IMPROVING WATER LEVELS FORECAST IN THE GIRONDE ESTUARY USING DATA ASSIMILATION ON A 2D NUMERICAL MODEL : CORRECTION OF TIME-DEPENDENT BOUNDARY CONDITIONS THROUGH A TRUNCATED KARHUNEN-LOÈVE DECOMPOSITION WITHIN AN ENSEMBLE KALMAN FILTER

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LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

Plan

Context and motivation

Uncertainty quantification

Improving water levels forecast with data assimilation

Conclusions and perspectives

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Plan

The Gironde estuary

The Gironde estuary

- 635 km²

- **Confluence between 2 rivers**
- **mean discharges**
  - **Dordogne : 380 m³/s**
  - **Garonne : 630 m³/s**

- 75 km long (Bec d'Ambès to the mouth)
- Dowstream width : 12 km

- Maritime influence
- Inflows from the Atlantic Ocean :
  15 à 25000 m³ / tide cycle

Stakes

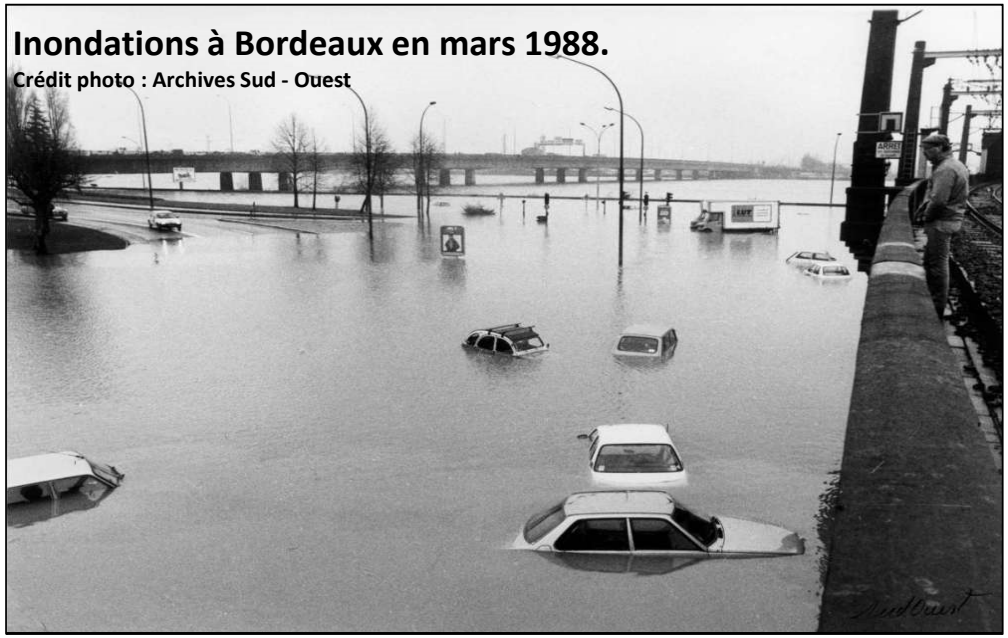
- Human : 185 cities, 1 million inhabitants ; agriculture
- Industrial stakes: Blayais hydroelectric power station, Pauil petrol terminal

Natural Hazards

- Sea river flooding
- Climate change

=> Marine submersions

=> floods



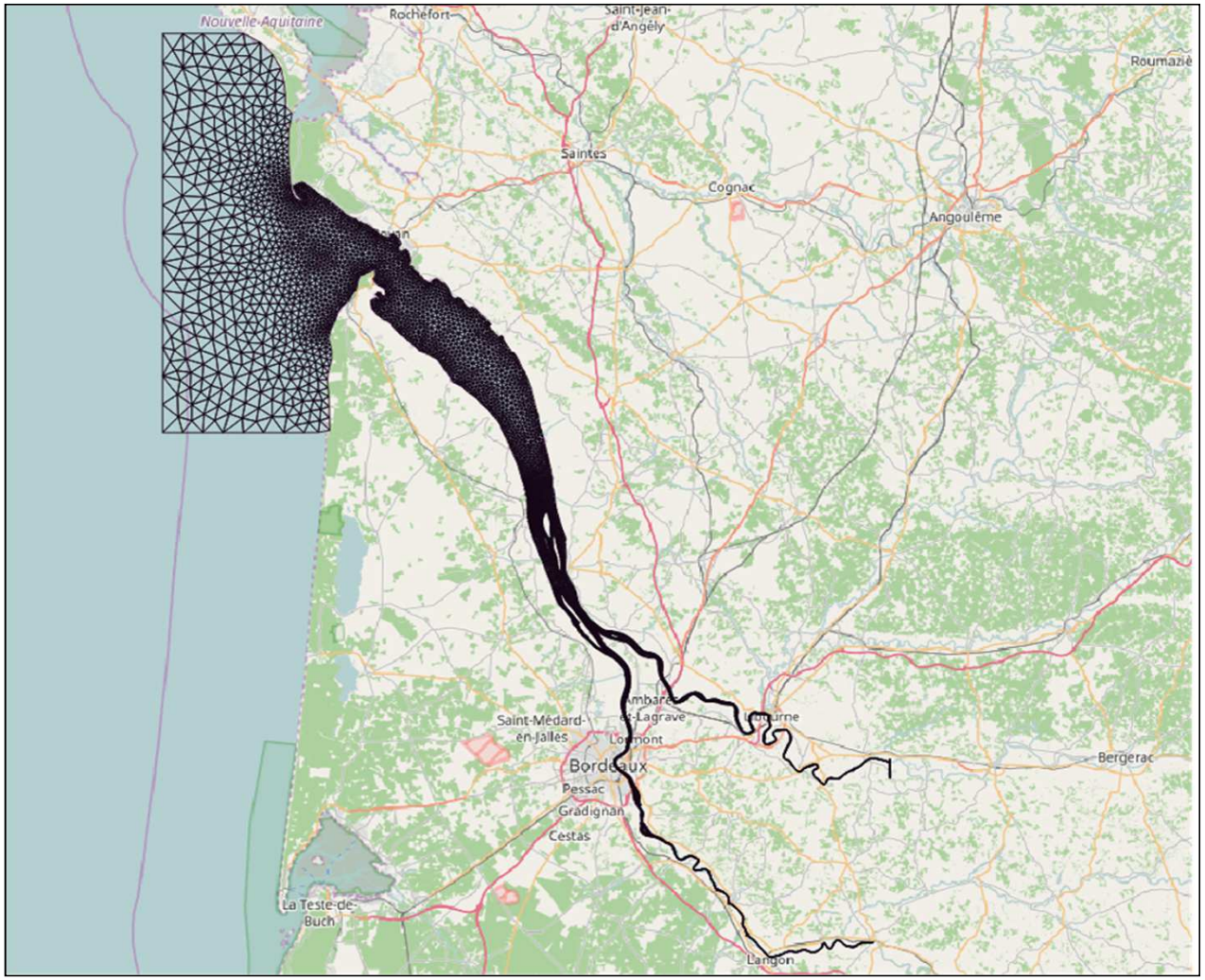
Inondations à Bordeaux en mars 1988.

Crédit photo : Archives Sud - Ouest

Source : Schéma directeur de prévision des crues Adour-Garonne , DREAL Midi-Pyrénées, 29/12/2015

Water levels forecast in Gironde estuary using a Telemac2D numerical model

- Based on :
  - ✓ 2D shallow water equations
  - ✓ Unstructured mesh (space discretization) : 7351 nodes, 12838 elements (**mesh0**)
  - ✓ Output on each node : (H,U,V)



Water levels forecast in Gironde estuary using a Telemac2D numerical model

Calibration parameters

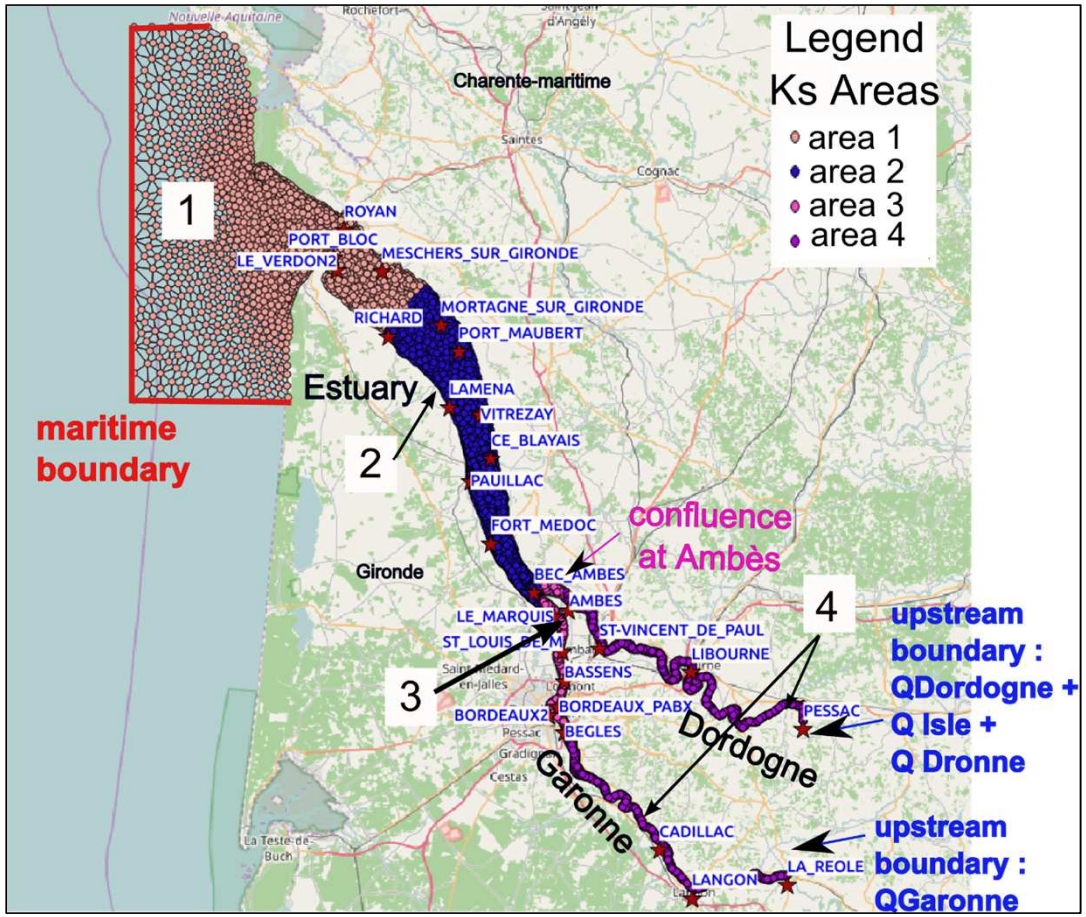
- Friction coefficients : Ks1, Ks2, Ks3, Ks4
- Wind influence coefficient : Cdz

Forcings

- Meteorological : wind and pressure
- Maritime boundary conditions (CLMAR)
- River discharges : in Garonne (QGAR) and Dordogne (QDOR)

Other inputs: topography and bathymetry

- No overflowing
- Bathymetry provided by GPMB



Water levels forecast in Gironde estuary using a Telemac2D numerical model

EVENTS

- **calibration :** 4 events among which 2003
- **validation :** 6 events among which 1999

Événement	Débits sur la Dordogne	Débits sur la Garonne	Plage de variation du coefficient de marée
10 au 14/03/2006	850 à 1550 m^3/s	1700 à 4700 m^3/s	37 à 83
27 au 31/03/2006	500 à 950 m^3/s	650 à 1200 m^3/s	78 à 115
3 au 6/05/2004	450 à 700 m^3/s	1650 à 2450 m^3/s	86 à 105
2 au 9/02/2003	600 à 2200 m^3/s	1200 à 5900 m^3/s	43 à 90
25 au 31/12/1999	430 à 1830 m^3/s	400 à 3600 m^3/s	45 à 102
24 au 30/04/1998	300 à 1200 m^3/s	630 à 3100 m^3/s	70 à 105
3 au 10/02/1996	300 à 850 m^3/s	880 à 2550 m^3/s	71 à 87
20 au 26/12/1995	250 à 550 m^3/s	500 à 1200 m^3/s	79 à 107
17 au 20/03/1988	500 à 1800 m^3/s	1250 à 5500 m^3/s	99 à 115
12 au 17/12/1981	1000 à 2350 m^3/s	1700 à 7050 m^3/s	57 à 106

Water levels forecast in Gironde estuary using a Telemac2D numerical model

EVENTS

- **calibration :** 4 events among which 2003
- **validation :** 6 events among which 1999

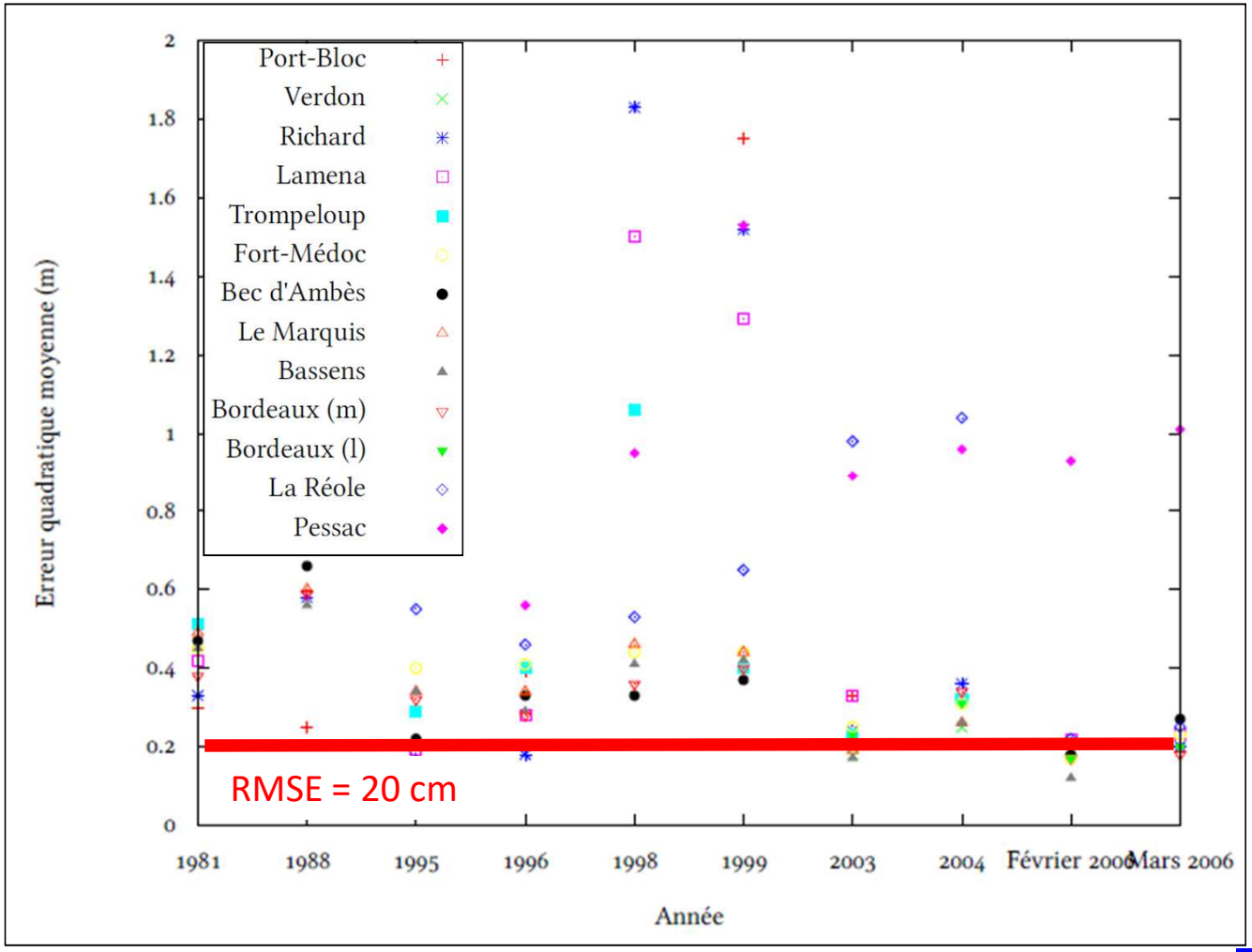
Stations

- 13 stations

Criteria

- Root mean square error (RMSE)
- **High tide nash (PM)**

=> Data assimilation techniques



Source : Hissel (2010), Projet Gironde : rapport final d'évaluation du modèle Gironde

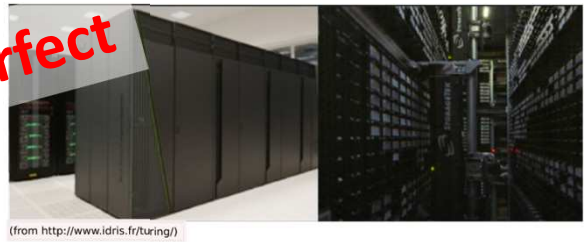
Data assimilation

Observations

Measurement errors
Ad hoc measures

Parcellaires and imperfect

Numerical model



Equations
Calibration
Forcings

What do we know ?

- the "true" state of the system is **unknown** and must be estimated
- measurements and models are **imperfect**

What do we want ?

- Identify **the most influential variables in time and space**
- find an **optimal combination** of measurements and simulations

(from Rochoux & al, 2015)

Improve **the prediction of water levels at the most sensitive stations of the estuary using ensemble data assimilation techniques.**

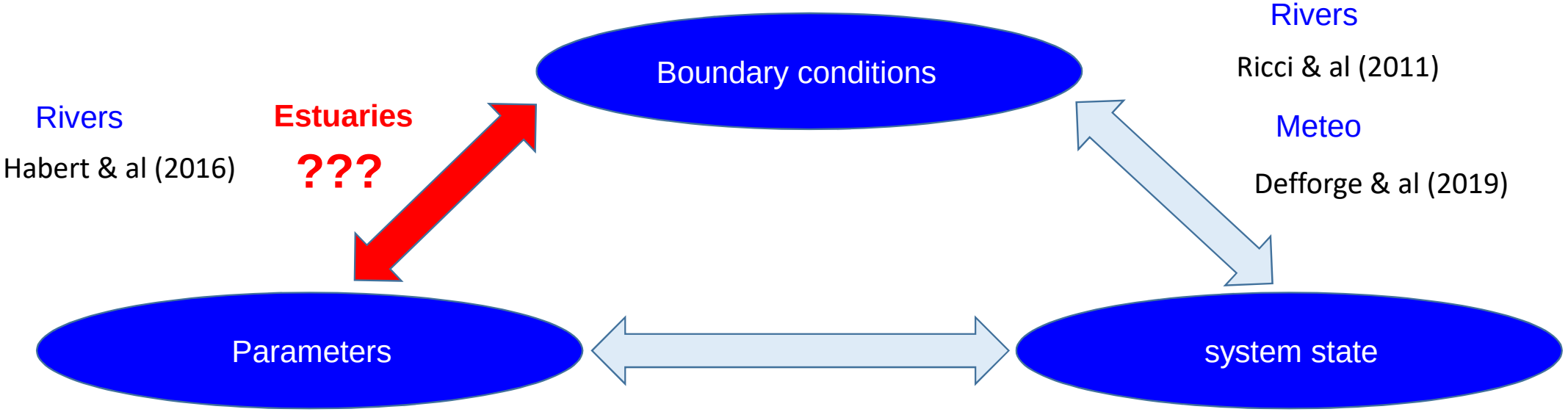
Partie I : uncertainty quantification (UQ-GSA)

- Objective : identify the most influential variables and establish a space-time hierarchy
- Scientific latch: space-time variables / forcings (maritime influence)
- Technological lock: 2D code (resources / environment)

Partie II : data assimilation using ensemble method (EnKF-ɣ-KLBC)

- Objective : correct relevant variables by optimizing the observation network
- Scientific locks :
  - ✓ Dispersion/characterization of the ensemble
  - ✓ Interactions between variables and equifinality
- Technology lock: 2D code (HPC / sequential task farming)

State of the art for the control vector



Rivers

Habert & al (2016)

Estuaries

???

Rivers

Ricci & al (2011)

Meteo

Defforge & al (2019)

Rivers

Vrugt &al (2006)
Moradkhani (2005)
Oubanas & al (2018)

Estuaries

Tamura & al (2014)
Siripatana (2018)

Uncertainties put on

Meteo

Almeida & al (2015)
Etala & al (2015)
Raboudi & al (2019)

Boundary conditions

Bertino & al (2002)
Frolov & al (2009)
Canas & al
Barthélémy (2017)

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Plan

Context and motivation

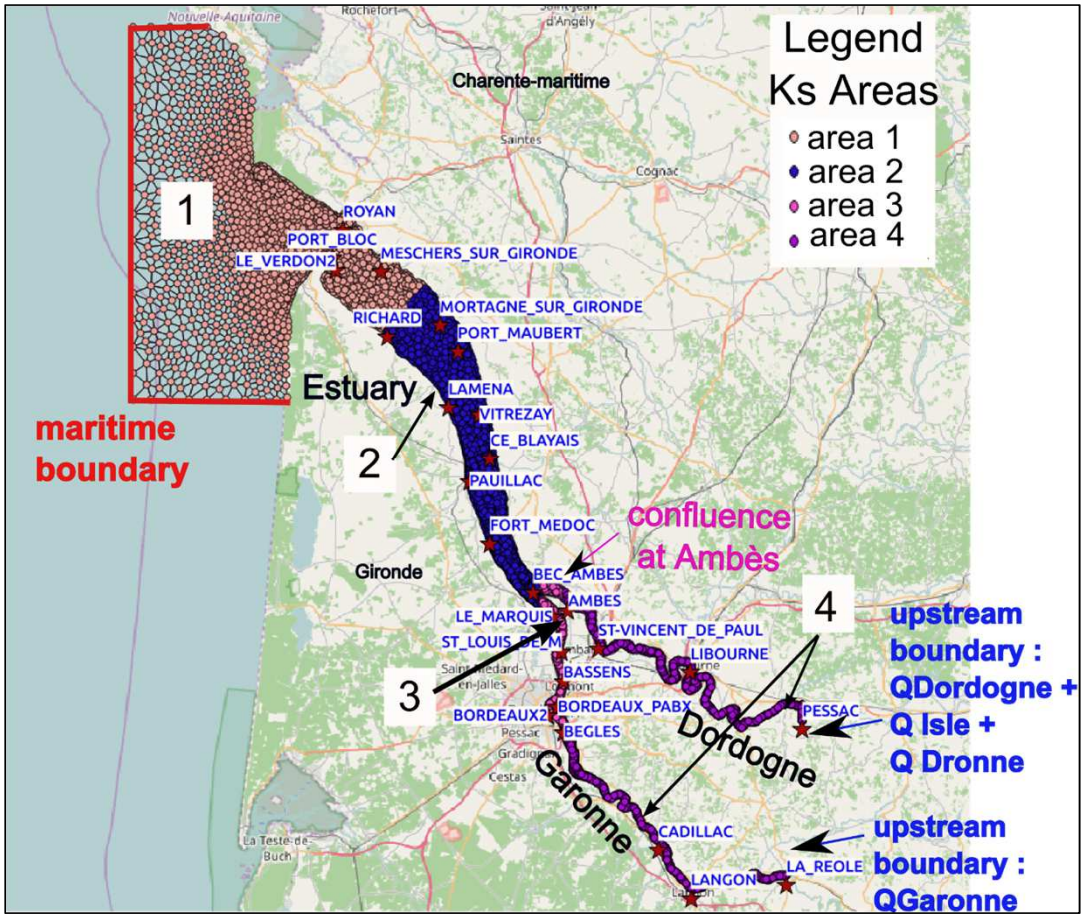
Uncertainty quantification : most influential inputs in time and space

Improving water levels forecast with data assimilation

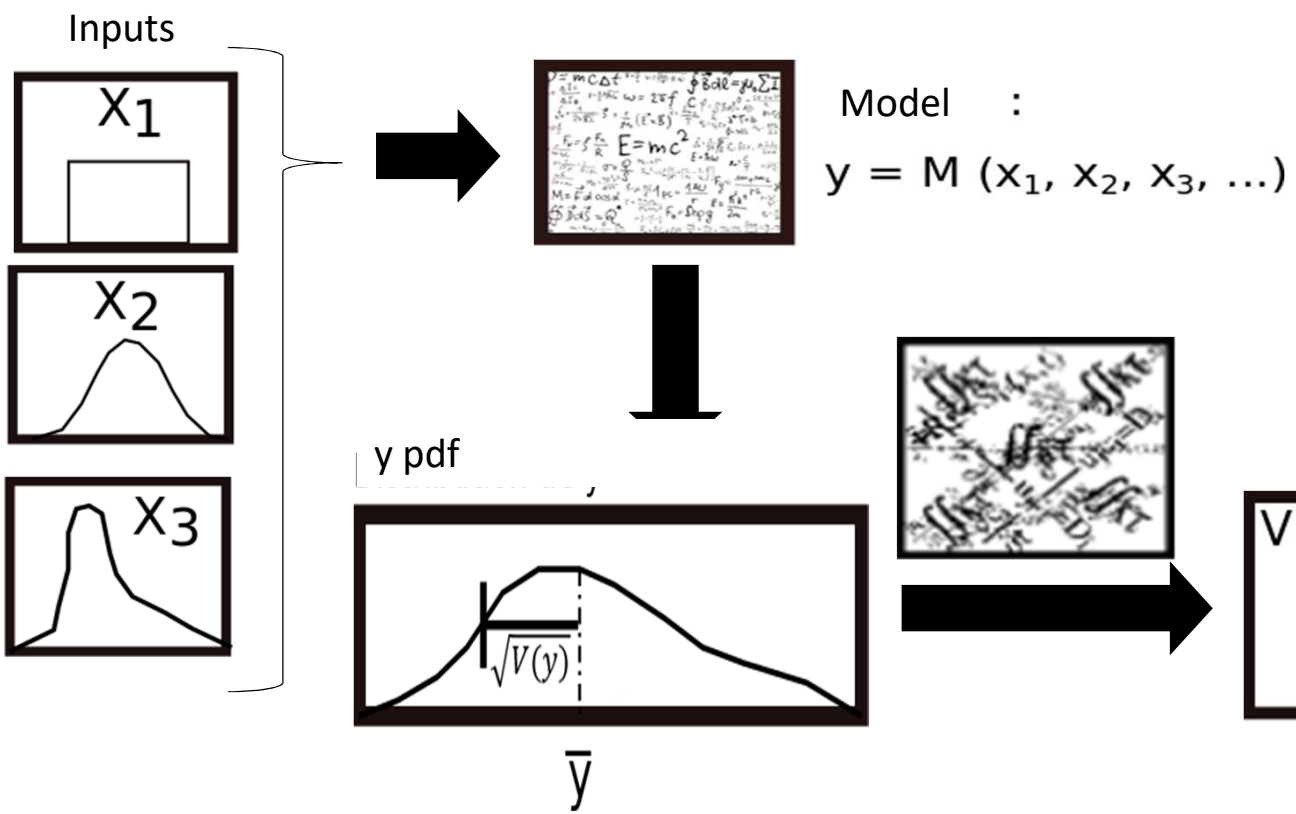
Conclusions and perspectives

Global sensitivity analysis (GSA) using variance decomposition (ANOVA) : Methodology for perturbing inputs

- Sobol‘ sequence
- 8 uncertain variables:
  - ✓ scalar : Ks, CDz
  - ✓ **Time-dependent :**
    CLMAR, QDOR, QGAR
- Mesh and number convergence study



Global sensitivity analysis (GSA) using variance decomposition (ANOVA)



Why « global » ?

- Statistical approach based on the **resampling** of the input space
- parameters **varying simultaneously** in the complete range of values

- **Very large** number of simulations

(**Ne***(**d**+2))

$$ST_i = E_{X_i}(V_{X_i}(Y|X_i))$$

D'après Saltelli & al, 2000

Global sensitivity analysis (GSA) using variance decomposition (ANOVA) : Methodology for perturbing time-dependent inputs

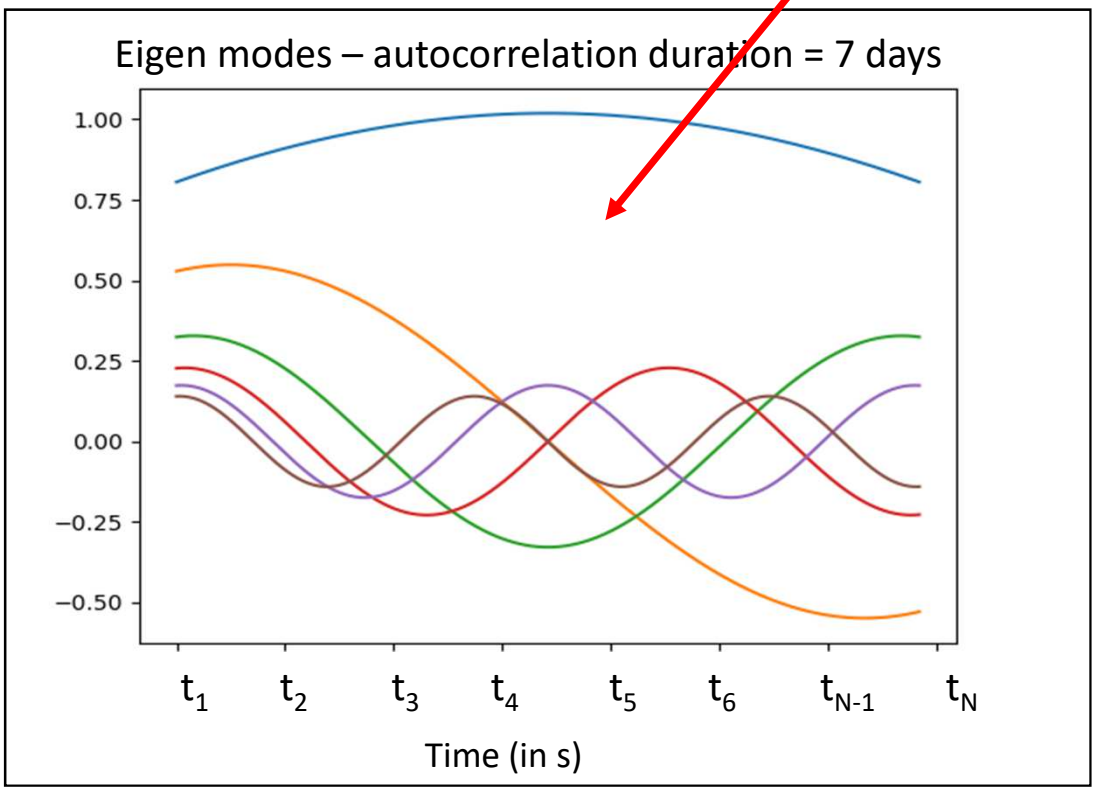
Objective
Preserve the temporal error correlation

Assumption
Time chronicles represented by Gaussian processes

Method
Reduction of the input space with a Karhunen Loève decomposition

Temporal vector : perturbed member p over Ne

$$q_p = (q_p(t_1), \ldots, q_p(t_N))^T = \sum_{i=1,n_{modes}} \sqrt{\lambda_i}\,\Phi_i \xi_i.$$



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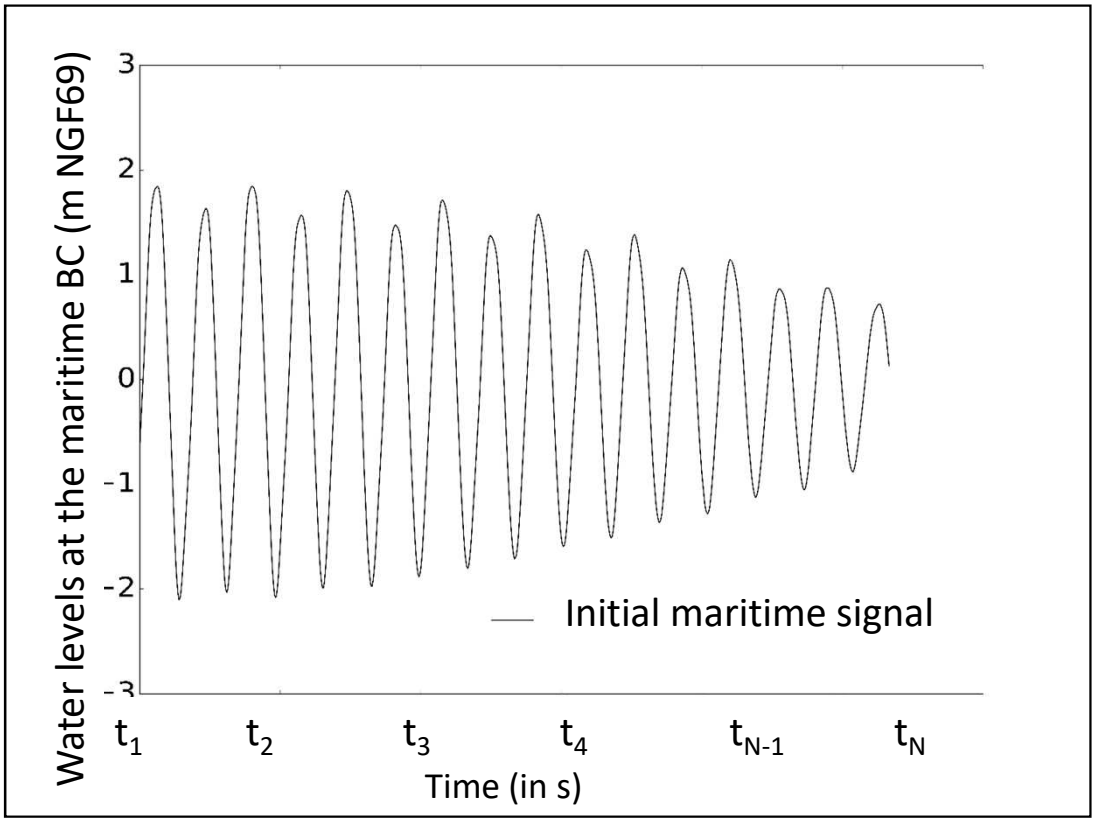

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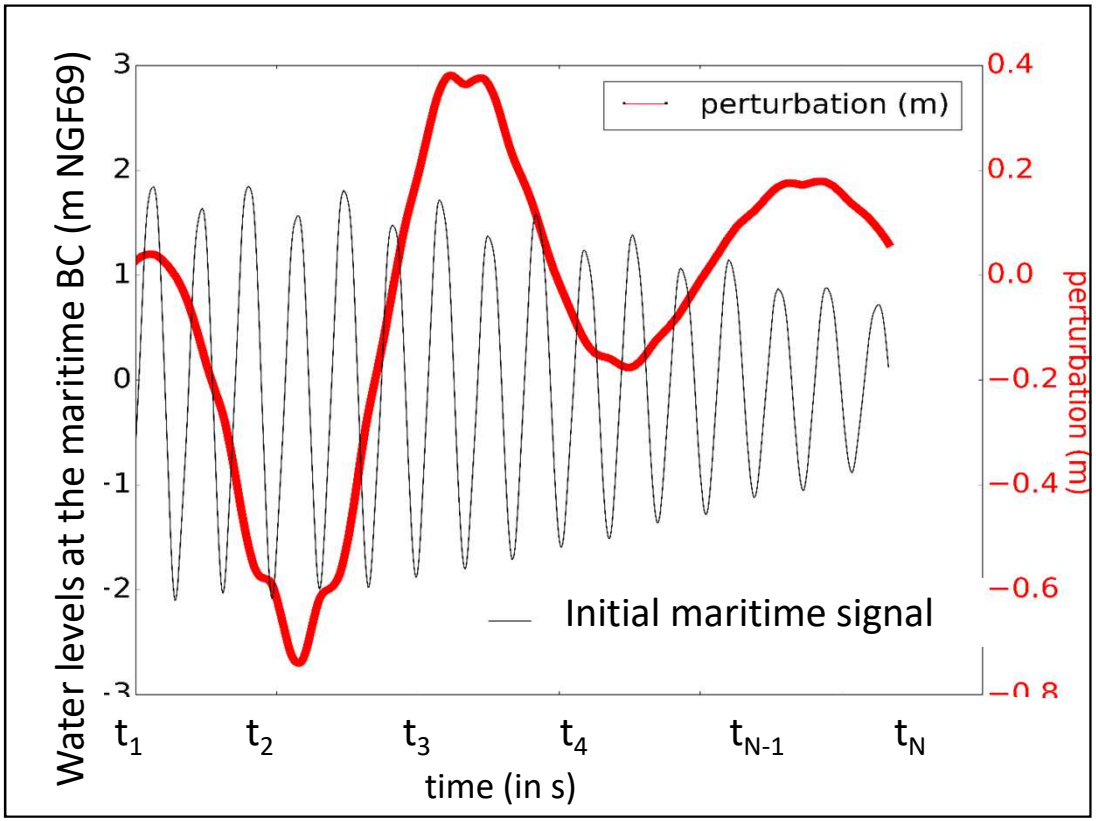

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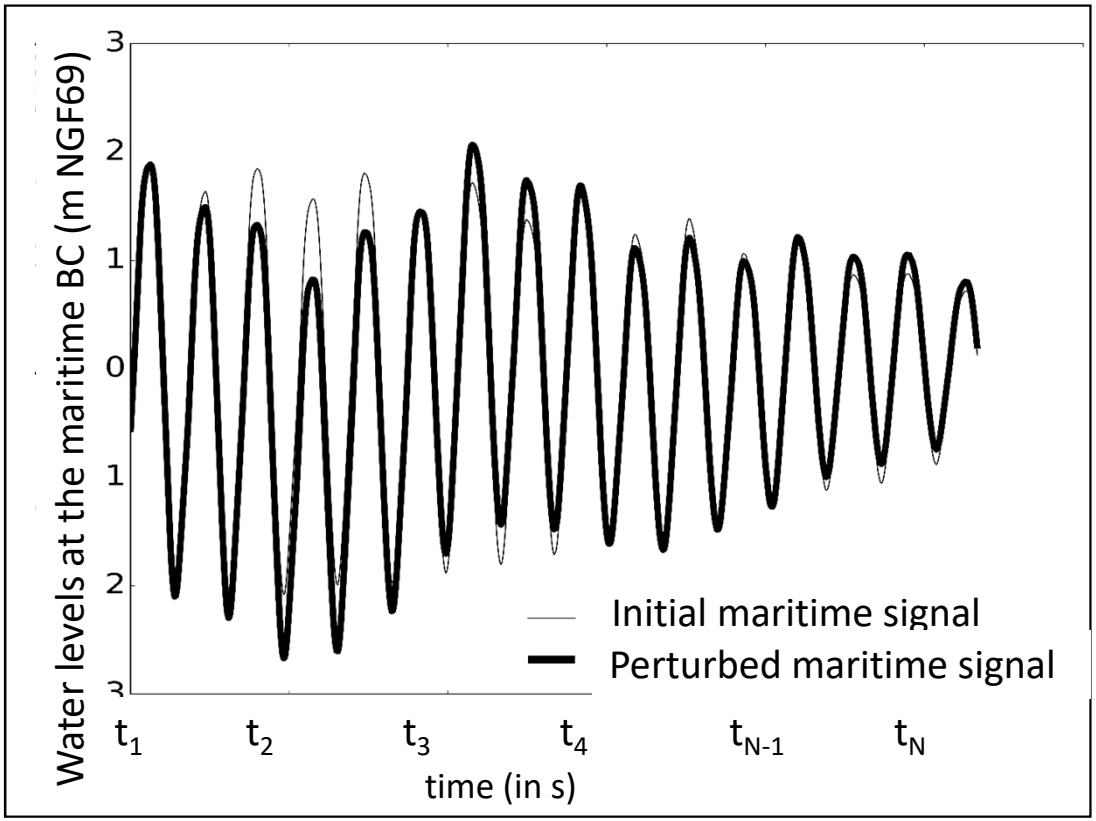


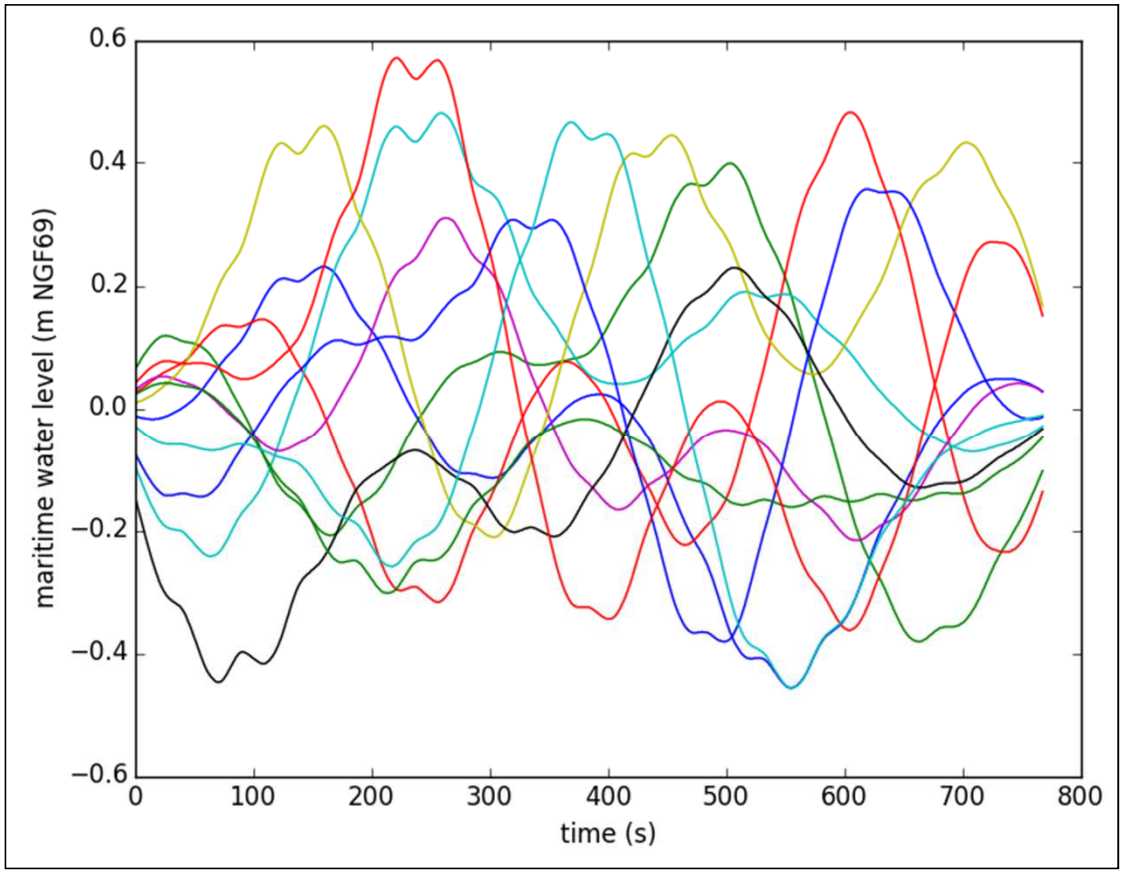
Global sensitivity analysis (GSA) using variance decomposition (ANOVA) : Methodology for perturbing time-dependent inputs

Objective
Preserve the temporal error correlation

Assumption
Temporel chronicals Time Chronicles represented by Gaussian Processes

Method
Reduction of the input space with a Karhunen Loève decomposition

Ensemble of Ne members of perturbed temporal vectors

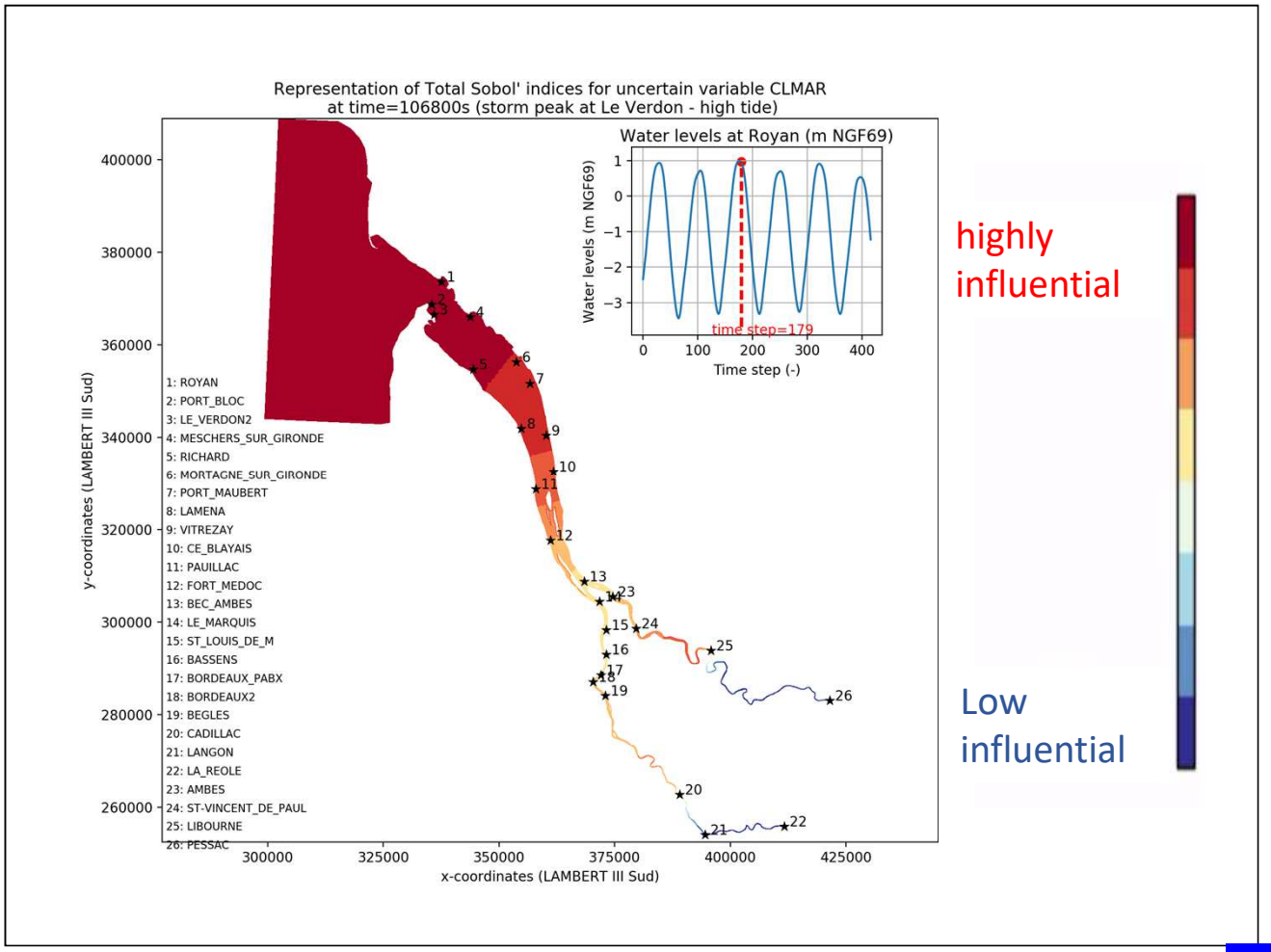


Global sensitivity analysis (GSA) using variance decomposition (ANOVA) : results

Method
Computation of **Sobol' indices**

Results
Determination of the **spatio-temporal evolution of the zone of influence**

Exemple
Space-time homogeneity



Laborie, V & al (2019), Quantifying forcing uncertainties in the hydrodynamics of the Gironde estuary , J. of Comp. Geosciences

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The Ensemble Kalman filter

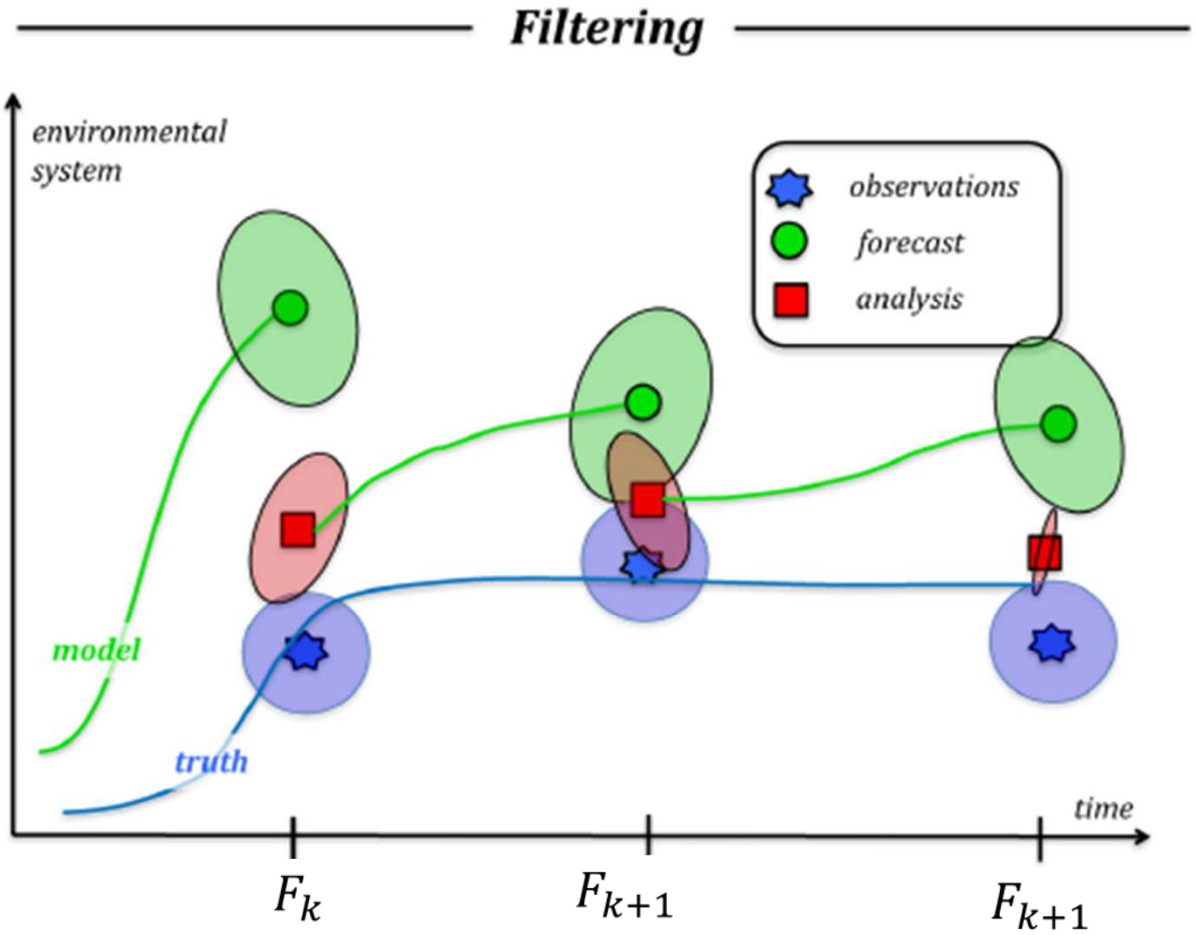
- Choice of a control vector
- Construction of the ensemble

$$\gamma \rightarrow \begin{cases} Ks_i \text{ with } i \in (1,..,4) \\ \alpha_i \text{ with } i \in (1,..,n_{modes,CLMAR}) \\ Cd_z \\ \alpha_{i,GAR} \text{ with } i \in (1,..,n_{modes,QGAR}) \\ \alpha_{i,DOR} \text{ with } i \in (1,..,n_{modes,QDOR}) \end{cases}$$

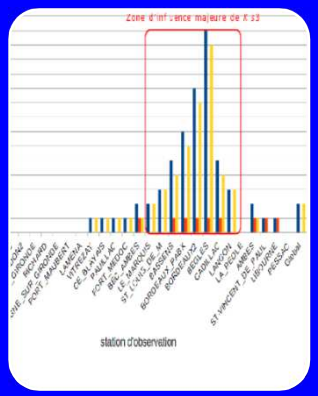
The Ensemble Kalman filter

- Choice of a control vector
- construction of the ensemble
- **Sequential in 2 steps (analysis and prediction)**

$$\mathbf{K} = \mathbf{P}^{y,y}\left(\mathbf{P}^{y,y} + \mathbf{R}\right)^{-1}$$



(Source: Carrassi & al (2018))



Validation with twin experiments

- Influence zone validation
- Time-varying parameters
- Simultaneous reconstruction of parameters and forcings

Evaluation on real experiments

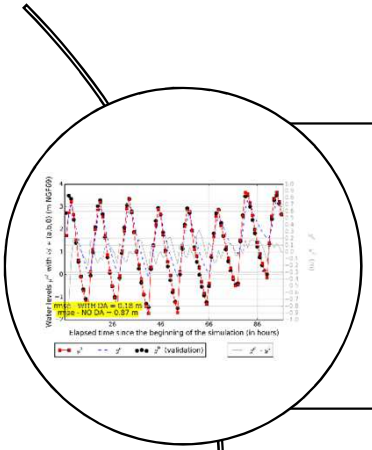
- Evolution of parameters and forcings
- Performances

Constant and periodic coefficients of friction

Control variable
Ks1, Ks2, Ks3
Ne = 100

Observations
3 stations: Le Verdon, Pauillac, Bordeaux
Frequency
1 hour

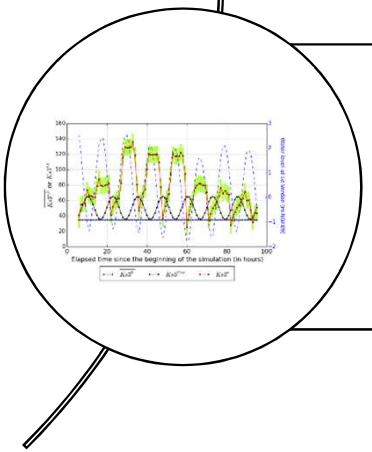
Assimilation window
1 hour
Overlapping
1 hour



Validation of influence zones

Good **estimation** of constant or periodic parameters

Improvement of water level forecasting



Over-estimation of the amplitude of the parameters

Difficulties in estimating Ks3 (**confluence** zone)

Highlighting the **equifinality** on the Ks

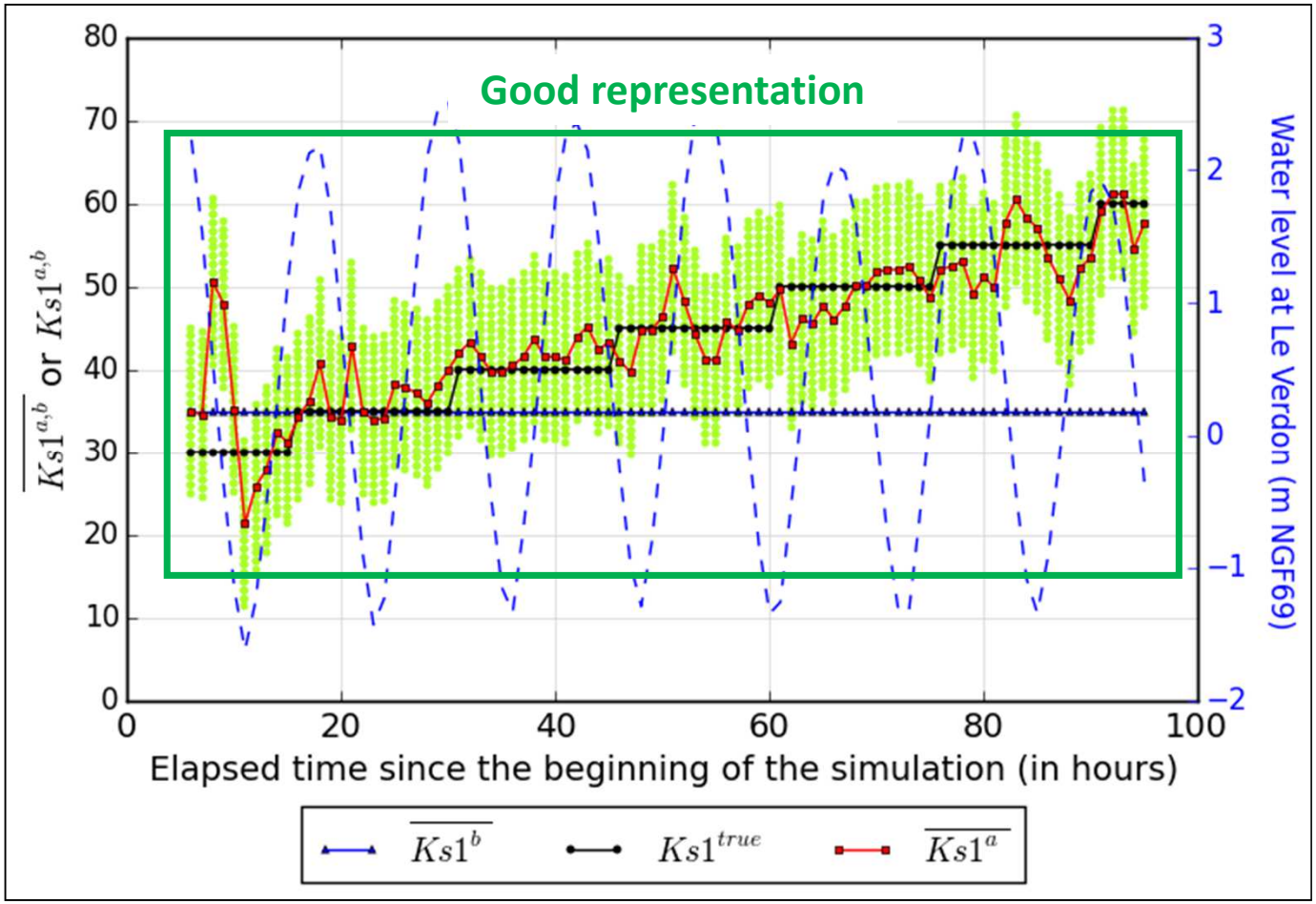
Joint estimation of forcing by decomposition of KL and parameters

Control variable
Ks1, Ks2, Ks3, α_{CLMAR} $\alpha_{GARONNE}$, $\alpha_{DORDOGNE}$
Ne = 100

Observations
12 stations
Frequency
1 hour

Assimilation window
1 hour
Overlapping
1 hour

Evolution of the mean of the analysed ensemble WITH redispersion for Ks1



Joint estimation of forcing by decomposition of KL and parameters

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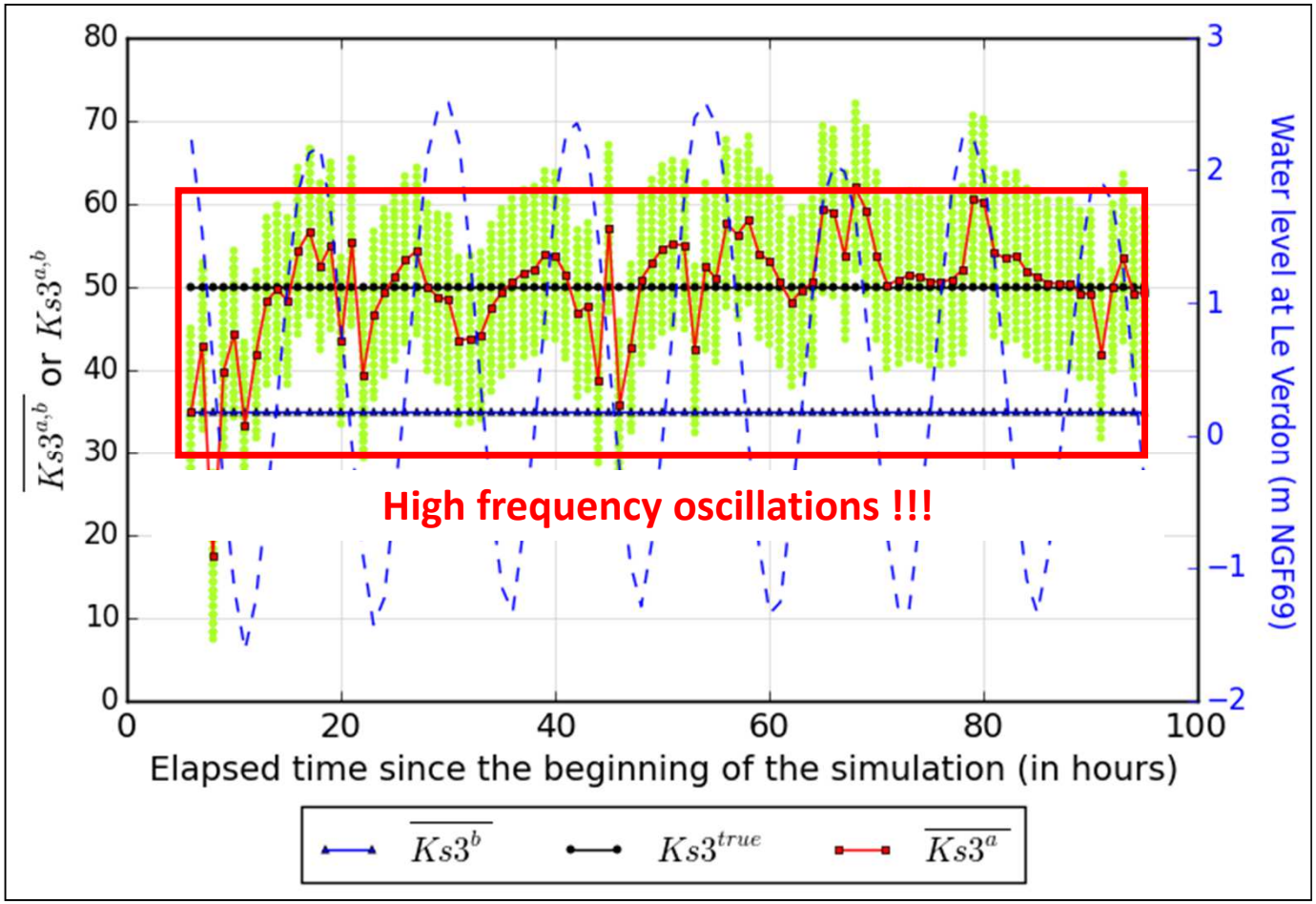
Observations
12 stations
Frequency
1 hour

Assimilation window
1 hour
Overlapping
1 hour

Evolution of the mean of the analysed ensemble WITH redispersion for Ks3



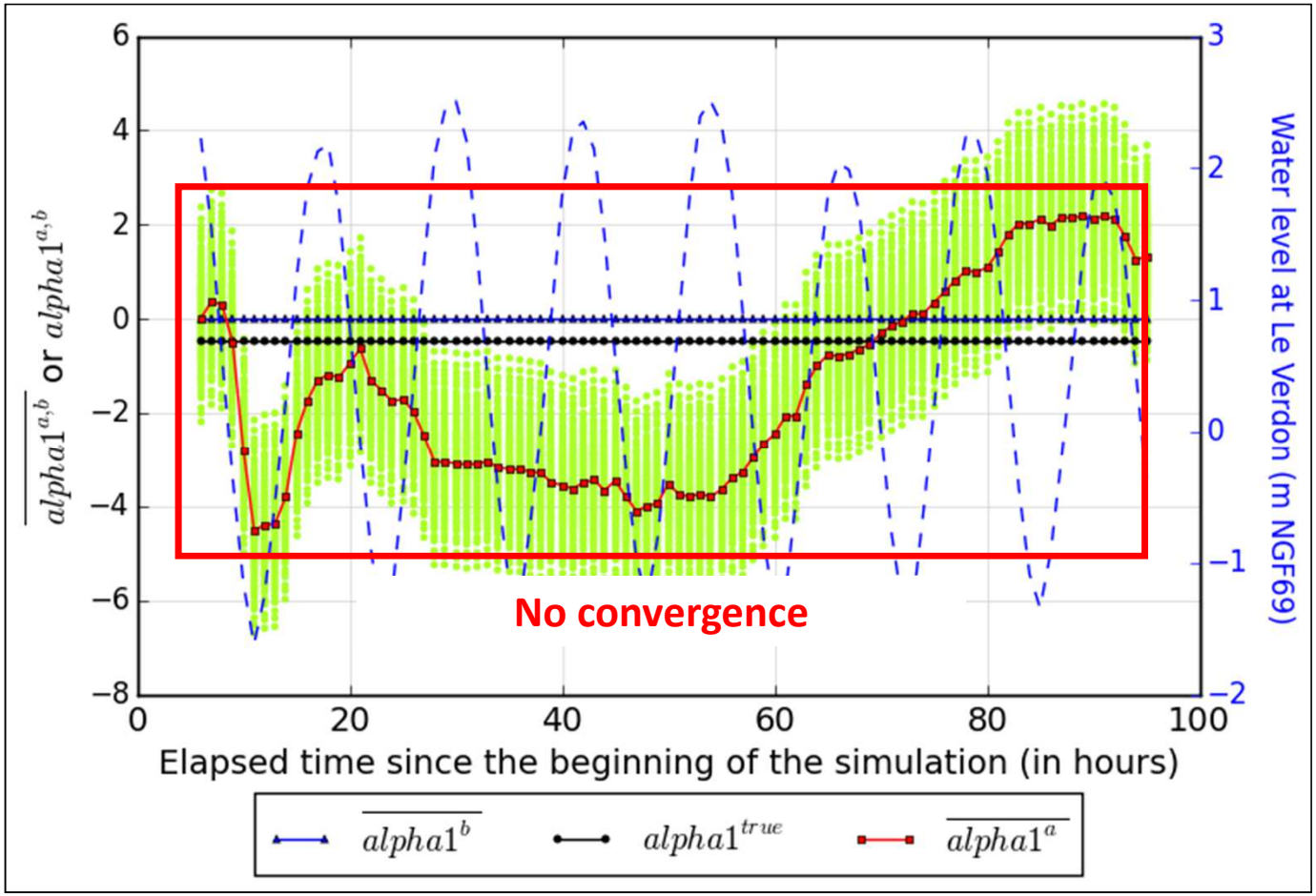
Joint estimation of forcing by decomposition of KL and parameters

Control variable
Ks1, Ks2, Ks3, α_{CLMAR}
$\alpha_{GARONNE}$, $\alpha_{DORDOGNE}$
Ne = 100

Observations
12 stations
Frequency
1 hour

Assimilation window
1 hour
Overlapping
1 hour

Evolution of the mean of the analysed ensemble WITH redispersion for α_{CLMAR}



Joint estimation of forcing by decomposition of KL and parameters

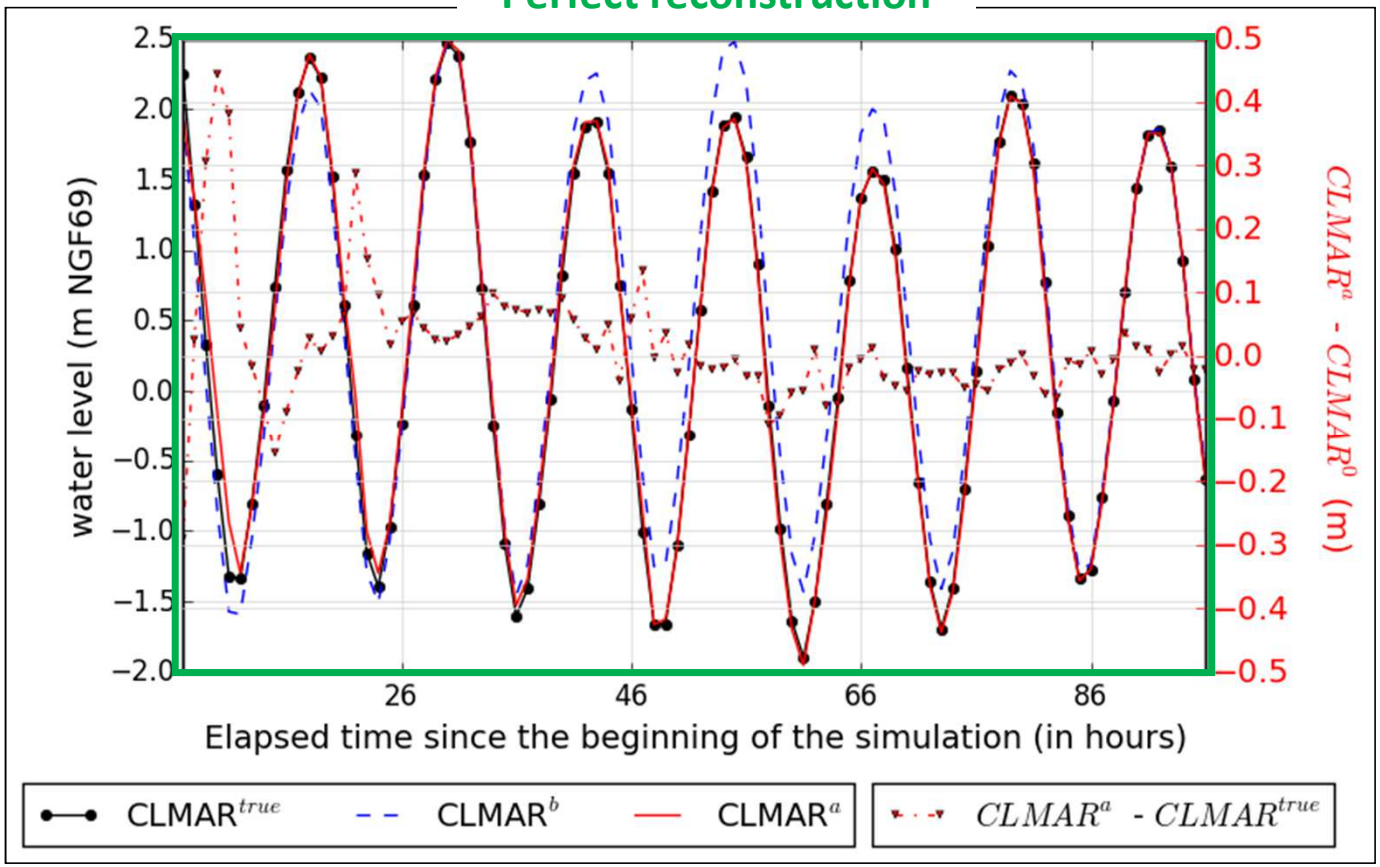
Control variable
Ks1, Ks2, Ks3, α_{CLMAR} $\alpha_{GARONNE}$, $\alpha_{DORDOGNE}$
Ne = 100

Observations
12 stations
Frequency
1 hour

Assimilation window
1 hour
Overlapping
1 hour

Reconstruction of the maritime boundary condition CLMAR

Perfect reconstruction



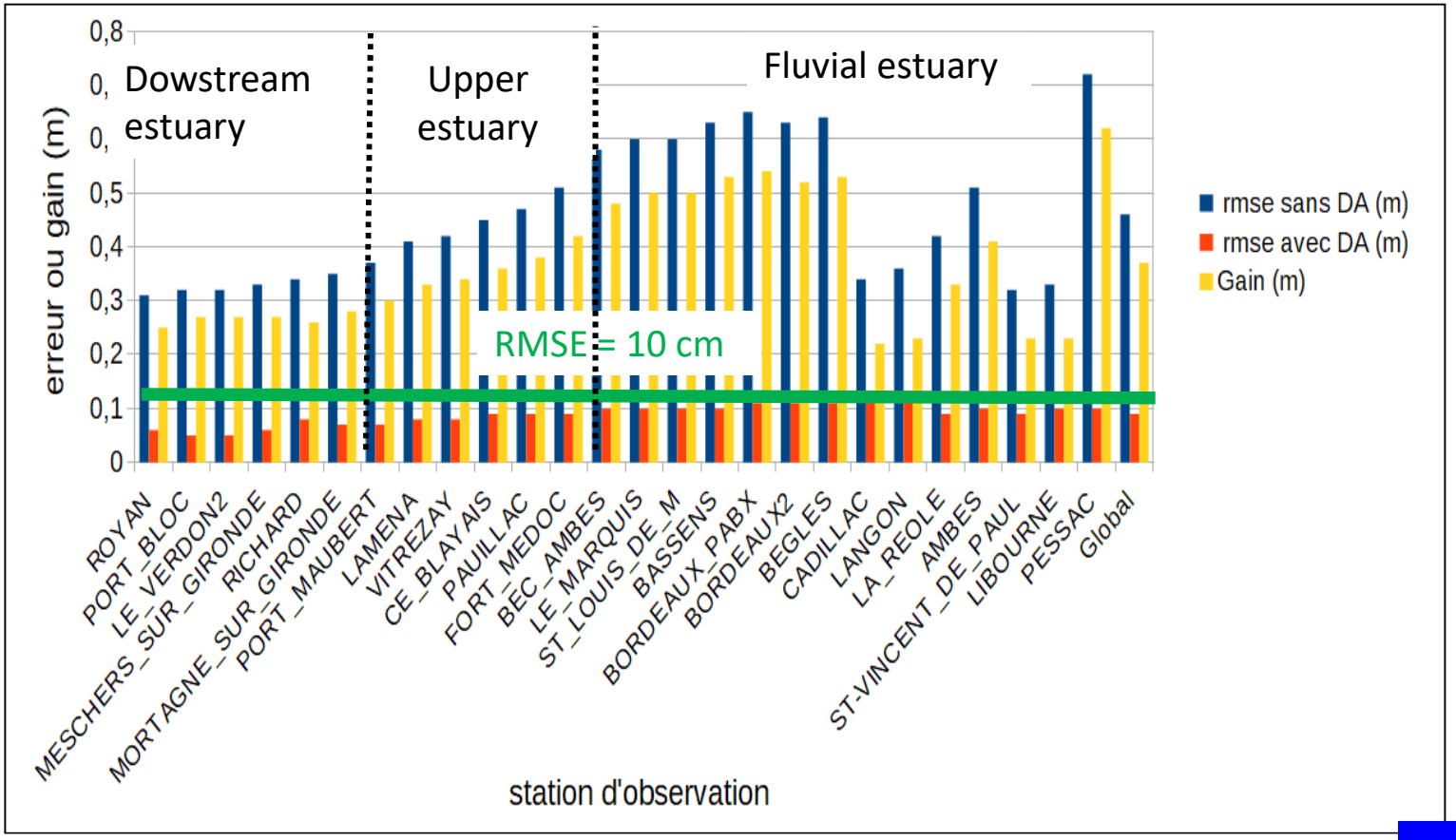
Joint estimation of forcing by decomposition of KL and parameters

Control variable
Ks1, Ks2, Ks3, α_{CLMAR} $\alpha_{GARONNE}$, $\alpha_{DORDOGNE}$
Ne = 100

Observations
12 stations
Frequency
1 hour

Assimilation window
1 hour
Overlapping
1 hour

Root mean square error without and with assimilation



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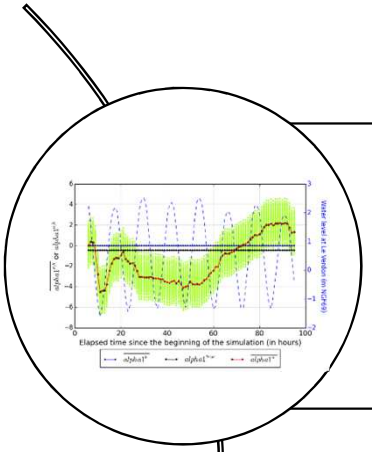
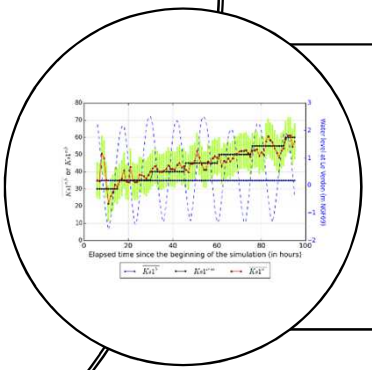


No convergence of modal coefficients

High-frequency oscillations for parameters

Difficulties in estimating Ks3 (confluence zone**)**

Equifinality on Ks and α



Good **estimation** of friction parameters

Very good **reconstruction** of time-dependent forcings

Improvement of water levels forecast

Joint estimation of forcing by decomposition of KL and parameters

Control variable
Ks1, Ks2, Ks3, α_{CLMAR}
$\alpha_{GARONNE}$, $\alpha_{DORDOGNE}$
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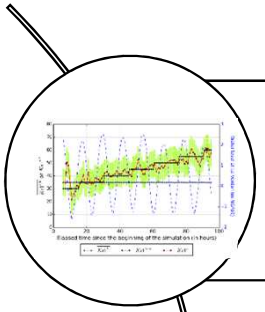
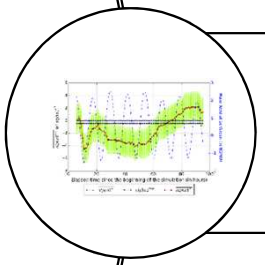
Observations
12 stations
Frequency
1 hour

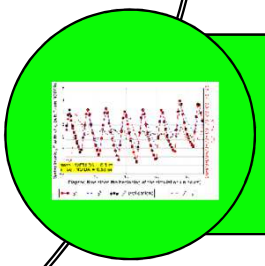
Assimilation window
1 hour
Overlapping
1 hour



Good **estimation** of friction parameters
Very good **reconstruction** of time-dependent forcings
Improvement of water levels forecast



No convergence of modal coefficients
High-frequency oscillations for parameters
Difficulties in estimating Ks3 (confluence zone)
Equifinality on Ks and α



Study of the **most efficient configuration** of the method
Control variables: time-dependent (discharges, maritime boundary): modes, parameters: Ks1, Ks2, Ks3
Optimal observation network: 7 tide gauges, Ne =100

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Plan

Context and motivation

Uncertainty quantification

Improving water levels forecast with data assimilation

Conclusions and perspectives

1. Identification of the spatio-temporal evolution of the zones of influence of time-dependent variables

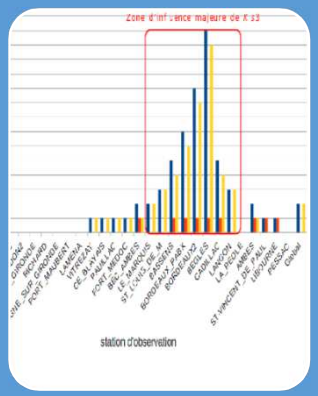
⇒ **Uncertainty Quantification** Study (ANOVA-GSA) for the 2003 storm
⇒ **Ensemble kalman filter**

2. Joint Estimation of Parameters and time-dependent forcings

⇒ **Correlations** and **specific equifinality**
⇒ **reconstruction** of **maritime** boundary conditions
⇒ **Sensitive area of the confluence**
⇒ **NO convergence of modal coefficients, variability of friction coefficients**

3. Improvement of water levels estimation along the estuary under reanalysis

⇒ **Better estimation** of high tides, storm peaks downstream of the estuary, signal amplitude
⇒ Most **efficient** configuration in a **synthetic** setting



Validation with twin experiments

Influence zone validation

Time-varying parameters

Simultaneous reconstruction of parameters and forcings

Evaluation on real experiments

Evolution of parameters and forcings

Performances

⇒ **Perspective 1**

2. Improvement of the methodology for a better representation of physical processes

⇒ **Localisation** based on the analysis of the **spatio-temporal evolution of sensitivity indices** (Sobol')
⇒ **Emulation** of the Ensemble Kalman filter (Raboudi & al, Frolov & al)
⇒ **Iterative Kalman Filter** (Sakov & al, 2012)

3. Extension of the control vector to 2D uncertain time and space dependent fields

⇒ **Integration of additional forcings:** meteorological forcing, bathymetry

4. Diversification of observations

⇒ **Satellite data (SWOT project)**

5. Model reduction and operationnability

⇒ **Metamodels**
⇒ **Predictive mode**

FIN

Thank you for your attention.

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