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The CMCC Global Ocean Physical Reanalysis System (C-GLORS) version 3.1: Configuration and basic validation

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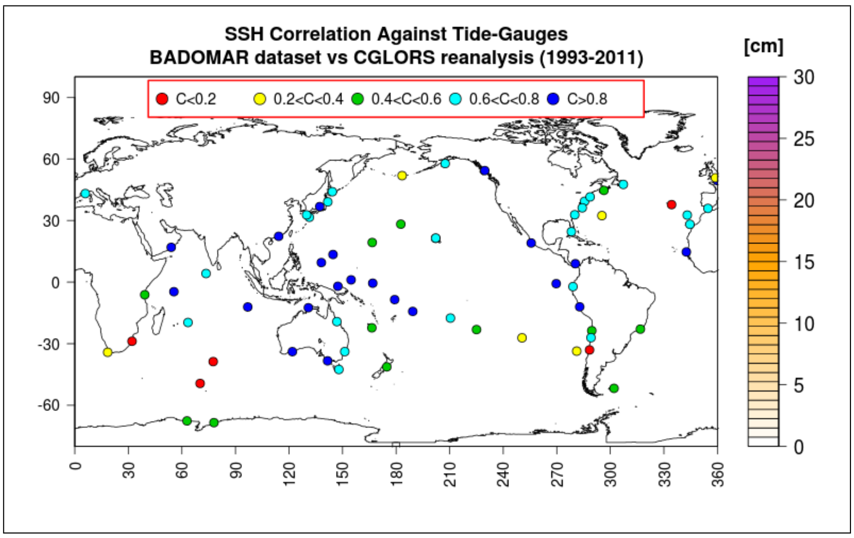
SUMMARY Ocean reanalyses are data assimilative simulations designed for a wide range of climate applications and downstream applications. An eddy-permitting global ocean reanalysis system is in continuous development at CMCC and we describe here the configuration of the reanalysis system (version 3.1) recently used to produce an ocean reanalysis for the altimetry era (1993-2011), which was released in December 2013. The system includes i) a three-dimensional variational analysis system able to assimilate all the in-situ observations of temperature and salinity along with altimetry data and ii) a weekly model integration performed by the NEMO ocean model coupled with the LIM2 sea-ice model and forced by the ERA-Interim atmospheric reanalysis. We detail the configuration of both the components. The validation results performed in a coordinated way are summarized in the paper, and suggest that the overall performance of the reanalysis is satisfactory, while a few problems linked to the sea-ice concentration minima and the sea level data assimilation still remain and are being improved for the next release.

Ocean Climate



The research leading to these results has received funding from the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea under the GEMINA project and from the European Commission Copernicus programme, previously known as GMES programme, under the MyOcean and MyOcean2 projects.

THE ASSESSMENT OF THE STATE OF THE OCEAN for the past decades is referred to as ocean reanalysis (or *ocean synthesis*) when observational measurements are optimally combined with an Ocean General Circulation Model (OGCM). Reanalyses have the primary target of evaluating and monitor the ocean variability, along with several downstream applications (e.g. initial conditions for coupled long-range predictions, offline bio-geochemical models, assessment of the value of the observing network, etc.). CMCC has devoted many efforts in the past years to build a state-of-the-art reanalysis system able to run at different resolutions and to assimilate several observing networks. In this paper we review the reanalysis system used at eddy-permitting resolution for producing ocean reanalyses for the altimetry era. Hereafter we refer to the CMCC global ocean reanalysis system as C-GLORS. [8] extensively reports the validation of C-GLORS v3.1 and the reader is referred to that document for more details.

CONFIGURATION

C-GLORS consists of a weekly three-dimensional variational analysis (3DVAR), followed by a 1-week Ocean General Circulation Model (OGCM) integration, which brings the analysis forward to the next assimilation step. The three-dimensional variational data assimilation system is a global implementation [20] of OceanVar [6]. The OGCM is NEMO [15] in its ORCA025 configuration, coupled with the (Louvain La Neuve) sea-ice model [9]. Details of the two steps are given below.

THE 3DVAR/FGAT SCHEME

The data assimilation step is used to correct three-dimensional fields of temperature and salinity. The analysis is performed every 7 days. Within the 3DVAR scheme, we minimize a cost function given by the sum of the distance between the analysis state, unknown, and a prior knowledge of the state of the ocean (the background) and the distance between the analysis state and the observations, in observation space, scaled by the background- and observational error covariance matrices, respectively. Since the observations are compared to the background field closer in time to the observations within 2-hourly time slots of the weekly assimilation time-window, this scheme is usually referred to as 3DVAR/FGAT (First Guess at Appropriate Time). The analysis time is centered with respect to the assimilation time-window.

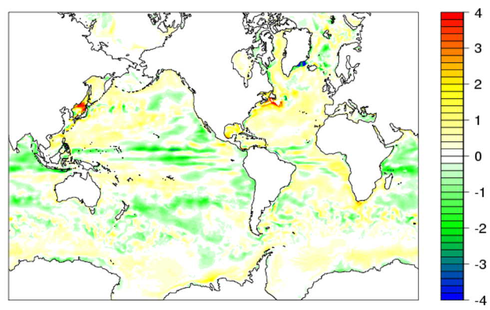


Figure 1:
Difference between long-term mean (1993-2011) C-GLORS temperature (left) and salinity (right) and World Ocean Atlas 2009 climatology at 100 m of depth. Units are degC and psu, respectively. The figure shows a 0.5-1 degC cold bias in the Tropics and warm poleward.

The background-error covariance matrix is decomposed onto two linear terms accounting, respectively, for vertical covariances and horizontal correlations. In our scheme, vertical covariances are represented by a 1-degree resolution set of 10-mode seasonal bivariate Empirical Orthogonal Functions (EOFs) of salinity and temperature at full model vertical resolution. Horizontal correlations are modeled by means of a four-iteration first-order recursive filter, with three-dimensional, parameter- and direction- dependent correlation length-scales. Thus, the problem of defining the background-error covariance matrix simplifies to the three-dimensional definition of the horizontal correlation length-scales and a coarse-resolution computation of vertical bivariate EOFs. Both the vertical EOFS and the correlation length-scales were calculated from the monthly anomalies (with respect to the climatology) of a non-assimilative OGCM run for the reanalysis period.

In order to impose cyclic condition on the western and eastern boundaries, the global domain is replaced by an extended domain, with symmetric extension zones westward of the western boundary and eastward of the eastern boundary. Within these extension zones, observations are duplicated in order to have very close analysis increments at the two boundaries.

USE OF OBSERVATIONS. The variational data assimilation system of C-GLORS assimilates in-situ observations of temperature and salinity and satellite sea level anomalies (SLAs). All the in-situ observations from moorings, ARGO floats, Expandable Bathy Termographs (XBTs), Conductivity-Temperature-Depth (CTDs) and sea mammals are extracted from the CORA 3.4 dataset [3]. These data are collected, quality-checked and distributed by CORIOLIS. More information on the in-situ data processing is available in [3].

The dataset of sea level anomalies is the AVISO along-track delayed mode dataset that includes observations from ERS-1 and -2, Envisat, GFO, Jason-1 and -2 and Topex/Poseidon. Observations are subjected to the usual geophysical corrections and multi-satellite cross-calibration [13]. Sea level corrections are covariated with vertical profiles of temperature and salinity by means of the *dynamic height* formulation and according to the bivariate definition of the background-error vertical covariances. The Mean Dynamic Topography (MDT) used in this simulation follows an optimization process that accounts for all altimetry observations misfits as in [20] over the period 1993-2001.

Observations pre-processing includes i) a background quality-check – which rejects observations for which the ratio between the squared departure from the background and the sum of the observational and background error variances exceeds an observation type-dependent threshold; ii) an horizontal data thinning in order to reject altimetry observations too close in space, provided that observations are assumed to be spatially (and temporally) uncorrelated and iii) a vertical data thinning for in-situ observations only, to avoid that several assimilated observations from a same platform lie within the same vertical model layer. Furthermore, observations close to the sea-ice are rejected in order to avoid analysis increments inconsistent with the sea-ice model.

The observational errors for in-situ observations were initially set equal to those found by [11] and subsequently tuned via the *Desroziers method* [5]. The latter iteratively adjusts the observational error standard deviations by using assimilation output statistics. Maxima of the observational errors are located approximately in correspondence of the mixing layer depth and at the surface for temperature and salinity, respectively. For SLA observations, the error variance is calculated a sum of observational (satellite-dependent), MDT, representativeness and inverse barometer correction error variances [20].

THE OGCM CONFIGURATION

The C-GLORS forecast model step is performed by the NEMO ocean model in configuration ORCA025. The version of the model is the release 3.2.1. The model has a resolution of about a 1/4 of degree and 50 vertical depth levels with partial steps [1]. The grid is tripolar [16].

INITIALIZATION STRATEGY. The strategy for initializing the reanalysis has been chosen as follows:

- a 1950-1979 assimilation-free run initialized at 1/2 degree resolution (ORCA05) forced with ERA40, with relaxation to the EN3 monthly objective analyses, initialized from the NODC World Ocean Atlas 1998 Series [14] blended with the PHC2.1 climatology for the Arctic region [19];
- a 1979-1989 assimilative run at the 1/2 degree resolution;
- the fields valid at 1st Jan 1989 have been interpolated onto the ORCA025 grid and the 1/4 degree C-GLORS system has started.

SURFACE FORCING FIELDS. The CORE bulk formulas forcing method [12] has been adopted. The following atmospheric variables have been used:

- 3-hourly turbulent variables (10 meters winds and 2 meters temperature and specific humidity);
- daily radiative fluxes variables (downward short-wave and long-wave radiations) with shortwave radiation modulated to have a diurnal cycle [2];
- daily fresh water flux variables (total precipitation and snow).

All the forcing fields are provided by the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim atmospheric reanalysis project [18].

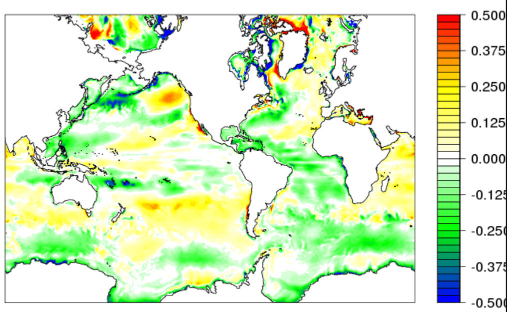


Figure 2:
Difference between long-term mean (1993-2011) C-GLORS temperature (left) and salinity (right) and World Ocean Atlas 2009 climatology at 100 m of depth. Units are degC and psu, respectively. The figure shows a 0.5-1 degC cold bias in the Tropics and warm poleward.

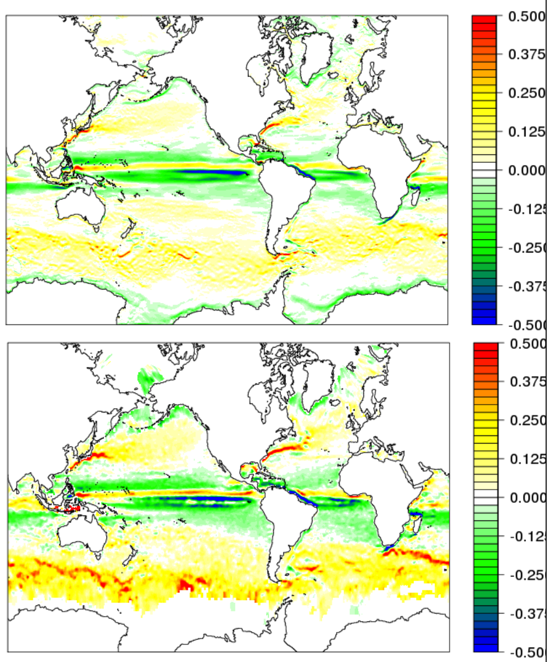


Figure 3:
Climatology of zonal currents from C-GLORS (top) and NOAA/Drifters (bottom). Units are m/s. All the circulation patterns are correctly reproduced, although it is possible to note a rather stronger ACC zonal surface current in NOAA/Drifters.

CORRECTIONS OF SURFACE FORCING FIELDS. ERA-Interim radiative fluxes and wind fields have been corrected as follows: large-scale short-wave and downward long-wave radiation fluxes have been corrected by means of a large-scale climatological correction coefficient derived by the GEWEX Surface Radiation Budget project; precipitation fields were corrected by using a climatological coefficient derived from the REMSS/PMWC dataset [21]. Furthermore, in order to avoid artificial drifts of the globally-averaged sea-surface height due to the unbalanced fresh water budget, the global evaporation minus precipitation minus runoff has been set equal to zero at each model time-step.

LARGE-SCALE BIAS CORRECTION. A large scale bias correction (LSBC) is performed during the model integration to avoid spurious model biases and drifts. The LSBC corrects the model tendencies every 6-hours using differences between model and monthly univariate objective analyses [11] to estimate the model bias. The differences are filtered with a low-pass filter configured to filter out time scale smaller than 3 months and spatial scale smaller than 1200 Km, in order to bias correct the large scale signals only. The filtered differences are then added to the tracer tendencies.

RUNOFF. The runoff files used in the simulation uses the climatology from [4] and was provided by MERCATOR-Ocean. It is a monthly climatology that includes 99 major rivers and coastal runoffs.

BOUNDARY CONDITIONS. The lateral boundary condition on momentum allows for a free slip. For the upper boundary a filtered free-surface formulation has been used. At the ocean bottom, a linear friction is assumed and no geothermal heat flux has been considered as a bottom boundary condition. Neither diffusive nor advective bottom boundary layer parametrization for tracers and momentum have been used.

SEA SURFACE RELAXATION. C-GLORS also assimilates SST observations from the NOAA high-resolution daily analyses, which uses AVHRR infrared and (from 2002) AMSR-E microwave radiances [17]. These observations are assimilated during the model integration through a simple nudging scheme that corrects the net heat flux at the sea surface by means of the difference between observed and modeled sea surface temperature. The strength of this relaxation was set equal to -200 W K-1 s-1 (corresponding to a relaxation time scale of 12 days for an ideal 50 m deep mixed layer). Similarly, the net freshwater flux is corrected using differences between observed and modeled sea surface salinity. The observational dataset is the EN3 monthly objective analyses [11]. The strength of the freshwater relaxation is -166.7

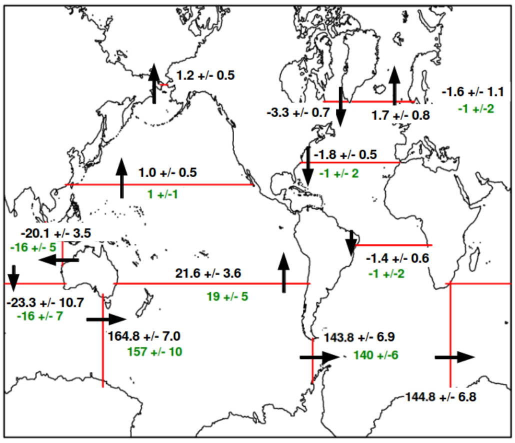


Figure 4:
Integrated volume transports (mean and standard deviation) through some notable WOCE sections from C-GLORS (black) and [10] (green). The arrows indicate the direction of the mean flow. C-GLORS mean values are everywhere within the [10] estimate error bars, although C-GLORS ha generally larger transports. Note the section at 59N in the Atlantic is computed as a sum of Labrador Sea and Arctic Ocean income contributions for comparison with the provided estimate.

mm/day, corresponding to a time scale of 300 days for a 50 m deep mixed layer.

LIM2 SEA-ICE MODEL. The sea-ice model used in the reanalyses is the LIM2 dynamical and thermodynamical sea-ice model. The rheology used is the EVP (elasto-visco-plastic). The assimilation of sea-ice concentration is performed through a simple nudging scheme that assimilates the gridded NOAA sea-ice daily analysis at 1/4 degree, with a relaxation time scale of 15 days.

PHYSICS. The Turbulent Eddy Kinetic (TKE) dependent vertical diffusion scheme has been used to compute the eddy vertical mixing coefficient. The vertical parametrizations include: i) the Enhanced Vertical Diffusion (EVD) scheme, ii) double diffusion mixing parametrization for temperature and salinity, iii) a mixing length scale surface value as function of wind stress. The advection scheme used for tracers is the MUSCL scheme (Monotone Upstream-centered Schemes for Conservation Laws). For lateral diffusion a laplacian isopycnal diffusion scheme has been used with horizontal eddy diffusivity equal to 300 m^2/s (the coefficient is grid size dependent). A bilaplacian operator has been used for lateral viscosity of momentum, with horizontal eddy viscosity coefficient equal to -1.0e11 m^2/s. The coefficient is grid size power 3 dependent.

COMPUTATIONAL DETAILS

C-GLORS has run on the IBM iDataplex dx360 system with Intel Xeon processors (*Athena* cluster). The ocean model domain is decomposed into 320 processors for the forecast step and 80 for the assimilation step. Wall-clock time for the simulation was about 38 hours per year of simulation, depending on observations amount and number of 3DVAR iterations performed, of which about 80 % spent on the OGCM run and the rest on the assimilation part. The model outputs have been saved as weekly means, subsequently post-processed to generate monthly means. Surface parameters were also saved as daily means.

CHANGES WITH RESPECT TO THE PREVIOUS VERSION

With respect to the previous version (MyOcean v2) the main changes can be summarized in the following issues:

- Re-introduction of SLA observations assimilation in the 3DVAR scheme;
- Re-calibration of background-error covariances;
- Assimilation of SST observations with a nudging scheme instead of the 3DVAR scheme;
- Use of the in-situ observations CORA 3.4 dataset instead of the EN3 v2a datasets;
- Introduction of a large-scale bias correction scheme;
- Introduction of the EVP sea-ice dynamics;
- Use of the MUSCL advection scheme instead of the TVD scheme.

VALIDATION

An extensive validation of the reanalyses has been conducted after the reanalysis production was completed. The methodology used during the validation phase is detailed in [7]. Here, we report the main findings from the validation exercise.

TEMPERATURE. We found a very small bias at surface (below 0.5 degC), a 0.5-1 degC cold bias in the Tropics and warm poleward for the 100 and 300 m depth levels with respect to the

WOA09 climatology. Figure 1 shows the difference (model minus climatology) at 100 m of depth. At 800 m the bias is relevant only in correspondence of the ACC front (cold north of it, warm south of) while at 2000 m is negligible in practice. This suggests that the reanalysis mislocates the northern boundary of the ACC. Globally averaged values and linear trends of SST are in great consistency with NOAA/AVHRR SST analyses. With respect to the EN3 analyses, both the variability and the anomalies are well reproduced by C-GLORS for the vertical layers investigated (0-700 m, 0-2000 m and 2000 m-bottom), although an offset between the two datasets is clearly visible in all layers. Both datasets show a comparable warming below 100 m, while more inconsistency exists near the surface. The RMSE against all the in-situ observations of temperature shows a reasonable decreasing behavior with time.

SALINITY. Sea surface salinity is generally greater in the Arctic compared to WOA2009 probably due to sea-ice edge misplacement. Elsewhere, the bias presents values generally below 0.2 psu. At 100 m similar patterns are present (Figure 2), with a fresh bias (about 0.1 psu) in the Indonesian region and in the Tropical Atlantic and generally salty at mid-latitudes, which remains visible at 300 m of depth. Below, biases are rather negligible. The sea surface salinity trends patterns are generally similar to those from EN3 SSS except in the Indian Ocean, although the ones in C-GLORS are slightly more pronounced. In the comparison with the selected moorings, values of standard deviation of observations minus model equivalents are maximum near the surface, ranging from 0.15 to 0.35 psu. We found a larger initial SSS variability w.r.t. to EN3 SSS, which may be due to the lack of a dense salinity observation network in the 90s and beginning of 2000s. Time-mean values and inter-annual anomaly in some selected layers (0-700 m, 0-2000 m and 2000 m-bottom) are generally well captured by C-GLORS with respect to the EN3 objective analyses. The increase in salinity below 100 m visible in the EN3 dataset is repro-

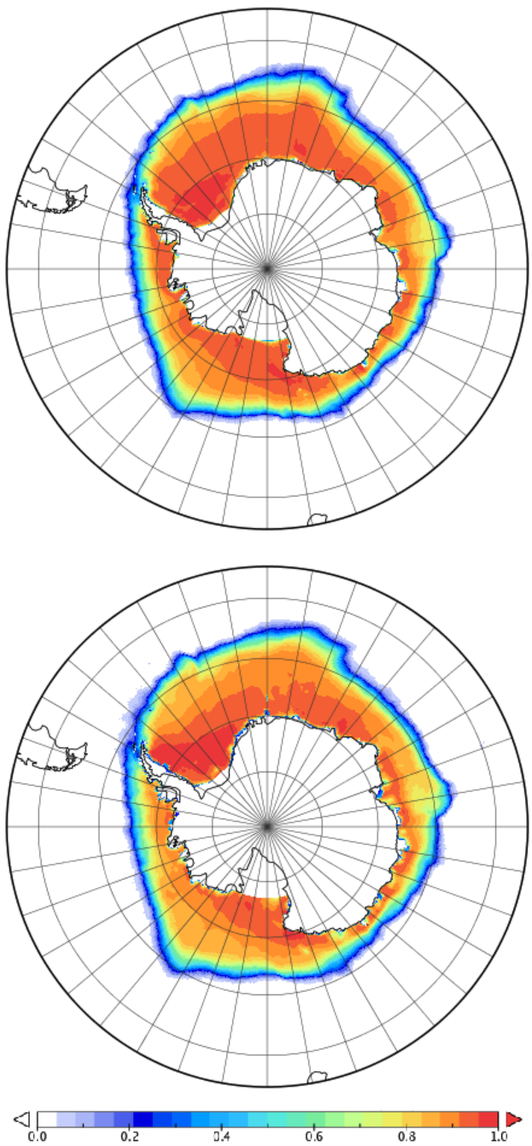


Figure 5:
September Antarctic sea ice concentration 1993-2011 climatology from C-GLORS (top) and NOAA/AVHRR analyses (bottom).

duced by C-GLORS, while its partial freshening near the surface within the last decade is not present in EN3. As for temperature observations, the in-situ observation minus model statistics show the improvements of the system with time and with the assimilation of Argo floats, which lead to smaller negative bias and a decreasing RMSE.

CURRENTS. All the near-surface circulation patterns are correctly reproduced in the comparison with the drifter-derived climatology, although it is possible to note a rather stronger ACC zonal surface current in NOAA/Drifters. This is shown in Figure 3.

Vertical profiles in correspondence of the equatorial moorings are reproduced correctly except at 90E, and C-GLORS generally presents slightly weaker currents, while standard deviations range from about 20 to 30 cm/s.

SEA LEVEL. Sea level trends show similar patterns in C-GLORS and AVISO, but C-GLORS is affected by larger trends in correspondence of the ACC front and in the Gulf Stream region, which depend on the SLA data assimilation for the last 5 years of simulation due to the optimization process of the MDT.

In the comparison with tide-gauge observations (shown in the front page), values of the correlation are generally satisfactory except in some tide gauge stations within the ACC, where the model presents a variability higher then tide-gauge observation. The RMSE against along-track altimetry observations suggests that the SLA data assimilation for the last 5-10 years of simulation is affected by a slight increase in the error due to the optimization process of the MDT (not shown).

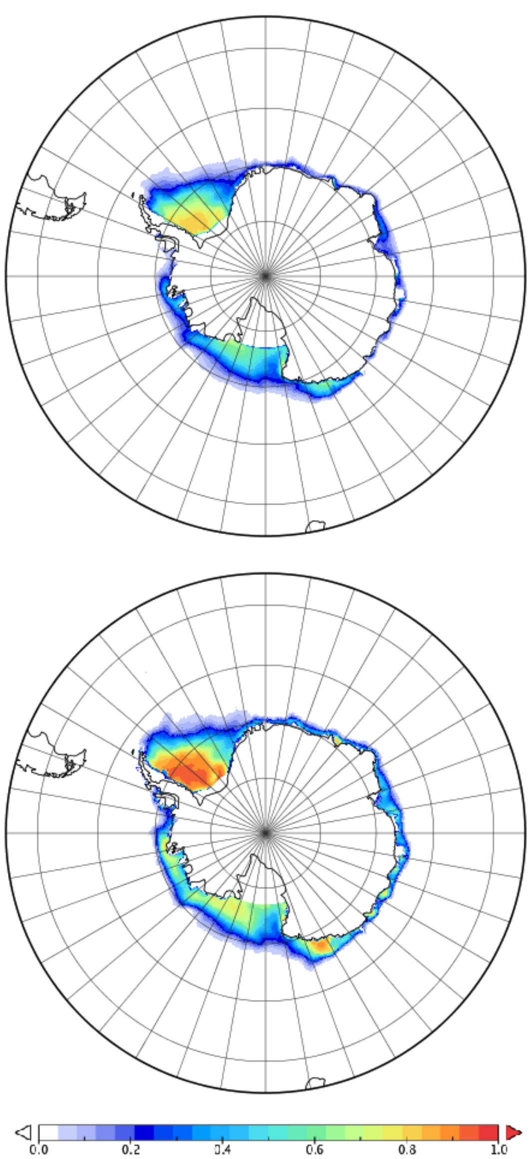


Figure 6:
March Antarctic sea ice concentration 1993-2011 climatology from C-GLORS (top) and NOAA/AVHRR analyses (bottom).The concentration in March (minima) is underestimated, especially in the Weddel Sea.

TRANSPORTS. C-GLORS shows an Atlantic Meridional Overturning circulation (AMOC), on the average, about 2.5 Sv too weak (with respect to the 17 Sv of RAPID-MOC for the period 2004-2011, not shown), although the temporal variability is well captured, with a correlation equal to 0.6.

Recent sensitivity studies suggested that the reintroducing the TVD tracer advection scheme instead of the MUSCL scheme can help in alleviating the underestimation of the AMOC.

Volume transports are in close agreement with the values found in literature, although the transports in the Southern Ocean are slightly over-estimated. Figure 4 represents volume transports for some notable WOCE sections for C-GLORS, compared with the estimates from [10].

SEA ICE. While sea-ice concentration interannual variability and winter-time maxima are simulated correctly, concentrations in March for the Antarctic and in September for the Arctic are generally underestimated. This is visible in Figures 5 and 6 for the Antarctic sea-ice: while the extension during the maximum sea ice concentration is well captured, in correspondence of the yearly minima (March) the concentration is under-estimated with respect to NOAA analyses based on AVHRR data. An anomalous increase is also seen for the last two years of simulations, which is currently under investigation.

MIXED LAYER DEPTH. Mixed layer depth (MLD) patterns are well reproduced (not shown), although C-GLORS overestimates the MLD in correspondence of the North Atlantic Ocean deep convection areas.

PLANNED IMPROVEMENTS FOR THE NEXT RELEASE

A new release of C-GLORS is planned for official release in September 2014 at the latest. The main improvements and extension that are currently under testing are:

- **Initial Conditions**: The new reanalysis system is initialized in 1979 from a 10-year spinup with 1978 repeated atmospheric forcing. The new reanalysis will therefore cover all the ERA-Interim and AVHRR period.
- **Sea-ice**: A stronger sea-ice concentration nudging, whose time-scale depends on the sea-ice misfit, has been succesfully tested and is able to provide a better representation of Arctic and Antarctic sea-ice minima;
- **Mean Dynamic Topography**: is being recalculated taking into account the sea level anomaly statistics for the all reanalysis period. Sensitivity experiments are planned;
- **Advection scheme**: the MUSCL scheme, while faster, has been proved detrimental to the reanalysis system as it leads to under-estimated thermo-haline circulation. The TVD scheme will be therefore re-introduced.

KNOWN ISSUES. C-GLORS v3.1 is affected by two known issues: i) underestimation of sea-ice minima in summer, which is not sufficiently corrected by the sea-ice nudging; ii) the MDT optimization was performed on a 1993-2001 reference period. Accordingly, there is an increase in SLA misfit RMSE for the last period of the simulation, due to the lack of these observations within the MDT optimization procedure; iii) the use of MUSCL advection scheme was validated near-surface, while later we found that it leads to under-estimated transports at depth.

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