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An optimal definition for ocean mixed layer depth

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Abstract. A new method is introduced for determining ocean isothermal layer depth (ILD) from temperature profiles and ocean mixed layer depth (MLD) from density profiles that can be applied in all regions of the world's oceans. This method can accommodate not only in situ data but also climatological data sets that typically have much lower vertical resolution. The sensitivity of the ILD and MLD to the temperature difference criteria used in the surface layer depth definition is discussed by using temperature and density data, respectively: (1) from 11 ocean weather stations in the northeast Pacific and (2) from the *World Ocean Atlas 1994*. Using these two data sets, a detailed statistical error analysis is presented for the ILD and MLD estimation by season. MLD variations with location due to temperature and salinity are properly accounted for in the defining density ($\Delta\sigma_t$) criterion. Overall, the optimal estimate of turbulent mixing penetration is obtained using a MLD definition of ΔT=0.8°C, although in the northeast Pacific region the optimal MLD criterion is found to vary seasonally. The method is shown to produce layer depths that are accurate to within 20 m or better in 85% or more of the cases. The MLD definition presented in this investigation accurately represents the depth to which turbulent mixing has penetrated and would be a useful aid for validation of one-dimensional bulk mixed layer models and ocean general circulation models with an embedded mixed layer.

1. Introduction

The ocean mixed layer is generally considered a quasi-homogeneous region in the upper ocean where there is little variation in temperature or density with depth. This definition is based on profiles from in situ data that clearly reveal the presence of approximately uniform vertical regions of temperature and salinity starting at the ocean surfaces or at some shallow depth below [e.g., *Roden*, 1979; *Pickard and Emery*, 1990; *Monterey and Levitus*, 1997]. These regions of vertical uniformity owe their existence to turbulent mixing generated from the energy input by the action of wind stress and heat fluxes at the ocean surface. This turbulent origin is what has motivated many successful theoretical descriptions of the ocean mixed layer through different representations of turbulence in numerical models [*Welander*, 1981; *Large et al.*, 1994; *Skyllingstad et al.*, 1996].

A common difficulty encountered is relating the mixed layer depth (MLD) predicted by turbulence models to the observations. One reason for this is that the depth of turbulent mixing is sensitive to the thermal and density stratification at the base of the mixed layer and, thereby, to the criteria chosen to define MLD. The other reason is because the retreat of turbulent mixing to shallower depths proceeds much faster than the erosion of the stratification at the base, making a turbulent definition of MLD inconsistent with an in situ data definition when there is a relaxation in winds. One-dimensional models with high vertical resolution do quite well at reproducing observed MLDs from their modeled temperature and density profiles when forced with observational winds and heat fluxes [*Kantha and Clayson*, 1994]. However, this is much more of a challenge when implementing such mixing models into ocean general circulation models (OGCMs), as the latter are typically constrained to using lower vertical resolution and higher "background" diapycnal diffusion, and they often use climatological surface forcing [e.g., *Cherniawsky and Holloway*, 1991]. Moreover, an OGCM often uses vertical interpolation or a prognostic equation to predict the MLD [e.g., *McCreary et al.*, 1993; *Sterl and Kattenberg*, 1994].

Comparison against a MLD climatology is frequently desired when developing an OGCM with an embedded mixed layer as it helps to validate the implemented tur-

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bulent physics over ocean basins on monthly to annual timescales [*Sterl and Kattenberg*, 1994]. A MLD definition that seeks to represent turbulent mixing as well as possible and yet is also robust enough for construction of a global MLD climatology from existing in situ climatologies would be a useful aid for validating mixed layer performance in OGCMs. The benefits of such a MLD definition extend far beyond OGCM validation as many MLD climatologies have been used to investigate a variety of ocean properties. These include investigating where penetrative solar radiant heat fluxes affect ocean mixed layer heating [*Ohlmann et al.*, 1996], determining regions of barrier layers where salinity effects impede vertical heat flux out of the base of the mixed layer [*Sprintall and Tomczak*, 1992], and using MLD climatologies as part of constraints or inputs for an OGCM in various heat flux, sea surface temperature (SST), and circulation studies [*Spall*, 1991; *Huang and Russel*, 1994]. Moreover, having such valuable MLD information would help modelers to couple atmosphere and ocean models realistically and to understand the seasonal variations in the productivity of ocean ecosystems [*Obata et al.*, 1996]. MLD is also of particular importance not only because thin mixed layers are more conducive to surface cooling by wind-induced upwelling but more importantly because the mixed layer thickness determines the volume or mass over which the net surface heat flux comes to be distributed [*Chen et al.*, 1994].

Several isothermal and MLD criteria that have been used in the literature are given in Table 1. All the definitions in the studies applied a simple criterion for determining ocean surface layer depth from in situ data on the basis of changes in the properties with depth. They can be separated into two general categories. The first is to define an isothermal layer depth (ILD) from a temperature profile and assume this to be the MLD and the second is to define a MLD from a density profile. Either a property difference or a gradient criterion is used for this definition. For the former the ILD is defined as the depth at which the in situ temperature has decreased to SST$-\Delta T$, for some chosen temperature difference ΔT, while for the MLD it is the depth at which the calculated in situ density has increased by $\Delta\sigma_t$ ($\sigma_t = \rho - 1000\,\mathrm{kg\,m^{-3}}$) from the surface value. With a gradient criterion [e.g., *Bathen*, 1972; *Lukas and Lindstrom*, 1991; *Richards et al.*, 1995] the ILD (MLD) is defined as the depth at which the gradient $\partial T/\partial z$ ($\partial\sigma_t/\partial z$) exceeds a specific value, assuming that a sharp interface exists at the base of the surface layer. Temperature and salinity variations with location are typically ignored in the MLD definitions.

None of the studies above (see also Table 1) presented a quantitative analysis justifying a particular ΔT value as the most appropriate criterion, and only *You* [1995] and *Monterey and Levitus* [1997] compared their results with different approaches. Given the sensitivity of turbulent mixing to the thermal and density stratification at the base of the mixed layer, asking whether these criteria are suitable seems appropriate. Differences in the criteria can lead to considerable differences in the ILD and MLD, which in turn, could influence the study findings, such as the phase and amplitude of the seasonal cycle of MLD. In that regard, one question to investigate is whether the defining criteria for the ILD or MLD should include the influence of seasonal changes in the thermocline or pycnocline, respectively.

In this paper we investigate the sensitivity of the ILD and MLD to various finite difference criteria using a new method for determining such layer depths in the ocean. We chose to develop our method using a finite difference criterion rather than a gradient criterion for two reasons: (1) the latter can only be used with profiles of temperature and salinity that adequately resolve sharp gradients, and (2) a recent experimental study has shown that the ILD based on difference criteria is more stable than the ILD based on gradient criteria [*Brainerd and Gregg*, 1995]. The method introduced here is applicable for both the ILD and MLD defini-

Table 1. Commonly Used ILD and MLD Criteria

Temperature–Based Criterion		Density–Based Criterion	
Author	ΔT	Author	$\Delta\sigma_t$
Thompson [1976]	SST–0.2°C	*Miller* [1976]	$0.125\,\sigma_t$
Lamb [1984]	SST–1.0°C	*Levitus* [1982]	$0.125\,\sigma_t$
Price et al. [1986]	SST–0.5°C	*Lewis et al.* [1990]	$0.13\,\sigma_t$
Kelly and Qiu [1995]	SST–0.5°C	*Spall* [1991]	$0.125\,\sigma_t$
Martin [1985]	SST–0.1°C	*Sprintall and Tomczak* [1992]	$0.5\,(\partial\sigma_t/\partial T)$
Wagner [1996]	SST–1.0°C	*Huang and Russell* [1994]	$0.125\,\sigma_t$
Obata et al. [1996]	SST–0.5°C	*Ohlmann et al.* [1996]	$0.5\,(\partial\sigma_t/\partial T)$
Monterey and Levitus [1997]	SST–0.5°C	*Monterey and Levitus* [1997]	$0.5\,(\partial\sigma_t/\partial T)$

Temperature– and density–based criteria (ILD and MLD, respectively) used for determining the ocean surface layer depth. SST–0.2°C, for example, indicates that the layer depth is defined as the depth where the temperature is 0.2°C less than the SST. Note that most use $0.125\sigma_t$ for the MLD definition because it corresponds to the water mass characteristics of Subtropical Mode Water in the North Atlantic as explained by *Levitus* [1982].

tions at all latitudes and can accomodate the presence of all cases of vertical stratification in the ocean (e.g., fossil layers, inversion layers, and dicothermal layers). We present a thorough analysis of the errors associated with estimating layer depths using different criteria to determine the optimal definition.

Section 2 describes the data sets used in this study, and section 3 explains the detailed methodology for estimating the ILD and MLD. Section 4 verifies the consistency of our methodology by comparing layer depths obtained from the two data sets: a monthly climatology from the *World Ocean Atlas 1994* [*Levitus et al.*, 1994; *Levitus and Boyer*, 1994] (hereinafter referred to as the Levitus data) and a monthly climatology from 11 ocean weather station observations. Section 5 investigates the sensitivity of the ILD (MLD) to temperature differences in the temperature (density) criteria. Section 6 presents the results of the analysis.

2. Data

Monthly averaged temperature and density profiles are used from two different data sources. One of them is the monthly climatology from the Levitus data. The Levitus data contain uniformly gridded monthly climatologies of temperature and salinity at a latitude-longitude grid resolution of 1° × 1°, with 19 standard depth levels to 1000 m. The vertical resolution decreases with depth by 0, 10, 20, 30, 50, 75, 100, 125, and 150 m, every 50 m to a depth of 300 m, and then every 100 m to a depth of 1000 m. The other data source used in this study is the monthly climatology constructed from ocean weather station (OWS) observations in the North Pacific from 1959 to 1990 [*Tabata and Weichselbaumer*, 1992; *Tabata and Peart*, 1992], hereinafter referred to as the OWS data. The 11 stations used in this study (Figure 1) are located at a range of ocean depths, as given in Table 2. Monthly means of OWS temperature and salinity are averaged at each standard level over a 31 year period. The standard levels used in the OWS data set are all at 10 m increments from the surface to a depth of 1000 m. We use these two data sets to confirm that inferring the MLD from Levitus data using our methodology yields values that are consistent with those obtained using long–term monthly time series of higher vertical resolution. The OWS data set is chosen for this purpose because of its easy availability, reliability, and widespread use for one–dimensional mixed layer studies.

For both data sets used in this study the density is calculated using temperature and salinity values at given depths based on the standard United Nations Educational, Scientific, and Cultural Organization (UNESCO) equation of state with no pressure dependence, i.e., zero pressure [*Millero et al.*, 1980; *Millero and Poisson*, 1981]. The inclusion of pressure effects increases the density gradient sufficiently rapidly with depth that it produces a markedly shallower MLD that is strongly inconsistent with the MLDs inferred from the corresponding temperature and salinity profiles. This is illustrated with the Levitus and OWS temperature, density, and salinity profiles to 300 m depth at station J

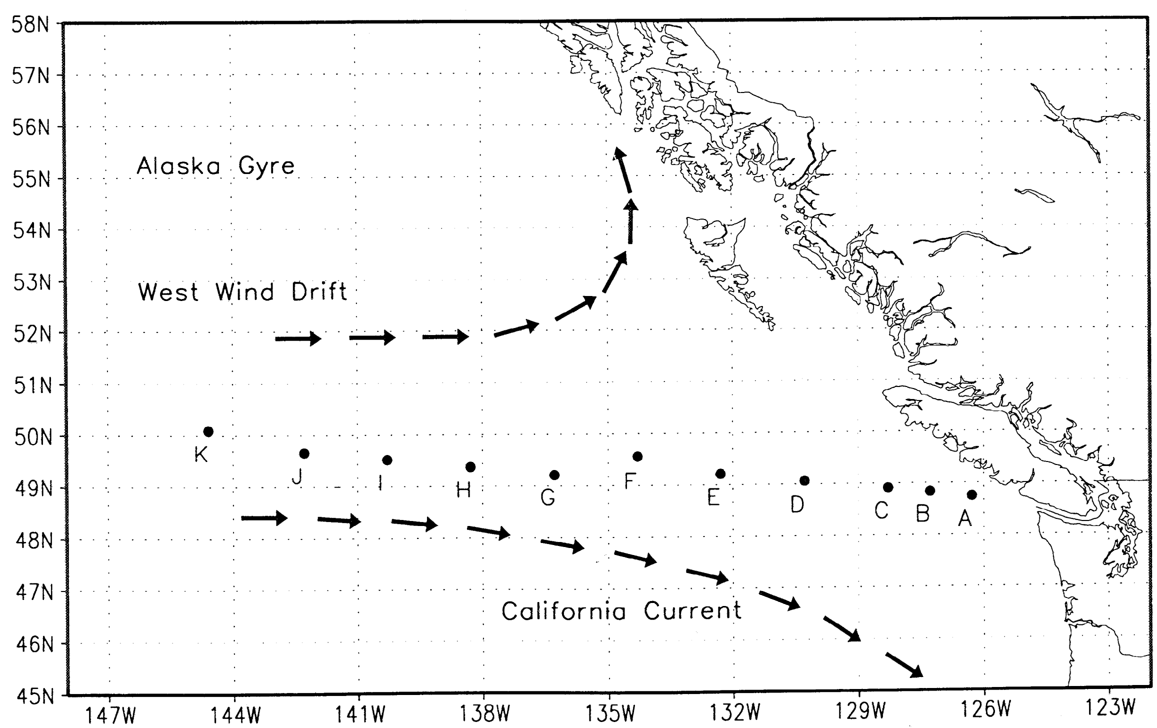

Figure 1. The locations of 11 OWSs in the northeast Pacific Ocean labeled alphabetically from A through K. Major oceanic features include the California Current, the west wind drift, and the Alaska gyre [see *Lynn and Simpson*, 1987].

Table 2. North Pacific Ocean Weather Stations

	OWS	Latitude	Longitude	Depth, m	Distance, km
1	A	48°39.0′N	126°40.0′W	1300	87
2	B	48°44.6′N	127°40.0′W	2500	161
3	C	48°49.0′N	128°40.0′W	2440	233
4	D	48°58.2′N	130°40.0′W	3300	380
5	E	49°07.4′N	132°40.0′W	3275	526
6	F	49°17.0′N	134°40.0′W	3550	672
7	G	49°26.0′N	136°40.0′W	3775	817
8	H	49°34.0′N	138°40.0′W	3890	961
9	I	49°42.0′N	140°40.0′W	3880	1106
10	J	49°50.2′N	142°40.0′W	3910	1250
11	K	50°00.0′N	145°00.0′W	4200	1420

Listed are the maximum depths and offshore distances of the North Pacific OWSs used in this study. Station K located at (50°N, 145°W) is also known as "Ocean Weather Station Papa," and observations from this station have been used in many studies to validate models. Values given are adopted from *Tabata and Brown* [1994].

in February (Figure 2). The temperature, density, and salinity values in both data sets are in very good agreement with each other and corroborate the reliability of these two data sources. The temperatures and salinities in the upper regions of the profiles are, in general, at much the same values as at the surface and clearly show the mixed layer formed due to turbulent mixing from winds and surface heating/cooling. From the profiles it is evident that one must use a pressure–independent equation of state if one is to be consistent with the temperature and salinity profiles in determining a MLD. (Note here that the pressure–dependent

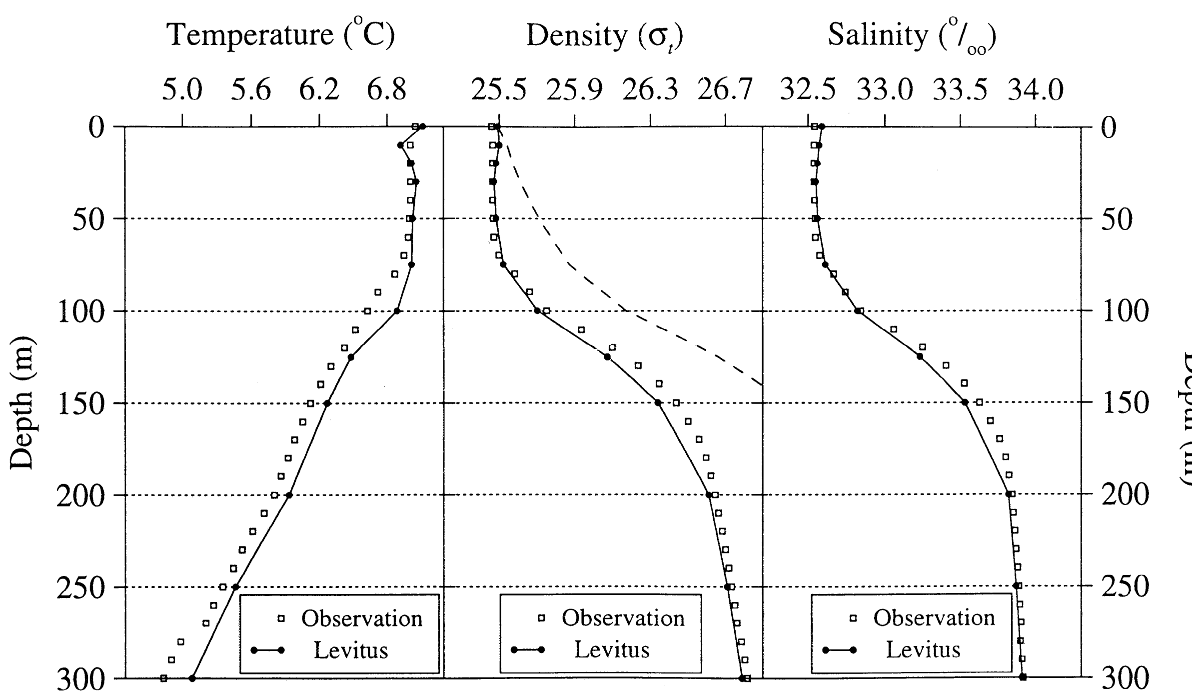

Figure 2. Profiles of temperature, density σ_t and salinity to 300 m depth at station J in February. Standard vertical levels for the Levitus data are shown with solid circles, while the ones for the OWS data are shown with open squares. Note that the vertical resolution for OWS data is 10 m. Density profiles for both data sets were obtained by using the pressure–independent equation of state as explained in the text. The pressure–dependent density profile for Levitus data is shown with a dashed line.

equation of state can be used if one considers the difference in density for a parcel of seawater relative to the background value. If one uses the potential temperature, this gives the exact density difference for water transported to a given depth.) As we have found, this can be easily overlooked when using the UNESCO equation of state for the first time in a mixed layer model. Note that an incompressible equation of state is consistent with the incompressibility assumption inherent within the majority of one-dimensional mixed layer models and OGCMs and that defining a MLD that can be used for OGCM validation is one of the goals of this study.

3. Methodology

The method given here is able to accommodate the wide variety of temperature profiles that occur within the global ocean. This includes temperature inversions that occur at high latitudes, a subsurface mixed layer underlying a surface thermal inversion, multiple fossil layers beneath the surface mixed layer, a dicothermal layer, as well as the typical temperature profiles with strong and weak thermoclines found in the middle and low latitudes [e.g., *Brainerd and Gregg*, 1995]. For a discussion that defines and explains the formation of some of these various characteristics we refer the reader to *Sprintall and Roemmich* [1999].

Here the criteria for defining a MLD are developed through subjective analysis of temperature and density profiles from the Levitus data with the view that the mixed layer is the region just below the ocean surface where the temperature or density is approximately uniform. The same methodology is later applied to OWS data. This goes beyond the work of previous authors (Table 1), who used only a fixed decrease in temperature or increase in density from a value at a reference depth near the surface. The greater complexity of our algorithm was necessary in order to obtain a MLD that is consistent with what one would infer from inspection of the profiles in many regions of the world ocean. The simpler criteria used in previous studies were found to fail in many cases in the presence of fossil layers, inversion layers, and dicothermal layers. These yielded MLD values that differed by more than 20 m from those obtained using our methodology, often reaching differences as large as hundreds of meters. The criteria we apply for the ILD and MLD become similar to those of other authors (Table 1) for those cases where there is no subsurface region of uniform temperature and density, for example, a stable thermocline.

From an examination of the global MLD fields we obtained using our methodology, we find no need to impose a maximum depth for the mixed layer [e.g., *Levitus,* 1982] as reasonable values are obtained over 99% of the world ocean area. The remaining 1% of the cases are consequences of highly uniform vertical profiles occurring at high southern latitudes, and these could be indicative of regions of extremely deep convective mixing associated with the global overturning circulation.

The implementation of the criteria used here requires a multiple-step procedure that is separately applied when determining an ILD or MLD. A schematic diagram (Figure 3) shows the determination of ILD (MLD) when using the Levitus data according to a temperature-based (density-based) criterion. We first describe the procedure for determining an ILD.

1. The temperature at 10 m depth is chosen as the initial reference temperature value (T_{ref}) for determining the ILD. This depth is chosen to eliminate any possible bias in the profile data due to "skin effects" at the ocean surface [*Fairall et al.*, 1996]. In the majority of cases for the Levitus data the temperature at 10 m is very close to the surface temperature value. While this reference depth imposes a minimum value of 10 m for the ILD, we note that OGCMs typically limit their minimum MLD to 10 m or more [e.g., *Cherniawsky and Holloway*, 1991; *McCreary et al.*, 1993; *Schopf and Loughe*, 1995].

2. A search is then made of the temperature profile data for a uniform temperature region. We define a uniform "well-mixed" temperature region as any pair of temperature values (T_n and T_{n+1}) at adjacent depths (h_n and h_{n+1}) in the profile that differ by less than one-tenth the temperature difference criteria ΔT defining the ILD (e.g., ΔT=0.2°, 0.5°, 0.8°, and 1.0°C), i.e., differences less than or equal to $0.1\,\Delta T$. For the example profiles shown in Figure 3, the standard levels h_n and h_{n+1} correspond to 100 and 125 m, respectively.

3. If a uniform temperature region is found, the value of reference temperature T_{ref} is updated to the temperature value T_n at the shallower depth h_n of the pair of profile points. This is done for every occurrence of a pair of points occurring within the first uniform temperature region so that the reference temperature is that at the base of the well-mixed region. The ILD will then be the depth at which the temperature has changed by an absolute value of ΔT from this reference value. For reference purposes we shall refer to this latter temperature as the base temperature T_b.

4. Temperature changes with depth of either sign are used in determining ILD. Thus the value of the base temperature is given by

$$T_b = \begin{cases} T_{\text{ref}} - \Delta T & T_n < T_{n+1}, \\ T_{\text{ref}} + \Delta T & T_n \geq T_{n+1}. \end{cases}$$

If found, the depth of T_b is determined by linear interpolation within the depth interval (h_n, h_{n+1}). This depth defines the ILD for the applied temperature criteria ΔT.

5. If no depth range (h_n and h_{n+1}) is found such that (T_n and T_{n+1}) contains T_b, then the profile data is searched again, starting from the 10 m reference depth, for a temperature change of ΔT from the 10 m reference temperature. This can be a positive or negative change according to the temperature variation with

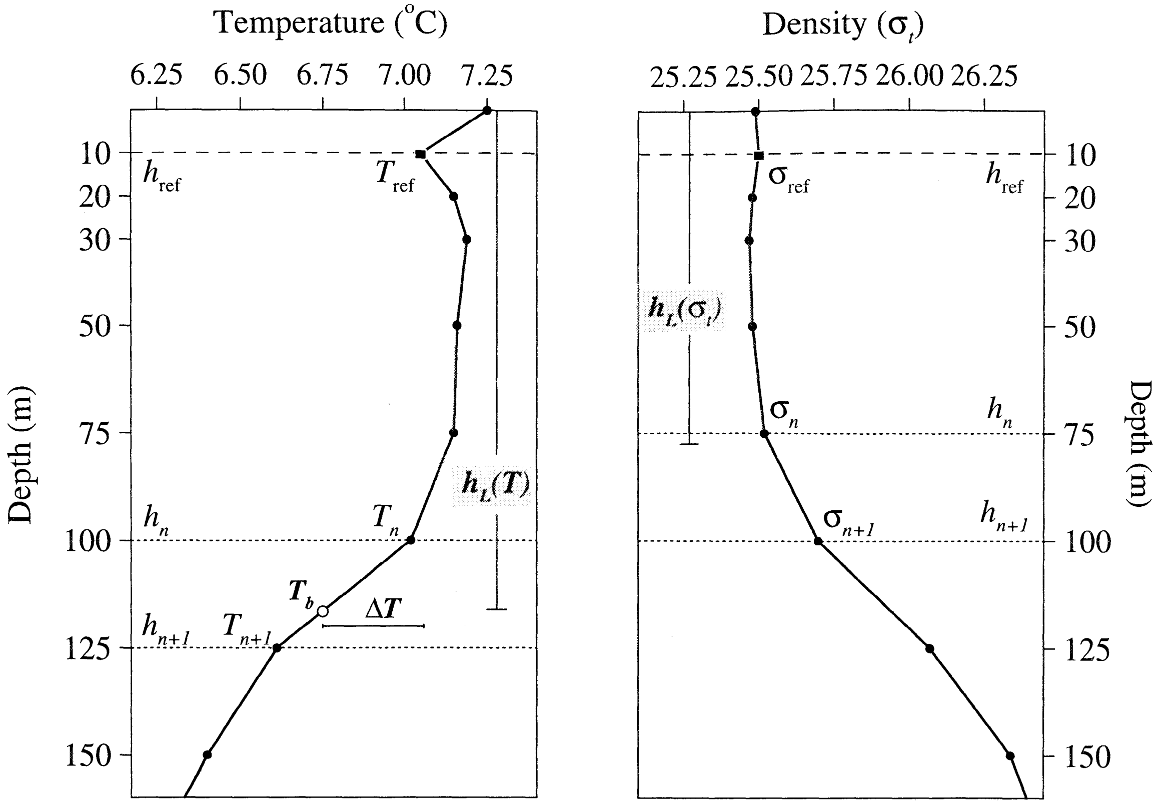

Figure 3. A schematic illustration of the ILD ($h_L(T)$) and MLD ($h_L(\sigma_t)$) determination using the temperature and density profiles at the location of station J (Figure 2) from the Levitus data in February. For ease of notation we use the same symbols for the standard levels (h_n and h_{n+1}) when describing the procedure for both criteria. The depth at which the ILD is found is shown with an open circle on the temperature profile, and the temperature at this level is denoted as the base temperature T_b.

depth. This occurs at high latitudes for two general cases: (1) when there is a large temperature inversion at the surface and the temperature at depth never decreases to as low a value and (2) when the temperature remains almost constant to the bottom of the ocean. In both cases the ILD is set to the depth of the ocean bottom if no depth is found at which the temperature has changed by ΔT.

Note that this method does not use temperature gradients as part of its criteria for determining the ILD for the reasons given in section 1. Reliable application of such criteria requires sufficiently high resolution in the profile data to determine accurately the temperature gradients. With climatological data sets such as Levitus, which have only 19 standard levels distributed over a 1000 m depth, such vertical resolution is not available. To have a robust algorithm, we have therefore adopted a simple approach based on a ΔT change.

The MLD determined from density follows the same procedure as for temperature but with a density variation determined from the corresponding temperature change ΔT in the equation of state

$$\Delta\sigma_t = \sigma_t(T + \Delta T, S, P) - \sigma_t(T, S, P), \qquad (1)$$

where S is the salinity and the pressure P is set to zero [*Millero and Poisson*, 1981; *Millero et al.*, 1980]. For our example (Figure 3) the ILD (i.e., $h_L(T)$) is found between the 100 and 125 m standard levels, while the MLD (i.e., $h_L(\sigma_t)$) is found between the 75 and 100 m standard levels for the same location. This is a more careful treatment of $\Delta\sigma_t$ in a density-based definition of MLD than has been considered in the literature to date (Table 1) as it takes full account of density changes due to temperature and salinity variations with location.

For each station A through K (see Figure 1) the ILD and MLD are obtained using the Levitus data according to a temperature- or density-based criterion, respectively. The same procedures are applied to the OWS temperature (density) profiles at the same locations to determine the ILD (MLD). The higher 10 m resolution of the OWS data enables the layer depths to be more accurately obtained. The OWS data also exhibit a shallower and sharper thermocline because no horizontal averaging of the temperature and salinity profiles was done as for the Levitus data. For simplicity the ILD obtained from the Levitus data set will henceforth be represented by $h_L(T)$, and the one from the OWS data set will be represented by $h_O(T)$. Similarly, $h_L(\sigma_t)$ and

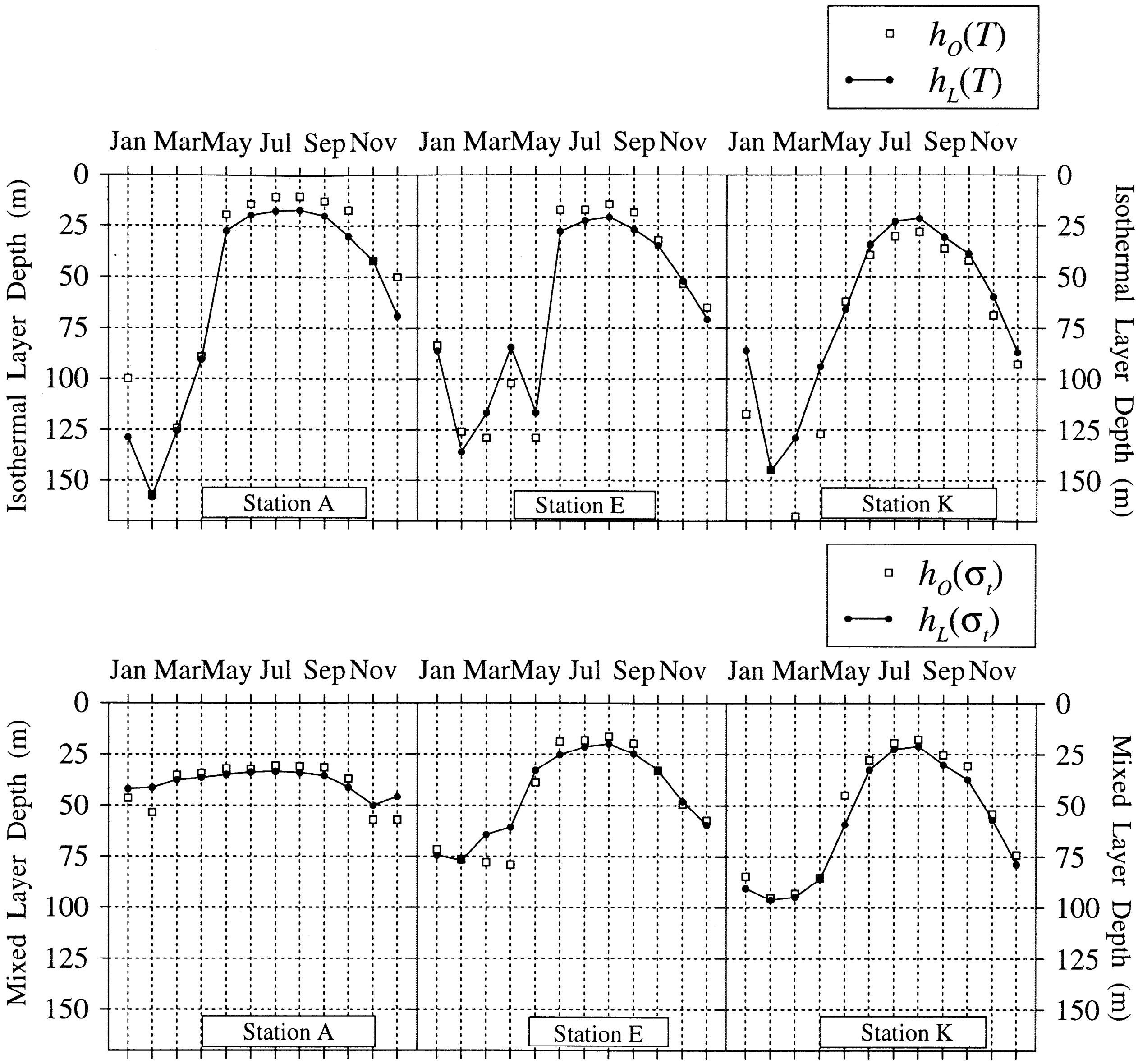

Figure 4. ILDs ($h_O(T)$ and $h_L(T)$) and MLDs ($h_O(\sigma_t)$ and $h_L(\sigma_t)$) at stations A, E, and K for the months from January to December. A ΔT interval of 0.8°C is used for the ILDs and MLDs. Note that the axis labeling is for every other month.

$h_O(\sigma_t)$ will denote the MLD obtained from the Levitus and OWS profiles, respectively.

Figure 4 shows the monthly ILD and MLD values obtained for stations A, E, and K when using a ΔT value of 0.8°C. In general, $h_O(T)$ and $h_L(T)$ agree quite well with each other for all stations, and the same is true for $h_O(\sigma_t)$ and $h_L(\sigma_t)$. However, the MLD are shallower than the ILD for both data sets. In particular, for station A the $h_O(T)$ and $h_L(T)$ values are quite different from their $h_O(\sigma_t)$ and $h_L(\sigma_t)$ counterparts. The corresponding differences are minor for stations E and K, which are farther offshore. The larger difference between ILD and MLD at station A is because of offshore advection of fresh water, which causes this station closest to the coast (Table 2) to have a shallower halocline. This is likely due to the high continental rainfall known to occur in this region.

A comparison of monthly layer depths when using different ΔT values (Figure 5) shows that the ILD and MLD both increase with larger ΔT, as expected. Varying ΔT causes greater changes in the MLD than in the ILD because of the additional effects of salinity. This is especially true for ΔT values of 0.2° and 0.5°C. We also note that the MLD are once again shallower than the ILD for the same ΔT value.

4. Comparison of the Layer Depths

Here we examine layer depths obtained from two different data sets for the same ΔT value to determine

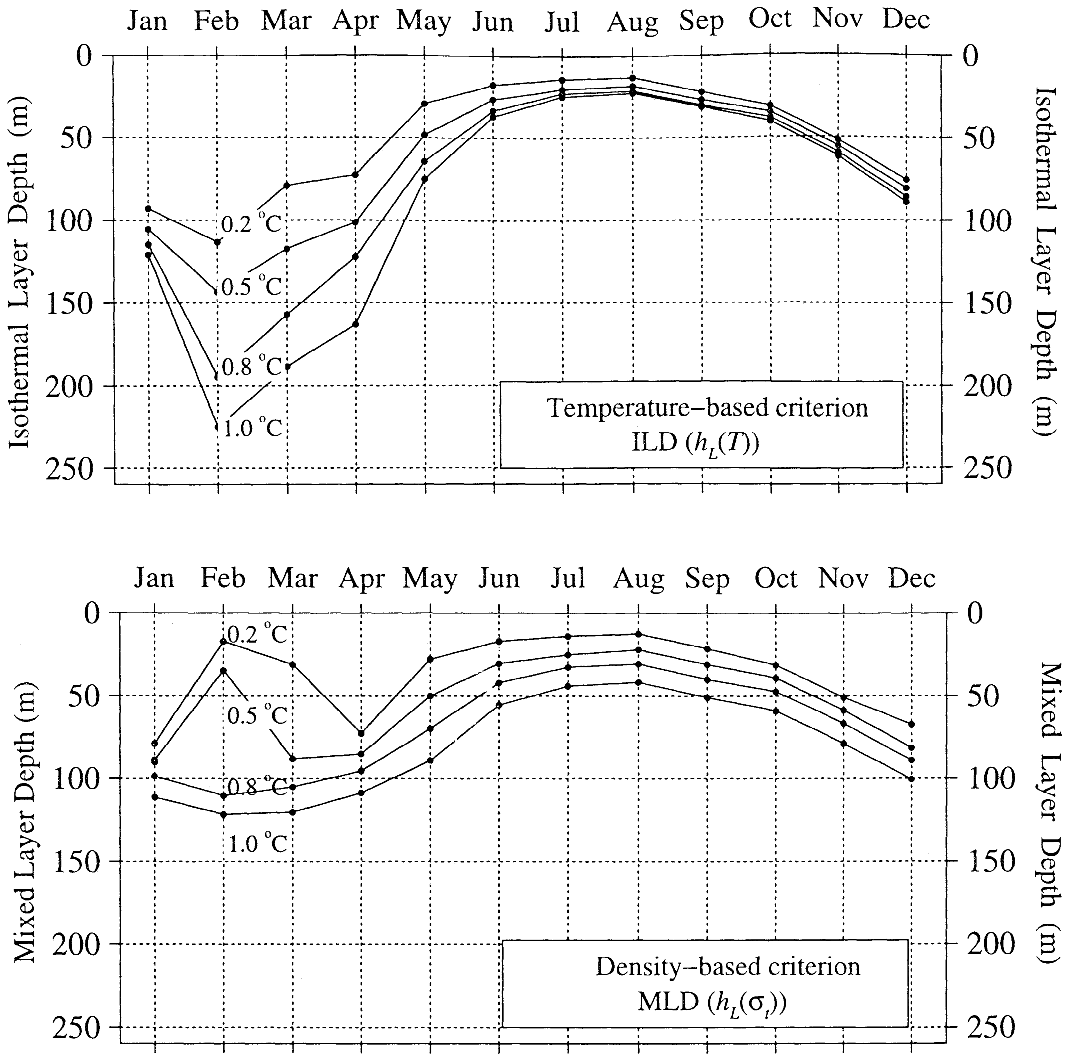

Figure 5. Layer depths (ILD and MLD) by month at station H obtained using the Levitus data ($h_L(T)$ and $h_L(\sigma_t)$) for a range of ΔT values: 0.2°, 0.5°, 0.8°, and 1.0°C.

the difference when using the ILD as the MLD. We have used ΔT values of 0.2°, 0.5°, 0.8° and 1.0°C to obtain the ILD and MLD at each station by month for both criteria. For the ocean weather stations (see Figure 1) this provides 11 ILD (MLD) for each month for the Levitus and OWS data, separately, for a given ΔT value and temperature- (density-) based criterion.

To provide sufficiently accurate statistics, the mean of the ILD and MLD for each ΔT value are calculated by season. We follow *Levitus et al.* [1994] in our definition of seasons: January, February, and March (winter); April, May, and June (spring); July, August, and September (summer); and October, November, and December (fall). The mean values for the ILD and MLD (Figure 6) are very close to each other in summer and fall, indicating that they produce comparable layer depths in these seasons. In winter and spring, increasingly larger differences occur with larger ΔT value, with a difference of up to 80 m resulting in winter for ΔT=1.0°C. The mean values of $h_O(\sigma_t)$ are always larger than $h_L(\sigma_t)$ in winter and spring, while the reverse is true overall for the $h_O(T)$ and $h_L(T)$ values. In general, the mean values for the given ΔT interval and state variable criterion (T or σ_t) show close agreement for the two data sets.

For each station we also examine the difference between the ILD and MLD by month and present the results grouped by season (Figure 7). An interesting trend is found when examining the number of cases where the h_L–h_O difference is positive or negative (Table 3). The $h(T)$ layer depths obtained from Levitus are typically greater than those obtained from OWS in all seasons, especially in winter. In fact, no cases exist where $h_L(T) < h_O(T)$ in winter, spring, and summer when using a ΔT=0.5°C. Note that differences between $h_L(\sigma_t)$ and $h_O(\sigma_t)$ in spring are quite small relative to those in winter and fall and that the scatter in winter and fall is larger, as will be discussed in more detail in section 5. In summer and fall we again notice the $h_L(T)$ values are usually greater than the $h_O(T)$ values, while

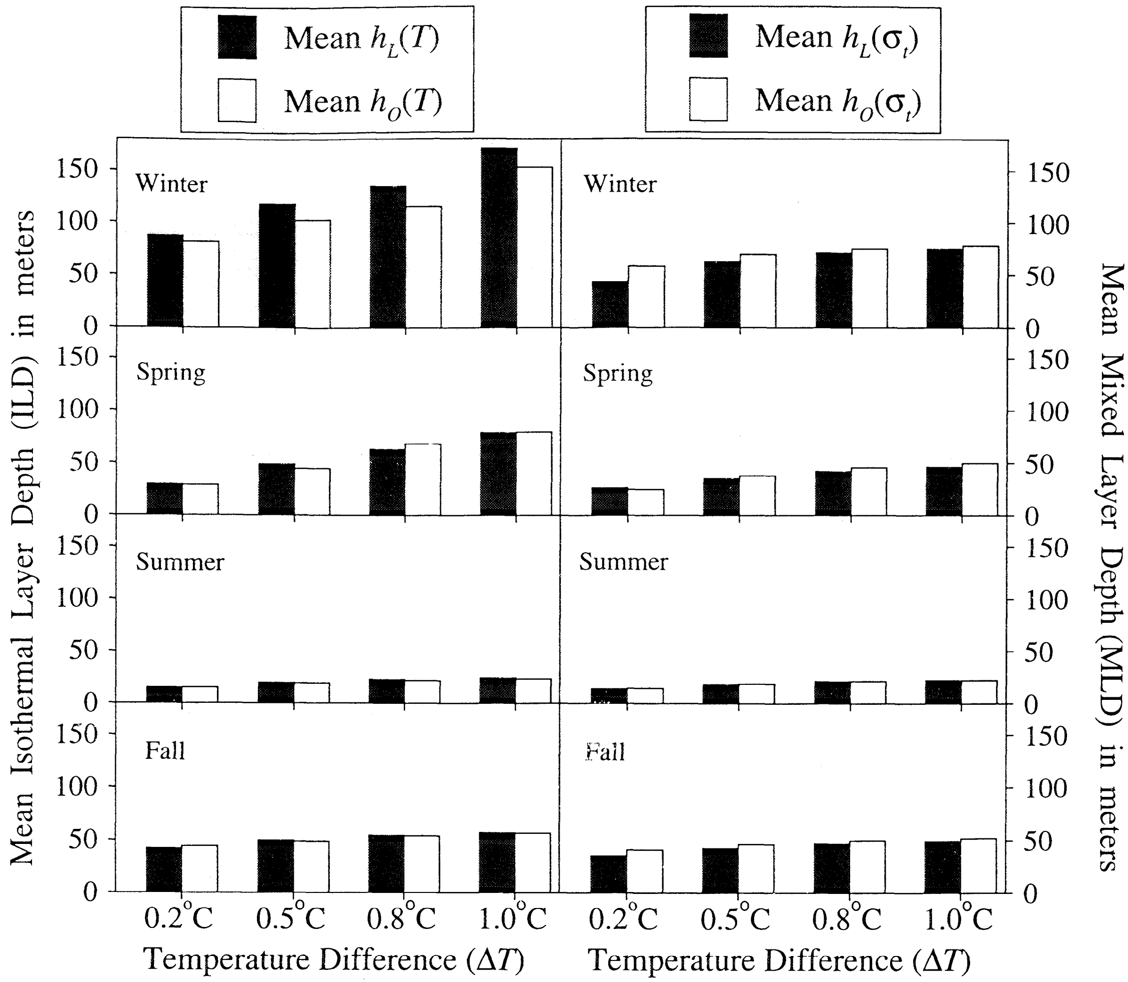

Figure 6. Mean layer depths (ILD and MLD) obtained using the Levitus ($h_L(T)$ and $h_L(\sigma_t)$) and OWS observations ($h_O(T)$ and $h_O(\sigma_t)$) when using ΔT values of 0.2°, 0.5°, 0.8°, and 1.0°C. The number of cases for each ΔT category in a given season is 33. The mean values obtained from the ILD and MLD are shown separately.

the reverse is true for $h_L(\sigma_t)$ and $h_O(\sigma_t)$. The reason $h_L(T) > h_O(T)$ overall is because the vertical resolution of the Levitus data is coarser than that of the OWS data at greater depths and because of the horizontal averaging in constructing the Levitus data. This results in a broader and deeper thermocline in Levitus. This bias is larger in winter and spring when the $h_L(T)$ values are large. Note that the variability in the number of cases where $h_L(\sigma_t)$–$h_O(\sigma_t)$ is positive or negative is much less than for the $h_L(T)$–$h_O(T)$ cases in each season (left to right in Figure 7). This reveals that the density-based criterion is a more reliable indicator of MLD as it provides a consistent trend between different data sources that is relatively insensitive to the ΔT value used.

5. Sensitivity to Temperature Differences

In this section we undertake a sensitivity study to determine the best ΔT value to be used for the ILD and MLD. For this study the pairs of values ($h_L(T)$ and $h_O(T)$) and ($h_L(\sigma_t)$ and $h_O(\sigma_t)$) are compared under the same ΔT criteria for each season using several different statistical measures. Several measures are used because evaluating the performance of estimating the ILD and MLD in arriving at the best choice for ΔT is important. We subsequently investigate the differences that arise when using an ILD versus MLD definition for a given ΔT in order to assess the relative error introduced by the former relative to the latter.

We consider various statistical measures together to measure the strength of the relationship between the pairs $h_L(T)$ and $h_O(T)$ or $h_L(\sigma_t)$ and $h_O(\sigma_t)$. The preferred indicator of the strength of the statististical relationship between the layer depths from the Levitus data (h_L) and the ones from the OWS data in the northeast Pacific Ocean (h_O) is the coefficient of determination (r^2). The reason is that the correlation coefficient r may give a misleading impression of a closer relationship between h_L and h_O than actually exists [*Neter et al.*, 1988]. Furthermore, r^2 possesses a meaningful operational interpretation as a measure of the propor-

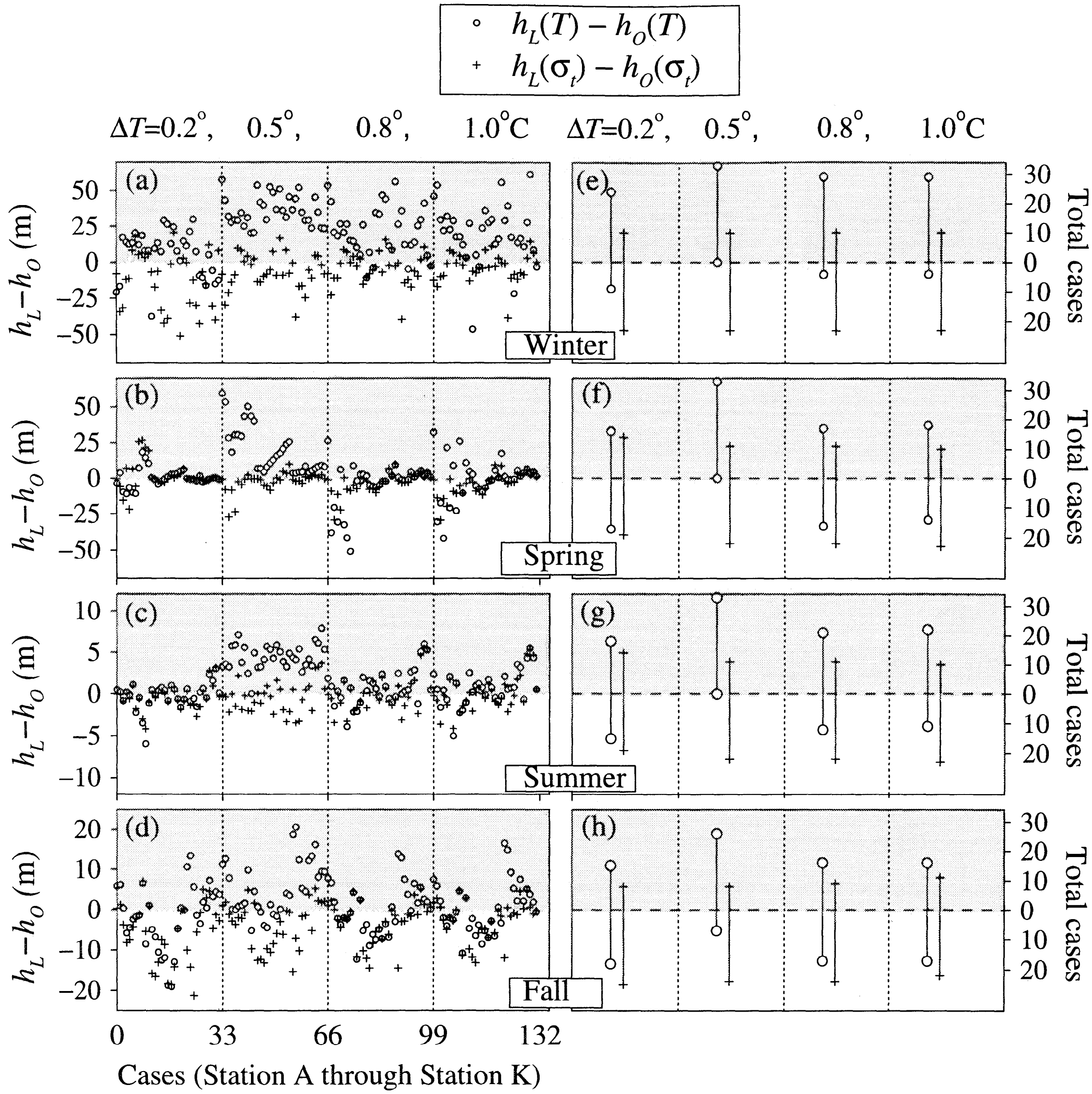

Figure 7. The scatter diagram of differences in the ILD ($h_L(T)$-$h_O(T)$) and MLD ($h_L(\sigma_t)$-$h_O(\sigma_t)$) between Levitus and OWS observations. Panels (a)–(d) show the number of cases when $h_L > h_O$ or when $h_L \leq h_O$. The symbols on the bars denote correspondence with the data in panels (e)-(h). The y axes are different for each season.

tion of the variability in the observations accounted for by a linear model in the forecasts [*Murphy*, 1988]. For example, a 0.90 r^2 value shows that 90% of the variance in the observations is reproduced by the estimates. The mean square error (mse) and skill score (SS) are also used to verify our results since r^2 ignores both conditional and unconditional bias (B_{cond} and B_{uncond}, respectively), which are basic aspects of assessing performance [*Murphy*, 1995]. Unconditional bias (also called systematic bias) is a measure of the difference between the means of two data sets, while conditional bias is a measure of the relative amplitude of the variability in the two data sets as explained by *Murphy and Epstein* [1989]. These statistical measures are given by the relations

$$r^2 = \left[\frac{S_{h_L h_O}}{S_{h_L} S_{h_O}}\right]^2, \tag{2}$$

$$\text{mse} = (\overline{h}_L - \overline{h}_O)^2 + S_{h_L}^2 + S_{h_O}^2 - 2\,r\,S_{h_L}\,S_{h_O}, \tag{3}$$

$$\text{SS} = r^2 - \underbrace{[r - (S_{h_L}/S_{h_O})]^2}_{B_{\text{cond}}} - \underbrace{[(\overline{h}_L - \overline{h}_O)/S_{h_O}]^2}_{B_{\text{uncond}}}, \tag{4}$$

Table 3. Comparison of Levitus and OWS Layer Depths

ΔT	Criterion	Winter	Spring	Summer	Fall
0.2°C	ILD	24 (73%)	16 (48%)	18 (55%)	15 (45%)
	MLD	10 (30%)	14 (42%)	11 (33%)	8 (24%)
0.5°C	ILD	33 (100%)	33 (100%)	33 (100%)	26 (79%)
	MLD	10 (30%)	11 (33%)	13 (39%)	9 (27%)
0.8°C	ILD	29 (88%)	17 (52%)	21 (64%)	16 (48%)
	MLD	10 (30%)	11 (33%)	14 (42%)	9 (27%)
1.0°C	ILD	29 (88%)	18 (55%)	22 (67%)	16 (48%)
	MLD	10 (30%)	10 (30%)	14 (42%)	11 (33%)

The number of cases by season when $h_L > h_O$ for the ILD and MLD for given ΔT values. For each category the percentage is given in parentheses.

where $S^2_{h_L h_O}$ is the covariance between h_L and h_O; $S^2_{h_L}$ and $S^2_{h_O}$ are the sample variances of the h_L and h_O values, respectively; and S_{h_L} and S_{h_O} are the standard deviations of h_L and h_O values, respectively. The mean values for h_L and h_O are represented by $\overline{h}_L$ and $\overline{h}_O$, respectively.

5.1. Determination of the Best ΔT Value

For winter a large scatter exists between the h_L and h_O ILD (Figure 8) for all ΔT values. In contrast, the MLD agreement is quite good for $\Delta T \geq 0.5$°C. The computed SS and r^2 values for the winter ILD and MLD values between the Levitus and OWS data (Table 4) show that the skill score and linear association are greater for the MLD. The negative skill scores reveal that h_L is not a skillful measure of h_O for the given criteria. The statistical measures given in Table 4 indicate that use of a 0.8° or 1.0°C value for ΔT for the winter MLD yields the best agreement between h_L and h_O. Furthermore, the use of 1.0°C is superior to 0.8°C because the mse and B_{uncond} values are larger for the latter case. However, the differences between using these

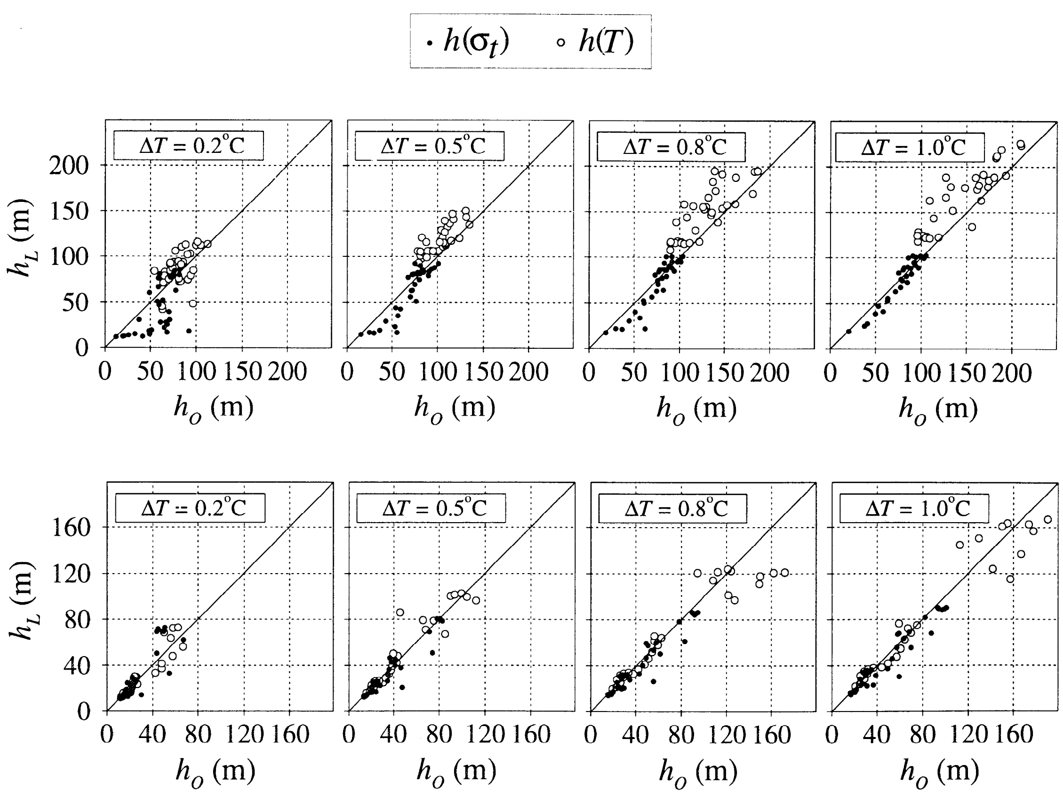

Figure 8. Prediction of (top) winter and (bottom) spring ILDs and MLDs at the OWSs A through K (h_O) (see Figure 1) versus those from Levitus (h_L) when using ΔT intervals of 0.2°, 0.5°, 0.8°, and 1.0°C. The number of cases ($h(T)$ and $h(\sigma_t)$) is 33 (i.e., 11 stations × 3 months/season) for each ΔT category. Note here that we use Levitus winter (i.e., January, February, and March) and Levitus spring (April, May, and June) to describe seasons. Axis scales are different for each season.

Table 4. Seasonal Comparisons of ILD and MLD

ΔT	Criterion	SS	r^2	rmse	B_{cond}	B_{uncond}
			Winter			
0.2°C	ILD	-0.67	0.26	17.8	0.7514	0.1766
	MLD	-0.86	0.35	26.7	0.6446	0.5625
0.5°C	ILD	-0.34	0.64	18.4	0.0306	0.9503
	MLD	0.59	0.83	13.3	0.1432	0.0947
0.8°C	ILD	-0.84	0.49	23.7	0.0618	1.2672
	MLD	0.70	0.86	11.5	0.1241	0.0423
1.0°C	ILD	0.40	0.55	35.8	0.0003	0.1514
	MLD	0.75	0.88	10.3	0.1110	0.0275
			Spring			
0.2°C	ILD	0.86	0.88	6.2	0.0245	0.0006
	MLD	0.53	0.77	10.0	0.2244	0.0150
0.5°C	ILD	0.67	0.72	16.8	0.0327	0.0186
	MLD	0.89	0.90	7.7	0.0011	0.0107
0.8°C	ILD	0.87	0.90	17.1	0.0185	0.0094
	MLD	0.91	0.92	8.1	0.0006	0.0159
1.0°C	ILD	0.94	0.94	13.9	0.0004	0.0001
	MLD	0.90	0.92	8.6	0.0008	0.0181
			Summer			
0.2°C	ILD	0.79	0.81	1.6	0.0165	0.0033
	MLD	0.81	0.85	1.5	0.0193	0.0216
0.5°C	ILD	0.54	0.59	2.6	0.0319	0.0237
	MLD	0.75	0.79	1.9	0.0357	0.0111
0.8°C	ILD	0.61	0.71	2.3	0.0465	0.0494
	MLD	0.70	0.77	2.2	0.0729	0.0006
1.0°C	ILD	0.62	0.71	2.2	0.0353	0.0494
	MLD	0.71	0.79	2.1	0.0812	0.0006
			Fall			
0.2°C	ILD	0.72	0.77	8.2	0.0445	0.0137
	MLD	0.62	0.81	9.2	0.0484	0.1394
0.5°C	ILD	0.70	0.72	9.5	0.0243	0.0016
	MLD	0.83	0.90	6.5	0.0231	0.0526
0.8°C	ILD	0.87	0.89	6.0	0.0125	0.0001
	MLD	0.85	0.90	6.1	0.0141	0.0352
1.0°C	ILD	0.77	0.84	7.9	0.0548	0.0711
	MLD	0.79	0.82	7.1	0.0180	0.0338

Comparisons between the ILD and MLD from the OWS observations (h_O) and from the Levitus data (h_O) obtained using the methodology in section 3 for the 11 stations by season. Both the ILD and MLD are included for the same ΔT. All r values are statistically significant at 95% confidence interval based on the Student's t test. Note that a SS of 1 is equivalent to a perfect match between 2 data sets, while a SS< 0 is an unacceptable match. The rmse is in meters and the number of cases (n) is 33 for each category.

two ΔT would be negligible. In general, the MLD gives much more consistent h_L and h_O values than the ILD in winter. For the spring, again, a large scatter exists between h_L and h_O when using the ILD with ΔT=0.8 and 1.0°C (Figure 8) but only for large layer depths. The SS and r^2 values (Table 4) confirm that the $h_L(\sigma_t)$ values are in very good agreement with $h_O(\sigma_t)$ when using ΔT=0.5° and 0.8°C. Analysis of SS for MLD indicates that good agreement exists between $h_L(\sigma_t)$ and $h_O(\sigma_t)$ for all ΔT values. A MLD obtained using ΔT=0.5° or 0.8°C is optimal because both of them yield very large SS values (0.89 and 0.91, respectively).

The summer ILD and MLD are very shallow and typically have depths of $\approx$ 25 m (Figure 9). This is not surprising because the upper ocean temperature increases in the summer, often leading to the development of a seasonal thermocline with a shallow mixed layer and a stable water column. The highest SS and r^2 values occur for the 0.2°C criterion (Table 4), and the relatively small bias and root mean square error (rmse) values confirm that the best agreement between $h_L(T)$ and $h_O(T)$, as well as between $h_L(\sigma_t)$ and $h_O(\sigma_t)$, occurs for this ΔT value. Use of the density–based criterion is always better than the temperature–based criterion for defining the mixed layer because the SS and r^2 values for the MLD are always larger than for the ILD for any ΔT value. The ILD and MLD comparisons for fall show more scatter when using ΔT=0.2° and 0.5°C than for the larger ΔT values (Figure 9). A comparison of the layer depths between the Levitus and OWS

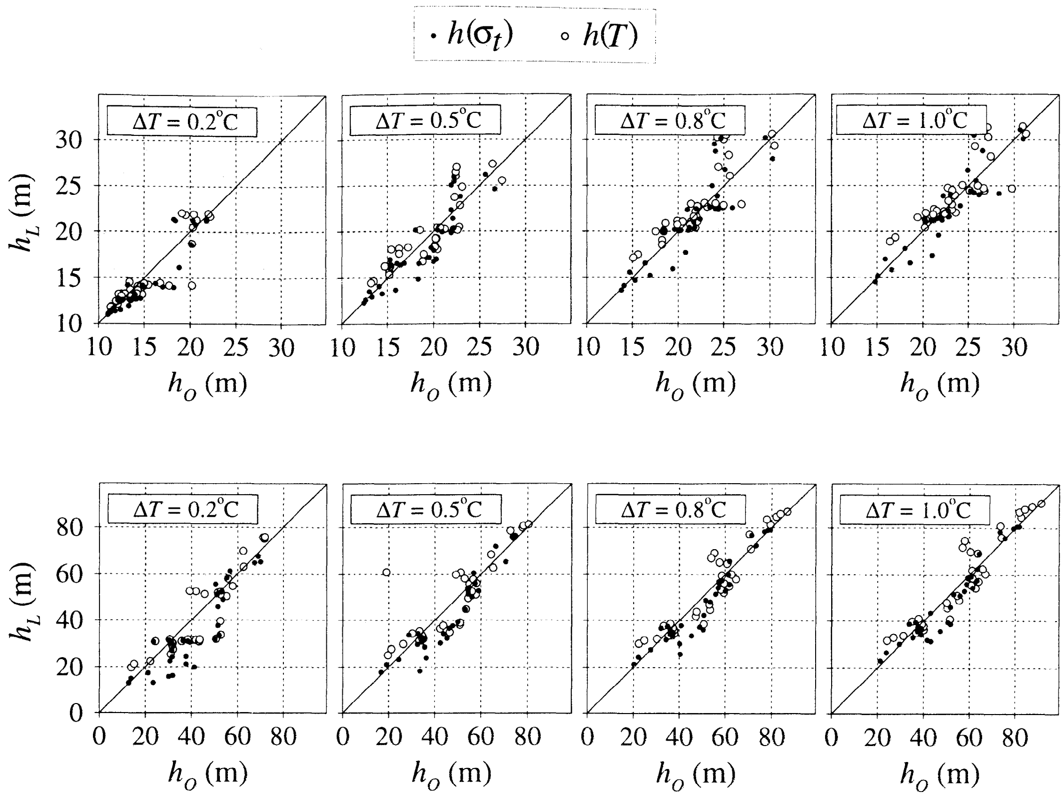

Figure 9. The same as Figure 8 but for Levitus summer (i.e., July, August, and September) and Levitus fall (i.e., October, November, and December).

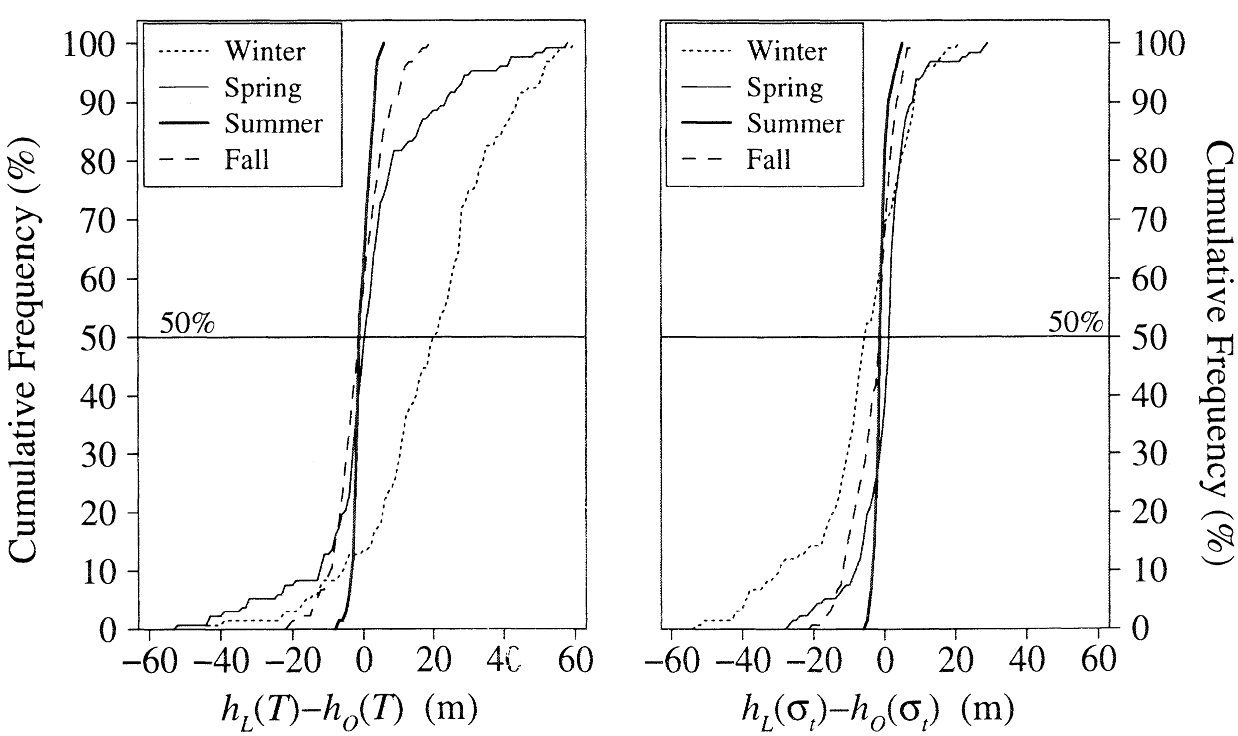

Figure 10. Percentage cumulative frequency of (left) ILD ($h_L(T)$-$h_O(T)$) and (right) MLD ($h_L(\sigma_t)$-$h_O(\sigma_t)$) differences between the Levitus data and the OWS data. Results are shown for each season separately. The horizontal line represents the fiftieth percentile, which corresponds to the median layer depth difference for each season.

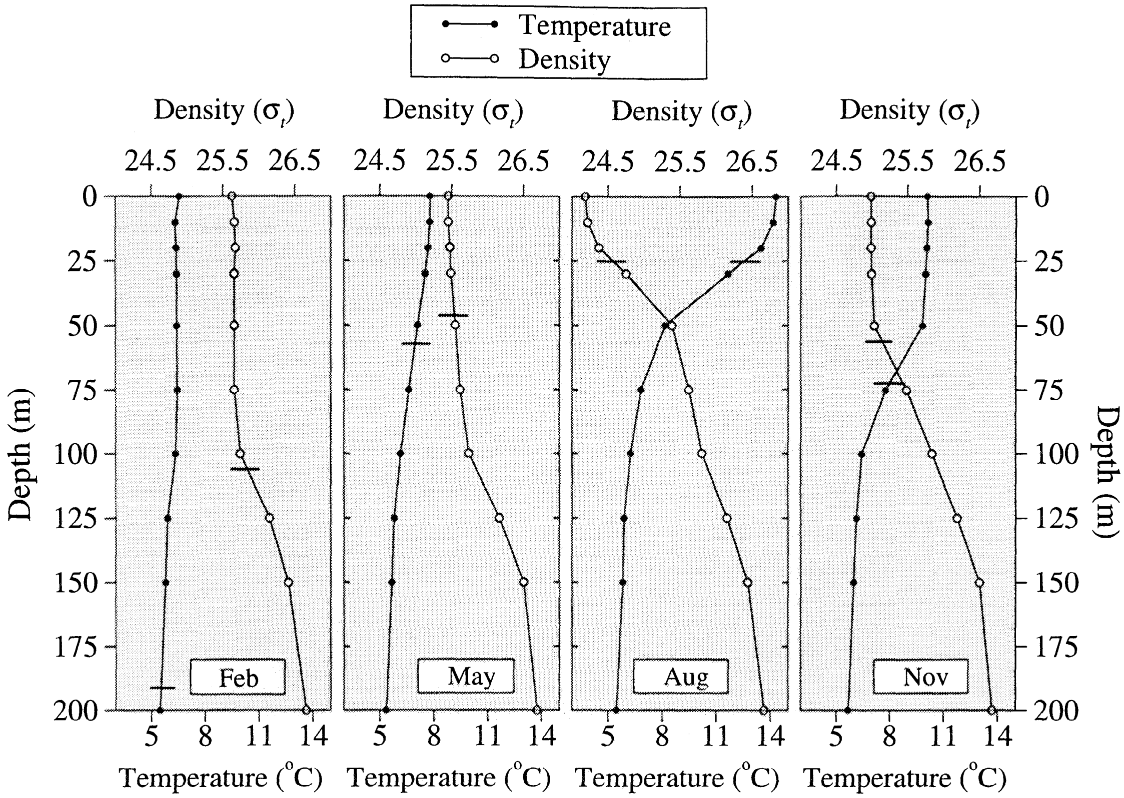

Figure 11. Temperature and density profiles constructed from the monthly Levitus data at station H for the months of February, May, August, and November. The layer depth obtained from the temperature-based criterion ILD ($h_L(T)$) is marked with a solid line on the temperature profiles, and the one obtained from the density-based criterion MLD ($h_L(\sigma_t)$) is also marked with a solid line on the density profile. Note that in both criteria a ΔT value of 0.8°C is used.

data based on r^2 values alone suggests that agreement is always poorer for the ILD than for the MLD. These r^2 values reflect the relatively close agreement between $h_L(\sigma_t)$ and $h_O(\sigma_t)$. An examination of all the B_{cond} and B_{uncond} values along with the rmse and SS values indicates that the best overall agreement between the Levitus and OWS data are obtained when using a MLD with a ΔT=0.8°C criterion.

Given that one of our ultimate goals is to construct a MLD climatology for use in model validation, quantitatively determining the inherent uncertainty in the ILD and MLD obtained using our methodology is important. To determine this, we perform a final analysis for each season by combining together by season the ILD and MLD differences between the two data sets ($h_L - h_O$) for all values of ΔT. Figure 10 shows the separate cumulative distribution of the ILD and MLD differences for each season. In winter, $\approx$ 45% of the differences for the ILD ($h_L(T)$-$h_O(T)$) are between −20 and 20 m, while 85% fall within this range for the MLD ($h_L(\sigma_t)$-$h_O(\sigma_t)$). For this season the median values are 21 m (-7 m) for the ILD (MLD). In spring and fall the same $-20 < h_L - h_O < 20$ m interval yields percentage values that are even higher (94 and 98%, respectively) than in winter. These results verify that our method for determining layer depth produces values that agree to within 20 m or better on average for comparable temperature and density profiles.

5.2. Relative Error of the ILD as the MLD

Using OWS H as an example, clearly the use of an ILD ($h(T)$) as a MLD ($h(\sigma_t)$) can result in large errors when estimating winter MLD. For example, the error is as high as 87 m for the case shown in Figure 11. The differences for spring and fall have relatively small values of 12 and 23 m, respectively, and almost no difference in August. The latter is due to the shallow seasonal thermocline and pycnocline and because of generally weak turbulent mixing in the summer months. To determine if this is a general trend when using the same ΔT values, we extend our analysis to all 11 OWSs and examine the differences between the ILD and MLD by season using both the OWS and Levitus data. The scatter is found to be very large for the winter MLD using either the OWS or Levitus data (Figure 12). The large scatter is especially apparent for the ΔT value of 1.0°C when using the Levitus data. In most of the cases the 150–200 m depths obtained for the ILD are deeper by 20–100 m, than those of the MLD. For spring the ILD

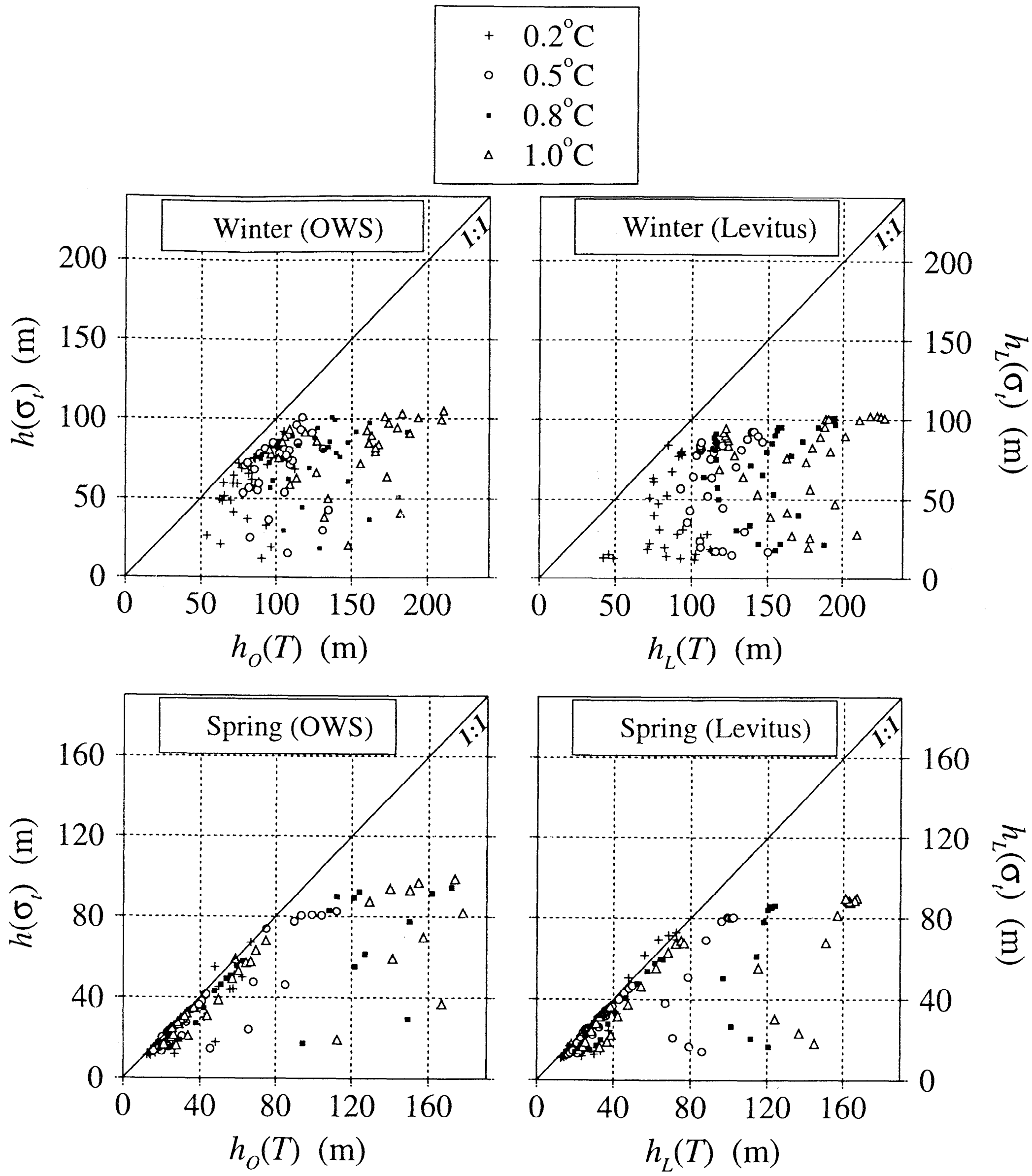

Figure 12. Scatterplot of the ILD ($h(T)$) versus the MLD ($h(\sigma_t)$) from OWS and Levitus data in winter and spring, separately. The OWS and Levitus layer depth are denoted by the O and L subscripts, respectively. The analysis is shown for ΔT values of 0.2°, 0.5°, 0.8°, and 1.0°C. The number of cases (n) is 33 for each category (11 stations × 3 months/season). Note here that we use Levitus winter (January, February, and March) and Levitus spring (April, May, and June) to describe seasons.

is almost equal to the MLD for 0.2°C (Figure 12) and is in close agreement for the 0.5°C criterion in all but a few cases. On the other hand, an ILD estimate for the spring MLD using 0.8° and 1.0°C is still largely an underestimate. While the differences between ILD and MLD for the Levitus data are larger than for the OWS data, especially in winter, this difference is quite small.

In summer the prediction of the ILD as the MLD does not yield any significant over-estimation/underestimation for both data sets when considering all different ΔT values (Figure 13). Although a little more scatter occurs in the summer layer depth when using the Levitus data, the largest difference between the ILD ($h_L(T)$) and the MLD ($h_L(\sigma_t)$) is only 6 m. Figure 13 shows that the layer depths from Levitus often do not agree well with those obtained from OWS. This is because the OWS temperature and density profiles have much higher vertical resolution, resulting in better estimates of the actual MLD over the region.

To indicate statistically the agreement between the ILD and MLD criteria for both data sets, we use the r^2, SS and B_{cond} and B_{uncond} values. The one exception is that we only show the total dimensionless bias as the sum of the conditional and unconditional biases for

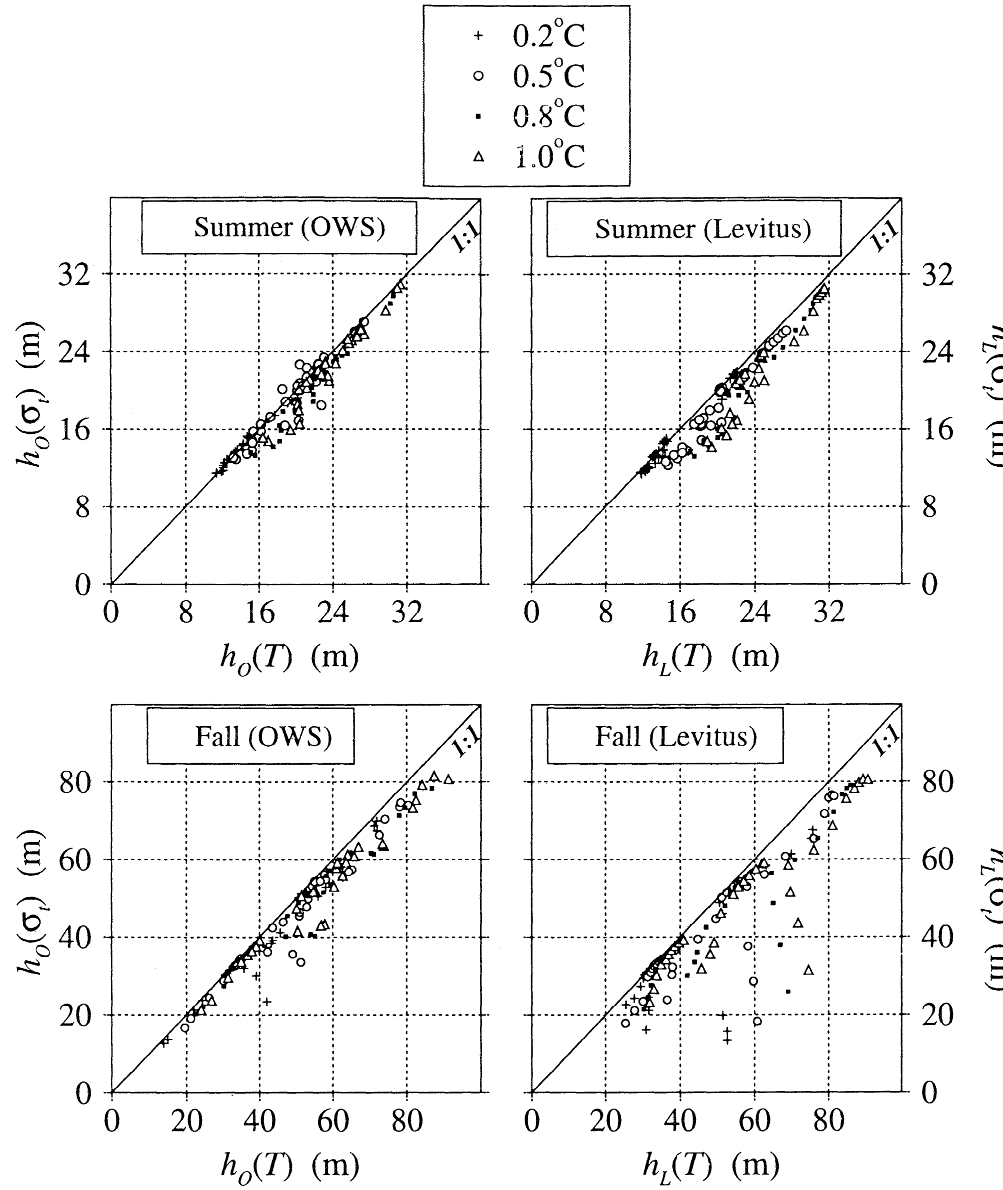

Figure 13. The same as Figure 12 but for summer (July, August, and September) and fall (October, November, and December).

simplicity. From the small r^2 values (< 0.2) for winter (Figure 14), no linear relationship exists between the ILD and MLD values during this season. Under the standard Student's t test [e.g., *Wilks*, 1995] an absolute value of at least 0.33 (0.11) is needed for r (r^2) to be statistically significant at 95% for n=33. The r^2 values are always < 0.11 in winter for both data sets and for all ΔT values (Figures 14a and 14d), except ΔT=0.2°C for OWS. The winter SS have large negative values, with the largest negative value occurring for ΔT=1.0°C (Figures 14b and 14e). This indicates that the thermocline and pycnocline occur at different depths during winter for the region of the North Pacific Ocean occupied by the OWSs. Even though the r^2 values are large for OWS and Levitus in spring, the SS values are negative for ΔT=0.8° and 1.0°C. These negative SS values again indicate that the thermocline and pycnocline do not occur at the same depth. The best agreement between the isothermal and isopycnal layers occurs for summer for both data sets. The values of r^2 and SS are the highest for this season, and the bias values are also negligible. In fall the biases are modestly larger than those for summer.

Finally, we note that cases may exist where determining the ILD and MLD for the same ΔT criterion is desirable, even though the MLD yields the true depth of the mixed layer. A particular example is in determining where barrier layers exist (ILD>MLD) or possible subduction regions exist (ILD<MLD), as these have implications for the ocean heat budget. Cases may also exist where knowing how to obtain an optimal MLD via a suitable ΔT definition for the ILD is useful. For exam-

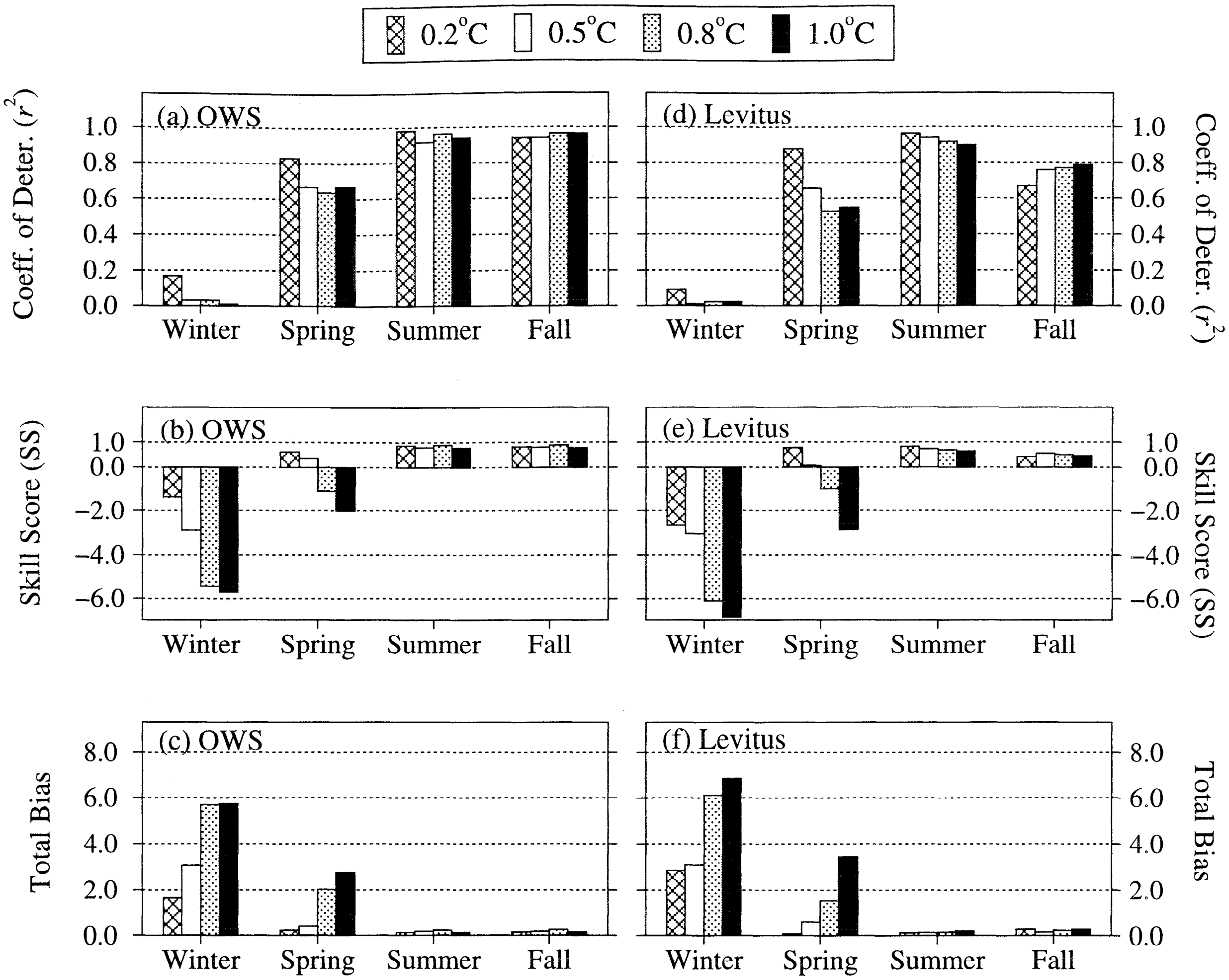

Figure 14. Coefficient of determination (r^2), skill score (SS) and bias (unitless conditional plus unconditional bias) values for the layer depth obtained from the ILD versus the MLD. The statistics are illustrated for layer depth from OWS data ($h_O(T)$ versus $h_O(\sigma_t)$) and Levitus data ($h_L(T)$ versus $h_L(\sigma_t)$), separately. Note that the metrics are shown for each ΔT value in each season.

ple, this information would be especially important for determining the MLD when no salinity measurements are available, a situation that commonly occurs in many in situ samplings over most of the global ocean.

6. Summary and Conclusions

In this paper we introduced a new method for accurately determining the ocean isothermal layer depth (ILD) and mixed layer depth (MLD) from temperature and density profiles that can be applied throughout the world ocean. It differs from earlier approaches in that here the ILD (MLD) is defined as an absolute change in ΔT ($\Delta\sigma_t$) with respect to an approximately uniform region of temperature (density) just below the ocean surface. The method has been validated by applying it to an observational data set of the northeast Pacific (OWS) and a global monthly climatology (Levitus) and comparing the resulting MLDs. They are found to be consistent with each other to within 20 m or better on average. Our statistical analysis indicates that overall, the optimal estimate of the MLD is obtained using a density–based criterion with ΔT=0.8°C. Here optimal is defined as the MLD definition that provides the most consistent agreement between the MLD values of the two data sets. For the northeast Pacific region the optimal criterion for MLD is found to vary seasonally: winter ($h(\sigma_t)$, ΔT=0.8° or 1.0°C), spring ($h(\sigma_t)$, ΔT=0.5° or 0.8°C), summer ($h(T)$, $\Delta T = 0.2$°C), and fall ($h(\sigma_t)$, $\Delta T = 0.8$°C). This seasonal dependence merely reflects the seasonal changes in the stratification of the upper ocean that are produced by turbulent mixing. During the nonsummer months the surface forcing of winds, moderate heating, and strong cooling produces a weaker thermocline and pycnocline, whereas a much sharper stratification at shallower depth develops under the strong surface heating of summer. The seasonal dependence of the optimal MLD criteria is therefore not surprising, and the optimal criteria may vary with other regions of the world ocean. However, if one accepts the universality of turbulence theory, and in particular the dependence of buoyant fluxes on thermal stratification, then one would expect the overall criterion given above to apply. The work presented here provides researchers with some guidance as to the best choice of criterion for defining the MLD.

The detailed comparison between MLDs inferred from two independent data sets has shown that the inherent variability of the MLD for any definition only allows for an accuracy of 20 m in 85% of the cases. This implies that one can only expect the ocean MLDs from models and climatology to agree within the same order of accuracy. This is an important limit of uncertainty for developers of OGCMs to keep in mind when validating their models against MLD climatologies.Constructing a MLD field using a ΔT=0.8°C criterion applied to density profiles may provide a more meaningful data set for validation of OGCMs with embedded mixed layers. For this reason we have used our optimal definition to construct global MLD climatologies from annual, seasonal, and monthly global climatologies of Levitus temperature and salinity. We refer to these layer depth climatologies as the Naval Research Laboratory Mixed Layer Depth (NMLD) climatology.

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