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Comparison of objective descriptions of the thermocline

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Abstract

Temperature-depth profiles, including the thermocline, are typically described or characterized by mixed layer depth, thermocline depth, and thermocline strength. Objective methods of estimating these parameters are compared with empirical determinations for 200 CTD profiles collected in the eastern and central tropical Pacific, the subtropical North Pacific, and the California Current. The objective methods are (1) maximum slope by difference, (2) maximum slope by regression, (3) four-segment profile model, (4) inflection point, and (5) variable representative isotherm. Mixed layer depth is well estimated by the temperature criterion of (SST-0.8°C) independent of the estimation of thermocline parameters. Thermocline depth and strength are well estimated by the variable representative isotherm method. However, thermocline strength measured as the slope of the temperature-depth profile does not provide a good measure of stratification of the water column. Therefore, it is recommended that the thermocline strength estimate for a profile be supplemented by an estimate of the standard deviation of temperature in the near-surface layer including the thermocline.

The thermocline (Fig. 1) is a layer of water in which temperature changes more rapidly with depth than it does in the layers above (surface or mixed layer) or below (deep water). The thermocline is also a density gradient (pycnocline) because density is determined primarily by temperature, except at high latitudes. The thermocline/pycnocline is a physical gradient that affects buoyancy, heat budgets, circulation, and exchange of properties. The theory of the structure and formation of the thermocline is a fundamental problem in physical oceanography (Pedlosky 2006). The thermocline is also an ecological boundary both because it may include a physiological temperature limit and because it often corresponds to gradients in nutrients, oxygen, or other limiting factors. The characteristics or parameters that might be physically or ecologically important are mixed layer depth (the top of the thermocline), thermocline depth, and thermocline strength. Thermocline strength describes the shape of the thermocline and depends on the ranges of both temperature and depth (thickness) of the gradient. It should give a measure not only of the effectiveness of the thermocline as a physical or ecological boundary, but also of the stratification or stability of the water column through the thermocline layer. The characterization of other fine-scale structures within the mixed layer and thermocline layer—alternating levels of greater and lesser stratification that may include distinct structures such as "inversion layers, fossil mixed layers, and salinity barrier layers" (Sprintall and Roemmich 1999)—may be important in studies of various physical processes, but will not be addressed here.

The depth and shape of the thermocline vary with season, latitude and longitude, and local environmental conditions. The mid-latitude "seasonal thermocline" (Fig. 1, BATS) has been described as an enhancement or strengthening of the upper thermocline during summer, when heat flux at the surface is positive and wind mixing is low. The seasonal thermocline has also been described as a distinct secondary thermocline that forms above the deeper permanent thermocline due to these processes (Sprintall and Cronin 2001). I will not differentiate a seasonal and permanent thermocline because it is rarely feasible to do so in the regions covered by this study. A "diurnal thermocline" can form in the top few meters of the water column due to daily insolation. However, this superficial warming cannot be discerned in XBT profiles, because the first 3-4 m of the profiles are unreliable due to the nominal 0.63 s response time of the thermistor (Guide to MK12-XBT System, Defense Oceanographic Data Center, Australia, DODC Technical Publication 2/2006). CTD profilers will also not detect this fine-scale structure near the surface unless special care is taken in sampling.

The low-latitude "warm pool" temperature-depth profile in Fig. 1 shows a strong temperature gradient between 100 and 200 m, with a thermocline depth of ~150 m. Observed tem-

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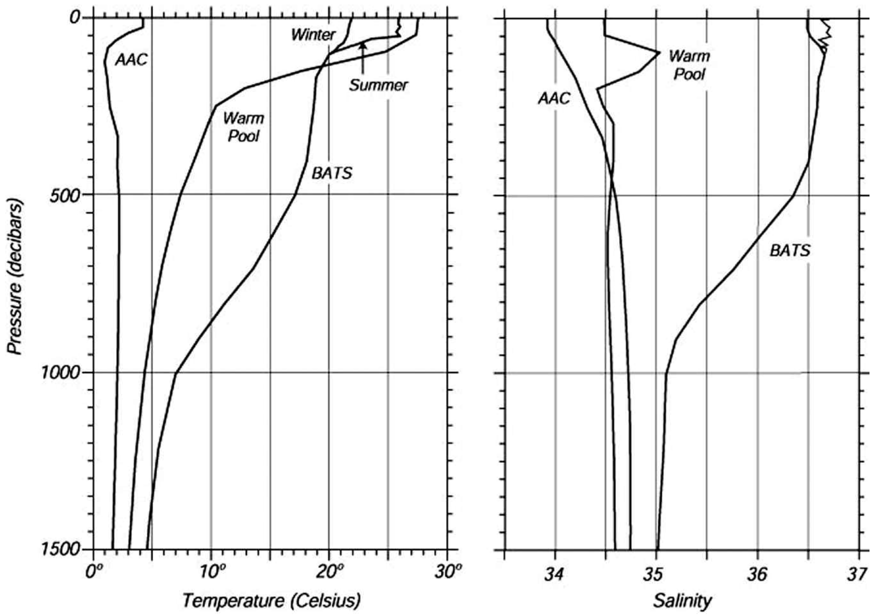

Fig. 1. Typical ocean temperature (left) and salinity profiles (right). AAC: At 62.0°S, 170.0°E in the Antarctic Circumpolar Current, Warm Pool: At 9.5°N, 176.3°E in the tropical west Pacific warm pool, BATS: At 31.8°N, 64.1°W near Bermuda. From http://oceanworld.tamu.edu/resources/ocng_textbook/chapter06/chapter06_04.htm.

perature profiles almost never look like this ideal (see Fig. 4). Due to the presence of multiple gradients, temperature inversions, and measurement noise, there is usually some ambiguity in estimating thermocline parameters objectively, by computer algorithm, or even empirically, by examining individual profiles by eye.

The obvious method to estimate thermocline depth and strength is to find the maximum slope (dT/dz) in a temperature-depth profile (actually the maximum negative slope). With sufficient depth resolution and smooth temperature variation with depth, this method gives useful and unambiguous results. In two recent studies of the California Current, for example, Kim and Miller (2007) used piecewise cubic spline interpolations of observed profiles that had been reduced to standard depths, and Palacios et al. (2004) used cubic spline interpolations of monthly mean profiles at standard depths. Even in such smoothed profiles, however, the maximum slope is often just below the mixed layer, and the thermocline gradually weakens with depth. Thus, thermocline depth estimated as the depth of maximum slope does not represent the center of the thermocline layer (Wang et al. 2000).

A widely used, and operationally very simple, alternative is to use a representative isotherm depth as a proxy for thermocline depth. In the tropical Pacific, the 20°C isotherm has often been used to represent the thermocline (Donguy and Meyers 1987; Kessler 1990; Kessler et al. 1995). The NOAA/NWS/NCEP Global Ocean Data Assimilation System uses maps of 20°C isotherm depth to monitor global tropical thermocline variations (30°N to 30°S, http://www.cpc.noaa.gov/products/GODAS). The 14°C isotherm, which is typically at the base of the main thermocline at low latitudes, was found to be useful in studies of surface layer transport in the tropical Indo-Pacific (Meyers 1979a, 1979b). The 14°C isotherm, since it has not outcropped at extratropical latitudes, has also been used to index the "thickness of the thermally active surface waters along the west coast of the Americas" (Sharp and McLain 1993).

At higher latitudes, where SST is less than 20°C, the 20°C isotherm clearly does not lie within the thermocline (Fig. 2). Therefore, different representative isotherms have been used to identify the thermocline in these regions. For example, Pizarro and Montecinos (2004) selected local representative isotherm values based on mean temperature profiles along the western coast of South America. Wang et al. (2000) used a regionally variable representative temperature to characterize the temperature at the center of the thermocline in the tropical Pacific (20°S to 20°N). They set TT (thermocline temperature) equal to the average of 12°C (representing the temperature at the bottom of the thermocline layer) and the local climatological SST (representing the temperature at the top of the thermocline layer). This resulted in a TT ranging from about 20.5°C in the western Pacific warm pool to 16°C near the coast of Peru.

Another type of thermocline index or proxy has been used in studies of spatial-temporal patterns of thermocline variability. Miller et al. (1997) used 400 m temperature to quantify the propagation of thermocline variations across the North Pacific. Qian and Hu (2006) used the maximum subsurface temperature anomaly (among standard depths in a profile) as an index to study ENSO-related thermocline variations in the

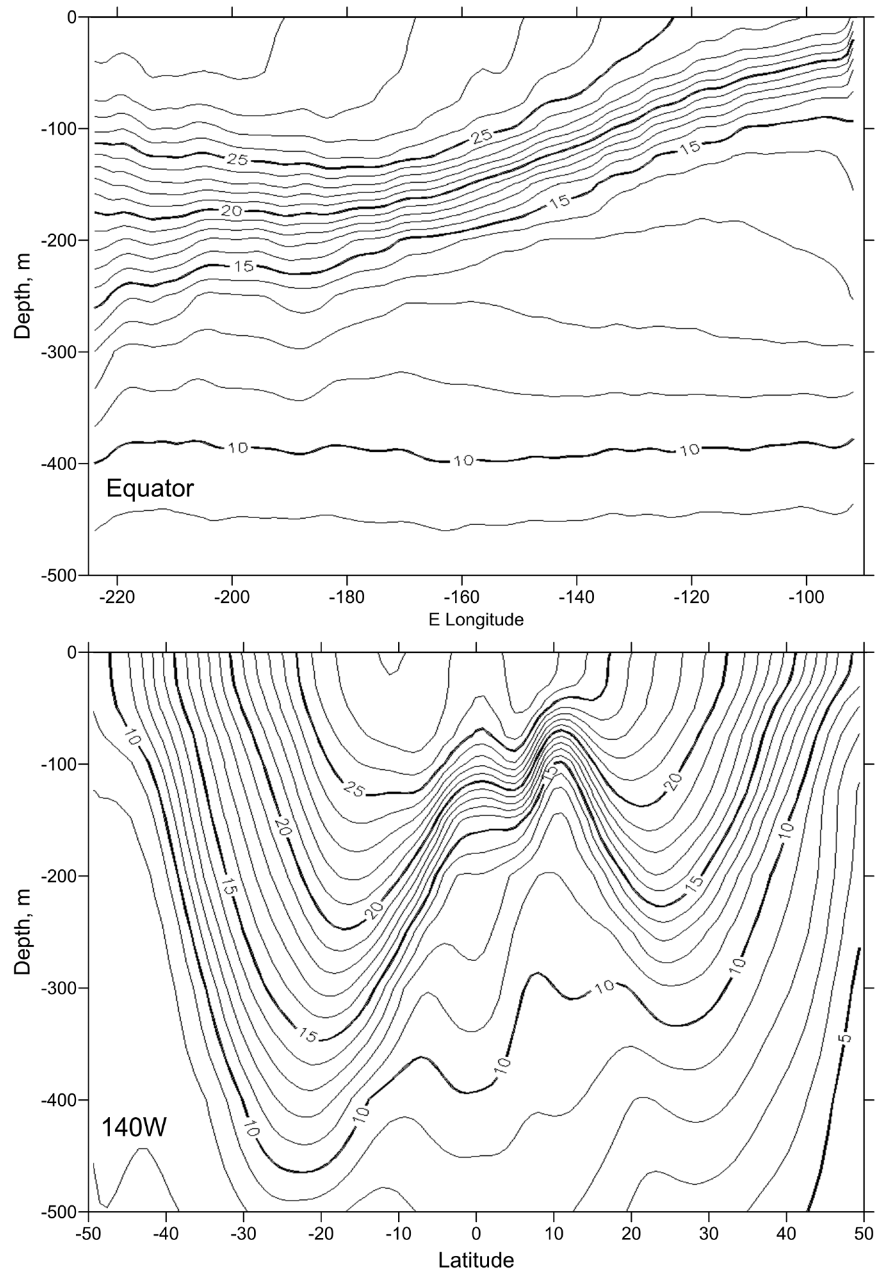

Fig. 2. Climatological temperature sections in the Pacific Ocean along the equator (top) and 140°W (bottom). From NODC World Ocean Atlas 2005 through the National Virtual Ocean Data System (http://ferret.pmel.noaa.gov/NVODS/).

tropical Pacific. This kind of index gives no information about the shape of the thermocline, so will not be considered here.

This article compares five methods to objectively estimate thermocline parameters for 200 CTD profiles collected in a wide area of the tropical and North Pacific Ocean. Mixed layer depth, thermocline depth, and thermocline strength are compared with values determined empirically.

Materials and procedures

Data—The Protected Resources Division of the NOAA/National Marine Fisheries Service Southwest Fisheries Science Center has collected CTD temperature and salinity profiles on cetacean survey cruises since 1986. Two hundred profiles collected since 2005 were selected from three surveys (Fig. 3): PICEAS 2005 (Pacific Islands Cetacean Ecosystem Assessment Survey, 11 August–15 November, 40 of 135 CTD stations SW of the Hawaiian Islands), STAR 2006 (Stenella Abundance Research, 28 July –7 December, 100 of 343 CTD stations between Baja California, Peru, and Hawaii), and ORCAWALE 2008 (Oregon California Washington Line-Transect and Ecosystem, 28 July –7 December, 60 of 86 CTD stations off the west coast of the United States). The profiles were

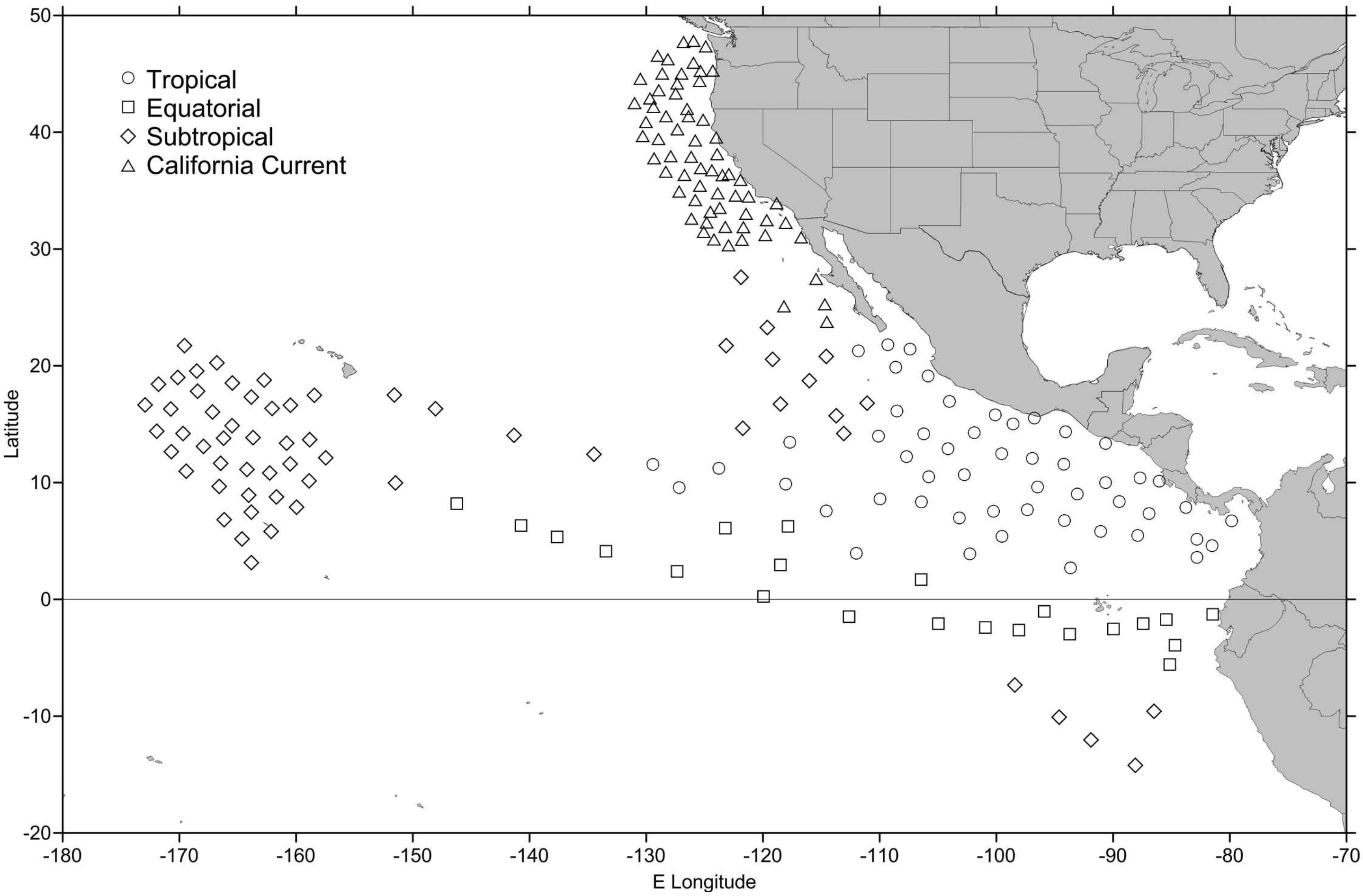

Fig. 3. Locations of selected CTD profiles, classified as in Fig. 4.

selected to cover the entire geographical range and the variety of observed profile shapes in each survey area. All profiles were collected with a Sea-Bird 911plus CTD and deck unit and a current version of Sea-Bird's Seasave software; data were processed using Sea-Bird's SBE Data Processing, Version 7. Profile data were averaged in 1-m bins for subsequent analyses.

Figure 4 shows plots of the selected temperature profiles grouped into four regional classes that have reasonably consistent characteristics. Tropical profiles show the shallow and intense thermocline, underlying warm, low-salinity Tropical Surface Water, which is characteristic of the eastern tropical Pacific (Fiedler and Talley 2006). Equatorial profiles show thermoclines that can be just as steep as tropical profiles, but underlie cooler and higher-salinity Equatorial Surface Water so that there is not a pronounced halocline. Subtropical thermoclines tend to underlie warm and high-salinity Subtropical Surface Water and are relatively deep and weak, often with a characteristic double thermocline (Polton and Marshall 2003). California Current profiles show thermoclines that can be as steep as in the tropics, although surface waters are not as warm. These profiles often have temperature inversions either within or below the thermocline, caused by interleaving of cold, low-salinity Subarctic Water in the core of the California Current with warm, high-salinity North Pacific Subtropical Water (Sprintall and Cronin 2001).

Estimating thermocline parameters—

Empirical determination: The 200 selected profiles were examined by eye to estimate thermocline parameter values. A Visual Basic program, ProfileViewer, had been written to facilitate viewing and editing of XBT and CTD profiles. ProfileViewer allows the user to place a line segment along the thermocline and move the endpoints until a satisfactory approximation of the thermocline is obtained. The upper endpoint is placed where the decline of temperature in the mixed layer changes significantly, usually a sharp or rounded "corner" in the profile. Mixed layer depth, MLD, is the depth of this endpoint. The lower endpoint is placed at the bottom of the thermocline, ideally where the temperature gradient lessens in subthermocline waters. Thermocline depth, TD, is the midpoint of the line segment; thermocline strength (TS) is the slope of the line segment. In practice, there is a great deal of subjective uncertainty in this process. Identifying the bot-

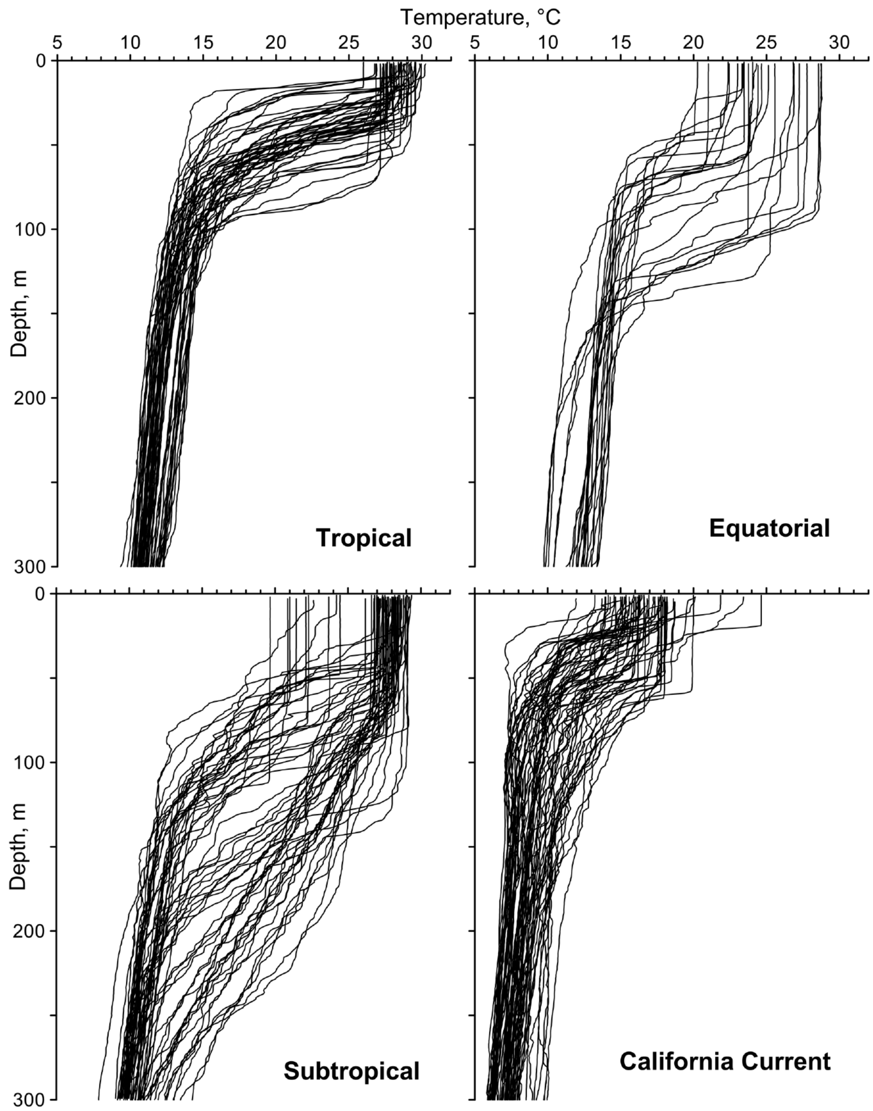

Fig. 4. Selected CTD temperature profiles in four regional classes from three surveys (Fig. 3).

tom of the mixed layer is usually easy, but this point does not correspond to the top of the thermocline if there is not a sharp "corner" or change in slope. In this case, the point marking the top of the thermocline is moved deeper than MLD to better define the thermocline. Likewise, there is often not an obvious discontinuity at the bottom of the thermocline layer. When the profile shows more than one depth interval with a steep temperature gradient (for example, the double "subtropical" thermoclines in Fig. 4), only one thermocline is marked to encompass the steepest gradient. The values of thermocline parameters determined using the best judgment of the author are used as the standard for comparison of values estimated by the five automated, objective methods described below.

(1) Maximum slope by difference: This method was used in earlier analyses and applications of our survey data (e.g., Reilly and Fiedler 1994) and was also used by Fiedler and Talley (2006). The thermocline is defined as the line segment with maximum slope ($-dT/dz$), between any two temperature-depth observations with $dz \geq 20$ m, or with both $dz \geq 10$ m and $dT \geq 2$°C. Thermocline depth is the depth of the midpoint of this line segment. Thermocline strength is the slope of this line segment. Mixed layer depth is estimated independently of the thermocline, as the depth at which T = SST-0.5°C, the temperature criterion of Monterey and Levitus (1997).

(2) Maximum slope by regression: This method is a modification of (1), motivated by the observation that the depth and temperature intervals used to define the thermocline by that method were too narrow. Instead, the line segments were fit by linear regression through points in the observed profile that covered a temperature range equal to at least $0.6 \times [T(MLD) - T(400m)]$, to find the line segment with the maximum slope ($-dT/dz$). The factor of 0.6 was selected after trials

using values from 0.3 to 0.8. Thermocline depth is the depth of the midpoint of this line segment. Thermocline strength is the slope of this line segment. It is important to note that the thermocline segment fit by this method covers a greater temperature interval than does the segment fit by method (1); the endpoints of the line segment fit by linear regression do not even have to be on the profile itself. Mixed layer depth is estimated independently of the thermocline, as the depth at which T = SST-0.8°C (Kara et al. 2000, 2003).

(3) Four-segment profile model: This method fits four contiguous line segments to the temperature profile. The segments are defined by 8 parameters: (1) temperature at 0 m, (2) change in temperature from the surface to the bottom of the mixed layer, (3) change in depth from the surface to the bottom of the mixed layer (mixed layer depth), (4) change in temperature from the bottom of the mixed layer to the bottom of the thermocline, (5) change in depth from the bottom of the mixed layer to the bottom of the thermocline (thermocline depth is the midpoint of this range, thermocline strength is the change in temperature divided by the change in depth), (6) change in temperature from the bottom of the thermocline to the deep-water segment, (7) change in depth from the bottom of the thermocline to the deep-water segment, (8) change in temperature over the deep-water segment (depth interval fixed at 100 m). Parameter values were selected to minimize the deviations of predicted from observed temperature, using the AMOEBA subroutine (Numerical Recipes in Fortran 77, Second Edition [1992], 10.4 Downhill Simplex Method in Multidimensions). AMOEBA iteratively searches in multidimensional space for the parameter values defining the segments that give the best fit to the observed profile. Examples of the four-segment profile model can be seen in Fig. 5.

This method differs from the maximum slope methods (1 and 2) in that the top of the thermocline is identical to the base of the mixed layer. Other authors have fit ideal functions, usually sigmoid in shape, to observed temperature profiles (Chan and Matthews 2005; González-Pola et al. 2007).

(4) Inflection point: This method also fits line segments to the temperature-depth profile. It was tested as a surrogate of the split-and-merge algorithm proposed by Thomson and Fine (2003) for the estimation of mixed layer depth. Their algorithm consists of a piecewise fit of contiguous line segments to the standardized temperature-depth profile by an iterative adjustment procedure until no temperature observation departs from the linear fit value at that depth by more than a specified amount. They found a slight improvement in esti-

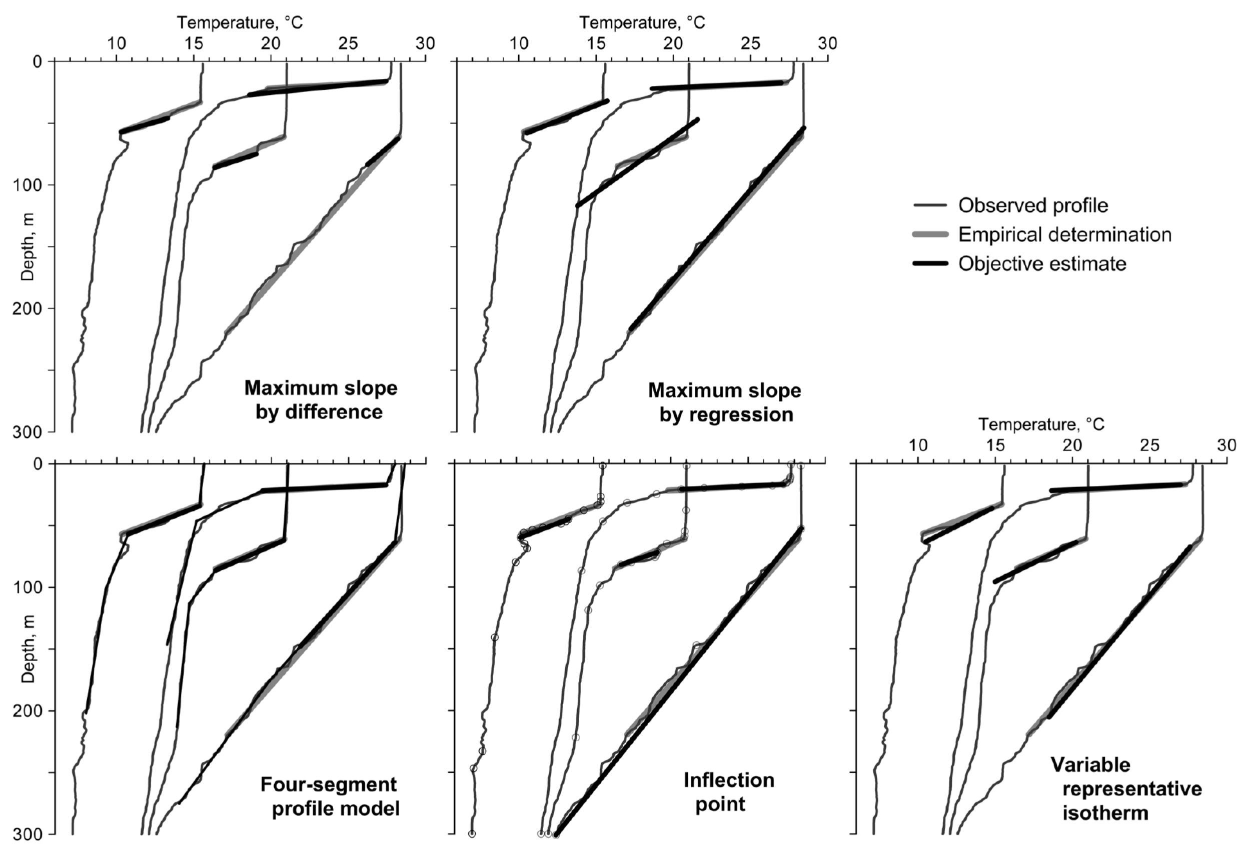

Fig. 5. Estimated thermoclines from the five objective methods compared with empirically determined thermoclines (identical in each panel) for four typical observed profiles: from left to right in each panel, California Current, tropical, equatorial, subtropical. In the four-segment profile model panel, all four segments are plotted along with the thermocline segment. In the inflection point method panel, inflection points are plotted (circles).

mates of the "true" mixed layer depth using their method compared with temperature threshold methods for the continental margin waters of British Columbia, and suggested that the method might be used to "simultaneously determine other structural features of the upper ocean" such as thermocline depth.

The inflection point algorithm was formerly used to compress MBT or XBT profiles for radio transmission by reducing the number of observed points needed to adequately approximate the observed full-resolution profile. The first inflection point is the first temperature-depth observation. Subsequent inflection points are found by sequentially testing deeper observations, determining the maximum departure of intervening observed temperatures from the line segment between the previous inflection point and the test point, until a specified departure is exceeded. The only difference between the inflection point algorithm and the split-and-merge algorithm is that the endpoints of the piecewise line segments are observed temperature-depth points. Thus, split-and-merge adjustments are not required.

The permissible maximum departure of standardized temperature was 0.03 (3% of the temperature range from 0 to 300 m). Mixed layer depth is defined as the depth of the second inflection point. Thermocline depth is defined as the midpoint of the segment connecting inflection points that has the maximum slope (–dT/dz). In trials to determine the optimum maximum departure, it was observed that the relatively small intervals between inflection points resulted in biased estimates of thermocline parameters (see discussion of the results of the maximum slope by difference method below). Therefore, segments adjacent to the initial thermocline segment with maximum slope were combined with the initial segment as long as the maximum departure of standardized temperature did not exceed twice the value used to find inflection points (0.06). This procedure resulted in extending the thermocline segment upwards by up to 6 inflection points (average 2.05) and downwards by up to 4 inflection points (average 1.3), for a final number of inflection points ranging from 5 to 29 (average = 12.3).

Both the inflection point and four-segment profile model methods approximate the observed temperature-depth profile with line segments. The major difference is that the number of line segments between inflection points fit to the profile is not fixed. Other differences are (1) inflection points defining the fitted line segments are observed temperature-depth points, and (2) the top of the thermocline segment is not necessarily the base of the mixed layer.

(5) Variable representative isotherm: This method is a modification of Wang et al. (2000). The isotherm representing the thermocline is defined as thermocline temperature TT = T(MLD) – 0.25 [T(MLD) – T(400 m)], where the temperature at the base of the mixed layer T(MLD) = SST – 0.8. In other words, the thermocline is the layer from the base of the mixed layer to the depth at which temperature has dropped halfway toward the deep-water temperature at 400 m; thermocline depth is the midpoint of that layer. Mean temperature at 400 m is 8°–10°C in the tropical Pacific and 5°–8°C in the California Current (Levitus and Boyer 1994). Wang et al. (2000) used TT = 0.5 (SST + 12), where SST is a local climatological sea-surface temperature and 12°C is a typical temperature at 350 m in the tropical Pacific. This is equivalent to TT = SST – 0.5 (SST-12). Thus, the modification should be applicable over a wider geographical range where SST < 12°C. Thermocline strength is the slope of the temperature-depth segment connecting a point below the mixed layer representing the top of the thermocline and the thermocline depth.

Fig. 5 shows thermoclines objectively estimated for a typical CTD profile of each of the four regional types, along with the empirically determined thermocline. The estimated thermoclines are represented by line segments, the midpoint and slope of which are the estimated thermocline depth and strength. It is apparent that the two maximum slope methods give different results because they examine slopes over intervals of different size. Regression allows line segments covering larger intervals than does differencing. Both of these methods picked the deeper of the double subtropical thermocline, which is not desirable because the pycnocline corresponds more closely to the shallow thermocline. The four-segment profile model does fit the subtropical thermocline as intended. Further tuning of this algorithm might improve results, but it is very difficult to get good results fitting the model to a wide variety of thermocline shapes. The thermocline line segment illustrating the result of the variable representative isotherm method can extend beyond the "shoulders" at the base of the mixed layer or thermocline, but this has only a small effect on the estimated depth of the thermocline.

Comparison of parameter value estimates is quantified as the mean and standard deviation of differences between objective and empirical estimates. The standard deviation of differences is equivalent to RMSE since the departure of the objectively estimated value from the empirically-determined "real" value can be considered an error. This statistic differs from a residual mean square or a correlation coefficient, because the covariation of values should be 1:1.

An additional measure of stratification was tested as an alternative to thermocline strength as defined above, the standard deviation of temperature with depth between 0 and 200m (sdT). This measure requires only a temperature profile and will vary with both the temperature range and the slope of temperature gradients within the upper 200 m of the water column. Standard deviation of temperature was compared to a stratification parameter that is widely used, but requires both temperature and salinity profiles - potential energy anomaly (φ, J m^{-3}; Simpson et al. 1981):

$$\varphi = \frac{1}{h}\int_{-h}^{0}\left(\rho - \bar{\rho}\right) gz\,dz \qquad (1)$$

where ρ is density, and departures from mean density were integrated from z = 0 to 200 m (*h*). φ is the amount of work per unit volume required to redistribute the mass in a complete mixing to depth *h*.

Assessment

As expected, there is no single isotherm that represents the depth of the thermocline as determined empirically (Fig. 6). Even in the tropical Pacific, the thermocline temperature ranges from 16 to 26°C. This result confirms the need for a better method to objectively determine thermocline depth and other parameters describing the shape of the temperature profile.

Four methods were tested to estimate mixed layer depth including two temperature threshold criteria (Fig. 7). The temperature criterion of (SST-0.5°C) gives fairly good estimates

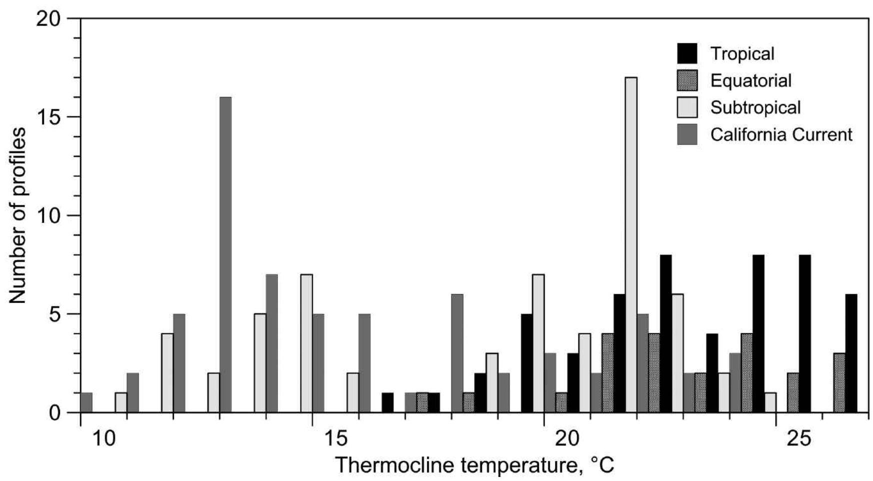

Fig. 6. Distribution of temperatures at the empirically determined thermocline depth in 200 CTD casts.

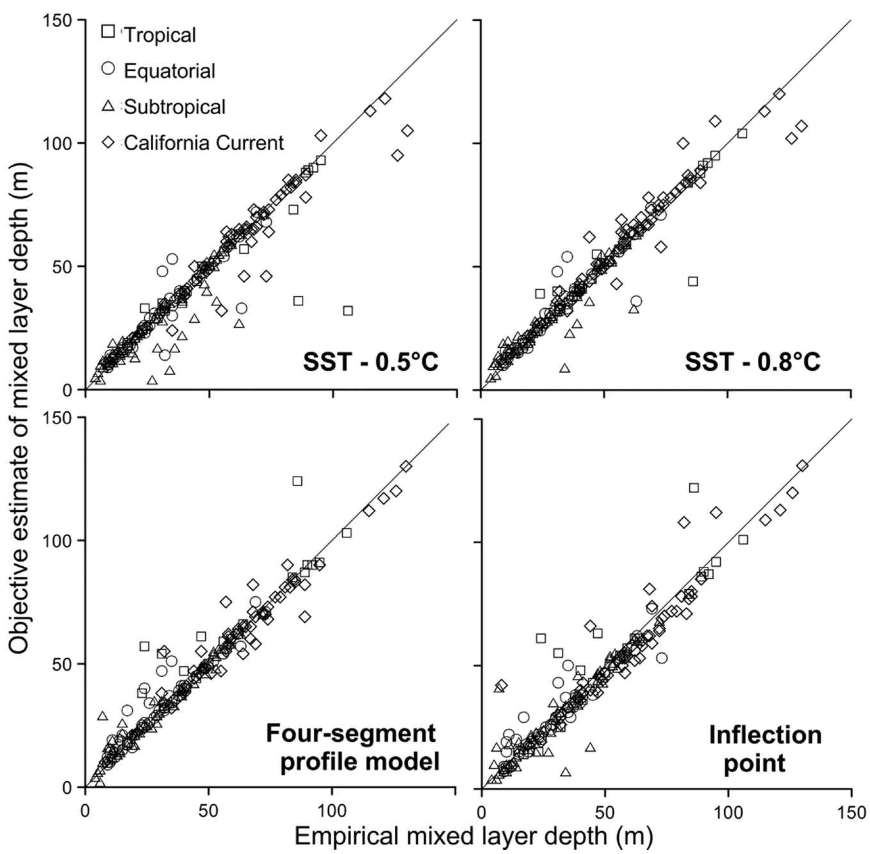

Fig. 7. Mixed layer depth (MLD, m) estimated by four objective methods, compared with the empirically determined MLD (x-axis).

(RMSE = 9.4 m), with a tendency to slightly overestimate the depths of mixed layers that are nearly isothermal and have a clear discontinuity at the base (the plotted points along the 1:1 line), but to underestimate the depths of mixed layers that have some stratification (the points below the 1:1 line). The temperature criterion of (SST-0.8°C) gives better estimates (RMSE = 6.7m), but has the same pattern of errors. Mixed layer depth estimated from the four-segment profile model method is slightly more accurate overall (RMSE = 6.3 m), but tends to overestimate. The inflection point method gives less accurate estimates (RMSE = 8.1 m)(Table 1).

Five objective methods to estimate thermocline depth were tested (Fig. 8). The simple maximum slope by difference method does not give a good estimate (mean error = +0.4 m, but RMSE = 23.1 m), especially for deeper subtropical thermoclines. The modified maximum slope by regression method gives more consistent but biased estimates (mean error = +9.1 m, RMSE = 14.4 m), tending to overestimate the depth of subtropical thermoclines. The four-segment profile model gives good estimates for some profiles (mean error = –5.3 m, RMSE = 15.2 m), but underestimates the depth of deeper subtropical thermoclines. Inspection of individual fits shows very good model fits for profiles with a well-defined mixed layer and pronounced thermocline, but the fitting algorithm fails for profiles that are not well described by the model (e.g., subtropical double thermoclines). The variable representative isotherm method gives the best estimates (mean error = –1.2 m, RMSE = 10.0 m). This method does tend to overestimate some deeper subtropical thermocline depths, but the errors are much less than for other methods (Table 2).

Table 1. Differences from empirically determined mixed layer depths for four methods of objective estimation.

Mixed layer depth	(objective – empirical), m Mean	RMSE
Temperature threshold (SST –0.5°C)	–1.8	9.4
Temperature threshold (SST –0.8°C)	+1.2	6.7
Four-segment profile model	+1.5	6.3
Inflection point	–1.1	8.1

Objective estimates of thermocline strength gave similar results (Fig. 9, Table 3). Note that TS values were log-transformed, since frequency distributions were highly skewed. Therefore, RMSE values are a unitless ratio. As expected, the deeper subtropical thermoclines had lower values of thermocline strength, because the base of the thermocline deepened while the top of the thermocline remained at the base of the mixed layer. The maximum slope by difference method gives

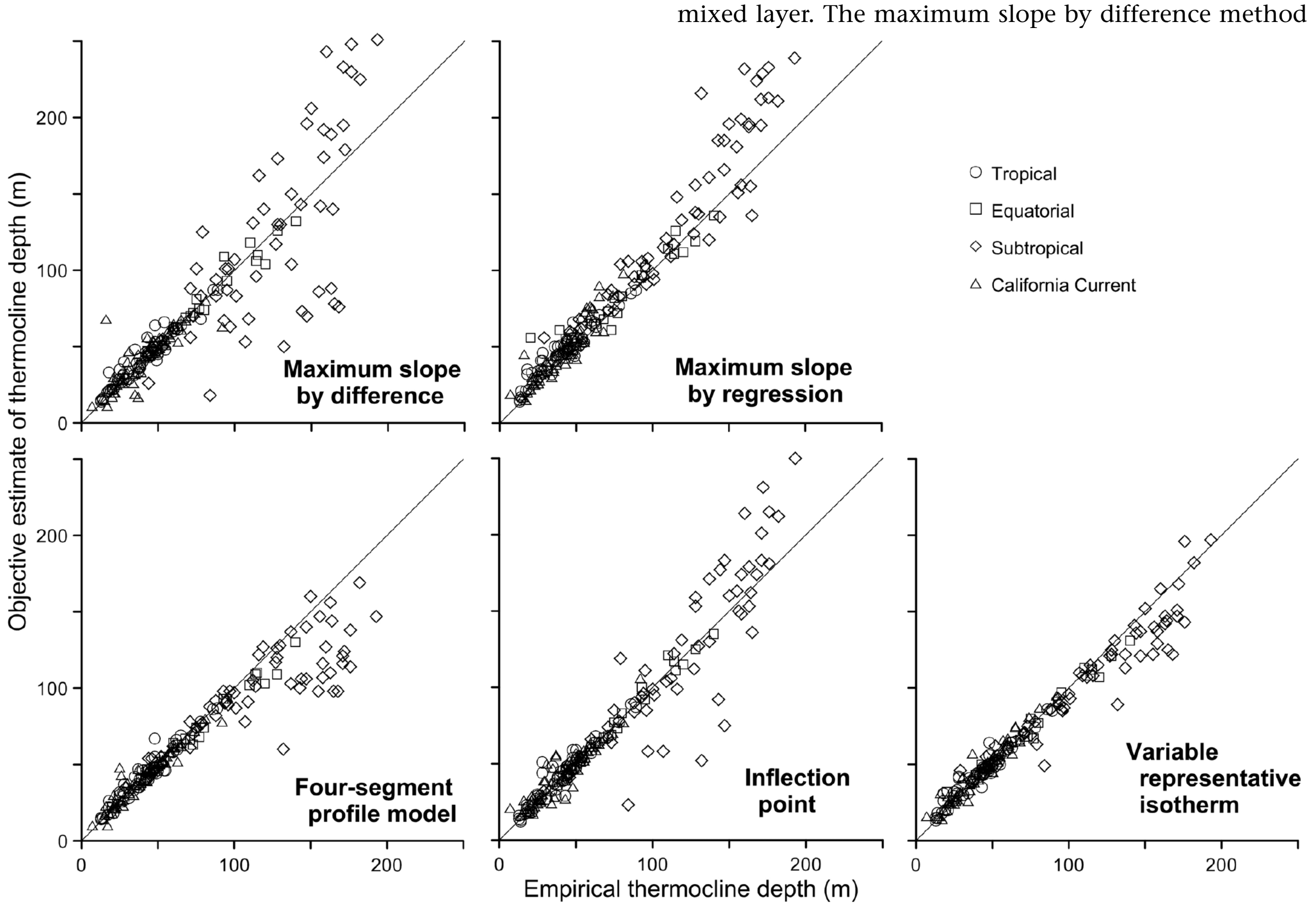

Fig. 8. Thermocline depth (TD, m) estimated by five objective methods, compared with the empirically determined thermocline depth (x-axis).

biased estimates (mean error = 1.22, RMSE = 1.45) that are too high for weaker thermoclines, because it tests slopes over a smaller interval than was used to empirically define the thermocline. The maximum slope by regression method tends to underestimate TS (mean error = 0.72, RMSE = 1.62), because it tests slope over wider intervals of the profile. Both the four-segment profile model and inflection point method give good estimates (mean error = 1.04 and 1.02, RMSE = 1.32 and 1.34, respectively) with a slight tendency to overestimate thermocline strength. The variable representative isotherm method gives somewhat less accurate estimates of thermocline strength (mean error = 0.89, RMSE = 1.56), with a slight tendency to underestimate (Table 3).

Table 2. Differences from empirically determined thermocline depths for five methods of objective estimation.

	(objective – empirical), m	
Thermocline depth	**Mean**	**RMSE**
Maximum slope by difference	+0.4	23.1
Maximum slope by regression	+9.1	14.4
Four-segment profile model	–5.1	15.8
Inflection point	+1.4	15.8
Variable representative isotherm	–1.2	10.0

Discussion

Mixed layer depth is well estimated by the temperature criterion of (SST-0.8°C), confirming the results of Kara et al. (2000). Other studies have used temperature criteria varying between –0.1 and –1.0°C relative to a reference temperature representing SST (Table 1 in de Boyer et al. [2004]). If the mixed layer must be differentiated from the isothermal layer, as in studies of the barrier layer (e.g., Qu and Meyers 2005), this criterion would not be appropriate, and mixed layer depth should be determined from density data.

Thermocline depth is well estimated by the variable representative isotherm method. As mentioned above, maximum

Table 3. Ratios relative to empirically determined thermocline strengths for five methods of objective estimation.

	(objective – empirical), m	
Thermocline strength	**Mean**	**RMSE**
Maximum slope by difference	1.22	1.45
Maximum slope by regression	0.72	1.62
Four-segment profile model	1.04	1.32
Inflection point	1.02	1.34
Variable representative isotherm	0.89	1.56

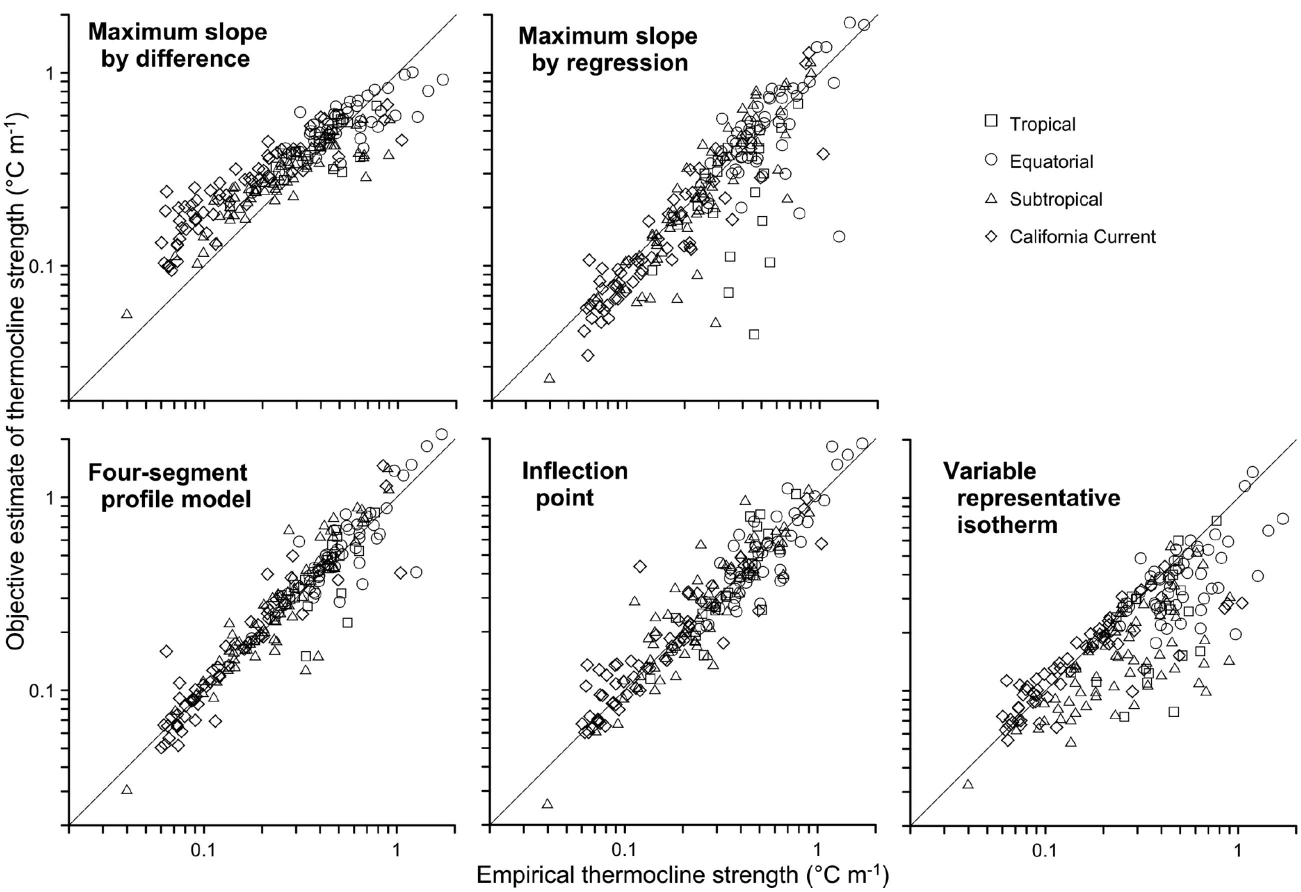

Fig. 9. Thermocline strength (TS,°C m^{-1}) estimated by four objective methods, compared with the empirically determined TS (x-axis).

slope method estimates are affected by the interval over which slope is tested. The four-segment profile model gives very good estimates of thermocline depth, but only for profiles that can be described by the model. The inflection point method also gives relatively good estimates, but seems to require tuning that would restrict its general applicability. Therefore, mixed layer and thermocline depths should be estimated by the (SST-0.8°C) temperature criterion and by the variable representative isotherm method, respectively. The variable representative isotherm method is the computationally least demanding of the four methods tested. This might be important when hundreds of thousands of profiles are analyzed for climatological studies.

Fig. 10 plots thermocline strength against the stratification parameter. Figure 11 shows that temperature accounts for most of the stratification in these CTD profiles. The halocline usually reinforces stratification (points below or to the right of the 1:1 line, φ decreases if salinity variation is not included), but occasionally compensates for thermal stratification (points above or to the left of the 1:1 line, φ increases if salinity variation is not included).

Thermocline strength, quantified as the slope of the temperature-depth profile within the thermocline, does not give a good measure of the degree of stratification of the near-surface water column (r^2 = 0.02). On the other hand, the standard deviation of temperature is a very good index of stratification (r^2 = 0.89). Therefore, it is recommended that the thermocline strength, estimated by slope in the variable representative isotherm method, be augmented with the standard deviation of temperature index of stratification. Standard deviation of temperature is better than range of temperature as an index of stratification because it is influenced by the steepness of the

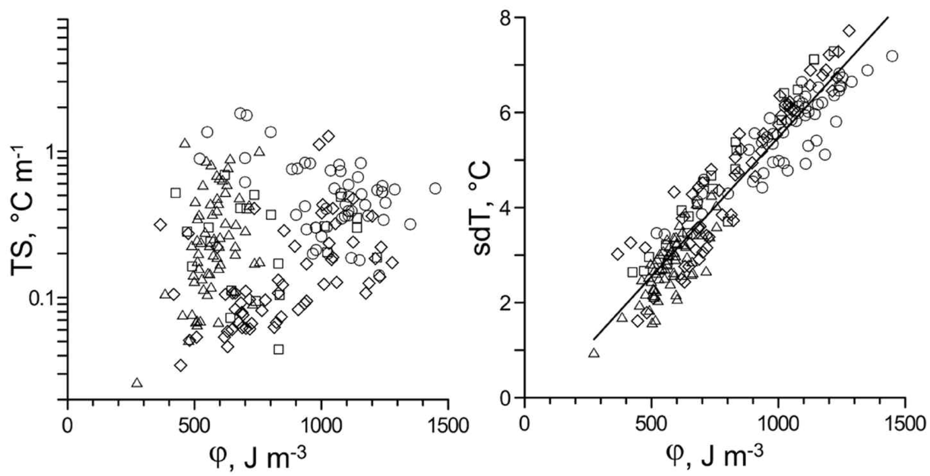

Fig. 10. Thermocline strength (TS) estimated by the variable representative isotherm method (left) and standard deviation of temperature (sdT, 0-200 m, right) plotted against potential energy anomaly (φ), a measure of water column stratification. Symbols indicate regional class of profile as in Figs. 7-9.

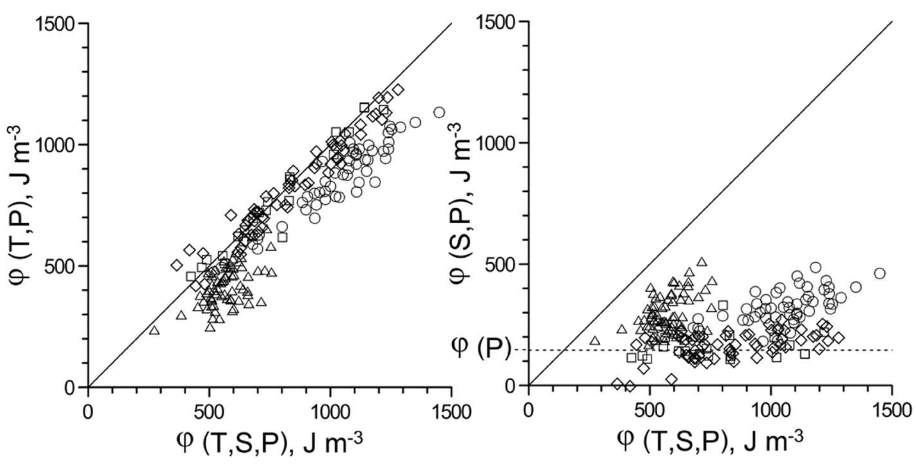

Fig. 11. Potential energy anomaly (φ, 0-200 m) determined from CTD profiles of observed temperature and mean salinity (left) and observed salinity and mean temperature (right) compared with values calculated from observed temperature and salinity (x-axis). The horizontal dashed line is the value of φ calculated using both mean temperature and salinity and thus due only to the effect of increasing pressure on density. Symbols indicate regional class of profile as in Figs. 7-9.

temperature gradient as well as by the temperature difference across the gradient.

The variable representative isotherm method uses observed mixed layer and 400 m temperatures to define thermocline temperature. Use of climatological temperatures, as in Wang et al. (2000), might be necessary when observed profiles do not extend to 400 m. However, experience has shown that this can lead to significant biases at higher latitudes, where the range of temperature through the water column is low and surface or mixed layer temperature can be close to climatological deep-water temperature. Therefore, the variable representative isotherm method may not be the best method for estimating thermocline parameters poleward of 40° latitude. It is certainly not applicable in the North Atlantic at these latitudes, where the mixed layer depth can exceed 400 m during winter (Kara et al. 2003).

In a recent paper, Yang and Wang (2009) show that in studies of climate change, trends in thermocline depth measured as a representative isotherm depth and as the depth of maximum dT/dz can be of opposite sign. They wrote that "During the transient period of global warming, the tropical thermocline is usually enhanced because the surface layer warms more and faster than the lower layers. The depth of maximum vertical temperature gradient shoals, which is consistent with the enhanced thermocline. However, the 20°C isotherm depth deepens, which suggests a weakened thermocline." (p. 3856). Differential heating of the water column (surface versus deep water) will alter the value of the isotherm used to represent the thermocline in the variable representative isotherm method. Therefore, this method of objectively estimating parameters to characterize the thermocline should be useful not only for studies of spatial and annual patterns as in Wang et al. (2000), but also for studies of longer term temporal change.

The results presented here on the objective determination of thermocline characteristics may not be applicable for all problems concerning thermocline structure, function, and variability. However, for purposes of objectively characterizing and monitoring the thermocline as a boundary influencing biological processes and distributions in the marine environment, recommendations are as follows.

Comments and recommendations

1) Thermocline depth in most tropical and temperate waters can be accurately estimated as the depth of a representative isotherm intermediate between the base of the mixed layer and deep water (400 m).

2) The depth of weak and broad subtropical thermoclines are difficult to estimate precisely by any method, but the variable representative isotherm method gave the best results of the five objective methods tested here.

3) Thermocline strength estimated as the slope of the line segment representing the thermocline, as fit by any method, is not a valid index of density stratification. However, standard deviation of temperature over the near-surface layer is a good index of the stratification of this layer in waters where salinity gradients have a minor influence.

References

Chan, V., and R. Matthews. 2005. Using the generalized F distribution to model limnetic temperature profile and estimate thermocline depth. Ecol. Model. 188:374-385 [doi:10.1016/j.ecolmodel.2005.04.018].

de Boyer Montégut, C., G. Madec, A. S. Fischer, A. Lazar, and D. Iudicone. 2004. Mixed layer depth over the global ocean: an examination of profile data and a profile-based climatology. J. Geophys. Res. 109, C12003. [doi:10.1029/2004JC002378].

Donguy, J. R., and G. Meyers. 1987. Observed and modeled topography of the 20°C isotherm in the tropical Pacific. Oceanol. Acta 10(1):41-48.

Fiedler, P. C., and L. D. Talley. 2006. Hydrography of the eastern tropical Pacific: A review. Prog. Oceanogr. 69(2-4):143-180 [doi:10.1016/j.pocean.2006.03.008].

González-Pola, C., J. M. Fernández-Diaz, and A. Lavín. 2007. Vertical structure of the upper ocean from profiles fitted to physically consistent functional forms. Deep-Sea Res. I 54:1985-2004 [doi:10.1016/j.dsr.2007.08.007].

Kara, A. B., P. A. Rochford, and H. E. Hurlburt. 2000. An optimal definition for ocean mixed layer depth. J. Geophys. Res. 105:16803-16821 [doi:10.1029/2000JC900072].

———, P. A. Rochford, and H. E. Hurlburt. 2003. Mixed layer depth variability over the global ocean. J. Geophys. Res. 108:3079 [doi:10.1029/2000JC000736].

Kessler, W. S. 1990. Observations of long Rossby waves in the northern tropical Pacific. J. Geophys. Res. 95:5183-5217 [doi:10.1029/JC095iC04p05183].

———, M. J. McPhaden, and K. M. Weickmann. 1995. Forcing of intraseasonal Kelvin waves in the equatorial Pacific. J. Geophys. Res. 100:10613-10631 [doi:10.1029/95JC00382].

Kim, H.-J., and A. J. Miller. 2007. Did the thermocline deepen in the California Current after the 1976/77 climate regime shift? J. Phys. Oceanogr. 37:1733-1739 [doi:10.1175/JPO3058.1].

Levitus, S., and T. P. Boyer. 1994. World ocean atlas 1994, Vol. 4: temperature. NOAA Atlas NESDIS 4, U. S. Govt. Printing Office.

Meyers, G. 1979a. Annual variation in the slope of the 14°C isotherm along the equator in the Pacific Ocean. J. Phys. Oceanogr. 9:885-891 [doi:10.1175/1520-0485(1979)009<0885:AVITSO>2.0.CO;2].

Meyers, G. 1979b. On the annual Rossby wave in the tropical north Pacific Ocean. J. Phys. Oceanogr. 9:663-674 [doi:10.1175/1520-0485(1979)009<0663:OTARWI>2.0.CO;2].

Miller, A. J., W. B. White, and D. R. Cayan. 1997. North Pacific thermocline variations on ENSO timescales. J. Phys. Oceanogr. 27:2023-2039 [doi:10.1175/1520-0485(1997)027<2023:NPTVOE>2.0.CO;2].

Monterey, G., and S. Levitus. 1997. Seasonal variability of mixed layer depth for the world ocean. NOAA Atlas NESDIS 14, U. S. Govt. Printing Office.

Palacios, D. M., S. J. Bograd, R. Mendelssohn, and F. B. Schwing. 2004. Long-term and seasonal trends in stratification in the California Current, 1950-1993. J. Geophys. Res. 109:C10016 [doi: 10.1029/2004JC002380].

Pedlosky, J. 2006. A history of thermocline theory, p.139-152. *In*: M. Jochum and R. Murtugudde [eds.], Physical oceanography: Developments since 1950. Springer.

Pizarro, O., and A. Montecinos. 2004. Interdecadal variability of the thermocline along the west coast of South America. Geophys. Res. Letters 31:L20307 [doi:10.1029/2004GL020998].

Polton, J. A., and D. P. Marshall. 2003. Understanding the structure of the subtropical thermocline. J. Phys. Oceanogr. 33:1240-1249 [doi:10.1175/1520-0485(2003)033<1240:UTSOTS>2.0.CO;2].

Qian, W., and H. Hu. 2006. Interannual thermocline signals and El Niño–La Niña turnabout in the tropical Pacific Ocean. Adv. Atmos. Sci. 23:1003-1019 [doi:10.1007/s00376-006-1003-4].

Qu, T., and G. Meyers. 2005. Seasonal variation of barrier layer in the southeastern tropical Indian Ocean. J. Geophys. Res. 110:C11003 [doi:10.1029/2004JC002816].

Reilly, S. B., and P.C. Fiedler. 1994. Interannual variability of dolphin habitats in the eastern tropical Pacific. I: Research vessel surveys, 1986-1990. Fish. B.-NOAA 92(2):434-450.

Sharp, D. G., and D. R. McLain. 1993. Fisheries, El Niño-Southern Oscillation and upper-ocean temperature records: an eastern Pacific example. Oceanography 6(1):13-22.

Simpson, J. H., D. J. Crisp, and C. Hearn. 1981. The shelf-sea fronts: implications of their existence and behaviour. Phil. Trans. R. Soc. Lond., Ser. A 302(1472):531-546.

Sprintall, J., and D. Roemmich. 1999. Characterizing the structure of the surface layer in the Pacific Ocean. J. Geophys. Res. 104:23292-23311 [doi:10.1029/1999JC900179].

———, and M. F. Cronin. 2001. Upper ocean vertical structure, p. 3120-3128. *In*: J. H. Steele [ed.], Encyclopedia of ocean sciences. Elsevier.

Thomson, R. E., and I. V. Fine. 2003. Estimating mixed layer depth from oceanic profile data. J. Atmos. Ocean. Tech. 20:319-329 [doi:10.1175/1520-0426(2003)020<0319:EMLDFO>2.0.CO;2].

Wang, B., R. Wu, and R. Lukas. 2000. Annual adjustment of the thermocline in the tropical Pacific Ocean. J. Climate 13:596-616 [doi:10.1175/1520-0442(2000)013<0596:AAOTTI>2.0.CO;2].

Yang, H., and F. Wang. 2009. Revisiting the thermocline depth in the equatorial Pacific. J. Climate 22:3856-3863 [doi:10.1175/2009JCLI2836.1].

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