THE INGV/CMCC GLOBAL OCEAN VARIATIONAL ASSIMILATION SYSTEM: APPLICATIONS, DEVELOPMENTS AND PERSPECTIVES

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WELL-ESTABLISHED EXPERIENCES

1. OPTIMAL INTERPOLATION SCHEME

The INGV/CMCC Optimal Interpolation (OI) scheme is based on a reduced-order analysis with bivariate vertical covariances of temperature and salinity (Bellucci et al., 2007). It is used for long-term (1960-2009) studies of the Global Ocean variability, and the continuous refining of the observational dataset and processing and vertical covariances tuning allowed constant improvements during the years (**Figure 1** shows the improvements among different version of the OI scheme in terms of temperature RMSE against selected TAO/TRITON moored buoys measurements). **Figure 2** demonstrates a climatological application of the system: the zonally-averaged climatological heat transport (PW, left panel) and fresh-water transport (Sv, right-panel) compared with other observation- and atmospheric reanalysis- derived datasets (Masina et al., 2011).

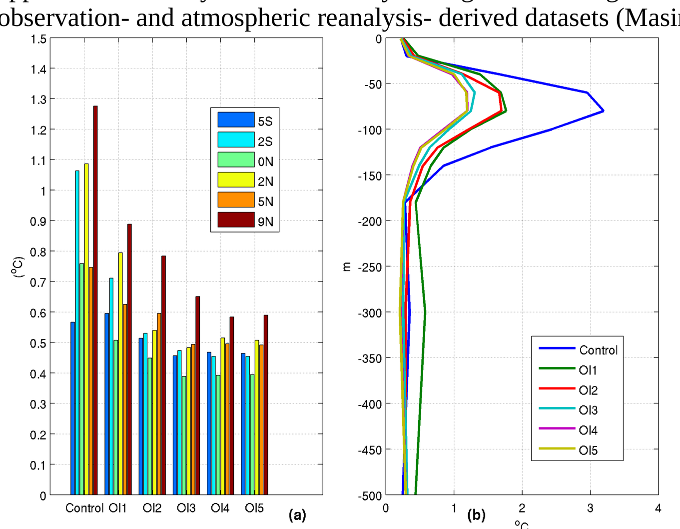

Figure 1

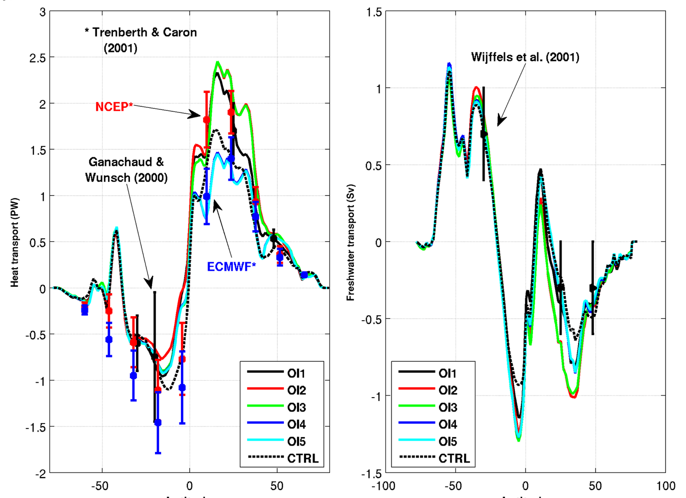

Figure 2

2. THE 2-DEGREE RESOLUTION 3DVAR

In order to assimilate sea-level anomaly observations and provide a globally optimal analysis, the OceanVar 3DVAR/FGAT scheme (Dobricic and Pinardi, 2008) in use for operations within the Mediterranean Forecasting System was implemented for the Global Ocean (Storto et al., 2011). It takes advantage of 10-mode seasonal Extended Empirical Orthogonal Functions (EEOFs) of temperature and salinity at full model resolution (2 degrees, up to 0.5 close to the Equator) 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. The OGCM counterpart is OPA8.2 in configuration ORCA2. Below, we present the general formulation, the strategy for cyclic conditions imposition, which consists in artificially defining an extended domain at the two global domain boundaries with duplicated observations (**Figure 3**), and the strategy and selected results on the assimilation of sea-level anomaly observations.

Formulation

$$J = \frac{1}{2}\underbrace{\mathbf{v}}_{\text{Control variable}}^{\mathsf{T}}\mathbf{v} + \frac{1}{2}\left(\underbrace{\mathbf{d}}_{\text{Innovation (misfit)}} - \mathbf{HVv}\right)^{\mathsf{T}}\mathbf{R}^{-1}\left(\mathbf{d} - \mathbf{HVv}\right)$$

$$\mathbf{x} - \mathbf{x}^{\mathrm{b}} = \mathbf{V}\mathbf{v} \qquad \mathbf{d} = \mathbf{y} - \mathcal{H}(\mathbf{x}^{\mathrm{b}})$$

TL obs op

obs-error covariances

Background-error covariances

$$\mathbf{B} = \mathbf{V}\mathbf{V}^{\mathsf{T}}$$

Fully non-linear obs op

$$\mathbf{V} = \mathbf{V}_{\mathrm{h}}\mathbf{V}_{\mathrm{v}}$$

1st order Recursive filter (homog. vert.-varying correlation length-scales)

10-mode seasonal EEOFs of (T,S) (full model resolution)

Cyclic conditions

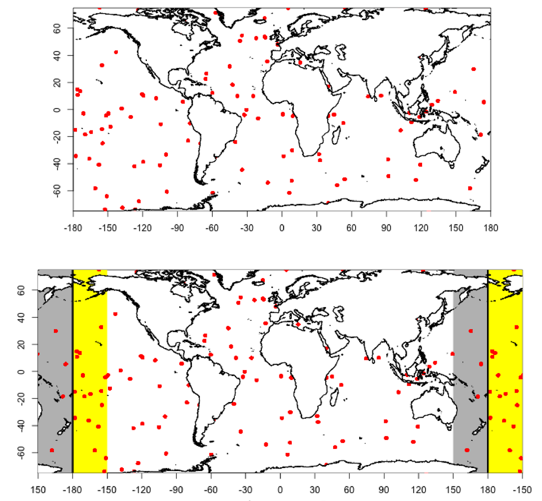
Figure 3

Assimilation of along-track SLA

Sea-level anomaly observations are assimilated by inverting the dynamic height equation, therefore splitting the sea-level anomaly increment into vertical profiles of T and S. The T and S contribution are then driven by the definition of the vertical bivariate covariances (Storto et al., 2011).

The mean dynamic topography (MDT) was calculated from the model Mean SSH and adjusted via assimilation output diagnostics, as in Dobricic (2005). In **Figure 4**, the impact of the SLA observations is shown in terms of increased correlation of model near-surface currents with the satellite-derived OSCAR dataset. **Figure 5** depicts the impact of SLA and the MDT on tropical skill scores of T and S against the mooring arrays.

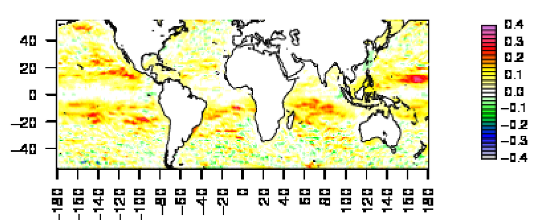
Figure 4

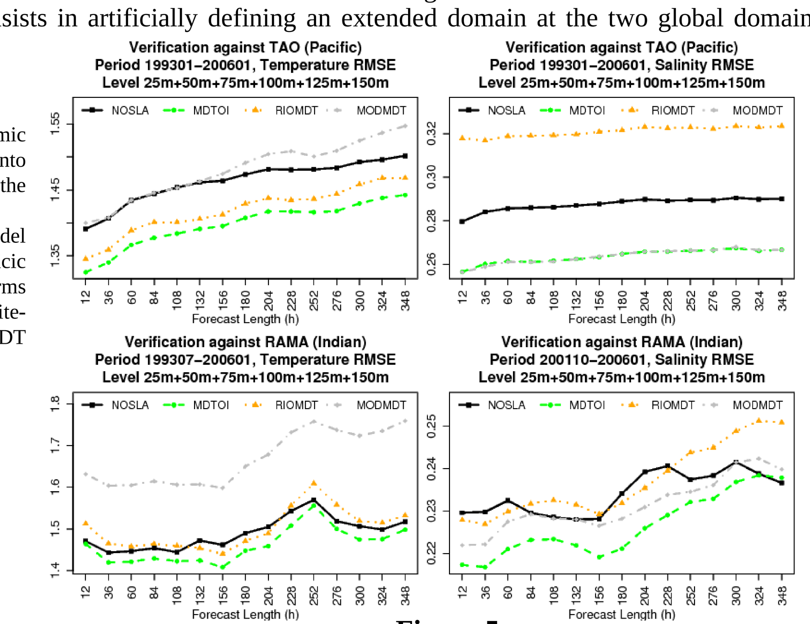

Figure 5

THE ¼-DEGREE RESOLUTION ANALYSIS SYSTEM DEVELOPMENTS

Within the MyOcean WP04 activities, CMCC is providing Global Ocean reanalysis for the period 1993-2009 at ¼ degree resolution. The data assimilation system is a 3DVAR with some improvements related to the higher resolution, which are detailed in this Section. The OGCM model is NEMO 3.2.1 coupled with the LIM2 sea-ice model

1. RELEASING THE ASSUMPTION OF UNIFORM CORRELATION LENGTH-SCALES

One important improvement to the system has been the revision of the recursive filter (RF) coefficients definition, which now allows for non-homogeneous, parameter- and direction- dependent correlation length-scales, derived from model climatological anomalies with the "Belo Pereira" approximation (Belo Pereira and Berre, 2006). The RF coefficients are computed offline. In **Figure 6** the 0-100 m averaged T and S correlation length-scale are presented, showing the importance of the zonal/meridional separation, and the general geography of the horizontal correlations.

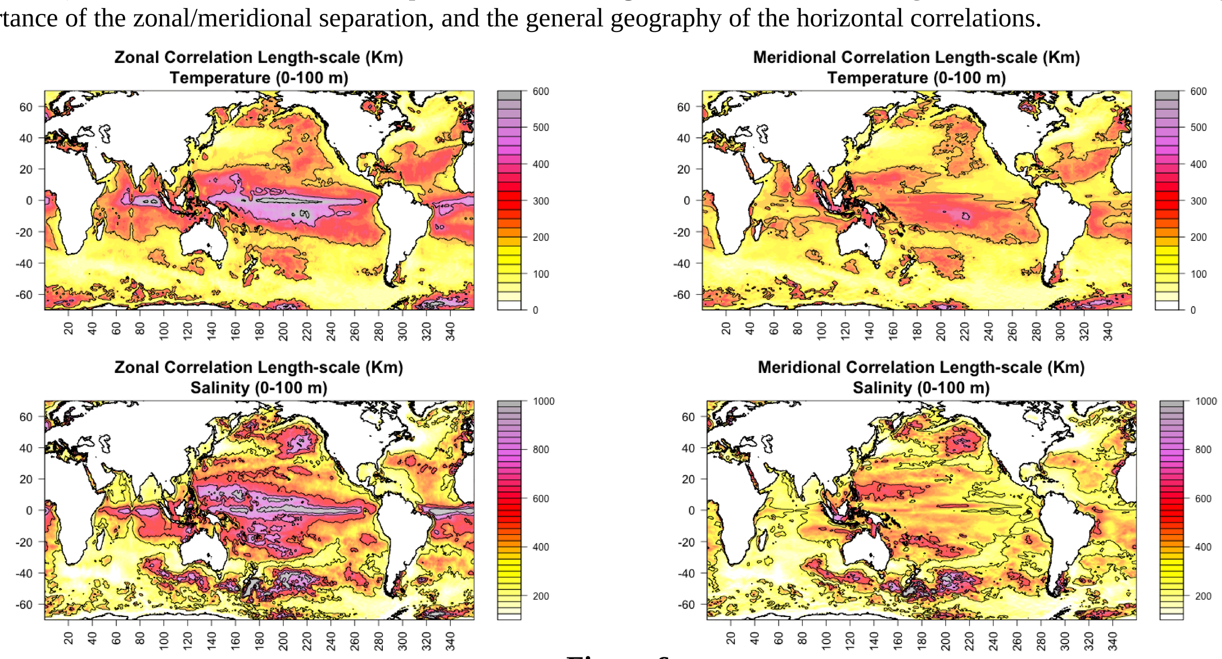

Figure 6

2. TUNING OF OBSERVATION ERRORS

Due to the smaller representativeness error for the resolution increase, observational error profiles of *in-situ* observations have been tuned via the "Desroziers" method (Desroziers et al., 2005) starting from the error values given by Ingleby and Huddleston, 2007, as shown for temperature in **Figure 7**.

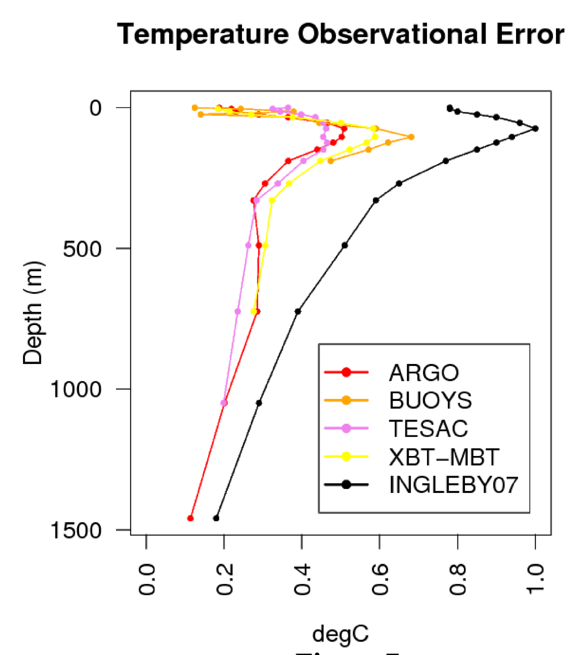

Figure 7

3. TUNING OF VERTICAL CORRELATIONS

Vertical correlations have been recalculated for taking into account the new vertical meshing and resolution.

Computation was done at coarse-resolution (1°x1° degree grid) using climatological anomalies.

Figure 8 shows the T and S auto- and cross-vertical correlations in the Tropics, reconstructed from the 10-mode vertical EEOFs. Note the asymmetric (T,S) coupling below 200 meters of depth.

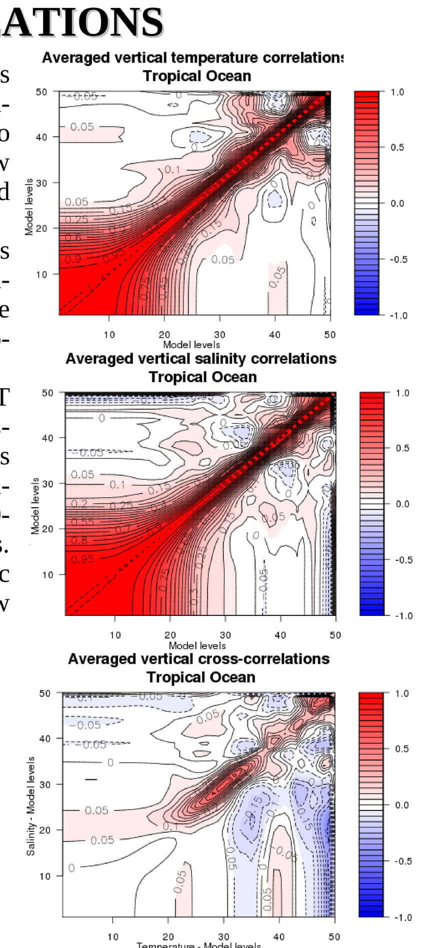

Figure 8

4. PARALLELIZATION

The 3DVAR ¼ degree scheme is parallelized via the shared-memory paradigm. In **Figure 9** the speedup results are given for both the observation processing part and the recursive filter, highlighting the good performances of the OMP parallelization.

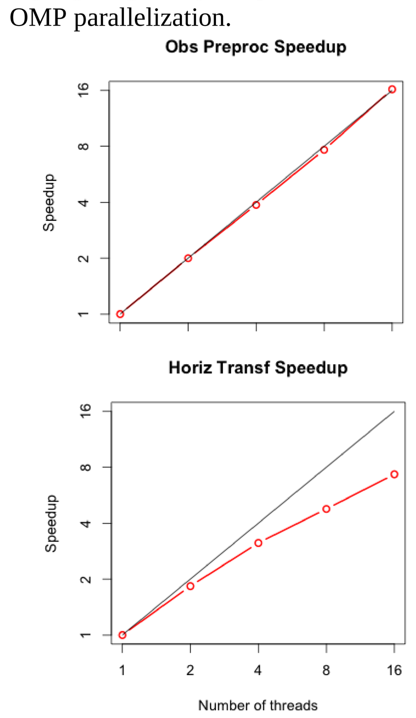

Figure 9

5. CONFIGURATION AND SELECTED RESULTS

The ¼ degree analysis system was run from 1989 to 1993 for producing global ocean reanalyses, starting from a climatological spinup. Forcing fields were taken from the ECMWF ERA-Interim dataset.

In **Figure 10** the number of observations assimilated per year are shown, grouped by observation type. The increase of resolution led to a larger number of assimilated observations (especially SLA) with respect to the 2-degree system, due to the different spatial thinning procedure. **Figure 11** shows the comparison of near-surface zonal currents climatology with that derived from drifters by NOAA/AOML, which shows the good location of the main current systems in our reanalysis. Finally, **Figure 12** compares the boreal winter (DJF) mixed layer depth of our reanalysis with the Argo-derived one of De Boyet Montégut et al. (2004). Spatial patterns in both hemisphere between the two figures are very similar.

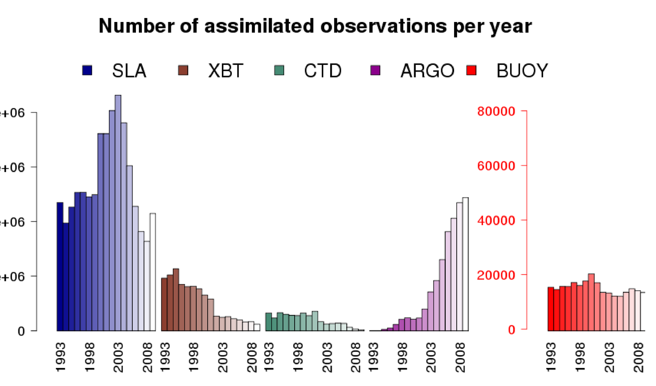

Figure 10

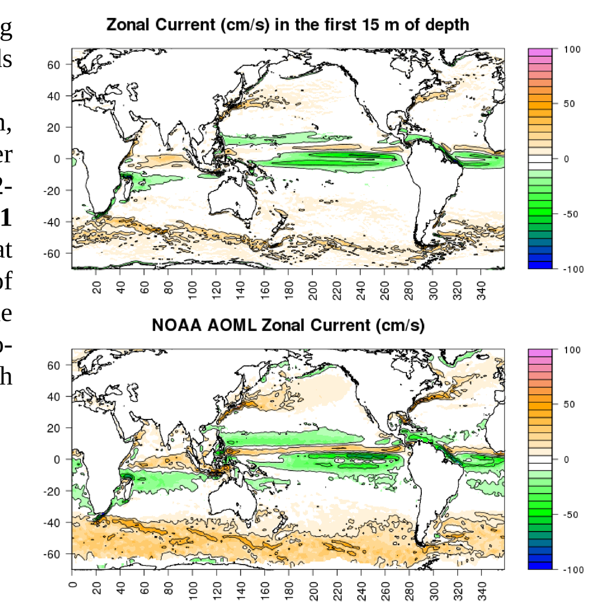

Figure 11

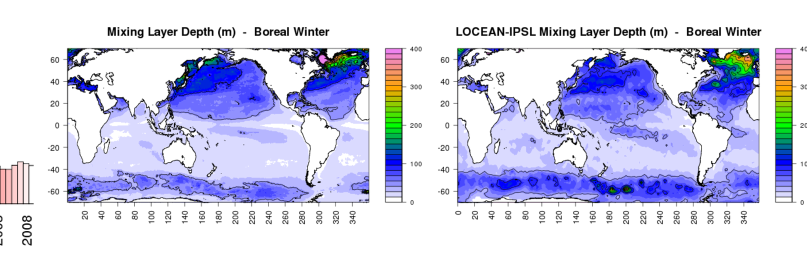

Figure 12

FUTURE DIRECTIONS

1. ASSIMILATION OF SST

SST assimilation was proved to improve near-surface temperature skill scores, but requires a deeper testing phase and, in particular, an evaluation of possible biases due to diurnal overwarming. In the **Figures 13** and **14**: improved SST skill scores against Reynolds ¼ degree daily analyses by means of the assimilation of microwave SST (AMSR-E and TMI in the period 2003-2005) processed and distributed by Remote Sensing Systems.

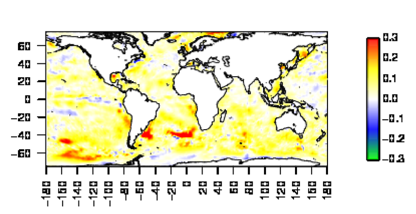
Figure 13

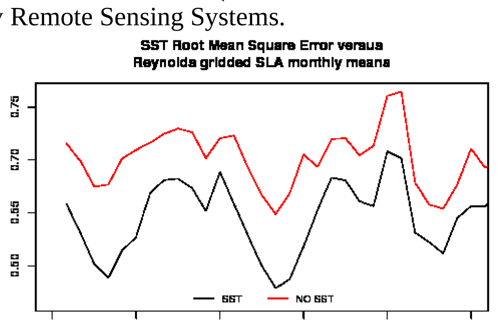

Figure 14

2. BIAS-CORRECTING THE MDT

The assimilation of sea-level anomaly observations was proved crucial for our analysis system (see Storto et al., 2011 and the Oral Presentation in the Operational Oceanography Session in this EGU Assembly). Nevertheless, we found that some of the SLA bias (**Figure 15**) may be explained by the difference between the CLS09 MDT (Rio and Hernandez., 2004) and the model mean sea-surface height (**Figure 16**), suggesting that some of the observational bias can be reduced by proper adjustment of the MDT.

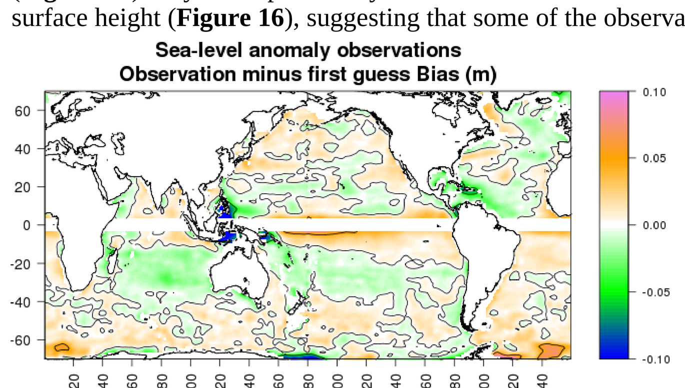

Figure 15

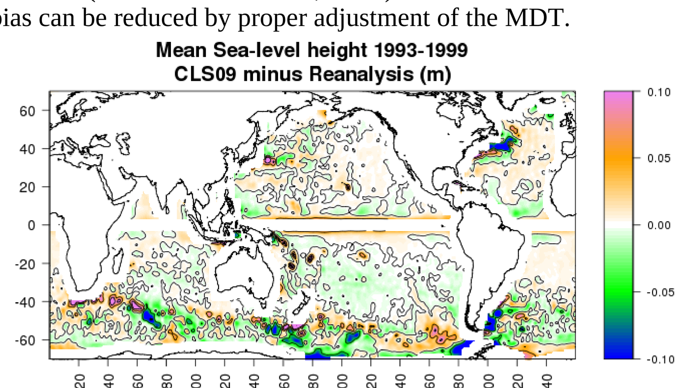

Figure 16

3. IMPACT OF EEOFs TEMPORAL RESOLUTION

The errors reconstructed from EEOFs computed from monthly climatological anomalies appear too high, especially within near-surface levels. In the **Figures 17** and **18**, contours of 0-100m averaged summer temperature standard deviation (°C) are shown for the case of monthly and weekly climatological anomalies, respectively. The signal in case of weekly anomalies better highlights the mesoscale variability and is significantly smaller at mid-latitudes. The increase of spatial resolution (from 1° to 0.5°) of vertical EEOFs is also under evaluation.

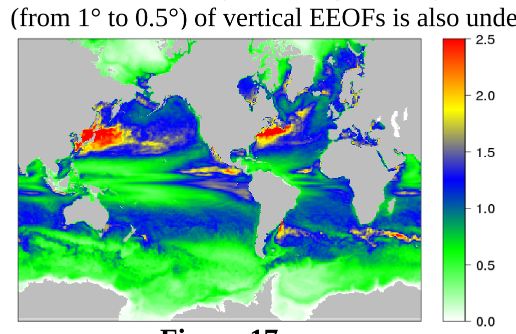
Figure 17

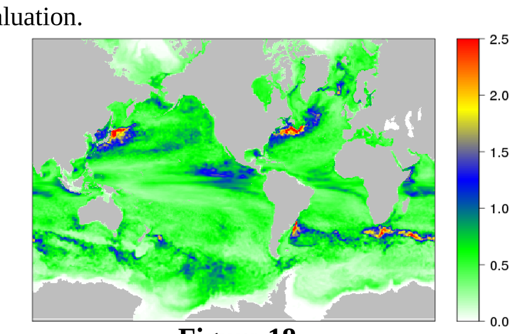
Figure 18

4. ASSESSING THE IMPACT OF ENSEMBLE-DERIVED B-MATRIX

The use of ensemble-derived B covariances is proved to better represent the model-error covariances. Ensemble-derived covariances will be calculated by using an Ensemble data assimilation system, which is the same as presented above with perturbed observations. In **Figures 19** and **20**, we compare in sea-level anomaly space the "observed sigmab" (Desroziers et al., 2005) with those derived either from climatological anomalies or ensemble data assimilation, which much better bring the information on small-scale model errors.

diag(HBH^T) in SLA space was computed by means of a Monte Carlo calculation using the TL model of the SLA observation operator linearized around the Autumn 2005 climatology.

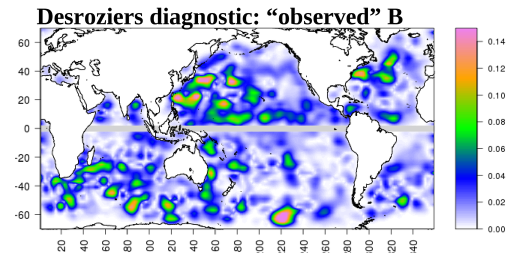

Figure 19

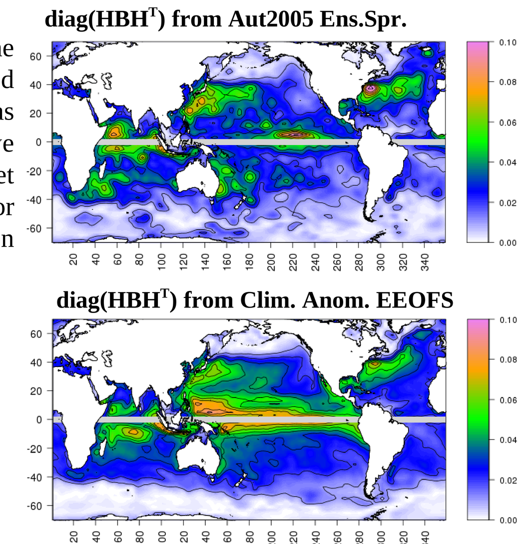

Figure 20

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Summary

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 covariances tuning and observation 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.

We have recently increased the resolution of the 3DVAR/FGAT to an eddy-permitting resolution (¼ degree). The system is quite young and we are devoting most of efforts in the tuning of the observation- and background- error covariances, to the support of SST assimilation and to an improved assimilation of SLAs.

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