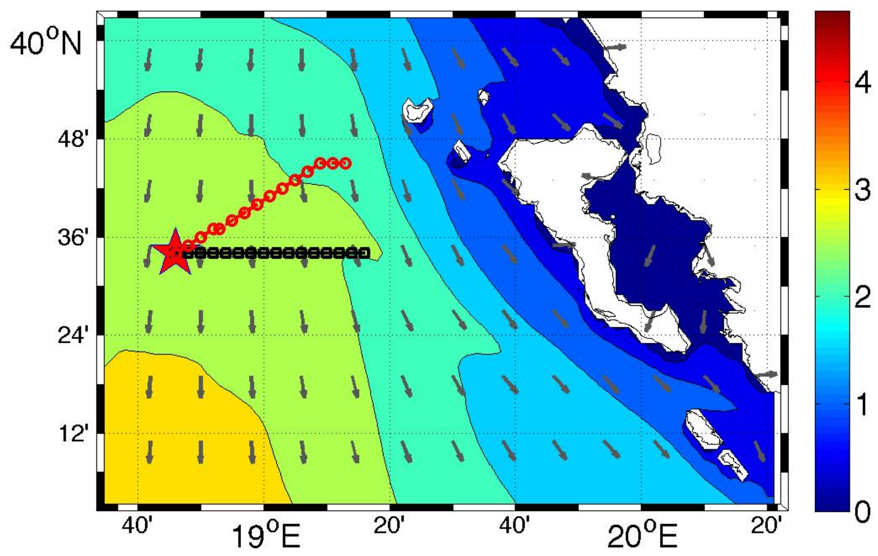
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

After 3 hours



After 3 hours



SHIP ROUTING

WWIII large scale prediction

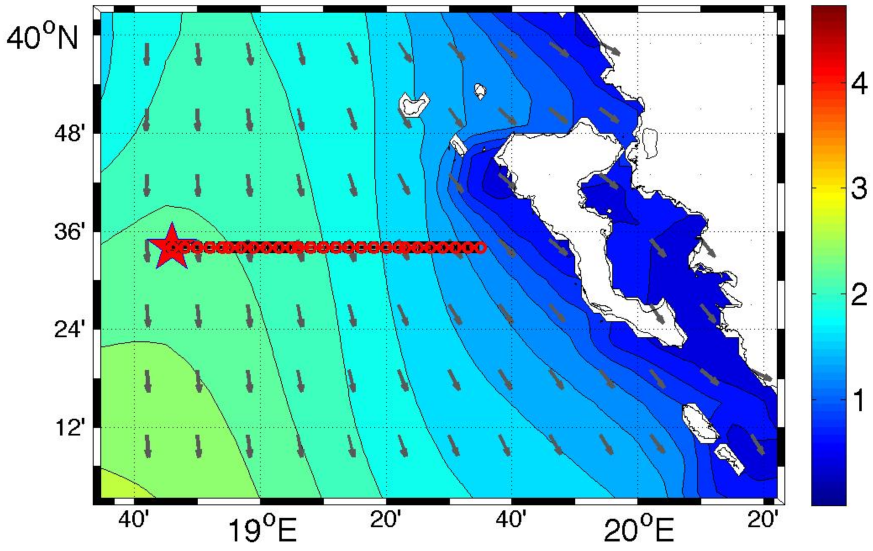
ECMWF Wind (Interpolated)

SURF_SWAN prediction

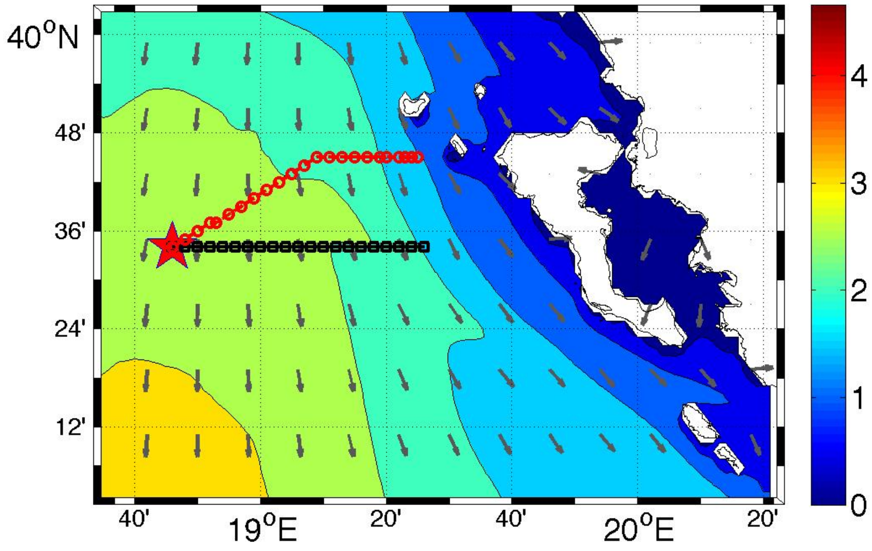
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

After 4 hours



After 4 hours



SHIP ROUTING

WW3 prediction

Wave fields (VTDH,VTZA,VDIR)

ECMWF Wind (Interpolated)

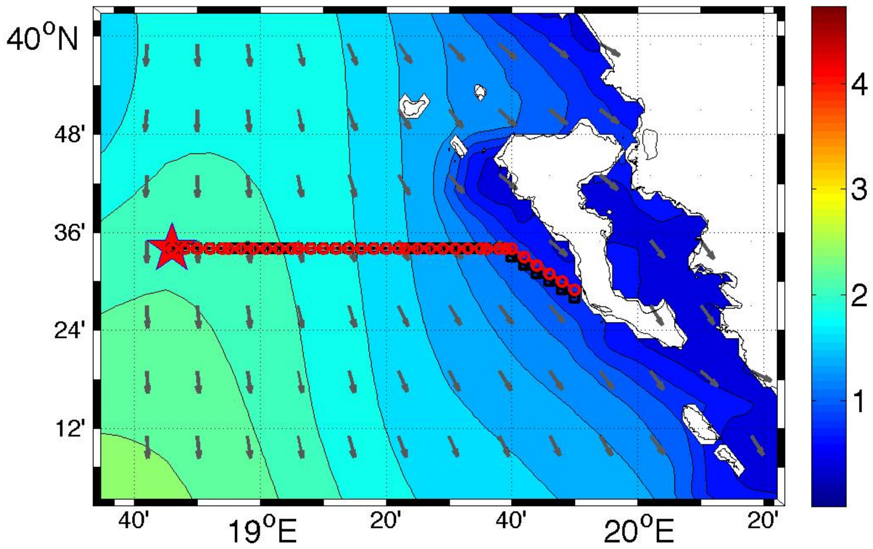
SURF_SWAN prediction

Wave fields (VTDH,VTZA,VDIR)

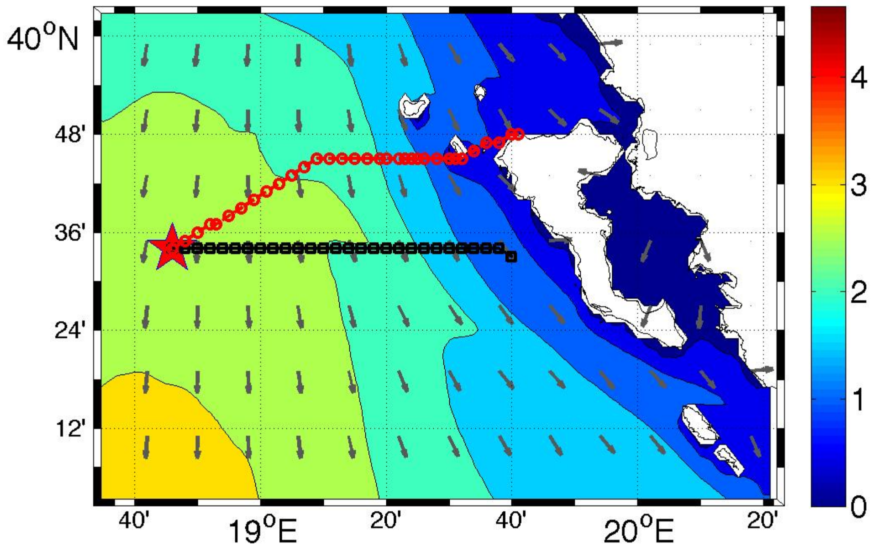
ECMWF Wind (Interpolated)

Trajectory of the Ship
(+significant wave height and Direction)

After 5 hours



After 5 hours



SHIP ROUTING

WWIII large scale prediction

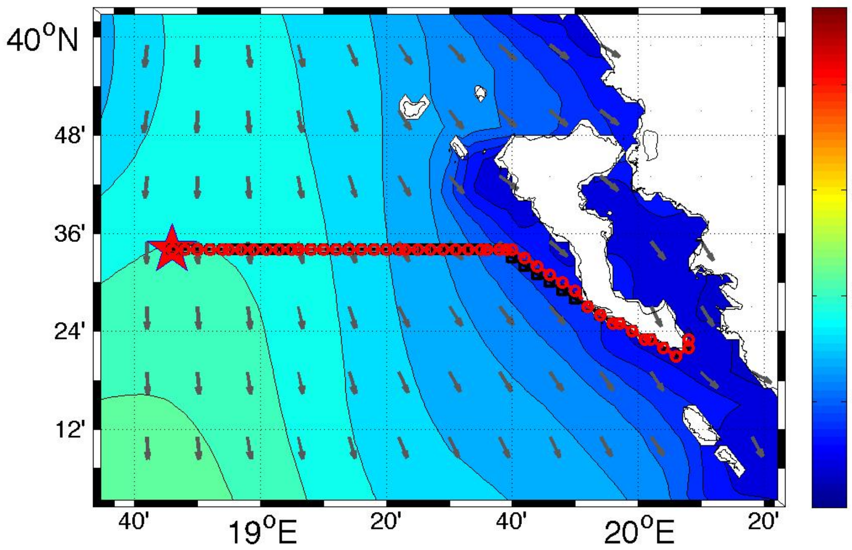
ECMWF Wind (Interpolated)

SURF_SWAN prediction

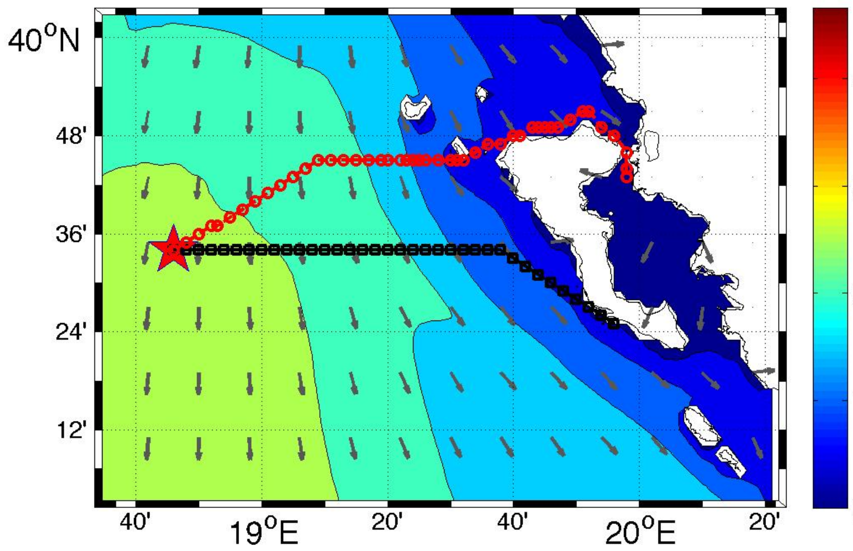
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

After 6 hours



After 6 hours



SHIP ROUTING

WWIII large scale prediction

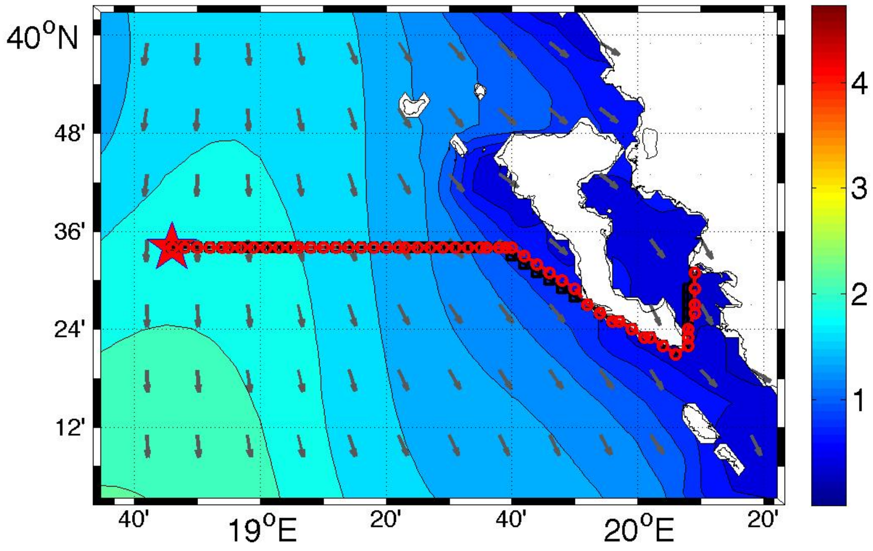
ECMWF Wind (Interpolated)

SURF_SWAN prediction

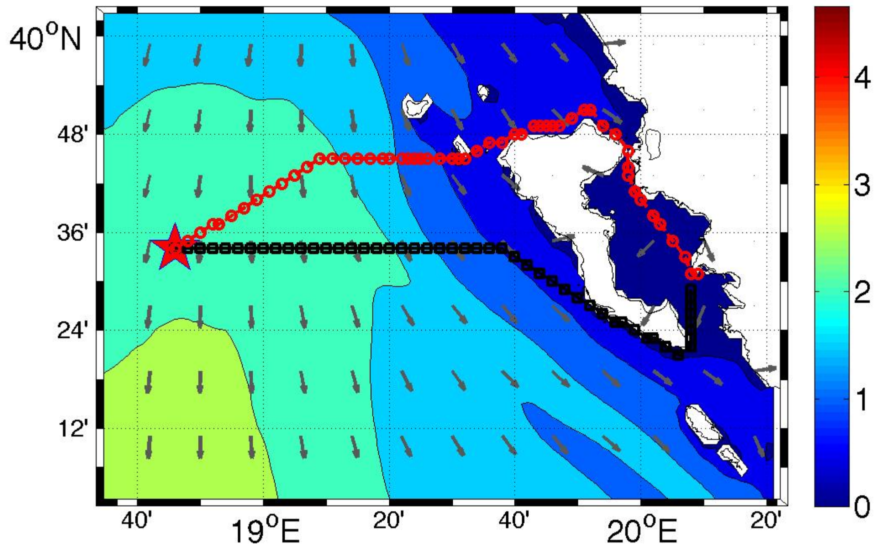
ECMWF Wind (Interpolated)

Simulated SAFE Ship route
(& significant wave height and Direction)

After 7 hours



After 7 hours



Conclusions and Outlook

- European Copernicus Marine Environment Service started operations and will continue thereafter
- Analysis errors and forecast uncertainty are being quantified. Ensemble methods with atmospheric forcing perturbations is a basic method for oceanography
- Open and free global and regional operational products make possible limited area, coastal short term forecasting
- Limited area forecasting IMPROVES forecast skill near coastal areas and in the open ocean with both structured and unstructured models
- When DSS are coupled to limited area models results show sensitivities

Scale selective versus non-scale selective generalized Flather: idealized case