MERCATOR OCEAN INTERNATIONAL

Evaluation of Ocean Reanalyses

Marie Drevillon, Chunxue Yang, Romain Bourdallé-Badie, Gilles Garric, Jean-Michel Lellouche, Eric Greiner, Hao Zuo, Eric de Boisseson, Andrea Cipollone, Suzanna Winkelbauer, Michael Mayer, Davide Cavaliere, Andrea Storto, Richard Renshaw, Stephane Law Chune, Lotfi Aouf, Coralie Perruche, Emanuela Clementi, Simona Masina, Doroteacino Iovino, Karina von Schuckmann et al.
+ many colleagues from the Copernicus Marine Service product quality working group
+ ORA IP & EOS projetcs people …

6th September, ECMWF 2023 Seminar on Earth System Reanalysis

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Overview

Ocean Reanalyses of the Copernicus Marine Service

- Blue, Green and White Ocean reanalyses
- Evaluation framework
- Strengths and weaknesses of reanalyses

The international Ocean Reanalyses intercomparison projets

- evaluation of essential ocean variables
- perspectives

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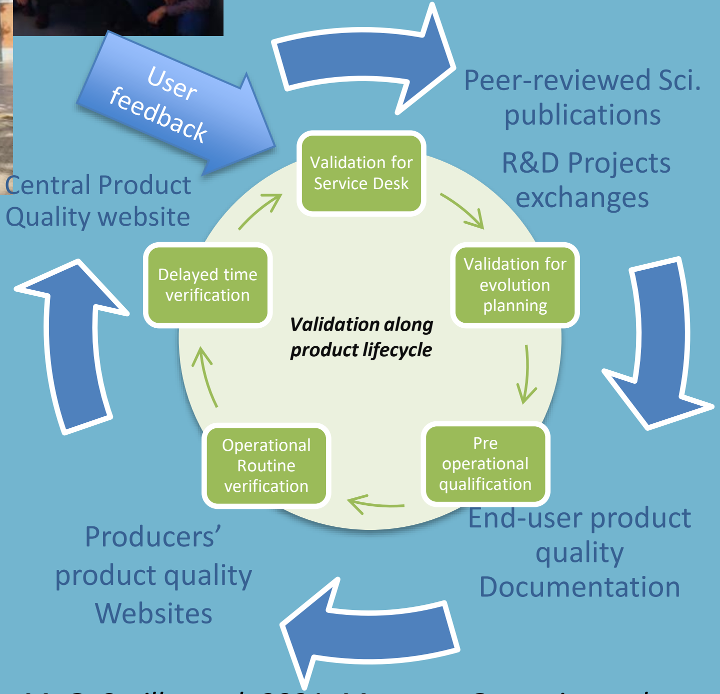
Copernicus Marine Service



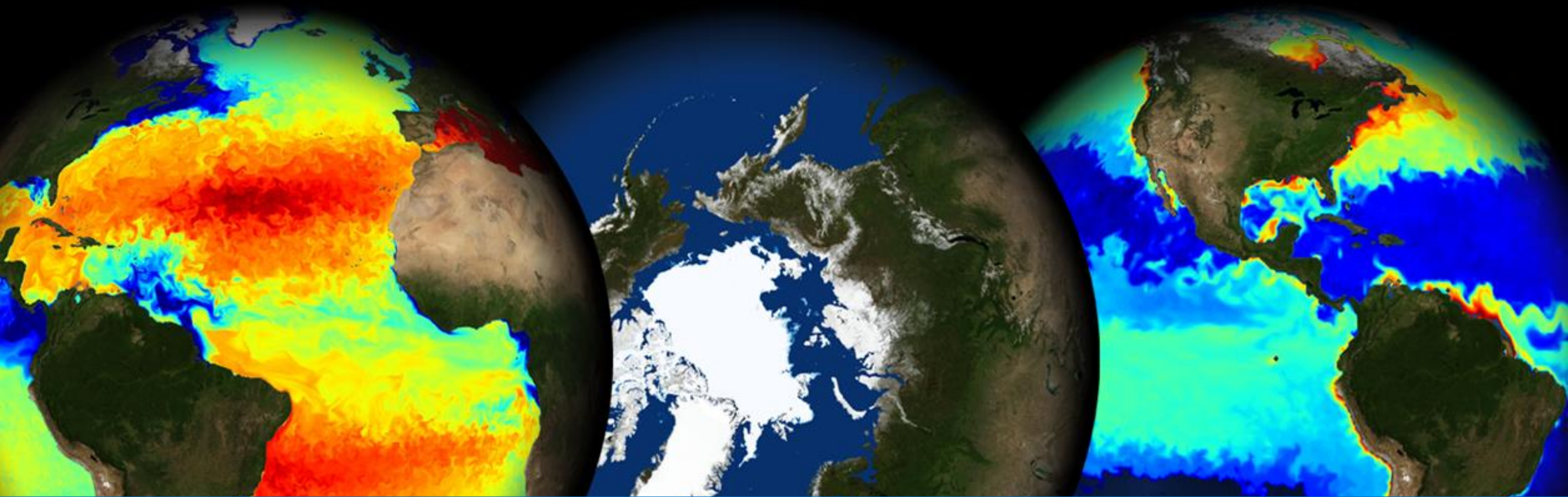
a scientific quality evaluation framework

Ocean reanalyses of the Copernicus Marine Service

From M. G. Sotillo et al, 2021, Mercator Ocean journal

https://doi.org/10.48670/moi-cafr-n813

« The Ocean », according to marine.copernicus.eu



Satellite, in situ observations and 3D models for Essential Ocean Variables, translated by experts into verified data, indicators, reports and training sessions, seen by 700,000 users worldwide/year, and integrated as regular information by more than 55 000 subscribers.

Global and Regional Ocean Monitoring and Forecasting

COPERNICUS MARINE REGIONAL OCEAN PRODUCT DIVISIONS

1. Global Ocean
2. Arctic Ocean
3. Baltic Sea
4. European North West Shelf Seas
5. Iberian Biscay Ireland Seas
6. Mediterranean Sea
7. Black Sea

MULTI-YEAR 10 to 45 years › **REAL-TIME** 2 years › **FORECAST** 2 to 10 days

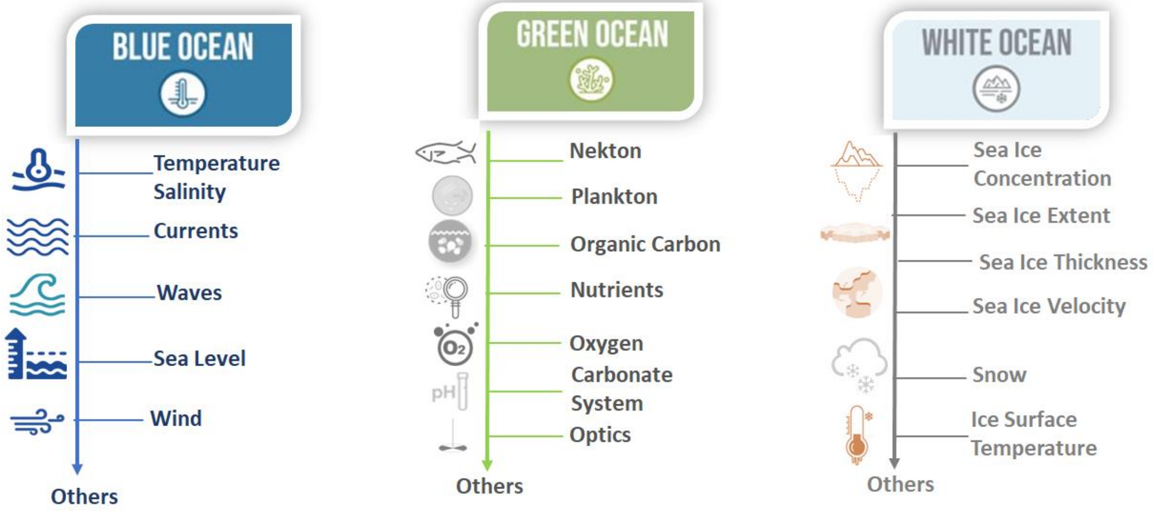
ESSENTIAL MARINE VARIABLES

BLUE OCEAN	WHITE OCEAN	GREEN OCEAN
Physics	Sea Ice	Biogeochemistry

OBSERVATIONS In-situ & satellites › **NUMERICAL MODELS** & data assimilation

Copernicus
Marine Service

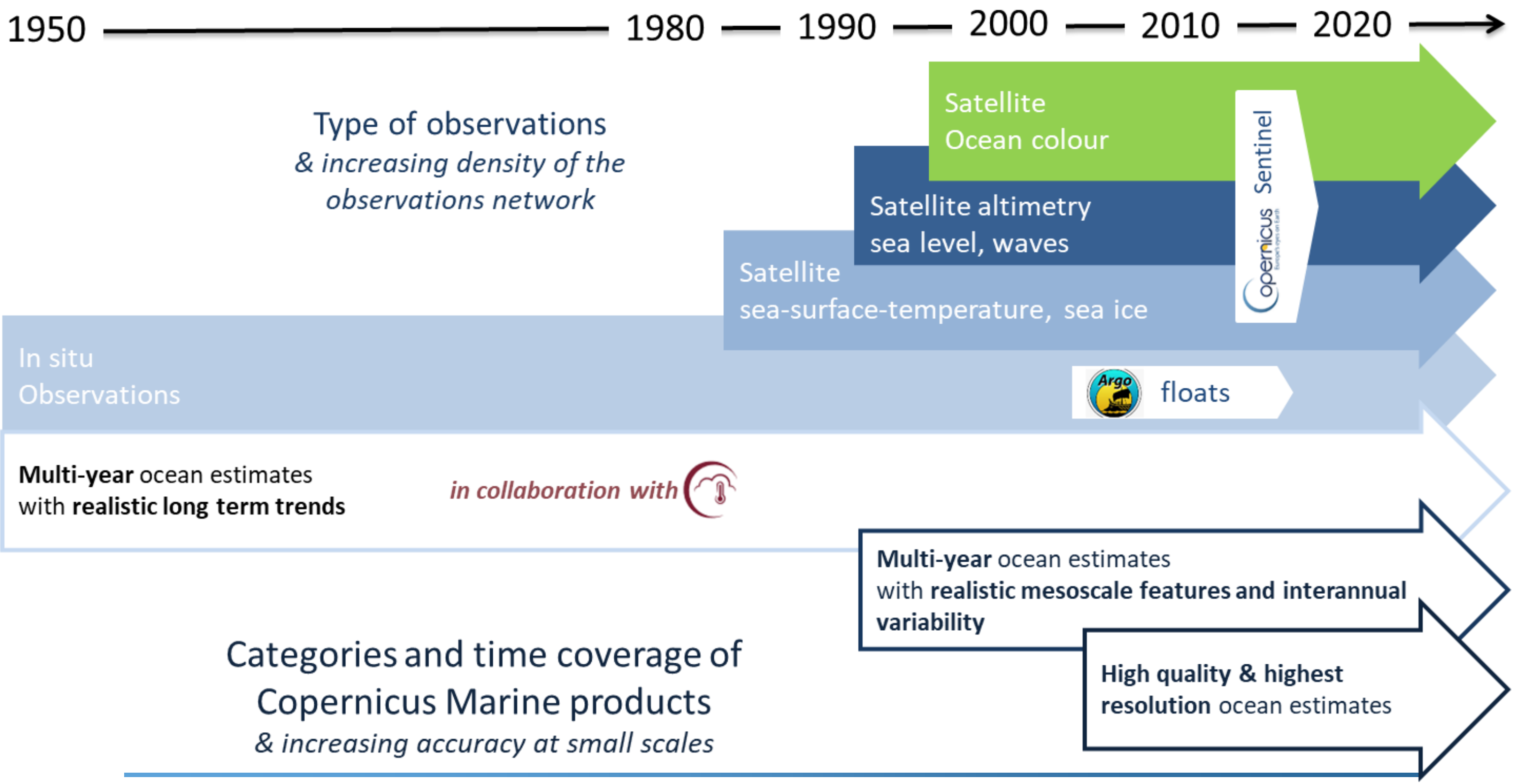
Copernicus Marine Offer : Observation and Model products



- ❑ Observation products
- ❑ Model products (data assimilation)
- ❑ Access to products: A cloud-based infrastructure (Marine Data Store)
- ❑ Description of each product
- ❑ Information on quality
- ❑ Service desk / expert advice

Extensive use of Sentinel data (S1, S2, S3 and S6) and contributing missions

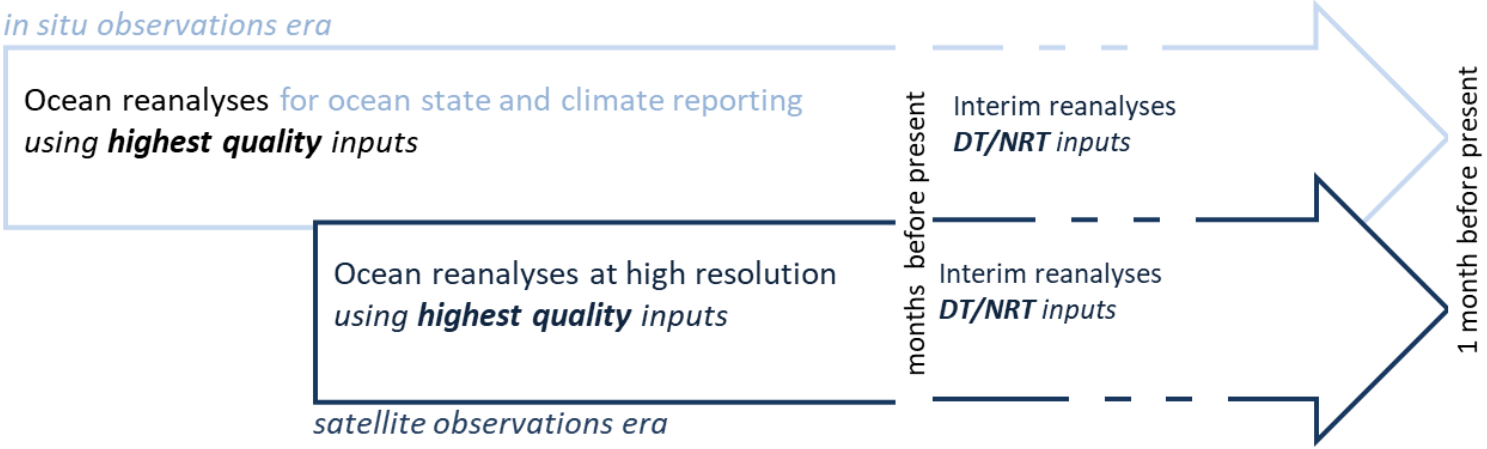
Ocean reanalyses and obs reprocessing



Categories and time coverage of Copernicus Marine products
& increasing accuracy at small scales

Ocean Reanalysis *interim up to real time*

Reanalyses are homogeneous, continuous, high quality descriptions of the past
Two main types of products/streams, use of ERA5 forcing + interim production

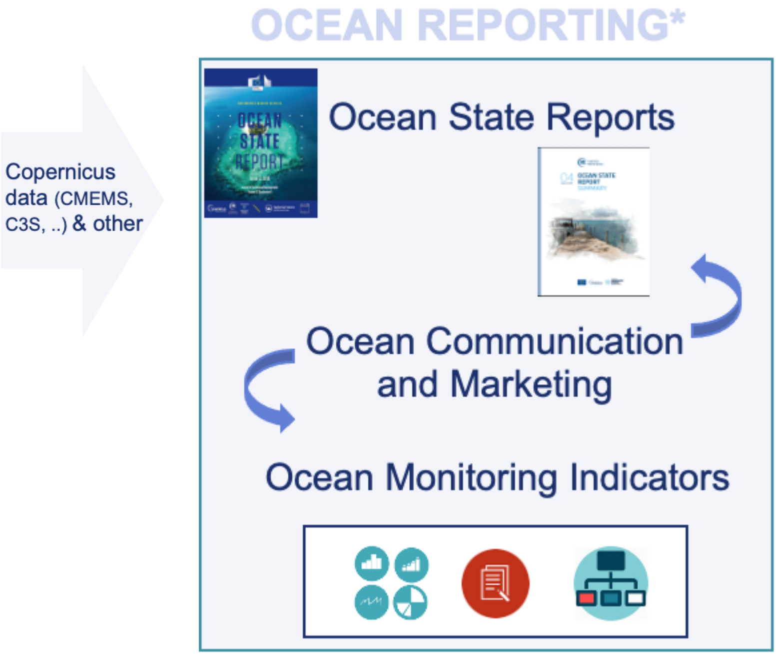


The Copernicus Ocean Reporting Activity

Copernicus Marine Service

Knowlegde transfer of science-based information for physics, biogeochemistry and biodiversity to a wide range of audience, and the needs of downstream applications.

Ocean observations reprocessing **and reanalyses**



- With the publication of the Copernicus Ocean State Report (OSR), its summary for policy makers, and the dissemination of Ocean Monitoring Indicators (OMIs), the Copernicus Marine Service provides expert assessment on the state of the European seas and the global ocean.
- OMIs track the marine environment evolution to monitor and communicate otherwise complex changes to decision makers, policy and agencies (e.g. EEA, EuroStat), stakeholders for sustainable development (MSFD, SDGs) and the public

Copernicus
Marine Service

The Copernicus Ocean state report

ISSUE #7: Under development
➔ publication:
early September 2023

ISSUE #8: In preparation

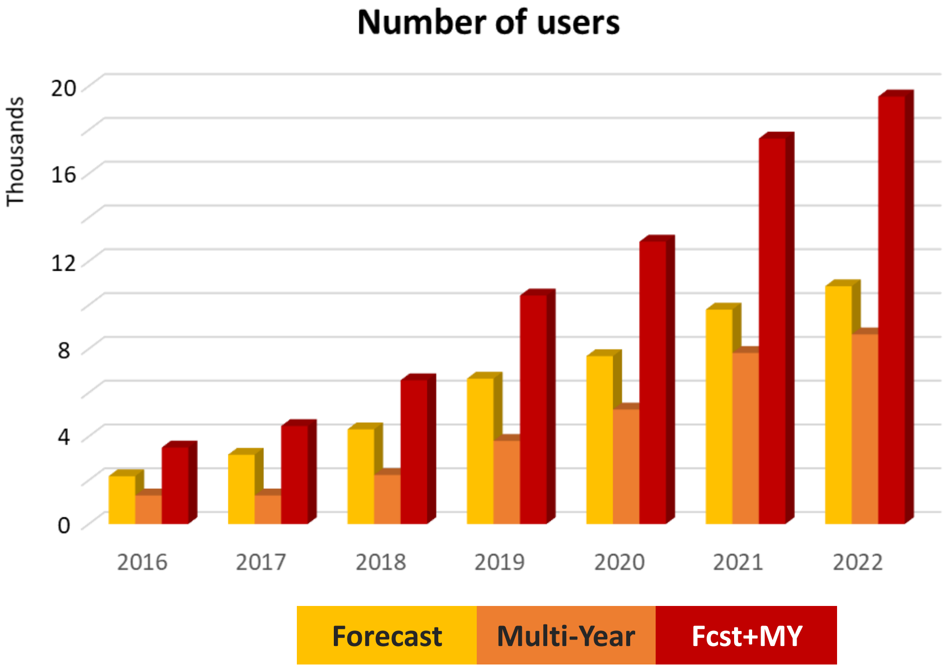
http://marine.copernicus.eu/science-learning/ocean-state-report/

Fundamental driver of the Copernicus Ocean Reporting Activity

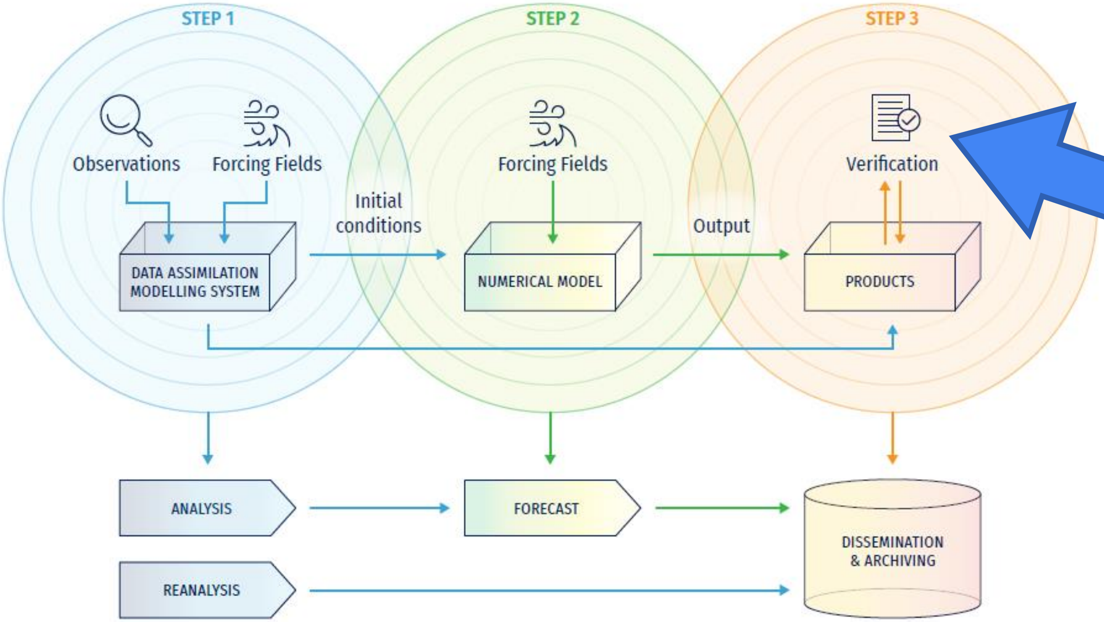
- Collaboration of more than 150 scientific experts
- Collaboration of more than 25 European institutions
- Fundamental step forward into the development of regular Copernicus regular Ocean reporting
- Already in the 8^{th} cycle

Analysis/reanalysis products in numbers

Forecast Released every day	23	4	7
Multi-Year Number of products	12	4	6
Ocean Monitor Indicators	17	4	1



Evaluation of operational oceanography products

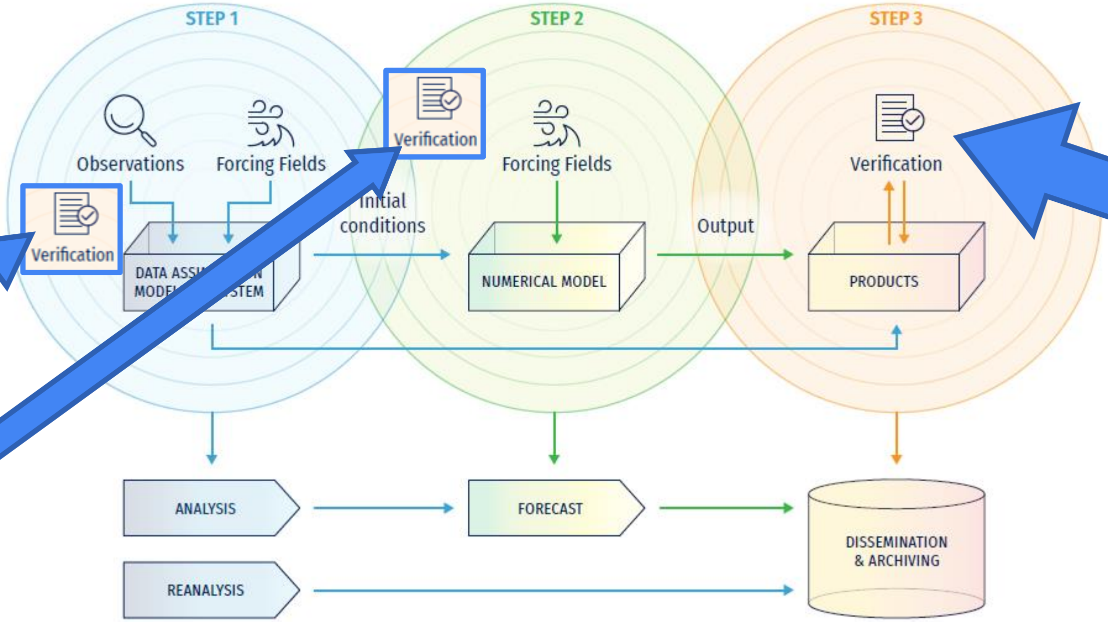


producers derive quality information for users:

- *Reference documents (reports, articles)*
- *Monitoring metrics on website*

https://www.mercator-ocean.eu/en/guide-etoofs/
ETOOFS guide (IOC-UNESCO, 2022).

Evaluation of operational oceanography products



producers perform validation that drives the evolution of the service

producers derive quality information for users:

- *Reference documents (reports, articles)*
- *Monitoring metrics on website*

https://www.mercator-ocean.eu/en/guide-etoofs/

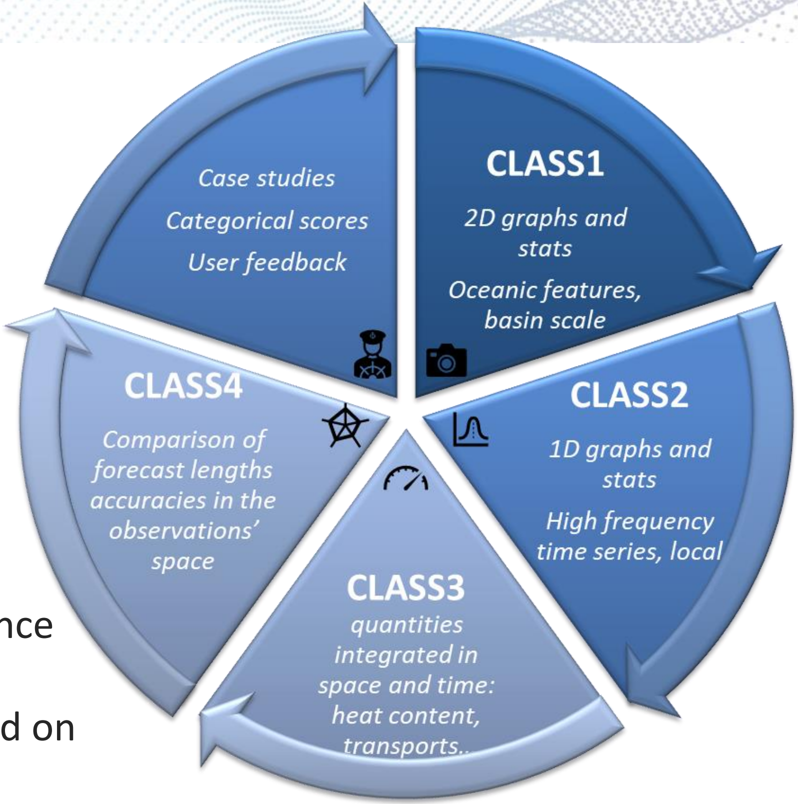
ETOOFS guide (IOC-UNESCO, 2022).

Evaluation of operational oceanography products

What has to be checked?

- statistical behaviour vs reference observations/values, in time and space
- Physical/biological behaviour of ocean processes, at all scales
- variability and trends

classes of metrics are defined for model products
Oceanpredict International standards endorsed by ETOOFs (IOC/WMO)

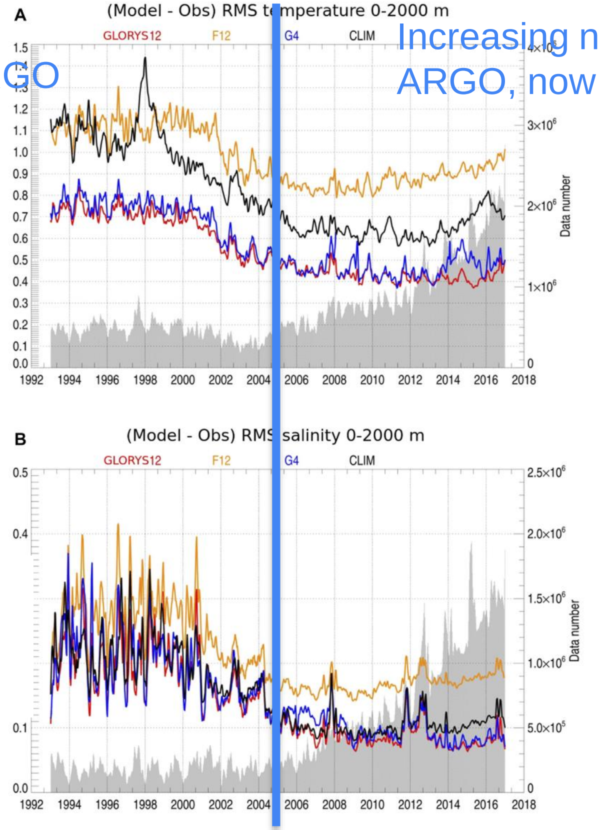


Expertise summarized (strength / limitations) in reference **quality information documents** including average accuracy estimates at basin scale, and on dynamically coherent areas

Evaluation of blue reanalyses

Before ARGO

Increasing number of ARGO, now ~4000



Free 1/12° run
Climatology
GLORYS4 ¼°
GLORYS12 1/12°

From GLORYS12 Lellouche et al, (2021)

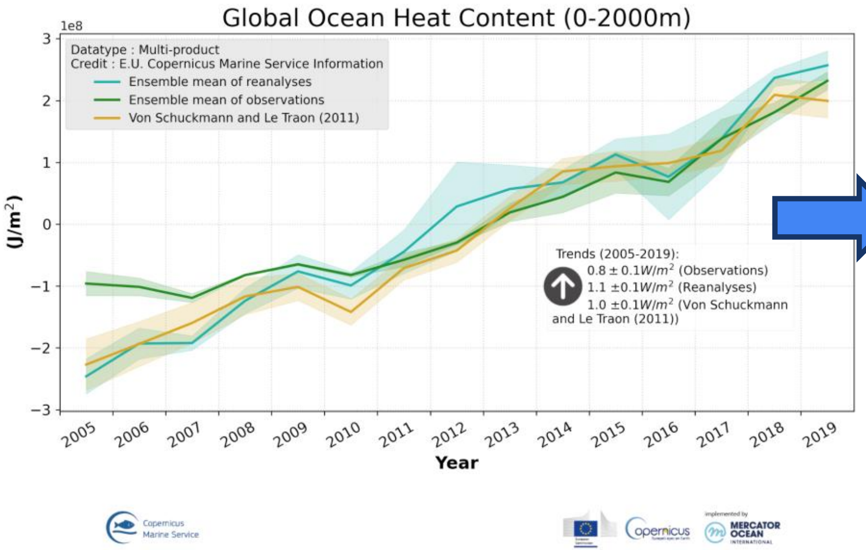
Comparisons of temperature and salinity in the in situ profiles observations' space

reanalysis more accurate than free runs or climatologies

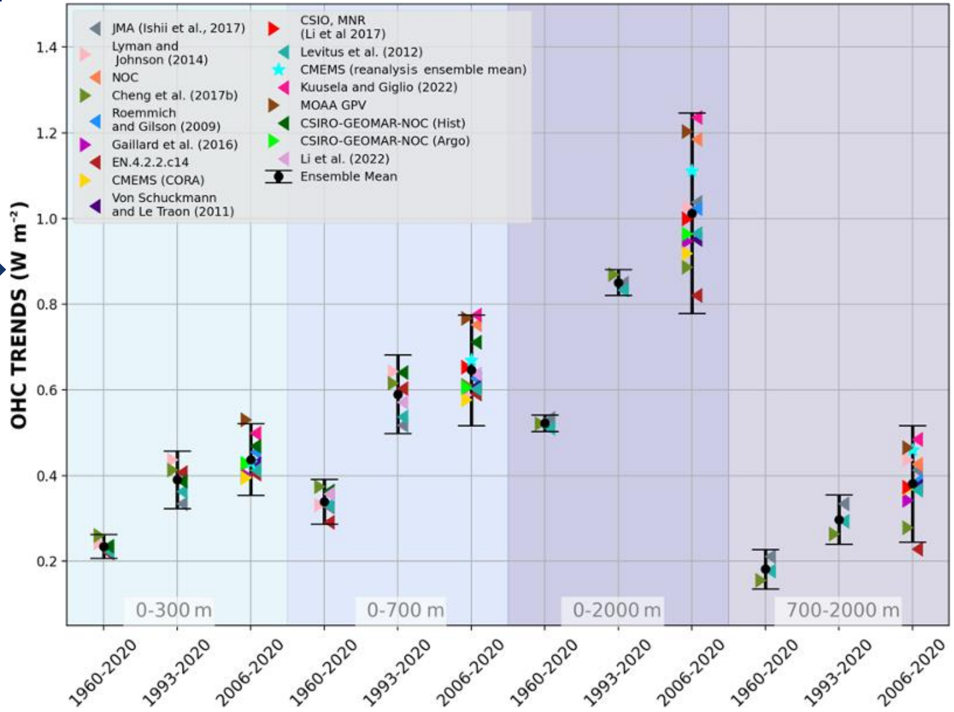
-> getting better as the ARGO network strengthens

Use of ocean reanalysis for the Earth heat inventory

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



von Schuckmann et al., 2023

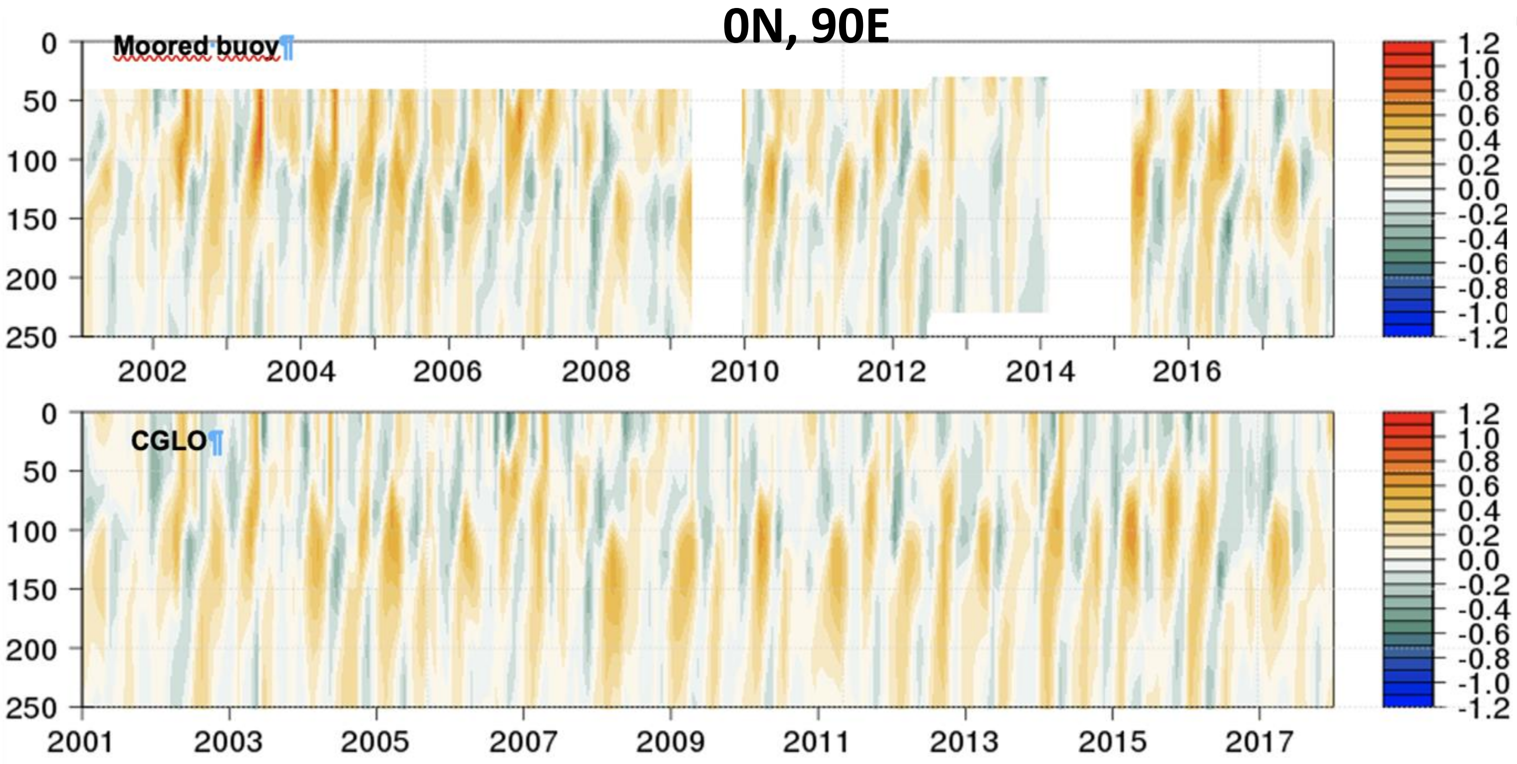


Future studies needed to further assess regional to global ocean warming in ocean reanalyses

Global ocean Reanalyses Ensemble Product (1993-2020) GREP

Reanalysis	Common Features	Model Version	Surface Forcing	Assimilation
GLORYS4v2 (Mercator Ocean)	NEMO ORCA1/4°, 75 verical level, ERA-Interm 1993-2018, ERA5 from 2019-present, Observations_ SST, SLA, T/S profiles, SIC,	NEMO3.1 LIM2	No surface Nudging, Precipitation and Flux correction, Climatological run-off and ice shelf and iceberg melting	SAM2 (SEEK), Large-scale bias correction, 7-day assimilation window, Merge MDT (obs+model) Reynolds SST, CORA
FOAM (UK Met Office)		NEMO3.4 CICE4.1	A model correction is applied to net freshwater flux into the ocean. Precipitation and evaporation by a global scaling factor every cycle	NEMOVAR, Large-scale bias correction, MDT from CNES-CLS18, 1-day assimilation window, EN4 weak relaxation (1-year timescale) to 3D T/S EN4 2011-2015 climatology (vEN4.1.1.)
C-GLORS (CMCC)		NEMO3.4 LIM2	Heat and freshwater flux correction from SST SSS, SIC, SIC nudging	OceanVar, Large-Scale bias correction, 7-day assmi, Model MDT, Reynolds SST, EN4 (4.2.1) with error based on Ingleby and Huddleston (2007)
ORAS5 (ECMWF)		NEMO3.4 LIM2	SST nudging to OSTIA L4 NRT, SSS nudging to WOA09 climatology, 3D damping to WOA09 climatology (restoration scale=20 years)	NEMOVAR, Large-scale bias correction, 5-day assmi, MDT from pre-reanalysis, HadISSTv2 SST, EN4.2.1. (Switch to GTS at 01/12/2020)

Tropics - Currents validation



Validation of individual members

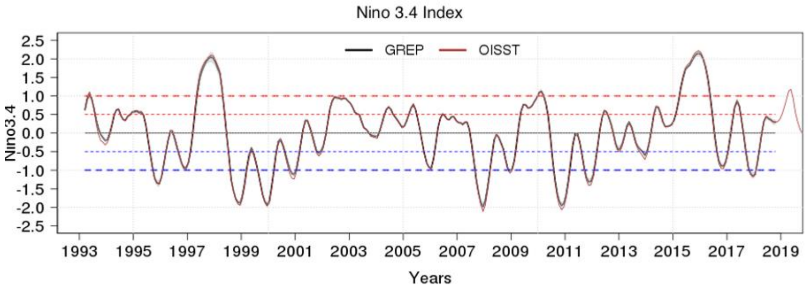
Ocean currents validation: surface drifters, argo floats (yomaha), hull-mounted ADCP

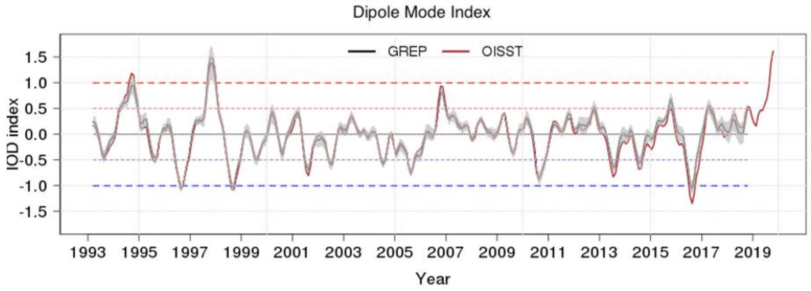
Tropics - Validation of variability

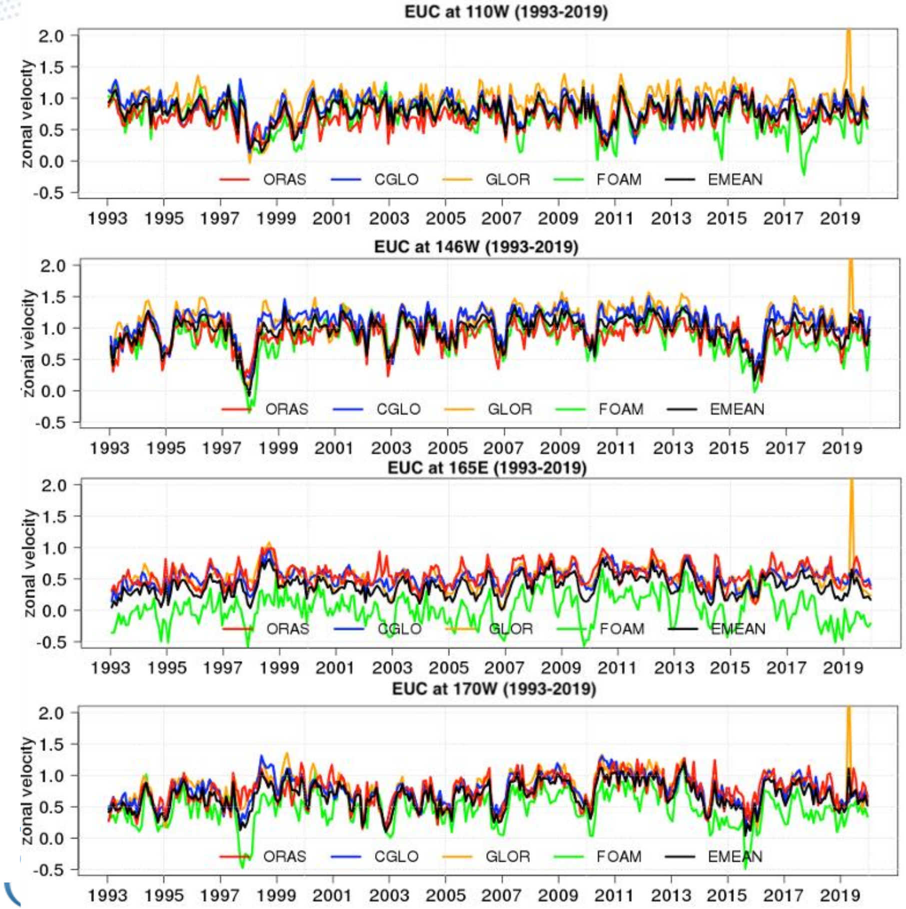
Copernicus Marine Service

BLUE OCEAN

Validation of multi-model mean and intercomparison

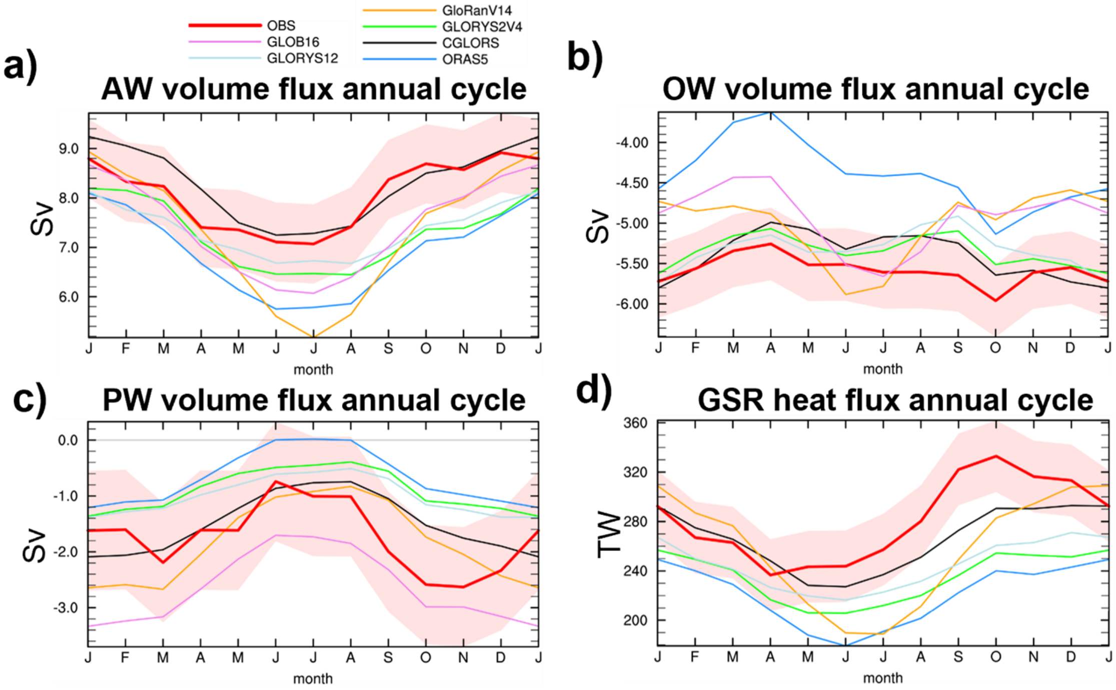




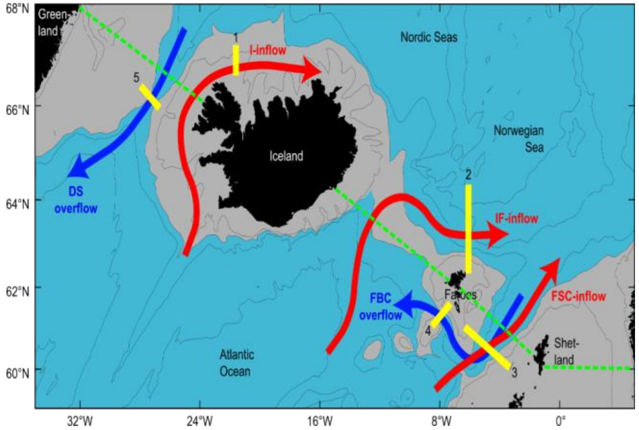


Polar Regions (Greenland-Scotland Ridge-GSR transport)

BLUE OCEAN

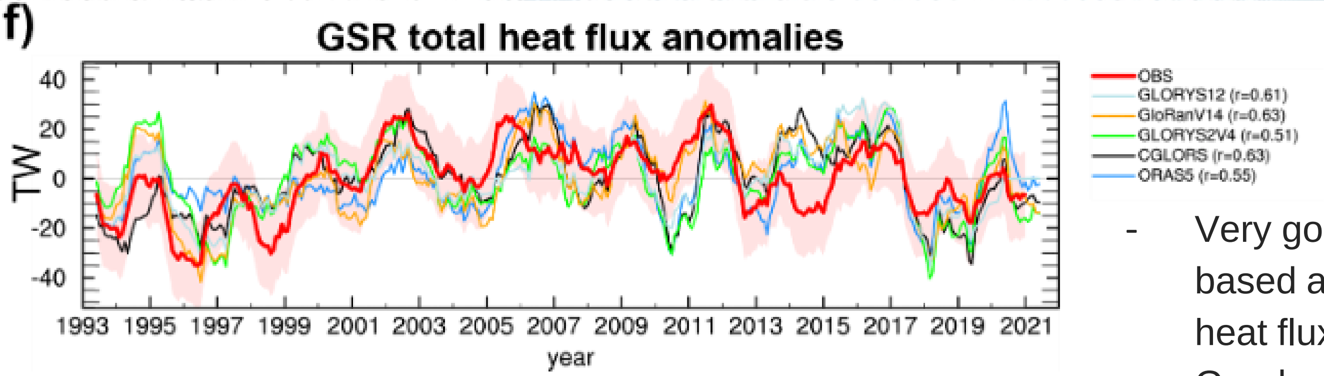


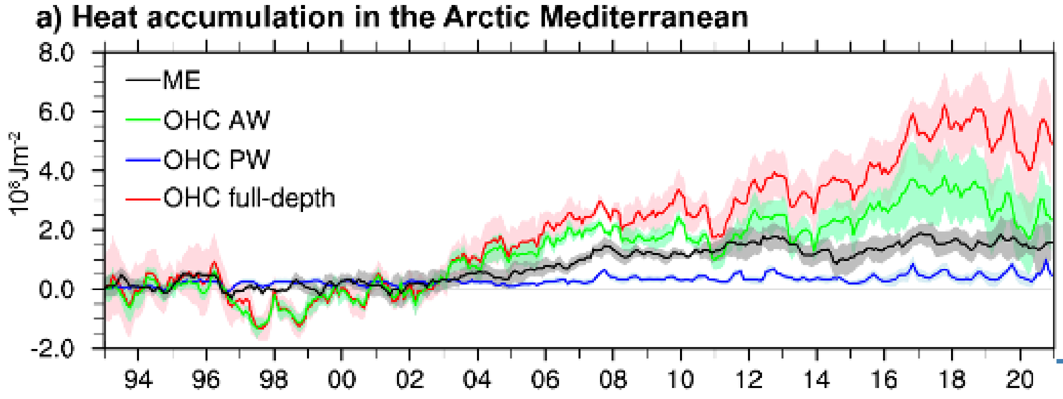
(Mayer et al. 2023)



- most ORAs underestimate inflow of warm and saline waters from the Atlantic (AW), which is largely balanced by too weak dense overflow (OW)
- As a result of too weak AW inflow, heat flux across GSR is underestimated by all ORAs

Polar Regions (Greenland-Scotland Ridge-GSR transport)





- Very good agreement between ORA-based and OBS-based temporal heat flux anomalies at GSR
- Good agreement also on decadal variations, with enhanced transports between ~2002 and ~2017
- The period of enhanced transport coincides with period of accelerated ocean heat uptake

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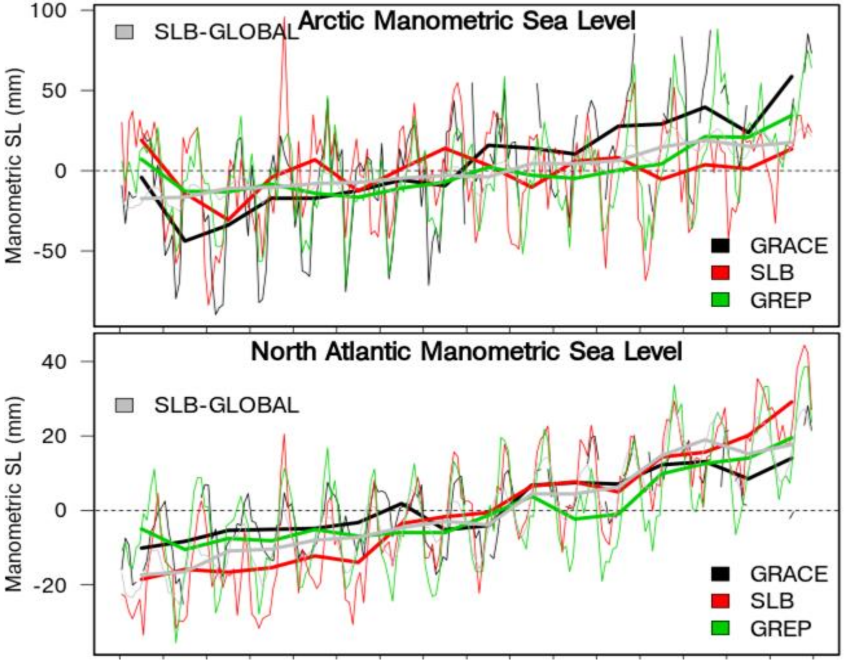
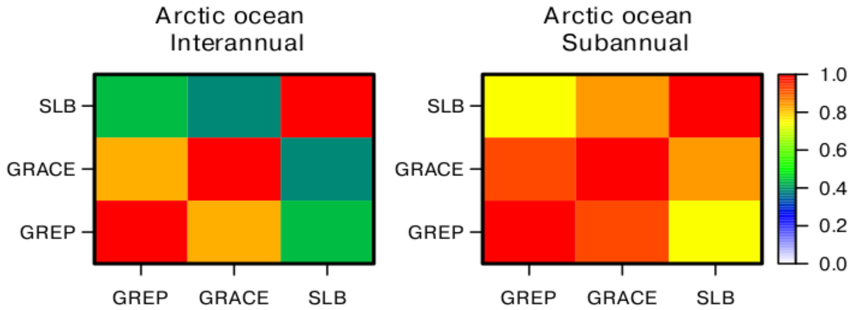
Marine Service

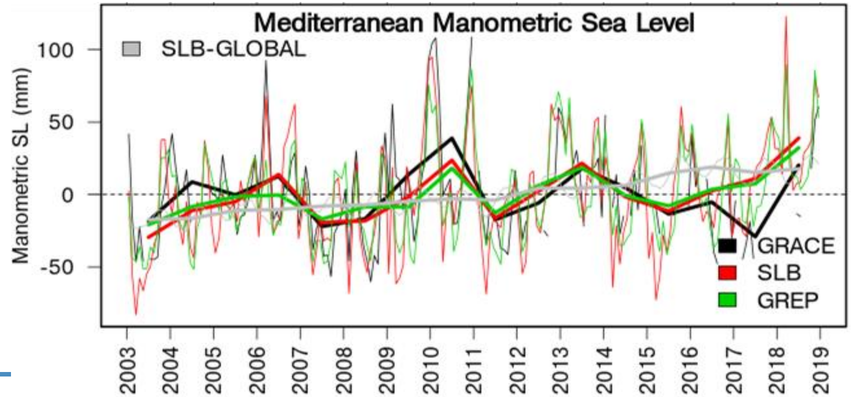
Long-term changes

BLUE OCEAN

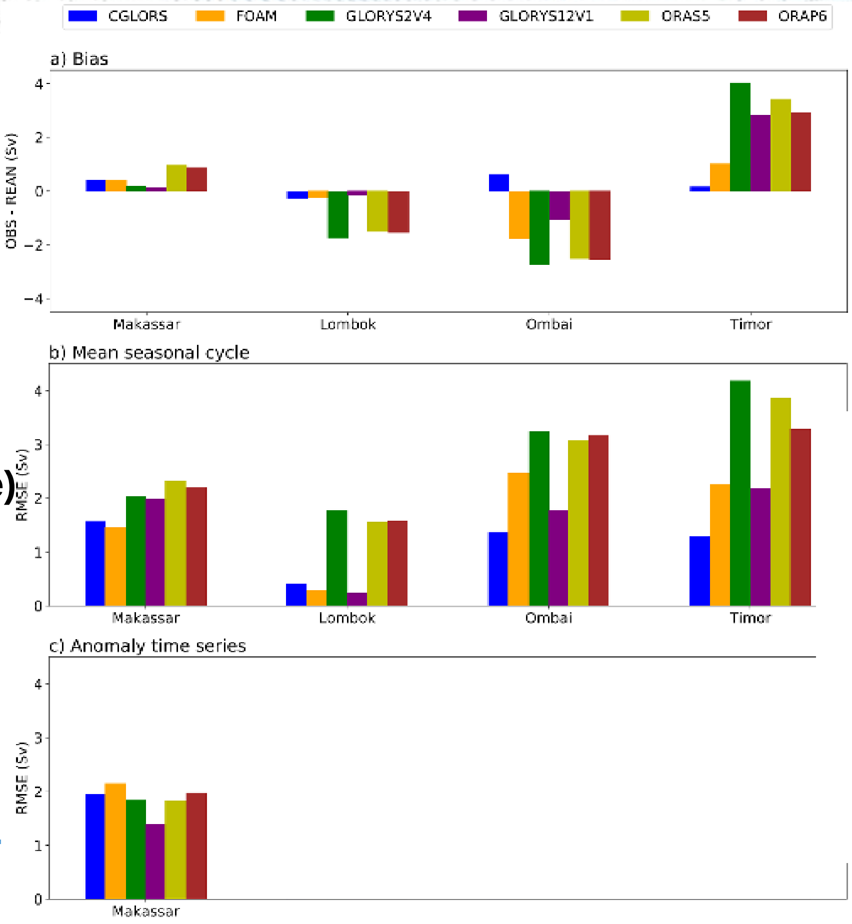
basin-average manometric sea level compare well with independent estimates







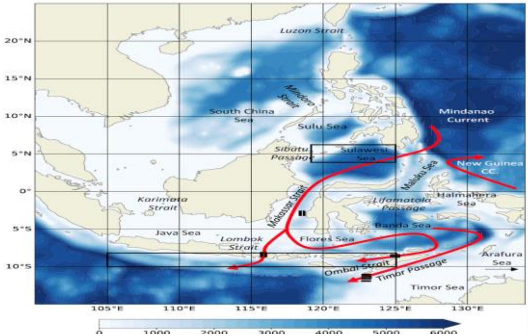
Transports (Indonesian Throughflow)



Bias
Negative means too strong flow, positive means too weak flow

RMSE (Mean Seasonal Cycle)

Anomaly RMSE



- ORAs have generally too weak mean flow in Makassar and Timor, and too strong flow in Ombai Strait and Timor Passage
- Relatively large spread amongst products, with CGLORS performing well in all passages
- GLORYS12 (1/12°) performs comparatively well in narrow passages Lombok and Ombai Straits

Wave reanalyses (vs altimetry)

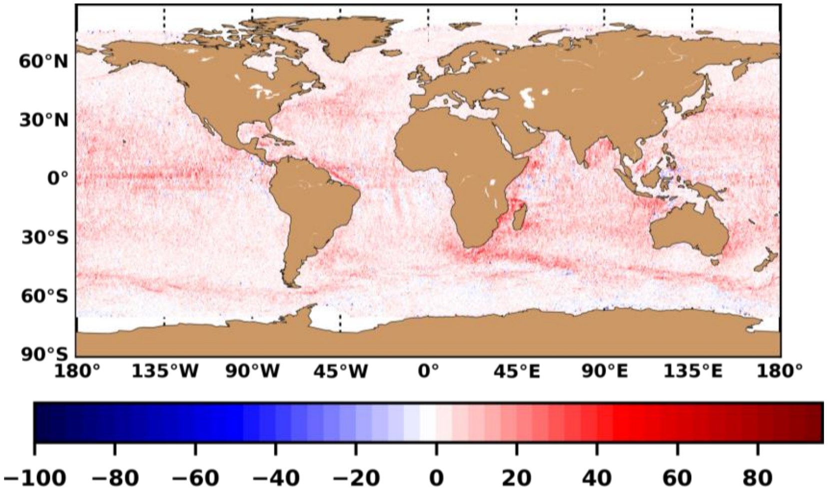
Introducing a physical processes may drastically improves the results its zone of effect

→ Illustration with large-scale ocean current refraction on wave trains

What is ocean current impact on other wave quantities such as ocean/atm/wave coupling parameters ?

HH Gain (%) for accounting oceanic currents

4-year 2014-2017 sensitivity test with Global wave Reanalysis

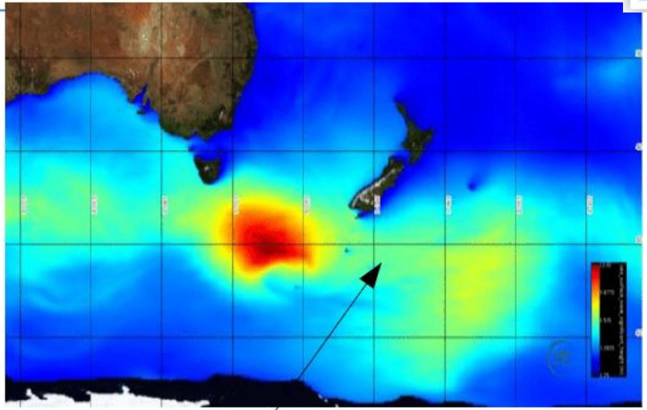


$$HH = \frac{\sqrt{\overline{((Model(t) - Obs(t))^2}}}{\overline{Model(t).Obs(t)}}$$

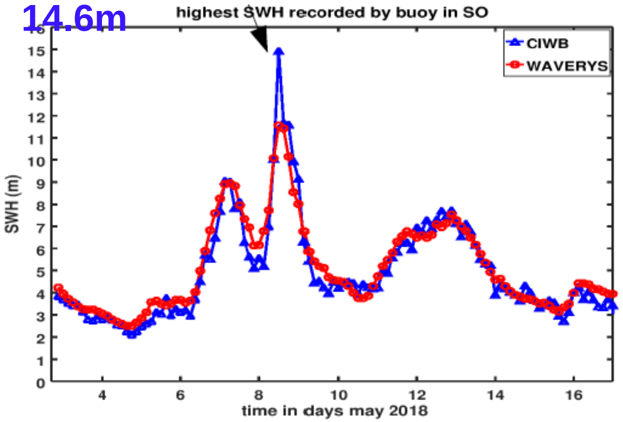
HH index: (Mentaschi et al. 2013), unbiased RMSE based metrics HY2-A altimeter as Obs

Wave extremes (at buoys)

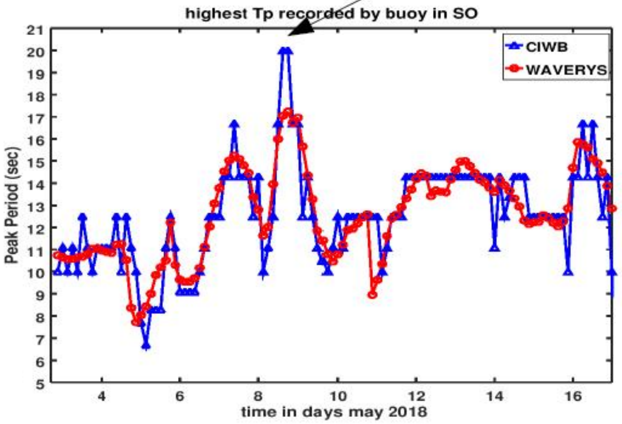
- Hs and Tp timeseries from WAVERYS and buoys at **Campbell island** during a severe storm
- Very good phasing, but underestimation due to lack of resolution, ERA5 winds
- Long waves captured by wave spectra assim (Aouf et al 2021)



Underestimated Hs peak of 14.6m



Long wave of Tp 20 sec



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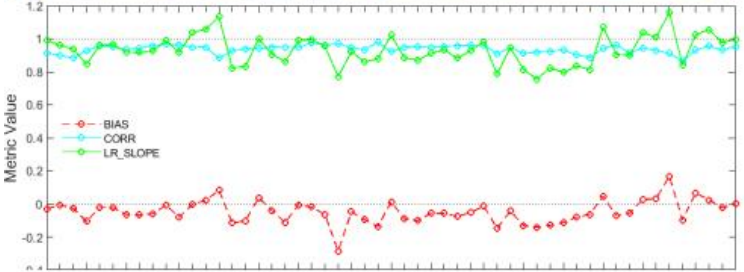
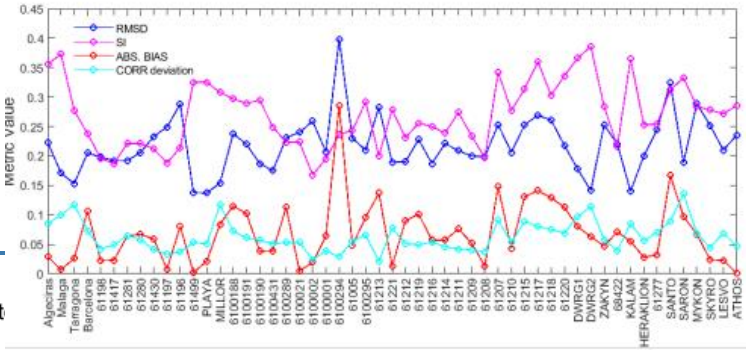
Mediterranean wave reanalysis validation

BLUE OCEAN

- Wave data validation rely mainly on
  - Satellite-derived altimetry (SWH only), good coverage and repetitivity but must stay independent
  - In-situ observation from mooring buoys (multivariate: SWH, Peak and Mean periods, Mean wave direction), very limited in number, more coastal than deep waters
  - HF radars : limited to small coastal areas

Validation of Med wave MYP from wave buoys (SWH) →

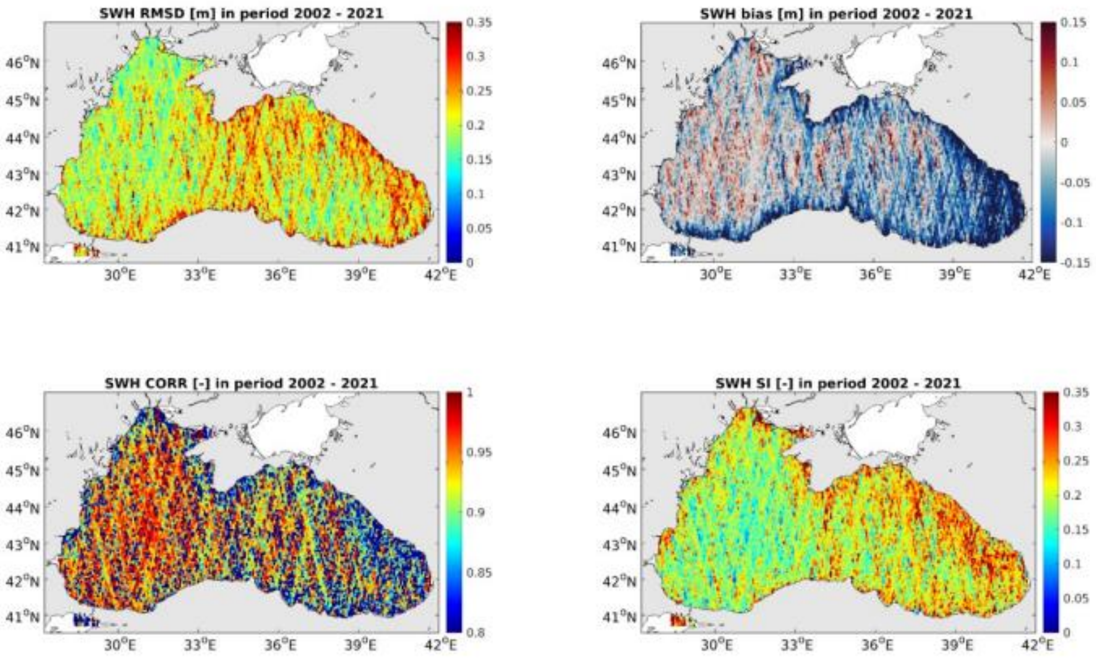


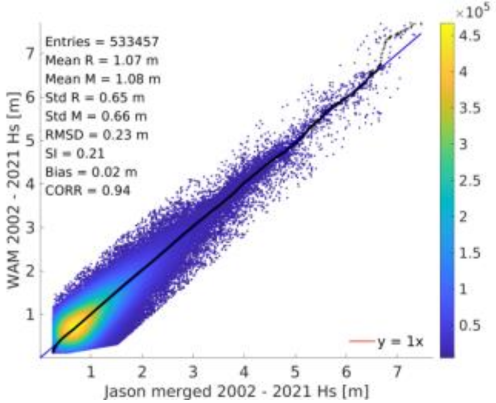


Intercomparison looks at seasonal variability, mean annual and interannual and quantiles/ extremes / trends

Black Sea wave reanalysis validation

Validation of BS wave MYP from Jason 1,2 & 3 : no wave buoys available locally and satellite data starts in 2002 !



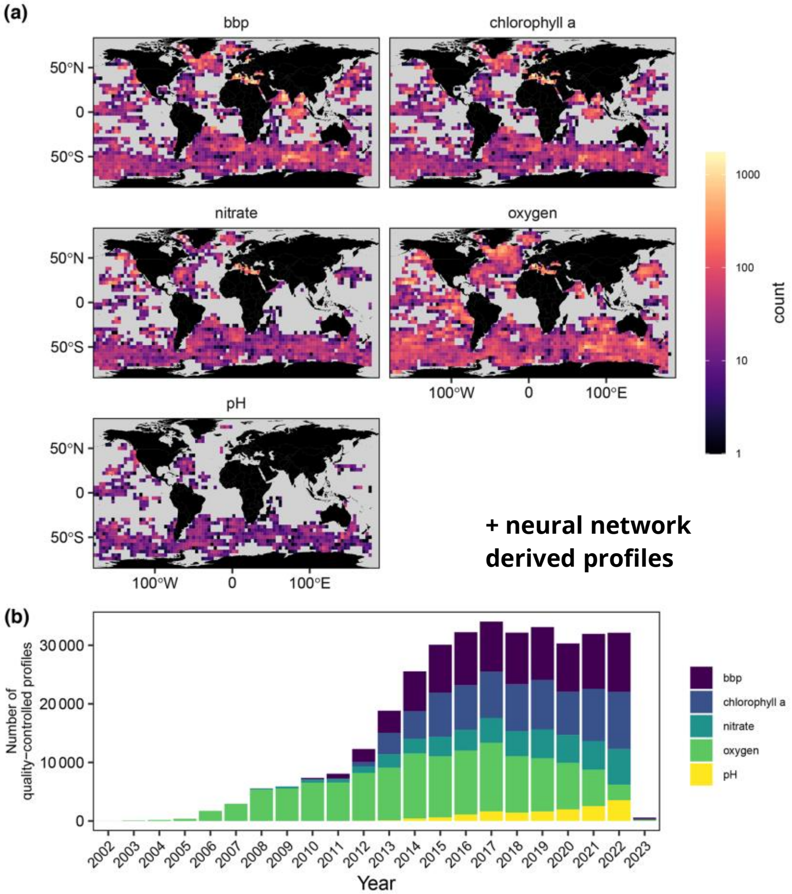


Evaluation of Ocean Reanalyses – Green Ocean

Copernicus Marine Service

GREEN OCEAN

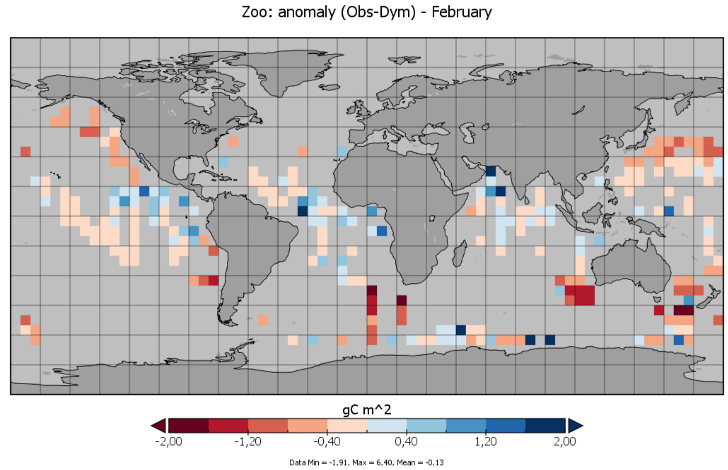
Bio Argo floats



+ neural network derived profiles

From Mignot et al, 2023 EGU biogeosciences https://doi.org/10.5194/bg-20-1405-2023

Example for Micronekton reanalysis :
Zooplankton model-observation difference maps



Observations from COPEPOD database
https://www.st.nmfs.noaa.gov/copepod/

implemented by MERCATOR OCEAN INTERNATIONAL

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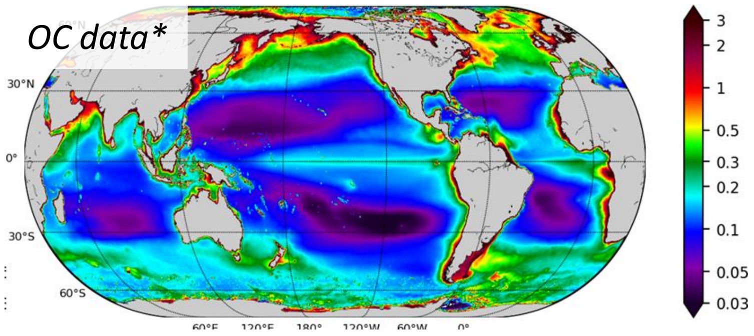
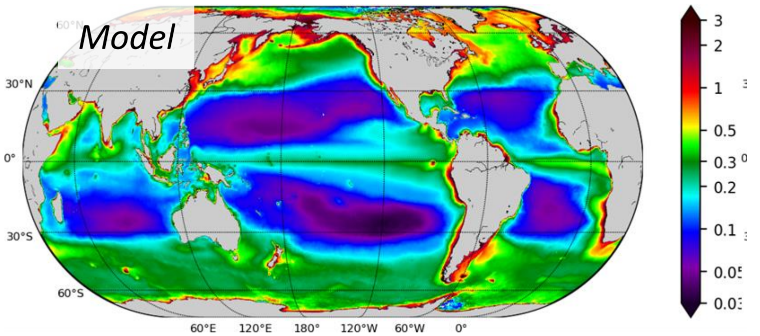
Evaluation of Ocean Reanalyses – Green Ocean

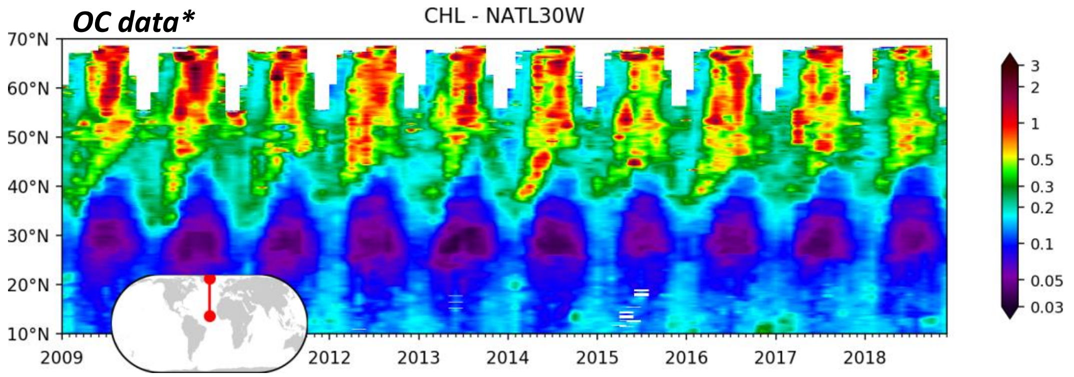
GREEN OCEAN

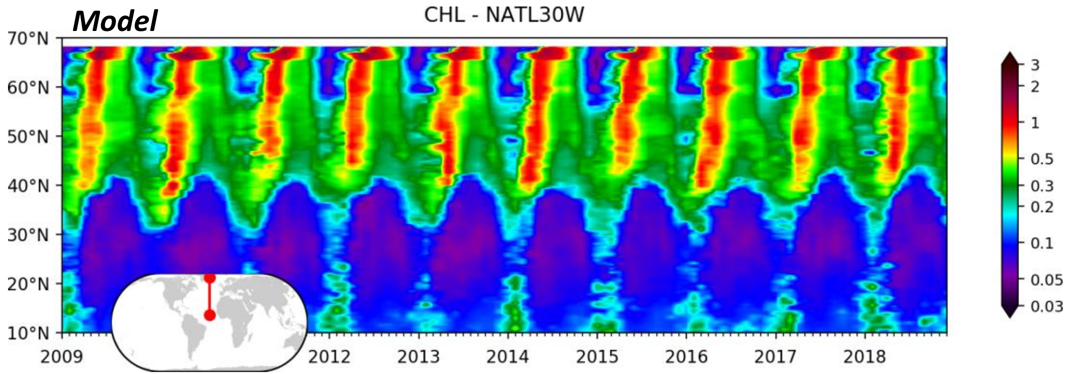
Surface CHL 2009-2018 mean





Bloom in North ATL – seasonal dynamics

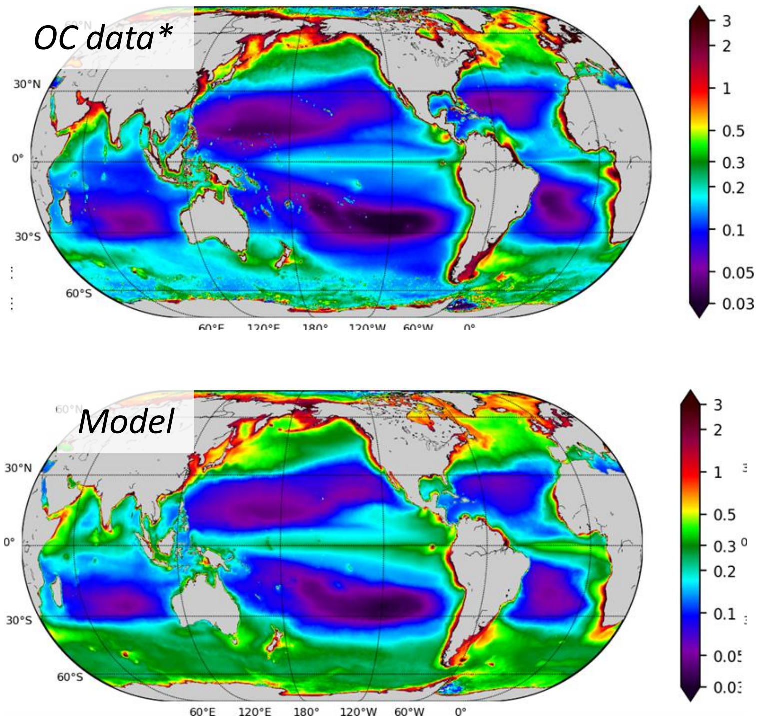




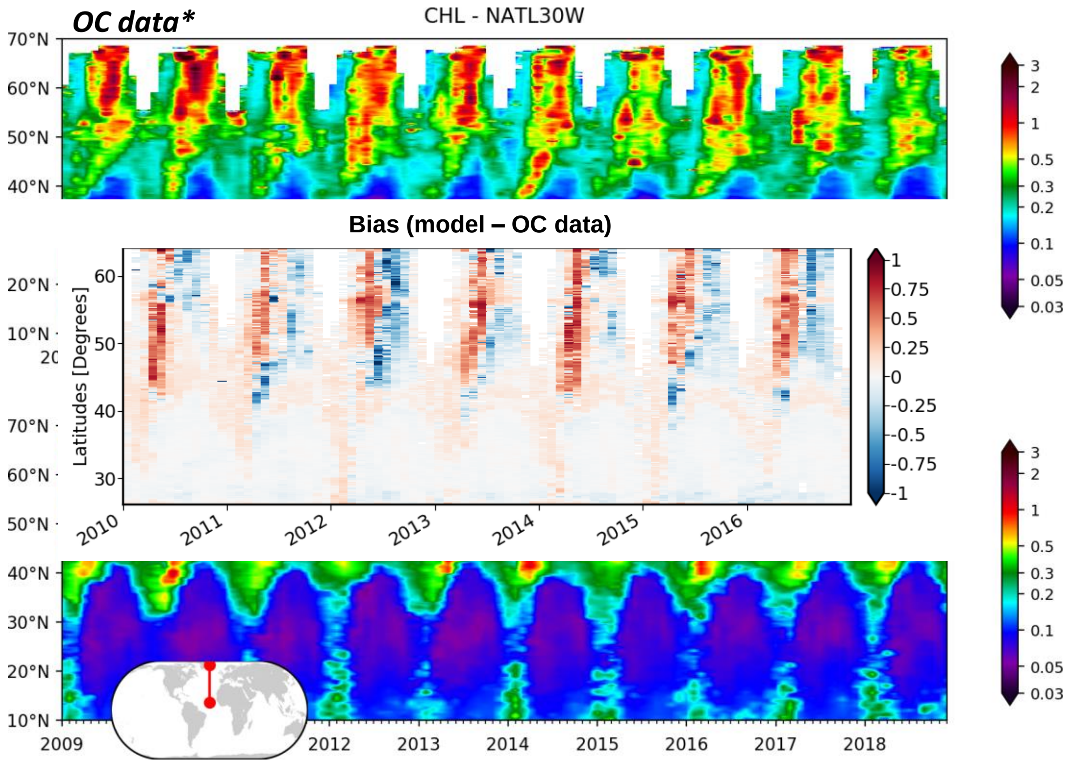
** CMEMS L4 monthly product (not the assimilated data, but still only partially independant…)*

Evaluation of Ocean Reanalyses – Green Ocean

Surface CHL 2009-2018 mean



Bloom in North ATL – seasonal dynamics



** CMEMS L4 monthly product (not the assimilated data, but still only partially independant…)*

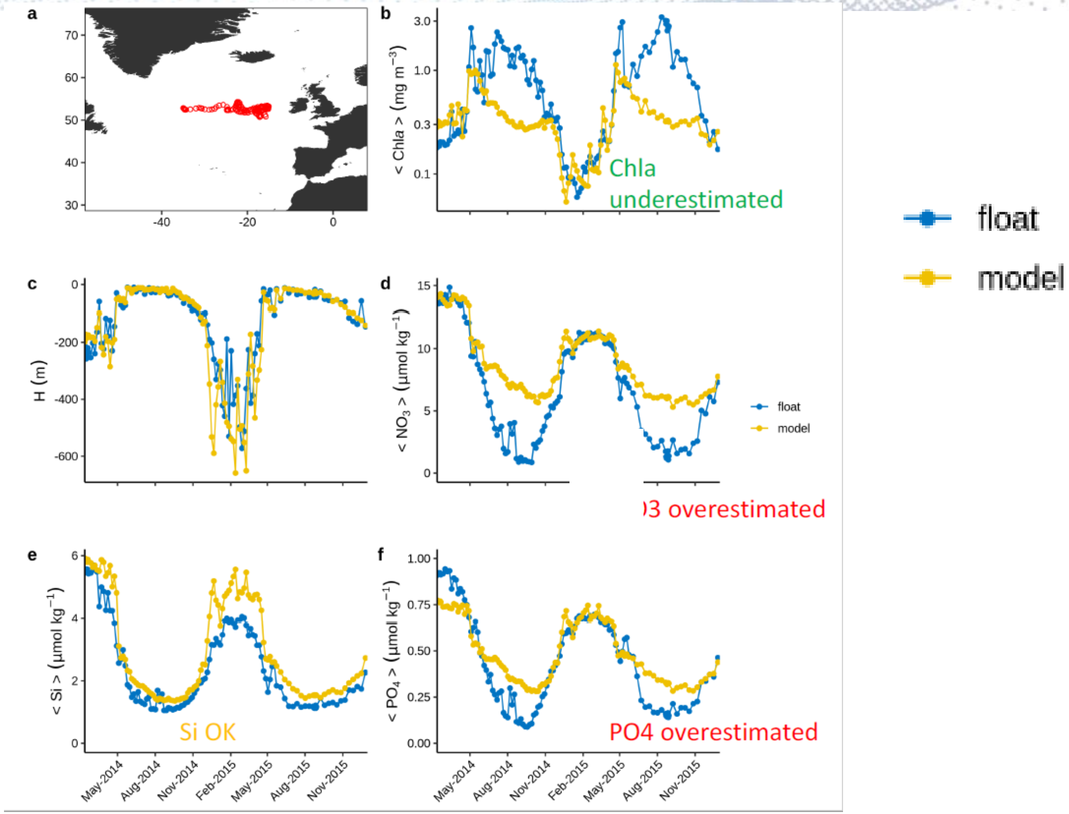
North Atlantic Bloom

Focus on the North Atlantic Bloom

- The seasonal cycle of the mixed layer depth, Chla and nutrients is typical of the North Atlantic bloom dynamics

- The seasonal cycle of <Chl*a*> and nutrients is well approximated by the model with the timings of minima, maxima and the onset of the bloom being correctly represented

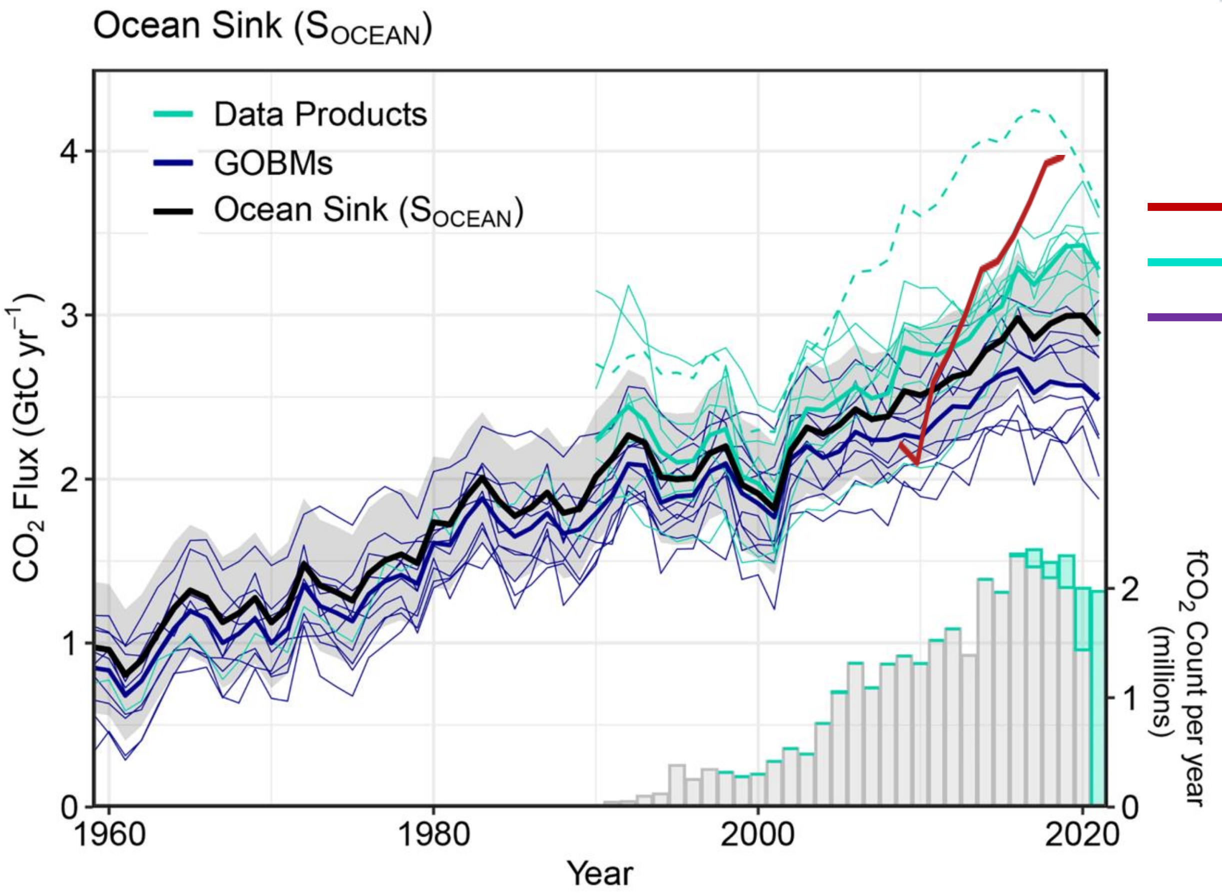
- the summer-<Chl*a*>-maximum is underestimated and the summer-<NO_3>-minimum and summer-<PO_4>-minimum are overestimated while the summer-<Si>-minimum is correctly represented.



Mignot et al, personal communication

Ocean carbon sink

From the Global Carbon Budget, (Friedlingstein et al 2022)



NRT analyses

Obs-based products

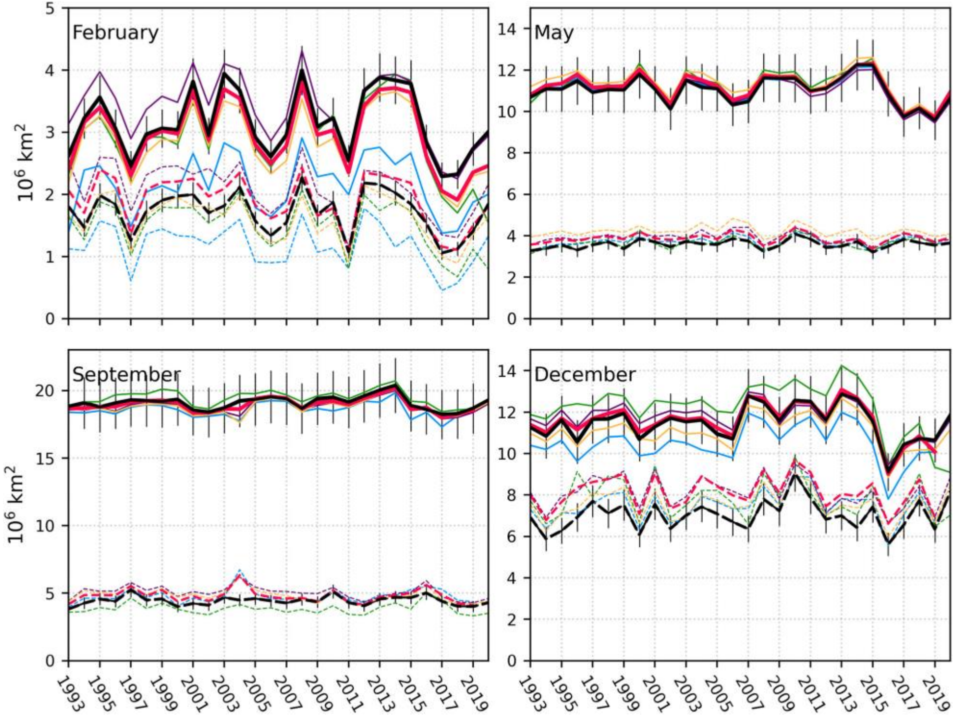
Model-based products

Development of pCO2 assimilation in progress

Copernicus Marine Service

Evaluation of Ocean Reanalysis – White Ocean

WHITE OCEAN



Iovino et al. (2022)

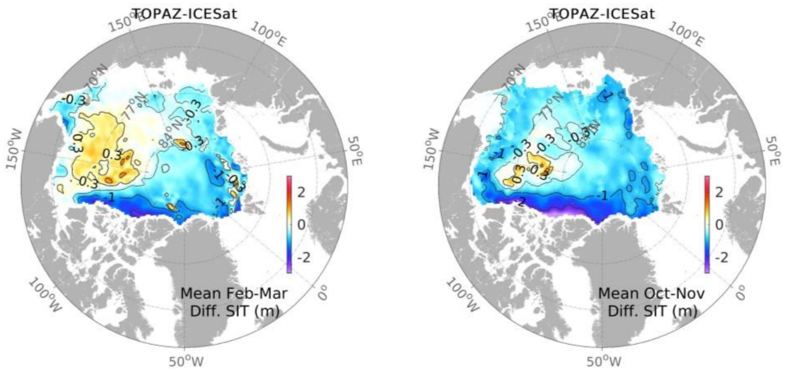
- Sea ice extent is generally well reproduced in reanalysis, within the uncertainties of observations
- Derived quantities from the prognosed sea ice concentration such as MIZ (Marginal Ice Zone) are improving.

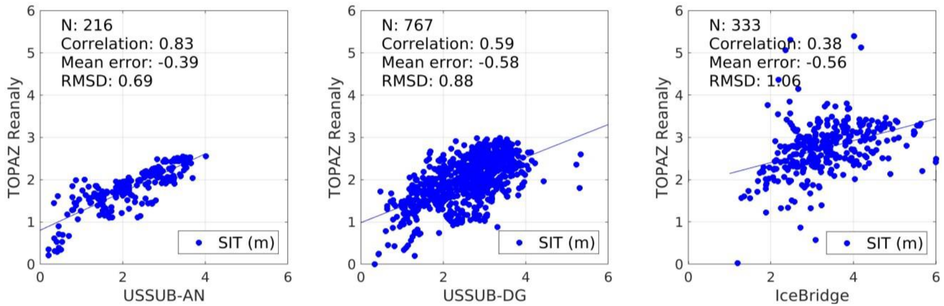
Antarctic SIE GREP
Antarctic SIE CDR/NSIDC
Antarctic MIZ GREP
Antarctic MIZ CDR/NSIDC

thin lines: individual members

… MIZ interannual variability is better captured by the ensemble-mean GREP than by individual reanalyses.

Sea ice thickness and volume



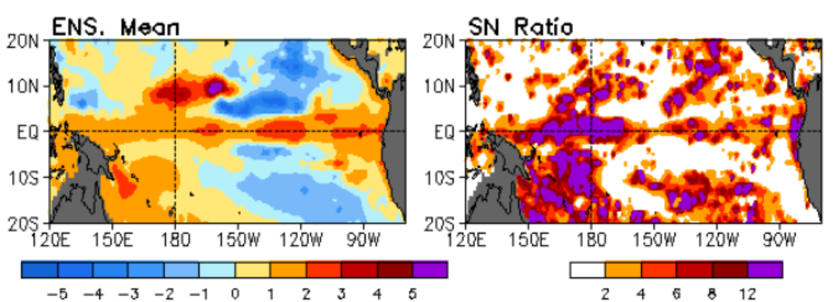


- Large uncertainties in reanalyses and in the observations in terms of thickness (measured by satellite and in situ) and volume
- Typical bias: underestimation along the North American continent and overestimation in Beaufort gyre

MERCATOR OCEAN INTERNATIONAL

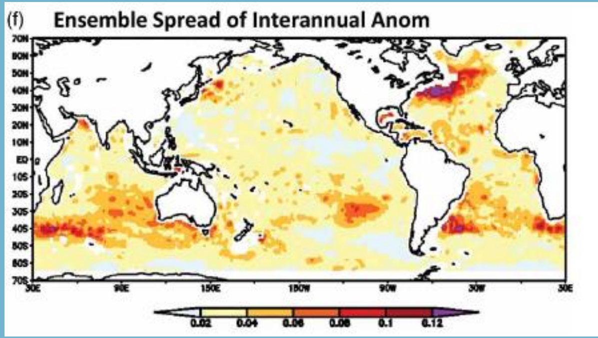
100 m temperature anomaly

From https://www.cpc.ncep.noaa.gov/products/GODAS/multiora_body.html



Ensemble spread 0-700m salinity anomaly

From Balmaseda et al (2015)

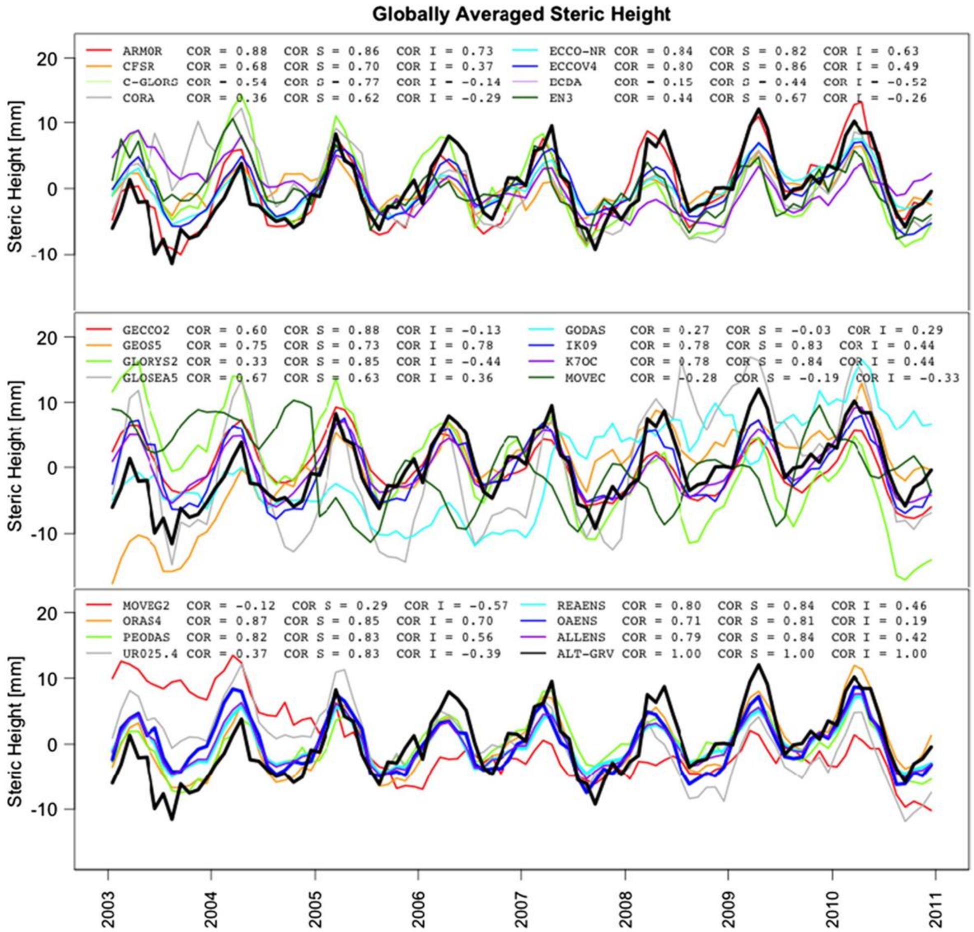


Validation/intercomparison

The Ocean Reanalyses Intercomparison Projects (ORA-IP, EOS COST, multi ORA)

Steric Sea Level (ORA-IP)

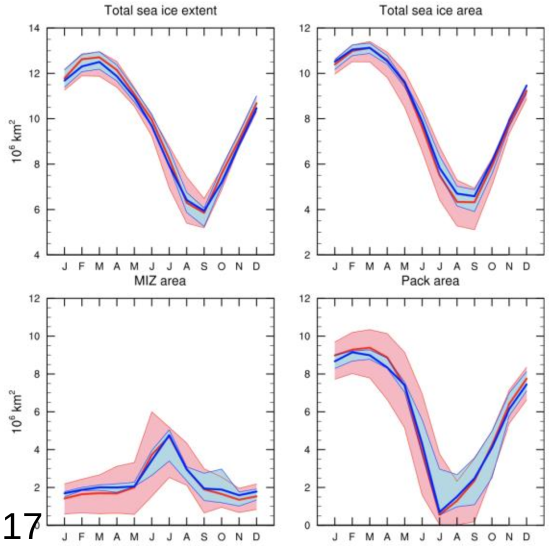
- A significant high correlation at both global and regional scale with satellite observations , and the ensemble of ocean reanalyses outperforms that of objective analyses, in particular in the Southern Ocean.
- The ensemble of reanalyses and objective analyses are in good agreement
- large uncertainties remain for the inter-annual trends.

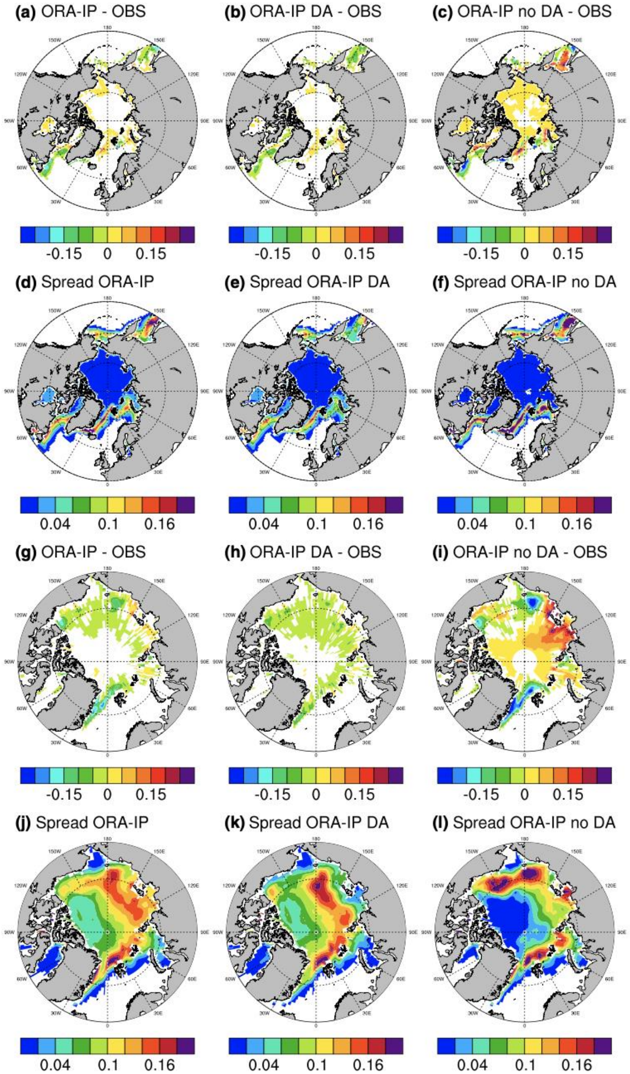


Storto et al., 2017

Sea Ice (ORA-IP)

- The comparison reveals an overall agreement in the reconstructed concentration fields, mainly because of the constraints in surface temperature imposed by direct assimilation of ocean observations, prescribed or assimilated atmospheric forcing and assimilation of sea ice concentration.
- The seasonal cycle is consistent as well.

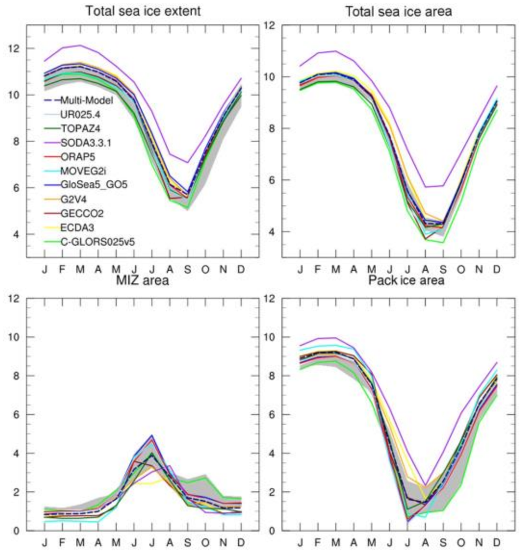




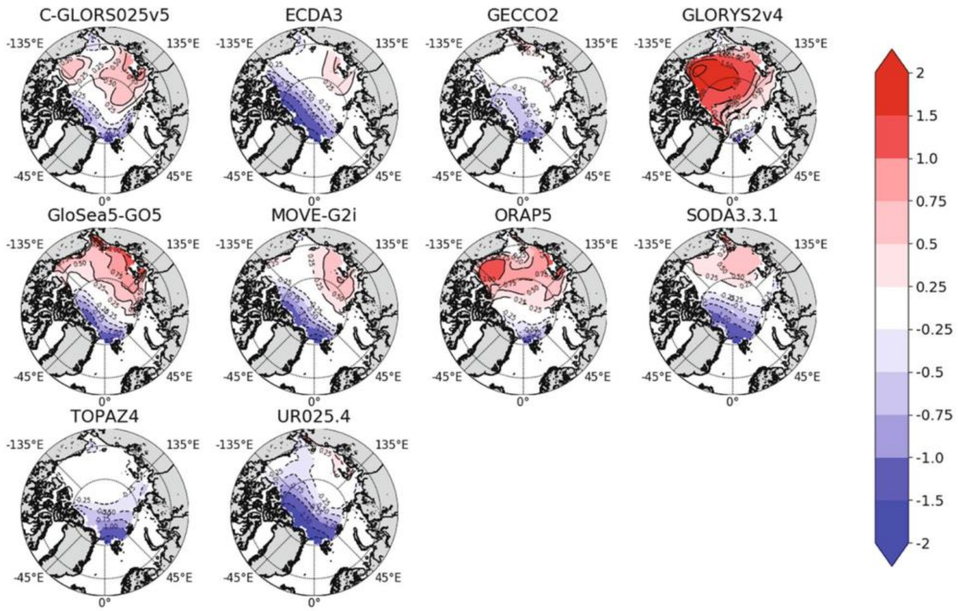
Chevallier et al., 2017

Sea Ice (ORA-IP) - Latest work

- For the multi-ORA mean state, we found that deviations from observations were typically smaller than individual ORA anomalies, often attributed to offsetting biases of individual ORAs.



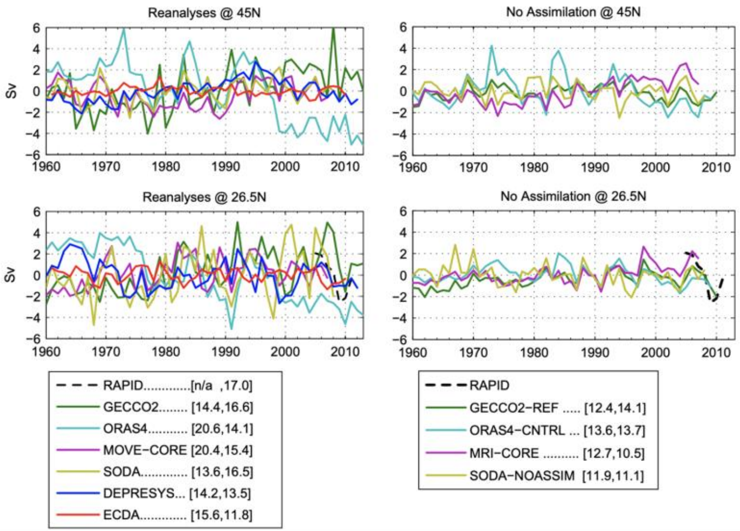
The 2000–2012 mean difference of the ORAs to the ITRP sea-ice thickness (m) in February–March

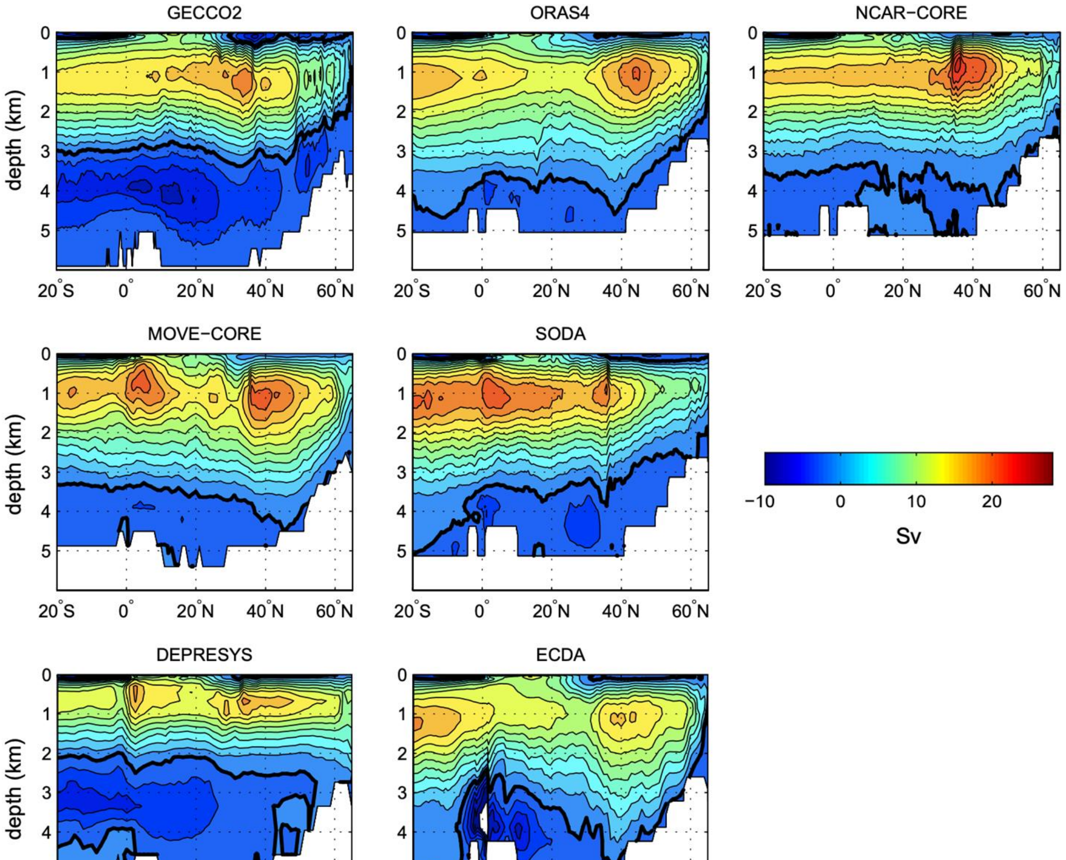


Uotila et al., 2019

AMOC (ORA-IP)

- the reanalysis products tend to have greater AMOC mean strength and enhanced variance
- the reanalysis products are less consistent in their year-to-year AMOC changes.

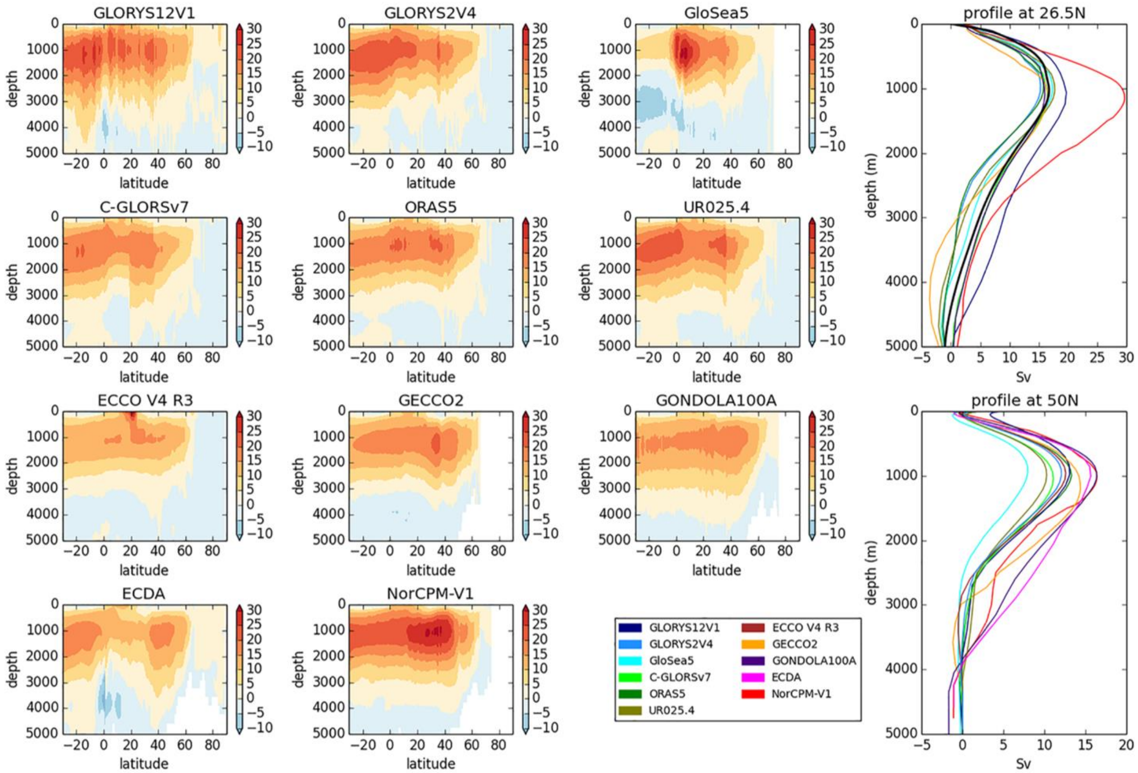




Karspeck et al., 2017

AMOC (ORA-IP) - Latest work

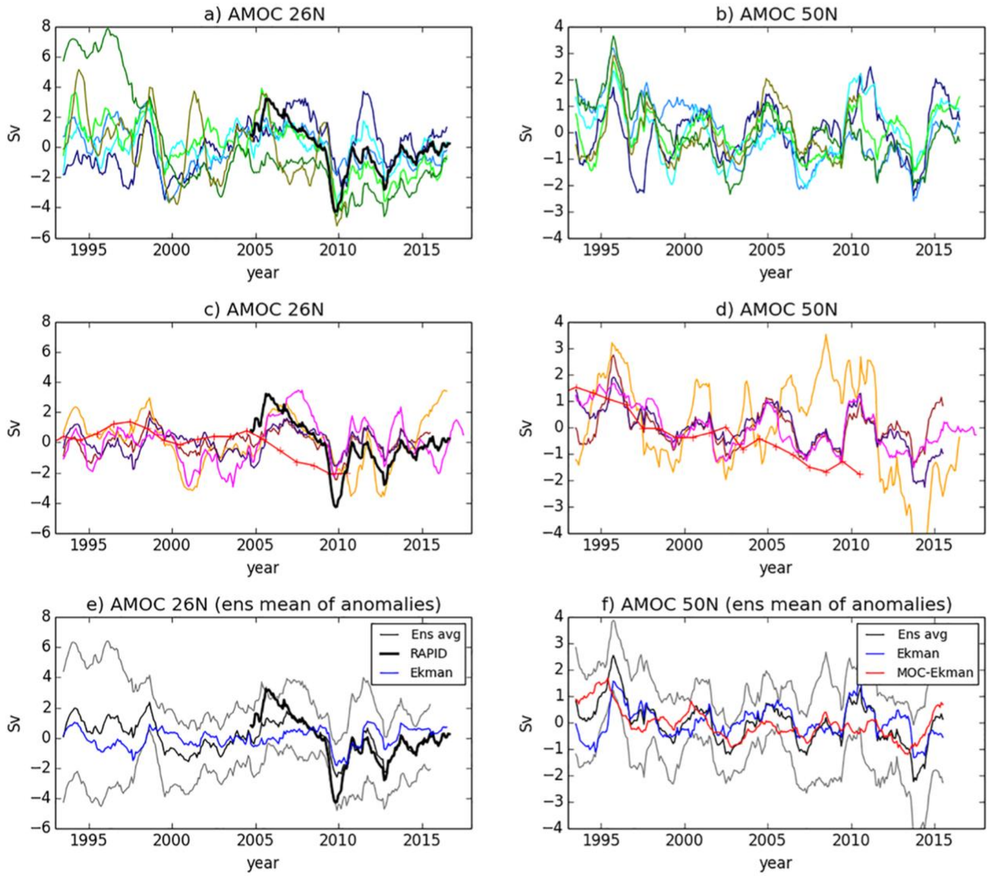
- At 26.5°N the reanalyses mostly agree with the independent observational estimates of mean AMOC strength
- NorCPM-v1 is an outlier in the mean comparisons because it uses anomaly assimilation. GECCO2 is also an outlier in several comparisons, particularly of variability. This may be because it was run over several short (5 year) windows.



Jackson et al. 2019

AMOC (ORA-IP) - Latest work

- variability in the AMOC at both 26.5°N and 50°N is consistent across the ensemble and in agreement with independent observations, which contrasts with previous intercomparison results from Karspeck et al. (2017).



Jackson et al. 2019

Summary

Ocean reanalyses are the only information we have for many areas of the ocean

It is important to keep intercomparing them on a regular basis: intercomparison exercizes for in depth assessment + multi-model ocean state monitoring tools

Ensembles of reanalyses : already done by some groups -> a challenge for Copernicus Marine Service in the coming years

- Blue Ocean reanalyses :
  - good results during the ARGO era -> 20 years in 2025
  - Some challenges for the coming years: historical reanalyses, deep ocean and coastal zones …
- Green Ocean reanalyses :
  - Good results in terms of interannual signals of Chl
  - Seasonal signals are phased thanks to data assimilation
  - some challenges for the coming years: assimilation of pCO2, bio argo …
- White Ocean reanalyses :
  - Good results in terms of sea Ice concentration and average sea ice extent
  - improvements needed in sea ice thickness and leads
  - Some challenges for the coming years: Marginal Ice Zones …

- **Objectives:** Refine our knowledge of the users' needs in terms of model reanalyses of the ocean, better define what historical reanalyses are needed, make the link with ocean reanalyses specialists worldwide

- All ocean reanalysis products will be considered, from ocean **physics**, including surface **waves**, to **sea ice** and **biogeochemistry** or biology, from **global** to **regional** scales, from long reanalyses covering the 20th century to reanalyses targeted for ocean variability monitoring over the recent decades.

- **New ORA-IP initiative**
    1) Strengths and weakness of current ocean reanalyses
    2) Improvement of reanalyses compared to the last ORA-IP evaluation
    3) Guidance for future developments
    4) Provide reference assessments for ocean reanalyses users