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MARINE

# Ocean reanalyses and their use in ocean and climate

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**Headquarter (VENICE)**



**8 Branch Research Centres**



**311 Staff members**

- **179** Researchers and technologists, **42** technicians and **9** administrative
- **46** research grants and 19 and Ph.D students
- **27** associates

Fundamental and Applied Research in physical, chemical, biological oceanography and marine geology



**TOTAL GENERAL BUDGET (2024) 54.389.312,67 €**

## Our ocean and climate group:

- 8 Ph.D students
- 2 postdocs
- 1 project manager
- 2 visitors

## Research Projects

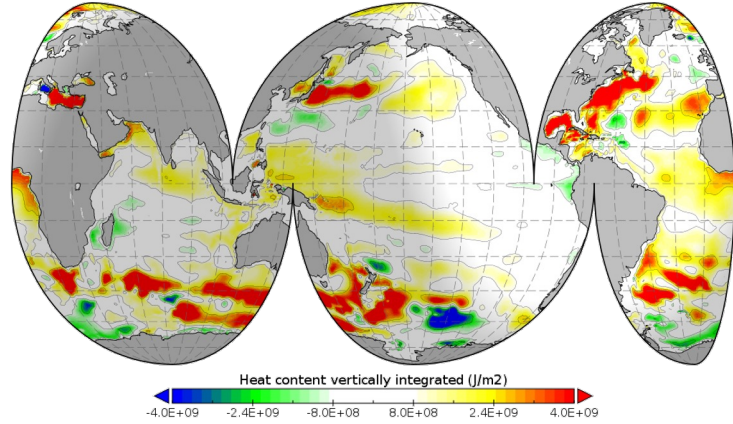
- Copernicus Climate and Marine Services (GLO-RAN Lot 1, Lot 3, C3S2\_520, C3S2\_601\_bis, ORACS, F3O, DE\_374)
- ESA Projects (XHEAT, ESA-CCI heat fluxes, ESA-CCI SLBC)
- Horizon Europe (COMEDI, ACCIBERG)

## Research Topics:

- Ocean modelling and data assimilation (e.g. global and regional reanalyses, data assimilation schemes)
- Ocean and climate dynamics (e.g. meso-scale eddies, North Atlantic ocean dynamics, extreme events)

## Global Ocean models

Heat content vertically integrated  
2021 anomaly (1961-2020 climatology)



**NEMO 4.0.7**  
**ORCA1 (1°) L75 - ORCA025 (1/4°) L75**  
Forced by ERA5 or 20CRv3

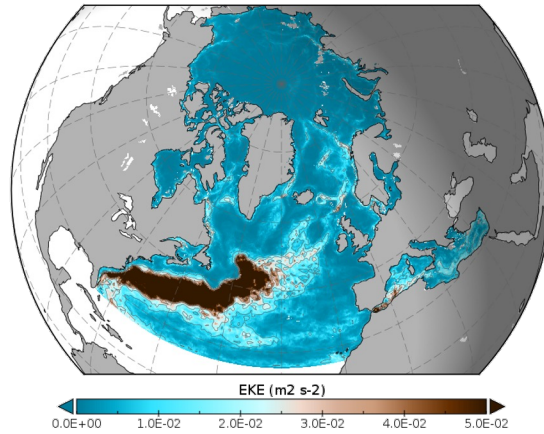
Data assimilation enabled:  
Variational DA in the ocean

Applications  
Historical ensemble reanalyses  
Land-sea coupling experiments

Storto, A., Yang, C. Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. Nat Commun 15, 545 (2024).

## Regional models

Eddy kinetic energy



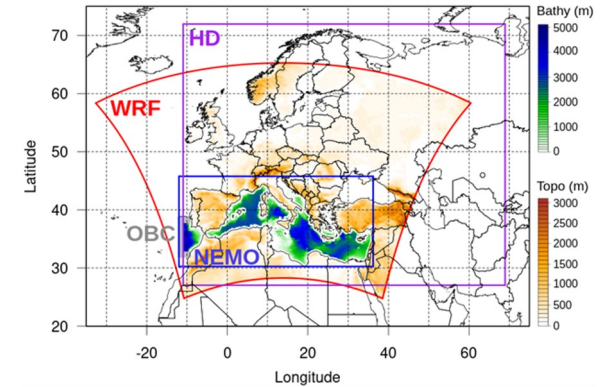
**NEMO 4.0.7**  
**CREG025 (1/4°L75) CREG12 (1/12°L75)**  
**CREG36 (1/36°L75)**  
Forced by ERA5/GLORYS12

Data assimilation enabled:  
Variational DA in the ocean

Applications  
Interannual variability in the NA  
Stochastic physics developments  
DA developments (e.g. new obs types)

Storto A and Yang C (2023) Stochastic schemes for the perturbation of the atmospheric boundary conditions in ocean general circulation models. Front. Mar. Sci. 10:1155803

MESMARv1 regional climate model domain

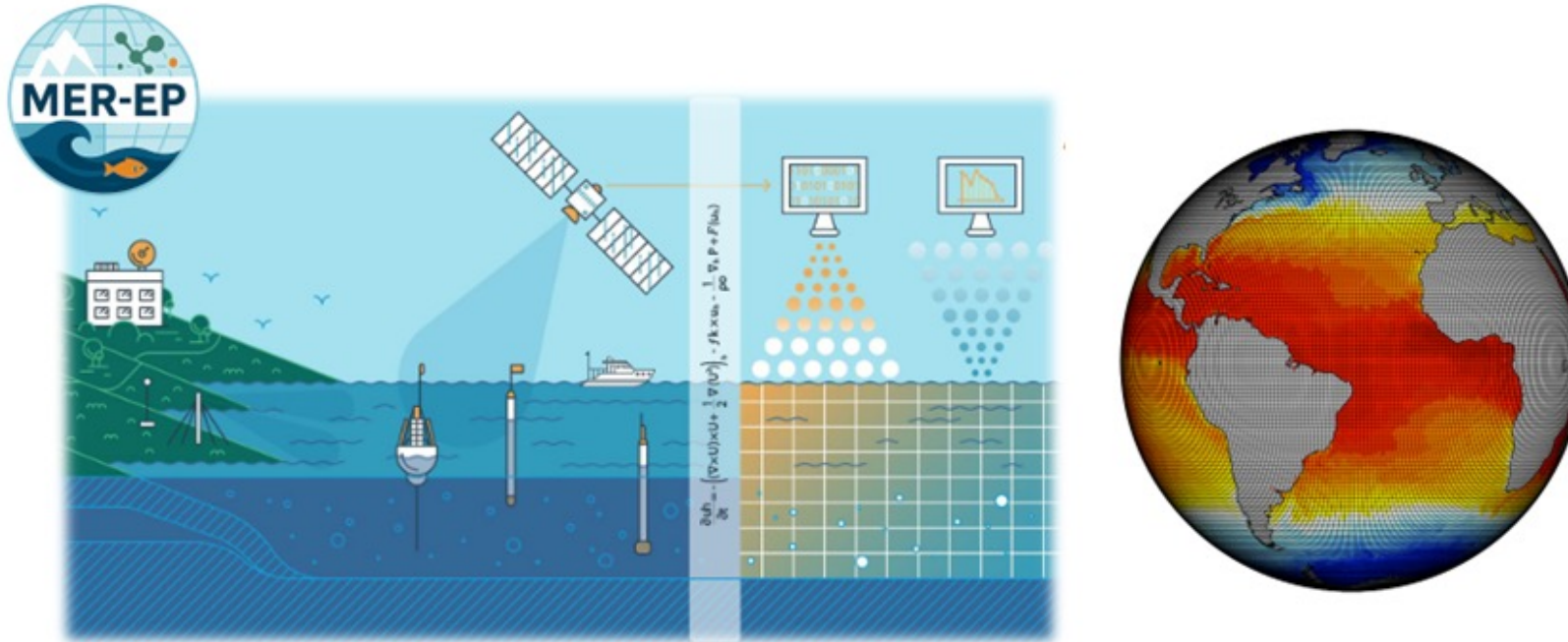


**NEMO 4.0.7 (7kmL72)**  
**WRF 4.3.3 (14kmL41)**  
**HD 5.1 (1/12°) OASIS3-MCT 5.0**  
Forced by ERA5/ORAS5 laterally

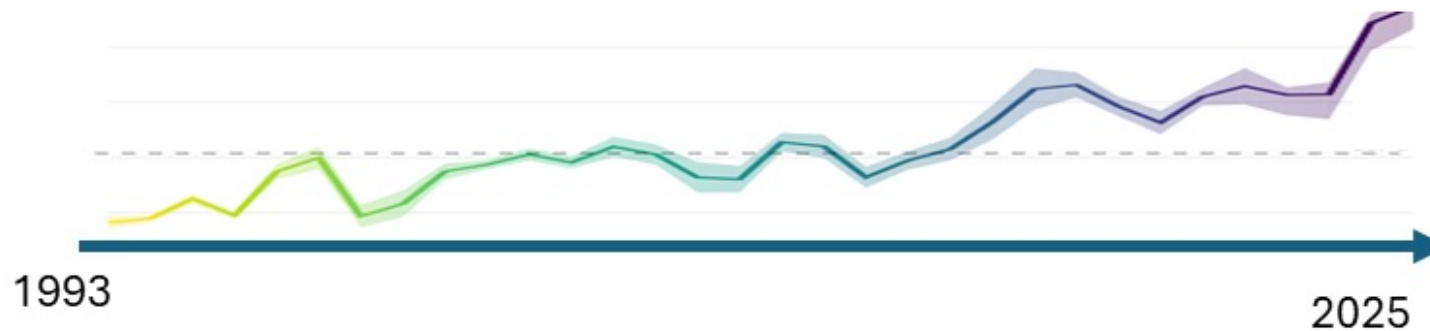
Data assimilation enabled:  
Variational DA in the ocean  
Spectral nudging (~800km) in the atmosphere

Applications  
Coupled DA  
Air-sea interaction (skinSST schemes)  
Storto, A., ..., Sannino, G., Santoleri, R., ...: MESMAR v1: a new regional coupled climate model for downscaling, predictability, and data assimilation studies in the Mediterranean region, Geosci. Model Dev., 16, 4811–4833

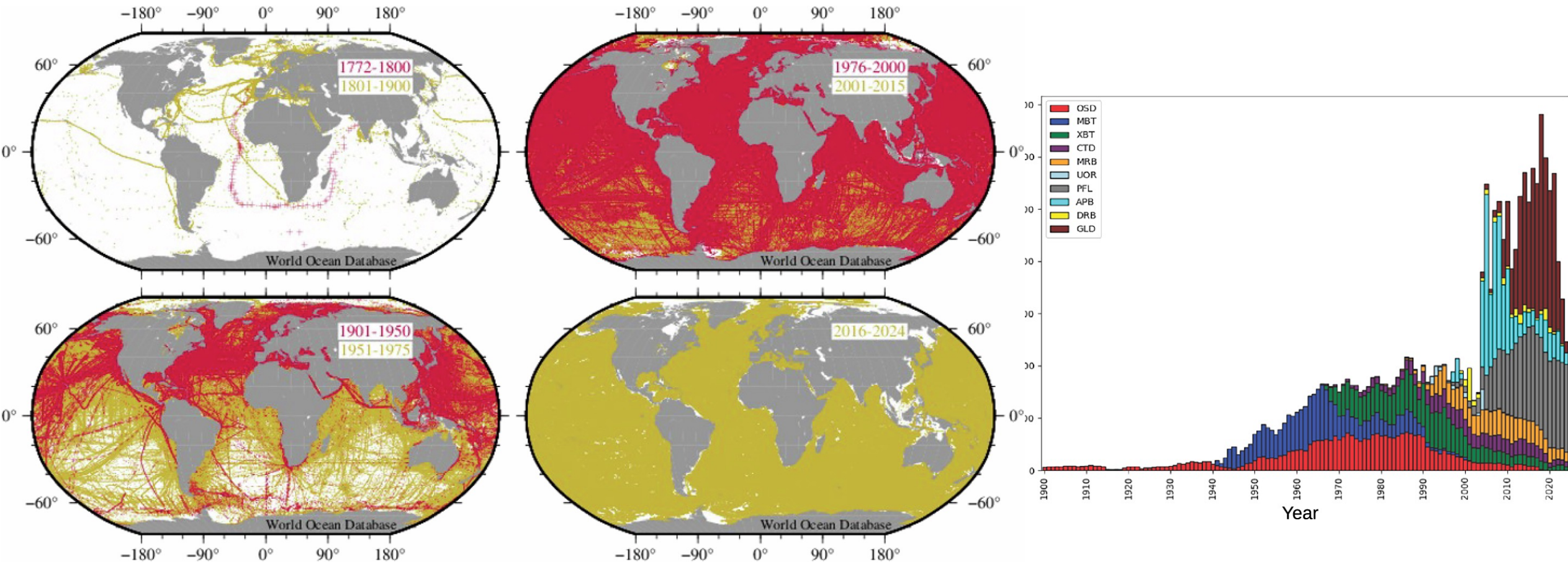
Ocean Reanalyses are the reconstruction of the past of ocean state.



- Ocean models
- Ocean observations
- Data assimilation schemes

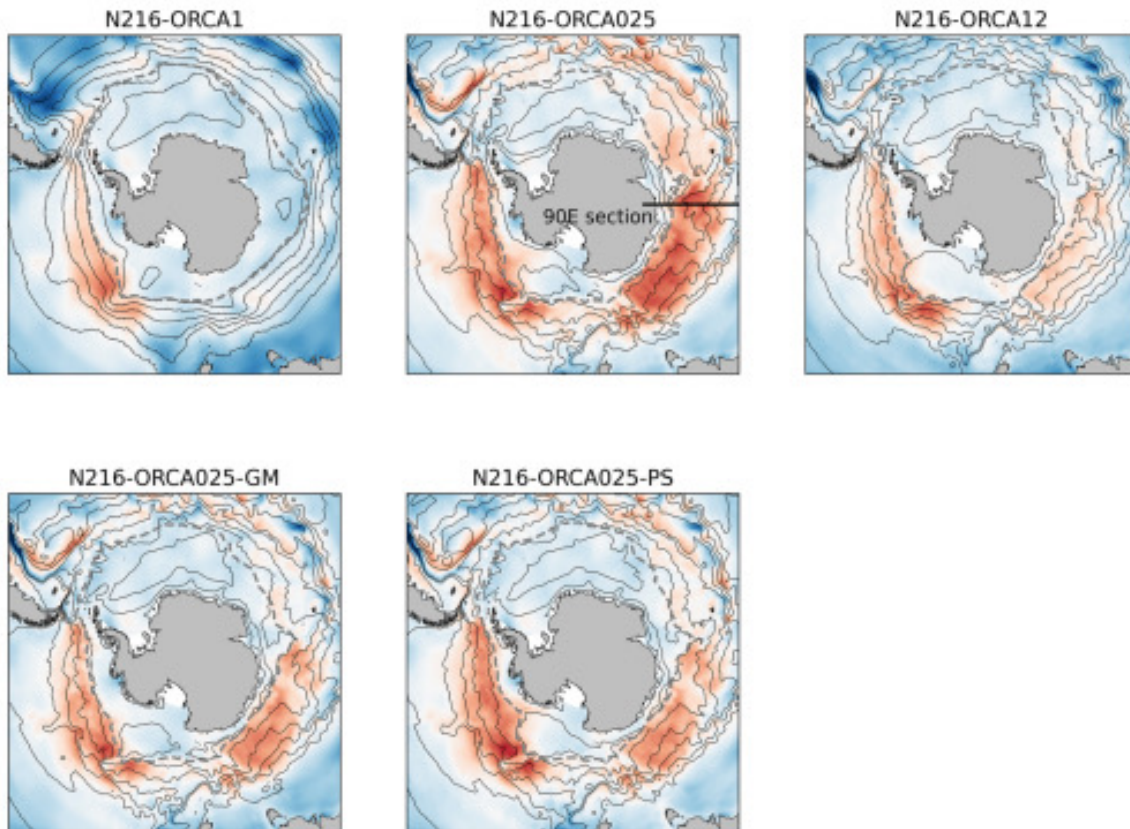


# Why do we need?

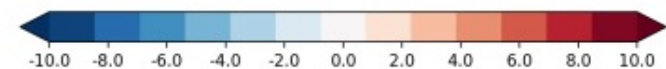
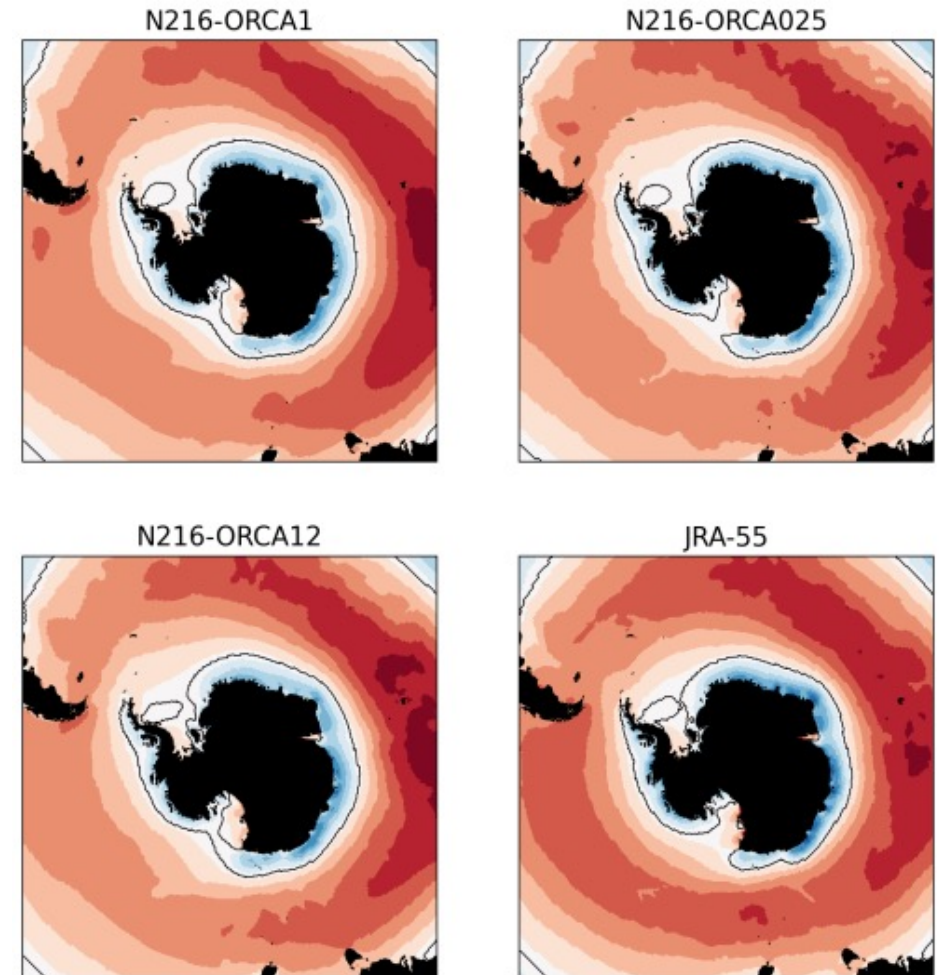


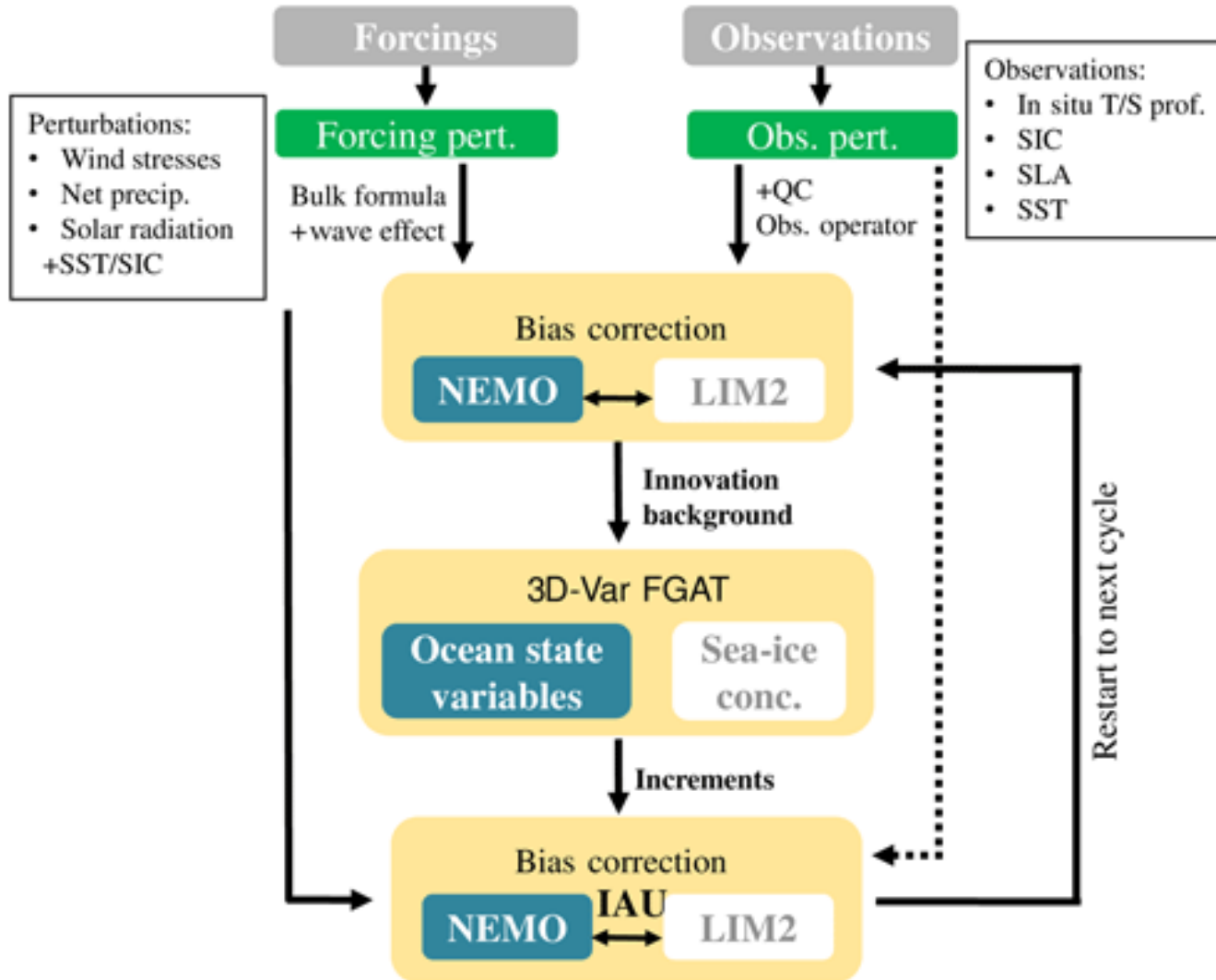
Garcia et al., 2026

## SST Anomalies



## Zonal Winds





Zuo et al., 2019

## *Methods for ocean climate monitoring (e.g. ocean warming)*

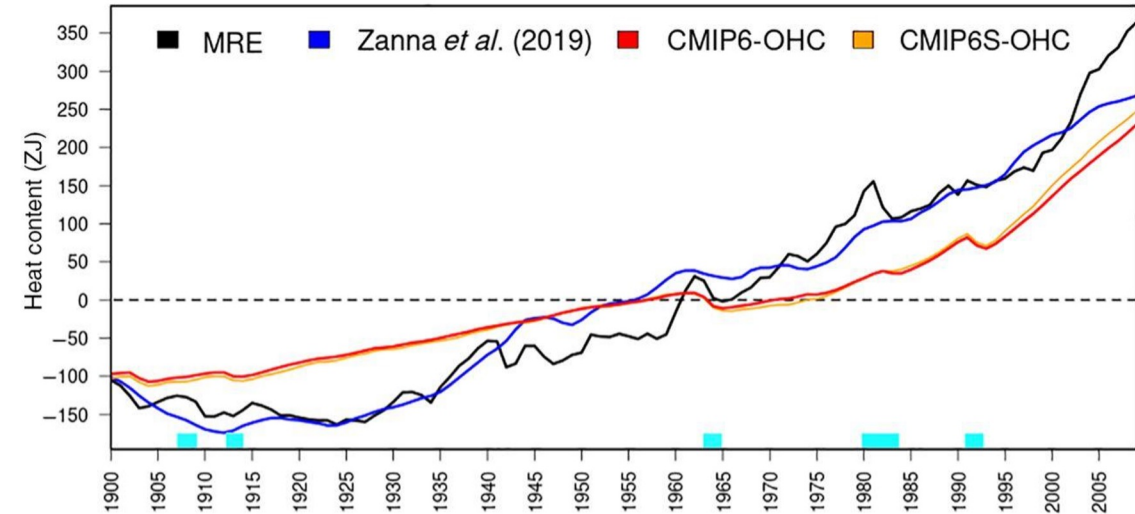
- Statistical mapping (objective analyses)
- CMIP simulations
- OMIP simulations
- **Reanalyses**
- Proxy data (e.g. O<sub>2</sub> & CO<sub>2</sub>)
- Indirect remotely sensed data (geodetic approach; acoustic measurements)
- AI reconstructions from sea surface data or sparse data

Reanalyses:  
Value for historical investigations

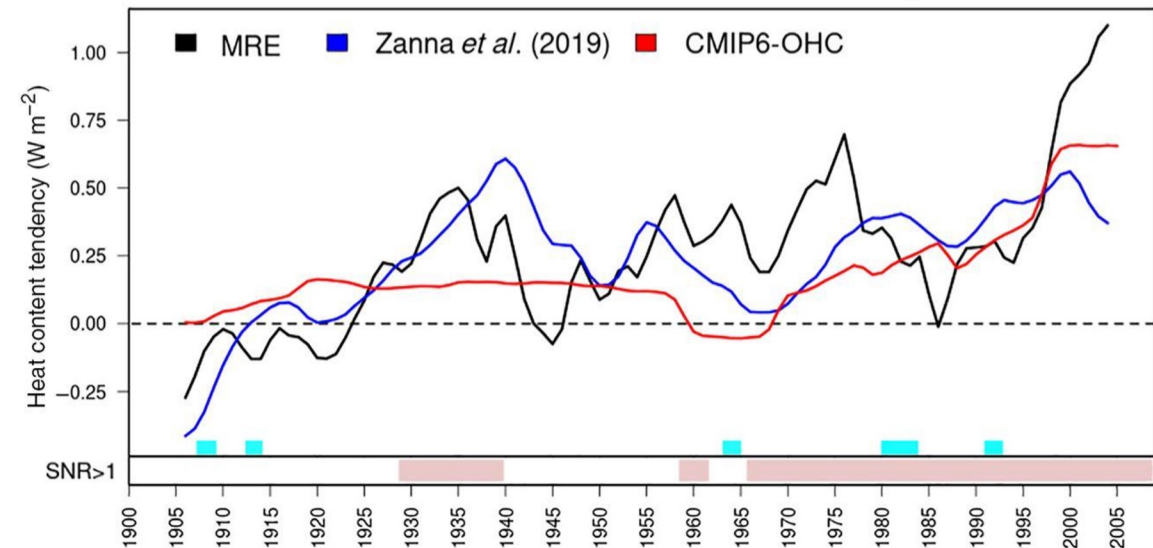
Use of multi-system historical  
ensemble system

(4 families, 16 members)  
CHOR, ORA20C, CERA20C, SODA

Global ocean heat content anomaly



Global ocean heat content tendency





**ORCA1 → ORCA025:**  
 $4^3=64$  CPU increase

## *The ensemble historical reanalysis system (CIGAR)*

- Moderate resolution (ORCA1,  $1^\circ$  with  $1/3^\circ$  increase in the Tropics, 75 levels)
- Relatively large ensemble (32 to 48 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 (1st iter)
- Air-sea flux corrections (nudging to SST, SSS)
- Deep-ocean large-scale bias-correction w.r.t. AI-based yearly mean reconstructions (ARANN)
- Model tendency correction with climatological analysis increments
- Realistic discharge into the ocean (daily discharge from JRA55-do)

**Contemporary period**  
1960-2022  
(ERA5 reanalysis forcing)

*Completed (published)*

Storto, A., Yang, C. Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. Nature Commun. 15, 545 (2024).

**Historical period**  
1860-2015  
(20CRV3 reanalysis forcing)

*Completed (under evaluation)*

## ***The ensemble historical reanalysis system (ENS-REA)***

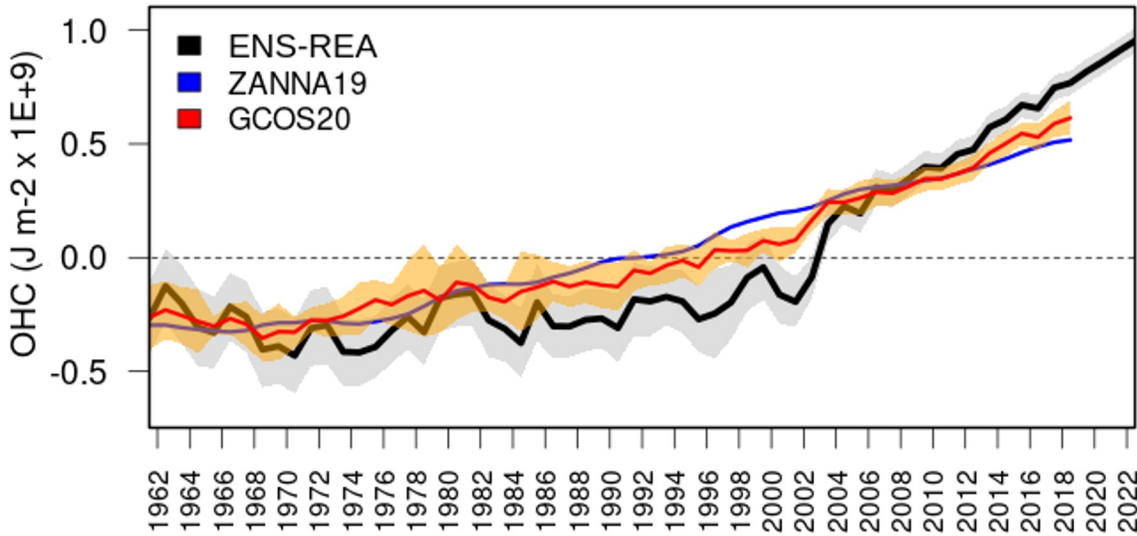
- Perturbation of atmospheric forcing
  - Multiple ensemble anomalies from ERA5 selected through clustering OR different 20CRv3 members
- SST Surface nudging
  - Multiple SST datasets (UKMO HadISST and COBE SST, and ERSST)
- In-situ observations
  - Multiple in-situ observation datasets (different MBT/XBT drifts OR EN4, IQuOD)
- Initial conditions
  - Multiple Lagged initial conditions from prototypical runs
- Bulk formulas for air-sea flux
  - Multiple 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  $\sim \mathcal{N}(0, \sigma_{\text{rep}}^2)$

Name	Institute	Resolution	General information
C-GLORSv8	CMCC	1/4°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> NEMO4.2</li> <li>• <b>Forcing field:</b> ERA5</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; sea ice concentration; in situ</li> </ul>
CIGAR-CS	CNR-ISMAR	1°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> NEMO4.2</li> <li>• <b>Forcing field:</b> ERA5</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; sea ice concentration; in situ</li> </ul>
ECCOV4r4	MIT	1/4°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> MITgcm</li> <li>• <b>Forcing field:</b> ERA Interim</li> <li>• <b>Assimilation method:</b> 4D-Var</li> <li>• <b>Assimilated data:</b> SSH (ERS-1/2, TOPEX/Poseidon, GFO, ENVISAT, Jason-1/2/3, CryoSat-2, SARAL/AltiKa); SST (AVHRR); SSS (Aquarius); OBP (GRACE); sea ice; in situ (CTD, XBT, Argo)</li> </ul>
JCOPE-FGO	JAMSTEC	1°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> quasi-Global (75S-75N)</li> <li>• <b>Ocean model:</b> -</li> <li>• <b>Forcing field:</b> NCEP</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; in situ</li> </ul>

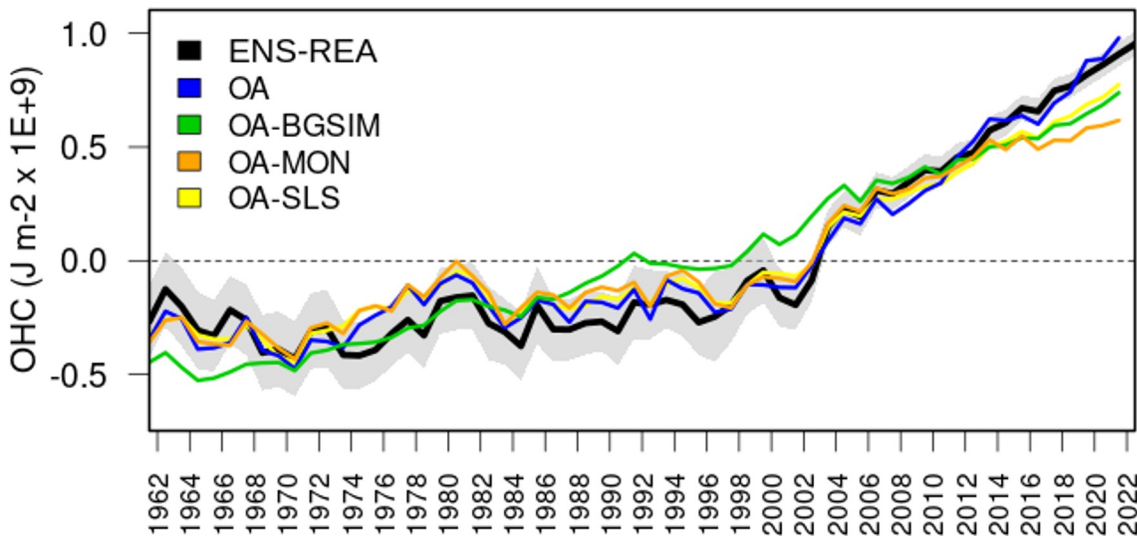
GloSia9	UK MetOffice	1/4°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> NEMO4.2</li> <li>• <b>Forcing field:</b> ERA5</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; sea ice concentration; in situ</li> </ul>
GLORYS4V2	Mercator Ocean	1/4°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> NEMO3.6</li> <li>• <b>Forcing field:</b> ERA5</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; sea ice concentration; in situ</li> </ul>
GLORYS12V1	Mercator Ocean	1/12°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> NEMO3.1</li> <li>• <b>Forcing field:</b> -</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; sea ice concentration; in situ</li> </ul>
ORAS5	ECMWF	1/4°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> NEMO3.6</li> <li>• <b>Forcing field:</b> ERA5</li> <li>• <b>Assimilation method:</b> -</li> <li>• <b>Assimilated data:</b> SSH; SST; sea ice concentration; in situ</li> </ul>
SODA3	Uni.Maryland	1/4°	<ul style="list-style-type: none"> <li>• <b>Domain:</b> Global</li> <li>• <b>Ocean model:</b> -</li> <li>• <b>Forcing field:</b> -</li> </ul>

- Resolution
- Models and model physics
- Data assimilation schemes
- Atmospheric forcing
- Bulk formula
- Observations assimilated

### Global Ocean Heat content anomaly

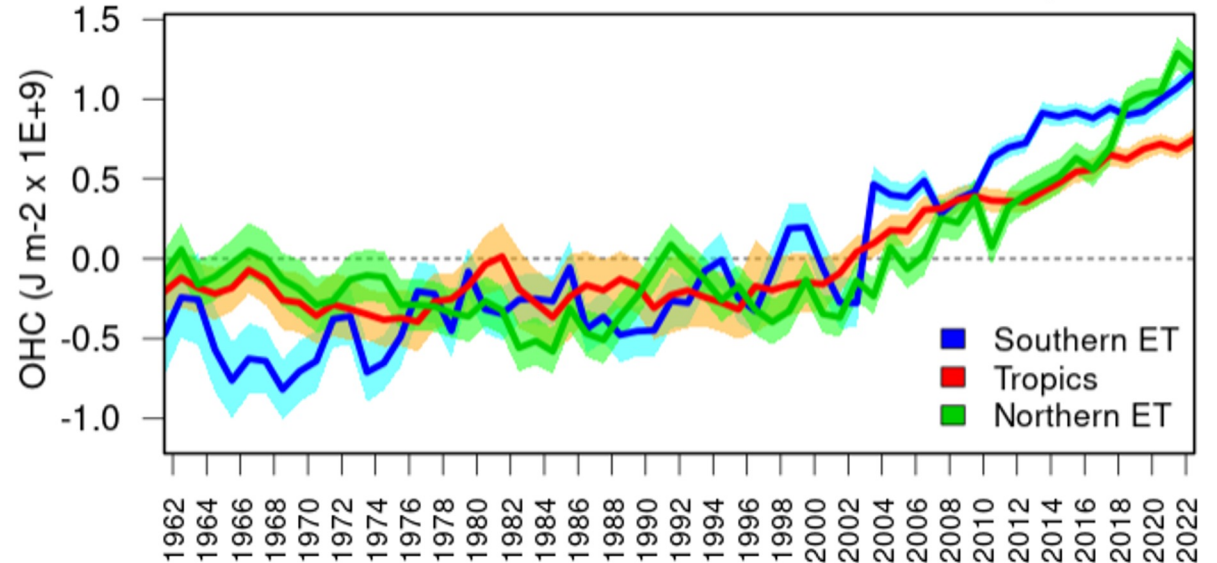


### Global Ocean Heat content anomaly

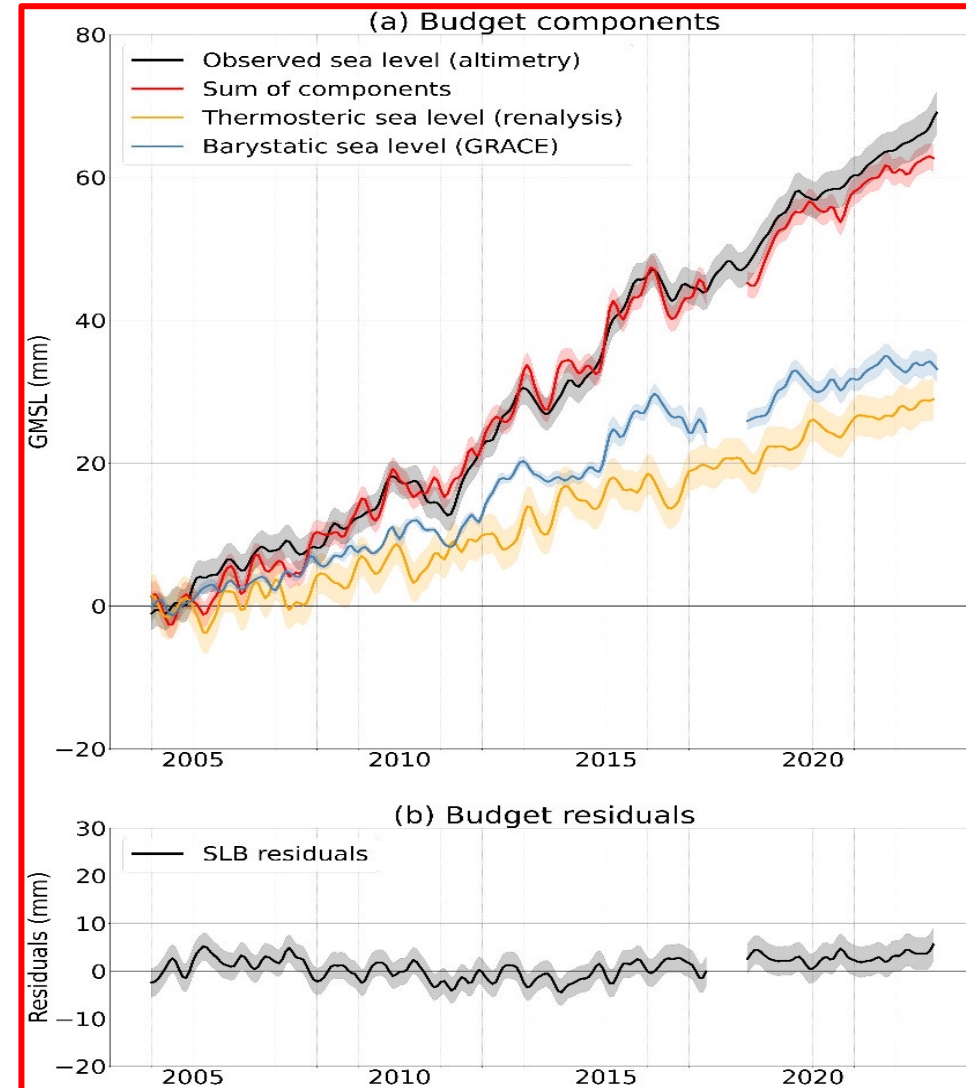
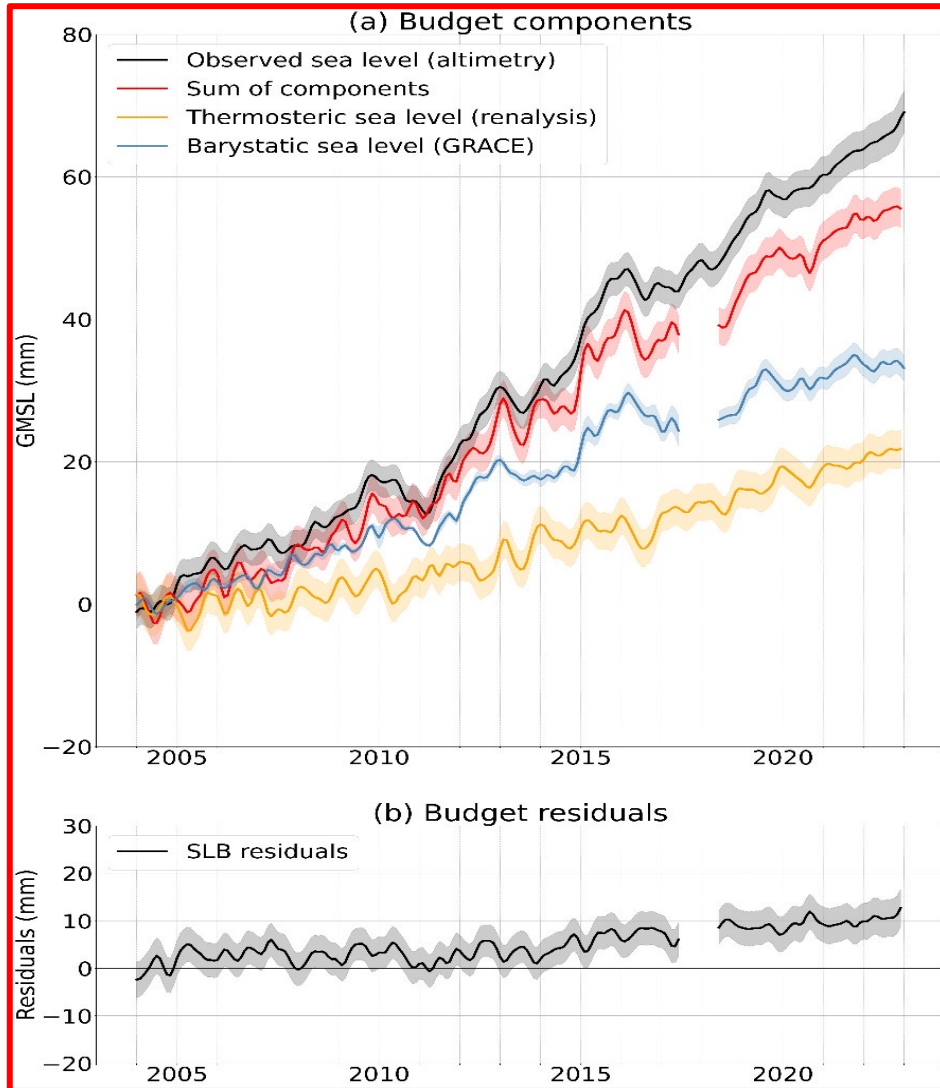


Dataset	Global warming ( $\text{W m}^{-2}$ ) 1961-2022	Global warming ( $\text{W m}^{-2}$ ) 1961-2020	
<i>ENS-REA</i>	$0.43 \pm 0.08$	$0.41 \pm 0.09$	
<i>GCOS22</i>	NA	$0.41 \pm 0.10$	
Dataset	OHC Trend ( $\text{W m}^{-2}$ ) (1961-2018)	Interannual Variability ( $1\text{E}9 \text{ J m}^{-2}$ ) (1961-2018)	Acceleration ( $\text{W m}^{-2} \text{ dec}^{-1}$ ) (1961-2018)
<i>ENS-REA</i>	0.42	0.20	0.13
<i>GCOS20</i>	0.34	0.09	0.07
<i>OA</i>	0.41	0.19	0.12
<i>OA-BGSIM</i>	0.44	0.07	0.04
<i>OA-MON</i>	0.36	0.12	0.07
<i>OA-SLS</i>	0.37	0.14	0.09

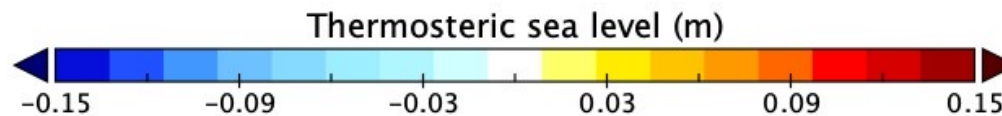
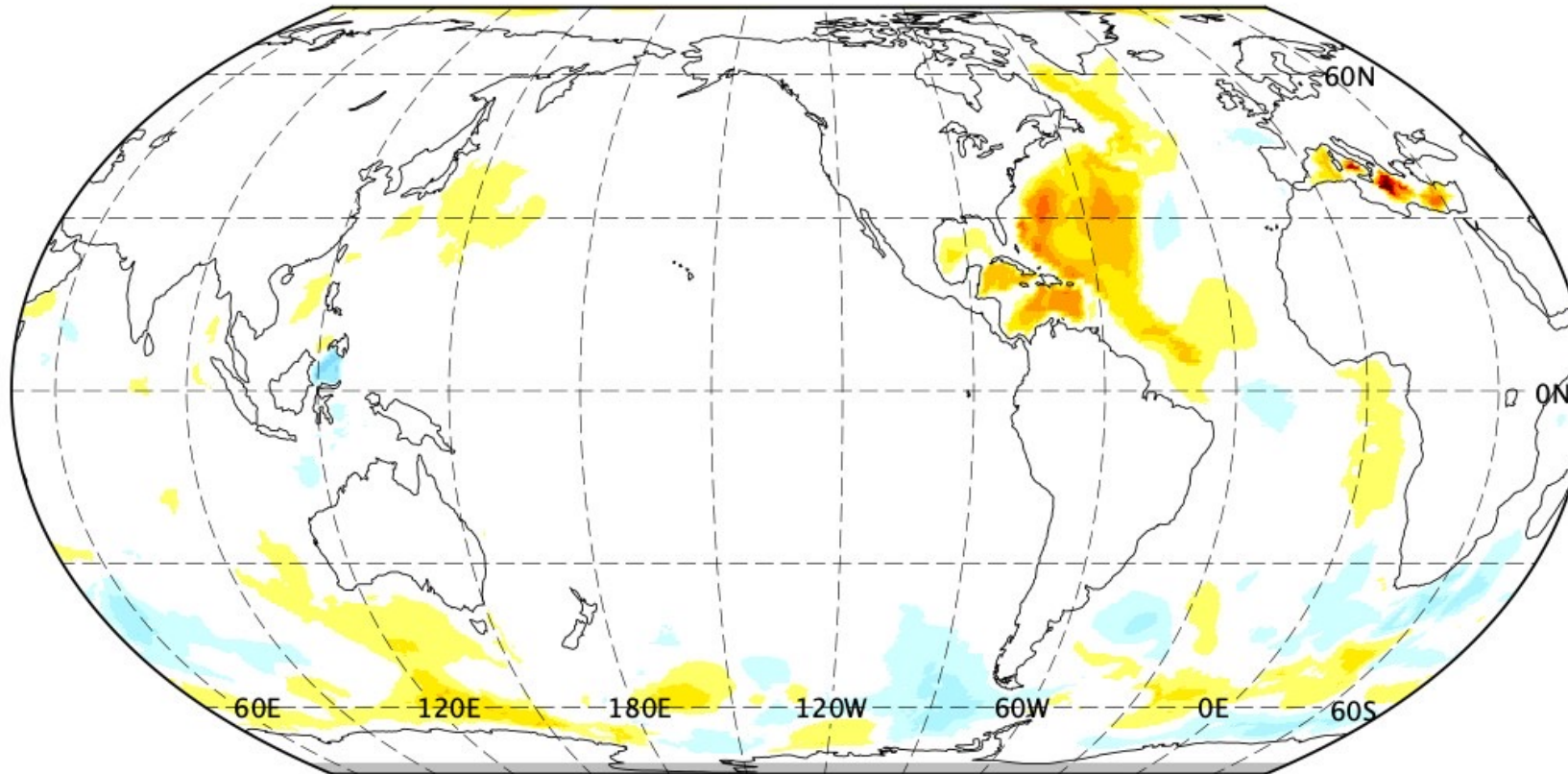
### Regional Ocean Heat content anomaly



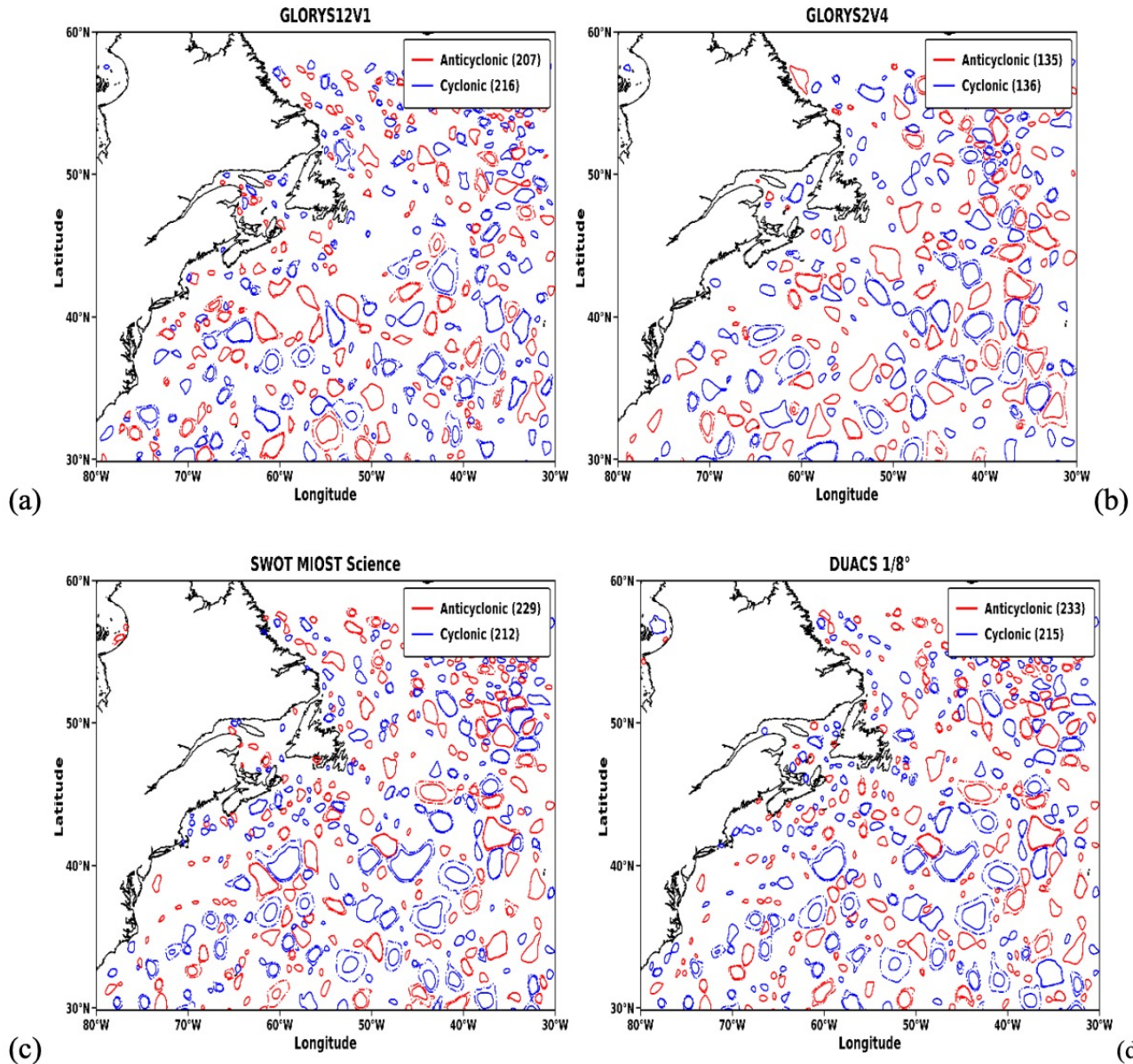
## Global mean sea level budget with the thermosteric sea level based on the CIGAR ensemble mean reanalysis



Thermosteric sea level (2000m-bottom) differences between (2016-2022)-(2009-2015)



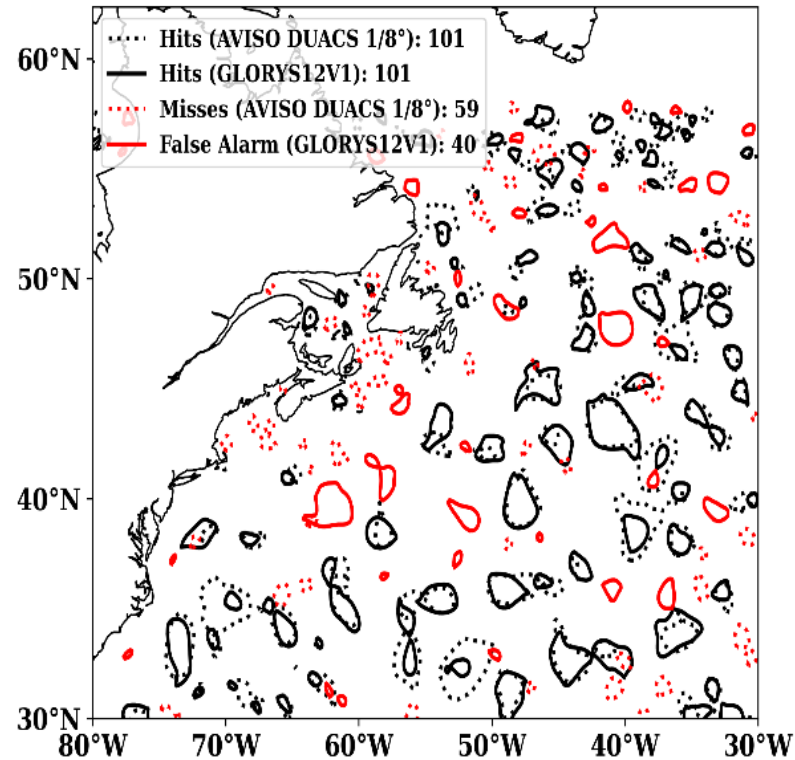
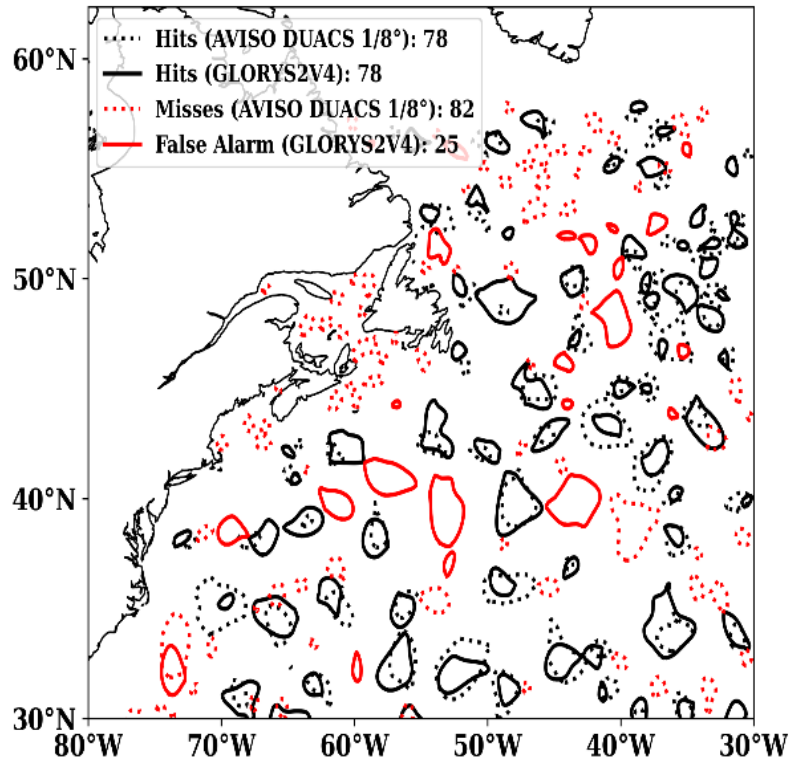
Data Min = -0.07, Max = 0.22, Mean = 0.00



Meso-scale eddies in

- GLORYS 1/12
- GLORYS ¼
- SWOT
- AVISO DUCAS

Mauriello et al., 2026



Meso-scale eddies in

- GLORYS 1/12
- GLORYS ¼
- AVISO DUCAS

**Continuous direct observations are short and spatially limited.**

RAPID, 26°N, since 2004 (McCarthy et al., 2015)

OSNAP, 57°N, since 2014 (Lozier et al., 2017)

Partial coverage: SAMBA, 34°S; and MOVE, 16°N

- **Yet AMOC is a key climate player.**



Connects hemispheres, transporting heat to the NH EU and US climate

Transports heat and CO<sub>2</sub> to deep ocean central to global warming

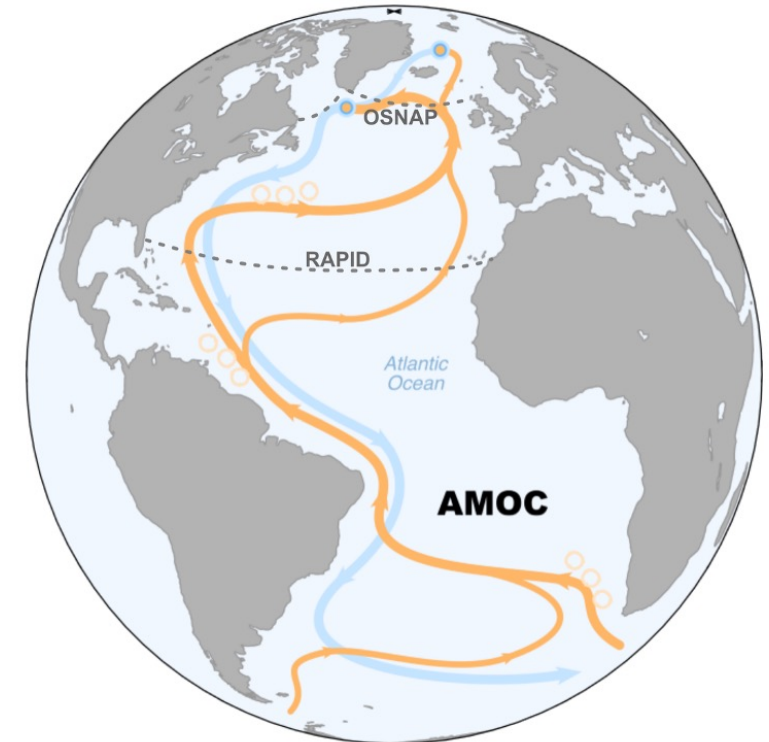
Influences ITCZ mean position tropical rainfall

Affects sea level changes US East Coast coastline

- **And likely changing.**

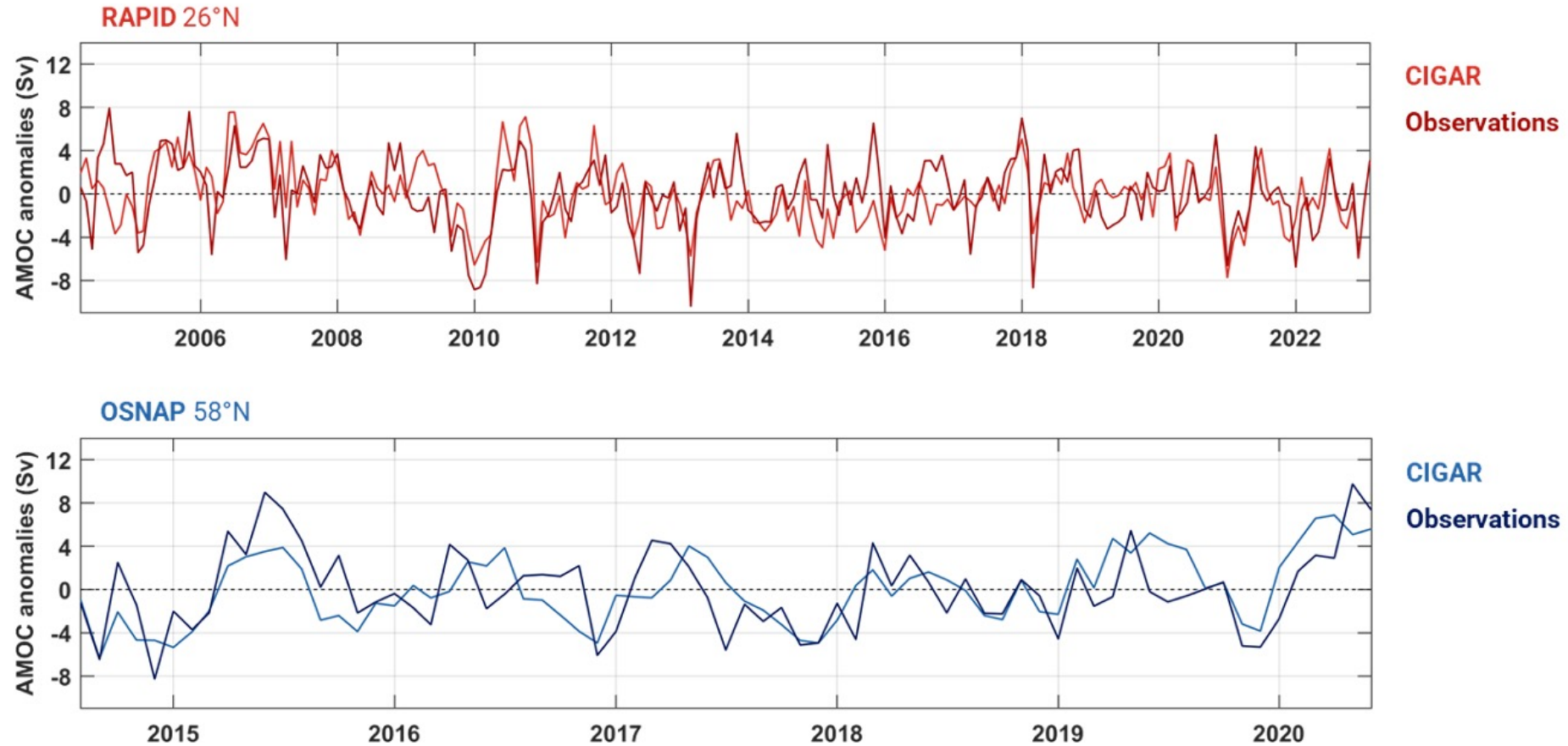
Projected continued weakening of the AMOC (IPCC AR6), and at its weakest in over a millennium (Caesar et al., 2021)

Open debate over the AMOC collapse after 2100



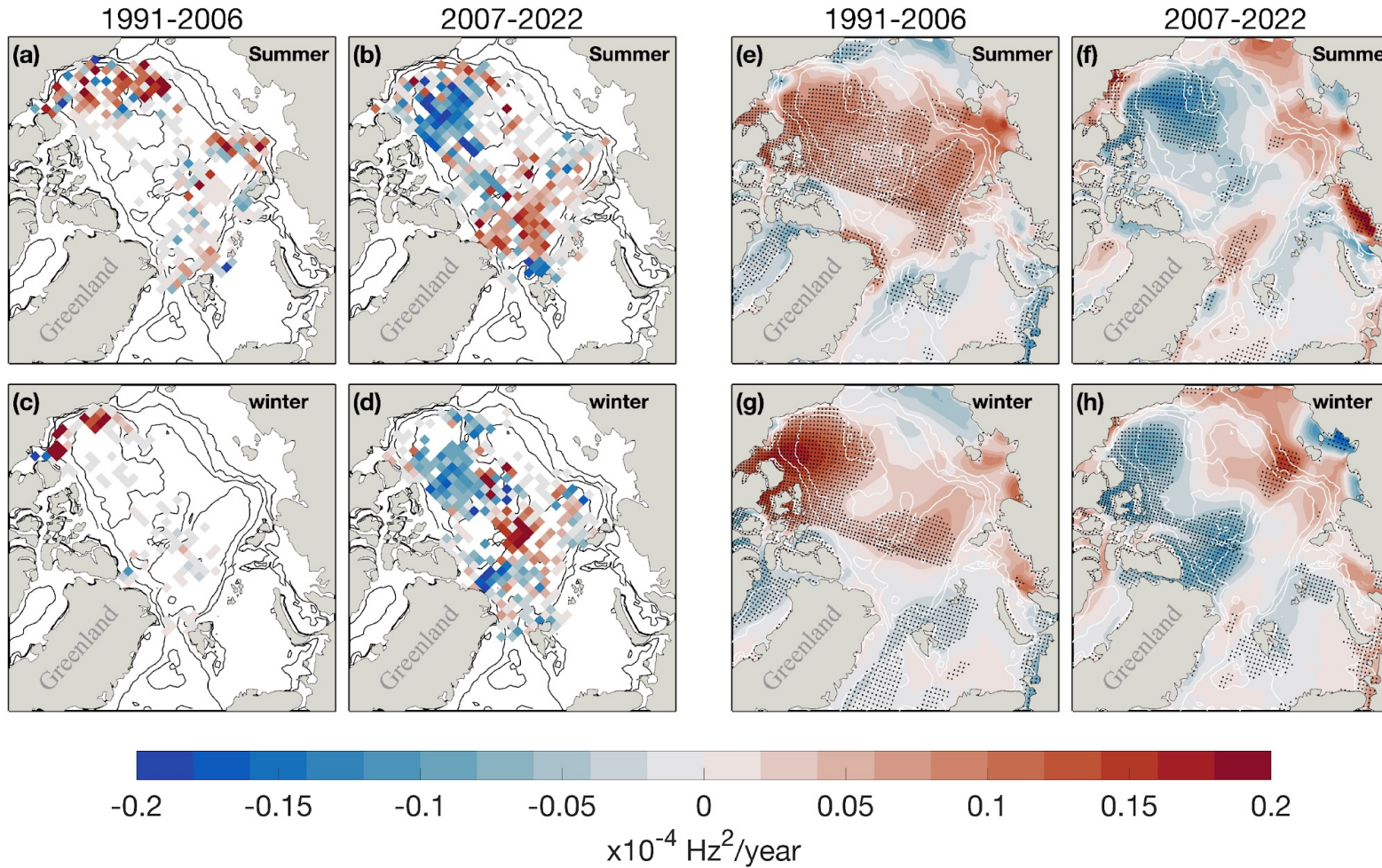
AMOC schematic – Araujo, J. (2024)

**We need indirect monitoring strategies**



**WOD**

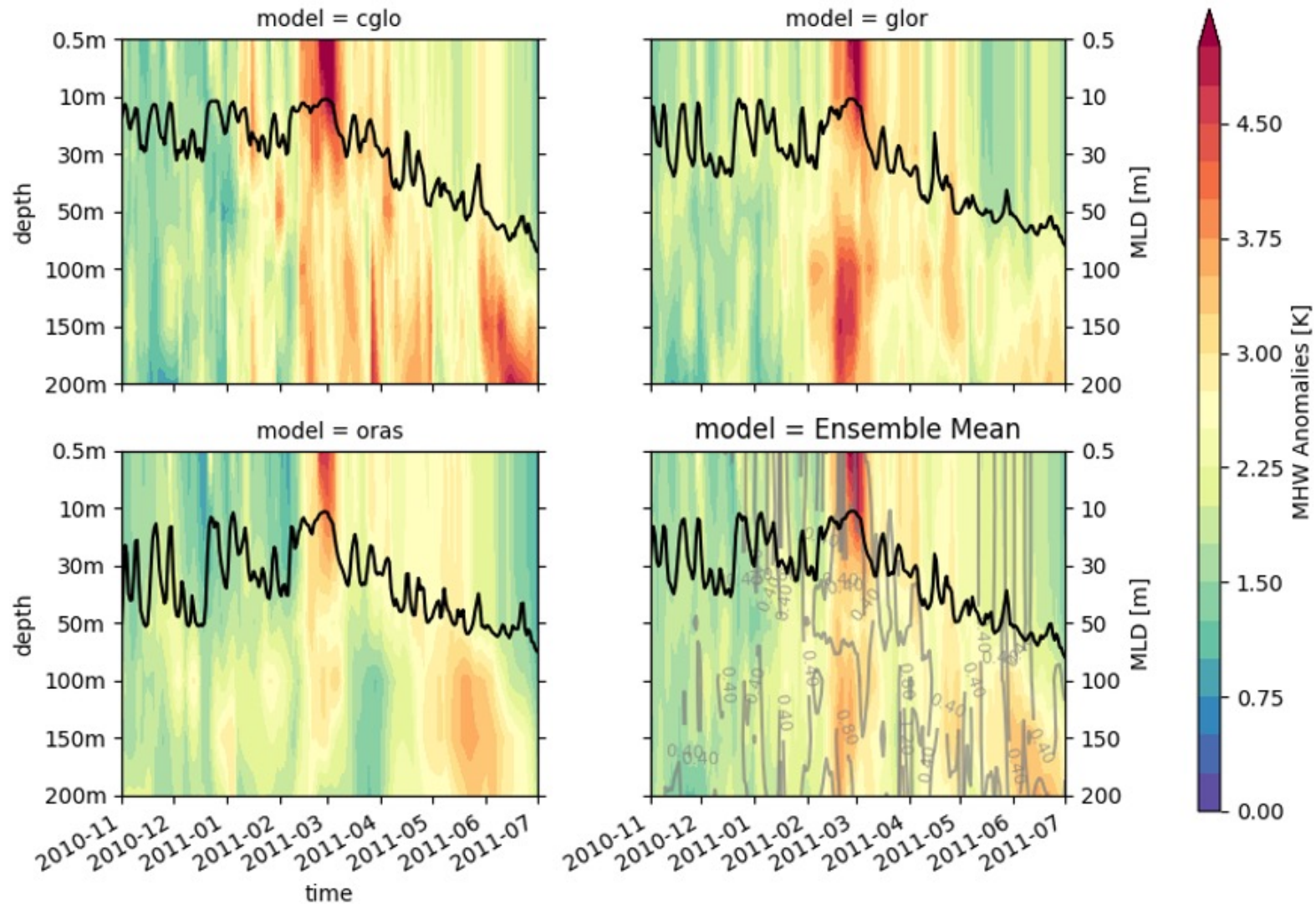
**CIGAR**



N2 (stratification index)

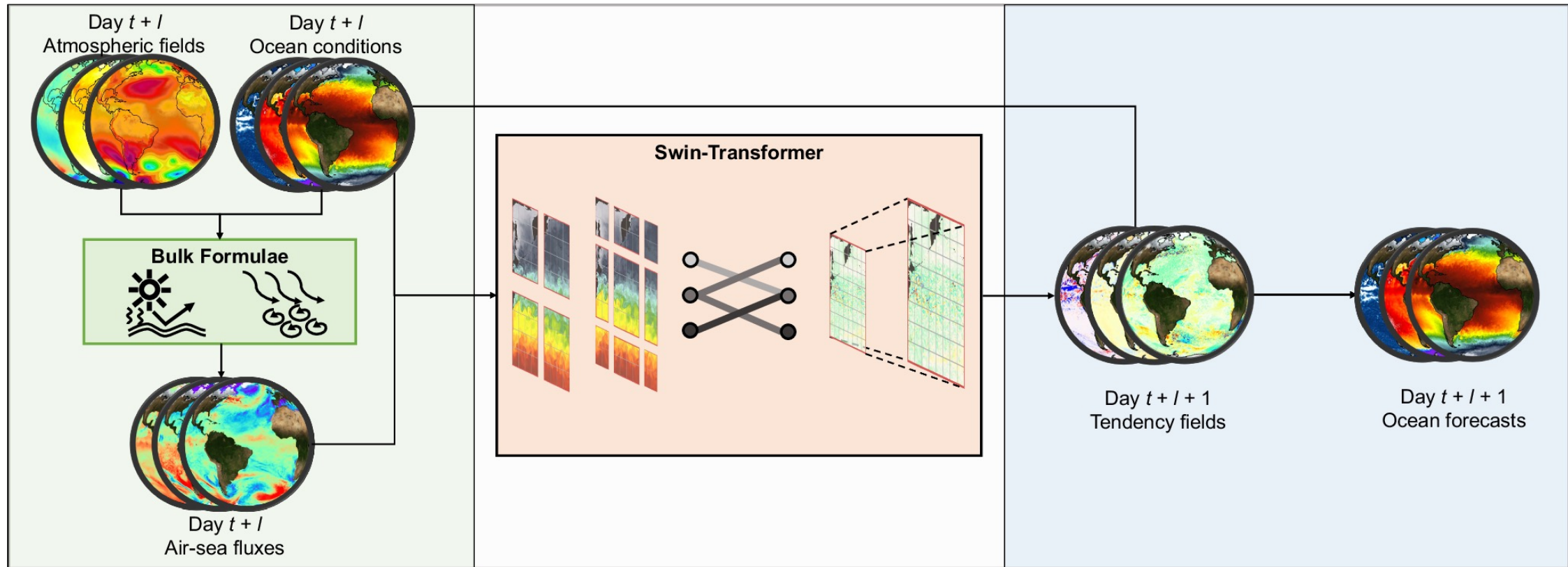
Zhang et al., 2026 in preparation

MHW Maximum Anomaly in Western Australia



De Toma et al., 2026, in preparation

# Training data for AI ocean forecasts



- Sparse observing networks (AI, non-conventional, uncertainty specific)
- Biases and drifts (3 BC schemes + AI + model enhancements)
- Temporal consistency leads to conservative choices for input observations (e.g. no sea-ice, use of nudging)
- Production is heavy (resolution versus ensemble size): difficulty with online BEC's estimation
- Reliable uncertainty is crucial for long-term applications (stochastic physics, input data)
- Verifying dataset are scarce and mostly proxy-based estimates
- Initial conditions at the beginning of reanalyses

- Long-term reanalyses enable robust monitoring of the ocean climate, and can benefit operational oceanography as well (e.g. through AI-based forecasting and bias-correction)
- For long-term applications, transitioning towards a fully probabilistic approach show large benefits (towards reliability and credibility)
- Complementarity with high-resolution systems to go further back in the past and allow for uncertainty estimates

- **MER-EP :**
- An international initiative to evaluate marine environment reanalyses to better use their potential for ocean and climate monitoring and prediction
- By sharing “best practices” derived from the studies and use cases:
  - **Guidelines** on how to use reanalyses
    - for monitoring the state of the ocean
    - for training AI forecasting models
    - as environmental forcing for ecosystem models
    - ...
  - **Methods and tools** to handle the data (Copernicus Marine Service EDITO)