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Naval Research Laboratory Mixed Layer Depth (NMLD) Climatologies

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14. ABSTRACT

Monthly isothermal layer depth (ILD) and mixed layer depth (MLD) fields for the global ocean are presented from the Naval Research Laboratory (NRL) Mixed Layer Depth (NMLD) climatologies. The ILD is defined using only temperature while the MLD is defined using a density-based criterion. These fields are constructed from the 1-degreee monthly mean climatologies of the World Ocean Atlas 1994 (WOA94) using a method for determining layer depth that can accommodate the wide variety of temperature and density profiles that occur within the global ocean. The MLD, constructed using a density criterion based on a 0.8 °C temperature difference (ΔT) that also accounts for variable salinity, provides an optimal representation of the depth of the mixed layer. This optimal MLD is recommended as the most appropriate depth to use for purposes of model validation, mixed layer heat budgets, and ocean biology studies. The NMLD climatologies are used to examine the spatial and seasonal variability of the ILD and MLD for the latitudes 65°N to 72°S. Strong seasonality in MLD is found in the subtropical Pacific Ocean at high latitudes. The very deep mixed layer in the North Atlantic Ocean in winter is reproduced as well as the very shallow mixed layer in the Antarctic throughout the year. The correspondence between ILD and the optimal definition of MLD is also investigated, and maps of ΔT values are provided to enable the best ILD to be determined for any month and location in the global ocean. Large variations in the NMLD climatologies constructed using different criteria highlight the importance of using an optimally defined MLD climatology.

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NAVAL RESEARCH LABORATORY MIXED LAYER DEPTH (NMLD) CLIMATOLOGIES

1. INTRODUCTION

The ocean surface mixed layer is generally considered a quasi–homogeneous region in the upper ocean where there is little variation in temperature or density with depth. It is this observed feature in profiles of in situ temperature and salinity data that has lead to the definition of mixed layer depth (MLD) as an upper ocean property (e.g., Roden 1979, Pickard and Emery 1990, Monterey and Levitus 1997). MLD is one of the most important quantities of the upper ocean because it defines the surface region that directly interacts with the atmosphere. For example, MLD is significant in determining the volume or mass over which the net surface heat flux comes to be distributed (Chen et al. 1994), near surface acoustic propagation (Sutton et al. 1993), and ocean biology (Polovina et al. 1995, Fasham 1995, Arrigo et al. 1999). Ocean MLD is primarily determined by the action of turbulent mixing due to wind stress and heat exchange at the air–sea interface, and its variability is not as well understood or observed as the atmospheric boundary layer. One of the reasons for this state of affairs is the lack of temperature and salinity data with depth in some regions of the global ocean. This lack of data in combination with an improper definition of MLD may yield misleading information on the surface mixed layer and, thereby, incorrect predictions for modeled upper ocean processes that depend upon them. An MLD obtained from reliable data sets using an optimal definition is therefore necessary if models of upper ocean processes are to be accurate.

Oceanic surface mixed layer definitions commonly used in the literature usually fall into two basic categories as summarized in Monterey and Levitus (1997) and Kara et al. (2000a). These are, namely, gradient criteria and difference criteria. The first one implies that the vertical derivative of temperature in the surface layer is small in comparison to the one in the underlying layer, while the latter implies that the deviation of temperature from its magnitude at the surface does not exceed a certain adjustable value. Various definitions have been introduced for surface layer depths in the scientific literature based on density (Spall 1991, Sprintall and Tomczak 1992, Ohlmann et al. 1996) and temperature (Kelly and Qiu 1995, Wagner 1996, Obata et al. 1996). To keep these two surface layer definitions distinct, we shall refer to the former here as the MLD and the latter as the isothermal layer depth (ILD). For a review of these various definitions, the interested reader is referred to Kara et al. (2000a).

While the ILD is generally coincident with the MLD over most of the global ocean because of the presence of strong thermoclines, there are regions such as the high latitudes of the Southern Ocean where there are large differences between the ILD and MLD. In the particular case of high southern latitudes, stable water columns can occur despite sharp temperature inversions because of the compensating effect of the salinity (Gloersen and Campbell 1988). This occurs because the thermal expansion coefficient is very small in this region, thereby allowing salinity variability to

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become relatively important. For other regions, a small temperature difference (ΔT) corresponds to a relatively large density change because of the nonlinear dependence of the thermal expansion coefficient on temperature (Webster 1994). Because of salinity differences, the ILD defined using a given ΔT criterion will not be coincident with the MLD defined using a density difference criterion based on the same ΔT value, although the difference is often quite small.

Because the ILD and MLD can vary strongly with the chosen criterion in some cases, we document those variations here to convincingly demonstrate the importance of using an optimally defined MLD. This undertaking leads to the Naval Research Laboratory (NRL) Ocean Mixed Layer Depth (NMLD) climatologies constructed using a method of obtaining an optimal MLD (Kara et al. 2000a).

Section 2 describes the surface layer depth definitions. Section 3 presents the ILD and MLD climatologies for the global ocean that are constructed using these definitions, and describes the main characteristics of the optimal MLD. Section 4 investigates the correspondence between ILD and the optimal definition of MLD. The latter is presented to determine the best ΔT criterion to use for the ILD for any month and location in the global ocean. Conclusions are given in Section 5.

2. SURFACE LAYER DEPTH DEFINITIONS

The ILD and MLD climatologies are constructed using the monthly averaged temperature and density profiles from the World Ocean Atlas 1994 (Levitus et al. 1994, Levitus and Boyer 1994). These data sets hereinafter are referred to as the Levitus data. The Levitus data contain uniformly gridded monthly climatologies of temperature and salinity at a horizontal resolution of $1^\circ \times 1^\circ$ and 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 300 m, and then every 100 m to a depth of 1000 m.

The density is calculated using temperature and salinity values at the given depths using the standard United Nations Educational, Scientific, and Cultural Organization (UNESCO) equation of state with no pressure dependence (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. 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. Note that a pressure–independent equation of state must be used to be consistent with the temperature and salinity profiles in determining an MLD (Kara et al. 2000a). (The pressure–dependent equation of state can be used to consider the difference in density for a parcel of seawater relative to the background value. If the potential temperature is used, 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 and ocean general circulation models (OGCM).

The method applied here (Kara et al. 2000a) can 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 (i.e.,"a layer of cold water, down to $-1.6\,^{\circ}$C, sandwiched between the warmer surface and deeper layers", [Pickard and Emery (1990), p. 40]), 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 the reader is referred to Sprintall and Roemmich (1999). The method applied here was 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 greater complexity of this method yields an ILD and an MLD that are 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 with the current methodology, sometimes reaching differences as large as hundreds of meters. The criteria applied here for the ILD and MLD become similar to those of other authors [c.f. Kara et al. (2000a) for a table of references] for those cases where there is no subsurface region of uniform temperature and density, for example, a stable thermocline.

From an examination of the resulting global MLD fields 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 (Fig. 1) 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$\,^{\circ}$, 0.5$\,^{\circ}$, 0.8$\,^{\circ}$, and 1.0$\,^{\circ}$C), i.e., differences less than or equal to $0.1\,\Delta T$. For the example profiles shown in Fig. 1, 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 the 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

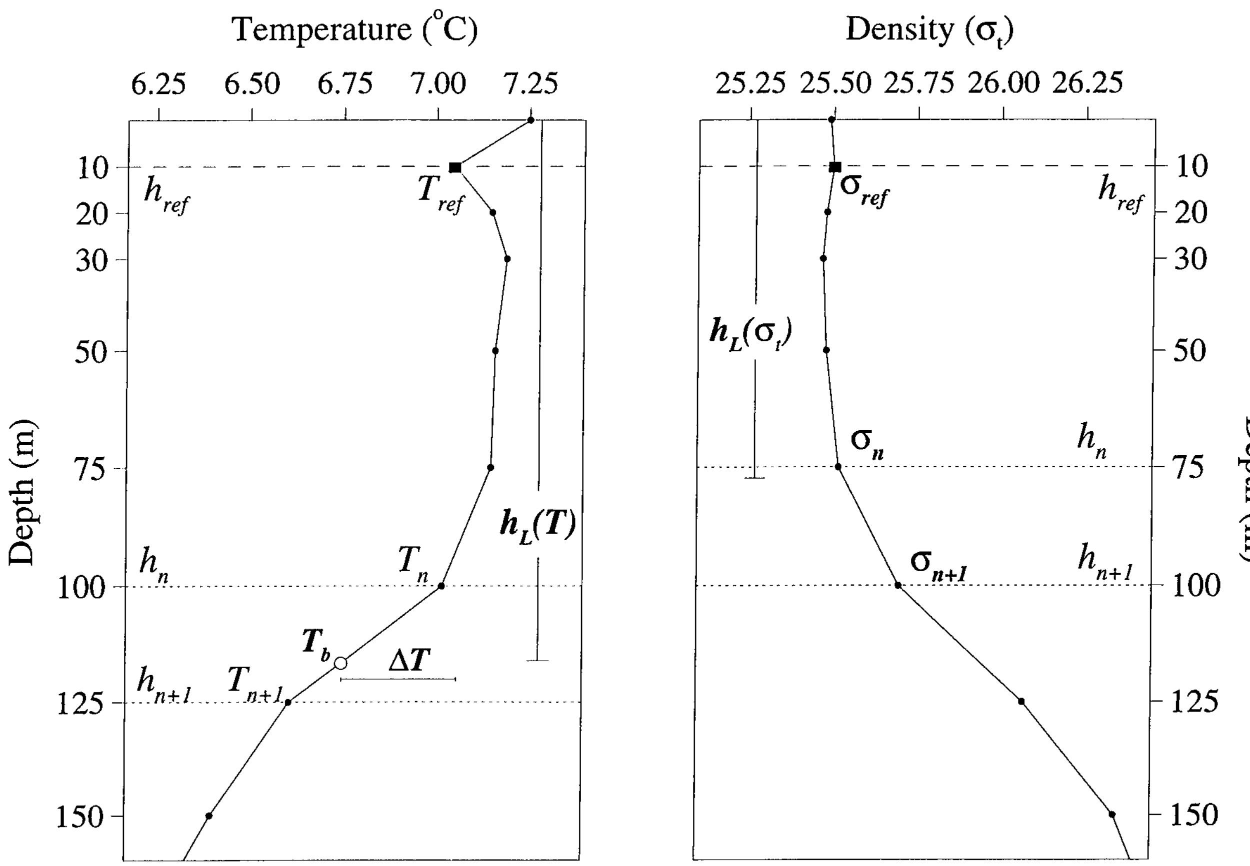

Fig. 1 — A schematic illustration of the ILD ($h_L(T)$) and MLD ($h_L(\sigma_t)$) determination using the temperature and density profiles at the Ocean Weather Station (OWS) station J from the Levitus data in February. For ease of notation we use the same symbols for the standard levels (h_n and h_{n+1}) 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.

be the depth at which the temperature has changed by an absolute value of ΔT from this reference value. For reference purposes, we 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 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 earlier in this section. 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

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

where S is the salinity and the pressure P is set to zero (Millero and Poisson 1981, Millero et al. 1980). For our example (Fig. 1), 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 [for a review, see Kara et al. (2000a)] as it takes full account of density changes due to temperature and salinity variations with location.

3. ILD AND MLD CLIMATOLOGIES

Using the method and datasets described in the previous section, we construct monthly ILD and MLD fields using ΔT values of 0.2, 0.5, 0.8, 1.0, 1.3, and 1.5 °C. This set of ΔT values is found to give sufficiently different ILD and MLD fields to merit considering them as distinct. Figures 2 through 7 show the ILD fields spanning the global ocean from 65°N to 72°S, while Figs. 8 through 13 show the corresponding MLD counterparts. As expected, both ILD and MLD deepen with increasing ΔT, although the deepening of MLD with ΔT is much less pronounced than for ILD because of salinity stratification. An interesting feature of the layer depths in the Antarctic and Southern Ocean (south of 40°S) is that for most of the year the ILD is always deep and greater than 250 m for ΔT values greater than 0.8 °C. Yet the MLD provides little evidence of very deep mixed layers. This clearly shows the importance of including salinity in a layer depth definition and that using ILD to define the depth of the mixed layer can be misleading in these regions.

A deep ILD begins to appear in the North Atlantic and North Pacific in January through April with a use of ΔT=0.5 °C, and these deep ILDs extend from 30°N and northwards at larger ΔTs. ILDs are always shallow (< 150 m) in the Equatorial Ocean (between 10°S and 10°N) and in the Northern Indian Ocean throughout the year for any given ΔT. The MLD fields for ΔT = 0.2° and 0.5 °C are consistent overall with the corresponding ILD fields created using the same ΔT. Deep MLDs appear with the use of ΔT = 0.5 °C in the North Atlantic Ocean (north of 40°N) in the boreal winter (January, February, and March) and in the Southern Ocean (between 40°S and 60°S) in the austral winter (July, August, and September). Deep MLDs greater than 250 m also appear in other regions with the use of ΔT > 1.0 °C: in the Southern Ocean (between 40°S and 60°S) from April through December, and in the North Pacific Ocean (between 20°N and 40 °N)

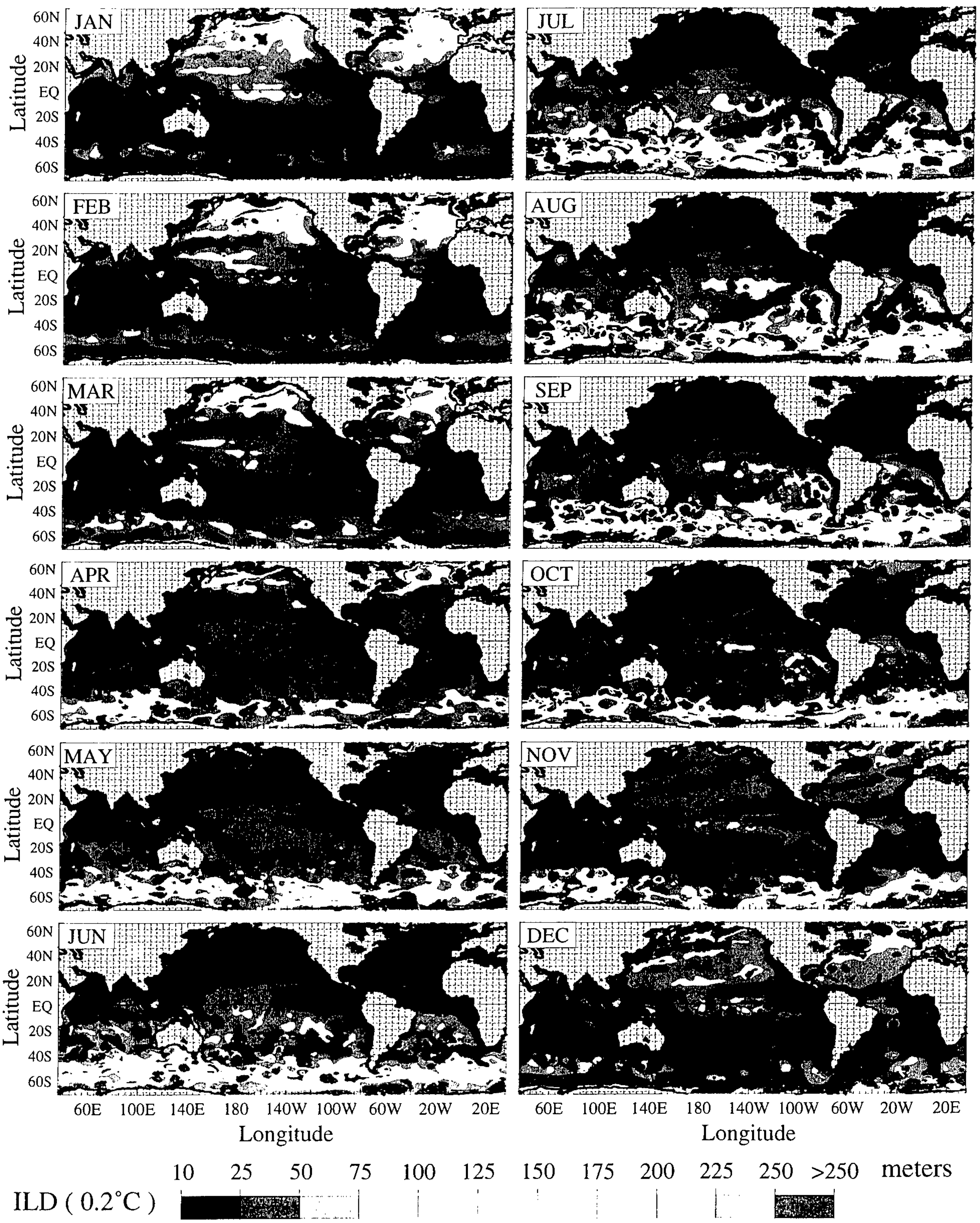

Fig. 2 — Climatological monthly mean isothermal layer depth defined using the temperature–based criterion with ΔT=0.2 °C

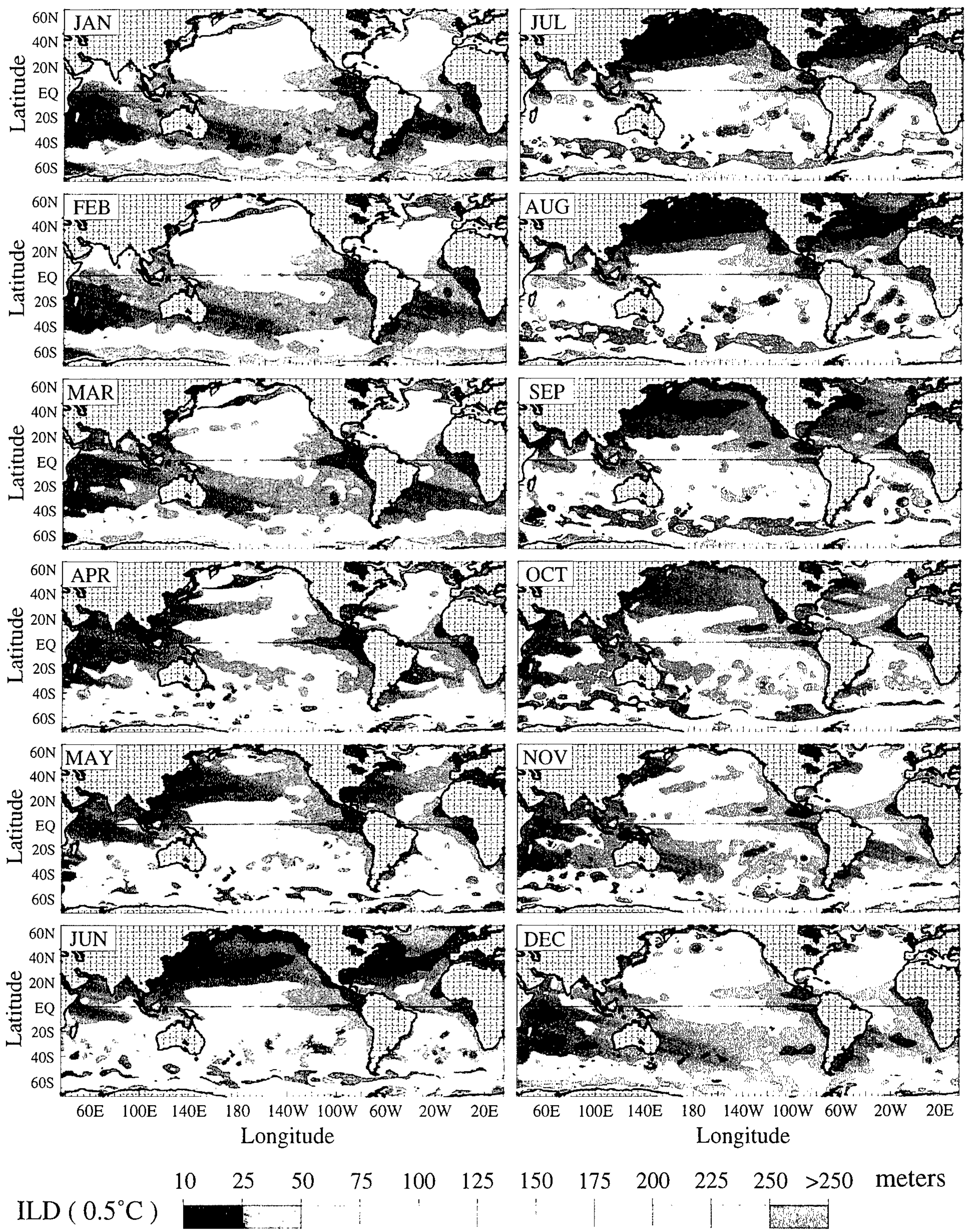

Fig. 3 — Climatological monthly mean isothermal layer depth defined using the temperature-based criterion with ΔT=0.5 °C

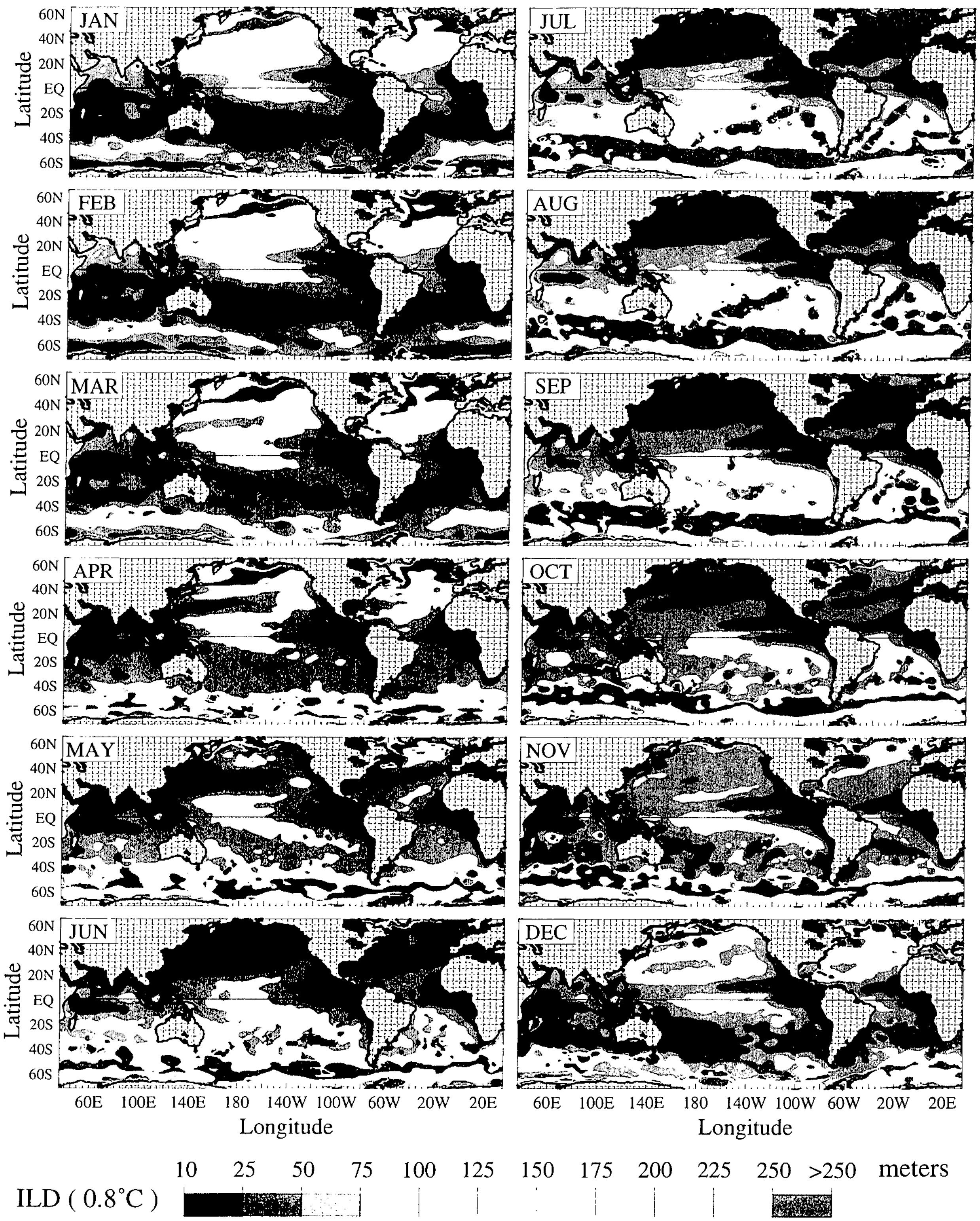

Fig. 4 — Climatological monthly mean isothermal layer depth defined using the temperature-based criterion with ΔT=0.8 °C

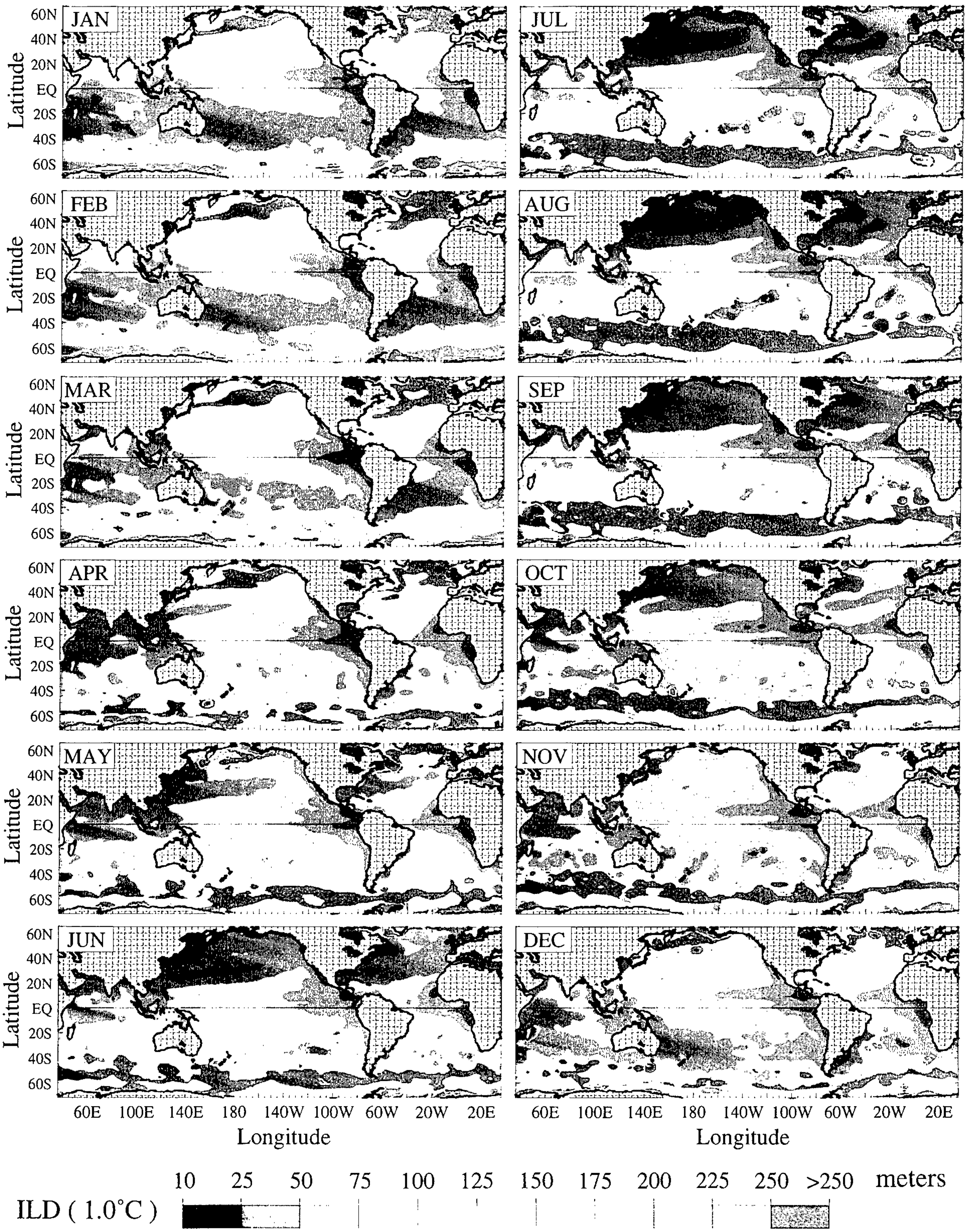

Fig. 5 — Climatological monthly mean isothermal layer depth defined using the temperature–based criterion with ΔT=1.0 °C

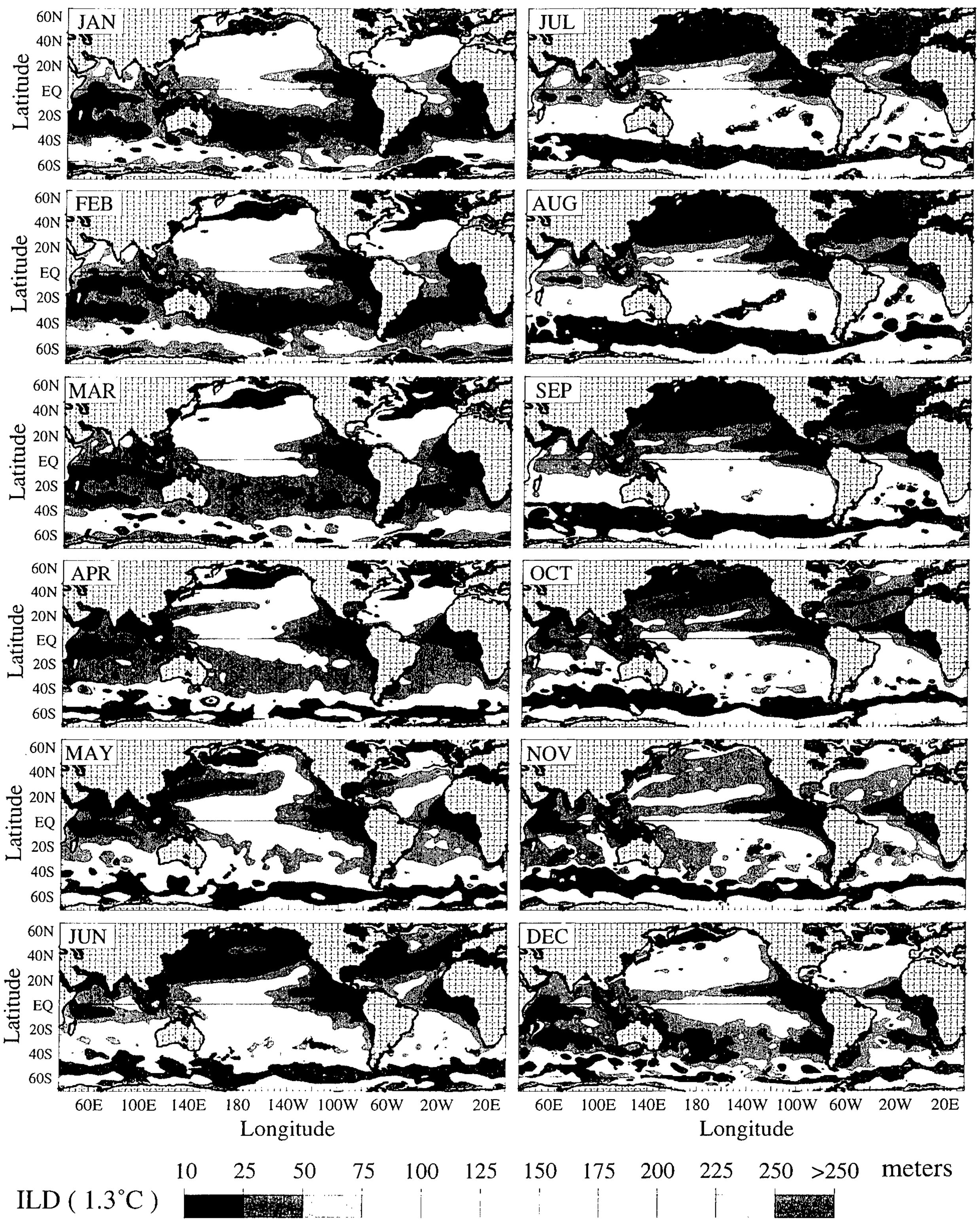

Fig. 6 — Climatological monthly mean isothermal layer depth defined using the temperature–based criterion with ΔT=1.3 °C

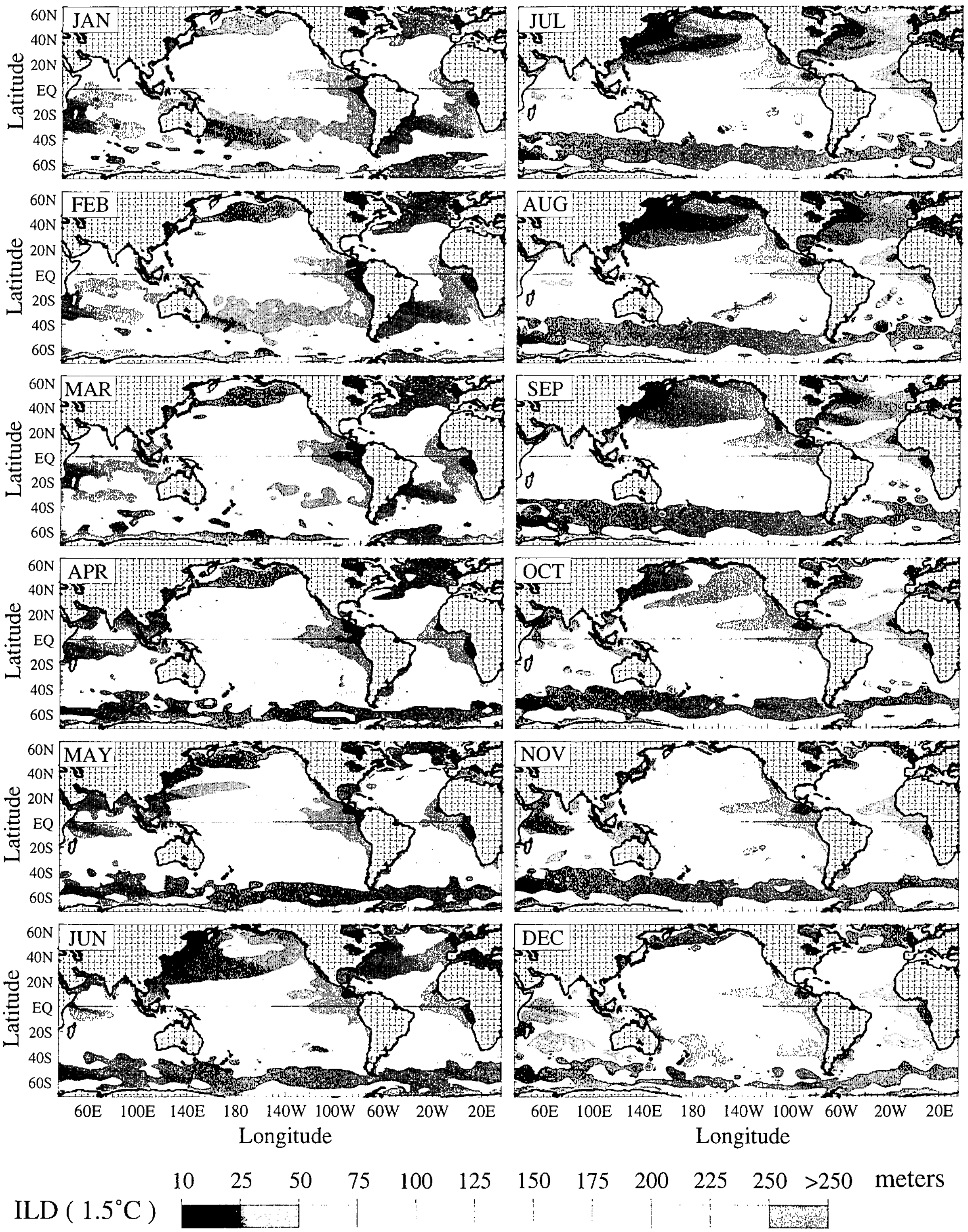

Fig. 7 — Climatological monthly mean isothermal layer depth defined using the temperature–based criterion with ΔT=1.5 °C

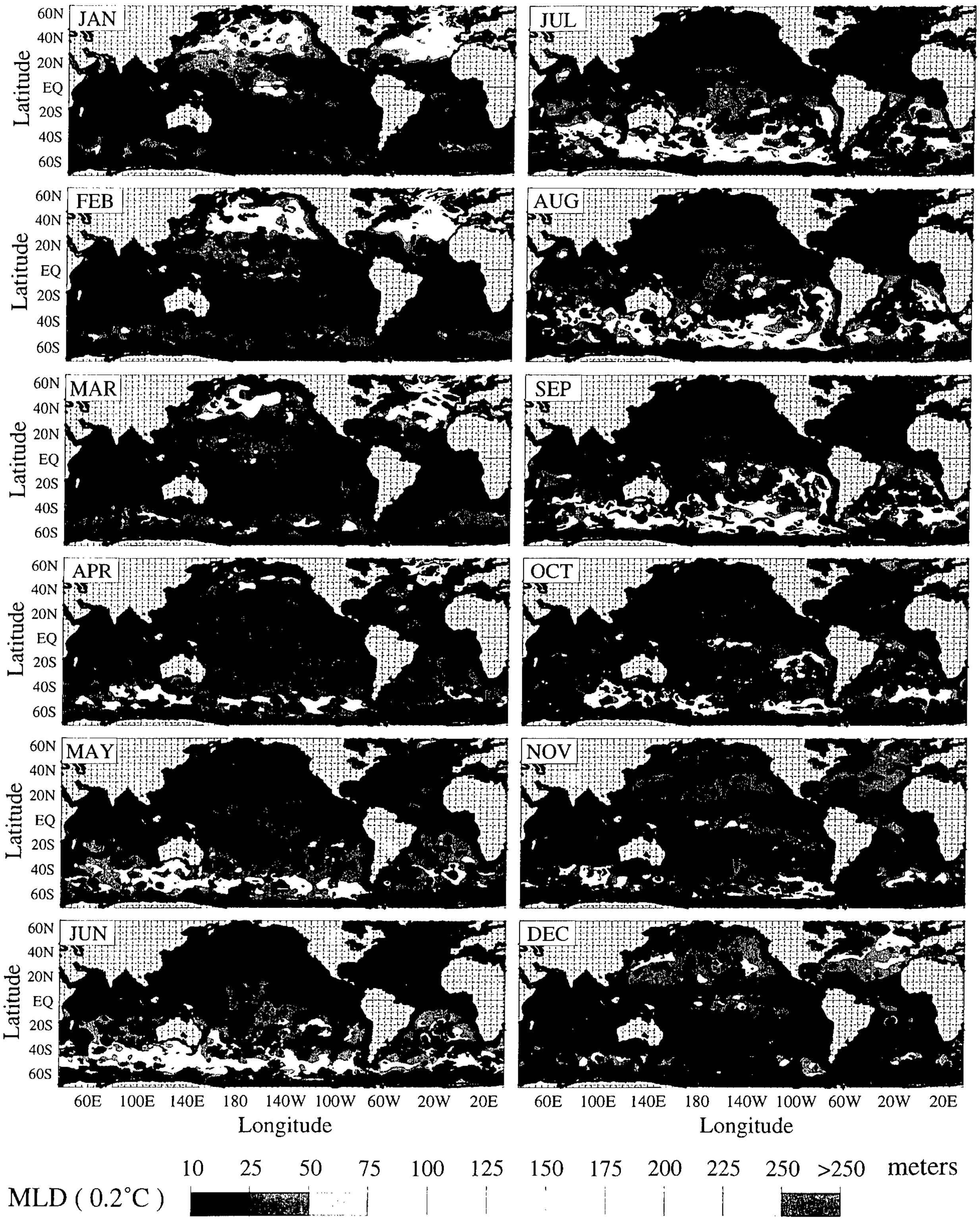

Fig. 8 — Climatological monthly mean mixed layer depth defined using the density–based criterion with ΔT=0.2 °C

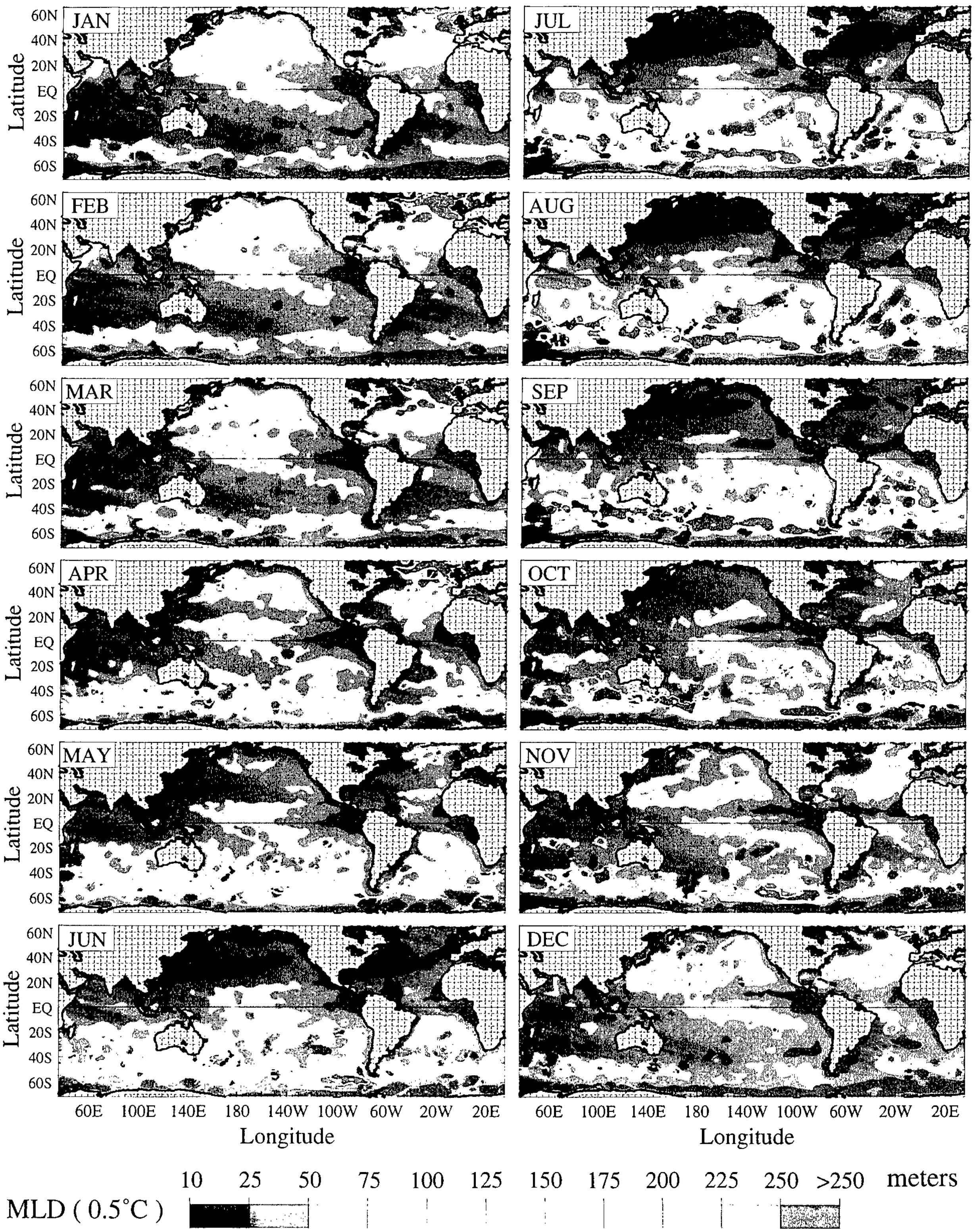

Fig. 9 — Climatological monthly mean mixed layer depth defined using the density–based criterion with ΔT=0.5 °C

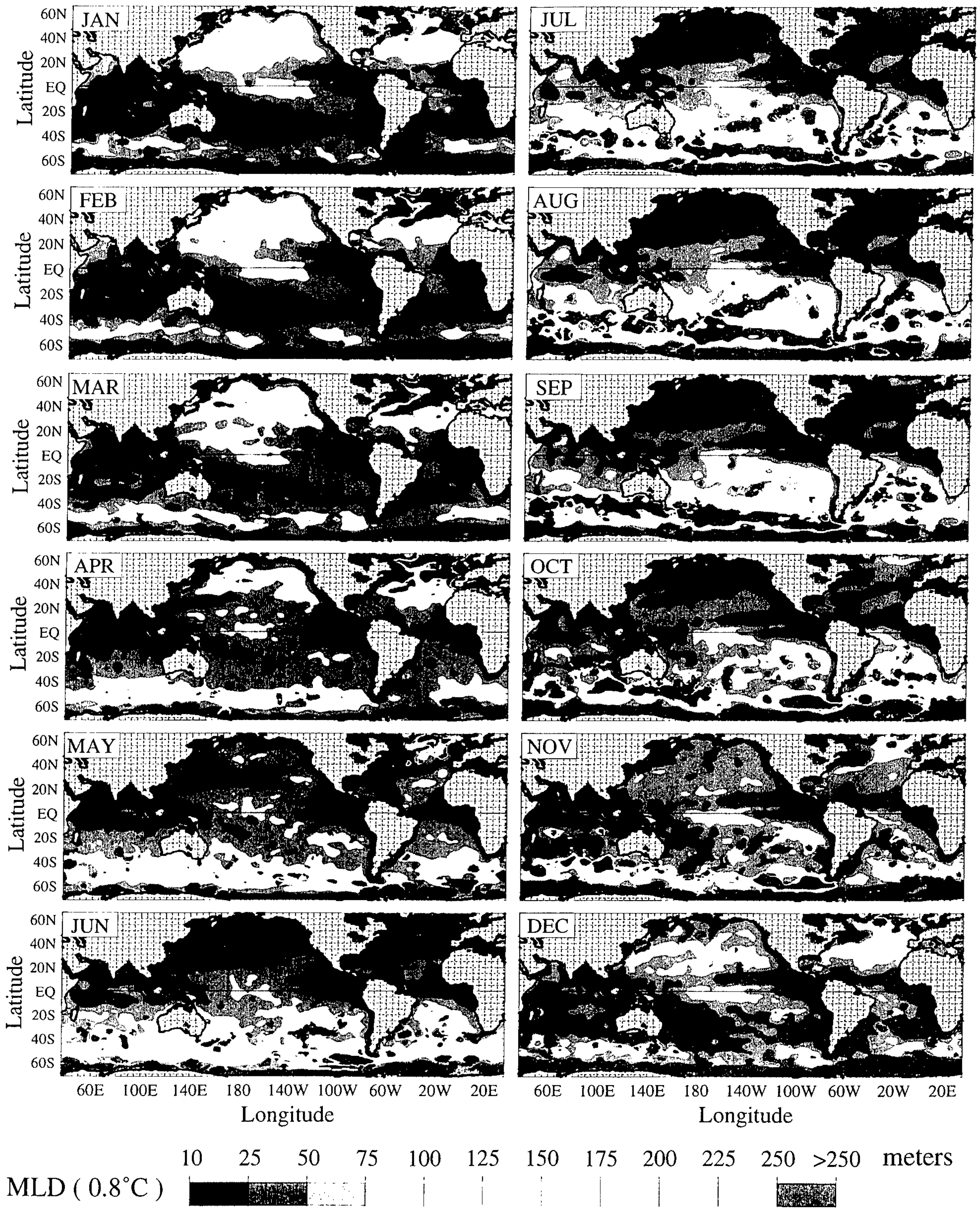

Fig. 10 — Climatological monthly mean mixed layer depth defined using the density–based criterion with ΔT=0.8 °C

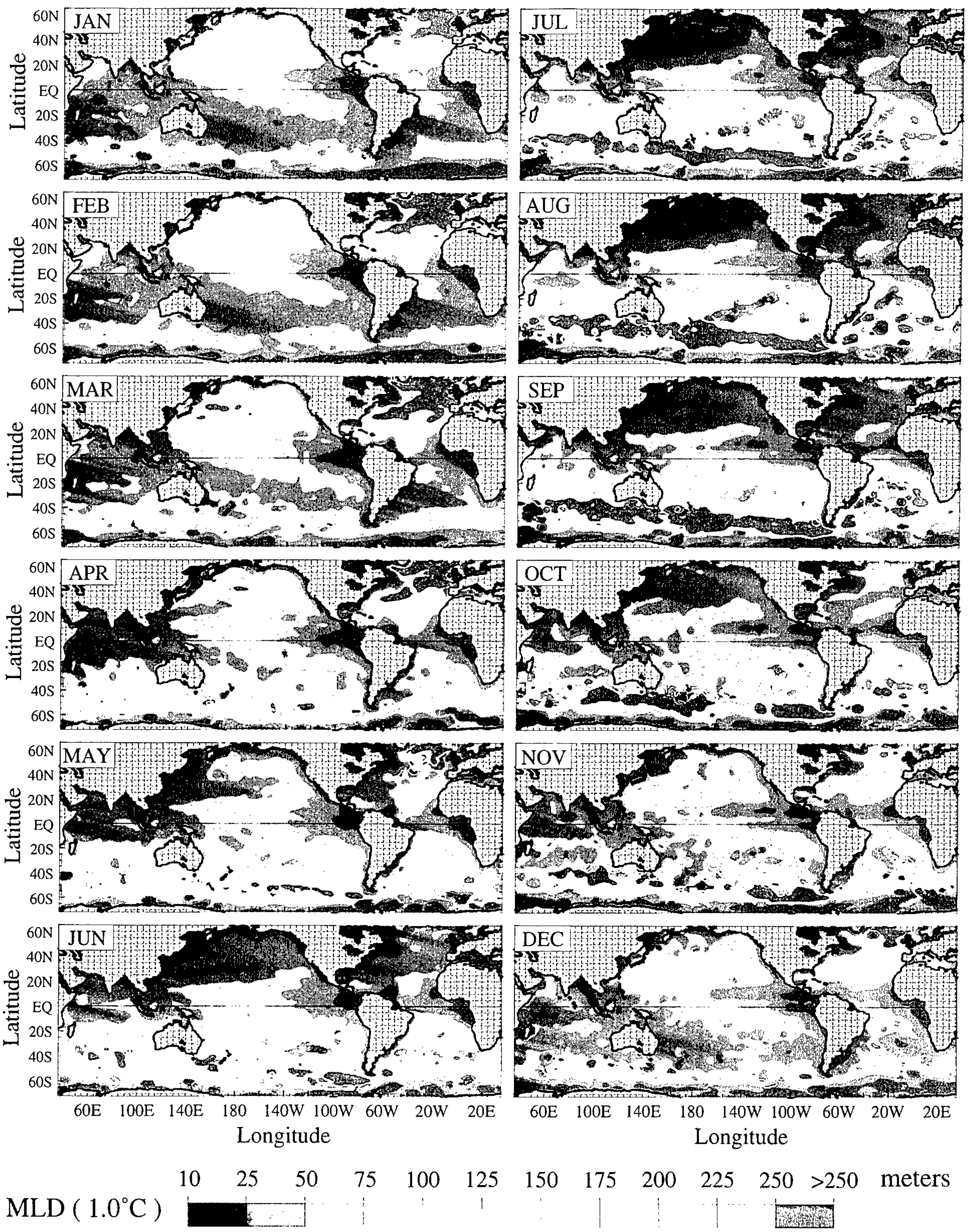

Fig. 11 — Climatological monthly mean mixed layer depth defined using the density–based criterion with ΔT=1.0 °C

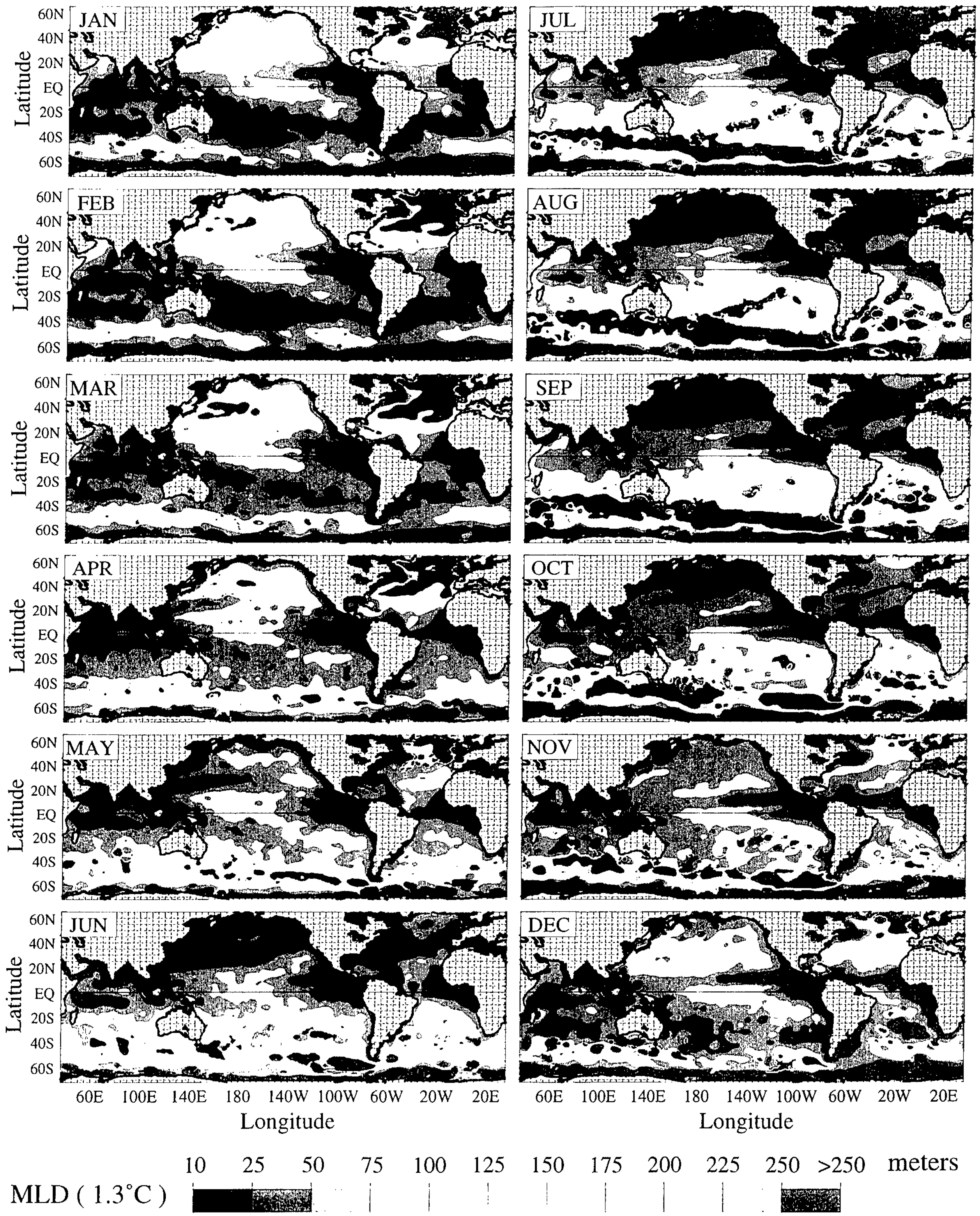

Fig. 12 — Climatological monthly mean mixed layer depth defined using the density–based criterion with ΔT=1.3 °C

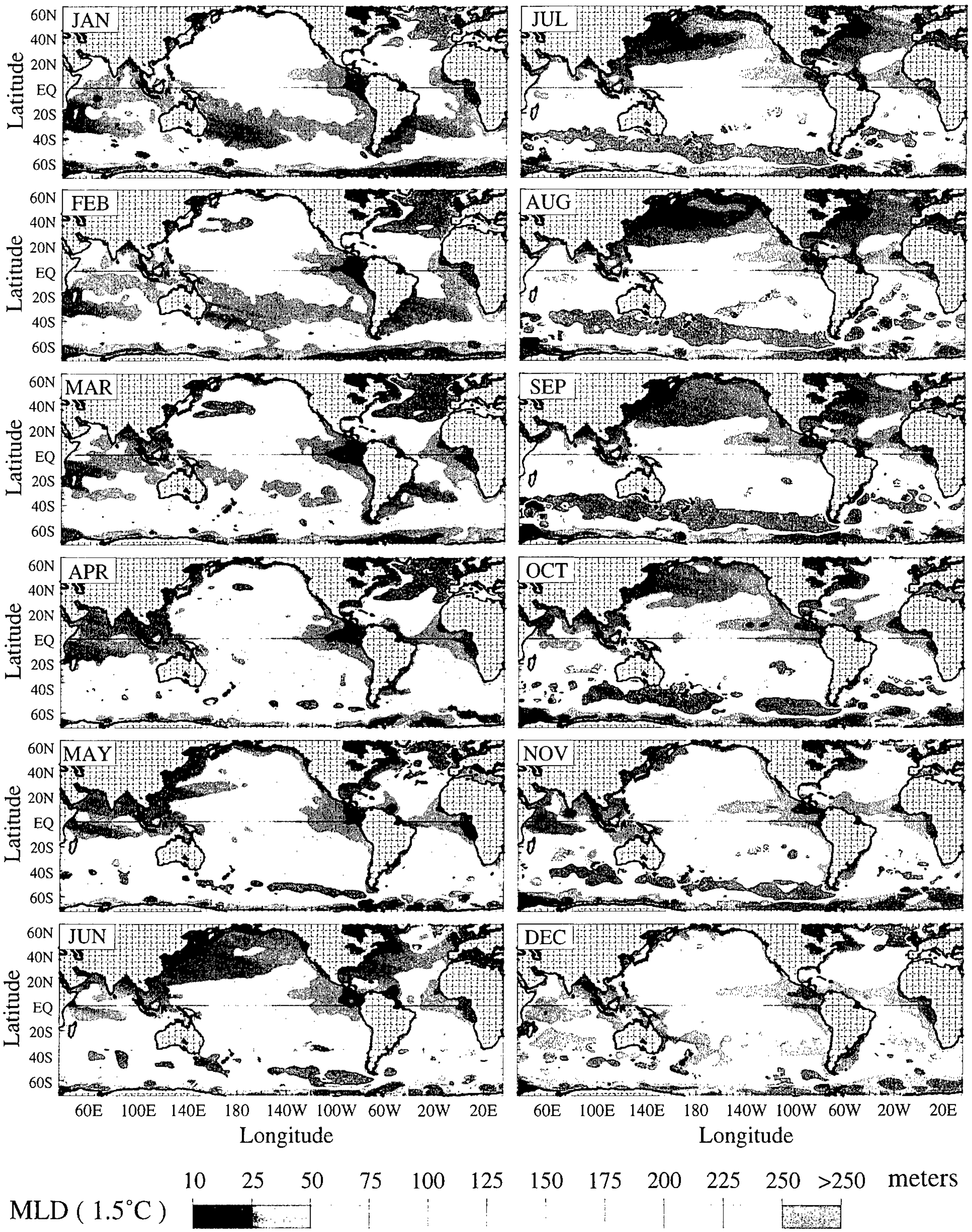

Fig. 13 — Climatological monthly mean mixed layer depth defined using the density–based criterion with ΔT=1.5 °C

in January, February, and March. Note that in the North Pacific Ocean the ILD obtained using $\Delta T > 1.0\,^{\circ}\mathrm{C}$ (Figs. 5 and 7) is greater than the corresponding MLD for the same ΔT values.

In a previous study (Kara et al. 2000a) it was determined that an MLD obtained using $\Delta T = 0.8\,^{\circ}\mathrm{C}$ defined a depth for the mixed layer that was near optimal. For this reason, we consider here the MLD obtained using this optimal criterion as the best representation of the ocean surface mixed layer. To gather insight into its properties, we next examine its spatial and temporal characteristics in detail.

The most obvious characteristic is that the mixed layer is shallow in summer vs. deep in winter for the boreal/austral season in each hemisphere. Deep mixed layers are seen in the North Pacific and North Atlantic in winter, with the deepest MLD in the North Atlantic Ocean occurring in the region of deep water formation poleward of 40°N from January through May. The MLD in these regions becomes much shallower in spring, with the region of deepest MLD occurring progressively further north and then disappearing. The regions of deep MLD reappear again in the fall to subsequently reach their maximum depth in winter. The wintertime mixed layer in the subpolar North Pacific does not deepen as much as in the Atlantic because of a halocline that is maintained by precipitation and slow upwelling from below (Kara et al. 2000b, 2000c). In general, the subpolar North Atlantic is one of the ocean regions where deep mixed layer formation is expected in winter (e.g., Kelly 1994, Whitehead et al. 1996, Roberts et al. 1996, Tang et al. 1999) and this is evident from our global MLD fields.

The summer MLD features in the North Atlantic and North Pacific are quite similar, and a similar structure is evident for the summer MLD in all the ocean basins of the southern hemisphere. This is consistent with summer heating of the upper ocean along with relatively weak winds generating shallow mixed layers. In the strong western boundary current regions of the Kuroshio and Gulf Stream, the MLD is at its deepest in winter and then shallows dramatically by summer. The Indian Ocean is dominated by two periods of strong winds during the year (i.e., the northeast and southwest monsoons). This strong seasonal variability in the surface winds and related sensible and latent heat fluxes dominate in determining the Indian Ocean MLD, especially in the Arabian Sea (e.g., Bauer et al. 1991). For the MLD fields at the equatorial ocean, a minimum MLD tongue is found to be centered in the eastern Equatorial Pacific during the northern hemisphere winter. Lukas and Lindstrom (1991), Sprintall and Tomczak (1992), and Delcroix et al. (1992) have previously explained the importance of salinity stratification in determining the MLD in the western equatorial Pacific due to the existence of a barrier layer. Note that the general zonal character of troughs and ridges in the tropical MLD are related to the presence of equatorial current–countercurrent systems (Bathen 1972). The region between 40°S and 60°S in the southern hemisphere is characterized by deep mixed layers that span a large zonal region over the globe. The shallowest MLD occurs in the Antarctic south of 60°S and is less than 25 m mainly due to fresh water flux from the Antarctic Continent (e.g., Parkinson 1991, Rintoul et al. 1997).

4. ILD AND MLD CORRESPONDENCE

Given the common use of ILD as the indication of MLD in the literature (e.g., Lamb 1984, Martin 1985), it is worthwhile to ask what ΔT defined ILD corresponds best to our optimal MLD (i.e., for a $\Delta\sigma_t$ with $\Delta T = 0.8\,^{\circ}\mathrm{C}$). This helps to assess the accuracy of the MLD determination in those instances where an ILD definition is applied. It is of considerable value for most cases of in situ data because contemporaneous temperature and salinity measurements are far less common than temperature alone. Such information can also be exploited in a global OGCM with an embedded mixed layer, as one may not wish to account for vertical changes of salinity on the MLD, when this effect can be easily taken into account by using vertical temperature profiles.

To determine the ΔT–defined ILD that most closely matches the MLD, we use the global monthly fields of ILD and MLD. The value of ΔT that yields an ILD equal to the MLD is determined at each ocean grid point ($1^\circ \times 1^\circ$ boxes) by applying a linear regression using the ILD(ΔT) for the ΔT values of 0.1, 0.2., 0.3, 0.5, 0.8, 1.0, 1.2 and 1.5 °C. The resulting monthly maps of ΔT values (Fig. 14) have substantial seasonal and regional variation over the global ocean. The subpolar Pacific Ocean exhibits a very small ΔT of $\sim 0.15\,^\circ$C during winter and much larger values of up to $\sim 0.75\,^\circ$C during summer. The North Atlantic Ocean generally shows large ΔT values (especially during winter). For the Antarctic Ocean, the ΔT values are substantially less than 0.6 °C. The ΔT values do not change significantly in the equatorial ocean, having values in the vicinity of $\sim 0.5\,^\circ$C. These regional variations are more easily seen in the annual mean of the ΔT values (Fig. 15). In general, the high southern latitudes and equatorial regions require ΔT values as low as 0.1 and 0.4 °C, respectively, regardless of the month. This reveals the influence of the strong salinity stratification on the MLD determination for these regions.

While it is possible to use this ΔT dataset directly within an OGCM, for computational efficiency it is preferable to use a simple functional equation whenever possible. Given that the ΔT values vary most strongly with latitude, we explore whether a simple and yet sufficiently accurate approximation can be obtained based on just zonal averages. From the zonal averages of the ΔT values for each month (Fig. 16) we note that for all seasons, the ΔT values over the global ocean can be easily expressed as a function of latitude between selected points. The corresponding mean, standard deviation, minimum, and maximum of the ΔT values are given for both the Global Ocean (defined as between 72°S to 65°N) and Equatorial Ocean (defined as between 10°S to 10°N) in Table 1.

To accurately capture this variation requires specifying the ΔT values in terms of turning points, as a single polynomial fit would yield too poor a representation. We use the annual mean of the zonal averages for the selection of our turning points. These are shown as open squares on the linear piecewise fit in Fig. 17. Also shown for comparison are the meridional variation in ΔT for the annual mean and the months of February and August. The generic linear fit between A and B (for example, between 72°S and 66°S) is $y(x) = y(A) + [(x - A)/(B - A)] \times [y(B) - y(A)]$ for $A \geq x \geq$ B. We have tested this function in the NRL Layered Ocean Model (NLOM) (Hurlburt et al. 1996) with an embedded Kraus–Turner type mixed layer (Rochford et al. 2001) where only a model constructed temperature profile is available. Use of this function allows the MLD to be estimated from an equivalent ILD, and for the temperature just below the mixed layer to be better represented, thereby improving the NLOM's predictive skill.

5. CONCLUSION

We have presented monthly ILD and MLD fields to show how strongly they vary with the chosen temperature difference criteria. They demonstrate that suitable care must be taken in the choice of defining criteria to avoid drawing misleading conclusions regarding the depth variability of the ocean surface mixed layer. The optimal MLD definition presented in this report using a

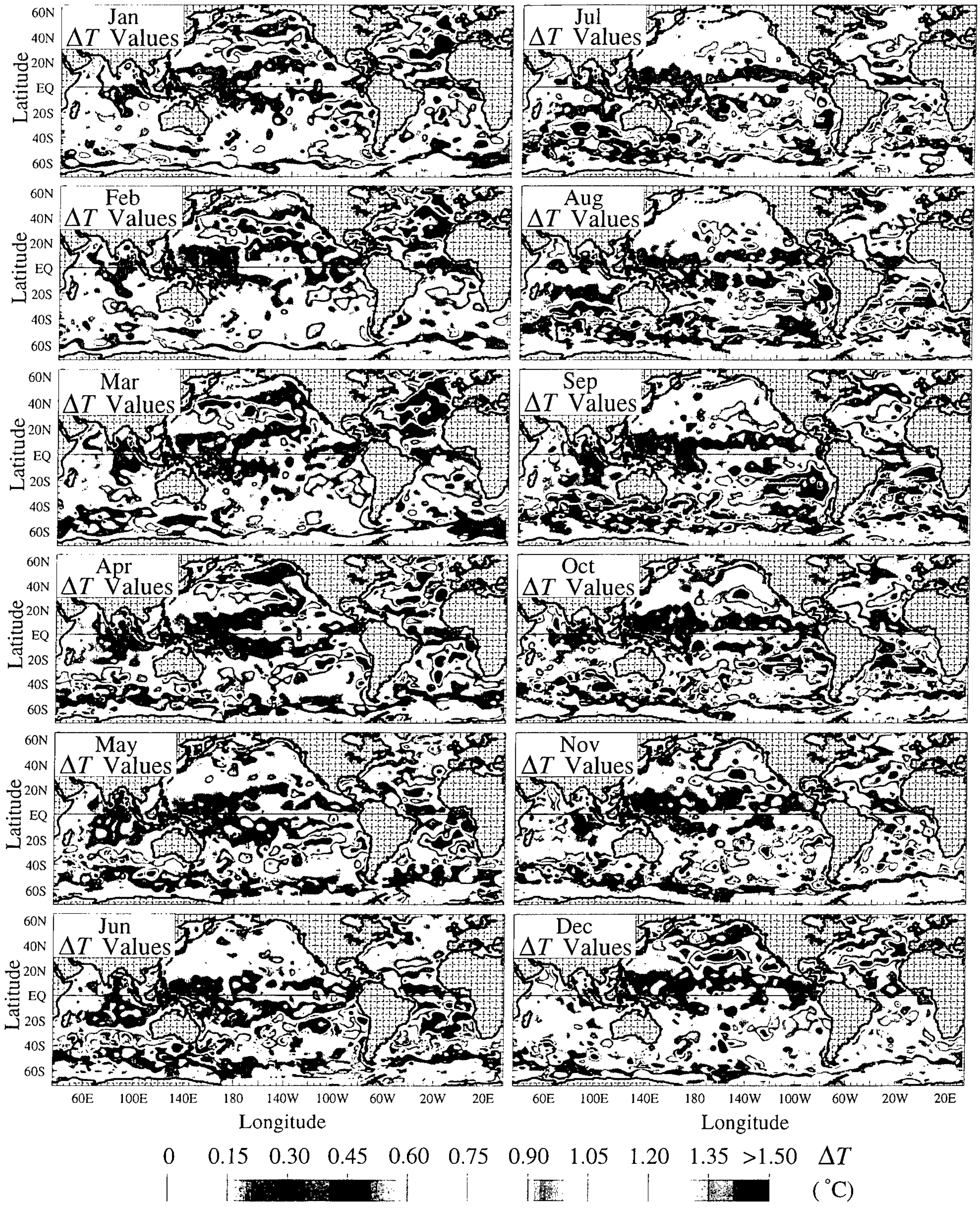

Fig. 14 — Monthly ΔT values that yield an ILD(ΔT) that is equivalent to the optimal MLD

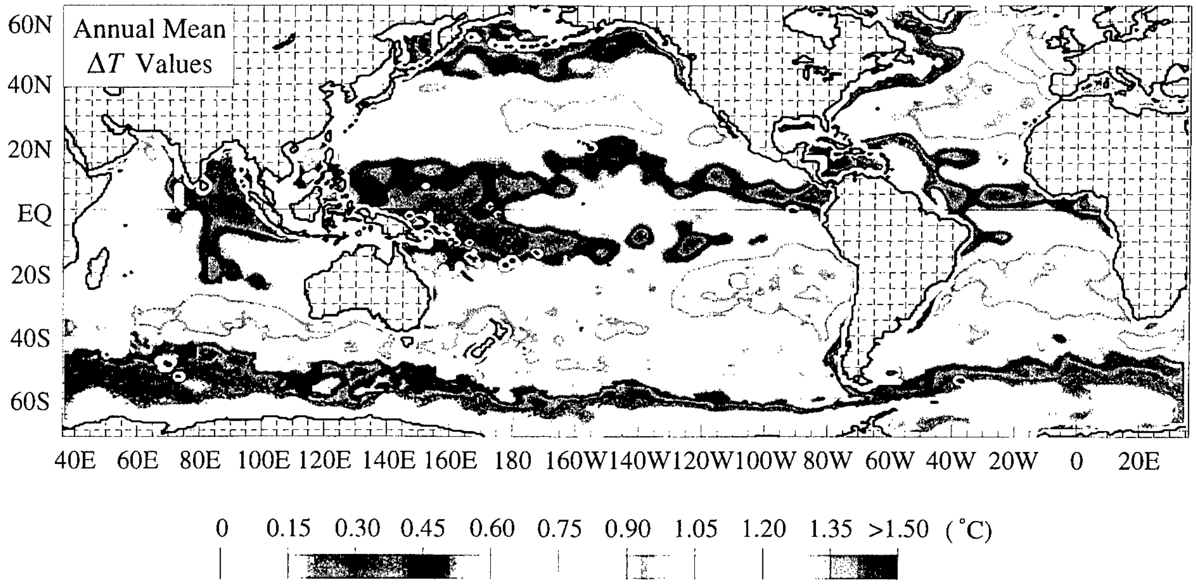

Fig. 15 — Annual average of the ΔT values

$\Delta T = 0.8\,°C$ criterion provides an optimal representation. The optimal MLD reveals that the mixed layer has a strong seasonal variation in mid–to–high latitudes. The well–known feature of a very deep mixed layer in the North Atlantic during the boreal winter is reproduced. The Pacific Ocean exhibits a clear winter (summer) deepening (shallowing) that follows the annual cycle in the Atlantic Ocean, although the depth penetration is not as great. In the Indian Ocean, the mixed layer has a semiannual cycle that follows the monsoons.

Table 1 — Zonally Averaged ΔT Statistics

	Global Ocean				Equatorial Ocean			
Month	Mean (°C)	Std (°C)	Min (°C)	Max (°C)	Mean (°C)	Std. (°C)	Min (°C)	Max (°C)
Jan	0.58	0.22	0.07	1.04	0.50	0.05	0.44	0.61
Feb	0.59	0.23	0.04	1.12	0.50	0.04	0.46	0.58
Mar	0.59	0.22	0.07	1.05	0.51	0.02	0.50	0.55
Apr	0.57	0.22	0.13	0.96	0.49	0.03	0.46	0.56
May	0.55	0.20	0.12	0.90	0.48	0.05	0.40	0.54
Jun	0.56	0.22	0.11	0.92	0.46	0.05	0.39	0.56
Jul	0.58	0.23	0.05	1.02	0.50	0.07	0.39	0.59
Aug	0.59	0.24	0.05	0.99	0.53	0.06	0.42	0.59
Sep	0.58	0.25	0.05	1.04	0.51	0.10	0.37	0.64
Oct	0.58	0.26	0.07	0.99	0.51	0.09	0.38	0.62
Nov	0.54	0.24	0.06	0.91	0.50	0.11	0.32	0.61
Dec	0.56	0.22	0.09	0.98	0.52	0.08	0.40	0.62

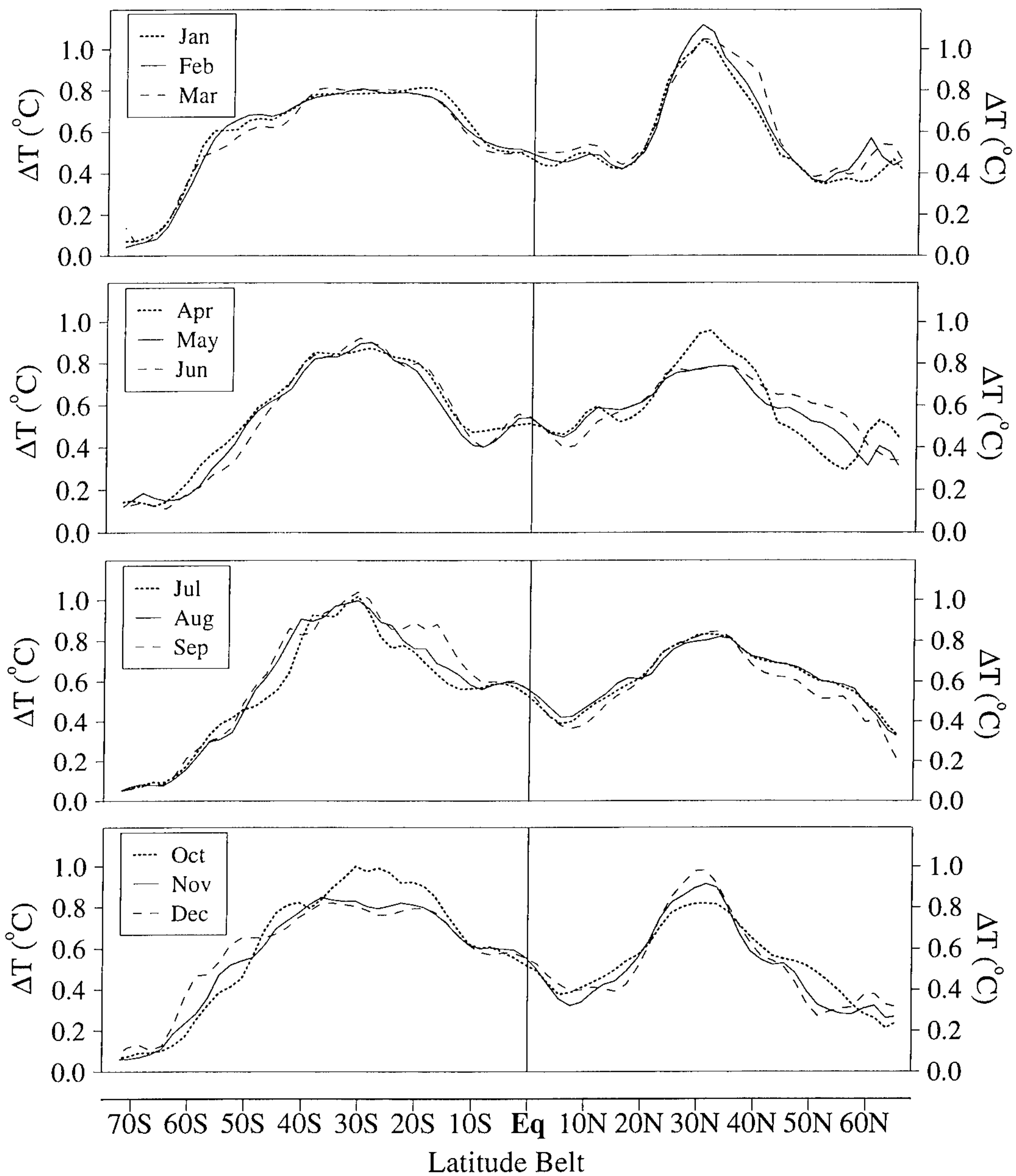

Fig. 16 — Zonally averaged values of ΔT for each month separately: (a) January, February, and March; (b) April, May, and June; (c) July, August, and September; and (d) October, November, and December

We have also investigated the correspondence between ILD and MLD to determine the ILD(ΔT) that corresponds best to our optimal definition of MLD. This provides an alternative to estimating the MLD in the case where only temperature information is available. There is considerable seasonal and regional variability in the choice of ΔT, and for this reason monthly maps are provided to aid in the best selection of ΔT. While there is strong spatial and temporal variability in the ΔT values, the zonally averaged values provide an ILD(ΔT) that approximates well the optimal MLD. A simple functional equation for this meridional variation in ΔT has been derived and found to be useful for OGCM applications.

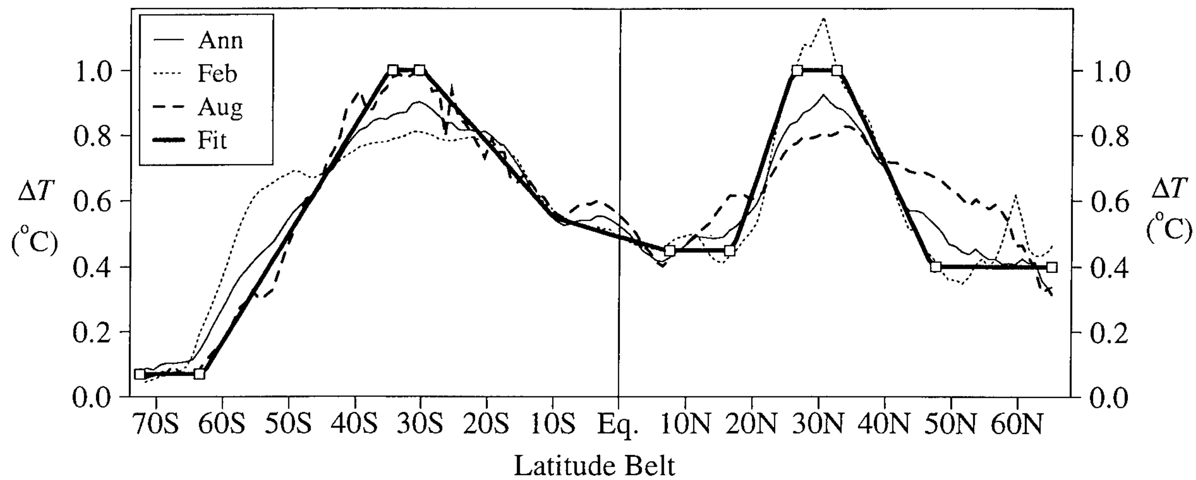

Fig. 17 — Linear piecewise fit applied to the global annual average of the ΔT values

The NMLD climatologies presented here serve as a reference for researchers wishing to compare the differences between ILD and MLD values published in the scientific literature using various definitions. They are useful for a wide variety of applications as outlined here, including model development and evaluation. Researchers should keep in mind that limitations still exist for the optimal MLD because of the inadequate salinity and temperature data in some regions such as the Southern Ocean. The MLD and ILD datasets presented in this report, and the algorithm to generate the layer depths, are publicly available at http://www7320.nrlssc.navy.mil/nmld/nmld.html.

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GLOSSARY

The acronyms appearing throughout this report are listed below for ease of reference.

ILD	Isothermal layer depth
MLD	Mixed layer depth
NLOM	NRL Layered Ocean Model
NMLD	NRL Ocean Mixed Layer Depth
NRL	Naval Research Laboratory
OWS	Ocean Weather Station
OGCM	Ocean General Circulation Model
SSC	Stennis Space Center
UNESCO	United Nations Educational, Scientific, and Cultural Organization