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How well can we derive Global Ocean Indicators from Argo data?

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Abstract

Argo deployments began in the year 2000 and by November 2007 the array was 100 % complete, covering the global ocean from the surface down to 2000 m depth. In this study, Argo temperature and salinity measurements during the period 2005 to 2010 are used to develop a revised estimation of Global Ocean Indicators (GOIs) such as heat content variability, freshwater content and steric height. These revised indices are based on a simple box averaging scheme using a weighted mean. They include a proper estimation of the errors due to data handling methods and climatology uncertainties. A global ocean heat content change (OHC) trend of $0.55 \pm 0.1\,\mathrm{W\,m^{-2}}$ is estimated over the time period 2005–2010. Similarly, a global steric sea level (GSSL) rise of $0.69 \pm 0.14\,\mathrm{mm\,yr^{-1}}$ is observed. The global ocean freshwater content (OFC) trend is barely significant. Results show that there is significant interannual variability at global scale, especially for global OFC. Annual mean GOIs from the today's Argo samling can be derived with an accuracy of ± 0.10 cm for GSSL, $\pm 0.21 \times 10^8\,\mathrm{J\,m^{-2}}$ for global OHC, and $\pm 700\,\mathrm{km^3}$ for global OFC. Long-term trends (15 yr) of GOIs based on the complete Argo sampling (10–1500 m depth) can be performed with an accuracy of about $\pm 0.03\,\mathrm{mm\,yr^{-1}}$ for steric rise, $\pm 0.02\,\mathrm{W\,m^{-2}}$ for ocean warming and $\pm 20\,\mathrm{km^3\,yr^{-1}}$ for global OFC trends – under the assumption that no systematic errors remain in the observing system.

1 Introduction

During the past decade, the international Argo programme has revolutionized the distribution of ocean data within the research and operational communities (Roemmich et al., 2009). Argo delivers temperature and salinity measurements throughout the deep global ocean down to 2000 m depth. The data are both received in real time for operational users and after careful scientific quality control they are used for climate research. Those data undergo greater quality control and validation procedures with strong involvement of scientific experts (e.g., Le Traon et al., 2009).

One way of observing and understanding the ocean's role in the Earth's energy balance is to evaluate the average temperature change from the surface down to the deep ocean. Argo provides the capability to assess global ocean heat content (OHC) by measuring subsurface in situ temperature, at least for the upper 2000 m depth. Moreover, the effect of internal global ocean salinity changes can be discussed which had been mostly neglected in previous global analyses due to a lack of large scale direct subsurface salinity observations. The subsurface in situ temperature and salinity measurements are the only possibility to describe the internal distribution of density. This, in turn, provides the capability to understand global sea level change by evaluating its steric component which is one of the major causes of global mean sea level changes (Bindoff et al., 2007; Cazenave et al., 2009). Estimations of sea level changes are of considerable interest because of its potential impact on human populations living in coastal regions and on islands (> 50 %). Accurate projections of future sea level changes, caused by a mixture of long-term climate change and natural variability, require an understanding of the causes of sea level change in the modern data record. While Argo provides data with unprecedented accuracy and coverage, estimating such small ocean signals remains a major challenge. It requires very careful data quality control and analysis as well as a proper estimation of errors for a sound interpretation of results.

Rise in global steric sea level (GSSL) 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. Together with satellite altimetry and satellite gravity measurements, this can partition global sea level rise into its steric and mass-related components (e.g., Cazenave et al., 2009; Leuliette and Miller, 2009). Several GSSL variations from Argo and other in situ observations have been derived over the past couple of years (e.g., Willis et al., 2008; Cazenave et al., 2009; Leuliette and Miller, 2009; von Schuckmann et al., 2009). There are substantial differences in these global statistical analyses which have been related to instrumental biases, quality control and processing issues, role

of salinity and influence of the reference depth for steric sea level calculation. Sparse global sampling before Argo sampling was 100 % complete also limits the statistical significance of some of the observed differences.

Many attempts have been made to estimate long-term as well as recent global OHC changes. But the underlying uncertainties in ocean warming are still unclear. An overview on the different analyses estimating OHC can be found in Lyman et al. (2010). For example, several teams have recently produced different multi-year estimates of the annually averaged global integral of upper-ocean heat content anomalies. Patterns of interannual variability, in particular, differ among methods. Especially correction methods of historical measurements (XBTs) dominate among method variability in estimating this GOI (Domingues et al., 2008; Lyman et al., 2010; Gouretski and Reseghetti, 2010). Recent short term estimations of global OHC are mostly based on Argo measurements, and thus reduce possible errors due to large data gaps in space and time as well as due to inhomogeneous sampling. But nevertheless, as interannual variability of OHC is large in the long-term estimations, analyses of global OHC during the last decade differ as well among methods (von Schuckmann et al., 2009; Willis et al., 2009; Trenberth and Fasullo, 2010).

Changes to the global hydrological cycle of either natural or anthropogenic nature induce fluctuations in its ability to store and transport water vapor. For example, a warmer ocean surface layer causes an increase in the global cycle of evaporation and rainfall. This in turn affects the salinity field of the global ocean. Evaluating global ocean freshwater content (OFC) as a salinity anomaly over a depth layer is an indirect but potentially sensitive indicator for detecting changes in precipitation, evaporation, river runoff and ice melt (sea ice, continental glaciers and ice sheets). While the impacts are local and regional, the causes and patterns are global. Large and coherent multi-decadal changes in the ocean's salinity field have already been reported on global and regional scales where large and spatially coherent multi-decadal linear trends in salinity to 2000 m depth are found (e.g., Antonov et al., 2002; Boyer et al., 2005; Delcroix et al., 2007; Durack and Wijffels, 2010). Results shown in von Schuckmann et al. (2009) document that ocean salinity and hence freshwater are changing on gyre and basin scales, with the near-surface waters in the more evaporative regions increasing in salinity in almost all ocean basins. Moreover, it could be shown that near global OFC is characterized by large interannual changes rather than by a significant trend during the last decade.

These discrepancies show that it is important to pursue a careful data handling and error estimation while defining GOIs like those discussed above. A revised estimation of GOIs such as global steric sea level variations, OHC and OFC are proposed here for the years 2005 to 2010 together with refined error estimates. The paper is organized as follows. Section 2 presents the data set and methods used and the method is tested and discussed in this section. A careful discussion on the error of GOIs due to the data handling is given in Sect. 3. Method validation using altimetry is presented in Sect. 4. Finally the revised estimations of GOIs are shown, together with a discussion on the global trend estimations.

2 Data sets and methods assessing GOIs

The basic material for this study encompasses the large in-situ data set provided by the Argo array of profiling floats (http://www.argo.net). The data (Argo only) were downloaded from the Coriolis data center (http://www.coriolis.eu.org/cdc), i.e. the Coriolis Ocean Database for Re-analyses (CORA2.2, Cabanes et al., 2010). The database – from which about 75 % of the observations undergo delayed mode quality control procedures (Cabanes, personal communication) – was received in June 2010 for the 2005–2009 period, and in January 2011 for the database during the year 2010. The datasets are processed by the processing tool "ISAS-STD" (Gaillard, 2010) which reads the selected variable, performs a climatological test and interpolates on standard levels.

To evaluate GOIs from the irregularly distributed global Argo data, temperature and salinity profiles during the years 2005 to 2010 are uploaded spanning 10 to 1500 m

depth. This depth layer is a compromise to maximize the number of selected profiles while going deep enough to assess ocean variability (von Schuckmann et al., 2009). We have started our calculation with the year 2005 as before there were major gaps in the global coverage, especially in the southern ocean. The monthly sampling of the global observing system for the northern, tropical and southern oceans sector is visualized in Fig. 1. Mostly during the years 2005 and 2006 – that is when Argo was not yet completed – sampling was reduced in the southern ocean basin and amplified in the summer month in the extra tropical sectors. This rapidly changed in the end of the year 2006 when Argo sampling was almost completed allowing a more homogenized global distribution of in situ measurements (Fig. 1). The gridded in situ product ARIVO (Gaillard, 2010) is used to extract a climatology field over the 2004–2009 period (ACLIM hereinafter). This climatology is interpolated on every profile position in order to fill gappy profiles at depth of each temperature and salinity profile. After the initial data processing, physical ocean properties are evaluated from the global in situ field at every profile position, i.e. in the frame of our study OHC, SSL and OFC as described in von Schuckmann et al. (2009). Finally, anomalies of the physical properties at every profile position are calculated with respect to the corresponding ACLIM.

We have carried out sensitivity tests to investigate changes of GOIs when using different climatologies, i.e. either ACLIM or WOA05 (Locarnini et al., 2006; Antonov et al., 2006) for evaluating the anomalies as described above. The results are presented in Fig. 2 for all three parameters. Differences occur mainly at the beginning of the time series at yearly and smaller periods and are largest for GSSL (Fig. 2, upper panel). The sensitivity of GOIs with respect to the choice of the climatology is generally small, but is is not negligible. Therefore, a climatology uncertainty for each GOI is included in the error estimation as discussed later in Sect. 3.1.

To estimate the GOIs from the irregularly distributed profiles, the global ocean is first divided into boxes of 5° latitude, 10° longitude and 3 month size. This provides a sufficient number of observations per box. To remove spurious data, measurements which depart from the mean at more than 3 times the standard deviation are excluded.

The variance information to build this criterion is derived from ARIVO 2004–2009 and this procedure excludes about 1 % of data from our analysis. Moreover, only data points which are located over bathymetry deeper than 1000 m depth are kept. Finally, boxes containing less then 10 measurements are considered as a measurement gap.

The mean for each $5^\circ \times 10^\circ \times 3$ month box is estimated using a a weighted averaging method based on the analysis of Bretherton et al. (1976). All observations Φ_i within a given box are averaged taking into account the space and time correlation of observations:

$$\bar{\Theta}_{\text{box}} = \frac{\sum_{i,j} A_{i,j}^{-1}\Phi_i}{\sum_{i,j} A_{i,j}^{-1}}, \tag{1}$$

where $A_{i,j} = \overline{\Phi_i \Phi_j}$ is the matrix of covariance between all pairs of observations within one box and i, j the spatial coordinates. This calculation provides an optimal estimation of the mean (in a least squares sense) assuming the ocean signal covariance is known. For the sake of simplicity, this covariance matrix is assumed to be the same for all GOIs. We used space and time correlation scales of 150 km and 15 d, respectively, for the correlation matrix. These are typical scales of mesoscale variability (e.g., Le Traon and Morrow, 2001). This calculation reduces the weight of observations that are too close from each other and thus do not provide independent estimations.

Before globally averaging the physical properties, one needs to address how to handle data gaps (i.e. boxes with less than 10 observations). Lyman et al. (2008) have assessed the effects of irregular in situ ocean sampling on estimates of global OHC anomalies by comparing two methods: the first one assumes zero anomalies in gaps and the second one assumes that areas that are not sampled have a mean equal to the spatial mean of observations. Their results imply that warming trends in the global integral of upper OHC anomalies are consistently estimated while assuming that the spatial mean of the anomalies in the unsampled regions is the same as the mean for

the sampled regions. Replacing the unsampled areas with zero anomalies results in an underestimation of the global trend. Consequently, we chose to replace gaps by the spatial mean. We do take into account, however, the impact of gaps on the error estimation (see next section).

Finally, GOIs are evaluated from the horizontal data distribution. We chose to limit our global estimation from 60° S to 60° N as this domain involves the effective coverage of the Argo array (Roemmich and Gilson, 2009). Mean estimations of physical parameters for each box are multiplied by a weighting matrix in order to take into account the box surface area. This includes the variations of box size according to latitude and the effect of reduced box size due to continental boarders. The global mean indicator GOI(t) weighted by its surface area $\mathbf{M}_{i,j}$ can be then calculated following:

$$\mathrm{GOI}(t) = \frac{\sum_{i,j} \bar{\Theta}_{\text{box}} \mathbf{W}_{i,j} \mathbf{M}_{i,j}}{\sum_{i,j} \mathbf{M}_{i,j}}. \tag{2}$$

To reduce large impacts of strong anomalies close to the coast, $\bar{\Theta}_{\text{box}}$ is multiplied by a weighting matrix $\mathbf{W}_{i,j}$ including values between 0 (box on continent) and 1 (ocean box). However, based on this method, Argo temperature and salinity measurements are used to derive a revised estimation of GOIs such as heat content variability, freshwater content and steric height. This method is easy to implement and run and can be used to set up a routine monitoring of the global ocean.

3 Error estimation

A sound interpretation of the GOIs requires a careful estimation of errors. Errors include measurement noise, systematic instrumental biases, sampling and data processing errors including the effect of unresolved ocean variability scales (e.g. mesoscale

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variability). Using the box-averaging method as described above, a simple but proper estimation of the errors on GOIs due to the sampling and data processing can be established. This is of indispensable importance to draw adequate interpretations and conclusions.

The large sensitivities of a GOI like global steric height to different data processing techniques are obvious when comparing different products of gridded Argo fields (Fig. 3). Three products have been downloaded from the Argo web-page (http://www.argo.ucsd.edu), i.e. two products based on Argo and other hydrographic data (ARIVO delivered by Ifremer, and MOAA delivered by JAMSTEC) and one product including Argo only measurements (delivered by Scripps Institution of Oceanography). Detailed information on the gridded fields can be found on the Argo webpage. We have chosen to evaluate the comparison during the time period 2004 to 2008 for consistency. Amplitudes of interannual fluctuations differ from one product to another. Largest deviations emerge in the beginning of the time series – in particular in the Southern Ocean due to sparse data coverage during that time period (Fig. 1). However, although the evaluation of global steric height in Fig. 3 is more or less based on the same data base, differences are clearly visible. These differences lead to a large spread of the estimation of global steric trends ranging from nearly $0\,\mathrm{mm\,yr^{-1}}$ to about $1\,\mathrm{mm\,yr^{-1}}$. This simple exercise already shows that a sensitivity study due to data handling is vital.

3.1 Error bars estimated for global GOIs

The error $\epsilon^2_{i,j}$ on the averaged physical parameter Φ_i in every $5^\circ \times 10^\circ \times 3$ month box using the formulation of Breterthon et al. (1976) can be written as

$$\epsilon^2_{i,j} = \frac{1}{\sum\limits_{i,j} A^{-1}_{i,j}} \sigma^2_{i,j},$$

where $\sigma^2_{i,j}$ is the variance of Φ_i within each box, respectively. This takes into account the reduced number of degrees of freedom to estimate the error on the mean value

for a given box (through the covariance matrix). Note that this effect is not negligible. Assuming independent observations would reduce the error variance by more than 10 %. To evaluate the error for the global estimation, we need to take into account the errors for all boxes. Boxes that have less than 10 observations are associated with a variance error equal to the total variance of the physical parameter. The global mean errors $E(t)^2$ can be then calculated following

$$E(t)^2 = \frac{\sum\limits_{i,j} (\epsilon_{i,j} \mathbf{W}_{i,j})^2 \cdot \mathbf{M}^2_{i,j}}{\sum\limits_{i,j} \mathbf{M}^2_{i,j}}. \tag{3}$$

An additional source of uncertainties arises from the choice of the climatology used to fill vertical gaps and to evaluate the anomaly fields. As discussed in Sect. 2 and shown in Fig. 2, the climatological uncertainty E^2_{clim} is small, but not negligible and needs to be included in the error bar calculation. To estimate the value for E^2_{clim}, the standard deviation of the residual of the two time series using either ACLIM or WOA05 shown in Fig. 2 has been derived for each GOI. Thus, the total error $E_{\mathrm{total}}(t)^2$ on GOIs can be defined as

$$E_{\mathrm{total}}(t)^2 = E(t)^2 + E^2_{\mathrm{clim}}. \tag{4}$$

This total error includes the uncertainties due to the data handling and the choice of the reference climatology, but it does not take into account possible unknown systematic measurement errors remaining in the global observing system and not precisely corrected for in the delayed mode Argo quality control (e.g. pressure errors, salinity sensor drift). Our method can be used, however, to discuss sampling issues for the estimation of GOIs and their errors. Table 1 shows the uncertainties due to data handling and the climatology of global mean GOIs during 2005 and 2010 for different time averages. Errors clearly decrease with the growing coverage of Argo. For example, the uncertainties of 3-monthly global OHC account for $\pm 0.51 \times 10^8\,\mathrm{J\,m^{-2}}$ during the year

2005 and reduce to $\pm 0.43 \times 10^8\,\mathrm{J\,m^{-2}}$ during 2010 where Argo sampling was complete. Estimating annual mean GOIs from the actual complete Argo observing system can be performed with an accuracy of ± 0.10 cm for GSSL, $\pm 0.21 \times 10^8\,\mathrm{J\,m^{-2}}$ for global OHC, and $\pm 700\,\mathrm{km^3}$ for global OFC.

3.2 Global trend error estimation

As a final step, the time evolution of GOIs over our study period is estimated. For this purpose, the method of weighted least square fit is used to retrieve 2005–2010 GOIs trends. The trend of each GOI time series is evaluated using a weighted least square solution where the weights are the error bars of our GOIs given by Eq. (4) (see Appendix A). This approach allows a reliable estimation of the capability of the Argo global observing array to derive global ocean indices. If these are discussed and carefully assessed – and included in the estimation of climate indices – misinterpretations during the analysis stage can be avoided. It is important to mention that error bars obtained from Eq. (4) only involve errors due to the sampling, data handling and climatology uncertainties. Thus, the uncertainty of global trend estimations might increase in future studies as systematic errors due to unknown instrument biases have not been taken into account.

The error on the trend of GOIs during the 6-yr time series is presented in Table 2. Uncertainties of trend estimations of GOIs derived from the in situ observing system in the upper 1500 m depth due to the data handling and climatology uncertainties amount to $\pm 0.14\,\mathrm{mm\,yr^{-1}}$ for steric rise, $\pm 0.1\,\mathrm{W\,m^{-2}}$ for ocean warming and $\pm 90\,\mathrm{km^3\,yr^{-1}}$ for the global OFC tendency. A "forecast calculation" of the uncertainties of global trend estimations has been established assuming GOI error bars during the year 2010 (i.e. when Argo sampling was complete) applying Eq. (A1) of the Appendix. This exercise reveals that long-term trends (15 yr) of GOIs based on the complete Argo sampling could be performed with an accuracy of about $\pm 0.03\,\mathrm{mm\,yr^{-1}}$ for steric rise, $\pm 0.02\,\mathrm{W\,m^{-2}}$ for ocean warming and $\pm 20\,\mathrm{km^3\,yr^{-1}}$ for global OFC trends – under the major assumption that no systematic errors remain in the observing system.

Note that our estimations provide an estimation of errors on the trend over a given time period. Such trends even if they are statistically significant cannot be interpreted as long term trends as they are certainly influenced by interannual signals. This is clearly the case for the OFC trend.

3.3 Method validation

Altimeter observations are a useful and nearly global observational record over the ice-free oceans that have been shown to be correlated with in situ upper ocean observations (e.g., Willis et al., 2004; Guinehut et al., 2006). For this purpose, maps of mean sea level anomalies (MSLA) are ideal to validate our simple box method based on irregular sampling. Using the high-resolution altimeter measurements as a proxy for global ocean in situ estimations has already been performed in previous studies (Lymann et al., 2008; Roemmich and Gilson, 2009). Although satellite MSLA fields are not truly global and have possibly undefined errors and also contain mass (bottom pressure) signals (Wunsch et al., 2007; Ponte, 1999), they are a very useful proxy to test our simple box method. We have used gridded fields downloaded from the AVISO webpage (merged gridded product, http://www.aviso.org). Weekly AVISO maps of MSLA on a $1/3^\circ$ Mercator grid are subsampled at the locations and time of the year of in situ data collected for all years during 2005 to the end of 2010 to see how well our box-averaging method simulates near global ocean changes. Then, global mean sea level anomalies have been evaluated as described in Sect. 2. During the study period in situ sampling has changed which is evident in Fig. 1. Large sampling variations from 2005 to 2010 are evident south of 30° S, and even further north. However, using the subsampled altimeter information helps us to investigate how well we can reproduce the "proxy for reality", i.e. the global mean derived from the gridded altimeter product. The comparison between the two global averages calculated in different ways shows reasonable agreement and their 6 yr increase are consistent (Fig. 4). There are differences in high frequency variability among the curves. For example, during 2005 and 2006, differences are largest and reach up to 0.2 cm which can be associated with the paucity of data in some parts of the global ocean (Fig. 1). After November 2007, i.e. when Argo sampling was almost 100 % complete, differences between the global estimation clearly decrease. However, this validation shows that our simple box averaging method depicts global mean changes reasonably well and can be used to assess GOIs for monitoring needs of the climate system. This is especially now the case as the Argo sampling is almost complete.

3.4 Revised estimation of GOIs

In this study, the calculation of GSSL, OHC and OFC from the Argo global ocean observing system has been chosen to represent GOIs for monitoring the ocean's role in the global climate system. The GOIs are quantified using the box averaging method discussed in Sect. 2. Figure 5a shows the variability of GSSL. The error decreases as the number of measurements increases. Consequently, error bars are large in the beginning of our time series and decrease when the Argo sampling was complete, e.g. at the end of the year 2007. However, a significant steric increase is visible from the year 2005 to 2010. The 6-yr positive trend evaluated using the method of weighted least square (Sect. 3.2) amounts to $0.69 \pm 0.14\,\mathrm{mm\,yr^{-1}}$. Changes in global OHC are characterized by an increase from 2005 to 2010 with a rate of $0.55 \pm 0.1\,\mathrm{W\,m^{-2}}$. Both values are lower to what was found in an earlier study (von Schuckmann et al., 2009). This can be due to the fact that the later period is confined to a period when the upper layers did not seem to be gaining much heat (Levitus et al., 2009; Lymann et al., 2010).

Interannual fluctuations of GSSL and global OHC exist but are small compared to the long-term variability. Moreover, estimations of global amplitudes at interannual time scales appear to be not significant due to the size of the error bars, at least for the beginning of the time series. This is different for global OFC. Large interannual fluctuations dominate the time series, and the trend estimation is barely significant. This implies that a longer time series is needed to be able to extract a significant tendency of global freshwater changes superimposed by large interannual fluctuations.

4 Conclusions

Global integrated time series from in situ observations are a useful model benchmark and an important diagnostic for changes in the Earth's climate system (Hansen et al., 2005; Levitus et al., 2005). But differences among various analyses and inconsistencies with other indicators merit attention (Trenberth, 2010). Lyman et al. (2010) have performed a detailed error analysis on long-term OHC estimations helping to determine the confidence in the results. Their conclusions provide a valuable caution for users of these data. Due to its global span, the Argo global observing system clearly opens up new scope to observe climate related changes. Comparisons of global steric height trends based on different gridded fields of Argo in situ measurements show a range of 0–1 $\mathrm{mm\,yr^{-1}}$ which can be lead back to data handling and climatology uncertainties. Our results show that GOIs derived from the Argo measurements are ideally suitable to monitor the state of the global ocean, especially after November 2007, i.e. when Argo sampling was 100 % complete. They also show that there is significant interannual global variability at global scale, especially for global OFC. Before the end of 2007, error bars are too large to deliver robust short-term trends of GOIs and thus an interpretation in terms of long-term climate signals are still questionable, especially since uncertainties due to interannual fluctuations are not included in our error estimation. This will certainly change with the growing set of Argo measurements as also denoted by our calculations.

We have developed a method of evaluating GOIs which is easy to implement and can be ideally used for a routine monitoring of the global ocean. With this method a simple but proper estimation of the errors on GOI estimations can be established and thus adequate interpretations and conclusions can be drawn. Our revised estimation of GOIs indicates a clear increase of global ocean heat content and steric height. Uncertainty estimations due to the data handling reveal that this increase is significant during the years 2005–2010 (this does not mean, of course, that these are long term trends). Global ocean heat content changes during this period account for $0.55 \pm 0.1\,\mathrm{W\,m^{-2}}$

and global steric rise amounts to $0.69 \pm 0.14\,\mathrm{mm\,yr^{-1}}$. Estimating annual mean GOIs from the actual complete Argo observing system can be performed with an accuracy of $\pm 0.17\,\mathrm{cm}$ for GSSL, $\pm 0.37 \times 10^8\,\mathrm{J\,m^{-2}}$ for global OHC, and $\pm 1200\,\mathrm{km^3}$ for global OFC. Long-term trends (15 yr) of GOIs based on the complete Argo sampling (10–1500 m depth) can be performed with an accuracy of about $\pm 0.03\,\mathrm{mm\,yr^{-1}}$ for steric rise, $\pm 0.02\,\mathrm{W\,m^{-2}}$ for ocean warming and $\pm 20\,\mathrm{km^3\,yr^{-1}}$ for global OFC trends – under the assumption that no systematic errors remain in the observing system.

We have defined the error on global trends of GOIs based on uncertainty estimates due to data handling and climatology uncertainties only. Our error estimations do not include remaining systematic biases in the Argo observing system (e.g. uncorrected drift of sensors, pressure errors). The sensitivity of GOIs to data processing and to different types of measurements (e.g. to detect instrumental biases) need to be tested which is the objective of present and future research. The estimation of GOIs based on our method are developed as part of the monitoring system in the frame of the European Comission project MyOcean. These ocean climate indicators are thus a useful tool to monitor on the one hand changes in the ocean climate and on the other hand to detect possible systematic errors in the global in situ observing system.

Appendix A

The global trend estimation and its uncertainty are derived from a converntional weighted least square method:

The set of observations $y_i = \alpha_i t_i + \beta$ can be written as:

$$\mathbf{y} = \mathbf{A}'\mathbf{x}, \qquad \mathbf{y} = \begin{pmatrix} y_1 \\ \vdots \\ y_N \end{pmatrix}, \qquad \mathbf{x} = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}, \qquad \mathbf{A}' = \mathbf{AW},$$

$$\mathbf{A} = \begin{pmatrix} t_1 & 1 \\ \vdots & \vdots \\ t_N & 1 \end{pmatrix}, \qquad \mathbf{W} = \begin{pmatrix} \frac{1}{E_1^2} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{1}{E_N^2} \end{pmatrix}.$$

The weighted least square solution where the weights are chosen to be the error bars of our GOIs (Eq. 4) can be written as:

$$\mathbf{X} = (\mathbf{A}'^{\mathbf{T}}\mathbf{A}')^{-1}\mathbf{A}'^{\mathbf{T}}\mathbf{y}.$$

Following Wunsch (1996) the variance of this estimation can be written as

$$\boldsymbol{\Pi}^2 = (\mathbf{A}'\mathbf{W}^{-\mathbf{1}}\mathbf{A})^{-1}. \tag{A1}$$

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Table 1. Uncertainties of global mean GOIs during 2005 and 2010 (bold) for different time averages, i.e. 3 month, 1 yr and 6 yr. See text for more details. These values do not take into account uncertainties induced by remaining systematic errors in the global observing system.

	GSSL [m]	Global OHC [10^8 J m^{-2}]	Global OFC [km^3]
3 months (2005/**2010**)	0.23/**0.19**	0.51/**0.43**	1700/**1400**
1 yr (2005/**2010**)	0.11/**0.10**	0.25/**0.21**	900/**700**
6 yr	0.07	0.16	550

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Table 2. A "forecast calculation" of the uncertainties of global trend estimations assuming GOI error bars during the year 2010 while applying Eq. (8) (Appendix) for 10 and 15 yr, together with the trend uncertainties of the current GOI estimation during 2005–2010. These values do not take into account uncertainties induced by remaining systematic errors in the global observing system.

	GSSL [m]	Global OHC [10^8 J m^{-2}]	Global OFC [km^3]
6 yr	±0.14	±0.10	±90
10 yr	±0.06	±0.04	±40
15 yr	±0.03	±0.02	±20

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

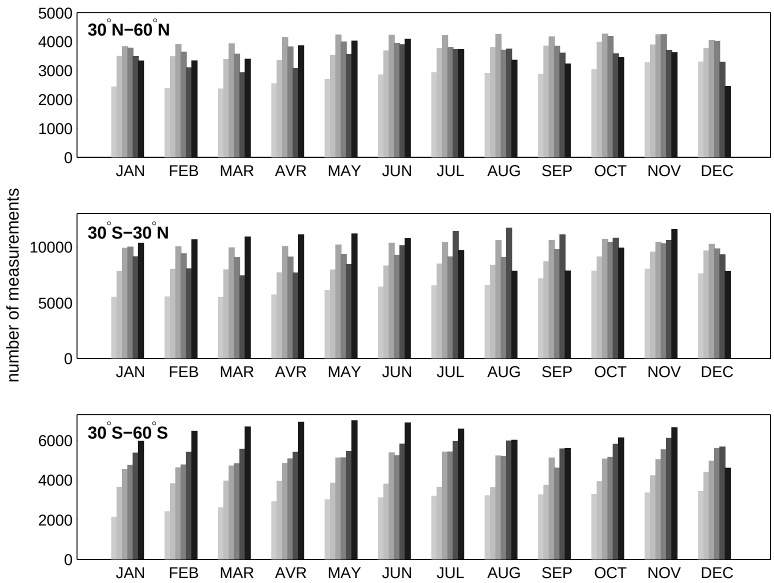

Fig. 1. Monthly number of measurements averaged for different ocean basins, i.e. northern basin 30° N–60° N (upper), southern basin 30° S–60° S (middle) and tropical basin 30° S–30° N (lower). Change of years from 2005 to 2010 shown from light to dark gray.

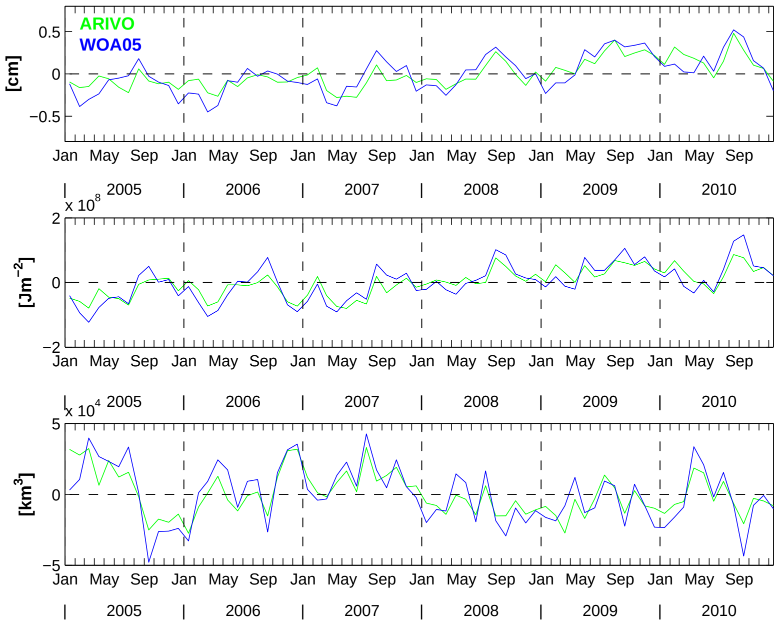

Fig. 2. Sensitivity test to estimate the climatology uncertainty for GSSL (10–1500 m, upper), global OHC (middle) and global OFC (lower) during 2005–2010. To fill missing measurements at depths as well as for the choice of the reference climatology evaluating the anomaly fields two different climatologies are used, i.e. either ACLIM (green) or WOA05 (blue).

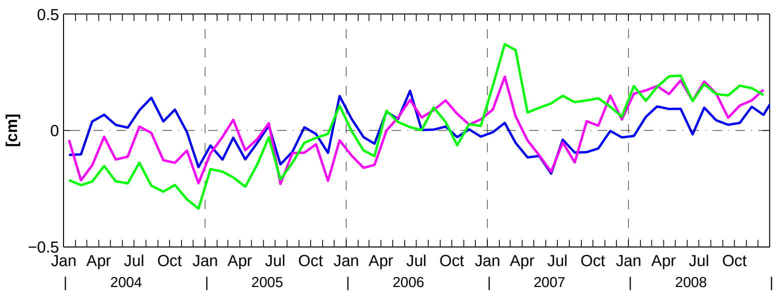

Fig. 3. Global (60° S–60° N) steric height (10–1500 m) during 2004–2008 based on three different gridded fields, i.e. ARIVO (green, Argo plus other data, Ifremer), from Scripps Institution of Oceanography (blue, Argo only) and MOAA (red, Argo plus other data, Japan Agency for Marine-Earth Science and Technology). The data have been downloaded from the Argo web page (http://www.argo.ucsd.edu).

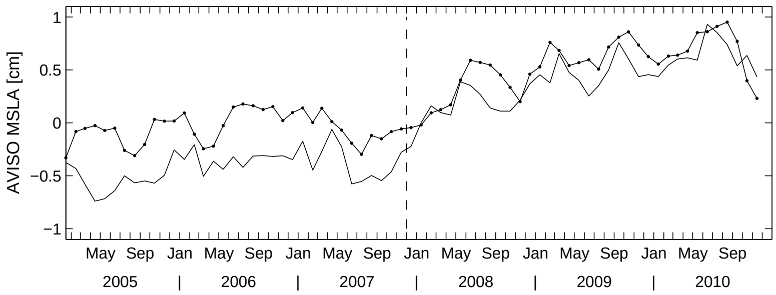

Fig. 4. Method validation using gridded altimeter SSH measurements (AVISO): gridded SSH during 2005–2010 has been subsampled to the Argo profile position and the simple box averaging method has been applied. Global mean SSH derived from the AVISO grid (bold line) is compared to its corresponding subsampled result, i.e. global SSH where gaps have been replaced by the total mean (bold + dots). Dashed line marks November 2007, i.e. when initial Argo sampling was achieved.

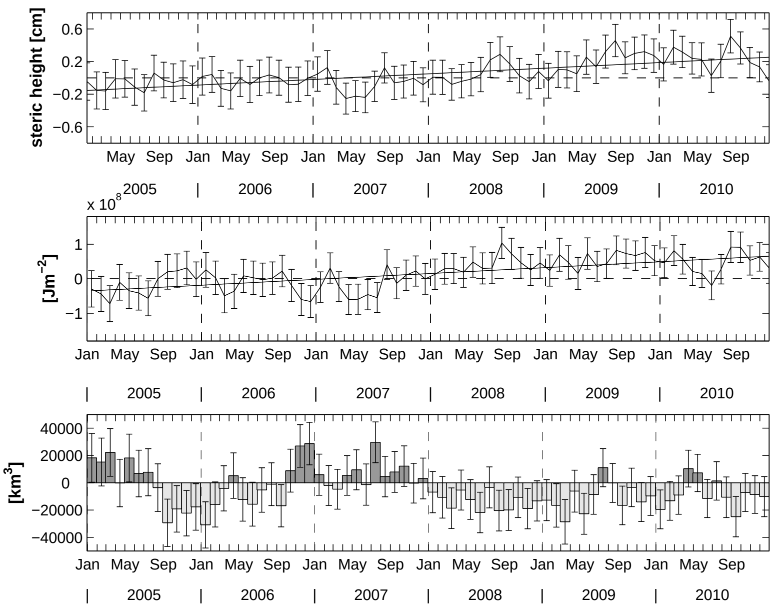

Fig. 5. Revised estimation of GSSL (upper), global OHC (middle) and global OFC (lower). The calculation is based on the simple box averaging method using a weighted mean derived from Argo measurements only. The 6-yr trend accounts for $0.69 \pm 0.14\,\mathrm{mm\,yr^{-1}}$, $0.55 \pm 0.10\,\mathrm{W\,m^{-2}}$ and $-180 \pm 90\,\mathrm{km^3\,yr^{-1}}$, respectively. Error bars and trend uncertainties exclude errors induced by remaining systematic errors in the global observing system.