MERCATOR OCEAN INTERNATIONAL

Evolution of the Mercator global system at 1/12° with a focus on data assimilation updates

Jean-Michel Lellouche
&
the Mercator Ocean team

Outline

1. Current data assimilation system

2. Main ingredients of the new system: some issues we faced and the solutions we implemented

3. Description of the main updates of the system

4. Performances of the new system compared to the current one

1. **Current data assimilation system**

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Current data assimilation system

- **Analysis kernel:**
  - Based on the SEEK kernel formulation

$$K = S_n \left[I + (H S_n)^T R^{-1} (H S_n) \right]^{-1} (H S_n)^T R^{-1}$$

  - 3DFGAT method to calculate innovation vector
  - $2D_{x,y}$ Localization technique

- **Background error covariances P^f: multivariate 3D anomalies**
  - State vector *SIC, SIU, SIV, SITHI, SITEM,SST, H, HBRST, HBAR, T, S, U, V*
  - Sub-space is built from an ensemble of anomalies (A)

$$P^f = \frac{1}{n} A A^T = S_n S_n^T$$

- **Adaptive scheme for the background error variance**

- **IAU:**
  Incremental Analysis Update → to distribute the correction in time on *H, T, S, U, V, SI*

- **Assimilated observations:**
  Altimetric along-track SLA, satellite SST, T/S vertical profiles (Argo network, XBTs, CTDs, …), satellite sea ice concentration

Current data assimilation system

- **Analysis kernel**: + **3D-Var T/S large scale bias correction**
  - Based on the SEEK kernel formulation

$$K = S_n \left[I + (HS_n)^T R^{-1} (HS_n) \right]^{-1} (HS_n)^T R^{-1}$$

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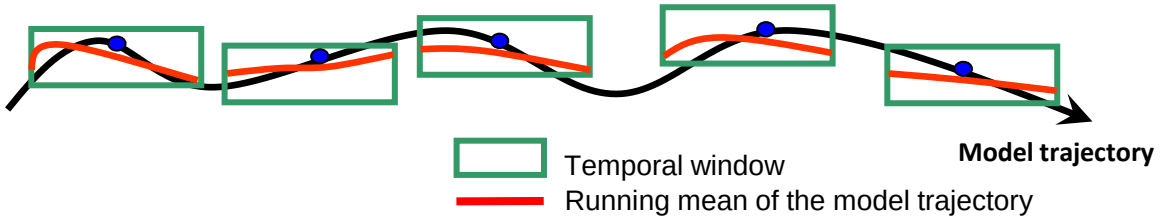
Background error covariances

Background error covariances:
Represented by 3D modes coming from a set of anomalies (statistical approach)

- **The method consists to generate a set of anomalies from a long simulation**



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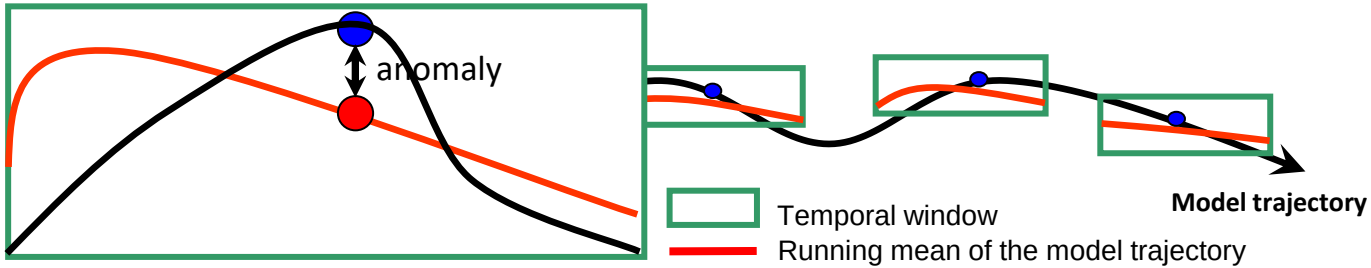

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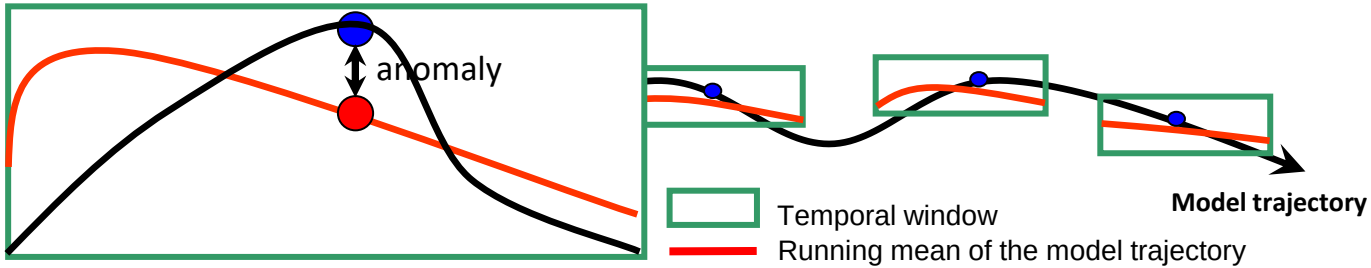

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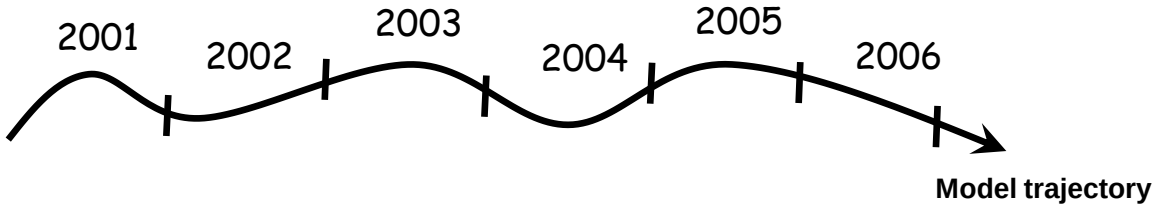

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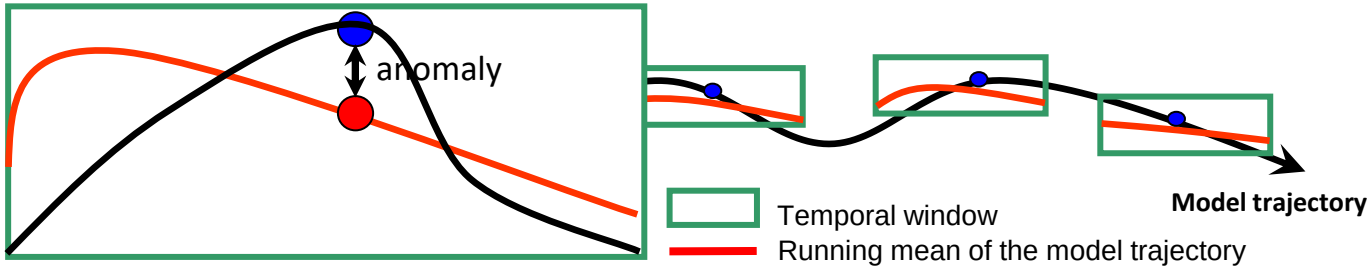

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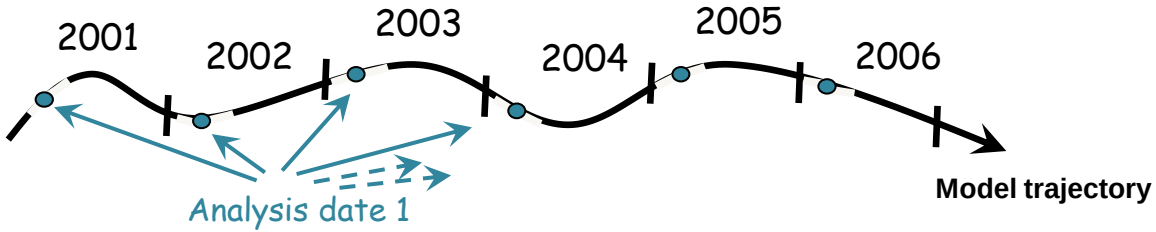

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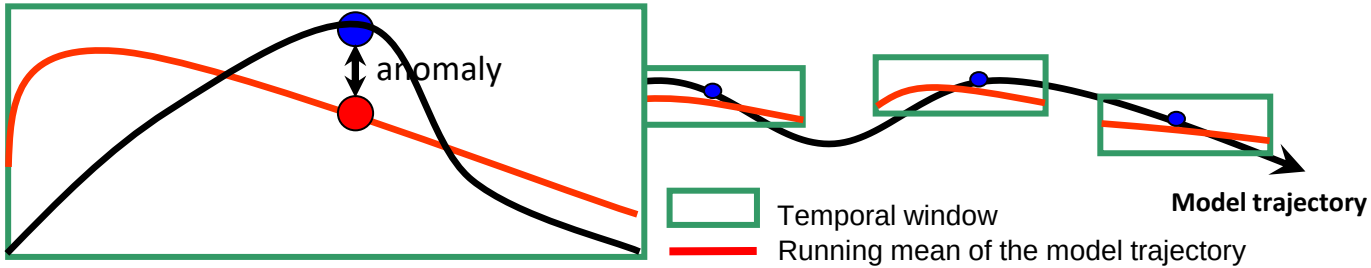

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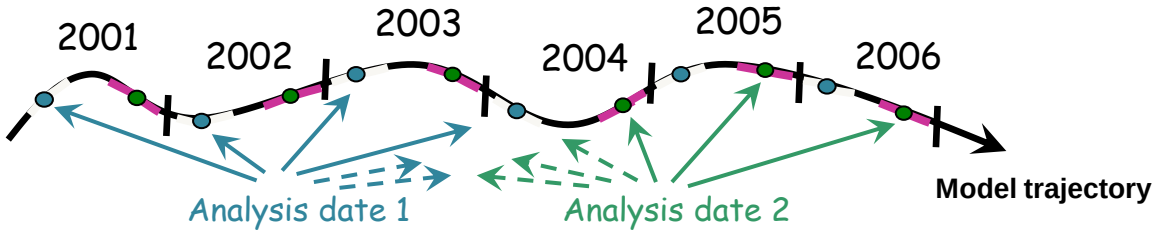

Adaptive Scheme for the background error variance

The adaptativity technic is based on the work of Desroziers and Ivanov (2001) and aims to estimate a scalar α for each local region, that multiplies the local restriction of **P** in order to be consistent with innovation statistics, so that the following equation is satisfied for each local region and each analysis cycle:

$$d^T [\alpha (HS)(HS)^T + R]\, d = n$$

$n = number\ of\ independent\ data$

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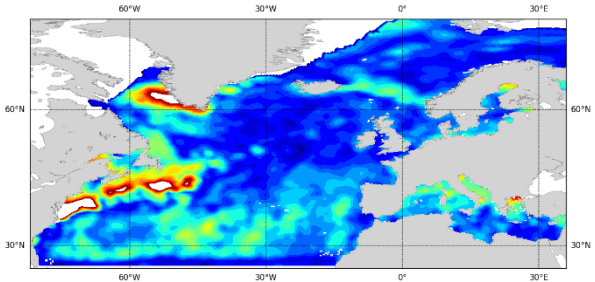
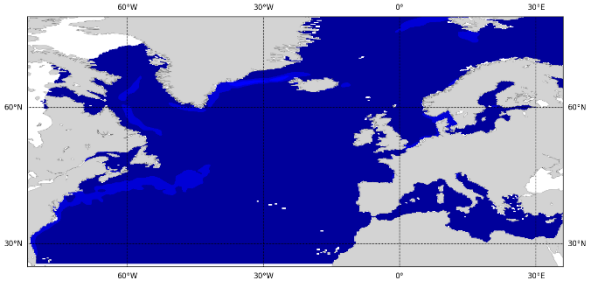
SST

$\sqrt{diag(dd^T)}$



Prior background error

$\sqrt{diag((HS)(HS)^T)}$



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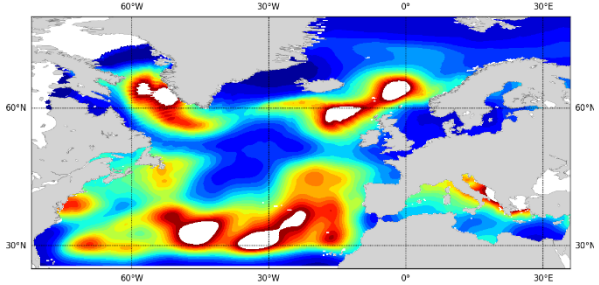
Amplification α of prior background error



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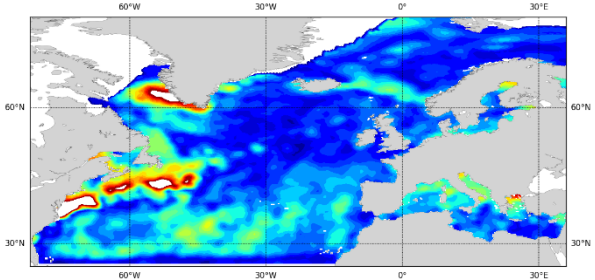
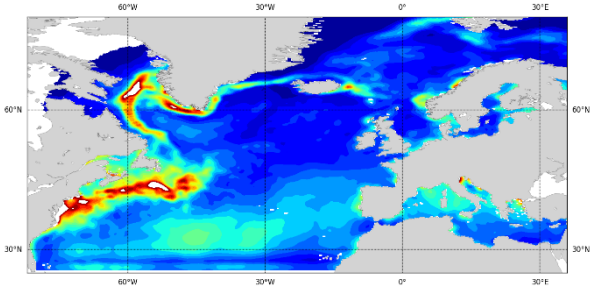


Adapted background error

$\sqrt{diag(\alpha(HS)(HS)^T)}$



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Objective and main updates

Objective: Develop a new version of PSY4 in order to improve, among others:

- Analysis and forecast skills, representation of mesoscale activity
- Mass / steric distribution (loss of mass and too much steric in the current system…)
- Equatorial dynamics and interaction with biogeochemistry

Main ingredients to achieve this objective:

- NEMO3.6 + LIM3 sea ice model
- HR spatial and temporal atmospheric forcing
- 5 bands light penetration + GLS

} Model

- SLA (new filtering) + new MDT
- SST HR ODYSSEA L3S instead of OSTIA L4 product

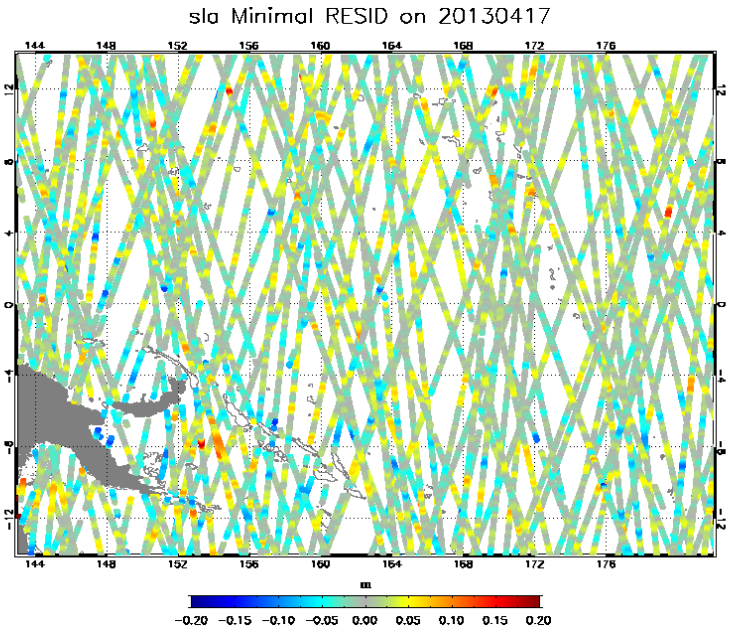
} New data

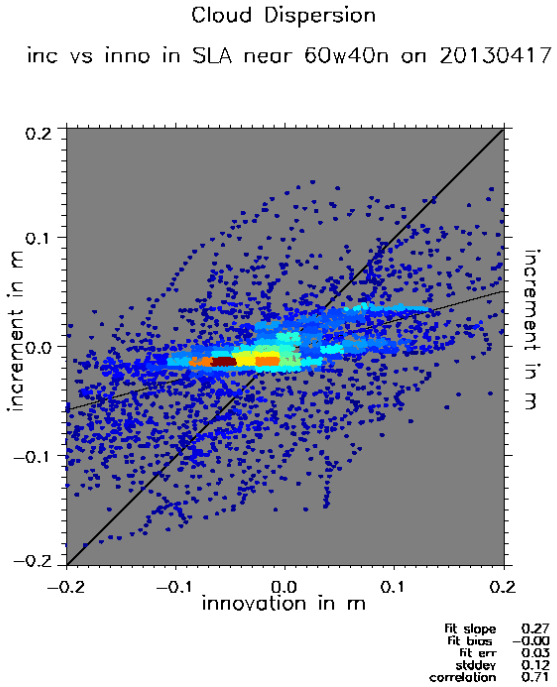
- SAM2 4D analysis
- New version of SAM2 (adaptativity, …)
- New multiscale anomalies bases from GLORYS12 reanalysis
- Bias correction optimized

} Assimilation

Some issues we faced and the solutions we implemented

The new **less filtered SLA** data contains **a lot of noise** (significant below 30 km)

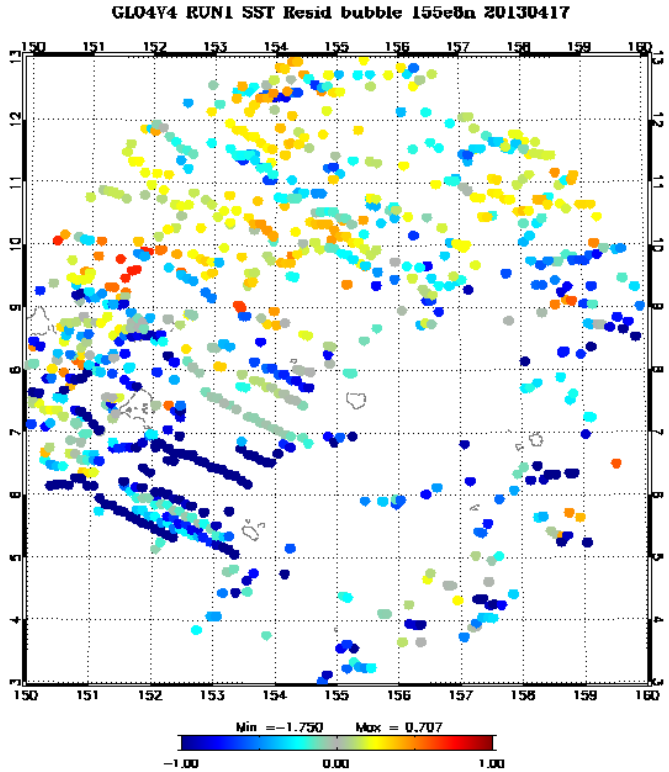




→ **A lot of spread** in the innovation !

Some issues we faced and the solutions we implemented

A lot of **correlated noise** in the SST L3S ODYSSEA



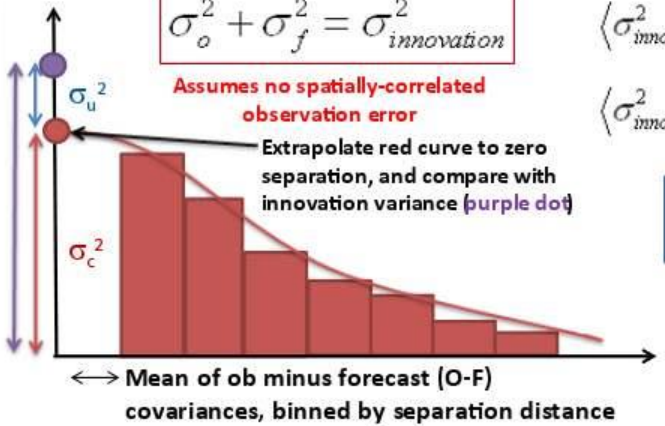
Some issues we faced and the solutions we implemented

Hollingsworth-Lönnberg Method

(Hollingsworth and Lönnberg, 1986)

$$\sigma_o^2 + \sigma_f^2 = \sigma_{innovation}^2$$

Assumes no spatially-correlated observation error



$$\left\langle \sigma_{innovation}^2 \right\rangle = \left\langle \left[\left(\bar{\varepsilon}_o + \varepsilon_o' \right) - \left(\bar{\varepsilon}_f + \varepsilon_f' \right) \right]^2 \right\rangle$$

$$\left\langle \sigma_{innovation}^2 \right\rangle = \sigma_o^2 + \sigma_f^2 + \left(\bar{\varepsilon}_o - \bar{\varepsilon}_f \right)^2 - 2\left\langle \varepsilon_o' \varepsilon_f' \right\rangle$$

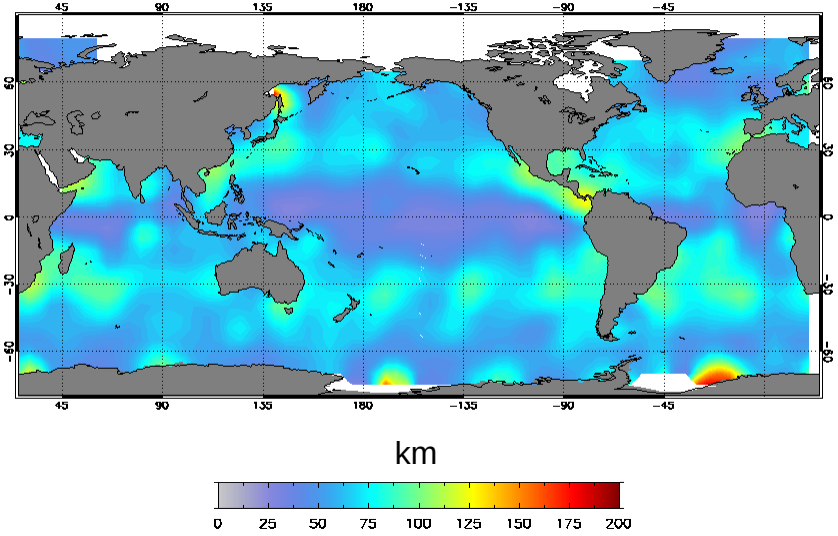
- Observation error variance
- Bias terms
- Correlation between observation error and forecast error: possibly induced by QC methods or bias correction methods

- Use innovation statistics from a dense observing network
- Assume horizontally uncorrelated observation errors
- Calculate a histogram of background innovation covariances binned by horizontal separation
- Fit an isotropic correlation model, extrapolate to zero separation to estimate the correlated (forecast) and uncorrelated (observation) error partition

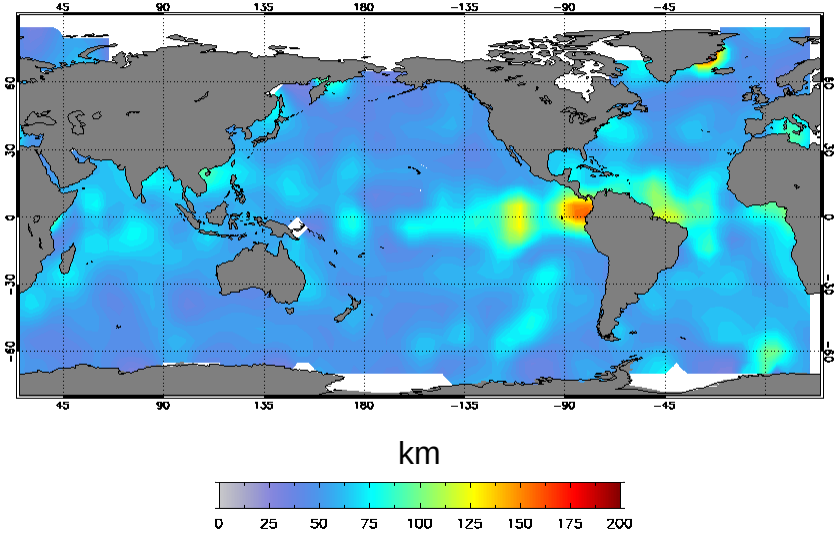
→ Estimation of the radius of observations decorrelation

Some issues we faced and the solutions we implemented

HL1986 decorrelation scale in SLA



HL1986 decorrelation scale in SST



→ The correlated noise of SLA under **70 km** is often dominant.

→ The correlated noise of SST under **40 km** is often dominant.

Some issues we faced and the solutions we implemented

→ Need for the SEEK analysis to use **super-observations** (SLA and SST) to filter out scales that the model does not resolve (we use the previous values of correlation estimated with the HL1986 method)

→ Use of **dedicated L3S SST observation errors**

→ Use of DUACS (SLA) and OSTIA (SST) **L4 gridded products** to adapt the background error variance. These data are different from those assimilated in the new system, which was not possible in the previous analysis system

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Update of NEMO version

- Update of the **NEMO** model with the possibility to activate **new numerical schemes** (Time-splitting, VVL) and **new functionalities** (parallel I/O management), update of sea-ice model (LIM2 → **LIM3**) and use of **multi sea ice categories**

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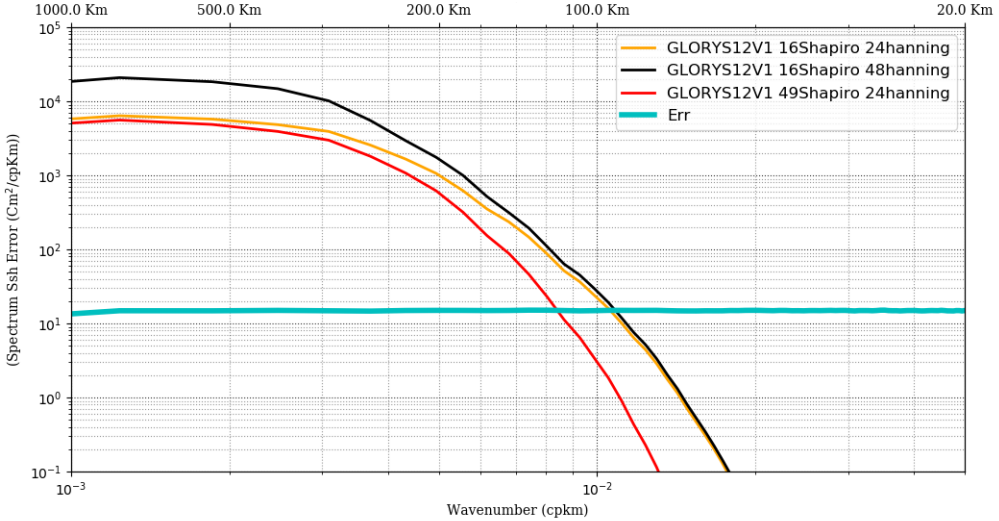
- Use of a **new anomalies base** computed from GLORYS12 reanalysis

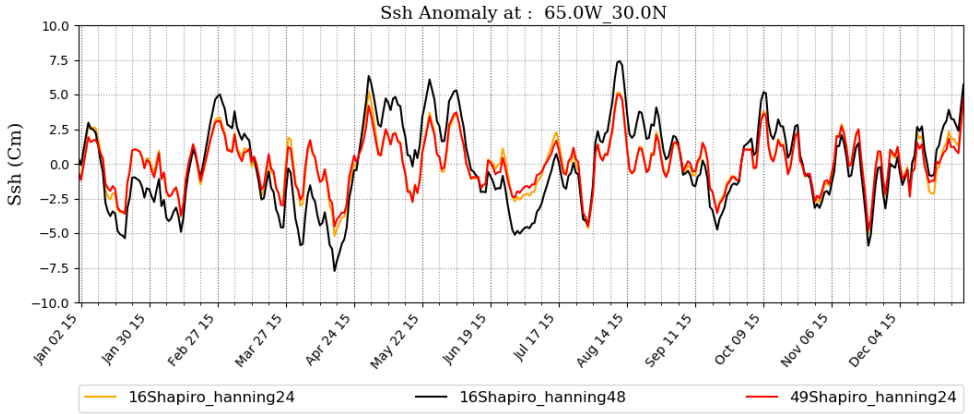
Use of new anomalies base

Power spectral density of the SSH anomalies over the Gulf Stream region



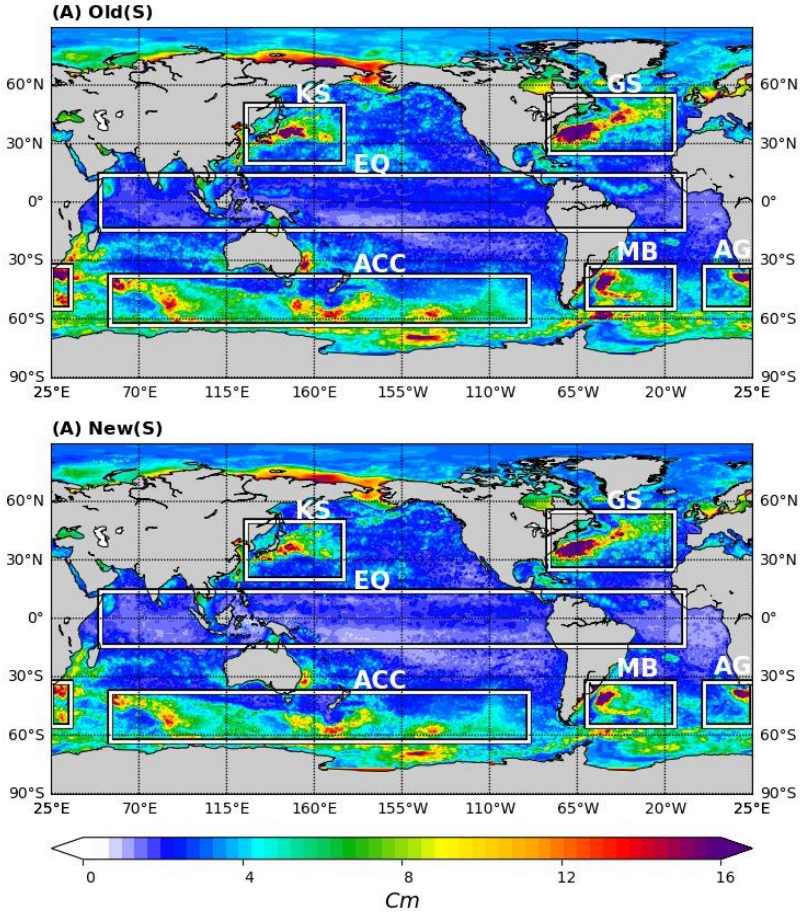
Anomalies bases	Spatial filtering (Shapiro)	Temporal filtering (Hanning)
-------	~ 7 dx	~ 24 days
-------	~ 4 dx	~ 24 days
-------	~ 4 dx	~ 48 days

As the analysis increment is a linear combination of anomalies, this allows us to get an idea of the scales that the analysis system will be able to correct.

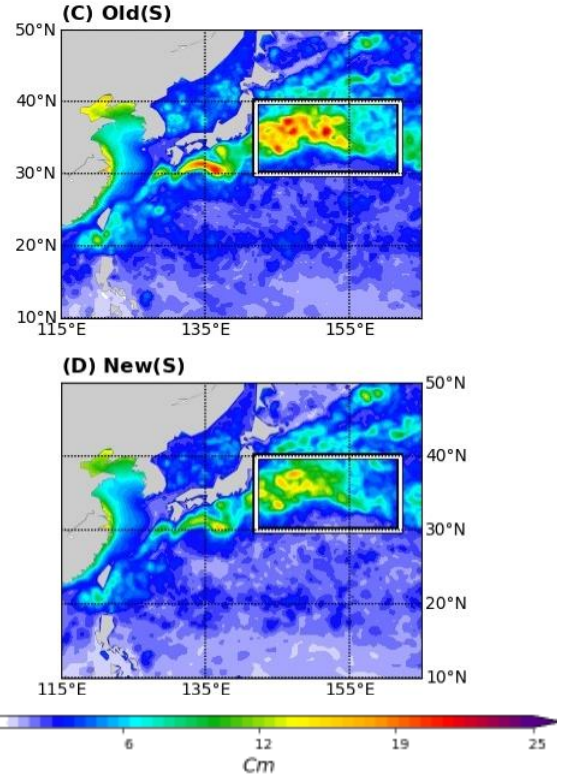


Impact of the new background error covariances

from Benkiran et al., 2021



Standard deviation of the SSH error



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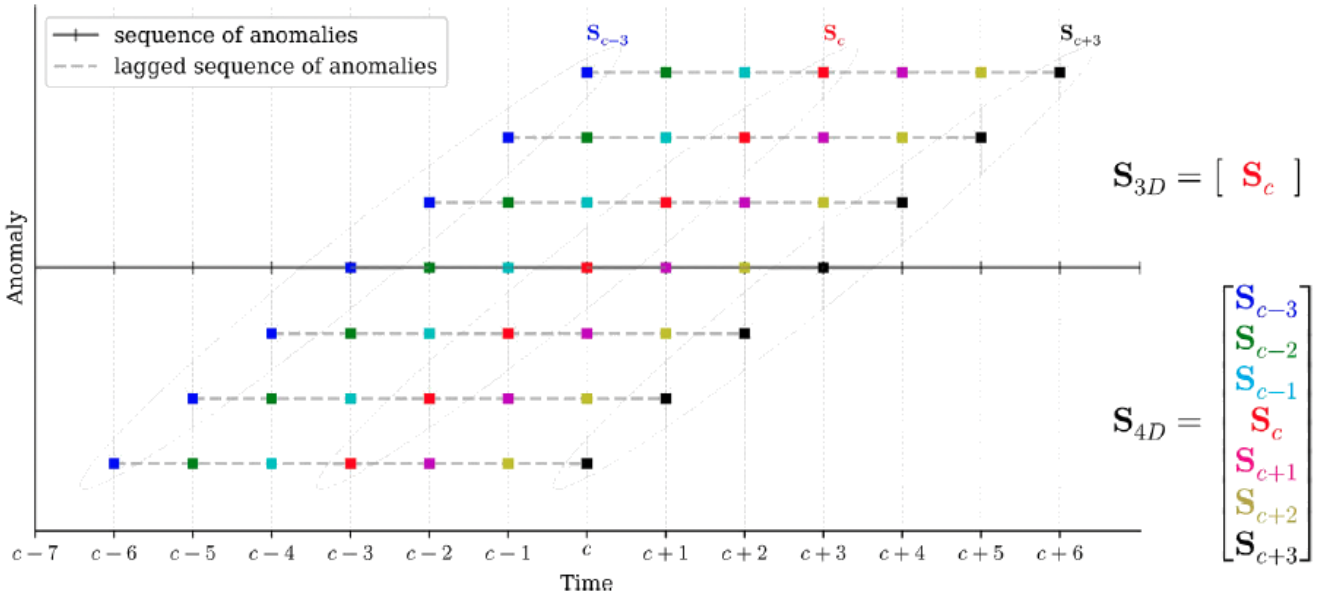
Use a 4D version of analysis

The 4D method uses an ensemble of trajectories of climatological model anomalies to fit the innovation in the Data Assimilation window. The 4D scheme allows a better approximation of the anomaly matrix.

from Benkiran et al., 2021



The S_{4D} covariance matrix corresponds to the S_{3D} matrix augmented with past and future anomaly matrices. In the 4D method the obs operator applied to the anomalies takes into account the temporal dimension.

3D

$$\mathbf{d} = vec(\{\mathbf{y}_i - \mathbf{H}_i\mathbf{x}_i^f\}_{i=0,\dots,n})$$
$$\delta\mathbf{x}_c^a = \mathbf{S}_c\gamma$$
$$\gamma = \left[\mathbf{I} + \mathbf{Y}_c^T\mathbf{R}^{-1}\mathbf{Y}_c\right]^{-1}\mathbf{Y}_c^T\mathbf{R}^{-1}\mathbf{d}$$
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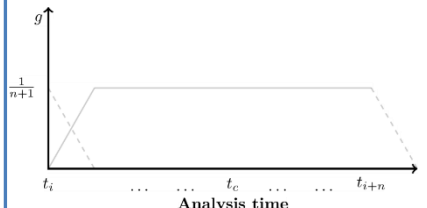

4D

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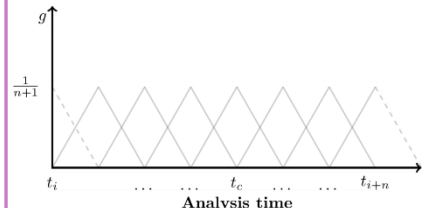

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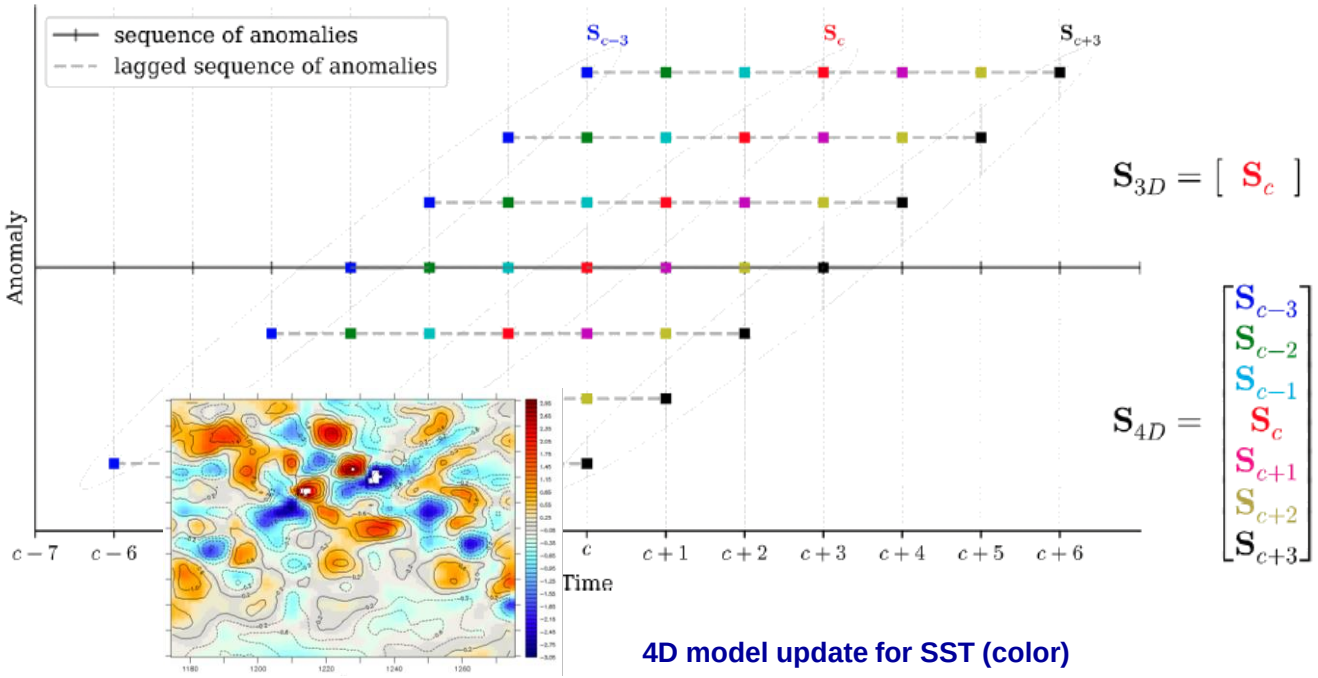

4D model update for SST (color)
vs
4D innovation of SST (isoline)

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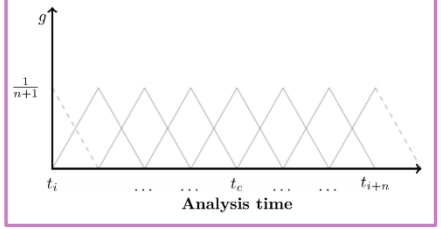

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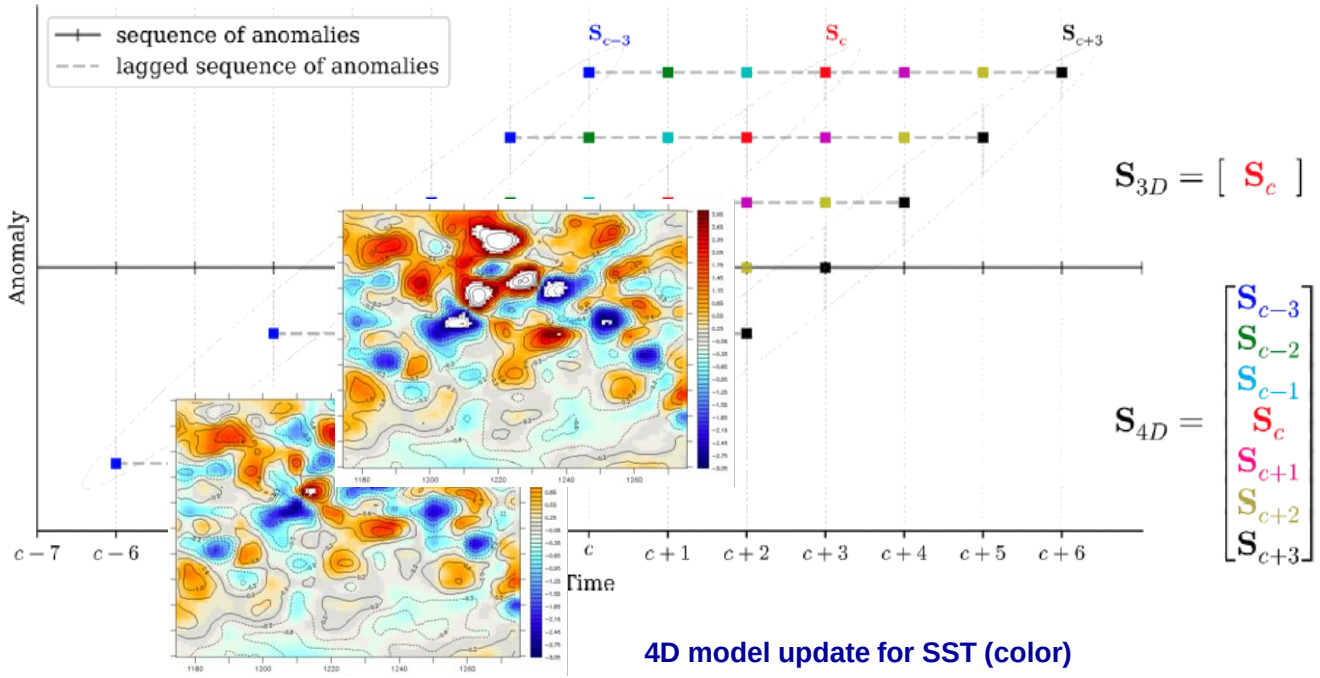

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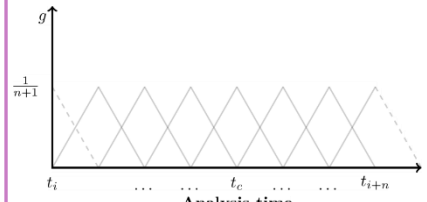
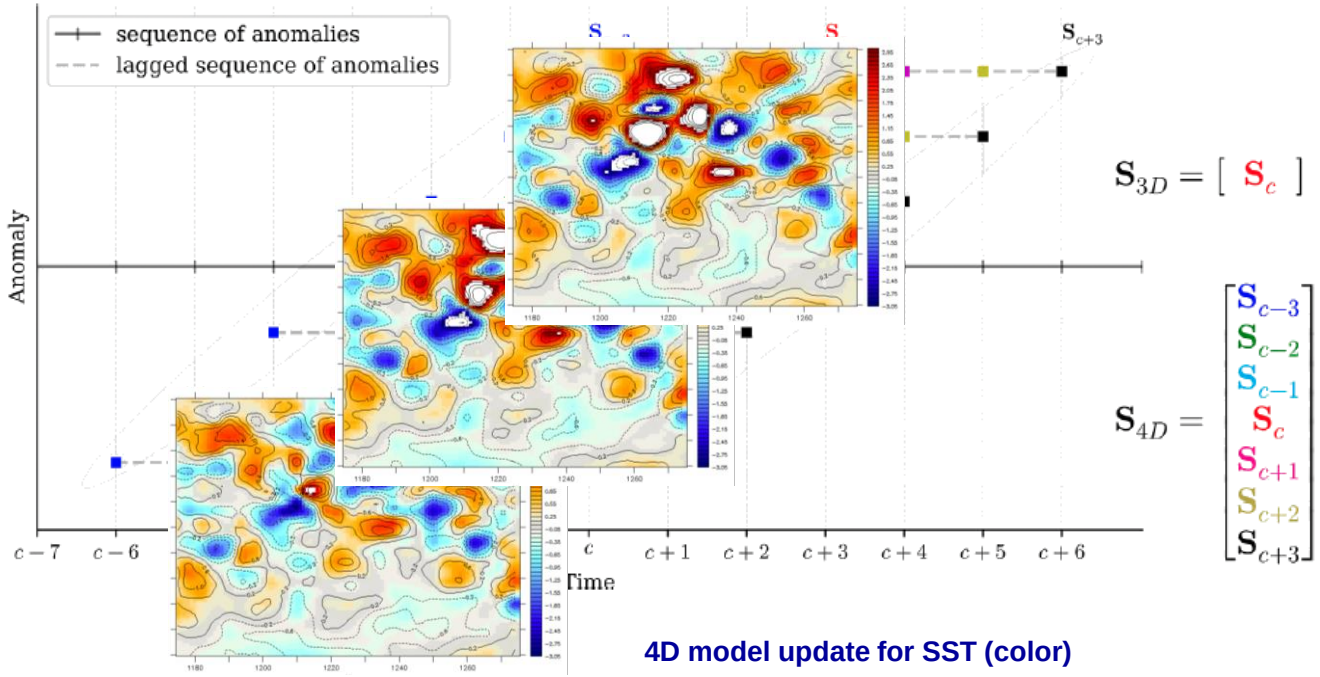


Use a 4D version of analysis

The 4D method uses an ensemble of trajectories of climatological model anomalies to fit the innovation in the Data Assimilation window. The 4D scheme allows a better approximation of the anomaly matrix.

from Benkiran et al., 2021



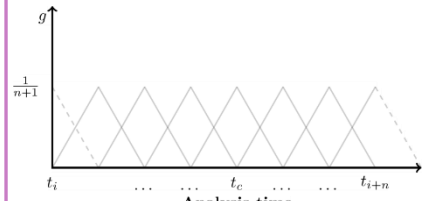
4D model update for SST (color)
vs
4D innovation of SST (isoline)

3D

$$\mathbf{d} = vec(\{\mathbf{y}_i - \mathbf{H}_i\mathbf{x}_i^f\}_{i=0,\dots,n})$$
$$\delta\mathbf{x}_c^a = \mathbf{S}_c\gamma$$
$$\gamma = \left[\mathbf{I} + \mathbf{Y}_c^T\mathbf{R}^{-1}\mathbf{Y}_c\right]^{-1}\mathbf{Y}_c^T\mathbf{R}^{-1}\mathbf{d}$$
$$\mathbf{Y}_c = vec(\{\mathbf{H}_i\mathbf{S}_c\}_{i=0,\dots,n})$$
$$\mathbf{R} = diag(\{\mathbf{R}_i\}_{i=0,\dots,n})$$

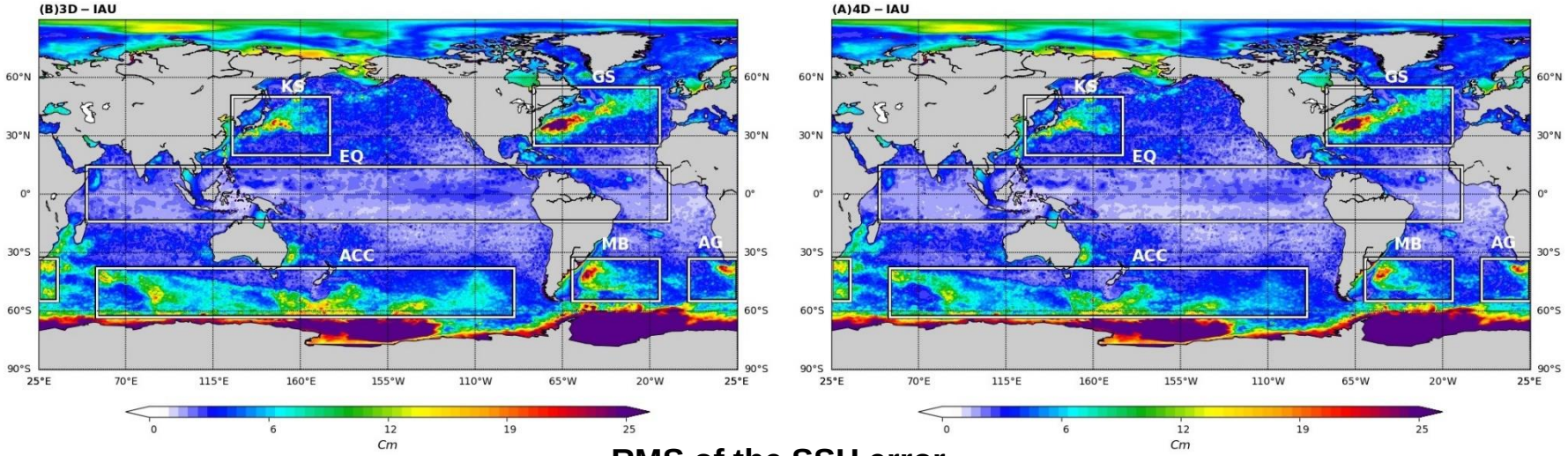
4D

$$\mathbf{d} = vec(\{\mathbf{y}_i - \mathbf{H}_i\mathbf{x}_i^f\}_{i=0,\dots,n})$$
$$\delta\mathbf{x}_i^a = \mathbf{S}_i\gamma, \forall i = 0,\dots,n$$
$$\gamma = \left[\mathbf{I} + \mathbf{Y}^T\mathbf{R}^{-1}\mathbf{Y}\right]^{-1}\mathbf{Y}^T\mathbf{R}^{-1}\mathbf{d}$$
$$\mathbf{Y} = vec(\{\mathbf{H}_i\mathbf{S}_i\}_{i=0,\dots,n})$$
$$\mathbf{R} = diag(\{\mathbf{R}_i\}_{i=0,\dots,n})$$

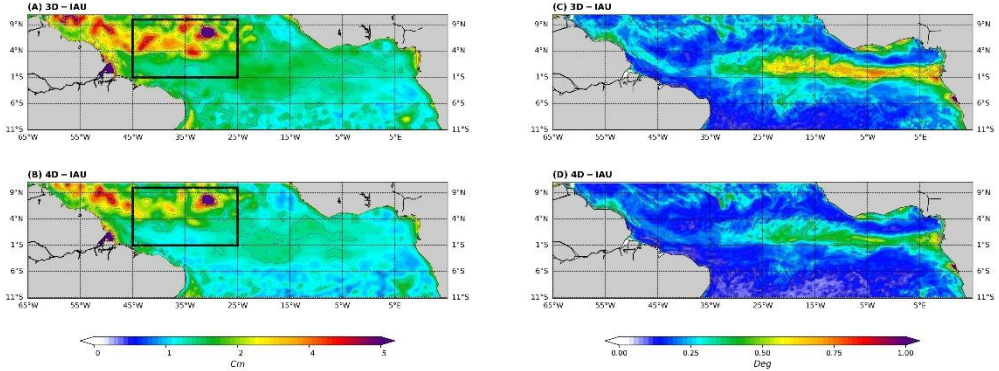


Use a 4D version of analysis

from Benkiran et al., 2021



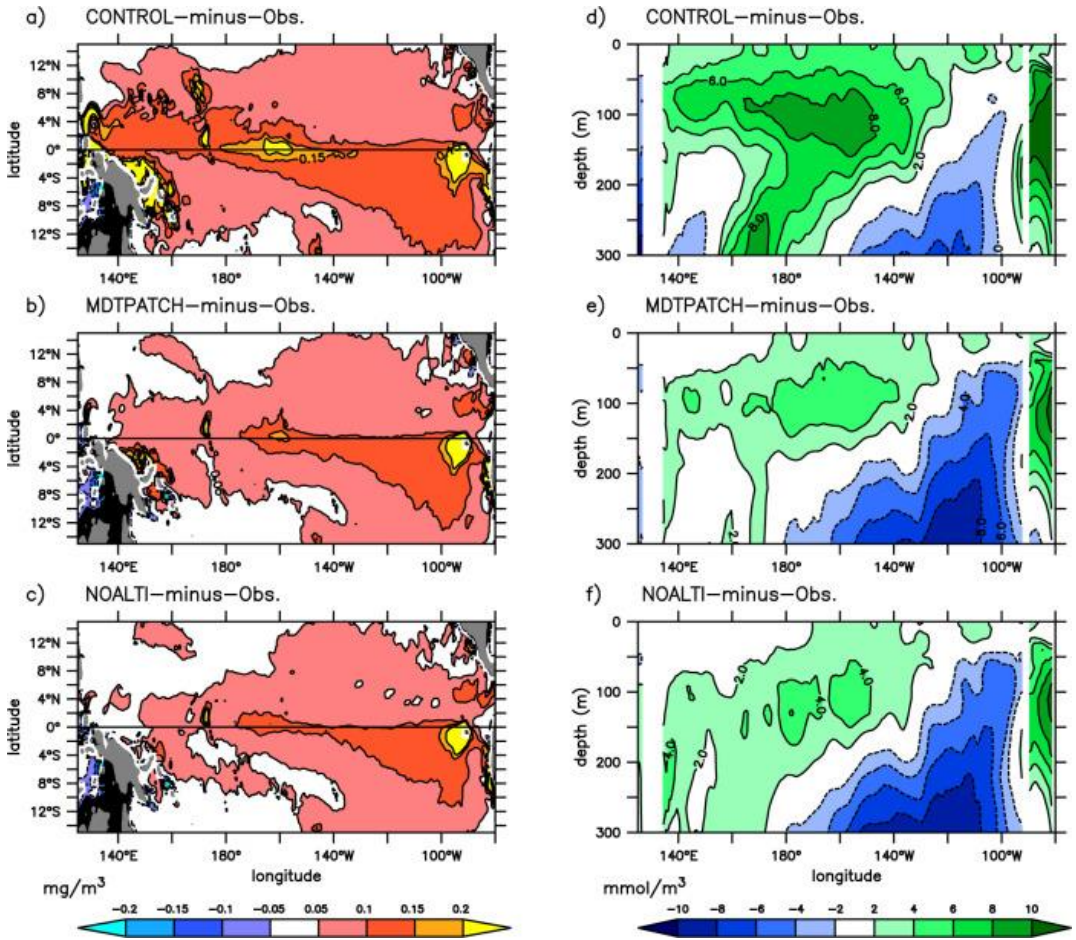
RMS of the SSH error



New hybrid MDT

- Update of the **NEMO** model with the possibility to activate **new numerical schemes** (Time-splitting, VVL) and **new functionalities** (parallel I/O management), update of sea-ice model (LIM2 → **LIM3**) and use of **multi sea ice categories**
- Use of a **new anomalies base** computed from GLORYS12 reanalysis
- Use a **4D version of analysis**
- **New hybrid MDT**

New hybrid MDT



from Gasparin et al., 2021

a-b-c : mean of surface Chl concentration *minus* obs.

d-e-f : equatorial section of mean nitrate concentration *minus* obs.

The use of biased MDT for the assimilation of altimetry causes **unrealistic upwelling** by reducing the horizontal convergence in the western equatorial Pacific.

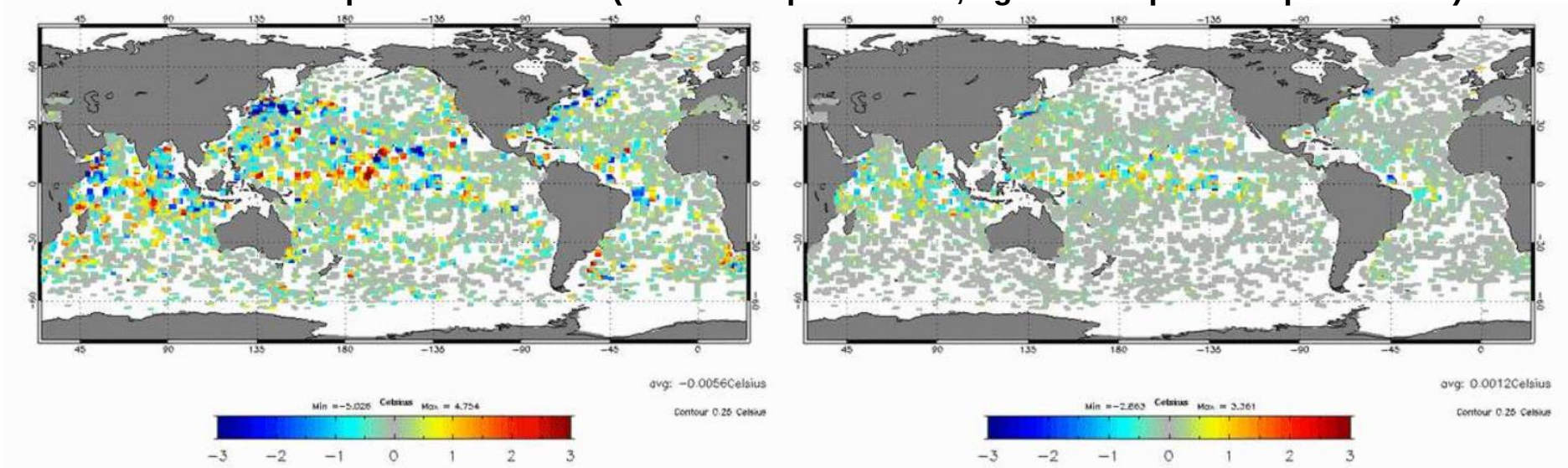
Optimization of bias correction

- Update of the **NEMO** model with the possibility to activate **new numerical schemes** (Time-splitting, VVL) and **new functionalities** (parallel I/O management), update of sea-ice model (LIM2 → **LIM3**) and use of **multi sea ice categories**
- Use of a **new anomalies base** computed from GLORYS12 reanalysis
- Use a **4D version of analysis**
- **New hybrid MDT**
- **Optimization of bias correction**

Optimization of bias correction

Parameters optimization for bias correction

Residual of temperature at 140 m (left: actual parameters, right: new optimized parameters)



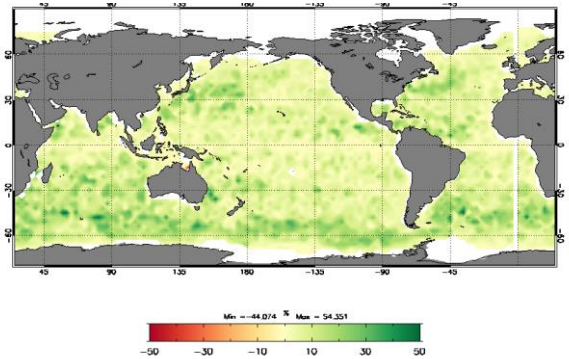
Outline

1. Current data assimilation system
2. Main ingredients of the new system: some issues we faced and the solutions we implemented
3. Description of the main updates of the system
4. **Performances of the new system compared to the current one**

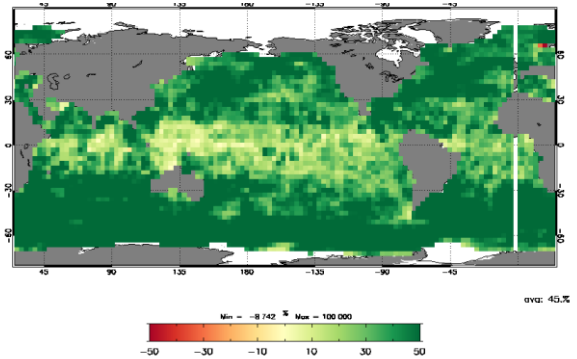
Performances of the system

The influence of SLA and SST L3S on the multivariate analysis, which is the slope between increment and innovation, **is strong in the new system** (a slope > 40% is ideal)

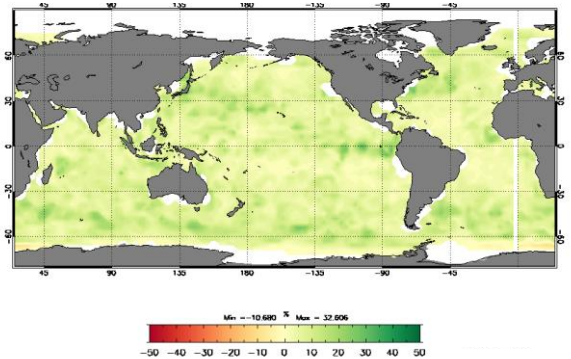
Influence of SLA (old system PSY4)



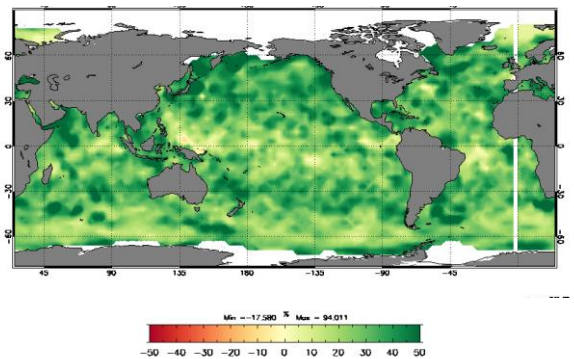
Influence of SLA (new system GLO12)



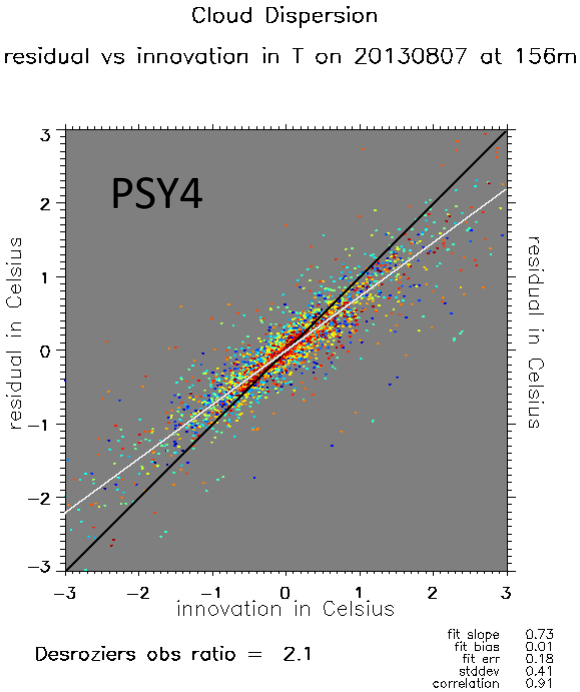
Influence of SST (old system PSY4)



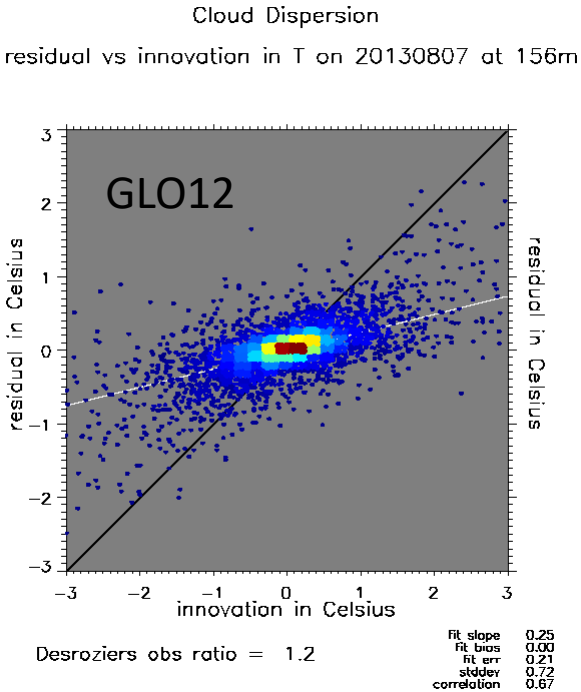
Influence of SST (new system GLO12)



Performances of the system

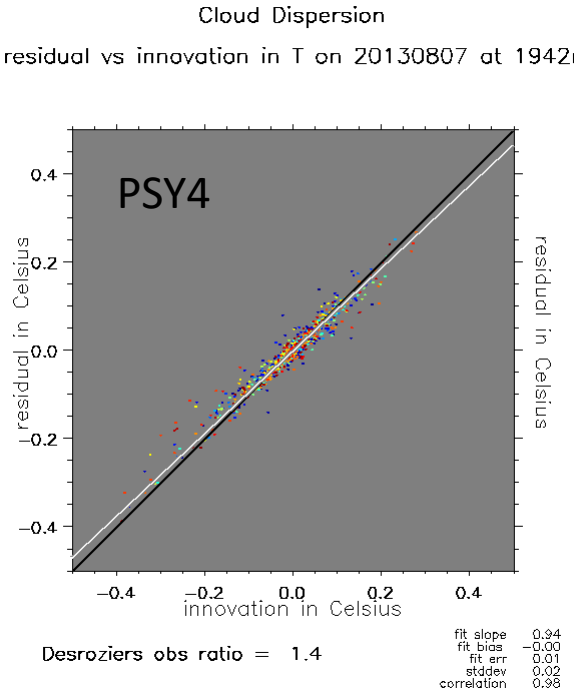


T
150 m

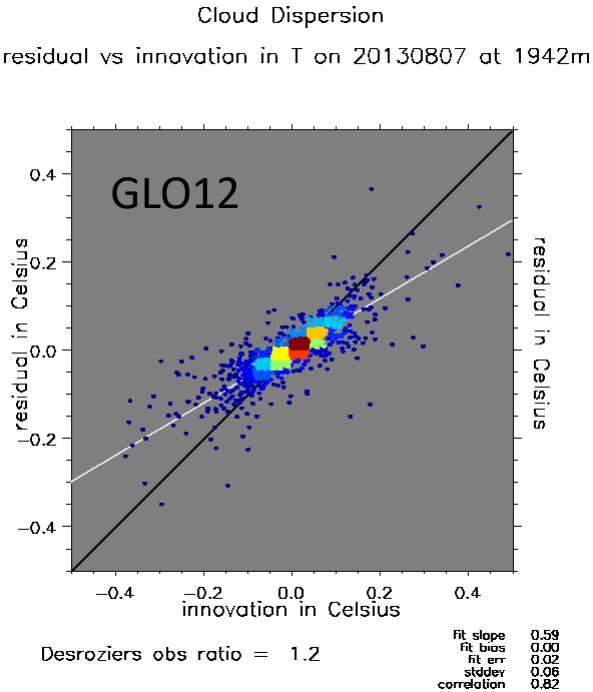


GLO12 corrects 3 times more with in situ than PSY4

Performances of the system

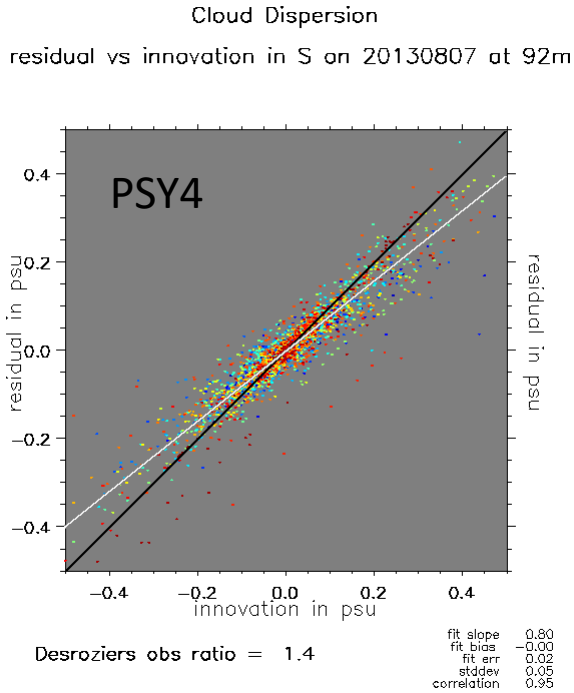


T
1950 m

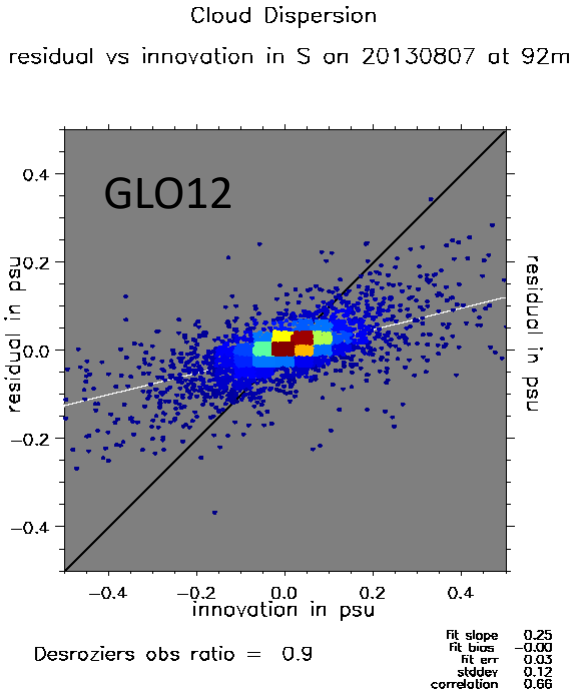


GLO12 corrects 3 times more with in situ than PSY4

Performances of the system

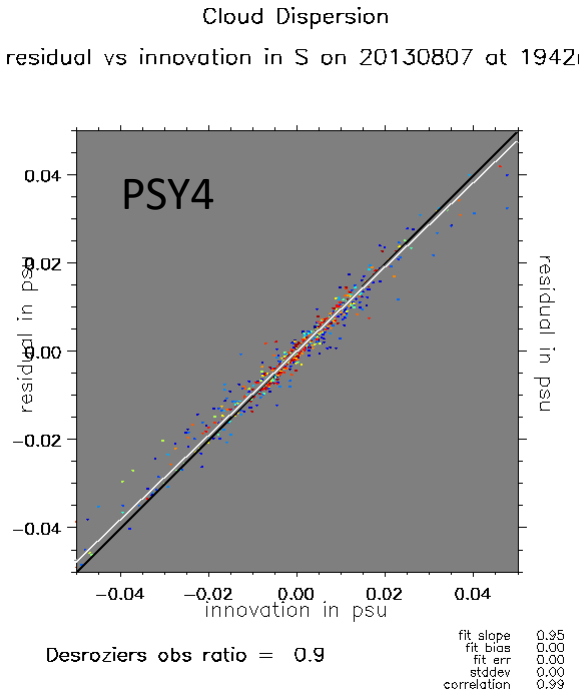


S
90 m

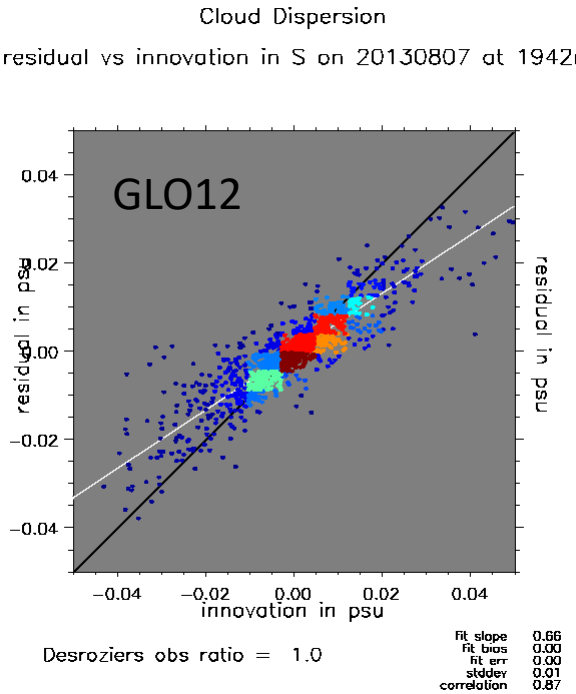


GLO12 corrects 3 times more with in situ than PSY4

Performances of the system



S
1950 m

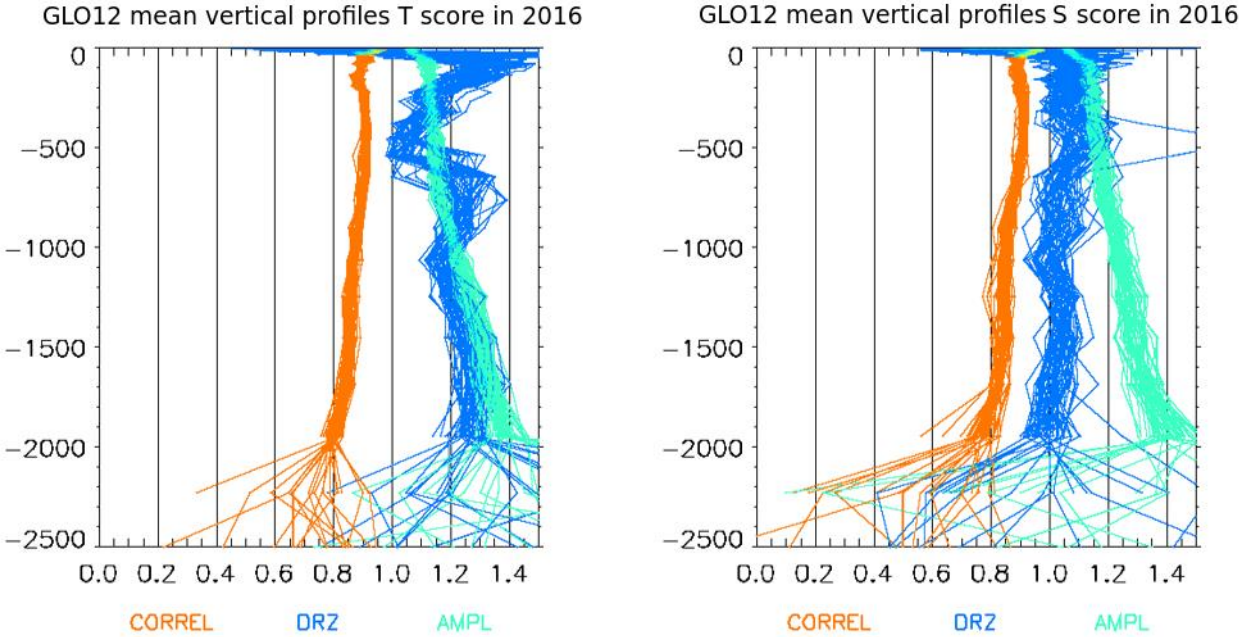


GLO12 corrects 3 times more with in situ than PSY4

Performances of the system

The SEEK analysis of GLO12 is well balanced on the vertical and between T and S

We are close to 1 which represents the optimum



CORREL = correlation between innovation and increment

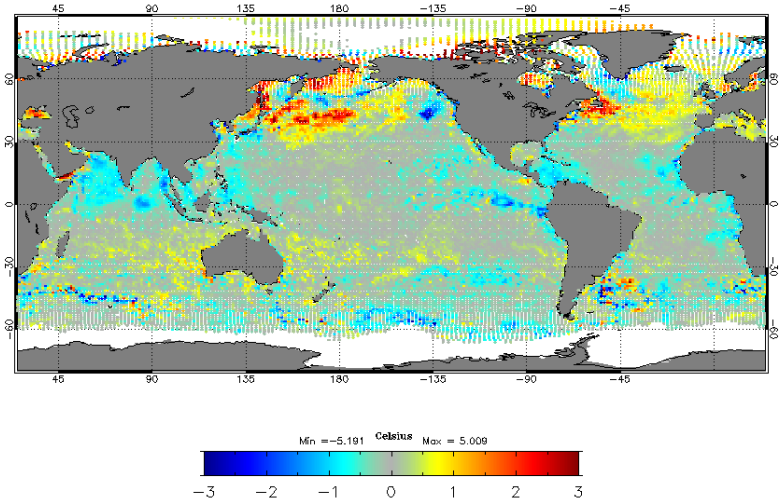
AMPL= optimal increment amplification that minimizes the analysis residual without taking into account system errors

DRZ = ratio from Desroziers diagnostic

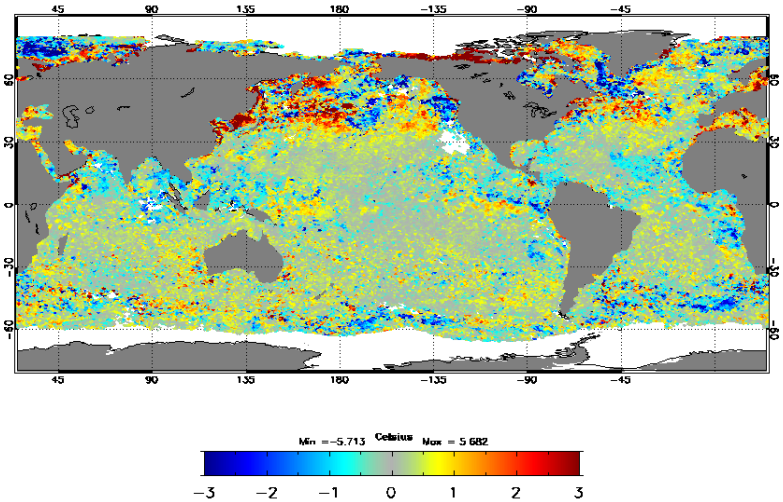
Performances of the system

SST innovations are larger and noisier with ODYSSEA than with OSTIA in cold stratified seas

OSTIA minus PSY4 on 07-08-2013



ODYSSEA minus GLO12 on 07-08-2013

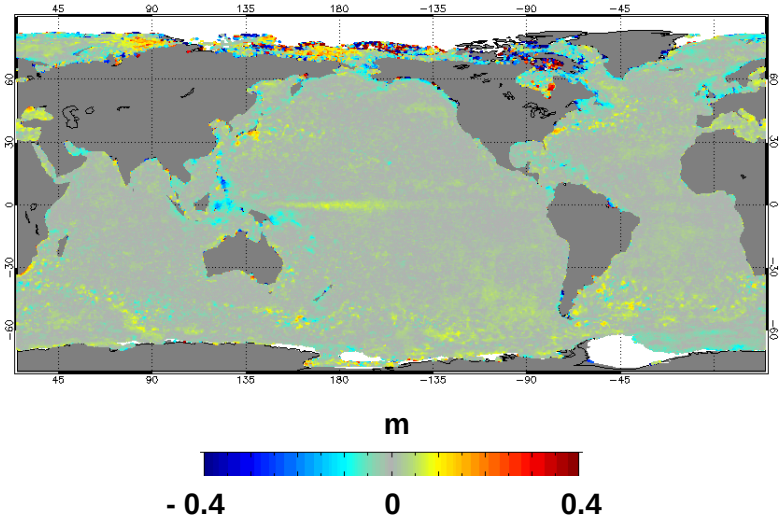


Performances of the system

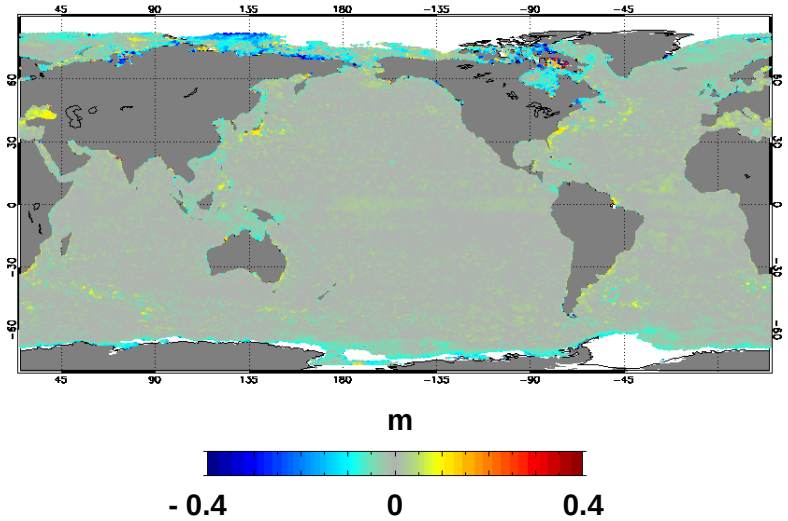
GLO12 has less regional bias in SLA

El Nino 2015 is better predicted

PSY4 mean SLA innovation in 2015

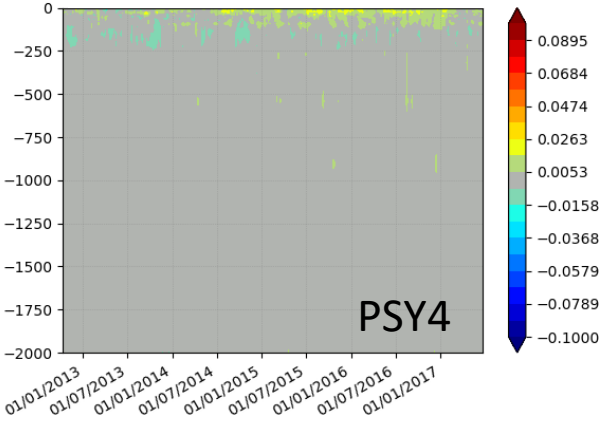


GLO12 mean SLA innovation in 2015

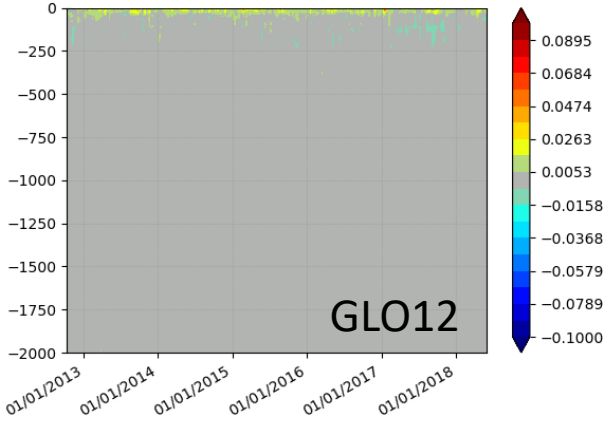


Performances of the system

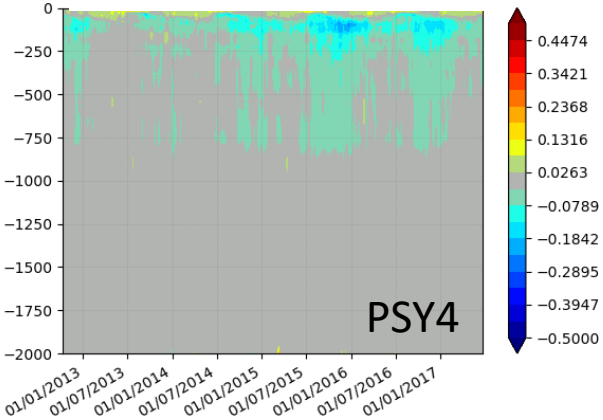
Mean salinity bias



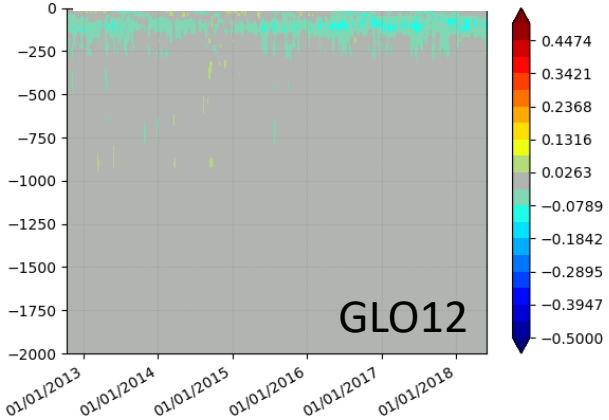
Mean salinity bias



Mean temperature bias

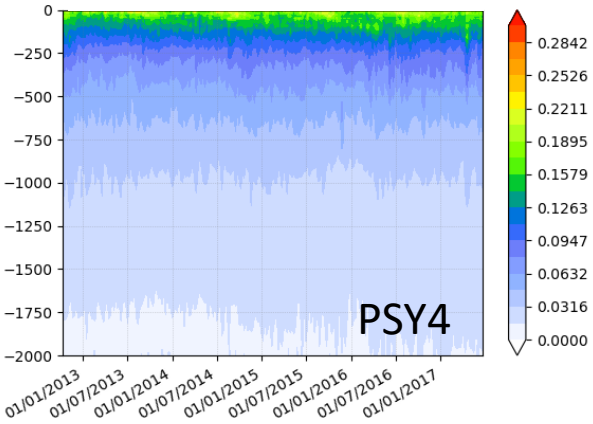


Mean temperature bias

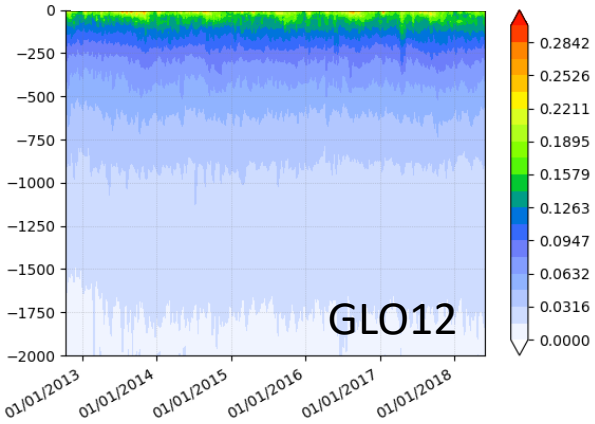


Performances of the system

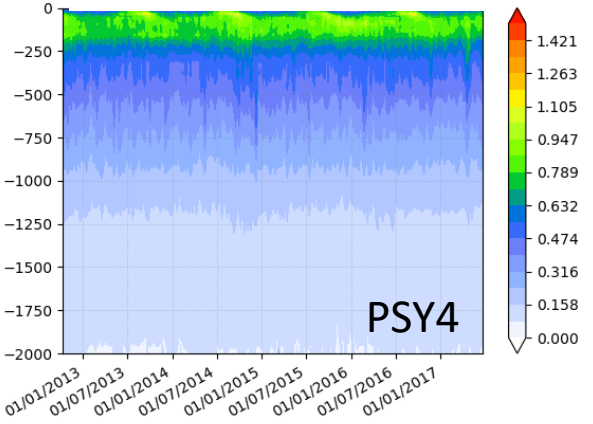
RMS salinity



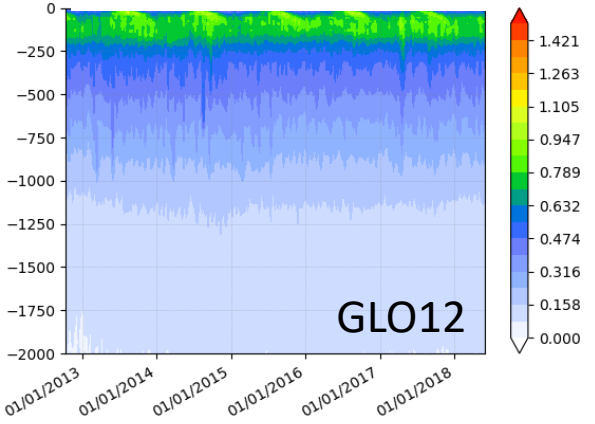
RMS salinity



RMS temperature



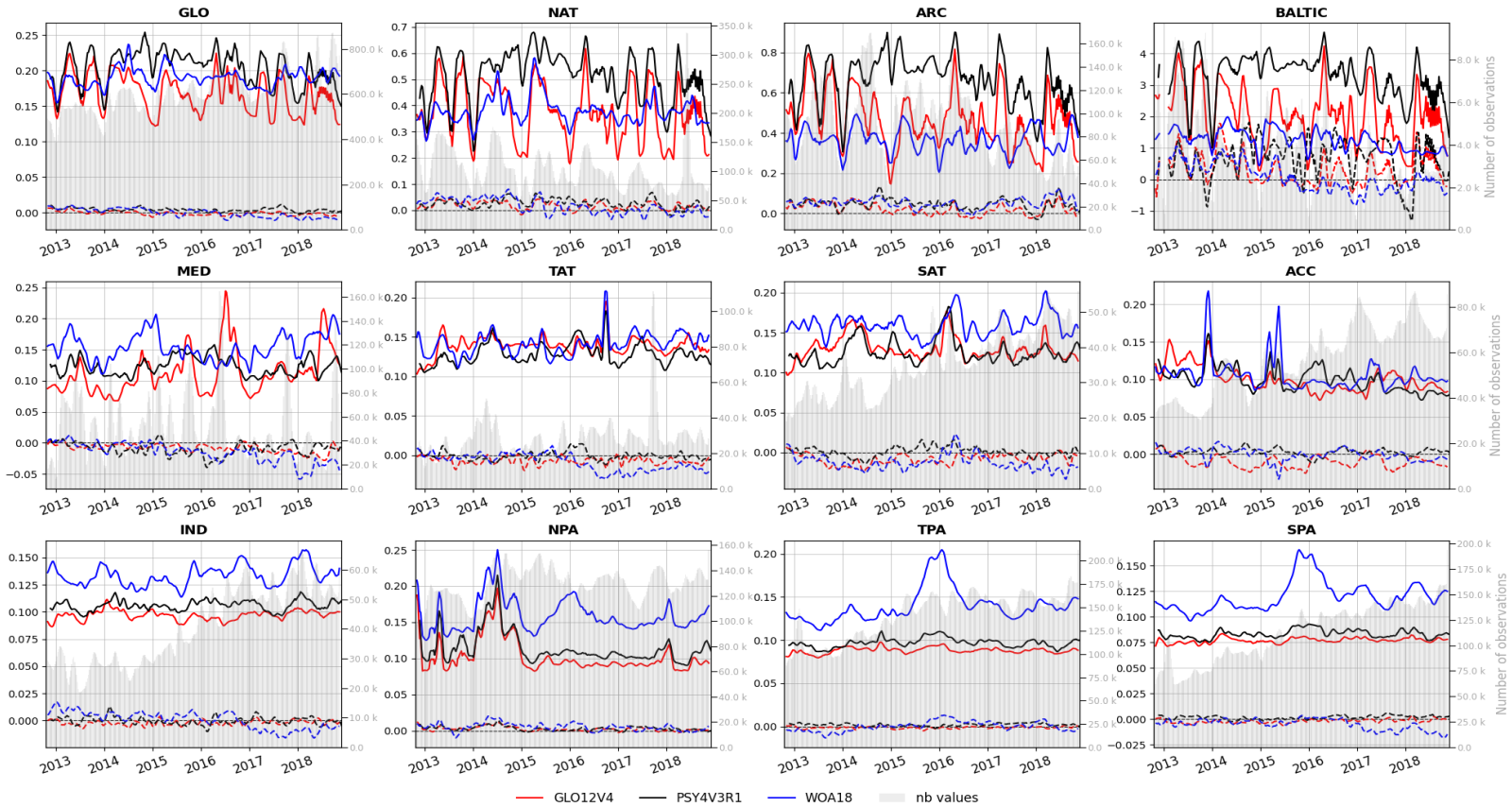
RMS temperature



Performances of the system

Salinity

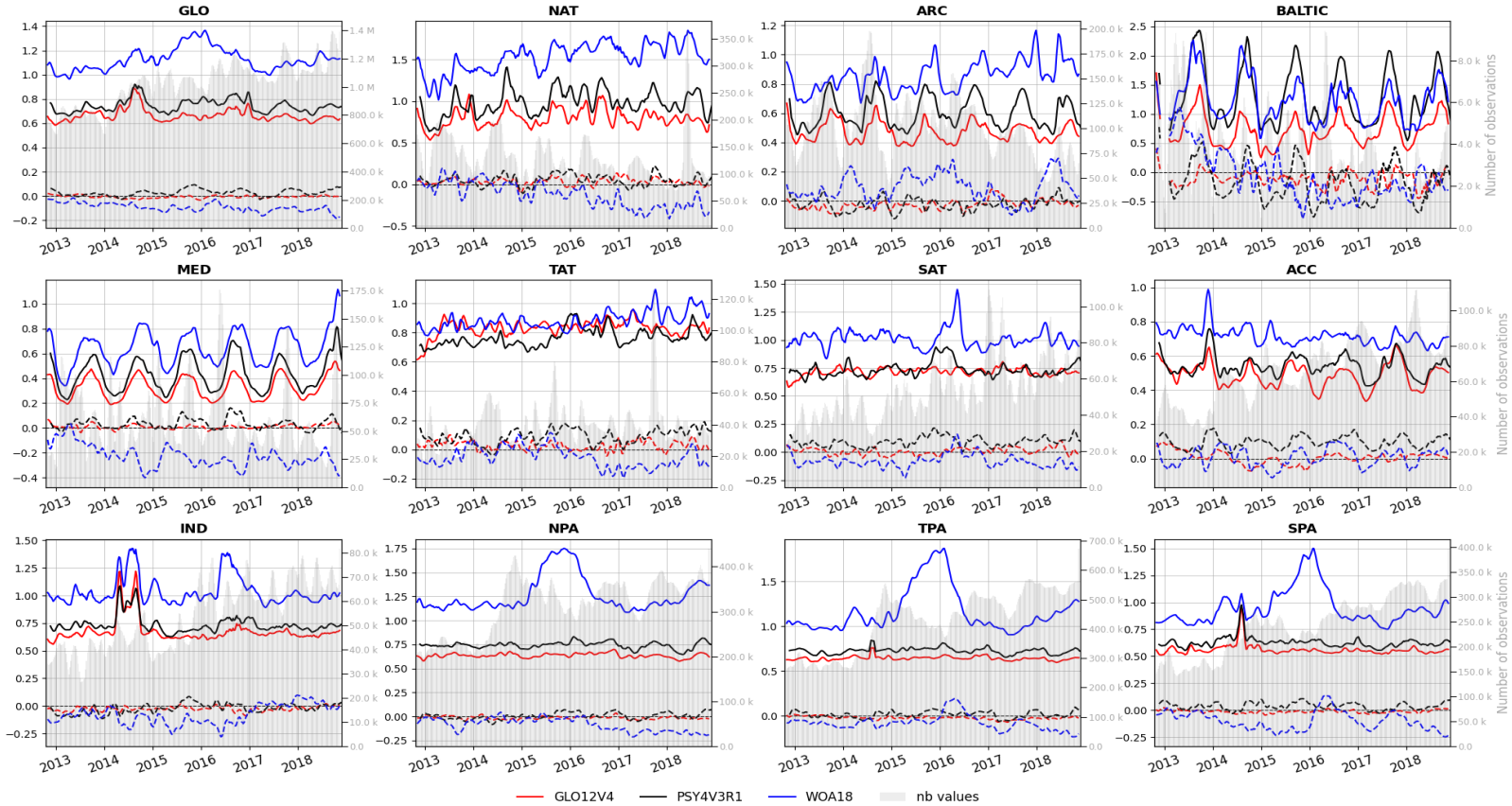
RMSE / Mean bias (analysis – obs) for Salinity 0 – 500 m



Performances of the system

Temperature

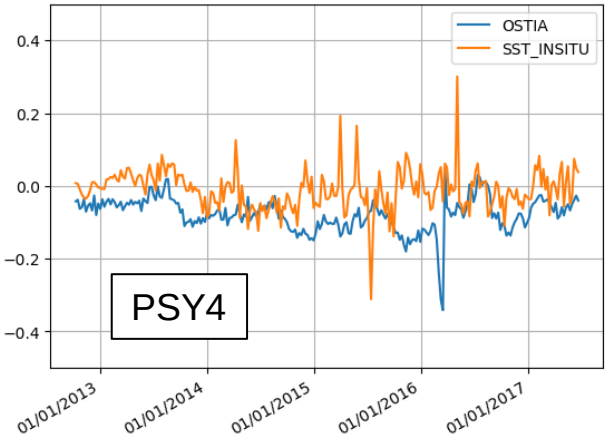
RMSE / Mean bias (analysis – obs) for Temperature 0 – 500 m



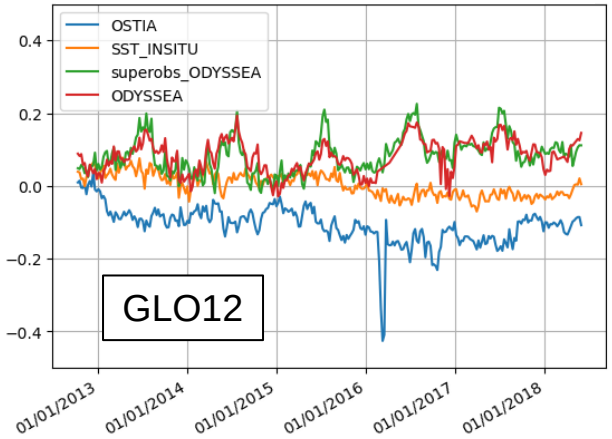
Performances of the system

SST

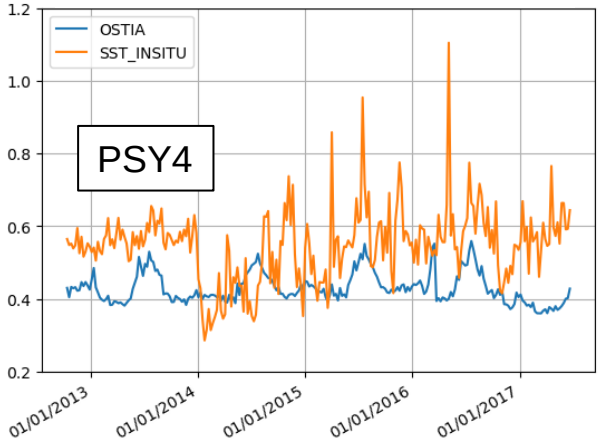
Mean bias (analysis – obs) for SST



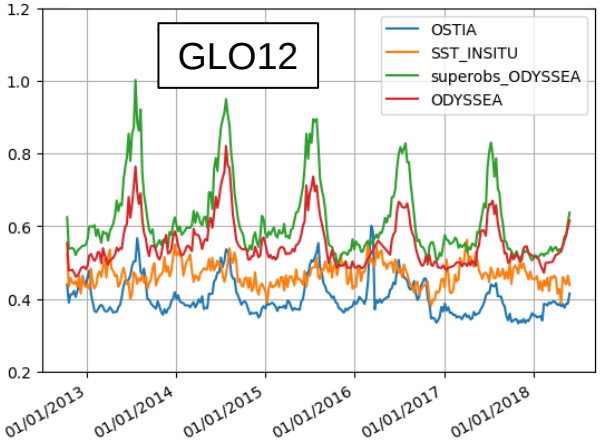
Mean bias (analysis – obs) for SST



RMS (analysis – obs) for SST



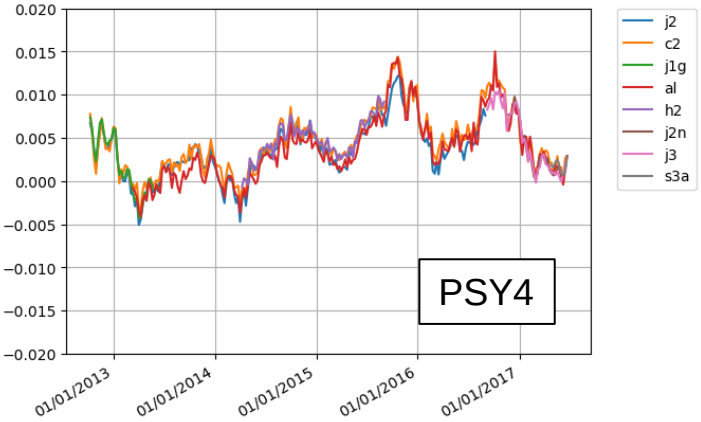
RMS (analysis – obs) for SST



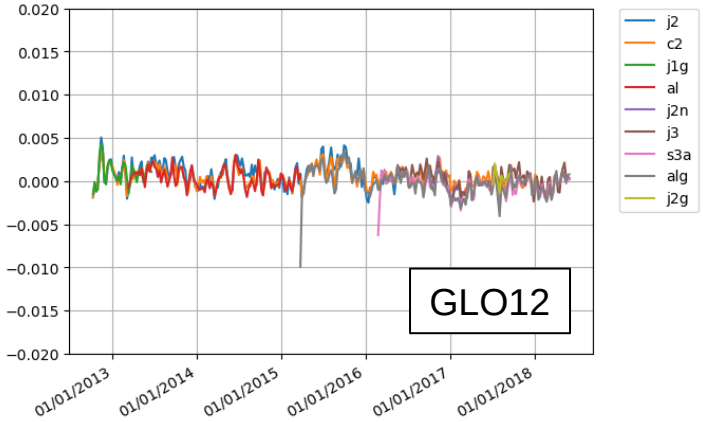
Performances of the system

SLA

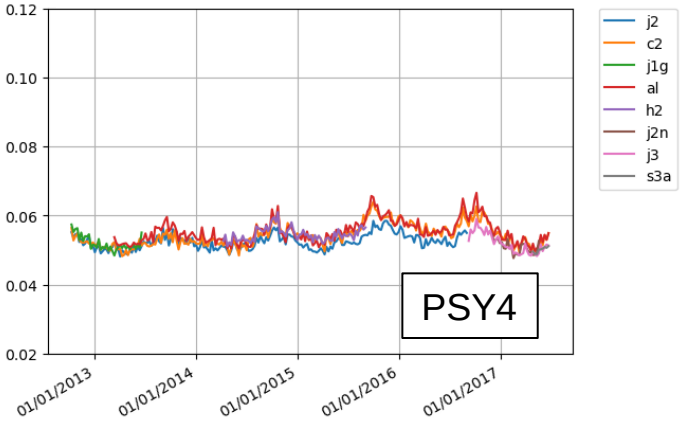
Mean bias (analysis – obs) for SLA



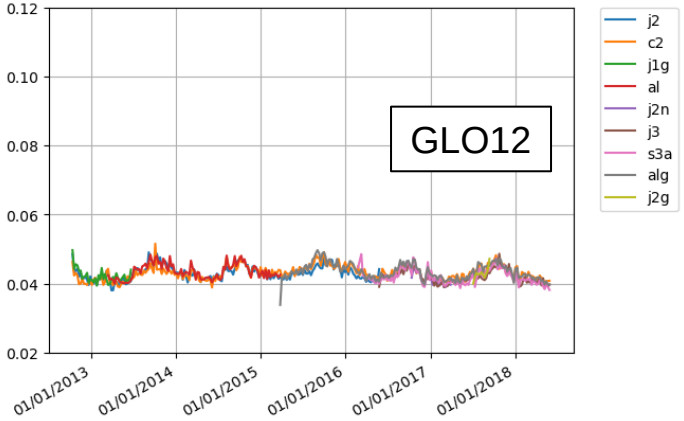
Mean bias (analysis – obs) for SLA



RMS (analysis – obs) for SLA



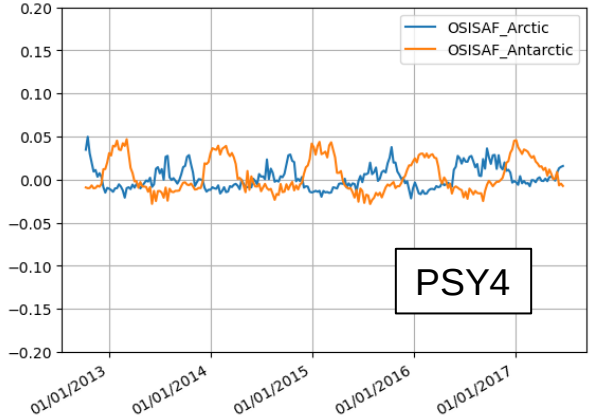
RMS (analysis – obs) for SLA



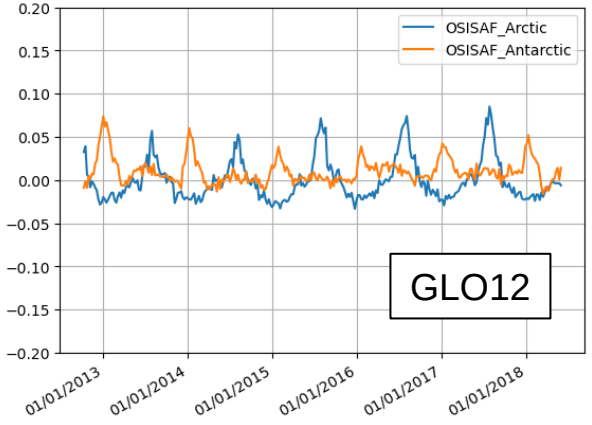
Performances of the system

SIC

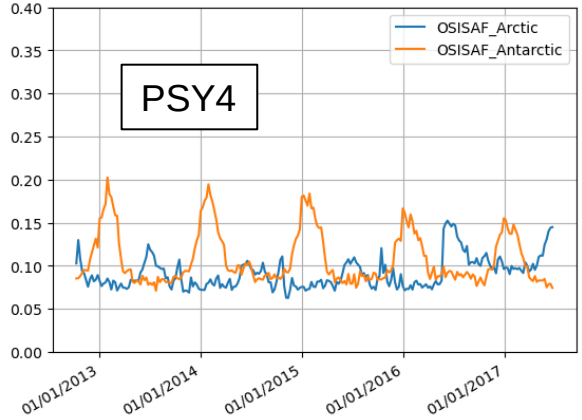
Mean bias (analysis – obs) for SIC



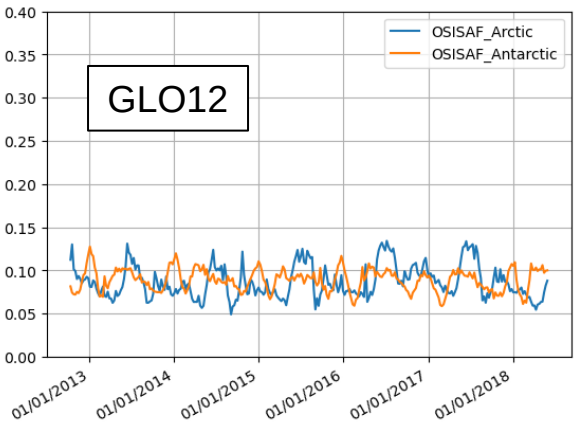
Mean bias (analysis – obs) for SIC



RMS (analysis – obs) for SIC

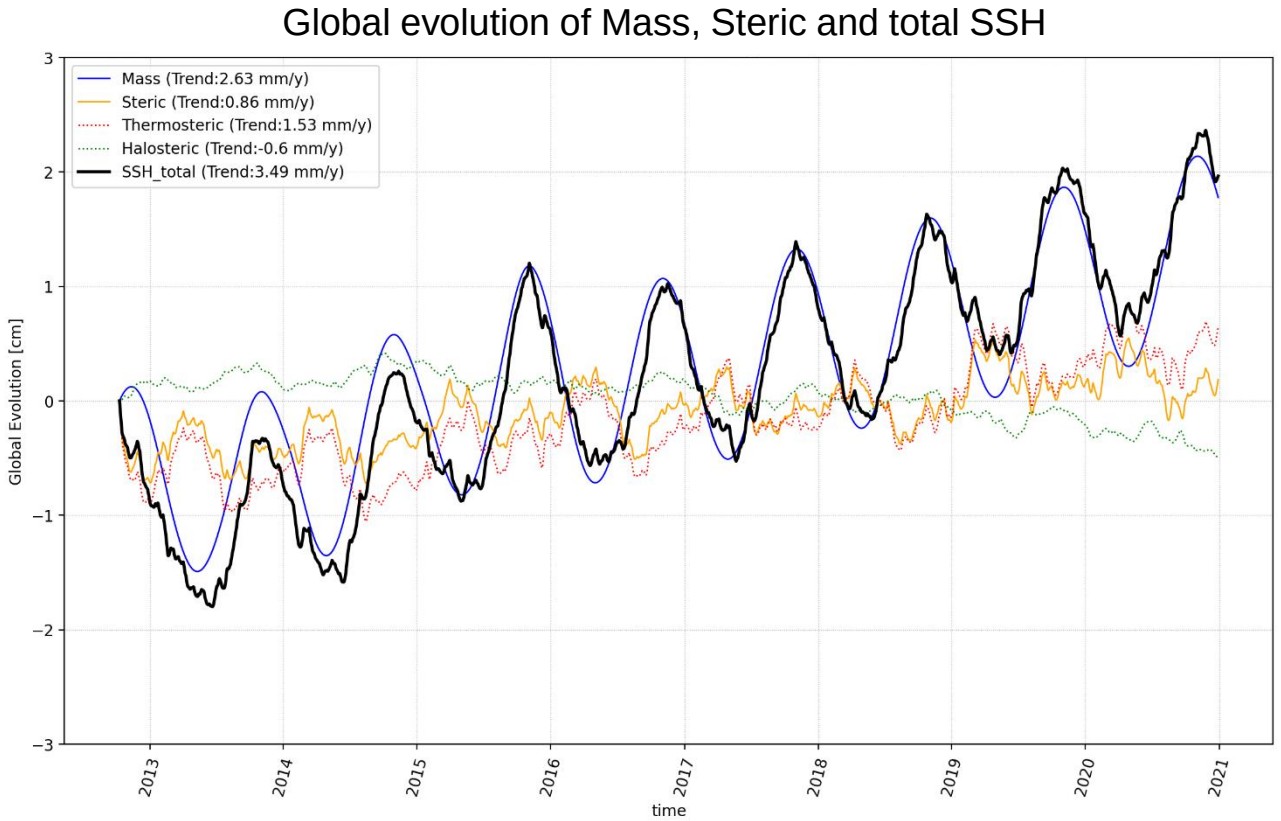


RMS (analysis – obs) for SIC



Mass balance closure and trend

from Bourdallé-Badie's heavy work…



Next steps

- Production of a new simulation at 1/12° from October 2016 to present
  → In parallel, two “twin” simulations will be performed (1/4° with assimilation, 1/12° without assimilation)

- Transfer to the “operational team” for a near-real time production

Extra slides

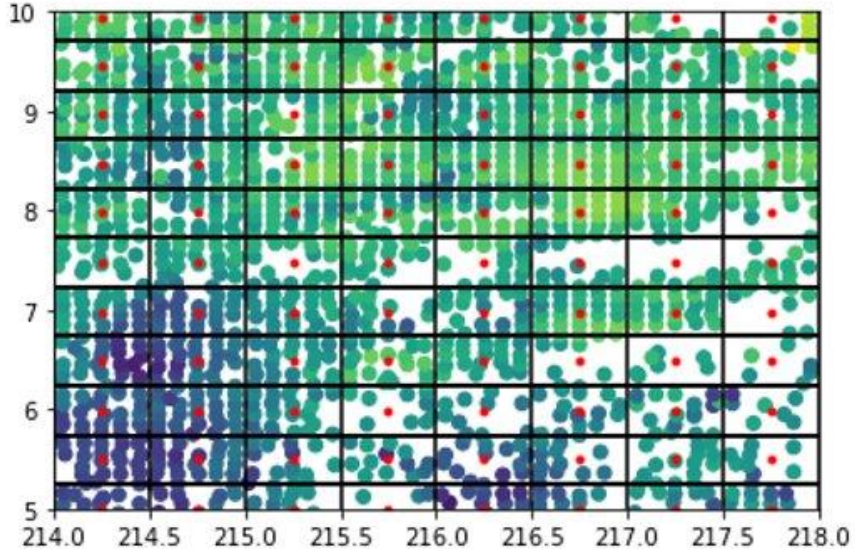
Summary

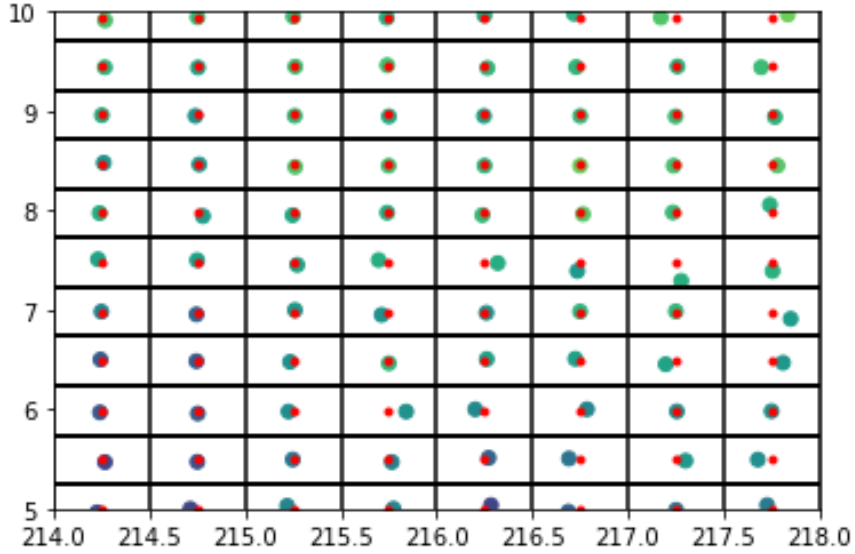
A major release is planned for the end of 2022. The objective is to improve, among others, the analysis and forecast skills, the representation of mesoscale activity, the mass/steric distribution (loss of mass and too much steric in the current system), the equatorial dynamics and interaction with biogeochemistry. This release will include:

- A new version of NEMO (more coherent bulk formulation, more advanced sea ice model with the possibility to represent the ice in different categories).
- The use of high resolution spatial and temporal atmospheric forcing.
- The assimilation of L3 ODYSSEA SST product instead of L4 OSTIA.
- The use of a refined Mean Dynamic Topography allowing, among others, to better represent the equatorial dynamics.
- The use of a new anomalies base from GLORYS12 Mercator reanalysis.
- The use of a 4D approach with the data assimilation scheme, allowing an improvement in the spatiotemporal continuity of mesoscale structures.
- The use of assimilated “super-observations” to filter out scales that the model does not resolve.
- An improvement of mass/steric separation during data assimilation with the inclusion of monthly corrections of GMSL instead of a trend.
- An improvement of the parameterizations of the temperature and salinity bias correction method.

Construction of super-observations

ODYSSEA SST L3S





- Red dots are ORCA0.5 T-grid points and black lines represent the grid element associated with the red dots
- NEMO fields are « average » values of the black mesh.
- SST L3S has a much higher resolution than ORCA0.5 (analysis resolution) in terms of number of data points and resolved structures.
- Gradients within each mesh are not resolved by the analysis.

Construction of super-observations

SLA