HEAT IN THE OCEAN

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Pre-workshop webinars on Future US Earth System Reanalysis
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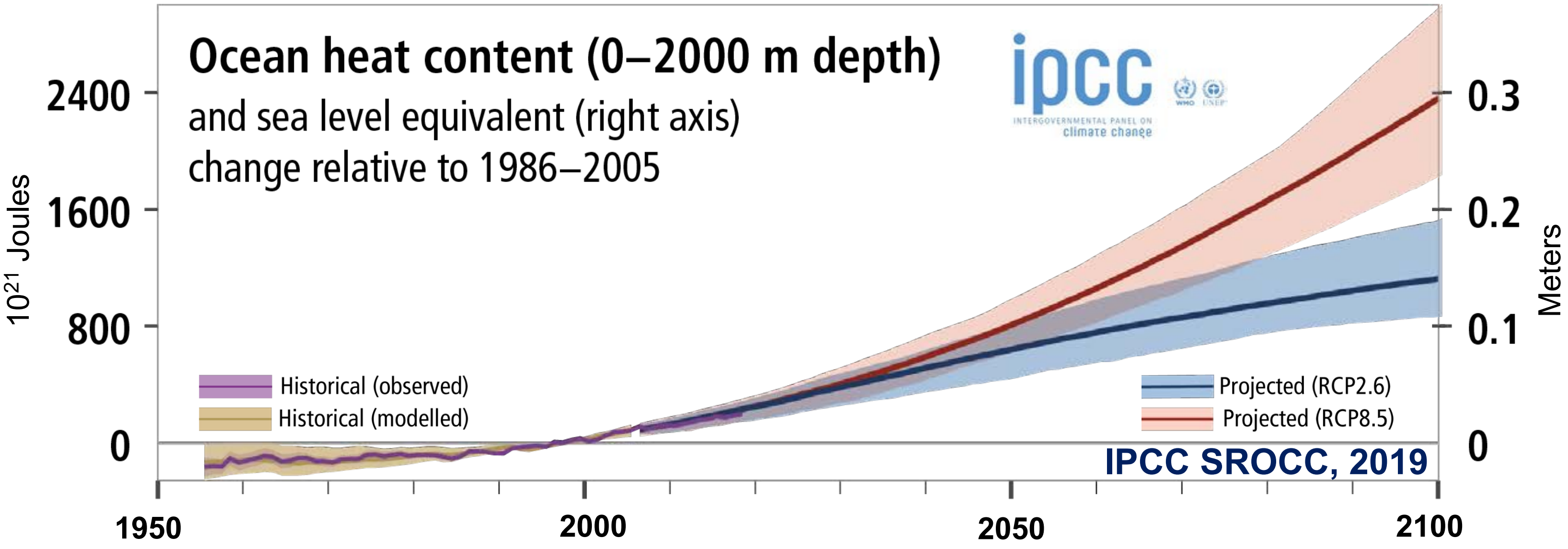
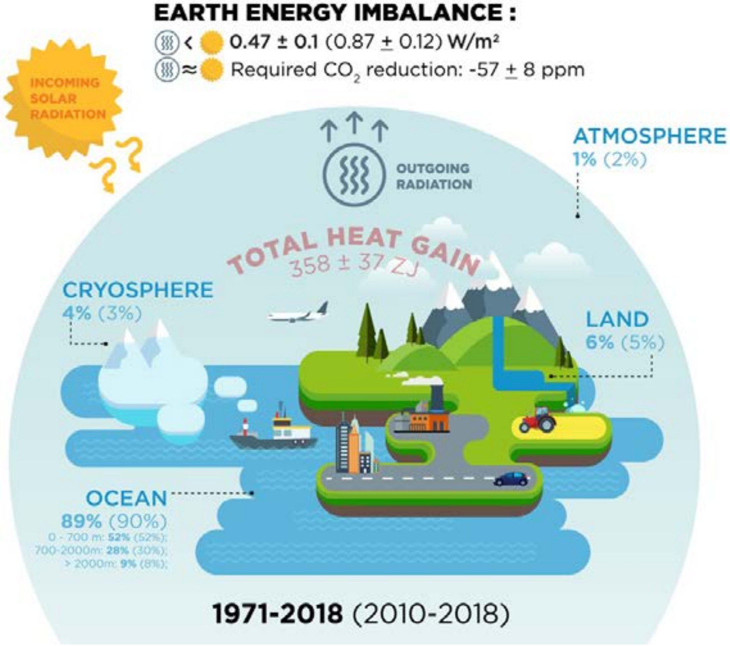
THE GLOBAL OCEAN IS WARMING.

Due to emissions of heat-trapping gases resulting from human activities, **the global ocean has warmed** as it has taken up more than 90% of the excess heat in the climate system, **making climate change irreversible**.



The ocean will continue to warm throughout the 21st century. By 2100, the ocean will take up 2 to 4 times more heat if global warming is limited to 2°C and up to 5 to 7 times at higher emissions.

THE EARTH HEAT INVENTORY



The **various facets and impacts** of observed climate change arise **due to the positive EEI**, which thus represents a **crucial measure of the rate of climate change**.

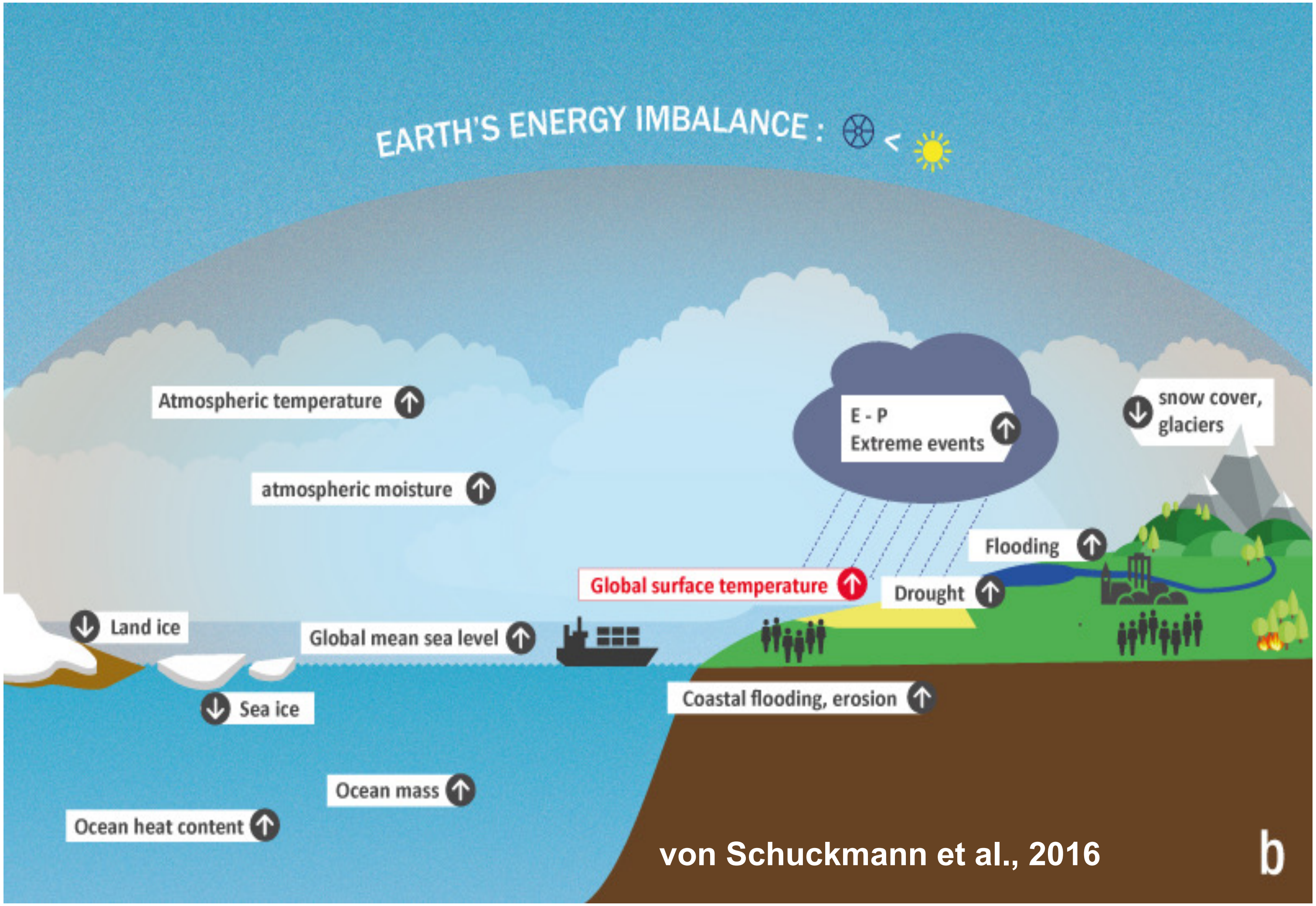
The EEI is the portion of the forcing that the Earth has not yet been responded to (F- ΔT/S) ➔ **How much heat is ‘in the pipeline’** ?

The EEI is the most critical number defining the prospects for continued global warming and climate change. This simple number, **EEI, is the most fundamental metric** that the scientific community and public must be aware of, as the **measure of how well the world is doing in the task of bringing climate change under control**

von Schuckmann et al., 2020

THE EARTH ENERGY IMBALANCE: WHY SHOULD WE CARE?

The accumulation of thermal energy in the Earth system is the root cause of the various facets of observed climate change



von Schuckmann et al., 2016

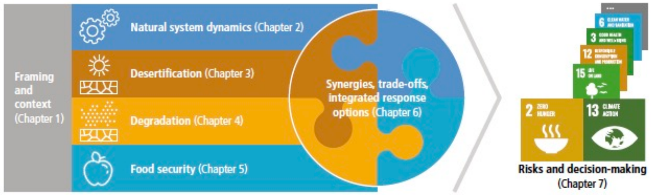
von Schuckmann at al., 2016, Nature Climate Change

THE EARTH HEAT INVENTORY

von Schuckmann et al., 2020

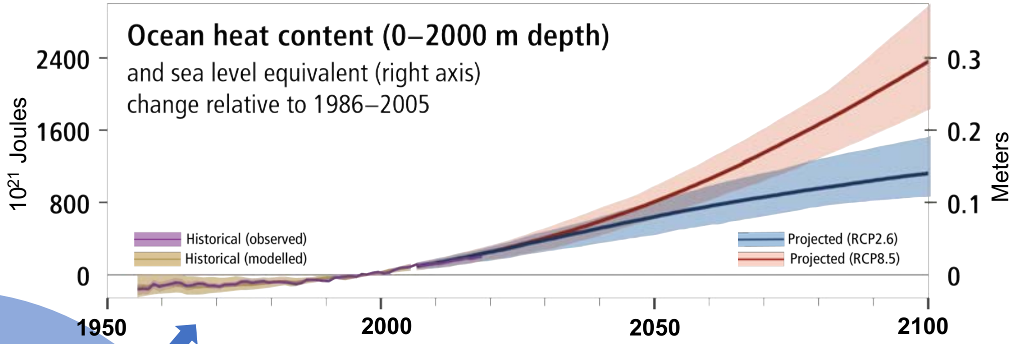
WHY SHOULD WE CARE?

LAND WARMING

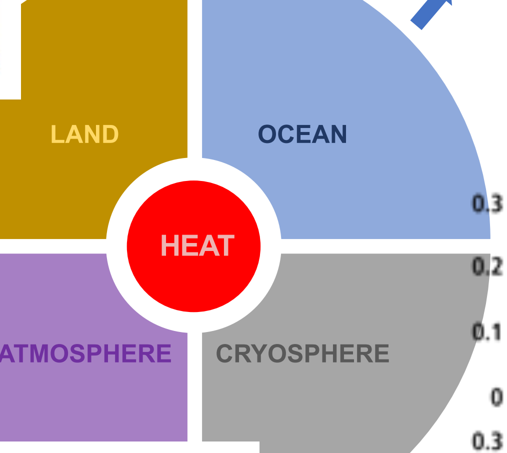


IPCC SRCCL, 2019

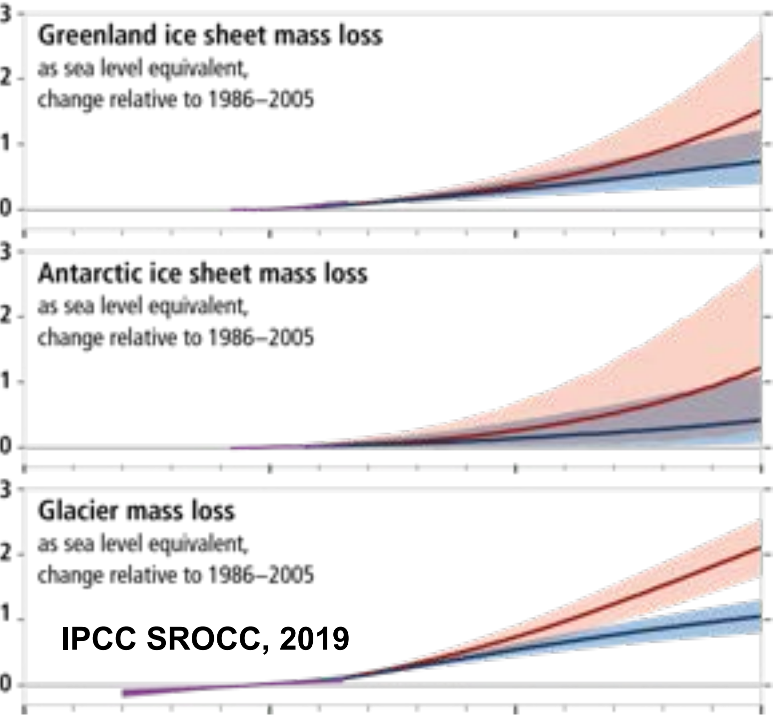
OCEAN WARMING



IPCC SROCC, 2019

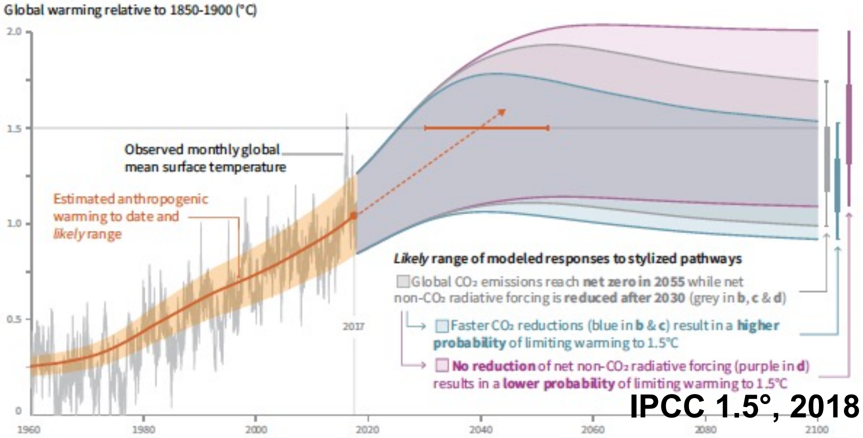


ICE LOSS



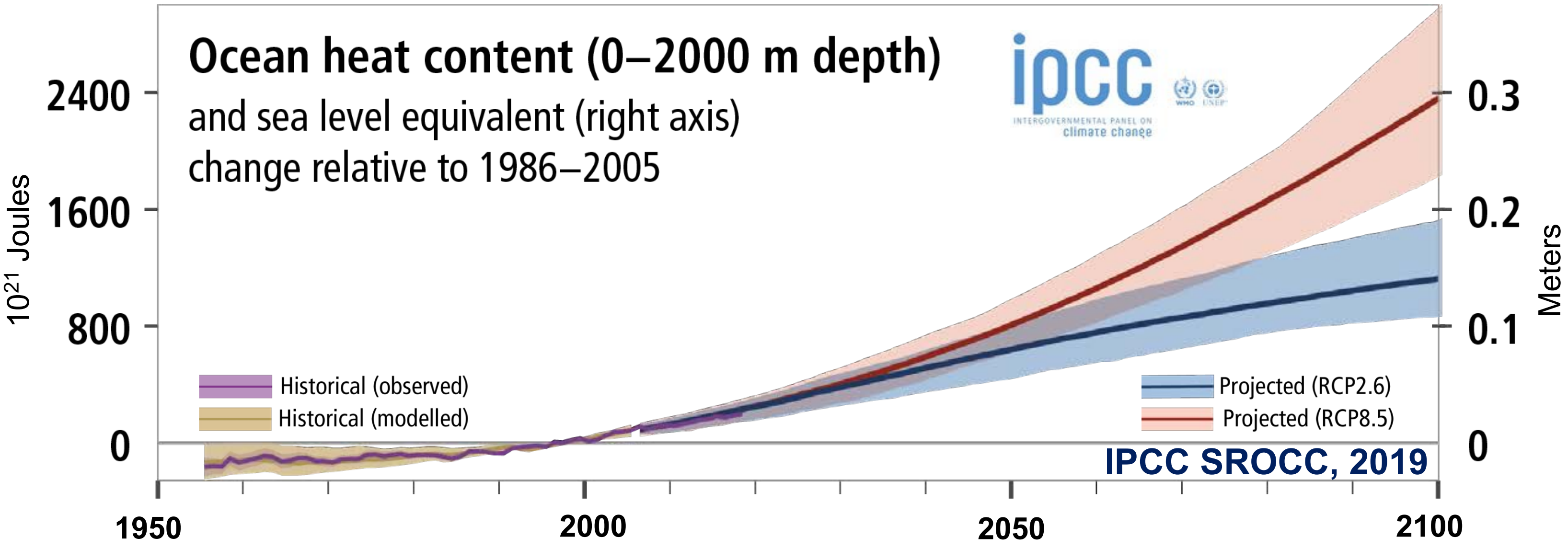
IPCC SROCC, 2019

ATMOSPHERE WARMING



IPCC 1.5°, 2018

Why and how do we know that the ocean is warming ?



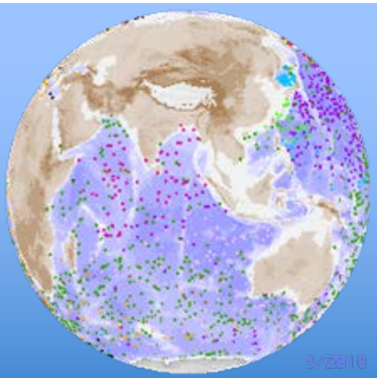
IPCC SROCC, 2019

$$OHC = \int_{z_1}^{z_2} \rho_0 c_p (T_{mth} - T_{clim}) dz$$

METHODS FOR OCEAN WARMING ESTIMATES

1

DIRECT ESTIMATES



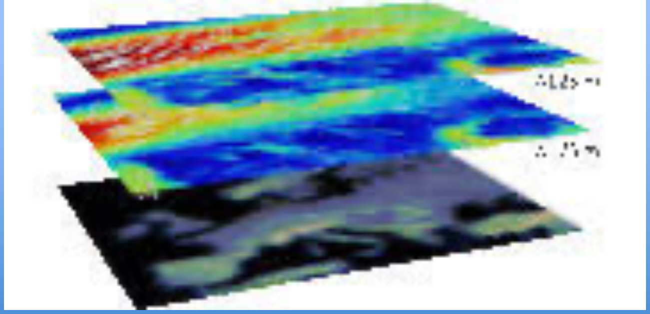
2

INDIRECT ESTIMATES

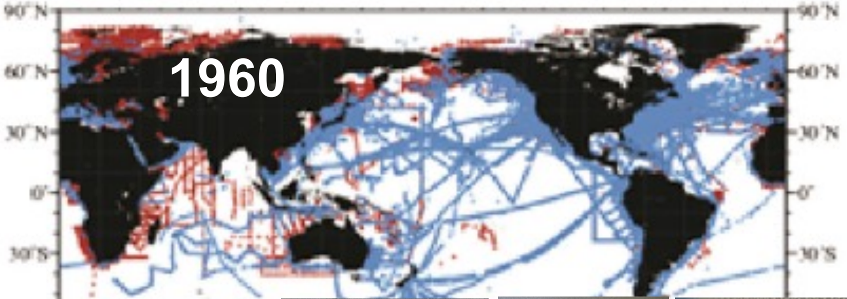
$$SL_{steric} = SL_{total} - SL_{mass}$$

3

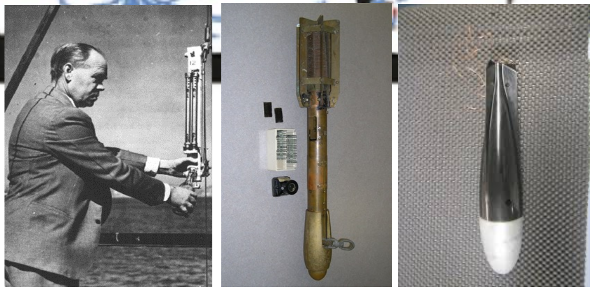
OCEAN REANALYSES

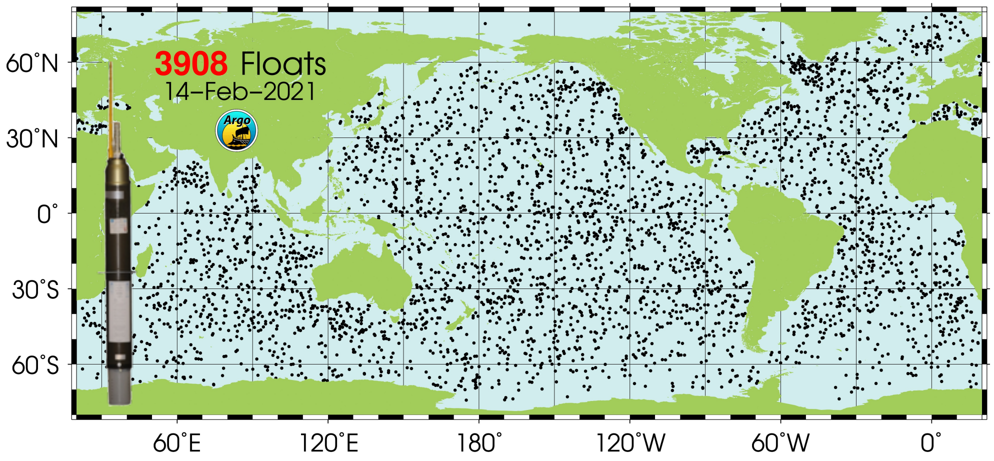


GLOBAL OCEAN IN SITU TEMPERATURE MEASUREMENTS



Abraham et al., 2013





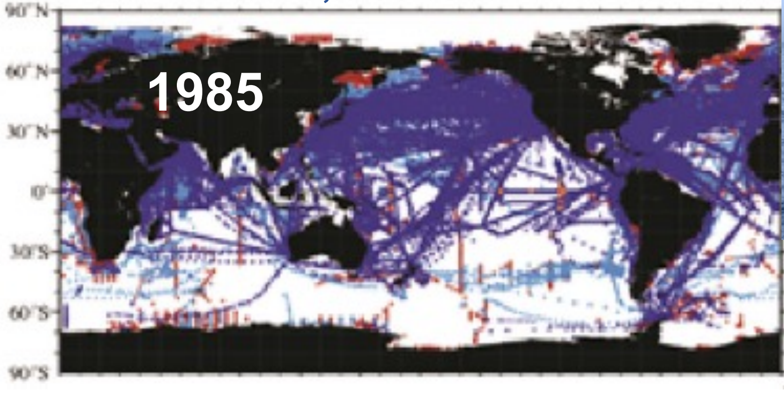
< 1950

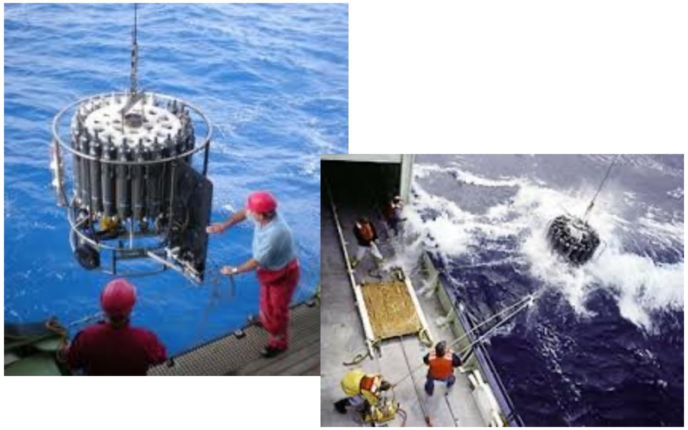
2000

ARGO ERA

ERA OF HISTORICAL MEASUREMENTS

Abraham et al., 2013

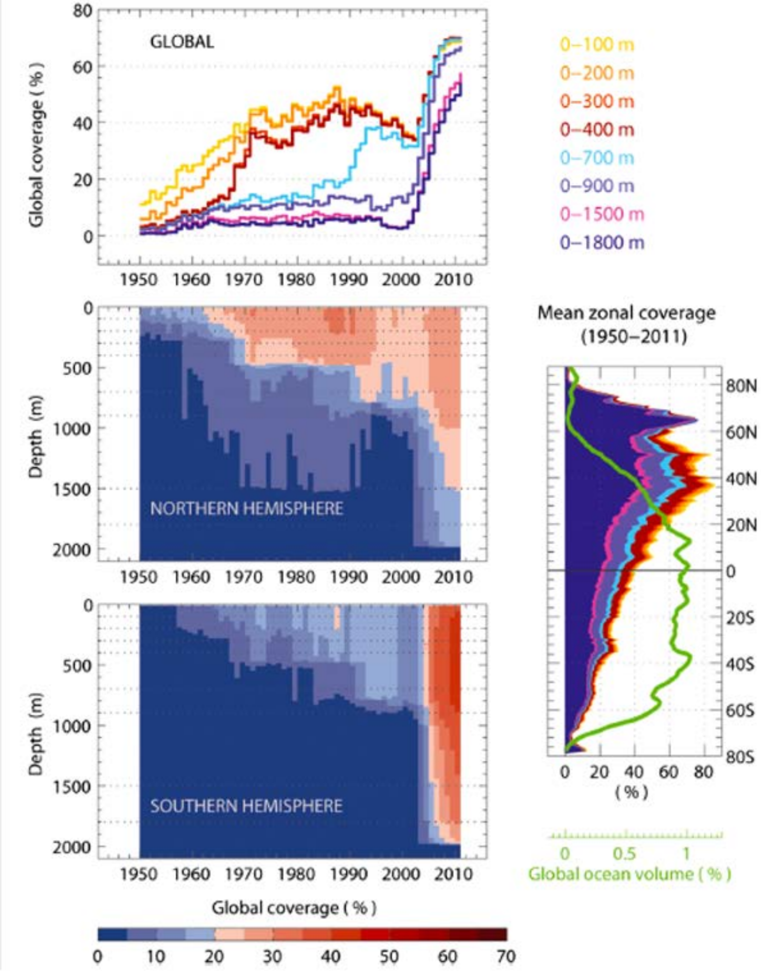




THE GLOBAL OCEAN HEAT CONTENT: DIRECT ESTIMATE

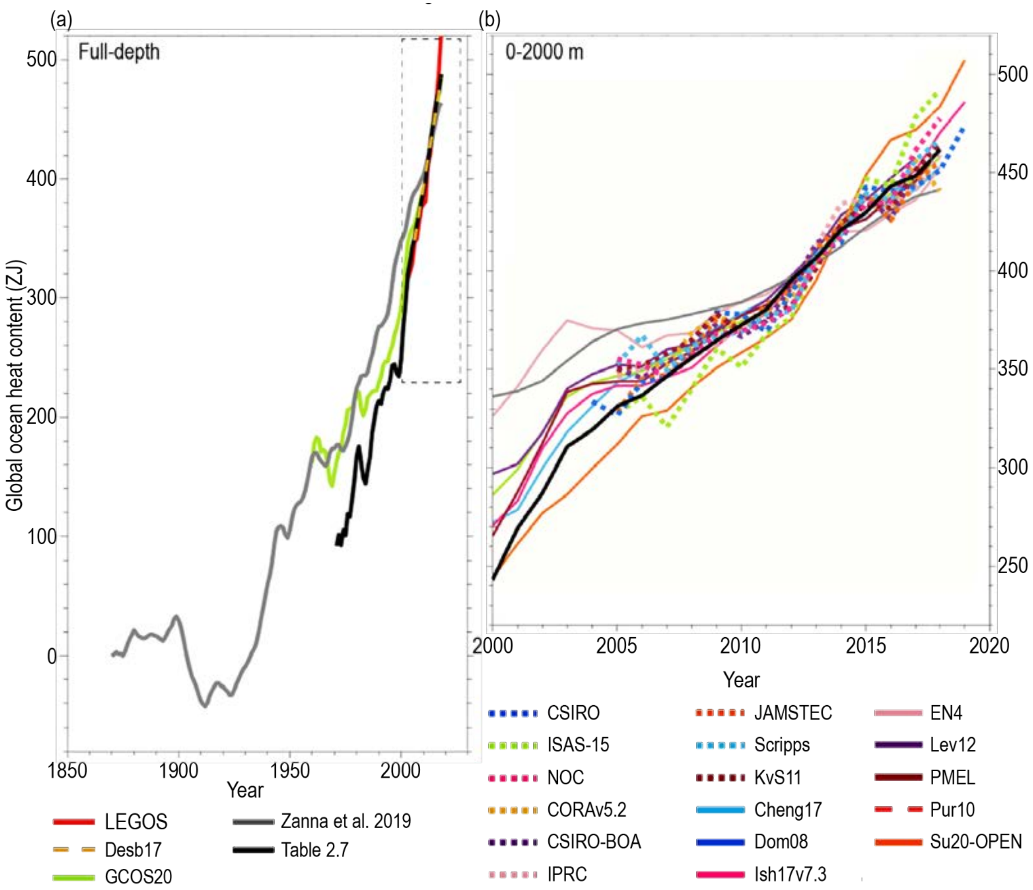
All estimates show a multi-decadal increase in OHC, albeit differences occur between analyses due to mapping, bias correction, baseline climatology & data quality

→ SAMPLING



Abraham et al., 2013

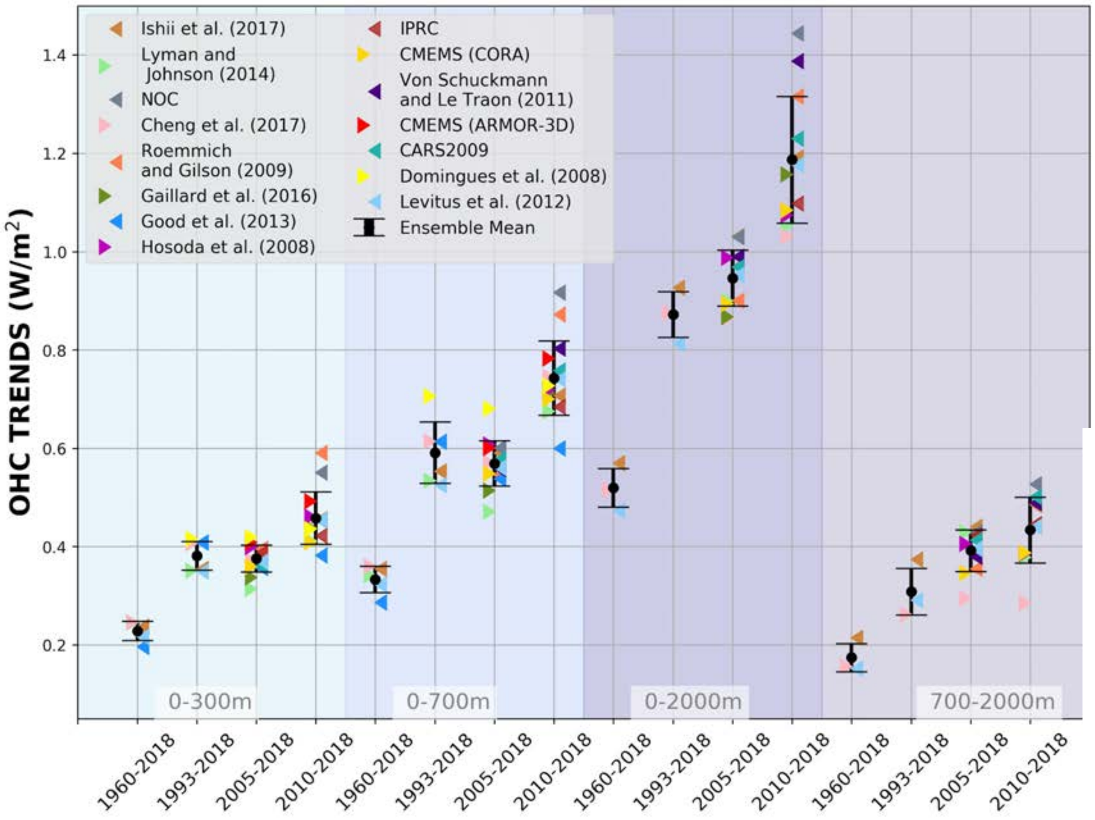
→ GLOBAL MEAN OHC ESTIMATES



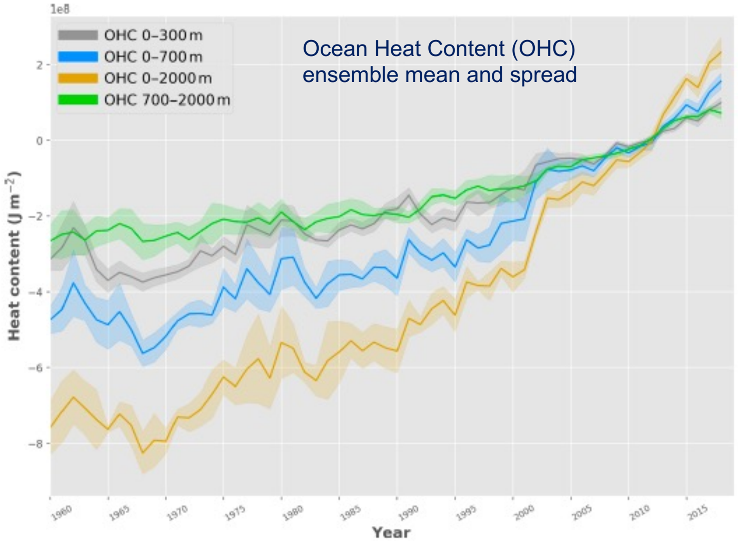
IPCC, AR6, Chapter 2 (Gulev et al., 2021)

GLOBAL OCEAN WARMING: A CONCERTED INTERNATIONAL APPROACH

New assessment based on 15 different international in situ based products to obtain an ensemble mean and spread of global mean ocean heat content to estimate ocean warming



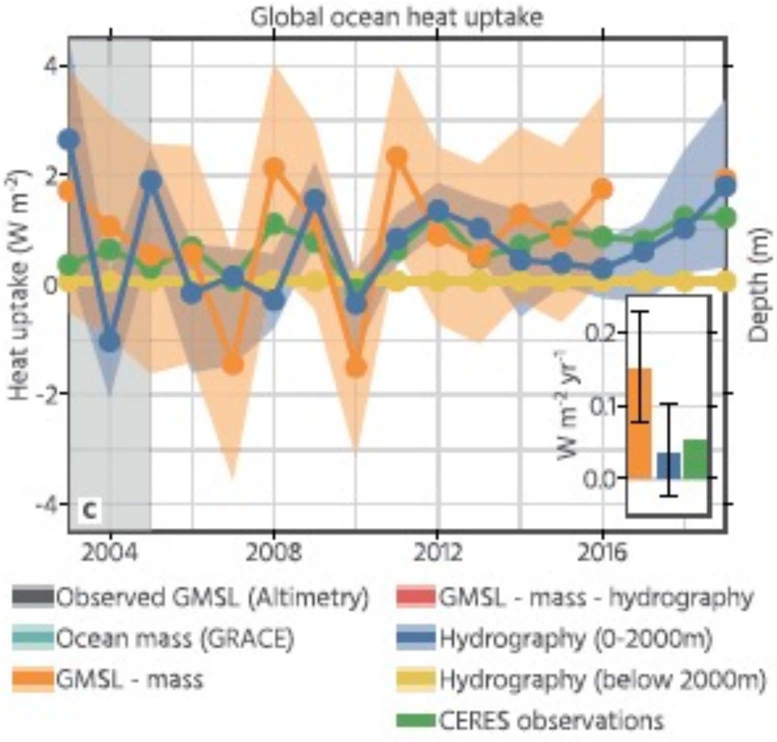
International ensemble mean & spread



von Schuckmann et al., 2020

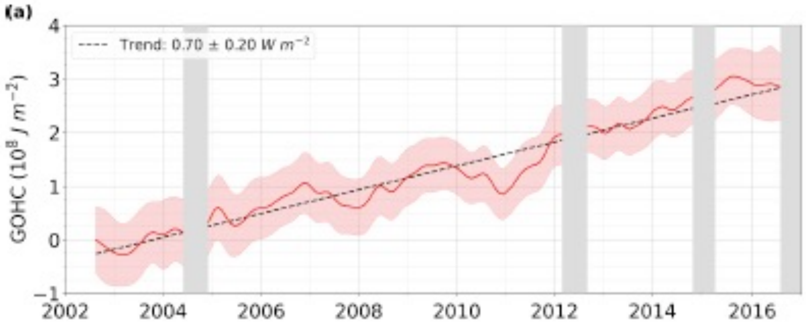
THE GLOBAL OCEAN HEAT CONTENT: INDIRECT ESTIMATE

Global estimates of OHC benefitting from the sea-level budget approach

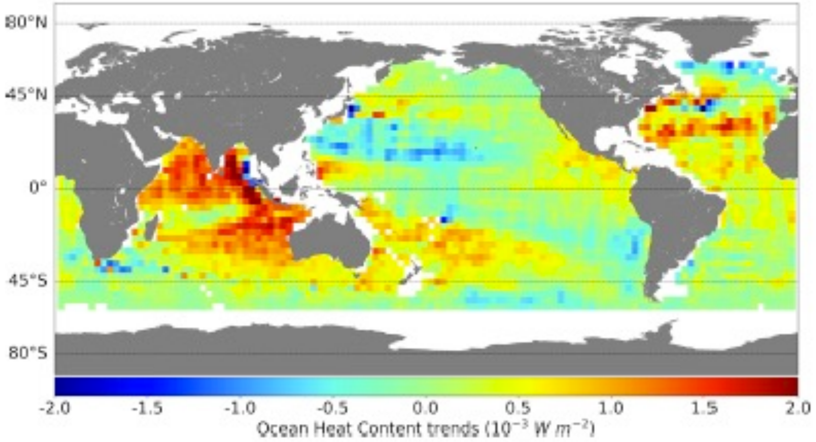


Hakuba et al., 2020

Global full-depth OHC (indirect estimate)



Regional full-depth OHC (indirect estimate, Aug. 2002-Aug. 2016)

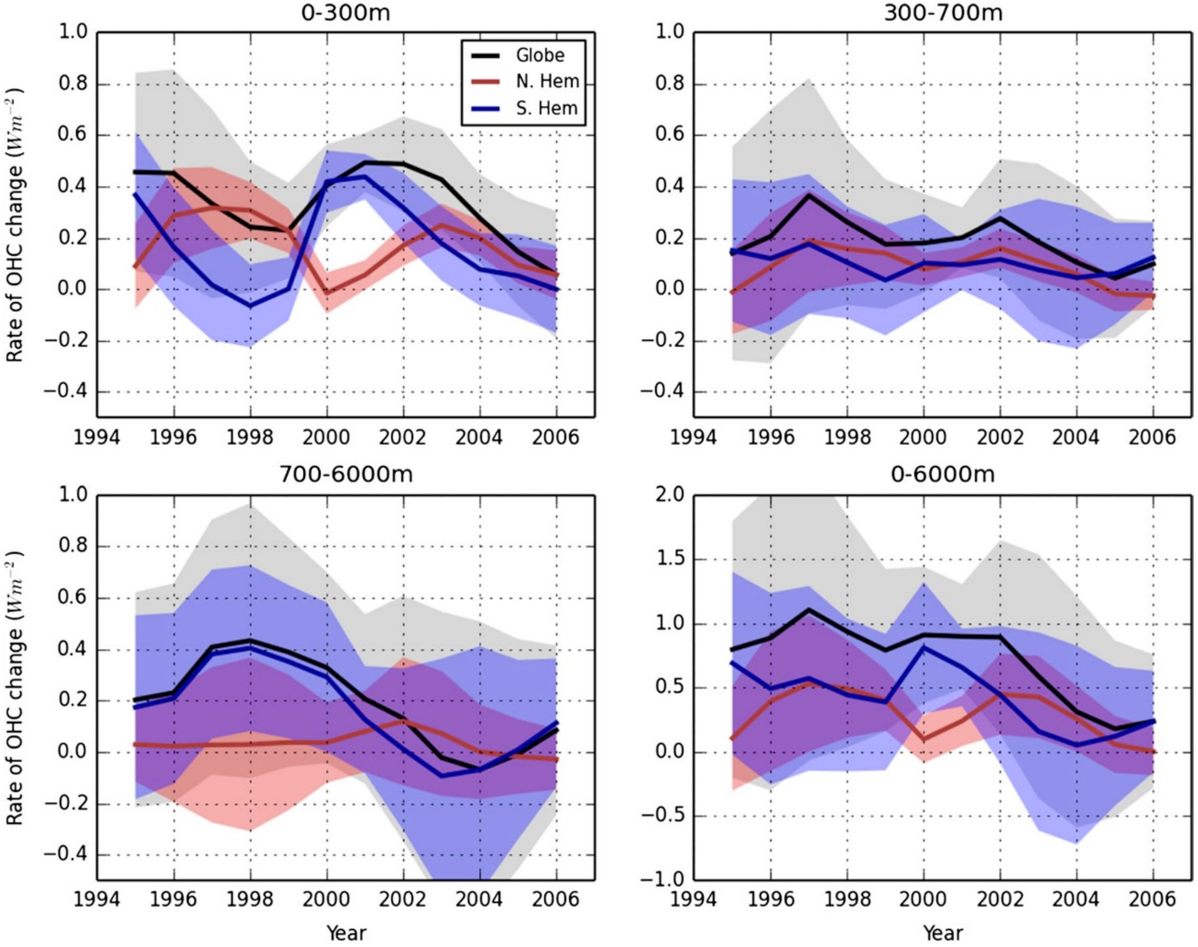


Marti et al., 2022

GLOBAL OCEAN WARMING: RESULTS FROM OCEAN REANALYSES

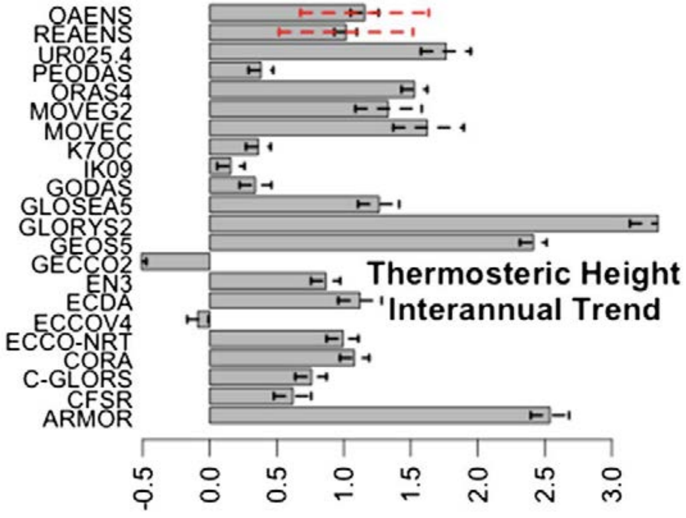
ORA-IP: Global OHC well constraint in the upper layer, less well at deeper levels, and large uncertainties remain for the inter-annual trends

Global mean OHC (ensemble mean) 1993–2009

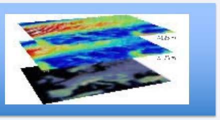


Palmer et al., 2017

Thermosteric sea level interannual trends1993–2010



Storto et al., 2017

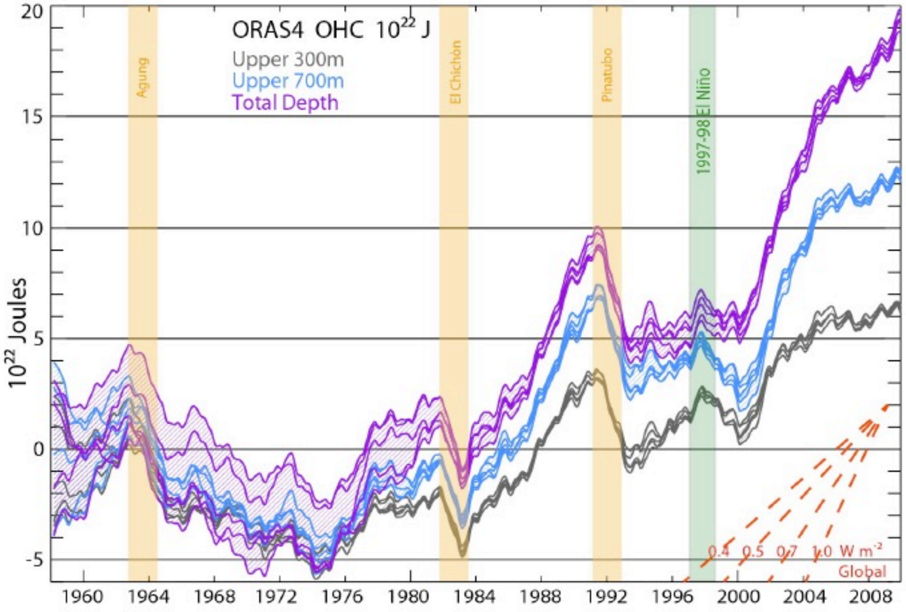


GLOBAL OCEAN WARMING: RESULTS FROM OCEAN REANALYSES

Global estimate from ORAS4 – constraint climate signals in full-depth OHC:

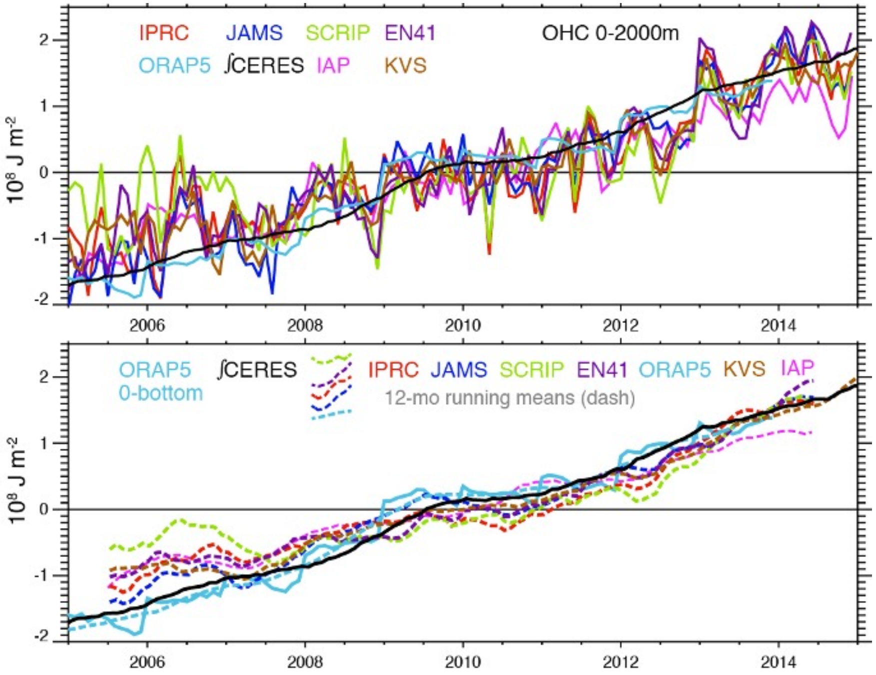
Vertical redistribution, and OHC variations (eg volcanic eruptions) resolved in this estimate

Global OHC integrated over different layers



Balmaseda et al., 2013

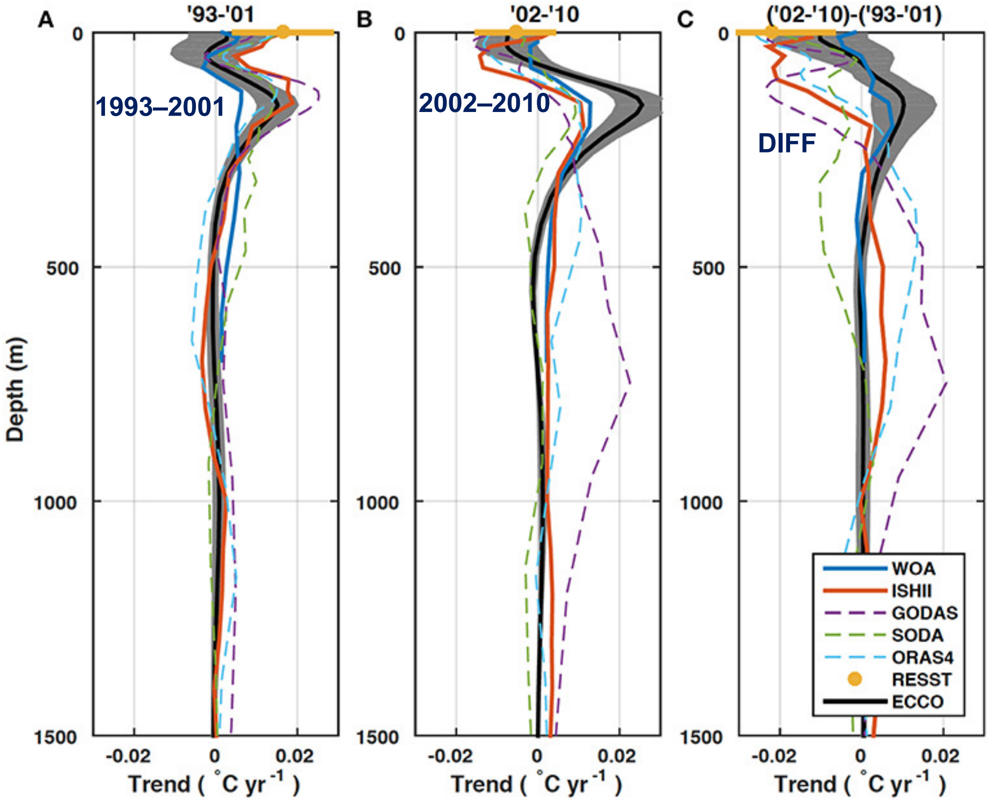
Global OHC & Argo & CERES net flux



Trenberth et al., 2016

ECCO – Estimating the Circulation and Climate of the Ocean

Decadal trends in global mean potential temperature



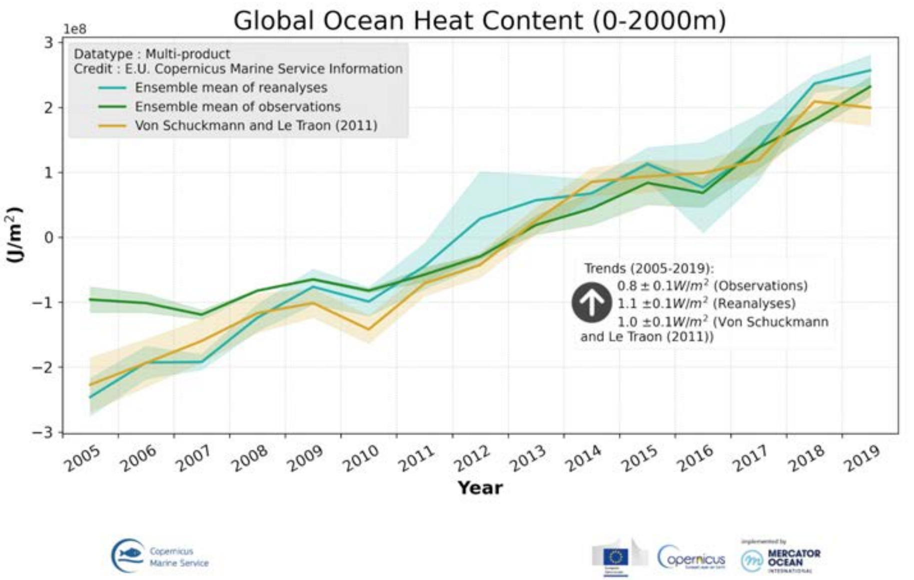
Heimbach et al., 2019

- ECCOv4 shows a credible fit to hydrography trends over much of the depth range 0–1,500 m.
- ECCOv4 also reproduces the apparent slowdown in surface temperature trends as compared to an optimally interpolated blend of *in-situ* and satellite SST data.

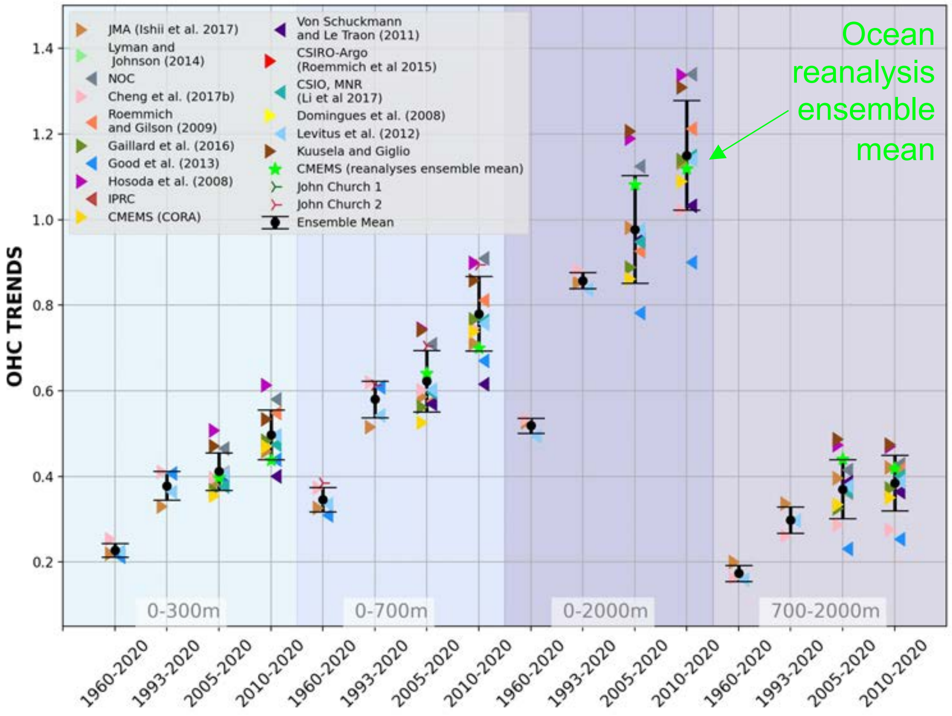
GLOBAL OCEAN WARMING: RESULTS FROM OCEAN REANALYSES

Copernicus Ocean Monitoring Indicators

Global OHC from observations and different global ocean reanalyses



https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/global-ocean-heat-content-0-2000m

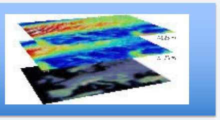


Ocean reanalysis ensemble mean

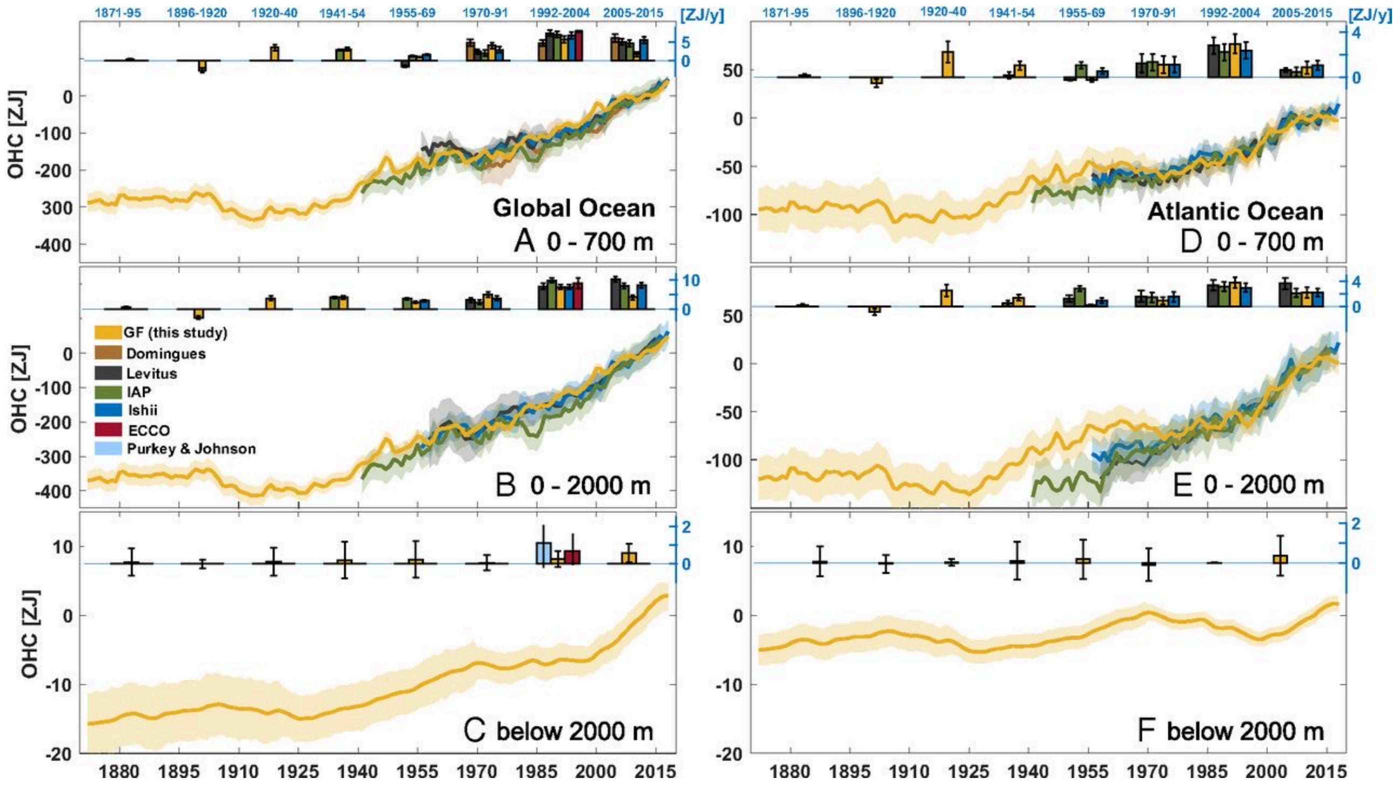
von Schuckmann et al., 2022, in prep.

Good agreement between observations and ocean reanalysis (ensemble mean of 3 global reanalyses (GLORYS, CGLORS, ORAS)

GLOBAL OCEAN WARMING: RESULTS FROM OCEAN REANALYSES



Reconstruction of ocean temperature changes with global, full-depth ocean coverage: Use of Green's function from ECCO GODDAE ocean state estimate (1992-2014) to connect surface properties from measured SST with those in the ocean interior



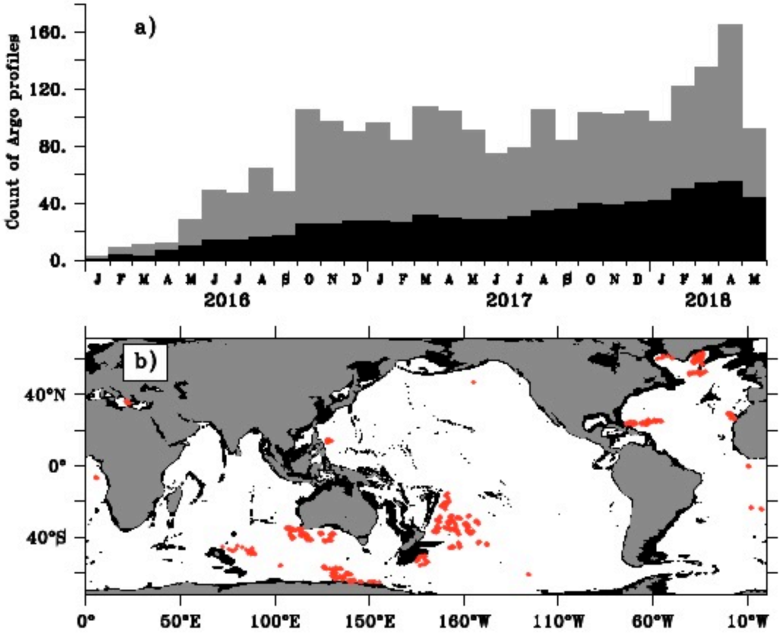
Zanna et al., 2019

Since the 1950s, up to one-half of excess heat in the Atlantic Ocean at midlatitudes has come from other regions via circulation-related changes in heat transport.

OCEAN REANALYSES – Ocean Observing System recommendations

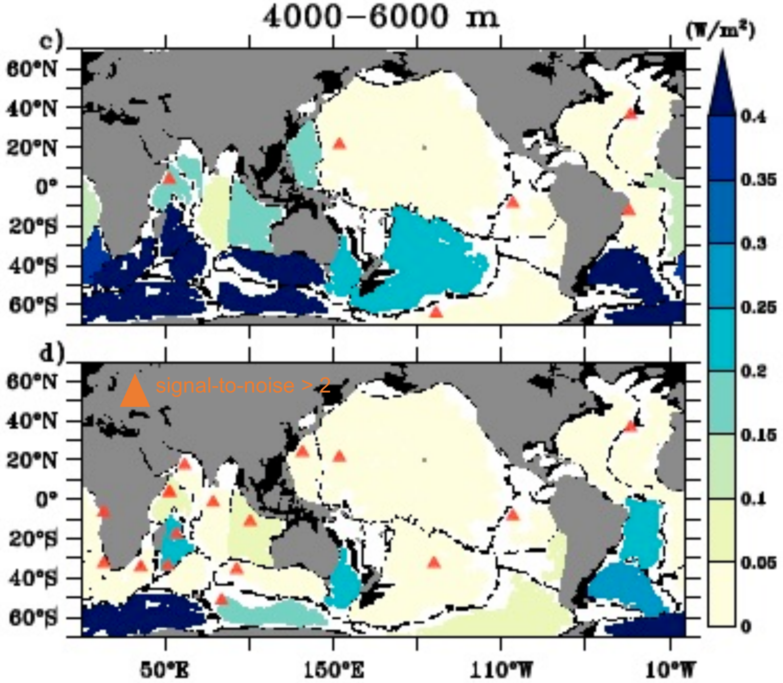
How does a global deep Argo array (5°x 5°x 30 days) will impact ocean reanalyses ?

Count of deep Argo **profiles** & **floats** from deep Argo pilot arrays, and their **location**



Current Obs. system →

Current Obs. system + global deep Argo array →

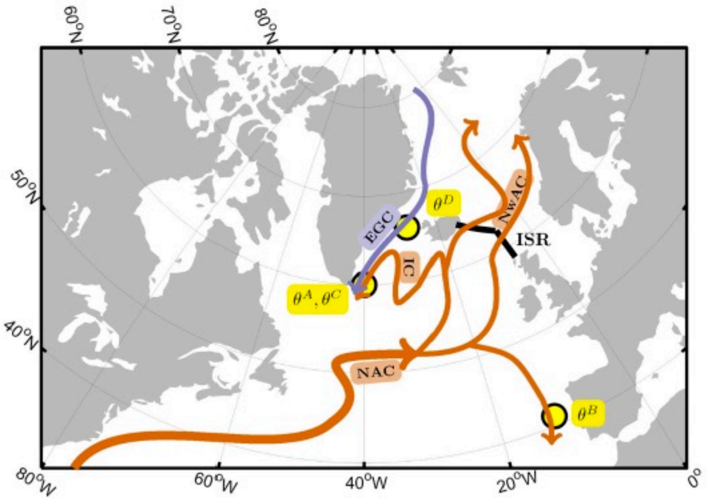


Gasparin et al., 2020

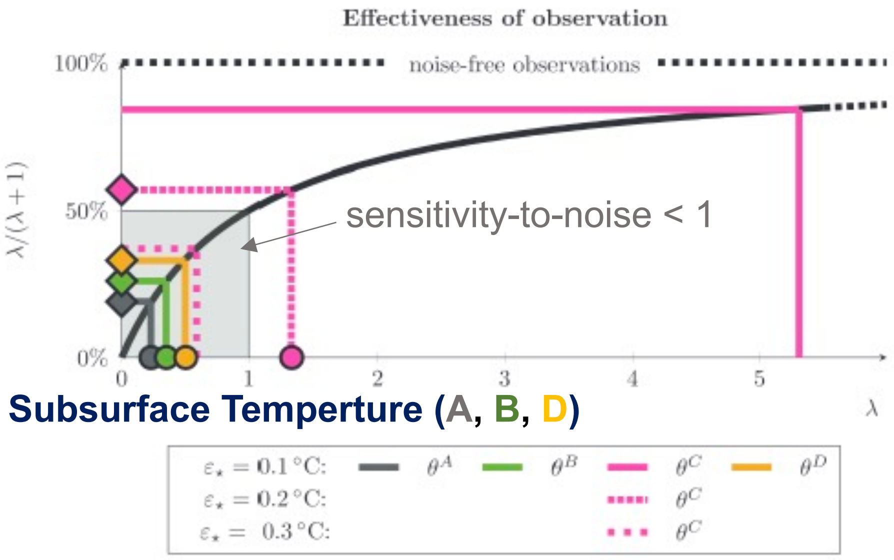
Results based on observing system simulation experiments (OSSE) study suggests that a global deep Argo array of 1200 floats will significantly constrain the deep ocean by reducing temperature and salinity errors by around 50%

OCEAN REANALYSES – Ocean Observing System recommendations

Uncertainty quantification within the ECCO framework: design strategy for an effective ocean climate observing system – Case study for North Atlantic regional heat content and transport



Location of experiment tracers



sensitivity-to-noise < 1

Subsurface Temperture (A, B, D)

Loose & Heimbach, 2021

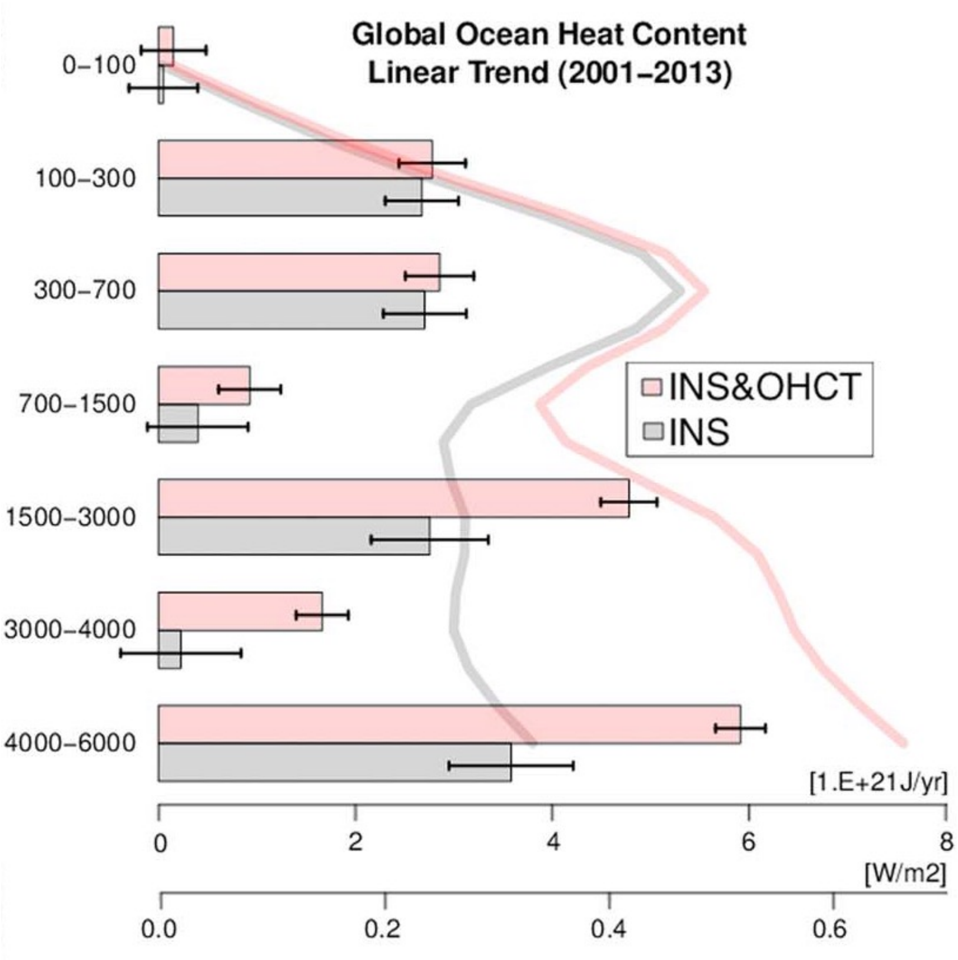
Sea Surface Temperature (C)

➔ Sea surface temperature observations inform mainly local air-sea fluxes

➔ Subsurface temperature observations reduce uncertainties over basin-wide scale, informing heat redistribution at great distances

OCEAN REANALYSES – assimilation of net flux at TOA

Constraining the Global Ocean Heat Content through assimilation of CERES-derived TOA energy imbalance estimates

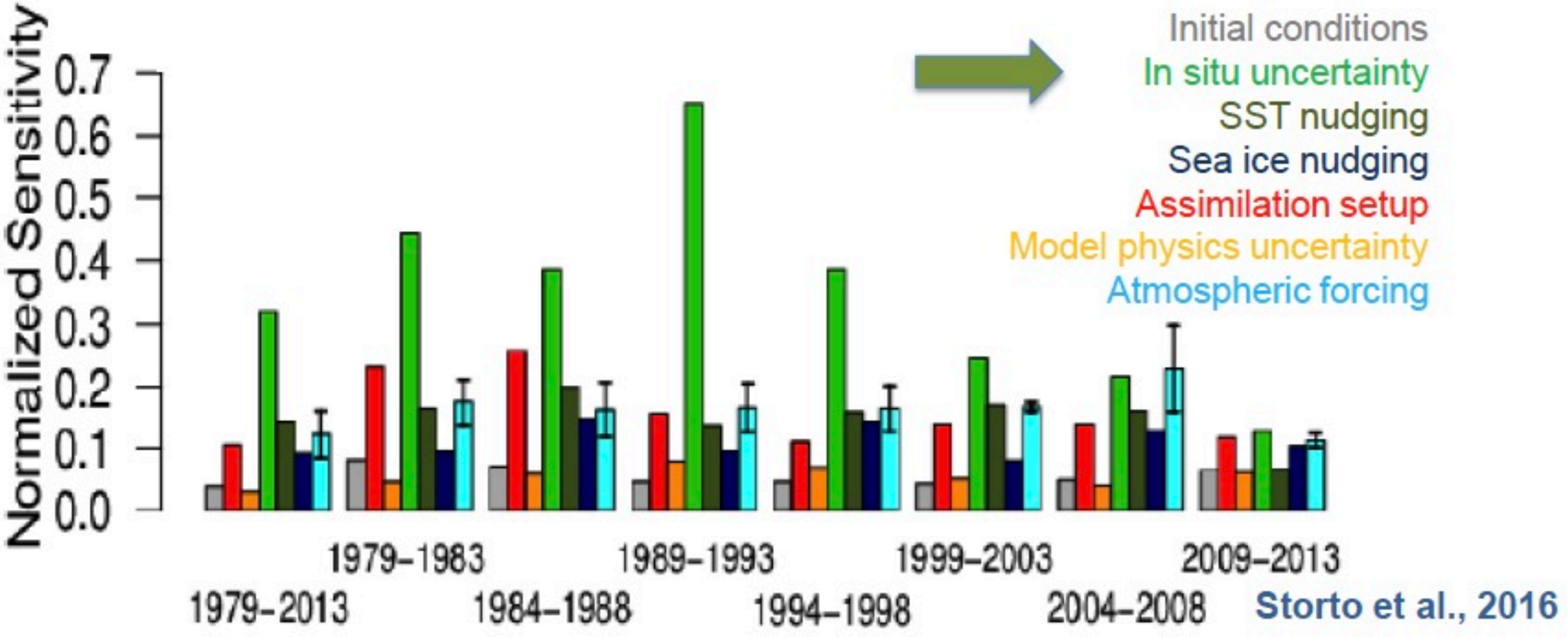


Storto et al., 2017

- The methodology proves able to shape heat content trends, without compromising the reanalysis accuracy.
- Spurious variability and biased estimates disappear when EEI data are assimilated.
- The representation of the warming hiatus present improves in accordance with recent studies.

OCEAN REANALYSES – assimilation of net flux at TOA

Sensitivity of global ocean heat content from reanalyses to the atmospheric reanalysis forcing



Storto et al., 2016

Bias correction and preprocessing of in situ observations represents the most crucial component of the reanalyses, whose perturbation accounts for up to 60% of the ocean heat content anomaly variability in the pre-Argo period

SOME TAKE AWAYS ….

The global scale estimate of heat in the ocean provides a crucial measure of the rate of climat change, and defines the prospects for continued global warming

The accumulation of thermal energy in the Earth system is the root cause of the various facets of observed climate change

There is an urgend need to further unravel the processes of heat sequestation in the ocean, to reduce uncertainties in our estimates and to assess regional implications

Concerted international efforts including the use of ocean reanalysis are a promising tool facing these challenges, and to foster advancements in climate science – such as for example heat budget closure at regional scale, and guiding observing system developments

OCEAN REANALYSES – some recommendations…

with contribution from M. Drevillon, G. Garric

1.) Future advancements:

- A digital Earth system with assimilation or consideration of observations in all compartments of the geophysical components: ocean, atmosphere, lithosphere, cryosphere, biosphere.
- Constraining additional data sources, such as ocean mass from GRACE, GRACE-follow on, CERES net flux
- Generalization of ensemble reanalysis together with multi-model products.
- High-resolution developments (1/12°) not only for physical components, but also for biogeochemical variables, waves and sea ice.
- Advancements for regional downscaling, which will amongst others also improve the representation of extreme events, and support guiding sustainable adaptation measures
- Strengthened role for informing observing system design

2.) Barriers:

- Historical observations: lack of data before the 1990
- A network of observations that is heterogeneous both in space and time, e.g. strong impact of ARGO -> regime change in 2004
- Boundary conditions: the boundary conditions with the atmosphere and with the continents are currently posing challenges to close the heat and mass balances of the global ocean.

OCEAN REANALYSES – some recommendations…

with contribution from M. Drevillon, G. Garric

3.) Collaborations:

- Continuation and refinement of ORA-IP like international initiative, including a common set of reference metrics
- Further strengthen the analysis of reanalysis data in climate science
- The modelling/assimilation value chain: how can the improvements provided by assimilation be better taken into account by the modelling community?

4.) Observing system:

- Maintenance of the current observing system, and extension into undersampled areas (eg for global OHC: deep ocean, marginal seas and shallow areas, polar areas)
- Better use of existing observations data sets either satellite or in situ data: a need of single access to in situ data (blue, green, white), a need in better use of L2 and L3 existing satellite data; towards assimilation of L1 data and closer collaboration with R&D teams elaborating spatial data base.

THANK YOU

Any questions?

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