GLOBAL OCEAN INDICATORS

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Abstract

Work is in progress in the context of MyOcean in order to define ocean climate indices computed both from observations and from monitoring and forecasting system outputs. Global Ocean indicators are evaluated from a field of hydrographic in situ observations provided by the Argo array (ARIVO), from global ocean reanalyses of the French Global Ocean Reanalysis and Simulations (GLORYS) project and a current field derived from multi-parametric observed products (SURCOUF3D). The in-situ measurements are used to define ocean indicators describing the state of the global ocean and its changes over the period 2004-2008. We find global rates of 0.65±0.13 Wm^{-2} for heat storage, 2700±1400 km^3 for freshwater content and 0.95±0.2 mm/yr for steric sea level. Changes of the deep ocean hydrographic field are assessed while determining regional linear trends of steric height and deep temperature anomalies. Areas of a positive trend of steric sea level - which contribute to the global steric rise – occur in all basins and dominate the Pacific Ocean. The global steric seal level rise is larger when evaluated from the GLORYS reanalysis temperature and salinity 3D monthly fields. Due to data assimilation of sea level anomalies, GLORYS total (barotopic and steric) mean sea level rise is very close to the satellite derived observations. Finally the intensity of the Meridional Overturning Circulation (MOC) is evaluated from SURCOUF3D and from GLORYS. Both reproduce the order of magnitude of ship cruise measurements of the MOC.

Introduction

Indicators are used to describe the state of the ocean and its changes. As commonly understood, an indicator is something that provides a clue to a matter of larger significance or makes perceptible a trend or phenomenon that is not immediately detectable (Hammond at al., 1995). In other words, an indicator's significance extends beyond what is actually measured to a larger phenomenon of interest. Indicators are used to communicate as they always simplify a complex reality. They focus on aspects which are regarded relevant and on which data are available.

Assessing global ocean indicators largely depends on the availability of data. Indeed, long time series of e.g. sea level changes exist, but are regionally restricted and thus are less indicative to provide information of the state of the ocean on global scales and its changes with time. Sea level as measured by satellite altimetry delivers global state estimates based on a homogeneous and continuous dataset during the last two decades. To promote information regarding the hydrographic state of the global ocean, all available in-situ measurements of temperature and salinity have been collected to construct a global climatology, thus indicating the state of the global ocean hydrographic field from the surface down to 3000m depth (Locarnini et al., 2006; Antonov et al., 2006, WOA05 hereinafter). This historical data set has been also used to describe global ocean changes from mid-1950s to present day (Levitus et al., 2009).

Global hydrographic estimations are limited before the beginning of this century due to sparseness and inhomogenity in spatial and temporal data distribution, especially in the southern hemisphere oceans. This situation changes drastically with the implementation of the Argo Program as it obtains more continuous, consistent, and accurate sampling of the present-day and future state of the oceans (Roemmich et al., 1999). At the beginning of 2002, Argo sampling covers about 40% of the global ocean, reaches around 70% in 2003, 80% in 2004 and more than 90% after mid-2006 (Cazenave et al., 2009). As a consequence, these data have been used to describe the state of the global ocean hydrographic field and its changes in the last decade (Antonov et al., 2005; Forget and Wunsch, 2007; Willis et al., 2008; Levitus et al., 2009; Cazenave et al., 2009; Leuliette and Miller, 2009; von Schuckmann et al., 2009).

Model reanalyses are precious tools to better understand the processes underlying climate change impacts in the ocean as they give access to a homogeneous time series of 3D ocean temperature, salinity and currents. As described in newsletter #33, the possibility of deducing ocean indicators from Mercator Ocean products (reanalyses and real time) has been evaluated: heat content, upwelling, sea surface temperature (SST) indices, sea ice extent, but also Sahel precipitations, tropical cyclones heat potential, coral bleaching. In the framework of real time monitoring and forecasting of the ocean, the BOSS4GMES project (http://www.boss4gmes.eu/) has tested the implementation of a small and robust ensemble of real time ocean indicators (for instance heat content, SST indices, Crosnier et al., 2008). Mercator Ocean maintains a web page displaying these indicators time series computed with the global analyses and forecast (http://indic.mercator-ocean.fr/html/produits/indic/index_en.html).

Comparing indicators deduced from observations (ARIVO, SURCOUF3D) and the same indicators but deduced from reanalyses like GLORYS is indeed a very promising cross validation process. This should improve reanalyses and data reprocessing validation on past time series but also confirm the interest of monitoring some of these integrated quantities and indicators computed with real time analysis and forecasting systems and with near real time observed products. In section 2, the data used for this study are introduced. In section 3, several global ocean indicators as derived from ARIVO, which is mainly based on Argo profiles, are presented and discussed. A comparison of the ARIVO and GLORYS steric sea level rise is performed in section 4, together with a comparison of the Atlantic MOC as derived from GLORYS and SURCOUF3D.

Data analysis method

Description of ARIVO

Monthly gridded fields of temperature and salinity from the surface down to 2000m depth are obtained by optimal analysis of a global field of in-situ measurements (Coriolis data center) during the years 2004-2008 under the French project ARIVO (http://www.ifremer.fr/lpo/arivo). This data field is based on the Argo array of profiling floats (95% of the data, see http://www.argo.net), drifting buoys, shipboard measurements and moorings. A small fraction of observations has been excluded from the analysis due to existing instrument biases as discussed above, i.e. gray-listed Argo floats of type SOLO FSI and XBTs. The gridding method is derived from estimation theory (Liebelt, 1967; Bretherton et al., 1976) and the method itself is described in detail by Gaillard et al., 2008 and will be not discussed in this context. The analyzed field is defined on a horizontal ½° Mercator isotropic grid and is limited from 77°S to 77°N. Th e vertical resolution between the surface and 2000m depth is gridded onto 152 vertical levels. The reference field is the monthly World Ocean Atlas 2005 (WOA05, Locarnini et al., 2006; Antonov et al., 2006). A discussion on the statistical description can be found in von Schuckmann et al. (2009).

Description of GLORYS

GLORYS is a project whose objective is to produce a series of realistic (i.e. close to the existing observations and consistent with the physical ocean) eddy permitting global ocean reanalyses. The version 1 of stream 1 (called GLORYS1V1) covering the Argo years (2002-2008) is used in this study (see article in newsletter # 36). The OGCM used in GLORYS1V1 is based on the ocean/sea-ice NEMO numerical framework (Madec, 2008). The configuration is global (-77°S to the North Pole) on a 1/4° ORCA grid. The data assimilation scheme is based on the Singular Evolutive Extended Kalman (SEEK) filter formulation proposed by Pham et al. (1998). A key aspect of the method is the use of a large number of model anomalies (a few hundreds) to model explicitly the background model error covariance. The control vector consists in the barotropic height, the temperature and salinity fields, as well as the zonal and meridional velocity fields. Because there is no simple relationship between the mass field and the circulation near the Equator (e.g. Benkiran and Greiner, 2008), the analyzed velocity near the equator is only partially applied. The velocity increments are set to zero at the equator and increase smoothly with latitude to become maximal at 7°. The length of the assimilation cycle is 7 days and the increment is applied directly to the model state at the analysis time. The assimilated data is sea level anomaly (SLA) corrected from the post-glacial rebound (W.R. Peltier, 2004), in conjunction with the RIO05 Mean Dynamic Topography (MDT, Rio and Hernandez, 2004, Rio and Schaeffer, 2005), SST and in situ profiles. An incremental analysis update is used for the initialization procedure (Bloom et al., 1996) which produces a time continuous ocean analysis. More details about GLORYS1V1 reanalysis can be found in Ferry et al. (2010).

Description of SURCOUF3D

Using the thermal wind equation 3D geostrophic velocity field can be deduced from surface geostrophic current and from a 3D temperature and salinity field. In the case of SURCOUF3D we use the products SURCOUF and ARMOR3D. The SURCOUF field provides geostrophic surface velocities deduced from altimetry. The altimetric data used in the computation of the multimission maps of Sea Level Anomaly (SLA) are from the ERS-1,2, ENVISAT,T/P,GFO, GEOSAT, Jason-1,2 satellites. The CMDT RIO05 (Rio and Schaeffer, 2005) MDT is added to the SLA maps to obtain maps of absolute dynamic topography, that are then used to infer through geostrophy the ocean surface currents. The SURCOUF geostrophic products are computed daily, on a global 1/3° MERCATOR grid. ARMOR3D field is a 3D thermohaline field computed at CLS. It consists first in deriving synthetic thermohaline fields through a multiple linear regression method using altimeter data (described above) and SST from (Reynolds et al., 1994). For the vertical projection, the baroclinic component of the altimeter data is extracted (Guinehut et al., 2006). Then, these synthetic profiles are merged with in-situ T/S profiles (Argo profiling floats, XBT and CTD) using an optimal interpolation method (Guinehut et al., 2004). The ARMOR-3D products are computed weekly, on a global 1/3° MERCATOR grid and on 24 vertical levels from 0 to 1500m depth.

Ocean indicators deduced from in situ observations

Global Ocean heat content

The world ocean is the dominant component of the earth's heat balance as the oceans cover roughly 72% of the planets surface and have the largest heat capacity of any single component of the climate system. The world ocean is responsible for more than 80% of the estimated possible total increase of heat content of the earth system during 1955-1998 (Levitus et al., 2005). Causes for the positive long-term trend in ocean heat content are due to the increase of greenhouse gases in the earth's atmosphere (Levitus et al., 2001). The estimation of ocean heat content implies a measure of the net climate forcing on interannual and long-term period scales (Levitus et al., 2005; Hansen et al., 2005). Therefore changes in globally integrated heat content variability (Figure 1) have very important implications for understanding the earth's energy balance and the evolution of anthropogenic climate change.

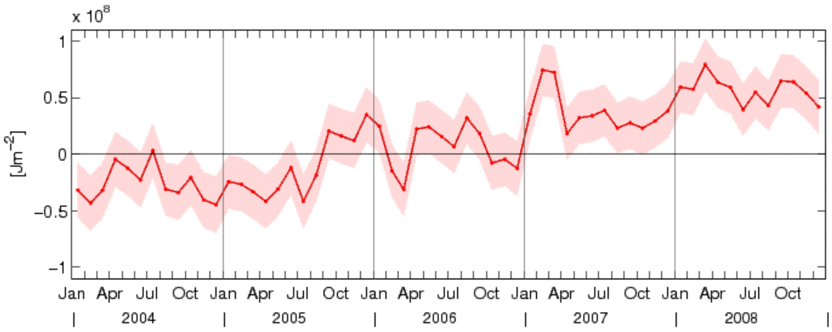

Figure 1

Time series of global mean heat content variability (J.m-2) calculated from the temperature measurements in the upper 2000m depth. The average global warming rate accounts for 0.65±0.13 Wm^{-2} during the years 2004-2008. The shaded area shows the error bar of the global mean heat content estimation.

Ocean heat content variability HS is defined here as the deviation from a reference period (2004-2008) and is closely proportional to the average temperature change from the surface to z = 2000 m depth of the global ocean:

$$HS = \int_{z_1}^{z_2} \rho_0 c_p (T_{mth} - T_{clim}) dz \,,$$

Where the reference density ρ_0 = 1030 kgm^{-3}, the specific heat capacity cp = 3980 J/kg°C, T_{mth} is the monthly gridded in situ temperature field. T_{clim} is the reference climatology derived from the gridded in-situ temperature measurements during 2004 to 2008. The units of HS correspond to Jm^{-2}. Note that ocean heat content is calculated from 60°S-60°N. It is of utmost importance to associate precise error bars to these estimations which is a non trivial exercise. The error bar which is composed of the measurement error and the mapping procedure (von Schuckmann et al., 2009) is marked in Figure 1. More work will be done on the error estimation. These efforts include comparisons to other data sets to improve the error estimation. The key message of Figure 1 includes a clear heat increase with an average warming rate of 0.65±0.13 Wm^{-2} for the 0-2000 m depth layer during 2004-2008. This number lies in the range of estimations during the last decade (e.g. Levitus et al., 2009, Willis et al., 2004), but discrepancies are quite large because of different estimation periods as decadal changes play an important role (e.g. von Schuckmann et al., 2009, Roemmich et al., 2007).

Global Freshwater content

Owing to a lack of direct salinity observations, previous discussions on signatures of ocean hydrographic changes have been concentrated on the temperature field. The salinity effect cannot be neglected. In the upper part of the global ocean, large salinity changes are mostly controlled by coupled ocean-atmosphere modes (e.g. Kessler, 1998; Delcroix et al., 2007; Reverdin et al., 2007). Large-scale coherent salinity trends are also detected in the deeper layers of the global ocean during the past 50 years (e.g. Antonov et al., 2002; Curry et al., 2003; Boyer et al., 2005; Böning et al., 2008). The monthly gridded salinity measurements in the upper 2000m depth are used to evaluate freshwater content FW:

$$FW = -a \int_z \frac{\rho(T,S,p)}{\rho(T,0,p)} \frac{S'}{(S_r + S')} dz \,,$$

Where *a* is the area of the near global ocean (60°S-60°N), ρ is the density of seawater, S_r the mean salinity derived from the ARIVO product (S_r = 34.63) and p is the pressure. Details of this method can be found in the paper by Boyer et al., 2007. This method is valid under the assumption that the salt content is relatively constant over the analysis time and that any changes in salinity are due to the addition or subtraction of freshwater to the water column – including vertical movements of the isopycnal surfaces and convection processes. Many mechanisms can lead to the addition or subtraction of freshwater, e.g. air-sea freshwater flux, river runoff, sea-ice formation as well as freshwater exchange of continental glaciers. However, the global average of FW is dominated by interannual changes (Figure 2). The average global freshwater rate is positive but small and accounts for 2700±1400 km^3 during the years 2004-2008.

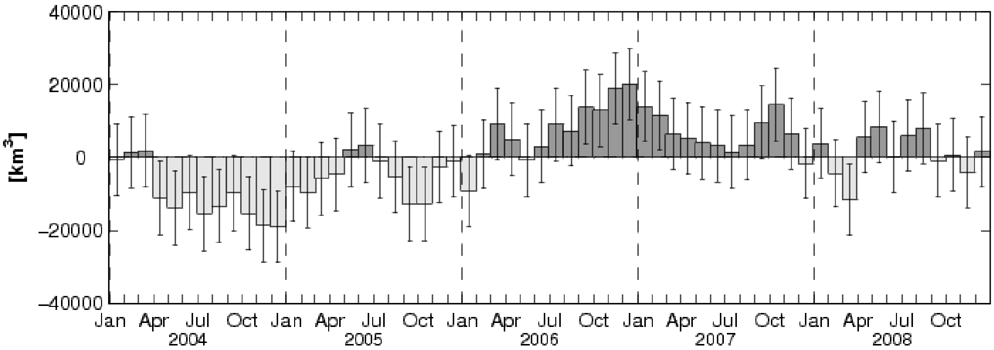

Figure 2

Time series of global mean freshwater content (km3) calculated from the salinity measurements in the upper 2000m depth. The average global freshwater rate accounts for 2700±1400 km^3 during the years 2004-2008. Error bars of the global mean freshwater content estimation are marked.

Global steric sea level

Steric expansion of the oceans is one of the major causes of global mean sea level rise, which is an alarming consequence of anthropogenic climate change (Bindoff et al., 2007). Estimations of sea level rise is of considerable interest because of its potential impact on human populations living in coastal regions and on islands (> 50% of the world population). The monthly temperature and salinity gridded in-situ measurements allow a direct calculation of global mean steric sea level (Figure 3). Rise in steric sea level is driven by volume increase through the decrease of ocean salinity (halosteric increase) and the increase of ocean temperature (thermosteric increase), from which the latter is known to play a dominant role in the global average. Combined with sea level rise derived from satellite, steric sea level rise allows a determination of the mass change of the ocean (e.g. due to the melting of continental ice).

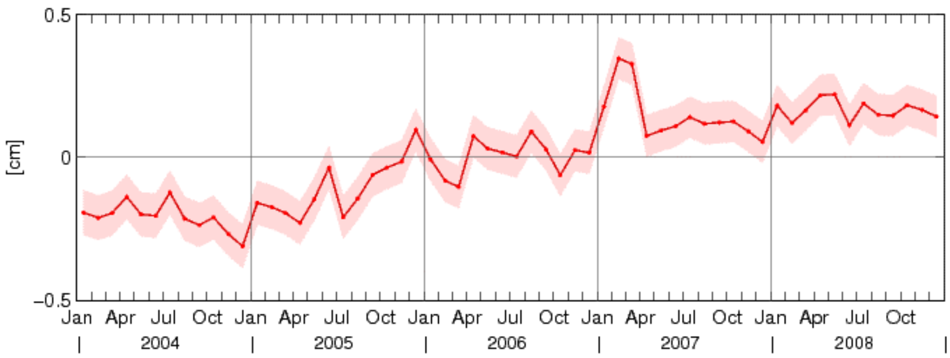

Figure 3

Time series of global mean steric sea level (cm) calculated from temperature and salinity measurements between 10-1500 m depths. The average steric rise accounts for 0.95±0.2 mm/yr during the years 2004-2008. The shaded area shows the error bar of the global mean steric sea level estimation.

The calculation of steric height between two depth layers $h(z_1,z_2)$ involves a vertical integration of ocean density ρ, which in turn can be estimated from temperature T and salinity S measurements, and the ocean pressure p (ρ(T,S,p)):

$$h(z_1,z_2) = \int_{z_1}^{z_2} \left(\frac{1}{\rho(T,S,p)} - \frac{1}{\rho(0,35,p)} \right) * \rho_0 dz \,,$$

Where ρ_0 is a reference density (Tomzcak and Godfrey, 1994). Steric height $h(z_1,z_2)$ has the dimension of height and is expressed in meters. Due to current data capacities, the density changes between the surface (z_1 = 10m) and z_2 = 1500m depth have been addressed in this calculation and the error bar which is composed of the measurement error and the mapping procedure (von Schuckmann et al., 2009) is indicated in Figure 3. Also for this parameter, more work will be done on the error estimation. The key message of Figure 3 includes a clear steric sea level rise of 0.95±0.2 mm/a for the 10-1500m depth layer during 2004-2008. Interannual fluctuations of global steric sea level exist but are small compared to the long-term variability. The 5-year changes based on steric contribution alone constitute about 40% to the total sea level rise during that time (von Schuckmann et al., 2009).

Regional linear trend of steric sea level

The major causes of global mean sea level rise are steric expansion of the ocean and eustatic rise due to increased melting of land-based ice as well as mass exchange between the oceans and other reservoirs (Bindoff et al., 2007). Together with fluctuations in ocean circulation, these processes cause geographically non-uniform sea level changes. In some regions, rates are up to several times the global mean rise, while in other regions sea level is falling. Ultimately the effect of climate change (e.g. sea level rise) is felt at regional level. Steric sea level will rise where the ocean warms and fall where it cools, since the density of the water column will change. More observations and understanding of regional changes of sea level rise must be developed which is of considerable interest because of its potential impact on human populations living in coastal regions and islands.

Regional changes of steric sea level from the year 2004 to 2008 are shown in Figure 4. The steric height estimations contain a considerable amount of interannual and decadal variability which are coherent throughout large parts of the ocean. For example, an approximately 15mm/year fall of steric sea level emerges in the tropical Pacific Ocean accompanying the El Niño Southern Oscillation event which accounts for the largest fraction of thermosteric ocean variability (Lombard et al., 2005). Areas of a positive trend of steric sea level - which contribute to the global steric rise - occur in all basins and dominate the Pacific Ocean.

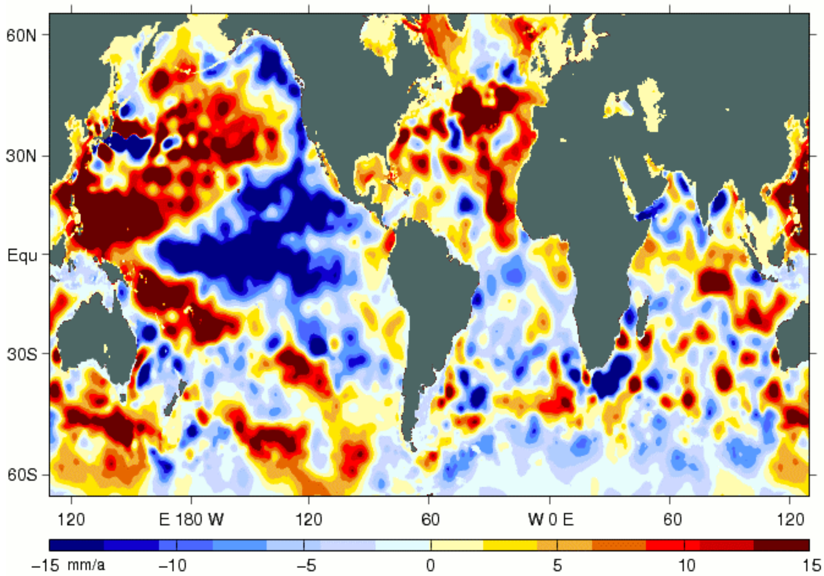

Figure 4: Linear trend (mm/year) during the years 2004-2008 of steric sea level calculated from gridded temperature and salinity in-situ measurements between 10-1500m depths**.**

Comparisons with a model reanalysis: GLORYS1V1

Atlantic MOC

As mentioned in Bryden et al. (2005) the Atlantic MOC carries warm upper waters into far-northern latitudes and returns cold deep waters southward across the equator. Its heat transport makes a substantial contribution to the moderate climate of maritime and continental Europe, and any slowdown in the overturning circulation would have profound implications for climate change. Volume transport along a section can be monitored from different complementary methods based on in-situ and satellite observations or a numerical model (Hirschi et al., 2003). In situ measurements are useful to validate models but they are spatially and temporally limited despite the current international effort to operate repetitive sections in all oceans over several years like what has been done in the framework of the WOCE, Rapid-MOC, or OVIDE projects. On the contrary the SURCOUF3D and GLORYS 3D velocity products are global. The former gives a picture of the observed ocean over the 15-year-altimetric time period, while the latter has been computed over a shorter period (the 'Argo' period, 2002-2008). The monthly average of SURCOUF3D MOC shows a very high variability with a standard deviation of 6.4 Sv (Figure 5). Over the common period 2002-2008 the four methods (Surcouf3D, Glorys, Rapid and Bryden et al., 2005) show reasonably good agreement. Note that the RAPID-MOC averages for 2004 and 2007 have been computed for incomplete years (April to December in 2004 and January to September in 2007). The corresponding mean values are given for the SURCOUF3D and the GLORYS products as red and black triangles, respectively, which improves the comparison with the RAPID data. Larger disagreements are observed in 2005 between SURCOUF3D and RAPID and in 2003 between SURCOUF3D and GLORYS. In 2005 this difference mostly comes from a strong discrepancy (higher than 8 Sv) in May and October that has to be further investigated. In 2003, the disagreement is due to the sampling of eddies in the western boundary current off the Bahamas. Between 73.5°W and 72°W SURCOUF3D resolves southward cur rent that count for -8Sv (integrated up to 1000m) while GLORYS field does not see southward current at this location.. Because of the high variability of the MOC, this kind of intercomparison is quite useful for the cross validation of the various datasets as well as for assessing the error on the MOC computation.

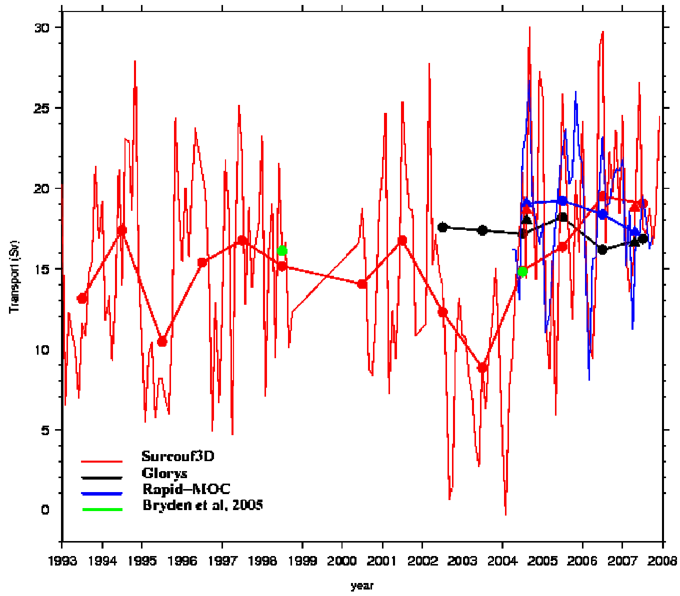

Figure 5

Atlantic Meridional Overturning Circulation at 26.5°N. In red: Sum of geostrophic transport (Sv) from Bahamas to Africa from the surface to 1000m computed from SURCOUF3D and the Ekman transport (Sv) from Bahamas to Africa computed using ERA-Interim reanalysis and Florida current transport monitoring using cable measurements. In black: volume transport from Florida to Africa and from the surface to 1000m computed with GLORYS. In blue: AMOC computed from RAPID-MOC data (Hirschi et al., 2003, Cunningham et al., 2007). In green: AMOC computed by Bryden et al, 2005. Thin lines are monthly average. Dots are yearly average (January to December). Triangles are incomplete yearly average (April to December in 2004 and January to September in 2007) to be coherent with RAPID-MOC data.

Conclusion

Here we present global ocean indicators reflecting the state of the ocean and its changes during the years 2004-2008. A global uniform field of gridded temperature and salinity measurements is used to derive those indicators. We find global rates of 0.65±0.13 Wm^{-2} for heat storage, 2700±1400 km^3 for freshwater content and 0.95±0.2 mm/yr for steric sea level. Freshwater content is dominated by interannual fluctuations. Areas of a positive trend of steric sea level - which contribute to the global steric rise – occur in all basins and dominate the Pacific Ocean.

Recently, the Argo array is fully developed and produces a uniform monitoring of the global ocean, thus reducing errors caused by undersampling and revealing consistent and accurate estimates of the ocean state. The global ocean indicators presented here will be updated every year from reprocessed and delayed mode data. With the growing data set of Argo a long-term and robust description of the state of the ocean and its changes will thus be available. The basic material to assess global indicators includes reprocessed data which have been mapped on a regular grid using statistical assumptions. Therefore, the sensitivity of ocean indices with respect to data processing and different types of measurements need to be tested which is the objective of present and future research of Mercator Ocean and Coriolis.

A second GLORYS1 experiment is in progress using reprocessed data (CORA02V2) as well as improvements such as bias correction, the use of a new MDT, a more recent version of NEMO and a new atmospheric surface forcing (INTERIM Reanalysis). ARIVO and GLORYS (which also include model experiments without data assimilation), together with ARMOR3D, SURCOUF3D all with different approaches make an optimal use of this unprecedented well observed period starting with the ARGO network. Observed products help to validate and improve the models and reanalyses, and reanalyses influence the reprocessing of observations or the design of new observation networks. Moreover, comparing observed products - for instance indicators - with reanalysis products yields a better understanding of the limitations of each approach.

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