An Integrated Method for Determining the Oceanic Bottom Mixed Layer Thickness Based on WOCE Potential Temperature Profiles

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ABSTRACT

In this study we examined the applicability of the threshold, curvature, maximum angle, and relative variance methods for identifying the oceanic bottom mixed layer (BML) thickness H_{BML} . Using full-depth temperature profiles along 17 WOCE sections covering the Atlantic, Indian, and Pacific Oceans, we found that the BML thicknesses determined based on the threshold, curvature, and maximum angle methods had wider 95% confidence intervals and much lower quality indexes ($\text{QI} < 0.57$) compared with those based on the visual inspection ($\text{QI} = 0.68$). The relative variance method appeared to perform better than the other methods because the 95% confidence interval and QI (0.60) values were closer to those determined based on the visual inspection, although differences were still present. We then proposed an integrated method by optimizing the possible H_{BML} values obtained from the four methods. The BML thicknesses determined using the integrated method were closest to those based on the visual inspection according to the higher QI (0.64) and more stations (71%) with $\text{QI} > 0.5$. Compared with the results in previous studies, the integrated method determined the consistent BML thicknesses in most regions (e.g., the northern Atlantic), and it also effectively identified the BML thicknesses in some regions where the BML was considered to be not readily detectable (e.g., the Madeira Abyssal Plain).

1. Introduction

In oceans, the bottom mixed layer (BML) is the region adjacent to the ocean floor, where active mixing promoted by bottom shear and internal wave breaking leads to a vertically quasi-homogeneous profile in terms of the temperature, salinity, density, and other properties. Many interrelated physical, geochemical, and biological processes actively take place inside the BML, and these processes communicate with the ocean interior and underlying sediments (Bowden 1978; Grant and Madsen 1986; Richards 1990). The BML was first observed in the 1970s (Amos et al. 1971; Weatherly 1972; Armi and Millard 1976; Caldwell 1976). Various mechanisms, such as ocean mixing (Ferrari et al. 2016; McDougall and Ferrari 2017), geothermal heating (Adcroft et al. 2001; Zhou and Lu 2013), and diffusion-driven flow (Wunsch

1970), may be responsible for the formation of the BML. The variance and dynamics of the BML were studied extensively in regional oceans (e.g., Armi and Millard 1976; Grant and Madsen 1986; Lentz and Trowbridge 1991; Perlin et al. 2005), and lakes (e.g., Gloor et al. 1994; Wüest and Lorke 2003). The BML can be characterized by several parameters, where the most important and fundamental is the thickness of the BML (H_{BML}). The BML is typically a few tens to hundreds of meters thick in the oceans (e.g., Armi and Millard 1976; Weatherly and Martin 1978; Hogg et al. 1982) but much less in lakes, with a thickness of only a few meters or less (see Wüest and Lorke 2003). Many studies have aimed to formulate H_{BML} so that the BML can be described well (Pollard et al. 1972; Armi and Millard 1976; Weatherly and Martin 1978; Richards 1982; Zilitinkevich and Esau 2002; Perlin et al. 2007), where both the ocean boundary layer and the atmosphere boundary layer have been considered. It is unclear whether the BML can be

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treated as the classical Ekman layer (Armi and Millard 1976) or whether more parameters need to be considered (Weatherly and Martin 1978; Richards 1982; Zilitinkevich and Esau 2002; Perlin et al. 2007). However, the accurate determination of H_{BML} is a priority when exploring the optimal parameterization of BML and the physical, biological, and geochemical processes within the BML.

In earlier studies a threshold method, based on temperature or density profiles, was the main approach employed to determine the thickness of the BML. However, the threshold values differ widely among various ocean regions. On the Oregon shelf, the temperature threshold was determined as 0.002°C by Caldwell (1976) and a density difference of 0.0006 kg m^{-3} , which is equivalent to a temperature difference of 0.01°C , was used as a criterion by Perlin et al. (2005). On the California shelf, the temperature threshold was 0.02°C for conductivity–temperature–depth (CTD) observations and 0.05°C for the moored measurements (Lentz and Trowbridge 1991). The temperature threshold was determined as 0.2° or 0.4°C on the southeastern Australian shelf (in water depths between 65 and 140 m) (Schaeffer et al. 2014). In the Madeira Abyssal Plain and the Vema Channel, a temperature departure of 0.001°C from the bottom temperature was employed to identify H_{BML} (Bowden 1978; Hogg et al. 1982). In some transoceanic sections in the Northern Atlantic, the temperature threshold was taken as 0.005°C (Lozovatsky et al. 2008; Lozovatsky and Shapovalov 2012). A temperature difference of 0.005°C was also used at an abyssal station off central California (Beaulieu and Baldwin 1998). In a study in the northwestern Mediterranean, a density difference of 0.0005 kg m^{-3} was used to identify H_{BML} (Durrieu de Madron et al. 2017). Banyte et al. (2018) recently mapped the weakly stratified bottom boundary layer of the global ocean with a density criteria of $1 \times 10^{-5}\text{ kg m}^{-4}$. In addition, buoyancy frequency N has been used occasionally. For example, N^2 falling below $2 \times 10^{-7}\text{ s}^{-2}$ was taken as the threshold value at the Blake Outer Ridge to survey the North Atlantic Deep Western Boundary Current (Stahr and Sanford 1999). In Lake Erie, the water density threshold was set as 0.001 kg m^{-3} (Valipour et al. 2015). According to Lentz and Trowbridge (1991), the determination of H_{BML} is highly sensitive to the temperature threshold, especially in a weakly stratified background.

Furthermore, many studies have attempted to developing methods for accurately calculating the oceanic surface mixed layer depth (Defant 1936; Wyrki 1964; Levitus 1982; Lukas and Lindstrom 1991; Brainerd and Gregg 1995; Obata et al. 1996; Kara et al. 2000; Lavender et al. 2002; Thomson and Fine 2003; Lorbacher et al. 2006; Holte and Talley 2009; Chu and Fan 2011; Huang et al. 2018).

In particular, the threshold method is the most popular one because it is simple and can presumably be applied to profiles with various vertical resolutions (see Kara et al. 2000; Thomson and Fine 2003; de Boyer Montégut et al. 2004; Lorbacher et al. 2006; Holte and Talley 2009). Many other relatively sophisticated approaches have been proposed, such as a curvature-based method (Lorbacher et al. 2006); a linear optimal fitting method, developed further as a maximum angle method (Chu and Fan 2010, 2011); and a relative variance method (Huang et al. 2018). These methods are less dependent on arbitrary criteria so that the surface mixed layer depth can be determined objectively.

In this study we examined the applicability of the threshold, curvature, maximum angle, and relative variance methods for determining H_{BML} using data along 17 World Ocean Circulation Experiment (WOCE) sections in different oceans. We also proposed an integrated method by optimizing all of these possible BML thicknesses obtained with these methods. The remainder of this paper is organized as follows. In section 2 we describe the hydrographic data and methodology. In section 3 we illustrate the performances of different methods for identifying H_{BML} by using potential temperature profiles along 17 WOCE sections in the Pacific, Indian, and Atlantic Oceans, and explain the proposed integrated method for detecting the BML thickness H_{BML} with higher credibility. In section 4 we compare the values of H_{BML} determined by the new method with those in previous studies. We summarize our results in section 5.

2. Data and methods

a. Hydrographical data

We used temperature and salinity data obtained from the CTD profilers in the WOCE, the U.S. Climate Variability and Predictability (CLIVAR) Program, and other programs, which were downloaded from the CLIVAR and Carbon Hydrographic Data Office website (<https://cchdo.ucsd.edu/>) on 9 July 2015. For most of the WOCE stations, the ocean depths (corrected or uncorrected depths) and the minimum distance from the bottom (DAB) could be downloaded from the same website. In this database, the temperature and salinity data were generally measured over the full ocean depth to the very bottom, thereby providing a robust view of the deep water column and the BML in regions with varying conditions. Seventeen WOCE sections [see Table 1 for the section names and expedition codes (EXPOCODEs) information], including 1680 stations, were selected to cover the Pacific, Indian, and Atlantic

TABLE 1. List of the 17 WOCE sections used in this study and their EXPOCODEs.

No.	Basin	WOCE section	EXPOCODE
1	Atlantic	A03	90CT40_1
2		A09	06MT15_3
3		A16S	33RO200501
4	Indian	AR21	3175MB93
5		I03	316N145_8
6		ISS01	74DI207
7	Pacific	IR04	3175MB95_07
8		P02T	49K6KY9401_1
9		P04E	32MW893_3
10		P04W	32MW893_1
11		P06E	49NZ200309_2
12		P14N	325023_1
13		P15N	18DD9403_2
14		P15S	3175CG90_1
15		P16S	33RR200501
16		PR06	18DD9403_1
17		PRS2	33KI165_1

Oceans, as shown in Fig. 1. The vertical resolution was 2 m for most of the profiles (14 sections) and 1 m for the other profiles (3 sections). To compare our results with previous observations, we also selected the WOCE stations nearest to the locations measured previously. At each location considered in previous studies, the three nearest stations were selected when many stations were within 100 km, or only one of the nearest stations was selected when no station was within 100 km. In total, 46 WOCE stations were identified, as marked in Fig. 1.

In CTD data, salinity is typically computed in terms of the temperature and conductivity data, and it is considerably much noisier because of the instrument's errors, which include the mismatch in response time of temperature and conductivity sensors, the thermal inertia of the conductivity cell, and so on (Galbraith and Kelley 1996). The potential density profiles are also rather spiky because of the effect of the salinity data. Moreover, the potential density is often affected by the selection of the reference pressures for stations at different ocean depths. Therefore, the potential temperature was used to determine the BML thickness at each station.¹

b. Methodology

As mentioned in section 1, H_{BML} is mainly determined using the threshold method, but it is difficult to select a suitable threshold. In this study we employed four

FIG. 1. Spatial distribution of WOCE data used in the study. In total, 17 WOCE sections (black) were selected to estimate the BML thickness with different methods. The 46 WOCE stations used to compare with earlier observations are marked (gray circles).

methods that have been used previously for detecting the surface ocean mixed layer depth in order to determine the BML based on the WOCE data and to examine their performances compared with the visual inspections. Rather than tracking the surface ocean mixed layer depth from the top (sea surface), we tracked the upper bound of the BML from the deepest CTD measurement, and the thickness in between is referred to as H_b . Finally, the sum of H_b and the minimum distance from the bottom dH yielded the BML thickness, that is, $H_{\text{BML}} = H_b + dH$. These methods used for detecting H_b are described as follows.

- 1) Threshold method (Thre): For abyssal ocean, we considered the threshold value employed in previous studies (Beaulieu and Baldwin 1998; Lozovatsky et al. 2008; Lozovatsky and Shapovalov 2012), where a temperature difference of 0.005°C was used. In addition, a linear interpolation between the observed levels was employed to determine H_b more accurately, in a similar manner to the determination of the surface ocean mixed layer depth (de Boyer Montégut et al. 2004). As reported in previous studies, this method could give a coarse representation of the mixed layer depths, which are generally thicker than the actual ones (Lorbacher et al. 2006; Holte and Talley 2009; Huang et al. 2018).
- 2) Curvature method (Curv): This method was proposed by Lorbacher et al. (2006) for detecting the oceanic surface mixed layer depth. By examining the second derivative of the temperature or density profiles, which is referred to as the curvature, the first maximum from the sea surface was used to identify the mixed layer depth, as well as certain criteria of the temperature (density) gradient and standard deviation. The algorithm for this method is publicly available in Lorbacher et al. (2006).

¹ One reviewer suggests that the integrated method would be much more compelling if it can be applied to analyze the potential density or salinity data.

The fluctuations in the abyssal temperature are much weaker than those in the upper ocean, so these criteria were changed accordingly for detecting the BML. Based on a comparison with the visual inspection results, a criterion, the ratio of the temperature gradient relative to its maximum gradient, was set as larger than 0.005; and the other, a temperature fluctuation parameter δ_{30} (the standard deviation of temperature over the 30-m-depth interval above the current level), was set as $\delta_{30} > 0.0003^\circ\text{C}$ so that the BML could be determined fairly with this method. The curvature method deals with the second derivative, so it is effective for a highly homogeneous mixed layer. However, this method often produces problematic results with “wiggly” profiles (Lorbacher et al. 2006; Chu and Fan 2011; Huang et al. 2018).

- 3) Maximum angle method (Max Ang): This method is relatively independent of the selection of a threshold (Chu and Fan 2011). From the sea surface, two linear regressions were applied to the temperature or density profiles, with one above and the other beneath the depth of interest. The depth that maximized the included angle between the two linear fits was identified as the surface ocean mixed layer depth. To detect the BML, the angle between two linear regressions of 15 m was tracked upward from the deepest CTD, and the depth of the maximum angle was defined as the upper bound of the BML. Chu and Fan (2011) suggested that this method is unsuitable for low-resolution profiles. However, the test of vertical resolutions from 0.04 to 25 dbar by Huang et al. (2018) demonstrated that this method works well for low-resolution profiles rather than high-resolution profiles.
- 4) Relative variance method (Rel Var): As in this method proposed by Huang et al. (2018), a relative variance is defined as the ratio of the root-mean-square relative to the absolute difference from a reference depth level. Then a relative variance profile is obtained for each temperature or density profile. The depth at the minimum value of the relative variance is used to identify the boundary of the mixed layer. Details of the algorithm were given by Huang et al. (2018). We adapted this method to detect the upper bound of the BML by tracking the minimum value of the relative variance upward from the deepest CTD. According to Huang et al. (2018), this method is robust for capturing the intersection of a homogeneous mixed layer with the underlying water of the sharp gradient in the temperature profiles at any depth resolution.

For the oceanic surface mixed layer, Lorbacher et al. (2006) proposed a quality index QI for evaluating

whether a method can clearly separate the homogeneous mixed layer from the attached strongly stratified water layer,

$$QI = 1 - \frac{\delta_H}{\delta_{1.5 \times H}}, \quad (1)$$

where δ_H is the standard deviation of temperature (density) within the mixed layer and $\delta_{1.5 \times H}$ is the standard deviation of temperature (density) over the depth range from the reference level to 1.5 times the mixed layer depth. Based on the definition of QI , it is expected that QI approaches 1 when the mixed layer is well developed. A low QI value corresponds to either a mixed layer with complex structures or that a well-mixed layer cannot be identified accurately. According to Lorbacher et al. (2006), the mixed layer interpretation is impossible when $QI < 0.5$.

3. Applicability of different methods

a. Examples of profiles

First, we show the efficiency of these methods at determining H_b using temperature profiles. As shown in Fig. 2, the minimum distance from the bottom dH is added to H_b to indicate H_{BML} .

At the station located at 29.98°N , 167.41°W in the Pacific Ocean (Fig. 2a), the BML had a homogeneous temperature and it was well separated from the overlying water column of the sharp temperature gradient. The upper bound of the BML was readily determined as 94 m based on visual inspection. Most of the methods were effective at detecting the upper bound of the BML, which was identified as 96.4, 90.6, and 88.7 m by the curvature, maximum angle, and relative variance methods, respectively; and QI was around 0.90. The threshold method approximately captured the upper bound of BML, but it was limited by the fixed threshold, which resulted in a thick H_{BML} of 131.93 m and a low QI of 0.57.

In some cases, a thick BML was identified by visual inspection, as shown in the example profile in Fig. 2b (44.00°N , 178.99°W in the Pacific Ocean), that is, $H_{BML} = 855$ m and $QI = 0.95$. The relative variance and curvature methods yielded the closest H_{BML} value to the visual inspection—that is, 847.7 and 898.2 m, respectively—with high $QI \geq 0.95$. The threshold method determined H_{BML} as 998.2 m with a slightly lower QI (0.89). The maximum angle methods clearly overestimated H_{BML} , which corresponded to the lowest QI in all the methods at 0.79.

In the cases where the temperature changed gradually as the depth increased—for example, as shown in Fig. 2c (24.50°N , 43.28°W in the Atlantic Ocean)— H_{BML} was visually inspected as 68.6 m, which corresponded to the

FIG. 2. Examples of potential temperature profiles at (a) 29.98°N, 167.41°W in the Pacific Ocean; (b) 44.00°N, 178.99°W in the Pacific Ocean; (c) 24.50°N, 43.28°W in the Atlantic Ocean; (d) 23.00°S, 15.00°E in the Atlantic Ocean; (e) 20.00°S, 52.78°E in the Indian Ocean; and (f) 22.14°S, 113.17°E in the Indian Ocean. The values of H_{BML} evaluated based on visual inspection and using different methods are marked by color symbols or lines: visual inspection (blue circle), threshold (cyan triangle), curvature (red cross), maximum angle (pink diamond), relative variance (green circle), and integrated (gray line) methods. The QI value for each method is also given using the corresponding color.

highest QI of 0.57. The H_{BML} values determined by different methods were highly scattered—that is, 72.5, 64.7, 46.9, and 31.5 m using the relative variance, maximum angle, threshold, and curvature methods, respectively—and QI varied from 0.57 to 0.29. However, the H_{BML} values obtained by the relative variance and maximum angle methods were closest to the visually inspected one.

When the temperature fluctuated strongly within the BML, as shown in Fig. 2d (23.00°S, 15.00°E in the

Atlantic Ocean), H_{BML} was visually inspected as 227.8 m with the highest QI of 0.94. The curvature and threshold methods approximately captured the H_{BML} values, which were 220.0 and 233.5 m, respectively, with the same QI of 0.93. The maximum angle and relative variance methods found the upper bound of the bottom depth range at a relatively homogeneous temperature with H_{BML} values of 124.7 and 148.0 m, respectively; and QI values were much lower at 0.43 and 0.38, respectively.

FIG. 3. PDFs for (a) H_b and (b) QI based on the temperature profiles of 17 WOCE sections determined by visual inspection (thick blue curve) and by using the threshold (thin cyan curve), curvature (thin red curve), maximum angle (thin pink curve), relative variance (thin green curve), and integrated (thick black curve) methods.

Occasionally, the water column near the deepest CTD had a strong temperature gradient, as shown in Fig. 2e (20.00°S, 52.78°E in the Indian Ocean). It was difficult to determine whether the strongly stratified water column was that above the BML, or whether it was caused by the error in CTD measurement or other reasons. For this profile, $dH = 4$ m was very small, so all the methods excluded this strong temperature gradient structure and selected the overlying water layer. As a result, H_{BML} values of 103.3, 97.3, and 93.4 m were obtained by the threshold, relative variance, and maximum angle methods, respectively, which were close to the visually inspected value of 94.0 m. The value of QI was about 0.8 for all of the methods. The curvature method underestimated H_{BML} as 66.2 m with a much lower QI (0.36) because it preferentially selected the depth range with a relatively homogeneous temperature.

When multilayered structures were present near the bottom, as shown in Fig. 2f (22.14°S, 113.17°E in the Indian Ocean), the BML could be readily identified and its H_{BML} was visually inspected as 17.6 m with QI = 0.92. The threshold method obtained the same H_{BML} value as the visual inspection. The curvature and maximum angle methods slightly underestimated H_{BML} as 14.9 and 12.9 m, respectively, with corresponding QI values of 0.82 and 0.38. The relative variance method ignored the bottom layer and captured one of the upper layers, thereby overestimating H_{BML} as 58.3 m with a low QI of 0.45.

b. Comparison with visual inspection

To reliably evaluate the applicability of these methods for detecting the BML, H_{BML} was visually inspected in

many more temperature profiles. Seventeen WOCE sections, including 1680 stations, were selected in the coverage of the Pacific, Indian, and Atlantic Oceans, as shown in Fig. 1. We focused on H_b rather than H_{BML} so that the influence of dH could not be considered. Among all the selected sections, the BML could be clearly identified for 1418 stations by visual inspection and using all of the methods.

Figure 3 shows the probability density functions (PDFs) of H_b and QI determined by visual inspection and using all of the methods. The visually inspected H_b had a lognormal distribution, which is similar to previous observations of the BML thickness (Lozovatsky et al. 2008) and the oceanic surface mixed layer depth (Huang et al. 2018). The median value was 46.8 m and the 95% confidence interval was [4.5, 491.8] m when H_b was assumed to follow the lognormal distribution. The PDF of QI (Fig. 3b) showed that visual inspection obtained the best estimate of H_b and its QI was the most skewed toward 1 with the fewest low values. As shown in Table 2, the median QI of 0.68 was higher than that obtained by any aforementioned method. When we followed the suggestion by Lorbacher et al. (2006) that interpreting the mixed layer is impossible when QI < 0.50, visual inspection showed that 81.0% of the stations had QI larger than 0.5, as shown in Table 2, thereby indicating that the BML could be detected at most stations in the selected WOCE sections.

As shown in Fig. 2a, the threshold method tended to overestimate H_b , which resulted in a PDF distribution skewed toward thicker values. The median value of

TABLE 2. Descriptive statistics for H_b and QI along the 17 WOCE sections, showing the corresponding median, and 95% confidence interval or standard deviation values, based on visual inspection and different methods; P is the percentage of those with the determined H_b of $QI > 0.5$ in all profiles.

Method	H_b (m)		QI		
	Median	95% confidence interval	Median	Std dev	$P(\%)$ ($QI > 0.5$)
Visual inspection	46.8	[4.5, 491.8]	0.68	0.20	81.0
Threshold	90.8	[5.9, 1391.1]	0.53	0.21	53.8
Curvature	50.4	[2.4, 1043.1]	0.57	0.28	55.4
Maximum angle	40.9	[1.3, 1336.0]	0.54	0.30	55.1
Relative variance	59.1	[10.8, 323.3]	0.60	0.21	64.2
Integrated	58.8	[3.7, 646.9]	0.64	0.21	71.3

90.8 m was much larger than that obtained by visual inspection and the upper limit of the 95% confidence interval was very thick at 1391.1 m. The threshold method obtained the lowest QI median value (0.53) and the smallest station percentage (53.8%) with $QI > 0.5$, which was consistent with the more severe deviation in H_b compared with the visual inspection (Fig. 3a). The median H_b value obtained by the curvature and maximum angle methods were 50.4 and 40.9 m, respectively, which were relatively close to the visually inspected value, as shown in Table 2. However, their PDFs deviated greatly from the lognormal distribution because both methods were prone to yield highly anomalous shallow or thick H_b , which resulted in wider PDF distributions with wider 95% confidence intervals ranging from 2.4 to 1043.1 m for the curvature method and from 1.3 to 1336.0 m for the maximum angle method. As reported by Lorbacher et al. (2006), the curvature method is not suitable for noisy data and is not highly applicable to the profiles of multistructures, although these types of data and profiles are common in the abyss ocean with weak temperature fluctuations (Armi 1978). Thus, the QI values also varied widely with the curvature and maximum angle methods, which resulted in large standard deviations for QI, as listed in Table 2. These two methods obtained some H_b values with high QI values, but they also often yielded H_b values with very low QI values, which affected their statistical performance and produced relatively low QI median values (0.57 and 0.54, respectively). The H_b values produced by the relative variance method had a lognormal distribution. The median value was slightly larger than the visually inspected one, possibly because this method was affected less by the spiky data and it preferentially selected the most obvious layered structure above the ocean floor, as shown in Fig. 2. The narrow PDF distribution led to the 95% confidence interval, [10.8, 323.3] m, closest to that of the visual inspection. Thus, the relative variance method appeared to determine H_b values with much higher QI among all of the methods. The median

value of H_b was 0.60, and 64.2% of the stations had $QI > 0.50$, superior to stations using the other methods.

c. An integrated method

Based on the results of H_b and QI shown in Fig. 3, the relative variance method had the highest capacity for determining H_b among all the methods. However, as listed in Table 2, the H_b values determined by the relative variance method still had rather large deviations compared with the visual inspection results. In some cases, the H_b values identified by the other methods were closer to the visually inspected values, as shown in Figs. 2d and 2f. Therefore, we updated the relative variance method by considering the results obtained by the other methods. In the integrated method, we assembled a suite of the possible H_b values obtained by the four methods and a final H_b value was selected to be closest to that of visual inspection by using the data from the 17 WOCE sections. In this approach, the criteria listed below are required in practice.

- (i) After comparing the H_b values obtained by different methods, we found that the maximum angle method tended to find spurious thicker H_b (Table 2). Thus, the H_b value determined by the maximum angle method was excluded from the suite of possible H_b values when its H_b value was larger than 500 m.
- (ii) Next, we found that the relative variance method could obtain similar H_b values to those of visual inspection when the QI value was larger than 0.7. Using the relative variance method, 389 stations had values of $QI > 0.7$, where the average BML thickness was 0.76 m larger than that determined by visual inspection. Thus, H_b obtained by the relative variance method was selected as the final value when QI was larger than 0.7.
- (iii) Otherwise, we used the method where H_b had the highest QI. The H_b value was selected when QI was either higher than 0.9 or 0.3 higher than that obtained by any other method.

- (iv) Or then, if any two methods found similar upper bounds for BML, their H_b values had a higher probability being the actual value. The H_b value closer to the ocean bottom was finally selected.
- (v) As shown in Fig. 3a, the threshold, curvature, and maximum angle methods were likely to obtain abnormally thick H_b values. When the selected H_b was determined from any of these methods and it was thicker than 200 m, this was the final choice only if QI was 0.1 higher than that using the relative variance method. Otherwise, the H_b value obtained by the relative variance method was selected.

As shown in Fig. 2, the integrated method captured H_{BML} values that were closer to the visually inspected ones in these profiles. Figure 3 also indicates that the integrated method made clear improvements compared with the four individual methods. In particular, in the range between 10 and 200 m, the H_b PDF produced by the integrated method agreed well with that produced by visual inspection. As listed in Table 2, the median H_b and QI values with the integrated method were 58.8 m and 0.64, respectively, which were closer to the visually inspected values than those produced using the four individual methods.

4. Comparison with previous studies on H_{BML}

We also compared our H_{BML} results obtained by the integrated method with those reported in previous studies. Most of the data used in these studies were unavailable. By using the WOCE database, we tried to find three stations at most located nearest to those used for earlier observations within 100 km, or only one station when the nearest station was more than 100 km apart from those in the earlier observations. These profiles and the determined H_{BML} are shown in Fig. 4, and they are compared with previous reported results in Table 3.

Most previous deep-ocean surveys were performed in the Atlantic Ocean. In the North Atlantic, such as in the Hatteras Abyssal Plain (Armi and Millard 1976), the Sohmi Abyssal Plain (Armi 1978), the Eastward Scarp of the Bermuda Rise (Bird et al. 1982), the Porcupine Abyssal Plain (Turnewitsch and Springer 2001), and other areas (Grant et al. 1985; Klein and Mittelstaedt 1992), the H_{BML} values for the nearest WOCE stations varied between 30 and 180 m with large QI values in most cases (Fig. 4a), as shown in Table 3, which were similar to the previous observations. In the Madeira Abyssal Plain, it was reported that the BML could not be readily recognized from November 1980 to July 1981 (Saunders 1983). We found that the nearest stations had

the well-shaped BMLs with H_{BML} values of 50–90 m (Fig. 4b), which were measured almost at the same locations in the summer 20 or 30 years later. In the Blake Ridge, H_{BML} appeared to be thicker than 100 m (Eittreim et al. 1975; Stahr and Sanford 1999). We found that the nearest ocean station had an H_{BML} value of 182 m (Fig. 4c). In the Brazil Basin, Vema Sill, and Vema Channel, it was reported that H_{BML} varied from 50 to 500 m (Hogg et al. 1982; Durrieu de Madron and Weatherly 1994; Zenk and Hogg 1996; Zenk 2008). The H_{BML} values of the nearest ocean stations were generally thinner (~ 50 m) except for some stations with thick H_{BML} up to 293.6 m. The different results compared with those in previous studies may be attributed to the different definitions of H_{BML} . For example, according to Durrieu de Madron and Weatherly (1994), a density anomaly, varying around 0.01 kg m^{-3} , was used to define H_{BML} , even though the density was inhomogeneous within the defined depth range (e.g., Fig. 14 in Durrieu de Madron and Weatherly 1994). As shown in Figs. 4d and 4e, we determined the H_{BML} values robustly for most of the nearest stations, which is confirmed by their high QI values.

Fewer previous deep-ocean surveys were performed in oceans other than the Atlantic. Off central California, the average value of H_{BML} was reported to be 40 m with a range of 15–80 m (Beaulieu and Baldwin 1998). The nearest WOCE stations (within 100 km) had H_{BML} values in the range of 20–60 m (Fig. 4f). In the eastern tropical Pacific, Hayes (1979, 1980) found that it was difficult to detect the presence of a mixed layer. As shown in Fig. 4g, almost half of the eight nearest stations had a well-shaped BML, and the integrated method determined a relatively thick BML in this region, which was confirmed by the fairly high QI values. In the Pacific margin of the Antarctic Peninsula, the Ekman layer thickness (170 m) was deduced based on the flow currents (Giorgetti et al. 2003). The closest WOCE stations had an obvious homogeneous BML, where H_{BML} varied from 33 to 171 m (Fig. 4h). In the western and southern regions of Indian Ocean, H_{BML} was inferred to be on the order of 50–100 m based on the bottom ^{222}Rn and potential temperature profiles (Chung and Kim 1980). The H_{BML} values for the closest WOCE stations ranged from 17 to 107 m, as shown in Fig. 4i. Most of the H_{BML} values had quite high QI values, as listed in Table 3. Compared with previous observations, our proposed integrated method is highly efficient at identifying the values of H_{BML} in different oceans.

5. Summary and discussion

In this study, using full-depth CTD profiles from the WOCE program, we first examined the applicability of

FIG. 4. Potential temperature profiles and the corresponding upper bound of BML at the nearest WOCE stations in comparison with previous observations in the (a) northeast Atlantic Ocean, (b) Madeira Abyssal Plain, (c) Hatteras Abyssal Plain and Blake Outer Ridge, (d) Brazil Basin, (e) Vema Sill and the Vema Channel, (f) off central California, (g) eastern tropical Pacific Ocean, (h) Antarctic Peninsula Pacific margin, and (i) Indian Ocean. The temperature profiles are plotted in the same order as those in Table 3. They are accordingly shifted by 0.01°C based on their bottom temperature in order to avoid overlapping, and they are plotted alternately as black and gray curves for clarity.

the threshold method for identifying H_{BML} as well as some other methods used for the surface ocean mixed layer depth, that is, the curvature (Lorbacher et al. 2006), maximum angle (Chu and Fan 2011), and relative variance (Huang et al. 2018) methods. For the temperature profiles examples, we found that any of these methods can be used to identify H_{BML} , but the obtained H_{BML} values were not always accurate compared with visual inspections. Based on comparisons with visual inspections of the temperature profiles along 17 WOCE sections covering the Atlantic, Indian, and Pacific Oceans, we evaluated the efficiency of each method, qualified by the median and 95% confidence interval of H_b and by the quality index QI. We found that the relative variance method performed best because the 95% confidence interval for H_b was closest to that based on the visual inspection and the median QI value (0.60) was highest among all of the methods. However, the quality of the H_b values determined by this method was still far below that based on the visual inspection, where the visual inspection found 81% of stations with $\text{QI} > 0.5$,

whereas the relative variance method found at most 64% of stations with $\text{QI} > 0.5$.

Based on the results obtained using the different methods, we developed an integrated method by assembling a suite of the possible H_{BML} values with these four methods. According to certain criteria, the final H_{BML} value was selected as that closest to the visually inspected value. It is confirmed by evidence that the median QI value (0.64) with the integrated method was closest to that produced by visual inspection, and many more stations (71%) had $\text{QI} > 0.5$. We also compared the H_{BML} values determined using the integrated method with those reported in previous studies. Most of the data from these studies were unavailable, so we tried to find the WOCE stations nearest to the previous observations. In most ocean regions, such as in the northeast Atlantic Ocean, Blake Ridge, off central California, and Indian Ocean, our H_{BML} values were consistent with earlier observations within the variance range. In the Madeira Abyssal Plain and the eastern tropical Pacific Ocean, the BML was reported as undetectable in earlier

TABLE 3. Comparisons with earlier H_{BML} observations. The H_{BML} values for the nearest WOCE stations are shown. Details are given for the distance from the previous station, the date and location of the station, the H_{BML} determined from the CTD profile, and the corresponding QI; (a)–(f) correspond to panels (a)–(f) in Fig. 4.

Source	Earlier observation			Nearest WOCE station				
	Location	Date	H_{BML} (m)	Distance (km)	Location	Date	H_{BML} (m)	QI
Armi and Millard (1976) Armi (1978)	29.20°N, 70.20°W	—	(a) Northeast Atlantic 10–100 50–150 50–150 40 30–70 10–150	204.8	26.50°N, 71.00°W	17 Feb 1998	14	0.60
	38.49°N, 54.89°W	—		211.3	38.17°N, 52.50°W	30 Sep 2003	67	0.74
	35.95°N, 53.76°W	—		114.5	35.75°N, 52.50°W	6 May 2012	55	0.37
	32.88°N, 57.48°W	Sep 1978–Apr 1979		92.9	33.11°N, 56.53°W	10 Oct 1981	36	−0.10
	40.40°N, 62.27°W	Apr, Jun–Sep 1983		169.5	41.04°N, 60.44°W	25 May 2011	154	0.83
Grant et al. (1985)	47.54°N, 19.65°W	Sep 1984	10–150	26.1	47.50°N, 20.00°W	13 May 1998	40	0.88
Klein and Mittelstaedt (1992)				26.6	47.48°N, 20.00°W	11 Aug 2013	183	0.93
				26.7	47.48°N, 20.00°W	28 Jun 2003	66	0.76
				39.7	48.52°N, 16.23°W	23 Jul 1993	47	0.54
Turnewitsch and Springer (2001)	48.83°N, 16.5°W	Jul 1997	10–65	51.7	48.50°N, 17.00°W	1 Dec 1996	69	0.78
				59.0	48.41°N, 16.99°W	4 May 1998	154.6	0.68
(b) Madeira Abyssal Plain Undetectable								
Saunders (1983)	33.00°N, 22.00°W	Nov 1980–Jul 1981		28.7	33.01°N, 21.69°W	27 Jul 2011	54	0.47
Stahr and Sanford (1999) Eittrheim et al. (1975)	32.00°N, 75.25°W	Jul–Aug 1992		29.2	33.00°N, 21.69°W	7 Jul 2003	88	0.84
	30.40°N, 73.60°W	—		29.5	33.00°N, 21.68°W	20 Aug 2013	79	0.72
				171.9	30.84°N, 74.05°W	10 Apr 1981	182	0.98
(c) Blake Outer Ridge >100 100–200								
(d) Brazil Basin								
Durrieu de Madron and Weatherly (1994)	9.68°S, 35.09°W	25 Nov 1987	110	0	9.68°S, 35.09°W	25 Nov 1987	37.5	0.45
	18.86°S, 37.79°W	21 Jan 1988	120	0	18.86°S, 37.79°W	21 Jan 1988	14.9	0.40
	23.71°S, 40.84°W	30 Jan 1988	240	0	23.71°S, 40.84°W	30 Jan 1988	42	0.94
(e) Vema Sill and Vema Channel 100–200								
Zenk (2008)	31.20°S, 39.40°W	22 Apr 1998		25.7	30.98°S, 39.48°W	22 Jan 1991	293.6	0.97
Hogg et al. (1982)	30.00°S, 40.00°W	Oct 1979, May 1980	50–500	25.9	31.08°S, 39.63°W	13 Jan 1991	42	0.71
				47.0	30.89°S, 39.74°W	30 Jan 1994	66	0.76
				1.1	30.01°S, 39.99°W	10 Nov 2003	25	0.72
Zenk and Hogg (1996)				37.4	29.88°S, 40.36°W	25 Oct 2011	63	0.40
				44.9	30.00°S, 39.53°W	25 Oct 2011	45	0.50
(f) Off central California ~40								
Beaulieu and Baldwin (1998)	34.83°N, 123°W	1993–96		65.3	35.30°N, 123.43°W	3 Jun 1991	57	0.91
				80.8	35.55°N, 122.86°W	3 Jun 1991	20	0.32
				96.6	35.08°N, 124.02°W	3 Jun 1991	28	0.80

TABLE 3. (Continued)

Source	Earlier observation			Nearest WOCE station				
	Location	Date	H_{BML} (m)	Distance (km)	Location	Date	H_{BML} (m)	QI
Hayes (1979) Hayes (1980)	8.45°N, 150.81°W	1976	(g) Eastern tropical Pacific Undetectable	90.9	8.00°N, 151.50°W	25 Feb 2006	386	0.51
				92.2	8.43°N, 151.65°W	22 Sep 1991	137	0.86
				99.5	7.97°N, 151.57°W	21 Sep 1991	104	0.73
	11.70°N, 138.40°W	—		246.7	9.50°N, 138.67°W	19 Apr 1989	86	0.85
	14.62°N, 125.5°W	4 Jul–8 Dec 1977		574.1	9.50°N, 126.17°W	25 Apr 1989	274	0.56
Giorgetti et al. (2003)	9.43°N, 151.28°W	12 Mar–22 May 1978		59.5	9.42°N, 151.82°W	22 Sep 1991	317	0.74
				63.5	9.00°N, 151.66°W	25 Feb 2006	85	0.88
				75.2	8.94°N, 151.76°W	22 Sep 1991	177	0.76
			(h) Antarctic Peninsula Pacific Margin Ekman layer thickness: 170 m	8.8	67.00°S, 75.80°W	17 Apr 2011	66	0.93
	67°S, 76°W	Mar 1997		36.8	67.00°S, 75.15°W	18 Apr 2011	33	0.76
Chung and Kim (1980)			(i) Indian Ocean 50–100	95.0	67.24°S, 73.89°W	24 Jan 2011	171	0.96
	12.97°N, 64.48°E	2 Jan 1978		35.9	12.70°N 64.67°E	7 Aug 1995	72	0.89
				36.6	13.24°N, 64.67°E	7 Aug 1995	51	0.57
	47.67°S, 57.86°E	3 Feb 1978		92.9	13.79°N, 64.67°E	7 Aug 1995	107	0.75
				36.3	47.87°S, 58.23°E	6 Mar 1993	16.9	0.69
	59.99°S, 60.98°E	6 Feb 1978		96.9	47.01°S, 58.71°E	26 Apr 1991	38	0.64
	59.32°S, 92.64°E	15 Feb 1978		203.8	61.77°S, 60.12°E	14 Jan 2006	31.7	0.25
	29.95°S, 109.97°E	22 Feb 1978		235.0	59.50°S, 88.50°E	8 Jun 1996	62	0.88
				7.7	40.02°S, 109.98°E	24 Sep 1995	76	0.42

works, but we found that some of the nearest WOCE stations had the well-shaped BMLs and their H_{BML} values could be determined accurately with the integrated method. In the Brazil Basin, the H_{BML} values determined from the WOCE stations were thinner than those reported previously, where density anomalies were used to define H_{BML} , even though the density was inhomogeneous within the defined depth range in some cases. According to the comparisons with the visual inspections and previous studies, the integrated method could be used to determine H_{BML} in different oceans, which might be useful for quantifying the spatial and temporal variances in BML globally.

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