Accuracy of Global Upper Ocean Heat Content Estimation Expected from Present Observational Data Sets

Masayoshi Ishii1, Yoshikazu Fukuda2, Shoji Hirahara3, Soichiro Yasui3, Toru Suzuki4, and Kanako Sato5

1Climate Research Department, Meteorological Research Institute, Tsukuba, Ibaraki, Japan
2Sendai Regional Headquarter, Japan Meteorological Agency, Sendai, Miyagi, Japan
3Climate Prediction Division, Japan Meteorological Agency, Tokyo, Japan
4Marine Information Research Center, Tokyo, Japan
5Japan Agency for Marine-Earth Science and Technology, Yokosuka, Kanagawa, Japan

Abstract

The simplest global mapping method and dense data coverage for the global oceans by the latest observation network ensure an estimate of global ocean heat content (OHC) within a satisfactory uncertainty for the last 60 years. The observational database conditionally presented a level high enough for practical use for the global OHC estimation when applying bias corrections of expendable bathythermograph, assuming that the other severe observational biases are not included in the database. Uncertainties in annual mean global temperatures averaged vertically from the surface to 1,500 m are within 0.01 K for the period from 1955 onward, when only sampling errors are taken into account. Those in annual mean global OHC are an improved objective analysis for 0–1,500 m depth is 16ZJ on average throughout the period. Compared to previous studies, the new objective analysis provides a higher estimation of the global 0–1,500 m OHC trend for a longer period from 1955 to 2015, which is an increase of 350 ± 57ZJ with a 95% confidence interval.

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1. Introduction

Past global ocean heat content (OHC) records the history of extra heating over the earth’s surface due to anthropogenic greenhouse gasses (AchutaRao et al. 2007; Gleckler et al. 2013). The current global OHC estimations range widely between various centers and institutes (Smith and Murphy 2007; Palmer et al. 2007; Domingues et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009). This is intrinsically due to ocean data sparseness, and the estimates are accordingly affected by different methodologies (Boyer et al. 2016). An accurate OHC estimation is needed for understanding the global energy balance (Murphy et al. 2009), sea level budget (Lombard et al. 2005; Cazenave and Llovel 2010), and earth system modeling (Watanabe et al. 2010; Yokimoto et al. 2012) for future climate predictions.

Estimating ocean subsurface temperatures in the upper 1,000 m or more is challenging because the frequency of ocean subsurface temperature observations is low, on the order of 1/10, compared to that of sea surface temperature (SST; Ishii et al. 2005; Ishii and Kimoto 2009). Furthermore, we have to determine the temperature values three dimensionally. Here we propose an approach for accurate estimation of global ocean heat content with the simplest global mapping method, i.e., averaging data in grid-box regions. Dense data coverage for the global oceans by the latest observation network is crucial in this approach. Only sampling errors in oceanographic observations are taken into account in evaluating the uncertainty after removing time-varying biases in expendable bathythermograph (Gouretski and Koltermann 2007; Lyman et al. 2010).

In this study, the ocean subsurface temperature analysis as a replacement of the previous analysis (Ishii and Kimoto 2009; IK09, hereafter) is conducted to obtain statistically optimal states of temperature on a regularly spaced grid at regular intervals. Here we applied a methodology used in an SST analysis (Hirahara et al. 2014; HIY14, hereafter) for computing monthly temperature values at the upper 3,000 m depths. The SST analysis of HIY14 was given as a sum of trend and short-term components, in which the grid box mean values of SST observations were used for estimating the trend component. In general among the past studies (Smith et al. 1996; Kaplan et al. 1998; Smith and Reynolds 2004; HIY14), SST fields for more than 100 years were estimated by analyzing long-term and short-term variations separately, and methodologies have been refined through long experience.

Results shown below are not only an update of the previous analysis but they provide evidences of potential abilities of the observational databases for ocean monitoring.

2. Grid box averaging

Three typical observational data sets: World Ocean Data 2013 edition (WOD13; Boyer et al. 2013), the Global Temperature-Salinity Profile Program (GTSPP), and the Argo Project, were used for estimating global OHC. Observations in the latter two data sets were used prior to WOD13, as they were updated later than WOD13. In addition, the duplicates in WOD13 were discarded in the following calculations. For easy handling and analyzing observed data distributed irregularly in space and time, observed anomalies relative to the climatology were arithmetically averaged monthly from 1945 to 2015 in 5°-longitude and 5°-latitude boxes allocated over the global oceans. A typical spatial decorrelation scale ranges from 300 to 900 km among literature (Levitus et al. 2000; Ishii et al. 2003; Willis et al. 2003; Ingleby and Huddleston 2007), and therefore, the 5°-box mean values are regarded as locally representative. The monthly box mean values of observed profiles were computed after taking averages of data observed by each ship or buoy in each 10-day interval and in each 5°-longitude and 5°-latitude square at 28 levels from surface to 3,000 m depth; biases from localized data in space and time from specific ships or buoys are minimized. The climatology used here is mean temperature fields of IK09 for the period from 1961 to 2005. The climatology is defined on a 1-degree grid. This minimizes spatial interpolation errors in computing 5-degree box mean values rather than the case of 5-degree climatology, particularly in areas where the horizontal temperature gradients are large. Vertically, the boxes were placed in the upper 3,000 m and the box heights, i.e., thickness, varied from 5 to 50 m in the upper.
300 m and from 100 to 500 m at greater depths as the grid of Levitus et al. (1994) was adopted. Observed values averaged in the boxes were not vertically interpolated at the 28 levels. This avoids uncertainties from vertical interpolation. SST analysis, that is COBE-SST2 by HY14, is used for grid box averaging at the sea surface. The quality control procedures for observed profiles are the same as previously described (Ishii et al. 2003). The merit of applying grid box averaging to estimation of ocean temperature variations is that any other errors originating from somewhat complicated procedures in mapping methods are not incorporated, and observational and sampling errors are ones needing to be taken into account.

As an example, Fig. 1 shows global mean time series of all box-mean anomalies available at the 1,200 m depth for the period from 1945 to 2015 which is denoted by red curve. The global means for years before 2003 were noisy due to the data sparseness, while after 2003, the Argo observation network dramatically increased the level of ocean monitoring thank to more than 3,000 floats deployed in the world oceans. Despite the noisy time series prior to 2003, the figure suggests a warming trend, together with less uncertain time series of objectively analyzed temperature (black curve) which is introduced later. In order to assess the statistical reliability of the warming trend, we need to determine the number of observational samples required for accurate estimations of global mean temperatures particularly before the Argo era. Or, averaging temperature observations with a certain coverage in the world oceans would yield a value equivalent to the truth of global mean, reflecting its number of degree of freedom.

3. Uncertainties in global mean temperatures

Historically, the global data coverage has been improved by temperature profile observations of shallow expendable bathythermographs (XBTs) starting from the end of the 1960s, deep XBTs commonly used from the 1990s, and Argo floats from 2003, and hence step-wise changes in the global data coverage is observed in Fig. 2a. At depths typically greater than 700 m where these observations did not reach the monthly coverage of observations in the global oceans is much less than the 40% level. In the case of SST analysis, the global means suffer from substantial uncertainties when the coverage is less than 40% (HIY14). There is no doubt that monthly global mean temperatures during the Argo era are accurate at all levels in the upper 2,000 m. We estimated uncertainties in the global mean temperatures for past decades by comparing global means of fully-sampled box mean values for a ten-year period from 2006 to 2015 with those sub-sampled from identical spatial distributions for years from 1945 to 2005 on a monthly basis. The time series shown in Fig. 3 are global means of box mean values integrated vertically from the sea surface to 1,500 m depth (VAT15) with thickness weights at each level. The upper 1,500 m layer occupies one third the volume of the global oceans. Here, all available box mean values are counted. The uncertainties in VAT15 were finally defined as the root-mean-square differences between sub-sampled and fully-sampled VAT15 for the latest 10 years.

Before discussing uncertainties in VAT15, we check signal-to-noise (S/N) ratios for global mean temperatures at each depth separately for one-month and 12-month means (Figs. 2b and 2c). Here, 12-month means were computed from monthly global box means in each year; more explicitly, 12-month interval boxes were not used here. This minimizes temporal biases in data sampling. Samples in low latitudes and in layers having large thickness contribute more to the global means geographically. In addition, uncertainties due to poor temporal data coverage on time scales and several months are reduced by temporal averaging, reflecting thermal inertia and slowly evolving ocean dynamics. Observational random noise is also reduced by averaging. Consequently, the S/N ratios for 12 months became much higher than those for one month. The annual global coverage, a counterpart of Fig. 2a, also become larger than 40% in depths and years where the S/N is larger than one.

The uncertainties in monthly VAT15 are pretty large (darkest shading in Fig. 3), but become smaller as temporal averaging lengthen to 12 months. The expected VAT15 one-sigma errors are the minimum for the case of 12-month average. They are about 0.01 K and less than 0.003 K respectively before and after year 2003. The depth of 1,500 m is the marginal depth of S/N ratio of 1 for the 12-month global mean (Fig. 2c), and therefore uncertainties in VATs for 0–2,000 m become larger than in VAT15 (not shown). For the period before 1955, the uncertainties increase drastically owing to severe data sparseness over the period. Lower uncertainties can be expected for averaging periods longer than 12 months. However, they are not presented because the Argo reference period is not so long.

Several important pieces of evidence are presented in Fig. 3. Additional VAT time series computed from two observational data sets from EN4.2.0 (Good et al. 2013) are shown for examining differences in quality control procedures between EN4.2.0 and the observational and sampling errors are ones needing to be taken into account.
and Ishii et al. (2003) and differences in time-varying XBT bias corrections of IK09, Levitus et al. (2009), and Gouretski and Reseghetti (2010). These bias corrections were used in addition to the common bias correction (Hanawa et al. 1995) which is not time-varying. XBT biases are one of major sources of uncertainty in OHC estimation (Lyman et al. 2010; Boyer et al. 2016). Three time-varying bias corrections reduced the biases efficiently as reported by the above-listed literature. Consequently, the differences in the quality control procedures and the additional XBT bias corrections are not a severe problem in estimating VAT15. A root mean square difference between red- and orange-colored time series from 1955 to 2005 is 0.009 K and that for red and green is 0.016 K. The former is comparable to the VAT uncertainty for the period before the Argo era.

In summary, robust global warming is detectable for the last 60 years from 1955 onward, and differences between three additional XBT bias corrections are minor for VAT15 estimation. This time, XBT bias corrections of IK09 were updated for WOD13, but they did not significantly affect the results.

4. Uncertainties in global OHC

To further reduce uncertainties in ocean subsurface temperatures, we conducted an objective analysis for monthly mean temperatures on a 1°-longitude and 1°-latitude grid at the 28 levels with a previously used methodology in IK09, except that the trend component was prescribed as done in HIY14. The objective analysis is a method which constructs statistically optimal states of variables on a regularly spaced grid at regular intervals, considering the uncertainties in observations and the background fields. Here the background is the climatology plus the prescribed trend, and the monthly anomalies, i.e., deviation from the background, are computed by the objective analysis. Because of this, the resultant analysis is unbiased as requested by objective analysis theory.

The prescribed trend was computed from 5-yearly box-mean temperatures as a sum of annual box mean values in the 5° boxes, and was defined as the leading empirical orthogonal function (EOF) interpolated to the 1° grid. Before calculating the EOF, annual means in missing boxes are filled by a variational reconstruction scheme similar to HY14. Here, the global mean values at each level are preserved, and VAT15 as well. Namely, EOFs used in the reconstruction were computed from annual 5°-box mean temperatures in the Argo era (2003–2015) from which the global means were subtracted. See the trend analysis of HY14 for more details. Temperature observations of WOD13, GTSP, and the Argo project were used in the objective analysis. Only at the sea surface was COBE-SST2 given as observations. The objective analysis was conducted for the period from 1955 to 2015 during which the VAT15 uncertainties are smaller than before (Fig. 3). Uncertainties in the analyzed temperature were defined as a sum of errors in the trend and objective analysis. Because the trend was computed from 5-year box mean values, about a half of the uncertainty in the 12-month mean VAT15 trend was used as the trend error, considering temporal decorrelation of VAT15 variations. In the mean time, uncertainties for interannual variations of ocean temperatures were computed using a similar method to the above-mentioned computation of VAT15 uncertainty (Fig. 3). Here observations merged in each 1°-longitude by 1°-latitude square for the years from 2006 to 2015 were sampled as observations whose spatio-temporal distribution resembles the one in years from 1955 to 2005, and they were input to the objective analysis scheme (pseudo analysis) on a monthly basis. The 1° square is a tolerance of similarity in data distributions between the sampled and actual observations. The uncertainties in the analyzed temperatures are defined as root-mean-square differences between the original and pseudo analyses.

The global OHC is the sum of local temperatures multiplied by seawater density and heat capacity. With a simple test, it was confirmed that VAT and OHC for the global oceans are equivalent to each other because the density changes are negligible. That is, global mean VAT multiplied by 2.03 × 10^{24} J/K presents an equivalent estimation of global OHC for 0–1,500 m (OHC15), where the constant means a globally integrated value of the products of density, heat capacity, and volume from surface to 1,500 m. In addition, it is confirmed that the prescribed trend was preserved even after conducting the objective analysis (HY14). A mean error of 1.82 ZJ in converting from monthly mean VAT of IK09 to OHC were obtained, but they are much smaller than the uncertainties. Therefore, the OHC15 time series (black) follows VAT15-derived OHC (red) in Fig. 4. The uncertainties in VAT15 shown in Fig. 3 are a sum of those in 5-year mean OHC trend and monthly temperature analysis both of which are mentioned above. The magnitude of the annual OHC15 uncertainty is 16ZJ (one sigma error) on average during the period. Those for OHC15 for 0–750 m depth is less than 10ZJ (Fig. S1 in Supplement). This value is close to that for 0–750 m depth reported by Lyman and Johnson (2008).
Finally we obtained OHC time series of the smallest uncertainty. According to the present estimation, the global 0−1,500 m OHC increases by about 350 ± 57 Z/n with a 95% confidence interval, whose equivalent heating is 182 TW, over the period from 1955 to 2015. A significant reduction of the uncertainties in monthly OHC15 compared with those for monthly VAT15 is mainly due to the reduction in the trend uncertainties. The 0−700 m OHC trend for 1971−2010 of the present analysis (Fig. S2 in Supplement) does not contradict the estimates presented in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Fig. 3.2 in Chapter 3); the equivalent heating rate for the linear trend is 1247 W. The present OHC time series shows rather a monotonic increase since 1955. Accordingly, the trend from 1955 onward appears larger than ever.

Estimates of OHC15 are significantly different between IK09 and present temperature analyses. The reason for this difference is primarily because of an improper procedure of the previous analysis in which SST, not SST anomaly, was given for the analysis of surface mixed layer temperatures at depths where the temperature changes by 0.5 K compared to SST. The procedure caused warm surface mixed layer temperatures at depths where the temperature was cooled by 0.5 K compared to SST. Consequently the previous global OHC trend was underestimated. Therefore, the SST analysis is given only at the sea surface in the present analysis.

5. Concluding remarks

In the above discussion, we primarily discussed uncertainties due to observational sampling frequencies, but did not consider the observational biases in subsurface temperature data except for XBT. Biases in XBT observations, however, have not been fully solved yet. Nor are those in the other observational types. Even in the objectively analyzed time series of OHC15, there still remain interannual or intradecadal signals and short-term noise observed largely before the Argo era. Although some of these might be signal induced for example by volcano eruptions and El Nino and Southern Oscillations, the OHC15 time series may suffer from artificial errors largely, inferring from smoothness of the time series during the Argo era. These bias problems remain unsolved, but maintaining the Argo observation network and the International Quality Controlled Ocean Database project (IQuOD 2015) will provide important solutions for more reliable estimates of global OHC.

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Supplement

Supplement 1 shows time series of OHC for 0−700m depths computed by several centers. Supplement 2 provides estimation errors of OHC15 depending on different box sizes.

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