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TOWARDS ROBUST ESTIMATIONS OF THE DEEP OCEAN IN OCEAN REANALYSES WITH DEEP ARGO

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Gasparin F., Hamon, M., Remy, E., and P.Y. Le Traon (2019). How deep Argo will improve the deep ocean in ocean reanalyses. *Under Review in Journal of Climate.*

OUTLINE

1. Motivations

2. Temperature and salinity in ocean reanalyses

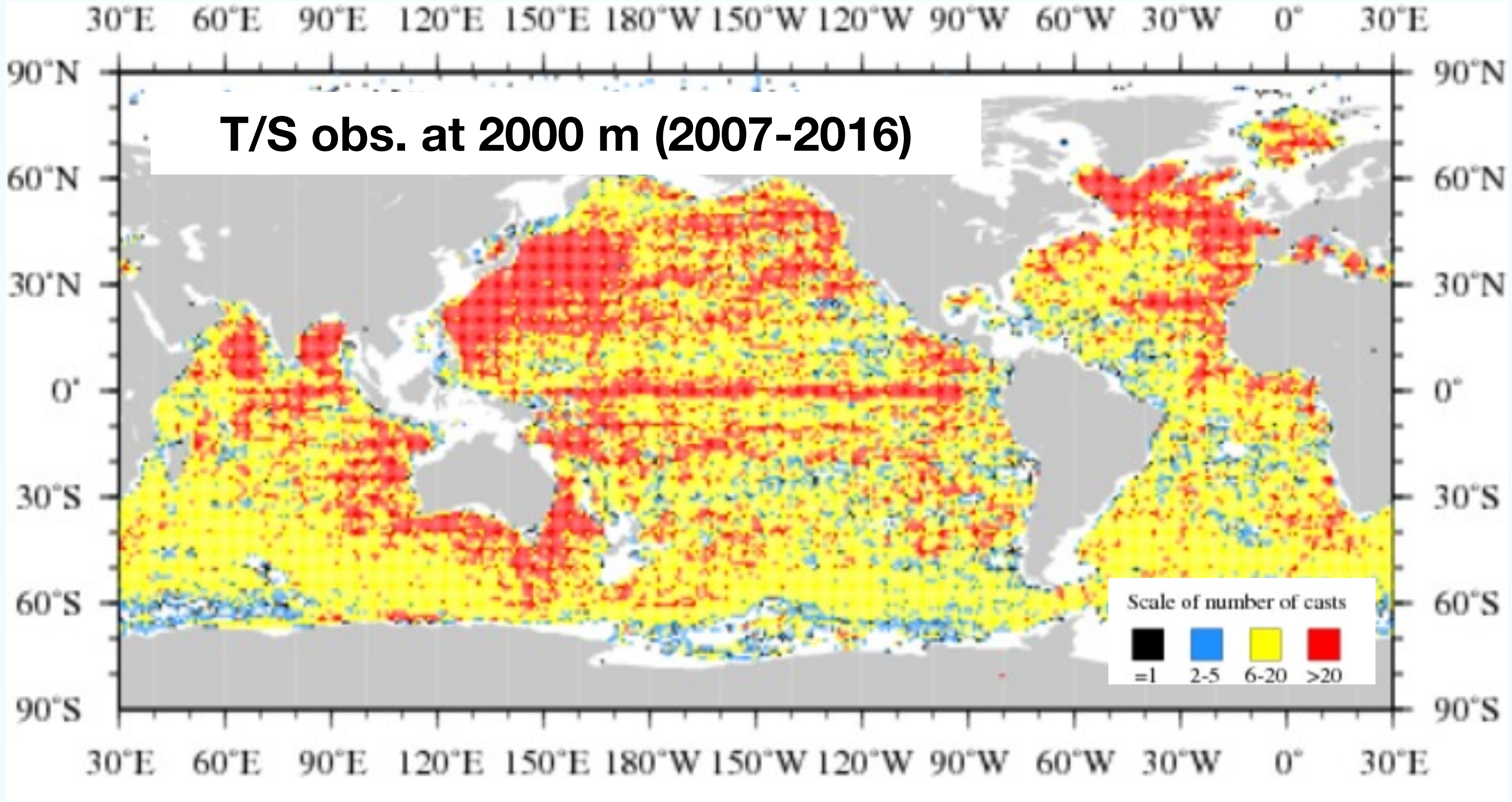
3. Numerical approach

4. Added value of a full-depth ocean observing system

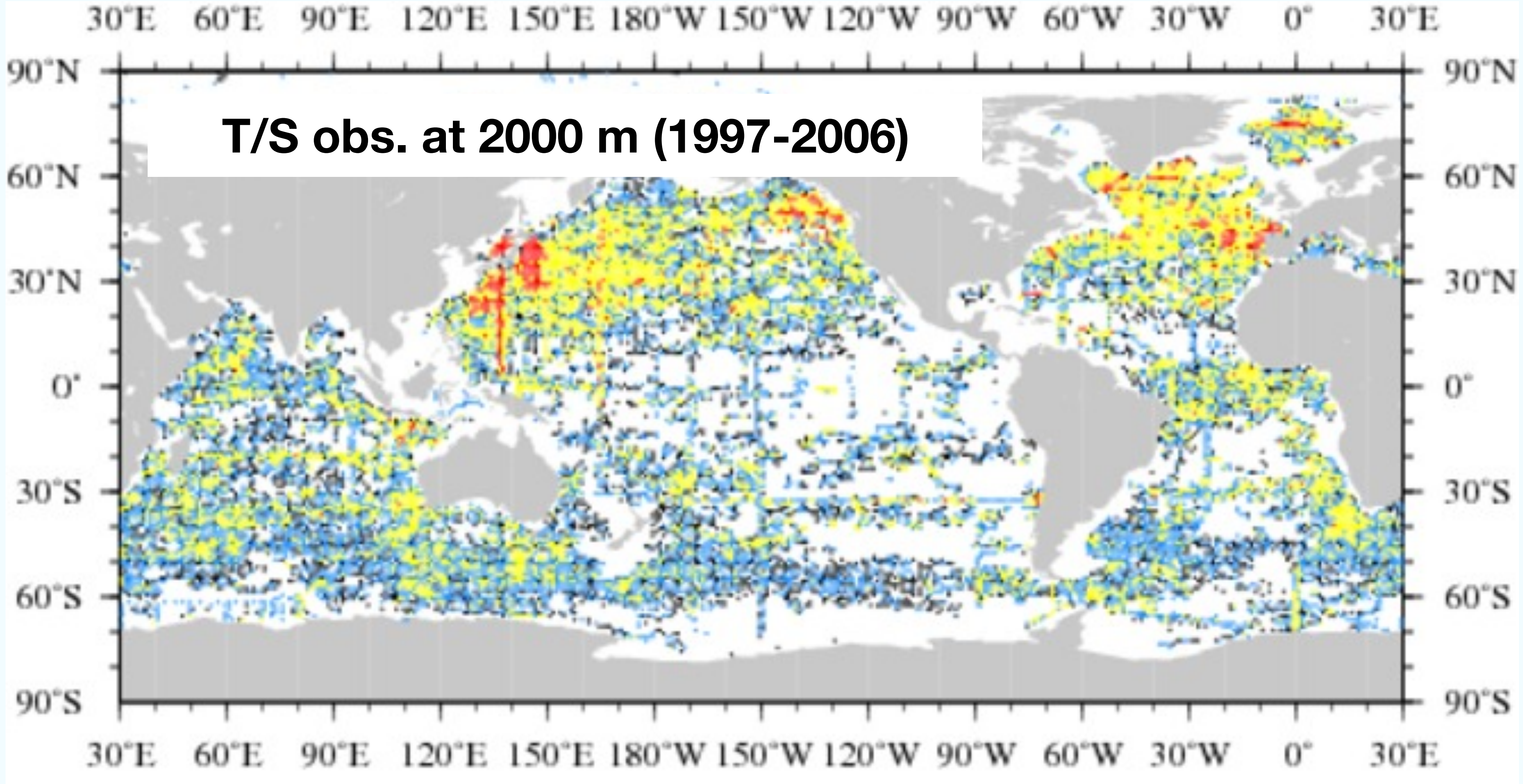
5. Conclusion

- *Argo* is now clearly identified as a central piece of operational oceanography
- *Operational centres* are now identified as a key stakeholder in supporting the evolution of the Argo array for improving large-scale ocean states. There is win-win collaboration

DENSITY OF THE *IN SITU* OBSERVING SYSTEM



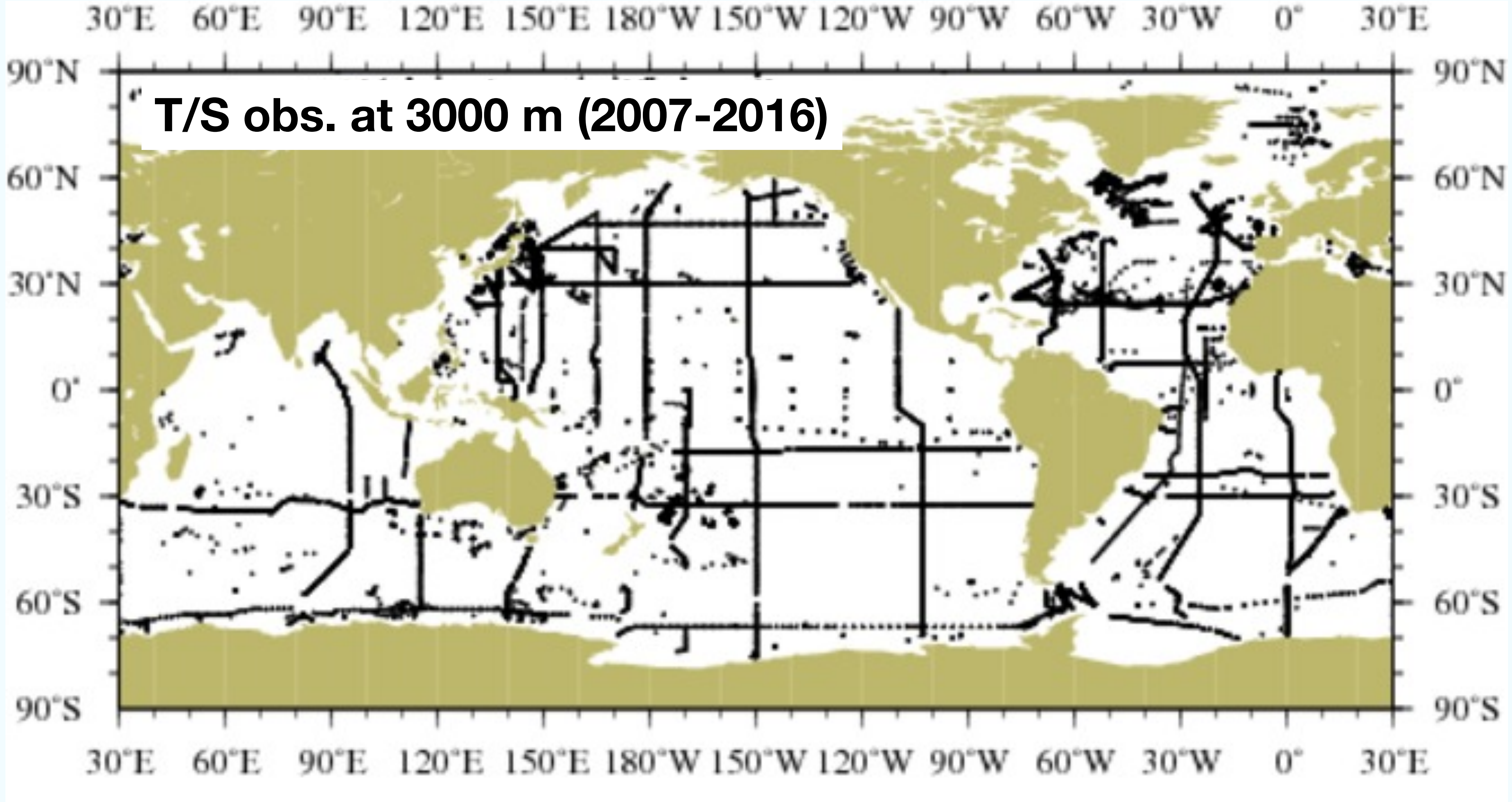
Casts per one-degree box (747219 casts)



Casts per one-degree box (136887 casts)

(from World Ocean Database)

- Northern hemisphere is higher sampled
- Argo's era (2004-present) has significantly increased the number of upper-ocean data
- **The deep ocean (below 2000m) remains significantly under-sampled**

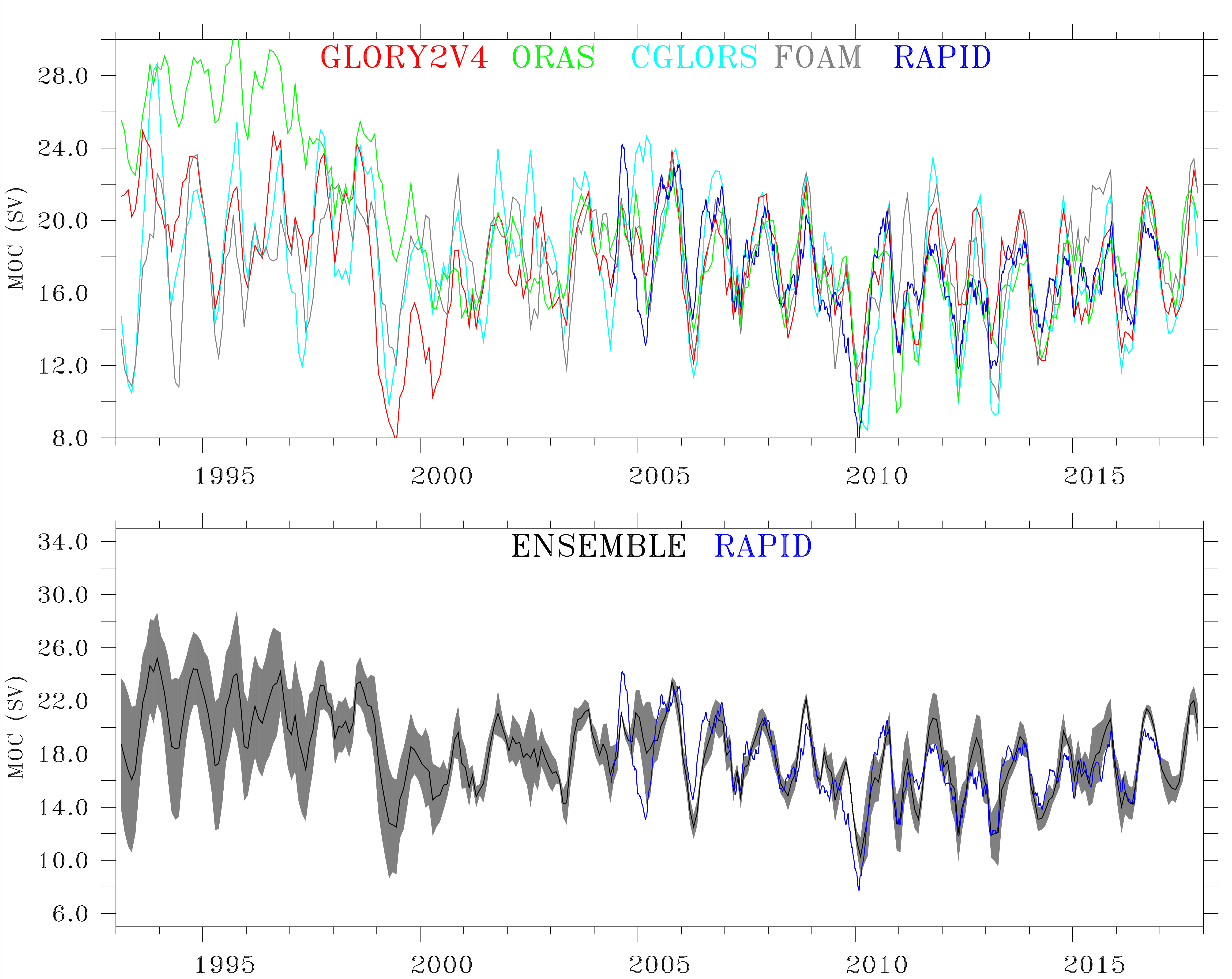


Geographic distribution of casts (16943 casts)

High dependency of ocean reanalyses on observations

Meridional transport (0-1200 meridional velocity) from the four GREP reanalyses and the RAPID data set (upper). The GREP ensemble mean (with its standard deviation) and the RAPID estimate (lower).

GREP = Global Ensemble Reanalysis Product composed of four 1/4° global ocean reanalyses distributed by CMEMS

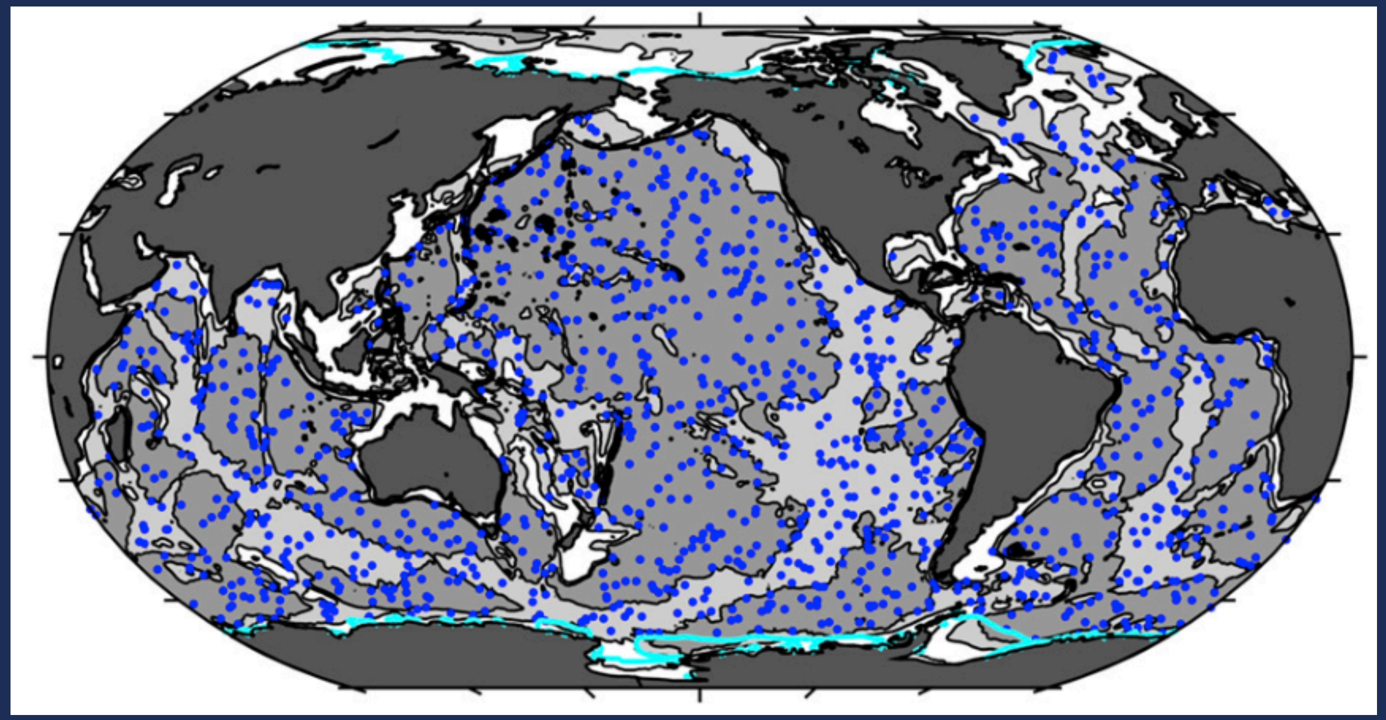


Numerous studies have shown that ocean reanalyses are consistent in representing the upper ocean physical conditions at interannual and longer time scales, but <u>strongly differ in representing the deeper ocean</u>

(Palmer et al. 2017; Storto et al. 2018; Garry et al. 2019)

HIGH DEPENDENCY OF OCEAN REANALYSES ON OBSERVATIONS

VERY LIMITED NUMBER OF STUDIES ON THE DEEP ARGO DESIGN

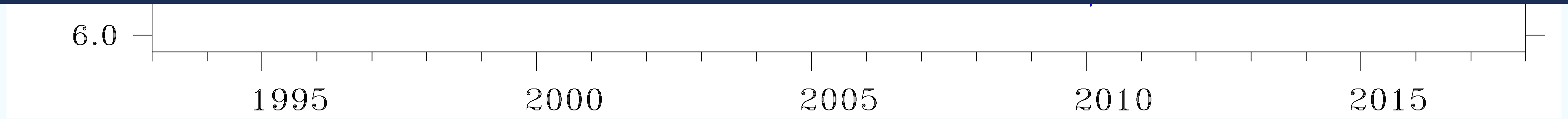


Scales analysis from WOCE/GO-SHIP lines
Johnson et al., (2015, JAOT)

1,200 deep Argo floats

How ocean reanalyses are able to estimate the deep ocean state ?

How numerical experiments can anticipate the added value of such global and frequent array in ocean reanalyses?



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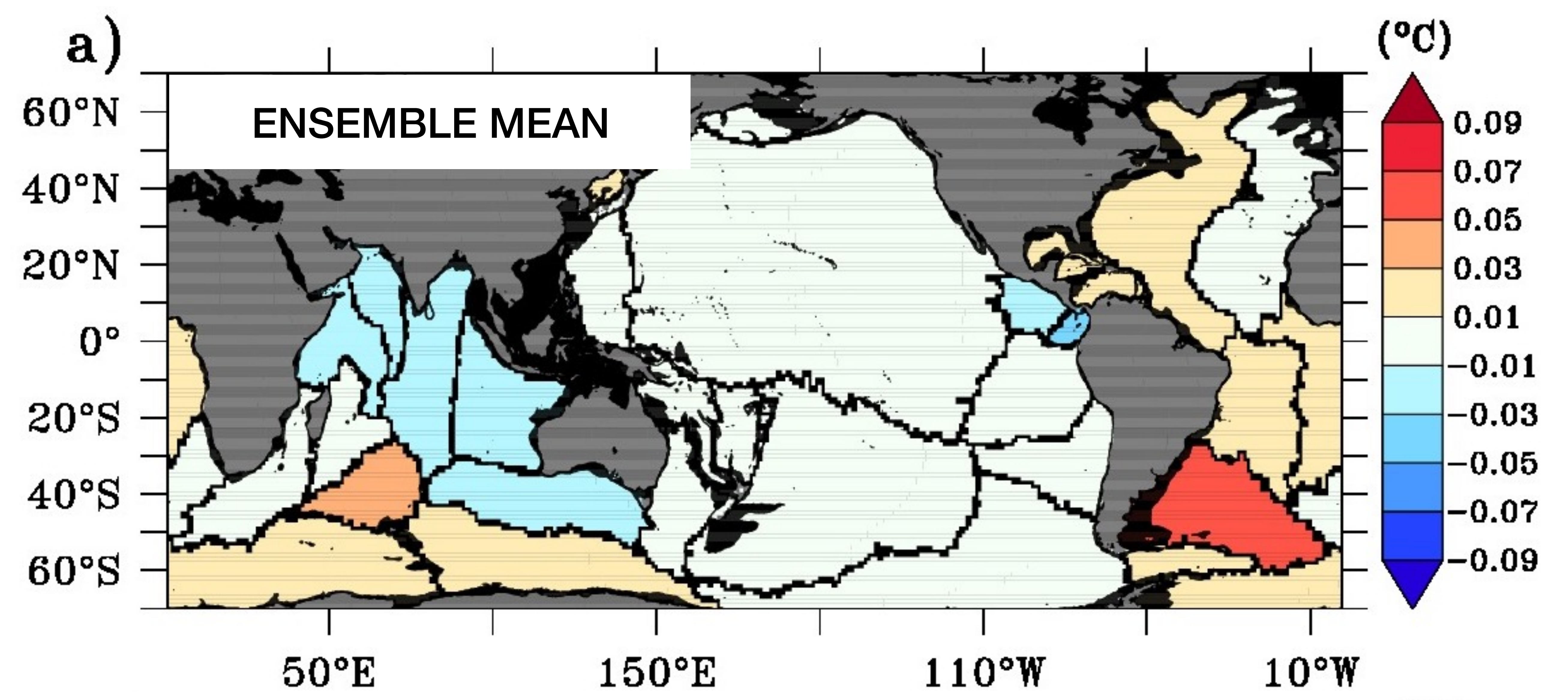
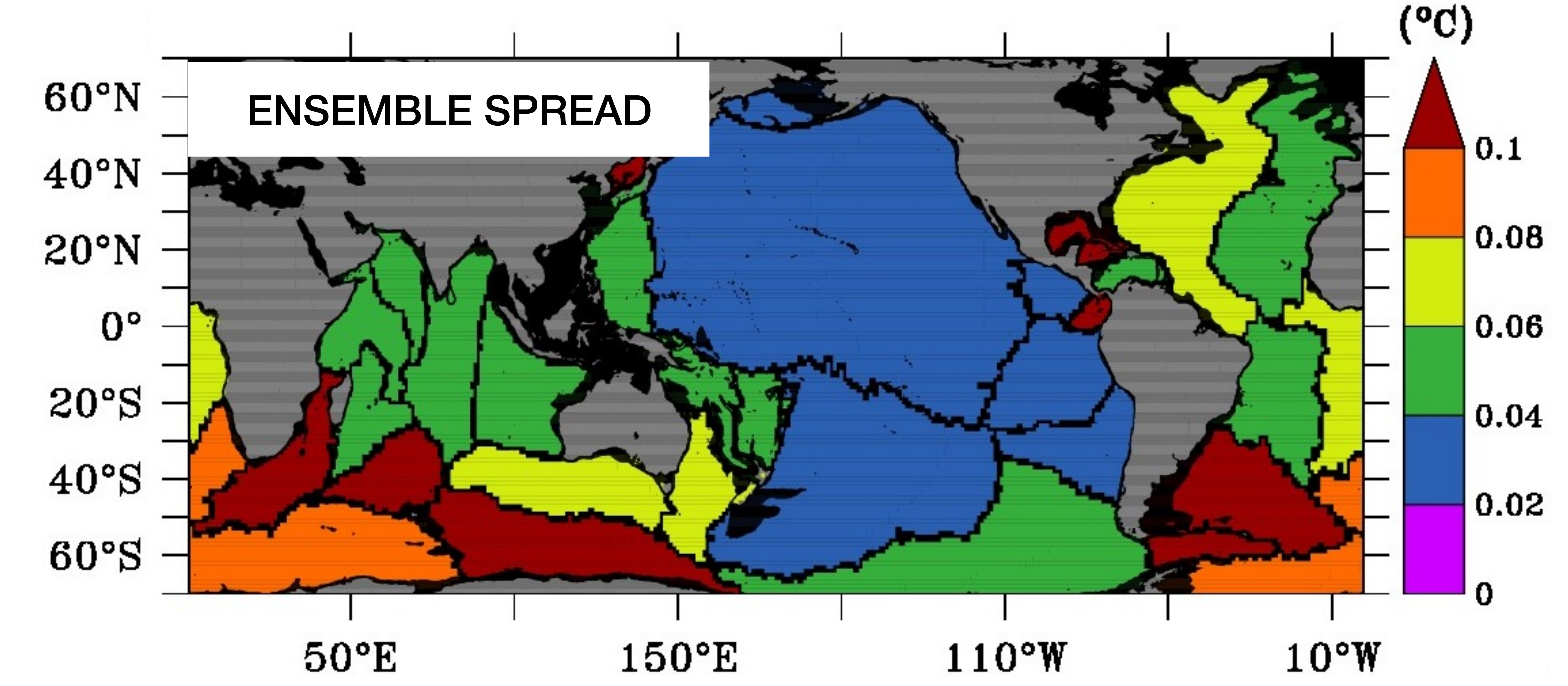
DIFFERENT BEHAVIOUR OF AN OCEAN REANALYSIS ENSEMBLE

2006-2015 minus 1996-2005 temperature difference at 3,000 m





Positive values indicate small warming around Antarctica (> 1 m◦C/yr), while negative values in the Indian ocean indicate a small cooling (< -1 m◦C/yr)

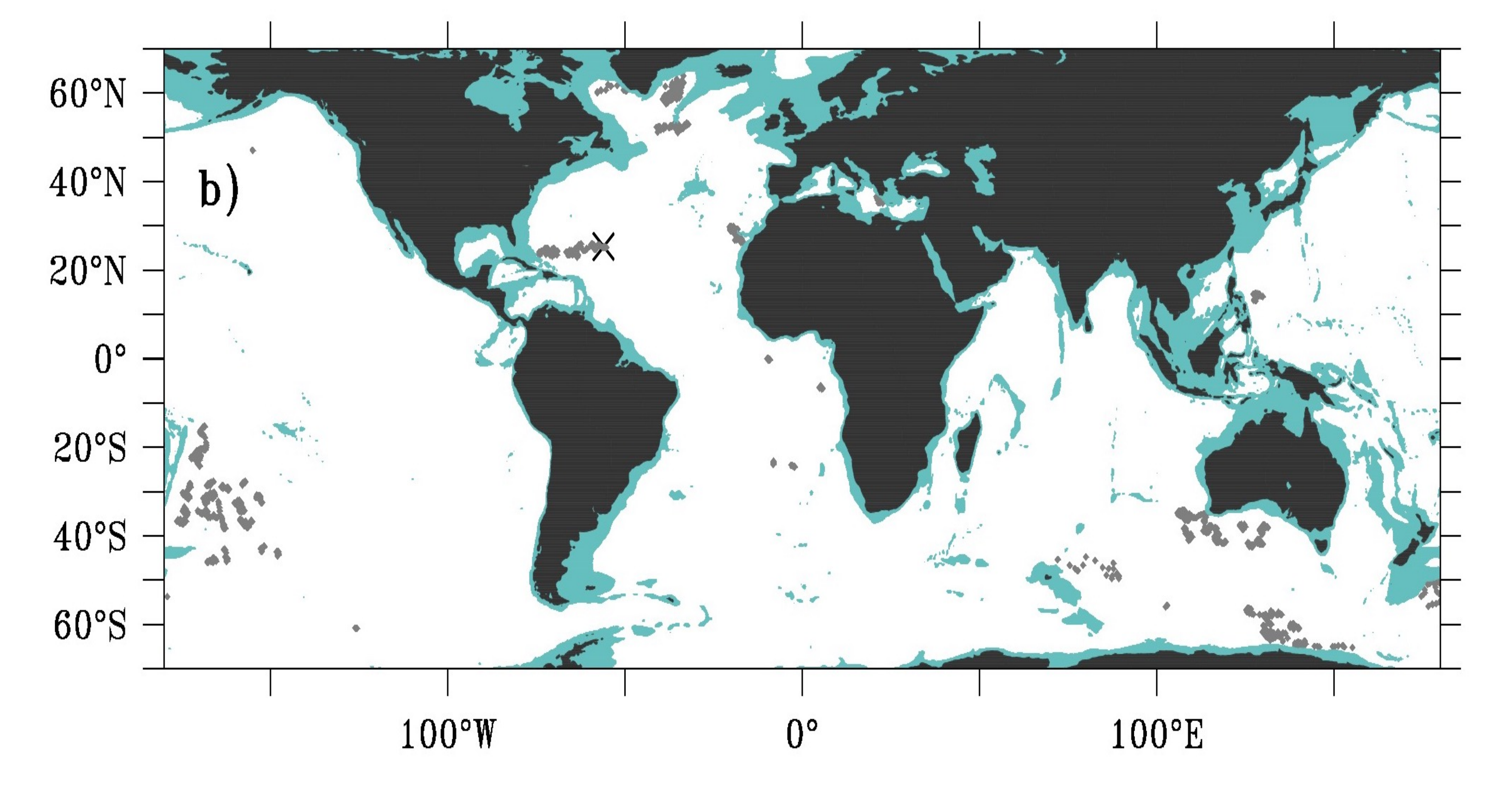
The ensemble spread amplitude reflects the distribution of the ensemble mean

Ensemble spread is more than 2 times higher than the amplitude of the signal

➔ Temperature and salinity changes are not statistically significantly different from zero

INDEPENDENT COMPARISON WITH THE ARGO PILOT ARRAYS

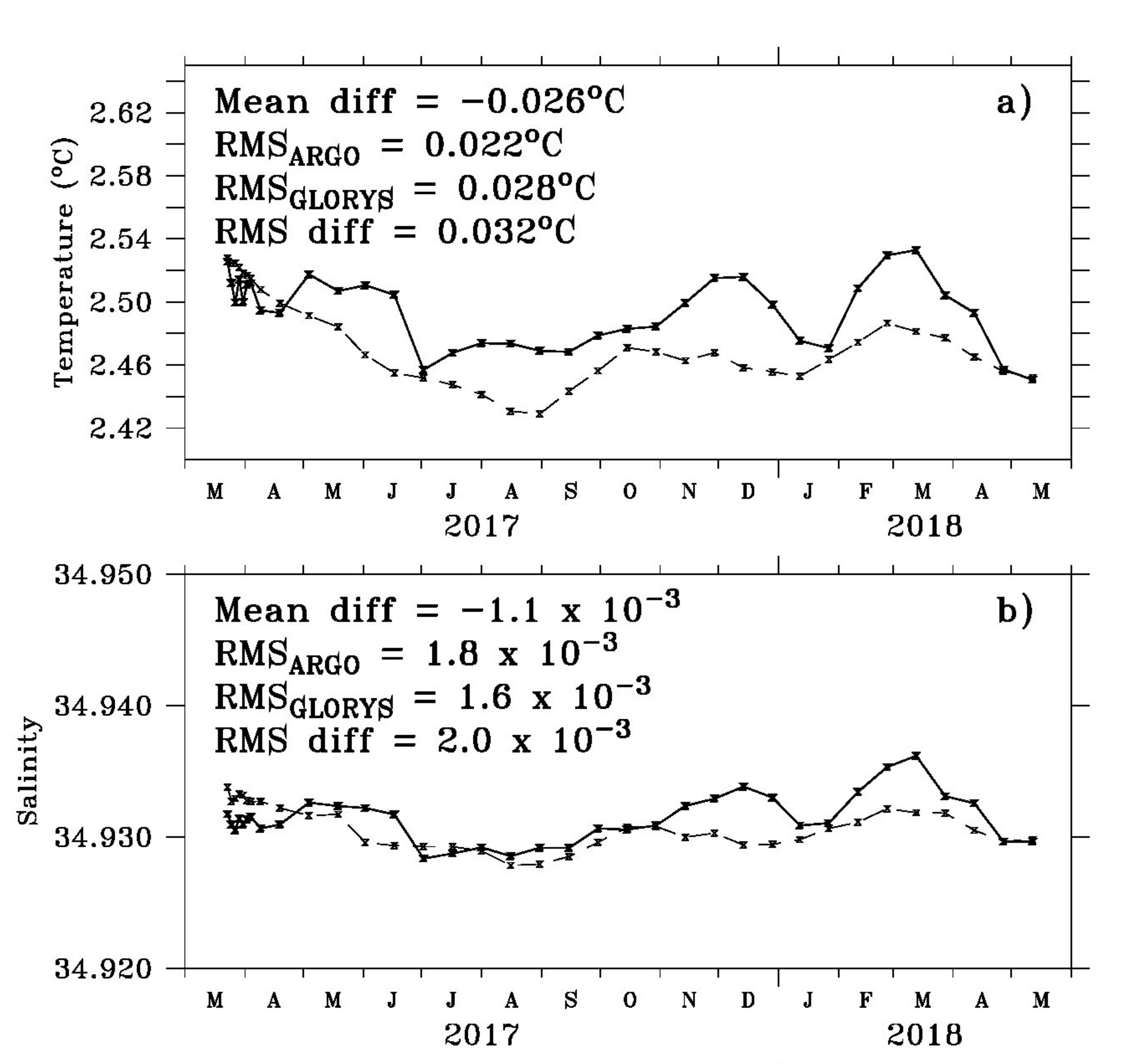
Location of 1,749 deep Argo profiles from the pilot arrays in 2017



- Technological development (sensors, prototype,…)
- Standard characteristics (cycle time, parking depth, …)
- Science objectives (deep ocean warming)
- Not yet assimilated at Mercator Ocean (QC from GDAC)

➔ The model-error amplitude is as strong as, or even stronger than the observed/modeled variability

Temperature and salinity at 3,000 m from a deep Argo float in the Northwest Atlantic (thick line) and GLORYS2V4 (thin line).



- GLORYS2V4 is colder and fresher than the deep float (depth differences of isopycnal surfaces can reach 300m)
- GLORYS and Argo have similar seasonal variations, but the RMS difference is stronger

Numerical Approach within the AtlantOS project

➔ **Multi-models / multi-approaches** exercise considering the **same synthetic observations**

Construction of **Synthetic Observations**

Nature Run

global HR Mercator Ocean - 1/12° - daily (CMEMS)
Forcing: 3h-ECMWF (operational)
Initialisation: EN4 climatology
No assimilation

An ocean **data assimilation system**

CLS: ARMOR-3D multivariate ocean state (observations only)

CMCC: Ensemble NEMO simulations

Met-Office: 1/4° global - NEMO/ NEMOVAR

Mercator-Ocean: 1/4° global
System: NEMO/SAM2
Forcing: 3h-ERA-Interim
Initialisation: Levitus13 climatology

Gasparin, et al., 2018, A large-scale view of oceanic variability from 2007 to 2015 in the global high resolution monitoring and forecasting system at Mercator-Ocean, Journal Marine Systems.

– OSSEs typically use two different ocean models. One model is used to perform a "truth" or **Nature Run** - and it is treated as if it is the real ocean.

– The truth run is subsampled in a manner that mimics either an existing or future observing system - yielding a set of **Synthetic observations.**

– The synthetic observations are assimilated into the **Ocean data assimilation system**, and the model performance is evaluated by comparing it against the truth run.

Observing System Experiments (OSE/OSSE) require heavy and dedicated infrastructure

NUMERICAL APPROACH WITHIN THE ATLANTOS PROJECT

➔ **Multi-models / multi-approaches** exercise considering the **same synthetic observations**

Construction of **Synthetic Observations**

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An ocean **data assimilation system**

CLS: ARMOR-3D multivariate ocean state (observations only)

CMCC: Ensemble NEMO simulations

Three 6-yr simulations (2008-2013):

1. **Realistic Nature Run**
2. **UPPER experiment, with the Backbone design (= Satellites, Argo, Mooring, XBT)**
3. **FULL experiment, with the Backbone design plus an extension of 1200 Argo floats to the bottom**

we will show : How determining the reliability of our sensitivity experiments for the deep ocean, and how assessing the added value of a full depth Argo array for ocean reanalyses

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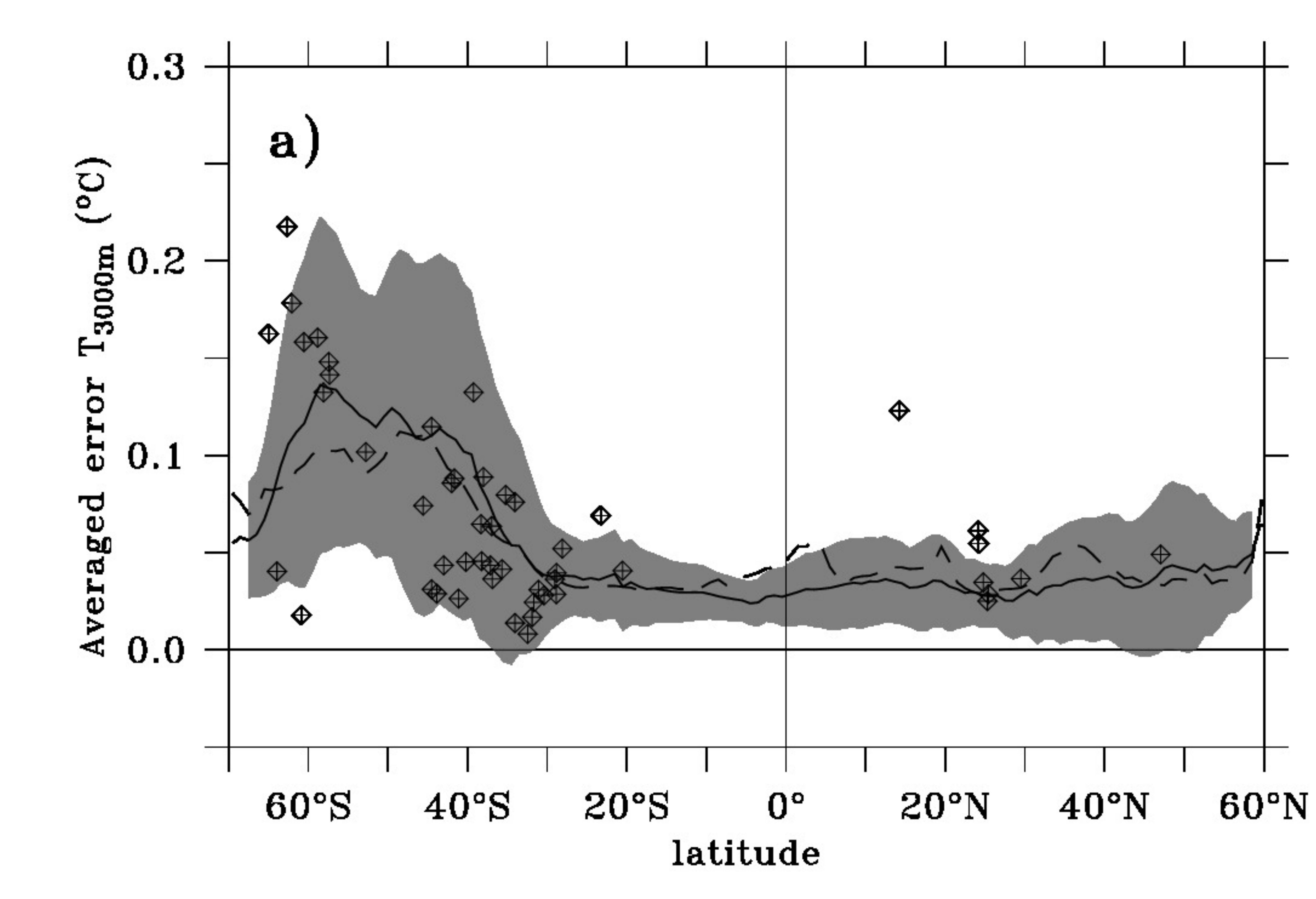
CONSISTENCY OF THE EXPERIMENTAL APPROACH



Zonally averaged absolute temperature error from the UPPER experiment (in ◦C) at 3,000 m on the 2009-2013 mean fields (full line) and its associated standard deviation (gray shading).

The dashed line is the corresponding zonally averaged ensemble-spread of the four GREP reanalyses.

The squares indicate the"GLORYS2V4 minus Argo" differences at 3,000 m versus latitude, profile-averaged for each deep Argo float.

- The UPPER error and ensemble-spread are remarkably similar in temperature, with values of around 0.05◦C north of 30◦S, and more than 0.1◦C south of 40◦S = *Ensemble-based uncertainty*

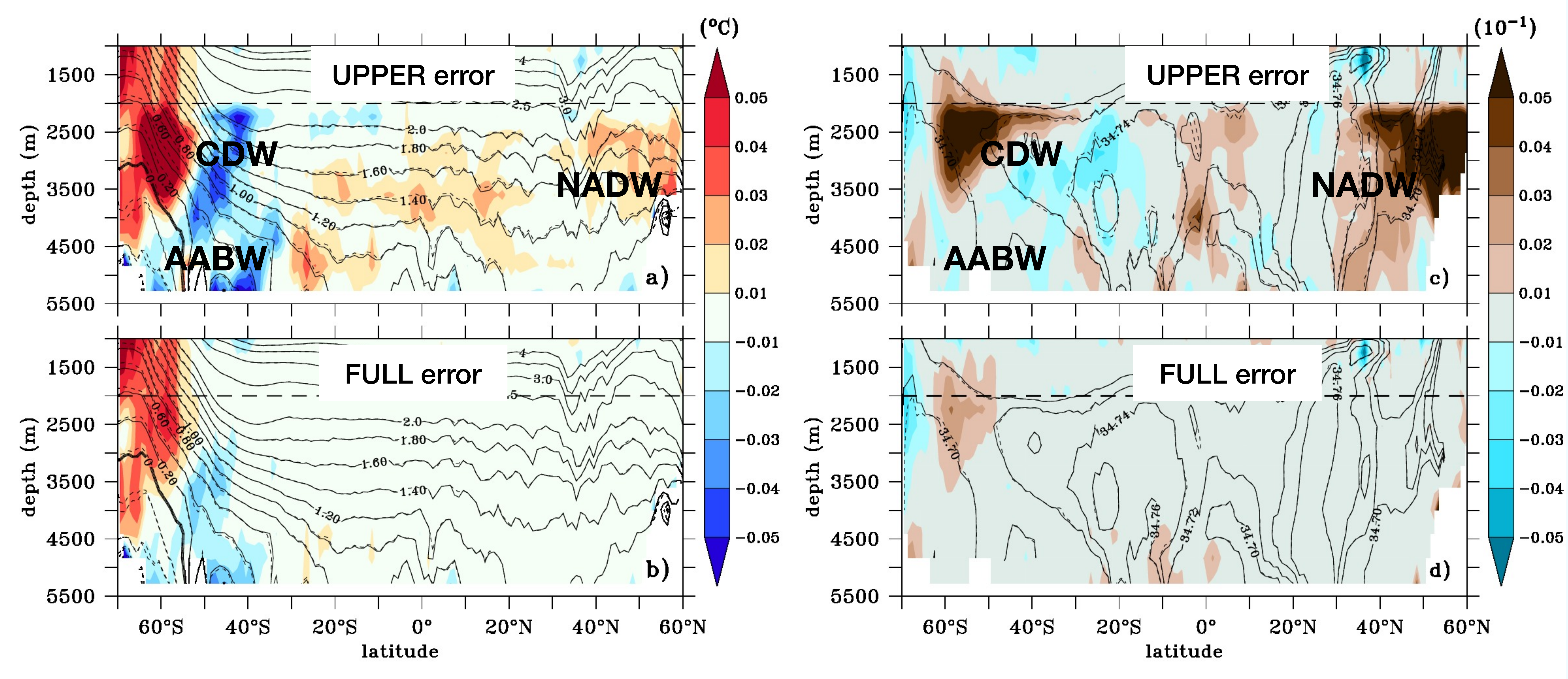
- *"GLORYS2V4 minus Argo"* differences have an amplitude of the same order than the UPPER errors and the ensemble spread (O(0.1◦C) for temperature and O(0.01) for salinity) = *Deviation from the pilot arrays*

➔ In agreement with the ensemble-based approach and the deep Argo comparison

➔ Good confidence in the calibration of our experimental approach

THE 2009-2013 MEAN TEMPERATURE AND SALINITY FIELDS

Zonally averaged 2009-2013 mean temperature and salinity errors versus depth.

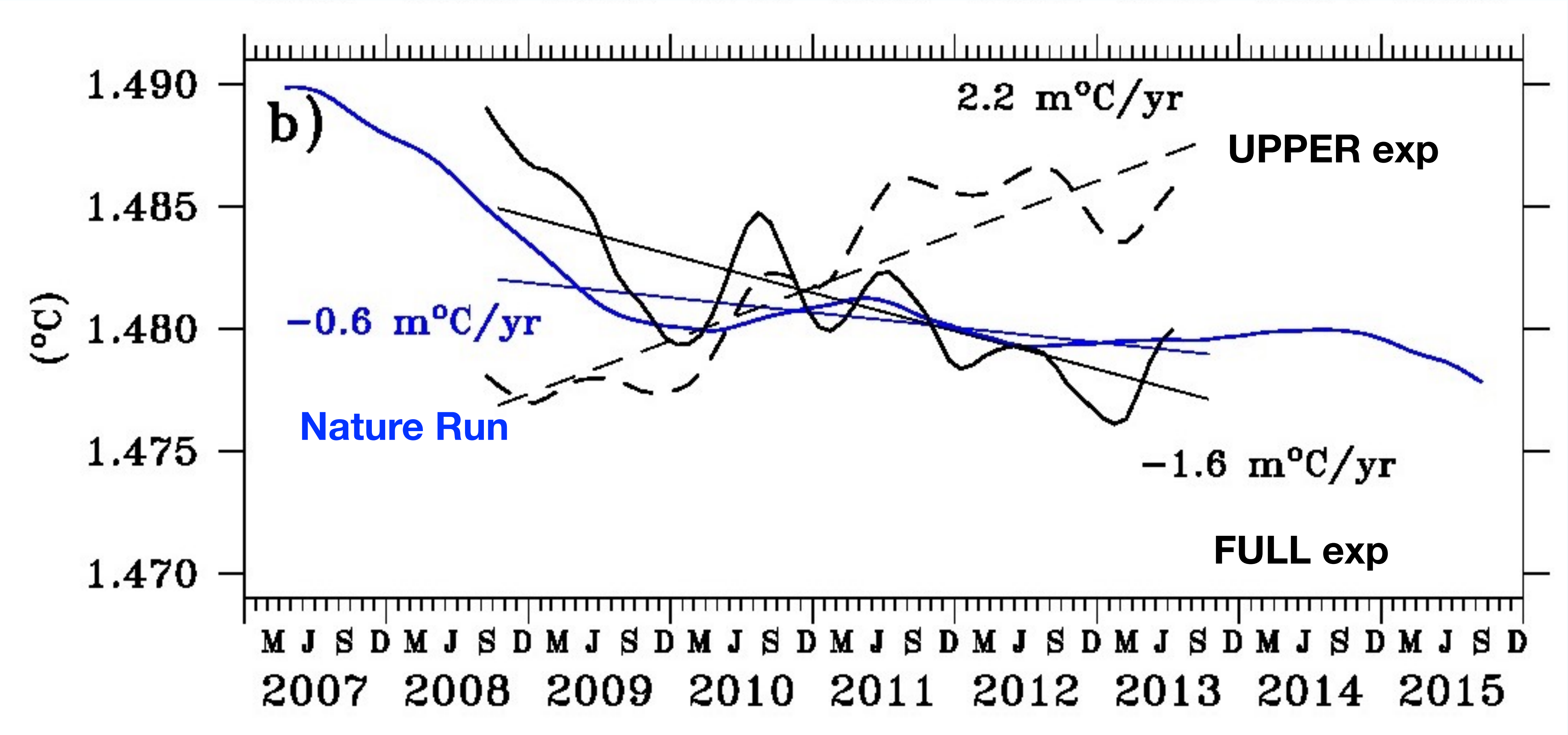


- Vertical discontinuity revealing the positive impact of upper ocean data sets in the upper 2,000 m
- Strong errors of the UPPER exp. found in the Southern and N. Atlantic oceans = *Water mass formations*

➔ Addition of deep Argo observations will improve the vertical stratification at all latitudes, allowing to recover the horizontal and vertical extensions of deep water masses

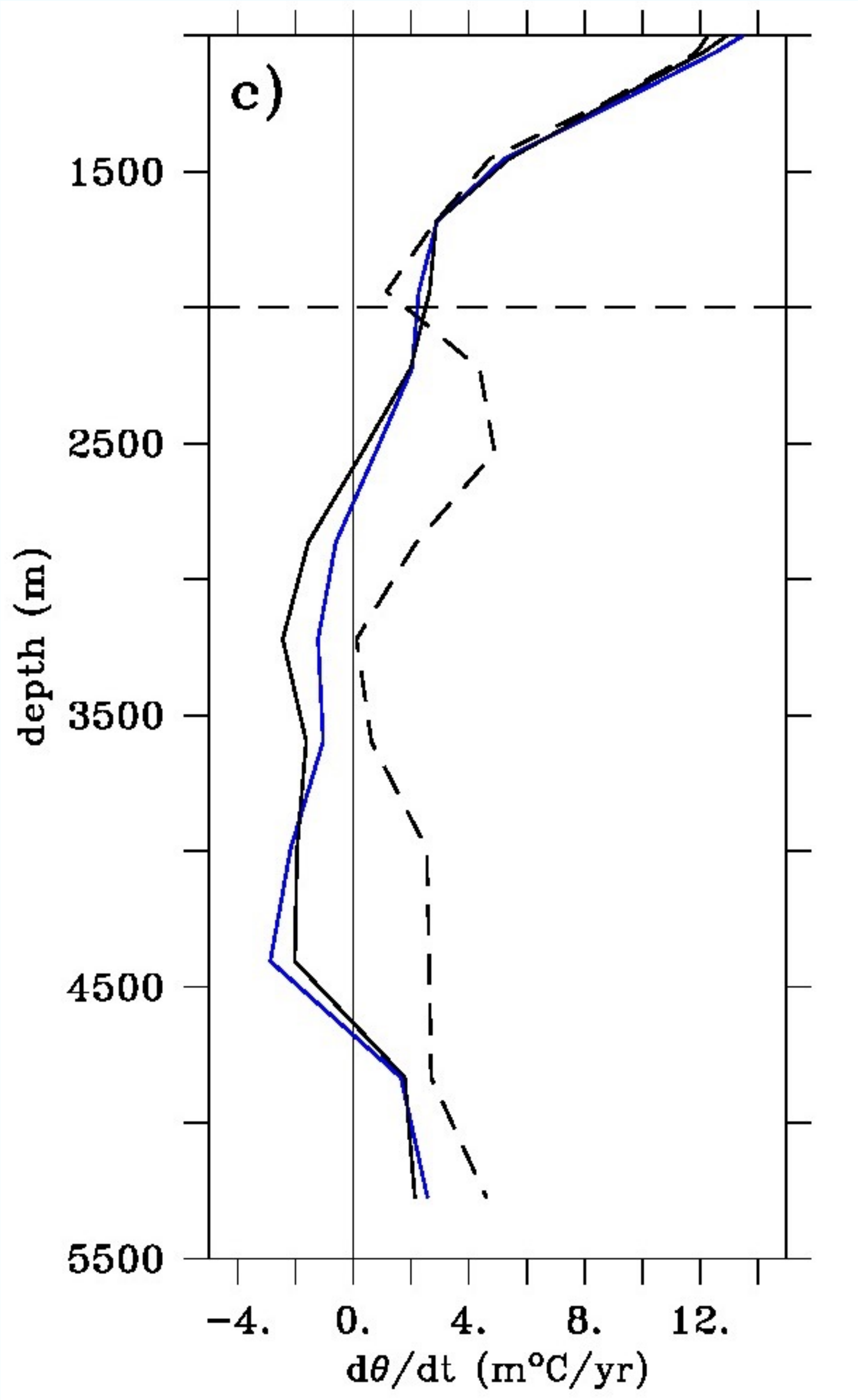
Long-term variations of deep ocean signals

Time-series of 3,000 m-temperature basin-averaged in the Amundsen-Bellinghausen (Southwest Pacific) estimated from the Nature Run, the UPPER and FULL exp.



- Temperature variations of the UPPER exp of opposite sign compared to the Nature Run
- Differences in temperature variations are strongly reduced in the FULL exp

Vertical profile of linear trend of temperature versus depth averaged in the Amundsen-Bellinghausen basin.

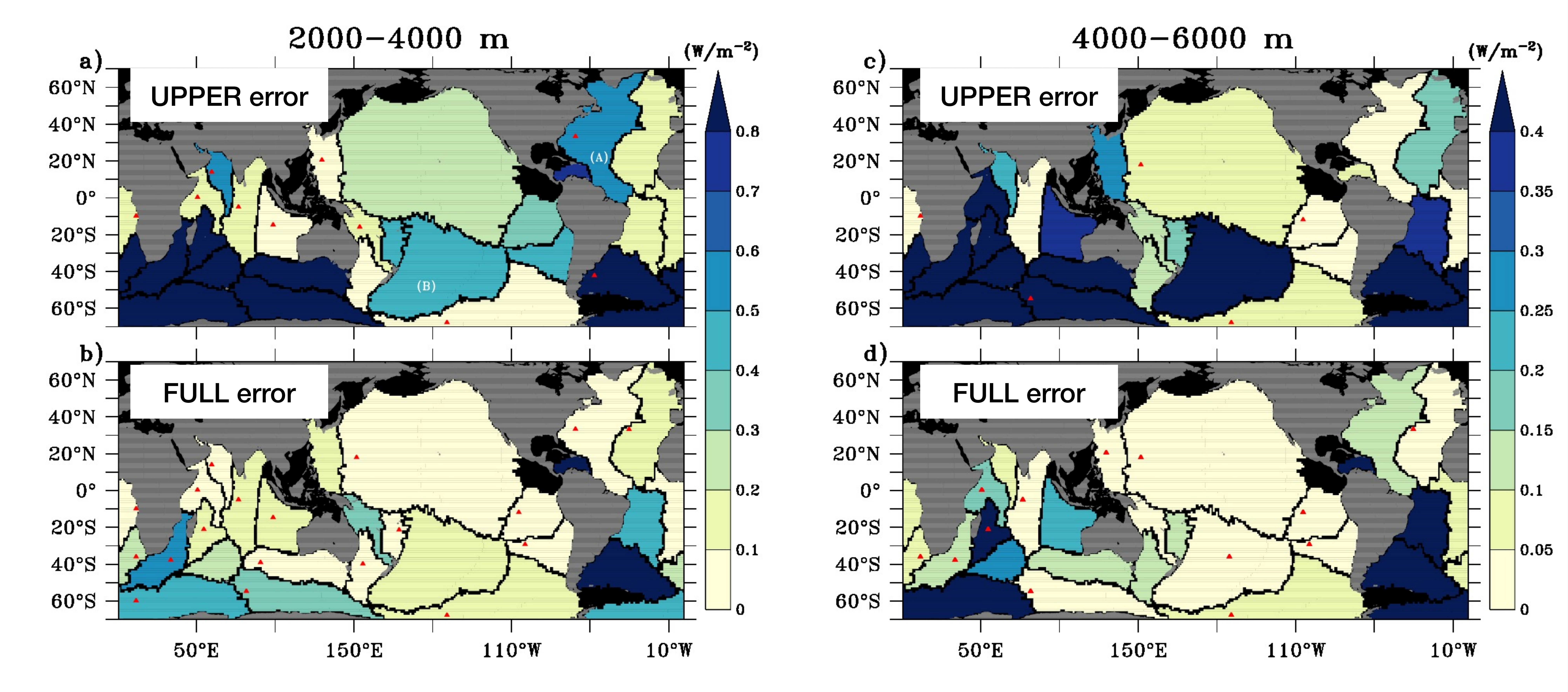


- While the UPPER experiment is characterized by an inconsistent warming below 2,000 m, the FULL experiment recovered the vertical shape of temperature changes

➔ Addition of deep Argo observations will allow to recover basin-scale temperature variations

DEEP OCEAN HEAT FLUX

Basin averaged linear ocean heat gain error for the 2000-4000 m and 4000-6000 m layers for the period 2009-2013. For each basin, red triangles indicate that basin-scale signal-to-error ratio is higher than 2.



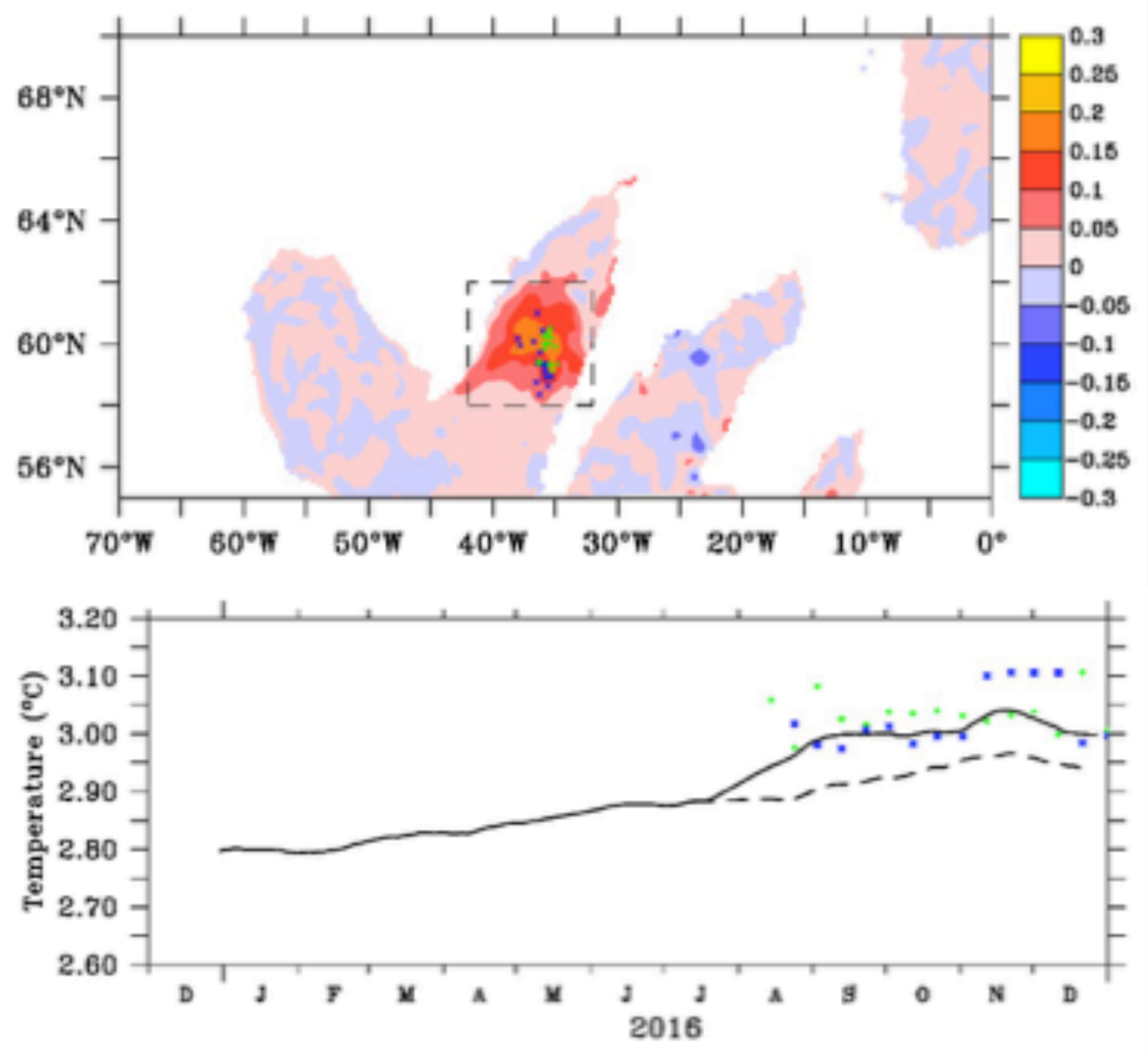
- Main discrepancies of the UPPER heat flux in the Atlantic and Southern oceans, with values exceeding 0.8 and 0.4 W/m2 for the 2000-4000 m and 4000-6000 m heat fluxes
- The FULL experiment induces a significant decrease of the heat flux errors in the two layers, with strong increased number of basins with high signal-to-error ratio

ASSIMILATING THE FULL-DEPTH PROFILES FROM THE PILOT ARRAYS

Observing System Experiment (OSE)

CONTROL : No deep part of profiles from pilot floats

ADD_DEEP : Full-Depth profiles from pilot floats



2500-m "CONTROL-minus-ADD_DEEP" temperature differences, averaged for the period Aug. 2016-Nov. 2016.

The crosses indicate the positions of the profiles from two deep Argo profile.

Area-averaged 2500-temperature from the CONTROL (dashed) and the ADD_DEEP (full) runs in the dashed square. The green and blue dots indicate the observations from the two deep floats.

- The assimilation of the deep part of the deep pilot Argo floats constrains the solution toward observations
- Both temperature and salinity show a southward extension along the coast in the southwest corner of the squarex (impact on large scales)

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SUMMARY

1. OSSE = A complementary approach to the climatic research
2. Based on *ensemble-based and pilot arrays comparison*, deep temperature and salinity uncertainty is higher than the size of the signal
3. An array of 1,200 deep Argo floats can successfully constrain ocean reanalyses by improving the deep ocean representation of water masses, and better capture large-scale variability
4. AtlantOS project has shown significant improvement of the T/S representation below 2000m for 4 different systems (Gasparin et al., 2019 Frontiers in Marine Science)
5. Modeling and assimilation data procedures have been developed for the upper ocean, and it will be necessary to refine them for the deep ocean

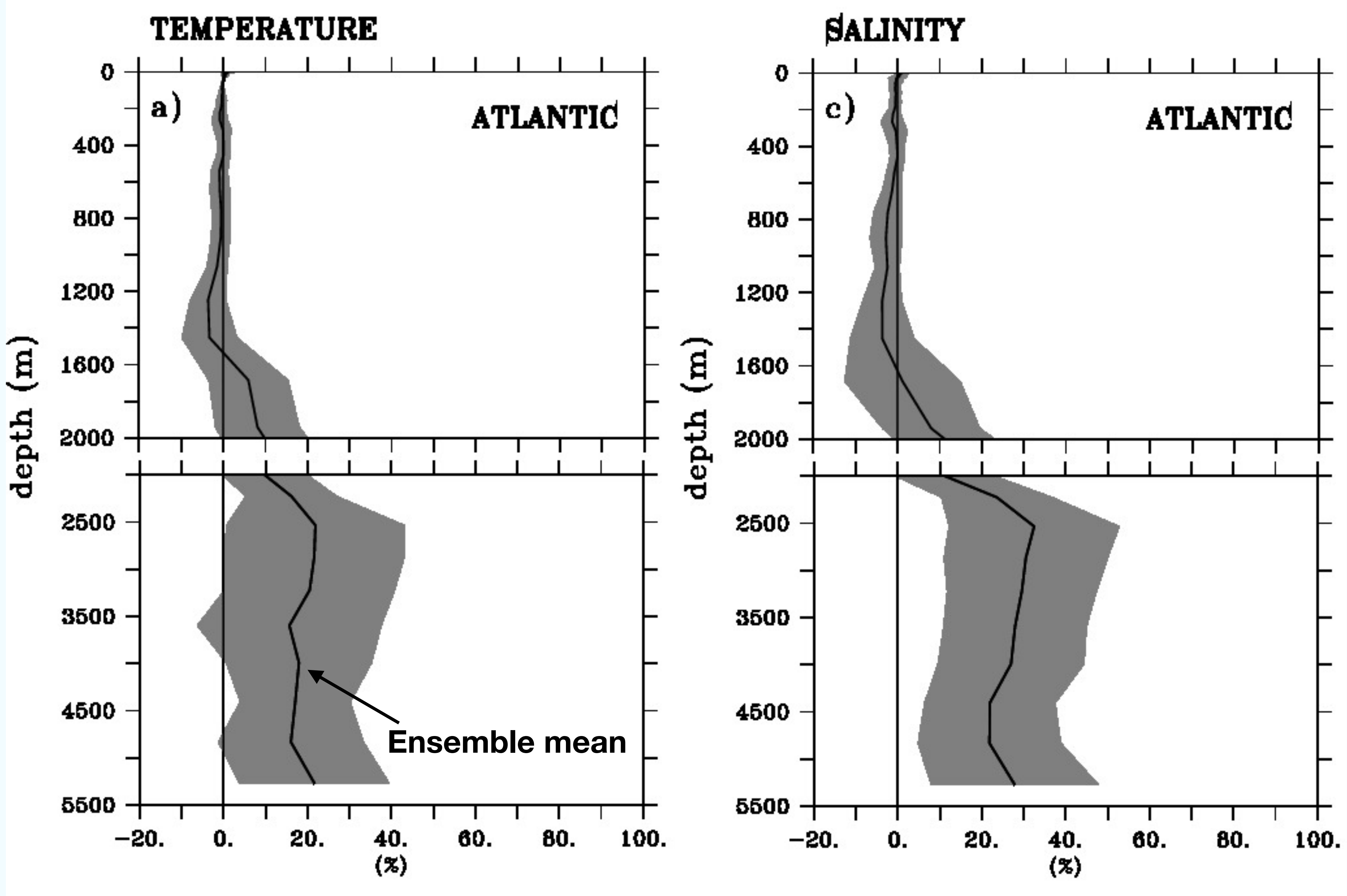
→ Next Mercator Ocean systems will assimilate the deep part of deep Argo profiles

→ Assimilation procedures - Correlation scales for the deep ocean, observations errors, analysis increment with/without deep observations

→ Model development - Deep water formations, deep convection processes

MULTI-SYSTEM COMPARISON BASED ON RMS ERROR REDUCTION

1 ensemble composed of 4 members from Mercator-Ocean (Fr), CLS (Fr), CMCC(It) and UKMetOffice (UK)



Temperature and salinity profiles of error reduction of the DEEP experiment as compared with the BACKBONE experiment, relative to the Nature Run fields, area-averaged in the Atlantic ocean.

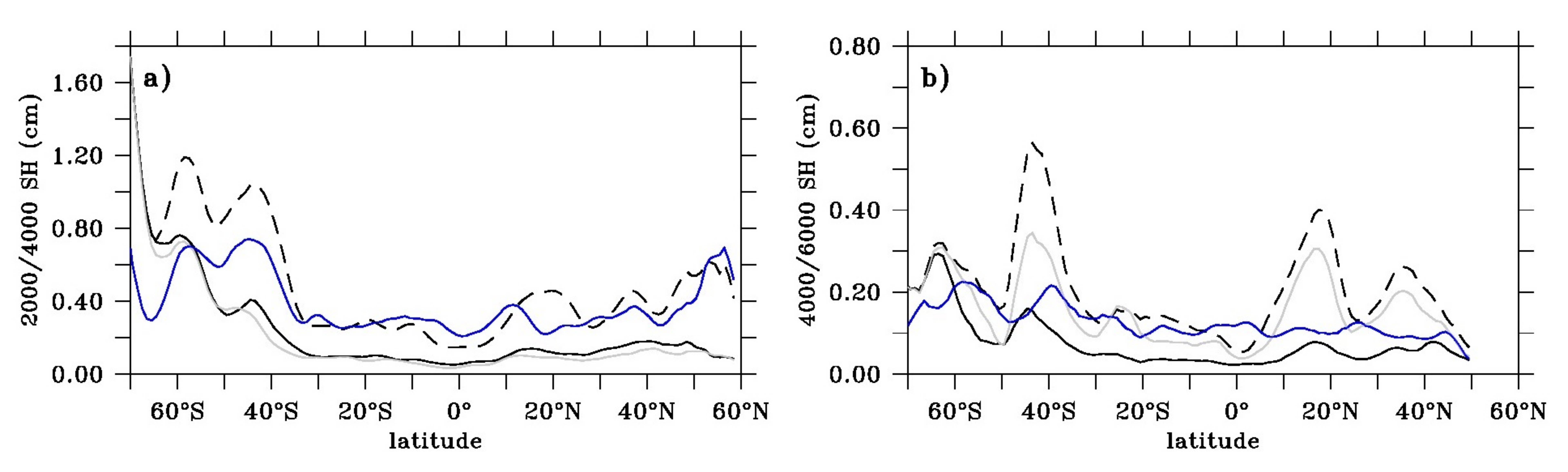
Gray indicates the standard deviation of the four members. Unit is percentage of mean square error reduction.

- Significant improvement of the T/S representation below 2000m, with a maximum for salinity (up to 60%)
- The spread indicates that the four reanalyses differ in the amplitude of the improvement

Gasparin, F., Guinehut, S., Mao, C., Mirouze, I., et al. (2019). Requirements for an integrated in situ Atlantic Ocean Observing System from coordinated Observing System Simulation Experiments. Frontiers in Marine Science, 6, 83.

ADDED VALUE OF A FULL-DEPTH OCEAN OBSERVING SYSTEM

4000m Vs 6000m



(a) Zonally averaged error of large-scale (5° x 5° x 12-month) 2,000/4,000 steric height from the UPPER (black dashed line), FULL (black full line), and the DEEP4000 experiments. For comparison to the error estimate, the zonally averaged ”2014 minus 2019” 2,000/4,000 steric height from the Nature Run is shown in blue. (b) Same as (a), but for 4,000/6,000 steric height. Unit is cm