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Key Points:
- This work presents a global climatology and database of mixed layer properties calculated from Argo profiles
- The database is used to examine three regions with deep winter mixed layers: Labrador Sea, Southern Ocean, and Gulf Stream region
- Algorithm MLDs are approximately 10% shallower than threshold MLDs in these regions

Correspondence to:
J. Holte,
jholte@whoi.edu

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An Argo mixed layer climatology and database

James Holte[1], Lynne D. Talley[2], John Gilson[2], and Dean Roemmich[2]

[1]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA, [2]Scripps Institution of Oceanography, La Jolla, California, USA

Abstract A global climatology and database of mixed layer properties are computed from nearly 1,250,000 Argo profiles. The climatology is calculated with both a hybrid algorithm for detecting the mixed layer depth (MLD) and a standard threshold method. The climatology provides accurate information about the depth, properties, extent, and seasonal patterns of global mixed layers. The individual profile results in the database can be used to construct time series of mixed layer properties in specific regions of interest. The climatology and database are available online at http://mixedlayer.ucsd.edu. The MLDs calculated by the hybrid algorithm are shallower and generally more accurate than those of the threshold method, particularly in regions of deep winter mixed layers; the new climatology differs the most from existing mixed layer climatologies in these regions. Examples are presented from the Labrador and Irminger Seas, the Southern Ocean, and the North Atlantic Ocean near the Gulf Stream. In these regions the threshold method tends to overestimate winter MLDs by approximately 10% compared to the algorithm.

1. Introduction

The ocean's surface mixed layer is a highly temporally and spatially variable feature that contributes to the large-scale ocean structure and circulation, as well as to numerous biological and chemical processes. In regions of deep and intermediate water formation, winter mixed layers are important in setting the ocean's subsurface properties [e.g., *Stommel*, 1979; *Talley*, 1999] and in sequestering anthropogenic CO_2 in the ocean interior [*Sabine et al.*, 2002]. The upper ocean circulation is driven by wind forcing acting through the mixed layer [*Chereskin and Roemmich*, 1991]. The mixed layer influences biological production by regulating the mixing of phytoplankton and nutrients into and out of the euphotic zone [*Chen et al.*, 1994; *Ohlmann et al.*, 1996]. Observations of global mixed layer depths (MLDs) are also important for assessing the surface layers of global climate models [*Belcher et al.*, 2012].

In this paper, as in other mixed layer studies, the mixed layer refers to the uniform surface layer that is assumed to owe its homogeneity to turbulent mixing. MLD climatologies aim to capture the variability of the mixed layer on monthly and greater time scales. In summer, the MLD can reach tens of meters or even be absent. Turbulent mixing driven by wind stress [*Risien and Chelton*, 2008] and convection driven by air-sea heat [*Yu and Weller*, 2007] and freshwater [*Schanze et al.*, 2010] fluxes at the ocean surface deepen the mixed layer during winter, when MLDs can reach thousands of meters in certain locations, such as the Labrador and Irminger Seas. The mixed layer is typically determined using temperature and density profiles. The mixed layer is not necessarily representative of the actively mixing layer [e.g., *Brainerd and Gregg*, 1995; *Sutherland et al.*, 2014], which can be identified with relatively scarce ocean turbulence and mixing measurements.

As an accurate knowledge of the mixed layer is important to many studies, in this work we present a global climatology and database of mixed layer properties computed from nearly 1,250,000 delayed-mode and real-time Argo profiles collected from 2000 to present. The climatology provides estimates of monthly mixed layer depth (mean, median, maximum, and standard deviation) and properties (mean density, temperature, and absolute salinity) on global 1° gridded maps. These fields are averages over the entire Argo record, producing a representative annual cycle of monthly mixed layer properties. Also provided is a database of the mixed layer properties, including the location and date, of every individual Argo profile used to assemble the climatology. The individual profile output can be used to construct time series of mixed layer properties in specific regions of interest. The climatology is calculated with a hybrid algorithm for detecting the MLD [*Holte and Talley*, 2009] as well as with standard threshold criteria [*de Boyer Montégut et al.*, 2004]; the MLDs calculated by the two methods are referred to as algorithm and threshold MLDs throughout the manuscript, respectively. The climatology and database are updated annually to include new profiles; these data sets, as well as the algorithm's MATLAB code, are available online at http://mixedlayer.ucsd.edu.

We employ *Lorbacher et al.*'s [2006] "quality index" (explained below in section 2) for assessing the capability of the algorithm and threshold methods but use potential density rather than temperature as the property most relevant to characterizing the stratification. Compared to the threshold-based climatology, the algorithm climatology MLDs are shallower and generally have higher quality indices, especially in regions with deep winter mixed layers, where some deep and intermediate waters form.

Our algorithm climatology and database complement a number of other mixed layer products already available. The primary advantage of our climatology is that it uses a more accurate method for identifying the MLD, as will be shown by a "quality index" analysis. It also incorporates more density profiles than have been available in previous climatologies. *De Boyer Montégut et al.*'s [2004] MLD climatology, updated through 2011, includes Argo and other profile data and uses the threshold method (density criterion of 0.03 kg m^{-3}) to identify the MLD (available online at http://www.ifremer.fr/cerweb/deboyer/mld/home.php). *Hosoda et al.* [2010] use Argo data collected between 2001 and 2009 and *de Boyer Montégut et al.*'s [2004] threshold values to construct a 10 day, 2° by 2° MLD climatology. The World Ocean Atlas mixed layer climatology [*Monterey and Levitus*, 1997] uses averaged profiles and, consequently, a larger threshold value (density criterion of 0.125 kg m^{-3}) than *de Boyer Montégut et al.* [2004] (available online at https://www.nodc.noaa.gov/OC5/indprod.html). *Schmidtko et al.* [2013] employ *Holte and Talley*'s [2009] density algorithm to compute the MLD in their Monthly Isopycnal and Mixed Layer Ocean Climatology (MIMOC); the sophisticated mapping used to create this climatology emphasizes data from 2007 to 2011 and produces a considerably smoothed MLD (available online at http://www.pmel.noaa.gov/mimoc/). The density algorithm is also utilized in *Johnson et al.* [2012], using Argo supplemented with additional profiles, to analyze the seasonal evolution of horizontal density gradients in the mixed layer.

Employing our online mixed layer database, we focus our analysis on three regions: the Labrador and Irminger Seas, the Southern Ocean, and the North Atlantic near the Gulf Stream. These and other regions where deep winter mixed layers form are major sinks for atmospheric gases and have a substantial influence on the ocean interior via their interannually varying winter properties. A global analysis of the differences between the algorithm and threshold methods is beyond the scope of this paper; however, these regions provide typical examples of how the algorithm and threshold MLDs differ.

The paper is organized as follows: section 2 details the data and methods used to create and evaluate the climatology and the database. Section 3 presents the climatology. Section 4 describes results from the three example regions. Section 5 summarizes the results.

2. Data and Methods

The Argo array of profiling floats [*Roemmich et al.*, 2009] is currently producing the most comprehensive data set of the temperature and salinity of the upper ocean, including the mixed layer. Argo floats have continuously sampled the world's oceans since 2000. Argo floats generally sample to a depth of 2000 m every 10 days and measure temperature, salinity, and pressure. Older profiles contain observations at roughly 75 depth levels; vertical sample spacing for these floats is less than 20 m to depths of 400 m, below which the spacing increases to 50 m; sampling is frequently limited to 2 or fewer observations in the upper 10 m. Newer floats, thanks to improved Iridium communications, can sample as frequently as every 2 m throughout the profile. The Argo array numbers more than 3000 floats which collect approximately 150,000 profiles annually. Argo data are available online at http://www.usgodae.org/argo/argo.html.

For each Argo profile, conservative temperature, Θ, absolute salinity, S_A, and surface-referenced potential density anomaly, ρ, are calculated from the reported temperature and practical salinity. Mixed layer potential densities and salinities in the climatology and database are reported on the TEOS-10 S_A scale [*Intergovernmental Oceanographic Commission et al.*, 2010] with S_A taken from version 3.0 of the *McDougall et al.* [2012] database.

As of June 2016, approximately 1,250,000 Argo real-time and delayed-mode potential density profiles are used to construct the MLD climatology (Figure 1d); mixed layer properties for these individual profiles are also available in the database. We exclude profiles that have bad quality flags, start deeper than 10 m, or have observations at fewer than 10 depth levels. The database includes the profile status (delayed-mode or

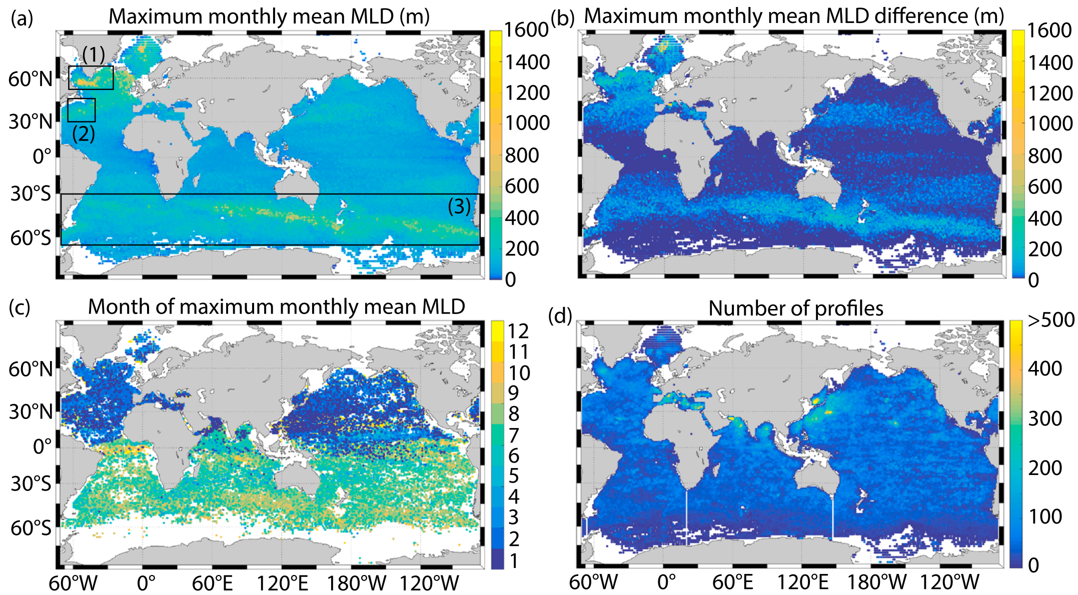

Figure 1. Maps of (a) density algorithm maximum monthly mean MLD, (b) maximum monthly mean MLD difference (threshold minus algorithm), (c) month of maximum monthly mean MLD, and (d) number of Argo profiles in 1° by 1° bins. The maximum monthly mean values are calculated independent of year. The month corresponding to the maximum monthly mean MLD is plotted in Figure 1c for bins with observations from 10 or more months. The boxed regions in Figure 1a are the following: (1) the Labrador and Irminger Seas, (2) the Gulf Stream region in the North Atlantic, and (3) the Southern Ocean; these regions are examined in section 4. The white lines in Figure 1d delineate the Atlantic, Indian, and Pacific Oceans for Figure 2.

real-time) so that users can limit the data set to delayed-mode profiles if desired. Every time that the climatology and database are updated, profiles that have been converted from real-time to delayed-mode are reprocessed. The lowest profile concentrations occur in the Southern Ocean. The highest concentrations are found in the Kuroshio region, with some 1° bins recording more than 600 profiles since 2000. Much of the climatology has observations from 10 or more months (Figure 1c), so the seasonal cycle is captured for much of the ocean. Until recently, Argo profile coverage has been strongly biased to regions with no sea ice, so mixed layer characterization in ice-covered regions is poor.

The Argo mixed layer properties of the individual Argo profiles are calculated using two methods: the density algorithm from *Holte and Talley* [2009] and the variable density threshold from *de Boyer Montégut et al.* [2004]. The algorithm works by modeling the general shape of each profile by fitting lines to the seasonal thermocline and the mixed layer. It calculates a suite of possible MLDs: threshold MLD, gradient MLD, intersection of seasonal thermocline, and mixed layer fits, property maxima and minima. It then analyzes the patterns in the suite to select a final MLD estimate. The threshold MLD serves as the algorithm's maximum possible MLD. Threshold methods identify the depth at which the temperature or density profile has changed by a predefined amount (the threshold value) relative to a near-surface reference value. We use *de Boyer Montégut et al.*'s [2004] variable density threshold, which alters the density threshold value for each profile depending on the local reference temperature and salinity; the variable density threshold is calculated as the density change that accompanies a temperature decrease of 0.2°C in the local reference conditions. This means that the threshold is smaller for very cold, dense mixed layers. For example, a reference S_A of 35 and a reference Θ of 8°C correspond to a density threshold of 0.03 kg m^{-3}; a reference S_A of 35 and a reference Θ of 0°C correspond to a density threshold of 0.011 kg m^{-3}. Following *de Boyer Montégut et al.* [2004], both the threshold and algorithm are initiated at 10 m depth; *de Boyer Montégut et al.* [2004] use this starting depth specifically to avoid diurnal mixed layers, as their climatology is designed to look at monthly and greater scales of variability. Consequently, extremely shallow (or nonexistent) mixed layers in regions like the eastern tropical Pacific Ocean are not captured by these methods. The coarse vertical sampling of older Argo floats also makes identifying shallow mixed layers difficult. However, avenues for studying shallow mixed layers are expanding due to the increasing proportion of Iridium Argo profiles.

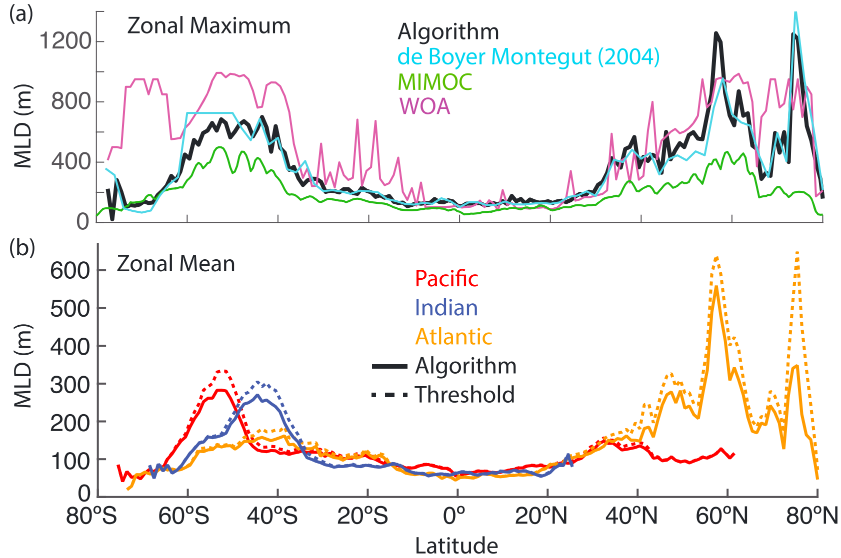

Figure 2. (a) Zonal maximum of the maximum monthly mean MLD calculated by the density algorithm (black line); also plotted are zonal maximums of the maximum monthly mean MLDs for the *de Boyer Montégut et al.* [2004] density threshold climatology (cyan line), the *Schmidtko et al.* [2013] MIMOC climatology (green line), and the *Monterey and Levitus* [1997] World Ocean Atlas (magenta line). (b) Zonal averages of maximum monthly mean MLDs calculated by the density algorithm (solid lines) and threshold method (dashed lines) separated by ocean basin: Pacific (red), Atlantic (orange), and Indian (blue). The ocean basin separation is shown in Figure 1d.

Our climatology provides algorithm and threshold estimates of monthly mixed layer depth (mean, median, maximum, and standard deviation) and properties (mean density, temperature, and absolute salinity) averaged over all years on global 1° gridded maps. The maximum monthly MLD is calculated as the mean of the three deepest MLDs from each month. Also provided in the database are the mixed layer properties, location, and date of every individual Argo profile used to assemble the climatology.

We employ a slight variation of *Lorbacher et al.*'s [2006] "quality index," QI_{MLD}, to assess the algorithm and threshold MLDs. This index compares the variance of a potential density profile above the MLD to the variance of the profile above a depth of 1.5 × MLD:

$$QI_{\mathrm{MLD}} = 1 - \frac{\sigma\left(\rho(z) - \left\langle \rho_{\mathrm{ML}} \right\rangle\right)|_{\mathrm{MLD}}}{\sigma\left(\rho(z) - \left\langle \rho_{\mathrm{ML}} \right\rangle\right)|_{1.5\times\mathrm{MLD}}}, \tag{1}$$

where $\sigma()$ denotes the standard deviation of the potential density profile from the mean mixed layer potential density $\left\langle \rho_{\mathrm{ML}} \right\rangle$. The standard deviation is calculated both over the MLD and over 1.5 × MLD. The standard deviation ratio is subtracted from 1, so for an accurate MLD estimate, the quality index is close to 1; if the MLD estimate is shallower or deeper than the actual MLD, the quality index is closer to 0. We use potential density for this calculation, whereas *Lorbacher et al.* [2006] used temperature. Although for a given profile the quality index depends on the profile resolution (usually lower for higher resolution profiles that capture more variance), the difference in the quality index between algorithm and threshold MLDs does not depend on the resolution.

3. Mixed Layer Depth Climatology

The monthly climatology captures many well known features of the surface ocean. Here we focus on the deepest extent of the winter mixed layer, represented as the maximum monthly mean MLD (Figure 1a). The maximum winter MLD determines the boundary between the ocean interior and the surface layer. These deep winter mixed layers set the ocean's subsurface properties in regions of deep and intermediate water formation. The global ocean's isolated deep convection regions, summarized in *Marshall and Schott* [1999], are evident in the maps of maximum winter MLDs; the deepest mixed layers, beyond 1500 m, are found in the Labrador and Nordic Seas and in the Gulf of Lion. Deep winter mixed layers reaching 400 m are also evident in the Gulf Stream and Kuroshio regions [e.g., *Kwon and Riser*, 2004]. MLDs reach 600 m in the Indian and Pacific

Ocean basins of the Southern Ocean [e.g., *McCartney*, 1982; *Hanawa and Talley*, 2001; *Dong et al.*, 2007; *Holte et al.*, 2012; *Cerovečki et al.*, 2013].

The zonal maximums of the monthly mean MLDs of the density algorithm and three other climatologies (*de Boyer Montégut et al.*'s [2004] density threshold climatology, *Schmidtko et al.*'s [2013] MIMOC climatology, and *Monterey and Levitus*'s [1997] World Ocean Atlas) provide an illustrative comparison (Figure 2). All of the climatologies exhibit similar large-scale patterns but differ in important ways, especially in regions with deep winter mixed layers. *Monterey and Levitus*'s [1997] World Ocean Atlas uses averaged profiles and a larger threshold value to produce mixed layers that are more than 900 m deep in much of the Southern Hemisphere. MIMOC features much shallower MLDs than any of the other climatologies, perhaps due to the smoothing inherent in their mapping scheme; *Schmidtko et al.* [2013] note that errors in MIMOC are likely largest where the mixed layer meets interior ocean isopycnals, particularly in regions with large surface density gradients, such as the Subantarctic Mode Water (SAMW) formation region. Some of the differences could also be due to interannual variability in the mixed layer, as the years emphasized by MIMOC were characterized by weak deep convection in the North Atlantic. *De Boyer Montégut et al.*'s [2004] climatology is quite similar to our climatology. The two differ over a swath of deep SAMW MLDs from 50° to 60°S, where *De Boyer Montégut et al.*'s [2004] climatology is deeper, and in the North Atlantic, particularly at 57°N, where our climatology is deeper. As will be shown subsequently (in Figure 2b and in section 4), some of these differences are due to the improved ability of the algorithm to identify the MLD compared to the threshold method. Some of the differences might be due to the improved sampling offered by Argo; *de Boyer Montégut et al.* [2004] utilize 780,000 density profiles, whereas our density climatology currently contains more than 1,250,000 profiles.

To get a sense of how our climatology differs from *de Boyer Montégut et al.* [2004], we explore the differences between the algorithm and threshold MLDs in our climatology. The largest differences between the algorithm and threshold MLDs occur in deep and intermediate water formation regions: the Nordic Seas, the Labrador and Irminger Seas, and the Southern Ocean (Figures 1b and 2b). Taking zonal means of the climatology's maximum winter MLD, the algorithm and threshold differ by approximately 50 $\pm$5 m (mean $\pm$ standard error) in the Indian and Pacific sectors of the Southern Ocean, 90 $\pm$10 m in the Labrador Sea, and 20 $\pm$1 m in the Kuroshio and Gulf Stream regions. The algorithm MLDs are always shallower by design; the threshold method serves as the algorithm's maximum possible MLD. The Nordic Seas are a difficult region for the methods to accurately identify the MLD because of the extremely low stratification throughout the depth range sampled by Argo profiles; the threshold method identifies a large region of 2000 m mixed layers, whereas the algorithm MLDs are considerably shallower (zonal mean maximum winter MLD difference of 200 $\pm$ 31 m). In the next section, we use the individual profile mixed layer database to examine the differences between the algorithm and threshold MLDs in three regions of very deep late winter mixed layers.

4. Example Applications

We focus our analysis of the MLDs on three regions: the Labrador and Irminger Seas, the Southern Ocean, and the North Atlantic near the Gulf Stream (Figure 1a). The water masses that form in these three areas each exhibit large interannual variability at their mixed layer sources, with resulting downstream impacts on thermocline properties; hence, it is important to be able to accurately identify the mixed layer properties of these water masses.

4.1. Labrador and Irminger Seas

Labrador Sea Water (LSW), an intermediate-depth (1000–2000 m) water mass, forms in the Labrador and Irminger Seas in winter, primarily through deep convection [*Lazier*, 1980; *Talley and McCartney*, 1982]. LSW contributes to the Atlantic Meridional Overturning Circulation. The properties of LSW are of great importance, as they change the temperature, salinity, and density structure of the entire subpolar North Atlantic and Nordic Seas [*Kieke and Yashayaev*, 2015] and are critical for the invasion of atmospheric gases, including anthropogenic CO_2, into the ocean [*Khatiwala et al.*, 2013].

The Labrador Sea's deepest mixed layers, to 1800 m, are concentrated in the southwest corner of the Labrador Sea (Figure 3a), as shown with the earliest profiling floats which provided coverage of the subpolar North Atlantic [*Lavender et al.*, 2002]. Another pocket of deep mixed layers is found in the central region between the Labrador and Irminger Seas, while relatively few mixed layers deeper than 800 m are found in the Irminger Sea. Irminger Sea Water (ISW) convection occurs effectively upstream of the LSW convection, in terms of the circulation and slightly lower density of ISW [*McCartney and Talley*, 1982].

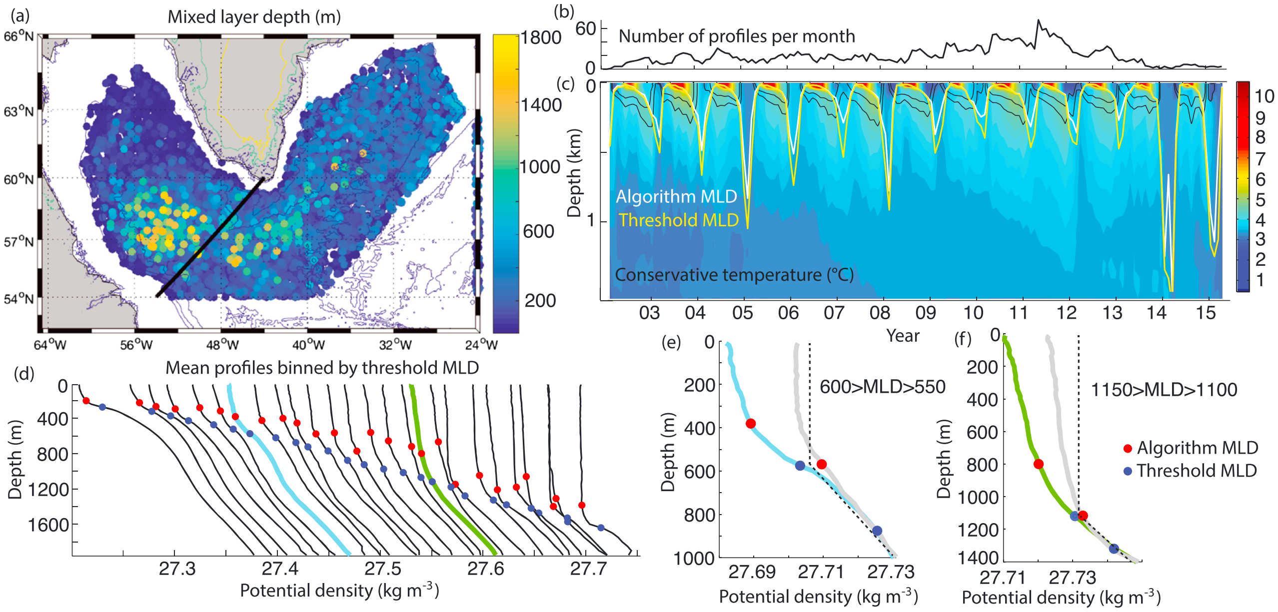

Figure 3. (a) Map of algorithm MLDs from individual Argo profiles (colored dots). Monthly time series from the Labrador Sea interior of (b) number of profiles and (c) conservative temperature. The interior comprises profiles west of the black line in Figure 3a collected over bathymetry deeper than 2800 m, which includes the region of deep MLDs in the Labrador Sea. Also plotted in Figure 3c are the monthly algorithm (white line) and threshold (yellow line) MLDs. (d) Mean density profiles (black lines) binned by threshold MLD (blue dots); the corresponding algorithm MLDs (red dots) are also plotted. The profiles are separated by an offset of 0.01 kg m^{-3}. The blue and green profiles correspond to the profiles in Figures 3e and 3f, respectively. (e) Mean density profiles composed of profiles with threshold (blue line) and algorithm (gray line) MLDs between 550 and 600 m. (f) Mean density profiles composed of profiles with threshold (green line) and algorithm (gray line) MLDs between 1110 and 1150 m. Hypothetical ideal profiles are denoted by dashed lines in Figures 3e and 3f. In Figures 3d–3f, algorithm MLDs are represented by red dots and threshold MLDs are represented by blue dots.

A time series is consistent with the sporadic nature of deep convection in the Labrador Sea that was demonstrated by *Yashayaev and Loder* [2009] and *Kieke and Yashayaev* [2015] (Figure 3c). The recent winters of 2014 and 2015 featured particularly deep mixed layers, to approximately 1500 m [*Yashayaev and Loder*, 2016].

The algorithm MLDs tend to be more accurate than the threshold MLDs (Figures 3d–3f and 4). The algorithm MLDs generally have higher quality indices than the threshold MLDs; the mean quality index for profiles with algorithm MLDs deeper than 200 m is 0.72, whereas the mean quality index for profiles with threshold MLDs deeper than 200 m is 0.55. The algorithm's higher mean quality index suggests that the algorithm's conservative MLD estimates are more representative of the actual MLDs than the threshold MLD estimates. The algorithm MLDs are too shallow in one bin, 1600–1700 m, resulting in the algorithm's lower quality index. The relatively low quality indices for MLDs ranging from 500 to 1100 m suggest that both methods struggle to accurately identify MLDs in this depth range, perhaps due to the low stratification throughout the Labrador and Irminger Seas. Mean profiles binned by algorithm MLD tend to have more vertically uniform mixed layers than mean profiles binned by threshold MLD; two typical examples of this are shown in Figures 3e and 3f. Each threshold bin contains profiles with MLDs that are actually much shallower than the bin, causing the mean mixed layer to deviate from a vertically uniform, ideal mixed layer.

4.2. Southern Ocean

The deepest mixed layers in the Southern Ocean are found equatorward of the Antarctic Circumpolar Current. These waters, termed Subantarctic Mode Water (SAMW) by *McCartney* [1977], contribute to the upper limb of the global overturning circulation [*Sloyan and Rintoul*, 2001] and replenish the thermocline in the subtropical gyres [*McCartney*, 1982].

In the Southern Ocean, the algorithm MLDs are again shallower than the threshold MLDs (Figures 1b, 2b, and 5b) and have higher quality indices (Figure 4). The mean quality index for profiles with algorithm MLDs deeper than 200 m is 0.81, whereas the mean quality index for profiles with threshold MLDs deeper than 200 m is 0.70. Averaging the profiles with algorithm MLDs deeper than 300 m zonally (Figure 5a), the corresponding mean threshold MLDs are approximately 30 m (or 8%) deeper (Figure 5b). *Holte and Talley* [2009] demonstrated

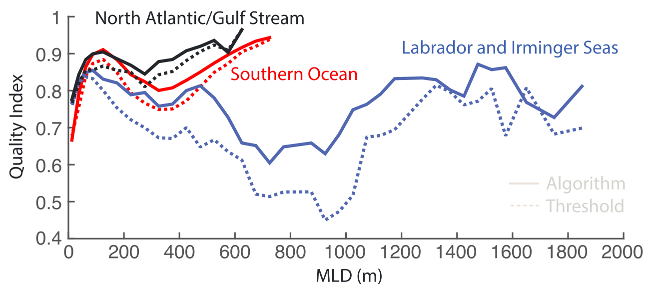

Figure 4. Quality indices of the algorithm (solid lines) and threshold (dashed lines) MLDs for three regions: North Atlantic/Gulf Stream (black lines), Labrador and Irminger Seas (blue lines), and the Southern Ocean (red lines). The regions are depicted in Figure 1a. The quality index is computed twice for each individual profile; once for the algorithm MLD and once for the threshold MLD. These indices are then binned and averaged according to the MLD identified by the algorithm or threshold method, respectively. Quality indices larger than 0.8 imply that the MLD is successfully identified.

that threshold methods overestimate the MLD in regions where deep winter mixed layers blend into deeper waters, such as the SAMW formation region in the southeast Pacific Ocean.

4.3. North Atlantic Near the Gulf Stream

Eighteen Degree Water (EDW) forms in the Atlantic Ocean near the Gulf Stream [*Kwon and Riser*, 2004]. EDW stores considerable heat from both the ocean and the atmosphere and so is climatically important to the region [*Kelly et al.*, 2010]; its formation varies annually [*Billheimer and Talley*, 2013].

Both the algorithm and the threshold MLDs have high quality indices for the EDW formation region (Figure 4). For profiles with algorithm MLDs (Figure 5c) deeper than 200 m, the mean quality index is 0.89; the mean quality index for profiles with threshold MLDs deeper than 200 m is 0.85. The relatively strong stratification beneath the seasonal mixed layer makes the MLD simpler to identify, even in winter, although compared to the algorithm, the threshold method tends to slightly overestimate the MLD (Figure 5d). The mean seasonal cycles for the algorithm and threshold methods are similar, though in the region of deepest EDW mixed layers the mean threshold winter MLDS are approximately 30 m (10%) deeper than the algorithm MLDs.

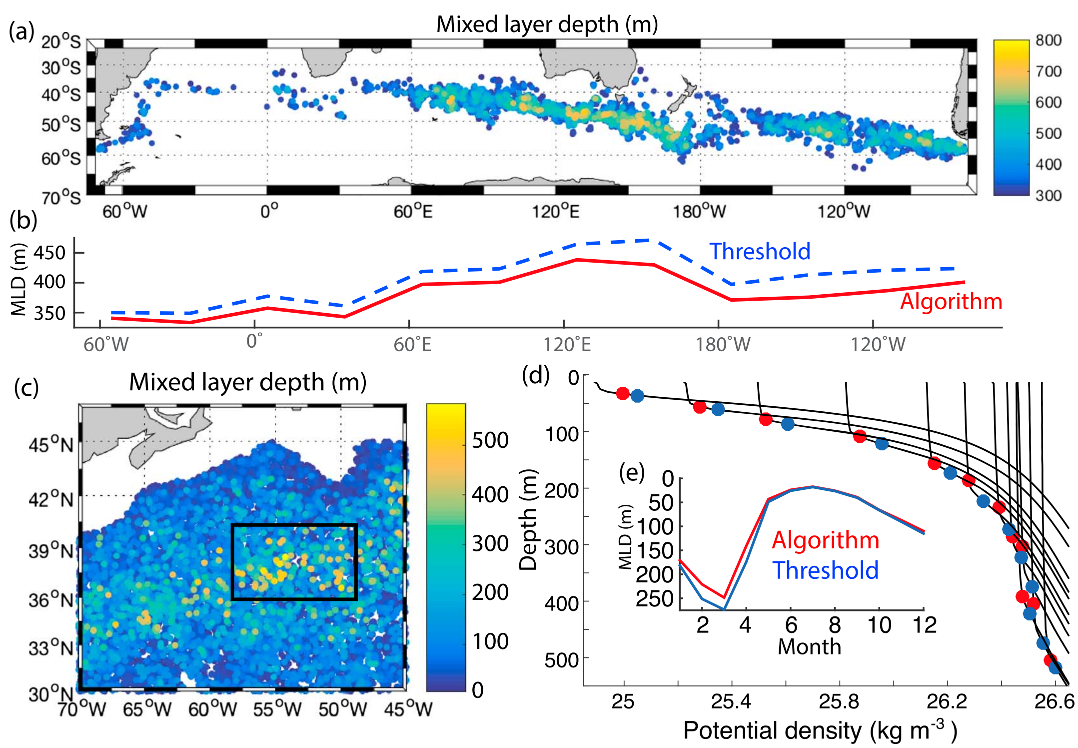

Figure 5. (a) Map of Southern Ocean algorithm MLDs deeper than 300 m and (b) zonal average of Southern Ocean (solid red line) algorithm and (dashed blue line) threshold MLDs deeper than 300 m. The means in Figure 5b are computed for 30° zonal bins. (c) Map of North Atlantic algorithm MLDs and (d) mean potential density profiles binned according to threshold MLD from the boxed region of deep MLDs in Figure 5c; the mean algorithm MLDs are represented by red dots, and the mean threshold MLDs are represented by blue dots. (e) The mean seasonal cycle of the MLD from the boxed region for the algorithm (red line) and threshold (blue line).

In general, the algorithm and threshold method are both successful at identifying shallow MLDs (MLD <150 m) due to the strong stratification in the seasonal thermocline; this is reflected in the relatively high quality indices for all but the shallowest MLDs (Figure 4). Figure 5d provides a typical example and demonstrates how the threshold method slightly overestimates the MLD compared to the algorithm. The low quality indices for the shallowest bin (MLD <25 m) are primarily due to two factors; both methods are initiated at 10 m and so cannot accurately identify MLDs shallower than 10 m, and the strong stratification markedly reduces the quality index for even a slight overestimation of the MLD.

5. Summary

In this work we present a global climatology and database of mixed layer properties (available online at http://mixedlayer.ucsd.edu) computed from nearly 1,250,000 delayed-mode and real-time Argo profiles. Argo coverage is still sparse in some regions, particularly the Southern Ocean, but allows us to construct a representative annual cycle of monthly mixed layer properties for much of the world's oceans. The MLD is calculated with *Holte and Talley*'s [2009] density algorithm and with *de Boyer Montégut et al.*'s [2004] variable density threshold. The climatology provides estimates of monthly mixed layer depth (mean, median, maximum, and standard deviation) and properties (mean density, temperature, and absolute salinity) on global 1° gridded maps. Also provided is a database of the mixed layer properties, as well as the location and date, of every individual Argo profile used to assemble the climatology.

Our climatology offers advantages over other available mixed layer climatologies. The algorithm MLDs are shallower and generally have higher quality indices than the threshold MLDs, especially in regions with deep winter mixed layers. In examples from the Labrador and Irminger Seas, the Southern Ocean, and the North Atlantic near the Gulf Stream, the threshold method tends to overestimate winter MLDs by approximately 10%; this is not an inconsequential amount. The algorithm's higher mean quality index suggests that the algorithm's conservative MLD estimates are more representative of the actual MLDs than the threshold MLD estimates. Our climatology already contains more profiles than previous climatologies based on density profiles, and approximately 150,000 profiles are added each year. The increased vertical resolution of Argo floats with Iridium communications will, with future modification of the algorithm, allow the climatology to better capture shallow mixed layers.

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