Influences of the Choice of Climatology on Ocean Heat Content Estimation

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ABSTRACT

The choice of climatology is an essential step in calculating the key climate indicators, such as historical ocean heat content (OHC) change. The anomaly field is required during the calculation and is obtained by subtracting the climatology from the absolute field. The climatology represents the ocean spatial variability and seasonal circle. This study found a considerable weaker long-term trend when historical climatologies (constructed by using historical observations within a long time period, i.e., 45 yr) were used rather than Argo-period climatologies (i.e., constructed by using observations during the Argo period, i.e., since 2004). The change of the locations of the observations (horizontal sampling) during the past 50 yr is responsible for this divergence, because the ship-based system pre-2000 has insufficient sampling of the global ocean, for instance, in the Southern Hemisphere, whereas this area began to achieve full sampling in this century by the Argo system. The horizontal sampling change leads to the change of the reference time (and reference OHC) when the historical-period climatology is used, which weakens the long-term OHC trend. Therefore, Argo-period climatologies should be used to accurately assess the long-term trend of the climate indicators, such as OHC.

1. Introduction

Climate indicators, such as sea level, ocean heat content (OHC), sea surface temperature, and global surface air temperature, provided solid evidences of global warming. But their estimates contained substantial uncertainties due to the temporal and spatial sparseness of the in situ observations and the various choices of methodologies. Taking OHC estimation as an example, it is indicative of the earth's energy imbalance (Abraham et al. 2013; Church et al. 2011; Domingues et al. 2008; Levitus et al. 2012; Palmer and Haines 2009; von Schuckmann et al. 2009). Analyses on observations indicated that global ocean experienced a remarkable and robust warming, suggestive of the heat input into the earth system (Levitus et al. 2012; Lyman et al. 2010). The recent IPCC Fifth Assessment Report (AR5; Rhein et al. 2013) concluded that the upper-700-m ocean warming rate since 1970 ranged from 74 to 137 TW, with uncertainties in values of ~100%. Studies implied that the uncertainties were sourced from various choices of methodology. For example, how were the instrumental biases of expendable bathythermograph (XBT) and mechanical bathythermograph (MBT) observations corrected (Cheng et al. 2014; Cowley et al. 2013; Gouretski and Koltermann 2007; Gouretski and Reseghetti 2010)? Because these biases were considered to be variable with calendar year, geography, and observing conditions (Gorman et al. 2014; Abraham et al. 2012; Cheng et al. 2014; Abraham et al. 2013), no consensus was made on the best correcting method. How do we fill the data gaps (i.e., mapping approaches) (Ishii and Kimoto 2009; Lyman and Johnson 2008; Willis et al. 2004)? Which climatology field was chosen (Lyman and Johnson 2014; Lyman et al. 2010)? How do we quality control the in situ measurements? The insufficiency of the vertical resolution of the historical observations was another problem, which induced additional uncertainty during OHC calculation (Cheng and Zhu. 2014b). Those problems listed above contributed to the overall uncertainties of ocean heat content estimation.

One of the essential choices is the climatology—that is because the anomaly field is always used to calculate ocean heat content change (or other climate indicators), rather than the absolute field. During the OHC calculation, the temperature climatology needs to be subtracted from each individual temperature profile to form

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a temperature anomaly dataset. Various climatologies were proposed and used previously by independent international groups. Could the choice of climatology impact the OHC estimation? How and why does the climatology contribute to the OHC uncertainties? A recent study by Lyman and Johnson (2014) raised the issue of the importance of the climatology in light of the two choices of gap-filling strategies. In brief, they found a considerable influence of climatology when the zero-filling method (data gaps are filled by zero when calculating global integral of OHC) was used, but the climatology would not affect the OHC estimate when the Gmean-filling method (data gaps are filled by the mean of OHC in the sampled area) was applied. They implied that whether climatology could impact the OHC trend depended on the choice of the gap-filling strategy. However, in this study, we chose several climatologies and applied the same gap-filling method, and then we found it resulted in a large divergence of long-term OHC trend. Therefore, we suspected that the impact of climatology should be different from the traditional view.

In this study, we are going to systematically investigate how the climatology could impact the OHC estimation. This study is organized as follows: the data and methods are presented in section 2, followed by section 3 with the key results and analyses. A summary and conclusions are given in section 4.

2. Data and methods

Ocean subsurface temperature profiles originate from the *World Ocean Database 2009 (WOD09)* (Boyer et al. 2009). All of the measurements passed the quality-control process and removed spurious data. The quality-control process includes a three standard deviation check, a temperature range check, a depth inversion check, a spike detection, and a depth duplication check, as indicated in Boyer and Levitus (1994). The instrumental bias of XBT was corrected using the correction scheme presented in Cheng et al. (2014), and the MBT bias was removed using the method proposed by Ishii and Kimoto. (2009). Argo data are sourced from the website of Argo Science Team, and profiles of the delayed mode with "flag = 1" were used. All of the data were collected to be a new dataset, named Institute of Atmospheric Physics Global Ocean Temperature (IGOT) dataset, version 1.0 (IGOT dataset), as used in Cheng and Zhu. (2014a).

Several climatologies are constructed by using the following method. The temperature profiles used to create the climatology were first interpolated to the standard vertical bins (from 1 to 99 m with 1-m intervals and from 100 to 700 m with 2-m intervals); standard-level temperature profiles were then grouped into $1° \times 1°$ grid boxes for each month regardless of the year. The arithmetic mean of the temperatures was calculated for each grid box at each depth. In this way, in each grid box, 12 standard-level temperature profiles were obtained corresponding to the 12 months. All of these profiles throughout the global ocean were collectively called a climatology. Three climatologies were constructed using different subsets of the data but using the same method described above. WODClim was obtained by averaging all of the subsurface observations from 1966 to 2010 (45 yr), and ArgoClim was obtained using all of the Argo data from 2004 to 2010 (7 yr). 2008–2012Clim was created using all of the data from 2008 to 2012 (5 yr) and was used for the final estimation of the ocean heat content trend in this study.

Two other climatologies created by two international research groups were collected. The first one was the *World Ocean Atlas 2009* (WOAClim) from the National Oceanic and Atmospheric Administration (NOAA) National Oceanographic Data Center (NODC) (Locarnini et al. 2010). WOAClim had a $1° \times 1°$ resolution over the global ocean from 0 to 2000 m. WOAClim was created by using more than 50 yr of observations. The other climatology was based on Argo data that were objectively analyzed according to Roemmich and Gilson (2009) using the updated version downloaded in April of 2013. This climatology was created using Argo data from 2005 to 2012 (7 yr) with $0.5° \times 0.5°$ resolution and 58 depth levels from 0 to 2000 m, covering the area of the global ocean within 65°S–65°N.

In this study, the historical upper-700-m ocean heat content is represented by a 0–700-m-averaged temperature anomaly. All of the temperature profiles were interpolated to standard levels (from 1 to 99 m with 1-m intervals and from 100 to 700 m with 2-m intervals) and a specific climatology [denoted as $T_{\mathrm{climatology}}(g)$, where g denotes the geographical location] was subtracted from each temperature profile [denoted as $T(g, t)$, where t denotes the observing time] to obtain the temperature anomaly profiles [denoted as $\mathrm{Ta}(g, t)$]:

$$\mathrm{Ta}(g,t) = T(g,t) - T_{\mathrm{climatology}}(g). \tag{1}$$

These 0–700-m-averaged temperature anomaly profiles were sorted into a $1° \times 1°$ and 1-yr grid box and averaged to obtain the grid-averaged temperature anomaly profile. The 0–700-m depth-averaged temperature anomaly was calculated for this grid-averaged anomaly profile. The annual mean of the global temperature anomaly was calculated by averaging the grid-averaged anomalies by weighting the area of grid boxes. By using this strategy, the OHC in the unsampled area (data gaps) was assumed to be equal to that in the sampled area, so we named this gap-filling strategy the

"Gmean filling" method, which is identical to that used in Lyman et al. (2010).

3. Results

a. Influence of the choice of climatology on the OHC calculation

Variant choices of reference climatology are tested in this study to calculate the OHC anomaly. When ArgoClim is used, a trend of ~0.0069°C yr^{-1} is obtained. By contrast, when WODClim is subtracted instead of ArgoClim, the OHC time series from 1966 to 2012 showed a trend of ~0.0035°C yr^{-1} (Fig. 1), which is approximately half of the value obtained using ArgoClim. We also note a downward trend during 2000–10 that is not present in the OHC time series using ArgoClim.

In addition, we used two classes of climatologies to calculate the OHC anomaly time series (Fig. 1): a Argo-period climatology [i.e., ArgoClim (Roemmich and Gilson 2009); 2008–2012Clim), which was created using data observed within the Argo era in this century; and historical climatology [i.e., WODClim and World Ocean Atlas 2009 (WOAClim) (Locarnini et al. 2010)] based on observations from a much longer time interval (i.e., at least 45 yr). Because the Argo system has approximately global coverage, a short period (i.e., less than 7 yr) of data would be enough to construct a climatology. We found a significantly stronger long-term OHC trend since 1966 using the Argo-period climatology (a short period but evenly sampled climatologies) in comparison to the historical climatology. All historical climatologies resulted in a much weaker or even reversed OHC trend from 2000 to 2010. Furthermore, even when we used two alternative mapping methods, Levitus mapping (Levitus et al. 2012) (an objective analyses to fill the data gaps) and zero filling (the OHC in the data gaps is assumed to be zero), we still found significant differences between the two types of climatologies (Fig. 1b) at a significance level of 90% based on a two-tailed Student's *t* test. The only non-significance that occurs is when comparing WOAClim and Roemmich and Gilson when the zero-filling method was used.

We should note here that the difference in the long-term trend when using different mapping methods is evident, suggesting that the mapping method is another major source of uncertainties during the OHC estimate. A discussion on mapping methods is out of the scope of this study, which requires further detailed study. We note here that the zero-filling method induces a much weaker long-term trend than the other two methods, because this method assumes a zero OHC anomaly in data gaps.

We subsequently attempted to understand how the choice of climatology can cause similar dramatic differences in the estimate of OHC anomalies and how

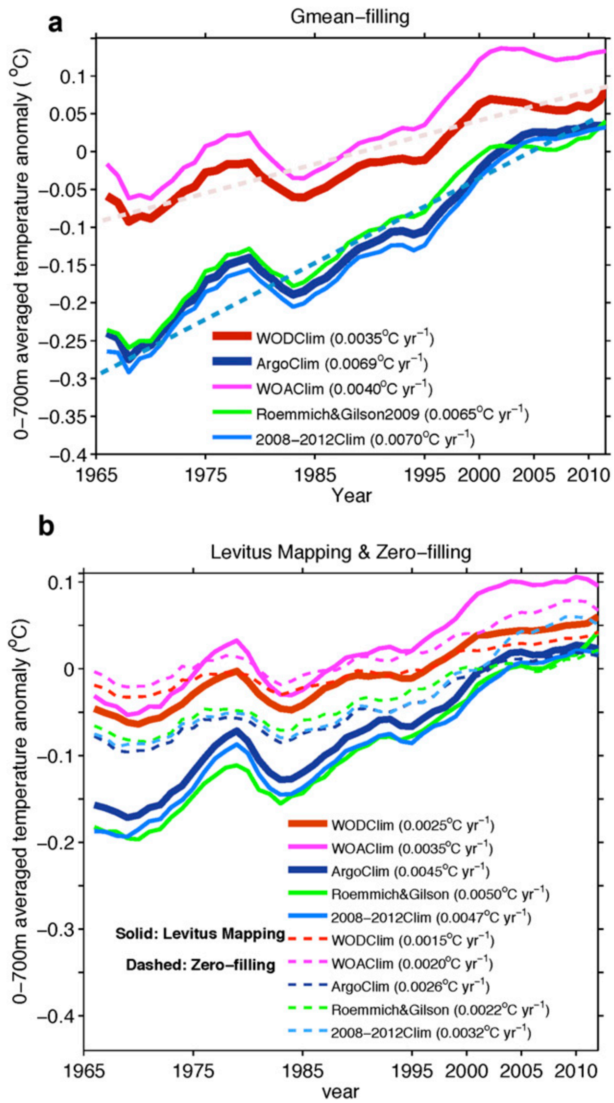

FIG. 1. OHC estimation under different climatologies and mapping methods. (a). The 0–700-m-averaged temperature anomaly from 1966 to 2012 calculated using the Gmean-filling method. Dark blue and dark red represent ArgoClim and WODClim, respectively, with linear trend shown in dashed lines. OHC with the alternate climatologies of 2008–2012Clim (dark cyan), WOAClim (Locarnini et al. 2010, purple), and Roemmich and Gilson (2009, light green) are included. All of the time series are 5-yr periods of data that are smoothed to show multidecadal signals. (b). As in (a), but the Levitus mapping method (solid) and the zero-filling method (dashed) are applied.

they are related to changes in the observation systems. First, we sought to analyze the role and importance of the climatology in the OHC anomaly calculations. Because of the large spatial variation and seasonal variation of the ocean heat content, it is necessary to remove a spatial and seasonal baseline from each temperature profile measurement before obtaining a global-averaged OHC estimation. Our aim was to reduce the sampling

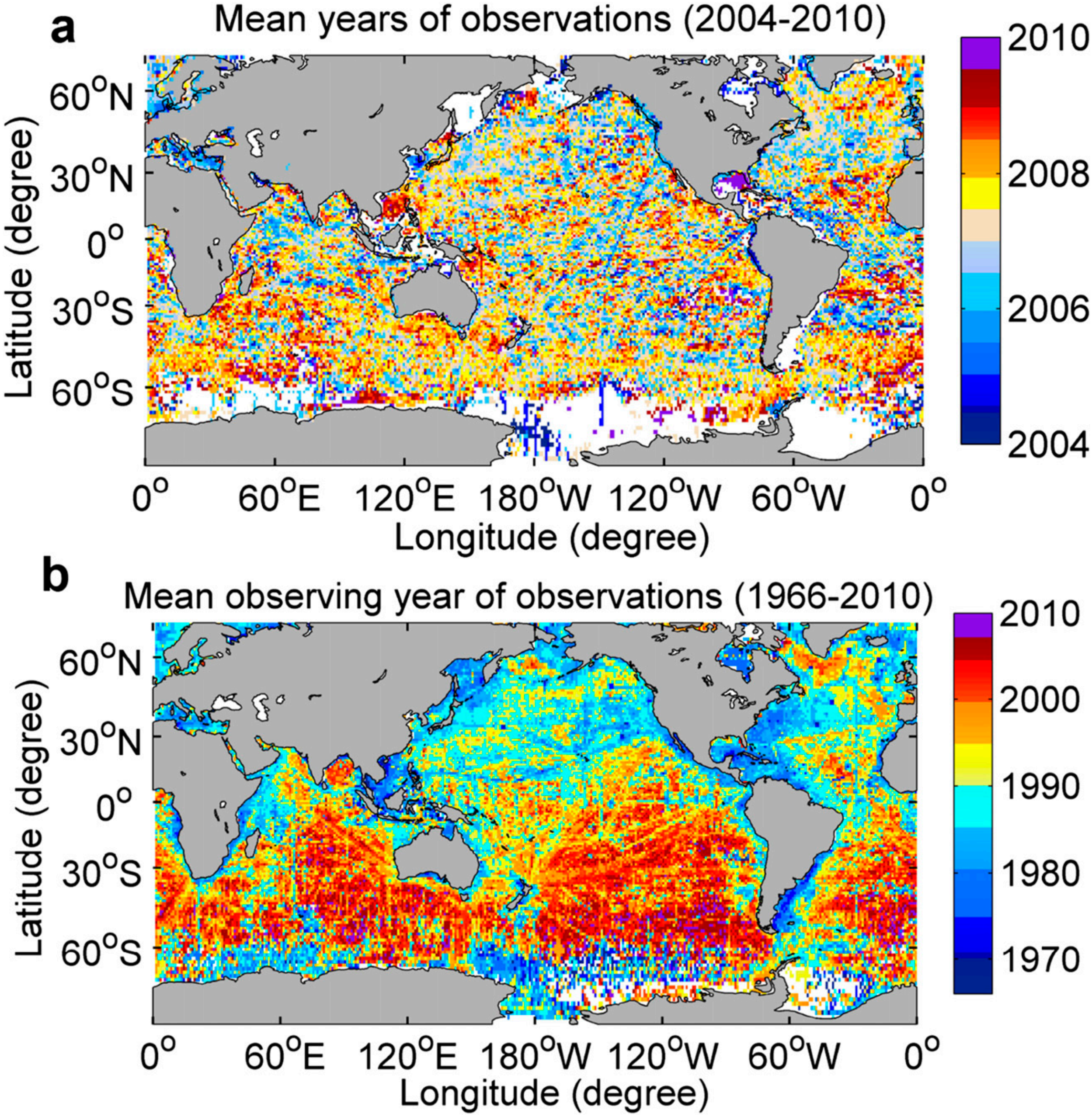

FIG. 2. (a) Mean observing time of the observations from 2004 to 2010 (ArgoClim) in each 1° × 1° grid box. (b) As in (a), but for WODClim, showing the mean observing time of observations from 1966 to 2010.

error induced by the spatial and seasonal sparseness of observations. Each temperature measurement in the geographical grid g at time t can be separated into a combination of various independent signals on various scales, including the spatial variability over a given geographic area at reference time t_0 and the temporal variability of a long-term trend on a multidecadal scale superimposed by seasonal, interannual variation, represented as follows:

$$T(g,t) = T_{\mathrm{baseline}}(g,t_0) + dT_{\mathrm{seasonal}}(g) + dT_{\mathrm{interannual}}(g,t) + dT_{\mathrm{multidecadal}}(g,t). \quad (2)$$

The reference time denotes a specific year, which represents the starting point of the long-term variation.

ArgoClim used 2004–10 Argo data, and therefore t_0 was within 2004–10 (Fig. 2a), nearly consistent over the global ocean. Therefore, it should be reasonable to use ArgoClim to calculate the OHC anomaly.

However, WODClim was constructed by averaging all data collected over a 45-yr span. The WODClim reference times in the Northern Hemisphere mainly occur from 1980 to 1990, which corresponds to the middle of the 45-yr period (Fig. 2b). In the Southern Hemisphere, the reference time occurs within the years 2000–10 because most of the data in this region have been collected by the Argo system in this century. Therefore, the reference time for WODClim was not consistent over the global ocean; for example, there were older reference times in the ship-sampled area and younger reference times in the Argo-complementary area. Because the overall global ocean has been warming in both areas, a more recent reference time (i.e., in the Argo-complementary area, such as the Southern Hemisphere) is associated with a warmer reference OHC, and an earlier reference time is associated with a colder reference OHC (i.e., in the ship-sampled area, such as the Northern Hemisphere). When WODClim is used, an artificial bias in the global OHC trend is introduced because a colder reference OHC is subtracted to determine OHC anomalies prior to 2001, but a warmer reference OHC is subtracted post-2001.

If our explanation shown above is true, then the difference of OHC time series between WODClim and ArgoClim is largely controlled by the change of the reference time when using WODClim. Figure 3a presents the OHC difference between WODClim and ArgoClim, compared with the mean reference time of WODClim, showing the same variability. They are significant correlated at the 99% confidence interval ($r = 0.97$) as shown in Fig. 3b, confirming that the reference time is responsible for the OHC difference of the two different climatologies (WODClim and ArgoClim).

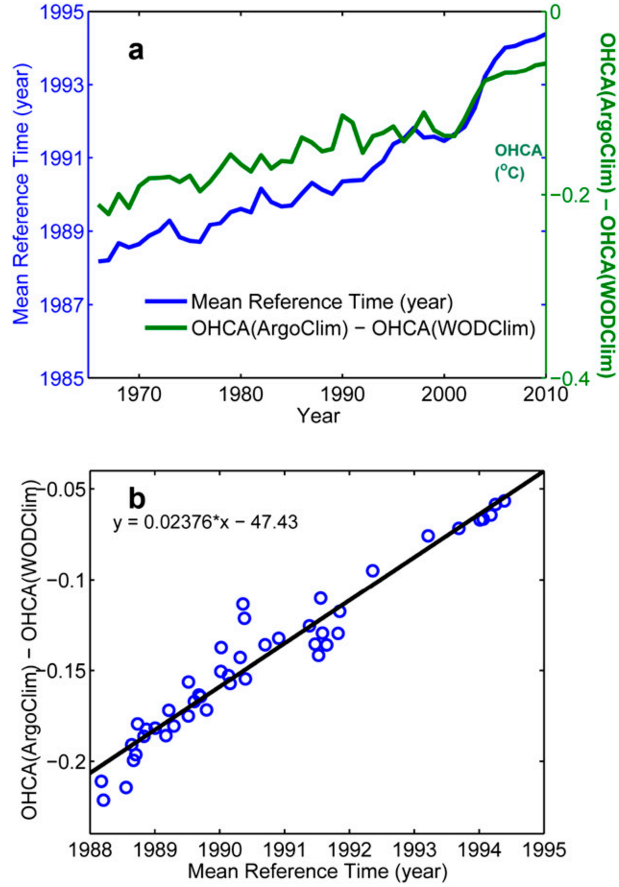

FIG. 3. Statistical test of the link between reference time and OHC divergence using different climatologies. (a) Global mean reference time in each year from 1966 to 2010 (blue), together with OHC difference between ArgoClim and WODClim (green). (b) Correlation between mean reference year of WODClim and OHC difference between ArgoClim and WODClim. They are highly correlated with $R = 0.97$.

b. Synthetic tests of the effect of climatology

To confirm the impact of the climatology on the long-term OHC trend, three simple synthetic tests were conducted.

A synthetic uniformly warming ocean was created under the assumption that each $1^\circ \times 1^\circ$ ocean grid had the same linear warming rate of $\sim 0.0052^\circ \mathrm{C\,yr^{-1}}$ from 1966 to 2010 (the time series is shown in black in Fig. 4a). This geographically uniform warming ocean was sampled according to the locations of the historical ocean observations to construct two anomaly series based on an Argo period and an historical climatology to mimic ArgoClim and WODClim, respectively. As shown in Fig. 4a, ArgoClim and the synthetic climatology produced a nearly identical OHC anomaly time series as in the dashed blue curve. Conversely, WODClim reduced the OHC anomaly trend in the past 45 yr by 22% (dashed red curve in Fig. 4a).

Based on the premise that global warming is not geographically uniform, we subsequently modified the synthetic test shown above by removing the requirement of a uniform warming rate. Two nonuniformly warming synthetic oceans were constructed by assuming two different warming rates according to the following two scenarios: (i) scenario 1: an ocean warmed linearly in each $5^\circ \times 5^\circ$ bin with the trend in each grid box calculated using realistic temperature data from 1966 to 2010 (the global OHC time series from 1966 to 2010 is shown by the black line in Fig. 4a, the same values in the uniformly warming ocean as described in the previous paragraph); and (ii) scenario 2: an ocean warmed linearly in each $1^\circ \times 1^\circ$ grid with a trend in each grid box calculated using sea level anomaly (SLA) data from 1993 to 2012 (the annual mean of global SLA is shown with the black line in Fig. 4b). The results strongly

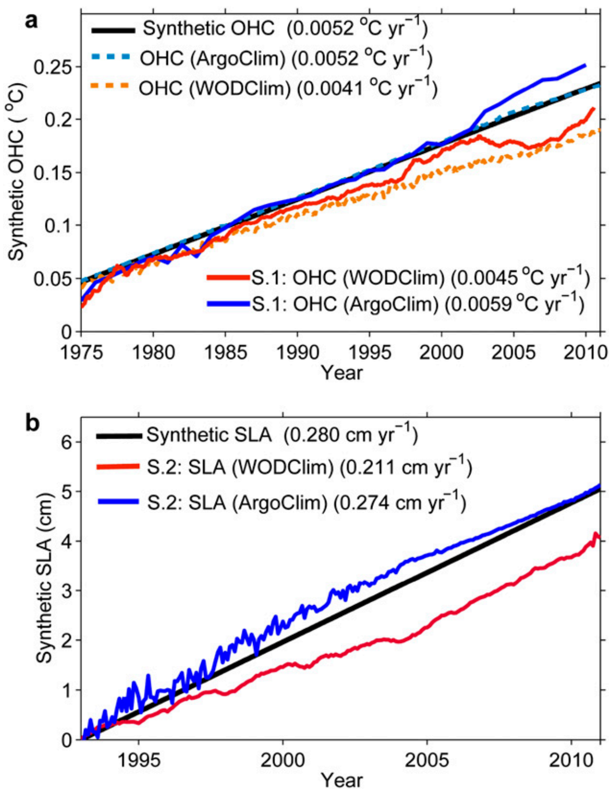

FIG. 4. Synthetic analyses of the climatology effects. (a) OHC time series (black) of a synthetic ocean with a uniform warming rate of ~0.0052°C yr^{-1} over the global ocean. Two other OHC series are shown—ArgoClim (blue dashed) and WODClim (orange dashed)—when sampling the synthetic ocean according to historical observations. The OHC time series of the synthetic ocean with a geographically variable warming rate (OHC synthetic ocean) is also presented using ArgoClim (blue solid) and WODClim (red solid). (b) SLA time series of the SLA synthetic ocean (black) determined according to the sea level trend. SLA results of subsampled synthetic ocean are also shown for ArgoClim (blue) and for WODClim (red).

suggest that weaker warming is obtained when WODClim is used: scenario 1 (Fig. 4a, solid curves) produces a 15% weaker OHC trend from 1975 to 2010, whereas scenario 2 (Fig. 4b) gives a 25% slower SLA increase from 1993 to 2012. In addition, during 2001–03, a stronger ocean warming rate appears when ArgoClim is used for both scenarios 1 and 2. In contrast, the rate of ocean warming for WODClim reaches a minimum during 2001–06, suggesting weaker ocean warming (scenario 2) or even ocean cooling during this period (scenario 1). These specific variations are consistent with the results of the observation-based OHC estimation shown in Fig. 1.

According to these synthetic tests, in a warming world under various scenarios, WODClim (45 yr) indicates approximately 20% slower ocean warming compared with ArgoClim (7 years), in general agreement with the results based on in situ OHC observations (Fig. 1). And the OHC–SLA estimates based on ArgoClim are much closer to the truths than WODClim. The global coverage of data in a short period during the Argo era is responsible for the better performance of the Argo-period climatology as explained in the previous section.

In conclusion, we confirmed the impact of climatology: Historical-climatology always leaded to weaker long-term variation due to the observation system change (horizontal sampling change).

4. Discussion

In this study, the impact of the climatology on the long-term OHC trend was investigated. First, we indicated that different climatologies lead to different values of long-term OHC trend: the weaker trend was always obtained when historical climatologies were used. A detailed revisit of the calculation of the OHC clarified the role of climatology. We supposed that the change of the reference time in the climatology due to the horizontal sampling change might be responsible and a synthetic test confirmed this idea. Therefore, we concluded that an Argo-period climatology should always be used to calculate the ocean heat content, in order to provide a consistent reference time.

Most of the analyses done in this study were based on the Gmean-filling method, so two alternative methods—Levitus mapping and zero filling—were also tested in Fig. 1. It appears that the impact of climatology holds for all three mapping methods, but how much impact the climatology has is not consistent in values among the mapping strategies. Historically, several plausible mapping methods had been used to fill the data gaps based on a variety of potential assumptions. Although it is still unclear how and how well the various mapping methods could fill the data gaps, the impact of the choice of climatology will be minimized if an Argo-period climatology is used rather historical climatology.

Furthermore, the problem of climatology will also appear in the estimates of other climate indicators, such as global surface temperature, sea surface temperature, sea level, etc. Careful examination of climatology is required for future studies in climate sciences.

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