Regional Interdecadal Variability in Bias-Corrected Ocean Temperature Data*

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ABSTRACT

Regional interdecadal variability, on subbasin to basin scales, is shown to be a robust feature of the post–World War II (WWII) historical temperature record, even after a recently proposed bias correction to XBT fall rates is applied. This study shows that the previously reported strong regional variability is generally unaffected by this correction, even though the interdecadal variability in the most recently published estimates of global ocean heat content is much reduced after a correction is applied. Following methods used in previous trend analysis work, estimates of interdecadal trends are calculated for individual regions of the global ocean where there are sufficient data. Spatial maps of temperature trends for the surface and three subsurface depths (50, 100, and 300 m) are presented, with both bias-corrected and uncorrected data trends at 100 and 300 m shown for comparison. In the upper two depths and at the surface, interdecadal variability is shown to be present and strong in most of the analysis regions. At 100 m, the differences between trends based on bias-corrected versus uncorrected data are small, and barely distinguishable for much of the ocean analyzed. There are more differences at 300 m between the two data treatments, but large-scale patterns are still present in the bias-corrected trends, especially where the trends are stronger.

Given the sampling issues discussed in previous works, the presence of strong interdecadal variability on smaller scales raises concerns that global interdecadal variability in the historical record still may not be properly resolved.

1. Introduction

In our previous work, we explored regional long-term temperature trends in the subsurface ocean. We found that there are large-scale coherent trend patterns over 20-yr periods, and that these interdecadal trends change sign for different analysis periods nearly everywhere (Harrison and Carson 2007). These patterns of strong regional interdecadal variability at subsurface levels are robust to varying grid sizes and anomaly versus mean temperature fields (Harrison and Carson 2008). Strong interdecadal variability is also evident in global estimates of ocean heat content, based on the same data sources as our studies (e.g., Levitus et al. 2000, 2005). However, newer estimates of global ocean heat content show a significant reduction in global interdecadal variability after certain bias corrections are applied to the historical temperature data (Domingues et al. 2008; Wijffels et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009). These results have motivated the present work, which is to explore the effects of these bias corrections on regional interdecadal trends.

Recent studies have revealed a systematic, decadally varying bias in expendable bathythermographs (XBTs), which account for well over a third of all temperature profiles taken between 1970 and 2000 (Gouretski and Koltermann 2007; Wijffels et al. 2008; Ishii and Kimoto 2009; Levitus et al. 2009). The heavy use of this type of instrument created the potential for significant changes to the historical temperature record after correcting for...
this systematic bias. Methods for calculating a bias correction for XBT profiles can be found, for example, in Wijffels et al. (2008), Ishii and Kimoto (2009), and Levitus et al. (2009). In this paper, we follow the Wijffels et al. (2008) bias correction.

To explore the extent to which surface interdecadal variability is similar to the subsurface, we have also computed regional maps of SST interdecadal trends. There are regions in the ocean that are connected to the surface through the mixed layer for much of the year. Potentially, this allows for a comparison between datasets with unrelated sources of instrument and systematic bias, and sampling error.

Similar to the XBT bias problem, Kent and Kaplan (2006) found evidence in the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) observational SST data (Worley et al. 2006) of instrument biases that could potentially create spurious variability on decadal time scales. These biases are of a different character and origin (involving engine intake temperature) than the XBT bias issue in the subsurface data. Casey and Cornillon (2001) previously demonstrated the similarity of regional and global SST trends between the ICOADS dataset and the surface data from the World Ocean Atlas 1994 dataset. They also showed that SST trends can change sign when the analyzed time interval is shifted, which was examined for subsurface regions in Harrison and Carson (2007). However, much more data has been added to surface and subsurface datasets since that study, and the analysis carried out here highlights the interdecadal nature of local trends over better-sampled periods.

The results presented in this paper show that regional trends of bias-corrected temperature data continue to have strong interdecadal variability in most ocean regions. The instrument biases and uneven spatial sampling do not affect the coherent patterns of large-scale, large-amplitude trends except in some small details.

The datasets and methods employed are outlined in section 2. The spatial maps of 20-yr trends are displayed in section 3, with a discussion following in section 4.

2. Data and methods

Spatial maps of trends were calculated using data from the World Ocean Database 2005 (WOD05; Boyer et al. 2006), for subsurface levels, and ICOADS version 2.4 (Worley et al. 2006), for SST. To apply the XBT bias correction suggested by Wijffels et al. (2008), we use the observed-level data in WOD05, apply the Hanawa et al. (1995) XBT depth correction (where the WOD05 metadata indicate no previous correction was applied), calculate the new bias-corrected depths for each XBT profile [both as a function of the time when the XBT cast occurred, and whether it was a “shallow” or “deep” XBT, as per Table 1 in Wijffels et al. (2008)], and then interpolate the data to standard depths, for easier comparison to previous studies. The vertical interpolation scheme used here follows the methods laid out in World Ocean Atlas 2005 (WOA05; Locarnini et al. 2006). The same vertical interpolation scheme was run on the WOD05 observed-level data to compute our own standard-level (SL) dataset, without the XBT bias correction, so as to avoid any confusion regarding the source of the differences between the bias-corrected and uncorrected datasets. There are small differences between our SL dataset and the WOD05 SL dataset that could not be eliminated completely using our interpolation algorithm—most differences are less than 30% RMSE (normalized by the standard deviation); these are small compared to the size of the signals studied here. The ICOADS data are not bias corrected at all [referring to the engine intake temperature bias concerns raised by Kent and Kaplan (2006)], since there is no similar algorithm for correction at present; however, this is useful to allow for comparisons between corrected subsurface and uncorrected surface data.

Maps of trend magnitude for particular time intervals are the main graphic used here to demonstrate the spatial patterns of interdecadal variability, with various periods explored to show temporal patterns. Maps were made for individual depth levels: 50, 100, and 300 m. These upper-ocean depths have reasonably good coverage and capture mixed layer and thermocline variability. These maps were calculated as per Harrison and Carson (2007): a trend line is fit to the temperature time series associated with each grid box (calculated from averaging monthly 1° × 1° anomalies in that box). The trend magnitude over the period in question for each box is the difference between the endpoints of the fitted line constrained to the data within that period. The grid size is 2.5° × 2.5° square latitude–longitude for all maps, which is a good choice for capturing trend features at most spatial scales, while gaining good coverage globally [see Harrison and Carson (2008) for further discussion of grid size effects on trend maps]. No further spatial smoothing is applied. The period length is 20 yr throughout (calculated using January data of the first year through January data of the last year), which was found to be a reasonable length to capture decadal temperature variations (shorter intervals tend to alias strong interannual variability into decadal scale trends more than the 20-yr interval).

An important feature applied to these trend maps is a data distribution requirement for each box. Trends are only shown for locations that have at least 2 months with observations in both the first and last 5-yr periods of the 20-yr interval in question. This requirement is to reduce the likelihood that the trend shown for each box is due to data
covering a time period much shorter than 20 yr (though, for pathological sampling patterns within an interval, it could be as short as an 11-yr trend; see Harrison and Carson (2008) for further discussion on sampling issues).

3. Results

a. SST and 50 m: Different datasets

A comparison of regional interdecadal variability between the ocean surface (ICOADS SST) and the XBT bias-corrected (XBTC) standard-level data for 50-m depth is depicted in Fig. 1. Across the top row are the trend magnitudes for the interval 1960–80 (panels a and b), the middle row is for 1970–90 (panels c and d), and the bottom row is for 1980–2000 (panels e and f). It is striking that the maps have very similar coherent patterns, in location and intensity, in the better-sampled regions (particularly, the Northern Hemisphere). Large-scale patterns are evident over many parts of the ocean especially in the later, better-sampled periods. The 1960–80 period has the worst
sampling frequency for both datasets. However, there are regions that have similar trends for this period, including the east coast of Madagascar, the central North Pacific, the northeastern coast of the United States, the subpolar and eastern North Atlantic, and the eastern equatorial Pacific near the coastal region off of Peru (Figs. 1a and 1b). There are large regions of discrepancy between the surface and subsurface records in this and the later periods, especially in regions where the subsurface sampling may not be sufficient to distinguish between the decadal and interannual variability. The horseshoe-shaped pattern in the North Pacific often identified with the Pacific decadal oscillation (PDO) is coherent with depth, even in the coastal region of the western United States, where the mixed layer often does not reach 50 m (Figs. 1c and 1d). The cooling and subsequent warming in the subpolar North Atlantic, and much of the warming pattern in the central North Atlantic, are present in both datasets. The warming in the Indian Ocean during 1970–90 (Figs. 1c and 1d) appears to be present at both depths, but later the datasets diverge there (Figs. 1e and 1f). Much of the region off the coast of eastern Australia and north of New Zealand has mostly similar trends across all three periods. Overall, though, the proportion of ocean areas with trends of the same sign (relative to the sparser 50 m maps) is only as high as 65% of the total (common) analysis area for the 1970–90 trends and is lower for the other two periods.

These discrepancies are hard to systematically qualify as being due to any one cause. The frequency of the mixed layer depth penetration to beneath 50 m is likely important to some regions and time periods. In other cases, the weaker and statistically insignificant trends can easily differ. And the sampling differences between the two levels can be large, given that they occur in a background of strong interannual variability in many regions. The details of these causes and discrepancies are beyond the scope of this paper. The important point is that these two datasets, which have different sources of instrument and sampling biases, demonstrate a fairly common regional interdecadal variability in large portions of the ocean. These results confirm that there are coherent large-amplitude patterns of regional, subbasin-scale, interdecadal variability in SST found in all basins—as was found for the subsurface ocean (Harrison and Carson 2007). The strength of this variability is larger than the instrument bias and perhaps to some degree sampling differences, as the samplings at the surface and 50 m are different for all periods.

b. Effects of XBT bias correction

Trend comparisons of our standard-level data product to that same data modified by the Wijffels et al. (2008) XBTC are presented in Figs. 2 and 3. At 100 m (Fig. 2), the differences in regional interdecadal variability are very small and are often constrained to small regions where historical temperature sampling is sparse. The large-scale, large-amplitude patterns of trend magnitude are the same with most differences occurring in the weaker trends \( |\Delta T| < 0.1^\circ C \) (20 yr \(^{-1}\)) on the fringes of these patterns (e.g., the regions nearer the tropics, south of the PDO horseshoe pattern in the North Pacific, Figs. 2c and 2d; the regions northwest of Hawaii to the west coast of the United States in the earlier period, Figs. 2a and 2b; and the regions surrounding the large warming patch in the central midlatitude North Atlantic in the same early period, Figs. 2a and 2b). The differences between the two maps in the early period (1960–80; Figs. 2a and 2b) are due to the presence of many more XBT casts in the second half of this period than in the first; these XBT casts outnumber all other instruments’ observations during the 1970s in much of the central and eastern North Pacific and the North Atlantic northward of about 20°N (not shown). There are discrepancies in the tropical Indian Ocean for 1960–80 and 1970–90 (Figs. 2a–d), but the later period shows little difference (Figs. 2e and 2f). Overall, the bias correction does not have a large impact on the intensity or spatial patterns of the large-scale regional interdecadal variability. This holds true down to about 200 m (not shown). At 100 m, the proportion of ocean area where the two analyses’ trends agree in sign is higher than 90% of the total analysis area for all three periods and is approximately 97% for the 1980–2000 period.

Figure 3 shows the trend maps at 300 m for comparison. For the early period (Figs. 3a and 3b), the regions of strongest trend mostly agree. There is a difference northwest from Hawaii to the coast that was similar to that seen at 100 m, and the western subtropical to midlatitude North Atlantic is not as strongly warming in the XBTC data. Note that there is a tendency in this period for the bias-corrected data to yield less warming in trends relative to the uncorrected SL data; about 83% of the uncorrected data trends are warmer.

Over the middle period (1970–90; Figs. 3c and 3d), this tendency is reversed, and the bias-corrected trends tend to indicate stronger warming (or weaker cooling, depending on the sign of the trends) than the uncorrected trends—about 90% of them. The large-amplitude trends still form much the same patterns in both datasets during this period, with the strong exception of the western North Pacific around 20°N. Regions of SL trends with absolute magnitude less than about 0.3°C (20 yr \(^{-1}\)) are more likely to be of opposite trend sign after applying the bias correction. The cooling around Australia and north of New Zealand is weaker in the XBTC trends, and there are small-amplitude trends changing sign in

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this broad region when the bias correction is applied. The tropical Indian Ocean has weak trends, but the XBTC and SL datasets disagree during this and the previous period (Figs. 3a–d).

For the later period (1980–2000; Figs. 3e and 3f), trend maps for the two data treatments are much more similar in their large-scale patterns and magnitudes than are the earlier period trends (Figs. 3a–d), which is also the result for 100 m (Figs. 2e and 2f). Some reasons that this period differs from the earlier two include the following: more of the ocean is better sampled throughout the later period, the 1970s (part of both earlier analysis periods) had the largest XBT depth correction values, and the 1980s and 1990s have the most consistent spatial densities of XBT versus other instrument observations of these three periods. Different correction methods could make a small difference for this period as suggested recently by Palmer et al. (2010), who indicated that the global temperature
anomalies from different bias-corrected analyses vary the most after 1990 (cf. Fig. 4 in Palmer et al. 2010). However, the Wijffels et al. 2008 correction, which is applied in this paper, varies more from the uncorrected analysis than corrections from Levitus et al. (2009) or Ishii and Kimoto (2009). The proportion of ocean area where the trends agree in sign is between 81% and 85% of the total analysis area for the early periods, and is approximately 93% for the 1980–2000 period.

Figure 4 displays the trend difference maps of the SL trends minus the XBTC trends at 100 m on the left (panels a, c, and e) and 300 m on the right (panels b, d, and f). These maps show the difference of the trend maps in Fig. 2 for 100 m, and Fig. 3 for 300 m, for the three 20-yr periods. It is clear that the SL trends are nearly globally warmer than the XBTC trends for 1960–80, and nearly globally cooler for 1970–90. The trend differences are small relative to most of the 100-m trends but are substantial relative to all but the larger 300-m trends. Most of the differences are locally smaller than 0.25°C (20 yr)−1, and many are smaller than 0.1°C (20 yr)−1.

Averaged over latitude bands (tropical, northern, and southern) for each ocean basin, the averages are less than 0.25°C (20 yr)−1 in all cases, and less than 0.1°C...
(20 yr)$^{-1}$ in 75% of all combinations of latitude bands and 20-yr periods. The net effect for the global averages of the small XBT depth correction is a significant change of the globally averaged 20-yr trend, but the regional effect of the correction is mostly unimportant.

Levitus et al. (2009) reported that the Wijffels et al. (2008) bias correction might still contain some significant unresolved discrepancies between XBT and CTD/bottle data, which vary decadally. Overlapping 20-yr trends calculated on both the Levitus et al. (2009) and Ishii and Kimoto (2009) corrected datasets still show strong regional interdecadal variability for the same periods presented here, with similar spatial patterns of warming and cooling (not shown). The global long-term trend is much more sensitive to the bias correction and differences in the correction method than the larger 20-yr trends in well-measured regions.

For the longer 50-yr trend from 1955 to 2004, the trend differences are much smaller at each depth level (not shown), though the regional trend magnitudes are still significantly greater than the 20-yr period trends.
large and similar to those in Carson and Harrison (2008, their Fig. 3c). This is due to the interdecadal nature of the bias correction (for details, see Wijffels et al. 2008).

4. Conclusions

We have shown that regional interdecadal variability is still very much a feature of the historical temperature record after applying a typical bias correction, and there is little change in the strength and spatial patterns of the large-scale, large-amplitude interdecadal trend variability. Thus, the regional situation is qualitatively different than that for the global-ocean average, where recent estimates of global ocean heat content, based on XBT bias-corrected data, show significantly reduced interdecadal variability. Also, we demonstrated that there are large areas of ocean that have a coherent decadal signal between the surface and the upper subsurface ocean, despite depending on largely different surface and subsurface data sources with different data characteristics. Thus, regional interdecadal variability is a robust signal in ocean temperature records that is stronger than these sources of bias.

It has been shown in multiple studies that there is strong evidence of some bias between XBTs and most of the other instrumentation used in constructing global ocean subsurface temperature records, and the new estimates of global ocean heat content with an applied bias-correction are important results. There is no consensus yet on a best-possible XBT bias correction, and research is still continuing that may provide improved correction methods. However, none of the corrections published so far have shown much of an effect on the stronger regional 20-yr trends presented here, although most of them have a substantial impact on estimates of global variability on such time scales.

As has been noted previously, introducing corrections for XBT bias in subsurface temperature data leads to less interdecadal variability in the estimates of the globally averaged upper-ocean heat content (e.g., Domingues et al. 2008, their Fig. 1; Ishii and Kimoto 2009, their Fig. 6). This leads to the historical record more closely resembling the upper-ocean heat content results from the coupled models used in the recent Intergovernmental Panel on Climate Change’s Fourth Assessment Report (Bindoff et al. 2007). In our previous work on upper-ocean temperature trend estimation (Harrison and Carson 2007, 2008), we have illustrated how sparse and irregular the sampling of the ocean has been, even since 1970. The consequences of the sampling gaps in the historical record are not affected by bias correction. We suggest that it is not clear that the existence of significant interdecadal variability in globally averaged upper-ocean heat content should be ruled out, particularly as such variability is suggested in long records of sea level from tide gauges (Douglas 1992; Church and White 2006; Jevrejeva et al. 2008). Only if routine accurate observation of the World Ocean, as is now being done by the Argo profiling float program and precision altimetry satellites, is sustained through the coming decades will the true characteristics of low-frequency temperature variability be known.

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