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Estimating ocean climatologies for short periods: A simple technique for removing the effect of eddies from temperature and salinity profiles

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[1] Existing temperature and salinity ocean climatologies are usually mean fields based on observations collected over many decades. Because of low frequency variability of major features such as the Gulf Stream it is often more appropriate to define the mean for shorter periods, but there are subsequently fewer observations and more problems with aliasing of mesoscale variability. We present a method for removing eddy-related noise from observations using satellite altimeter sea surface height measurements. We demonstrate the technique using Argo observations from the northwest Atlantic and produce mean temperature and salinity fields for an eight year period. The reduction in variance achieved is quantified. Comparison with an existing climatology shows that there is good agreement between the two analyses but that the representation of the Gulf Stream is more realistic in the new climatology. **Citation:** Higginson, S., K. R. Thompson, and Y. Liu (2009), Estimating ocean climatologies for short periods: A simple technique for removing the effect of eddies from temperature and salinity profiles, *Geophys. Res. Lett.*, *36*, L19602, doi:10.1029/2009GL039647.

1. Introduction

[2] Temperature and salinity (TS) climatologies define the mean state of the ocean. They are also used, for example, to quality control data and to initialize and sometimes constrain ocean models. Vertical TS profiles have been measured for more than a century and, although non-uniform in their spatial and temporal coverage, they have been analyzed extensively to produce TS climatologies. This requires averaging and spatial smoothing of the sparse source data. Examples include the global $\frac{1}{4}°$ World Ocean Atlas 2001 climatology (WOA01) [*Boyer et al.*, 2005] and the North Atlantic climatology of *Lozier et al.* [1995]. However major ocean features can vary on timescales of years to decades (and longer) so it is sometimes more appropriate to define the mean for shorter, specific periods but this has not been feasible in the past because of data sparseness.

[3] The availability of TS data has increased significantly in recent years as a result of the Argo program. The network of drifting autonomous profilers presently measures 100,000 TS profiles each year compared with 20,000–30,000 profiles annually from all sources during the 1950s [*Boyer et al.*, 2006]. The increase in observation density offers the possibility of defining a mean using observations from a single decade or pentad. Problems with low frequency variability will be much less than in the multi-decadal dataset but aliasing of mesoscale variability remains an issue. This variability is reduced in conventional analyses by temporal averaging but for a shorter observation period such averaging is less effective.

[4] One way to deal with mesoscale variability is to average along potential density surfaces [*Lozier et al.*, 1995] and another is to assimilate data into an ocean model. Here we introduce a new technique for removing the mesoscale variability from TS profiles thereby reducing the noise whilst retaining valuable data. The standard error of the sample mean is given by $\sigma/\sqrt{n}$, where σ is the population standard deviation of a random sample of n independent observations, and so reducing the standard deviation of the observations by half is equivalent to increasing the sample size by a factor of four.

[5] The new scheme uses satellite altimeter measurements of sea surface height anomalies (η_a) to estimate isopycnal displacements and reduce the associated TS variability. It is based on the assimilation technique developed by *Cooper and Haines* [1996], requires no prior knowledge of the TS fields and averaging is across depth surfaces, as for the widely-used WOA01 climatology. We calculate the isopycnal displacement which would produce a steric height anomaly equal to η_a, and lift or depress the TS profile by an equal amount in the opposite direction. The method assumes vertical advection is the dominant process influencing the water properties locally, although this is not the case near the surface or in shallow water. This restricts application of the technique to below the mixed layer of the deep ocean. The method also will not work where the barotropic effect is dominant (e.g., high latitude regions, including those where TS changes are density compensating) but these are areas where there are fewer problems with existing climatologies.

[6] There are similarities between our approach and the methods developed by *Guinehut et al.* [2004] and *Willis et al.* [2003]. These authors also used remote sensing data to reduce the error in observations of the subsurface temperature field, but they used linear regression techniques whereas our scheme is based on dynamical balances.

[7] The structure of the paper is as follows. The data is introduced in Section 2 and our application of the method is described in Section 3. The effectiveness of the technique is described in Section 4 and its uses are discussed in Section 5.

2. Data

[8] To illustrate the method we consider the most eddy-rich region of the northwest Atlantic, 80°W–20°W 20°N–50°N (Figure 1, top).

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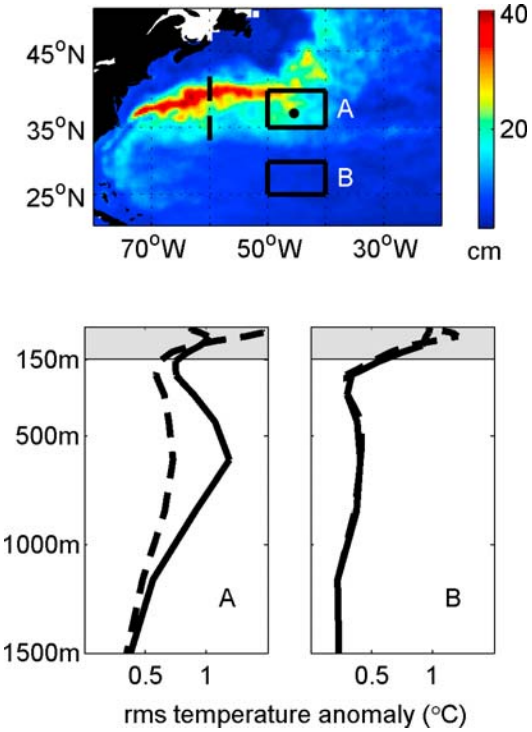

Figure 1. (top) Standard deviation (cm) of sea surface height variability for the period 1 January 2000 to 31 December 2007 using AVISO $\frac{1}{4}^\circ$ gridded altimeter data. The solid boxes show the subdomains used in Figure 1 (bottom), the filled circle indicates the location of data plotted in Figure 2, and the dashed line identifies the section plotted in Figure 3. (bottom) RMS temperature anomaly (°C) of Argo temperature relative to the WOA01 $\frac{1}{4}^\circ$ climatology [*Boyer et al.*, 2005], before (solid line) and after (dashed line) adjustment, plotted against depth for subdomains A and B. The shaded zone represents the surface mixed layer where processes other than vertical advection are believed to dominate.

2.1. Argo

[9] The Argo network comprises an array of approximately 3000 drifting profilers. Each measures a vertical TS profile of the upper ocean, to a maximum depth of 2000 m, every ten days [*Roemmich et al.*, 2000]. The first floats were launched in 2000 with full deployment by 2007. All profiles from the northwest Atlantic between 1 January 2000 and 31 December 2007 are examined, a total of more than 31,000 profiles. Floats affected by a pressure offset error identified by the Argo project team (details available at http://www-argo.ucsd.edu/Acpres_offset2.html) are excluded from this study.

2.2. Altimeter

[10] A continuous record of sea surface height variability is available from October 1992 to date based on altimeter measurements made by the Topex/Poseidon, ERS-1/2, Envisat and Jason-1 satellites. We use the "Reference Series Delayed-Time" maps of sea surface height anomaly distributed by AVISO with a grid spacing of $\frac{1}{4}^\circ$ and a time interval of 1 week [*Ducet et al.*, 2000]. Instrument, atmospheric and geophysical corrections have been applied. We focus on the period 2000–2007 and the mean for this period has been removed.

[11] The standard deviation of η_a is largest along the path of the Gulf Stream (Figure 1, top). This is an indicator of eddy activity and corresponds closely with the pattern of eddy kinetic energy estimated from drifter tracks [*Fratantoni*, 2001]. Maps of the variance of temperature and salinity measured by Argo floats (not shown) exhibit a similar pattern.

3. A Simple "De-eddying" Technique

[12] Measurements below the mixed layer in mesoscale eddies show vertical isopycnal displacements of up to several hundred metres [e.g., *Richardson et al.*, 1978]. The displacement is upwards (downwards) in cold-core (warm-core) eddies, producing horizontal temperature differences of up to 5°C relative to water outside the eddy. Repeat sampling at a given depth and location will, in the presence of eddies, likely include TS measurements corresponding to water normally found higher and/or lower in the water column. Observations are consistent with this, showing local TS properties that are not identical but aligned with the local climatological TS relationship (Figure 2, left).

[13] Isopycnal displacements are likely the cause of TS variability seen below the mixed layer (Figure 1, bottom, solid lines), with other processes such as heating contributing to the near-surface variability. The isopycnal displacements produce changes in steric height and we find η_a is a reasonable approximation of steric height (calculated between 1500 m and 150 m to exclude the effect of other processes in the mixed layer) with a high correlation between the two (r=0.67 for our northwest Atlantic domain). Hence we use η_a from the AVISO fields to estimate the isopycnal displacement and adjust the Argo profiles using a method based on the assimilation technique developed by *Cooper and Haines* [1996] (hereinafter referred to as CH96).

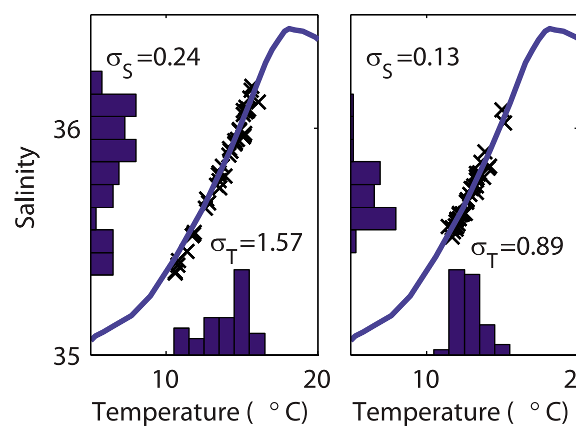

Figure 2. Crosses show the TS relationship at a depth of 610 m for all Argo profiles recorded within 100 km of 37°N 46°W between 1 January 2000 and 31 December 2007 (left) before and (right) after the de-eddying adjustment. The line shows the annual mean climatological TS relation for all depths from the surface to 1500 m depth at this location from the WOA01 $\frac{1}{4}^\circ$ climatology. The distributions of temperature and salinity values are plotted as histograms against the x-axis and y-axis respectively along with the corresponding standard deviations (σ_T and σ_S).

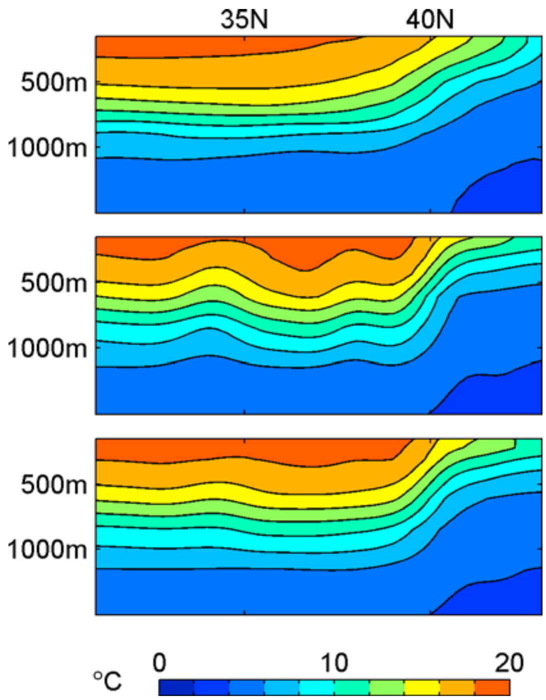

Figure 3. (top) The climatological temperature field for April, from the WOA01 $\frac{1}{4}°$ climatology, plotted from 150 m to 1500 m depth along a meridional section at 60°W from 31°N to 43°N. (middle and bottom) The corresponding temperature fields derived from all Argo profiles recorded during April from 2000 to 2007 inclusive, before and after applying the de-eddying adjustment, with the same spatial smoothing applied to each.

[14] CH96 used a hydrostatic relation and a bottom constraint to develop a balance between changes in surface pressure and the weight of the water column. They assumed that changes to the density field are achieved by a simple vertical displacement of the water column (δh) that is constant with depth. Changes due to horizontal advection, mixing and heat/salt inputs are ignored but the local TS relationship is conserved. Motivated by their technique we calculate the vertical displacement as follows:

$$\delta h = \gamma \frac{\rho_t}{\rho_t - \rho_b} \eta_a$$

where η_a is the altimeter sea level anomaly and ρ_t and ρ_b are potential density at the top and bottom of the water column. This formula reduces to that used by CH96 when $\gamma = 1$. There is some subjectivity in the choice of top and bottom levels. We choose to consider the water column between the surface and 1500 m. We introduce the adjustment factor γ which varies seasonally but not spatially for this relatively small domain. After applying the adjustment to the Argo data we plotted the variance of temperature, salinity and steric height against γ. By visual inspection we were able to identify a single monthly value of γ which, for practical purposes, simultaneously minimized the variance of all three variables.

[15] In order to allow de-eddying of incomplete profiles, ρ_t and ρ_b are calculated from the WOA01 $\frac{1}{4}°$ monthly climatology [*Boyer et al.*, 2005] rather than the measured values, but this does not seem to significantly alter the typical magnitudes of the adjustment.

4. Results From the Northwest Atlantic

[16] Applying the de-eddying adjustment to the Argo profiles from the northwest Atlantic domain we find values of γ between 0.6 (March) and 1.2 (September) minimizes the variance. Using these values the strong correlation (r=0.67) between steric height and the corresponding η_a is almost totally removed by applying the adjustment (r=−0.11 afterwards).

[17] Subdomains A and B (Figure 1, top) are representative regions of high and low hydrographic and sea level variability. The rms temperature anomaly relative to the WOA01 $\frac{1}{4}°$ climatology was calculated for all profiles within each subdomain before and after the method is applied (Figure 1, bottom). The de-eddying technique has little effect on profiles in the region of low variability, as

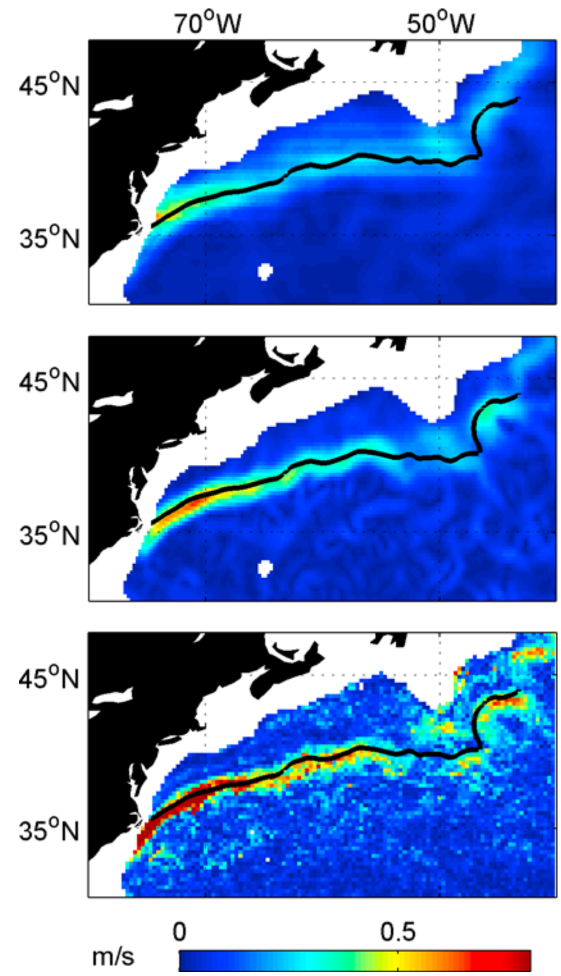

Figure 4. Total geostrophic current velocity derived from steric height calculated relative to 1500 m depth using (top) the WOA01 $\frac{1}{4}°$ climatology and (middle) the Argo-derived TS climatology. (bottom) Drifter observations of total geostrophic velocity are shown for the period 1980 to 2005, calculated as the drifter velocity minus Ekman transport [see *Thompson et al.*, 2009]. The altimeter sea surface height anomaly zero-skewness line is shown on all three plots.

expected. In the high variability region the maximum effect (a reduction of approximately 40%) is achieved at a depth of 600 m. There is an increase in the surface mixed layer, almost certainly because processes other than vertical advection become important.

[18] The scatter in the TS relation for profiles close to 37°N 46°W (the filled circle in Figure 1, top) illustrates the vertical displacements associated with eddies (Figure 2, left). This scatter is reduced when the method is applied (Figure 2, right), with the standard deviation of both temperature and salinity reduced by near 50%. This is a region of high sea surface height variability where the technique is expected to have most effect.

[19] To further illustrate the method the profiles are used to create climatological TS maps before and after the de-eddying adjustment is applied. The TS fields are smoothed at each vertical level using a Gaussian filter with a radius of 1° and a standard deviation of $\frac{1}{2}°$. For example Figure 3 shows the climatological temperature field for April along a meridional section at 60°W before and after the adjustment is applied. Note that the method reduces eddy-like features around 34°N and 37°N.

[20] To test the new climatology we present the surface geostrophic currents calculated from the WOA01 $\frac{1}{4}°$ annual climatology (Figure 4, top) and the annual climatology based on the de-eddying technique (Figure 4, middle). The currents are based on geostrophic balance using steric heights calculated relative to 1500 m. Figure 4 (bottom) shows near surface velocities calculated from drifter tracks for the period 1980 to 2005 with the Ekman contribution removed. (See *Thompson et al.* [2009] for details.) Figure 4 also shows the contour line of zero sea level skewness which we take to be an indicator of the mean path of the Gulf Stream. (Skewness was calculated from gridded altimeter data. See *Thompson and Demirov* [2006] for details of the calculation and justification for its use in identifying the mean path of unstable ocean currents.) Overall, the mean path of the Gulf Stream inferred from the two steric height fields, surface drifters and sea level skewness are in good agreement. An important difference is that the new climatology produces a velocity field that is much closer to the drifter observations than the WOA01 climatology in terms of the speed and width of the Gulf Stream.

5. Discussion

[21] This study was motivated by the poor representation of currents such as the Gulf Stream in existing climatologies based on many decades of observations. Here we have shown how it is possible to define a climatology with data from a single decade using a simple technique, based on the idea of CH96, to reduce the mesoscale noise in the observations.

[22] Generally there is good agreement between our new TS climatology and other analyses. This in itself is worth noting given that our approach is based on just eight years of data. The comparison of geostrophic currents in the vicinity of the Gulf Stream (Figure 4) illustrates how the cross-Gulf Stream gradients in the WOA01 climatology have been smoothed out whereas this new approach maintains a more realistic gradient.

[23] The technique is simple, transparent and reproducible, requiring only η_a and the seasonally-varying γ. There are areas where it will not work well, for example the surface mixed layer. This is not surprising because the method assumes that vertical advection is the only process affecting local TS properties, which is clearly not the case near the surface. The value of the technique is in improving existing climatologies in dynamic regions such as the western boundary currents where low frequency and mesoscale variability make it difficult to define a meaningful climatology. This study uses TS profiles from the Argo network but other in situ observations recorded since the satellite altimeter record began in 1992 can be similarly adjusted (including other variables with a strong vertical gradient, e.g., nutrients). Ultimately the test of this technique will be to apply it to a larger domain and use the resulting climatology to initialize and constrain an ocean model to see whether predictions of the future state of the ocean are improved. Such work is underway.

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References

Boyer, T., S. Levitus, H. Garcia, R. Locarnini, C. Stephens, and J. Antonov (2005), Objective analyses of annual, seasonal, and monthly temperature and salinity for the world ocean on a 0.25 grid, *Int. J. Climatol*, *25*, 931–945, doi:10.1002/joc.1173.

Boyer, T., J. Antonov, H. Garcia, D. Johnson, R. Locamini, A. Mishonov, M. Pitcher, O. Baranova, and I. Smolyar (2006), *World Ocean Database 2005*, *NOAA Atlas NESDIS*, vol. 60, edited by S. Levitus, 190 pp., NOAA, Silver Spring, Md.

Cooper, M., and K. Haines (1996), Altimetric assimilation with water property conservation, *J. Geophys. Res.*, *101*(C1), 1059–1078.

Ducet, N., P. Le Traon, and G. Reverdin (2000), Global high resolution mapping of ocean circulation from Topex/Poseidon and ERS1/EES2, *J. Geophys. Res.*, *105*, 19,477–19,498.

Fratantoni, D. (2001), North Atlantic surface circulation during the 1990's observed with satellite-tracked drifters, *J. Geophys. Res.*, *106*(C10), 22,067–22,093.

Guinehut, S., P. Le Traon, G. Larnicol, and S. Philipps (2004), Combining Argo and remote-sensing data to estimate the ocean three-dimensional temperature fields—A first approach based on simulated observations, *J. Mar. Syst.*, *46*(1–4), 85–98, doi:10.1016/j.jmarsys.2003.11.022.

Lozier, M., W. Owens, and R. Curry (1995), The climatology of the North Atlantic, *Prog. Oceanogr.*, *36*(1), 1–44.

Richardson, P., R. Cheney, and L. Worthington (1978), A census of Gulf Stream rings, spring 1975, *J. Geophys. Res.*, *83*(C12), 6136–6144.

Roemmich, D., et al. (2000), Argo: The global array of profiling floats, in *Observing the Oceans in the 21st Century*, edited by C. Koblinsky and N. Smith, pp. 248–258, GODAE Proj. Off. and Bur. of Meteorol., Melbourne, Victoria, Australia.

Thompson, K. R., and E. Demirov (2006), Skewness of sea level variability of the world's oceans, *J. Geophys. Res.*, *111*, C05005, doi:10.1029/2004JC002839.

Thompson, K. R., J. Huang, M. Véronneau, D. G. Wright, and Y. Lu (2009), Mean surface topography of the northwest Atlantic: Comparison of estimates based on satellite, terrestrial gravity, and oceanographic observations, *J. Geophys. Res.*, *114*, C07015, doi:10.1029/2008JC004859.

Willis, J. K., D. Roemmich, and B. Cornuelle (2003), Combining altimetric height with broadscale profile data to estimate steric height, heat storage, subsurface temperature, and sea-surface temperature variability, *J. Geophys. Res.*, *108*(C9), 3292, doi:10.1029/2002JC001755.

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