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GOSML: A Global Ocean Surface Mixed Layer Statistical Monthly Climatology: Means, Percentiles, Skewness, and Kurtosis

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Key Points:

- A monthly climatology of mixed layer property means, variances, percentiles (5th, 50th, and 95th), skewness, and kurtosis is analyzed
- Mixed layer depth 95th percentiles, reasonable ventilation indicators, substantially exceed mean values at many locations and times
- Mixed layer properties are not normally distributed, with depths often positively skew, especially between late spring and early summer

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Abstract Here we discuss a global ocean surface mixed layer statistical monthly climatology (GOSML) of depth, temperature, and salinity that includes means; variances; 5th, 50th, and 95th percentiles; as well as skewness and kurtosis. Ocean surface mixed layer properties are influenced by gravity and a wide variety of factors that operate over a wide variety of time scales. Mixed layer depths can shoal very quickly as a result of surface heating, precipitation, or "slumping" of horizontal density gradients. However, deepening the mixed layer in the presence of a strong pycnocline requires substantial buoyancy loss or strong wind mixing, which often takes more time. This pattern is clear in the annual cycle monthly mixed layer depth values, with deepening in the fall much slower than shoaling in the spring. The 95th percentile values are chosen as a reasonable indicator of ventilation depth, robust to extreme outliers. Mean mixed layer depths are on average 0.56 of 95th percentile mixed layer depths, with only 1% of values below 0.31% and 1% above 0.81. Over 71% of mixed layer depth distributions are skewed positive, usually when there are more shallow mixed layer depths than not and deep mixed layer tails are strong. Comparing 95th percentile depth conditions to mean values shows in late winter temperatures are generally lower in the subtropics and salinities generally higher in the subpolar regions, consistent with the importance of temperature in the midlatitudes and salinity in the higher latitudes in setting stratification.

Plain Language Summary The ocean surface mixed layer is key to exchanges of heat, freshwater, momentum, and dissolved gasses between atmosphere and ocean. Hence, it affects marine life, weather, and climate. Mixed layer depths shoal suddenly with warming from the sun, rainfall, riverine outflow, or currents that slide lighter water over denser. However, mixed layer deepening requires loss of heat or freshwater to the atmosphere or strong wind mixing to overcome ocean density stratification below. The monthly mixed layer climatology presented here illustrates that asymmetry, with slow deepening from summer to winter, and fast shoaling during the spring. Likewise, shallower mixed layers often predominate over deeper ones for many months and locations. Since the deeper mixed layers determine the local exchange of surface properties with the ocean interior (known as ventilation), mean values are not a good indicator of those processes. Here we choose 95th percentile mixed layer depths in a given month (and the associated temperature and salinity values) as an indicator of the ventilation conditions that is not impacted by extreme outliers. These 95th percentile depths are on average about 85% deeper than the means, but can reach over five times deeper in a few locations at a few times.

1. Introduction

Ocean surface mixed layer (hereafter mixed layer) dynamics are asymmetrical, as is visible even on diurnal time scales (Price et al., 1986). Pronounced mixed layer shoaling can occur relatively rapidly, through buoyancy gains by surface heating (Price et al., 1986), surface precipitation (Sprintall & Tomczak, 1992), riverine input (Rao & Sivakumar, 2003), or ice melt (Vernet et al., 2008); through advection via "slumpling" of horizontal density gradients in the mixed layer (Boccaletti et al., 2007); or some combination thereof. In other words, it is easy for mixed layer depth to shoal rapidly and drastically, especially in low wind conditions. On the other hand, in order to deepen, the surface mixed layer has to become denser and mix through an underlying stratified pycnocline, which requires buoyancy losses by surface cooling, evaporation, or ice formation; wind mixing; or some combination thereof. Hence, it typically takes more time for a mixed layer to deepen than to shoal (Damerell et al., 2020). This asymmetry suggests that mixed layer properties (e.g., depth, temperature, salinity, and density) may not be normally distributed. Nonetheless, many (de Boyer Montegut et al., 2004; Kara et al., 2003), although not all (Holte et al., 2017) mixed layer climatologies are computed from averages of data distributions, which assume a normal distribution.

Mixed layer properties are determined by surface fluxes of buoyancy (e.g., heat and freshwater) and kinetic energy (e.g., wind; Price et al., 1986) that all vary on time scales from minutes to hours (microscale weather), hours to days (mesoscale weather and the diurnal cycle), days to weeks (synoptic-scale weather), weeks to months (global-scale weather and the seasonal cycle), and months to millennia (climate variations). This wide range of time scales for interactions between the ocean surface mixed layer and the atmosphere also suggests that mixed layer properties may not be normally distributed.

Means and variances are especially useful for describing normal distributions. Here, because of the issues discussed above, we present additional statistics for mixed layer properties (depth, and also temperature and salinity), including the median (50th percentile), 5th, and 95th percentiles. We chose the 95th percentile of the depth distribution for a given location and month as a reasonable indicator of the depth to which the ocean is ventilated on seasonal time scales. While this choice is similar in intent to the average of the three deepest values (Holte et al., 2017), it is more independent of the number of samples taken (the average of the deepest three values could be very different when considering 3,000 samples vs. 30, but the 95th percentile remains constant in meaning) and more robustly excludes extreme outliers. We also include the 5th percentile of the depth distribution for a given location and month to illustrate the mixed layer properties at times when it is lighter and shallower. Finally, we present and discuss the skewness (the third standardized moment of a distribution, which typically indicates which side of the distribution has a larger tail), and kurtosis (the fourth standardized moment of a distribution, which indicates the prominence of the tails of the distribution) of mixed layer properties.

Argo floats have been collecting vertical profiles of temperature and salinity versus pressure from the ocean surface to pressures of 2,000 dbar since the inception of the program around the turn of the millennium (Johnson et al., 2022). These publicly available data, collected globally and year-round, allow a more detailed examination of monthly ocean surface mixed layer statistics. Here we estimate the mean, variance, skewness, and kurtosis for mixed layer depth, temperature, salinity, and density, as well as 5th, 50th, and 95th percentiles of mixed layer properties sorted by depth and then smoothed.

2. Data and Methods

Argo data were downloaded from the US Global Data Assembly Centre in January 2021 (https://doi.org/10.17882/42182). Only data with quality flags of 1 (good) or 2 (probably good) were used. Adjusted fields (delayed-mode scientific quality controlled) were used where available, and unadjusted fields (real-time automated quality controlled) were used otherwise.

Mixed layer properties (average temperature, practical salinity, and depth) were determined from each Argo profile using the density algorithm of Holte and Talley (2009). With its relatively sensitive thresholds and use of temperature and salinity data, this algorithm is well suited to the Argo data set. Following that the absolute salinity, conservative temperature, and potential density were calculated using the 2010 equation of state (TEOS-10) for seawater (Feistel, 2012).

A monthly climatology of mixed layer properties was estimated using the following methods: The data were analyzed on a global grid with resolution of one month in time, 1° in latitude, and 1° in longitude. Bottom depth values were set for each mixed layer estimate and the grid locations through linear interpolation of ETOP01 bathymetry data (Smith & Sandwell, 1997) that had been smoothed with a 30’ (latitude and longitude) half-width Hanning filter and subsampled at 15’ intervals. For each point a LOESS weighting (Cleveland & Devlin, 1988) w was constructed with a 1-month time scale, a 500-km length scale, and a bottom depth weighting as follows:

$$q = \left|\frac{y_g - y_f}{4.521^\circ}\right| + \left|\frac{(x_g - x_f)\times\cos(y_g)}{4.521^\circ}\right| + \left|\frac{t_g - t_f}{1\ \text{month}}\right| + \frac{1}{\log(10)} \times \left|\log\left(\frac{h_g}{h_f}\right)\right| \tag{1}$$

where y is longitude, x is latitude (both in degrees), t is time (in months), h is bottom depth (in meters), the subscript g indicates the grid points, and the subscript f the individual floats, and

$$w = (1 - q^3)^3 \quad \text{for } q < 1 \text{ and } w = 0 \quad \text{for } q \geq 1. \tag{2}$$

The length scales for the weighting are chosen to emphasize large-scale distributions and to match the nominal Argo 3° lat. x 3° long. sampling, the time scale is set to resolve the seasonal cycle, and the bottom depth weighting serves to separate grid points in the open ocean, the continental slopes, and the shelves.

At each grid point the data selected are first screened for really extreme outliers, rejecting data points with mixed layer depths, temperatures, or salinities that are 6 times the interquartile range greater than the 75th percentiles or 6 times less than the 25th percentiles. (These outliers can result from bad data points that have escaped quality control or very non-normal property distributions of valid data. On average, outliers comprise <0.2% of the total number of points used in the mapping. Of the grid points mapped, 92% contain no outliers, 5% contain more than 1% outliers, and only 0.4% contain more than 10% outliers.) After removing outliers, the weighted mean, variance, skewness, and kurtosis are calculated for mixed layer depth, absolute salinity, conservative temperature, and potential density using the remaining points.

Skewness, Skew(x), at a grid point for a variable x is defined as

$$\mathrm{Skew}(x) = \frac{\sum\left[(x_i - \bar{x})^3 \cdot w_i\right]}{\sigma^3 \cdot \sum w_i}, \tag{3}$$

where x_i is the variable in question for a given sample i, w_i is the weight of that sample as defined in Equations 1 and 2, $\bar{x}$ is the weighted mean at the grid point, and σ is the weighted standard deviation at the grid point. Skewness is a signed quantity that is generally positive when the distribution has a stronger tail on the right side and negative when the distribution has a stronger tail on the left side.

Similarly, kurtosis, Kurt(x), at a grid point for that same variable x is defined as

$$\mathrm{Kurt}(x) = \frac{\sum\left[(x_i - \bar{x})^4 \cdot w_i\right]}{\sigma^4 \cdot \sum w_i}. \tag{4}$$

In contrast to skewness, kurtosis is a positive definite quantity. $\mathrm{Kurt}(x) = 3$ for a normal distribution. When $\mathrm{Kurt}(x) < 3$ the distribution has small tails. When $\mathrm{Kurt}(x) > 3$ the distribution has large tails.

Retained data for all four variables used at each grid point are then sorted by mixed layer depth to find 5th, 50th, and 95th percentile values at those depths. They are smoothed in percentile space with a weighted local linear fit, a LOWESS filter (Cleveland & Devlin, 1988), with a length scale of 25% of the sorted, weighted distribution. The weighting used is the product of the distance in this depth-sorted percentile space and the geographic distance/time/bottom depth weighting of the data point from the grid point weighting described in Equation 1. Smoothed 5th, 50th (median), and 95th percentile values are determined for all four variables.

3. Results

This section has four subsections. First, we discuss the number of points used in each map, and the weighted number (i.e., the effective number) of points. Second, we move onto looking at seasonal cycles of mixed layer properties (depth, temperature, and salinity; their means; and values at the 5th, 50th, and 95th percentile mixed layer depths) in four locations where prominent mode waters are formed. These are the Labrador Sea where Labrador Sea Water (LSW) is formed by deep convection (Yashayaev & Loder, 2016), the western North Atlantic subtropical gyre, where Eighteen Degree Water (EDW) is formed by subduction (Billheimer & Talley, 2016), the subantarctic Southeast Pacific, where the most extreme form of SubAntarctic Mode Water (SAMW) is formed by subduction (Sallée et al., 2010), and the eastern subtropical South Pacific, where South Pacific Eastern SubTropical Mode Water (SPESTMW) is formed by subduction (Wong & Johnson, 2003). Third, we discuss the mixed layer properties sorted by mixed layer depth around the time of maximum mixed layer depths (mid-March and mid-September; late winter in the Northern and Southern hemispheres, respectively) in these regions. We also discuss mid-March and mid-September 95th percentile mixed layer depths globally, as well as their ratios to the mean depths. In addition, we discuss the differences between temperature and salinity at the 95th percentile in depth to the means in terms of whether warmer or colder and saltier or fresher conditions are associated with 95% percentile mixed layer depths relative to the mean properties. Fourth, we discuss higher order moments (skewness and kurtosis) of the mixed layer properties, focusing on mixed layer depths during the transition months of mid-May and mid-November, when their regional patterns are most pronounced. While the number of figures in the

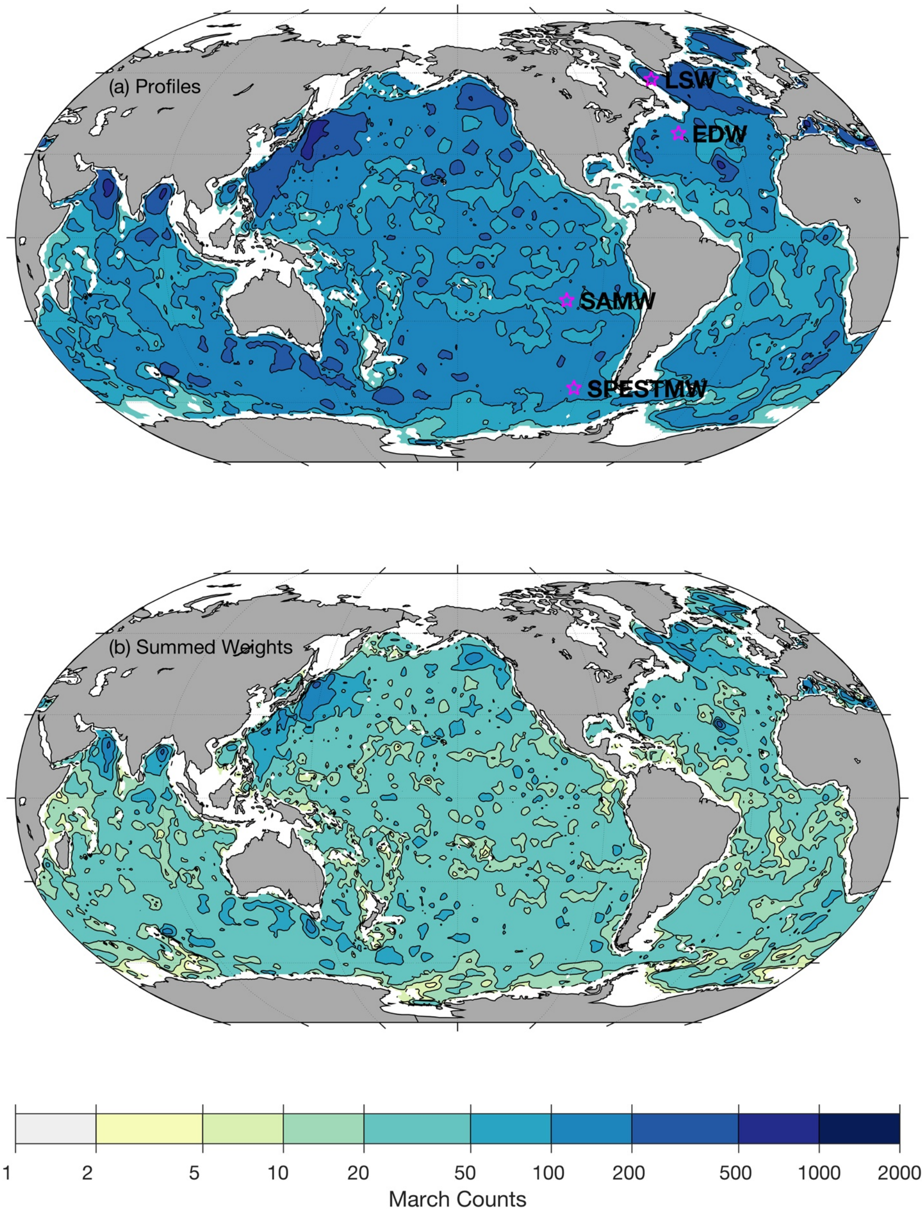

Figure 1. (a) Number of profiles used at each grid point and (b) sum of weights for profiles for the mid-March maps contoured at roughly logarithmic intervals (see colorbar). Formation regions (magenta pentagrams in a) for mode waters at which the seasonal cycles of mixed layer properties and late winter mixed layer property distributions are examined include, from north to south: Labrador Sea Water (LSW), Eighteen Degree Water (EDW), South Pacific Eastern SubTropical Mode Water (SPESTMW), and SubAntarctic Mode Water (SAMW) in the southeastern Pacific Ocean.

article is limited, the climatology itself and global maps of seasonal cycles of all of these fields are available at https://www.pmel.noaa.gov/gosml.

3.1. Data Distribution and Number of Data Used

While the data are generally evenly distributed throughout the year, there is considerable geographic variation in the sampling density, even for Argo. The most sampled regions are in the North Atlantic, North Pacific, and North Indian oceans with the number of data points used in March (Figure 1a) exceeding 500 in a few regions as well as other months (not shown) and the sum of the sample weights (Figure 1b) exceeding 100. There are only small regions where the number of points used falls below 50, or the sum of the sample weights falls below 10.

The sum of the weights for the grid points is on average about one quarter of the sum of the number of samples used at each grid point. The mean sum of the number of samples for grid points is 122 and the median is 111. About 5% of the grid points have a number of samples exceeding 242% and 5% of the grid points have a number of samples less than 36. If the number of samples originally selected for a given grid point is less than 20, statistics there are not computed, to ensure at least a minimal basis for the 5th and 95th percentile values reported. The mean sum of the weights for grid points is 30 and the median is 27. About 5% of the grid points have a sum of the weights exceeding 62 and about 5% of the grid points have a sum of the weights less than 8.

3.2. Seasonal Cycles at Select Mode Water Formation Regions

The seasonal cycles of mixed layer depth, temperature, and salinity (Figure 2), in a few select locations (see magenta pentagrams in Figure 1a) show distinct patterns. We choose the cores of formation for the LSW in the Labrador Sea, the EDW in the western subtropical North Atlantic, the SPESTMW in the eastern subtropical South Pacific, and the most extreme (coldest and freshest, and close to thickest) variety of SAMW in the Southeast Pacific.

In the center of the Labrador Sea, where LSW is formed, the mixed layer depth (Figure 2a) is a maximum in March, with cold temperatures (Figure 2e), and relatively salty (Figure 2i) conditions in that month. The 95th percentile mixed layer depths in winter are considerably larger than the mean or the median values. The mean values exceed the median values considerably in the winter and early spring, when very deep mixed layer depths are episodically present. The 5th percentile values are relatively shallow throughout the year, reflecting the fact that temporary shallow mixed layers can form in calm conditions year-round through either freshening or warming. Mixed layer depths at this location are relatively shallow from June until November with a minimum in August (around 35 m at the 95th percentile), deepen rapidly from December to February with a maximum in March (around 1,760 m at the 95th percentile), and then shoal very rapidly from April to May. In contrast, mixed layer temperatures and salinities are relatively cold and salty from December through April (with a March minimum of 3.2°C and a maximum of 35.02 g kg^{-1} at the 95th percentile), warm and freshen steadily from April through August (with an August maximum of 9.3°C and a September minimum of 34.66 g kg^{-1} at the 95th percentile), and then cool and salinify relatively steadily from August (or September) through November. The 5th percentile mixed layer salinity values are generally fresher than the 95th percentile values, with the means and medians very similar and in between. The 95th percentile temperature values are colder than the 5th percentile values except in the winter months, when that tendency reverses. As for salinity, the 5th percentile values are fresher than the 95th percentile values, with the mean and median values generally between, but approaching the 5th percentile values in summer (as detailed above, the 5th and 95th percentile temperature and salinity values were sorted by depth and then smoothed prior to evaluation).

Moving from the subpolar to the western subtropical mode waters of the North Atlantic, where EDW is formed, the mixed layer depth patterns follow a similar seasonal cycle, but with a muted amplitude. The March maximum of the 95th percentile depth values reaches 500 m, and the July minimum is about 42 m (Figure 2b). The late winter and early spring mean depths are again larger than the median depths, but the spring shoaling is less rapid, with the bulk taking place from March through May, so starting a month earlier than further north. Mixed layer temperatures (Figure 2f) and salinities (Figure 2j) are again relatively cold and salty during winter months with a 95th percentile temperature minimum of 17.9°C in March (fitting for EDW) and a 95th percentile maximum salinity of 36.75 g kg^{-1} in January. Temperatures rise fairly steadily from May through August, reaching a maximum value of 27.0°C in August, then decrease steadily from August through December. Salinity follows a similar (although opposite in sign, hence reinforcing each other in their effect on mixed layer density) pattern to temperature, with a 95th percentile value minimum of 36.40 g kg^{-1} in August. The 5th percentile salinity values are often substantially fresher than the 95th percentile values, indicating the role of surface freshening in mixed layer shoaling in the region.

Moving to the Southern Hemisphere, in the Southeast Pacific where the winter mixed layers are quite deep and the most extreme form of SAMW is produced, the 95th percentile mixed layer depth (Figure 2c) reaches a minimum of about 92 m in January and a maximum of 611 m in September. Most of the mixed layer shoaling takes place from October to November, and the deepening from April to August. Hence, there is substantial seasonal asymmetry, with faster shoaling than deepening, like in the Labrador Sea. The mean and median mixed layer depth values are generally pretty similar. The 5th percentile mixed layer depth is relatively deep compared to the

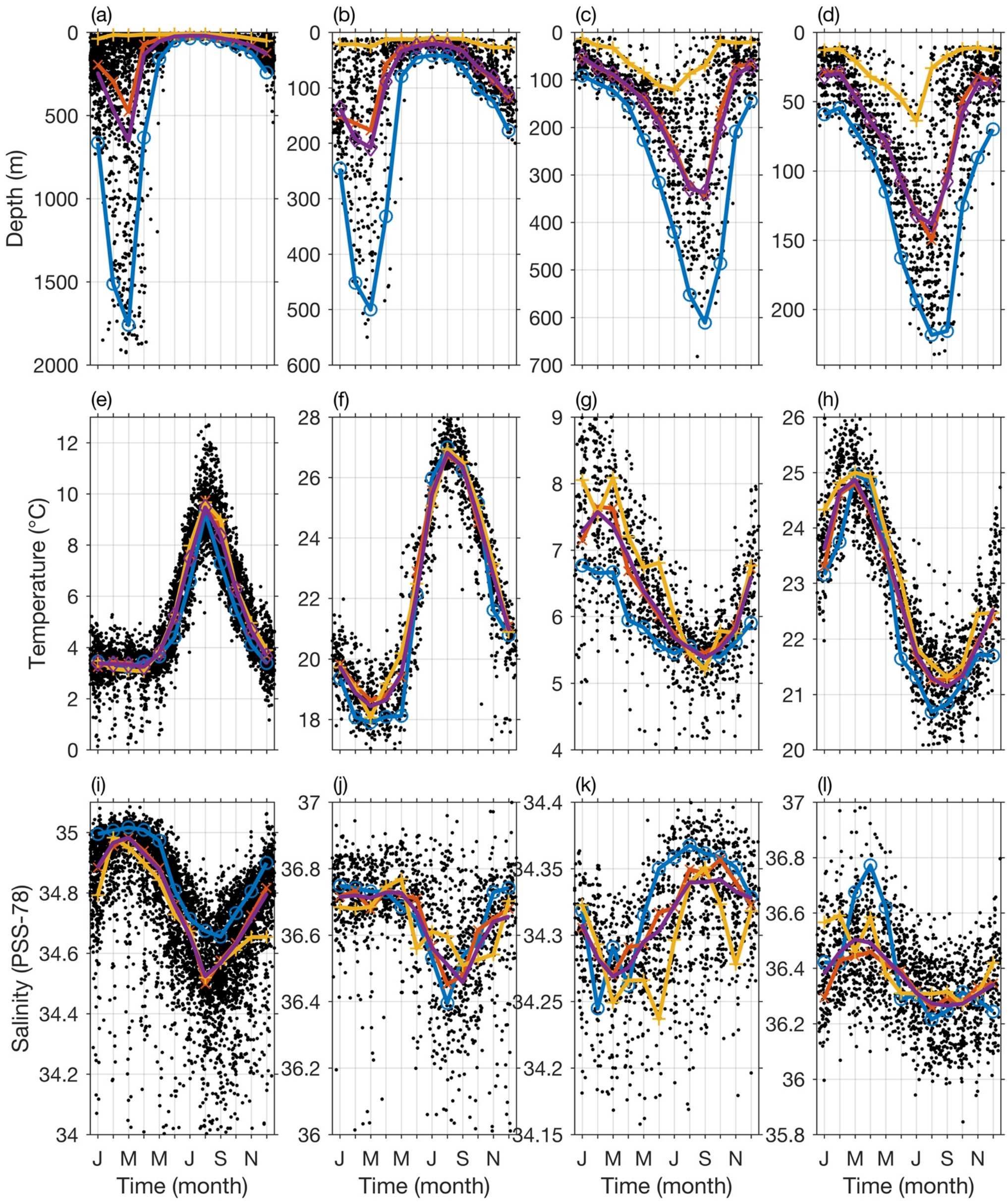

Figure 2. Seasonal cycles of mixed layer depths (top row), conservative temperature (middle row), and salinity (bottom row) for Labrador Sea Water (far left column), Eighteen Degree Water (middle left column), South Pacific Eastern SubTropical Mode Water (middle right column), and SubAntarctic Mode Water (far right column) in the southeastern Pacific Ocean (see magenta pentagrams in Figure 1a for locations). Raw values (black dots), mapped monthly values corresponding to 95th percentile mixed layer depths (blue line with circles), 50th percentile mixed layer depths (orange line with crosses), 5th percentile mixed layer depths (yellow line with plusses), and mean values (purple line with diamonds) are shown.

Labrador Sea, reaching a maximum around 121 m in July, suggesting that fresh or warm caps are comparatively infrequent in this portion of the Southeast Pacific in fall and winter. The summer warm period is also pretty short (Figure 2g), with a 95th percentile temperature value maximum of 6.8°C in January, and the winter cold period is pretty long, from about May through November, with a minimum 95th percentile temperature of 5.4°C in September. The 5th percentile mixed layer temperature is warmer than the 95th, with the mean and median similar and in between, except in the dead of winter, when all values are quite similar. The mixed layer salinity distribution (Figure 2k) is more sinusoidal than the temperature, with a maximum 95th percentile salinity of 34.37 g kg^{-1} in August and a salinity minimum of 34.24 g kg^{-1} in February. The 5th percentile salinity is often considerably fresher than the 95th percentile salinity, again stressing the importance of fresher surface conditions during periods of shallower mixed layers. In this case some of that variability is likely to be spatial, as the surface mixed layer gets fresher and shallower toward the south within 500 km of this location.

Finally, in the heart of the SPESTMW formation in the Southeast Pacific, 95th percentile mixed layer depth values (Figure 2d) reach a maximum of 218 m in August, and a minimum of 55 m in February. The mean and median values of mixed layer depth are fairly similar to each other. Again, the 5th percentile mixed layer depth values are larger than in the Northern Hemisphere subtropical EDW formation region, reaching maximum values of 64 m in July. Mixed layers deepen from March to August and shoal, more rapidly, from September to December. The annual harmonic is strong in the mixed layer temperature seasonal cycle here (Figure 2h), with a 95th percentile (again, in terms of sorted weighted depths) maximum of 25.0°C in March and a minimum of 20.7°C in August. The 5th percentile temperature values are generally warmer than the 95th percentile values, especially in austral winter, with mean and median values fairly similar and in between the 5th and 95th percentile values. The mixed layer salinity values are also sinusoidal in character (Figure 2l), with a maximum 95th percentile value of 36.77 g kg^{-1} in March and a minimum of 36.22 g kg^{-1} in August. The seasonal cycle of salinity values at 5th percentile depth mixed layers is muted compared to that for the 95th percentile depth mixed layers, reflecting the prevalence of high salinities in relatively deep summertime mixed layers, and relatively low salinities (but much colder temperatures) in deep wintertime mixed layers.

Examination of the late-winter mixed layer properties sorted (and smoothed) as a function of mixed layer depth (weighted by distance, time, and depth difference from the grid point) is illuminating. In the Labrador Sea in mid-March, a substantial portion of the mixed layer depths is relatively shallow, with a smaller portion of very deep values (Figure 3a). Hence, the distribution is non-normal with a median value substantially less than the mean value, a skewness of 0.59 (positive, so a stronger tail of deep values) and a kurtosis of 1.95 (<3.0, so relatively light tails). Shallower (5th percentile) mixed layer depths are associated with colder (Figure 3e) and fresher (Figure 3i) conditions, and deeper (95th percentile) mixed layer depths are near average in temperature and saltier than average. In the EDW formation region in March, the mean mixed layer depth (Figure 3b) is again larger than the median value, with a skewness of 0.53 (again, a stronger tail of deep values) and a kurtosis of 2.08 (again, light tails relative to a normal distribution of 3). Shallower mixed layer depths are again associated with colder (Figure 3f) and fresher (Figure 3j) conditions, and deep mixed layers with colder and saltier than average conditions. In the subantarctic Southeast Pacific in mid-September, the mean and median mixed layer depths (Figure 3c) are quite similar, with a skewness of 0.07 (a faintly stronger tail of deep values) and a kurtosis of 2.90 (very close to the value of 3 for normal tails). Those values are consistent with a depth distribution that is very close to normal, as is visually apparent. The very shallowest mixed layers are associated with colder (Figure 3g) and saltier (Figure 3k) conditions, which is puzzling, whereas deeper mixed layers are more intuitively associated with near-mean temperatures, but saltier than mean conditions. Finally, in the core of the SPESTMW formation region, the mid-September mean mixed layer depth value (Figure 3d) is slightly larger than the median, with a skewness of 0.24 (a slightly stronger tail of deep values) and a kurtosis of 1.86 (<3, so weaker than normal tails). Here deeper mixed layers are associated with colder (Figure 3h) and saltier (Figure 3l) conditions, and shallower mixed layers with warmer than average temperatures and saltier than average salinities.

3.3. Late Winter and Late Summer Mixed Layer Properties at 95th Percentile Depths

Northern Hemisphere mixed layer values are deepest in late winter to early spring, generally around mid-March. In that month mixed layer depth 95th percentile values (Figure 4a) exceed 1,600 m in the Labrador and Greenland seas, 566 m in the western subtropical North Atlantic, and 400 m in the western subtropical North Pacific. They are less than 25 m in the eastern equatorial Pacific, and only exceed 200 m in a few isolated regions of the Southern Ocean, being less than 100 m deep across much of the subtropical Southern Hemisphere oceans during austral late summer, although exceeding 100 m in the central tropical South Pacific, where trade winds are strong.

The ratio of mean to 95th percentile depths in March (Figure 5a) is smaller (so 95th percentile mixed layer depths are relatively deep compared to the mean values) in the Northern Hemisphere than in the south, with generally smaller values (0.3–0.4) in the western subtropics than in the tropics of that hemisphere. The subpolar North Pacific and Bering Sea have a relatively large ratio in March, about 0.6–0.8, so 95th percentile mixed layer depths are not so much larger than mean values. In contrast, in the center of the Labrador Sea of the subpolar North Atlantic, that ratio dips below 0.2, so there 95th percentile mixed layer depths exceed mean values by a factor of more than five. In the Southern Hemisphere the ratio generally increases poleward, being about 0.4 near the

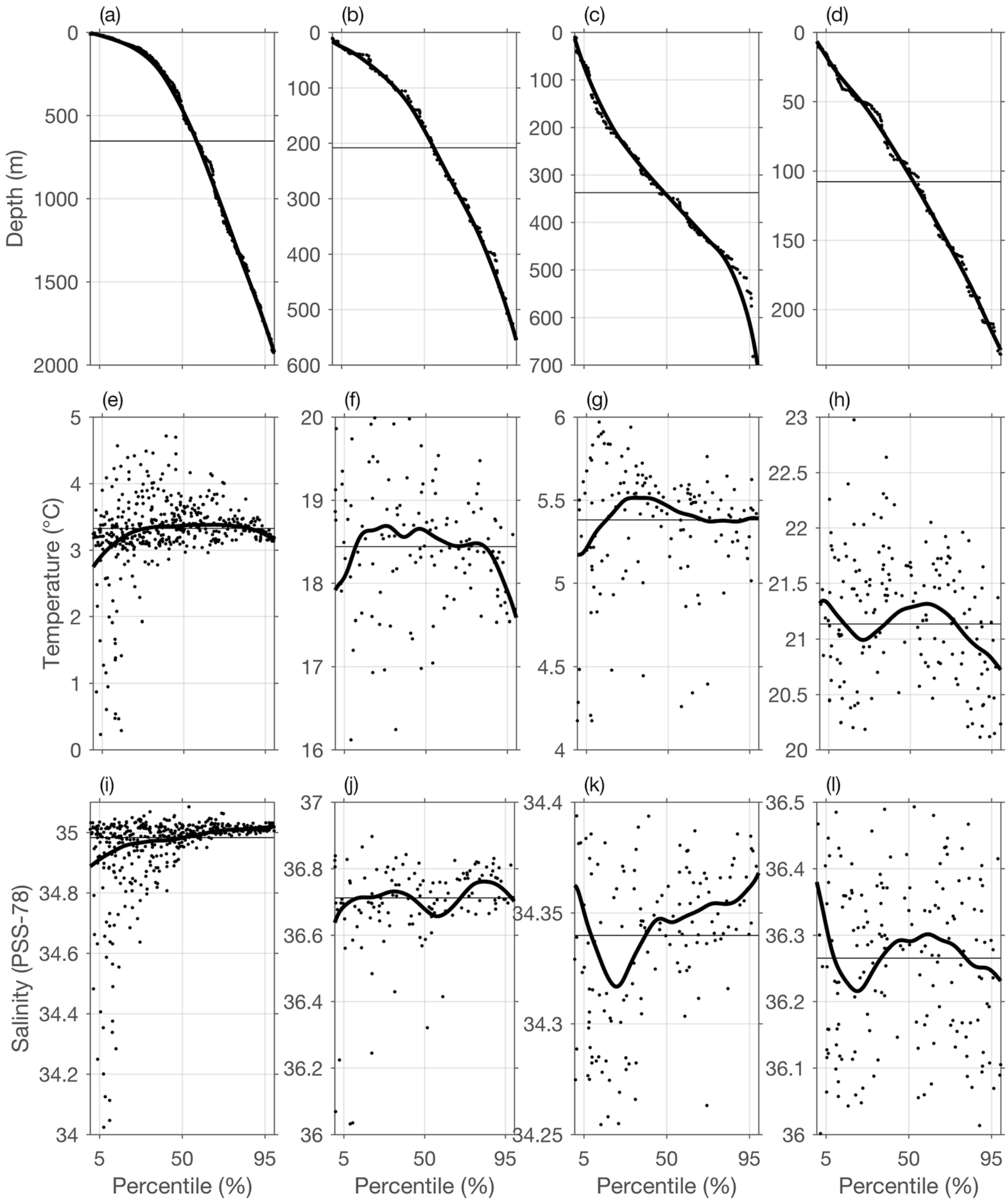

Figure 3. Late winter mixed layer depth (top row), conservative temperature (middle row), and salinity (bottom row) distributions for Labrador Sea Water (far left column) and Eighteen Degree Water (middle left column) in mid-March, as well as South Pacific Eastern SubTropical Mode Water (middle right column) and SAMW (far right column) in the southeastern Pacific Ocean in mid-September (see magenta pentagrams in Figure 1a for locations). Raw values (black dots) sorted by mixed layer depth and weighted by distance, time, and depth separation from the grid point, and LOWESS smoothed values for those properties using a length scale of 25% (black lines) are shown.

equator, increasing to about 0.5 and 0.6 in the tropical Pacific and Indian oceans, closer to 0.6–0.7 in the eastern subtropical Pacific and tropical South Atlantic. Within and south of the Antarctic Circumpolar Current (ACC) the ratio exceeds 0.6 and even 0.8 in a few isolated locations.

The temperatures and salinities for the 95th percentile mixed layer depths are not so different from many other climatologies, so they are not discussed here. Instead, temperature and salinity differences for the 95th percentile depths minus the mean mixed layer values of temperature and salinities are discussed to reveal some of what is driving the variations in mixed layer depths. Since the global average of the thermal expansion coefficient α to the haline contraction coefficient β at the surface is about 0.4, these temperature differences are contoured at 0.5°C intervals and the salinity differences at 0.2 g kg^{-1}. Hence, in the subtropics one contour of salinity difference is

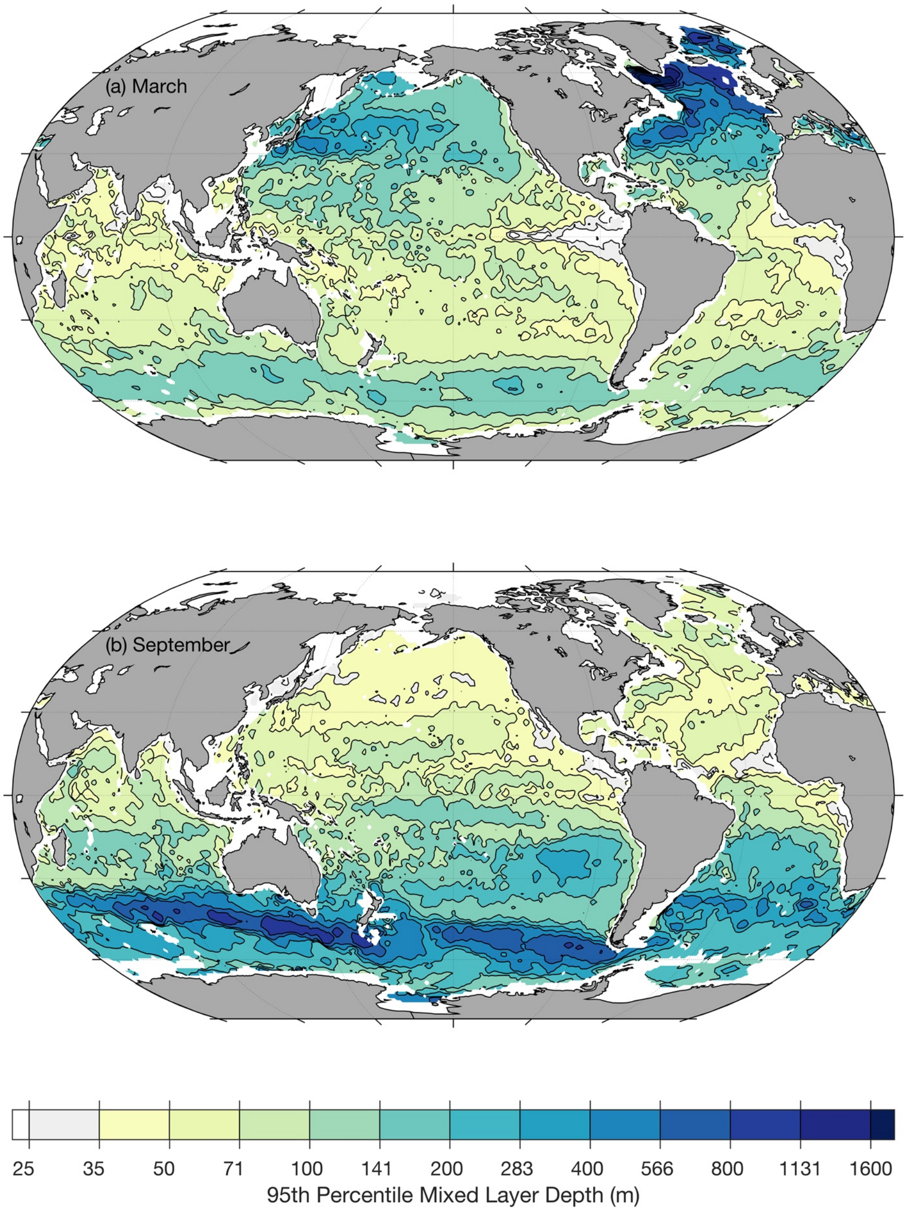

Figure 4. (a) Mid-March and (b) mid-September 95th percentile mixed layer depths contoured on a logarithmic scale (colorbar) from 25 to 1,600 m.

roughly equivalent in magnitude (although opposite in sign) with respect to the effect on density of one contour of temperature difference. At higher latitudes the contouring choice substantially overemphasizes the effect of temperature on density compared to salinity, since α/β at higher latitudes can drop below 0.1. In the tropics the contouring choice slightly underemphasizes the effect of temperature on density, since α/β can approach 0.5 there.

In March, deep (95th percentile) mixed layers are generally warmer (Figure 6a) and saltier (Figure 7a) than mean mixed layer conditions in the western subpolar northwest Pacific, and anomalously fresh and cool mixed layers are shallower, as expected in a predominantly salt-stratified high-latitude pycnocline. In the eastern subpolar North Pacific and the Bering Sea the deeper late winter mixed layers are also saltier but slightly cooler too. In the subtropical North Pacific and North Atlantic deep mixed layers are cooler than the mean mixed layer values, but tend toward fresher in the west and saltier in the east (where subsurface salinity is higher). Around the edges of the Labrador Sea, east of Canada's Maritime Provinces and USA's New England, and in the vicinity of the North Atlantic Current, deep mixed layers are generally warmer and much saltier than mean mixed layer values,

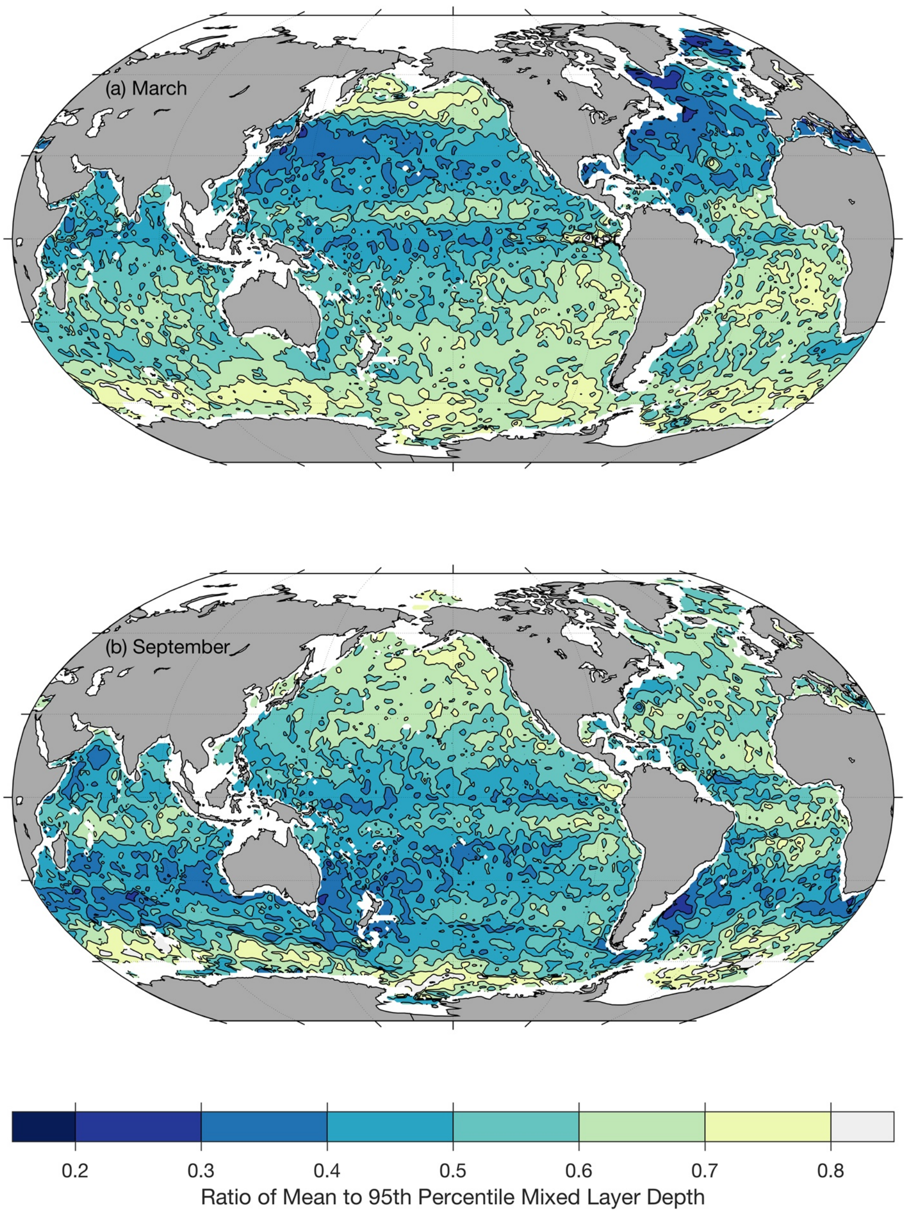

Figure 5. (a) Mid-March and (b) mid-September ratios of mean to 95th percentile mixed layer depths contoured at 0.1 intervals (colorbar).

again reflecting the stratifying influence of colder, fresher surface waters in the region. In the tropics, and very prominently in the Bay of Bengal, deep mixed layers are generally slightly cooler, and saltier, again reflecting the stratifying influence of shallow fresh surface mixed layers there. In the subtropical Southern Hemisphere, deep March mixed layers are substantially cooler (and usually slightly saltier) than mean mixed layers, likely reflecting the importance of insolation in creating shallow mixed layers in winter, probably during calm conditions, as precipitation is relatively uncommon there. At higher southern latitudes, deep March mixed layers are often warmer and saltier than mean mixed layer properties, again reflecting the importance of freshwater near the surface in setting the subpolar stratification.

In mid-September, 95th percentile mixed layer depths (Figure 4b) are deepest north of the Subantarctic Front, exceeding 800 m south of Australia and New Zealand and in a very small region of the Southeast Pacific. They exceed 400 m in a portion of the subtropical gyre in the South Atlantic Ocean, and 283 m in the subtropical Southeast Pacific Ocean. In the Northern Hemisphere, September mixed layer 95th percentile depths are generally

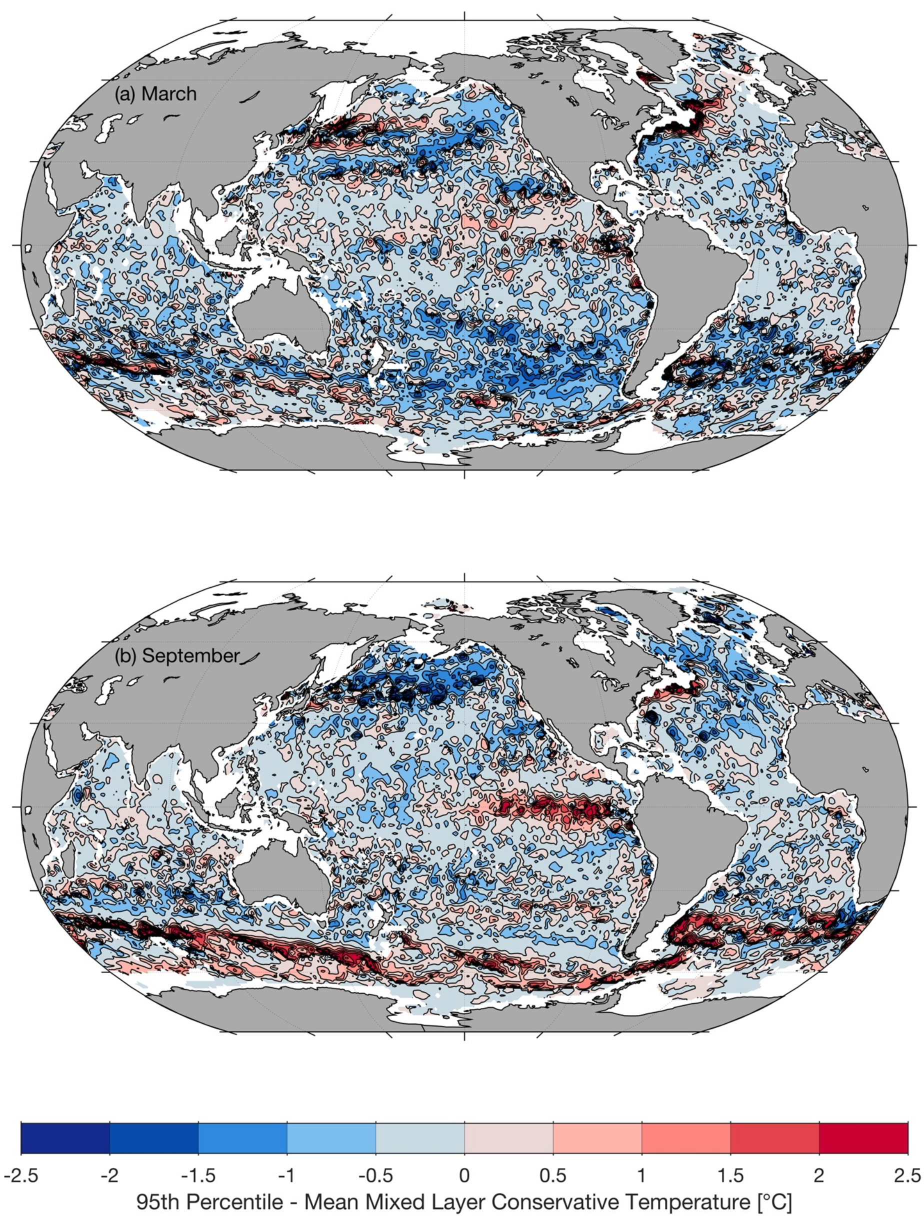

Figure 6. (a) Mid-March and (b) mid-September differences of conservative temperature for the 95th percentile mixed layer depth minus the mean mixed layer temperature contoured at 0.5°C intervals (colorbar).

shallower than 100 m, except in small portions of the western subtropical North Pacific, the subpolar North Atlantic, and again in the central tropical Pacific under the trade winds. In the Pacific they reach values shallower than 35 m in isolated regions of the central North Pacific, south of Baja, west of Central America, and the eastern equatorial Pacific. In the Atlantic in September the 95th percentile mixed layer depth is shallower than 35 m east of the Amazon, and west of Africa on both sides of the equator.

The ratio of 95th percentile to mean mixed layer depths in September (Figure 5b) in the Northern Hemisphere subtropical and subpolar regions generally exceeds 0.5 or 0.6 (and in a few locations of the subpolar North Pacific tops 0.7). This ratio is lower in the Arabian Sea, where it dips below 0.4, consistent with some relatively deep mixed layers at the end of the Southwest Monsoon season, but with more frequent shallower mixed layers as well. In the western portions of the Southern Hemisphere subtropical regions the ratio drops to below 0.4 in places, and even below 0.3 in the western South Atlantic, off Southeast Australia, and off South Africa. South of the ACC the

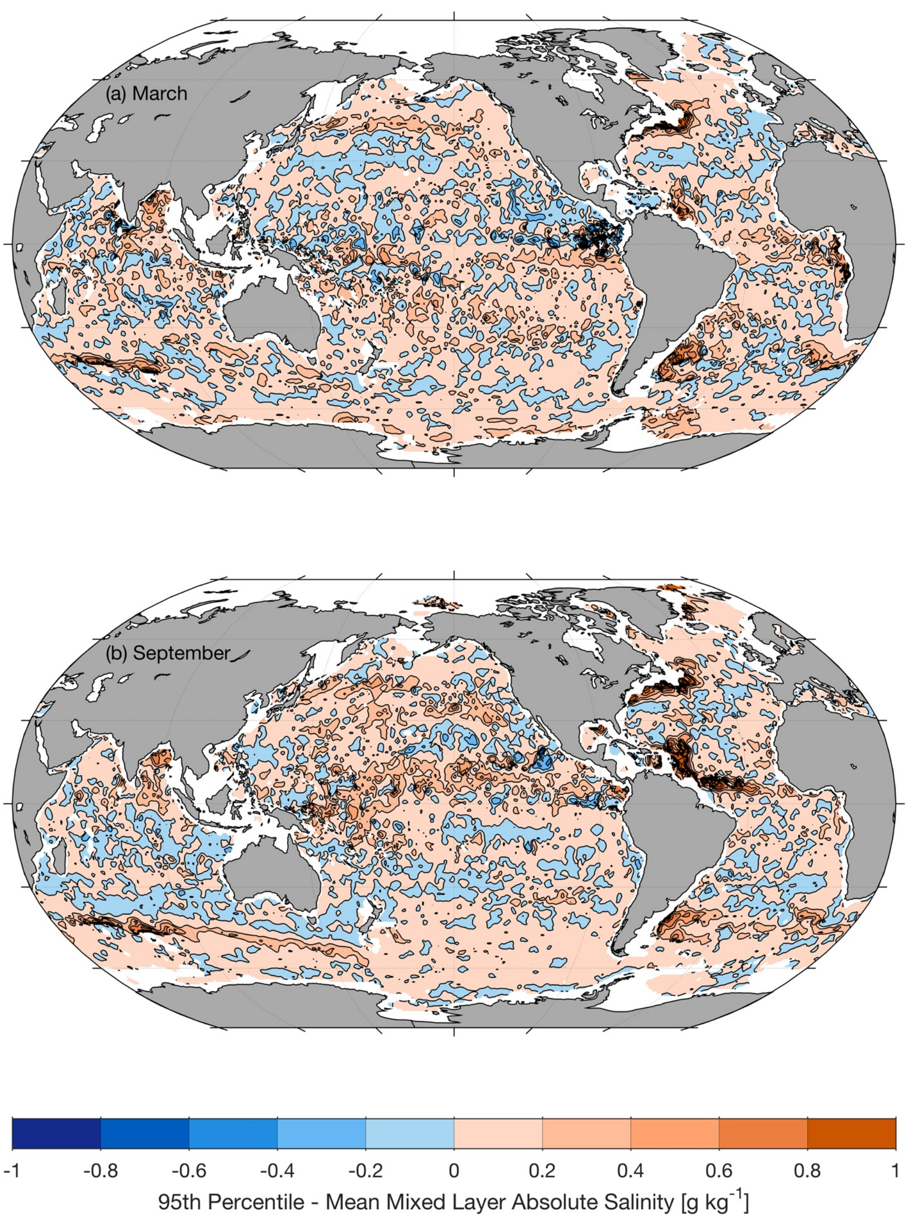

Figure 7. (a) Mid-March and (b) mid-September differences of absolute salinity for the 95th percentile mixed layer depth minus the mean mixed layer absolute salinity contoured at 0.2 g kg^{-1} intervals (colorbar).

ratio exceeds values of 0.6 in many locations and 0.8 in some locations, so the mean and 95th percentile depths are not so different in this location in late winter or early spring (mid-September).

In mid-September in the subpolar North Pacific and subpolar North Atlantic the temperatures at mixed layer 95th percentile depths (Figure 6b) are substantially lower than the mean mixed layer temperatures and corresponding salinity values (Figure 7b) are only slightly saltier. This is to be expected since warmer shallower mixed layers will be prevalent in these months, punctuated by colder, deeper, and saltier mixed layers during the first fall season storms. Moving south into the subtropics deep (95th percentile) mixed layers appear associated with substantially saltier, but only slightly colder mixed layers in the North Pacific, whereas in the interior of the subtropical North Atlantic deep mixed layers in mid-September are substantially colder, but not much saltier than the mean. Off the east coast of North America deep mixed layers are much saltier and warmer, reflecting the correlation of colder, fresher, subpolar waters with shallower mixed layers in that region. In the tropics of all three oceans, deep mixed layers are saltier, but generally not much different in temperature from the mean values, reflecting the association of fresh surface conditions with shallower mixed layers. This pattern includes the Bay of Bengal and east of the Amazon, where shallow relatively fresh mixed layers of riverine influence may also be prevalent. The one exception in terms of mixed layer temperatures in the tropical band is the eastern equatorial Pacific, where deep mixed layers are also substantially warmer. This occurs because in this region upwelling cold waters are generally associated with shallower mixed layers, and deep warmer mixed layers can more easily form when or where that upwelling is not present. In the Southern Hemisphere subtropics there is not a clear large-scale pattern of temperature or salinity with deep mixed layers. However, just north of the ACC, deep mixed layers are generally colder and fresher in the Atlantic and Indian oceans, but colder and slightly saltier in the Pacific Ocean in mid-September. Within the ACC, deep mixed layers are substantially warmer and saltier in the Atlantic and Indian oceans, and substantially warmer but only a bit saltier in the Pacific Ocean. This pattern reflects the association of cold and fresh Antarctic waters with shallower mixed layers in these regions, and the relatively fresh subsurface waters in the Pacific compared to the other oceans. South of the ACC deep mixed layers are generally substantially warmer, but only slightly saltier.

3.4. Skewness and Kurtosis of Mixed Layer Properties

Mixed layer depth skewness and kurtosis are both strongest in the transitions between spring and summer, when very shallow mixed layers often form but much deeper mixed layers are occasionally still present. In mid-May, skewness (Figure 8a) exceeds +1 in most of the Northern Hemisphere, and is often higher, even exceeding +3, in small portions of the North Atlantic Current, the Labrador Sea, and the Greenland-Iceland-Norwegian (GIN) Sea. In all these regions with positive skewness, the tail of the deep mixed layer values is strong, consistent with prevalence of shallower values in times of restratification, punctuated by a few much deeper values which constitute that strong tail. In the Southern Hemisphere in mid-May, skewness is generally negative but only falls below −1 or −2 in a few small regions. Hence, while deeper mixed layers are favored in this time period, shallower mixed layers are also not infrequent. Kurtosis in mid-May (Figure 9a) is generally high when skewness is high or low, so mixed layer depth tails are generally stronger when the distribution is either positive or negatively skew in that month. Hence, kurtosis is higher than normal (> + 3, and indeed > + 5 and much more in many locations) in much of the extratropical Northern Hemisphere in mid-May where skewness is positive and large, and kurtosis is also high in smaller portions of the Southern Ocean where skewness is large and of either sign. Kurtosis is almost never < + 1 in this month.

In November mixed layer depth skewness (Figure 8b) is positive throughout much of the Northern Hemisphere tropics and almost all of the Southern Hemisphere. It exceeds +1 in many Southern Hemisphere locations, and exceeds +2 in some parts of the ACC. It is also mildly positive in much of the subpolar North Atlantic and the GIN Sea. Hence, shallow mixed layer depths are more prevalent in these locations, with more infrequent deep mixed layers on the positive side of the distribution. Mixed layer depth skewness is mildly negative in most of the subtropical North Pacific and North Atlantic, and most of the Subpolar North Pacific as well. However, it is less than −1 in only very limited scattered regions. Kurtosis in mid-November (Figure 9b) exceeds +3 along the equator in much of the Southern Hemisphere subtropics, and exceeds +5 in smaller areas of these regions, but it is highest in the ACC, where mixed layer depth tails are large (and positively skewed). So, in this transition month in the ACC, shallower mixed layer values are prevalent, but there are strong positive tails because of a few much deeper values. Kurtosis in mid-November is < + 3 in large portions of the Northern Hemisphere subtropical gyres, in the tropics (excepting the equator), and south of the ACC, but it is never < + 1. So, in these regions in mid-November the tails are weaker than they would be for a normal distribution.

Regional patterns in mixed layer temperature skewness and kurtosis (not shown) are generally not as striking as those for mixed layer depth. Mixed layer temperature is strongly positively skew with high kurtosis around Antarctica in the austral winter through spring because most mixed layer temperatures are near the freezing point of seawater, so any warmer values that are present create a strong positive tail. In addition, there is strong negative skewness and strong positive kurtosis in winter and spring off the east coast of North America, probably owing to occasional offshore sampling of cold high latitude water masses usually found near the coast. Mixed layer salinity distributions exhibit large negative skewness and high kurtosis in that same region, present year-round, owing to the freshness of these same high latitude water masses. There is also considerable structure in salinity skewness north of much of the ACC, with bands of positive and negative skewness, each associated with high kurtosis, and low kurtosis between them. This pattern is especially prominent in the Indian Ocean sector of the Southern

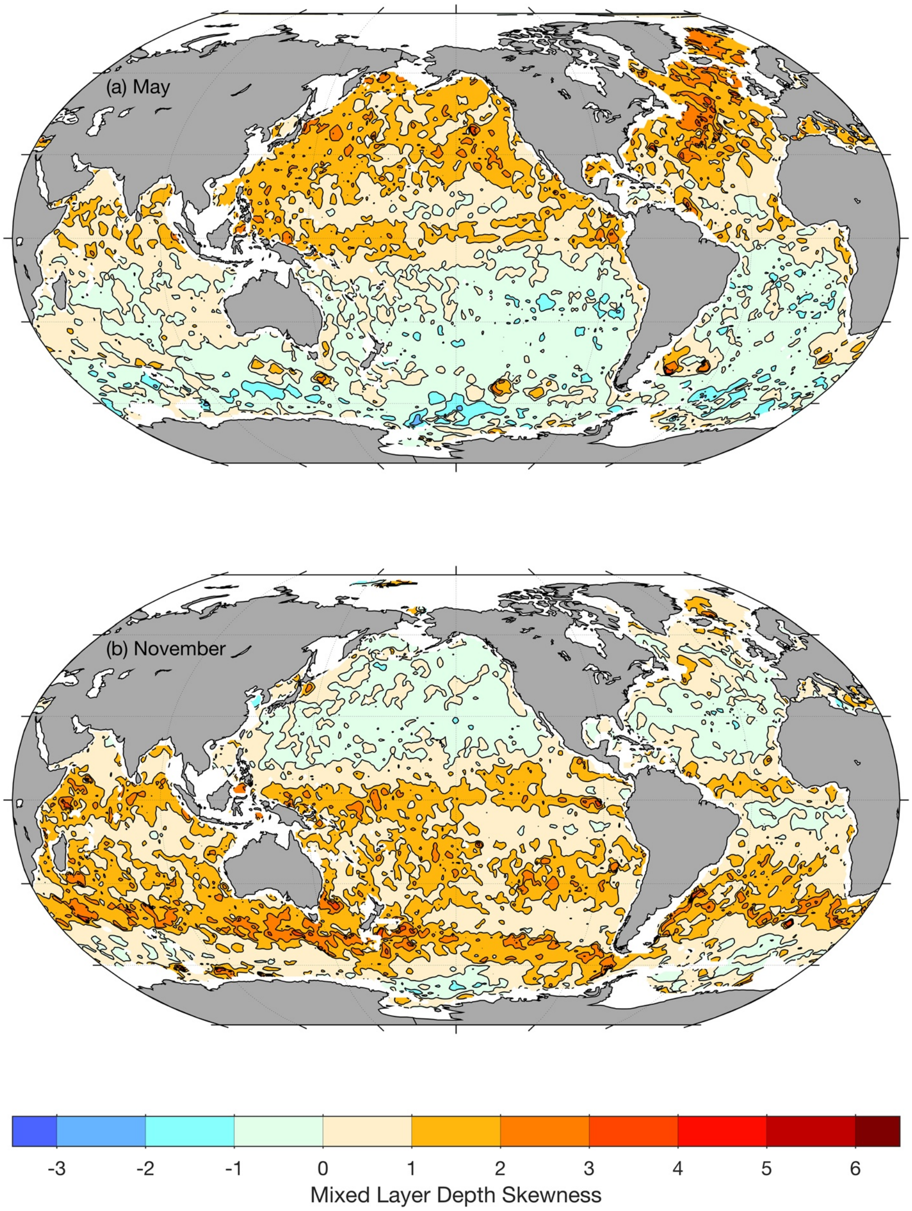

Figure 8. (a) Mid-May and (b) mid-November mixed layer depth distribution skewness (colorbar). Positive values (yellow to red) indicate a strong tail of deeper mixed layer values, and negative values (green to blue) indicate a strong tail of shallower mixed layer values.

Ocean, where conditions in the northern negative skew band are on the whole relatively salty but occasional fresh conditions create strong tails, and conditions in the negative skew band to the south are on the whole relatively fresh but occasional salty conditions favor strong tails. Some of this pattern may be local and temporal, but some is very likely to be spatial, a result of the ~500 km length-scale used in the weighting extending across fronts.

4. Summary

We constructed a global monthly mixed layer climatology by applying the Holte and Talley (2009) density algorithm to Argo data and putting the mixed layer depths, conservative temperatures, and absolute salinities obtained on a grid using a weighting of nearby data considering differences of location, time, and bottom depth between the data and the grid points. In addition to computing weighted means, variances, skewness, and kurtosis for these properties at each grid point at each month, we sorted by all three variables by mixed layer depth, weighted them

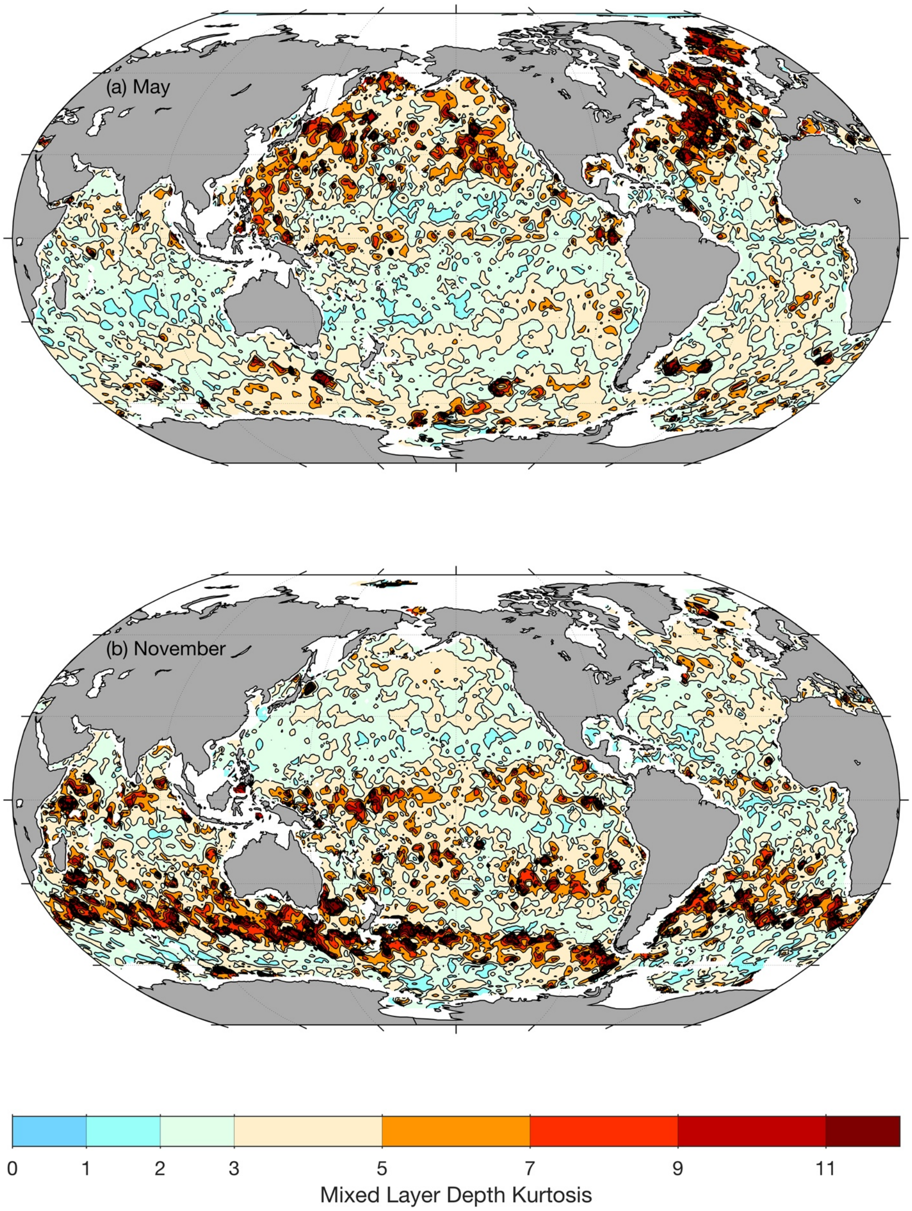

Figure 9. (a) Mid-May and (b) mid-November mixed layer depth distribution kurtosis (colorbar). Values exceeding three (yellow to red) indicate that mixed layer depth tails are stronger than for a normal distribution and values less than three (green to blue) indicate that mixed layer depth tails are weaker than for a normal distribution.

all in terms of distance, time, and depth difference from the grid point, and then smoothed all three depth-sorted variables to find values at the 5th, 50th, and 95th percentiles of mixed layer depth.

The mean number of data points used for each grid point is 122, although there is substantial spatial variability (Figure 1a). Since the sum of the weights for the grid points is on average about one quarter of the sum of the number of samples used at each grid point, the mean sum of the weights is 30, again with spatial variability (Figure 1b).

Seasonal cycles (Figure 2) of 5th, 50th, 95th, and mean values of depth, temperature, and salinity at the centers of four mode water formation regions (one each in the subtropics and subpolar regions of each hemisphere) reveal the striking asymmetry where seasonally mixed layers deepen more slowly during the fall than they do in spring. They also show that in a few locations and times the 95th percentile depth values can exceed mean values by a factor of five or more. Additionally, sometimes the median mixed layer properties can differ substantially from the mean values. Late winter mixed layer depths at 95th percentiles can be more than three times the mean values in some regions (Figure 5), but there is again considerable spatial variability. Late winter temperatures of the 95th percentile depth mixed layers (Figure 6) are often lower than mean mixed layer temperatures in the subtropics, and late winter salinities of the 95th percentile depth are often higher than the means in the subpolar regions and portions of the tropics. These patterns are consistent with the importance of temperature in upper ocean stratification in the subtropics and salinity in the subpolar regions. While mixed layer depth distributions are rarely close to normal, they tend to be most skew (Figure 8) with the highest kurtosis (Figure 9) in the spring transition months of May (in the Northern Hemisphere) and September (in the Southern Hemisphere), when frequent shallow mixed layer depths are punctuated by occasional deep mixed layers.

The monthly climatological values for mixed layer depth, temperature, and salinity we make available (at https://www.pmel.noaa.gov/gosml) include the usual means and variances. In addition, skewness and kurtosis allow assessment of how non-normal the variable distributions are in a given location and month of the year. Values of temperature, salinity, and depth at the 5th, 50th, and 95th percentiles of mixed layer depth are useful for studying the mixed layer under a variety of states. First, the 95th percentile values are of interest as they are representative of ventilated conditions, robust to extreme outliers and more statistically uniform than the average of the three deepest samples in a bin (Holte et al., 2017). The 50% values may be useful as alternatives to, or for comparison with, the mean values, since mixed layer property distributions are often non-normal. Those interested in the ocean state when mixed layers are shallow may find the 5th percentile values of use. Finally, the differences between the 5th and 95th percentile values give alternative indicators of the ranges of conditions experienced in a given month and location, perhaps better suited than the mean and variance for non-normal distributions.

Data Availability Statement

The data used for this study were collected and made freely available by the International Argo Program and the national programs that contribute to it (https://doi.org/10.17882/42182). The GOSML climatology is freely available at https://www.pmel.noaa.gov/gosml. PMEL Contribution Number 5294. CIMAR Contribution Number 21-401.

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