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Ocean Observing System Experiments

E. Remy, the Mercator Ocean team and the Ocean Predict OSEval Task Team

Outline

- Motivations
- Methods for Observing System Evaluation studies
- Ocean Observing System Experiments (OSEs)
- Ocean Observing System Simulation Experiments (OSSEs)
- Challenges
- Recommendations for Observing System Evaluation studies

Motivations

Ocean analysis and forecasts have a **high dependency on observation availability and quality**.

Main physical ocean observations that are routinely assimilated:
Satellite observations:

- sea level anomaly
- SST
- sea ice concentration

-> regular, dense and global coverage.

In situ observations:

- Argo temperature and salinity profiles
- surface drifting buoys
- Coastal and tropical moorings
- ship based observations (TSG, ferrybox)
- research vessel cruise (CTD, XBT)
- marine mammals

-> quite sparse coverage except at the surface, deeper than 2000 m depth very few observations.

Motivations

Observing system evaluation studies have several objectives:

For present observing networks:

- **Improve** the use of the observation information in the assimilation system,
- **Quantify** the impact of the present observation networks on ocean analyses and forecasts,
- ➢ **Demonstrate** their value for operational purposes and advocate for their sustainability.

For future observing networks:

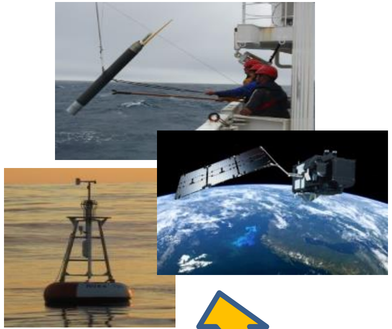
- **Develop the capacity** of monitoring and forecasting systems **to benefit from future/improved observations**.
- **Evaluate** the impact of new mission/evolution of existing networks or new observation products, from an integrated system perspective,
- ➢ **Provide guidance on observing system evolutions and future ones** from ocean monitoring and forecasting centers perspective.
- ➢ Help **defining suitable observation products** for operational oceanography.

Motivations

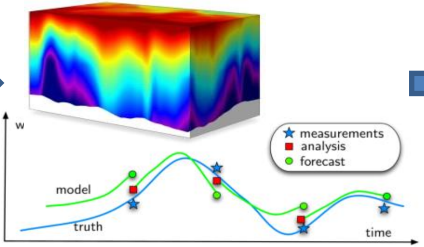
Historically, ocean modeling/data assimilation and observing communities has less interactions than in atmosphere, especially for in situ networks (except Argo).

Strengthening the link between the ocean observing community and the monitoring and forecasting centers is crucial to give **feedback on the use, <u>impact</u> and expected evolution from ocean monitoring and forecasting centers**.

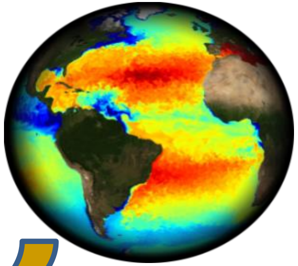
Ocean observing systems



Data integration into model (physics and BGC)



Provision of Ocean, ice and BGC analysis and forecasts



Feedback from ocean monitoring centers to observing networks.

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Methods

Impact assessment methods used in ocean (operational) global and regional centers:

- **OSEs (Observing System Evaluations):** assessing the impact of existing data sets by withholding some observations. The impact of the withheld observations is evaluated by comparison between 2 assimilation runs with and without the given observations.
- **OSSEs (Observing System Simulation Experiments):** help designing new observing systems and to perform preparatory data assimilation work. Observations are simulated from a model simulation.
- **Dedicated diagnostics to assess the impact of observations:**

  - Forecast Sensitivity to Observation Impact (FSOI): evaluates observations contribution to reducing forecast errors.

  - Degree of Freedom of the System (DFS): sensitivity of the analysis to observations at the observation points.

All of those methods are inherited from the atmospheric community.

They are based on assumptions and approximations that need to be taken into account when interpreting the results.

Results are highly system dependent.

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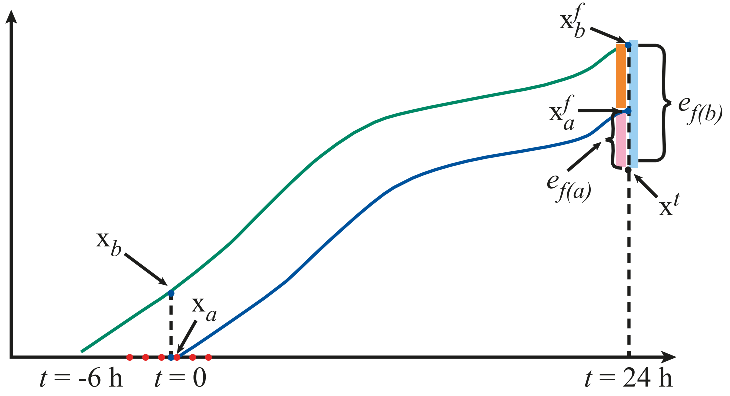
- Perspectives

Observation impact diagnostics

FSOI (Forecast Sensitivity Observation Impact)

Adjoint/ensemble-based approach to estimate the impact of all observations on reducing the short-range forecast error of a selected metrics:

$$\delta e = e_{f(b)} - e_{f(a)}$$



DFS (Degree of Freedom of the System)

Sensitivity of the analysis at observation points:

$$DFS = \partial(Hx_a)/ \partial y_{obs}$$

Information Content (*or Observation Influence*):

$$IC = DFS/ Nb\ Obs$$

It provides diagnostics on the influence of individual data on the analysis.

Langland, R. H., & Baker, N. L. (2004). https://doi.org/10.1111/j.1600-0870.2004.00056.x

Cardinali C. et al. (2004). https://doi.org/10.1256/qj.03.205

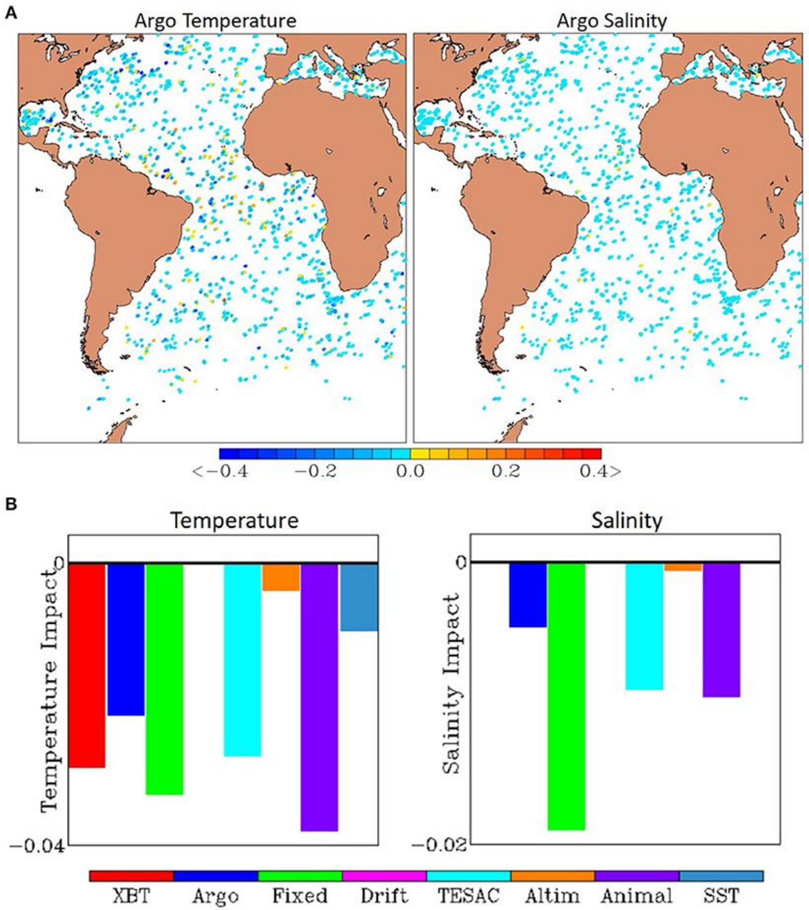
Observation impact diagnostics

FSOI evaluated for the ODAP system based on the global HYCOM Ocean Model.

(A) Impacts of Argo profiles on reducing 48-h forecast error in the Atlantic basin from 30 July through 18 August 2018. Cool colors indicate beneficial impacts; warm colors indicate non-beneficial impacts.

(B) Per observation impacts for temperature (left) and salinity (right) observing systems in the Atlantic for 30 July through 18 August, 2018. Temperature units are °C and salinity units are PSU.

Fujii Y. et al. (2019), Frontiers, https://doi.org/10.3389/fmars.2019.00417

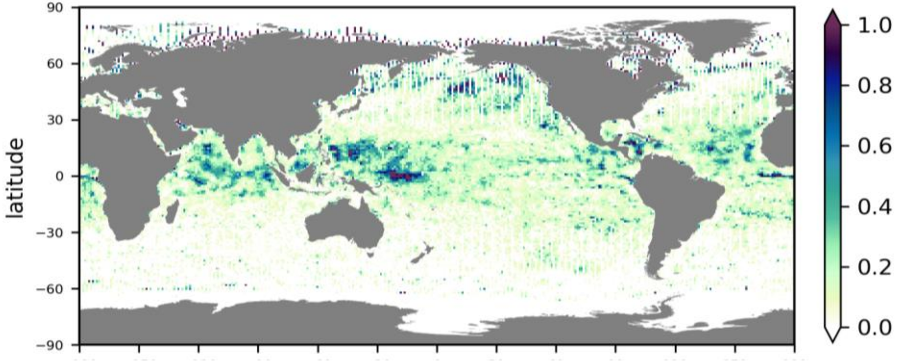


Observation impact diagnostics

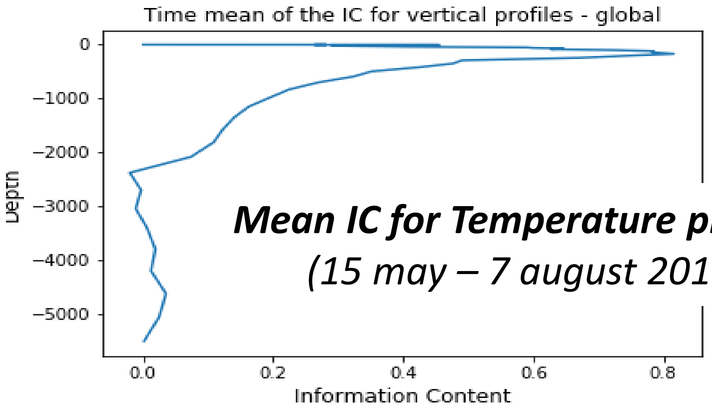
Influence of different type of observations on the 1/12° global analysis

Information Content = DFS/Nb Obs; DFS approximated as proposed by C. Lupu et al. (2011)

- IC close to 1: most of the observation information content is « used » by the assimilation scheme to correct the model forecast;
- IC close to 0: the model forecast is not changed by the data assimilation.



Mean SST IC *(15 may – 7 august 2019)*

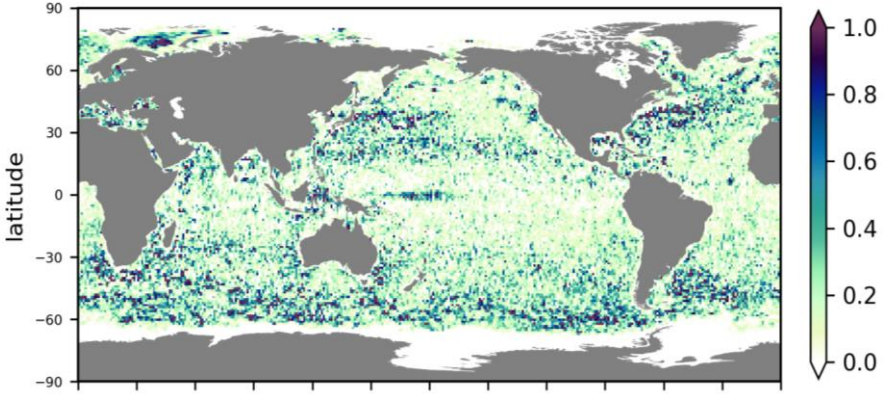


Mean IC for Temperature profiles
(15 may – 7 august 2019)

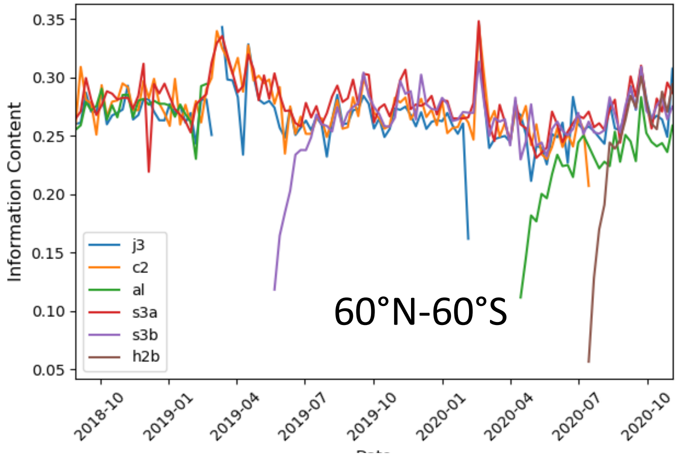
- ➢ SST observations have more influence in the tropics and in the « summer hemisphere »,
- ➢ In situ temperature observations at the thermocline depth have the largest impact.

Observation impact diagnostics

Impact of S3-B SLA observations on the global 1/12° CMEMS system



Mean IC for S3B (15 may to 7 august 2019)



Time evolution of the mean Information Content

- S3-B SLA observation are the most important for the analysis in turbulent regions (western boundary currents, Antartic circumpolar current).

Regions with high variability or small scale dominant processes require a higher number of altimeter observation to control their dynamical evolution.

Impact of the altimeter constellation on global ocean forecasts

Impact of the number of altimeters on the quality of Mercator Ocean global ocean analyses and forecasts (CNES study)

1-year OSEs with the global ¼° system assimilating 1 to 4 altimeters and different MDT based on the CNES/CLS MDTs

- The global SSH MSE is reduced by around **20% when going from 2 to 4 altimeters assimilated**.
- The SSH MSE is also sensitive to the **Mean Dynamic Topography (MDT) accuracy**.

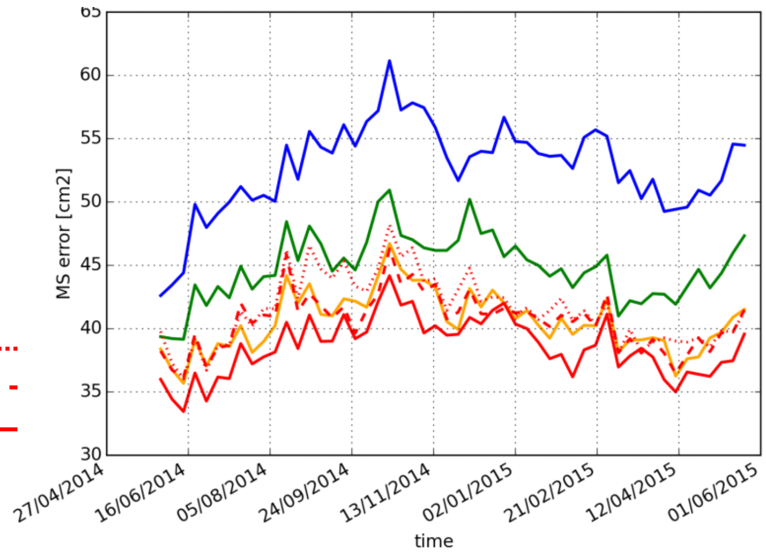
Model counter part of SLA observations:

$$SLA_{model} = SSH_{model} - \text{Mean Dynamical Topography}$$

Global SSH Mean Square misfit between Observations and model.

1 alt+MDTv3
2 alt+MDTv3
3 alt+MDTv3

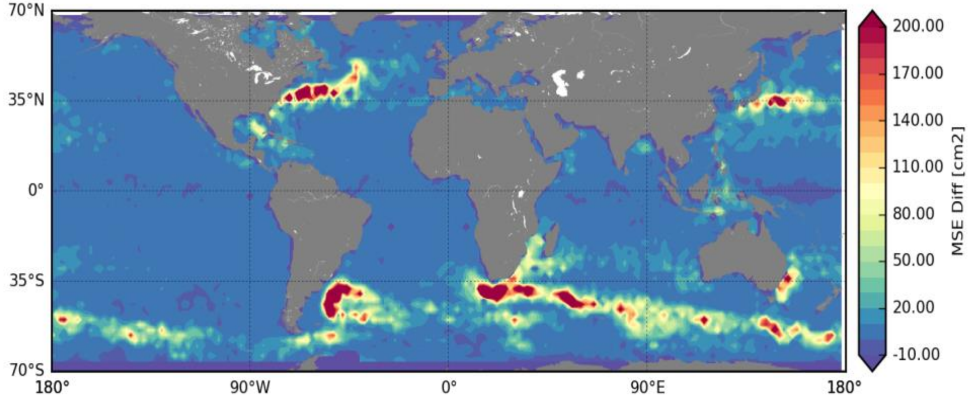
4 alt+MDTv2 .....
4 alt+MDTv3 - -
4 alt+MDTv4 —



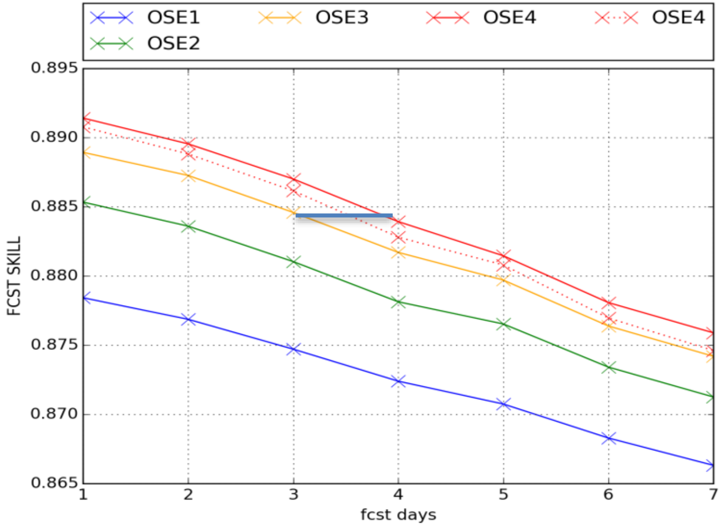
Hamon M. et al., J. Atmos. Tech. (2019).
https://doi.org/10.1175/JTECH-D-18-0236.1

Impact on the altimeter constellation on global ocean forecasts

- Forecast error is divided by 2 when moving from 1 to 4 altimeters.
- The error reduction brings by the **4th altimeter** is still significant, with a gain close to **1-day forecast**
- The error reduction is most important in the ACC and western boundary current.



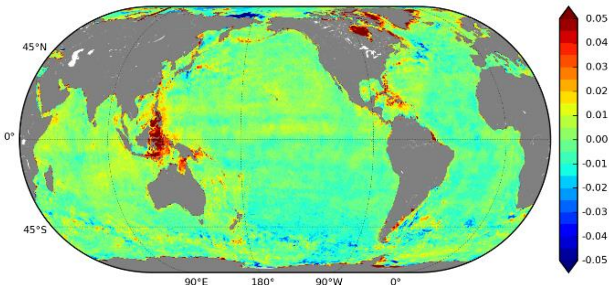
7-day sea level forecast errors : 4 versus 1



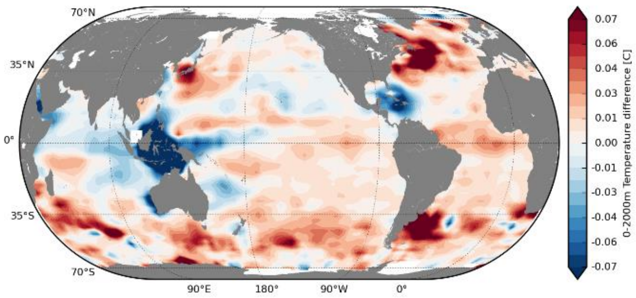
Forecast skill evolution when adding altimeters (from 1 to 4)

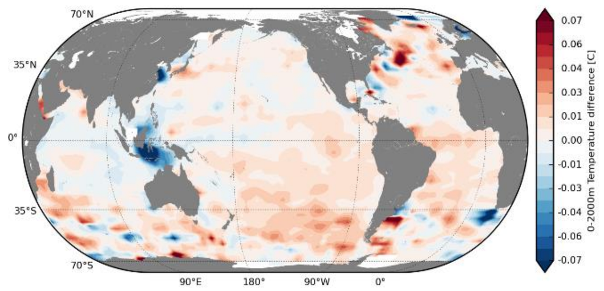
Hamon M. et al., J. Atmos. Tech. (2019).
https://doi.org/10.1175/JTECH-D-18-0236.1

Impact of MDT changes on the ¼° global system



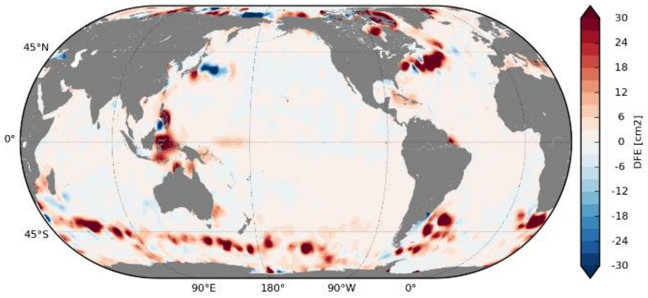
MDTv4-MDTv3 (c) (in meter)

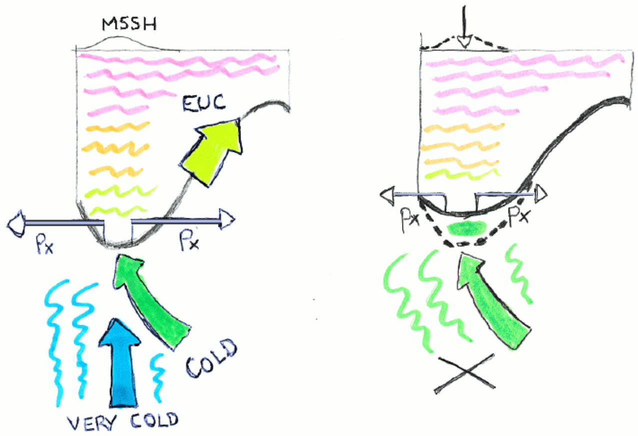




0-2000m temperature bias compared to in situ profiles: with MDTv3 (left); with MDTv4 (right).

Difference of SSH forecast MSE (OSE4v3 – OSE4v4)





Changes in the MDT lead to changes on the SLA statistics but also 3D T and S bias (M. Hamon, 2019), as well as on mass and tracer transport:

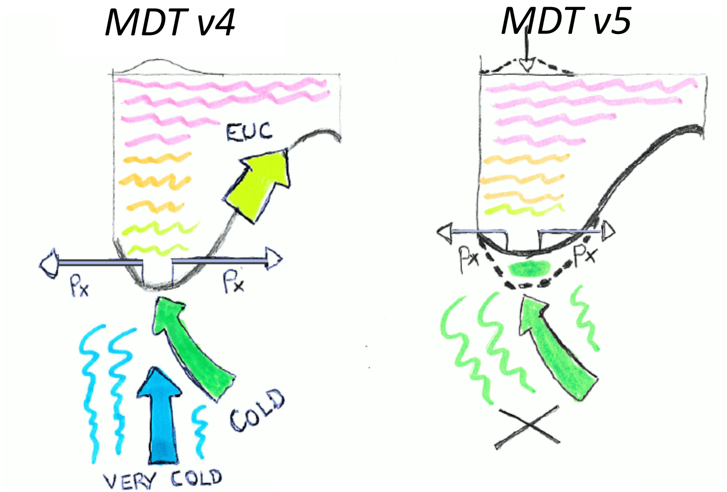
→ MDT changes can have none local “effect”.

An “ad-hoc” MDT correction was tested at the equator.

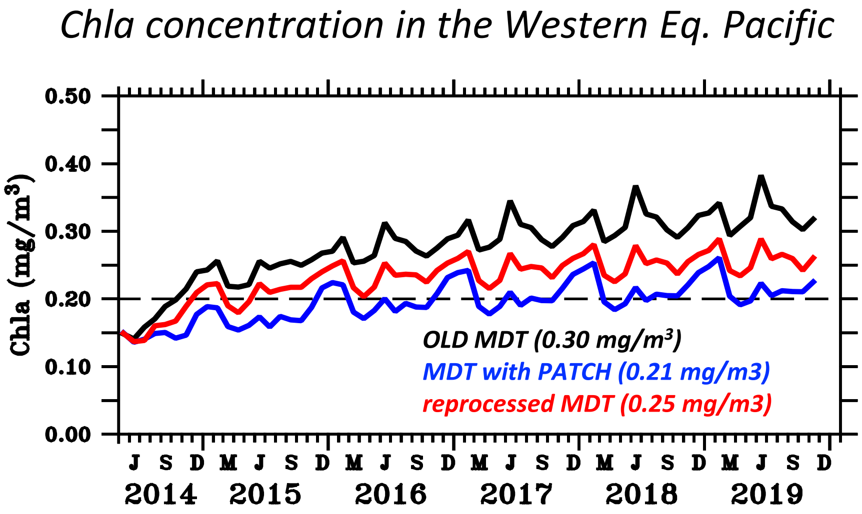
M. Hamon, E. Greiner

Impact of MDT changes on BGC variables

Lowering the MDT in the Western equatorial Pacific reduces the strength of the EUC and the upwelling of cold water that brought too much nutrients in the upper layers.



M. Hamon, E. Greiner



➔ Modification of the MDT impacts significantly the BGC forecasts (ChlA concentrations)

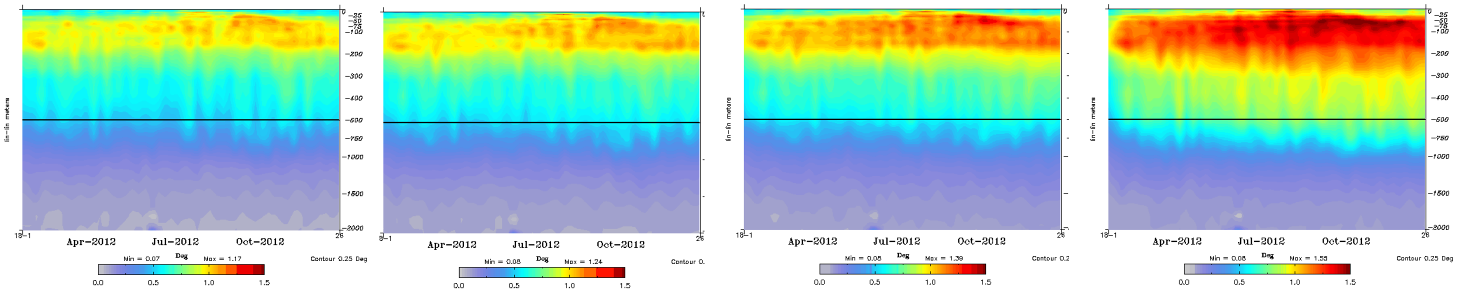
Gasparin F. et al., Ocean Modeling, (2021).
https://doi.org/10.1016/j.ocemod.2021.101768

Impact of the ARGO network on the global ¼° analysis

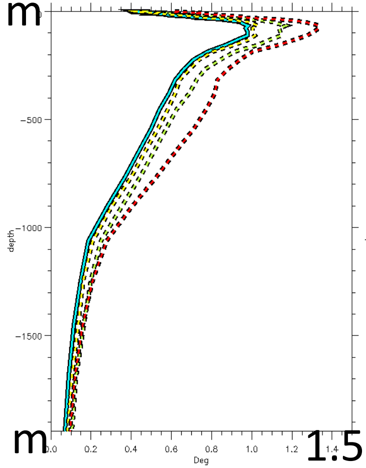
1-y OSEs	Assimilated data sets			
	SST	SLA	INSITU No-argo	INSITU argo
Run All Argo	X	X	X	X
Run No Argo	X	X	X	
Run Argo/2	X	X	X	50% only

RMS of 0-2000m temperature innovations for Run-AllArgo (blue), Run-Argo/2 (yellow), Run-NoArgo (green) and free Run (red)

All Argo floats | *½ ARGO floats* | *no ARGO floats* | *free run (no DA)*



0 m



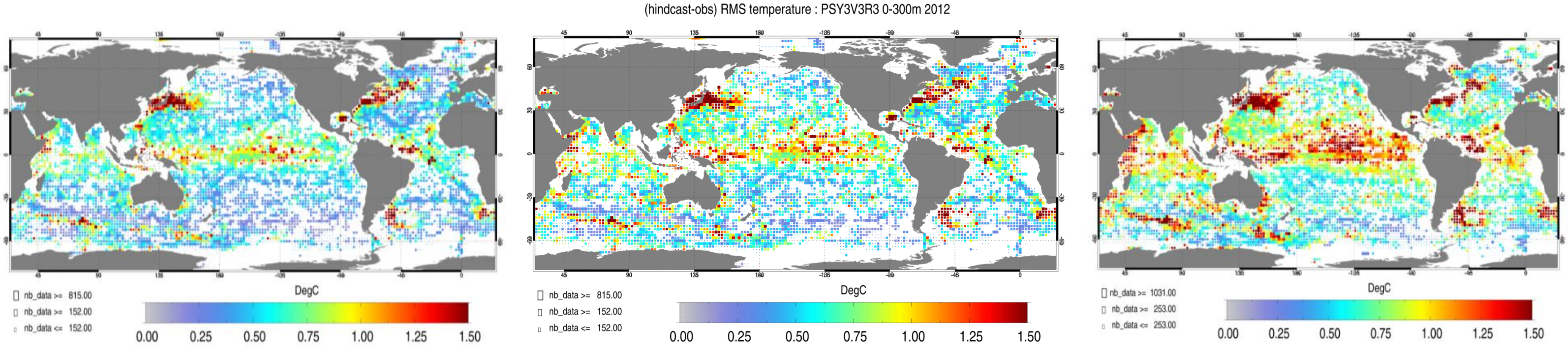
2000 m

1.5°C

Global RMS temperature innovations (obs – model forecast) for 2012

Impact of the ARGO network on the global ¼° analysis

Global RMS 0-300m misfit between the *in-situ* observations and OSEs analysis (last 6 months of 2012)



Run- All Argo *Run-Argo/2* *Run-No Argo*

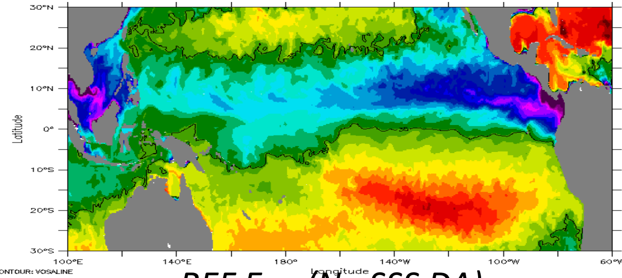
Regions of higher impact:

- at depth, water masses from outflow or deep convection are better represented,
- in the surface layers, the largest impact is found in the tropical band and energetic ocean regions (WBC,…),
- keeping only half of the ARGO floats degrades significantly the analysis.

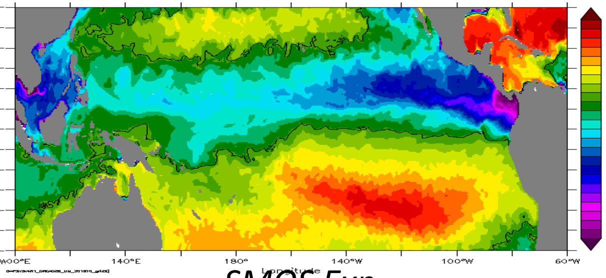
Turpin et al., Ocean Sci. (2016)

https://doi.org/10.5194/os-12-257-2016

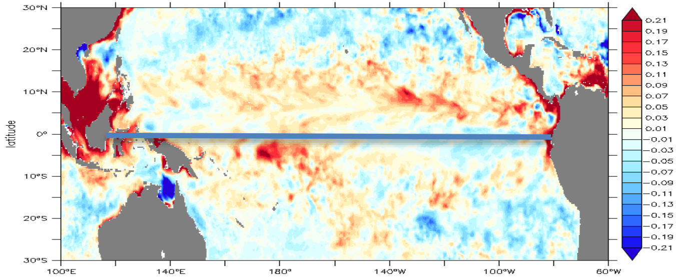
Impact of assimilating satellite SSS during the 2015/2016 El-Niño



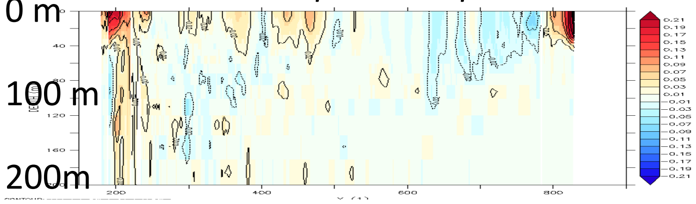
REF Exp (No SSS DA)



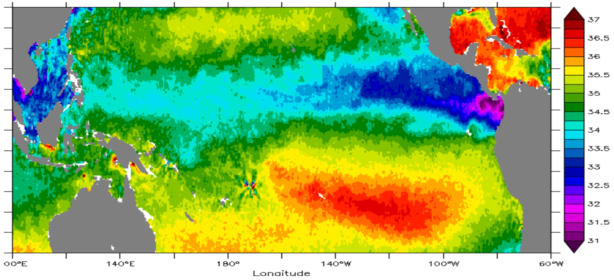
SMOS Exp



SMOS Exp –REF Exp

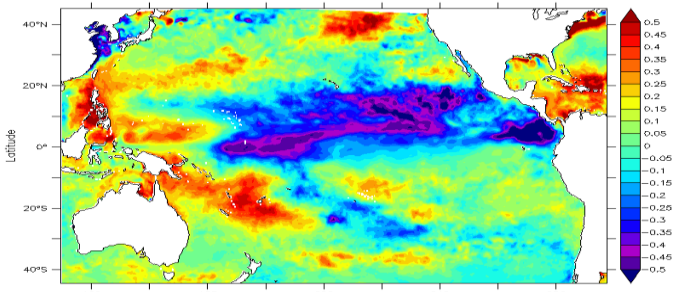


SMOS LOCEAN data



SSS DA effect in the Tropical Pacific in 2015:

- Weaken the SSS mean anomaly in the IPCZ and SPCZ (0.2 pss)
  - ➔ correction of the precipitation excess in the forecast
- Large changes in the freshwater pool and Indonesian archipelago
- SSS variability closer to the SMOS observations (river plumes)



2015 SSS anomaly in Glorys2v4

Tranchant B. et al., 2019

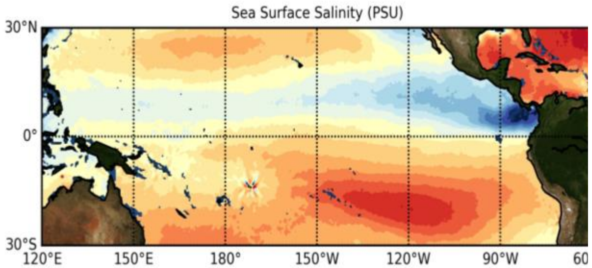
smos+ niño15
support to science element

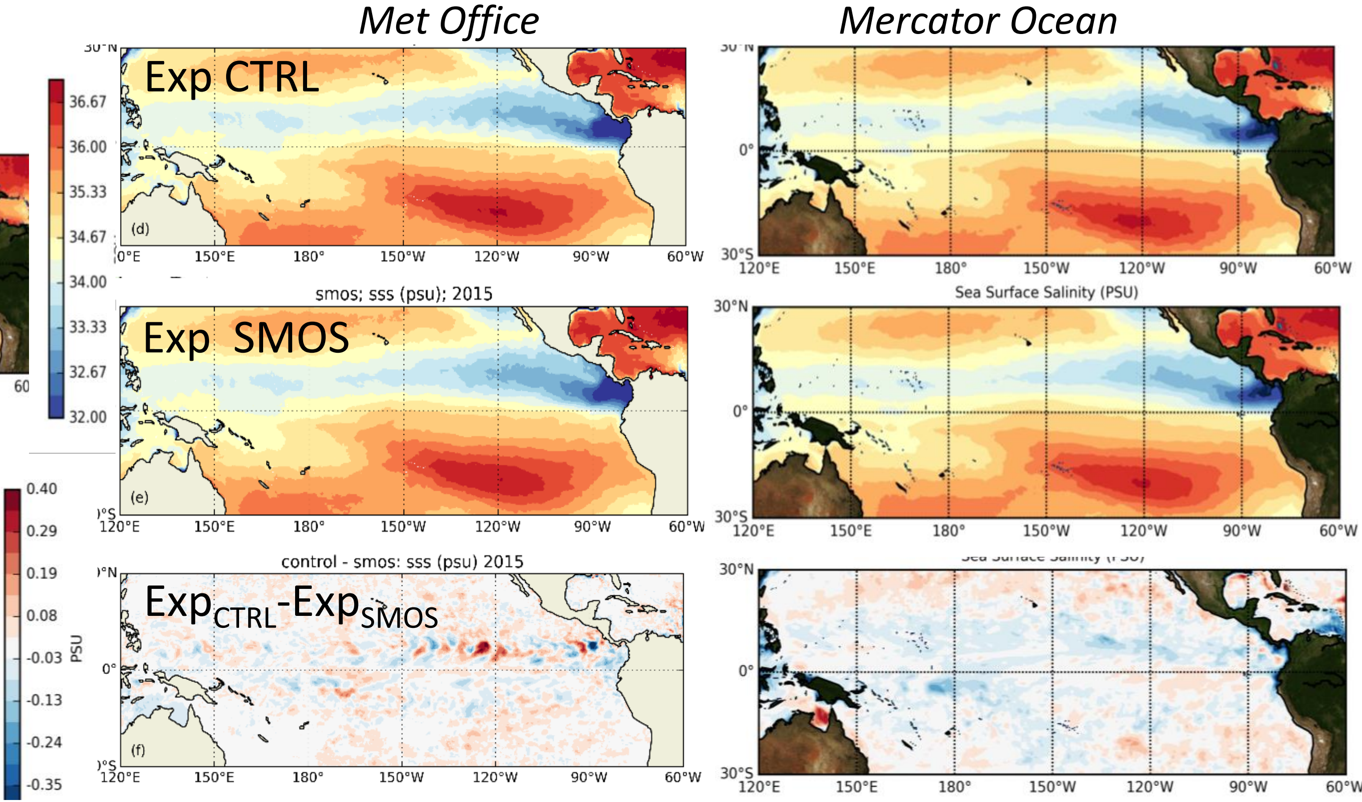
[ESA project with Met Office/CLS/ Mercator Ocean](https://www.godae-oceanview.org/projects/smos-nino15/)

https://www.godae-oceanview.org/projects/smos-nino15/

Impact of assimilating satellite SSS during the 2015/2016 El-Niño

SMOS L3 observations from CATDS





Annual average SSS (PSU) for 2015: SMOS observations (top); analysed SSS without and with SMOS DA; difference [control – smos]

- *Changes in the analysis is very different depending on the system, even if for both system the misfit to SSS observations is reduced.*

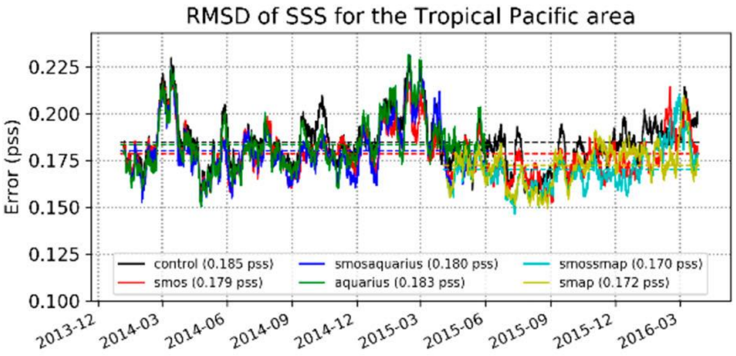
Martin M. et al., JOO (2021).

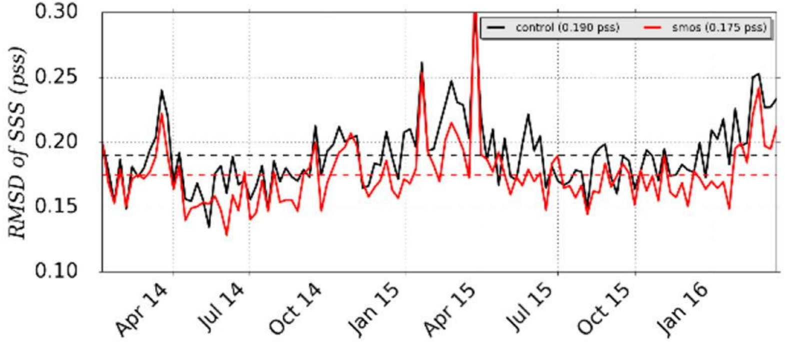
https://doi.org/10.1080/1755876X.2020.1771815

Impact of assimilating satellite SSS during the 2015/2016 El-Niño

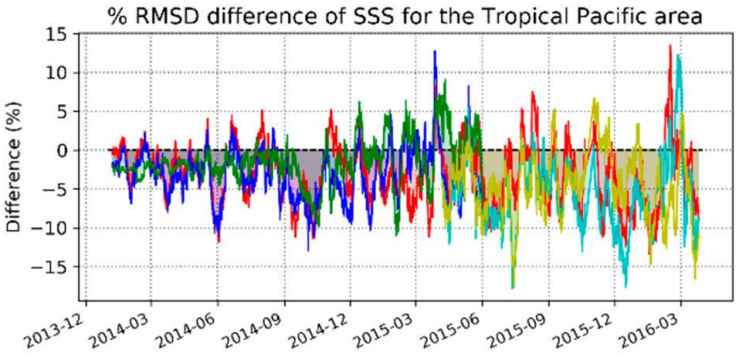
Met Office | *Mercator Ocean*

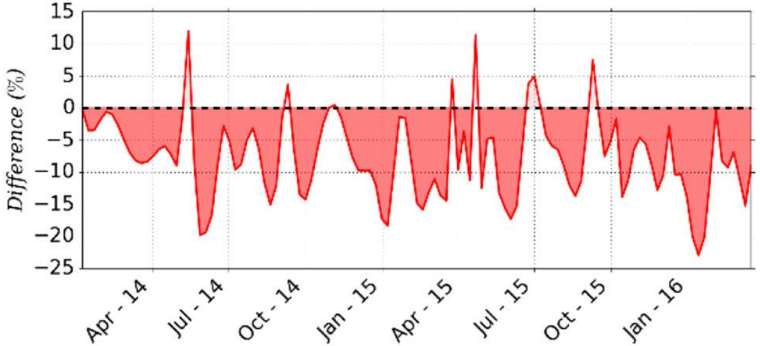
RMSD to ***in-situ*** *salinity observations*





% difference in RMSD compared to the control experiments





Time series of RMS Differences compared to near-surface Argo salinity (pss) in the tropical Pacific.

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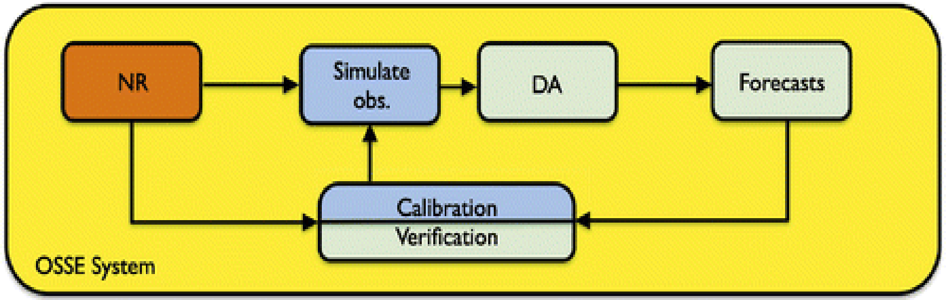
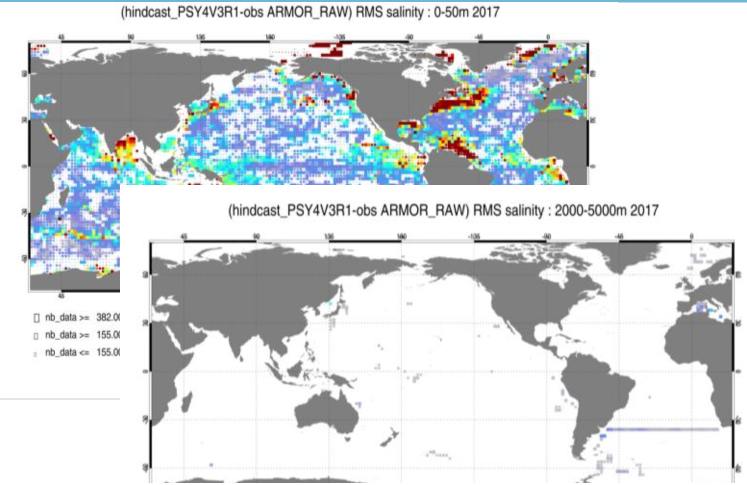
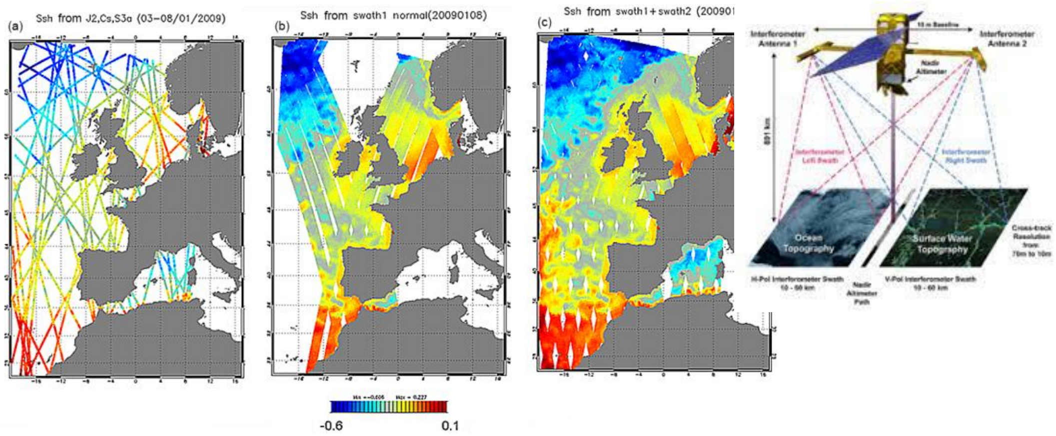
Testing different scenarii for Ocean Observation networks…



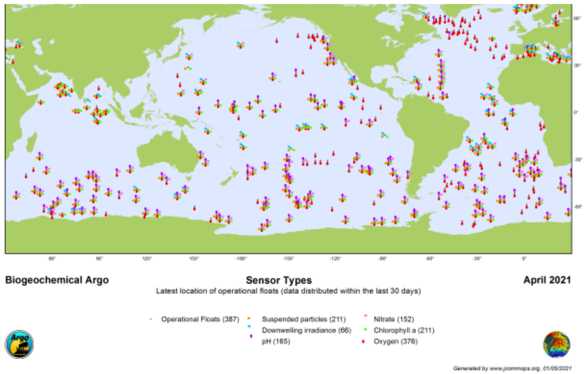
www.aoml.noaa.gov/qosap/osse-checklist/



Nadir versus large swath altimeters (and error level)?



Deployment strategy for BGC and deep Argo floats?



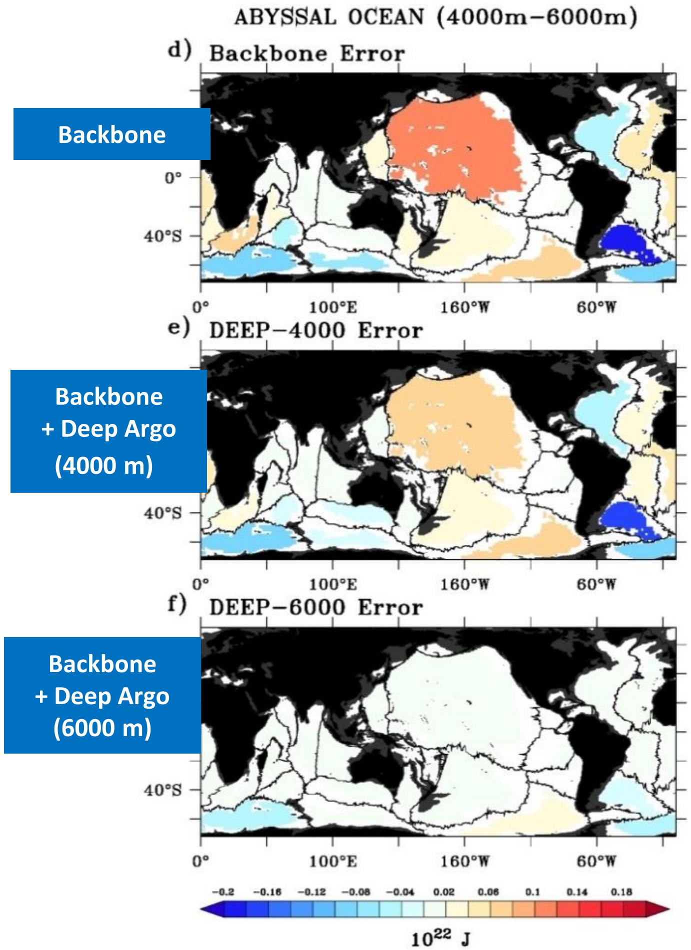
Multi System Deep Argo OSSEs

Different design for the deep Argo array have been tested in the global ¼° Mercator Ocean system

- Up to 4000 m depth
- Up to 6000 m depth

And compared to today situation.

- ➢ Observations were simulated from a 1/12° simulation. Impact of deep-Argo is evident on T and S in the 2000-4000m layer, the Southern Ocean remains undersampled.
- ➢ Compared with Argo4000, Argo6000 significantly reduces biases in the 4000-6000m layer.



2010 Ocean Heat Content error in abyssal oceans (4000-6000 m) for the different OSSEs

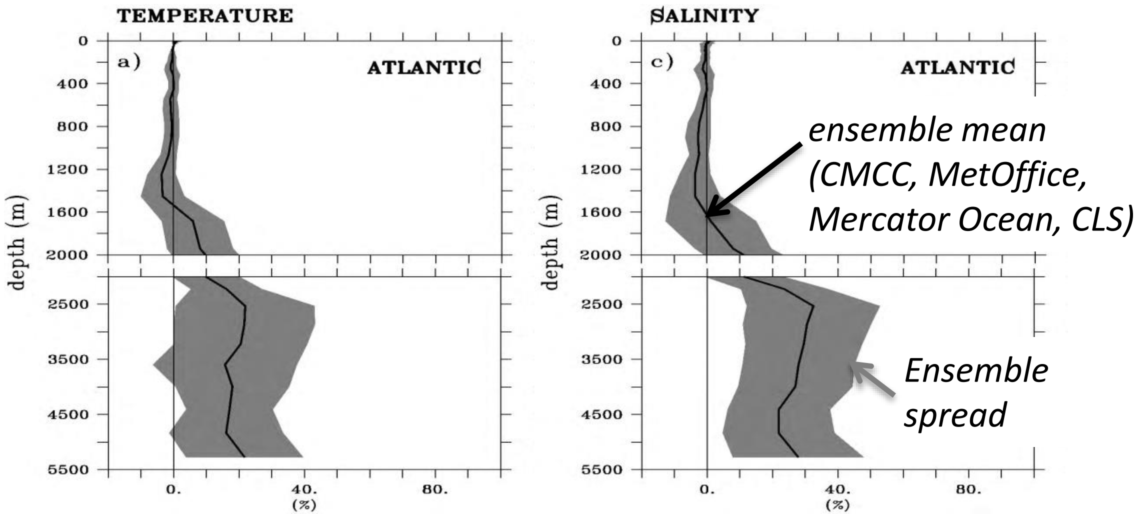
AtlantOS H2020 project

Gasparin F. et al., J. Climate (2020).

https://doi.org/10.1175/JCLI-D-19-0208.1

Multi System Deep Argo OSSEs

The same simulated observations were assimilated in different global systems (CMCC, MetOffice and CLS) to intercompare their impact and give more robust conclusions.



Temperature and salinity profiles of error reduction in % of the DEEP exp. as compared with the BACKBONE experiment, relative to the Nature Run fields.

- ➢ Significant improvement on the deep sea water properties when deep T,S Argo observations are assimilated for all systems.

Gasparin F. et al., Frontiers (2019). https://doi.org/10.3389/fmars.2019.00083

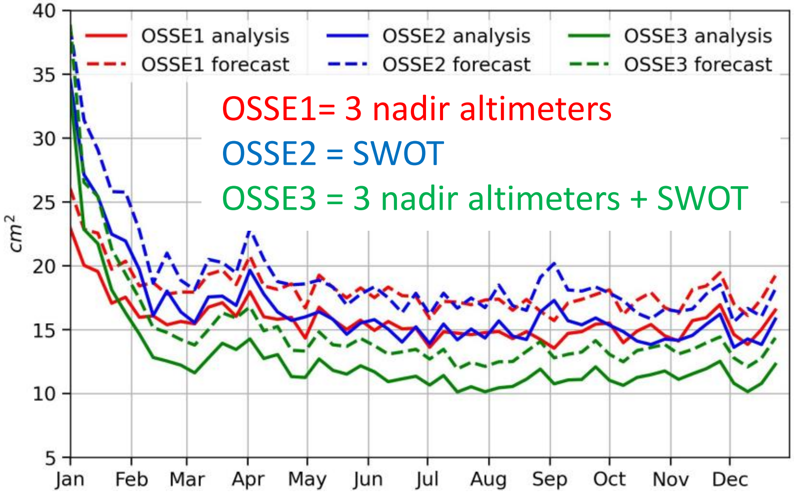
Assimilation of Wide Swath Altimetry observations

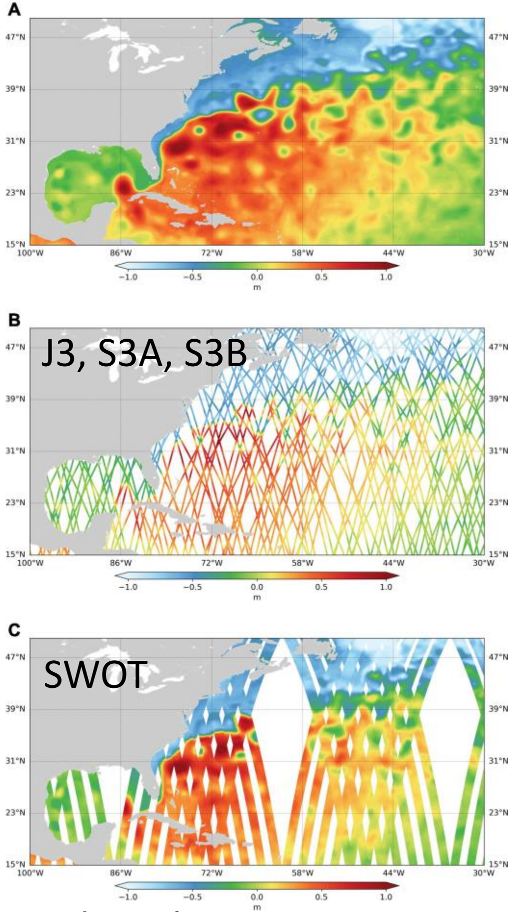
Estimation of the impact of SWOT data assimilation in a global system

1-year OSSEs with the global system at 1/12°, in situ and SST obs. assimilated to mimic a realistic context for observations.

Only the Karin error is considered for SWOT.

Temporal evolution of SSH error variance (in cm²) for 7-day analysis (plain lines) and forecast (dash lines)

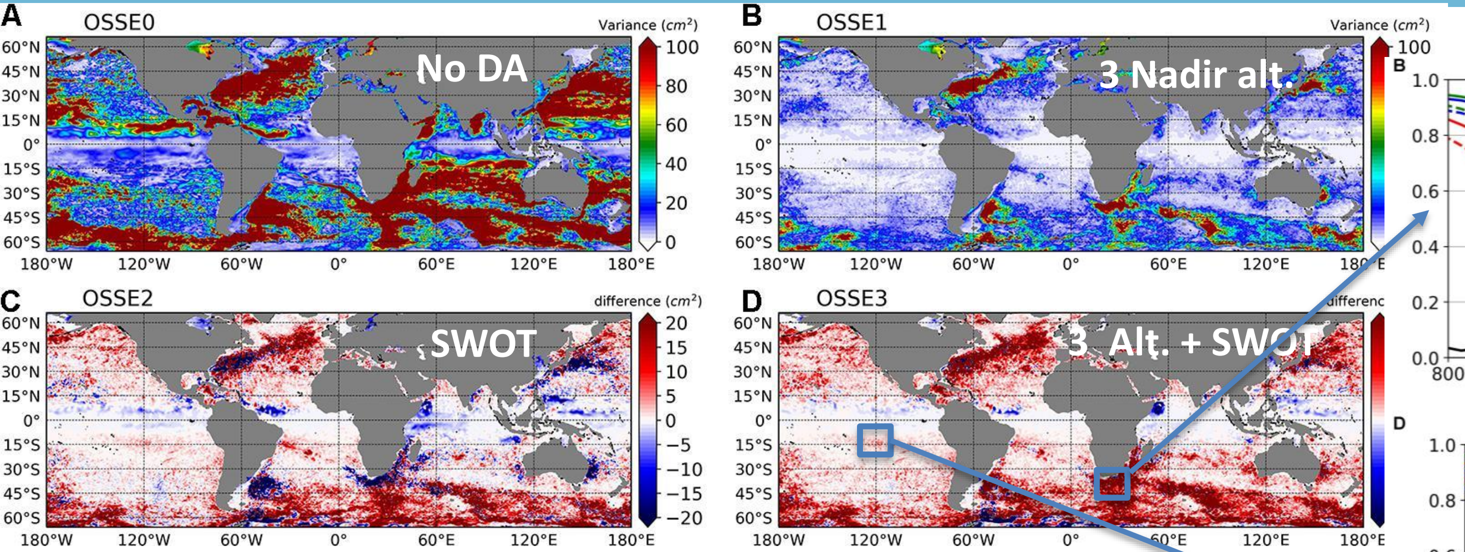




7-day observation coverage

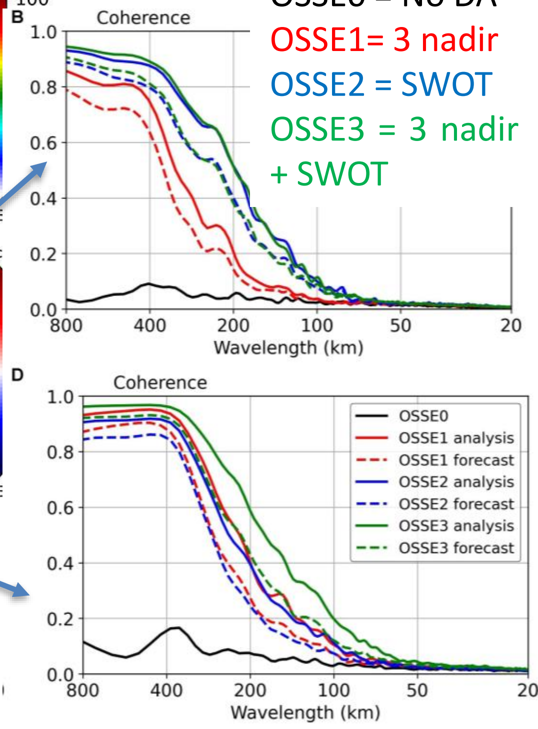
→ Considering a constellation of 3 nadir (SAR) and SWOT, ocean analysis errors on SSH is reduced by 30% (40% for L>200km) with respect to 3 nadir constellation.

Assimilation of Wide Swath Altimetry observations



*Global maps of SSH analysis error variance (in cm^2). FR - NR **(A)**, OSSE1 - NR **(B)**. OSSE2 – OSSE1 **(C)** and OSSE3 – OSSE1 **(D)**.*

OSSE0 = No DA
OSSE1= 3 nadir
OSSE2 = SWOT
OSSE3 = 3 nadir + SWOT



Spectral coherence between the NR and each OSSE: analysis (plains lines) and forecast (dash lines) of the SSH.

- Larger impact of SWOT at high latitude where the density of observations is higher.

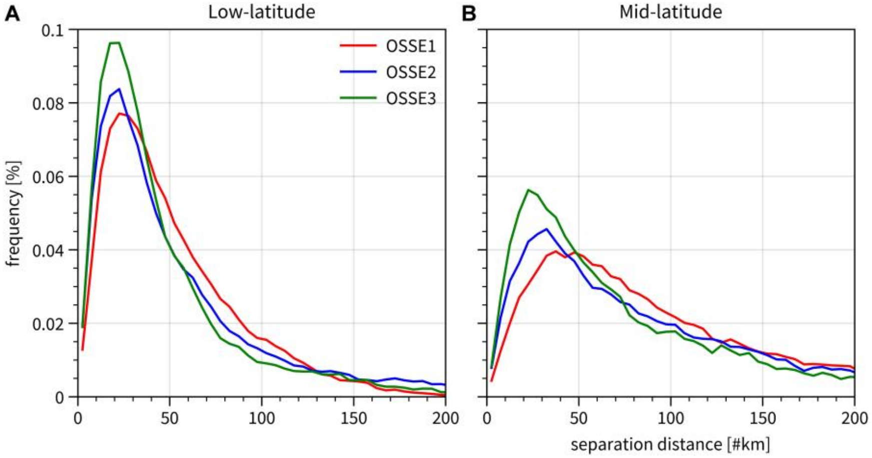
Next step: take into account correlated errors within the swath.

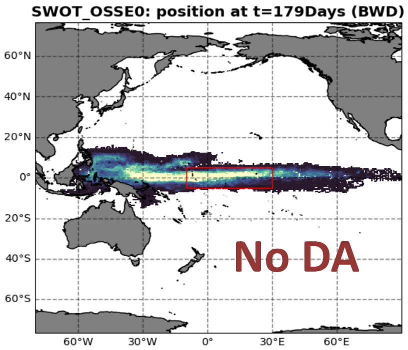
Assimilation of Wide Swath Altimetry observations

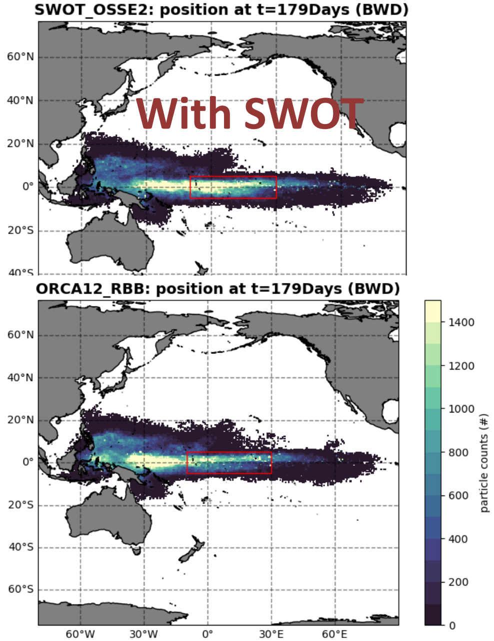
Significant reduction of the separation error distance between particles when SWOT data are assimilated.

After 7 days of drifting, globally:

- With 3 Nadir: 56% of particles are within 50km distance from Nature Run equivalent ("truth")
- With 1 SWOT: 64%
- With 1 SWOT + 3Nadir: 67%







Backward tracking of surface particles (0-30m) for 6 month

Benkiran M. et al. / Tchonang B. et al., part I and II, (2021): https://doi.org/10.3389/fmars.2021.691955 - fmars.2021.687414;

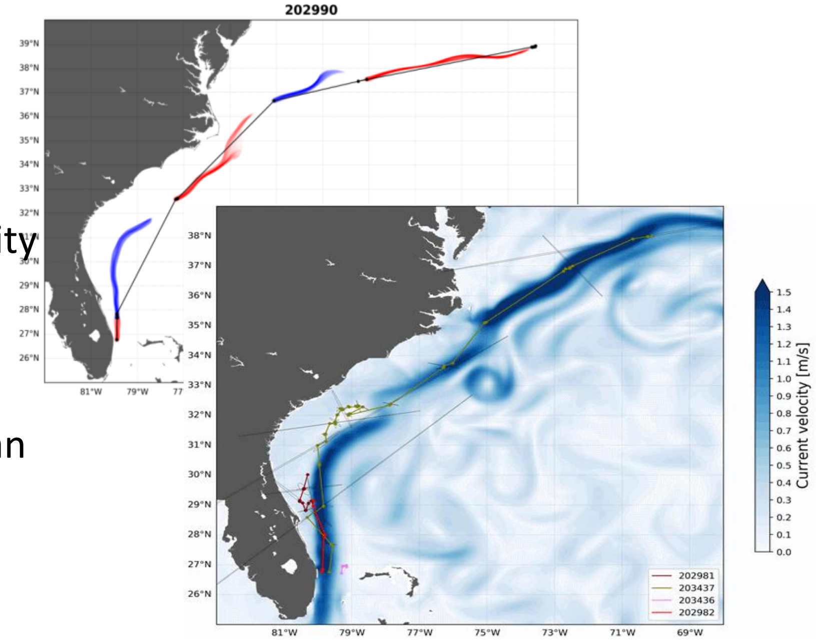
Assimilation of satellite Total Surface Current Velocities

Define a strategy and test the T-SCV assimilation at global scale (Multi system OSSEs)

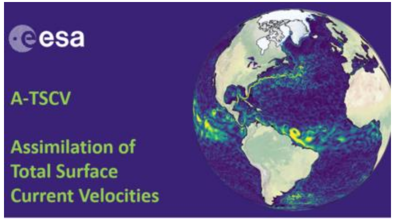
Open questions:

- Filter/control the balanced and unbalanced surface velocity component?
- How the model will « digest /forget» the increment?
- Does the wind need to be control?
- Definition of process and user oriented metrics (lagrangian approach)

ESA project with MetOffice and Ocean Data Lab (2019-2021)



Trajectories of 15 3-month leatherback sea turtles released in Florida (UPWELL/MOI project)



Challenges for improved impact of observation on ocean analysis and forecasts

Evolution of model and observation toward higher resolution in space and time:

- Global model with more resolved physical processes and increased spatio/temporal resolution (ex. : inclusion of tides in global ocean model, coupling with wave/other earth system component, …)
- Increased density and higher resolution/frequency content of the observations

➢ Need to refine the Data Assimilation strategy to control a larger spectrum of scales in the forecast (multi scale analysis, multi analysis, …).

Complex correlated observation error

Most of the ocean data assimilation systems rely on the hypothesis of uncorrelated observation error:

➢ ongoing work to better take into account correlated observation error (ex. for swath HR sea level observations): thinning / inflation of observation error / super obs…

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Recommendations for future assessment and design studies

1. Agree on standards and best practices on the way to perform OSEs (e.g. data denials, DFS/IC, FSOI) and OSSEs (e.g. NR and AR choices, calibration with OSSEs).
2. Agree on design options to test and define metrics for observing system evaluation taking into account user & application needs between observation and modeling/DA communities.

   Coordination between modelling/data assimilation experts and observation/network experts is essential for a proper design and interpretation of OSSEs, especially to extract compelling messages on the ability of the ocean observing system to resolve processes having different temporal and spatial scales.

3. Improve the robustness of the results by moderating system-dependency with multi-system evaluation and re-assess regularly the observation impact to follow the system evolutions.
4. Find an efficient and sustainable way for routine observation impact assessment and to inform on observation impact status.

   OSSEs require dedicated infrastructures. It is essential to strengthen the capabilities of operational centres to assess the impact of present and future observations to guide observing system agencies but also to improve the use of observations in models.

Observing systems are multi-purpose…

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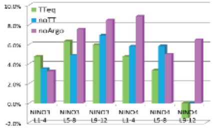
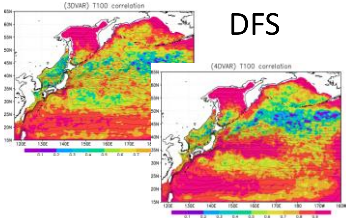
OceanObs'19 Community White Paper on OS-Eval

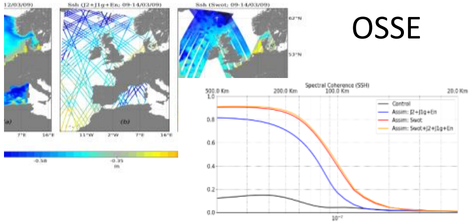
TPOS and Argo





DFS

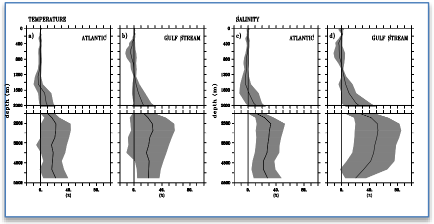
SWOT



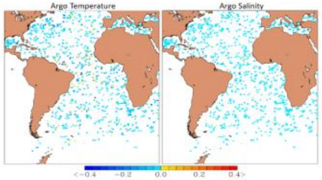
OSSE

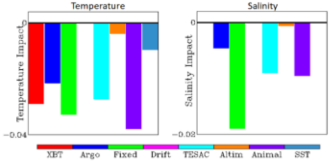
Atlant-OS

OSSE



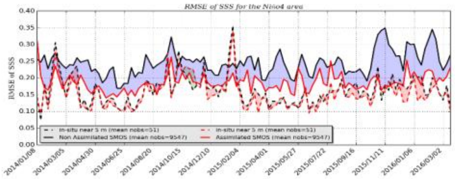
Adjoint Sensitivity



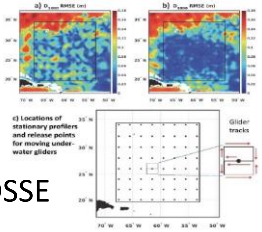


SMOS-NINO2015

OSE

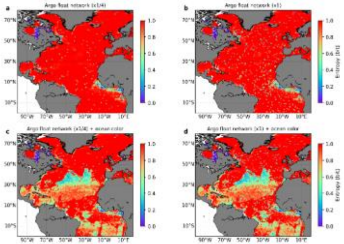


Coastal Obs System



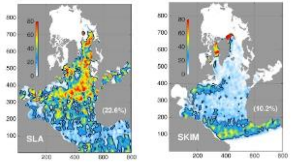
OSSE

BGC Argo



SKIM

SRF



Review papers:

- Fujii et al. (2019). Review of Observing System Evaluation studies in Ocean Predict centers. https://doi.org/10.3389/fmars.2019.00417 (OceanObs'19 Community White Paper)
- Oke et al. (2015a,b). J. of Oper. Oceanogr. (In the GODAE OceanView Special Issue.)

Ocean Predict OSEval Task Team:

https://oceanpredict.org/science/task-team-activities/observing-system-evaluation/#section-introduction