Recent North Pacific Climatology for ATOC

Dimitris Menemenlis and Carl Wunsch

August 18, 2004

1 Introduction

As part of an ongoing effort to estimate oceanic climate and climate shift using Acoustic Thermometry of Ocean Climate (ATOC) [8, 12], a recent climatology of the North Pacific has been constructed. The primary motivation is the obtainment of a priori estimates of the mean and covariance of the sound speed field for comparison with results from the ATOC Engineering Test [5, 6].

The climatology was constructed using data from 922 high-resolution vertical temperature profiles obtained within the last ten years in a region bounded by 135°-245° longitude East and 5°-65° latitude North (Figure 1). The profiles retained are of known and consistent quality, and span the water column in regions where the ocean depth is greater than 1600 dbar. Temperature, which is of more immediate oceanographic interest, is used as a proxy for sound speed [9].

In this report, we describe the approach used to construct the climatology, and compare the results with the Levitus atlas [7] and with a 1/4°, 20-level integration of the Semtner and Chervin global-ocean circulation model [11].

2 Methodology

The approach is based on a form of empirical orthogonal functions (EOFs) obtained by singular value decomposition [2, 4]. Temperature profiles are first projected

	depth (dbar)	spacing (dbar)		depth (dbar)	spacing (dbar)
1	0		20	1750	
2	50		21	2000	
3	100		22	2250	
4	150	50	23	2500	
5	200		24	2750	
6	250		25	3000	
7	300		26	3250	250
8	400		27	3500	
9	500		28	3750	
10	600		29	4000	
11	700		30	4250	
12	800		31	4500	
13	900	100	32	4750	
14	1000		33	5000	
15	1100		34	5500	500
16	1200		35	6000	
17	1300				
18	1400				
19	1500				

Table 1: Standard depths used in the present analysis.

onto the 35 depths listed in Table 1 (unless otherwise noted, temperature is *in situ* and depth is reported in units of pressure). The first standard depth is assigned the shallowest measurement of each cast. The remaining samples are obtained by averaging the high-resolution profiles 20 dbar above and below each standard depth. The subsampled profiles are normalized by subtracting mean temperature and dividing by the standard deviation at each depth (Figure 2).

A matrix $\mathbf{A}$ is constructed so that each column corresponds to a particular hydrographic station, and each row to a standard depth. Standard depths below the bottom are padded with zeros to make all columns of identical length. By singular value decomposition, $\mathbf{A} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^{\mathrm{T}}$, where the columns of $\mathbf{U}$ and of $\mathbf{V}$ are the vertical and the horizontal EOFs of the hydrographic data set, respectively.

Each element of diagonal matrix $\mathbf{\Lambda}$ measures the contribution of each corresponding pair of EOFs to the standard deviation of $\mathbf{A}$ (Figure 3). Figure 4 displays eleven vertical EOFs which account for 98.6% of the variance of $\mathbf{A}$.

The climate signal is separated from measurement noise, due to mesoscale, seasonal and interannual variability, by objective analysis [3] of the horizontal EOF coefficients. The signal is assumed to have stationary and horizontally isotropic covariance of form

$$C_s(r) = s^2 \left[1 + \frac{r}{l} - \frac{1}{3} \left(\frac{r}{l} \right)^3 \right] \exp \left(\frac{-r}{l} \right), \tag{1}$$

where r is the horizontal spatial separation, s^2 is the signal variance, and l is a characteristic length scale. This particular form was chosen to represent $C_s(r)$ because the associated spectrum is everywhere positive, and because it provides a reasonable fit to the data.

The noise is modeled as white and horizontally homogeneous, $C_n(r) = n^2 \delta(r)$. Signal and noise are assumed uncorrelated so that the data covariance can be written $C_d(r) = C_s(r) + C_n(r)$. Figure 5 shows the *a priori* signal spectrum and objective analysis response functions for the foregoing assumptions. The spectrum vanishes at zero frequency, and is consistent with the fact that the measurements are normalized to have zero mean. The figure also shows that given sufficiently dense measurements, the objective analysis procedure is a lossy bandpass spatial filter whose bandwidth increases with increasing signal to noise ratio (SNR). For example if SNR=1, the passband extends from 4.3 l to 41 l.

Figure 6a displays estimates of $C_d(r)$ for the horizontal EOF coefficients of modes 1 through 11. Estimates of s^2 and l are obtained by least-squares fit of (1) to the data for $r > 0$ (Figures 6b and 6c). Note that in general, EOFs with the largest vertical scales are associated with the largest horizontal scales. The noise variance is estimated by making use of $n^2 = C_d(0) - s^2$ (Figure 6d). A marked decrease in signal to noise ratio and length scale occurs after mode 11; for this reason all higher modes will be treated as part of the noise in the present analysis. The implications of this choice is that only wavelengths longer than 1860 km are adequately resolved. Given the paucity of the measurements (Figure 1) and the assumption of a stationary homogeneous ocean, smaller scales must be treated as part of the noise, and it is not possible to resolve narrow jets and sharp fronts.

With the above *a priori* assumptions, the Gauss-Markov theorem can be used to obtain objective estimates,

$$\widehat{\mathbf{v}_x} = \mathbf{C}_{xy}\,\mathbf{C}_{yy}{}^{-1}\,\mathbf{v}_y, \tag{2}$$

at arbitrary locations denoted by subscript x; $\mathbf{v}_y$ is a vector of measured horizontal EOF coefficients, and $\mathbf{C}_{xy} = \langle \mathbf{v}_x \mathbf{v}_y{}^{\mathrm{T}} \rangle$, $\mathbf{C}_{yy} = \langle \mathbf{v}_y \mathbf{v}_y{}^{\mathrm{T}} \rangle$, are *a priori* covariance matrices. The uncertainty of this estimate is

$$\mathbf{P} = \langle (\mathbf{v}_x - \widehat{\mathbf{v}_x})^2 \rangle = \mathbf{C}_{xx} - \mathbf{C}_{xy}\,\mathbf{C}_{yy}{}^{-1}\,\mathbf{C}_{xy}{}^{\mathrm{T}}. \tag{3}$$

A consistency check of this procedure is provided by the comparison of *a priori* and *a posteriori* statistics (Figure 7). As required, the estimated covariance functions of the analysis (Figure 7a) are similar to those of the raw data (Figure 8a) but with reduced amplitude at $r = 0$. The estimated covariance functions of the residuals (Figure 8b) are also reasonably consistent with the *a priori* assumption of white noise. Examples of calculated fields and their associated uncertainty are shown in Figures 8 and 9, and are discussed in the next section.

3 Discussion

Results from the foregoing analysis can be used for comparison with ATOC-type integrated temperature measurements, and provide *a priori* estimates of oceanic climate for constraining general circulation models to consistency with tomographic and altimetric data sets [8]. In this spirit, we have undertaken to compare the present analysis with a four-year mean of the Semtner and Chervin model. We also compare our results with the Levitus atlas which was used to initialize the Semtner and Chervin model.

For convenience, the Semtner and Chervin model output and the Levitus climatology are projected onto the standard depths of Table 1 by linear interpolation. The comparison is done along two pseudosections. The first is a zonal section along 24° N (Figure 8), and corresponds more or less to World Ocean Circulation Experiment (WOCE) line P3. The second is a meridional section along 208° E (Figure 9), WOCE line P16. These sections were chosen because they are in data rich regions, they are representative of the area covered by the proposed ATOC array, and they are sufficiently removed from the intense variability associated with Western boundary currents.

Figure 10 shows the mean difference between the Semtner and Chervin model and the recent climatology along the two sections defined above. The Semtner and Chervin model outputs potential temperature, and the model output labeled "uncorrected" has been converted to *in situ* temperature as required. It is seen to be several tenths of a °C too warm at depth. The cause for this large discrepancy is that the Levitus analysis provides *in situ* temperature (Sydney Levitus, personal communication 1994), but the model was initialized from Levitus without prior conversion from *in situ* to potential temperature (Bert Semtner, personal communication 1994). For this reason, we compare the potential temperature of the model (labeled "corrected" in Figure 10) to the *in situ* climatological analyses.

The four-year, 1/4° integration of the Semtner and Chervin model considered here is an extension of a previous lower-resolution run [11] during which the temperature and salinity fields below the thermocline were being relaxed to Levitus. The deep restoring terms were removed at the beginning of the high-resolution integration, and Figures 8, 9 and 10 show that the model is now drifting away from Levitus at depth. The most striking feature is cooling by several hundredths of a °C below 4500 m. We attribute this cooling to convective adjustment in the model in response to the unstable initial density stratification which resulted from failure to convert *in situ* Levitus temperature to potential temperature.

From 4500 to 2000 dbar, the model mean is 0.01°C warmer than Levitus, and this difference gradually increases to 0.1°C at 1000 dbar. Even though the model was initialized with temperatures that are several tenths of a °C warmer than those of the ocean, it essentially reproduces initial conditions following a four-year integration without deep restoring terms. On the contrary, a weak warming trend is detected in the deep Northeastern Pacific. Above 1000 dbar, the model is markedly warmer than the climatological analyses, especially at mid-latitudes, 25 to 45° N (Figure 9f).

It is interesting to compare the Levitus climatology with the recent analysis. To the eye, both analyses produce substantially similar temperature profiles along the two sections (Figure 8a, 8b, 9a and 9b). The smoother contours of the present analysis can be attributed to the following reasons. Because of denser data coverage, the Levitus atlas [7] was constructed using an objective analysis response function with horizontal cutoff wavelength of 1400 as opposed to 1860 km. In addition, the Levitus analysis is two dimensional, *i.e.* each level is analyzed separately, as opposed to the inherently three-dimensional character of the EOF approach.

Below 1500 dbar, the Levitus climatology is on average too warm by 0.01°C (Figure 10). Levitus makes use of measurements obtained from the turn of the century up to and including the year 1978, while the recent analysis uses measurements taken after 1984. So it is conceivable that the observed difference is an indication of climate shift. However, there may be other explanations for the discrepancy, *e.g.* changes in the measuring technology, or idiosyncrasies of the analysis methods. For illustration, a 30 m measurement bias at 3000 m depth corresponds to a temperature error of 0.01°C, while the required pressure (in dbar) to depth (in m) correction is of order 40 m at mid-latitudes.

At 500 dbar, the recent climatology is warmer than Levitus by 0.1°C (Figure 10). If this difference is attributable to oceanic climate shift in the North Pacific, then the pattern of change would be markedly different from that reported by Parilla *et al.*[10] for the subtropical North Atlantic, where they observed a maximum warming of 1°C per century occurring at 1100 m depth.

From an acoustical point of view, a warming of 0.1°C at 500 dbar corresponds to a 0.4 m s^{-1} increase in soundspeed, or a 900 ms travel-time decrease over a 5 Mm path. The expected precision of the acoustical measurements is of order 10 ms [1], and is adequate for detecting this change. However, a conservative estimate of mesoscale noise at that depth based on the Semtner and Chervin model output is of order 0.1°C for 5 Mm paths [8]. Therefore, it is unlikely that the week-long ATOC engineering test would be able to discriminate between the two climatologies near the surface. Below 1600 dbar, the 5 Mm noise level in the model is of order 0.002°C. Assuming this value to be representative of the real ocean, then it is conceivable that the 0.01°C difference between the two climatologies can be acoustically detected at depth.

References

[1] A. Baggeroer and W. Munk. The Heard Island feasibility test. *Physics Today*, pages 22–30, Sept. 1992.

[2] N. L. Bindoff and C. Wunsch. Comparison of synoptic and climatologically mapped sections in the South Pacific Ocean. *J. Clim.*, 5(6):631–645, June 1992.

[3] F. P. Bretherton, R. E. Davis, and C. B. Fandry. A technique for objective analysis and design of oceanographic experiments applied to MODE-73. *Deep Sea Res.*, 23:559–582, 1976.

[4] I. Fukumori and C. Wunsch. Efficient representation of the North Atlantic hydrographic and chemical distributions. *Prog. Oceanogr.*, 27:111–195, 1991.

[5] B. Howe and P. Worcester. *ATOC Acoustic Engineering Test*, 20 September 1994.

[6] A. U. Kerr and W. E. Farrell. *ATOC Acoustic Engineering Test Data Management and Distribution Plan*, 4 November 1994.

[7] S. Levitus. Climatological atlas of the world ocean. Professional Paper 13, National Oceanic and Atmospheric Administration, 1982.

[8] D. Menemenlis and C. Wunsch. Ocean-climate estimation using ATOC. Technical Report 23, ATOC Occasional Notes, Dec. 1994.

[9] W. Munk and C. Wunsch. Ocean acoustic tomography: A scheme for large scale monitoring. *Deep Sea Res.*, 26A:123–161, 1979.

[10] G. Parrilla, A. Lavín, H. Bryden, M. García, and R. Millard. Rising temperatures in the subtropical North Atlantic Ocean over the past 35 years. *Nature*, 369:48–51, 5 May 1994.

[11] A. J. Semtner, Jr. and R. M. Chervin. Ocean general circulation from a global eddy-resolving model. *J. Geophys. Res.*, 97(C4):5493–5550, April 15, 1992.

[12] D. Stammer and C. Wunsch. Large scale modeling in the ATOC context. Technical Report 14, ATOC Occasional Notes, Sept. 1993.

Figure 1: Location of hydrographic stations used in the present analysis.

Figure 2: Mean and standard deviation of temperature profiles.

Figure 3: Normalized singular values and cumulative explained variance.

Figure 4: Vertical EOFs of modes 1 through 11.

Figure 5: Normalized autospectral density function associated with $C_s(r)$, and objective analysis response functions for the statistical assumptions detailed in the text. The response of the analysis depends on the *a priori* length scale l and signal to noise ratio SNR=s^2/n^2.

Figure 6: Estimation of *a priori* statistics. a) Normalized data autocovariance function, $C_d(r)$, for modes 1 through 11, assuming homogeneous and isotropic distribution of the horizontal EOF coefficients. The error bars represent $\pm 2\sigma$, and the solid lines are best fits for signal autocovariance function, $C_s(r)$, as discussed in the text. b) Normalized signal variance, s^2. c) Characteristic length scale of the signal, l. d) Signal to noise ratio, s^2/n^2.

Figure 7: Comparison of *a priori* (solid line) and *a posteriori* (error bars) statistics. a) Signal covariance. b) Noise covariance.

Figure 8: Zonal temperature pseudosections along 24° N. The sections are normalized by subtracting the mean and dividing by the standard deviation shown on Figure 2. a) Recent climatology using an 11-mode reconstruction. b) Levitus climatology. c) Semtner and Chervin model mean. d) Uncertainty of the reconstruction (square root of diagonal elements of $\mathbf{P}$). e) Difference between Levitus climatology and 11-mode reconstruction. f) Difference between Semtner and Chervin model mean and 11-mode reconstruction.

Figure 9: Meridional temperature pseudosections along 208° E (see legend of Figure 8 for details).

Figure 10: Comparison of mean temperature along the pseudosections of Figures 8 and 9. Difference relative to the 11-mode reconstruction is plotted for Levitus climatology and for Semtner and Chervin model output. The Semtner and Chervin model output is here corrected for erroneous initialization by subtracting the adiabatic temperature gradient.