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The frequency and cause of shallow winter mixed layers in the Gulf of Maine

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[1] The frequency and cause of shallow winter mixed layers in the Gulf of Maine (GOM) is investigated using hydrographic profiles, Gulf of Maine Ocean Observing System (GOMOOS) moorings, and National Center for Environmental Prediction wind data. Historical and recent observations of mixed layer depth reveal distinct spatial variability. Mooring data show that shallow mixed layers often occur and persist through the entire winter in the coastal and eastern GOM. In the interior GOM, however, cast data suggest that deep mixing is more common. Both mooring and cast data show that the presence of shallow wintertime mixed layers throughout the GOM is primarily controlled by salinity increase (not temperature decrease) with depth. Additionally, mooring data indicate that periods of increased stratification are caused by freshening at both 1 and 20 m, with more freshening occurring at the surface (1 m) than at depth (20 m). Comparison of wind stress and stratification at the GOMOOS moorings shows that winter wind events are not responsible for long-term temporal variability in salinity-driven stratification.

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1. Introduction

[2] The Gulf of Maine (GOM) is a continental shelf sea on the east coast of North America, situated between Cape Cod, Massachusetts, and Nova Scotia, Canada [*Townsend et al.*, 1994]. Here as in many areas of the northwest Atlantic, it is believed that the stabilization of the water column and the initiation of a phytoplankton bloom are linked [*Ji et al.*, 2008]. Stabilization occurs under conditions of reduced turbulence, for example, during periods of low wind stress or water column stratification [*van Oostveen et al.*, 1999]. According to this model, given sufficient light and nutrients, shallow stratification will limit the depth that phytoplankton can be mixed, and provide the right conditions for biomass to build up in the surface layer [*Sverdrup*, 1953]. Motivated by this, we investigate upper ocean stratification and mixed layer depth in the GOM during the winter. The mixed layer is defined by its nearly uniform density, active vertical mixing, and homogeneous salinity and temperature [*Thomson and Fine*, 2003]. In section 4, we argue that this work provides the physical oceanography context for future work studying the relationship between shallow stratification and wintertime phytoplankton blooms in the GOM.

[3] Salinity, temperature, and stability vary spatially, temporally, and vertically with depth across the GOM [*Mountain and Manning*, 1994]. Large interannual variability in salinity, temperature, and stability is common since seasonal cycles in water temperature and salinity are strongly influenced by strong seasonal cycles in insolation, river discharge, evaporation, winds, and currents [*Benway et al.*, 1993]. External forcing factors such as the variability in the inflow of Scotian Shelf Water (SSW) and deep slope water also affects patterns in salinity, temperature, and stratification. Stratification in the surface ocean is at a minimum during the winter and at a maximum in the late summer [*Mountain and Manning*, 1994]. Stratification between the surface and 20 m are examined since the highest phytoplankton growth rates occur in this region [*Smetacek and Passow*, 1990]. Factors that increase upper ocean stratification and reduce mixed layer depth include fresh river input, precipitation, and heating of the surface layer by the sun. Alternatively, wind, breaking waves, current shear, and tides in shallow areas break down stratification and increase mixed layer depth by physically stirring the water column. Heat loss to the atmosphere is also an important mechanism in reducing the buoyancy of surface waters and causing density-driven, convective overturn.

[4] A comprehensive set of salinity and temperature data from hydrographic profiles is used to investigate spatial trends in wintertime mixed layer depth and causes of stratification throughout the GOM. Hydrographic profile data (cast data), are obtained from conductivity, temperature, and depth (CTD) measurements at different locations. Cast data, which provides good spatial coverage of the entire GOM, are taken from the Bedford Institute of Oceanography (BIO) and the Coastal Ocean Observation and Analysis data banks. Cast data are supplemented with high temporal resolution buoy data from the Gulf of Maine Ocean Observing System (GOMOOS) to determine how often shallow mixed layers are present during the winter. The goals of this study are

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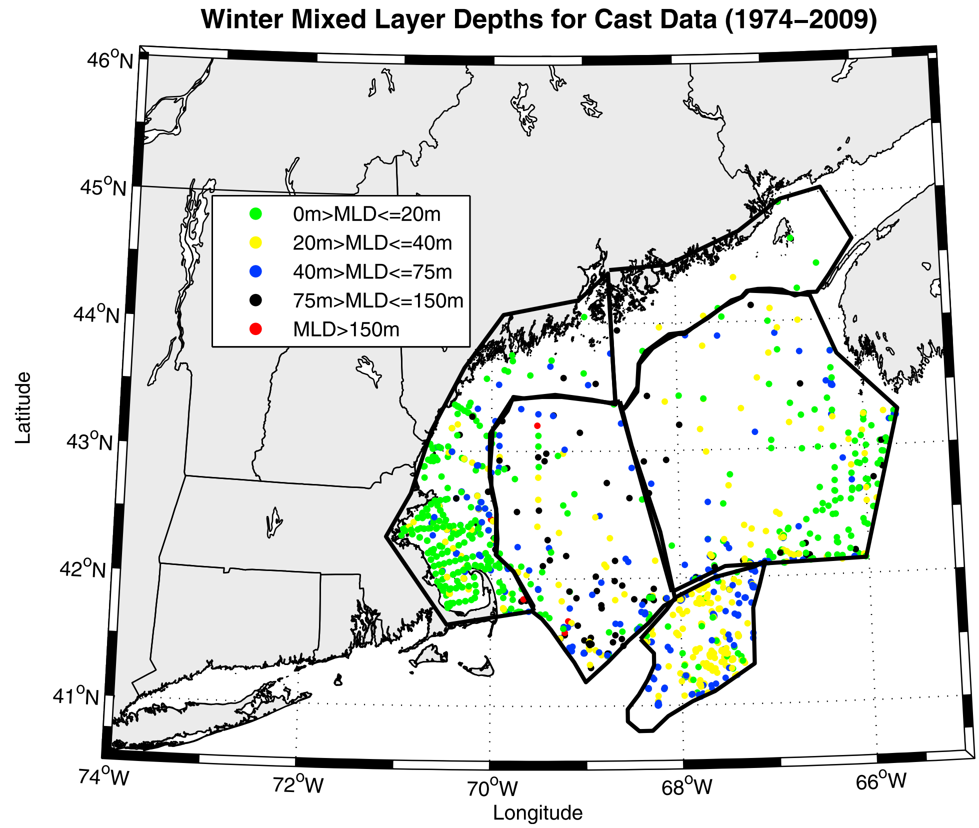

Figure 1. Map of wintertime mixed layer depths generated from Bedford Institute of Oceanography (BIO) and Coastal Ocean Observing and Analysis (COOA) cast data. Mixed layer depths are generally shallowest in the coastal and eastern zones.

(1) to describe the timescales and spatial patterns in shallow winter mixed layers, (2) to investigate how salinity and temperature affect region-wide patterns in stratification, and (3) to explore the relationship between wind stress and stratification at the GOMOOS buoys using wind data from the National Center for Environmental Prediction (NCEP) Reanalysis model.

2. Data and Methods

2.1. Data Sources

[5] Data analyzed in this study comes from the Gulf of Maine Ocean Observing System (GOMOOS), the Bedford Institute of Oceanography (BIO), the University of New Hampshire's Coastal Ocean Observing and Analysis (COOA) data set, and the National Centers for Environmental Prediction (NCEP). Only wintertime (January, February, and March) data are considered. The combined BIO and COOA cast data provide good spatial coverage of the GOM with 1383 wintertime data points spanning from 1974 to 2009 (Figure 1). GOMOOS data complements the BIO and COOA data by providing a high-resolution time series from roughly 2001 to 2010 for six buoys (Figure 2). NCEP Reanalysis II wind data given by *Kanamitsu et al.* [2002] are used to calculate daily pseudostress values (wind speed squared) in the GOM. The grid coverage of NCEP wind data is 42.856°N to 44.76°N and 65.6250°W to 69.375°W. From this area the daily wind stress values calculated represent the spatial average of six equally spaced points.

2.2. Defining Zones in the Gulf of Maine

[6] The Gulf of Maine is divided into five regions (Figure 2). These regions include the coastal, western, northern, and eastern zones as well as Georges Bank. Regions are delineated on the basis of spatial patterns in averaged wintertime salinities and temperatures (1970–2003) at 2 and 25 m gathered from the BIO data bank. Sources of the BIO data include the National Marine Fisheries Surveys, Canadian and U.S government surveys, and U.S. and Canadian academic sources [*Gregory*, 2004].

[7] The coastal zone extends from just east of Cape Cod to Penobscot Bay and is defined as the area from the coastline to the 150 m depth contour. The northern zone similarly follows the 150 m depth contour and extends from Penobscot Bay into the Bay of Fundy. The western zone is adjacent to the coastal zone. It is bounded to the south by Georges Bank and includes the Wilkinson Basin. The eastern zone is adjacent to the northern zone and includes both Georges and Jordan Basin. The eastern zone also includes much of the area southwest of Nova Scotia, and extends eastward to 65.5°W. The number of casts used from the coastal, northern, western, Georges Bank, and eastern zones is 460, 58, 223, 385, and 257, respectively.

2.3. Estimation of the Mixed Layer Depth

[8] Consistent with the work of *Peters et al.* [1988], *Schneider and Muller* [1990], *Wijffels et al.* [1994], and *Skyllingstad et al.* [1999], the mixed layer is defined as the

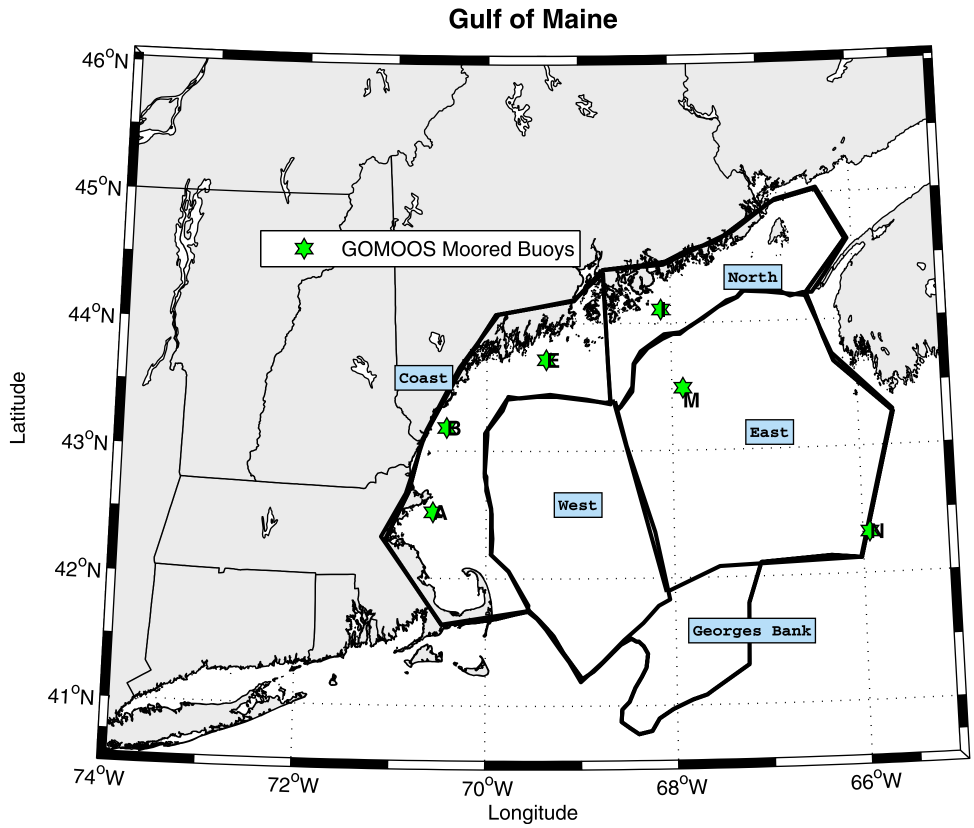

Figure 2. A map of the Gulf of Maine with green stars marking the locations of Gulf of Maine Ocean Observing System (GOMOOS) buoys used in this study, and the black lines delineating different "zones."

depth at which the difference in potential density from the surface is equal to 0.01 kg/m^3 [*Thomson and Fine*, 2003]. This mixed layer definition is preferred over the gradient method used by *Casault et al.* [2003] in their GOM mixed layer depth study. The gradient method defines the mixed layer depth as the depth at which the change in density with depth exceeds a certain value. Using this method is problematic and avoided in this work because it assumes that there is a definite interface between the mixed layer and underlying water mass.

[9] The 0.01 kg/m^3 density difference used in this study is easily resolved since the accuracy and resolution of both modern and historical conductivity, temperature, and depth (CTD) equipment is much better than this. Since not all casts have data at the surface, the reference surface for mixed layer depth calculations is defined as the minimum depth data are available shallower than 5 m. To account for between-cast variability in depth resolution, salinity and temperature data are linearly interpolated at a 0.125 m interval. Potential density is found at each depth with the Matlab function sw_pden developed by P. Morgan (SEAWATER library for Matlab version 3.2, 1992), and part of the seawater toolbox for Matlab. Calculations of potential density are based on the equation of state for seawater given by *Gill* [1982]. This equation is used since historical data from the GOM is given with temperatures in °C and salinity in practical salinity units (psu). In cases when the potential density at the deepest recorded depth is not greater than 0.01 kg/m^3, the deepest depth is assigned as the mixed layer depth. To test how sensitive our analysis was to this data limitation, casts were removed when the mixed layer depth coincided with the deepest recorded depth. Removing these casts had little effect on spatial patterns in mixed layer depth.

2.4. Frequency of Shallow Mixed Layers

[10] Shallow mixed layers are defined as mixed layers less than or equal to 20 m since data are only available at 1, 20, and 50 m for many coastal GOMOOS buoys. The percent of winter with a shallow mixed layer is found using 2 day rolling averages of potential density at 1 and 20 m. Although 2 day rolling averages do not capture hourly variability in stratification, it is the average stratification over a period of days that will be most biologically significant. The number of days during the winter with a shallow mixed layer is found by adding all the days where the density at 20 m is at least 0.01 kg/m^3 greater than the density at 1 m. This value is then expressed as a percent by dividing by the length of the study season, 90 days.

2.5. The Contributions of Salinity and Temperature

[11] The density of seawater is directly influenced by its salinity and temperature. Cold, salty water is more dense than warm, fresh water. To find the individual contribution of salinity to the density gradient in the upper water column, it is necessary to find the difference in potential densities between 1 and 20 m while holding temperature constant. These depths are chosen since they are the first depths with data at the GOMOOS moorings. For consistency, the same depths are considered for the casts even though data are available between 1 and 20 m. The potential density (σ_θ) at 20 m is a function of salinity at 20 m (S_d), the potential

Table 1. Comparison of Average Wintertime Mixed Layer Depth Between Zones[a]

	West	East	North	Georges Bank
Coast	(W-C) = 35 ± 12, p = 0.007, df = 21	(E-C) = 8 ± 8, p = 0.35, df = 40	(N-C) = 22 ± 11, p = 0.05, df = 23	(GB-C) = 14 ± 6, p = 0.03, df = 34
West		(W-E) = 28 ± 12, p = 0.03, df = 24	(W-N) = 13 ± 14, p = 0.35, df = 29	(W-GB) = 22 ± 11, p = 0.07, df = 17
East			(N-E) = 14 ± 11, p = 0.21, df = 27	(GB-E) = 6 ± 7, p = 0.38, df = 28
North				(N-GB) = 8 ± 10, p = 0.41, df = 18

[a]Differences and ±1 standard error are given in meters. Here p is the probability of incorrectly rejecting the null hypothesis. The null hypothesis is that there is no difference in mixed layer depth between different regions. Results are considered significant for $p < 0.05$. C, coast; W, west; E, east; N, north; GB, Georges Banks; df, degrees of freedom.

temperature of water moved adiabatically from 1 to 20 m (T_θ), the pressure at 20 m (P_d), and the reference pressure (R_p). A reference pressure of 0 db is used in all potential density calculations. (T_θ) is used since temperature increases adiabatically with depth. The potential density at 1 m is a function of salinity at 1 m (S_s), temperature at 1 m (T_s), pressure at 1 m (P_s), and R_p. The salinity contribution to the density gradient in the upper water column is found by holding temperature constant between the surface and 20 m and subtracting $(\sigma_\theta)_{1m}$ from $(\sigma_\theta)_{20m}$:

$$\text{Salinity Contribution} = \sigma_{\theta(20m)}(S_d, T_\theta, P_d, R_p) - \sigma_{\theta(1m)}(S_s, T_s, P_s, R_p) \quad (1)$$

The temperature contribution to the density gradient in the upper water column is found by holding salinity constant between the surface and 20 m. In this case the potential density at 20 m is a function of S_s, temperature at 20 m (T_d), P_d, and R_p. The temperature contribution is found from

$$\text{Temperature Contribution} = \sigma_{\theta(20m)}(S_s, T_d, P_d, R_p) - \sigma_{\theta(1m)}(S_s, T_s, P_s, R_p) \quad (2)$$

where $(\sigma_\theta)_{1m}$ is subtracted from the $(\sigma_\theta)_{20m}$ assuming constant salinity with depth.

[12] Equations (1) and (2) are used to determine if salinity or temperature has a bigger effect in increasing the density gradient in the upper 20 m. Using these equations, the relative contribution is defined as the salinity contribution minus the temperature contribution:

$$\text{Relative Contribution} = \text{Salinity Contribution} - \text{Temperature Contribution} \quad (3)$$

If the relative contribution is positive then salinity is the dominant player in increasing stability. Conversely, negative values for the relative contribution indicate that temperature is more important in driving increased stability in the upper water column. Although the equation of state for seawater given by *Gill* [1982] is nonlinear, the assumption of linearity when subtracting the temperature contribution from the salinity contribution is adequate since the resulting error is small.

$$\sigma_{\theta(20m)} - \sigma_{\theta(1m)} \approx \sigma_{\theta(20m)}(T_d, S_s, P_d, R_p) + \sigma_{\theta(20m)}(T_\theta, S_d, P_d, R_p) - [2 \times \sigma_{\theta(1m)}] \quad (4)$$

Equation (4) compares the true potential density difference between 1 m and 20 m with the difference calculated considering the individual contributions of salinity and temperature. Maximum error found using typical wintertime salinity and temperatures values and equation (4) is $\ll$1%.

2.6. Quantifying the Relationship Between Wind Stress and Stratification

[13] To understand how wind stress affects stratification, the density difference between 1 m and 20 m is compared before and after wind events each winter. Wind events are defined as exceeding the average wintertime wind stress in the GOM (70 m^2/s^2) given by the NCEP Reanalysis II model. Before and after wind event stratification values are based on 2 day rolling averages to match the decorrelation time of winds in this area [*Pringle*, 2006]. At each GOMOOS mooring, the number of times when stratification decreased after a wind event is recorded and compared to the number of times when stratification increased after an event. The percentage of time that wind events coincided with destratification is then calculated. The significance of this value is found by comparing it to an alternate percentage based on random chance but which allows for the seasonal cycle in stratification. The null hypothesis is generated using a bootstrapping technique in which the start and end year-day from a particular wind event are used with a random year between 2004 and 2010, and the fraction of time that the new end date is less stratified than the new start date is calculated. One thousand randomly chosen (stratification before minus stratification after) values are generated for each wind event at a particular GOMOOS buoy. Comparison of the actual percent of time when stratification decreased after a wind event to the null hypothesis percentage based on random chance is performed using a two-sample Z test for proportions.

3. Results

3.1. Spatial and Temporal Patterns in Mixed Layer Depth

[14] Spatially, the BIO and COOA cast data show that shallow winter mixed layers occur most often in the coastal and eastern zones of the GOM. In these zones, average mixed layer depths with ±1 standard error are 22 m ± 5 m and 29 m ± 6 m, respectively (Figure 1). Average wintertime mixed layer depths in the western and northern zones are 57 m ± 10 m and 43 m ± 9 m, respectively. On Georges Bank, the average mixed layer depth (35 m ± 3 m) reflects the top-to-bottom tidal mixing that occurs in this area [*Townsend*, 1991]. With the exception of the northern zone, the difference in average mixed layer depth between the

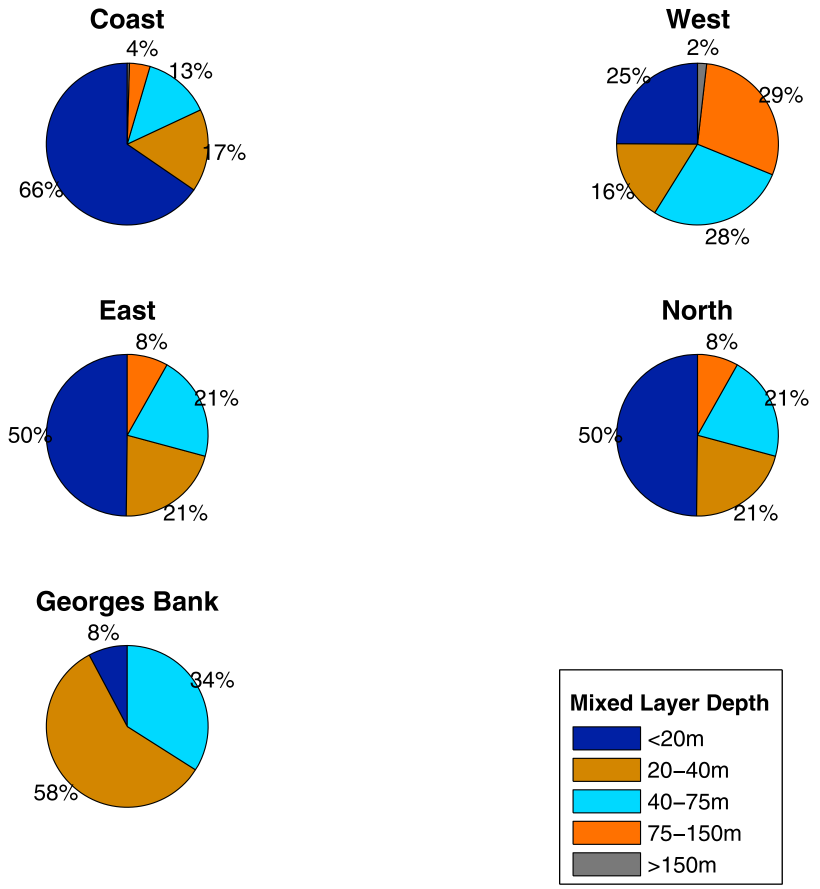

Figure 3. Percentage of wintertime mixed layers within given ranges of mixed layer depth. Percentages come from BIO and COOA cast data.

western zone and all other zones is significant at the 10% level (Table 1).

[15] Deep mixing in the western zone is possible since the water column is on average less stratified than other regions in the GOM [*Pringle*, 2006]. Top-to-bottom density differences in western GOM are typically less pronounced because deep, saline slope water is modified by mixing with fresh, cool SSW as it circulates in the GOM [*Brown and Beardsley*, 1978]. In the western zone, as in other areas, mixing is initiated by events such as the passage of winter storms or atmosphere-induced cooling of surface waters [*Brown and Beardsley*, 1978]. Using the BIO cast data, *Pringle* [2006] found that the density in Wilkinson Basin, in the western zone, is positively correlated with winter cooling from 30–170 m.

[16] The pattern in wintertime mixed layer depths is less clear in the northern zone where mixed layers shallower than 20 m account for 50% of casts, and mixed layer depths greater than 40 m represent 29% of casts (Figure 3). This variability might be the result of insufficient data (58 casts), or it might reflect that the mixed layer depth in this region is affected by year-to-year variability in the Eastern Maine Coastal Current (EMCC) or changes in river discharge [*Pettigrew et al.*, 1998].

[17] Time series potential density data from the GOMOOS buoys indicate that shallow mixed layers often persist for the entire winter. Table 2 presents this result by showing the percent of time with a shallow mixed layer during the winter. All buoys had years where shallow stratification was present for the duration of the winter (90 days). To test the sensitivity of this result to the mixed layer definition given in section 2.3, the percent of winter with a shallow mixed layer was recalculated at each buoy using a mixed layer depth criteria of 0.02 or 0.03 kg/m^3. Using double and triple the mixed layer definition made little difference in the percent of time with a shallow mixed layer. Buoy M in Jordan Basin typically had fewer days during the winter with a shallow mixed layer. No information on the duration of wintertime shallow mixed layer events is available for the western zone

Table 2. The Percent of Winter With a Shallow Mixed Layer (≤20 m) at Each Buoy Based on 2 Day Rolling Averages of Potential Density at 1 and 20 m

	Coast				East	
	A	B	E	North I	M	N
2004	99	100	100	77	100	
2005	78	99	97	36	100	100
2006	100	77	77	98	58	100
2007	39	99	93	94	100	74
2008	100	100	98	100	19	100
2009	100	100[a]	100	100	6	97
2010	100		93	97	38	

[a]Some data are missing, and the result is calculated for days with data.

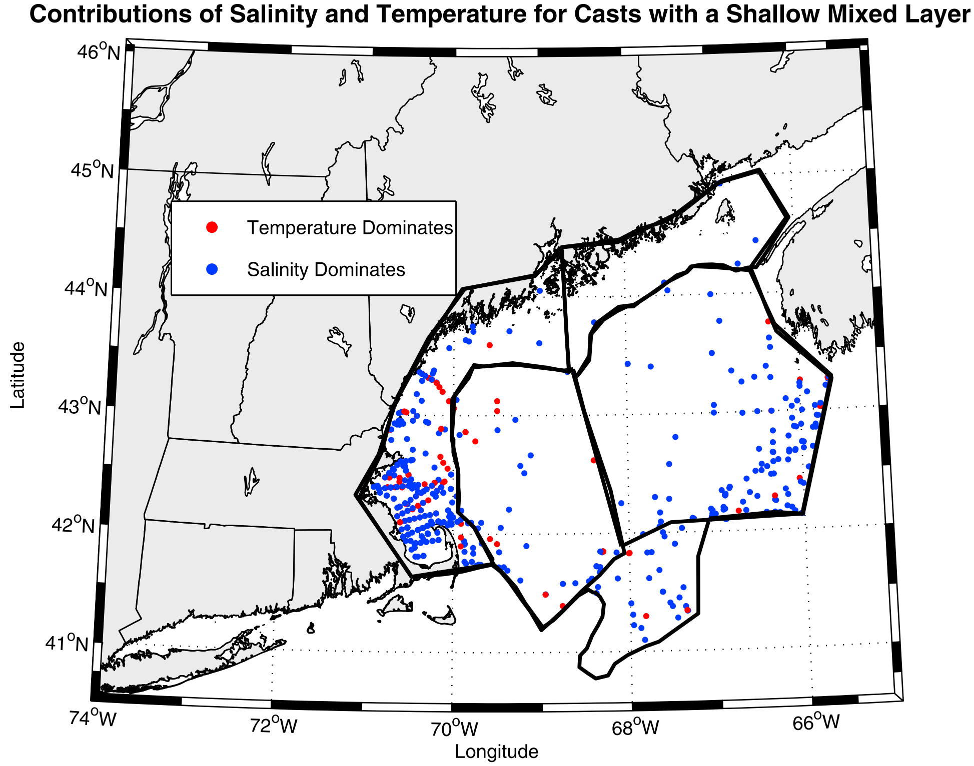

Figure 4. A map of the Gulf of Maine showing relative contributions for casts with a mixed layer ≤20 m. Relative contributions are calculated between the surface depth and the mixed layer depth using the same form as equation (3).

or over Georges Bank since no GOMOOS moorings are located in these areas. On the basis of spatial patterns in mixed layer depth given by the cast data, however, it appears that the western zone and Georges Bank are characterized by deeper mixing, and will likely have fewer days during the winter with a shallow mixed layer than the coastal or eastern zones. This idea is supported by cast data which showed only 8% and 25% of the total casts taken over Georges Bank and in the western zone, respectively, had a shallow mixed layer. The cause of shallow mixed layers is explored in section 3.2.

3.2. Salinity and Temperature Contributions

[18] Each zone has casts which owe their upper water column density increase to salinity, temperature, or both. Focusing on shallow mixed layers (≤20 m), however, indicates that salinity increase (not temperature decrease) with depth is the primary factor responsible for shallow wintertime stratification throughout the GOM (Figure 4). Consideration of only casts with a shallow mixed layer revealed that average salinity contribution was greater than the average temperature contribution in all zones (Table 3). Since cast data represent measurements from specific times and places, it is not possible to determine how salinity and temperature change over time with good temporal resolution. To deal with this limitation and to explore how surface and subsurface changes in salinity drive shallow stratification, high-resolution temporal data from the GOMOOS moorings are employed.

[19] The dominance of salinity in increasing the density in the upper water column during wintertime stratification events is supported by GOMOOS time series data (Figure 5). Here we discuss results for buoys B, M, and N since these moorings are representative of the areas covered by the GOMOOS buoy network. Buoy B, located on the western Maine Shelf, has patterns in stratification typical of all the coastal GOMOOS moorings. Buoy M, located in Jordan

Table 3. Relative Contributions by Zone During the Winter[a]

	Coast	West	East	North	G. Bank
Salinity contribution (kg/m^3)	0.0082**	0.0070**	0.0108**	0.0093**	0.0080**
	±0.0018	±0.0015	±0.0022	±0.0008	±0.0011
Temperature contribution (kg/m^3)	0.0005	0.0022*	−0.0024	0.0001	0.0006
	±0.0017	±.0015	±.0021	±.0007	±0.0009
Relative contribution (kg/m^3)	0.0077**	0.0048*	0.0131**	0.0092**	0.0074**
	±0.0035	±0.0030	±0.0043	±0.0014	±0.0018

[a]For each cast with a shallow mixed layer, the relative contributions are calculated by subtracting the temperature contribution from the salinity contribution. Relative contributions are calculated between the surface depth and the mixed layer depth using the same form as (3). Relative contribution values are averaged by zone, and ±1 standard error is calculated by dividing the standard deviation of the relative contribution values by the square root of the number of years with data available. Positive relative contribution values indicate that salinity is the primary cause of density increase with depth. Asterisks indicate the following: *, significance at 10% level; **, significance at the 5% level.

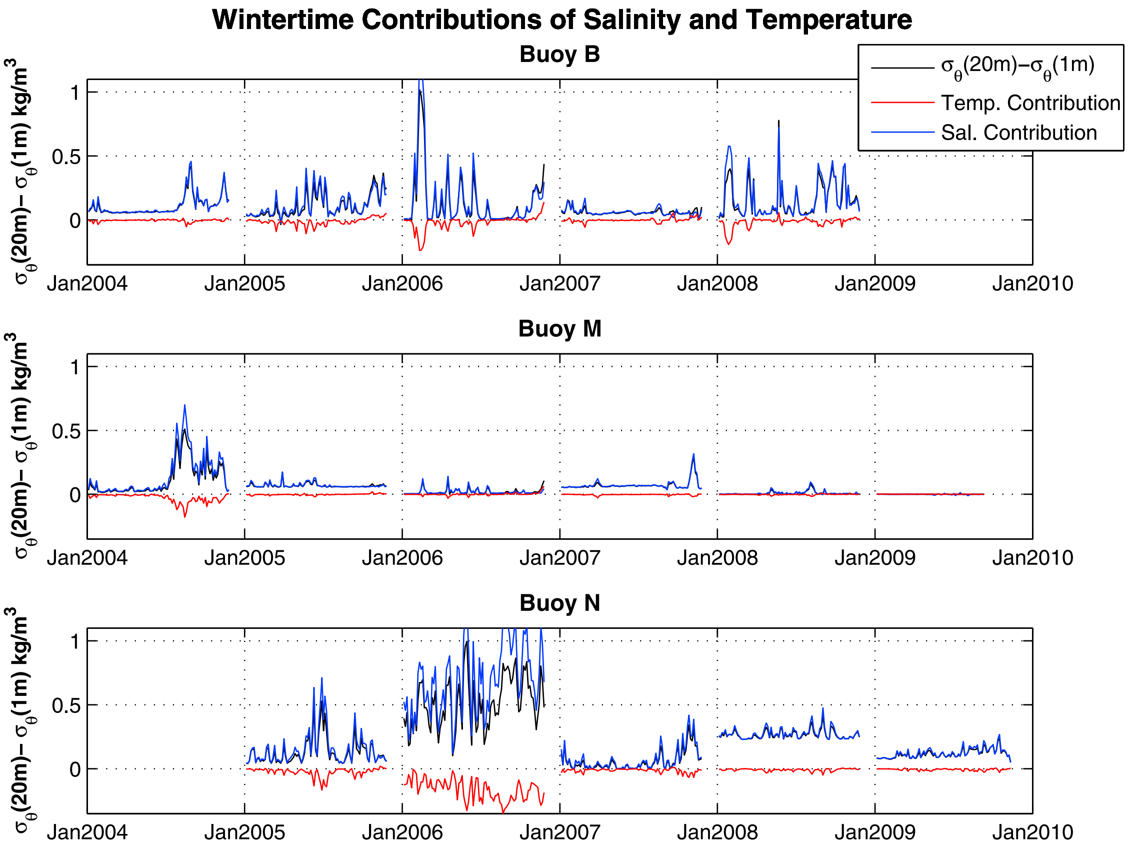

Figure 5. Stratification between 1 and 20 m is plotted for buoys B, M, and N. Salinity and temperature contributions are also shown by the blue and red lines, respectively. Only wintertime (January, February, and March) data are shown.

Basin, provides the only time series data from the interior GOM. Buoy N, over the Northeast Channel, is unique since it strongly impacted by the inflow of SSW during the winter. Although trends in stratification differ between GOMOOS moorings, it is clear from Figure 5 that in all cases, variability in upper water column stratification is salinity driven. A linear regression comparing surface and subsurface salinities at buoy B indicate that variability in stratification is not simply controlled by changes in surface salinity, however, since salinities at 1 and 20 m are strongly correlated ($R^2 = 0.88$; $p \ll 0.01$). Instead, stratification events occur when freshening occurs at both depths because the relative magnitude of freshening at the surface is usually greater than freshening at depth.

[20] At all GOMOOS buoys temperature contributions during periods of increased stratification are negative reflecting the presence of temperature inversions (warming with depth). The phrase "warming with depth" is misleading, however, as in most cases temperature inversions are actually caused by cooling at the surface (Figure 6). Observations from buoys B, M, and N show that during many stratification events both salinity and temperature at 1 m decrease with respect to observed values at 20 m. This finding hints that surface advection of cooler, fresher water may be responsible for trends in upper water column stratification seen at the GOMOOS moorings. The source of cold, less salty water will vary from river outflow in coastal regions to SSW inflow in the eastern GOM [*Mountain and Manning*, 1994]. Calculation of salinity change caused by both average and historically large precipitation events indicate that individual rainfall events falling directly on the coastal ocean do not provide enough freshwater to cause the substantial surface and subsurface salinity changes (0.5–1 psu/d) sometimes observed during stratification events. Calculations of salinity change were done assuming a very shallow mixed layer (5–10 m) and an average rainfall per event of 1.8 cm (based on historical precipitation data from Boston, Massachusetts) [*Driscoll et al.*, 1986]. Precipitation data from Boston, MA are used not only because of their proximity to moorings in the western, coastal GOM, but also since there is no extensive precipitation time series available within the GOM. Salinity change values calculated using historically large rainfall events of 5.08 cm and 7.62 cm (exceedance probabilities of 5.9% and 1.46%, respectively), were again not large enough to explain surface and subsurface salinity decreases observed during some stratification events. Rain events that occur on land are important, however, because watersheds deliver rain from a large area to the coastal ocean in the form of increased river discharge. These large volumes of freshwater from rivers after rainfall can impact hydrographic conditions offshore [*Fong et al.*, 1997]. Advection, river inflow, and their impact on upper water column stratification will be explored further in section 4.5.

[21] Using GOMOOS data, *Deese-Riordan* [2009] found that the destabilizing effects of temperature inversions in the upper 20 m were not strong enough to break down stability established by salinity increase with depth. Our results agree

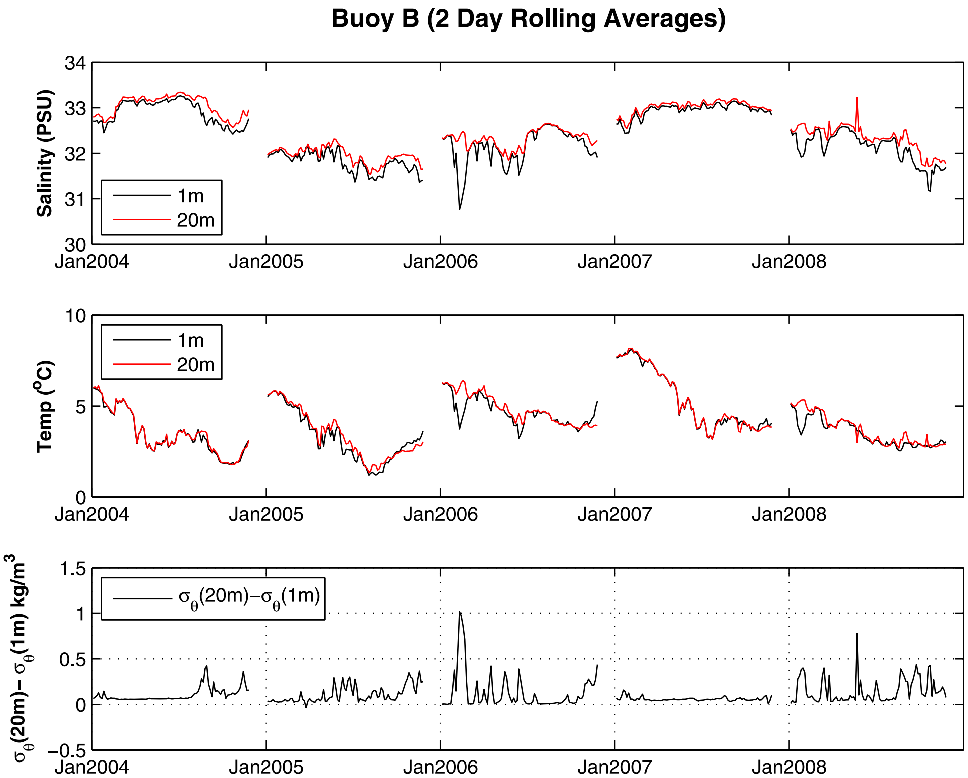

Figure 6. (top) Salinity at 1 m (black) and 20 m (red). (middle) Temperature at 1 m (black) and 20 m (red). (bottom) Potential density difference between 1 and 20 m. Only wintertime (January, February, and March) data are shown.

with those of *Deese-Riordan* [2009], and indicate average salinity contributions are 5–20 times larger than temperature contributions at the GOMOOS buoys. This finding is not unexpected, however, given the typical wintertime salinity and temperatures in the GOM. For the cold temperatures at this time of the year, a small change in salinity with depth has a far greater impact on density than a small change in temperature [*Knauss*, 1996]. The observation that salinity and temperature contributions track inversely of each other through the winter is evidence that temperature inversions may be further augmented by continued heat loss to the overlying atmosphere during salinity-driven stratification events. Heat loss estimates calculated using average wintertime heat flux values given by *Mountain et al.* [1996] and *Beardsley et al.* [2003], indicate that for a 1 m^2 area, a drop of 0.5°C/d is possible assuming that the mixed layer is very shallow (≤10 m). Although this value agrees with some temperature changes observed at 1 m during stratification events, it must be used with caution since the depth of the mixed layer is not well constrained at the GOMOOS moorings. Furthermore, heat loss as the single cause of temperature inversions does not take into account decreases in surface salinity often seen during stratification events. It is therefore likely, that both heat loss from the mixed layer, as well as advection of cool, fresh surface water contribute to patterns in salinity and temperature contribution observed during stratification events.

3.3. Wind Stress and Stratification

[22] The relationship between wind stress and stratification is often difficult to measure accurately. One would expect stratification to decrease following periods of high wind stress. For example, in the GOM region, it is well accepted that destratification during the fall coincides with increasing frequency of strong wind events [*Lentz et al.*, 2003]. During the winter, however, this relationship was not found at the GOMOOS buoys (Table 4). In fact, stratification at most locations was significantly greater following wind stress events. Although this finding seems counterintuitive, advection of a less dense surface water mass provides a reasonable explanation for greater stratification following a wind event. Advection, and its function in driving spatial and temporal patterns in upper water column stratification, is discussed in section 4.5. The finding that stratification was greater following wind events was robust

Table 4. Percent of the Time After a Wind Event That Stratification Decreased[a]

	τ = 30 m^2/s^2	*τ = 70 m^2/s^2	τ = 150 m^2/s^2
A	44**	52*	44**
B	46**	46**	48
E	45**	44**	39**
I	43**	52*	49
M	47**	53	(72)**
N	36**	33**	37**

[a]Values of stratification are compared for the upper water column (0–20 m) before and after wind events of various magnitudes. The percent of time that stratification decreased after a wind event is calculated for each GOMOOS buoy using different wind stress thresholds. The wind stress thresholds chosen represent both sides of the average wintertime wind stress magnitude (*τ). The average is based on wind stress magnitudes during the winter for 2004–2010. All values reported (except in parenthesis) are less than those found by random chance using a bootstrapping technique. Asterisks indicate the following: *, significance at 10% level; **, significance at the 5% level.

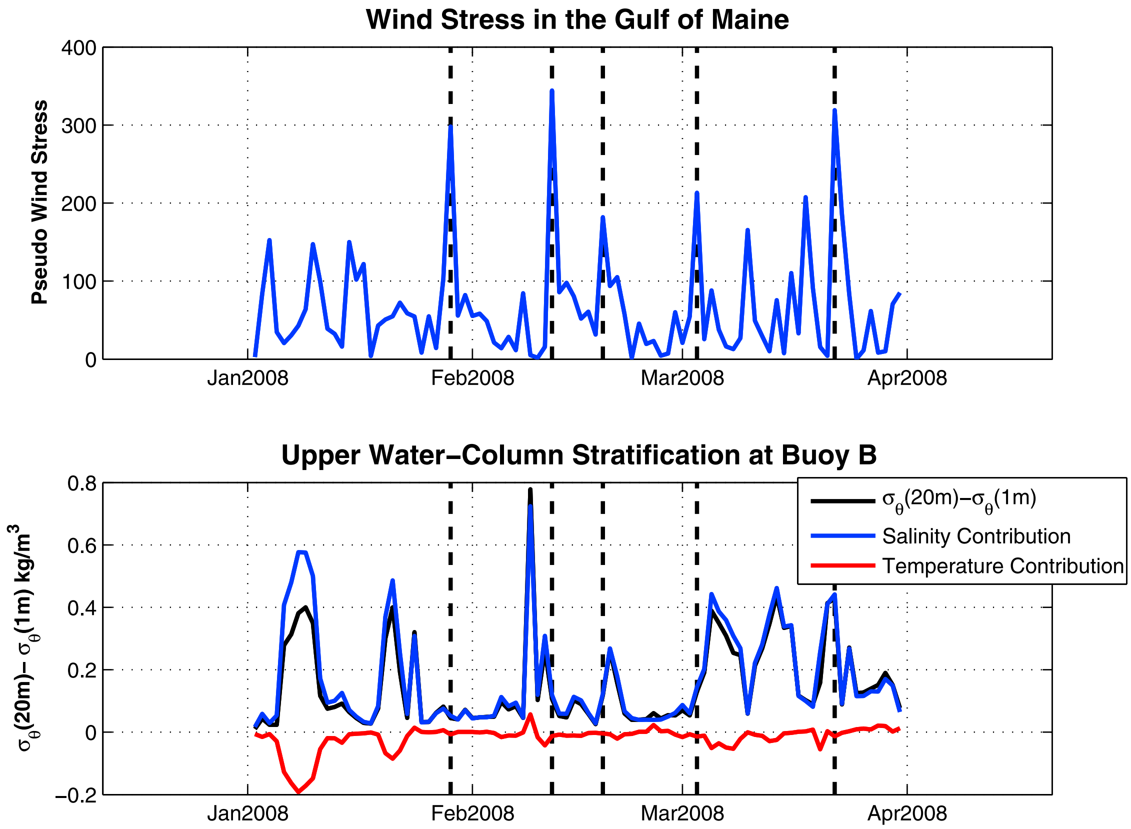

Figure 7. (top) Wind stress during 2008 in the GOM. (bottom) Density difference between 1 and 20 m (black line) and salinity (blue line) and temperature (red line) contributions plotted for buoy B. All time series data are based on 2 day rolling averages to conform with the decorrelation time of winds in this area [*Pringle*, 2006]. Vertical dashed lines highlight select wind events and corresponding stratification.

when tested with wind event magnitudes greater than 150 m^2/s^2 (≈27 mph) and smaller than 30 m^2/s^2 (≈12 mph). Buoy M was the exception in that stratification did decrease following wind stress events greater than 150 m^2/s^2. This finding is reasonable given that average salinity stratification was weaker at this location than anywhere else. Choosing wind event thresholds outside the 30–150 m^2/s^2 range greatly reduced the sample size and statistical confidence.

[23] Visual comparison of upper water column stratification with wind stress at buoy B during 2008 shows that salinity-driven stratification is rarely completely destroyed even during the strongest wind events (Figure 7). The relationship between wind stress and stratification at buoy B in 2008 is characteristic of trends seen at other GOMOOS moorings: stratification fluctuates throughout the winter, and is not tightly coupled with patterns in wind stress. For example, in February 2008 a period of high wind stress coincided with a time of increased upper water column stratification. Quantitative analysis and visual inspection of wind stress versus stratification time series suggest that temporal changes in salinity-driven stratification at the GOMOOS buoys are not driven by wind events.

4. Discussion

4.1. Regional Differences in Stratification

[24] Although routine deep convective overturn in the GOM during the winter is often taken as fact [*Bigelow*, 1926], we suggest that the opposite may be true. Using hydrographic profiles and time series data from the GOMOOS buoy network we find that shallow mixed layers are frequently found in the coastal and eastern zones of the GOM during the winter. Although upper water column stratification is not as strong in the winter as it is in the spring or summer, available hydrographic data indicate that weak, salinity-driven stratification is maintained in many areas of the GOM at this time of the year. Time series records from the GOMOOS moorings support this claim showing that shallow mixed layers persist throughout the winter at many coastal locations and in the far eastern GOM. Periods of increased stratification result from freshening at both 1 m and 20 m, with the strongest events occurring when the magnitude of salinity decrease at the surface (1 m) is greater than the decrease at depth (20 m). In the western zone, cast data suggest that deep mixing is more common. As in other regions, when shallow stratification does occur in the western zone, it is often salinity driven.

4.2. Patterns in the Coastal and Eastern Zones

[25] Stratification during the winter is most pronounced in the coastal and eastern zones of the GOM. On average, these areas have the shallowest wintertime mixed layer depths. A variety of factors impact stratification in the coastal zone. These include fresh river discharge, circulated SSW, tidal/wind mixing, and ocean-air heat flux [*Townsend*, 1991]. Tidal/wind mixing reduces stratification by physically

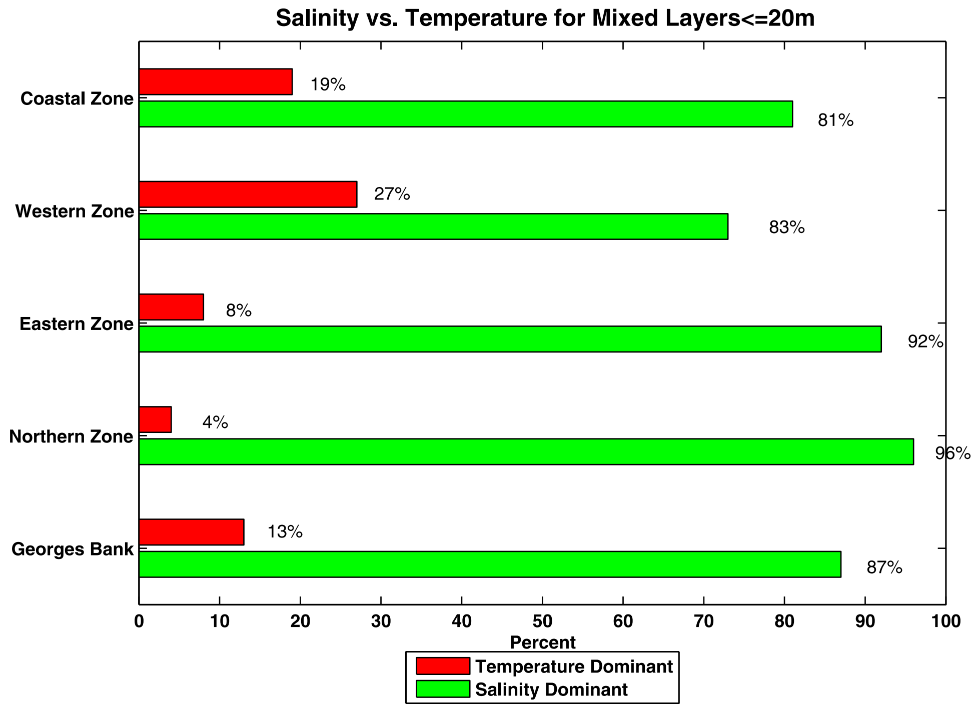

Figure 8. Percentage of casts with a shallow mixed layer in each zone whose density increases in the upper 20 m because of salinity or temperature.

stirring the water column. Cooling the surface waters initiates vertical mixing by creating dense water that sinks. Conversely, river discharge and SSW increase stratification by creating a salinity gradient in the upper water column. In this situation, the water column will resist overturning since less dense, fresher water is above more dense, saltier water. In the coastal zone, both the cast data and GOMOOS mooring data agree that salinity increase (not temperature decrease) with depth is the primary cause of shallow wintertime mixed layers. According to the cast data, 81% of casts with a shallow mixed layer (≤20 m) owe most or all their density increase to salinity (Figure 8). This result is confirmed by the GOMOOS moorings which show periods of increased stratification resulting from greater freshening at the surface relative to freshening at depth. Average wintertime salinity contribution values (not shown) at buoys A and B, in the southern coastal zone, are typically higher than other coastal GOMOOS moorings because fresh river discharge accumulates in the northern and coastal zones and flows southward in the WMCC [*Fong et al.*, 1997]. Since it takes a few months for the large volume of fresh SSW present in the eastern GOM during the early winter to circulate to buoys A and B, freshening at these sites will mainly be affected by river discharge or runoff [*Deese-Riordan*, 2009]. Farther north along the Maine Shelf, at buoys E and I, however, it is expected that both river discharge and SSW will influence the density structure of the water column [*Bisagni et al.*, 1996]. The degree to which SSW influences areas along the Northern Maine Shelf will depend on the total inflow volume during the winter as well as the extent of mixing with deeper, more saline waters [*Brown and Beardsley*, 1978; *Smith et al.*, 2001].

[26] The eastern zone is strongly impacted by the inflow of cool, fresh SSW at the surface, and by deep, warm saline slope water that enters the GOM through the Northeast Channel [*Ramp et al.*, 1985]. For the SSW, the maximum inflow volume and the lowest salinities occur during the winter [*Smith*, 1983]. Fresh SSW overrides dense, more saline water and creates a pronounced salinity gradient. This salinity gradient is responsible for the relatively stratified water column seen throughout the winter in the eastern zone [*Mountain and Manning*, 1994]. The presence of SSW in this region is clear from the spatial distribution of shallow mixed layers (≤20 m) seen in the eastern zone. In the eastern zone, 92% of casts with a shallow mixed layer owe their density increase to increased salinity with depth. This finding is supported by salinity contribution time series data from buoy N that shows upper water column density change is controlled by salinity. During all winter stratification events at buoy N, temperature contributions are negative. Negative temperature contributions result from decreased surface water temperatures with respect to those at 20 m.

4.3. Patterns in the Western Zone

[27] The western zone is characterized by greater average wintertime mixed layer depths. Of the casts with a shallow mixed layer, however, 73% have a salinity contribution greater than temperature contribution. This indicates that although deep mixing is the norm in the western zone, when shallow mixed layers do occur, it is salinity increase with depth that is responsible. The salinity gradient observed during these events may result from advection of SSW or offshore extension of the EMCC [*Brooks*, 1985]. For the shallow mixed layers whose density increase is primarily from temperature decrease with depth, however, warming of surface waters on relatively warm, sunny winter days may be important.

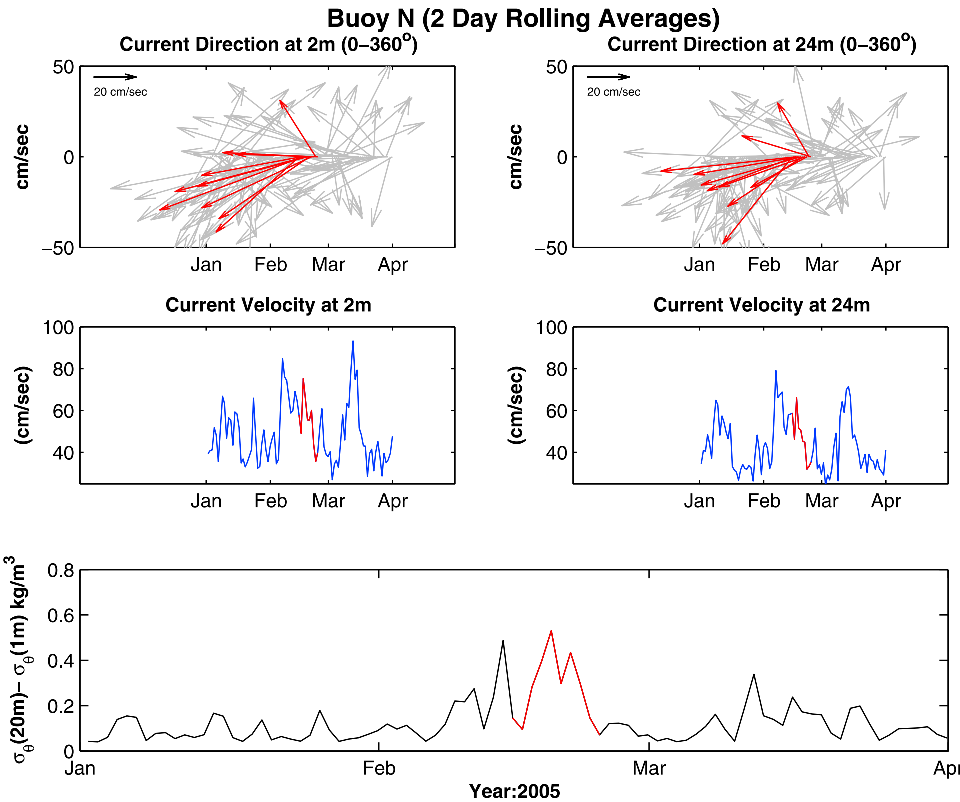

Figure 9. At buoy N (Northeast Channel), (top) current direction and (middle) velocity are shown at 2 and 24 m during 2005. (bottom) Potential density difference between 1 and 20 m. A stratification event that occurred in mid-February 2005 is shown in red. Corresponding current velocities and directions at 2 and 24 m during the stratification event are also shown in red.

4.4. Patterns in the Northern Zone and Over Georges Bank

[28] The northern zone and Georges Bank are heavily influenced by tidal mixing [*Townsend*, 1991]. On average, stratification in these areas is very low because of the physical mixing of the water column. The northern zone is influenced by fresh river discharge from the St. John and St. Croix rivers. SSW also contributes to the freshening of this region [*Bisagni et al.*, 1996]. In the northern zone, salinity contribution is larger than temperature contribution in 96% of casts with a shallow mixed layer. Data from buoy I, on the eastern Maine Shelf, supports this finding, showing that on average the salinity contribution to density increase in the upper 20 m is positive and significant ($P < 0.05$), while the temperature contribution not significantly different from zero ($P > 0.10$).

[29] On Georges Bank, like other areas in the GOM, it is salinity increase in the upper 20 m that sets up the majority (87%) of shallow mixed layers in this region. The likely cause of the observed salinity driven stratification during these events is the presence of SSW [*Smith et al.*, 2001]. Shallow mixed layers caused by temperature decrease with depth may be caused by atmospheric heating of the surface layer or the presence of warm-core Gulf Stream rings [*Brooks*, 1985].

4.5. Mechanisms Influencing Stratification

[30] On average, winter stratification between the surface and 20 m is greatest in the coastal and eastern zones. In both of these areas, salinity increase with depth in the upper 20 m is the primary factor responsible for density increase. The mechanism maintaining salinity-driven stratification, however, is not well understood. The role of vertical current shear, with fresh, less dense water overriding, more dense, salty water, provides one possible explanation. This mechanism seems especially applicable in the eastern zone where fresh, less dense SSW water flows into the GOM and overrides more dense, salty water [*Smith*, 1983]. Analysis of current velocity and direction at 2 and 24 m during several stratification events at buoy N provide results consistent with this hypothesis. For example, during a mid-February 2005 stratification event, average current speed at 2 m (53.82 cm/s) was stronger than at 24 m (46.34 cm/s) (Figure 9). During this event, current, salinity, and temperature time series indicate that cool, fresh SSW advected westward into the GOM while overriding warmer, more saline water also moving in this direction. This process resulted in a period of increased stratification at buoy N.

[31] At buoy B in the coastal zone, surface and subsurface hydrographic time series indicate that both river inflow and current shear drive spatial patterns in upper water column stratification. For example, at buoy B, on the western Maine Shelf, increased stratification in early January 2006 occurred at the same time as above average GOM river discharge [*Deese-Riordan*, 2009]. Inspection of current direction and velocity at 2 and 22 m at buoy B show that surface flow at

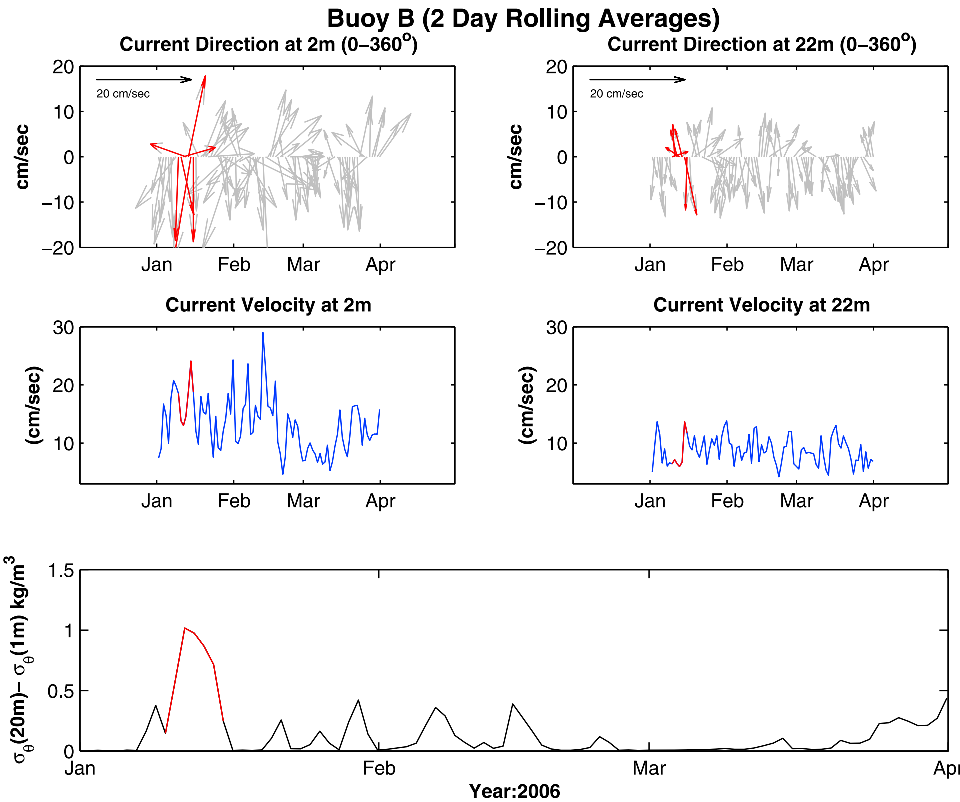

Figure 10. At buoy B (Western Maine Shelf), (top) current direction and (middle) velocity are shown at 2 and 22 m during 2006. (bottom) Potential density difference between 1 and 20 m. A stratification event that occurred in early January 2006 is shown in red. Corresponding current velocities and directions at 2 and 22 m during the stratification event are also shown in red.

the start of the January 2006 stratification event was from the north while deeper flow was from south. Average current speed was stronger at 2 m (17.41 cm/s) than at 22 m (8.31 cm/s) (Figure 10). At the start of the event, salinity and temperature at 1 m and 20 m both decreased (Figure 6). However, most of the freshening and cooling was observed at the surface (1 m) and not at depth (20 m). The greater decrease in surface salinity and temperature at buoy B is consistent with the advection of cool, fresh river discharge from the north. At 20 m, the small decrease in salinity and temperature indicate that the cold, fresh surface water mass did not strongly influence subsurface waters. Periods of increased stratification in the coastal zone, such as the 2006 event discussed here, highlight the importance of river inflow to local changes in hydrography.

4.6. Conclusions

[32] Shallow mixed layers are frequently found in the coastal and eastern zones of the GOM during the winter (Figure 1). Time series records from the GOMOOS moorings show that salinity-driven, shallow mixed layers persist throughout the winter in these regions (Figure 5). Periods of increased stratification at these buoys are often caused by freshening at the surface and at depth, with greater freshening occurring near the surface (Figure 6). The investigation of several stratification events at buoys B and N in the coastal and eastern GOM, respectively, suggests the importance of advection in controlling spatial patterns in upper water column stratification. In the western zone, the small percent of casts with a shallow mixed layer suggest that deeper mixing is more common in this region. In all zones, however, shallow winter mixed layers occur, and are primarily controlled by salinity increase (not temperature decrease) with depth (Figure 8).

[33] During periods of shallow, upper water column stratification, temperature inversions are not strong enough to break down salinity-induced upper water column stability. Since both surface salinity and temperature tend to decrease during stratification events, advection of fresher, cooler water must be considered as a possible cause of observed temperature inversions. Continued heat loss from the mixed layer also provides a mechanism by which temperature inversions can become more pronounced with time. Comparison of wind stress and stratification at the GOMOOS buoys showed that increased winds did not break down winter stratification. In fact, statistically, stratification was often greater following wind events than it was prior to the event (Table 4).This result is unexpected and again points to the role of advection in the GOM.

[34] Findings from this study provide a foundation for future work investigating how the physical structure of the upper water column influences the occurrence of wintertime phytoplankton blooms. Future studies should build on this work and aim to provide a more comprehensive

examination of all local and nonlocal forcings that influence patterns in upper water column stratification to better predict how climate change will impact the biological system.

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