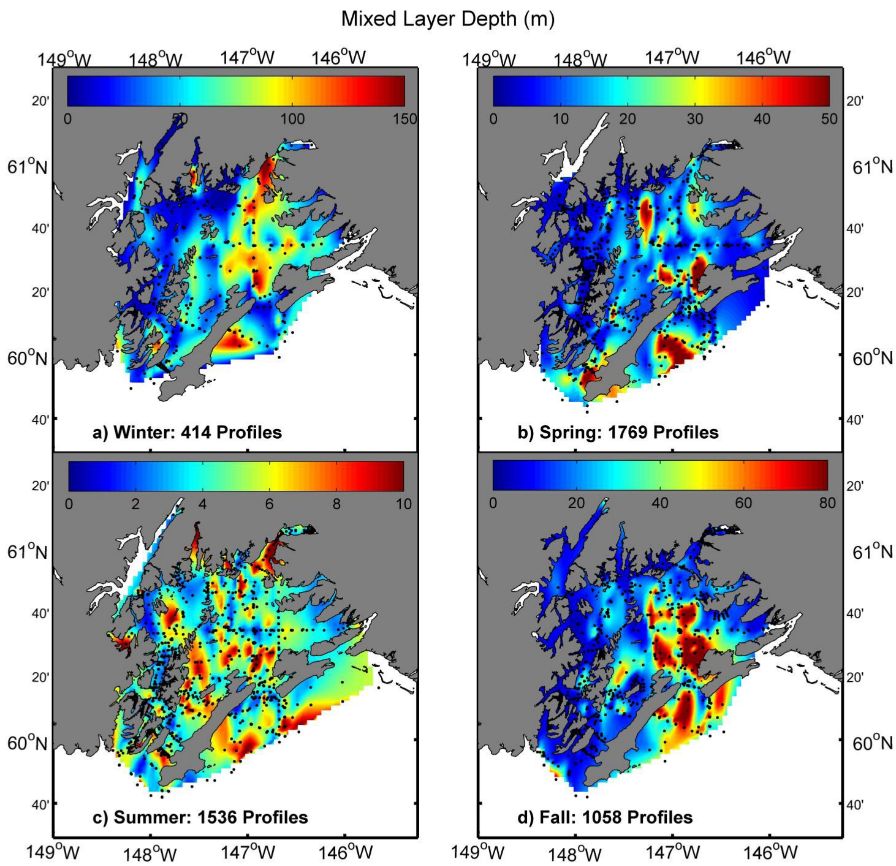
Saline Layering in Prince William Sound



This report was prepared for the Prince William Sound Regional Citizens' Advisory Council as part of a Memorandum of Agreement with the Prince William Sound Science Center. It was prepared by Dave Musgrave* on behalf of the Prince William Sound Science Center.

October 28, 2010

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PRINCE WILLIAM SOUND SCIENCE CENTER CORDOVA, ALASKA

Mixed Layer Analysis in Prince William Sound

A Report to the Prince William Sound Science Center in partial fulfillment of Contract 10-25-06

SUMMARY

From profiles of conductivity, temperature and depth provided by Prince William Sound Science Center (PWSSC) to Musgrave Oceanographic Analysis (MOA), we analyzed the mixed layer depth (MLD), the potential energy of mixing, and the salinity and temperature in the upper layers of Prince William Sound (PWS) by season and region. We defined the MLD as the depth at which a change from the surface density (expressed as σ_t) of 0.125 kg m^{-3} has occurred. As a better measure of the potential for mixing of the upper ocean, we calculated the potential energy of mixing to a depth of 10 m (PE_{10}), the minimum depth over which dispersed oil is expected to mix.

The results of this analysis show that the MLD is shallowest in the summer and deepest in the winter. The seasonal potential energy reflects the seasonal MLD with greatest values in summer and smallest values in winter. Near-surface salinity is lowest in the summer when freshwater runoff is greatest and near-surface temperature is greatest in summer.

Generally, in the periphery of the sound the MLD is less, the potential energy of mixing in the top 10 m is greater, and the salinity is less than in the central sound and the Gulf of Alaska. The temperature in the periphery of the sound, relative to the temperature in the central sound and Gulf of Alaska, depends on season. In winter it is less and in summer it is greater.

BACKGROUND

In cooperation with the Prince William Sound Regional Citizens' Advisory Council (PWSRCAC), the PWSSC collected "saline layering data" in PWS during the Alaska Ocean Observing System (AOOS)/ Oil Spill Response Institute (OSRI) model verification exercise in July and August 2009. The original agreement between PWSRCAC and PWSSC called for the analysis of this data for mixed layer properties. The purpose of this analysis was to assess the potential for vertical mixing of oil and oil dispersants near the surface.

The PWSSC had access to data collected from 1972 to 2010 in PWS using Conductivity-Temperature-Depth (CTD) and Expendable Conductivity-Temperature-Depth (XCTD) instruments and provided this data to MOA for a more robust analysis of mixed layer properties during seasons other than summer (Figure 1).

A surface mixed layer implies that all properties (*e.g.*, temperature, salinity, density, velocity) are homogeneous from the surface to the MLD and that active mixing due to surface wind stress or buoyancy flux occurs over the MLD. However, most property versus depth profiles in PWS show some heterogeneity in the surface layer due to addition of buoyancy at the surface by solar heating or freshwater layering. However, in many cases the barrier to mixing is small so that a small amount of surface wind stress (τ_s) can overcome the potential energy of stratification. Thus a working definition of the MLD is often used. A common definition (Levitus, 1982) is that depth at which a change from

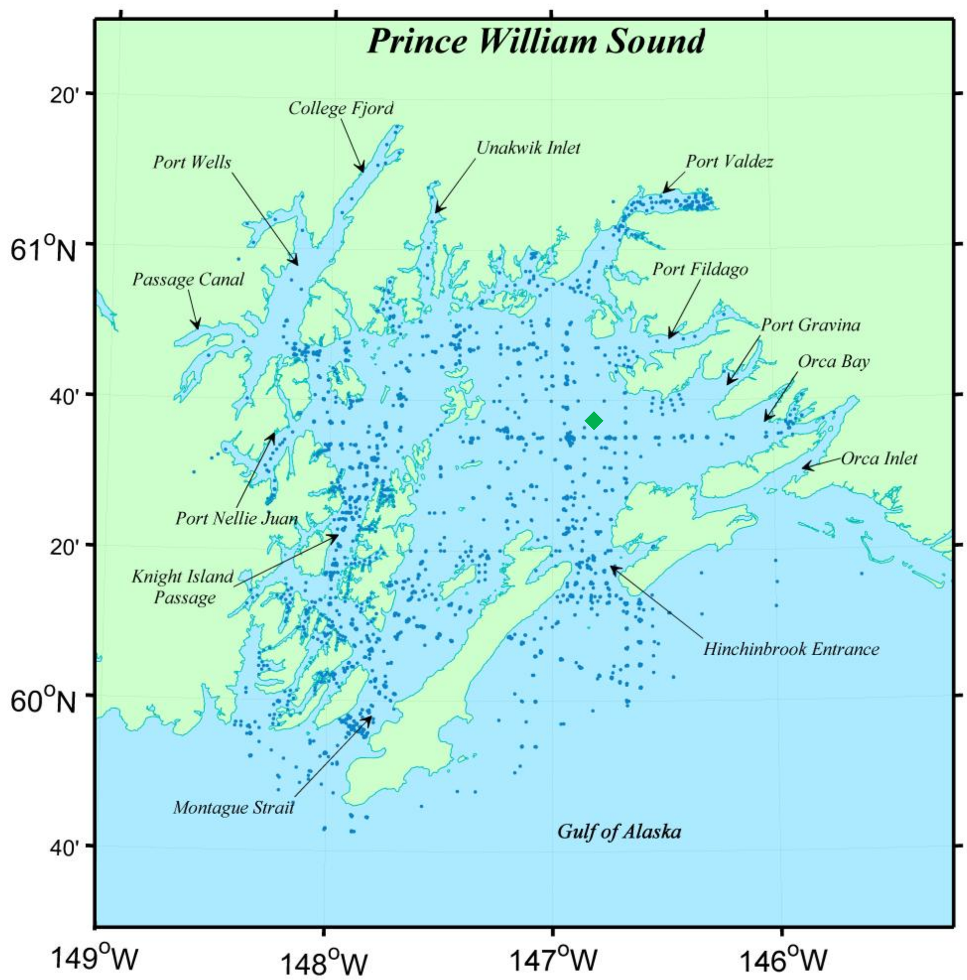

Figure 1. Map of Prince William Sound. The blue dots indicate the locations of the stations used in this report. The green diamond is the location of the meteorological buoy 46060, from which the work from winds are calculated.

the surface density of 0.125 kg m^{-3} has occurred. Density, here, is expressed as $\sigma_t = \rho(s,t,0) - 1000$ (kg m^{-3}), where $\rho(s,t,0)$ is the density of a parcel of water at salinity (s, Practical Salinity Units or PSU), temperature (t, °C), and pressure (p) at the surface (atmospheric pressure, $p = 0$). With this definition, the difference in density is presumed to be small enough that wind stress or buoyancy exchange at the surface can mix the water column over the MLD.

We used the Levitus definition for a preliminary analysis. In some cases the density is homogeneous over the MLD. However, there are many density profiles in which there is no homogenous layer at the surface. Therefore, for the purposes of determining the magnitude of the barrier to mixing to 10 m, we calculated the potential energy of mixing to 10 m, PE_{10}. In a stratified column of seawater, mixing requires that denser water must be moved up and lighter water must be moved down, thus raising the center of mass of the column and the potential energy. The amount of potential energy (PE) for mixing is given by

$$PE = \frac{1}{h}\int_{-\mathrm{h}}^{0}(\overline{\rho} - \rho)gzdz \quad ; \quad \overline{\rho} = \frac{1}{h}\int_{-\mathrm{h}}^{0}\rho dz \qquad (1)$$

where h is depth to which the water column is mixed, g is the acceleration due to gravity, z is depth and $\overline{\rho}$ is the average density over h (Simpson, 1981). This is the amount of work per unit volume required to homogenize a water column.

Surface wind stress and cooling are the most likely sources of work to overcome the potential energy of mixing. In this report we consider the work done by wind stress since this is the most likely source of MLD deepening in the summer in PWS, when the stratification is greatest and cooling is expected to be weak.

The amount of work done (per unit mass, ΔPE) over a period of time, ΔT, by wind stress is

$$\Delta PE = \delta C_d \rho_a \overline{W^2 V_s} \Delta T / h \qquad (2)$$

where δ is the efficiency of wind mixing, C_d is the coefficient of drag between air and water, ρ_a is the density of air, W is the wind speed close to the surface, V_s is the wind-induced surface water velocity and the overbar indicates an average over ΔT (Simpson, 1981). If $V_s = \gamma W$, then we can define a scaled work, PE^*, given by

$$\Delta T \overline{W^3} = h \Delta PE / \delta \gamma C_d \rho_a = PE^* \qquad (3)$$

Thus the work can be expressed as a product of the average of the wind speed cubed over a time ΔT. In general the average of the wind speed cubed is not equal to the cube of the average wind speed (*i.e.*, $\overline{W^3} \neq \overline{W}^3$), because high winds are raised to a power of three. But if winds are steady then $\overline{W^3} = \overline{W}^3$, and given any PE^* we can estimate the wind speed from the amount of time, or the amount of time for a from the wind speed. For example, if the scaled work is 1500 hr knot^3, then the wind speed must be about 10 knots for a period of 1.5 hours (Figure 2).

In calculating the scaled work done over 10 m ($h = 10$) we haved used ρ_a=1.3 kg m^{-3}, C_d=1.4 x 10^{-3} (dimensionless), $\gamma = .03$ (dimensionless, Henderson-Sellers, 1988), and $\delta = .023$ (dimensionless, Simpson and Bowers, 1981).

Actual values for C_d depend on wind speed and varies between 1-3 x 10^{-3} for wind speeds between 0 and 60 knots (Pond and Pickard, 1983). The value for the efficiency of wind mixing, γ, may decrease as the potential energy increases. Simpson and Bowers (1981) suggest that the value can decease to one-quarter its value at low potential energy. The value for γ depends on the fetch and has been

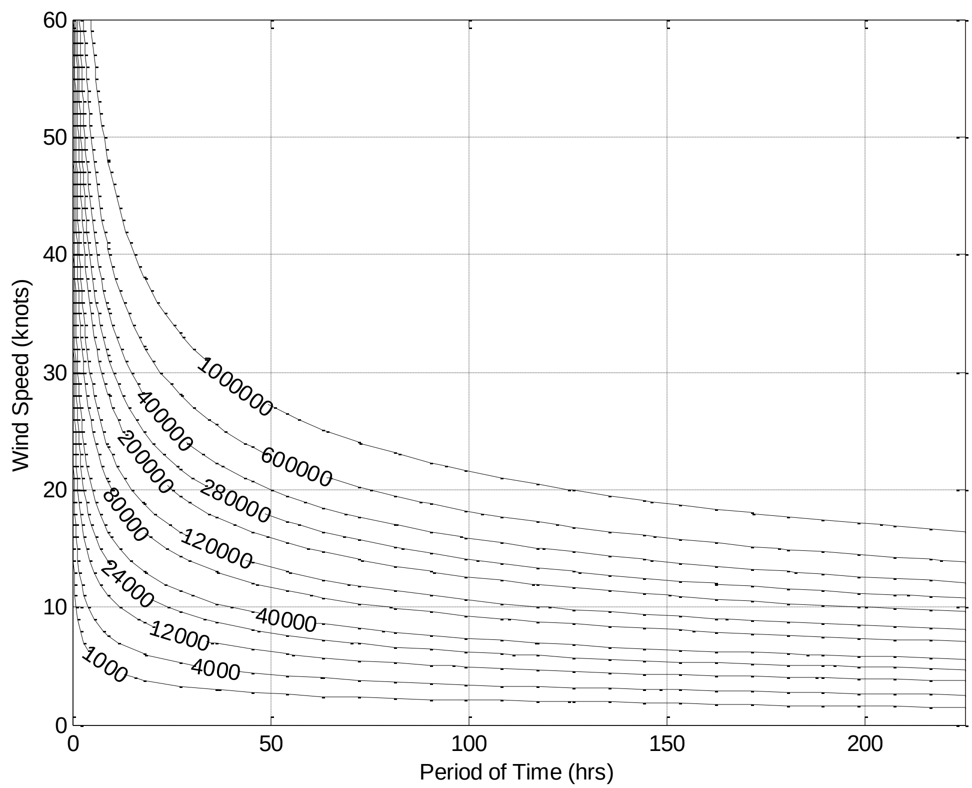

Figure 2. . The scaled potential energy (〚PE〛^*) contoured as a function of amount of time (x-axis) over which a constant wind (y-axis) blows.

estimated to be 3.0 percent for larger bodies of water and 1.5 percent for smaller bodies. Given these uncertainties, the actual values of PE^*can be greater by up to an order of magnitude and this must be considered when using the values in the figures and tables.

DATA SET

The data set of CTD and XCTD profiles contained 4,892 stations within the boundaries that we used for PWS, which included some areas outside of Hinchinbook Entrance and Montague Strait (Figure 1). This data was collected by various groups from a variety of ships and boats. In many cases, it was provided without indications of data quality. The nominal depth increment of each profile was 1.0. Missing, near-surface salinity and temperature were linearly extrapolated from the two depths nearest the surface. Most profiles had data within 2 meters of the surface.

A histogram of number of profiles by year of collection shows year-by-year variation with little data collected during the mid-1980s (Figure 3). The Outer Continental Shelf Environmental Assessment Program (OCSEAP) in the late 1970s, the Sound Ecosystem Assessment program in the mid 1990s, the Global Ocean Ecosystem Dynamics in the early 2000s, and the AOOS/OSRI PWS model verification experiment in 2009 contribute to the peaks in the histogram.

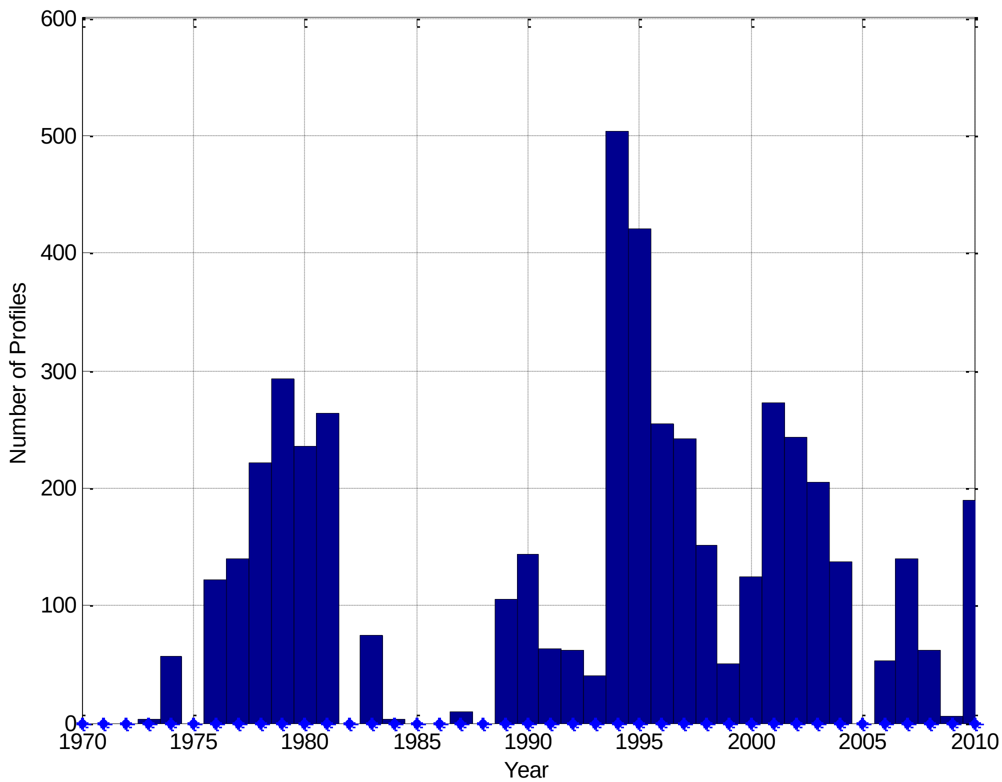

Figure 3. Histogram of profiles by year.

ANALYSIS

MLD was determined for each station by the Levitus criterion. Where the density difference between the surface and the bottom of the profile (not necessarily at the sea bottom) was less than 0.125 kg m^{-3}, the value for that station was given a missing value. The color scale changes with each season emphasize the spatial variation. Note, that the color scale for the scaled potential energy is reversed, with lesser values indicated by hotter colors.

The MLD was gridded onto a regular grid of about 2.4 km in both the east-west and north-south directions using Delaunay triangulation and then averaged over three grid points in each direction to make interpretation easier. There are color contours in some of the arms and inlets, e.g., Port Fidalgo, Port Gravina, that contain no data due to an artifact of Delaunay triangulation. In those areas, no conclusions can be made about the MLD(or other properties) from this data.

Maps of the MLD (Figure 5) are presented by season (winter = January, February, March; spring = April, May, June; summer = July, August, September; fall = October, November, December).

Similarly, maps of the scaled potential energy (PE_{10}^{*}) and the mean salinity and temperature over the upper 10 m are presented in Figures 7, 9 and 11. All maps of properties are repeated in the Appendix with a constant color scale for all seasons along with maps of the scaled potential energy of mixing to 5 and 20 m.

In order to address the spatial distributions of MLD, potential energy, salinity, and temperature, we divided the stations in Figure 1 into three regions: the periphery of the sound, the central sound, and the Gulf of Alaska (Figure 4).

The mean and standard deviation of all properties by season and region are presented in Tables 1-4.

The MLDs are greater in the winter and less in the summer and are intermediate in the spring and fall (Table 1). The deeper MLD in winter is due to surface cooling, more saline surface waters, and strong wind stress. Also, freshwater runoff in the summer freshens the surface waters leading to lower salinities (Table 3) and greater stratification, as indicated by greater potential energy (Table 2). Temperatures are greatest in the summer, enhancing stratification because temperature changes are small at depth.

The spatial distributions of potential energy, salinity, and temperature show some relationship to the distribution of MLD; generally, salinity is greater, temperature is less, and potential energy is less in regions of greater MLD.

The small scale variability within any region may be due to real variability in local sources of freshwater inputs, surface heat flux, surface wind stress, and small scale circulation. However, the central sound should experience less variability in these mechanisms. Therefore, it is somewhat odd that there is small scale variability in the properties there. This may be an artifact of the distribution of profiles in time within any one season. The triangulation method for gridding the data treats all data points with equal weight. Where points are collocated in space, it takes the average all of the points. So profiles that are collocated are averaged over any one season. However, profiles that are not collocated may have been collected in the early or late part of the season. Investigations of the relationships between potential energy, salinity, and temperature indicate that there is not a linear relationship between any of the paired variables.

Of particular interest to PWSRCAC are the upper layer properties in the summer, when the MLD is shallowest and the barrier to wind mixing is greatest. The distribution of MLD is variable with little large scale coherency. However, potential energy, the more robust measure of stability of the water column, shows a more coherent spatial variability with lowest values in the central sound and highest values around the periphery. The salinity is generally highest in the central sound and lowest in the peripheries. Temperatures are lowest and highest in the Gulf of Alaska, with intermediate values in the peripheries.

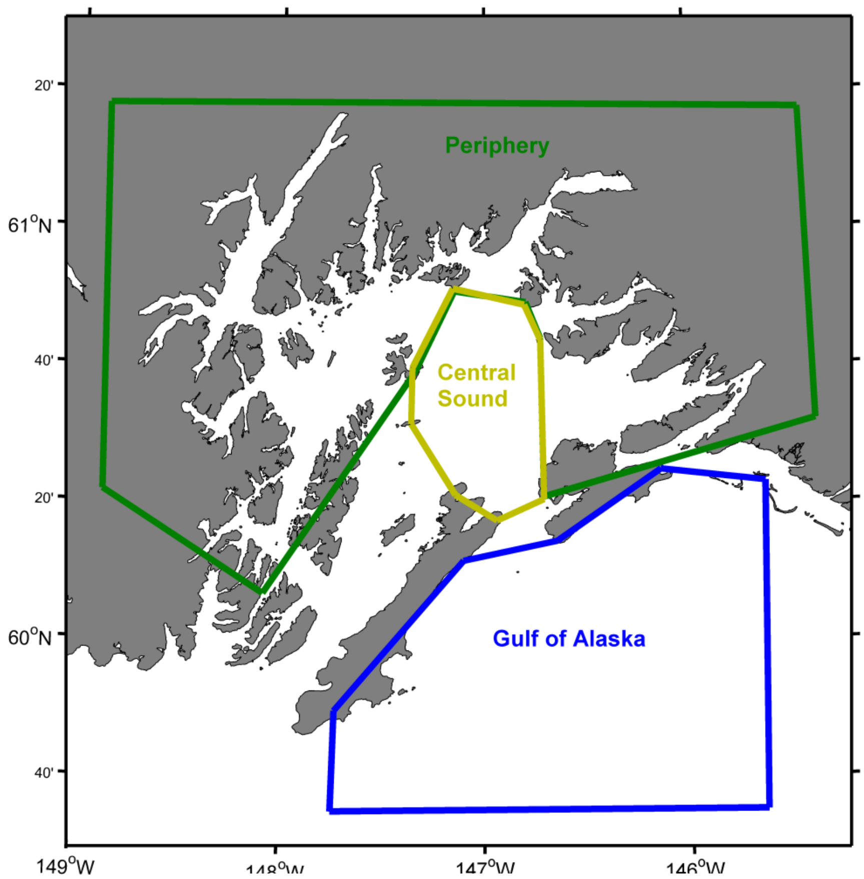

Figure 4. Regions of Prince William Sound.

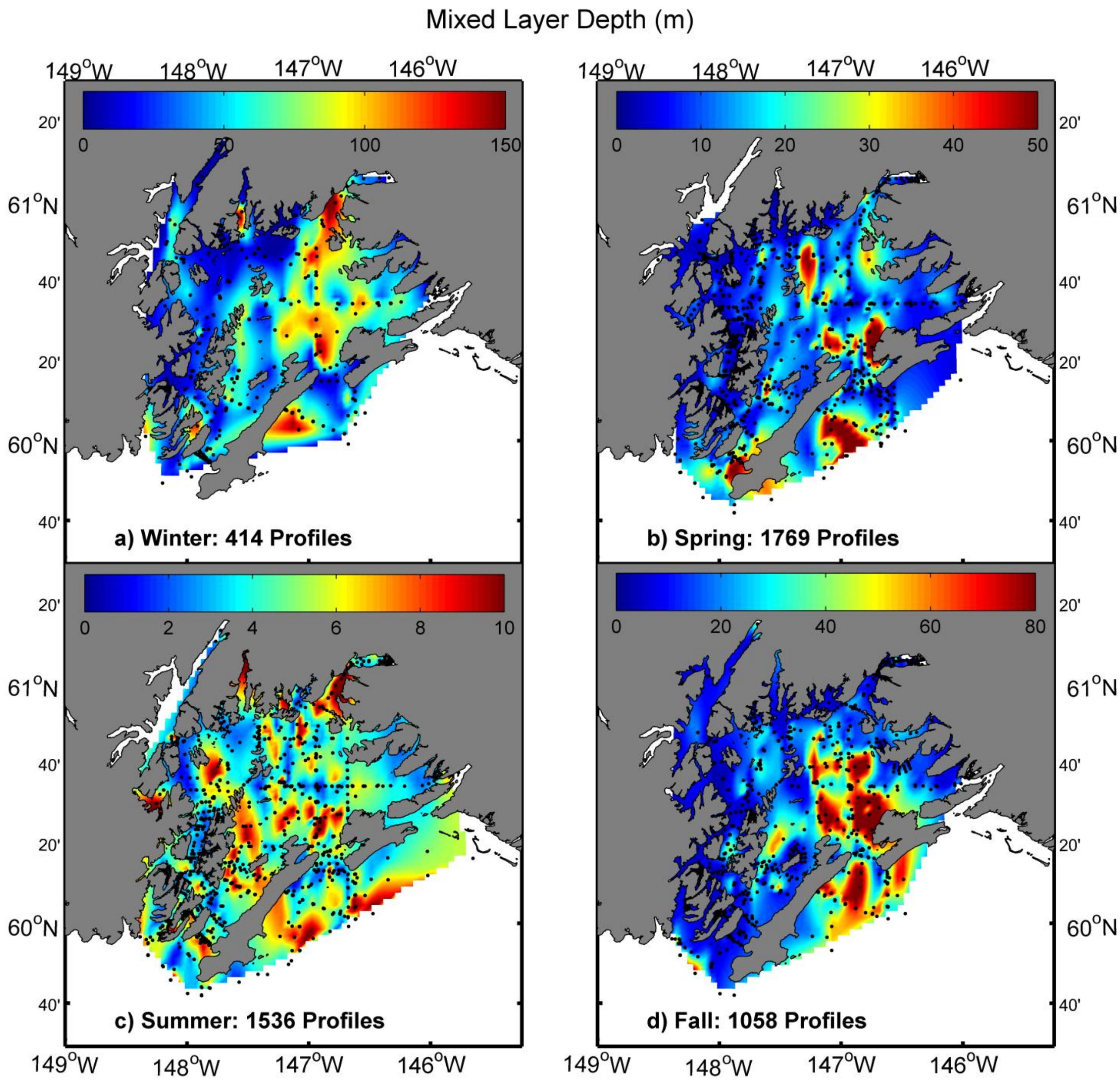

Figure 5. Mixed layer depth (m) by season contoured in color. The black dots indicate the location of the profiles; the color scale is at the top of the map. Many of the profiles are collocated so that a single dot may indicate more than one station. The total number of profiles in each season is indicated in each map.

MLD (m)	Periphery				Central				Gulf of Alaska			
	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Winter	1.0	296.0	28.5	40.7	1.0	269.0	83.8	61.2	2.0	178.0	74.9	49.3
Spring	0.0	211.0	7.9	16.2	1.0	172.0	18.4	26.2	1.0	132.0	22.8	29.5
Summer	1.0	55.0	4.5	4.2	1.0	30.7	5.1	4.3	1.0	42.6	5.7	5.2
Fall	1.0	160.0	10.4	14.7	1.0	187.1	39.5	37.7	4.0	152.0	49.8	38.7

Table 1. Mean and standard deviation of MLD (m) by season and region

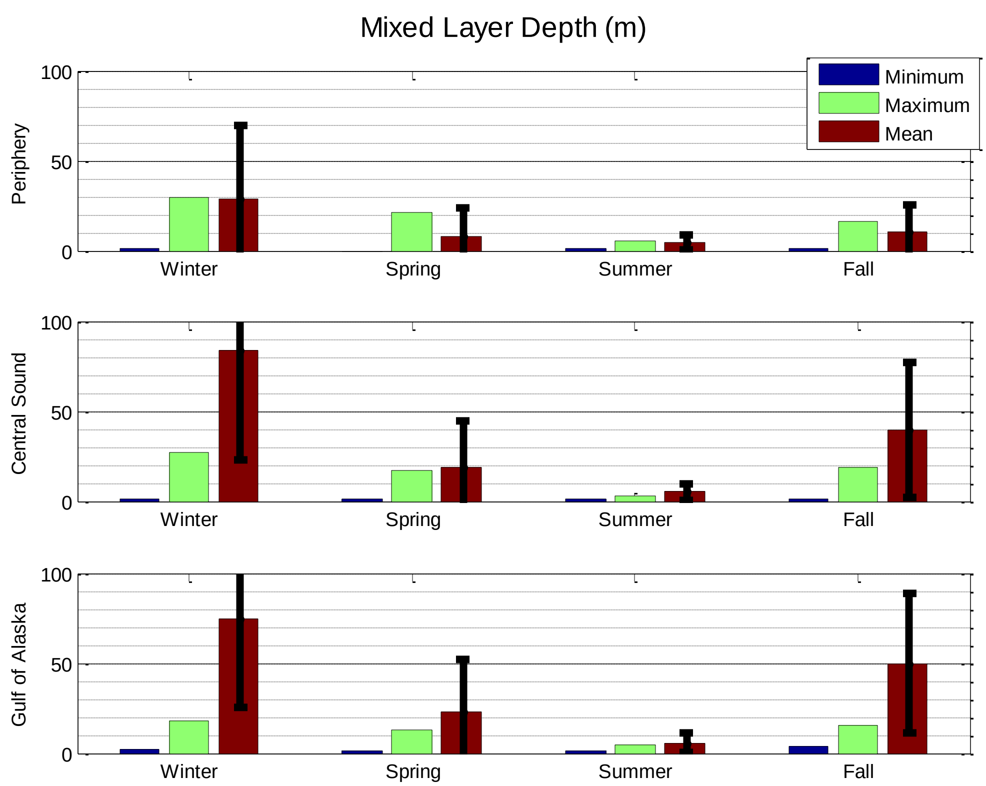

Figure 6. Minimum (blue), maximum (green), mean (brown), and standard deviation (error bar in black),of MLD (m) for each season and each region. The standard deviation bar is symmetric about the mean, but the bar cut off by the limits of the graph. The minimum MLD are all close to zero.Note that in this figure, the maxima values have been divided by 10 so that the minima and means are more readable.

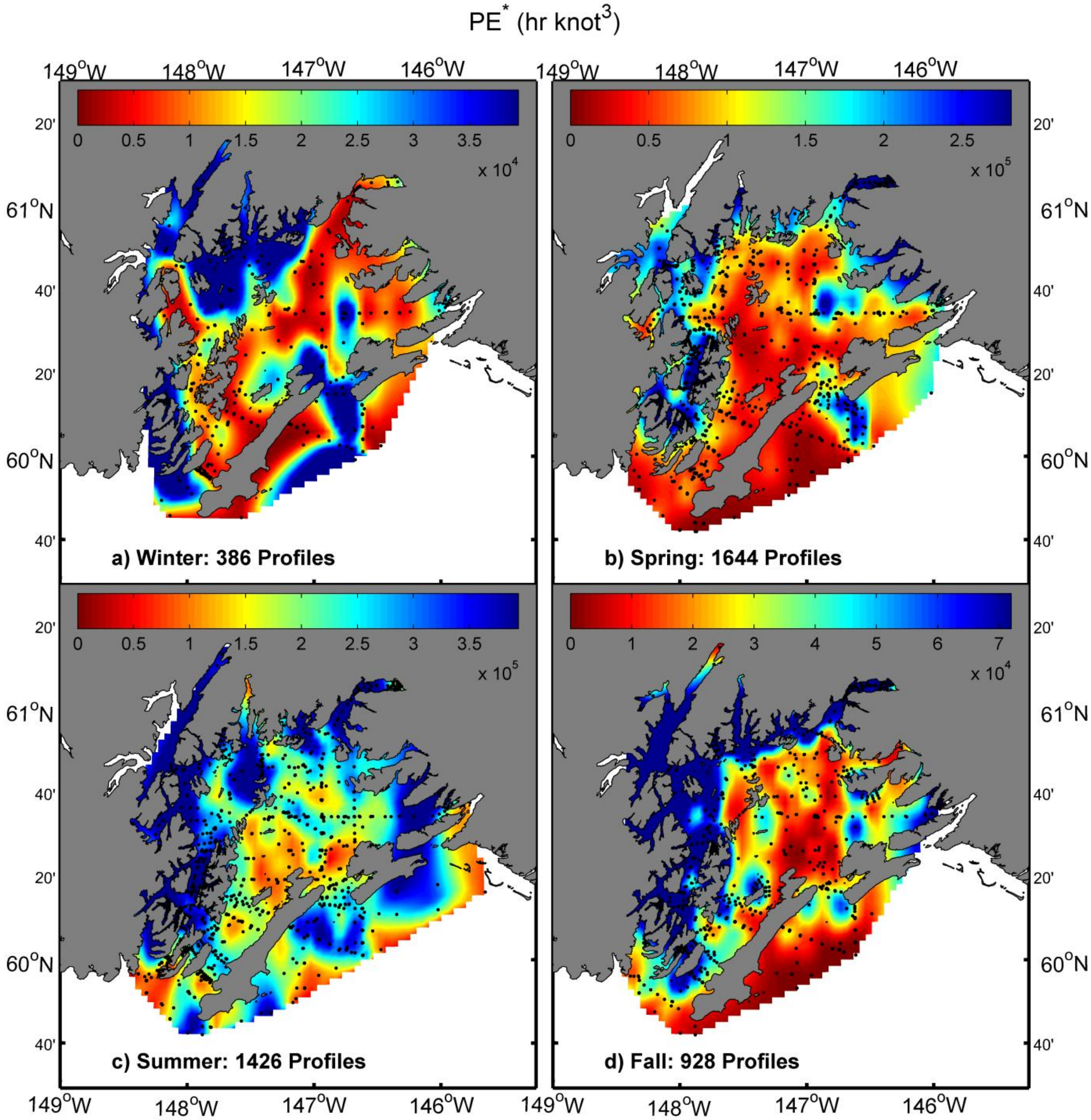

Figure 7. Same as Figure 5 for PE^*_{10} (hr knot^3).

PE*$_{10}$ (hr knots^3)	Periphery				Central Sound				Gulf of Alaska			
	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Winter	0	242271	31657	39228	33	175130	10836	28332	0	135889	7359	26696
Spring	0	751775	177645	180346	0	743302	62073	103833	0	741214	85310	159321
Summer	0	933072	364897	228000	0	911281	198780	172157	0	870434	299268	250462
Fall	0	317817	95908	87132	0	293681	18888	43489	0	319432	21788	59123

Table 2. Mean and standard deviation of PE*$_{10}$ (hr knot^3) by season and region.

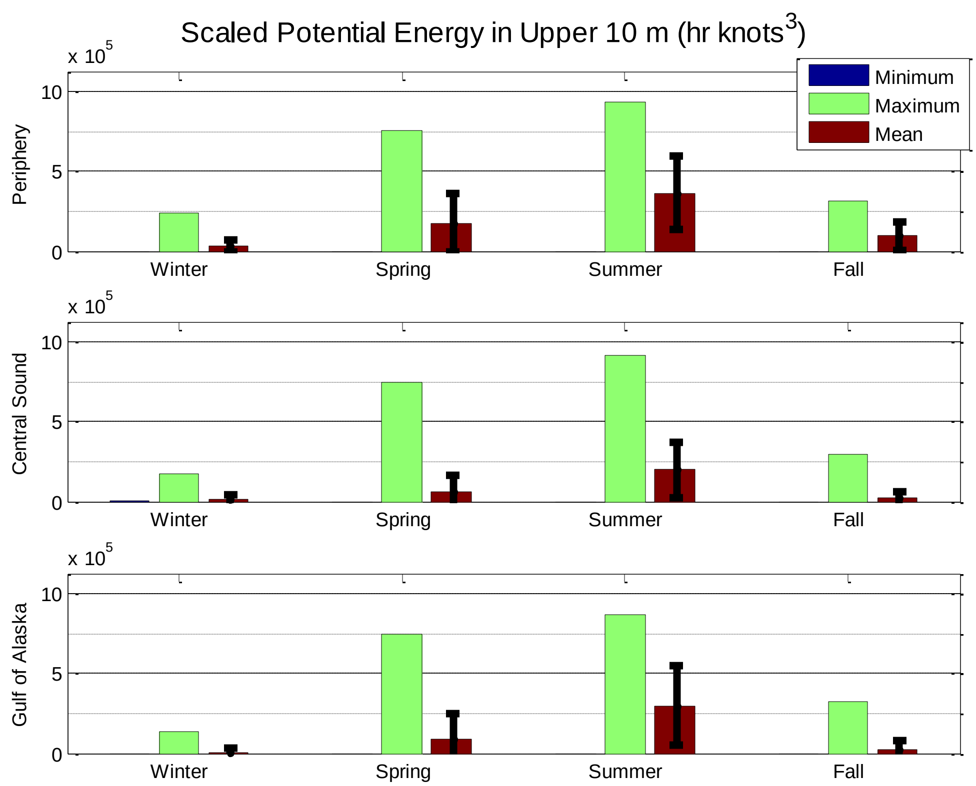

Figure 8. Same as Figure 6, for PE*$_{10}$ (hr knots^3). The minimum values are all near zero.

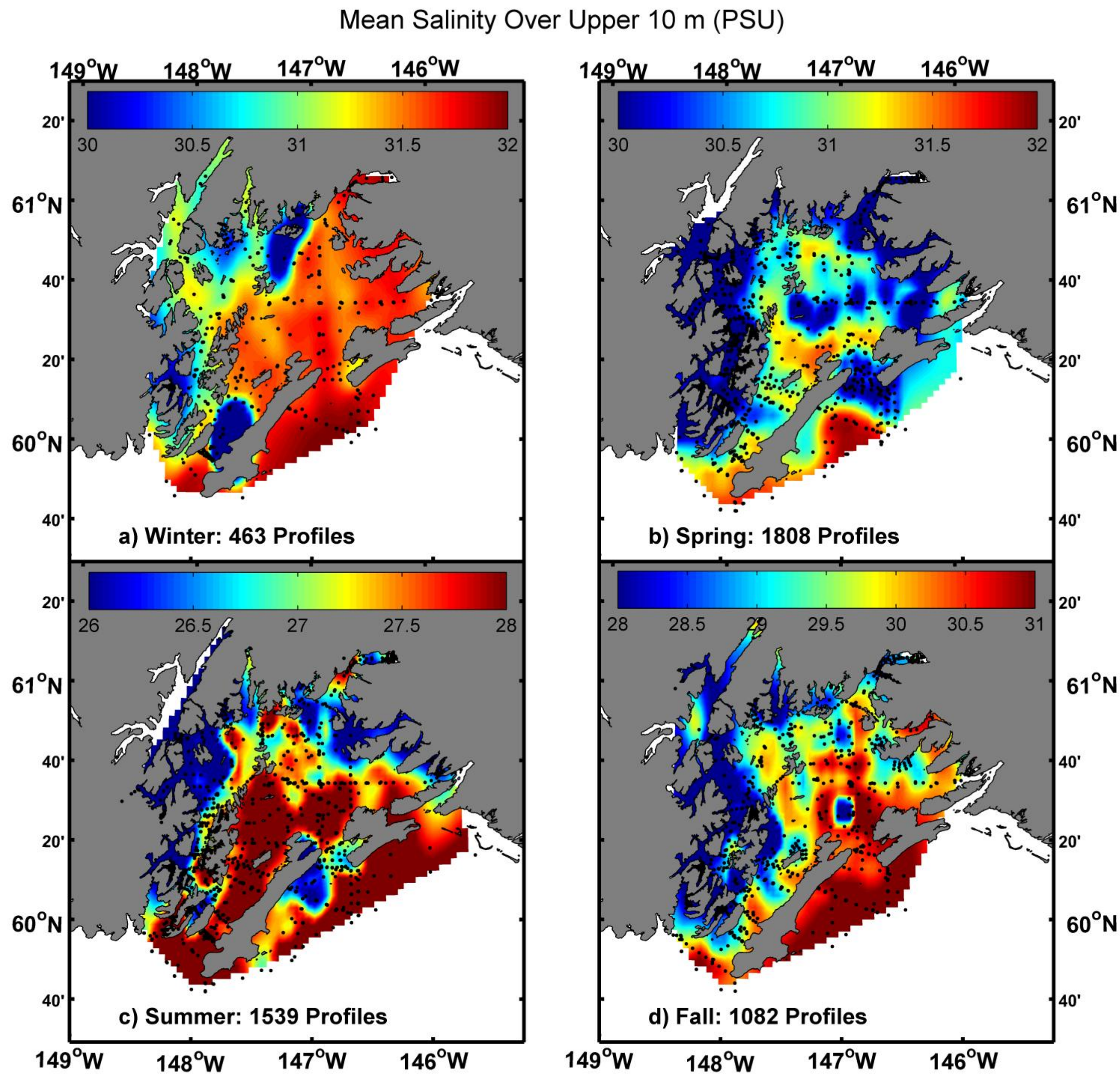

Figure 9. Same as Figure 5 for mean salinity (PSU) in upper 10 m .

Sal (PSU)	Periphery				Central				Gulf of Alaska			
	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Winter	22.9	32.0	30.9	0.9	27.0	32.1	31.5	0.6	30.7	32.2	31.8	0.3
Spring	16.2	32.7	29.7	1.8	17.9	32.4	30.8	1.7	20.0	32.3	31.1	1.5
Summer	20.1	32.8	26.1	1.9	21.7	32.6	27.9	1.6	18.3	31.6	27.5	2.6
Fall	20.7	32.7	28.3	2.0	24.2	32.4	30.2	1.3	27.2	32.2	31.2	0.9

Table 3. Mean and standard deviation of mean salinity in upper 10 m.

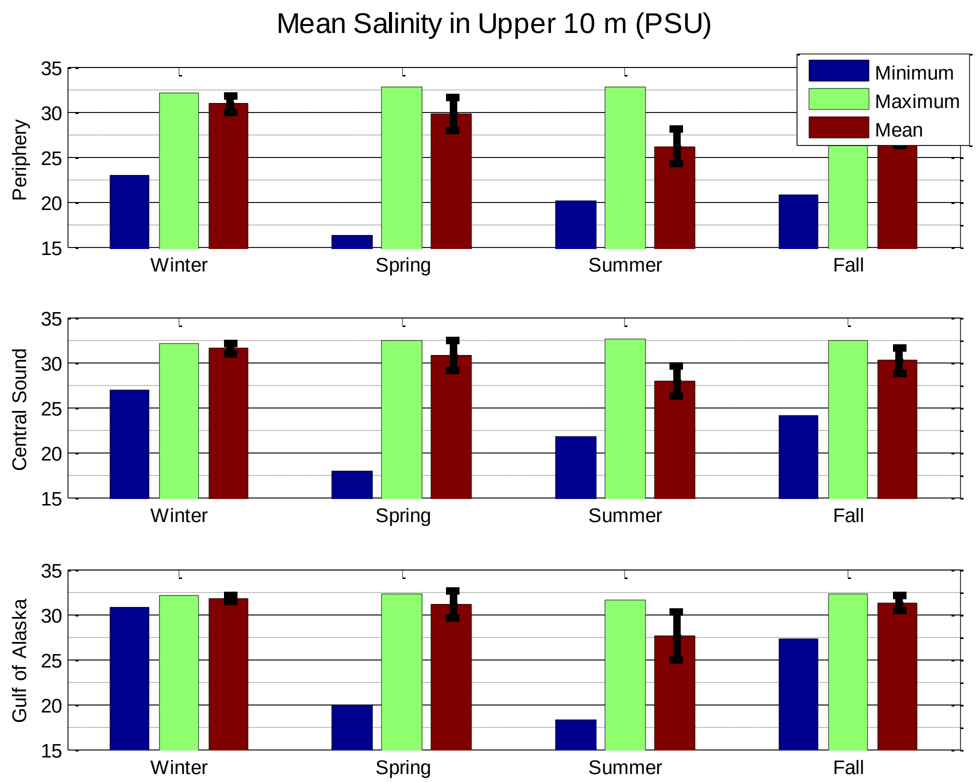

Figure 10. Same as Figure 6, for mean salinity (PSU) in upper 10 m.

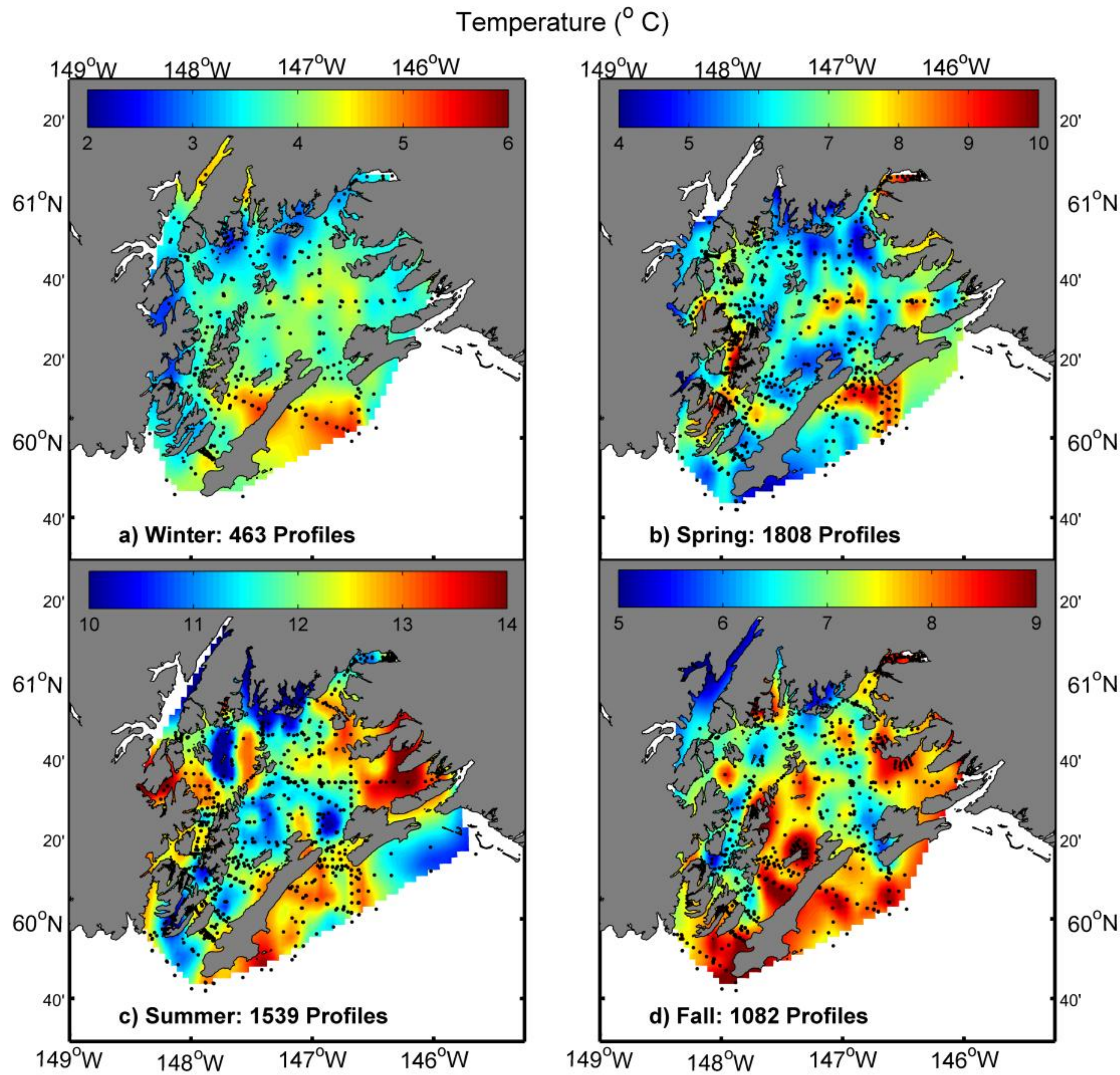

Figure 11. Same as Figure 5 for mean temperature (°C) in the upper 10 m.

Temperature (°C)	Periphery				Central Sound				Gulf of Alaska			
	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Winter	2.0	5.7	3.7	0.8	2.2	5.7	3.9	0.6	2.3	6.3	4.9	0.9
Spring	2.4	13.1	6.9	2.2	2.6	12.8	6.3	2.4	3.2	11.4	7.0	2.3
Summer	0.3	16.2	12.4	1.8	5.4	14.8	11.7	1.7	10.0	15.6	12.9	1.2
Fall	3.5	11.8	7.9	1.7	5.3	10.2	7.2	1.0	4.1	11.1	8.1	1.6

Table 4. Mean and standard deviation of mean temperature (°C) in upper 10 m

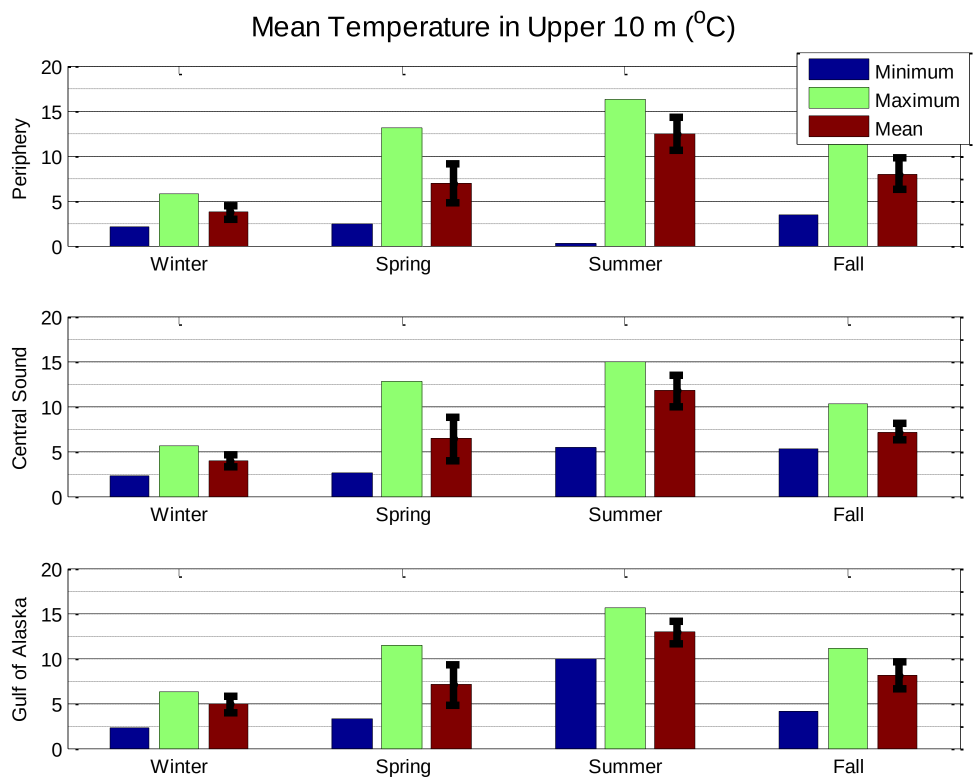

Figure 12. Same as Figure 6, for mean temperature (°C) in upper 10 m.

For comparison with actual values of work done by the winds, we calculated the scaled work (Equation 3) from hourly wind data collected at National Data Buoy Center Station 46060 located in the central sound (Figure 1). We calculated the work by taking a moving average of $\overline{W}^3$ over 12, 24, and 48 hours centered at each hour. Cumulative histograms of the work over the various averaging periods (Figure 13) indicate that percentage of higher values of work increases as the averaging period increases. For example in summer, the percentage of work greater than 1×10^5 hr knots^3 is 5%, 12% and 32% for periods of 12, 24, and 48 hours. The increase is not linear with averaging period because of the wind speed is cubed in the scaled work expression. The winter work is generally greater than the other seasons, but the spring work is less than in the summer, due to the lower wind speeds in spring 2009.

The work done by winds can be compared to the potential energy required for mixing to various depths. In the summer, when the potential energy for mixing is greatest (and the mixed layer depths are the shallowest) the average potential energy of mixing to 10 m is 3.6×10^5 hr knots^3 and the median work done by winds is 0.5×10^5, 0.2×10^5, and 0.1×10^5 hr knots^3 for averaging periods of 12, 24, and 48 hours. So only a small percentage of the winds are capable of mixing to 10 m even over 48 hours. However, the potential energy of mixing to 5 m is about an order of magnitude less (Figure 13) and the work done by the winds is more consistent with these values. This is reflected in the mixed layer depth value of about 5 m.

The uncertainties in the values of the coefficients in Equation 3 and the fact that the winds are taken from one location for one year in the Sound make comparison between the observed winds and the potential energy of mixing problematic. However, they seem to be consistent with the potential energy of mixing within an order of magnitude.

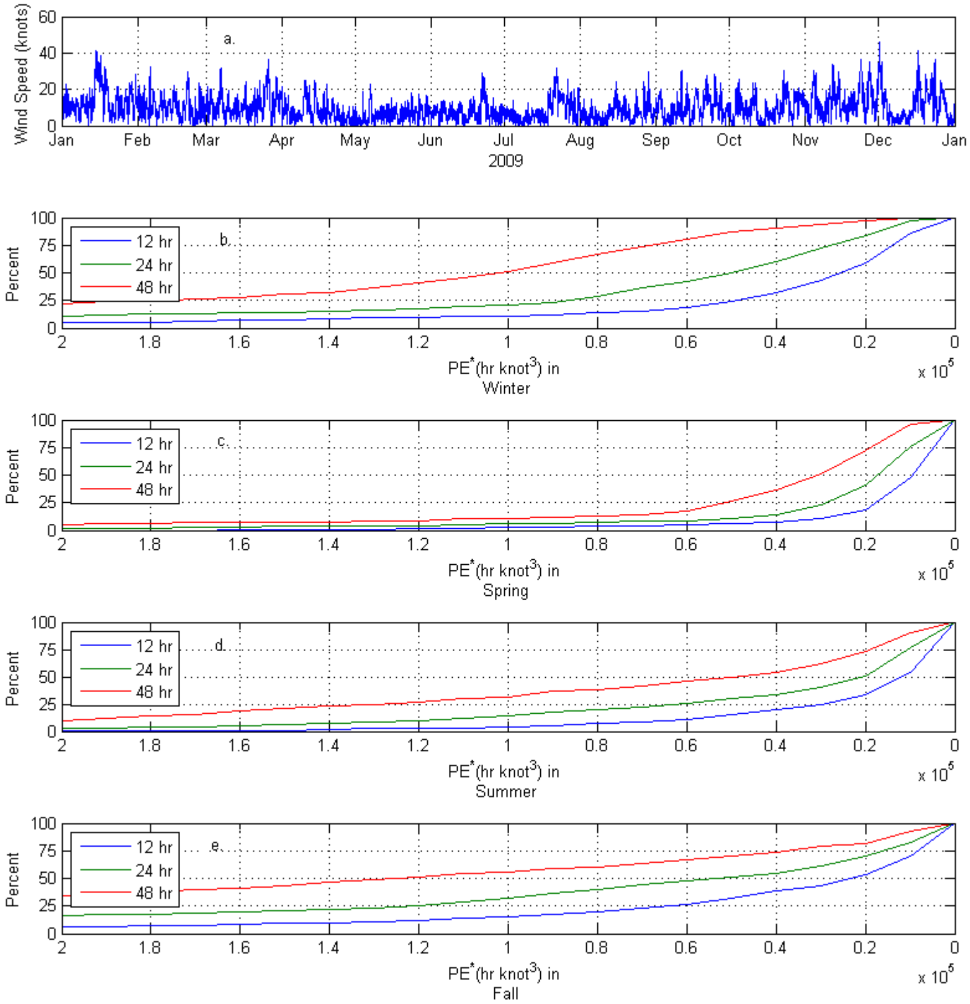

Figure 13. Wind speed (knots) in upper panel for 2009 from Buoy 46060. The cumulative histograms of scaled work done by winds for each season are presented in the lower four panels.

CONCLUSIONS

The mean MLD is shallowest in the summer and is less than 10 m in all regions (Table 1). Correspondingly, the potential energy is greatest in the summer and when the MLD is shallowest. The energy input required to mix fully to 10 m, PE_{10}^{*}, is greatest in the summer in the peripheries of the sound, where the mean value is as great as 365,000 hr knots^3 (Table 2). This is equivalent to the energy input by a steady wind of 10 knots over a period of 365 hours (~ 15 days) or a wind of 25 knots over 24 hours. In the central sound where the mean scaled potential energy is 199,000 hr knots^3, these values are 10 knots over a period of 200 hours (~ 8 days) or 20 knots over 24 hours.

The potential energy of mixing is a better measure of the depth over which properties in the upper water column could mix. The scaled potential energy can be used to quantify the level of winds and amount of time over which the winds blow to mix properties over a specified depth. In this report we used a depth of 10 m since this is the assumed depth of mixing of dispersed oil.

The salinity is greatest in the central sound in summer (mean = 27.9 PSU). In the peripheries of the sound, the mean salinity is reduced to 26.1 PSU, which reflects the freshwater input along the periphery of the sound in summer. The mean temperature in the summer in the central sound is 11.7°C and in the periphery is 12.4°C.

The computed values of the scaled potential energy, PE_{10}^{*}, can be underestimated due to the range of reported values of the efficiency of wind mixing, δ, the ratio of wind speed to surface water speed, γ, and the drag coefficient, C_d, The combined effect of the uncertainties may be as great as order of magnitude, which translates to a either a ten-fold increase in the time the wind blows or a two-fold increase in wind speed. However, comparison between computed values of the work due to actual winds and the potential energy of mixing suggest that the calculation of the potential energy is useful in determining the mixed layer depths.

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APPENDIX

The following four figures are similar to Figures 5, 7, 9, and 11, but the color scales have been held constant between seasons.

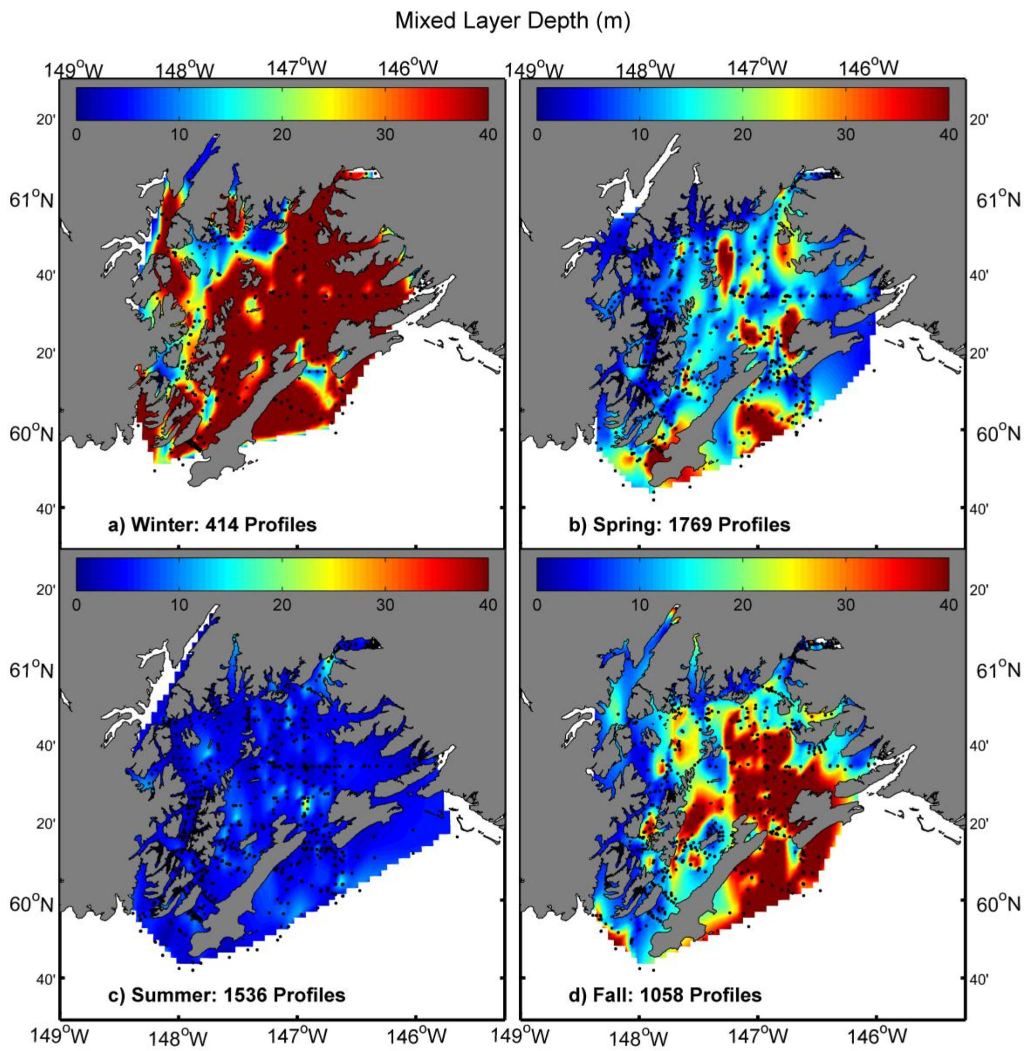

Figure 14. Same as Figure 5, but with a constant color scale for all seasons.

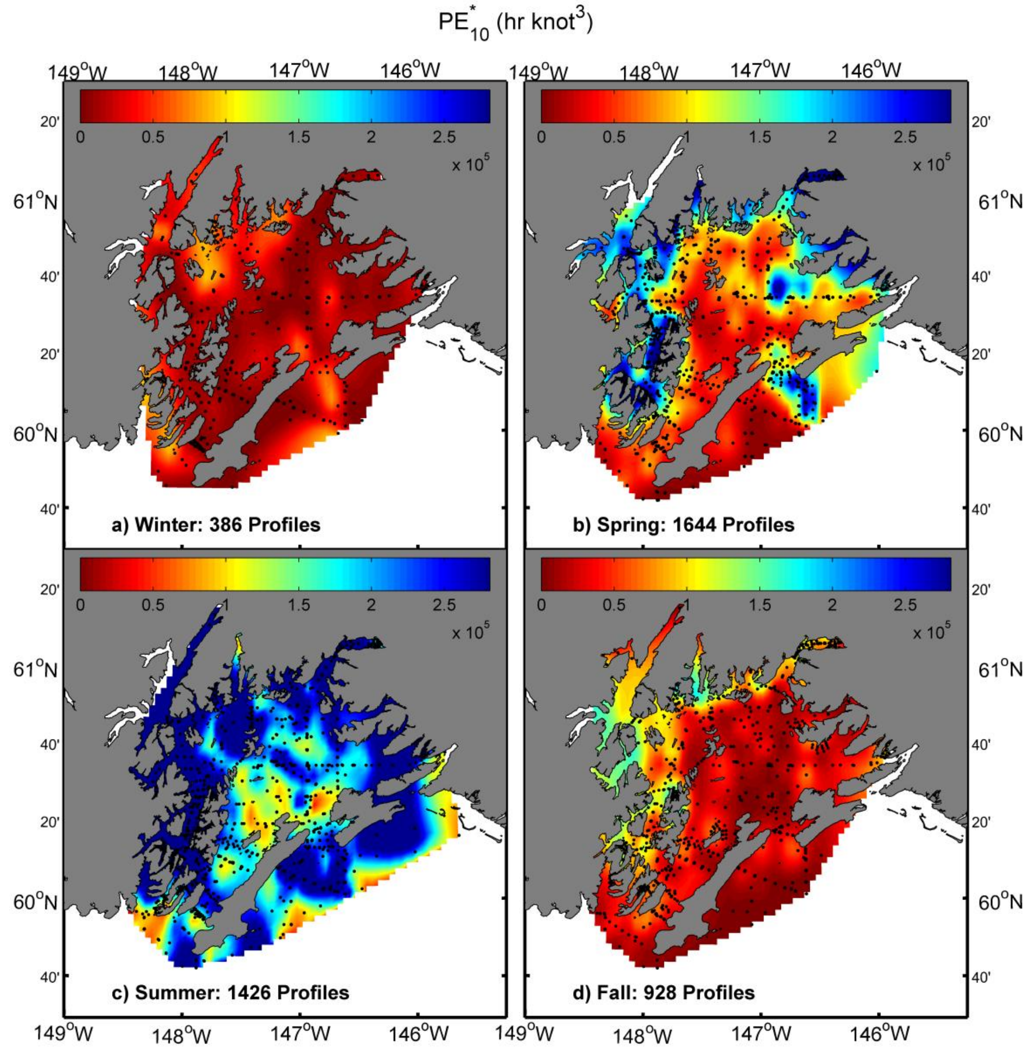

Figure 15. Same as Figure 7, but with a constant color scale for all seasons.

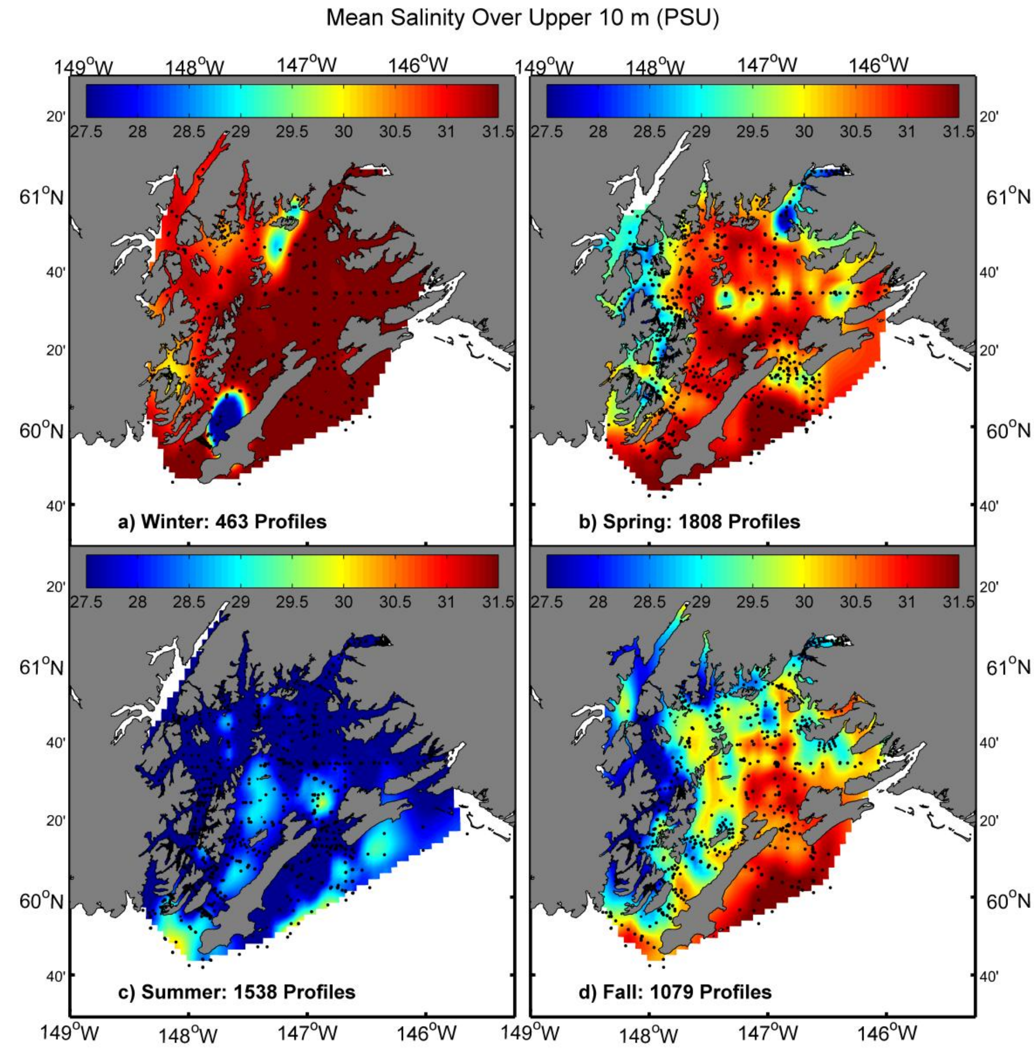

Figure 16. Same as Figure 9, but with a constant color scale for all seasons.

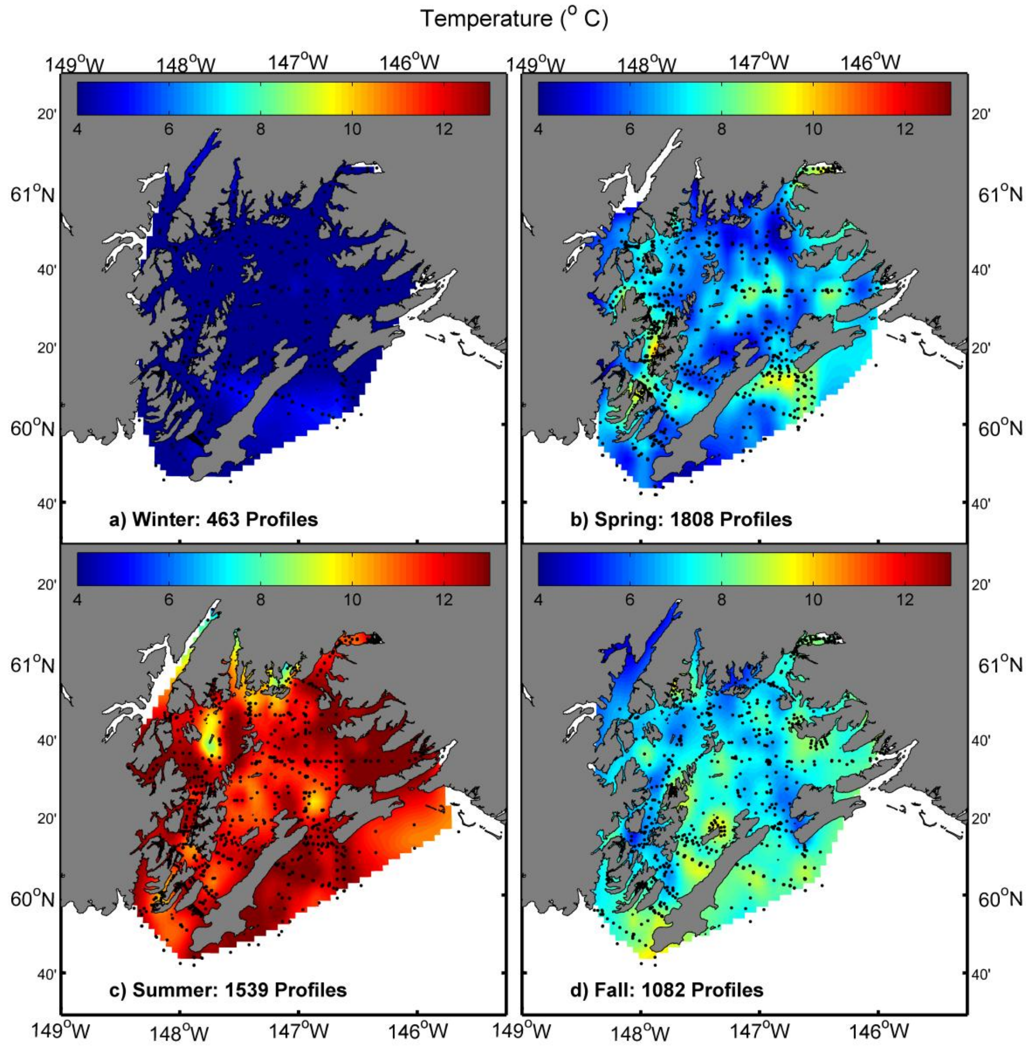

Figure 17. Same as Figure 11, but with constant color scale for all seasons.

The scaled potential energy of mixing to 5 and 20 m are presented in the following two figures. The color scale is constant between seasons.

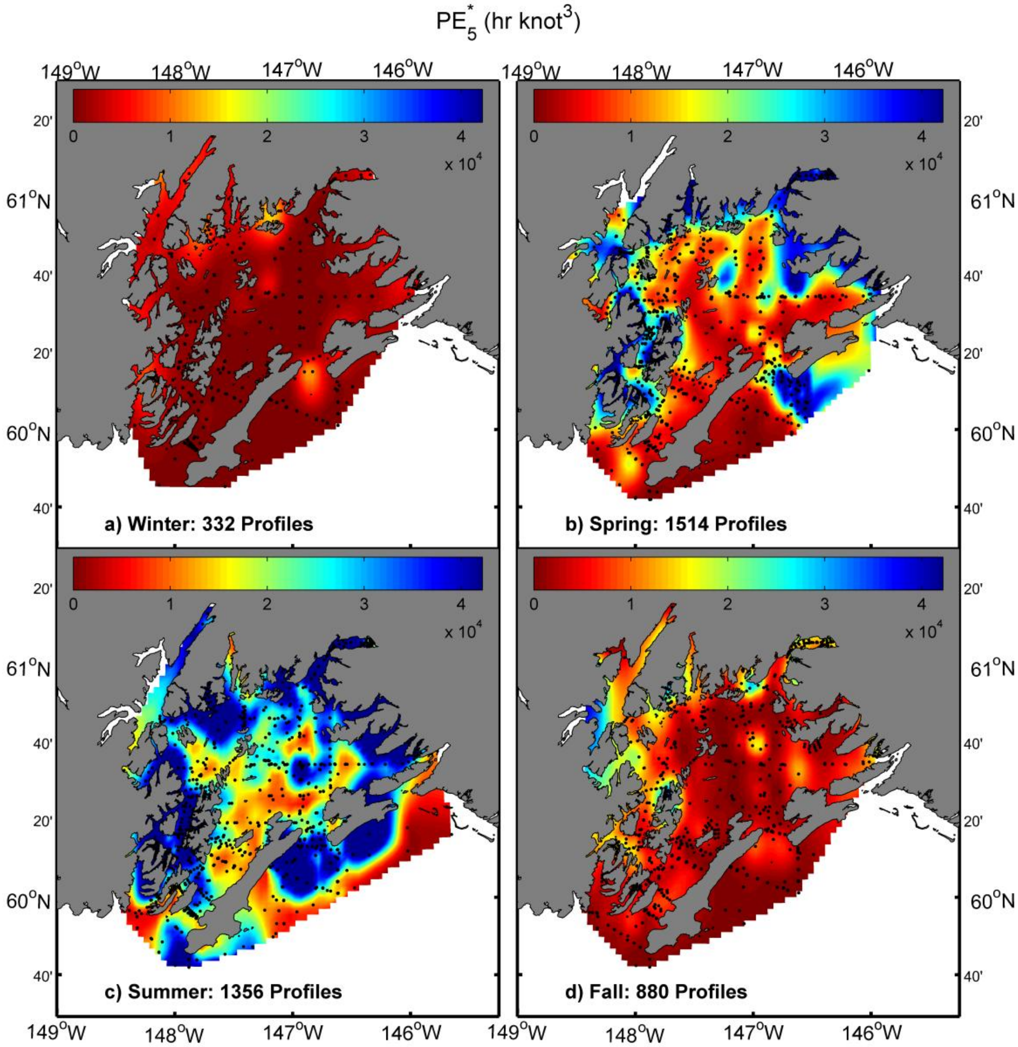

Figure 18. Scaled potential energy of mixing to 5 m.

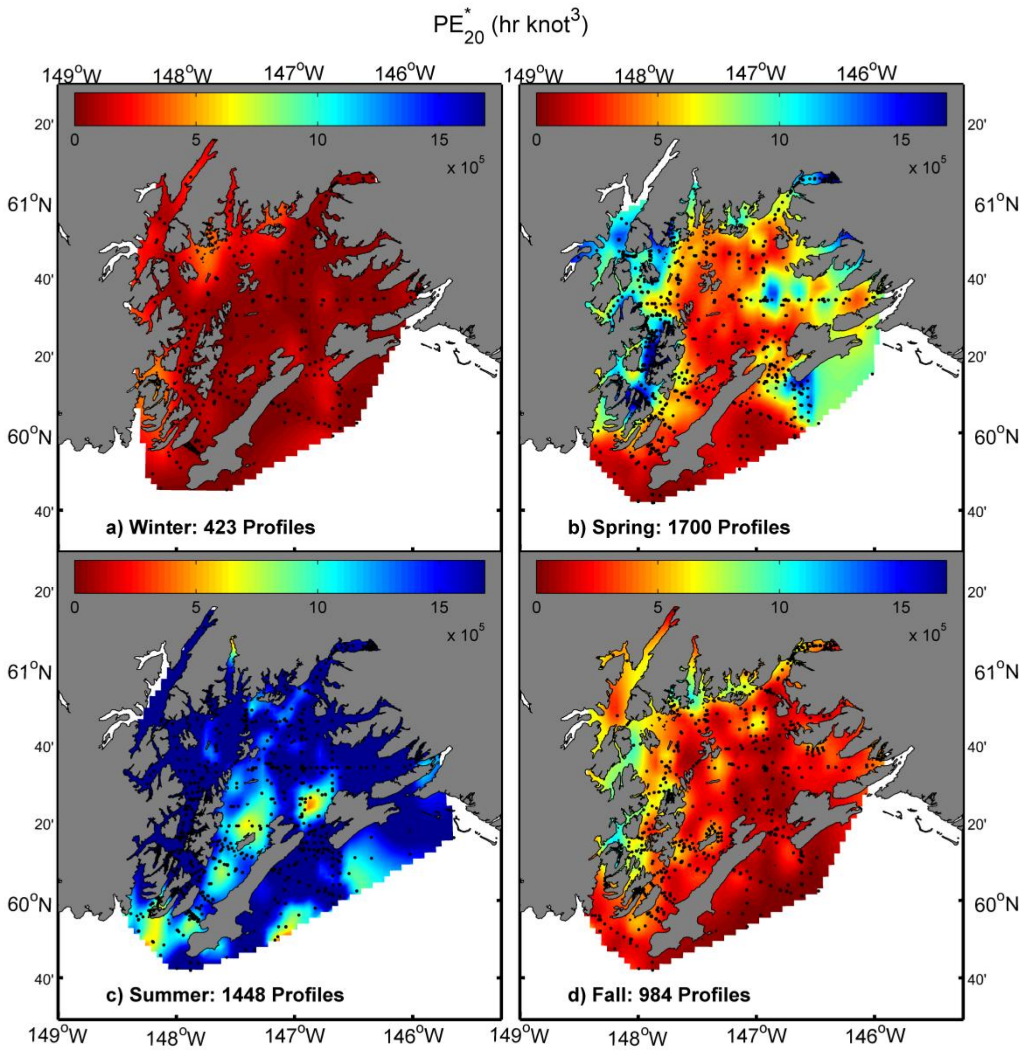

Figure 19. Scaled potential energy of mixing to 20 m.

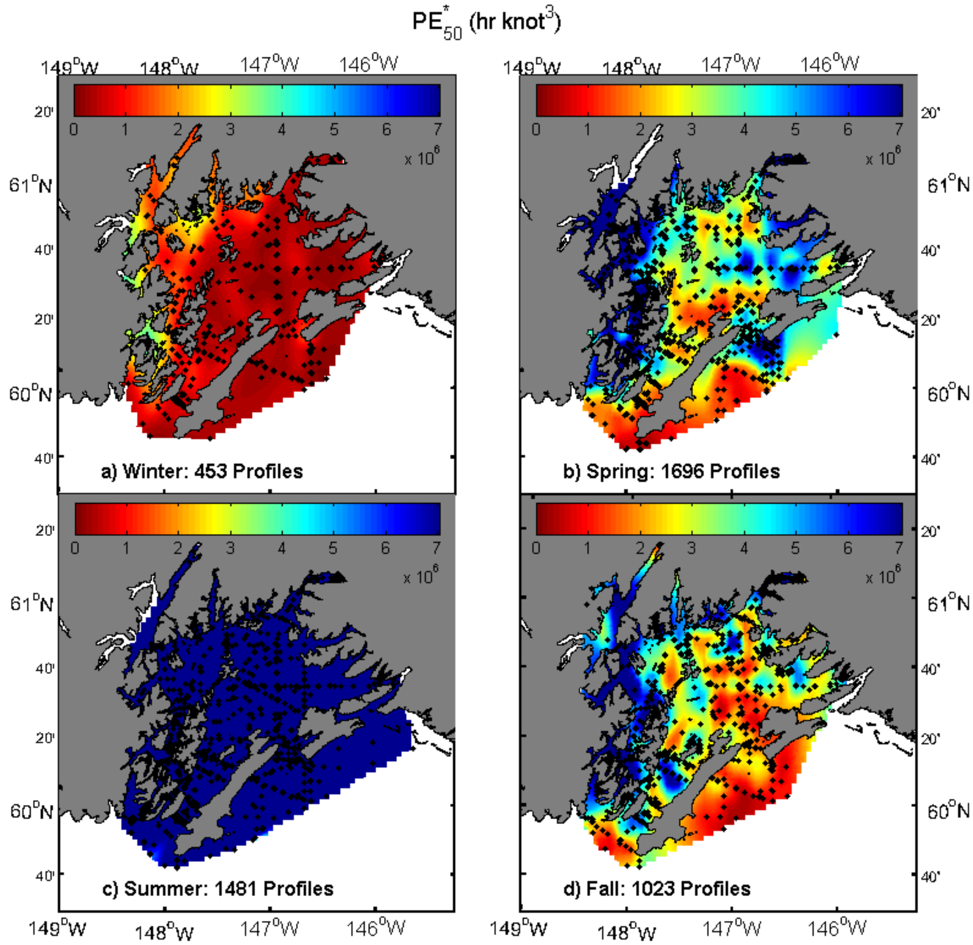

Figure 20. Scaled potential energy of mixing to 50 m.