CNR ISMAR
ISTITUTO
DI SCIENZE
MARINE

Reconstructing historical ocean heat content from reanalyses: an uncertainty assessment

Andrea Storto, Chunxue Yang
CNR ISMAR, Rome, Italy
andrea.storto@cnr.it

OceanPredict DA-TT
9-11/MAY/2023

CNR ISMAR ISTITUTO DI SCIENZE MARINE

Motivation

Why do we care about ocean heat content (OHC)?

- Changes in the Energy and Water Cycle are primarily responsible for the long-term changes affecting contemporary and future climate
- The problem at global scale is not well-posed in terms of fluxes:
  - **Energy:** Incoming solar radiation is of the order of 340 W m^{-2}. Uncertainty of air-sea fluxes in models, observation-based dataset, reanalyses, etc. is of the order of ± 5 W m^{-2}. The climate signal (OHU, EEI) is of the order of 0.5-1.0 W m^{-2} (ocean warming)
  - **Water:** Global precipitation (over ocean) is of the order of 12-14 Sv. Uncertainty of precipitation and evaporation is of the order of ± 1 Sv. The climate signal (barystatic sea level) is of the order of 0.01-0.03 Sv (≃ 2 mm/yr sea level rise).
- The global ocean, and some ocean observing networks, are however capable to record the changes with sufficient accuracy

Introduction

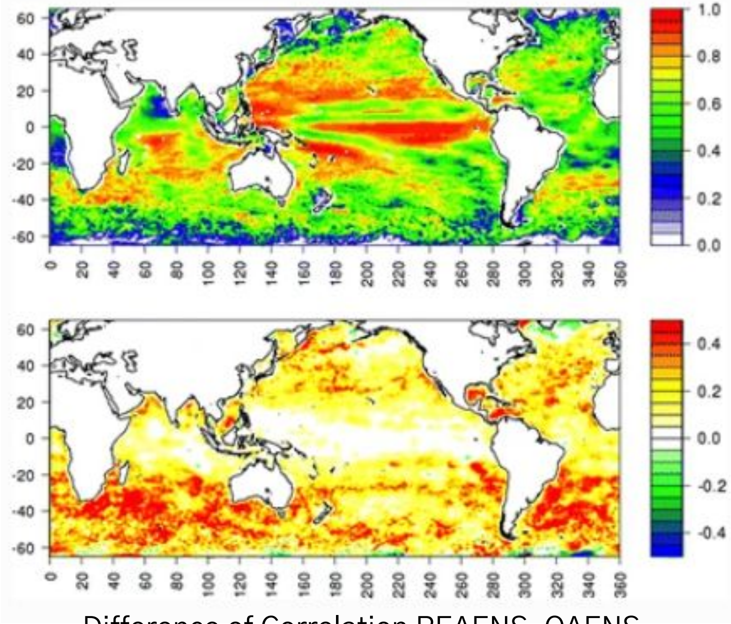
Methods

- Statistical mapping (objective analyses)
- CMIP model simulations
- **Reanalyses**
- Proxy data (e.g. O_2 & CO_2)
- Indirect remotely sensed data (geodetic approach; acoustic measurements)
- AI reconstructions from sea surface data

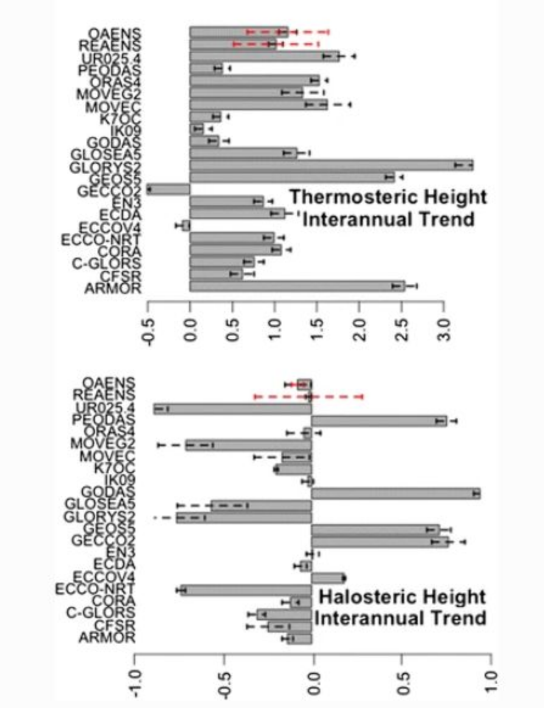
Introduction

Reanalyses: advantages and disadvantages in recent intercomparisons

Correlation of interannual steric sea level REAENS ALT−GRV



Difference of Correlation REAENS−OAENS



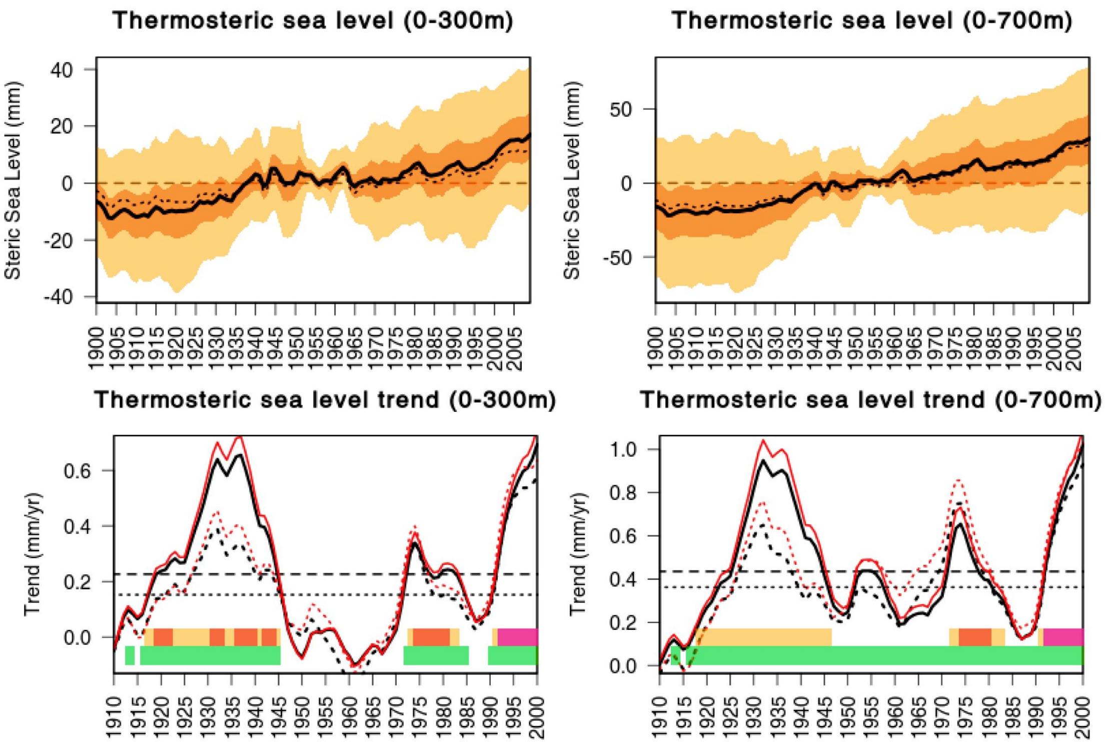
From ORA−IP Intercomparison (Storto et al., 2017)

Consistency (~accuracy?) increases with new vintages of reanalyses (see Storto et al., 2019, ClimDyn)

CNR ISMAR ISTITUTO DI SCIENZE MARINE

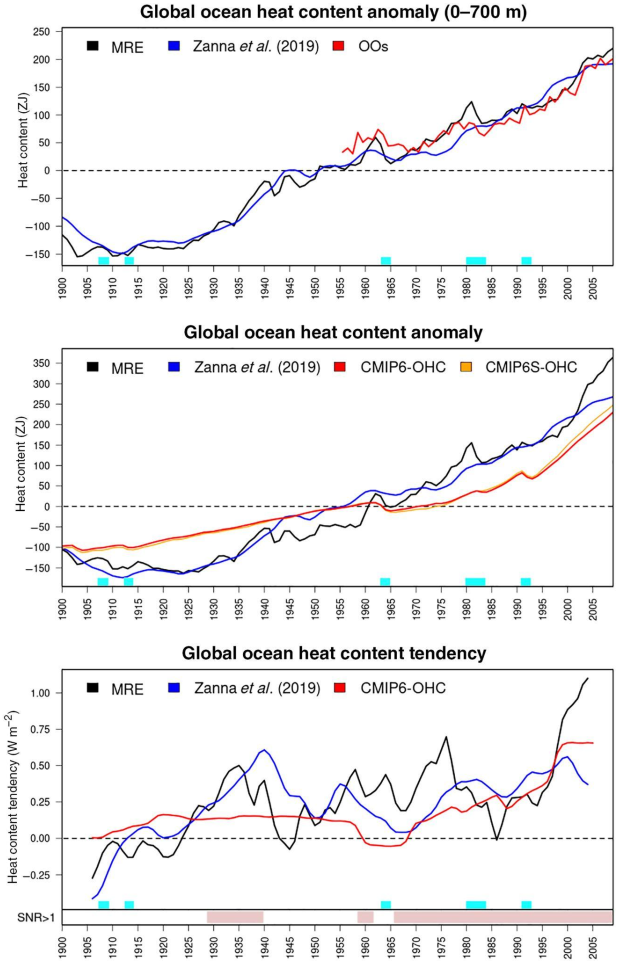
Introduction

Reanalyses: Value for historical investigations



Use of multi-system ensemble mean (4 families, 16 members)

From Historical reanalysis Intercomparison (Storto et al., 2019; 2021)



CNR ISMAR ISTITUTO DI SCIENZE MARINE

Reanalysis system

The ensemble historical reanalysis system (ENS-REA)

ORCA1 → ORCA025:
4^3=64 CPU increase

Moderate resolution (ORCA1, 1° with 1/3° increase in the Tropics, 75 levels)

Relatively large ensemble (32 members)

State-of-the art modelling system (NEMO4.0.7)

Variational data assimilation of all in-situ observations with VarQC

Monthly background-error covariances from long-term anomalies, modulated with EN4 obs sampling

Air-sea flux corrections (nudging to SST, SSS) and large-scale bias correction

Realistic discharge into the ocean (daily discharge from JRA55-do)

Historical period
1860–2015
(20CRV3 reanalysis forcing)

Contemporary period
1960–2022
(ERA5 reanalysis forcing)

Reanalysis system

CNR ISMAR ISTITUTO DI SCIENZE MARINE

The ensemble historical reanalysis system (ENS-REA)

ORCA1 → ORCA025:
4^3=64 CPU increase

Moderate resolution (ORCA1, 1° with 1/3° increase in the Tropics, 75 levels)

Relatively large ensemble (32 members)

State-of-the art modelling system (NEMO4.0.7)

Variational data assimilation of all in-situ observations with VarQC

Monthly background-error covariances from long-term anomalies, modulated with EN4 obs sampling

Air-sea flux corrections (nudging to SST, SSS) and large-scale bias correction

Realistic discharge into the ocean (daily discharge from JRA55-do)

Contemporary period
1960–2022
(ERA5 reanalysis forcing)

CNR ISMAR
ISTITUTO DI SCIENZE MARINE

Reanalysis system

The ensemble historical reanalysis system (ENS-REA)

ORCA1 → ORCA025:
4^3=64 CPU increase

Moderate resolution (ORCA1, 1° with 1/3° increase in the Tropics, 75 levels)

Relatively large ensemble (32 members)

State-of-the art modelling system (NEMO4.0.7)

Variational data assimilation of all in-situ observations with VarQC

Monthly background-error covariances from long-term anomalies, modulated with EN4 obs sampling

Air-sea flux corrections (nudging to SST, SSS) and large-scale bias correction

Realistic discharge into the ocean (daily discharge from JRA55-do)

An objective analysis system is run aside
Same 3DVAR formulation, no model integration but persistency used instead

Contemporary period
1960-2022
(ERA5 reanalysis forcing)

Ensemble generation

CNR ISMAR ISTITUTO DI SCIENZE MARINE

The ensemble historical reanalysis system (ENS-REA)

Perturbation of atmospheric forcing

- 2 ensemble anomalies from ERA5 selected through clustering OR different 20CRv3 members

SST Surface nudging

- 2 SST datasets (UKMO HadISST and COBE SST)

In-situ observations

- 2 in-situ observation datasets (2 different MBT/XBT drifts OR EN4, IQuoD)

Initial conditions

- 2 Lagged initial conditions from prototypical runs

Bulk formulas for air-sea flux

- 2 formulations (NCEP-CORE vs ECMWF)

Stochastic perturbations on top of the previous perturbations

- SPP: Stochastic perturbations of several parameters (solar extinction, TKE params, nudging, horiz. diffus.)
- Stochastic perturbation of observations $\sim\mathcal{N}(0, \boldsymbol{\sigma}_{\mathbf{rep}}^2)$

Ensemble generation

CNR ISMAR ISTITUTO DI SCIENZE MARINE

The ensemble historical reanalysis system (ENS-REA)

Perturbation of atmospheric forcing

- 2 ensemble anomalies from ERA5 selected through clustering OR different 20CRv3 members

SST Surface nudging

- 2 SST datasets (UKMO HadISST and COBE SST)

In-situ observations

- 2 in-situ observation datasets (2 different MBT/XBT drifts OR EN4, IQuoD)

Initial conditions

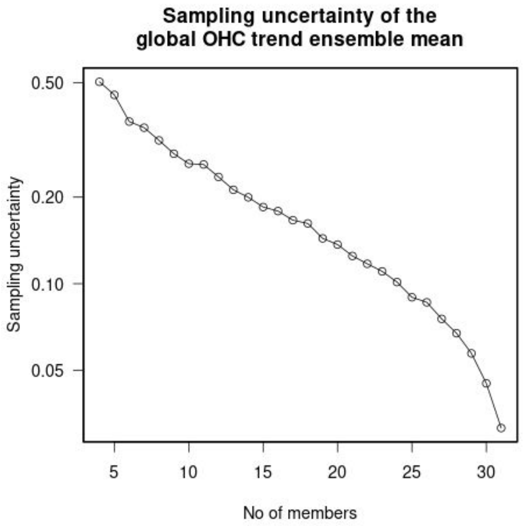
- 2 Lagged initial conditions from prototypical runs

Bulk formulas for air-sea flux

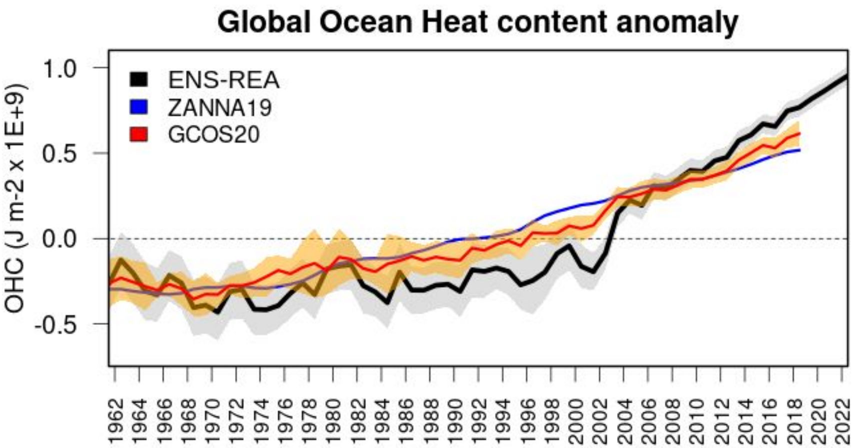
- 2 formulations (NCEP-CORE vs ECMWF)

Stochastic perturbations on top of the previous perturbations

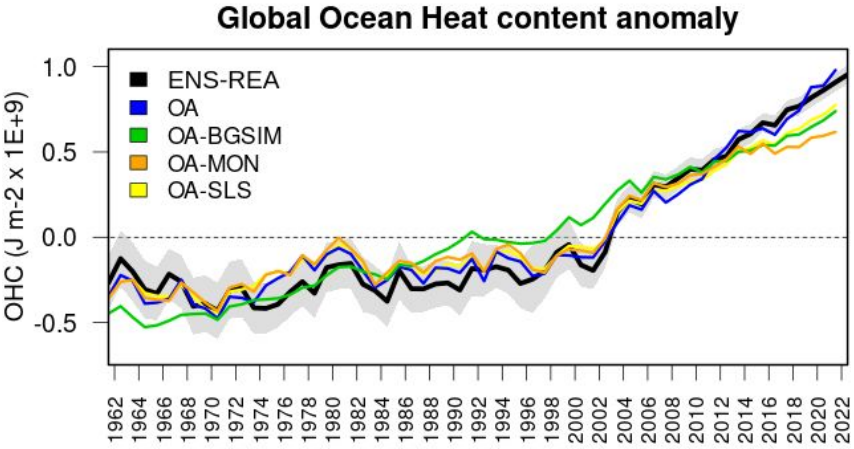
- SPP: Stochastic perturbations of several parameters (solar extinction, TKE params, nudging, horiz. diffus.)
- Stochastic perturbation of observations $\sim\mathcal{N}(0, \boldsymbol{\sigma}_{rep}^2)$

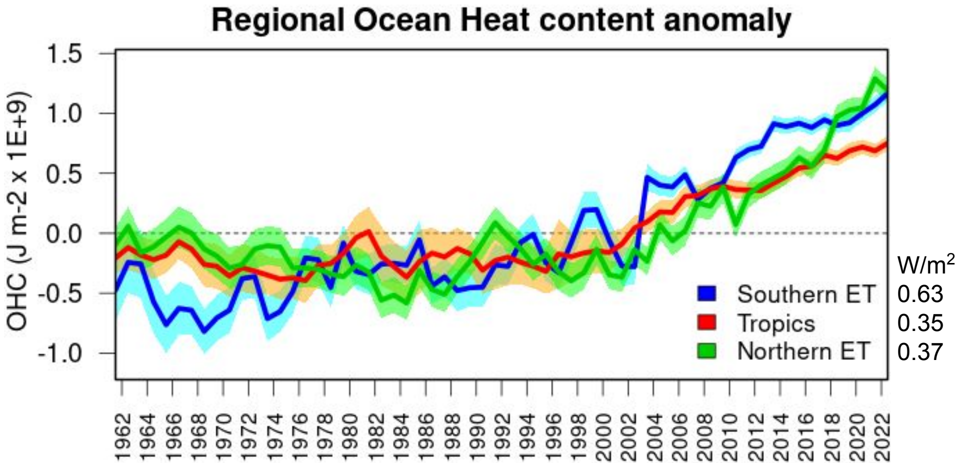


Results

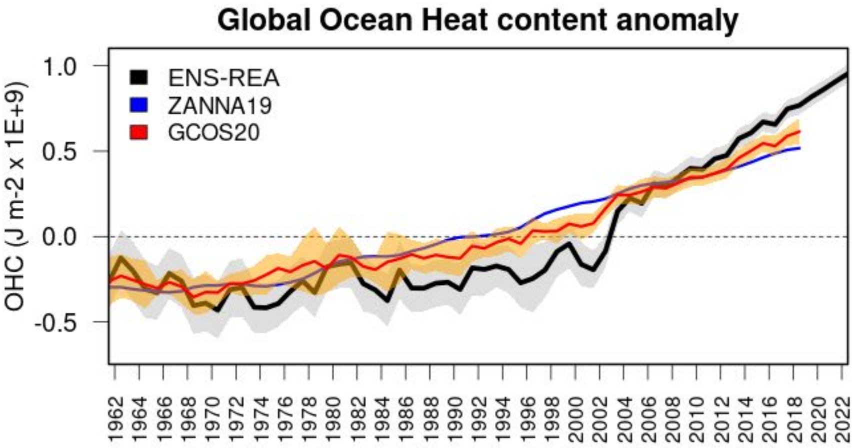


Dataset	Global warming (W m^{-2}) 1961-2022	Global warming (W m^{-2}) 1961-2020	
ENS-REA	0.43 ± 0.08	0.41 ± 0.09	
GCOS22	NA	0.41 ± 0.10	
Dataset	OHC Trend (W m^{-2}) (1961-2018)	Interannual Variability (1E9 J m^{-2}) (1961-2018)	Acceleration (W m^{-2} dec^{-1}) (1961-2018)
ENS-REA	0.42	0.20	0.13
GCOS20	0.34	0.09	0.07
OA	0.41	0.19	0.12
OA-BGSIM	0.44	0.07	0.04
OA-MON	0.36	0.12	0.07
OA-SLS	0.37	0.14	0.09

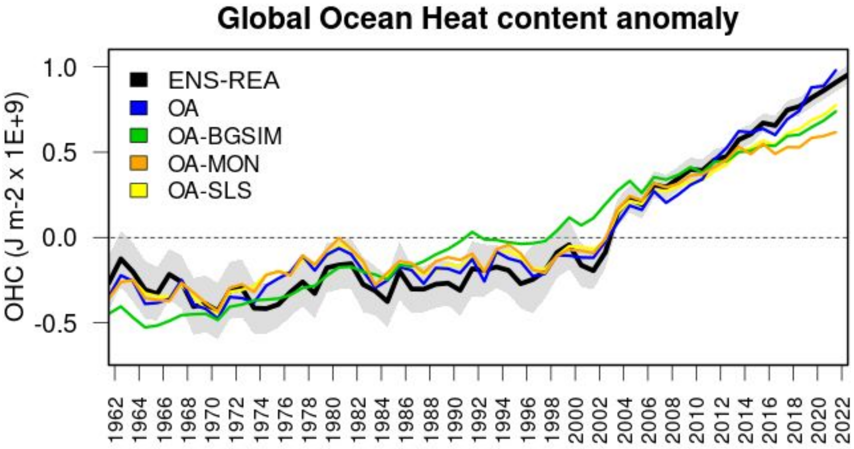




Results



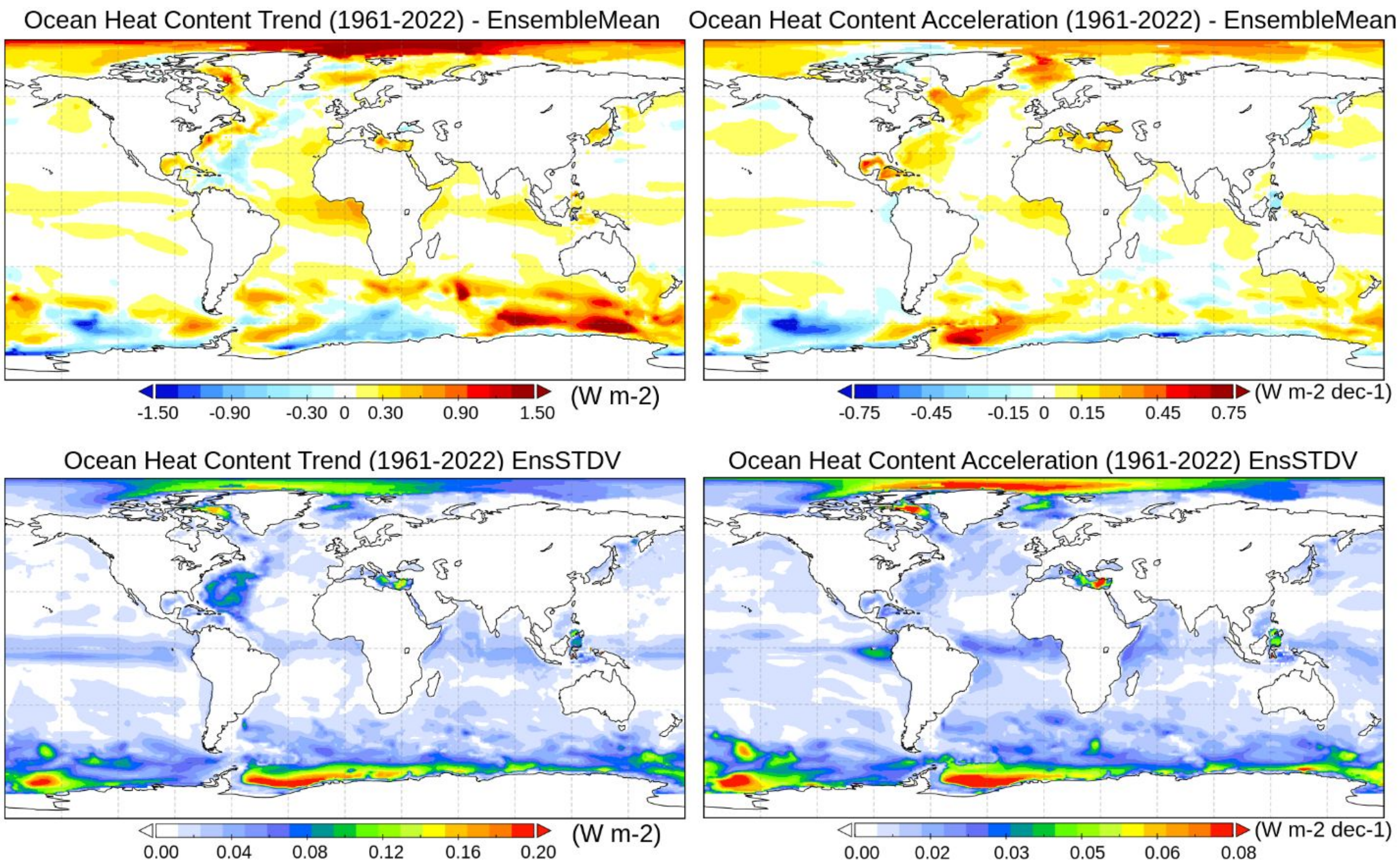
Dataset	Global warming ($W\ m^{-2}$) 1961-2022	Global warming ($W\ m^{-2}$) 1961-2020	
ENS-REA	0.43 ± 0.08	0.41 ± 0.09	
GCOS22	NA	0.41 ± 0.10	
Dataset	**OHC Trend ($W\ m^{-2}$) (1961-2018)**	**Interannual Variability (1E9 $J\ m^{-2}$) (1961-2018)**	**Acceleration ($W\ m^{-2}\ dec^{-1}$) (1961-2018)**
ENS-REA	0.42	0.20	0.13
GCOS20	0.34	0.09	0.07
OA	0.41	0.19	0.12
OA-BGSIM	0.44	0.07	0.04
OA-MON	0.36	0.12	0.07
OA-SLS	0.37	0.14	0.09



Acceleration **1961–2022**: 0.15 ± 0.04 W m −2 dec −1

Acceleration **2006–2018**: 0.20 ± 0.07 W m−2 dec−1,
(0.50 ± 0.47 W m−2 dec−1 Loeb et al., 2019;
0.25 from Habuba et al., 2021)

Results



OHC trend are large locally at high latitudes and within the Tropics.

OHC acceleration in the western NAtl.

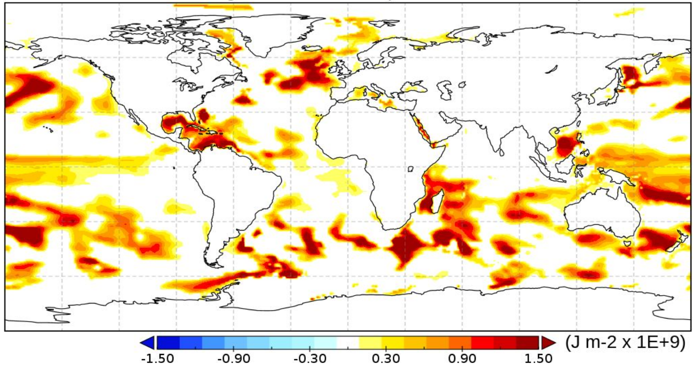
CNR ISMAR
ISTITUTO DI SCIENZE MARINE

Results

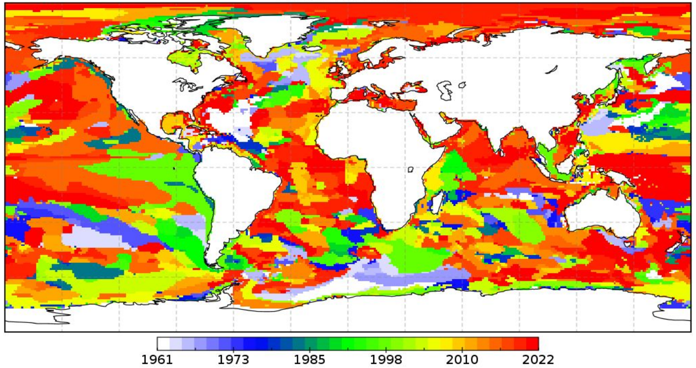
No obvious preference area for 2022 warming compared to 2021

Percent of ocean with 2022 as warmest year is very high (11.6%) and almost doubles any previous year

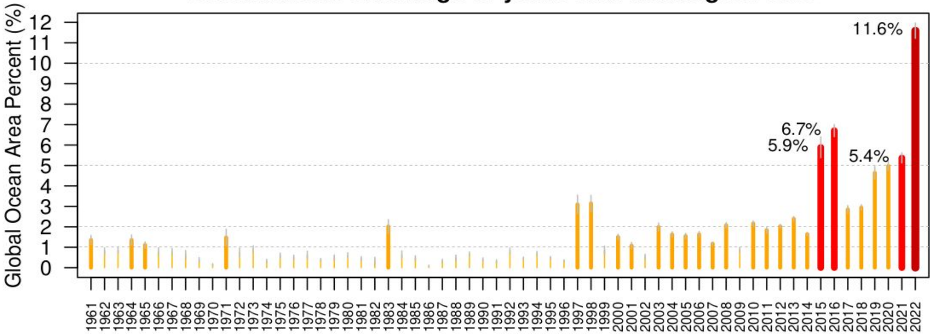
Ocean Heat Content Increase (2022 vs 2021)
Areas with significant increase (99% confidence level)



Year of Maximum Ocean Heat Content (1961-2022)
Ensemble Mean



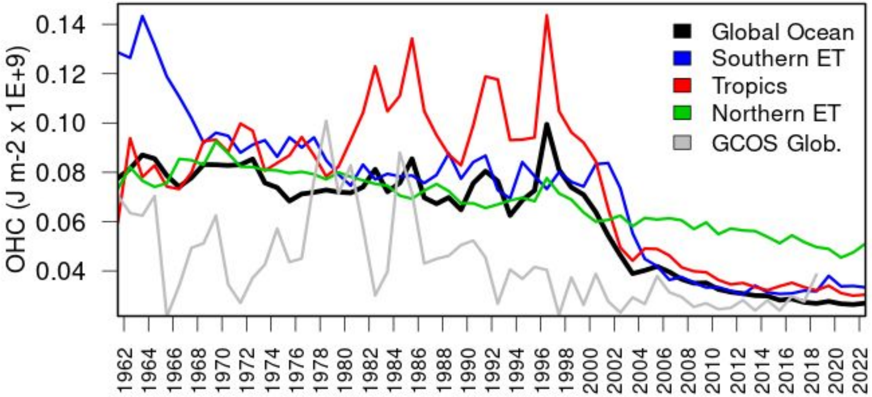
Ocean Area Percentage of years with the largest OHC



CNR ISMAR
ISTITUTO DI SCIENZE MARINE

Results

Ocean Heat Content Uncertainty

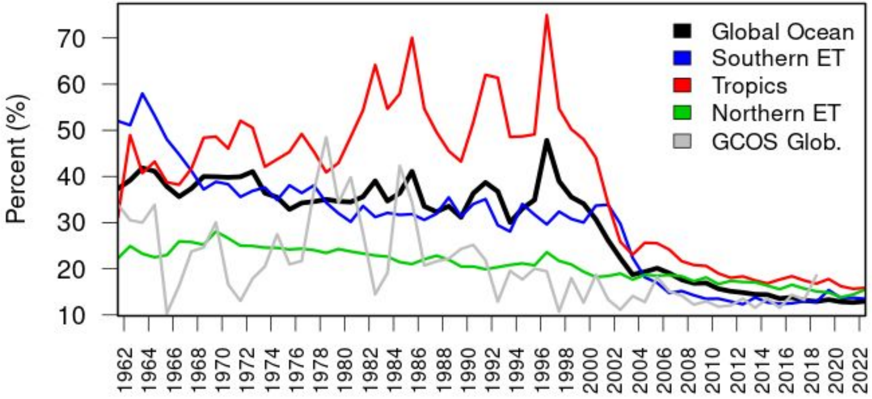


REA uncertainty comparable to GCOS (slightly larger) but more stable and around 40% (before Argo) converging towards 15% (with Argo)

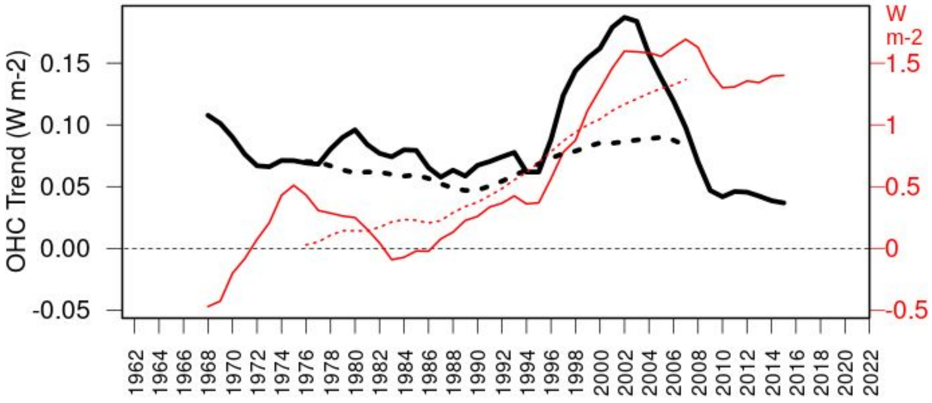
Tropics show the largest uncertainty, with peaks (often) corresponding to El Nino years

Running ensemble st.dev. of OHC trends (15yr vs 30yr)

Ocean Heat Content Normalized Uncertainty

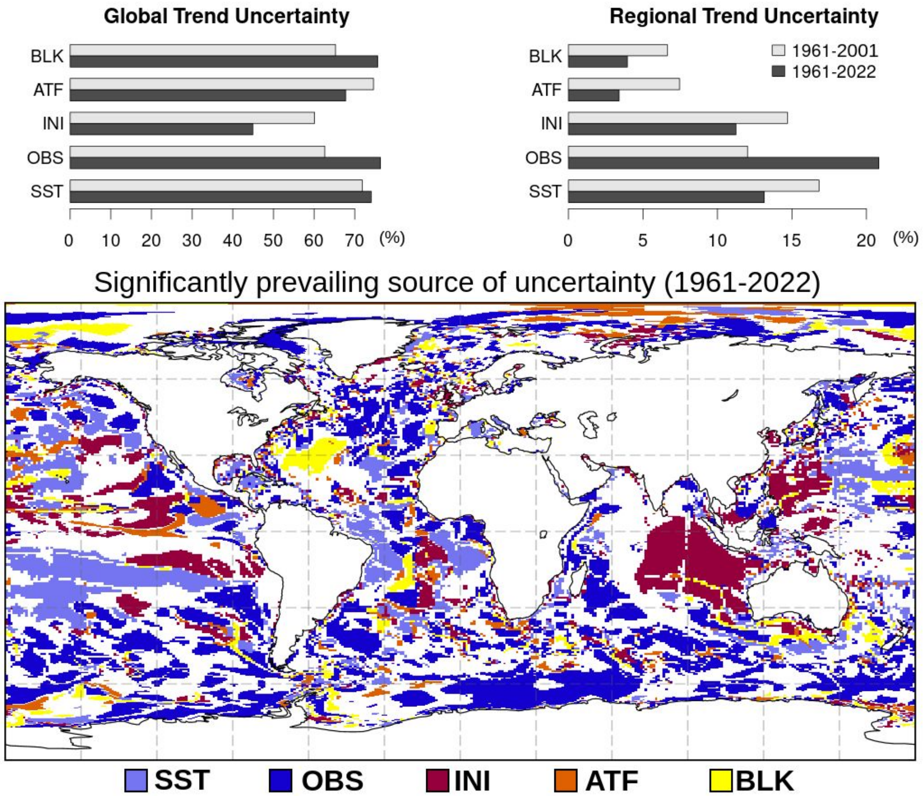


Ocean Heat Content Trend Uncertainty



CNR ISMAR
ISTITUTO DI SCIENZE MARINE

Results

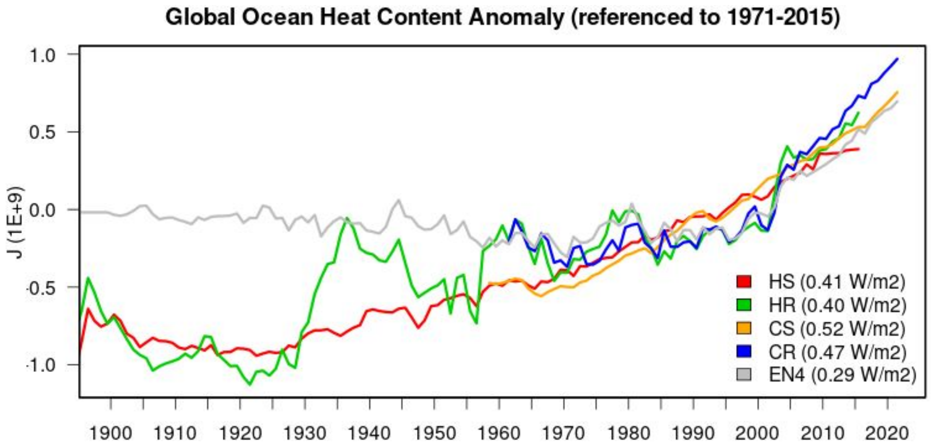


Global trend:
Except ICs, all sources of uncertainty contribute significantly to the total uncertainty.

Regional trends:
OBS uncertainty prevails at mid to high latitudes; SST at low latitudes; ICs locally; atmospheric forcing generally negligible

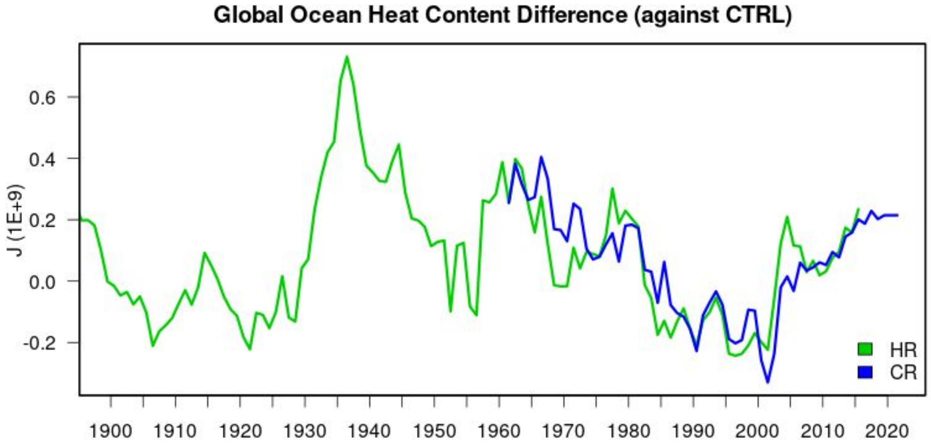
CNR ISMAR
ISTITUTO DI SCIENZE MARINE

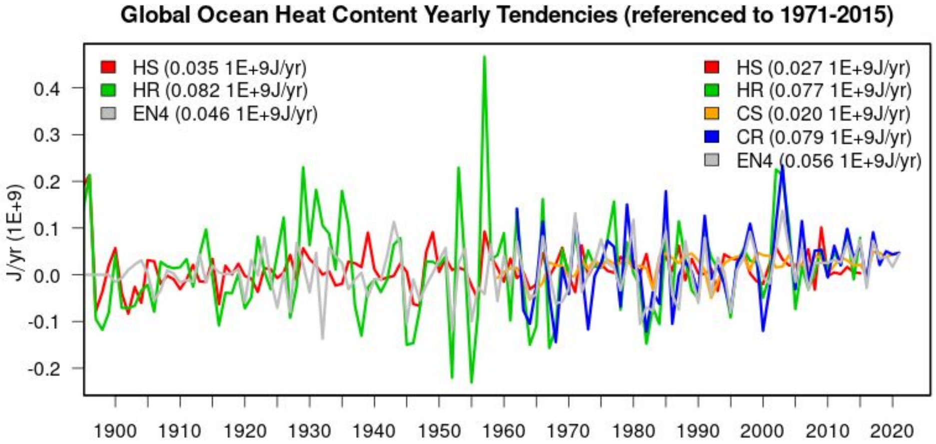
Results



Preliminary results show a very good consistency between Historical (H) and Contemporary (C) reanalyses in terms of trends and difference wrt their corresponding control run.

St.dev. of yearly tendency indicates large amount of information is available from observations even in early periods





Conclusions

A new ensemble reanalysis targeted to centennial timescale is introduced

A number of results suggests that the ensemble reanalysis is robust:

Significant acceleration

Similar variability as a corresponding objective analysis

Uncertainty comparable to GCOS (but more steady)

Consistency between contemporary and historical reanalysis system

The ensemble allows "ranking" of the uncertainty sources

A 32-member historical (1860-present) is ongoing