The generalized Flather lateral open boundary condition

Sub-title:

The need of operational oceanography for increased forecast skill near the coasts

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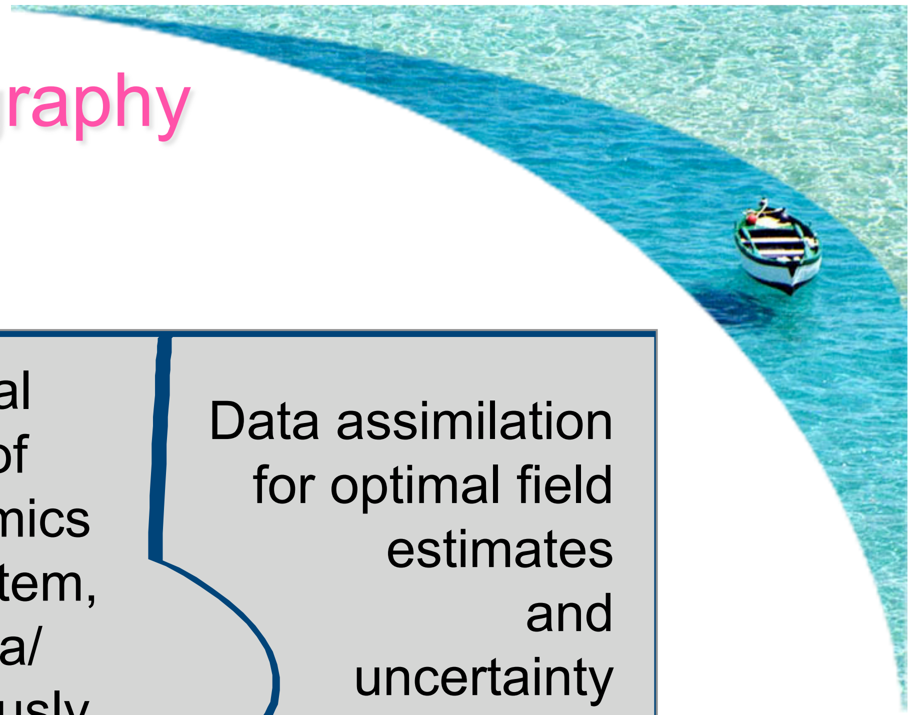
Outline

1. Operational Oceanography and the nesting approach
2. The nesting conundrum: the Lateral Boundary Condition problem
3. The generalized Flather boundary conditions
4. The Coastal Rapid Environmental Assessment (CREA) methodology: a possible framework for testing structured/unstructured grid models

The Operational Oceanography approach



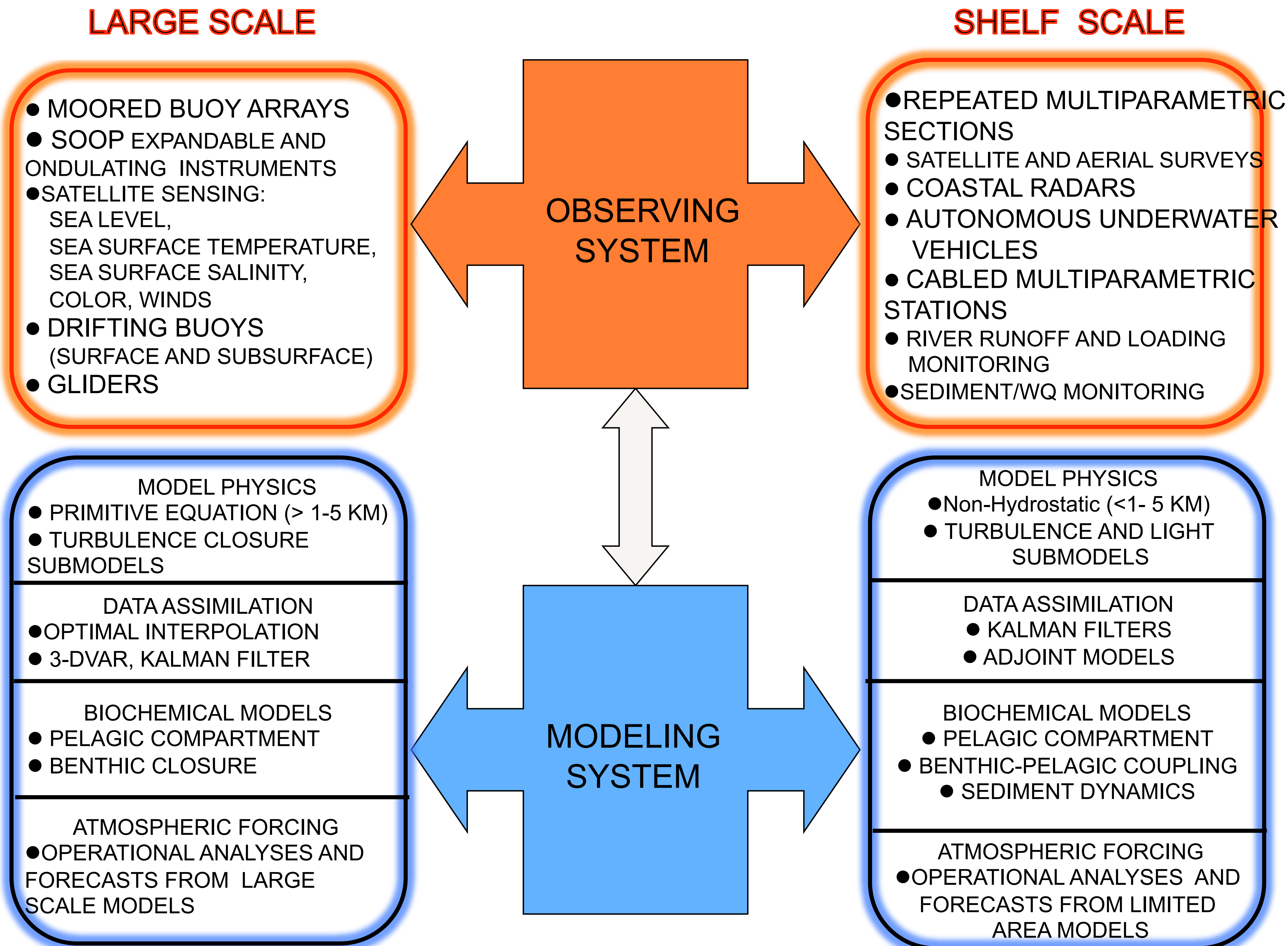
Multidisciplinary Multi-platform Observing system (permanent and relocatable)

Numerical models of hydrodynamics and ecosystem, coupled a/synchronously to atmospheric forecast

Data assimilation for optimal field estimates and uncertainty estimates

Continuos production of nowcasts/forecasts of relevant environmental state variables

The operational approach:
from large to coastal space scales (NESTING),
weekly to monthly time scales

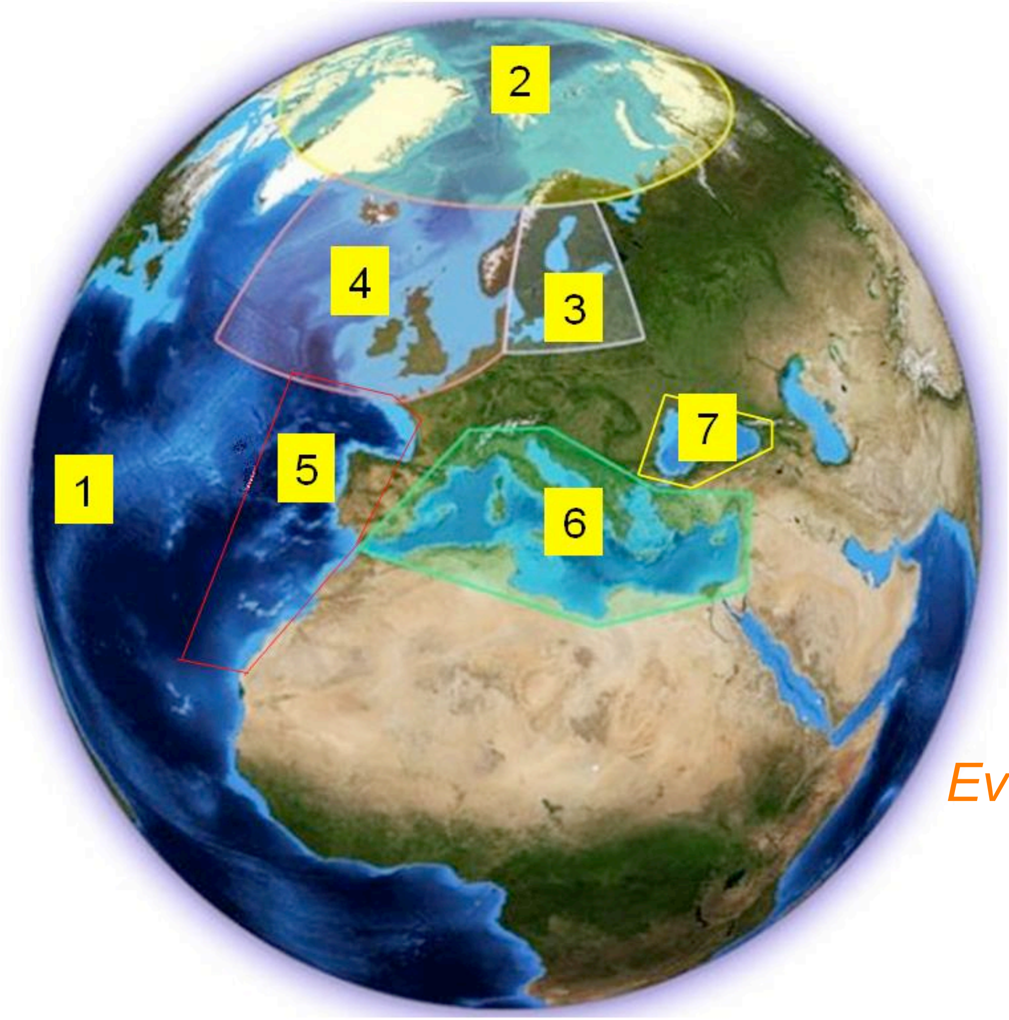

LARGE SCALE
SHELF SCALE
● MOORED BUOY ARRAYS
● SOOP EXPANDABLE AND ONDULATING INSTRUMENTS
●SATELLITE SENSING:
SEA LEVEL,
SEA SURFACE TEMPERATURE,
SEA SURFACE SALINITY,
COLOR, WINDS
● DRIFTING BUOYS
(SURFACE AND SUBSURFACE)
● GLIDERS
OBSERVING SYSTEM
●REPEATED MULTIPARAMETRIC SECTIONS
● SATELLITE AND AERIAL SURVEYS
● COASTAL RADARS
● AUTONOMOUS UNDERWATER VEHICLES
● CABLED MULTIPARAMETRIC STATIONS
● RIVER RUNOFF AND LOADING MONITORING
●SEDIMENT/WQ MONITORING
MODEL PHYSICS
● PRIMITIVE EQUATION (> 1-5 KM)
● TURBULENCE CLOSURE SUBMODELS
DATA ASSIMILATION
●OPTIMAL INTERPOLATION
● 3-DVAR, KALMAN FILTER
BIOCHEMICAL MODELS
● PELAGIC COMPARTMENT
● BENTHIC CLOSURE
ATMOSPHERIC FORCING
●OPERATIONAL ANALYSES AND FORECASTS FROM LARGE SCALE MODELS
MODELING SYSTEM
MODEL PHYSICS
●Non-Hydrostatic (<1- 5 KM)
● TURBULENCE AND LIGHT SUBMODELS
DATA ASSIMILATION
● KALMAN FILTERS
● ADJOINT MODELS
BIOCHEMICAL MODELS
● PELAGIC COMPARTMENT
● BENTHIC-PELAGIC COUPLING
● SEDIMENT DYNAMICS
ATMOSPHERIC FORCING
●OPERATIONAL ANALYSES AND FORECASTS FROM LIMITED AREA MODELS

Why nesting?

- Increase the resolution where users need it (especially coastal users)
- Operational oceanography products give basic first guess fields for high resolution coastal models
- Nesting allows the introduction of new physics (have resolution AND PROCESSES where and when you need them, Robinson et al., 1998)
- Practical and incremental way to implement new technology in the operational framework

The European Operational Oceanography Service

6 European Seas + Global Ocean



- 1. Global
- 2. Arctic
- 3. Baltic
- 4. NWS
- 5. IBI
- 6. Med Sea
- 7. Black Sea

Every day the ocean weather with uncertainty estimates

The European Operational Oceanography Service

- **Ocean Core Information**
  - Temperature, Salinity, Currents, Color, Sea Level, Ice variables, Bio variables
  - Hindcast, NowCast, Forecast
  - **Re-analyses**

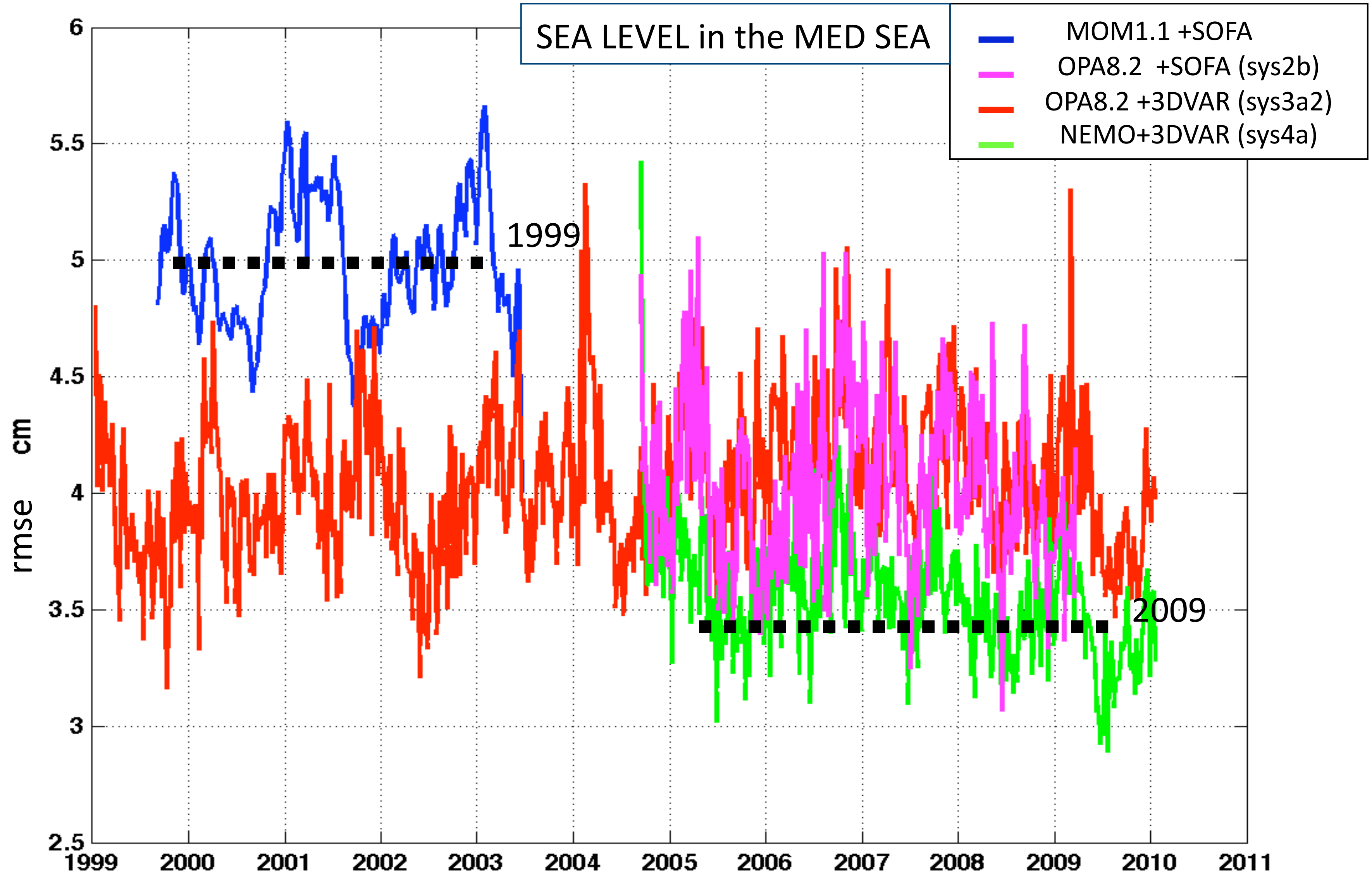
- One single desk
  - access point to the MyOcean pan-european information

- Open Data Policy
  - Open access
  - Free access

The operational forecasting models now

- Primitive equations in spherical coordinates with full ocean thermodynamics
- Physics:
  - Subgrid scale parametrizations for horizontal viscosity and diffusivity (fourth and sixth order laplacians)
  - High frequency atmospheric forcing and advanced air-sea interaction
  - Turbulence closure sub-models for the vertical viscosity and diffusivity
  - Bottom boundary layer parametrizations
  - Tidal potential included
  - Surface wave-current coupling
- Data assimilation components: multivariate schemes assimilating all available data in real time (satellite and in situ)
- Simplified physics forecasting models:
  - shallow water models for storm surge forecasting
  - Wave models for surface wave forecasting

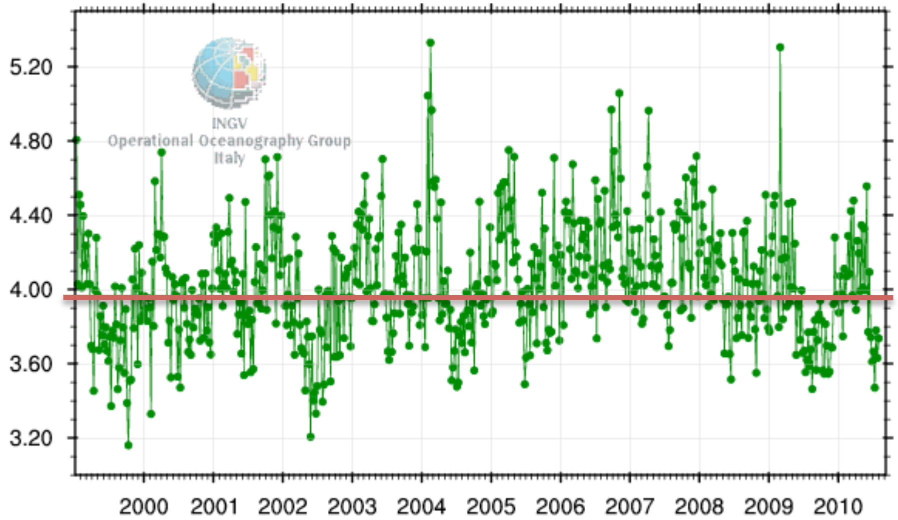
Operational oceanography: 10 years of quality increase



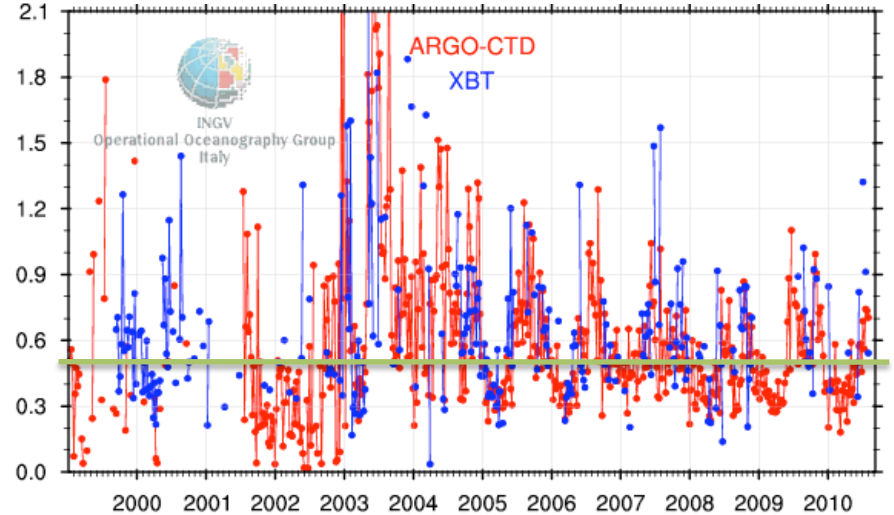
The errors of structured grid models

(past ten years of data in the Mediterranean)

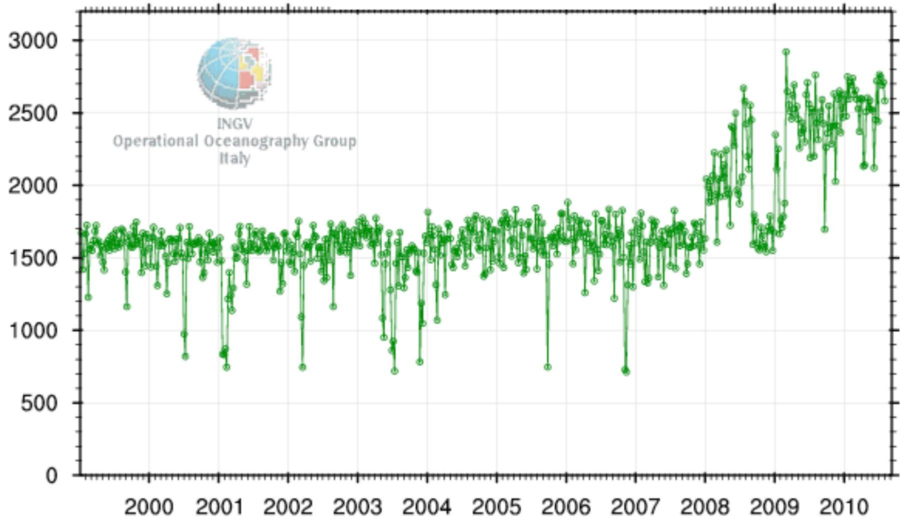
RMSE of SLA



RMSE of temperature at 8m

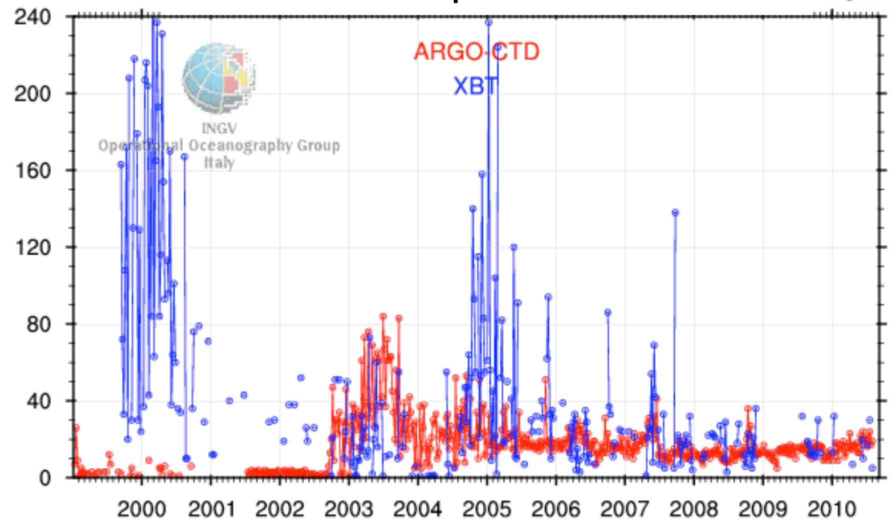


nb of SLA DATA



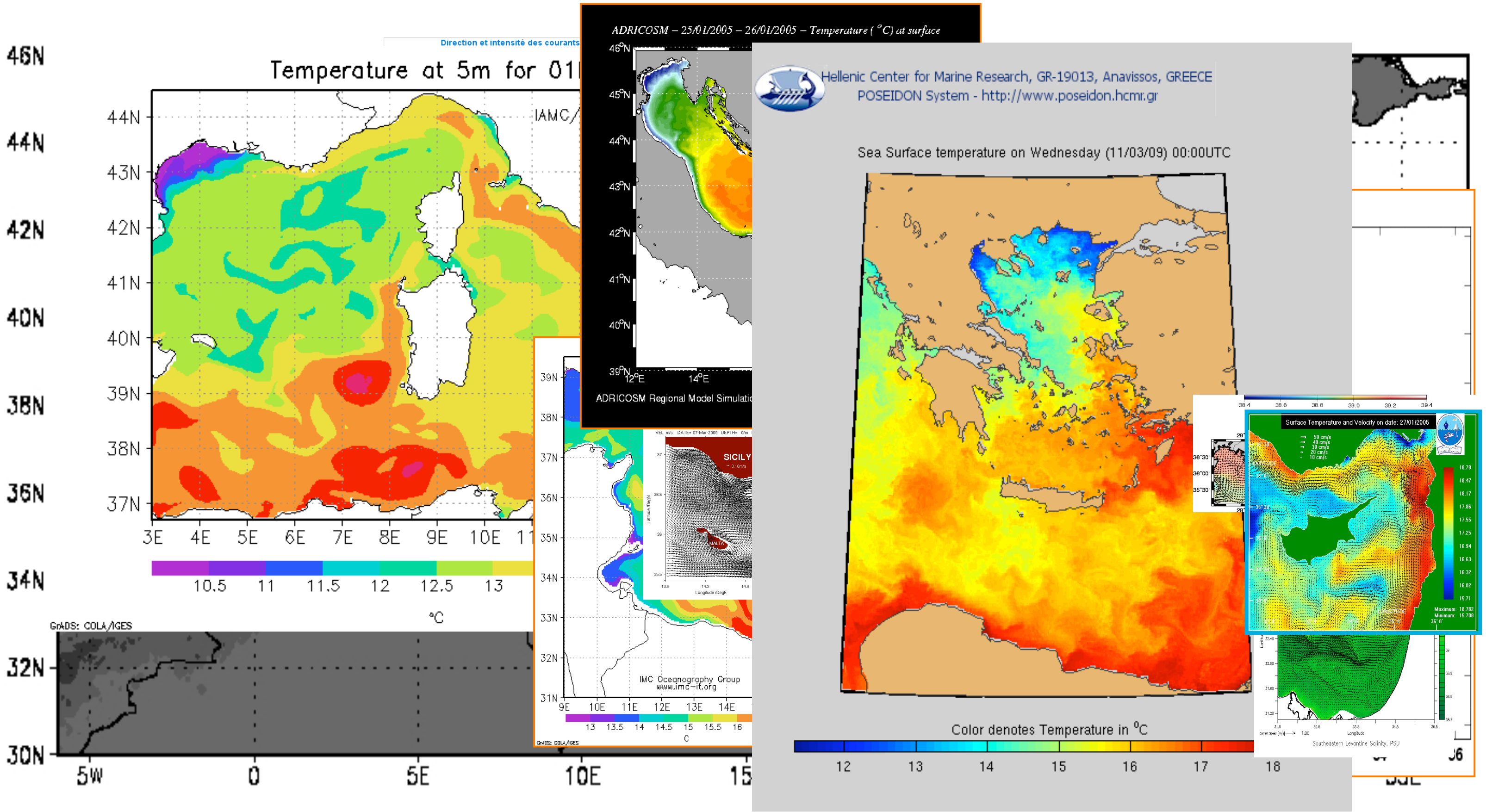
nb of Temperature DATA

8m



Operational Oceanography: the nesting deluge (all structured grids)

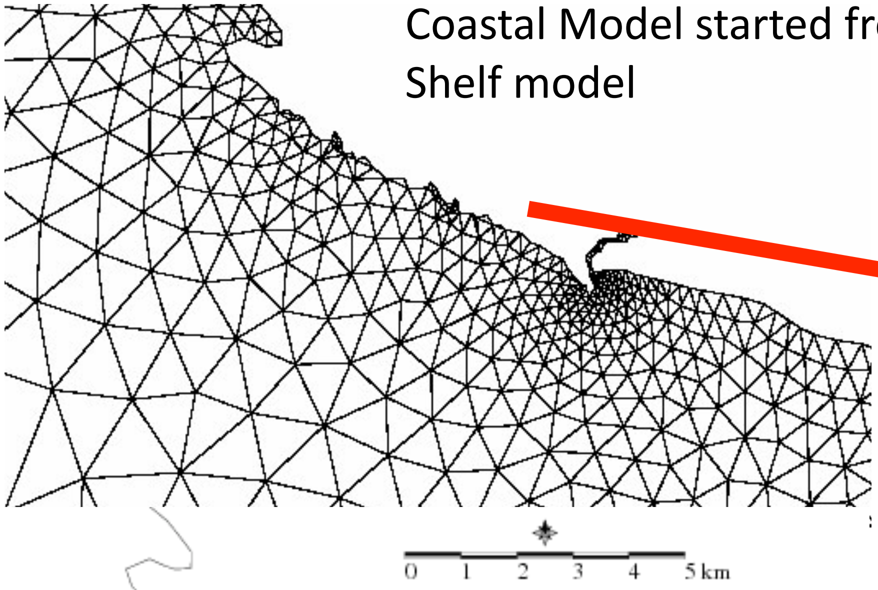
The Mediterranean Forecasting system disseminates daily forecasts to 13 nested national models every day

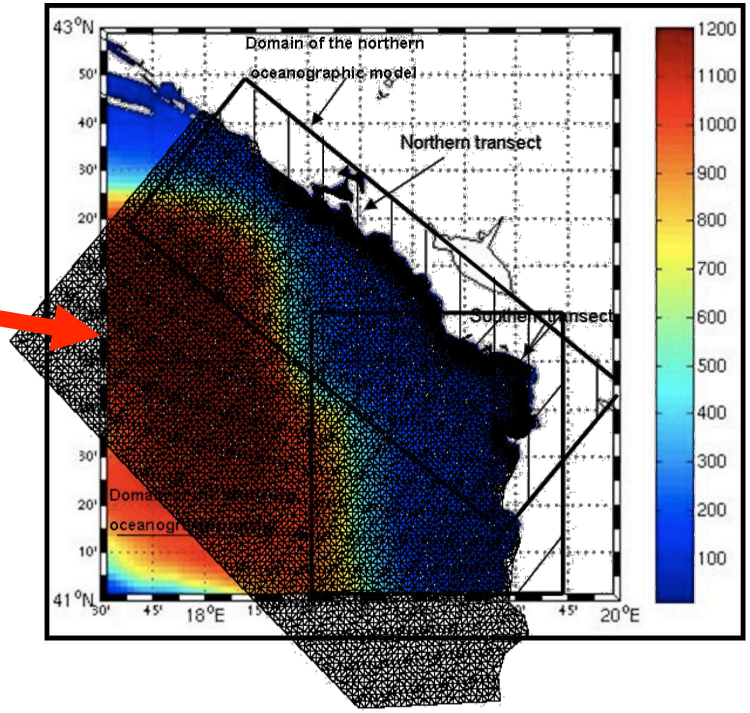


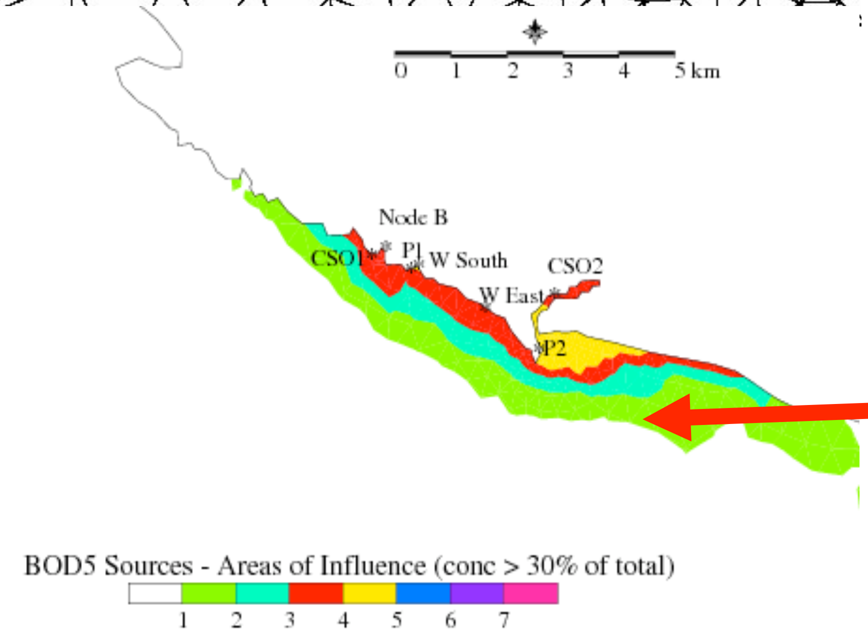
Shelf and sub-regional models now reach 1 - 3 km resolution

Operational oceanography Nesting with unstructured grids: SHYFEM 3-D

Coastal Model started from
Shelf model







Analysis of land sources
of pollution and their impact
In the sea

Bellafiore et al., 2010

Op.Oc. nesting issues with structured and unstructured grids

- Initialization problem: initializing all prognostic state variables from the coarse to the high resolution grid. VIFOP developed (Variational Initialization and Forcing Platform, Auclair et al., 1999, 2000, 2006) but more is needed (mass-conserving interpolation tools)
- Vertical Boundary Condition problem: higher resolution atmospheric forcing used in the nested model, need for consistency (?)
- Lateral Boundary Condition problem: delicate problem, we focused on that

The Lateral Boundary Condition problem

- Mainly solved in the 70's for limited area models
- Barotropic quasigeostropic equations are ill-posed (Bennett and Kloeden, 1978) but for short time scales errors can be kept below a threshold (Robinson and Haidvogel, 1978)
- Primitive equations for atmosphere (Oliger and Sundstrom, 1978, Orlansky, 1976, Miyakoda and Rosati, 1977)
- Primitive equations for the oceans (Flather, 1976), Spall and Robinson (1989), etc.
- More recently a very interesting revisit: Marchesiello et al. (2001) and Blayo and Debreu (2005)
- Interesting work by Teman and Tribbia (2003) showing that non-hydrostatic open boundary condition is less ill-posed than hydrostatic case

The Mediterranean nested models LBC strategy (Pinardi et al., 2003)

- For tracers, T and S, and baroclinic velocities, collectively θ, use:

$$\frac{\partial \theta}{\partial t} + u_{NORMAL}^{COARSE} \frac{\partial \theta}{\partial n} = 0$$

  at outflow points (inflow can be prescribed from coarse model)
- For barotropic velocity normal components, $U_N = \frac{1}{H+\eta} \int_{-H}^{\eta} u_{NORMAL} \, dz$ use instead 3 different forms:

$$U_N^F = \frac{H_C}{H_F} U_N^C \pm \sqrt{\frac{g}{H_F}} \, \eta_F \; ; \qquad U_N^F = \frac{H_C}{H_F} U_N^C \; ;$$

$$U_N^F = \frac{H_C}{H_F} U_N^C \pm \sqrt{\frac{g}{H_F}} \, (\eta_F - \eta_C)$$

- Why these different forms and what is the relationship to Flather (1976)?

The Mediterranean nested models LBC strategy (Pinardi et al., 2003)

- In addition, all models, need to consider the 'INTERPOLATION CONSTRAINT', i.e. the conservation of transport across the open boundary after interpolation

$$\int_{l1}^{l2} \int_{-H_C}^{\eta_C} u^C \, dz \, dl = \int_{l1}^{l2} \int_{-H_F}^{\eta_F} u_{INTERP} \, dz \, dl$$

- This amounts to have a corrections done each nesting time on the fine resolution velocity barotropic field of the type:

$$U^F = U_{INTERP} - \frac{\Delta T}{S} F(x, y, z)$$

The generalized Flather LBC (Oddo and Pinardi, OM, 2008)

- Flather (1976): $U_N^F = U_N^C - \sqrt{\frac{g}{H}}\left(\eta_C - \eta_F\right)$

- Where this formula comes from? Flather does not explain it. Our derivation is:

$$\nabla \cdot \vec{u} = 0 \quad \Rightarrow \quad \frac{\partial \eta}{\partial t} + \nabla \cdot \left[(H+\eta)\,\vec{U} \right] = 0$$

- Imposing an equality between the conservation of mass in the coarse (c) and fine resolution (F) domain:

$$\frac{\partial \eta_C}{\partial t} + \nabla \cdot \left[(H_C + \eta_C)\,\vec{U}^C \right] = \frac{\partial \eta_F}{\partial t} + \nabla \cdot \left[(H_F + \eta_F)\,\vec{U}^F \right]$$

The generalized Flather LBC, cont.

- From the equality before:

$$\frac{\partial \eta_C}{\partial t} + \nabla \cdot \left[(H_C + \eta_C)\,\vec{U}^C \right] = \frac{\partial \eta_F}{\partial t} + \nabla \cdot \left[(H_F + \eta_F)\,\vec{U}^F \right]$$

- Assuming that the free surface tendency can be written as: $\dfrac{\partial \eta}{\partial t} + \nabla \cdot \left[C\,\eta \right] = 0$

- We obtain the *generalized Flather boundary condition:*

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

The generalized Flather LBC, cont.

- The *generalized Flather boundary condition:*

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

- *Becomes the Flather (1976) only if*

$$H_C \approx H_F = H;$$

$$|\eta_{C,F}| \ll H;$$

$$C_N = \sqrt{gH}$$

$$\Longrightarrow \quad U_N^F = U_N^C - \sqrt{\frac{g}{H}} (\eta_C - \eta_F)$$

- *This is also why nesting and nested models bathymetry should not be very different at the open boundary if Flather (1976) is used*

Scale selective LBC

- Knowing the principles, now we can consider a scale separation in the fine resolution field: suppose one part spectrally overlap with the coarse field while the other is new. Thus

$$\eta_F = \eta'_F + \eta''_F$$

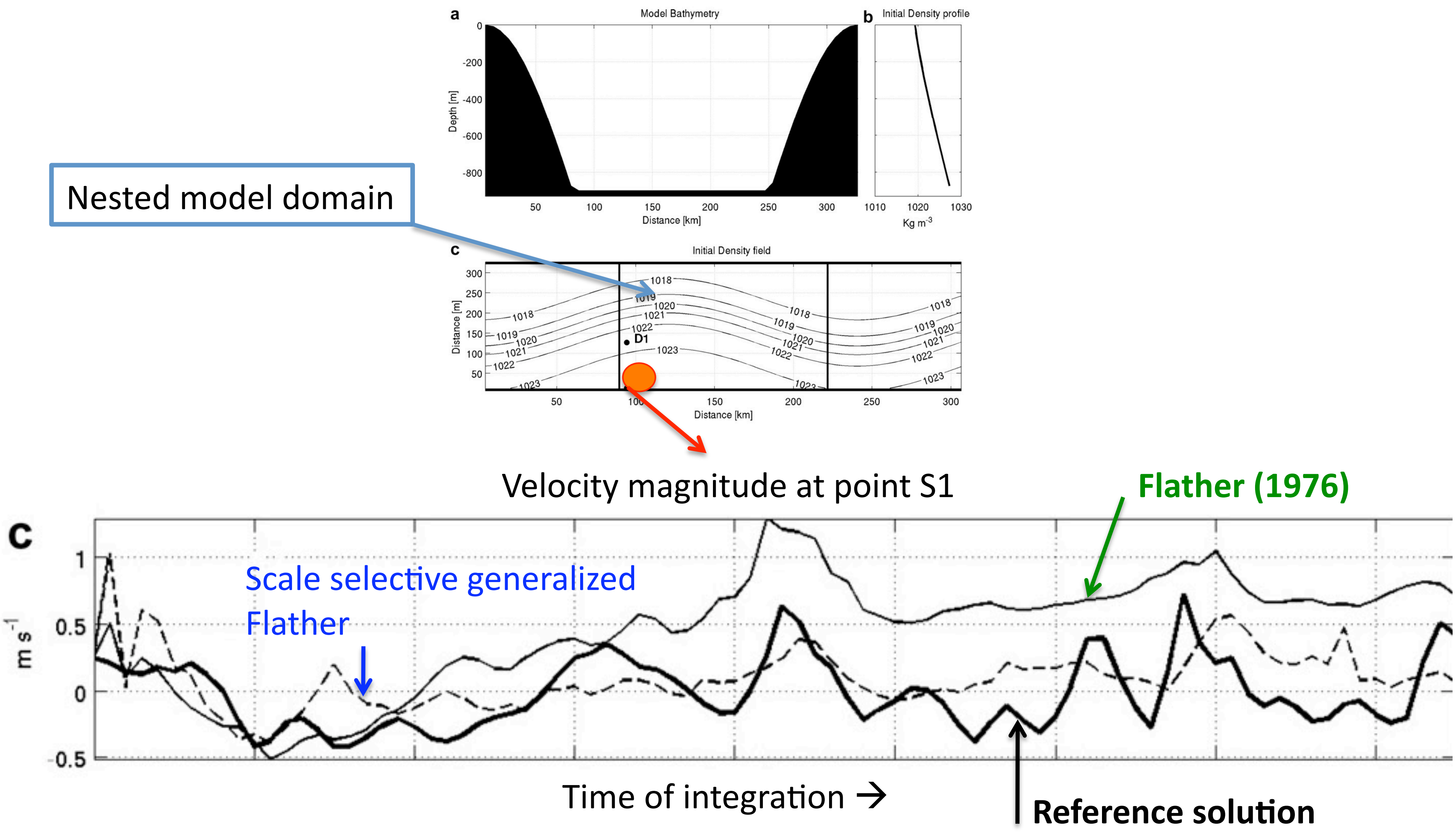
$$U^F = U'^F + U''^F$$

- After some algebra two new equations are formed for each portion of the solution:

$$U'^F_N = \frac{H_C + \eta_C}{H_F + \eta'_F} U^C_N - \frac{C'_N}{H_F + \eta'_F}\left(\eta_C - \eta'_F\right)$$

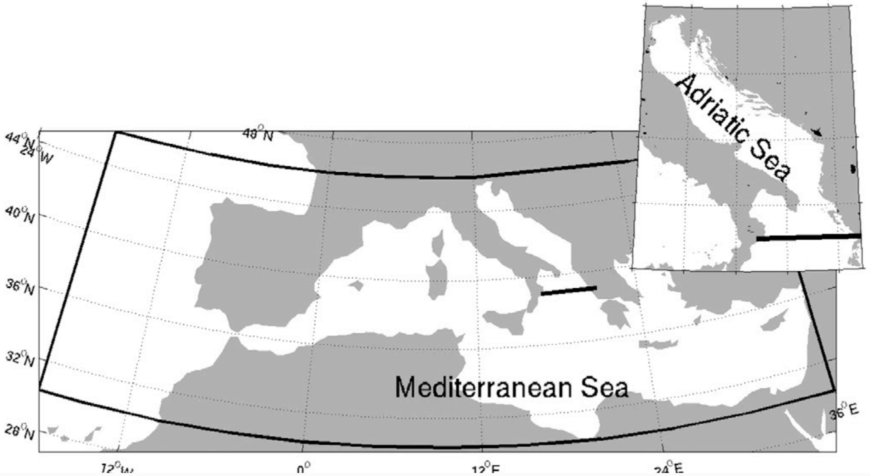
$$U''^F_N = \frac{\eta''_F}{H_F + \eta_F}\left(C''_N - U'^F_N\right)$$

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



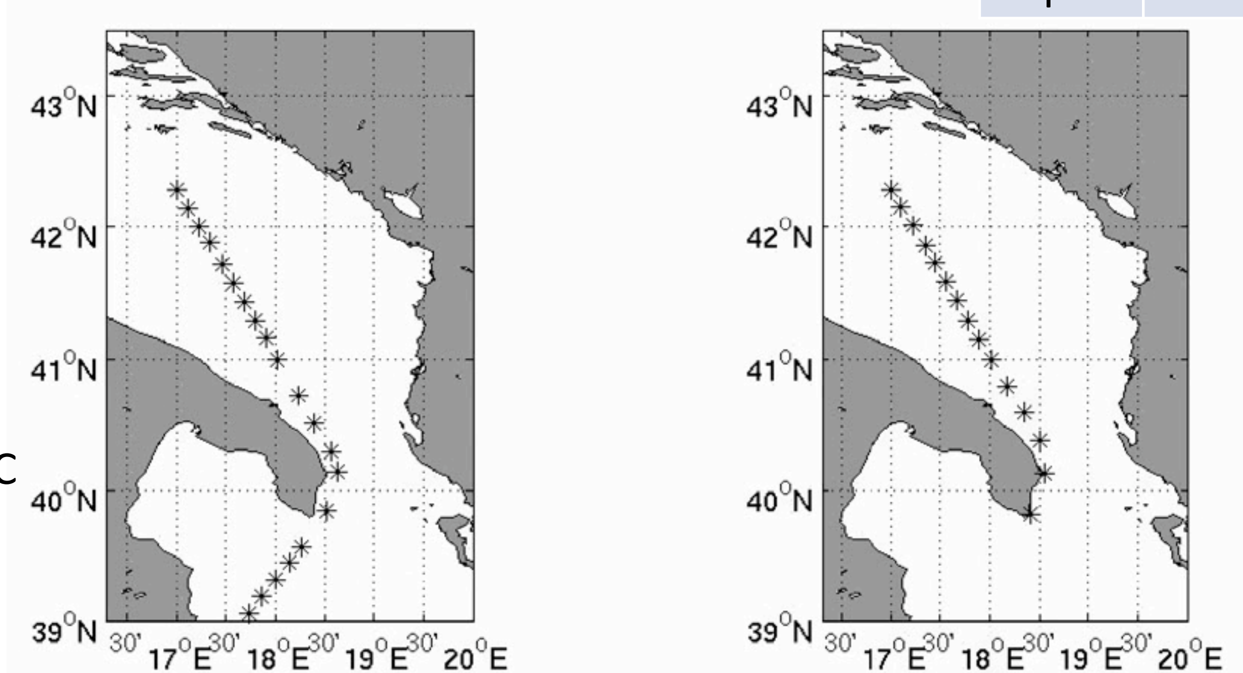
Scale selective versus non-scale selective generalized Flather: realistic case

Nested model: From 6-7 km to 2 km



Experiment	LBC
Exp1	Imposed
Exp2	Radiation
Exp3	Scale selective

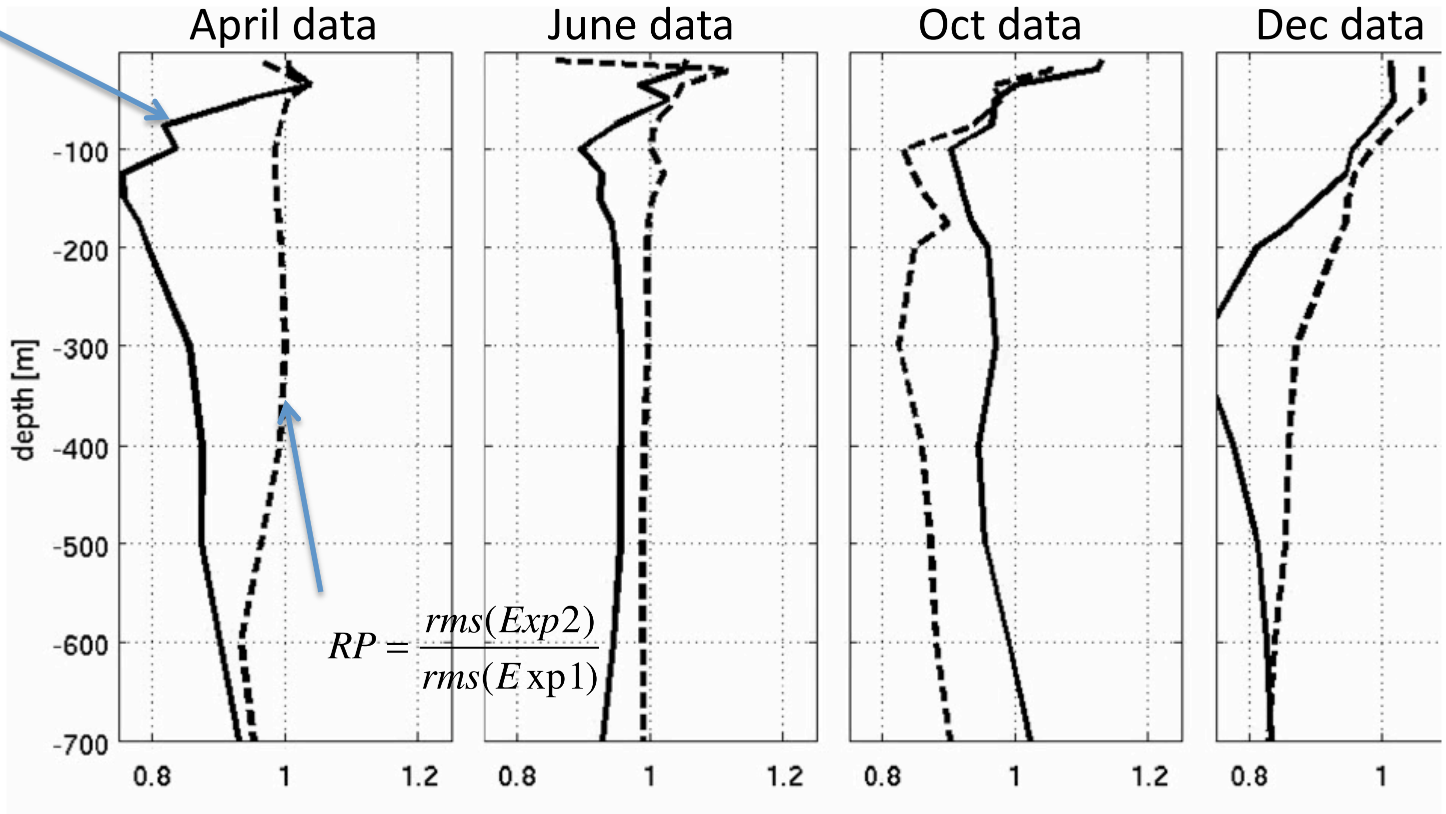
In situ data to validate the model Output with Different LBC



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

Relative Performance Index $$RP = \frac{rms(Exp2)\ or\ rms(Exp3)}{rms(Exp1)}$$

$$RP = \frac{rms(Exp3)}{rms(Exp1)}$$



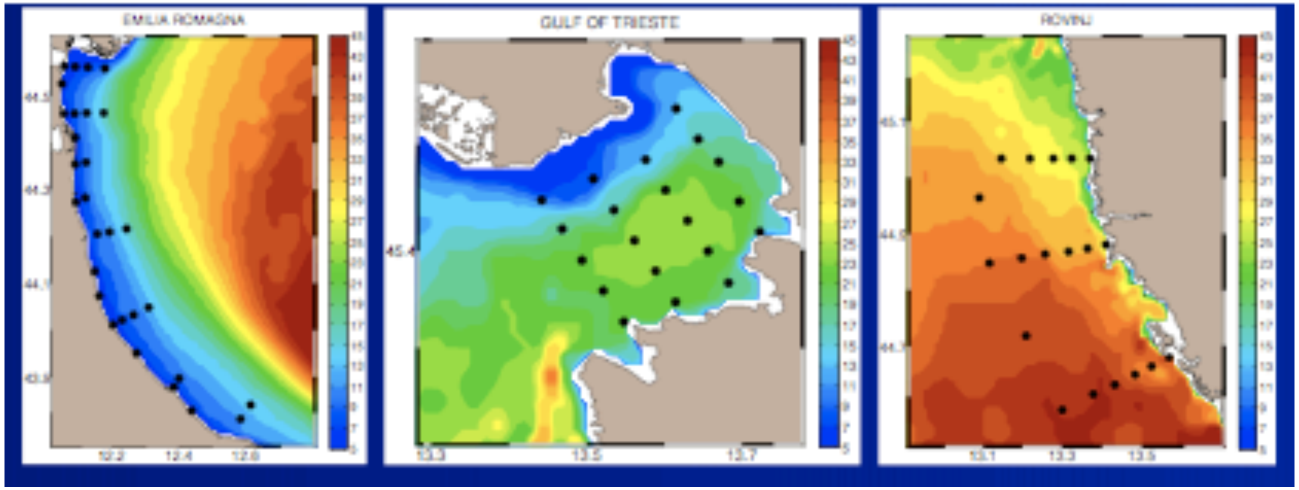
$$RP = \frac{rms(Exp2)}{rms(Exp1)}$$

The Coastal Rapid Environmental Assessment (CREA) framework

- CREA is the evolution of MREA concepts (Robinson et al., 2000) for the coastal area
- The aim is to use all information to reduce uncertainties in the 5-7 days forecast of currents, temperature and salinity near the coastal areas
- CREA is composed of:
  - Basic operational oceanography analyses and forecasts
  - A higher resolution nested model
  - Observations from coastal systems
  - A blending algorithm, multiscale optimal interpolation by Mariano and Brown (1992)
  - Initialization strategy

(This is a part of Simoncelli Ph.D. Thesis, 2010)

The CREA components



(1) The coastal Networks (Italian and Croatian EPA network)

(2) The nested models, 7, 2 km and 800 meters

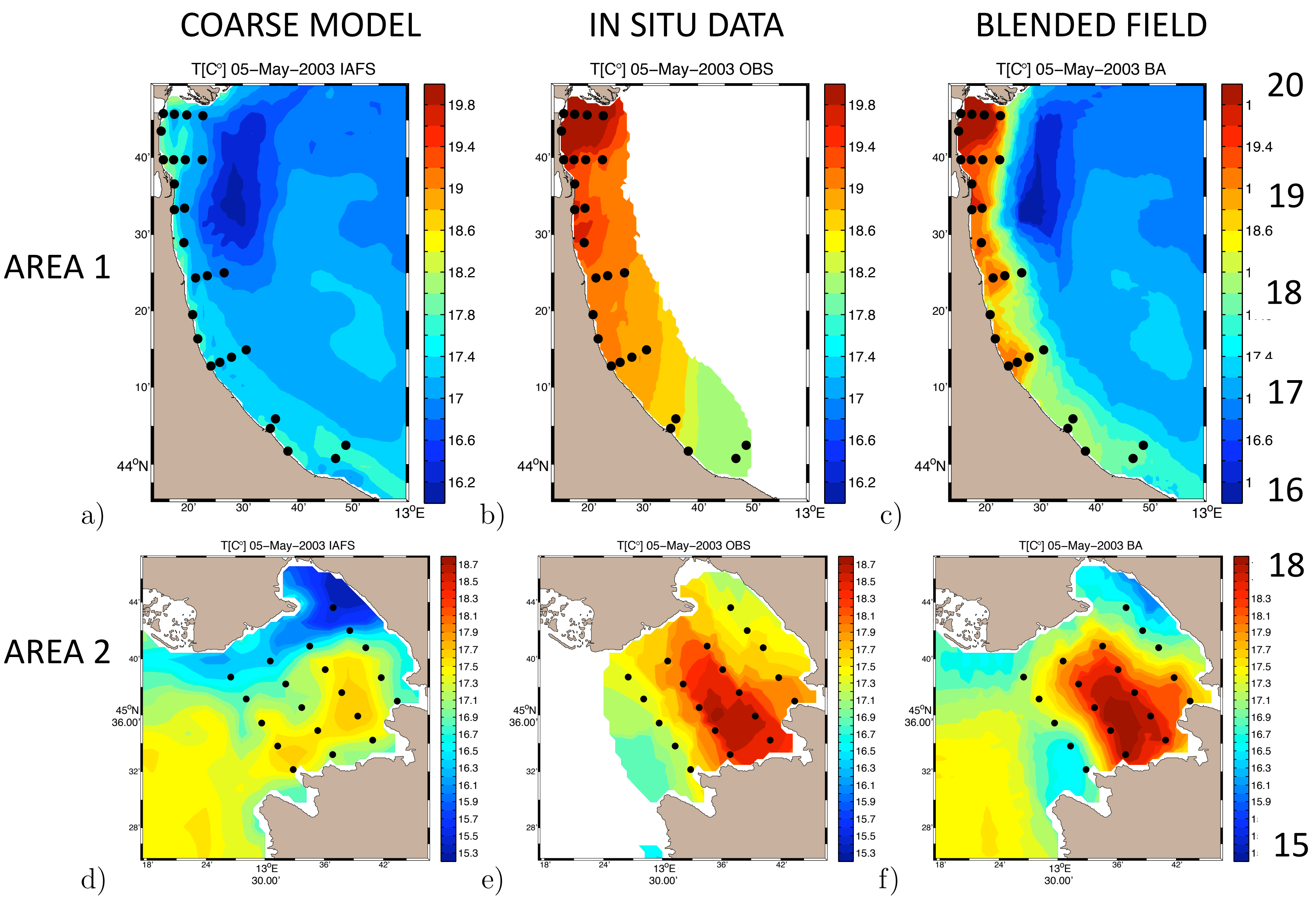
(3) The blending algorithm

Multi-input and multiscale OI

Two input data sets: coarse model data and local in situ data with different errors
Multiscale subdivision of the field

$$T(x,y,z,t) = T_M(x,y,z,t) + T_E(x,y,z,t) + \varepsilon$$

The Blending impact



The CREA strategy

- Interpolate from the coarse grid to the finer resolution grid and extrapolate if needed using climatology
- Blend the model information with the observations
- Spin-up the dynamics to have higher resolution scales in the IC
- Force with NWP analyses and forecasts

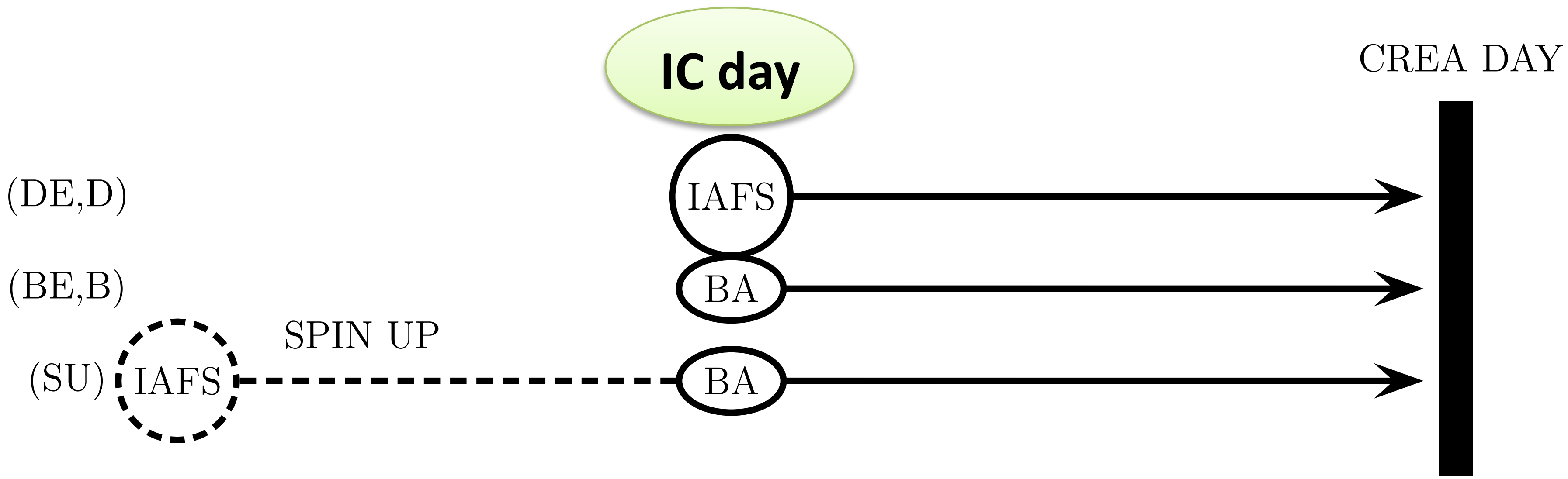
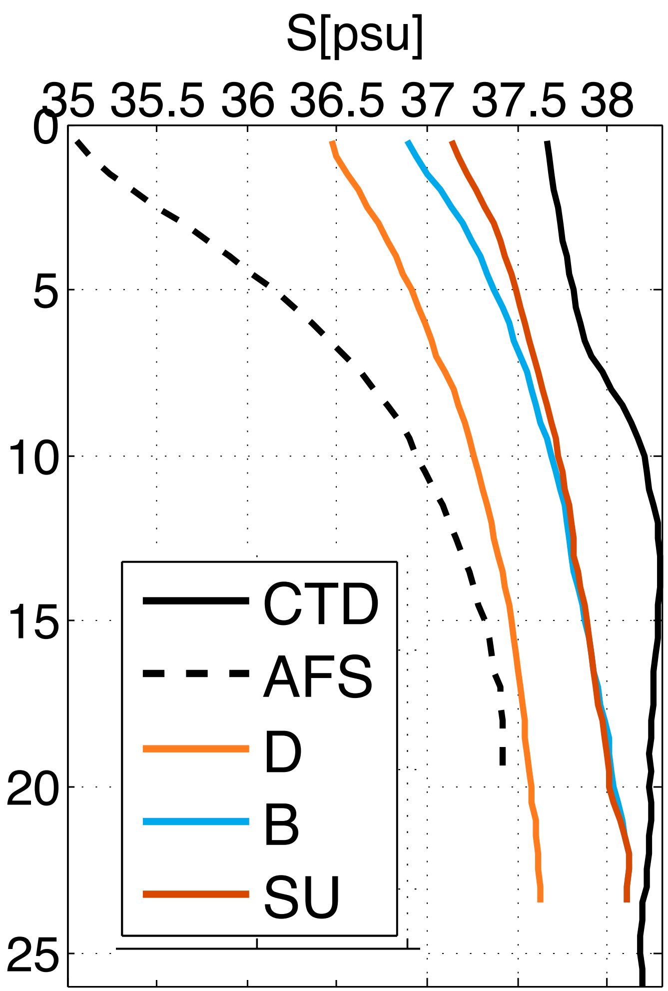


Fig. 4. CREA initialization and forecast procedure.

IAFS- Interpolation BA- Blending

Simoncelli et al., 2010

The improvement due to high resolution (structured), observations and spin-up



	Interpol IC	Blended IC	Spin-up plus blending
% RMSE decrease after one week forecast	10%	20-25%	30%

Conclusions

- Operational oceanography is providing basic analyses for model validation and development in many parts of the world ocean
- Baroclinic model nesting for the coastal areas working at all scales (open ocean too, not shown) but need for:
  - Robust initialization methods
  - Accurate or high resolution atmospheric forcing
  - Lateral Boundary conditions: new generalized Flather promising
- Possible test bed for unstructured grid validation: CREA methods and databases. Data could be made available to the community for Northern Adriatic Sea