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ABSTRACT

Subsurface temperature trends in the better-sampled parts of the World Ocean are reported. Where there are sufficient observations for this analysis, there is large spatial variability of 51-yr trends in the upper ocean, with some regions showing cooling in excess of 3°C, and others warming of similar magnitude. Some 95% of the ocean area analyzed has both cooled and warmed over 20-yr subsets of this period. There is much space and time variability of 20-yr running trend estimates, indicating that trends over a decade or two may not be representative of longer-term trends. Results are based on sorting individual observations in World Ocean Database 2001 into 1° x 1° and 2° x 2° bins. Only bins with at least five observations per decade for four of the five decades since 1950 are used. Much of the World Ocean cannot be examined from this perspective. The 51-yr trends significant at the 90% level are given particular attention. Results are presented for depths of 100, 300, and 500 m. The patterns of the 90% significant trends are spatially coherent on scales resolved by the bin size. The vertical structure of the trends is coherent in some regions, but changes sign between the analysis depths in a number of others. It is suggested that additional attention should be given to uncertainty estimates for basin average and World Ocean average thermal trends.

1. Introduction

There is much interest in subsurface oceanic variability in the climate change and climate research communities. Estimates of basin average and World Ocean average trends and variability of ocean temperature and ocean heat content published prior to the Third Assessment Report of the Intergovernmental Panel on Climate Change received considerable attention (e.g., Levitus et al. 2000, 2001; Barnett et al. 2001). Other studies have appeared since then looking at basin and World Ocean average trends as well as more regional variability and shorter-term trends [e.g., Levitus et al. (2005) and Willis et al. (2004), respectively]. Regional trend variability has been noted previously (e.g., Parilla et al. 1994; Deser et al. 1996) but has never been discussed from a global perspective. The global-scale studies typically have involved removing a climatological ocean temperature field, followed by different amounts of interpolation, extrapolation, and averaging, or have otherwise depended on some analyzed field (e.g., a climatology). The consequences of these various manipulations of the observations have not received much attention within the ocean community, but aliasing of smaller-scale variability (whether space or time variability) into larger-scale variability merits scrutiny in any analysis that does not resolve the scales of the variability. We present results that involve very little manipulation of the data and do not depend upon an analyzed field. We seek to explore the scales of multidecadal trend variability, within the limitations of the data.

Levitus et al. (2000) first reported oceanic warming on a global scale that corresponded to a net 0.06°C increase by volume down to a depth of 3000 m over a 42-yr period (1955–96). This was later reduced slightly in the light of more data to a mean temperature increase of 0.037°C over the same depth range over a
49-yr period [1955–2003; Levitus et al. (2005)]. In both cases Levitus used the ocean temperature climatology calculated from the data in the World Ocean Database 2001 (WOD01; Conkright et al. 2002) and reported in the World Ocean Atlas 2001 (WOA01; Stephens et al. 2002) to derive a gridded global temperature anomaly field, which was then used to estimate the trend in ocean heat content. Other authors such as Willis et al. (2004) have also used the WOA01 as either a means to calculate temperature anomalies directly or as a first guess in objective mapping techniques.

Because the historical ocean subsurface dataset is quite sparse over much of the World Ocean (see section 2), we thought it worthwhile to look at subsurface thermal variability from a perspective that minimizes manipulations of the data themselves and also focuses on those depths and areas where statistically significant trends can be identified with minimum smoothing or averaging. We report our results here and compare them with the results from previous analyses.

Working within our analysis framework we are able to reproduce some of the regional results of Levitus et al. (1994, 2000) and those of Parilla et al. (1994) and Lysne and Deser (2002). Our analysis is able to shed light on the space and time scales and amplitude of multidecadal trends over less of the World Ocean than we had hoped, for in many regions there are not sufficient data to carry through our calculations. Our results raise a number of questions about the uncertainty that should be assigned at present to basin-scale integral ocean thermal quantities, whether zonal averages, basin averages, or averages over the World Ocean. They also indicate that it is unwise to attempt to infer long-term averages, or averages over the World Ocean. They also indicate that it is unwise to attempt to infer long-term trends based on data from only one or two decades. Additional exploration of the uncertainty of present estimates is needed.

In section 2 we describe the dataset and analysis procedures adopted here. Section 3 presents results for temperature trends over the period 1950–2000 and for trends over 20-yr subsets of this period. We discuss these results in section 4.

2. Data and methods

The dataset used was the WOD01 (see Conkright et al. 2002). A key challenge to working with this dataset is the sparse data distribution over much of the World Ocean. Figure 1 shows the total number of temperature observations (profiles) in 1° × 1° bins as reported in the WOA01 at several depths between 100 and 2000 m. Bins with fewer than 10 observations are shown as blank. The main shipping lanes are quite visible in Fig. 1; with the exception of coastal waters, it is along these lanes that the upper ocean is best sampled. Even at 100 m, large areas of the Southern Hemisphere ocean have fewer than 25 observations per bin, but broad regions of the North Atlantic and Pacific are sampled at 50–100 observations per bin. At 300 m the shipping lanes are sampled much the same, but there is less sampling off the main routes. By 500 m most of the ocean is sampled at less than 25 observations per bin. At depths greater than 600 m the data distribution becomes very sparse.

Counting observations over 2° × 2° bins leads to a substantial increase in numbers of observations per bin. Figure 2 follows the format of Fig. 1, but for 2° × 2° bins. At 100 and 300 m the North Atlantic and most of the North Pacific and North Indian Oceans have >150 observations per bin, but sampling deteriorates sharply as one moves southward across the equator and into the Southern Hemisphere. Ship tracks provide most of the observations in the latter regions at 500 and 600 m. By 1000 m, sampling has become limited even in the Northern Hemisphere.

It was found that the odds of obtaining a statistically significant trend in any particular qualified bin reach 50% only when there are approximately more than 100–150 observations within either a 1° × 1° bin or a 2° × 2° bin, which corresponds to bins colored pale blue (or warmer colors) in Figs. 1 and 2.

The standard deviations of temperature, to the extent that they can be determined satisfactorily from the dataset, provide important context for some of the sampling challenges faced in the identification of signals within a variable ocean. Figure 3 presents the standard deviations as reported in the WOA01; these include the seasonal cycle. It is useful to compare these with the sea surface height variability results from satellite altimetry (e.g., Wunsch and Stammer 1998, their Fig. 8a, which is included herein as Fig. 4 for comparison). Because much of the oceanic mesoscale has substantial energy in the barotropic and first vertical baroclinic mode, it is reasonable to expect at least rough correspondence between the temperature variance and the sea level height anomaly variance. The 100-m standard deviations (where the seasonal cycle is felt strongly in some regions) show broad agreement with Fig. 4, but reveal many differences in the more poorly sampled parts of the World Ocean and particularly in the energetic regions of the Southern Ocean. The 500-m standard deviations also are similar to their results in the western North Atlantic and North Pacific, and off the southeast coast of Australia, but can be quite different elsewhere. Overall, it appears that the broad range of standard deviations shown in Fig. 3 is reasonable, with regional values in excess of 3°C, in active boundary current and mesoscale eddy regions and in the interannually vary-
ing Tropics, and with minimum values around 0.5°C in the quieter parts of the ocean. Values south of about 30°S and in the more sparsely sampled regions of the rest of the ocean may not be well estimated.

Quality control of this dataset poses all of the familiar ocean dataset challenges. There are unflagged extreme outliers (above 30°C and below -2°C at 100, 300, 500 m) in WOD01 that are simple to exclude; about 5% of the 1° × 1° regions in our subsequent analysis contained such outliers. Standard deviations were recom-
puted after removing the extreme outliers and the observations were then filtered against both a three and four standard deviation criterion. Our analysis conclusions remain the same with both editing criteria, and all planview maps in the figures were made with the four-sigma-filtered data.

Those bins that contained at least 10 (and subsequently 5) observations in each of at least four of the five decades since 1950 were chosen for analysis. Estimates of linear trends over the period 1950–2000 were computed and found to be spatially variable and quite noisy. We were able to obtain plausible trend results from this subset of WOD01 and these results are presented here. In an attempt to clarify the spatial extent

**Fig. 2.** As in Fig. 1 but only for $2^\circ \times 2^\circ$ regions. The Northern Hemisphere ocean is more successfully sampled at this resolution, but the Southern Hemisphere ocean remains much less well sampled.
of the interdecadal variability, overlapping 20-yr trends were calculated and plotted for these same bins. Analysis was first attempted on 1° × 1° regions, in which the data are averaged together into daily averages and monthly averages, and later analyses were performed on 2° × 2° and 5° × 5° regions. The analysis of 2° × 2° regions was much better than 1° × 1° in coverage, so that analysis is the focus of much of the discussion.

Discouragingly few bins satisfied the 10 per decade for four or more decades threshold. There are substantially more bins using the weaker five per decade for four or more decades threshold, but even at this criterion nearly 70% of the ocean at 100 m, 85% at 300 m, and over 90% at 500 m are not adequately sampled when 1° × 1° bins are used (see Fig. 1). Better coverage is obtained using 2° × 2° bins, but even with these, global coverage is not achieved. Although the results from the 5-observation threshold are noisier than for the 10-observation threshold, the average variances in the trend magnitudes are greater for the 5-observation threshold due to basing the trend lines on fewer points in many of the bins, the broad patterns are similar, and the figures are much easier to look at; these results are presented here. Use of a weaker threshold did not add usefully to the results described here, because the trends over the additional regions were so noisy.

We present results only for nominal 100-, 300-, and 500-m depths. To create the analysis data record for each depth and region, data within a few meters of the nominal depth were included, since few observations fell exactly on the nominal depth. For nominal depth 100 m the acceptable range was ±5 m; at 300 m it was ±20 m and for 500 m it was ±20 m. The observations falling within these ranges were simply aggregated into the analysis records. It is noted that these criteria are substantially tighter than in previous analyses of the WOD01, but to use larger ranges was to enter into a variety of decisions about how to make adjustments for the relevant vertical temperature gradient. We did not make any such adjustments, because our method is to make the minimum number of data processing assumptions.

Because thermal profile data in WOD01 have been collected by several instrument types, another issue is the XBT fall-rate correction (see, e.g., Hanawa et al. 1995). Hanawa et al. suggested an approximate depth correction for the three major models of XBT (Sippican and TSK T-4/6/7s) using \( z_1 = 1.0336z \), where \( z_1 \) is the modified depth and \( z \) is the depth recorded in a dataset of unmodified measurements. This amounts to a 3.36% depth error. However, the only systematic problem with regard to XBT data in this analysis is that mechanical bathythermograph (MBT) data precede most of the XBT data. Since MBTs were mostly usable short of 300 m, this would only impact the 100-m results. But the trend magnitude at 100 m due to this effect is small enough that it would not be statistically significant—at most only about 0.1°C in most of the analysis regions.

The resulting analysis records exhibit a wide range of characteristics. Figure 5 provides examples. Figure 5a provides examples. Figure 5a from the middle-latitude western North Atlantic at 100 m is typical of the very best sampled 1° × 1° regions.
First note the very considerable range of temperature values—between 2° and 14°C; the standard deviation is large enough in this Gulf Stream region to make it difficult to see the multidecadal trends. It exhibits low-frequency variability on a number of time scales with some decades trending cooler and others trending warmer. The magnitude of the temperature change over some of the 20-yr periods is comparable to those over the full 51-yr period, even though the 20-yr periods were not selected to maximize their temperature changes. Figure 5b presents the 51-yr trend line in green and 20-yr trend lines over 1955–75, 1970–90, and 1980–2000 in other colors. The warmest temperatures in the one Gulf Stream region (Fig. 5a) were observed between 1975 and 1982.

Seldom are regions as well sampled as this. Figures 5c, 5d, and 5e present records with more typical data distributions. As in Figs. 5a and 5b, the 51-yr and 20-yr trends are shown, and as in Fig. 5b the temperature changes over a 20-yr period can be as large as or larger than the changes over the full 51-yr period. Interdecadal variability is pervasive and strong in these analysis records.

These trends are simple linear least square fits to the data. Cosine tapering of the data was applied to the data occurring in the first and last 10% of the time period, but this had no significant effect on the large-scale patterns, so all of the following results did not have that analysis applied to them. The trends are not sensitive to whether they are computed from daily or monthly averages of observations within the analysis records. Finally, it was determined which of the trends are statistically different from zero at the 90% level using a t test. With the number of data points (either daily or monthly averages) as N, the squared correlation coefficient as $r^2$, and $t_{90}$ as the two-tailed t statistic for $N - 1$ degrees of freedom, boxes pass the 90% CL if

$$r^2 > \frac{t_{90}^2}{t_{90}^2 + (N - 2)}.$$ 

Note that every data point has been assigned one degree of freedom. This assumption was made because of the difficulty in getting useful time autocorrelation statistics for most of the regions. If autocorrelation could be adequately estimated, adjustment would involve reducing the number of degrees of freedom in most regions, and fewer trends would be statistically significant at the 90% level.

3. Results

a. 51-yr trends

In this section temperature trends over the 51-yr analysis period are reported. These are presented as
Fig. 5. Time series of some individual 1° × 1° boxes at (a) 42°N, 66°W, 100 m; (b) trend lines for 42°N, 66°W, on same scale as other graphs; (c) 51°N, 131°W, 100 m; (d) 40°N, 155°W, 100 m; and (e) 23°N, 156°W, 500 m. Trend lines are fitted only by data within the periods they cover.
maps of the change in temperature over the 51-yr period, based on the end points of the fitted trend line. Figure 6 presents the $1^\circ \times 1^\circ$ results for temperature trends at depths of 100, 300, and 500 m. The $1^\circ \times 1^\circ$ bins meeting the data distribution requirement and with trends that are 90% statistically significant are shown in color in the left-hand panels (Figs. 6a–c). The panels on the right-hand side (Figs. 6d–f) show the trends estimated at every bin that met the data distribution requirement. Figure 7 presents the results of similar calculations but based on $2^\circ \times 2^\circ$ bins. Note that there is a band of boxes at the equator that has no boxes matching the data distribution requirement. These boxes, either $0^\circ$–$1^\circ$S or $0^\circ$–$2^\circ$S depending on
which domain, actually have fewer measurements recorded there within WOD01, especially prior to the 1980s.

Perhaps the most striking result from Figs. 6 and 7 is the extent of the existence of subbasin-scale trend patterns of alternating sign; significant parts of the ocean were warming and others cooling over this 51-yr period, with amplitude of $\pm 2^\circ C$. [Recall that the World Ocean average warming value from Levitus et al. (2005) is 0.0372$^\circ C$.] At all depths presented the larger-scale patterns are more easily seen in Fig. 7 than in Fig. 6.

At 100 m the North Atlantic shows perhaps the most zonally uniform behavior, with statistically significant warming extending across the basin between about 15$^\circ$ and about 50$^\circ$N. Farther north there is mostly cooling across the basin; farther south the patterns are noisier
with patches of warming and cooling. The North Pacific exhibits a broad band of warming from the coast out into the open sea all along the Americas; it is strongest and clearest between Baja California and southern Alaska. The central North Pacific exhibits equally strong cooling, particularly between about 20° and 50°N, which transitions to a less well defined band of warming between about 10° and 20°N. The Tropics are broadly cooling apart from the warming in the east noted above. There are spatially complex patterns of warming and cooling along the far western parts of the North Pacific, beginning with cooling in the southern Bering Sea then warming off the Kamchatka Peninsula and warming and cooling regions from Korea down to the Philippines. The main Indian Ocean trend feature is cooling roughly between 10°S and the equator; elsewhere, there are only scattered small areas of warming and cooling. The Mediterranean exhibits cooling over its eastern half and both warming and cooling over its western half.

At 300 m much less of the ocean exhibits statistically significant trends. The Mediterranean has cooling across its area and there is also cooling offshore of the Strait of Gibraltar. The western North Atlantic is again warming, now with clearly greater amplitude between about 30° and about 45°N than farther south; farther north the overall tendency appears to be cooling but there are patches of warming. In the North Pacific the great band of warming outward from the west coast of the Americas that is so prominent at 100 m is no longer present; in the Gulf of Alaska there is a tendency toward weak warming, but this changes to a band of cooling off of the western United States. The great central North Pacific region of cooling at 100 m is more weakly expressed at 300 m and is clearest only between 25° and 40°N and between 170° and 125°W. The strongest and broadest signal at 300 m is a band of warming between about 25° and 32°N and between the date line and about 130°E. The tropical Pacific has no statistically significant trends along the equator, but there is a band of cooling extending south and east of New Guinea roughly to the date line. There are only scattered areas of signal in the Indian Ocean, with patches of warming and cooling.

At 500 m there are only a few broad-scale patterns. The Gulf Stream and its recirculation region continue to exhibit warming but to the east, and generally to the north, the North Atlantic shows cooling. There is generally cooling in the northern Caribbean and warming in the Gulf of Mexico. In the North Pacific there is a broad but poorly defined arc of warming extending from the Gulf of Alaska across the southern Bering Sea and down across the Yellow Sea. South of this band is an even less well-defined band of cooling. There is a poorly defined region of cooling slightly south of the 300-m cooling region southeast of New Guinea. Elsewhere, there are only limited regions or small spots of warming and cooling around the World Ocean.

The analysis bins are small enough to resolve the spatial scales of the regions of warming and cooling. While there is considerable noise in the trend results prior to filtering for statistical significance, use of the 90% significance filter reduces the spatial noise in most regions.

The cooling in the western equatorial Pacific and warming in the eastern equatorial Pacific around 100 m appears to partially reproduce the results of the EOF analysis on the ocean heat content in Stephens et al. (2001). They suggest that this pattern may result from the equatorial thermocline tilt lessening due to the long-term weakening of easterly trade winds (e.g., Harrison 1989; Clarke and Lebedev 1997). The cause of significant cooling in the north equatorial region of the Pacific around 160°W may deserve further attention.

Insofar as the reader’s interest is in the estimation of 51-yr-long basin and World Ocean trends of upper-ocean temperature, these are the core results of our analysis. They show trends consistent in sign from bin to adjacent bins even though no spatial smoothing operations have been performed on the bin results themselves. There is substantial spatial structure in these patterns, both horizontally and vertically, in many areas and the trend amplitude of the patterns typically is nearly 100 times that of the global average trend estimate of Levitus et al. (2005). These analyses were repeated by removing the WOA01 climatology with no significant changes in these overall results, although generally the trends are smaller in magnitude, especially at 100 m.

b. Overlapping 20-yr trends

Because there is so much spatial structure to the 51-yr trends discussed above, and because the North Pacific trend pattern so much resembles the familiar Pacific decadal oscillation surface EOF pattern, estimates were made of the low-frequency trend variability. The low-frequency variability has been computed as running 20-yr trends, shifting midpoint year 5 yr at a time. Thus, the midpoint years are 1965, 1970, 1975, 1980, 1985, and 1990.

The results for 100 m in the 2° domain are presented in Fig. 8. No additional statistical significance filtering for these trend results was done, in order to show patterns over as much of the ocean as possible. Although there are clear patterns of trends in the better-sampled areas of the ocean, these results exhibit much more
spatial noise than do the significant 51-yr trend results presented above.

Three features stand out from examination of Fig. 8. First is that almost every 2 × 2 region underwent 20-yr periods with warming and cooling trends (statistically, about 95% of the regions change the sign of their trend sometime throughout the 51-yr period). The ocean neither cooled nor warmed systematically over the large parts of the ocean for the entire analysis period. Second is that the amplitude of these 20-yr trends is of the same order as that of the 51-yr trends, and the patterns of warming and cooling change very substantially over this
51-yr period. Third, the 51-yr trend results are, in a number of regions, determined by changes that took place over a particular 20- or 25-yr subperiod. Further, 51-yr warming over a substantial oceanic region like the middle-latitude North Atlantic should not be assumed to indicate that there was relatively uniform warming over the region; different subregions of the North Atlantic warmed in different 20-yr periods sufficiently to produce the 51-yr trend result.

Results from 300 m (see Fig. 9) show similarly great variability in space and time. The comments made for Fig. 8 are equally relevant for Fig. 9. As found in the 51-yr trend results, there are also a number of regions in which the 20-yr trends change sign between 100 and 300 m. Examples of this are found east of the Mediterranean, along and offshore of the west coast of North, Central, and South America, and along the east coast of the Americas from Brazil to Cape Hatteras.
The richness of structures in space and time invites much more interpretation than we shall provide here. One important finding from these 20-yr results is that oceanic trends estimated over any particular 20-yr period are very unlikely to provide even a sign-consistent estimate of the trends over a 50-yr period. And because trends can be so large over a particular 20- or 25-yr period, even trends estimated over 50 yr may be dominated by much shorter term events that occurred within that 50-yr period. Evidently, oceanic regional trend estimates pose substantial sampling challenges and very long records are needed.

4. Discussion

The results presented here offer a new perspective on the space and time scales of multidecadal temperature trends in the relatively well observed subsurface upper ocean. With the data from WOD01 binned into $1^\circ \times 1^\circ$ or $2^\circ \times 2^\circ$ regions that have at least five observations per decade for at least four of the last five decades, we find there are highly structured patterns of 51-yr trends of alternating sign at 100-, 300-, and 500-m depth. Examination of only the results that are statistically significant at 90% produces pleasingly spatially coherent horizontal patterns of trend, which are often not of consistent sign among the three analysis depths. Each of the ocean basins exhibits both warming and cooling trends over this 51-yr analysis period in the areas that our analysis permits us to study.

Examination of trends over 20-yr subperiods, 1950–70, 1955–75, 1960–80, . . ., 1980–2000, reveals that 20-yr trend variability has the same amplitude and is even more spatially structured than the 51-yr trends. Further, 95% of the $2 \times 2$ regions studied here had both warming and cooling trends over these sequential 20-yr periods. It also reveals that the 51-yr trends are determined in a number of regions by large trends over 20–25-yr subperiods.

The North Pacific provides one very clear example. The variability of patterns of 20-yr trends in the North Pacific shares many characteristics of the variability of the familiar Pacific decadal oscillation (PDO) surface pattern. In the 51-yr trend at 100 m, the large-scale pattern in the North Pacific is similar to the positive phase of the PDO (see, e.g., Miller and Schneider 2000). Lysne and Deser (2002) also found this pattern using single value decomposition (SVD) analysis and showed a strong temperature minimum at 400 m between 1982 and 1990. Comparing the 51-yr trend map to the 20-yr rolling trends shows that this pattern evolved throughout two periods in the 20-yr trends, 1965–85 and 1970–90. This pattern was strong enough to dominate the entire 51-yr record.

The upper ocean evidently is replete with variability in space and time, and multidecadal variability is quite energetic almost everywhere our analysis method permits examination of the historical dataset. These results suggest that trends based on records of one or two decades in length are unlikely to represent accurately longer-term trends. Further, the magnitude of the 20-yr trend variability is great enough to call into question how well even the statistically significant 51-yr trends identified here represent longer-term trends.

The analysis approach outlined does not allow examination of the less well-sampled regions of the World Ocean. There are no results to offer for most of the ocean south of $20^\circ$S. Thus, it remains to be determined what the characteristics are of multidecadal trend variability in these areas. We have explored the feasibility of coarser-resolution analyses of the less-sampled (as well as the better sampled!) ocean, but the results are much less clear and convincing than those presented here and will be described elsewhere after further work.

The better we are able to work with the historical ocean dataset (thanks to modern dataset structures and interactive data analysis software), the more we find variability on interannual and longer time scales. The identification of long-term trends poses significant challenges.

This work provides further illustration of the need to observe the World Ocean systematically and for the foreseeable future. A plan for an initial sustained global ocean observing system has been developed and widely agreed upon (GCOS 2004). Progress in the implementation of some elements of this system (the Argo profiling float array in particular) has been achieved. However, national commitments to fully implement the agreed upon system and to continue systematic observation are lacking at present. Understanding the roles of the ocean in climate variability and change will not be possible unless the nations of the world sustain at least the agreed upon initial system.

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It is a pleasure to offer the work described here in this special issue for Carl Wunsch. Carl’s interest in the large-scale, low-frequency characteristics of the World
Ocean has been made clear in many of his efforts. His tireless efforts in support of the World Ocean Circulation Experiment and of the TOPEX/Poseidon satellite altimetry mission, his many years of work on ocean inverse methods, and his statistical studies of the challenges of identifying decadal-scale changes from relatively short records from red geophysical time series are examples of this interest. He has also always done the best he could to estimate the uncertainty in his efforts and has always been willing to buck the conventional wisdom when the data suggested that this was needed. We offer the results here in this same spirit.

REFERENCES


