Uncertainties in reconstruction of the past ocean climate with ocean reanalyses

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Background

One of main challenges for Ocean and sea-ice Reanalyses is to reproduce a consistent long-term (century long) ocean and sea-ice states with reliable inter-annual variabilities (or at least with credible uncertainty estimations) in the context of climate monitoring. Climate signals (e.g AMOC strength, OHC trend, …) estimated could be very sensitivity to different reanalysis system setups and among different reanalysis products.

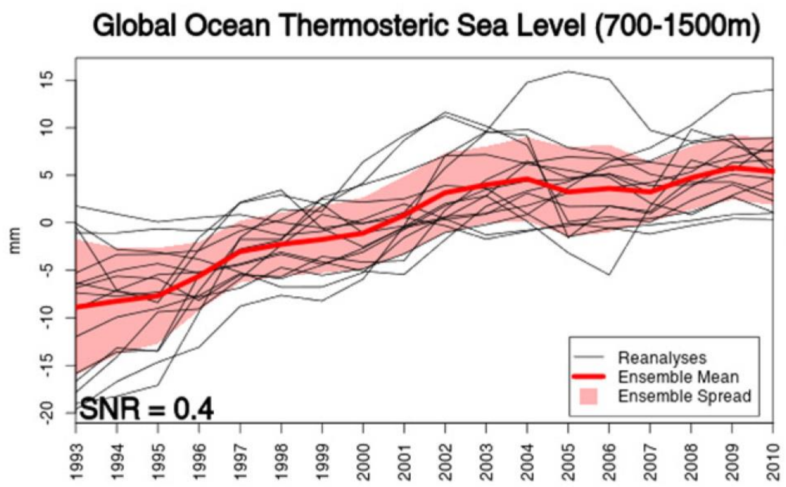
- One way to tackle this issue is taking an ensemble approach with a single ORA system, while perturbation of *boundary conditions (forcings), observations and initial conditions* are commonly used. One example is the ECMWF ORAS4/ORAS5 ocean and sea-ice reanalyses. However, uncertainties estimated with a single system is strongly bounded by the ORA system itself (e.g. same numerical model and DA method).
- Another way is taking a ensemble approach with multi-ORAs systems, as described in *Balmaseda et al., 2015*. This approaches has been taken extensively during the ORA-IP project for various OMIs (AMOC, OHC, sea-ice, Sea-level …). However, it could be quite difficult to interpret a multi-system ensemble spreads due to complexity of an ORA system, especially due when there is lack of coordination in designing multi-system experiments.

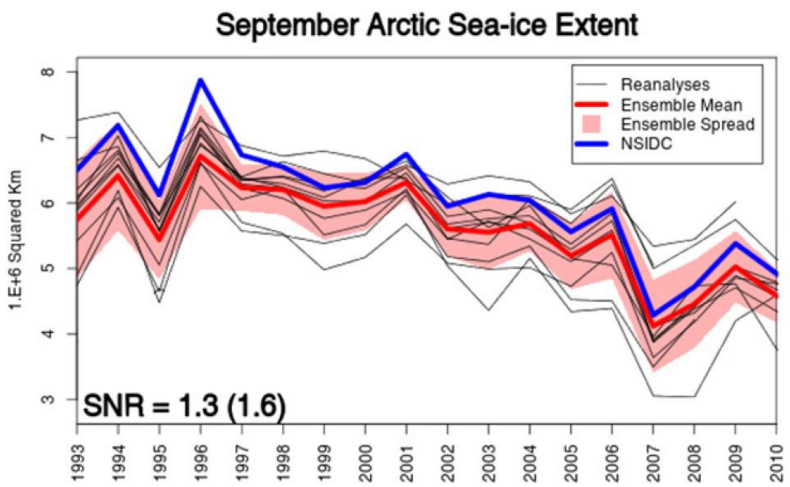
Here we discuss an extended ensemble approach based on a single system, by taking into account uncertainties in *observations, forcings, initial conditions,* as well as uncertainties in *numerical model (resolutions, model physics)* and *DA system settings*, using the ECMWF Ocean and sea-ice reanalysis system as a example.

Uncertainties estimated with multi-ORAs ensemble

- Signals in Sea-ice extend changes are relatively robust (SNR > 1)
- Signals in ocean state changes below 1000m are much less robust (SNR < 1)

Timeseries of OMIs from ORA-IP inter-comparison project





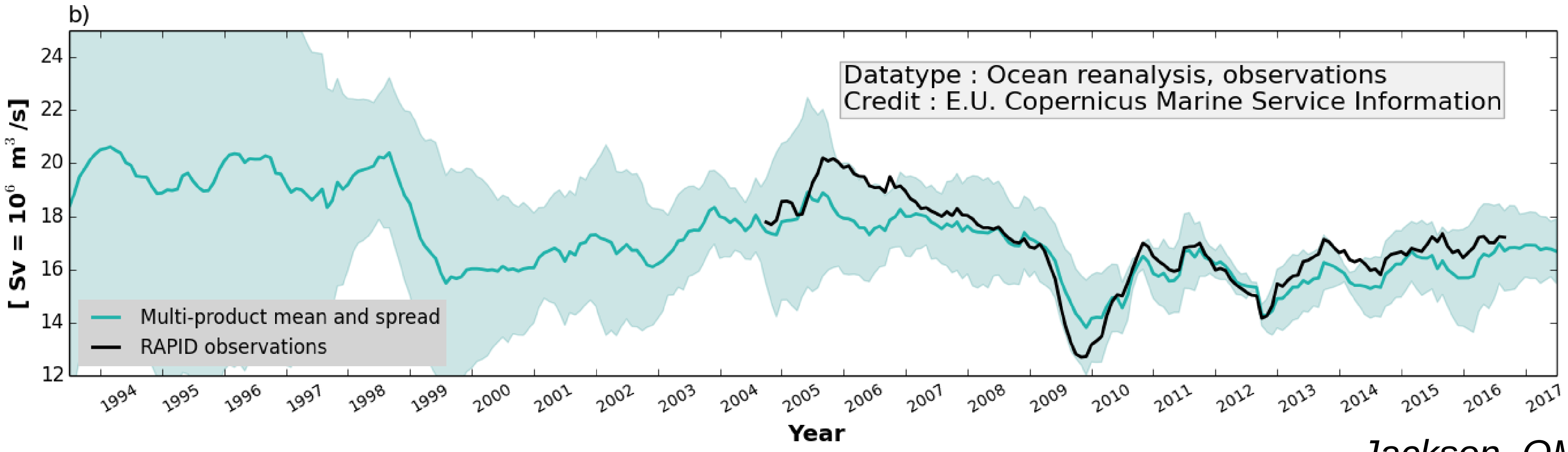
Signal-to-noise ratio (SNR), defined here for simplicity as the ratio between the temporal standard deviation of the ensemble mean divided by the temporal mean of the ensemble standard deviation.

Storto, et al., *Frontiers in Marine Science*, 2019

Uncertainties estimated with multi-ORAs ensemble

AMOC strength is well constrained during the Argo period, but with high uncertainty in the pre-Argo era.

Atlantic Meridional Overturning Circulation (AMOC) strengths at 26.5 N



Jackson, OMI of AMOC, CMEMS QUID report, 2018

Multi-ORAs ensemble estimation of AMOC strengths. The CMEMS GREP product is used here which includes ORAS5, GLOSEA, CGLORS and GLORYS.

ORA system of study

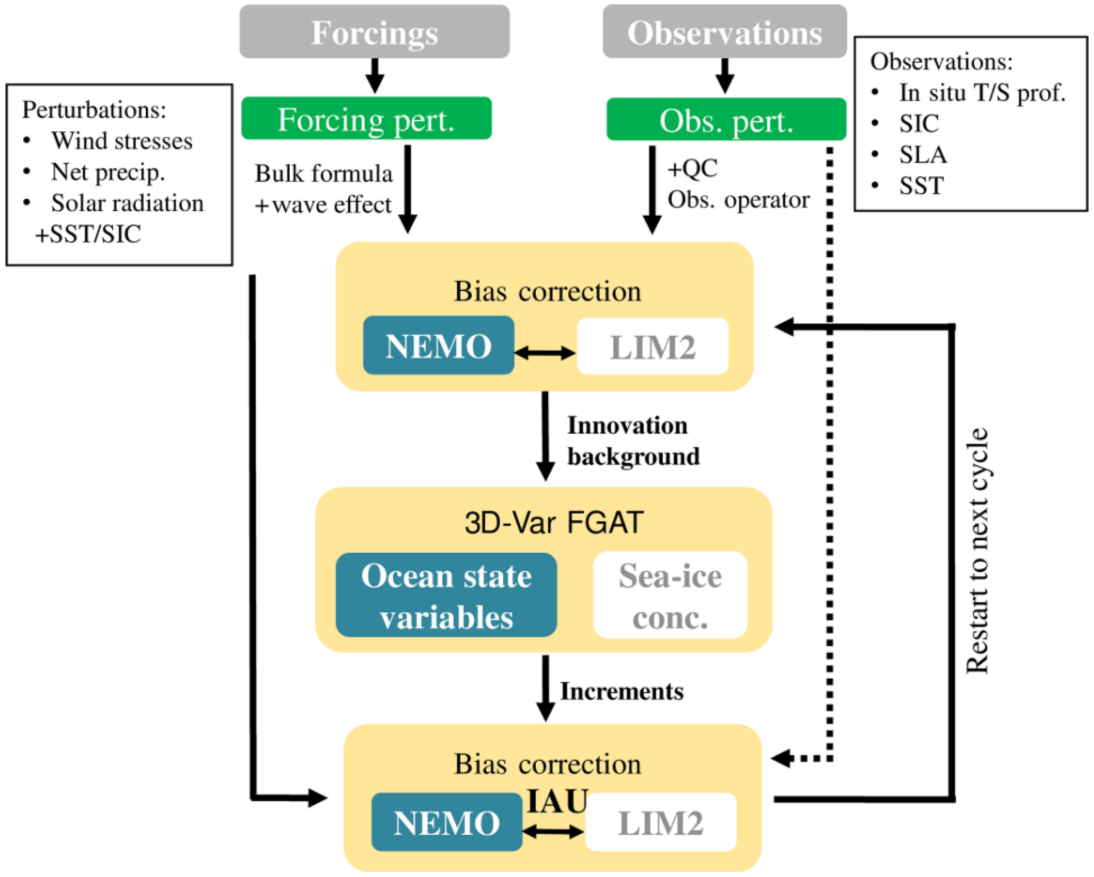


Figure 1. Schematic diagram of the ORAS5 system.

Zuo et al., 2019, OS

Account for source of uncertainties in the ECMWF ORA

	ECMWF ORA system
Resolutions	1 or 1/4 deg, 42 or 75 vertical levels ORCA vs eORCA (on-going)
Model	NEMO V3.4 + LIM2 NEMO V4 + SI3 (on-going)
Data assimilation method	• 3DVar-FGAT: R specifications (pre-processing, QC and OBE stds) • 3DVar-FGAT: B specifications (analytical vs ensemble vs hybrid); Talk by Marcin Chrust • SST/SSS nudging method • Bias Corrections scheme • GMSL constrain with MSLA data
Boundary forcings	• ERA-int vs ERA5 vs NWP forcings • Initial conditions • River discharges: datasets; clim vs reanalysis (on-going)
Observations	• In-situ: Argo/Ship-based/mooring/etc • Altimeter: DT2014 vs DT2018 vs NRT • SST: OSTIA vs HadISST vs OSTIAv2 • SIC: L4 vs L3 observations
Ensemble generations	• Forcing Pertbs (radiation, wind, …) • Observation pertbs (locations and values) • Model physics: stochastic perturbations (SPP/SPPT/SKEB); Talk by Andrea Storto

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Summary of different types of ORA ensemble

	ORA system setup	Ensemble generation
Model resolutions	**ORAS5** (5 members): ¼ degree + 75 levels; ERAint	Perturb: forcing, observations, initial conditions
	O5-LR (5 members): 1 degree + 42 levels; ERAint	Perturb: forcing, observations, initial conditions
Data assimilation method	**O5-pertDA** (5 members) • 3DVar-FGAT: R specifications (pre-processing, QC and OBE stds) • SST nudging method • Bias Corrections method	Perturb the DA system settings • 000=Ref (ORAS5) • O5-v2 (No BC) • O5-v3 (BC capping 1e-11) • O5-v4 (SST=-80) • O5-v5 (SST=-80, more coast obs)
Forcings	**ORAP6-LR** (15 members): 1 deg + 75 levels; ERA5	Perturb: forcing, observation, initial conditions
Observations	**O5-LR-OSEs** (5 members) Global withholding observation types: Ref/Argo/Ship-based/Mooring/Insitu	• 000=Ref: • 001=NoArgo: • 002=NoShip: • 003=NoMooring: • 004=Noinsitu:

Uncertainties in AMOC strengths

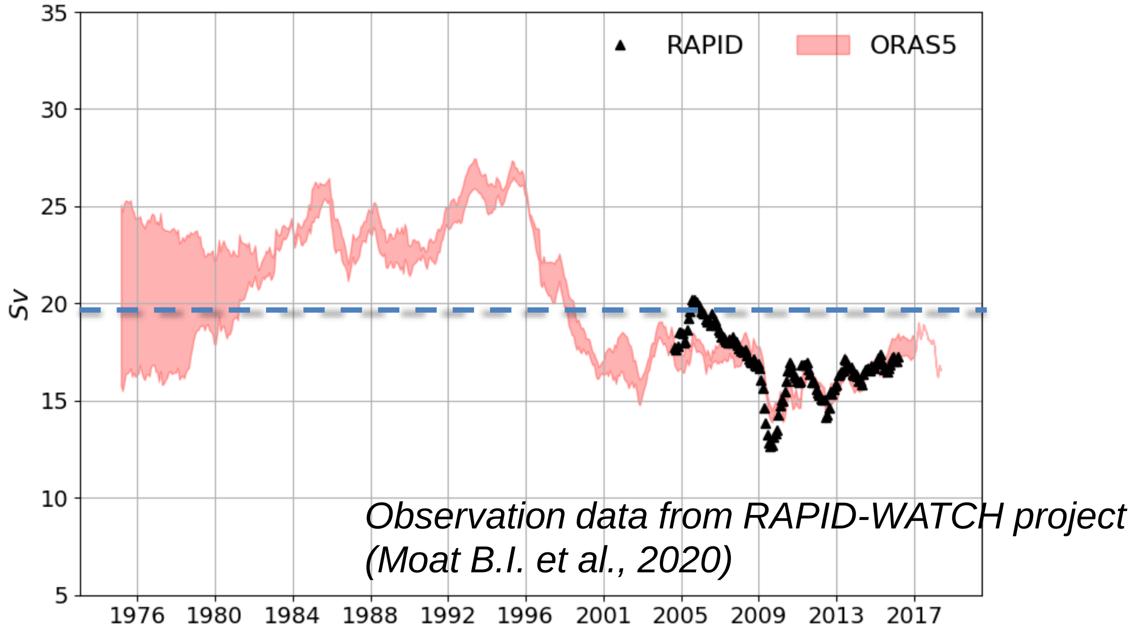
AMOC (in Sv) in RAPID period (200404 - 201612)

	AMOC at 26.5 N	
	Mean	SNR
ORAS5	16.47 ± 0.27	3.9
O5-pertDA		
O5-LR		
O5-LR-OSE		
ORAP6-LR		
RAPID	16.86	N/A

$1\ Sv = 10^6\ m^3\ /s$

AMOC at 26.5 N

ORAS5 with 5 members, perturb forcings, observations and initial conditions



- Larger spread in the early period comes from initialization perturbations
- A regime shift in AMOC transport that happens around 2000 was due to Argo floats. Early larger AMOC is related with inadequate SST nudging in the Labrador Sea region.

Uncertainties in AMOC strengths

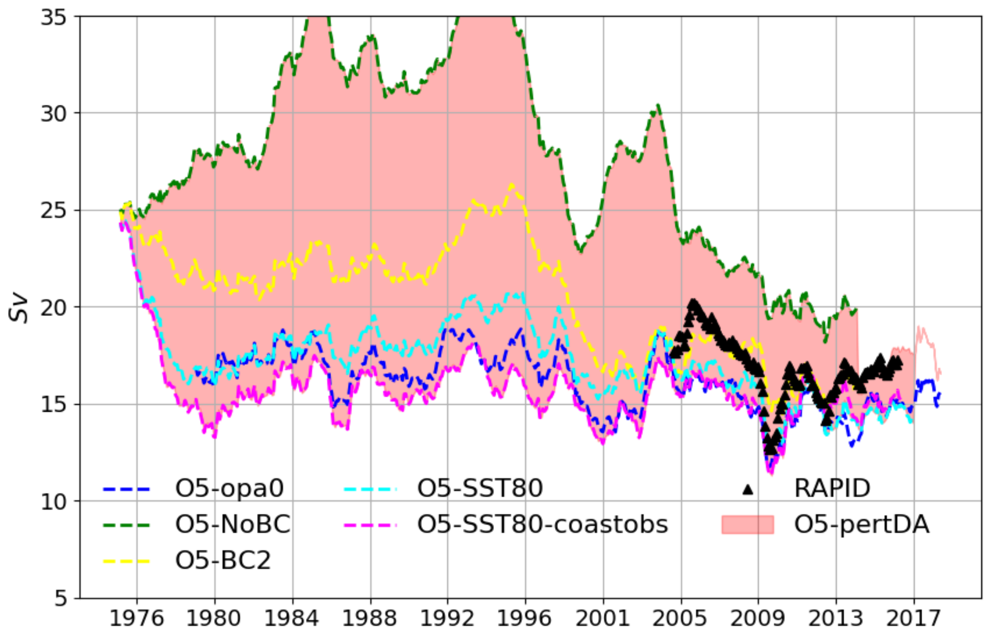
AMOC at 26.5 N

AMOC (in Sv) in RAPID period (200404 - 201612)

	AMOC at 26.5 N	
	Mean	SNR
ORAS5		
O5-pertDA	16.9 ± 2.1	0.58
O5-LR		
O5-LR-OSE		
ORAP6-LR		
RAPID	16.86	N/A

$1\ Sv = 10^6\ m^3\ /s$

O5-pertDA with 5 members, perturb SST nudging, BC and obs QC/errors



- Perturbing the strength of BC in ORA results in a very large spread in AMOC transports before the Argo era.
- AMOC strength is also sensitive to other DA settings like the SST nudging strength and usage of near coast observations.

Uncertainties in AMOC strengths

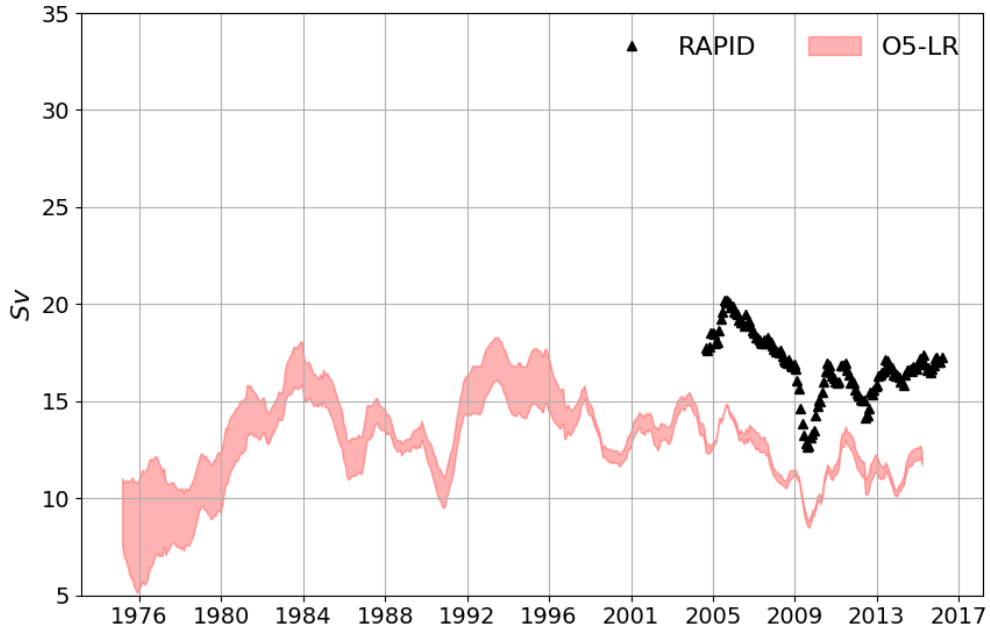
AMOC at 26.5 N

AMOC (in Sv) in RAPID period (200404 - 201612)

	AMOC at 26.5 N	
	Mean	SNR
ORAS5		
O5-pertDA		
O5-LR	11.9 ± 0.18	7.37
O5-LR-OSE		
ORAP6-LR		
RAPID	16.86	N/A

$1\ Sv = 10^6\ m^3\ /s$

O5-LR with 5 member, perturbs forcing, observations and initial conditions



Uncertainties in AMOC strengths

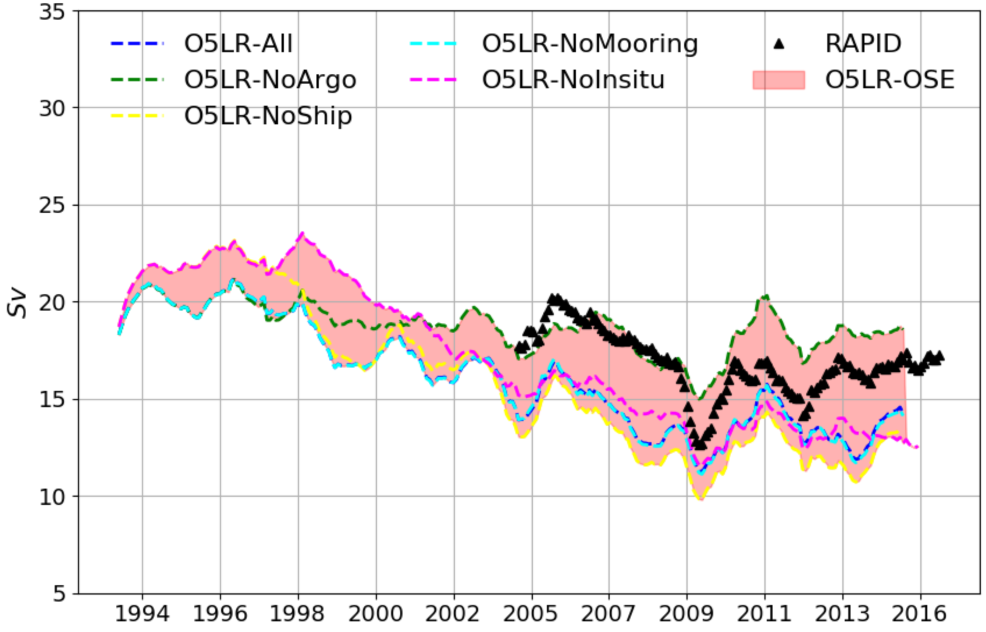
AMOC at 26.5 N

O5-LR-OSE with 5 members, each member withholds one obs type (Ref/NoArgo/NoShip/NoMooring/NoInsitu)

AMOC (in Sv) in RAPID period (200404 - 201612)

	AMOC at 26.5 N	
	Mean	SNR
ORAS5		
O5-pertDA		
O5-LR		
O5-LR-OSE	14.40 ± 1.76	0.69
ORAP6-LR		
RAPID	16.86	N/A

$1\ Sv = 10^6\ m^3\ /s$



- Trends of AMOC signal derived from O5LR-NoArgo and O5LR-NoInsitu do not consist, indicating compensating effect (on AMOC strength) from assimilating different obs types?

Uncertainties in AMOC strengths

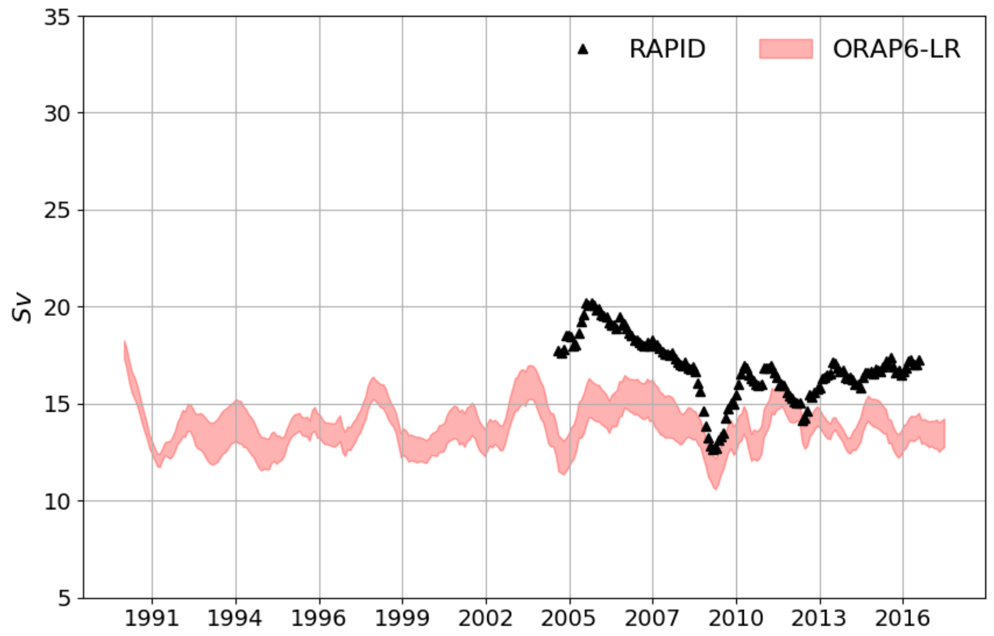
AMOC (in Sv) in RAPID period (200404 - 201612)

	AMOC at 26.5 N	
	Mean	SNR
ORAS5		
O5-pertDA		
O5-LR		
O5-LR-OSE		
ORAP6-LR	14.0 ± 0.44	2.2
RAPID	16.86	N/A

$1\ Sv = 10^6\ m^3\ /s$

AMOC at 26.5 N

ORAP6-LR with 15 members, **ERA5**, perturb forcings, observations and initial conditions



- Magnitude of AMOC transports in ORAP6-LR sits between ORAS5 and O5-LR, suggesting that AMOC strength is sensitive to model horizontal and vertical resolutions.
- AMOC inter-annual variabilities in ORAP6-LR (with ERA5 forcing) is different from other experiments driven by ERA-int forcing.

Uncertainties in AMOC strengths

AMOC at 26.5 N

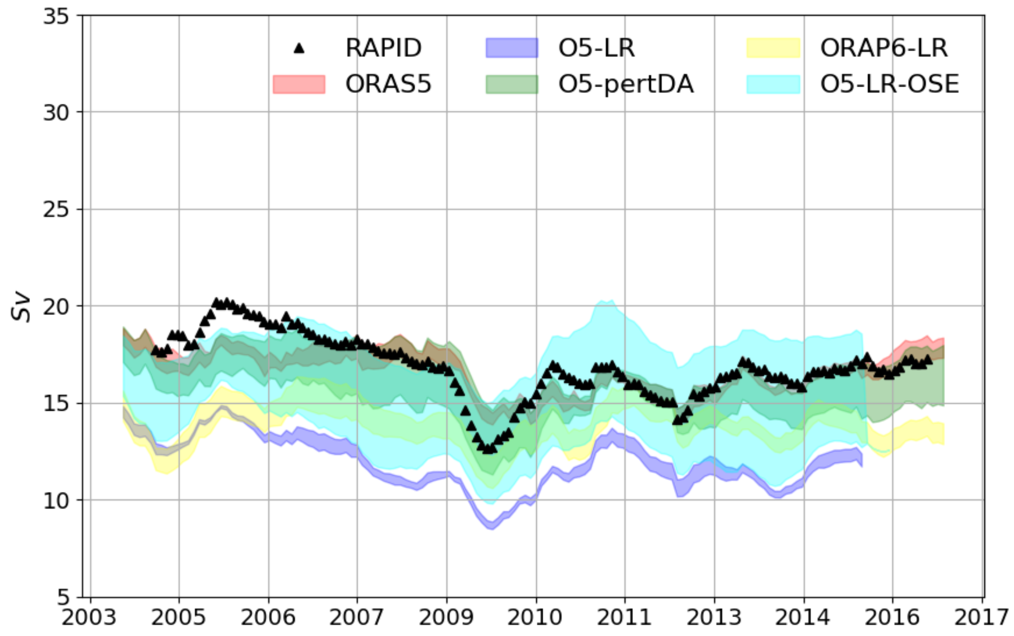
All ORA ensemble sets

AMOC (in Sv) in RAPID period (200404 - 201612)

	AMOC at 26.5 N	
	Mean	SNR
ORAS5	16.47 ± 0.27	3.9
O5-pertDA	16.0 ± 0.86	1.3
O5-LR	11.9 ± 0.18	7.37
O5-LR-OSE	14.40 ± 1.76	0.69
ORAP6-LR	14.0 ± 0.44	2.2
RAPID	16.86	N/A

$1\ Sv = 10^6\ m^3\ /s$

O5-NoBC is excluded in O5-pertDA



Signal-to-noise ratio (SNR), defined as the ratio between the temporal standard deviation of the ensemble mean divided by the temporal mean of the ensemble standard deviation of AMOC transports

Observation data from RAPID-WATCH project (Moat B.I. et al., 2020)

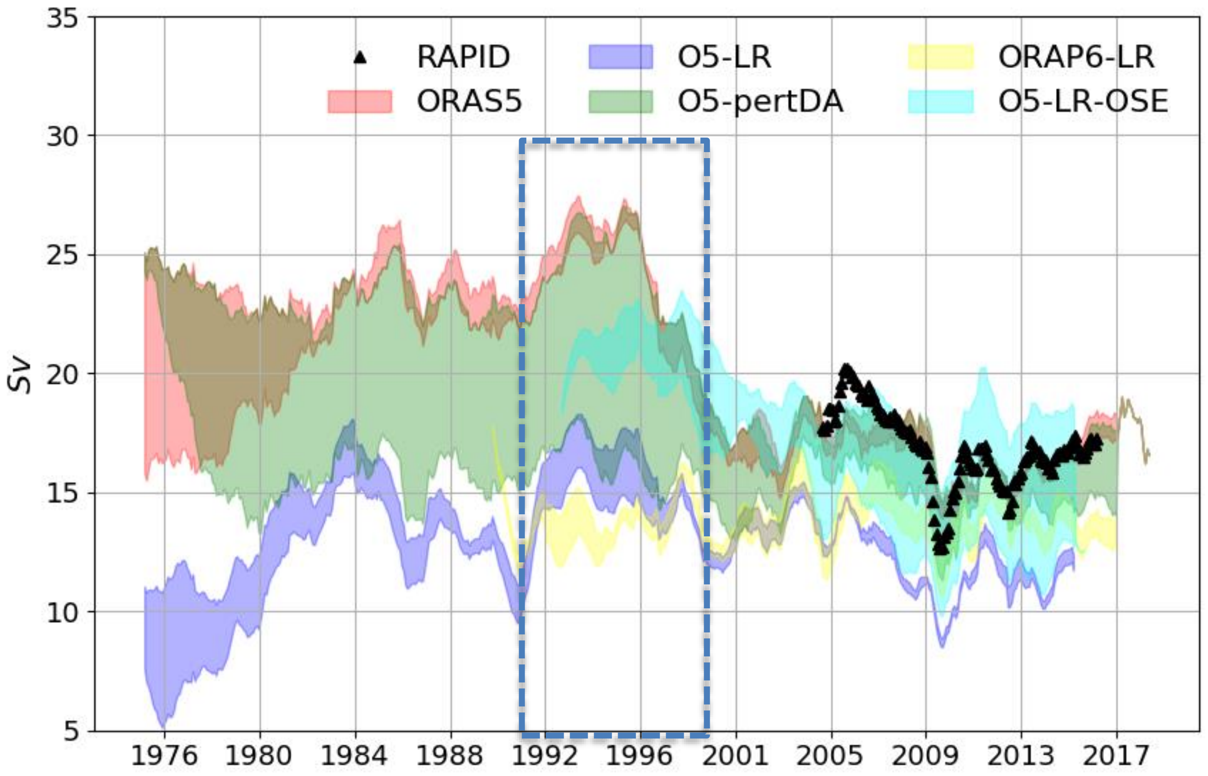
Uncertainties in AMOC strengths

- Mean state of the AMOC transports is mainly determined by the model horizontal resolutions (1/4 vs 1 degree).
- Interannual variabilities of the AMOC transports are mostly determined by atmospheric forcings, especially during the pre-Argo period.
- Perturbing DA settings results in larger ensemble spread than perturbing forcing and observations in our ORA system.

AMOC at 26.5 N

All ORA ensemble sets

O5-NoBC is excluded in O5-pertDA



ERAint vs ERA5

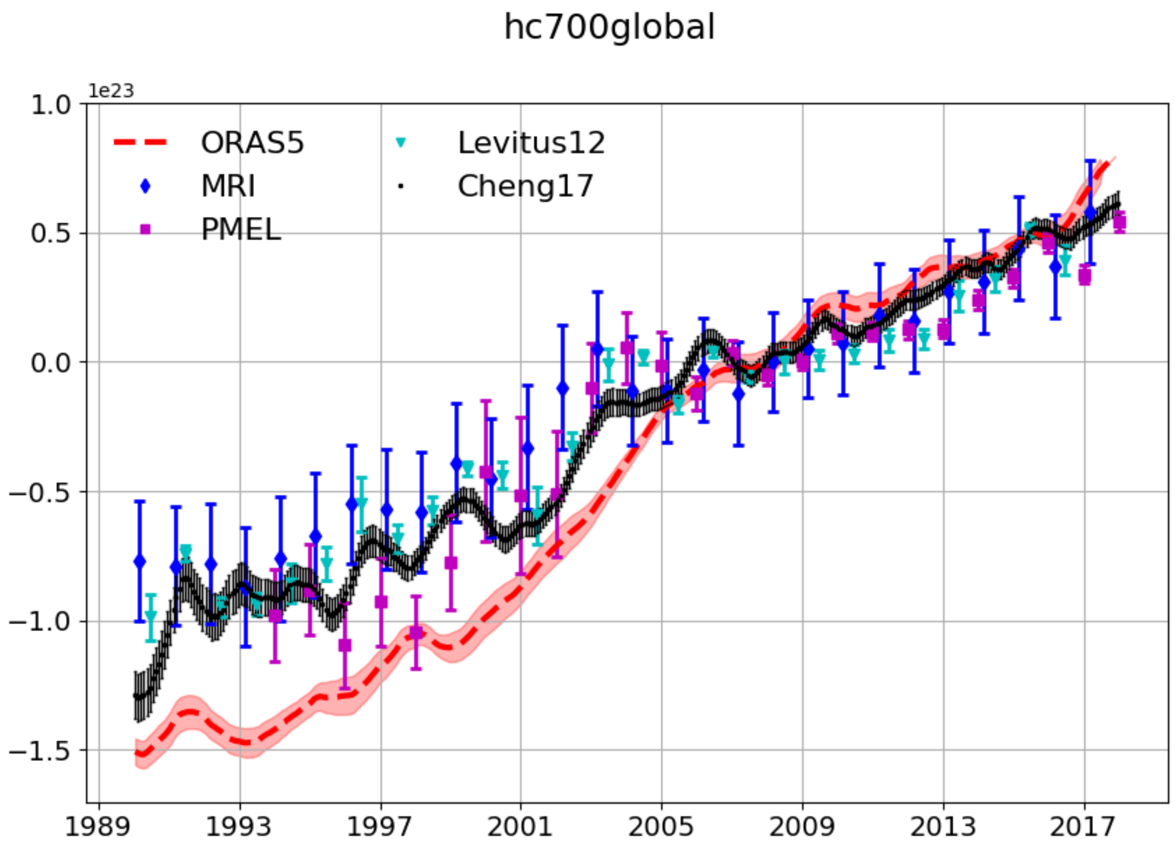
Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and observations

Trend of Global OHC (0-700m, in 10^{21} joules/yr)

	Global (1990-2017)	
	Trend	SNR
ORAS5	8.97 ± 0.05	14.6
O5-pertDA		
O5-LR		
O5-LR-OSE		
ORAP6-LR		
Cheng17	6.41	
Levitus12	5.45	
PMEL	6.47	
MRI	5.07	

Signal-to-noise ratio (SNR), defined as the ratio between the temporal standard deviation of the ensemble mean divided by the temporal mean of the ensemble standard deviation of filtered (anomalies) global OHC signals.



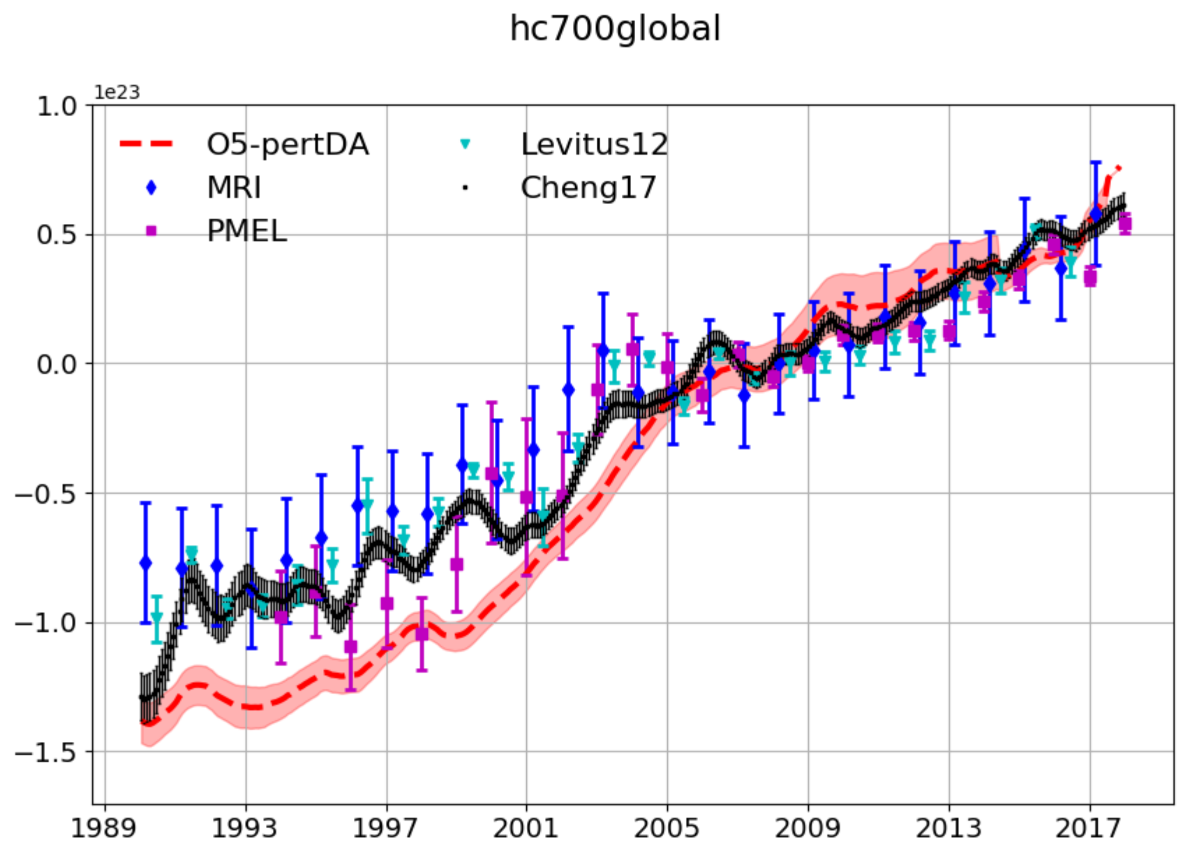
Cheng17: Cheng et al., *Sci. Adv*. **3**, e1601545 (2017)
Levitus12: Levitus et al, *Geophys. Res. Lett*. **39**, L10603 (2012)
PMEL: Johnson et al., *Am. Meteorol. Soc. Bull*. **98**, S66–S68 (2017)
MRI: Ishii et al., *Sci. Online Lett. Atmos*. **13**, 163–167 (2017)

Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and observations

Trend of Global OHC (0-700m, in 10^{21} joules/yr)

	Global (1990-2017)	
	Trend	SNR
ORAS5		
O5-pertDA	9.07 ± 1.37	7.21
O5-LR		
O5-LR-OSE		
ORAP6-LR		
Cheng17	6.41	
Levitus12	5.45	
PMEL	6.47	
MRI	5.07	



O5-pertDA has higher OHC trend w.r.t ORAS5, which mostly comes from O5-NoBC member. Without BC ocean warms up even faster.

Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and observations

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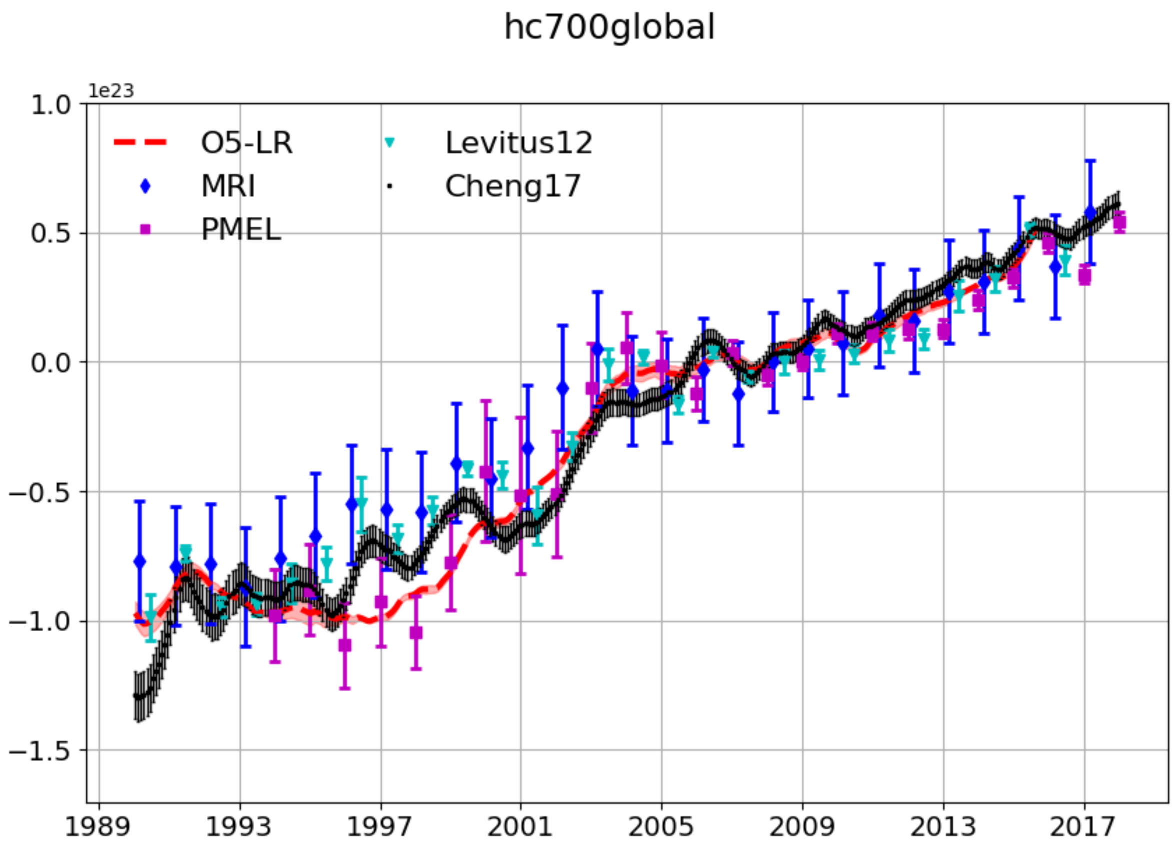
	Global (1990-2017)	
	Trend	SNR
ORAS5		
O5-pertDA		
O5-LR	*6.32 ± 0.03*	*24.5*
O5-LR-OSE		
ORAP6-LR		
Cheng17	6.41	
Levitus12	5.45	
PMEL	6.47	
MRI	5.07	



Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and observations

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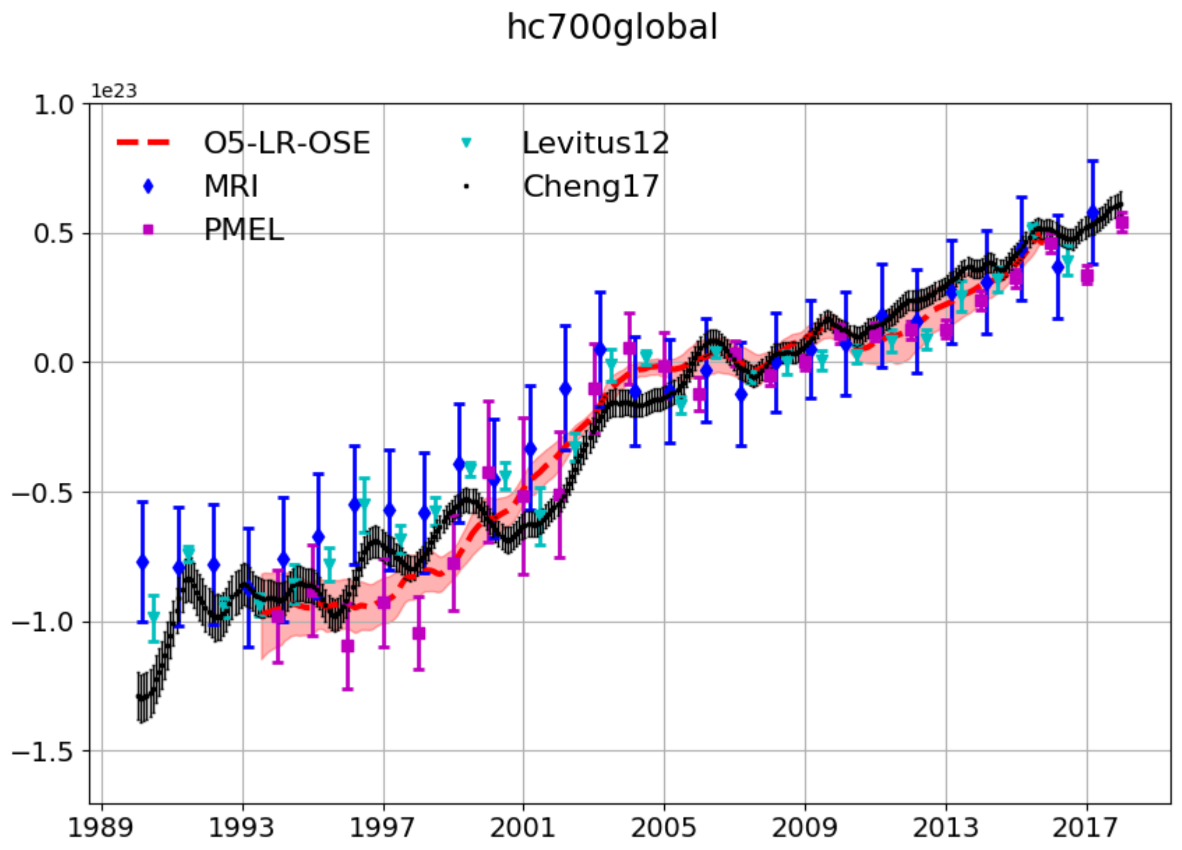
	Global (1990-2017)	
	Trend	SNR
ORAS5		
O5-pertDA		
O5-LR		
O5-LR-OSE	*6.62 ± 0.9*	*6.8*
ORAP6-LR		
Cheng17	6.41	
Levitus12	5.45	
PMEL	6.47	
MRI	5.07	

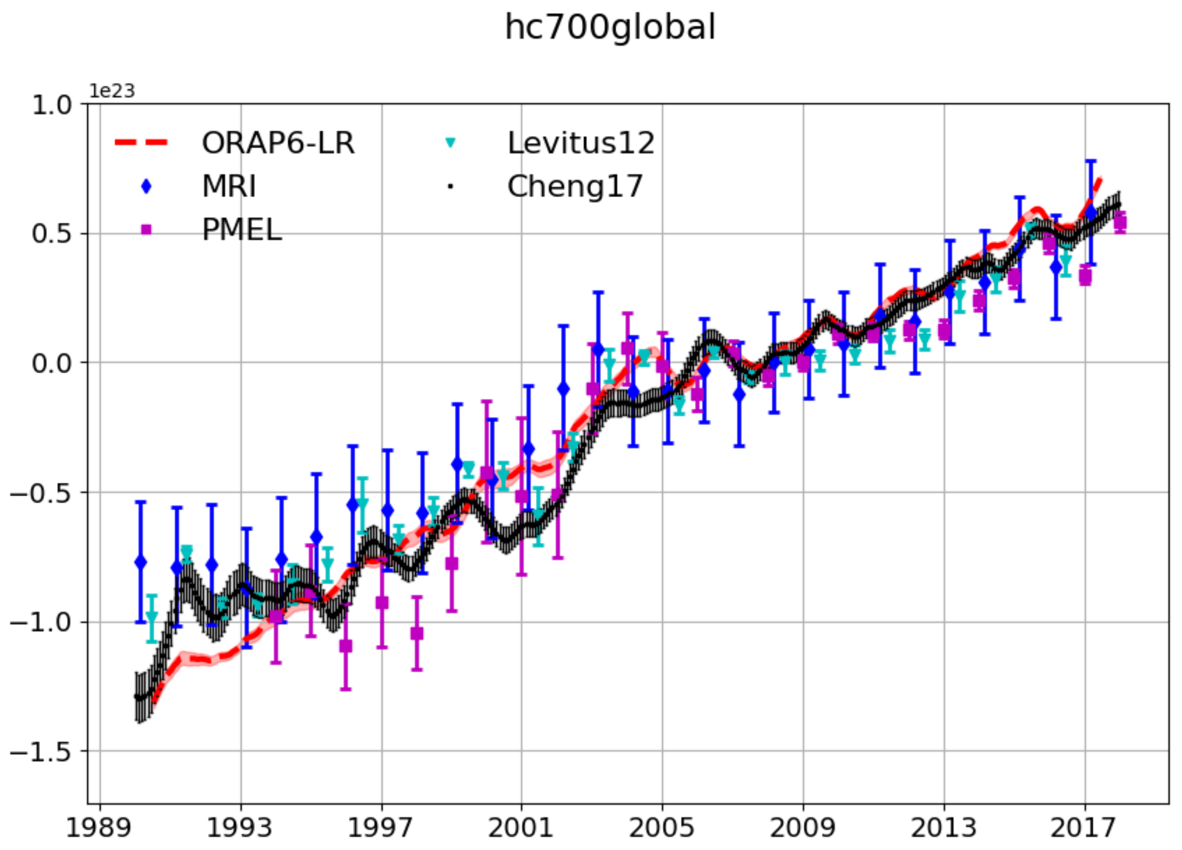


Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and observations

Trend of Global OHC (0-700m, in 10^{21} joules/yr)

	Global (1990-2017)	
	Trend	SNR
ORAS5		
O5-pertDA		
O5-LR		
O5-LR-OSE		
ORAP6-LR	*6.95 ± 0.08*	*26.4*
Cheng17	6.41	
Levitus12	5.45	
PMEL	6.47	
MRI	5.07	



Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and observations

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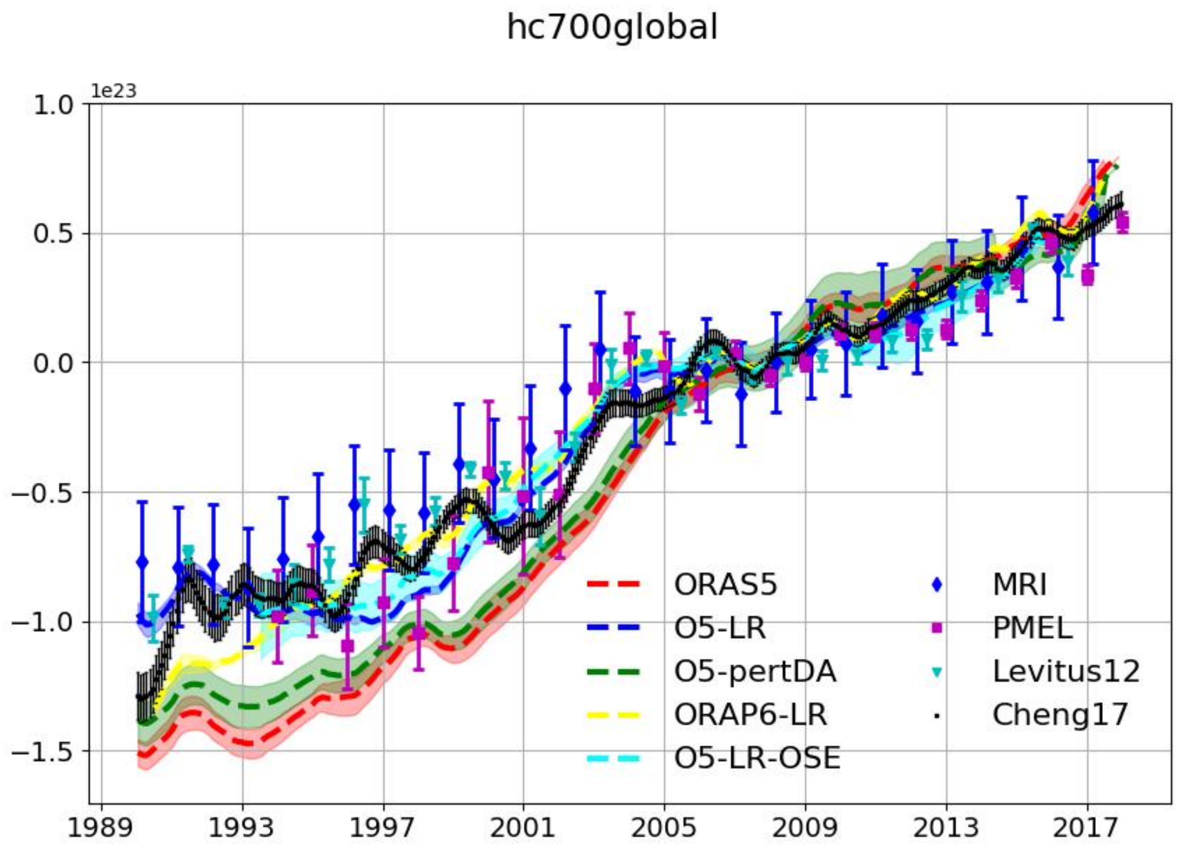
Cheng17	6.41	
Levitus12	5.45	
PMEL	6.47	
MRI	5.07	



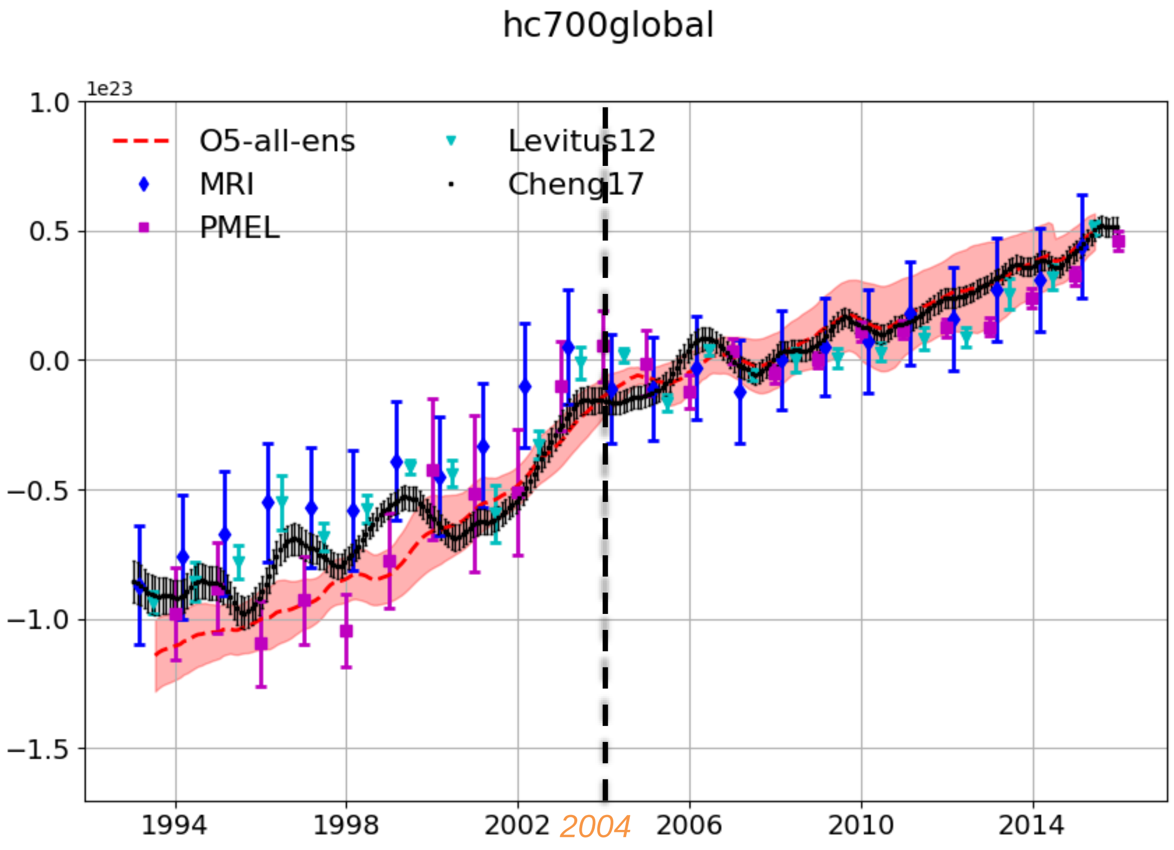
Uncertainties in ocean heat content changes

Anomalies of Ocean Heat content (0-700m) in ORAs and OBS

Trend of Global OHC (0-700m, in 10^{21} joules/yr)

	Global (1993-2004)		Global (2004-2015)	
	Trend	SNR	Trend	SNR
ORAs all	9.30 ± 0.67	6.2	5.21 ± 1.39	3.1
OBS all	8.09 ± 1.43		4.63 ± 0.43	
Cheng17	6.76		5.21	
Levitus12	7.67		4.28	
PMEL	10.51		4.16	
MRI	7.44		4.85	

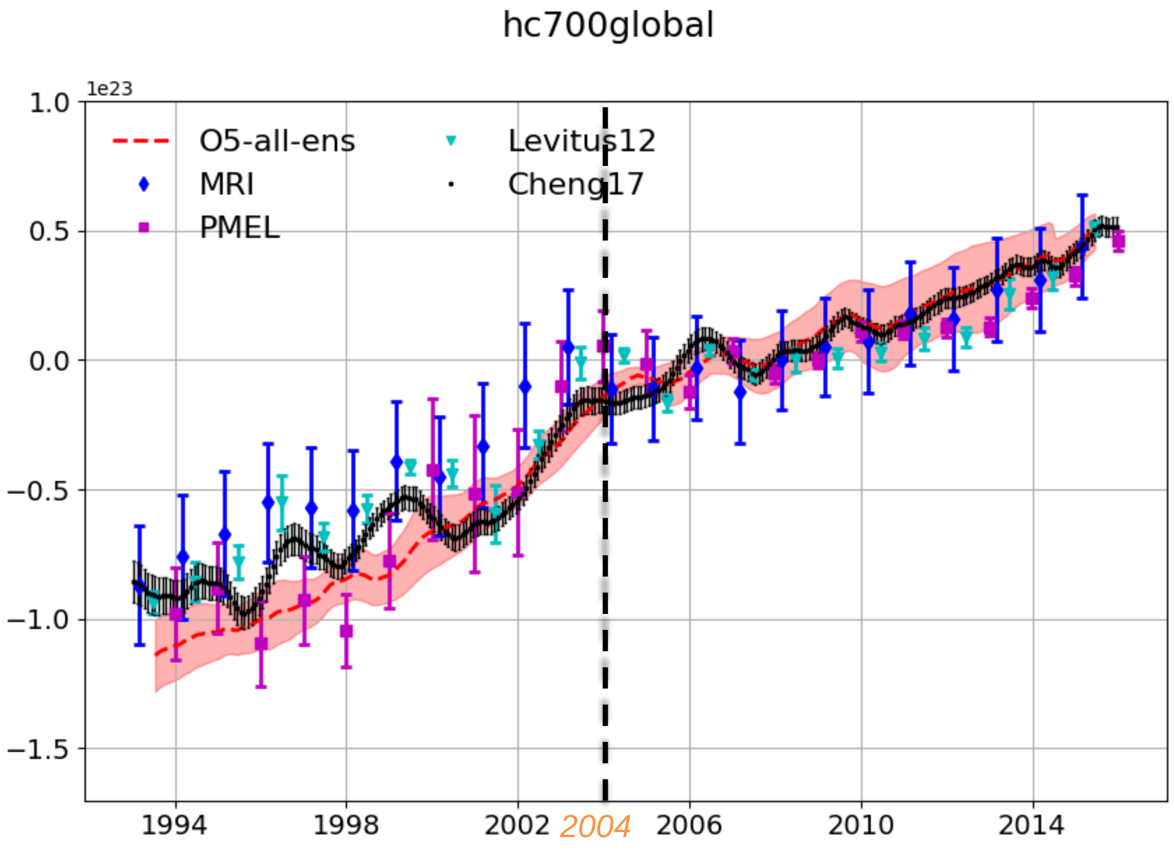
- *ORA ensemble includes all members from* ***ORAS5, O5-pertDA, O5-LR, O5-LR-OSE*** *and* ***ORAP6-LR****.*
- *OBS all include* ***Cheng17, Levitus12, PMEL and MRI***



Uncertainties in ocean heat content changes

- Both ORAs and observation based products show a slow down of global warming trend after 2004. Real or Argo impact?
- Compared to observation based estimations, ORA-all seems slightly overestimated global OHC warming trend both before and after 2004.
- Magnitude of ensemble spread from ORA-all is not reduced in the Argo period. To the contrary, OHC trend uncertainty has doubled after moving from pre-Argo to the Argo period. This large trend uncertainty mostly comes from OSE member (NoArgo) and pertDA member (NoBC).
- Observation based OHC trend estimation has higher uncertainty/spread in the pre-Argo period. Difference between different estimations mostly comes from their method of accounting (or not account) sampling errors, and gap-filling.

Anomalies of Ocean Heat content (0-700m) in ORAs and OBS



Summary

Sources of climate signal uncertainties estimated using Ocean and sea-ice (Re)analyses

Numerical Model

- Climate model and model physics: NEMO, HYCOM, ROM ….
- Resolutions: 1 vs 1/4 vs 1/12 vs 1/36 degree; vertical levels; gridded vs unstructed; ….

Boundary conditions:

- Atmospheric boundaries (forcings); Land boundaries (runoff); Initial conditions; …

Observing system

- Sparse data (low spatial and temporal data coverage/density), 1/1000 to 1/10000 compared to Atmospheric obs
- Insufficiency and irregularity in observation data coverage (sampling errors))

DA system

- QC/pre-processing of obs (coastal, high-latitude, thining/superobbing), balancing between different types (SLA vs in-situ T/S)
- (Marcin's talk) use of flow-dependent obs and bkg error covariances setup (important to deal with inhomogeneous observing network) and impact on the system

Other?

Challenges

Some challenges:

- *System Bias Correction and retrospectively usage of observations*
- *Better usage of satellite data in the pre-Argo era*
- *How to quantify/characterize of (re)analysis uncertainties?*
- *Perspective: The earth system approach and strongly coupled DA*

An earth system approach with fully coupled data assimilation system should be considered in order to mitigate large uncertainties that are associated with boundary conditions (atmospheric and land forcings), or errors due to using a non flow-dependent background error covariances in the data assimilation matrices.