PHC: A Global Ocean Hydrography with a High-Quality Arctic Ocean

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(Manuscript received 29 January 2000, in final form 30 August 2000)

ABSTRACT

A new gridded ocean climatology, the Polar Science Center Hydrographic Climatology (PHC), has been created that merges the 1998 version of the World Ocean Atlas with the new regional Arctic Ocean Atlas. The result is a global climatology for temperature and salinity that contains a good description of the Arctic Ocean and its environs. Monthly, seasonal, and annual average products have been generated. How the original datasets were prepared for merging, how the optimal interpolation procedure was performed, and characteristics of the resulting dataset are discussed, followed by a summary and discussion of future plans.

1. Introduction

Oceanographic data from the Arctic Ocean have until recently been quite sparse in space and time. This is because of the harsh conditions and frequently classified status of data taken in this region. Figure 1a shows the distribution of all historical surface temperature observations used in the 1998 version of the World Ocean Atlas (WOA98) published by the National Oceanographic Data Center (NODC; Antonov et al. 1998). Two periods are shown: March–May and July–September. The arctic seas clearly represent a data-poor region, although the situation is better in the summer than in the winter. Surface salinity observations are generally more sparse than the temperature observations shown in Fig. 1.

Luckily, previously classified data from Western and Russian sources have recently been made available by the Environmental Working Group (EWG 1997, 1998) in a gridded, interpolated format known as the Arctic Ocean Atlas (AOA). The AOA provides winter and summer data on temperature and salinity in the arctic seas. Figure 1b shows the distribution of surface temperature observations in this dataset over the time period 1950–89. Most observations were taken in the 1970s and 1980s, although significant data also exist for the 1950s and 1960s. The figure shows how the AOA is a regional dataset that “fills the gap” in the WOA98.

This paper describes how we merged the AOA and the WOA98 using optimal interpolation to provide a global hydrographic dataset with a high-quality Arctic Ocean that we call the Polar Science Center Hydrographic Climatology (PHC). The need for this product has recently become acute, as the role of the Arctic in global climate has become more clear (e.g., Aagaard and Carmack 1989; Rind et al. 1995; Thompson and Wallace 1998). As a result, the interaction between regional arctic modelers and more global-scale modelers has accelerated in recent years (e.g., Häkkinen 1999; Delworth et al. 1997). These modelers need a global gridded hydrography for initialization, validation, and in some cases, climate restoring (e.g., Zhang et al. 1998).

Our goal in this project was to provide an “updated WOA98” in order to make it simple for current WOA98 users to use the PHC. Thus in merging the WOA98 and AOA, we interpolated the latter onto the former’s grid configuration and set up the data files identically to those provided by NODC. Other steps in the interpolation procedure were also taken to ensure minimal change to the WOA98 outside of the arctic seas (section 3).

The following section describes how the two input datasets (AOA and WOA98) were modified to prepare them for merging, while the next sections describe our optimal interpolation procedure and the resulting fields. We close with a discussion of the remaining problems and issues to be addressed in future work.

2. Data preparation

a. WOA

The WOA98 climatology was produced by the NODC as a set of 3 CD-ROMs containing gridded, interpolated global fields. The first of these contains in situ temper-
Figure 1. The number of surface temperature observations north of 50°N used in (a) the WOA (Antonov et al. 1998) and (b) the AOA (EWG 1997; 1998). The 1997 and 1998 AOAs provide gridded, interpolated products for winter (Mar–May) and summer (Jul–Sep) averages; these definitions have also been used for the WOA data by summing WOA monthly standard level observation counts. WOA data are provided in 1° × 1° lat–long bins, and AOA observation counts are provided on a Cartesian grid with 200-km resolution in the Arctic Ocean and 50-km resolution in the Nordic Seas. Bins with no data have not been plotted.

Temperature and salinity fields (Antonov et al. 1998; Boyer et al. 1998), which we hereinafter refer to simply as WOA. The interpolation uses as input original data collected by various methods (e.g., bottles, expendable, and non-expendable profilers) and by a host of international programs (e.g., academic, governmental, and ship-of-opportunity). These are available from NODC on a separate series of CD-ROMs called the World Ocean Database 1998. To produce the gridded product, original data are first eliminated if they contain any of several documented errors, and then vertically interpolated to standard NODC depths (Table 1). The next step is horizontal interpolation on each of 33 depth levels using an objective analysis technique described in Antonov et al. (1998). A final two-dimensional smoothing is performed using running median and mean filters. The horizontal interpolation uses a “background field,” which is defined for the seasonal products by regional zonal averages of the climatological annual mean field. The final result is influenced most strongly by the background in data-poor regions (e.g., the Arctic Ocean).

WOA products include climatological gridded
Temperature and salinity on a 1 °C horizontal spacing 1° × 1° lat/long grid. Most of the arctic data used in creating the WOA were taken in the summer. This influences the annual means that are used to define the background field, with a resulting bias toward fresh and warm conditions in the data-poor seasons of autumn, winter, and spring. Figure 2a shows an example from the WOA for the mean surface salinity averaged over the months of March, April, and May. Regions of unrealistically fresh water can be seen extending toward the North Pole from the Siberian and North American coasts, a phenomenon that appears at all depths and in temperature as well as salinity. These anomalies are consistent with sparse high latitude data and an algorithm that prevents interpolation across the North Pole, such as one based on a Cartesian latitude/longitude grid.

To prepare the WOA data for merging, we discarded 1° × 1° latitude–longitude grid cells within a region shown in Fig. 3 that contained fewer than two original profiles. This region is roughly the domain of the AOA, minus the Nordic Seas and plus the Canadian and west Greenland sectors. Grid cells are left unchanged outside of this region in order to minimize the change relative to the WOA. Further justification of this partition will be provided in the following section. Temperature grid cells with below-freezing temperature values also were discarded. The resulting field for surface salinity averaged over March, April, and May is shown in Fig. 2b. This procedure was performed on all WOA fields used to create the PHC.

b. AOA

The AOA was created by the Environmental Working Group (EWG), a collaboration between Russian and Western scientists for the purpose of disseminating previously classified or otherwise unavailable data from the arctic regions. Two atlases have been produced to date (Table 1). The first (EWG 1997) provides winter average gridded hydrographic fields (potential temperature and salinity) but does not include the original profile data. Many of these profiles were collected on year-round Soviet drifting ice camps (the “North Pole stations”) and as part of an annual aircraft-based springtime survey (the “Sever” project). The earlier data derive mostly from bottle casts, while more recent data were obtained mostly by digital sensors. The second atlas (EWG 1998) provides summer averages and includes some original profile data, although only a small subset of the data used in creating the gridded fields. Some of these data were collected by American autonomous drifting buoys (Morison 1989).

The default horizontal interpolation method used in the AOA is called spectral objective analysis, or SA (EWG 1997) in which hydrographic fields are generated using a series of empirical basis functions. Further details are provided within the atlases. The AOA also provides alternate hydrographic fields that were generated using other interpolation methods, although our qualitative analysis indicated that these are inferior to the default. We thus use the fields generated by the SA method; Fig. 2c shows an example for winter surface salinity. Note the generally higher salinities relative to...
those predicted by the WOA and the absence of pole-centered anomalies. The Atlantic–Pacific front (e.g., Morison et al. 1998) is realistically portrayed within the Eurasian sector of the Arctic Ocean.

On the other hand, the AOA indicates an unrealistically weak exchange of Arctic and Atlantic waters in the wintertime Fram Strait region, that is, a near-collapse of the fresh East Greenland Current and a weakening of the salty West Spitsbergen Current. These exchanges are more realistically vigorous in the WOA, although this is due more to the influence of the summer-dominated background field rather than from superior wintertime data coverage in the WOA relative to the AOA (Fig. 1). In any case, this argues for retaining WOA data within the Nordic Seas, which became our course of action (section 3).
To prepare the AOA data for merging, we first had to convert AOA potential temperatures to the in situ temperatures provided by the WOA. To determine the best algorithm to use, we first identified a region (the Nordic Seas) with extensive coverage in both datasets. We found that a numerical inversion of the 25-term potential temperature polynomial provided by Caldwell and Eide (1980) gave a smaller root-mean-square difference than other schemes (e.g., Bryden 1973). We then linearly interpolated in the vertical to the 33 standard WOA depths (Table 1). Future work may explore the use of more sophisticated Lagrangian interpolation techniques. No further modifications to the AOA data were made before merging with the WOA seasonal products.

A partial mismatch exists in the seasonal definitions used by the WOA and the AOA (Table 1), which we address in section 4 below.

Discussions with various modeling centers indicated to us the need for a monthly product, which is provided by the WOA but not by the AOA. To create a monthly AOA product, we fit each point in the original AOA 50-km grid to analytical functions. For salinity $S$, the maximum annual value $S_w$ was taken from the winter climatology and was assumed to occur on 15 April and the minimum annual value $S_s$ was taken from the summer climatology and was assumed to occur on 15 August. The seasonal range is then defined as $\Delta S = S_w - S_s$, while the annual mean is defined as $S = (S_s + S_w)/2$. Similar assumptions were made for temperature, except that maximum values were set to summer and minimum to winter. The function for summer salinity $S_s$ applies for $\Delta t_s = 122$ days (i.e., 4 months) and is given by

$$S_s = \frac{\Delta S}{2} \cos(\pi t_s / \Delta t_s) + S,$$  \hspace{1cm} (1)

where $\Delta t_s = 122$ days (4 months) and is given by

$$S_s = \left[ \left( S_s - 1 \right) \frac{\Delta S}{2} \cos(\pi t_s / \Delta t_s) \right] + S_s,$$  \hspace{1cm} (2)

where the parameter $\phi$ depends on time during the winter $t_w$ according to

$$t_w = \frac{\Delta t_w [a\phi - (\Delta S/2) \sin(\phi)]/a \pi, (3)}{1 \over \pi}$$

and $t_w$ varies from day 0 on 15 August to day 243.25 on 14 April. This parametric solution is formally known as a curtate cycloid (Selby 1970) and has the desirable property of allowing a rapid autumn transition between summer and winter conditions. For example, at midwinter (15 December) a simple cosine function predicts that the salinity is 50% of the way between the summer minimum and the winter maximum. Observations (e.g., Morison and Smith 1981) and models (e.g., Hakkinen and Mellor 1990) indicate a more rapid transition, although the exact timing is variable in space and time and has been only rarely sampled. We thus tuned the free parameter $a$ in Eq. (3) so that on 15 December, every temperature and salinity point was already 70% of the way from its summer value toward its winter value. Functions $S_s$ and $S_w$ (and their analytical first derivatives) match at the seasonal tie points provided by the AOA climatologies. Similar functions were defined for temperature. Figure 4 shows an example from the North Pole monthly time series, where temperature
The background field was generated by zonal averaging of the combined inputs at 1° latitude intervals, followed by meridional 15° running median and then running mean parametric smoothers. A spatially varying correlation length scale and error variance were employed according to the scheme shown in Fig. 3. The length scales were chosen to minimize changes to the WOA data within the Nordic Seas and south of 65°N, while allowing for some smoothing within the data-sparse Canadian sector. Additional smoothing in the Fram Strait region was necessary to transition between the two datasets so that realistic Arctic–Atlantic exchanges could be reproduced, as discussed in section 2b.

The error variance of original oceanographic observations depends in general on instrument error and on unobserved variability arising from small-scale phenomena such as eddies, waves, and fronts. Here our inputs (WOA and AOA) are two previously interpolated fields with their own internal length scales and interpolation errors. Thus we view our input error variances mostly as tuning parameters used to give more or less weight to one or the other of the input fields. At each WOA depth, we first determine the variance of the combined total (WOA plus AOA) field over all latitudes and longitudes: \( \sigma^2_{\text{tot}} \). Within the Arctic region shown in Fig. 3, the error variance of the WOA field is then fixed at 0.5\( \sigma^2_{\text{tot}} \), while that of the AOA field is smaller by a factor of 5000, that is, 0.0001\( \sigma^2_{\text{tot}} \). For a simple case in which the interpolation takes as input one AOA observation and one WOA observation, both equidistant from a PHC grid point, these errors imply that AOA data are weighted 50% more than WOA data. Outside of the Arctic region shown in Fig. 3, the error variances are opposite to those inside the region. Careful analysis revealed no discontinuities in the resulting fields across this boundary.

Numerical efficiency is accelerated by introducing another parameter, which limits the number of observations considered in defining the estimated field at each grid point. Here we have used a value of 20 points except in the Fram Strait transition zone, where the value is 100 points to allow for smoothing across the zone. In addition, the search is limited within a radius of influence of 1000 km (which in data-sparse regions reduces the number of input points below 20) to minimize contamination by nearby ocean basins with distinctive characteristics. (The WOA algorithm treats this problem by defining several dozen ocean basins within which input data searches are confined.) Last, an a posteriori check is made on the estimated field for subfreezing temperature values that arise occasionally in data-sparse regions; these are set back to freezing. A summary of the input data and algorithm parameters is provided in Table 2.

4. Results

The summer season is defined by the same three months (July, August, and September) in both the WOA
and the AOA gridded, interpolated fields (Tables 1 and 2). However, WOA winter is defined as January, February, and March, while AOA winter is defined for the gridded, interpolated fields as March, April, and May. We followed the AOA seasonal definitions in creating the seasonal PHC fields. For the PHC winter season, this entailed creating a new WOA field using the monthly mean fields from March, April, and May. Monthly PHC fields were generated using monthly WOA fields and synthetic monthly AOA fields as described in section 2. Annual mean PHC fields were created by averaging the PHC monthly fields.

An example for winter (March, April, May) surface salinity is shown in Fig. 2d. Broadly speaking, the result looks like the AOA within the Arctic region defined in Fig. 3 and like the WOA outside of this region. Anomalies found in the WOA Arctic Ocean have been eliminated in the PHC. The absence of an East Greenland Current in the AOA winter surface salinity field has been corrected, and the salinity signature of the West Spitsbergen Current is also stronger.

Differences between the WOA and the PHC are explicitly shown in Fig. 5a for winter surface temperature. Figure 5b shows a histogram of the areal-mean standard deviation of these differences north of 65°N. For as salinity (Fig. 2), large differences are observed in the Arctic regions, mostly indicating a warm bias in the WOA (which is dominated by summer observations) relative to the AOA. Note substantial differences between the PHC and the AOA in the Canadian sector, which result in part from unrealistically warm waters in the WOA Hudson Bay that are retained (and through the OI procedure extend their influence) in the PHC solution. Winter waters in the Canadian sector are perhaps the most poorly sampled of all Arctic regions, at least in regard to international databases. Last, note that the additional smoothing imposed on WOA fields in creating the PHC is very small, generally less than 0.02 in both temperature and salinity units.

PHC fields demonstrate the key role of the Arctic seas within the global ocean. For example, Fig. 2d shows the convergence within the Arctic Ocean and the Canadian Archipelago of relatively salty North Atlantic waters with relatively fresh North Pacific waters. The latter have experienced additional freshening as they transit northward through Bering Strait and mix with especially low salinity waters of riverine origins (e.g., Aagaard and Carmack 1989). Together with the corresponding fields for summer salinity and for temperature (not shown), these data may be used for studying the global freshwater cycle and thermal budgets, among other topics. Thus the PHC allows the first-ever "big picture" view of the warm and salty North Atlantic, the cool and fresh North Pacific, and the cold and even fresher Arctic Ocean regimes, all within a global climatology.

5. Summary and discussion

We have produced monthly, seasonal, and annual mean climatological hydrographic (i.e., temperature and salinity) fields that include a high-quality Arctic Ocean and its environs. The data are provided on an Internet Web site in the same format as the gridded products in WOA98, that is, global 1° × 1° latitude–longitude fields on 33 depth levels in ASCII format. Also provided is
a FORTRAN program that fills the default land mask with interpolated values for use with models having higher spatial resolution than the WOA grid. These datasets should prove useful for climatological analyses as well as for numerical model initialization, climate restoring, and validation.

Near-term plans for updating the PHC include the analysis of error variance across both WOA and AOA datasets. Some data merging techniques may be revisited, such as the use of physical constraints. We recognize, however, that the "lifetime" of this dataset may be limited as Russian and other formerly classified data are publicly released, made available to the NODC, and incorporated into future versions of the WOA. In the meantime, we provide the PHC as a community service to climate researchers. At the time of writing, the data are available for downloading at an Internet Web site (http://psc.apl.washington.edu/Climatology.html), which also provides sample graphics and further explanation of our methods.

Acknowledgments. We thank M. Ortmeyer and A. Schweiger for their unfailing technical support. R. Colony, R. Lindsay, I. Rigor, and especially H. Stern provided insight into the workings of optimal interpolation, both theoretical and practical. Our understanding of the climatologies benefited from conversations with S. Levitus and T. Boyer (WOA) and J. Morison, G. Holloway, and A. Proshutinsky (AOA). We also sincerely appreciate the valuable feedback provided by current users of this dataset. This project was funded by the NASA program POLES (Polar Exchange at the Sea Surface), Grant NAG5-4375, and by the Office of Naval Research’s High Latitude Program, Grant N00014-99-1-0780.

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