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The Copernicus global 1/12° oceanic and sea ice GLORYS12 reanalysis

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Description of GLORYS12

The eddy-resolving reanalysis GLORYS12 (G12)

- Based on the current CMEMS global real-time forecasting system PSY4V3
- Much more modern than the previous reanalysis at ¼° GLORYS2V4
- First European high-resolution global reanalysis
- Covers the 1993-present altimetry period
- Ocean and sea ice model based on the NEMO platform
- Horizontal resolution of 1/12° (9.25 km at the equator and around 4.5 km at subpolar latitudes)
- 50 vertical levels
- Ocean model driven at the surface by ERA-Interim atmospheric reanalysis
- Observations assimilated by means of a reduced-order Kalman filter
- Along track altimeter SLA, satellite SST and sea ice concentration, and in situ T/S vertical profiles jointly assimilated
- 3D-VAR scheme providing an additional correction for the slowly-evolving large-scale biases in T/S.

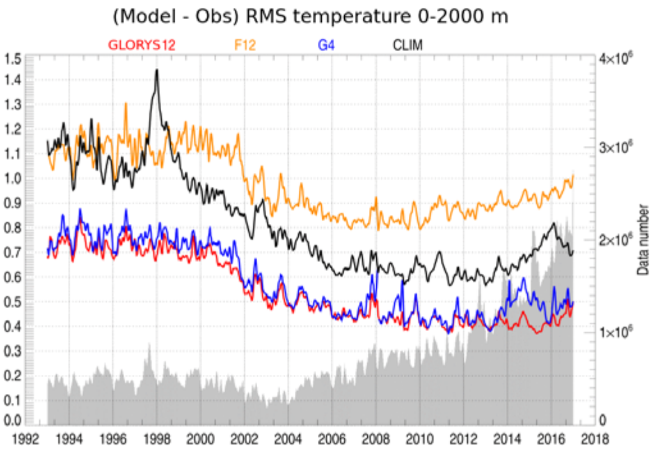
Many updates / improvements compared to GLORYS2V4

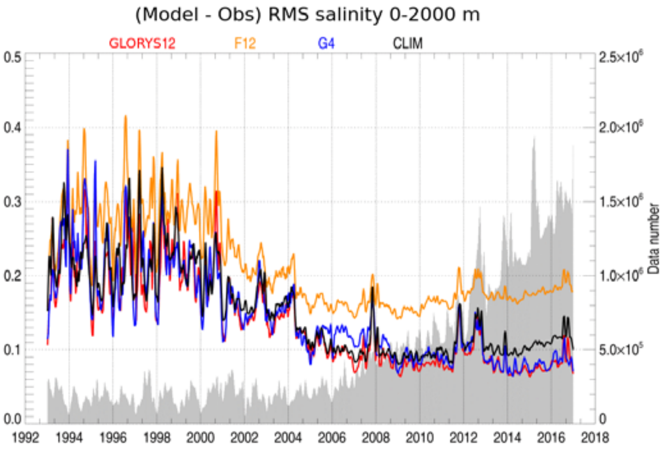
- Accounting for the global steric effect in the model sea level
- New seasonal T/S observation errors for the assimilation of in situ T/S vertical profiles
- Adaptive tuning of observational SLA and SST errors
- Additional quality control on the assimilated T/S vertical profiles based on dynamical height criteria
- Assimilation in the deep ocean (below 2000 m) of climatological T/S vertical profiles

Sister simulations starting from the same initial condition as GLORYS12

- Free simulation at 1/12° maintaining the same ocean model tunings (F12)
- Reanalysis at 1/4° only differs from GLORYS12 by the spatial resolution (G4)

Comparison with T/S vertical profiles (in °C/psu)





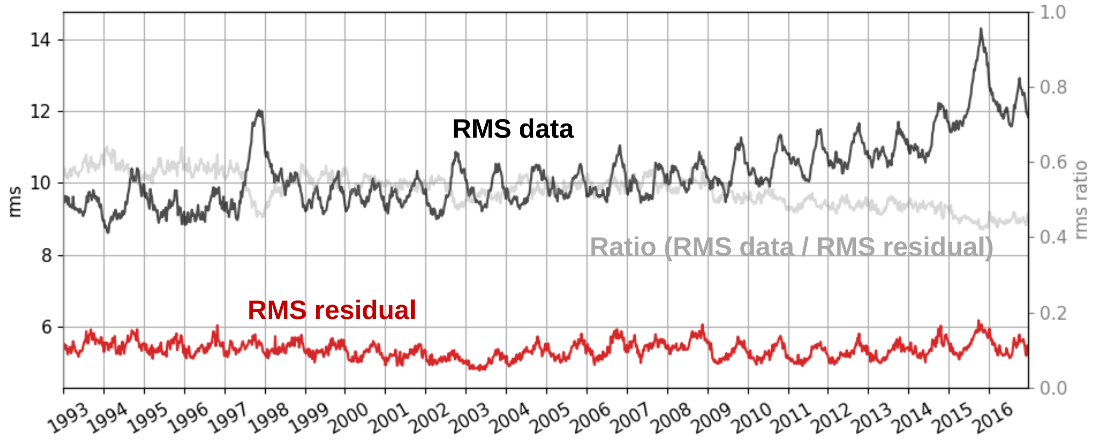
Between 1993 and 2002, departures from in situ observations are around 0.75 °C for temperature and 0.2 psu for salinity.

The average accuracy reaches **0.45 °C** in temperature and **0.1 psu** in salinity during the Argo period, thanks to the increase of the number of observations assimilated.

The departure between climatology and observations is an indicator of the minimum performance that the system must achieve. G4 and GLORYS12 temperatures are both significantly more accurate than the climatological temperature throughout the period.

The free simulation (F12) RMS differences reach **0.1 °C** for temperature and **0.2 psu** for salinity, twice the RMS departures obtained with GLORYS12. Worse, we can observe a tendency for these errors to increase between 2008 and 2016, showing the drift of the system without data assimilation.

Comparison with satellite Sea Level Anomaly (SLA in cm)



GLORYS12 is close to altimetric observations with a residual RMS difference of the order of **5.5 cm** on global average (red curve). This RMS difference is consistent with the a priori prescribed observation error, which is equal to the sum (in variance) of the SLA instrumental error (about 2 cm on average) plus the Mean Dynamic Topography error (about 5 cm on average, with the largest values being located on shelves, along the coast and mesoscale activity or sharp front areas).

Moreover, the model is able to explain the observed signal (black curve) as shown by the ratio of RMS residual to RMS data (light grey curve), which decreases with time and converges towards a value much less than one. The performance of GLORYS12 remains stable and even improves while the variance of observations increases.

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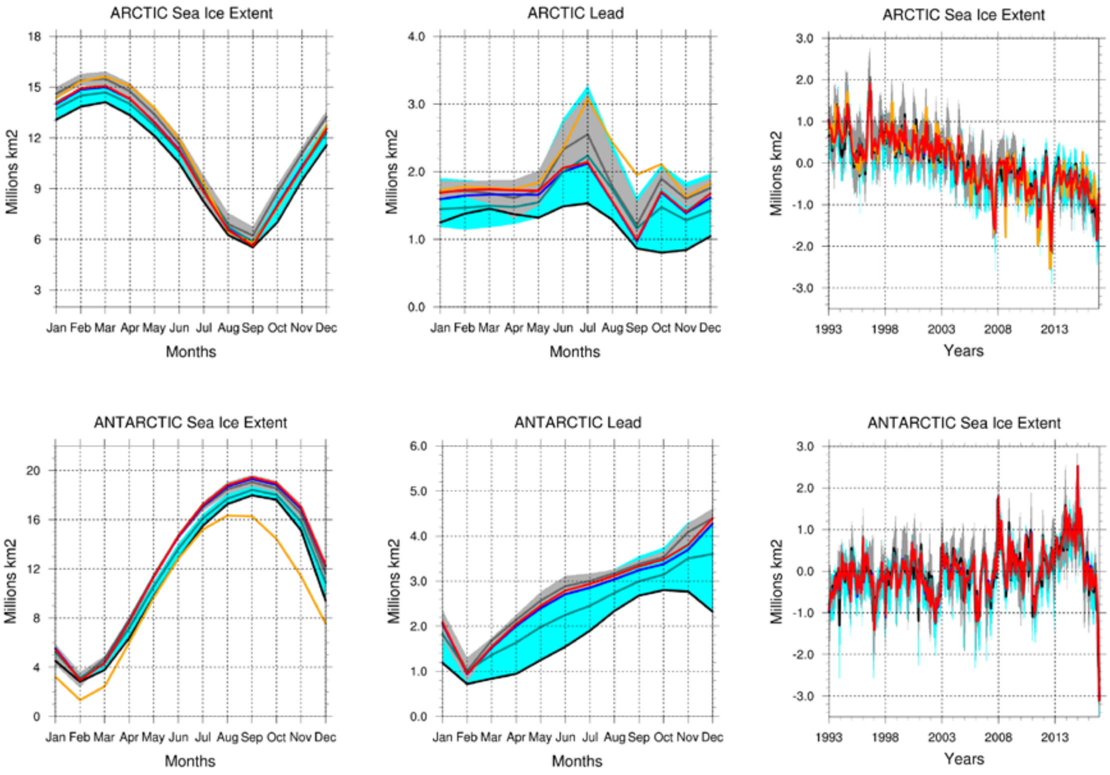
Comparison with satellite sea ice observations

GLORYS12 F12 G4 GREP (spread) obs (spread)

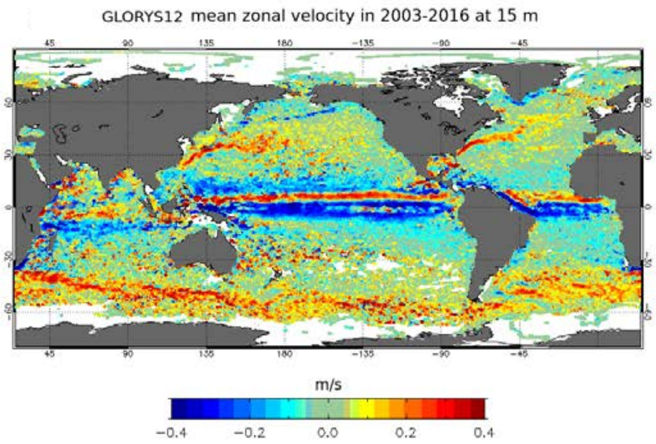


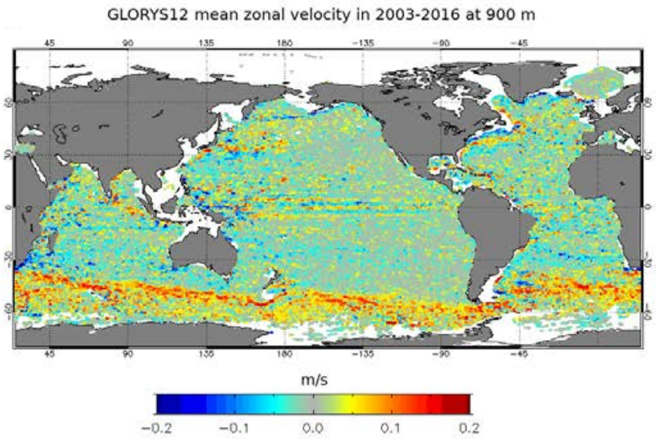
Mean seasonal cycle **Interranual monthly variability**

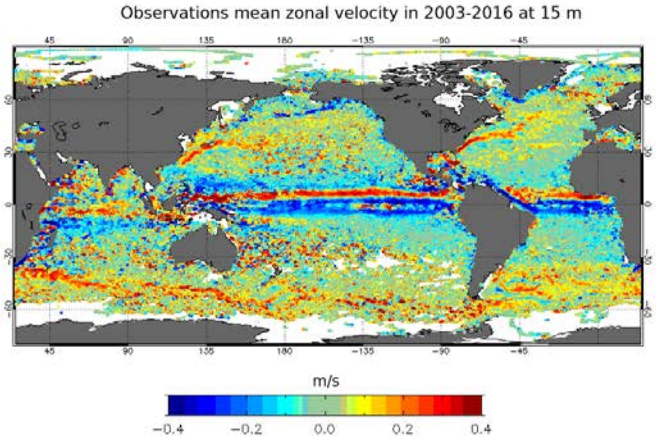
GLORYS12 captures well the low frequency variability (interannual and long-term variability) of the sea ice extent both in the Arctic and Antarctic Oceans.

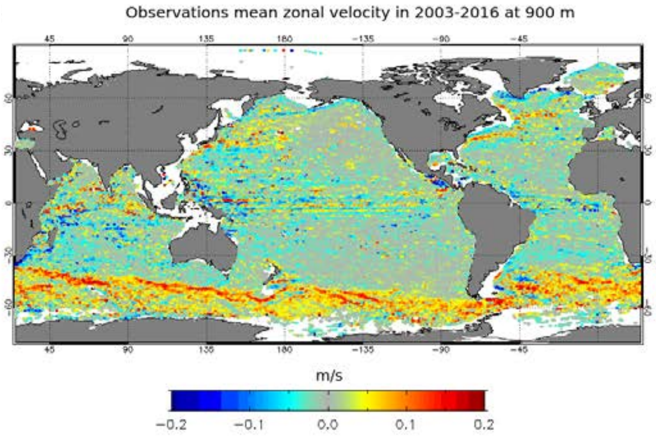
The assimilation of sea ice concentration improves the seasonal cycle of the Arctic sea ice extent but, in the same time, weakens the presence of leads and creates thicker ice. The representation of the sea ice cover is also significantly improved in Antarctica, where the model alone has difficulties in stabilizing the coupling between the sea ice and the ocean underneath. Estimates of leads are found larger in models than in observations which exhibit large uncertainties.

Velocity validation against drifter's estimation









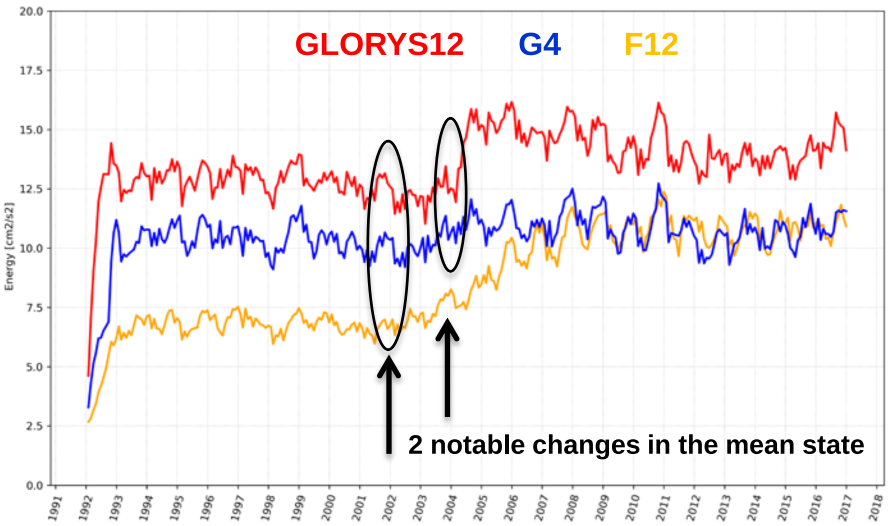
We use velocity obs from the drogued-only 15 meters drifter dataset.

The general circulation with major currents is well represented. The main shortcoming concerns the tropical Pacific South Equatorial Current which is too strong in GLORYS12. The ACC is slightly too strong near the surface.

We now use estimated velocities near 900 m derived from Argo profiling floats.

There is a good general agreement between the observations and GLORYS12. The ACC has the right intensity. The only notable differences concern the striations of the equatorial band which are slightly underestimated and not reproduced at the right latitude by GLORYS12.

Ocean variability: three-dimensional EKE time evolution

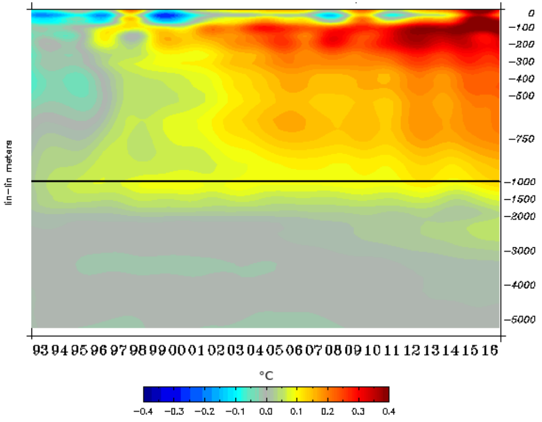


The **January 2002 change** of mean state and seasonal amplitude occurs in the three simulations. This change can therefore only come from atmospheric forcing. The spatial resolution of SST products used during the production of ERA-interim changed to 1° to 0.5° and this change resulted in an increase in small-scale variability in the atmospheric reanalysis winds, and part of this wind variability increase is transmitted to the ocean model.

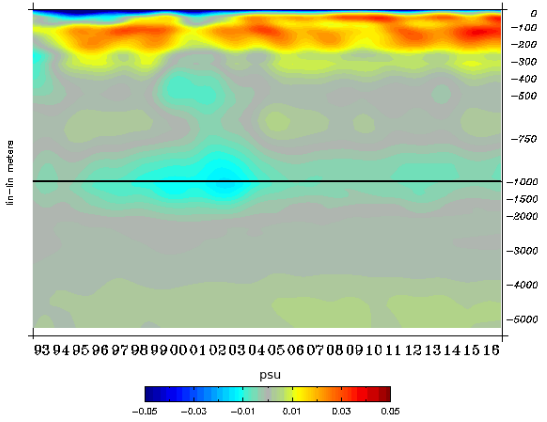
The **January 2004 change** is explained by the change in the time window (from 3 months to 1 month) to compute the T/S bias correction and by the increase in the number of profiles entering in the reanalysis.

Time evolution of T/S anomalies

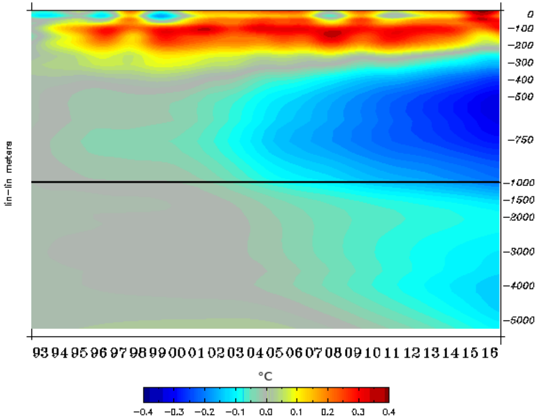
GLORYS12 temperature anomaly



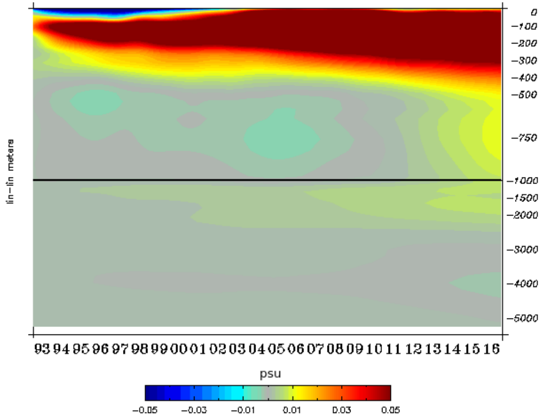
GLORYS12 salinity anomaly



F12 temperature anomaly



F12 salinity anomaly

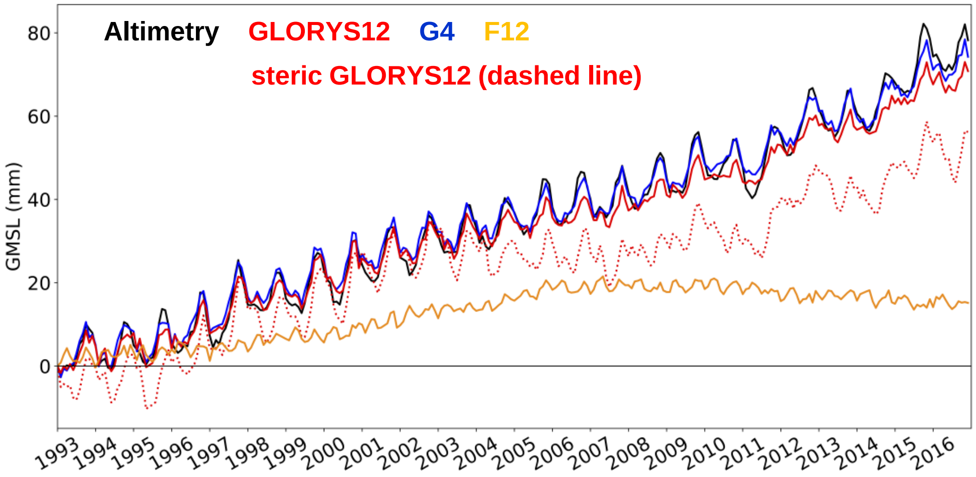


An anomaly for a specific date is defined as the difference between the value at this current date and the initial state of the simulation.

GLORYS12 show a warming (a little too strong) in the 0-1000 m layer and a freshening in the first 1500 m (which occurs notably in the ACC) before the arrival of Argo floats in large quantity at the start of 2004.

January 2002 seems to be a crucial date for F12 which presents a strong cooling in temperature in the 200-1000 m layer, spreading at depth aftertimes. This behavior can be correlated to the change in the atmospheric fields. The salting of the F12 simulation in the first 500 m shows a strong salty drift of the model without data assimilation.

Time evolution of sea level

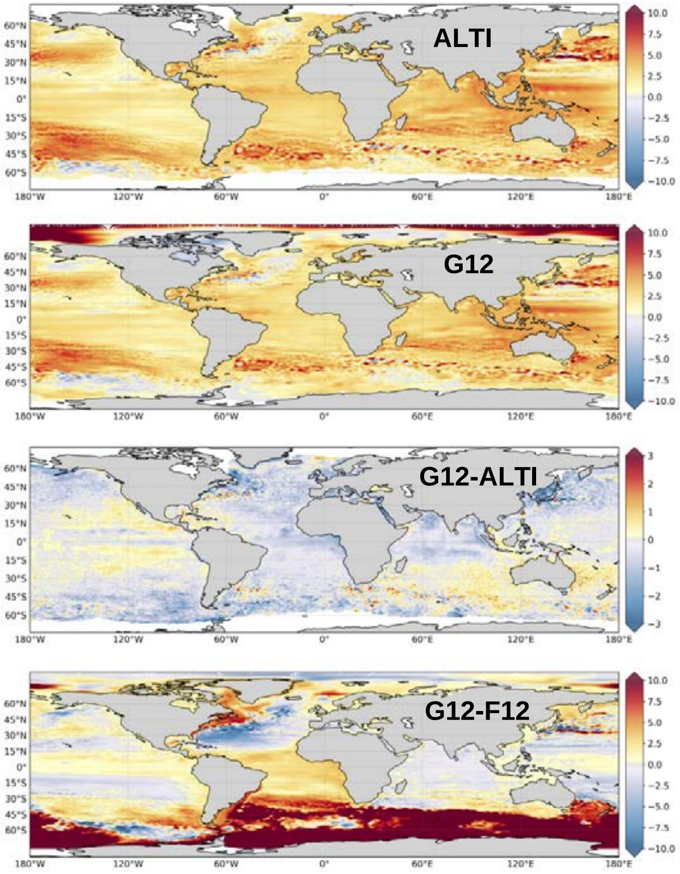


The evolution of GMSL in **GLORYS12 (2.77 mm/year)** is in agreement with that from **altimetric data (3.00 mm/year)**.

However, decomposing the steric and mass components of GMSL rise shows that the reanalyses have a too large steric component. In GLORYS12, the global mean thermosteric sea level trend over 2005-2016 is 2.43 mm/year. Thus, thermal expansion explains 70% of the GMSL trend of 3.20 mm/year over the same period in GLORYS12, while it should only account for around 40% of the GMSL.

The reanalyses clearly outperform the free simulation which shows a modest sea level rise (0.75 mm/year) mostly due to a large cooling of the Southern Ocean.

Regional sea level trends over the 1993-2016 period



Regional sea level trends are correctly represented in GLORYS12. The main patterns of sea level trends observed by altimetry are captured in GLORYS12, with the largest trends in the western tropical Pacific, northwestern Pacific, northern Southern Ocean, and the lowest trends in the subpolar North Atlantic, off Alaska, in the eastern tropical Pacific and in the southern most parts of the Pacific sector of the Southern Ocean. Over the global ocean (covered by altimetry), the trend differences between GLORYS12 and altimetry have a median value of **- 0.26 mm/yr** and a standard deviation of **0.60 mm/year**.

Data assimilation clearly and strongly improves the representation of regional sea level trends. This is especially true in the Southern Ocean, where the large negative sea level trends in F12 caused by a strong cooling and unrealistic loss of sea ice cover have been corrected through data assimilation in GLORYS12.

Conclusion

As the first European high-resolution global reanalysis, GLORYS12 is a success with:

- A realistic representation of key oceanic quantities (sea level, water mass properties, mesoscale activity and sea ice extent).
- A good representation of oceanic variability on a large range of scales going from meso to global and from daily to decadal scales.
- Trends better controlled and no compensation (exotic transient signals in the previous GLORYS2V4 reanalysis).

GLORYS12 outperforms its sister simulations at lower horizontal resolution (1/4°) or at the same resolution but without data assimilation, even though it slightly suffers from the unregular evolution of the in situ global ocean observing system.

Several key developments should significantly improve the performance of the next version of GLORYS12:

- New version of NEMO (more coherent Bulk formulation, access to a boundary layer model dedicated to high resolution ocean coupling atmosphere, more advanced sea ice model with the possibility to represent the ice in different categories).
- Inclusion of waves improving surface currents with a change in vertical physics.
- Use of a refined MDT allowing to better represent the equatorial dynamics.
- Use of a 4D approach with the data assimilation scheme, allowing an improvement in the spatiotemporal continuity of mesoscale structures.
- Analysis in a smoothing mode, allowing taking into account observations outside the time window of the current assimilation cycle. This could be efficient in reducing errors, especially in regions where the observations have very heterogeneous spatial coverage in time.
- Improve mass/steric separation during data assimilation with the inclusion of monthly corrections of GMSL instead of a trend.
- Assimilation of sea ice thickness with the aim of improving and better controlling the sea ice volume.
- Use of a systematic correction of the seasonal cycle, estimated over the Argo period and applied for the full reanalysis period, in order to overcome the discontinuity due to the arrival of the Argo array.