A set of global ocean re-analyses for climate applications

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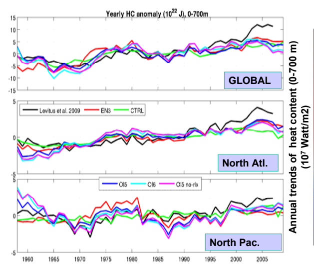
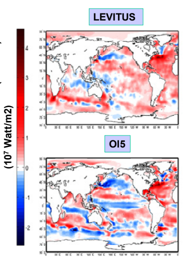
Abstract

This work is intended to provide the description of a set of global ocean re-analyses produced over the last few years at the authors' institutes with the purpose to show the applicability of these products for studies of climate change and variability.
The first re-analyses were conducted with an Optimal Interpolation (OI) assimilation scheme which assimilates only temperature and salinity taken from the EN3 and previous versions of the data set (http://www.metoffice.gov.uk/hadobs/en3) which did not implement any kind of time varying XBTs corrections. On the other way a 3D-Variational approach (3DVAR) was used more recently to produce another set of re-analyses. In 3DVAR, besides the above mentioned hydrographic EN3_v2a data set but with a time-dependent fall rate correction applied to the XBTs, along-track sea-level anomaly (SLA) observations were also assimilated from 1992 onward via a local hydrostatic adjustment scheme. Within this scheme, the sea-level increment is assumed proportional to the water-column integrated density increment, and split into thermo- and halo-steric contributions according to the local structure of the bivariate background-error vertical covariances. We have investigated in particular the impact of the altimeter data and the use of different Mean Dynamic Topographies (MDT) by comparing the re-analyses with observed temperature, salinity and velocity observations.
All the above re-analyses have been validated against a set of high quality in situ observations and independent data. Differences among the re-analyses are evaluated in terms of improvements in the method used to assimilate the data and the quality and amount of observations themselves with the purpose to detect possible sources of uncertainty of the long-term changes of climate indicators, such as the integrated ocean heat content, heat and fresh-water transports and the meridional overturning circulation.
Finally, we highlight the most recent developments along with the future directions of an eddy-permitting re-analysis system.

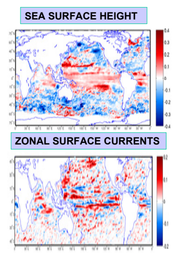
Optimal Interpolation Assimilation of T and S: Heat Content trends (1960-2009)

The INGV/CMCC Optimal Interpolation (OI) scheme is based on a reduced-order analysis with bivariate vertical covariances of temperature and salinity [1]. It is used for long-term (1960-2009) studies of the global ocean variability [7].





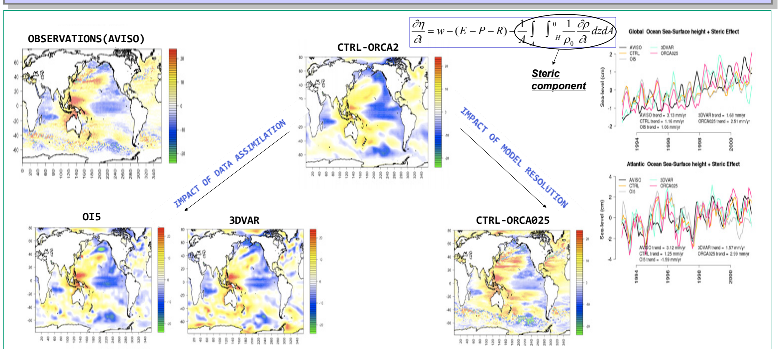
Assimilation improves the performance of variables not directly corrected in some regions (**right:** difference between correlations of OI5 and CTRL with respect to observations)



The warming trends over the last decades obtained by the set of our re-analyses (Table) differ significantly with respect to [5] especially over the most recent period. The differences are smaller on the long-term trend (1962-2001). In general our estimates fall in the wide range of values (0.26-0.95 W m-2 for the years 1993-2006 in [6]) of other recent observation-based estimates of ocean heat content derived by using different methods to treat under-sampled areas or to correct biases from XBTs and other instruments. The two regions where the trends from our best re-analysis (OI5) and [5] show opposite signs are the equatorial upwelling regions in both the Atlantic and Pacific basins where our re-analysis show a cooling tendency.

$J/yr * 10^{22}$ (GLOBAL)	1962-2001	1993-2007
Levitus et al. (2009)	0.25±0.02	0.79±0.08
EN3_v2a objan	0.18±0.04	0.42±0.08
OI5	0.16±0.03	0.42±0.07
OI5-no relax	0.27±0.04	0.30±0.08
OI6	0.25±0.04	0.23±0.07
CTRL (ORCA2)	0.15±0.02	0.38±0.04
CTRL-no relax	0.57±0.02	0.85±0.04

Impact of assim. and resolution: Sea Surface Height trends (mm/yr), 1993-2001



$$\frac{\partial\eta}{\partial t} = w - (E - P - R) - \frac{1}{A}\int_A \int_{-H}^{0} \frac{1}{\rho_0}\frac{\partial\rho}{\partial t}\, dz\, dA$$

Spatial patterns of SSH trends are well reproduced by the model with respect to AVISO, even if values are generally too low. This problem is partially overcome by data assimilation, both with OI and 3DVAR schemes.

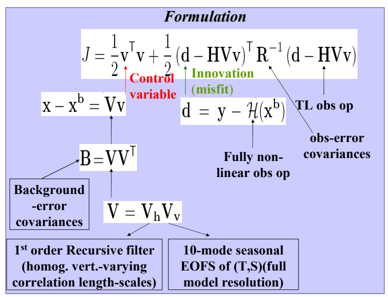
Due to the coarse resolution, ORCA2 cannot realistically reproduce local SSH trends; on the other hand ORCA025 can better reproduce regional SSH trends and their spatial variability.

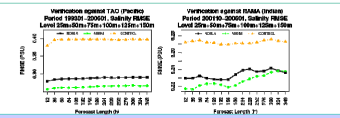
Experiments

Experiment	Duration (years)	OGCM version	Assimilation Scheme	Assimilated Data	Forcing	Surface Damping	Water column damping	River runoff E-P correction
CTRL-ORCA2	52-yr (1958-2009)	OPA8.2 (ORCA2 configuration: 2 degrees, up to 0.5 in lat close to the Equator)	n/a	n/a	Daily ERA40 fluxes, Op. ECMWF fluxes from 2002	SST (Hadisst 1958-1981, Reynolds 1982-2002, op. ECMWF from 2003)	Levitus98 (T,S) climatology, poleward of 60S/60N. Small damping (3 yrs folding time) between 60S/60N	Monthly climatological / daily freshwater fluxes correction
CTRL-ORCA025	44-yr (1958-2001)	NEMO 2.3 (ORCA025 configuration)	n/a	n/a	Daily ERA40 fluxes	SST (Hadisst 1958-1981, Reynolds 1982-2001)	Levitus98 (T,S) climatology, poleward of 60S/60N	Same as in **CTRL-ORCA2**
OI5	50-yr (1960-2009)	OPA8.2 (ORCA2 configuration)	ROOI (SOFA)[(1),(7)]	T,S from EN3_v2a[(4)] (no time-dependent XBTs correction)	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**
OI6	50-yr (1960-2009)	OPA8.2 (ORCA2 configuration)	ROOI (SOFA)[(1),(7)]	T,S from EN3_v2a [(4)] (assimilation procedure and obs. error set to match 3DVAR setup)	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	n/a	Same as in **CTRL-ORCA2**
3DVAR/NOSLA	46-yr (1960-2005)	OPA8.2 (ORCA2 configuration)	3DVAR/FGAT[(3),(9)]	T,S from EN3_v2a[(4)]	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	n/a	Same as in **CTRL-ORCA2**
3DVAR/MDTOI	46-yr (1960-2005)	OPA8.2 (ORCA2 configuration)	3DVAR/FGAT[(3),(9)]	T,S from EN3_v2a[(4)] along-track SLA (from Oct 1992) and OI mean dynamic topography[(2)]	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	n/a	Same as in **CTRL-ORCA2**
3DVAR/RIOMDT	46-yr (1960-2005)	OPA8.2 (ORCA2 configuration)	3DVAR/FGAT[(3),(9)]	T,S from EN3_v2a[(4)] along-track SLA (from Oct 1992) and Rio MDT[(8)]	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	n/a	Same as in **CTRL-ORCA2**
3DVAR/MODMDT	46-yr (1960-2005)	OPA8.2 (ORCA2 configuration)	3DVAR/FGAT[(2),(5)]	T,S from EN3_v2a[(4)] along-track SLA (from Oct 1992) and MDT from CTRL-ORCA2	Same as in **CTRL-ORCA2**	Same as in **CTRL-ORCA2**	n/a	Same as in **CTRL-ORCA2**

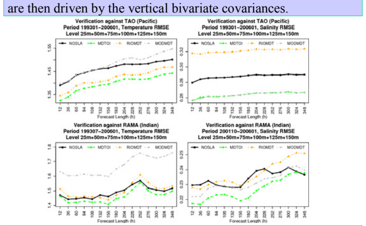
3DVAR System: Impact of Sea Level Assimilation with different MDTs (1993-2005)

In order to assimilate sea-level anomaly observations and provide a globally optimal analysis, the OceanVar 3DVAR/FGAT scheme by [3] was implemented for the global ocean [9]. It takes advantage of 10-mode seasonal Empirical Orthogonal Functions (EOFs) of temperature and salinity at full model resolution for the representation of vertical covariances, while horizontal correlations are modelled through a first-order recursive filter with homogeneous and vertically-varying correlation length-scales.





Sea-level anomaly obs. are assimilated by inverting the dynamic height equation, splitting the sea-level anomaly increment into its thermo- and halosteric contributions. The T and S increments are then driven by the vertical bivariate covariances.



The mean dynamic topography was calculated from the model Mean SSH (MODMDT) and adjusted (MDTOI) via assimilation output diagnostics, as in [2]. The Figure above depicts the impact of SLA assimilation using different MDTs on tropical skill scores of T and S against the mooring arrays.

Conclusions

An Optimal Interpolation system at 2-degree resolution is used for long-term climate variability studies at inter-annual and decadal scale and has been continuously improved by means of vertical covariance tuning and observational dataset selection.
We have also developed a global oceanographic 3DVAR/FGAT data assimilation system, which is able to successfully assimilate satellite altimetric observations through a local hydrostatic adjustment scheme.
The increased resolution (from 2 to ¼ degree) of the forced ocean model has been shown beneficial in the simulation of spatial patterns of SSH as well as in its trends.

Work in progress

We have recently increased the resolution of the 3DVAR/FGAT to an eddy-permitting resolution (¼ degree) and implemented this assimilation scheme on the OGCM model NEMO 3.2.1 coupled with the LIM2 sea-ice model. The system is quite young and we are devoting most of the efforts to the tuning of the observation- and background- error covariances, to the support of SST assimilation and to an improved assimilation of SLAs.
Part of this work is going on in the framework of the MyOcean Project (www.myocean.eu.org) granted by the the European Commission within the GMES Program . Within MyOcean CMCC is providing a global ocean reanalysis for the period 1993-2009 at ¼ degree resolution.

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