Image-Based Forecast of the Surface Circulation of Black Sea

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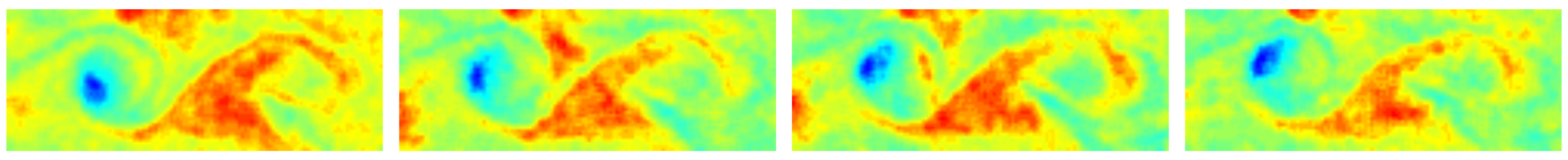
ABSTRACT

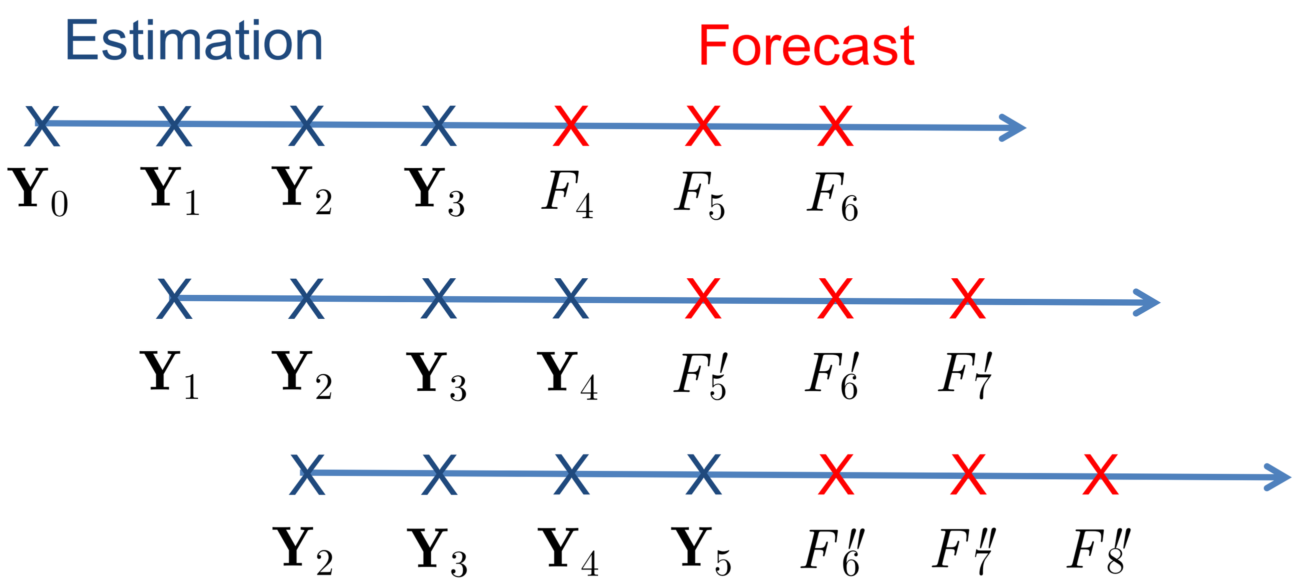
Satellite data allow vizualising the surface circulation and the meso-scale structures at the spatial resolution and time frequency of the sensor. These images provide continuous information at fine scale and permit analysing eddies, jets, filaments, mushroom-shaped vortices. Many applications, such as oil spill monitoring, also require the forecast of surface circulation at short temporal horizon. This nowcasting includes two main components: one in charge of estimating the surface dynamics and one of the forecast of future images at a given temporal horizon.

OBJECTIVES

A sliding-window technique processes the last 4 images:



$\mathbf{Y}_0$ $\mathbf{Y}_1$ $\mathbf{Y}_2$ $\mathbf{Y}_3$



The state vector $\mathbf{X}$ is composed of motion $\mathbf{w}$ and synthetic image I:

$$\mathbf{X}(\mathbf{x},t) = \big(\mathbf{w}(\mathbf{x},t)\ I(\mathbf{x},t)\big)^T$$

SURFACE DYNAMICS ESTIMATION

The surface dynamics is estimated with a data assimilation approach from four image acquisitions and the evolution laws of $\mathbf{w}$ and I, summarized in the numerical model $\mathbb{M}_e$:

$$\begin{cases} \dfrac{\partial \mathbf{w}}{\partial t} = 0 \\ \dfrac{\partial I}{\partial t} + \mathbf{w} \cdot \nabla I = 0 \end{cases}$$

- Estimation is computed from the comparison between the satellite images $\mathbf{Y}(t)$ and the synthetic images $I(t)$.
  Images $I(t)$ are obtained from the integration of the evolution model $\mathbb{M}_e$.
  The discrepancy beween $\mathbf{Y}(t)$ and $I(t)$ is equal to $\varepsilon_I(\mathbf{x},t)$:
  $$\varepsilon_I(\mathbf{x},t) = \mathbf{Y}(\mathbf{x},t) - I(\mathbf{x},t)$$
- The minimization of the discrepancy ε_I is obtained through the minimization of the energy:
  $$J(\mathbf{X}(0)) = \iint \frac{\varepsilon_I(\mathbf{x},t)^2}{R_I(\mathbf{x},t)} d\mathbf{x}dt + \text{additional terms}$$
  and a steepest descent method (L-BFGS algorithm).
  R_I is taken as the variance of the acquisition error.
- The issue of missing data, due to the cloud cover for instance, is solved with $R_I(\mathbf{x},t) = 10^8$, which excludes these pixels from the energy J.

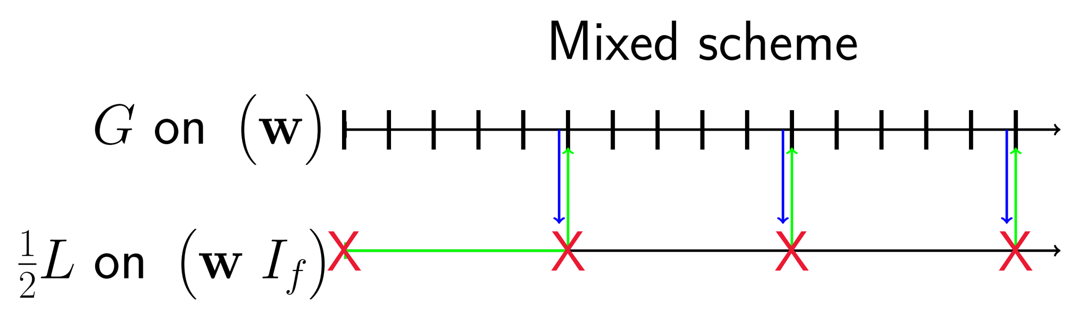
FORECAST

The forecast synthetizes future images based on the estimated dynamics and on the last acquisition with the numerical model $\mathbb{M}_f$:

$$\begin{cases} \dfrac{\partial \mathbf{w}}{\partial t} + \mathbf{w} \cdot \nabla \mathbf{w} = 0 \\ \dfrac{\partial I}{\partial t} + \mathbf{w} \cdot \nabla I = 0 \end{cases}$$

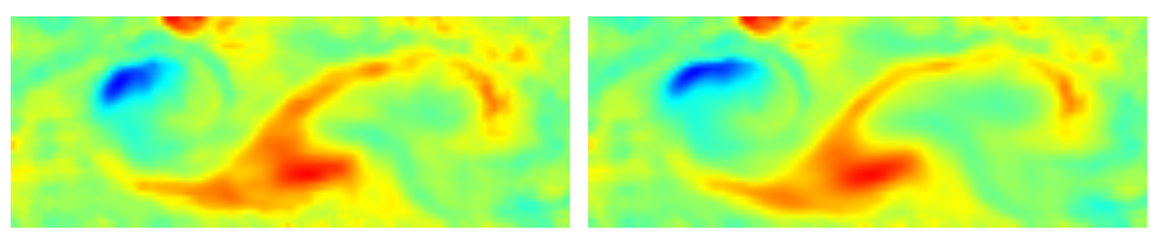
The numerical accuracy of the synthetized images is crucial for the effective exploitation of the forecasts. Two spatial discretization schemes are combined during the temporal integration:

- A semi-Lagrangian scheme, denoted $\frac{1}{2}L$, which is unconditionally stable and allows a large time step.
- A Godunov scheme, denoted G, which solves the Riemann problem at each inter-pixels boundary. It is adapted for an accurate advection of functions with high spatial gradient values (but CFL conditions).



Forecast results:

$\mathbf{w}$ from $(\mathbf{Y}_0, \mathbf{Y}_1, \mathbf{Y}_2, \mathbf{Y}_3)$
Last Obs $\mathbf{Y}_3$ $\rightarrow$



Forecast F_4 F_5

VALIDATION

Comparison of the acquisitions $\mathbf{Y}_i$ to the corresponding forecasts (at the same time) F_i, F'_i, F''_i:

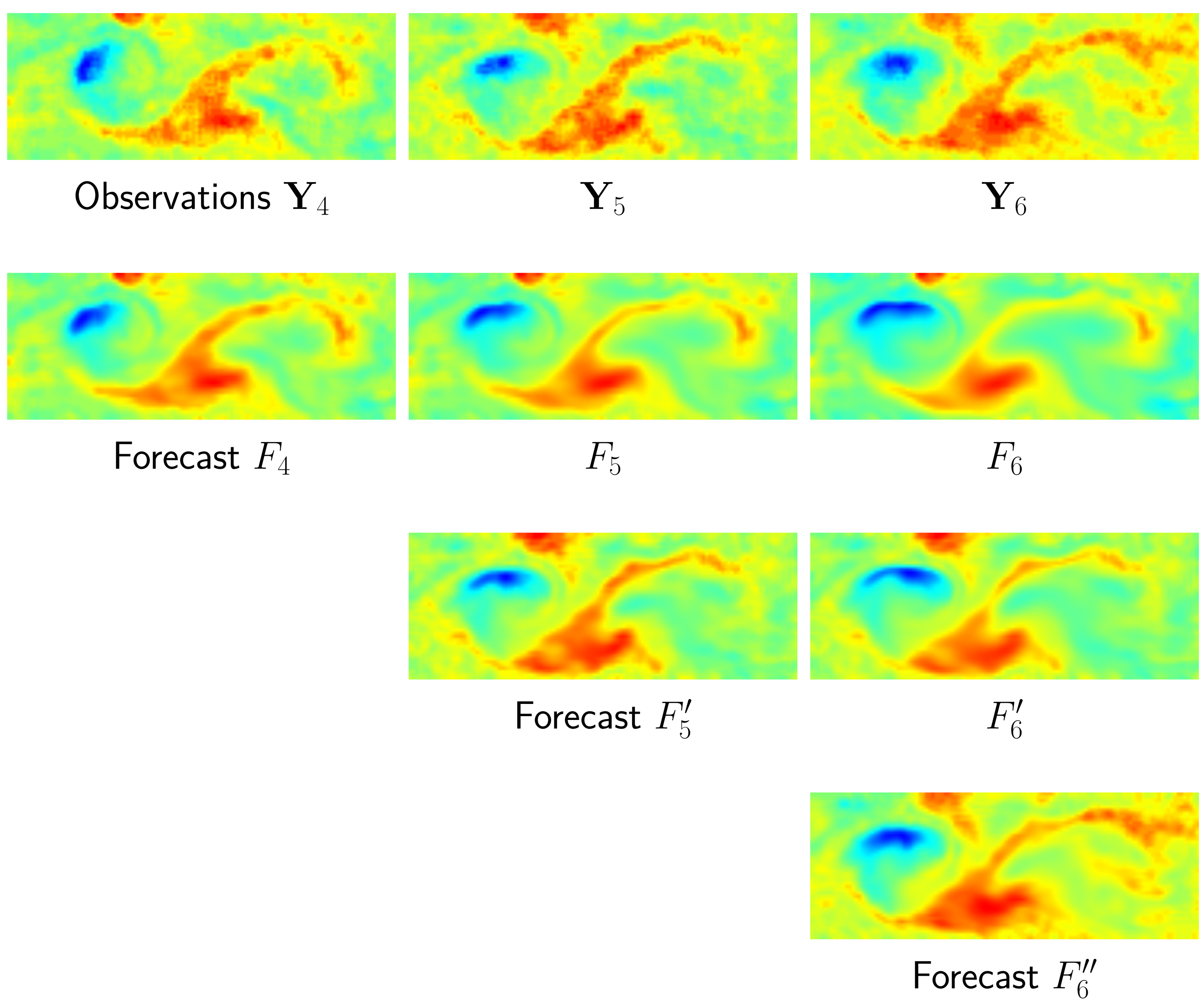


Image courtesy: Gennady Korotaev, Marine Hydrophysical Institute, Sevastopol.