Variability of the Oceanic Mixed Layer, 1960–2004

JAMES A. CARTON, SEMYON A. GRODSKY, AND HAILONG LIU

Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, Maryland

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ABSTRACT

A new monthly uniformly gridded analysis of mixed layer properties based on the World Ocean Atlas 2005 global ocean dataset is used to examine interannual and longer changes in mixed layer properties during the 45-yr period 1960–2004. The analysis reveals substantial variability in the winter–spring depth of the mixed layer in the subtropics and midlatitudes. In the North Pacific an empirical orthogonal function analysis shows a pattern of mixed layer depth variability peaking in the central subtropics. This pattern occurs coincident with intensification of local surface winds and may be responsible for the SST changes associated with the Pacific decadal oscillation. Years with deep winter–spring mixed layers coincide with years in which winter–spring SST is low. In the North Atlantic a pattern of winter–spring mixed layer depth variability occurs that is not so obviously connected to local changes in winds or SST, suggesting that other processes such as advection are more important. Interestingly, at decadal periods the winter–spring mixed layers of both basins show trends, deepening by 10–40 m over the 45-yr period of this analysis. The long-term mixed layer deepening is even stronger (50–100 m) in the North Atlantic subpolar gyre. At tropical latitudes the boreal winter mixed layer varies in phase with the Southern Oscillation index, deepening in the eastern Pacific and shallowing in the western Pacific and eastern Indian Oceans during El Niños. In boreal summer the mixed layer in the Arabian Sea region of the western Indian Ocean varies in response to changes in the strength of the southwest monsoon.

1. Introduction

The oceanic mixed layer provides a connection between atmosphere and ocean and thus plays a central role in climate variability. For example, recent studies suggest that changes in the maximum depth of the mixed layer from one winter to the next may explain the reemergence of sea surface temperature (SST) anomalies and thus persistence of wintertime SST patterns (Alexander et al. 2001; Timlin et al. 2002; Deser et al. 2003). Here we exploit the availability of a newly expanded archive of profile observations to determine the spatial and temporal structure of mixed layer depth variability during the 45-yr period 1960–2004. Our goal is to document these changes to the extent possible given the limitations of the historical observational record.

In the extratropics mixed layers undergo large seasononal depth variations as a result of seasonally varying balances in the mixed layer heat and salt budgets. Summer conditions of high sunlight and mild winds produce shallow, strongly stratified mixed layers. The maximum mixed layer depths (MLDs), in excess of 100 m at 40°N, occur in winter and early spring as the result of reductions in surface buoyancy flux and increases in turbulent mixing (e.g., Monterey and Levitus 1997; Kara et al. 2002; de Boyer Montegut et al. 2004).

A number of studies have examined mixed layer dynamics at fixed mooring sites such as the Freeland et al. (1997) examination of Ocean Station Papa (50°N, 145°W) in the North Pacific. These examinations reveal the presence of substantial subseasonal (interannual and longer) variations of MLD. At Ocean Station Papa, Freeland et al. found 10–20-m year-to-year depth variations as well as a long-term 6 m decade^{-1} shallowing trend. These subseasonal variations are linked to the seasonal cycle because they result from terms in the heat and salt balances of the mixed layer that are important when the mixed layer is deepening. The variations are masked by the appearance of shallow mixed layers in summer.
In addition to understanding temporal variations of MLD we would like to explore their spatial structure. For the North Pacific winter–spring mixed layer Polovina et al. (1995) examined the historical profile dataset for the years 1977–88 relative to 1960–76 looking for evidence of a “climate transition.” In contrast to the shallowing trend noted at Ocean Station Papa, they found a 30%–80% deepening in MLD in the subtropics between these two time periods. The authors ascribe this dramatic change to the deepening of the Aleutian low pressure system and the consequent intensification of surface winds.

Indeed, since 1960 meteorological conditions in the subtropical North Pacific do appear to have undergone a transition (Bond et al. 2003). The period prior to the mid-1970s is characterized by winters with warm subtropical SSTs, cool eastern tropical SSTs, weakened midlatitude westerly winds, and the Aleutian low pressure system [the negative phase of the Pacific decadal oscillation (PDO)] (Mantua et al. 1997). More recent decades are characterized by conditions where these anomalies are reversed (the positive phase of the PDO). Incidentally, the transition seems to have induced corresponding changes in the ecosystem of the North Pacific because of the impact of changing MLD on nutrient supply to the mixed layer (Polovina et al. 1995; Chavez et al. 2003; Chai et al. 2003). Studies of the anomaly mixed layer heat balance in this region (see e.g., Alexander et al. 2002; Qu 2003) indicate the importance of forcing by surface heat flux, while Ekman transport acts to dampen temperature anomalies.

Like the North Pacific, the wintertime climate of the subtropical-to-subpolar North Atlantic is also subject to decadal variability. Since the 1960s this region has experienced a gradual increase in the latitude and strength of wintertime storms as reflected in an increasing value of the North Atlantic Oscillation (NAO) index (Hurrell 1995). These decades have also seen a warming of SST and rising upper-ocean heat storage in the subtropical gyre and cooling and freshening in the subpolar gyre (Dickson et al. 2000; Flatau et al. 2003; Curry et al. 2003; Boyer et al. 2005; Levitus et al. 2005). One subtropical Atlantic location where the decadal trends of mixed layer properties have been explored is at Hydrostation S (32°N, 64°W) in the Sargasso Sea. There Michaels and Knap (1996) reviewed historical mixed layer properties from 1955 to 1994 relying mainly on bottle data and found quasi-decadal time-scale variations and variations with periods longer than the Hydrostation S record. In the late 1950s–60s the time series show winter MLDs of 200–450 m. After 1970, the mixing is shallower (100–300 m), with short periods of deeper MLDs. Our own reexamination of the Hydrostation S bottle data shows that the winter MLD deepened since 1990. So, the linear trend of winter MLD over the whole period 1960–2005 is quite weak. Before 1980, interannual deepening events of winter MLD at the Hydrostation S were found to be correlated with the El Niño events in the Pacific, but this correspondence is less evident in the records after 1980. The relationship to SST was explored by Bates (2001) who found a negative relationship ($r = -0.56$) for the MLD–SST correlation.

The most dramatic changes of the mixed layer occur in the North Atlantic subpolar gyre. At the Ocean Weather Station Bravo in the Labrador Sea the upper and intermediate layers have cooled and freshened during the past three–four decades causing deeper mixed layers. These changes have apparently been caused by the changes in storminess associated with the rising NAO index (Dickson et al. 2002). At the station M at 66°N, 2°E in the Norwegian Sea, in contrast, the winter MLD has no significant long-term trend. At this eastern North Atlantic location outside the subpolar gyre the mixed layer cannot penetrate through the base of the near-surface water mass known as Atlantic Water (~300 m), and thus here MLD variability is mostly governed by horizontal advection rather than surface forcing (Nilsen and Falck 2006).

Low-frequency changes in MLD in the tropics are somewhat different than those at higher latitudes. Wang and McPhaden (2000) and Cronin and Kessler (2002) both examine the moored time series at 110°W in the eastern equatorial Pacific and show that increases in MLD are associated with decreases in winds and increases in SST, rather than the reverse. In an analysis of observations since 1992 Lorbacher et al. (2006) examine the spatial structure of MLD variations associated with the 1997 El Niño and show an out-of-phase relationship between changes in MLD in the eastern and western equatorial Pacific (see their Fig. 16).

In this study we take an advantage of the 7.9 million stations contained in the newly available World Ocean Database 2005 (Boyer et al. 2006) as well as recent work on mixed layer estimation by de Boyer Montegut et al. (2004) to reexamine the geographic and temporal variability of mixed layer properties during the 45-yr period 1960–2004. We begin with a brief comparison to the alternative analysis of White (1995) and an examination of the impact of limitations in the salinity profile database on data coverage. The remainder of the paper examines interannual and decadal variability in the Northern Hemisphere and tropical mixed layer and the relationship between subseasonal changes in MLD, winds, and SST.
2. Data and methods

The estimates of mixed layer properties presented here are based on the combined set of temperature and salinity vertical profiles from all available instruments contained in the World Ocean Database 2005 archive for the period 1960–2004. We use data from the mechanical bathythermographs (MBTs), expendable bathythermographs (XBTs), conductivity–temperature–depth casts (CTD), as well ocean station data (OSD), moored buoys (MRBs), and drifting buoys (DRBs). The final 4 yr of the database contain an increasing number of profiles from the new ARGO system of profiling floats (PFL), causing the amount of salinity information to increase dramatically. This approach (based on individual vertical profiles) minimizes possible dependence of the results on biases in temperature and salinity if these biases are depth independent for each profile.

Many different criteria have been suggested in the literature for determining the depth of the base of the mixed layer (see de Boyer Montegut et al. 2004; Lorbacher et al. 2006 for recent discussions). Here we generally follow the methodology of de Boyer Montegut et al. (2004) who define this depth for each profile based on the temperature or density difference from the temperature or density at a reference depth of 10 m. This reference depth was shown to be sufficiently deep to avoid aliasing by the diurnal signal, but shallow enough to give a reasonable approximation of monthly SST.

Our temperature-based criterion defines MLD as the depth at which temperature changes by $|\Delta T| = 0.2^\circ C$ relative to its value at 10-m depth. The $0.2^\circ C$ value is chosen following de Boyer Montegut et al. (2004) partly as a compromise between the need to account for accuracy of MLD retrieval and the need to avoid sensitivity of the results to measurement error. Here we define the depth of the mixed layer by the absolute difference of temperature, $|\Delta T|$, rather than only the negative difference of temperature to account for mixed layers with temperature inversions in salt-stratified situations (most common at high latitudes; see the appendix). For comparison, an alternative analysis by White (1995), uses a reference level of 0 m and a larger $|\Delta T| = 1^\circ C$ temperature criterion.

In addition to a temperature-based estimate of MLD, if profiles include both temperature and salinity (approximately 25% of all casts), we may also compute a density-based MLD estimate. The increase in density, $\Delta \rho$, which defines the depth of the base of the mixed layer is chosen, following the variable density criterion of Monterey and Levitus (1997), to be locally compatible with the temperature-based estimates [i.e., $\Delta \sigma = (\partial \sigma / \partial T)|_{0.2^\circ C}$]. This study relies primarily on temperature-based estimates because of their superior spatial and temporal coverage [unless specified, MLD (i.e., mixed layer depth), will refer to the temperature-based estimates exclusively]. The differences between the two estimates are briefly discussed in section 3.

In our processing we have eliminated all profiles if flagged by the World Ocean database quality control procedure. One condition we reconsider before rejecting a profile is its vertical resolution. We retain profiles with coarse vertical resolution within the mixed layer itself, but we reject the profile if the vertical resolution is insufficient to resolve the bottom of the mixed layer (i.e., if the deepest horizon within the mixed layer is separated from the shallowest horizon below the mixed layer by more than 20% of the mixed layer depth estimate), or if the profile is shallower than the MLD. This latter restriction is important because insufficient vertical resolution leads systematically to the underestimation of MLD.

After estimating MLD, mixed layer temperature, and mixed layer salinity at each profile location we then apply subjective quality control to remove “bull’s eyes” and bin the data into $2^\circ \times 2^\circ \times 1$ month bins with no attempt to fill in empty bins. The data coverage provided by each instrument is illustrated in Fig. 1a, expressed as the number of data-filled points for each monthly grid (there are approximately 11 000 ocean grid points on a $2^\circ \times 2^\circ$ grid). The data coverage is relatively sparse. Even the XBT data never covers more than 20% of the ocean surface in a month.

As indicated in Fig. 1a, the data coverage provided by each instrument is inhomogeneous in time. Moreover, significant changes in instrumentation have occurred at the beginning of the 1970s due to the introduction of high vertical resolution XBTs. We evaluate the possible introduction of instrument bias into the MLD estimates by comparing the December–April MLD calculated from high vertical resolution data (XBT) with MLD calculated from low vertical resolution data (MBT) during 1970–75 (Fig. 1b). The mean MBT-based MLD in the North Atlantic ($0^\circ–70^\circ$N) is 67 m while the XBT-based MLD is 74 m. The mean MBT-based MLD in the North Pacific is 67 m while the XBT-based MLD is 66 m. The comparison shows little evidence of instrument bias in the MLD estimates.

Much of the interesting variability of the mixed layer is linked to a particular phase of the seasonal cycle. Thus, in many of the analyses presented here we examine year-to-year variations of seasonal or biseasonal average values. For comparisons to surface winds and SST we rely on the National Centers for Environmental Prediction–National Center for Atmospheric Research...
Fig. 1. (a) Number of grid points on a $2^\circ \times 2^\circ$ grid filled with data. Data are stratified by instruments. Instrument abbreviations are the same as those adopted in the NODC World Ocean Database 2005. Full ocean surface coverage corresponds to approximately 11 000 points. (b) December–April MLD difference (in m) between MBT- and XBT-based estimates where both observations are available for the same month.
(NCEP–NCAR) reanalysis (Kalnay et al. 1996) and the Hadley Centre SST analysis (Rayner et al. 2003).

3. Gross statistics

The climatological monthly maximum and minimum MLDs are shown in Fig. 2 (left-hand panels show estimates based on temperature, while middle panels show estimates based on density). In the Northern Hemisphere the seasonal maximum depths occur in the subpolar North Atlantic in winter and early spring, with depths exceeding 150 m in a region extending well into the western subtropical Atlantic. There the temperature-based estimates of MLD are shallower by around 50 m in boreal winter than the density-based estimates because of the compensation of temperature and salinity contributions to density (Figs. 2a–b; also see Fig. 9 in de Boyer Montégut et al. 2004 for comparisons). Maximum MLDs in the North Pacific are somewhat shallower than the North Atlantic, falling in the range of 100–200 m. Both regions have shallow 10–30-m capping mixed layers in boreal summer and fall.

In the tropical Pacific the maximum MLD may exceed 75 m in the central basin, decreasing to less than 40 m in the east. In the western equatorial Atlantic the temperature criterion indicates the presence of mixed layers deeper than 75 m, but the density-based criterion shows that this region of high precipitation and river discharge has a barrier layer at a shallower depth (Pailier et al. 1999; Foltz et al. 2004). The maximum MLD develops by the end of February–March in the North Pacific and Atlantic (Figs. 2j,k). The annual phase of the maximum mixed layer changes approaching the equator reflecting the seasonal changes in winds and clouds over the tropics. In the Indian Ocean MLDs in excess of 75 m appear in the Arabian Sea during the southwest monsoon beginning in June (Figs. 2a–j).

We compare our analysis to the analysis of White (1995) (our Fig. 2, right-hand panels). This alternative analysis has been used extensively to examine the impact of interannually varying mixed layers on winter SST in the northern oceans (e.g., Schneider et al. 1999; Alexander et al. 1999; Timlin et al. 2002; Deser et al. 2003). The differences in the analysis procedures lead to deeper estimates of MLD in the White analysis in the North Pacific as well as the North Atlantic during winter and spring when the upper ocean is weakly stratified. The summer mixed layers, in contrast, are generally shallower in northern latitudes and so the annual range of MLDs is larger and implied entrainment greater in the White analysis than in either our temperature-based or density-based analyses. These differences can be attributed to the larger $\Delta T = 1^\circ C$ criterion (referenced to the surface rather than to 10-m depth temperature) adopted in the White analysis. In the tropics, mixed layers in the White analysis show a similar or smaller annual range, implying similar rates of entrainment produced by the mixed layer deepening (cf. Figs. 2g–i). Maximum deepening of the mixed layer and thus maximum entrainment occurs approximately a month later in the White analysis.

We next consider the root-mean-square variability in MLD about its climatological monthly average (Fig. 3). Here data is segregated by season and is only plotted if available for at least 15 of the 45 yr. The available data is mainly confined to the Northern Hemisphere, coastal zones of the Southern Hemisphere, and parts of the west Pacific. The largest variability is confined to the subpolar Atlantic in winter and spring where values in excess of 100 m are common. Winter–spring mixed layer variability in the Kuroshio extension region of the western North Pacific (40–75 m) is weaker than that in the Gulf Stream and Gulf Stream extension regions of the North Atlantic where it ranges from 50 to 100 m. In all of these regions the variability of MLD is 25%–50% of the seasonal maximum MLD (cf. Figs. 2 and 3). Elsewhere the variability is less than 40 m. In the tropics variability in the range of 15–30 m occurs in all seasons in the Pacific and during the monsoon season [June–August (JJA)] in the Arabian Sea. Low variability, below 15 m, is a feature of the subtropical oceans during summer as well as the eastern tropical Pacific and Atlantic where the mixed layer is shallower. A zonal band of weak variability is particular noticeable along 10°N in boreal winter in the Pacific and Atlantic Oceans (Figs. 3a–d). This low variability band is the result of the shoaling of the thermocline on the northern side of the North Equatorial Countercurrent.

The corresponding estimates of MLD variability for the White (1995) analysis (Fig. 3 right-hand panels) also have a higher level of MLD variability in the winter Hemisphere. But MLD variability is substantially lower in the highest variability region of the North Atlantic, a difference that probably reflects the higher spatial averaging of the White analysis. In the North Pacific the seasonal timing and geographic location of the maximum variability both differ. The maximum MLD variability according to the White analysis is shifted toward the Gulf of Alaska sector of the eastern North Pacific with low variability in the Kuroshio extension region of the western North Pacific. The maximum variability is concentrated in boreal winter and spring (in line with our estimates) but persists into the boreal summer in the central North Pacific. In the White analysis the tropics have significantly lower variability throughout the year than in our analysis.
Fig. 2. Monthly climatology of the MLD extremes computed over the 1960–2004 period. (left), (middle) Extremes based on the temperature-based definition ($|\Delta T| = 0.2^\circ$C) and the variable density-based definition. (right) Extremes based on the White (1995) analysis averaged over a similar period (1960–2003). (a), (b), (c) Maximum MLD; (d), (e), (f) minimum MLD; (g), (h), (i) maximum entrainment rate; and the month (annual phase) of the (j), (k), (l) maximum MLD; (m), (n), (o) minimum MLD; and (p), (q), (r) maximum entrainment rate. Multiply entrainment rate in (g) by $(C_p\Delta T) = -0.3$ to convert to entrainment heat flux in W m$^{-2}$. Estimates are plotted only if observations are available for at least 15 yr. Units are in m, m month$^{-1}$, and month. The month color scale begins in March in order to align with seasonal changes.
FIG. 3. Standard deviation of the mixed layer depth from its climatological seasonal average computed over the full 45-yr period. (a)–(d) The results for this study. Estimates are plotted only if observations are available for at least 15 yr. (f)–(i) The results for the White (1995) analysis over 1960–2003. Units are in m. Color scaling is shown in the right-hand palette. (e), (j) The normalized standard deviation of MLD during the month of maximum deepening.
Throughout much of the midlatitudes the normalized standard deviation of MLD during the month of maximum deepening exceeds 30% of its depth (Fig. 3e). In contrast the White analysis has significantly lower variability (Fig. 3j). MLD variability weakens in the tropics, but is amplified in the equatorial Pacific reflecting the ENSO variability (Fig. 3e). The normalized mixed layer variability in the Atlantic is stronger than in the Pacific. This stronger variability is particularly noticeable in the southern Labrador Sea (prone to deep convection) and along the western boundary region. Higher MLD variability in the Gulf Stream area as compared to the Kuroshio extension area may be explained by larger spatial gradients of the maximum MLD (see Fig. 2a). These larger spatial gradients cause a stronger contribution of the advective processes than elsewhere, which augments variability due to the local forcing.

The frequency dependence of the MLD variability is presented in Fig. 4 by decomposing the variability into frequencies between 1 and 1/5 yr$^{-1}$ (interannual) and frequencies below 1/5 yr$^{-1}$ (decadal). To improve the reliability of the statistics we average the results over a winter–spring season (December–April) and a summer–fall season (June–October). During December–April most variability at both interannual and decadal frequencies is confined to higher latitudes. There the variability is at least a factor of 2 larger in the interannual band than the decadal band. In contrast to this, during July–October the variability at higher latitudes of the Northern Hemisphere is greatly reduced while it is increased in the Southern Hemisphere during local winter.

In the tropical Pacific the mixed layer variability has a weak seasonal dependence, while in the eastern tropical Indian Ocean and the Arabian Sea the boreal summer variability at interannual frequencies (10–15 m) is higher than that in the boreal winter variability (8–12 m). Boreal summer mixed layer variability is also higher than winter variability in the western tropical Atlantic reflecting the northward shift of the intertropical convergence zone and the accompanying seasonal amplification of the southeasterly trade winds. It should be noted that the partitioning of variance in Fig. 4 depends on the definition of the decadal and interannual bands. We found that for the 45-yr-long time series the standard deviation of the MLD in the decadal band drops by around 25% if the frequency separating the two bands is shifted to $f = 1/8 \text{ yr}^{-1}$.

Interestingly, part of the decadal variability reflects deepening trends in MLD in the subtropics and midlatitudes (Fig. 5). In the North Pacific the most rapid changes occur early in the record from 1960–74 to 1975–89, consistent with the independent MLD analysis of Polovina et al. (1995). Polovina et al. have attributed...
this deepening of the MLD to the climate shift over the North Pacific in the mid-1970s, which is reflected in changes in the PDO index.

Detection of decadal trends is complicated by a change in the ocean instrumentation discussed in section 2. To determine the impact of instrumentation we also present decadal averages using only high vertical resolution instruments (Fig. 5; XBTs and CTDs). The deepening of the mixed layer in the North Pacific between 1960–74 and 1975–89 seen in the “all data” analysis is also evident in the high-resolution analysis (cf. Figs. 5a,c with Figs. 5b,d). In contrast, there is only a weak suggestion of the mixed layer deepening in the North Pacific between 1975–89 and 1990–2004. In the tropical Pacific and Atlantic Oceans there is little evidence of decadal trends in MLD.

In the Atlantic the all data analysis suggests a steady mixed layer deepening along and south of the Gulf Stream front. The high vertical resolution analysis is patchier due to lower data coverage. North of 45°N, both the all data and high-resolution analyses show a transition from shallow mixed layers during 1960–74 (Figs. 5a,b) to deeper mixed layers during 1990–2004 (Figs. 5e,f). This long-term deepening reflects the impact of the strengthening surface forcing and the associated strengthening of westerly winds and increasing net surface heat loss.

In the North Atlantic subpolar gyre the deepening of the mixed layer has occurred while the water column has cooled and freshened (Dickson et al. 2002). Because of its relationship to surface forcing as well as to entrainment cooling of the mixed layer, these variables may not be independent. We examine the potential connection between MLD and SST by computing the time regression of their anomalies with respect to the climatological seasonal cycle (Fig. 6). During all sea-

Fig. 5. Winter–spring (December–April) MLD anomalies averaged into 15-yr intervals based on (a), (c), (e) the whole dataset and (b), (d), (f) the XBT and CTD data only. (a), (c), (e) Grid points with fewer than 15 monthly samples in any 15-yr interval are masked out. A deepening trend is evident in the North Pacific and North Atlantic.
Fig. 6. Time regression of mixed layer depth and temperature anomalies from their climatological monthly values averaged by season. Data are shown at grid points where there is at least 15 yr of data. Units are m °C⁻¹. Temperature is taken from profiles used to calculate MLD.
sons this correlation analysis reveals the importance of surface forcing in northern latitudes where deeper-than-normal MLDs are associated with cooler-than-normal mixed layer temperatures. The regression coefficient is larger in winter reflecting the impact of entrainment deepening. In contrast, in the eastern half of the tropical Pacific we have the relationship frequently assumed in models of ENSO that deeper-than-normal MLDs are associated with warmer-than-normal mixed layer temperatures. A similar relationship is evident in the tropical Indian and Atlantic basins during June–August and in the western tropical Pacific during December–February, and along the western boundaries. This positively correlated relationship suggests that the anomalous heat budget of the mixed layer is dominated either by heat exchange across the bottom of the mixed layer (in the upwelling areas) or by horizontal heat advection (in the frontal areas along the western boundaries).

4. Variability in the northern oceans during winter–spring

Despite similar latitudes, SSTs, and the presence of winter storms, mixed layers in the North Pacific and North Atlantic differ in several fundamental ways. The near-surface waters of the North Pacific are more stratified, while the higher salinity waters of the North Atlantic mixed layers are affected by episodic freshening events (Belkin 2004). In this section we explore the relationships between MLD, SST, and winds in these two regions by application of empirical orthogonal function (EOFs) analysis.

The domain for the first EOF analysis spans the North Pacific and is similar to that chosen by Bond et al. (2003) for their EOF analysis of November–March SST. Our analysis is based on the 5-month December–April averages when the mixed layer depth is at its seasonal maximum. The primary EOF of MLD explains 9.5% of the record variance with maximum variance in the central basin between 30° and 50°N and positive values almost everywhere, indicating an in-phase response across the basin (Fig. 7a). The projection of the component time series on surface winds shows that the region of maximum MLD change is almost precisely associated with the corresponding region of maximum wind speed change (Fig. 7c). The second EOF of MLD (not shown), explains 6.5% of the record variance. This second EOF has a dipole pattern with a peak in the subtropical western basin along the climatological position of the Kuroshio front and peaks of opposite phase in the northern central and eastern regions.

The principal component time series associated with this primary EOF (Fig. 7b) shows a long-term deepening trend including a rapid 10-m deepening in the mid-1970s, consistent with the 15-yr averages shown in Fig. 5. Superimposed on this long-term trend, the time series in Fig. 7b also reveals strong winter-to-winter fluctuations with an alternating succession of shallow and deep wintertime mixed layers in the mid-1970s through the 1980s.

Modeling studies (e.g., Alexander et al. 2000; Xie et al. 2000) have connected the year-to-year fluctuations in MLD to changes in local competing processes of turbulent exchange and buoyancy flux, which together regulate entrainment rate. We explore this connection by comparing the first principal component time series with the December–April PDO index reflecting low-frequency changes of SST in the North Pacific. The PDO index and the first principal component time series are positively correlated ($r = 0.75$ with modest smoothing) with similar year-to-year variability as well as long-term trends. Interestingly, Cummins et al. (2005) have demonstrated that the sea level in this region also varies in phase with the PDO index, suggesting that the changes of temperature and salinity penetrate throughout the upper-ocean water column.

Finally, we examine the connection between wintertime MLD and SST in the region of strong MLD-wind coherence (35°–45°N, 180°–150°W box is shown in Fig. 7a). In this region SST has a negative phase relationship with MLD where a 10-m deepening of the MLD is associated with a 0.5°C drop in SST (correlation is $r = -0.48$, Fig. 8a). Thus, anomalously deep MLD is associated with anomalously cool SST. The physics of this relationship is not entirely clear. The regression patterns in Fig. 7c also show a positive relationship between mixed layer deepening and surface heat loss with both patterns centered at around 40°N and positive values almost everywhere, indicating an in-phase response across the basin (Fig. 7a). The projection of the component time series on surface winds shows that the region of maximum MLD change is almost precisely associated with the corresponding region of maximum wind speed change (Fig. 7c). The second EOF of MLD (not shown), explains 6.5% of the record variance. This second EOF has a dipole pattern with a peak in the subtropical western basin along the climatological position of the Kuroshio front and peaks of opposite phase in the northern central and eastern regions.

We next turn to the North Atlantic where depth variability is a factor of 2 larger than the North Pacific (Fig. 3) and where variability in excess of 75 m extends from the eastern subpolar region to the western sub-tropics. This zone is also where winter–spring MLDs extend deeper than 100 m. Here we address the nature of this high variability and its connection to changes in surface meteorology.
FIG. 7. Climate variability in the North Pacific during the months December–April. (a) Spatial pattern of leading EOF of MLD. (b) Principal component time series and PDO index time series of Mantua et al. (1997). (c) Projection of anomaly vector winds, wind speed (shading), and the net surface heat flux (contours interval 5 W m$^{-2}$, negative is dashed) on the principal component time series. Location of station Papa is indicated in (a) as “P.”
The primary EOF in a domain extending from the equator to 70°N explains 13% of the record variance and is mainly confined to the high MLD variability zone extending from the eastern subpolar region to the western subtropics (Fig. 9). The western half of this zone lies just to the east of the Gulf Stream front. The relative position of features suggests that the variability of MLD may be associated with shifts in the Gulf Stream frontal position rather than with variability of local winds. Indeed, the projection of the surface winds onto the primary principal component time series shows that deepening of the MLD is correlated with increasing westerly winds at subpolar latitudes and increasing northeast trade winds in the tropics. This wind pattern resembles the wind pattern associated with strengthening of the Azores high in sea level pressure.

The corresponding principal component time series (Fig. 9b) shows that the mixed layer has deepened in this zone since the 1960s by more than 40 m. A similar long-term change is evident in the NAO index, reflecting changes in the position of the storm tracks. Relationships between changes in the NAO index and...
changes in the Gulf Stream frontal position have been explored by Taylor and Stephens (1998) who showed a delayed (by a few years) northward/southward shift of the front in response to amplification/attenuation of the NAO index. As in the case of the North Pacific, the time series shows considerable year-to-year variability. The relationship of MLD, wind, and SST variability is also not nearly as close in the North Atlantic as in the North Pacific. Time series of these variables are displayed in Fig. 8b for a rectangular box spanning the central basin (35°–45°N, 60°–30°W see Fig. 9a). Within this box, MLD and SST both exhibit a positive trend since the mid-1960s, but correlations between those variables at year-to-year time scales are quite weak.

5. Tropics

While mixed layer variability is weaker in the tropics than in the northern oceans (Fig. 3) some coherent features are evident. The predominant pattern of MLD variability in the tropical Pacific is coherent with the Southern Oscillation index (SOI) and thus is associated with ENSO (Fig. 10). Here we restrict our analysis to the peak months of the mature phase of ENSO (November–March). A 10–20 decrease in the SOI, corresponding to the appearance of El Niño, is correlated with a concurrent deepening of the tropical MLD in the eastern Pacific by 5–15 m and a shallowing in the western Pacific and eastern Indian Ocean by 10–20 m.

In the eastern equatorial Pacific Wang and McPhaden (2000) found that the strong El Niños of 1982–83 and 1997 were associated with mixed layer deepenings of 30 m or more at 0°, 110°W (Cronin and Kessler 2002 also examine the 1997 event). The weakening of upwelling associated with these deepening mixed layers was found to be an important modification of the mixed layer heat budget at this location. In Fig. 11a we determine a similar relationship for oceanic variables averaged over the Niño-3 region (5°S–5°N, 150°–90°W). Averaged annually (to improve the statistics), the vertical excursions of MLD reduce to a more modest 10 m. However, there remains a similarly close relationship between increasing SST and a deepening mixed layer (with a ratio of 0.1°C m⁻¹) and Niño-3 MLD leading Niño-3 SST by a few months (Fig. 11c), as well as between increasing Niño-3 SST and decreasing zonal wind speed in the west (Figs. 11a,b). Winds in the west lead SST in the east by a few months (Fig. 11c). In the western equatorial Pacific we find, similar to Wang and McPhaden, that substantial variations in MLD are evident (Fig. 11b), which lag variations in local winds by several months (Fig. 11c). These MLD variations are not closely related to variations in local SST (Fig. 11b) suggesting a minor impact of entrainment on the mixed layer heat balance in the west.

The extension of the ENSO response into the mid-latitude North Pacific has been examined by Alexander et al. (2002, see their Fig. 9). Consistent with their results, we find anomalous mixed layer deepening in the central North Pacific in the latitude range 30°–45°N during El Niños. This anomalous deepening of the mixed layer occurs concurrent with anomalous cooling (our Fig. 8a, see also Fig. 5 of Alexander et al. 2002) suggesting the importance of anomalous surface heat loss. In contrast, in the tropics the mixed layer warms as it deepens (Figs. 6 and 10a) in response to heat exchanges across the base of the mixed layer.

As discussed in the introduction, it has been suggested that anomaly mixed layer patterns can persist from one winter to the next in conjunction with the reemergence of SST patterns. We explore the persistence of MLD patterns between successive winters by
examining the regression of the SOI index on the next winter \((Y + 1)\) anomaly MLD. The midlatitude mixed layer during the next winter (Fig. 10b) shows the persistence of a deepening pattern around 35°N with shallowing to the north and south. Interestingly, net surface flux response does not show similar persistence. In the tropics, in contrast, the mixed layer is anomalously shallow during the following winter.

The extension of the ENSO response into the eastern tropical Indian Ocean (Fig. 10a) is also evident in our examination of the primary EOF of MLD during December–February (Fig. 12a). The spatial pattern of the mixed layer response associated with this EOF, which explains 9.5% of the record variance, has a maximum in the eastern tropics. The pattern extends farther south along the Sumatra coast, with a minimum south of the...
6. Summary and discussion

In this work we apply the methodology of de Boyer Montegut et al. (2004) to construct a monthly analysis of global mixed layer depth during the 45-yr period 1960–2004 based on profiles from the new World Ocean Atlas 2005 dataset. The dataset is limited in temporal and geographic coverage, and thus averaging is required to identify year-to-year variability. The problem of limited data is magnified since much of the MLD variability is linked to the seasonal cycle.

Despite the data limitations (which restrict our analysis to the Northern Hemisphere and tropics) we explore the historical record for variability that is coherent with variability appearing in winds and SST. We begin by comparing the new analysis with the widely used analysis of White (1995). Our analysis differs in having shallower winter mixed layers, especially in the North Pacific. Our analysis also has shallower summer mixed layers, while the climatological peak in entrainment rate occurs a month earlier than in the White analysis. The distribution of MLD variability about its climatological monthly cycle also differs between the two datasets, with shifts in amplitude, structure, and seasonality.

We next consider the spatial and temporal structure of MLD variability in each of the three ocean basins and their relationship to winds and SST. In the Pacific the highest variability occurs in the subtropics and mid-latitudes in the western half of the basin during boreal winter–spring. During this season 2/3 of the variability occurs at frequencies less than 1/5 yr\(^{-1}\). An EOF decomposition of winter–spring MLD in the North Pacific reveals that some of this interannual variability is associated with a stationary pattern with a maximum in the domain 35°–45°N, 180°–150°W. The time variability of this primary EOF closely resembles the winter–spring PDO index, reflecting a correspondence between increases in the MLD and increases in local wind speed. SST varies out of phase with wind speed, and thus increases in winter–spring SST are associated with shallower-than-normal MLD.

In boreal summer MLD variability in both the Pacific and Atlantic is reduced and tropical variability becomes more distinct. In the Atlantic the highest variability also occurs in the subtropics and mid-latitudes during boreal winter–spring, and with much of the variability at interannual
frequencies. An EOF analysis shows that the maximum coherent MLD variability occurs in a zone extending along the eastern edge of the Gulf Stream in the western subtropics northeastward toward the eastern subpolar region. In contrast to the North Pacific, the MLD variability in this region is not closely related to variations in local wind speed, and does not result in coherent variations in winter SST.

A notable feature of both the central North Pacific and North Atlantic is the presence of trends that have caused the mixed layer to deepen by 10–40 m over the past 45 yr. In the North Pacific this deepening trend is matched by a corresponding increasing trend in the PDO index. The presence of this trend in PDO, indeed, explains much of the decadal variability in the North Pacific MLD. Strikingly, much of the change in MLD occurred early in the record, prior to the 1980s. In the North Atlantic this deepening trend is likewise reflected in a positive trend in the NAO index.

The salinity data coverage is still a limiting factor to address the interannual variations of the barrier- and density-compensated layers.

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APPENDIX

Comparison of Temperature-Based and Density-Based Mixed-Layer Depth

We use both temperature–salinity and temperature-only profiles to compute mixed layer depth. Here we consider three situations in which the estimates may differ. The examples are from the North Atlantic during boreal winter when the temperature stratification is weak and the impact of salinity is stronger. In Fig. A1a
the temperature drops below the density-based mixed layer producing a 50-m-width barrier layer. In contrast, in Fig. A1b the temperature increases below the salinity-based mixed layer producing a density-compensated layer. To provide an MLD estimate consistent with its description as a layer of uniform properties in this situation we modify the definition of the mixed layer chosen by de Boyer Montegut et al. (2004). We define the base of the mixed layer to be the depth at which temperature either drops or rises by 0.2°C. Finally in Fig. A1c we see a second example of a density-compensated mixed layer in which both temperature and salinity decrease below the mixed layer. Our modified definition also produces consistent estimates in this situation.

REFERENCES


Cronin, M. F., and W. S. Kessler, 2002: Seasonal and interannual


