Characterizing the structure of the surface layer in the Pacific Ocean

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Abstract. The structure and statistics of the oceanic surface layer are characterized using quarterly surveyed, eddy-resolving expendable bathythermograph (XBT) and expendable conductivity-temperature-depth (XCTD) data collected along a number of routes spanning the Pacific Ocean. This data set consists of more than 18,000 temperature casts to 800 m, with station spacing of 10 to 40 km along transects between Auckland and Seattle (beginning in 1986), San Francisco and Taiwan (1991), Auckland and Valparaiso (1993), and Honolulu and Valdez (1993). The surface layer can assume many different shapes. It can include strongly stratified layers, actively mixed layers, salinity barrier layers, fossil mixed layers, and inversions. The spatial and temporal distribution of these features within the XBT and XCTD profiles is examined. Fossil layers are predominantly a springtime feature and are associated with regions of Subtropical Mode Water formation in the southwest Pacific (near New Zealand) and the northeast Pacific (near San Francisco). Inversions are less seasonally dependent and most commonly related to interleaving of different water masses in the high shear regions of the California Transition Zone and its counterpart eastern boundary systems in the far northeast and southeast Pacific and in the tropical zonal current system. The XCTD casts show a rich and varied surface layer structure in the equatorial and subpolar regions of the Pacific Ocean that is strongly influenced by the salinity stratification. This highlights the need for complementary salinity and density information in these areas to accurately categorize the true nature of the active mixed layer.

1. Introduction

In conceptual models the surface layer of the ocean has a very simple structure, a well mixed layer of variable depth at the sea surface and a seasonal thermocline connecting the mixed layer to the permanent thermocline. Reality is usually far more complex. The surface layer includes the mixed layer, which is the site of active air-sea exchanges, plus underlying intervals of stratification determined by the recent history of surface heat and freshwater fluxes, wind events, and turbulence. It is rendered three-dimensional by velocity and shear. Temperature and salinity may be stratified in distinctly different ways. The structure of the surface layer contains the ocean’s "memory" of air-sea exchange out to periods of a year or longer. An accurate characterization of surface layer structure and evolution is necessary for progress in understanding mixing, entrainment, subduction, and restratification processes. The poorly understood diabatic physics of the upper ocean is a key not only to understanding wind- and buoyancy-forced ocean circulations but also the coupled air-sea climate system and the ocean’s role in sequestering and releasing heat and freshwater.

The surface layer assumes many shapes and forms. Occasionally, the simplest forms are seen. More commonly, there are alternating levels of greater and lesser stratification, sometimes including distinctive structures such as "inversion layers", "fossil mixed layers", and "salinity barrier layers". In the following we will quantitatively characterize the variability of the surface layer by defining the distinctive structures and determining the statistics of their occurrence over a wide range of Pacific Ocean settings, from the equator to the subpolar zone. This study is an exploration of the rich variability of surface layer structure, using an ocean-wide domain in order to illustrate the systematic nature of the distributions that are seen. Wherever possible, the causes of observed geographic and temporal variability are discussed, although a detailed examination of causality is beyond the scope of this work.

Data used in the study come from a network of high-resolution expendable bathythermograph / expendable conductivity-temperature-depth (XBT/XCTD) transects. The data set has several distinguishing characteristics that make it uniquely valuable in the present work. First, transects are almost exactly repeating, allowing separation of temporal from spatial variability. Second, temperature profiles are closely spaced (10-40 km). Coherent sampling is used to define the spatial scale of features and double drops for distinguishing real from erroneous profiles. Regular, although sparse, XCTD sampling permits us to characterize salinity in addition to temperature structure. Overall, the data set used here consists of more than 18,000 temperature casts to 800 m, plus a smaller set of XCTDs, collected quarterly along four ocean-spanning routes (Figure 1) over periods ranging from 5 to 12 years.

Section 2 describes the XBT/XCTD data set. Section 3 discusses conceptual and practical definitions of the surface layer and the mixed layer and the definitions of inversion layers, fossil mixed layers, and salinity barrier layers. In section 4 the geographic and temporal variability of surface
layer structure is statistically categorized and discussed. Results show distinctive regimes with regularly recurring features at the same locations and seasons. Finally, section 5 relates the occurrence of surface layer structures to different forcing mechanisms within the context of the large-scale circulation of the Pacific, and section 6 concludes.

3. The Data

Since 1986, precisely repeating high-resolution XBT/XCTD transects have been collected along a number of routes spanning the Pacific Ocean (Figure 1) [see Roemmich et al., 1991; Sprintall et al., 1996]. Along each of the transects nominally four surveys per year are conducted, with an eddy-resolving station spacing of 30-40 km along track, narrowing to 10 km near boundaries, at the equator, and in topographically varying regions. The XBT probes are Sippican Deep Blue and return temperature data to a depth of around 800 m.

For this particular study we focus on four lines in the Pacific Ocean network. The line between Auckland and Suva was initiated in 1986, extended northward to Hawaii in 1987, and extended farther northward to Seattle in 1993. The line traverses the North and South Pacific subtropical gyres and the tropical current systems, with an equatorial crossing at 170°W. With 51 cruise realizations as of September 1998, this track presents a substantial database with which to observe differences in surface layer structure for dynamically different regimes on annual to interannual timescales. A second line from San Francisco to Taiwan, via Honolulu and Guam, is a complete zonal slice of the central subtropical North Pacific Ocean, crossing both the eastern boundary California Current and the western boundary Kuroshio Current system. Sampling began in 1991, and there are 26 complete realizations as of August 1998. The third track between Auckland, New Zealand, and Valparaiso, Chile, began in 1993. It crosses the South Pacific subtropical gyre at about 30°S, near the gyre's southern rim. There are 19 realizations of this transect as of August 1998. Finally, the transect between Honolulu, Hawaii, and Valdez, Alaska, crosses the eastern North Pacific subpolar gyre. Sampling began in 1993, and there are 17 cruises as of August 1998.

Since 1991, measurements from XCTD probes have also been included in the network along the four lines. The XCTDs provide valuable complementary information, revealing salinity and density structure, which aids in the interpretation of the temperature profiles. The XCTDs are sparsely deployed along track to estimate large-scale variations in the temperature/salinity (T/S) relation, although in regions where salinity variability is thought to be important, such as in boundary regions and on the equator, they are more concentrated.

3. Definitions of Surface Layer and Mixed Layer.

3.1 Surface Layer

Conceptually, the surface layer includes the mixed layer where active air-sea exchanges are occurring and any waters below the mixed layer that have been exposed to the atmosphere in the previous days, weeks, or months. The base of the surface layer is the top of the main thermocline. One way to specify this level could be the depth where temperature is equal to the previous winter's minimum sea surface temperature (SST). However, for practical reasons, we do not want to specify the base of the surface layer in a way that varies from year to year. By choosing a static definition for the base of the surface layer, the possibility of interannual as well as higher-frequency variability is permitted. Therefore, the base of the surface layer is defined as the depth where temperature is equal to the coldest SST observed at that particular location using the monthly SST data set from the Integrated Global Ocean Station System (IGOSS) National Meteorological Center (NMC) (now National Center for Environmental Prediction) [Reynolds and Smith, 1994]. The monthly Reynolds data set begins in November 1981, thus representing a longer time series than the XBT/XCTD program. The surface layer depth determined using the Reynolds series minimum SST did not differ much from that determined using the XBT's minimum SST. The surface layer defined in this way is analogous to a local "ventilation" depth, the deepest surface to which atmospheric influence can be felt through local wind stirring or heat loss. Lateral advection may also play a role in the surface layer structure, although its influence is harder to quantify. The relationship of advection to surface layer variability is considered in section 5.

Defined in this way, the temperature at the base of the surface layer is shown in Figure 2 as a function of position along each of the four transects and compared to the temporal mean SST. Differences (ΔT) between the minimum SST and the mean SST range from about 1° to 5°C, depending on location. On the San Francisco-Taiwan line the larger values of ΔT are associated with the Kuroshio and its tight recirculation out to
Figure 2. The coldest sea surface temperature (thick solid line) from the Reynolds sea surface temperature (SST) data set used to define the surface layer and the mean sea surface temperature (thin solid line) along the (a) San Francisco-Taiwan, (b) Auckland-Valparaiso, (c) Auckland-Seattle, and (d) Honolulu-Valdez XBT tracks. The mean depth of the surface layer (dashed line) determined from the depth of the coldest sea surface temperature is also shown for each transect.

about 127°E. Auckland-Valparaiso shows a fairly uniform δT of 2.5° to 3°C, indicative of the strong seasonality in this midlatitude crossing. Superimposed on this, however, is a high degree of small-scale variability midtrack, perhaps indicative of eddy activity in the region. Along the Auckland-Suva-Seattle section the largest values of δT are near the equator, where the strong dip in minimum SST is due to equatorial upwelling, and at high northern latitudes, where the seasonality of air-sea flux is great. The Honolulu-Valdez transect shows the same northward increase in δT as Hawaii-Seattle.

For every cruise along the four transects, the depth of the surface layer, i.e., the depth of the "minimum SST" isotherm, is determined. The mean depth of the surface layer from all cruises along each transect is shown in Figure 2. Plate 1 illustrates the surface layer depth determined for a single cruise along each of the transects. The corresponding temperature stratification (i.e., the vertical temperature gradient) for these same cruises is illustrated in Plate 2. For comparison purposes, the depth of the isotherm corresponding to (SST-1°C) at that place and time is also shown. The latter is a possible alternative definition for the base of the surface layer. The depth of the surface layer and of the (SST-1°C) isotherm are generally similar, except where there is a strong seasonal thermocline present. They tend to be similar in the tropics and at middle latitudes in winter. At middle latitudes in spring-autumn, the base of the surface layer is beneath the well-stratified seasonal thermocline and often much deeper than (SST-1°C).

On the San Francisco-Taiwan November 1994 cruise (Plate 1a), there is little difference between the two definitions of surface layer in the tropics west of Honolulu. Both definitions locate the top of the main thermocline, as illustrated in Plate 2a by the increase in dT/dz occurring just below the weak stratification in the upper layer. In the east the Californian Transition Zone separates the fresh Californian Current from the saltier subtropical interior waters. Here the surface layer definition to the depth of the minimum SST lies deeper in the water column than (SST-1°C), and below a second layer of relatively low stratification. The deeper, weakly stratified
Plate 1. Temperature along the (a) San Francisco-Taiwan transect in November 1994, (b) Auckland-Valparaiso transect in January 1995, (c) Auckland-Seattle transect in March 1995, and (d) Honolulu-Valdez transect in October 1996. The solid line indicates the depth of the surface layer. For comparison, we also indicate the depth of SST-1°C (crosses).
Plate 2. Temperature gradient with depth \( (dT/dz) \) along the (a) San Francisco-Taiwan transect in November 1994, (b) Auckland-Valparaiso transect in January 1995, (c) Auckland-Seattle transect in March 1995, and (d) Honolulu-Valdez transect in October 1996. The solid line indicates the depth of the surface layer. For comparison, we also indicate the depth of SST-1°C (crosses).
layer indicates the presence of fossil layers. Fossil layers are nearly isothermal layers that occur below the upper well-mixed layer and are separated by a well-stratified layer. The fact that these layers are warmer than the local minimum SST indicates that they may have, at some period, been subjected to local surface forcing. In section 4 we find that the fossil layers and inversions, seen in the surface layer near 134°W in this particular cruise, are persistently observed in both XBT and XCTD profiles of the region.

The Auckland-Valparaiso transect (Plate 1b) of January 1995 depicts a typical midsummer thermal scenario. A strong seasonal thermocline is located between the sea surface and 60 m depth, and it is this feature that the (SST-1°C) criterion delineates. The depth of the minimum SST isotherm during this period is much deeper, lying well below the seasonal thermocline and at the top of a deeper weakly stratified layer. Near New Zealand the surface layer shows features associated with the dynamic regime of the western boundary flow. During this cruise the East Cape Eddy, which lies just to the east of New Zealand, is bifurcated [Roemmich and Sutton, 1998], as seen by the double dip in the deep surface layers near the dateline.

The cross-equatorial section between Auckland and Seattle of March 1995 (Plate 1c) contains several of the features described in the above two zonal transects. In the austral summer segment between Auckland and Suva, the surface layer extends to depths well over 100 m and below the seasonal thermocline depicted by the (SST-1°C) criterion. This transect crosses the East Auckland Current and North Cape Eddy [Roemmich and Sutton, 1998], where surface layers to 240 m at 33°S indicate deep winter mixing. In the winter segment between Honolulu and Seattle, the minimum SST isotherm nearly outcrops, and active ventilation is occurring on that surface. SST was near 14 year record low levels at 21°N and 27°N. In the tropical regions the surface layer and the (SST-1°C) criteria are nearly coincident.

During the October 1996 transect between Honolulu and Valdez (Plate 1d), the base of the surface layer was again deeper than (SST-1°C), separated by a weakly stratified layer plus the remnant of an eroding seasonal thermocline. North of ~50°N, the temperature-based definition of the surface layer fails (Figure 2). Here a cold, fresh mixed layer is seen in winter above a temperature inversion layer and above the characteristic doming isotherms of the subpolar gyre. Stratification at the base of the mixed layer is controlled by salinity. This will be further discussed in section 5. A definition of the surface layer based on density would be preferable, but, at present, we do not have sufficient Pacific-wide XCTD profiles to implement this criterion.

### 3.2 Structures Within the Surface Layer

Having defined the surface layer as the local ventilation depth of the sea, we focus on the recurring structures within that layer in order to characterize the observable effects of air-sea exchanges, mixing, restratification, and advection. At the sea surface a mixed layer usually thick enough to observe with the XBT profiles. Below this the stratification is highly variable (Plate 2), although in individual profiles the eye can clearly identify well-stratified layers, as well as deeper layers that are nearly unstratified, or where temperature inversions (i.e., temperature increasing downward) occur. These layers will be referred to as fossil mixed layers and inversion layers, respectively. In XCTD profiles an additional structure, the salinity barrier layer, is sometimes seen. This is a layer where the temperature is uniform but the salinity and density are increasing downward within the isothermal layer. The process of defining these structures has been an iterative one. Thousands of profiles were examined and sorted by eye for the presence of fossil mixed layers and inversion layers. Various criteria were tested until automatic sorting based on those criteria came close to duplicating the authors' judgment. It is clear that there is a degree of arbitrary choice in this sorting/classification process. However, the particular choices tend to affect the frequency of occurrence of structures but not, in general, the regional comparisons which are sought here.

The criteria we selected are fairly coarse ones. Diurnal cycling at the sea surface and other short-timescale phenomena contributing to variability on vertical scales of a few meters are excluded. A relatively loose definition of "mixed" is adopted, but one which is common in the literature as follows:

1. A sea surface mixed layer or a fossil mixed layer is identified where the temperature decreases by 0.1°C over an interval >15 m. For the sea surface mixed layer the reference temperature for this change is the temperature at 10 m depth. Elsewhere, the reference temperature is that at the top of the layer.
2. An inversion layer is identified wherever the temperature increases by 0.1°C over any depth interval. The top 10 m are excluded in the search for inversions.

In regions where XCTD profiles are available, the thickness of mixed layers is defined in terms of density in a manner that is consistent with the above definition based on temperature alone. Following Sprintall and Tomczak [1992], the base of a mixed layer is the depth at which

\[ \rho = \rho(z = z_{ref}) + \Delta T \frac{\partial \rho}{\partial T} \]  

where the reference depth is as noted above. The thermal expansion coefficient \( \frac{\partial \rho}{\partial T} \) is calculated from the temperature and salinity values at the reference depth, while \( \Delta T \) is the temperature change of 0.1°C. As in the temperature criterion, only mixed layers thicker than 15 m are counted. By selecting the same \( \Delta T \) of 0.1°C as used in the mixed layers determined by temperature alone, the density criterion of (1) will produce equivalent mixed layer depths if salinity stratification is negligible. However, in regions where salinity influence is important, such as where salinity barrier layers exist, this structure will be revealed by the different mixed layer depths determined from the two criteria. There are not sufficient XCTD profiles to determine the statistics of barrier layer occurrence in these data, but examples will be shown.

The richness of surface layer structure is illustrated in Figure 3. Different types of mixed layers are illustrated using both XBTs and XCTDs in the latitude range from 19°S to 12°N in a single transect, the March 1995 cruise from Auckland to Seattle (Plate 1c). In Figure 3a, successive XBT profiles (offset by 1°C) between 17°S and 19°S exhibit a strongly stratified surface layer where no mixed layer is evident. A nearby XCTD profile at 15°S shows similar strongly stratified profiles in density and salinity. Contrasting this are successive XBT profiles at 1°-3°S (Figure 3b) where the sea surface mixed layer, as defined by the 0.1°C temperature change, extends to 80-100 m depth. Density and salinity are also well mixed above the salinity maximum. Figure 3c shows an example of a number of successive casts that contain a fossil mixed layer.
occurring below the sea surface mixed layer. The sea surface mixed layer and the underlying fossil layer are separated by a thin stratified interval at 40-50 m depth. In some cases, although not in the casts shown here, three or four fossil layers can be observed within the one profile. A fossil layer is also depicted by the mixed layer density-defined criterion in the XCFD profile at 12°N. The salinity profile is isohaline throughout the top 100 m, indicating that, in this profile at least, density is a strong function of temperature. Figure 3d displays temperature inversions of between 0.1° and 0.3°C magnitude, occurring at the base of the sea surface mixed layer. The six successive profiles shown here are each separated in space by ~40 km and in time by ~1 hour, demonstrating the spatial persistence of this feature. The XCTD profile at 11°S indicates the expected salinity compensation in the inversion. The temperature inversion occurs just below the density-defined mixed layer and at the top of the pycnocline. In the following section, inversions are shown to be ubiquitous in this region between 9° and 11°S in the South Pacific; they are also prevalent in small bands along the other XBT transects in the Pacific Ocean. The same March 1995 cruise produced XCTD profiles with salinity barrier layers. These are shown and discussed in section 5.

4. Statistics of the Structure of the Surface Layer in the Pacific Ocean

Here we determine the statistics of the fossil layers and inversion layer occurrence for all cruises along each XBT/XCTD transect. Along a particular transect the percentage of casts containing fossil layers and inversion layers, as defined in section 3, is calculated for each 5° interval of latitude (meridional tracks) or longitude (zonal tracks). The calculation is repeated for all cruises along each track, and where the number of cruises permits, the statistics are also computed by season. Standard errors for these statistics are calculated assuming the XBT casts in each of the 5° bins between cruises, along a track, are independent.

For the 26 cruises between San Francisco and Taiwan, ~52-54% of casts between 130°W and 140°W contain inversions and 14-16% of casts contain fossil layers between 135°W and 145°W (Figure 4a). Elsewhere along the track the rate is between 1% and 8% of casts for both inversions and fossil layers, except for a small peak of 13% in fossil layer occurrence around Guam. In the region 130°-140°W the high percentage of casts that contain inversions shows no real seasonal preference (Figure 5a). Fossil layers are most likely
casts contain fossil layers while less than 6% of casts contain inversions. In this region, fossil layers are present during all seasons (Figure 5b) but are most likely (70%) to occur in the region west of the dateline near New Zealand, where 40% of casts contain fossil layers. This area is during austral winter (July, August, September (JAS), 33% of casts), when deep mixed layers form and are subsequently capped by a shallower and warmer mixed layer. The probabilities of fossil layers and inversions along the transect between Auckland and Seattle tend to vary in phase in the subtropical regions, but out of phase in the tropics (Figures 4c and 5c). Inversions are more likely to occur in the region between 15°S and 10°S (-38% of casts) and between 5°N and 10°N (-22% of casts). In the Southern Hemisphere, inversions are more likely to occur during austral autumn (-60% of casts, AMJ), while in the Northern Hemisphere the maximum in inversions is closer to the equator and the seasonal signal less dominant (Figure 5c). In the equatorial band from 5°S to 5°N, more than 20% of casts contain fossil layers during all time periods except AMJ.

Along the Honolulu-Valdez transect most fossil layers and inversions (>50% of casts) occur in the region from 40°-50°N (Figure 4d). There is a high correlation along track between the occurrence of inversions and fossil layers, with a definite tendency for both to increase in occurrence northward along the transect to 50°N. The few cruise realizations prevent statistical analysis by season, and problems with the temperature-based surface layer definition in the far north have been noted above. Salinity plays a controlling role in the surface layer structure in this region and will be discussed further in the following section. However, the subpolar regime provides an interesting contrast to the subtropical and tropical regimes of the other transects and has been included in this analysis for that reason.

5. Synthesis and Discussion

This synthesis is organized into subsections of broad-scale regions defined by the Pacific Ocean circulation. This selection provides a natural basis for regularly recurring features in the surface layer structure such as fossil layers and inversions. Where possible, XCTD profiles will be used to illustrate any possible salinity variability associated with the surface layer features of a region. Differences and similarities in the form of the features and their occurrence with respect to known variability in the regional circulation will allow speculation of possible formation mechanisms.
5.1 Fossil Layers in the Southwest Pacific Ocean

In the region near New Zealand a high incidence of casts along the Auckland-Seattle transect and the Auckland-Valparaiso transect contained fossil layers (23% and 40%, respectively). The fossil layers show a predominance during the late austral winter and spring (Figures 5b and 5c). As noted previously, this region of the southwest Pacific Ocean is a known formation area of STMW. Roemmich and Cornuelle [1992] define STMW in this region as water with temperatures between 14 and 20 °C with a vertical gradient of < 2°C / 100 m. The fossil layers observed along the XBT transects near New Zealand have these same characteristics. How are the fossilized mixed layers associated with the formation of this water mass? The fossil layers are isothermal layers that occur below a more recently formed upper mixed layer and above the permanent thermocline. The fossil layers themselves are remnants of the deep well-mixed layers formed here during winter, as evidenced by the corresponding maximum in surface layer depths (Figure 2) that occurs along the XBT transects in the vicinity of New Zealand. The water in the fossil layer is then isolated from the upper mixed layer, formed in response to a change in the surface boundary forcing of heat flux, freshwater flux, or wind stress. The subsequent thermocline that exists between the upper mixed layer and the fossil layer isolates the fossil layer from further modification of its properties. The thermostat of winter water trapped in the fossilized layers is then subject to subduction into the thermocline through the action of Ekman pumping and horizontal flow within the South Pacific subtropical gyre. Its characteristics have become synonymous with the STMW water mass.

During a hydrographic World Ocean Circulation Experiment (WOCE) cruise (P14C) of September 1992 between Auckland
and Suva, the surface layer was unseasonably cold to depths of ~200 m close to the New Zealand coast. Just offshore, well-developed fossil layers were found below the surface mixed layer with signatures in both temperature and salinity (for example, Figure 6). Oxygen levels were high throughout the upper mixed layer and within the fossil layers, indicating their recent contact with the surface. The oxygen minimum (90-100 m) within the stratified region between the upper mixed layer and the fossil layer implies the advection of lower-oxygen water in this region after the fossil layer was formed. This cruise coincided with an unusually cold period in the southwest Pacific that was attributed to preconditioning by earlier heat loss due to oceanic advection of warm water out of the region [Sprintall et al., 1995]. The conditions induced by the cool winter sea surface and air temperatures led to a relative maximum occurrence in STMW formation in the region during this period, as suggested by the high incidence of fossil layers observed during the cruise.

Not all fossil layers in the southwest Pacific Ocean need be associated with the formation of STMW. Somewhat fortuitously, a June 1997 cruise along a high-resolution XBT transect between Lautoka, Fiji, and Brisbane, Australia (see Figure 1), captured the presence of fossil layers in a sequence of XBT profiles between 156.99°E and 158°E, some casts separated by only 1 km in space (Figure 7). Thirty kilometers to either side of these profiles, the fossil layers have disappeared. The surface mixed layer extended to 120 m on the western edge and to 145 m depth on the eastern edge. A relationship of the depth of the upper mixed layer and fossil layers of the intervening casts to the depth of the upper mixed layers observed in the edge profiles is evident. This region is not a known mode water formation area, although the alternate processes of heating/cooling and wind mixing that formed the fossil layers observed in the region around New Zealand could still be responsible for their existence. Alternatively, the region lies in close proximity to New Caledonia and may readily be influenced by the strong currents associated with the abrupt topography of the area. The fossil layers may be formed by the advection of water with properties different than those found in the upper mixed layer.

5.2 Tropical Central Pacific Ocean

Inversions in the profiles along the Auckland-Seattle transect are most likely a result of vertical shear in the water masses associated with the tropical countercurrents and their seasonal variability. In the 5°-15°S latitude band the inversions are generally found at the base of a well mixed layer and are typically small, abrupt features of ~10-20 m in thickness (Figure 3d). The corresponding XCTD profile at 11°S (Figure 3d) shows the mixed layer is relatively fresh with salinity increasing abruptly from the top of the pycnocline.
throughout the inversion layer to a salinity maximum at ~160 m. The salinity maximum is a signature of the subtropical Pacific Equatorial Water from the east [Tomczak and Hao, 1989], whereas the South Equatorial Countercurrent has advected the fresher surface waters from the west [Eldin, 1983]. The inversions are formed when the salinity maximum water slides under the fresher surface waters found locally during this period. In the Northern Hemisphere (5°-10°N) the overall probability of the occurrence of inversions is lower and its seasonality much less distinct compared to the Southern Hemisphere counterpart current system. Nonetheless, their presence in the Northern Hemisphere within the North Equatorial Countercurrent regime suggests a formation mechanism similar to that of the Southern Hemisphere.

In the central equatorial Pacific Ocean between 5°S and 5°N, the surface layer is characterized by a high incidence of fossil layers. More than 20% of casts contain fossil layers during all time periods except AMJ. Figure 8 shows a sequence of four consecutive XCTD profiles at 2°N, 4°N, 6°N, and 9°N from a cruise along the Auckland-Seattle transect during September 1995. The surface layer of the XCTD profile at 2°N is well mixed in both temperature and salinity to 120 m. It is markedly contrasted to the XCTD profile at 9°N, which is both warmer and fresher and well mixed to only 40 m. Fossil layers are present in the two intervening XCTD profiles at 4°N and 6°N. In both the profiles at 4°N and 6°N, the upper mixed layer corresponds most closely in depth of the upper mixed layer at 9°N, whereas the fossil layers extend to the same mixed layer depth as the profile at 2°N. The properties of the intervening casts at 4°N and 6°N indicate some mixing has occurred, with the upper mixed layer being warmer and fresher (cooler and saltier) than the profile at 2°N (9°N). Clearly, advection plays a role in fossil layer formation of the equatorial central Pacific.

Figure 9 shows three XCTD casts where salinity strongly influences the structure of the surface layer in the central Pacific. In Figure 9a a halocline throughout the temperature fossil layer weakens the signature in the density structure, so that the fossil layer is not detected by the density criterion. In Figure 9b the surface layer is well mixed to 90 m in temperature with no fossil layers, but a halocline occurs within the isothermal region and the corresponding pycnocline defines the density mixed layer at 60 m. Finally, in Figure 9c the density-defined mixed layer criterion picks out two mixed layers, one at the top of the halocline at 40 m depth and another at the base of the isothermal layer at 100 m depth. In all three casts the difference between the shallower density mixed layer and the deeper isothermal mixed layer results in a salinity-stratified barrier layer. In these casts the barrier layer thickness ranges from 30-60 m. Using an earlier subset (1991-1992) of the XCTD data set that we employ in this study, Roemmich et al. [1994] noted the presence of barrier layers in many equatorial XCTD casts during December 1991 and January and March 1992. Roemmich et al. [1994] suggest that the barrier layers formed during early 1992 were created as fresher surface water from the west flows eastward over the saltier central Pacific water in an equatorial surface jet. They note, as do Sprintall and McPhaden [1994], that barrier layers are more likely to form under El Niño conditions such as
existed during 1991-1992. Few barrier layers were observed in the 1993-1996 XCTD profiles of the equatorial bands apart from the examples presented in Figure 9. With the onset of the 1997-1998 El Niño event, barrier layers are again becoming evident in the XCTD casts of the equatorial Pacific region.

5.3 California Current Regime

Along the San Francisco-Taiwan XBT/XCTD transect there is a high probability of finding inversions in the surface layer all year round between 130°W and 140°W. This region is commonly referred to as the California Current Transition Zone and separates the low-temperature, low-salinity properties of the Subarctic Water mass found in the eastern boundary California Current from the higher-salinity Eastern North Pacific Central Water mass formed midgyre. The transition zone is characterized by sharp gradients in temperature and salinity, both horizontally at the surface separating the eastern Californian Front from the western Subtropical Front and vertically at depth through the

Figure 8. (left) Temperature, (middle) salinity and (right) density of XCTD casts located at (a) 2°N (solid line), (b) 4°N (dashed line), (c) 6°N (dotted line), and (d) 9°N (dash-dotted line) along the Auckland-Seattle transect during September 1995. Mixed layers and fossil layers are indicated by squares, and surface layer depth is denoted by circles. The upper mixed layer in the 4°N and 6°N casts corresponds closely in depth to the upper mixed layer at 9°N, whereas the fossil layers extend to the same mixed layer depth as the cast at 2°N.

Figure 9. XCTD casts located at (a) 0°, 168.9°W in June 1994, (b) 7°S, 173.2°W in March 1995, and (c) 1°S, 169.6°W in June 1994. Mixed layers and fossil layers are indicated by squares, and surface layer depth is denoted by circles. The difference in the shallower density-defined mixed layer and the deeper temperature-defined mixed layer indicates the presence of a salinity-stratified barrier layer. Temperature is a solid line, salinity is a dashed line, and sigma-t is a dotted line.
The inversions of the transition zone are very different in structure to those found and described earlier in the equatorial central Pacific. In the transition zone the inversions are generally much thicker and occur within the pycnocline itself, not at the base of a well-mixed layer and at the top of the pycnocline as in the equatorial region. Typically within the broad region of the inversion there is the high degree of vertical variability in both the temperature and salinity fields that is characteristic of water mass interleaving (Figure 10). The temperature and salinity reversals result from advective penetrations of the California Current that has been perturbed by eddies and jets with different salt contents along the frontal region.

The fossil layers that occur during spring (AMJ) in the California Transition Zone between 135° and 145°W are associated with Eastern STMW formation. Eastern STMW as identified in the San Francisco-Hawaii XBT section is the subject of a recent paper by Hautala and Roemmich [1998], and details can be found there. As in the southwest Pacific region of STMW formation, the eastern STMW formation region is associated with a maximum in surface layer depth (Figure 2).

There is a striking spring (AMJ) peak in fossil layer occurrence just upstream of the island of Guam (145°W). There is no documented STMW formation in this region. One possible interpretation is that the fossil layers result from topographic influences from the Marianas Island chain, as suggested for the fossil layer occurrence found near New Caledonia. The reason for springtime dominance in the occurrence of fossil layers in this region is also uncertain; however, we note that this period coincides with when the North Equatorial Current is weakest [Chiswell et al., 1995], and also with a minimum in wind strength in the Intertropical Convergence Zone. Combined with episodic springtime heating events, this may provide suitable conditions for fossil layer formation.
5.4 Subpolar Gyre of the Northeast Pacific Ocean

The high incidence of inversions and fossil layers found in the surface layer between 40° and 60°N along the Honolulu and Valdez transect is an artifact of the influence of salinity variability in this region of the North Pacific subpolar gyre. In Figure 11a the temperature profile from an XCTD cast at 48.6°N, 150.5°W during March 1996 shows little variation with depth, only a very gentle thermocline after a slight temperature increase at ~115 m. There is no mixed layer depth shallower than 300 m, picked out by the 0.1°C temperature criterion. However, the density-defined mixed layer occurs just above the slight temperature increase and at the top of a strong halocline with a corresponding pycnocline. Farther north at 56.8°N, 147.7°W during the same cruise, the temperature profile exhibits a 1.7°C inversion located just above 100 m that delimits the temperature mixed layer (Figure 11b). The halocline and pycnocline define a density mixed layer at the same depth as the temperature mixed layer. The inversions are a well-known feature of the surface layer in subpolar regions, forming when the summer surface water is capped by the cold, fresh surface conditions during the winter months. In this region of the North Pacific subpolar gyre a mixed layer definition based on temperature alone is misleading, particularly during the winter months. While the XBT temperature profiles may illustrate deep isothermal surface layers, such as during the October 1996 transect shown in Plate 1d, these layers are stratified by salinity, limiting the true depth of mixing in the water column. During the summer months the temperature inversions have all but disappeared and the vertical density gradient is now temperature dominated (Figure 11c). The large range in standard errors of the percentage casts in this region (Figure 4d) is indicative of the seasonal variations of the occurrence of fossil and inversion layers.

The structure of the subpolar inversions is remarkably different from those inversions found in the equatorial central Pacific and in the California Current Transition Zone. The subpolar inversions have much larger temperature increases and are characterized by an abrupt increase in temperature at the base of the upper mixed layer that then smoothly and monotonically decreases with depth.

6. Conclusions

The main objective of this work has been to investigate how the surface layer can best be categorized both qualitatively and statistically for dynamically different regimes of the large-scale circulation in the Pacific Ocean and under different conditions of atmospheric forcing. The examination of nearly a decade of high-density XBT/XCTD observations between Auckland and Hawaii and multiyear measurements on the two subtropical gyre transects and the subpolar gyre transect have revealed intricate detail about the structure of the mixed layer. Features such as fossil layers and inversions were demonstrated to be ubiquitous in well-defined regions of the Pacific Ocean and consistently appeared in the XBT/XCTD data during certain seasons of the year. We related their geographic occurrence to known flow patterns and water mass movements within the Pacific Ocean. In some regions, particularly in the equatorial bands and in the North Pacific subpolar gyre, the influence of salinity in controlling the depth of the surface layer is found to be an important factor. This highlights the need for continued complementary salinity information, such as provided by XCTD sampling, along the high-resolution transects.
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References

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