Uncertainties of the Ocean Heat Content Estimation Induced by Insufficient Vertical Resolution of Historical Ocean Subsurface Observations

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ABSTRACT
Assessment of the upper-ocean (0–700 m) heat content (OHC) is a key task for monitoring climate change. However, irregular spatial and temporal distribution of historical subsurface observations has induced uncertainties in OHC estimation. In this study, a new source of uncertainties in calculating OHC due to the insufficiency of vertical resolution in historical ocean subsurface temperature profile observations was diagnosed. This error was examined by sampling a high-vertical-resolution climatological ocean according to the depth intervals of in situ subsurface observations, and then the error was defined as the difference between the OHC calculated by subsampled profiles and the OHC of the climatological ocean. The obtained resolution-induced error appeared to be cold in the upper 100 m (with a peak of approximately 0.18°C), warm within 100–700 m (with a peak of approximately 0°C to 180 m), and warm when averaged over 0–700-m depths (with a global average of 0.01–0.02°C, or 1–2.5 × 10^22 J). Geographically, it showed a warm bias within 30°S–30°N and a cold bias at higher latitudes in both hemispheres, the sign of which depended on the concave or convex shape of the vertical temperature profiles. Finally, the authors recommend maintaining an unbiased observation system in the future: a minimal vertical depth bin of 5% of the depth was needed to reduce the vertical-resolution-induced bias to less than 0.005°C on global average (equal to Argo accuracy).

1. Introduction
Estimations of ocean heat content (OHC) have large uncertainties because of the spatial and temporal sparseness of the historical ocean subsurface observations and the quality of the instruments. Evidence suggests that OHC estimation could be greatly improved by addressing the following problems: instrumental biases [e.g., expendable bathythermograph (XBT), mechanical bathythermograph (MBT), and Argo; Gouretski and Koltermann 2007; Levitus et al. 2009; Wijffels et al. 2008; Willis et al. 2009; Cheng et al. 2011, 2014], the mapping strategy (used to fill the data gaps), the quality-control procedure, and the integration method (used to integrate the three spatial dimensional temperature anomalies to a global mean value) (Lyman and Johnson 2008). These uncertainties have been comprehensively examined in an independent study (Lyman et al. 2010) and reviewed in Abraham et al. (2013). All the previous studies suggested that it was vitally important to quantify each component of the uncertainties to improve the OHC estimation.

One of the problems with the historical subsurface data was that the observations also become more sparsely distributed with increasing depth. As shown in Fig. 1a, the globally averaged vertical resolution of historical data during the past 45 years was generally ~10 m near the surface but ~50–100 m at depths below 300 m. Circa 1992, the global vertical resolution experienced a significant change at all depths. For instance, the vertical resolution increased from 60 to 75 m pre-1992 and then from 10 to 49 m post-1992 at 400–700-m depths. This change occurred because deep XBTs (i.e., T7/Deep
Blue probe, with a terminal depth deeper than 700 m) began dominating the observational system, which helped to increase the global mean vertical resolution. Pre-1992, shallow XBTs (i.e., T4/T6 probes) with a terminal depth of 450 m were the major components of the observational system, such that the vertical resolution of the XBT data was ~30–60 m at depths from 100 to 450 m (Fig. 1b) and a clear “break line” at 450 m. At the same time, below 450 m, there is a similar resolution history as 100–450 m, suggesting a similar vertical resolution of XBT data between shallow XBTs (T4/T6) and deep XBTs (T7/DB/T5) pre-1992. Circa 2001, there was another significant change in the globally averaged vertical resolution that revealed another observation system change from the ship-based observation system prior to this century to the Argo-based system in this century. The vertical resolution of Argo profiles (labeled PFL in Fig. 1b) varied from ~5 to 40 m from the sea surface to 700-m depth. In general, the vertical resolution of historical subsurface observations continually increased during the past 45 years. However, there was no study that systematically investigated the effect of the vertical resolution and its change on OHC estimation.

How could the insufficiency of the vertical resolution affect the OHC estimation? An example is presented in Fig. 2. As presented in this plot, there was a typical temperature profile averaged among all of the
FIG. 2. Example showing how the bias was generated when the vertical resolution was reduced. (a) Mean vertical temperature profile averaged among profiles within 10°S and 10°N was used here as the truth. (b) Resolution-induced bias at depth was calculated under different vertical resolutions from 2 to 100 m, which were consistent over depths. (c) Zonally averaged temperature profiles at different latitudinal bounds for both the Northern and Southern Hemispheres (i.e., 0°–10°, 10°–20°, 20°–30°, 30°–50°, and 50°–60°) and two different months (January and July).
temperature profiles between 10°S and 10°N with 1-m vertical resolution. When we sampled this full-resolution temperature profile (in black) at depths from 1 to 700 m (depth sampling set to bin), a low-resolution profile was obtained. The resolution-induced error was defined by comparing the full-resolution profile (black line) with the low-resolution profile. To make this comparison, the low-resolution profile was first interpolated to the same depths as the full-resolution profile using linear interpolation (used to fill the temperature gaps at no-data depths in low-resolution profiles). The depth interval bin changed from 5 to 100 m at each run.

The errors using different vertical resolutions from 0 to 700 m are shown in Fig. 2b. In this case, within 100–200 m, the profile was concave, so it resulted in cold biases. By contrast, in the convex part of the profile within 200–400 m, it showed warm biases in general. Here concave means the second derivative of temperature with depth is positive, and convex means the second derivative of temperature with depth is negative. Apparently, this bias was caused by the loss of the high-order vertical temperature information, because the low-resolution profile was subsampled from the real ocean state (high-resolution profile). In addition, the sign of the bias depended on the shape of the vertical profile: a concave-shape profile tended to induce a cold bias and a convex-shape profile led to a warm bias. The magnitude of this bias depended on both the vertical resolution and the shape of the profile. In Fig. 2c, the zonally averaged temperature profile was calculated using profiles at different latitudinal bands, indicating different shapes of the vertical profiles at different latitudes.

In the example in Fig. 2, linear interpolation (a method of curve fitting using linear polynomials) was used, but different methods of vertical interpolation have been used. For instance, the Reiniger–Ross method [recommended by United Nations Educational, Scientific and Cultural Organization (UNESCO), 1991] is widely used in oceanographic studies (e.g., Boyer and Levitus 1994; Reimer and Ross 1968). This method uses four observed values (numbered from 1 to 4 with depths) surrounding a standard-level depth for which an interpolated value is to be calculated. From those four points, two above the standard level and two below, two 3-point Lagrangian interpolations are computed for points (1, 2, 3) and (2, 3, 4), respectively. The two interpolated values are then averaged and fit to a reference curve (Boyer and Levitus 1994). Spline interpolation is another approach widely accepted in the oceanographic community (Ishii and Kimoto 2009), which is piecewise defined and possesses a high degree of smoothness at the places where the polynomial pieces connect. Different interpolation methods have different behaviors in filling the vertical gaps, which may also potentially influence this resolution-induced error.

Based on the example and analyses presented above, we showed simply how the insufficiency of vertical resolution of subsurface profile data could incorporate bias into the OHC calculation. However, would this induce systematic bias in the estimation of global ocean heat content? To answer this question, this study was conducted and constructed as follows. In section 2, the data and methods we used are introduced. In section 3, the global mean of bias caused by low-vertical resolution is calculated and analyzed. We also introduce a test showing how much vertical resolution is needed in the future to maintain an unbiased global subsurface observation system. This study is summarized in section 4.

2. Data and methods

In situ ocean subsurface temperature observations within 1966–2010 from the World Ocean Database 2009 (WOD09; Boyer et al. 2009) were used in this study. The data were collected with different instruments, including XBT, Argo (PFL in the WOD09 dataset as in Fig. 1), ocean station data (OSD), undulating oceanographic recorder (UOR), glider (GLD), mooring and bottle (MBT), and CTD. The total amount of data from each instrument system in each year is presented in Fig. 1b in the left panel. Flags in the WOD09 dataset were used to remove problematic temperature measurements/profiles. The data then underwent standard deviation checks: measurements outside five standard deviations in each 5° × 5° grid box were removed. Systematic XBT bias correction was applied using a correction scheme as presented in Levitus et al. (2009), and systematic MBT bias was also removed using the method proposed in Ishii and Kimoto (2009).

Ideally, assessment of the bias caused by low vertical resolution of a given temperature profile requires the real ocean condition with full vertical resolution, so that one can make a comparison and determine how much vertical information was lost during the observation (vertical sampling) process. The idealized bias is calculated as

\[
B(i, g, y, m, z) = T_{\text{low}}(i, g, y, m, z) - T_{\text{real}}(i, g, y, m, z),
\]

where \((i, g, y, m, z)\) identifies a profile located in a 1° × 1° grid box ordered by \(g\) at a given year \(y\) (from 1966 to 2010) and month \(m\) (1–12); this profile is the \(i\)th profile of
the total $k$ profiles in this spatial and temporal box, and $z$ is the depth of an individual temperature measurement. Term $T_{\text{low}}(i, g, y, m, z)$ identifies a low vertical profile, and $T_{\text{real}}(i, g, y, m, z)$ is the corresponding real ocean state. It is worth noting here that $T_{\text{low}}$ is a combination of temperature measurements (which will themselves have errors) and interpolated estimates, which are what is being investigated here.

However, this idealized calculation is impossible, since the real ocean state is never known. To make a compromise, we used a high-resolution climatological ocean to represent the real ocean. We then sampled the climatological ocean according to the vertical intervals of the historical temperature profiles. By comparing the climatological ocean and the subsampled climatological ocean, we were able to check how vertical resolution leads to a bias in OHC estimation. In detail, the bias was estimated according to the following steps.

a. Creating the climatology ocean

The climatological ocean was created as follows. All of the in situ observations from 1966 to 2010 were collected and grouped into $1^\circ \times 1^\circ \times 1$ month grid boxes. All of the observational-level profiles were first interpolated to 1-m vertical interval profiles using the Reingruber–Ross method. Then all of the standard-level profiles (standard level means 1-m resolution) in each grid box from each month were averaged together into a grid-averaged high-resolution profile. In this way, 12 monthly profiles were obtained in each grid box. All of these high-resolution profiles over the global ocean were collected as the climatological ocean, named WOD09-composited climatological ocean in this study.

In addition, in this study, another choice of climatological ocean was made to check how sensitive our results were to the selection of climatological ocean: all of the high-resolution profiles (where the 0–700-m-averaged vertical resolution was less than 10 m) from the WOD09 dataset were collected and averaged to a new high-resolution climatological ocean. Because of the limited geographical coverage of these high-resolution profiles compared with that of the whole dataset, the standard optimal interpolation (as in Levitus et al. 2012) was used to create a full geographical map at each depth.

b. Sample the climatological ocean according to the vertical resolutions of historical subsurface observations

After the climatological ocean was obtained, we began the bias-estimation process as follows. For each specific temperature profile from the WOD09 dataset, we selected the high-resolution profile in the climatological ocean from the same grid box and the same month. We sampled this high-resolution profile from the climatological ocean according to the vertical intervals of the low-resolution profile. Then, a new quasi-low-resolution profile was obtained. This quasi-low-resolution profile was interpolated using the Reingruber–Ross method to standard 1-m depths and compared with the high-resolution profile from the climatological ocean. The difference between the two profiles was obtained and recorded as the resolution-induced bias profile.

c. Detect the resolution-induced bias

For each temperature profile in the WOD09 dataset, we repeated the process in section 2b, and a new dataset of resolution-induced bias profiles was obtained. Based on this dataset, the yearly mean of globally averaged bias was calculated. In this case, we were able to identify whether the insufficiency of the low vertical resolution of historical data could induce bias in estimates of OHC.

Finally, we noted that our method did not calculate the resolution-induced bias for each individual temperature profile directly, since the corresponding real ocean state was unknown. Instead, the bias of a profile from the climatological ocean was estimated. Three case studies are presented in the appendix, suggesting the capability of this method to detect the resolution-induced bias.

To clarify: by using the high-resolution climatological ocean as the “truth,” we essentially neglected the effect of changes in the ocean state on the bias estimation.

3. Results

a. Time variation of the resolution-induced bias

Figure 3a shows the yearly averaged bias estimated intervals of 1-m depth. This figure was obtained by first grouping the errors into a $2^\circ \times 2^\circ$ grid box, and then calculating the global mean at each depth and year. In general, the global mean bias appeared to be negative in the upper 100 m and positive between 100 and 700 m. Since the resolution-induced bias depended on the convex or concave features of the vertical temperature profile, our results confirmed that concave features of most temperature profiles over the global ocean at the bottom of the mixed layer (Fig. 2c) tended to induce cold biases, while the convex features of the profiles at the main thermocline tended to induce warm biases. After the year 2000, the biases at some depths were slightly reduced, such as 0–100 and 150–300 m, but at some depths, such as 400–700 m, the bias seems larger and more consistent. That indicates the difference of the Argo system (denoted as PFL in Fig. 1) compared with ship-based systems.
FIG. 3. Time evolution of resolution-induced bias by using high-resolution climatological ocean. (a) Monthly mean of bias from 1966 to 2010 at depths from 1 to 700 m. (b) Column-averaged bias within the upper 700 m during the past 45 years over the global ocean (black), Pacific Ocean (red), Atlantic Ocean (purple), and Indian Ocean (blue). (b) Annual circle of the resolution-induced bias for three periods: 2001–10, 1966–2000, and 1966–2010. Thick lines are the results of 24-month running means.
Time evolution of the resolution-induced bias within the upper 700-m ocean is presented in Fig. 3b, which was calculated as follows: at a specific depth, the resolution-induced bias in each 2° × 2° grid box and 1-month time period were averaged together into a single grid-averaged value, and the grid boxes without observations were filled with the global mean of the biases. In this case, the full global coverage of bias was obtained for each month/year. To calculate the global mean of the biases, all of these grid-averaged anomalies were averaged into a global mean based on the weights of their grid areas.

As in Fig. 3b, the resolution-induced bias had seasonal variation: the sea surface was deeper in winter than in summer, because of the deepening surface mixed layer in the winter, as in Fig. 2b. The annual cycle of this bias is presented in the Fig. 3b subplot; the bias reached a peak of ~0.025°C in summer and a minimum of ~0.015°C in winter. The magnitude of interannual variation was reduced in this century because the Argo system improved the vertical resolution over the global ocean.

The column-averaged bias (0–700 m) suggested a consistent warm bias of about 0.01–0.025°C from 1966 to 2010 over the global ocean (Fig. 3b). Different magnitudes of biases were found in different ocean basins. For instance, the resolution-induced bias is 0.01°–0.02°C in the Atlantic Ocean, 0.02°–0.04°C in the Indian Ocean, and 0.01°–0.025°C in the Pacific Ocean, but the global mean of the bias is dominated by the bias in the Pacific Ocean because of its large area.

In addition, it is important to examine the time variation of the resolution-induced bias, because it may bias the long-term OHC trend during its estimation. Figure 3b shows that the global-averaged bias slightly increased with time from 1966 to 1995, and since 1995 the bias seems to be stable. The maximum change of the bias in the past 45 years is as large as 0.015°C, equal to an OHC change of ~1 × 10^{22}–1.5 × 10^{22} J. Such a magnitude was equal to 5%–10% of the total change of the upper-ocean heat content (15 × 10^{22} – 20 × 10^{22} J) during the past 45 years. Among the three ocean basins, this bias had a more prominent long-term trend in the Pacific Ocean, increasing from 0.012°C in 1966 to 0.025°C in 2010 (Fig. 3b). Considering that the total increase of the 0–700-m-averaged temperature in the Pacific Ocean from 1966 to 2010 was about 0.15°C, the resolution-induced bias may bias the long-term OHC trend in the Pacific Ocean by ~15% (15% is a fraction defined as Fraction = Bias difference/OHC difference in the past 45 years). However, in both the Atlantic and Pacific Oceans, the bias seemed to have no or a weak multi-decadal trend over the past 45 years. In the Indian Ocean, the bias reaches the peak of ~0.04°C near 1985, indicating a strong decadal variation. Therefore, we suggest that the resolution-induced bias contributed a nonnegligible part to the global OHC estimation, especially in the Pacific Ocean.

It should be noted that the bias we detected here referred to a climatological ocean that considered the ocean seasonal and spatial variability, without taking into account the interannual and decadal variability. Therefore, our estimated bias was potentially conservative. How this bias influenced the OHCA time series in the past is still an open problem, since it is impossible to directly estimate this bias from the in situ observations due to the lack of high-resolution observations.

b. Geographical distribution of the resolution-induced bias

Considering that the convex/concave shape of the vertical profiles dominated the sign and magnitude of the resolution-induced bias, this kind of bias should be geographically dependent. The global distribution of biases is presented in Fig. 4, obtained by averaging resolution-induced biases from the past 45 years to a 2° × 2° grid box. The resulting geographical variation appeared as expected. Generally, the resolution-induced bias was positive at low and middle latitudes (~30°S–30°N), but cold at higher latitudes (greater than 30°N and 30°S). The peak of the positive bias occurred around 10°S and 10°N in the central Pacific Ocean, with a magnitude of more than 0.1°C. Similarly, within the same zonal bounds of 30°S–30°N in the Atlantic and Indian Oceans, a positive bias of ~0.02°–0.07°C also appeared. The warm bias at low and middle latitudes was linked to the strong temperature gradient in the main thermocline (concave), as in Fig. 2b. By contrast, in higher latitudes within 30°–70°S and 30°–60°N, the bias was neutral or slightly cold. The contradictory results between high and low
latitudes resulted from the different shapes of the vertical temperature profiles at different latitudes.

Was such a geographical pattern in Fig. 4 consistent over the past 45 years? In Fig. 5, we show this distribution in four time periods: 1966–79, 1980–89, 1990–99, and 2000–10. In these four decadal time periods, the patterns were consistent with each other. Additionally, since there was a smaller amount of data in the Southern Hemisphere pre-2000 than post-2000, the resolution-induced bias appeared with larger uncertainties than during the post-2000 period.

Furthermore, the zonally averaged biases in relation to depth are shown in Fig. 6, which shows symmetrical features north and south of the equator. The maximum warm bias occurred near 10°N and 10°S at ~180 m. The bottom of the upper-ocean cooling bias changed from 80 to 90 m at low latitudes to less than 50 m at middle and high latitudes, because the surface cooling bias reached the peak at the bottom of the mixed layer, as demonstrated by the isothermals in Fig. 6. Also, the peaks of the subsurface warm bias corresponded to the maximum vertical gradient of the temperature profile (the main thermocline) with concave shape.

Furthermore, it should be noted that this kind of error in the past observation system potentially induced bias in calculating the ocean mixed-layer depth or identifying the main thermocline, for instance in Helber et al. (2012).

c. Uncertainties of the bias estimation

In previous parts of this paper, bias caused by insufficient vertical resolution was detected using the high-resolution climatological ocean, the Reiniger–Ross interpolation method (Locarnini et al. 2010), and a mapping strategy that assumed a globally averaged anomaly in no-data regions. How was the bias sensitive to these
choices? In this section, different choices of interpolation method, climatology, and mapping method were used to calculate the resolution-induced bias.

First, how did different mapping strategies influence the resolution-induced bias when the time series of the bias was created, as in Fig. 3?

The 0–700-m-averaged temperature anomaly (hereinafter the OHC anomaly is represented by a 0–700-m-averaged temperature anomaly) in grid box $g$ (denotes the order of the grid box from 1 to $ga$, where $ga$ is the total number of the grid boxes) can be denoted as $dT_{0}(g) = T_{\text{real}} - T_{\text{clim}}$, where $T_{\text{clim}}$ is a climatology used to calculate the temperature anomaly. But in a real ocean, we can only get $dT(g) = T_{\text{low}} - T_{\text{clim}}$, where $dT(g)$ is the biased estimation due to the usage of a low-resolution temperature profile ($T_{\text{low}}$). Therefore, according to Eq. (1), the unbiased 0–700-m-averaged temperature anomaly calculation can be expressed as $dT_{0}(g) = dT(g) + B(g)$. The global-averaged 0–700-m temperature anomaly (which is used to represent OHC) can be formulated as

$$\text{OHC} = \frac{\sum_{g=1}^{ga} dT_{0}(g) A_{g}(g) + \sum_{g=1}^{ga} B_{g}(g) A_{g}(g)}{\sum_{g=1}^{ga} A_{g}(g)} + \frac{\sum_{g=1}^{ga} dT_{0}(g) A_{g}(g) + \sum_{g=1}^{ga} B_{g}(g) A_{g}(g)}{\sum_{g=1}^{ga} A_{g}(g)},$$

where $T_{r}$ and $T_{c}$ are the unbiased 0–700-m-averaged temperature anomaly in grid box $g$, and $B(g)$ is the resolution-induced bias in grid $g$. Hence, when the time series of the bias was created, as in Fig. 3, the resolution-induced bias when the time series of the bias was created, as in Fig. 3, the resolution-induced bias when the time series of the bias was created, as in Fig. 3, the resolution-induced bias when the time series of the bias was created, as in Fig. 3.

Alternatively, following the first assumption of the Levitus et al. (2012) mapping method, the temperature anomalies in gaps were set to zero (zero filling). Therefore, the global-averaged 0–700-m temperature anomaly was calculated as

$$\text{OHC}_{L} = \frac{\sum_{g=1}^{ga} dT_{0}(g) A_{g}(g) + \sum_{g=1}^{ga} B_{g}(g) A_{g}(g)}{\sum_{g=1}^{ga} A_{g}(g)},$$

where $\text{OHC}_{0L}$ and $S_{biasL}$ are the unbiased estimate of global-averaged 0–700-m temperature anomaly and the global Mean of the resolution-induced bias using the zero-filling strategy, respectively. The difference between Eqs. (4) and (5) is the summation on the denominator, where the Palmer-filling method in Eq. (4) only considers the area with observations, but the zero-filling strategy in Eq. (5) only considers the global ocean.
The 0–700-m-averaged biases from 1966 to 2010 using the two mapping strategies shown above are presented in Fig. 7a. Apparently, the biases differed between the two mapping methods. Although this bias only originated in grid boxes where there was a low-resolution profile, it propagated from its origin to the regions nearby when the mapping method was applied. The efficiency of this propagation was variable with different mapping strategies. For instance, zero-mean mapping potentially assumed that this bias can never propagate from its origin to the gap regions. In other words, the impact of this bias on historical OHC estimation relied on which mapping method was used.

Second, two other vertical interpolation methods were also used: spline interpolation and linear interpolation. Both of the two methods showed a similar increasing bias with calendar year compared with the Reiniger–Ross method, and the time variation using spline interpolation was strongest among the three methods. It appears that Reiniger–Ross method induced the smallest time variation of bias among the three interpolation methods.

Third, the high-resolution climatology (solid lines in Fig. 7b) always shows larger bias than WOD09-composited climatology (dashed lines in Fig. 7b). The larger bias using the high-resolution climatological ocean suggested that our estimation of the bias may be conservative. Because it is never perfect to use the WOD09-composited climatological ocean, since a lot of low-resolution data are included and since the climatology itself is biased because it is based on interpolated files, the WOD09-composited climatological ocean may have underestimated the resolution-induced biases. Despite the more limited coverage, the high-resolution climatological ocean is likely to be a better estimate of the size of the bias.

Based on the tests shown above, we detected similar biases when different climatological ocean and interpolation methods were applied, showing a consistently positive bias caused by the low vertical resolution of historical profile observations. The geographical and depth distribution of the biases under different choices were similar to what we obtained in the previous sections.

d. How much vertical resolution is needed to maintain an unbiased observation system?

In this study, vertical-resolution-induced bias was detected using a climatological ocean; the magnitude and structure of the bias were investigated in detail. However, in order to extend this study to the implications for the future observation system, one of the fundamental questions is, how much vertical resolution is needed to reduce this bias to a negligible level during OHC calculation?

To answer this question, an additional test was conducted. First, high-resolution temperature profiles from the high-resolution climatological ocean in each grid box were regarded as the real ocean state (truth profile). Second, we sampled the truth profile to a low-resolution profile by only extracting temperatures at some selected depths (i.e., when we used a 10-m depth interval consistently from 10 to 700 m, so 10 m was the vertical resolution of this profile). In this case, the resolution-induced bias could be detected when the low-resolution profile
was compared with the corresponding truth profile. This comparison was made after the low-resolution profile was vertically interpolated to standard vertical levels (vertical levels of the truth profile). This progress was repeated 99 times under different vertical resolutions ranging from 2 to 100 m with 1-m increments each time. Therefore, in this test, the vertical resolution was set to be consistent over depths at each run.

The resolution-induced bias using linear interpolation as a function of depth and vertical resolution is presented in Fig. 8. Linear interpolation was used here rather than the spline and Reiniger–Ross methods, since the results of the three methods were similar to each other. This bias was the average over two zonal bounds: 30°S–30°N and 30°–80°S or 30°–80°N separately, based on the fact that the bias at the two bands had different behaviors.

Apparently, the bias increased when the vertical resolution was reduced, since more vertical information was lost when the vertical resolution was reduced. The bias also decreased as the depth increased because of smaller temperature variability in the deeper ocean than in the upper ocean.

Therefore, in order to reduce the bias at low latitudes to a level of less than 0.005°C (the accuracy of the Argo sensor), the vertical resolution needs to be less than 35 at 700 m, equivalent to ~5% of the depth. Similarly, when we aim to reduce the globally averaged bias to 0.01°C (the accuracy of the XBT instrument), the vertical resolution should be less than 6.5% of the depth. Since the bias was smaller at latitudes higher than 30° in both hemispheres, this criterion can be relaxed to 13% for the 0.005°C criterion and 18% for the 0.01°C criterion.

As discussed above, more intense sampling is but one expensive way to reduce the resolution-induced bias. An alternative strategy might be to use more advanced statistical method that regards the insufficient sampling as an independent bias in the OHC calculation (as what we have done in this study). Another approach to improving the historical record would be to redigitize traces from continuously recording instruments such as XBTs and MBTs where this is feasible.

4. Summary

In this study, a previously undetected error caused by the low vertical resolution of historical subsurface observations in OHC estimation was diagnosed. When taking the global average, this bias appeared to be cold within the upper 100 m, warm within 100–700 m, and warm when integrated over the whole water column from 0 to 700 m. On a global average, this bias ranged from +0.01°C to +0.025°C during the past 45 years. Comparing the long-term change of this bias of ~0.015°C with global warming signals of 0.15°–0.2°C from 1966 to 2010, we concluded that this bias represents a non-negligible contribution to the global ocean heat content during the past 45 years. It will be a more important...
aspect in estimating regional ocean heat content: for instance, it was equal to 15% of the Pacific Ocean warming.

Based on the geographical pattern of the bias, we found that this bias reached the positive peak of $0.1^\circ$C at $10^\circ$N and $10^\circ$S in the Pacific Ocean and the negative peak of about $-0.05^\circ$C at $30^\circ$S in the Pacific Ocean. The bias also had a strong seasonal variation, arising from a deeper cooling near the bottom of the surface mixed layer in the winter than in summer. These geographical and seasonal variations were linked to the variation of the shape of the vertical temperature profile. The convex part of the vertical temperature profile tended to induce a warm bias and the concave part induced a bias with the opposite sign.

Furthermore, considering the biases caused by the insufficiency of vertical resolution in historical subsurface observations, we suggested maintaining an unbiased observation system in the future. We recommended the minimal vertical resolution of 5% depth, especially for the Argo system, which is the main component of the recent and near-future ocean observation system.

A recent study (Abraham et al. 2012) of XBT numerical simulation suggested that higher drop heights...
for XBTs lead to errors in the upper few meters of the ocean. It would make the sampling bias more important. If the devices move through the water faster than anticipated, then the surface-cooling-resolution-induced bias will be smaller and the column-averaged warm bias will be larger than the results presented in this study. Considering that the size of commercial or scientific ships increased over the past 50 years, it is possible that this induced a stronger time variation of the resolution-induced bias than was found in this study.

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**APPENDIX**

**Case Studies Exploring the Uncertainties of the Method**

Here we explore the uncertainties of our method, which is pertinent to the high-resolution climatology analysis, as follows:

If we have $n$ profiles in a grid box, we can calculate a climatological ocean from all $n$ profiles and then, for each profile with an order of $i$, calculate resolution-induced bias $B_{ij}$ using first the full-resolution profile and then using the climatological ocean. The difference between the two is the error $E_{i}$ that accrues from using the climatological ocean instead of the true profile. A distribution of errors (with $n$ members) can be built up by calculating the error for every profile. Therefore, in this grid box, the mean error of resolution-induced bias is assessed as

$$\text{Error}_{\text{grid}} = \frac{1}{n} \sum_{i=1}^{n} E_{i}/n.$$  

Three groups of high-resolution profiles from three typical grid boxes at different latitudes were selected arbitrarily: G1 (22°N, 157°W) for June; G2 (47°–48°N, 46°–47°W) from June to August; and G3 (72°–73°N, 4°–5°E) from June to August. G1 contained profiles within a 1° × 1° grid box and a 1-month period, the same as the spatial and temporal scale of our method. In contrast, G2 and G3 contained profiles within a 2° × 2° grid box and a 3-month period, so that one could find how the error was generated when the similarity of the profiles was reduced. In each selected grid box, all high-resolution profiles for the specific month were collected. In this case, high-resolution data were regarded as the real ocean state. By assuming different vertical resolutions (from 10 to 80 m with an increment of 1 m), the resolution-induced bias (as in Fig. A1, right panel) and the Error_{grid} (as in Fig. A1, right panel) can both be calculated. As seen in Fig. A1, the Error_{grid} was always around zero, compared with the significant systematic signal of the resolution-induced bias. However, for G3, the Error_{grid} was positively biased, because the main thermocline below 300 m was divergent over the profiles, which led to a significant generation of errors.

By analyzing the errors in this appendix and presenting some examples, we concluded that in each grid box if the profiles have similar shapes, then our method was capable of correctly detecting vertical-resolution-induced bias.

Furthermore, in an ideal world we would know what the true profile, $T_{\text{real}}$, is in each case. The calculation given here provides an estimate of the uncertainty arising if we do know $T_{\text{real}}$ but instead choose to use a climatological ocean calculated from many profiles for which we know $T_{\text{real}}$. Unfortunately, we do not know $T_{\text{real}}$ in any situation and the climatological ocean is constructed not from $T_{\text{real}}$ but from $T_{\text{low}}$, which adds an additional layer of uncertainty.

**REFERENCES**


