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Discussions

A global comparison of Argo and satellite altimetry observations

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Abstract

Differences and complementarities between Sea Level Anomalies (SLA) deduced from altimeter measurements and dynamic height anomalies (DHA) calculated from Argo in situ temperature (*T*) and salinity (*S*) profiles are globally analyzed. Compared to previous studies, Argo data allows a much better spatial coverage of all oceans and particularly the Southern Ocean, the use of salinity measurements and the use of a deeper reference level. The use of time series along the Argo float trajectories also provides a means to describe the vertical structure of the ocean both for the low frequency and the mesoscale part of the circulation. The comparison shows the very good consistency between Argo and altimeter observations. Correlations range from 0.9 in low latitudes to 0.3 in high latitudes where the contributions of deep baroclinic and barotropic signals are the largest. The study underlines the large influence of salinity observations on the consistency between altimetry and hydrographic observations. SLA/DHA consistency is thus improved by 35% (relative to the SLA minus DHA signal) by using measured *S* profiles instead of climatology data. The use of a deep reference level also significantly improves the correlation at mid and high latitudes. The role of seasonal signals on the correlation and regression analysis between altimeter and Argo observations is also analyzed. As they are mainly associated with the heating/cooling of surface layers, removing these large scale signals significantly reduces the correlation and impacts the geographical structure of the Argo/altimetry regression coefficients. These results emphasize the need to separate the different time and space scales in order to improve the merging of the two data sets. The study of seasonal to interannual SLA minus DHA signals finally reveals interesting signals related to deep ocean circulation variations. Future work is, however, needed to understand the observed differences and relate them to different forcing mechanisms.

1 Introduction

In November 2007, the global Argo array of profiling floats reached its initial target of 3000 operating floats worldwide. The array provides for the first time a global monitoring of ocean temperature and salinity data in real time (Roemmich et al., 2009). In the meantime, satellite altimeters continue to provide global and synoptic measurements of sea level variations. These observations are now the two most important and complementary components of the global ocean observing system required by climate and operational oceanography applications (Bell et al., 2009). The study of their consistency is an essential step before the data are jointly assimilated in ocean general circulation models.

Differences and complementarities between Sea Level Anomalies (SLA) deduced from altimeter measurements and dynamic height anomalies (DHA) calculated from in situ temperature (T) and salinity (S) profiles have already been studied globally by Guinehut et al. (2006) (hereafter referred to as GLL06). They showed very good correlation between the two data sets but also systematic large-scale differences that have been related to a barotropic, Sverdrup-like, response of the ocean to wind forcing. This previous study, focused on the 1993–2003 period, was limited by the in situ observations available at that time which were mainly composed of XBT instruments. The GLL06 study is revisited here using the new available Argo data sets. The Argo data sets allow a series of improvements ranging from: (1) a better global spatial coverage (i.e. Southern Ocean), (2) a deeper reference level (1000 m vs. 700 m), (3) the use of measured S profiles (versus climatological S), (4) the separation of the different temporal scales (low frequency versus mesoscale) and (5) the study of seasonal to interannual SLA minus DHA signals.

The paper is organized as follows. Data and method are presented in Sect. 2. The global correlations of Argo DHA and altimeter SLA observations are discussed in Sect. 3. Section 4 provides an analysis of the role of seasonal signals on the SLA and DHA consistency and provides an estimation of the correlation between SLA and

DHA data both for large-scale and mesoscale signals. Section 5 analyses the influence of the vertical structure of the ocean. Finally, SLA /DHA differences are analyzed in Sect. 6. Conclusions are given in Sect. 7.

2 Data and method

The full Argo dataset was uploaded from the Coriolis Global Data Acquisition Center as of September 2008 for the 2001–2007 periods and as of January 2009 for the year 2008 (http://www.coriolis.eu.org). The dataset went through the real-time quality control procedures applied by each Data Acquisition Center and about half of the profiles older than one year have went through delayed-mode procedures (see the Argo quality control manual for more details: Wong et al., 2008). For this study, when available, delayed-mode fields are preferred to real-time ones and only measurements having pressure, temperature, and salinity observations considered “good” (i.e. with a quality flag numerical grade of “1”) are used. In the GLL06 study, the reference level for the analyses was chosen at 700 m because the in situ observations were mainly composed of XBT instruments. 350 000 profiles were used for the 1993–2003 period. With the Argo dataset, it is possible to deepen the reference level to 1000 m. A total of 325 650 validated profiles are collected for the 2001–2008 period. As many floats do not profile deeper than 1000 m at low latitudes due to technical limitations, a 1500 m reference level reduces the number of profiles to 230 200 but mainly involves an undersampling of the tropical oceans. Using a 1000 m reference level reduces slightly the number of profiles compared to the previous study but improves the spatial coverage of the analyses particularly in the Southern Ocean thanks to a better spatial distribution of the measurements.

The altimeter data used are AVISO combined products, which provide maps of SLA obtained from an optimal combination of all available satellite altimeters (AVISO, 2008). The delayed-mode version of the products is used. The maps are available every 7 days on a $1/3^{\circ} \times 1/3^{\circ}$ Mercator grid. As this product provides SLA relative to a 7-yr time means from 1993 to 1999, to be fully consistent with the Argo dataset sampling period, the SLA maps are recalculated using the 7-year time mean from 2002 to 2007.

The method is very similar to the one described in GLL06. Dynamic heights relative to 1000 m depth are first calculated from Argo pressure, temperature and salinity profiles. A dedicated Argo mean dynamic height, calculated using the same Argo dataset is then used to calculate the anomalies of the dynamic height. Finally, SLA maps are interpolated to the time and location of each in situ DHA measurement using a linear space/time interpolation.

3 Correlation between Argo and altimeter observations

Correlation coefficients between all collocated SLA and DHA time series were first calculated. They were then averaged on a $1^\circ \times 1^\circ$ horizontal grid using observations available in a 5° longitude by 2° latitude radius of influence around each grid point (Fig. 1a and b). These parameters have been chosen in order to reduce the problems due to the non-uniform temporal and spatial distribution of in situ measurements, to take into account the latitudinal structure of the correlation signal and to obtain a relatively large-scale uniform map. Correlation coefficients show values greater than 0.8 in most part of the Indian and Pacific oceans. The Southern Oceans and the northern part of the North Atlantic Ocean show, as expected, lower values, in the order of 0.6 or less. This can be explained by the influence of deep baroclinic and barotropic signals in these regions. Three tropical sub-regions also show lower values of the same order: the South East Pacific Ocean and the South and North Tropical Atlantic Ocean. These regions correspond to areas where the sea level and steric sea level variabilities are very low (<3 cms rms) and thus high correlations are difficult to obtain between these two very low signals.

As in GLL06, the change of dynamic height relative to a reference level at 1000-m depth compared to the change of total sea level has been quantified by calculating regression coefficients between SLA and DHA. These regression coefficients are also useful to calculate DHA from SLA observations and to derive the 3-D ocean state from SLA observations through data assimilation. As expected, results are very similar to the one obtained by GLL06. Thanks to the Argo data sets, the estimation is now almost global. Values are of the order of 0.8 or higher in the tropical regions and decrease to 0.6 norths of 40° N and to 0.3–0.4 south of 40° S. The low values of the regression coefficients at high latitudes point to an underestimation of the steric sea level due to deep baroclinic signals (Fig. 1c).

Additionally to correlation coefficients and regression coefficients, variances of SLA and DHA, both calculated on a 1°×1° grid, display very similar patterns with very close amplitudes, showing again the very good consistency between Argo and altimeter observations (Fig. 2a and b). However and as expected, DHA variance shows lower amplitudes in the Confluence and Antarctic Circumpolar Current (ACC) regions where eddies deeper than 1000-m depth are found.

Given the higher number of observations available in each 5° longitude by 2° latitude radius of influence around each grid point (>500), the 95% confidence interval is of the order of ±0.05 for the correlation coefficient, ±0.07 for the regression coefficient and almost everywhere smaller then ±1 cm rms for the variance fields. These number increase up to 0.1 for the correlation coefficient and 0.15 for the regression coefficient in the three tropical sub-regions mentioned above and south of 55° S where the number of observations decrease to 100 or less. Error bounds associated to each global statistic given later on in the paper are much smaller and of the order of ±0.001 for the correlation coefficient and of the order of ±0.01 cm rms for the variance due to the 325 000 validated profiles used. All the results given thereafter are thus highly significant in the 95% confidence interval.

It is worth highlighting that the Argo mean dynamic height already provides improved comparison between SLA and DHA compared to the use of a climatological mean dynamic height. The rms difference between SLA and DHA is reduced from 6.1 cm rms when the World Ocean Atlas 2005 (WOA05: Antonov et al., 2006; Locarnini et al., 2006) is used to 5.6 cm rms when using the Argo mean dynamic height.

This corresponds to an improvement of 15% in the consistency of the two datasets. Their global correlation is also increased from 0.81 to 0.84. This is mainly the result of the reduction of the mean global bias of 1.0 cm that exists when using the World Ocean Atlas 2005.

Compared to the GLL06 study, improvements come, first, from the improved global spatial coverage of the Argo profiles. As the Southern Ocean and particularly its Pacific part was not completely covered in the previous study, the 60° S–60° N ocean is now well sampled.

The second improvement comes from the deeper reference level (1000 m vs. 700 m). Comparing Fig. 1 from GLL06 to Fig. 1b from the present study shows that the correlation coefficient has increased everywhere by a minimum of 0.1. In order to quantify the impact of the reference level using the Argo data sets, DHA have been calculated using two additional reference levels: 700 and 1500 m. The rms difference between SLA and DHA varied from 6.0 cm rms using a level at 700 m to 5.6 cm rms with 1000 m. This corresponds to an improvement of 12% in the consistency of the two datasets. Locally, the correlation coefficient increased by up to 0.3 in the Southern Ocean. Using a 1500 m reference level also increases the consistency of the two datasets but to a lesser extent. The general improvement is of the order of 2% of the SLA/DHA signal difference. Again the correlation coefficient increases up to 0.1 in the Southern Ocean. These results mean that the density changes below 1000 m are much less important than the one above and that this signal has only a small impact on the SLA/DHA differences.

The third improvement comes from the use of measured S profiles versus climatological S for the GLL06 study as the in situ observations came mainly from XBT instruments. The impact of the measured S profiles is illustrated on Fig. 2c and d. It shows the rms of the differences between SLA and DHA when using measured S profiles and when using climatological S profiles. The climatological salinity has been interpolated using a simple salinity-depth relationship as a function of the geographical position and using the WOA05 monthly fields. When using measured S profiles, the rms of the differences between the two time series shows values lower than the rms of SLA and of DHA in most parts of the Indian, Pacific and Atlantic Ocean (compare Fig. 2c and Fig. 2a and b). When using climatological S profiles, the rms of the differences increase everywhere by at least 1 to 2 cm rms and up to 8 to 10 cm rms in the Gulf Stream area, the Southern Oceans and in low variability regions like the North Tropical Atlantic Ocean. The rms of the differences (SLA-DHA) can even be larger than the rms of the referenced fields (SLA, DHA) (compare Fig. 2d and Fig. 2a and b). These results mean that measured S profiles are particularly critical in these regions. Globally, there is an improvement of 35% of the SLA minus DHA signal in the consistency of the two datasets, the rms differences reducing from 6.9 cm rms when the climatological S is used to 5.6 cm rms when using the measured S. The global correlation is also improved from 0.80 to 0.84 and up to 0.3 locally.

In summary, by using a complete consistent Argo data set it is possible to improve the SLA/DHA consistency by 15% by using an Argo mean dynamic height, by 12% by using a deeper reference level and by 35% by using measured S profiles; percentages being given as of the SLA minus DHA signal.

4 Removing the effect of seasonal signals

One of the great assets of the Argo data sets is the availability of time series along floats trajectories, with measurements usually available every ten days. To focus on the respective role of intra seasonal and mesoscale signals, compared to seasonal and inter-annual ones, SLA and DHA time series along the float trajectories have been filtered using a 200-day low pass filter. Low frequency signals are thus defined for frequencies lower than 200-days and mesoscale signals for frequencies higher than 200-days. As only time series with at least three years of measurements have been kept, the number of profiles available for the analyses is reduced slightly. Results indicate that keeping only mesoscale signals reduces the general correlation between the two times series (0.70 against 0.84) and inversely, keeping only the low frequency part of the signal increases the correlation but to a lesser extent (0.87 against 0.84) (Fig. 3, left). The decrease or the increase of the correlation are very similar as a function of latitude except for the northern part of the North Pacific and Atlantic Oceans where the decrease is twice as large as for other latitudes and where it is of the order of 0.3–0.4. This shows that most of correlated signals in the SLA and DHA comparisons for these two regions are low frequency signals (mainly seasonal signals related to the heating/cooling of the surface ocean). As the amplitude of this effect is smaller in the Southern Hemisphere, its effect on SLA/DHA comparisons is also smaller.

The impact on the regression coefficient is largely dependent on latitude (Fig. 3, right). In the tropics where the stratification is important and the vertical coupling is low, values are very similar for all scales. This means that both low frequency and mesoscale parts of the circulation are well restored by the dynamic height relative to a reference level at 1000 m depth. For latitudes higher than 30°–40°, the regression coefficients of the mesoscale part of the signal drops to 0.2–0.3 and the ones for the low frequency part of the signal increase slightly. At these latitudes, the weak stratification and the high vertical coherence of mesoscale variability mean that the low frequency part of the circulation is reasonably well restored by the dynamic height relative to a reference level at 1000 m depth but that deeper *T* and *S* measurements are needed to observe mesoscale structures.

5 Influence of the vertical structure of the ocean

To better understand the role of the vertical structure on the correlation between SLA and DHA, DHA have been calculated relative to several depths from 100 m to 1000 m every 100 m. The depth to which it is sufficient to integrate the DHA signals in order to explain 80% of the variance of the DHA calculated with a 1000-m depth reference level is first given on Fig. 4. In Fig. 4, the geographical structure is mostly latitudinal. At the equator, a depth of 300 to 400 m is sufficient while a depth of at least 700 m is needed at high latitudes and in the Gulf Stream and the ACC. The mean correlations between SLA and DHA have then been calculated by latitude bands (Fig. 5, left) as a function of depths used to calculate DHA. The latitudinal and hemispheric differences are clear. In the Northern Hemisphere, low latitudes reach the tangent value of 0.85 at only 200 m of depth. At mid-latitudes, the correlation is of the order 0.74 at 200 m and increases slowly until it reaches 0.85 around 600 m. At high latitudes, the correlation evolves more regularly from 0.68 at 200 m to 0.8 at 1000 m. For all Northern Hemisphere latitudes, the correlation between SLA and DHA reach a tangent value at depth, meaning than most part of the baroclinic signal is contained in the first 1000-m depth of the ocean. In the Southern Hemisphere, only the low latitudes reach a tangent value. Mid and high latitudes SLA/DHA correlation start at a lower value than for the Northern Hemisphere but increase twice as rapidly with depth and do not reach a plateau. This means that the deep baroclinic signals not represented using a 1000-m depth reference level would further improve the correlation between SLA and DHA.

The effects of seasonal signals have also been removed to focus on intra seasonal and mesoscale signals. To simplify the calculation, compared to what was done for the previous section, monthly climatological means have been removed from SLA and DHA time series. SLA monthly means have been calculated on the studied period and the Arivo monthly fields (Von Schuckmann et al., 2009) have been used for the DHA. Results have been compared to the ones obtained in the previous section and they show very similar patterns. For the intra seasonal signals, the evolutions of SLA/DHA correlation with depths (Fig. 5, right) show much smaller values than for the total signal. They show very similar behaviors for the Northern and Southern Hemisphere. Intra seasonal SLA/DHA correlation reaches rapidly a plateau of 0.6 at low latitude. For mid and high latitudes, the non tangent value is reached and the increase of correlation with depth is of the order of 0.3 between 200-m and 1000-m depth.

This study of the vertical structure of the ocean show that the high vertical coherence of the mesoscale variability is partly masked by the dominant signal due to heating/cooling of the surface ocean in the Northern Hemisphere. In the Southern Hemisphere, as the amplitude of the seasonal heating/cooling is half as large as in the

Northern Hemisphere (Stammer, 2007), the signature of mesoscale variability and its coherency with depth is already evident in the total SLA/DHA correlation (and even more obvious for intra-seasonal signals).

6 SLA minus DHA signals: from seasonal to interannual

Although SLA and DHA are very consistent with time at all latitudes, systematic differences between the two data sets can be observed. First, global mean differences at seasonal and interannual time scales are well explained by the ocean mass component (i.e. the exchange of water between the oceans and other reservoirs). Even if its amplitude is small and of the order of 5 to 10 mm, the impact on interannual time scales can be of 0.8 to 1.9 mm/yr according to different authors (Cazenave et al., 2008; Leuliette and Miller, 2009). What is very interesting is that with Argo, it is now possible to make a global map of the SLA minus DHA signals at seasonal but also interannual time scales.

At seasonal time scales, large-scale differences in several areas of the Pacific and Indian oceans have been related to a barotropic, Sverdrup-like, response of the ocean to wind forcing (GLL06). At 1000 m depth, seasonal SLA minus DHA signals differences (Fig. 6) are similar to the ones described at 700 m depth by GLL06. Amplitudes are nevertheless lower and of the order of 1 to 3 cm with minimum and maximum values in winter and summer. Thanks to the global coverage of the Argo data sets, new spatially coherent structures appear in the South Indian Ocean and the Confluence region with positive values in winter and fall (>2 cm) and negative values in summer and spring (<−2 cm). The dipole structure in the Indian Ocean is particularly interesting with negative value in the tropics and positives one at high latitudes in winter and the opposite in summer. Note that a mean value consistent to the above cited mass component has been subtracted from each map. Its amplitude varies from −6 mm in spring to 6 mm in fall.

At interannual time scales, the spatial structure of SLA and DHA signals is dominated by the interannual to decadal variability and not the long term drift (Fig. 7). SLA and DHA signals are very consistent in all three oceans. For example, the tropical Pacific Ocean which is dominated by the El-Niño/La-Niña events shows very similar patterns in both data sets. The strong La-Niña structure is particularly well reproduced in 2008 with enhanced sea level amplitudes in the Indian and Pacific oceans. Systematic differences between SLA and DHA are nevertheless visible at basin-scale. An interesting feature is that amplitudes of these differences are very similar to the ones observed for the seasonal signals and range from 1 to 3 cm. A shift from negative to positive values is for example observed for the whole Indian Ocean between the year 2005 and the year 2006. The South Pacific Ocean also shows negative differences in 2004, 2005 and 2006 but positives ones in 2007 and again mainly negatives values in 2008. The opposite is observed in the North Pacific Ocean. For the Atlantic Ocean, the structure of the anomalies seems to be noisier but vary from mainly negatives in 2005, 2006 and 2007 to positives in 2008.

7 Conclusions

The global Argo array of profiling floats has been used together with satellite altimeter measurements of SLA in order to study the differences and complementarities between the SLA and DHA calculated from the Argo temperature and salinity profiles. Results show very good correlation between the two data sets which means that the two complementary data sets can be jointly used in ocean forecasting models or data synthesis methodologies.

Compared to the previous study of GLL06, the newly available Argo data sets bring about a series of improvements. The first one is a much better spatial coverage of all oceans and particularly of the Southern Ocean. The Argo array now allows sampling everywhere by all weather. This is particularly true during the harsh winter time conditions at high latitudes. The second improvement arises from the availability of deeper measurements and hence the use of a deeper reference level of 1000-m compared to 700-m. The third one concerns the use of measured T and S profiles versus the use of climatological S. The Argo array also revolutionized the ocean salinity measurements and thus opens new insight on salinity variability studies.

The availability of time series along the Argo floats trajectories allows the description of the vertical structure of the ocean for the large-scale and mesoscale part of the circulation. These results emphasize the need to separate the different time and space scales when altimeter and Argo data are jointly assimilated to estimate the 3-D temperature and salinity structure of the ocean.

Given the actual sampling characteristics of the Argo array, the study of seasonal to interannual SLA minus DHA signals is now possible. These signals are related to deep ocean circulation variations or basin scale ocean mass variations. Future work is needed to understand the observed differences and relate them to different forcing mechanisms. The comparison with Argo deep velocity observations and GRACE ocean mass variations should be, in particular, very instructive.

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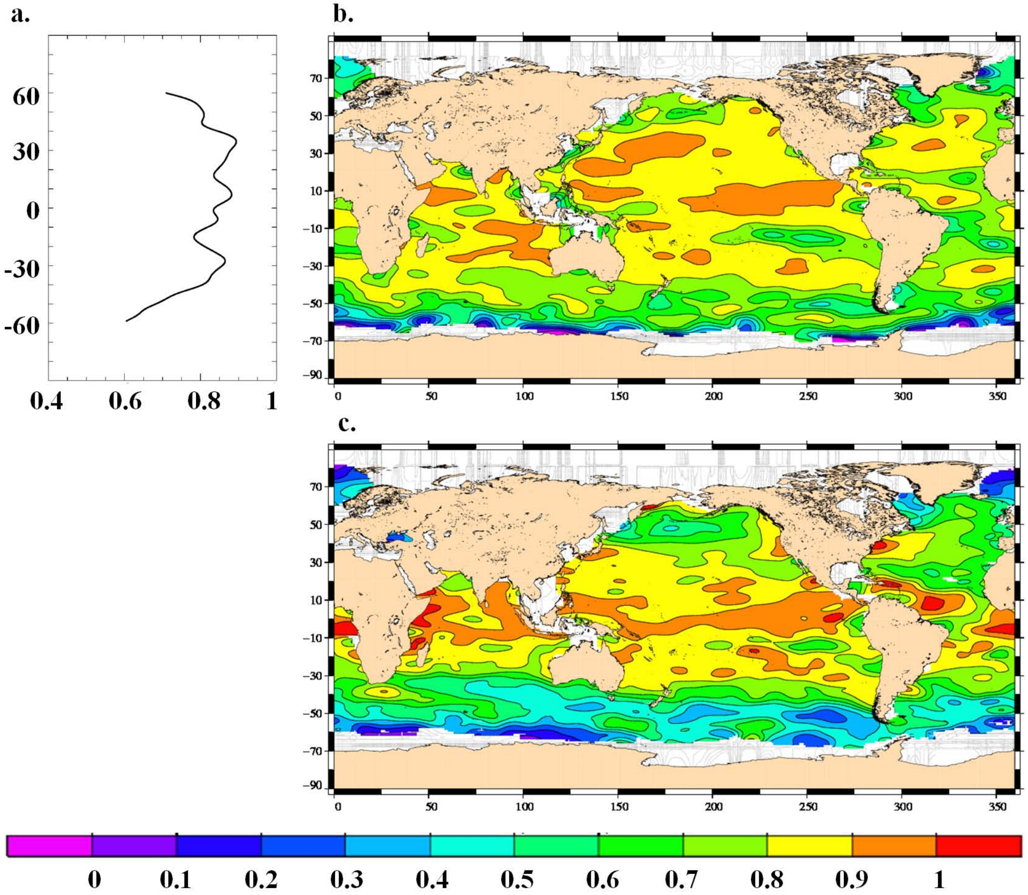

Fig. 1. Correlation coefficients **(b)** and regression coefficients **(c)** between SLA and DHA. The mean correlation as a function of latitude is also represented **(a)**.

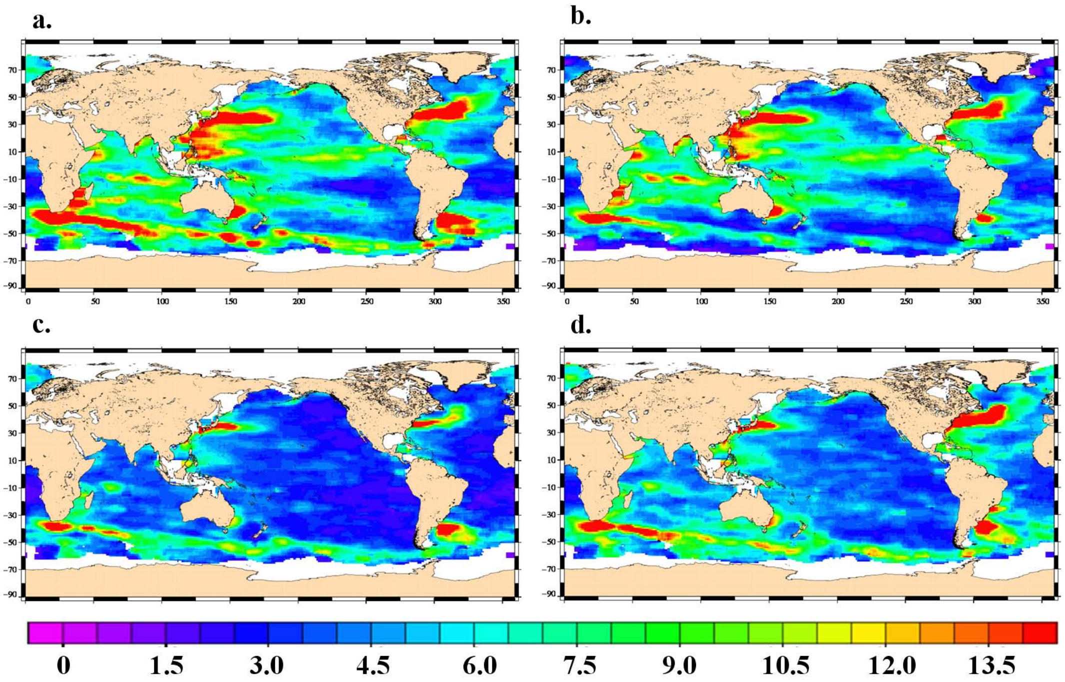

Fig. 2. Rms of SLA **(a)**, of DHA **(b)** and of the differences (SLA-DHA) when DHA are calculated from in situ T/S profiles **(c)** and when DHA are calculated from in situ T and S from the WOA05 climatology **(d)** (in cm).

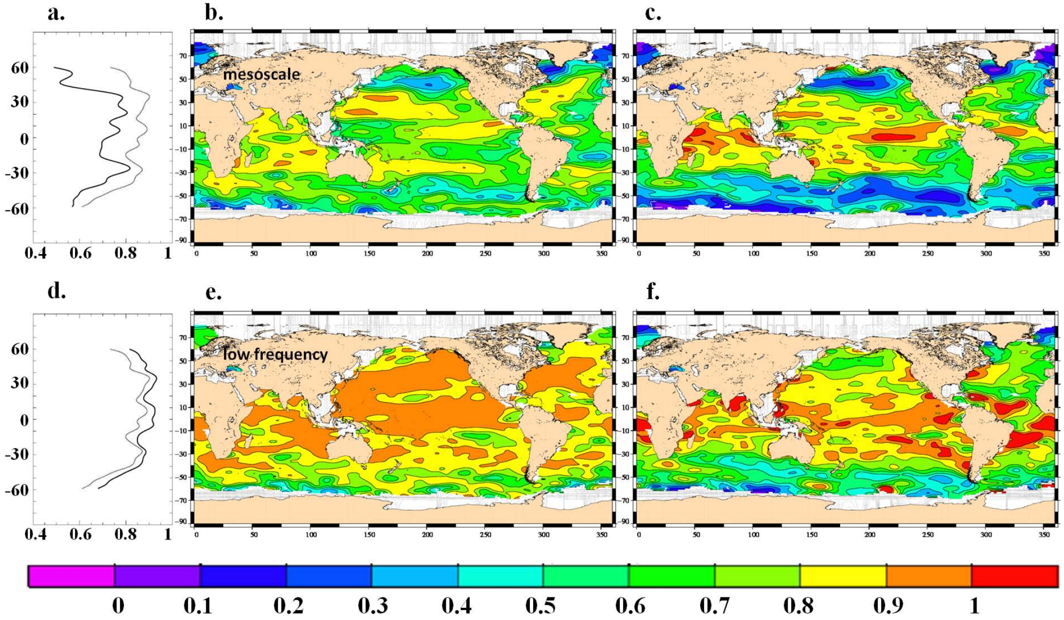

Fig. 3. Correlation coefficient **(b), (e)** and regression coefficient **(c), (f)** between SLA and DHA for the intra-seasonal (mesoscale, top) and low-frequency (bottom) signals. The mean correlation as a function of latitude is also represented **(a), (d)**, together with the curve obtains using the total fields (in grey).

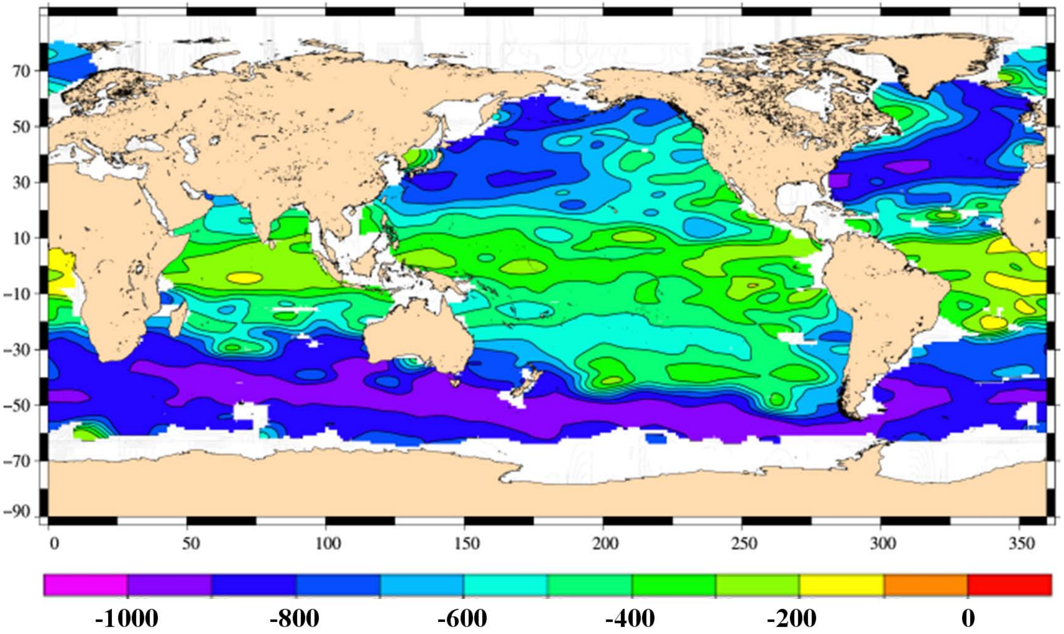

Fig. 4. Depth to which it is sufficient to integrate the DHA signals in order to explain 80% of the variance of the DHA calculated with a 1000-m depth reference level (the scale range from −1000 to 0, in m).

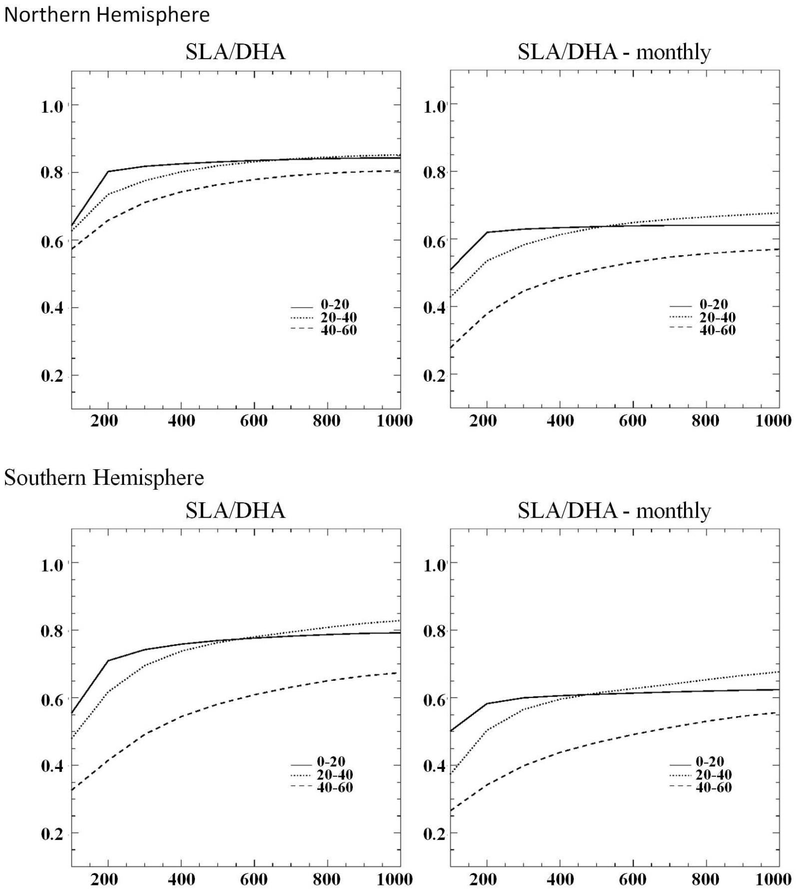

Fig. 5. Correlation between SLA and DHA by latitude bands as a function of depth used to calculated DHA, for the Northern Hemisphere (top) and the Southern Hemisphere (bottom) and for total SLA/DHA (left) and for SLA/DHA filtered from the seasonal means.

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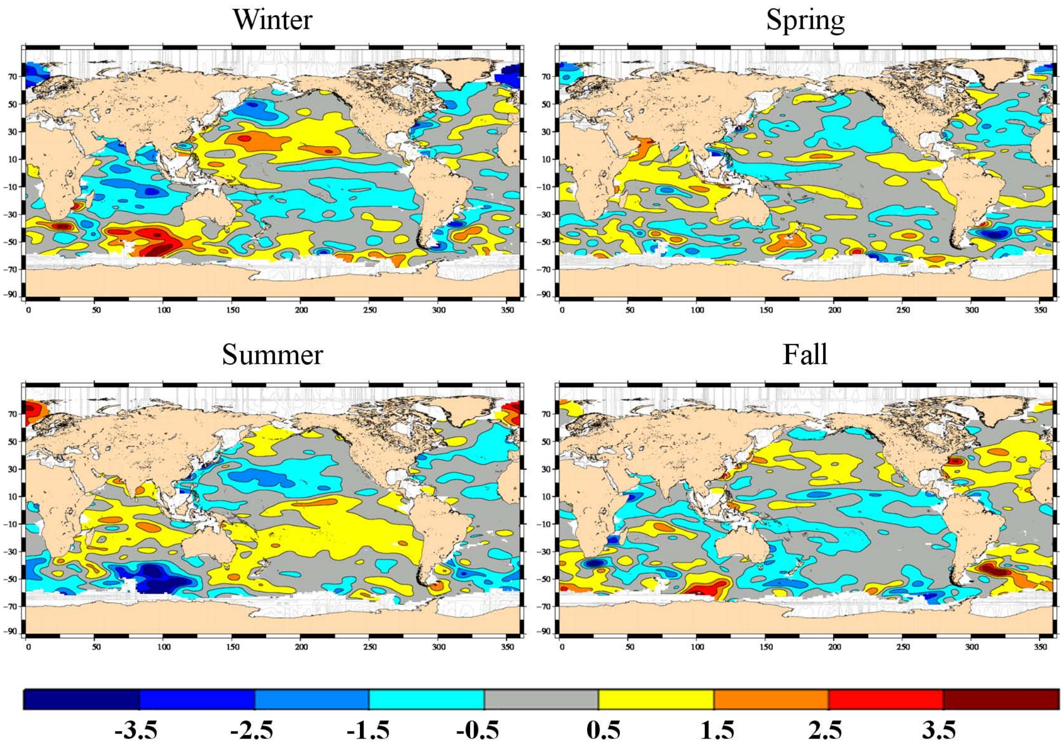

Fig. 6. Seasonal variation of the differences between SLA and DHA – Unit: cm.

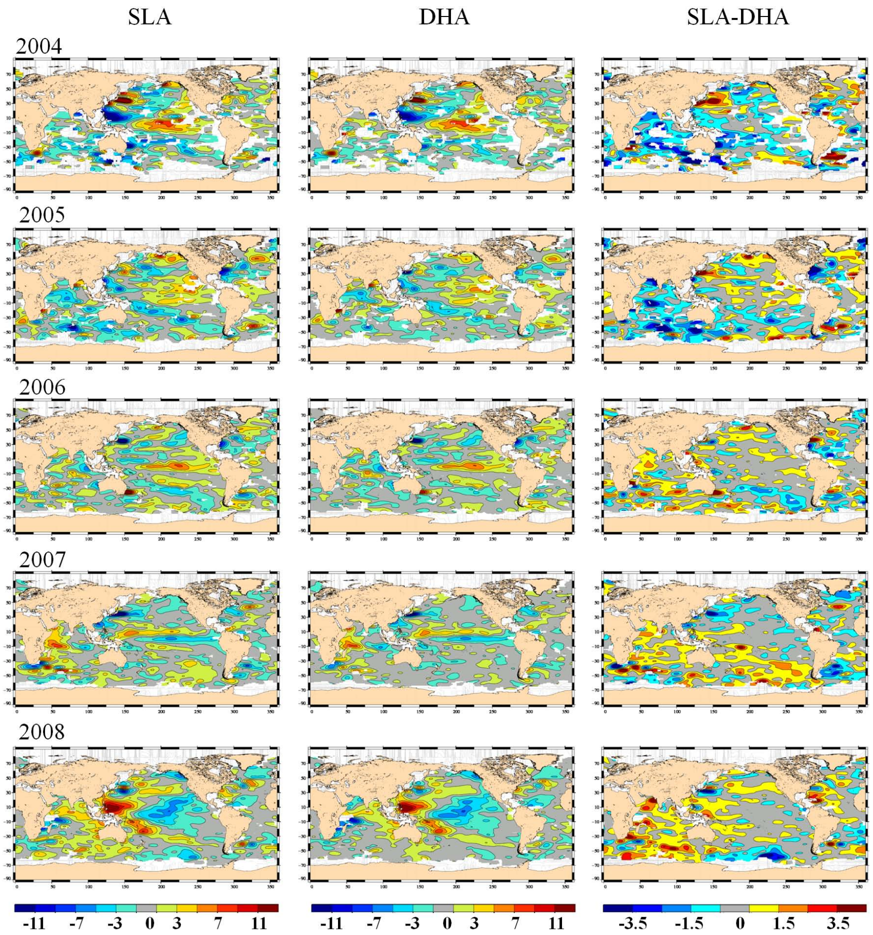

Fig. 7. Annual variations of SLA, DHA, and SLA-DHA for the years 2004 to 2008 – Unit: cm.