A climatology of salty intrusions over the continental shelf from Georges Bank to Cape Hatteras

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[1] Intrusions or lens of anomalously salty slope water (S_{max} intrusions) are often found over the continental shelf of the Middle Atlantic Bight (MAB). Salty intrusions were identified in 11% of 10,652 historical hydrographic profiles. Intrusions occurred primarily in summer, were observed across the entire shelf, but were most common over the outer shelf, and were concentrated at the depth of the seasonal pycnocline. The percentage of profiles with intrusions increased linearly along the MAB shelf from Georges Bank (3%) to Chesapeake Bay (15%), suggesting either a north to south increase in generation or an along-shelf accumulation associated with a decay timescale of 90 days or longer. Intrusions were typically less than 30 m thick, with a salinity anomaly of less than 0.5, though 10% of the anomalies were greater than 1. The thickness increased as the stratification decreased in a manner consistent with double-diffusively driven lateral intrusions. Intrusions did not preferentially occur during certain wind conditions. Salty intrusions increase the average salinity of the MAB shelf during summer by 0.3 or more, depending on how rapidly intrusions mix with the surrounding shelf water. *INDEX TERMS:* 4219 Oceanography: General: Continental shelf processes; 4223 Oceanography: General: Descriptive and regional oceanography; 4283 Oceanography: General: Water masses; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4536 Oceanography: Physical: Hydrography; *KEYWORDS:* salty intrusions, Middle Atlantic Bight, shelf-slope exchange, S_{max}, double diffusion

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1. Introduction

[2] Along the east coast of the U.S. from Georges Bank to Cape Hatteras (Middle Atlantic Bight) a shelf-slope front separates relatively fresh shelf water from saltier slope water [*Bigelow and Sears*, 1935; *Linder and Gawarkiewicz*, 1998]. Exchange across the shelf-slope front is important in determining shelf water properties [*Csanady and Magnell*, 1987], the extent to which the shelf is a source or sink of carbon [*Walsh et al.*, 1988], dispersal of pollutants, and the flux of nutrients to the shelf [*Houghton and Marra*, 1983; *Ryan et al.*, 1999]. However, exchange between the shelf and slope waters remains so poorly understood that even the dominant processes contributing to cross-frontal exchange are uncertain [*Loder et al.*, 1998; *Brink*, 1998; *Fratantoni and Pickart*, 2003].

[3] One potentially important mechanism for shelf-slope exchange is the generation of salty intrusions of slope water often found at middepth over the shelf (Figure 1) and commonly referred to as S_{max} intrusions [*Gordon and Aikman*, 1981]. (There are also intrusions of relatively fresh shelf water over the slope *Gordon and Aikman* [1981] that are not discussed here.) These intrusions are often observed in hydrographic surveys and occasionally in moored observations (e.g., Figure 1) as lenses or tongues of anomalously salty water that are order 10 m thick and 10 km in horizontal extent [*Bigelow and Sears*, 1935; *Boicourt and Hacker*, 1976; *Voorhis et al.*, 1976; *Gordon and Aikman*, 1981; *Houghton and Marra*, 1983; *Welch*, 1981; *Churchill*, 1985; *Burrage and Garvine*, 1988; *Gawarkiewicz et al.*, 1990; *Flagg et al.*, 1994; *Gawarkiewicz et al.*, 1996]. The tendency in these observations is for salty intrusions to occur during the spring and summer near the seasonal pycnocline. However, there has not been a systematic attempt to determine the general characteristics of salty intrusions or their spatial and temporal distributions over the Middle Atlantic Bight (MAB) shelf. As a result, it remains unclear whether these intrusions represent a substantial flux of salt from the slope to the shelf [*Voorhis et al.*, 1976; *Gordon and Aikman*, 1981]. The primary generating mechanism also remains uncertain. A number of different mechanisms have been proposed, including wind forcing [*Boicourt and Hacker*, 1976; *Churchill*, 1985], warm-core rings [*Gawarkiewicz et al.*, 1990, 1996; J. H. Churchill et al., Slope water intrusions onto Georges Bank, submitted to *Journal of Geophysical Research*, 2003], baroclinic pressure gradients [*Posmentier and Houghton*, 1981; *Aikman*, 1984], interfacial drag

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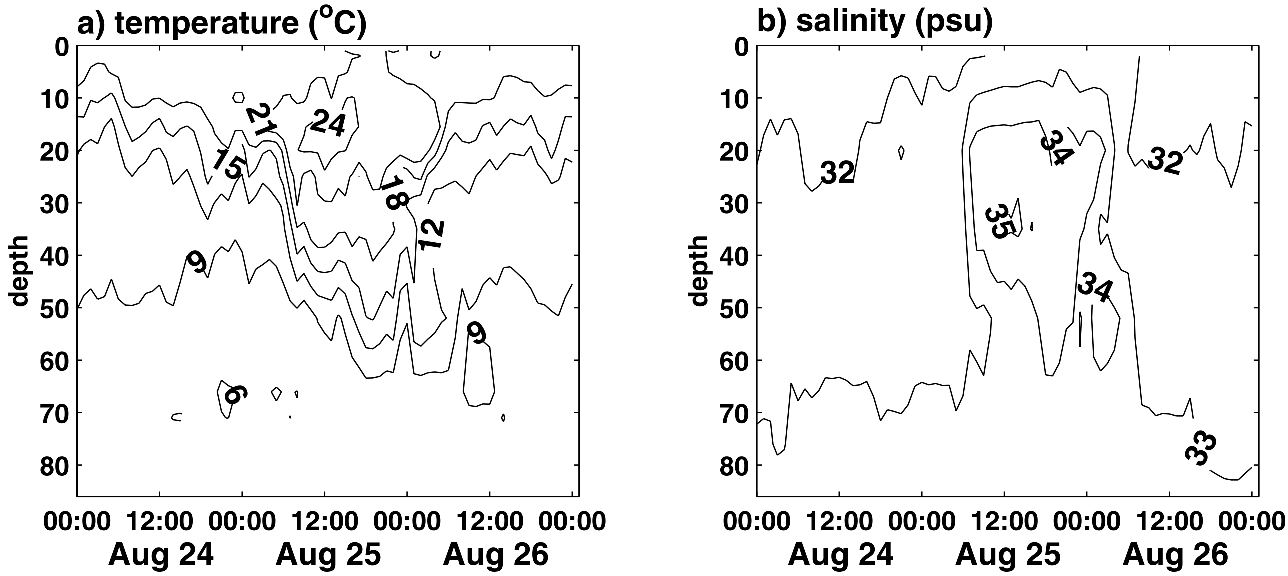

Figure 1. Example of a (a) warm and (b) salty intrusion sweeping past a mooring deployed in 86 m of water on the New England shelf in 1996.

[*Welch*, 1981], and double diffusion [*Voorhis et al.*, 1976; *Houghton and Marra*, 1983].

[4] In this paper, historical hydrographic observations are examined to determine the general characteristics of salty intrusions over the MAB shelf from Georges Bank to Cape Hatteras. The focus is on near-surface and middepth intrusions as opposed to near-bottom intrusions associated with onshore displacements of the foot of the shelf-slope front [*Boicourt and Hacker*, 1976; *Houghton et al.*, 1988; *Lentz et al.*, 2003]. The goals of this analysis include determining: how common salty intrusions are, their seasonal and spatial (vertical, cross-shelf, and along-shelf) distributions, and their characteristics (spatial structure and temperature/salinity). Potential forcing mechanisms and the importance of these intrusions to shelf-slope exchange are also discussed.

2. Data Processing

[5] A total of 10,652 "acceptable" hydrographic profiles, from both CTD and bottle samples, were extracted from the National Oceanographic Data Center (NODC) archive for the continental shelf (water depths less than 150 m) between Cape Hatteras and the northeastern tip of Georges Bank (Figure 2). The water depth of each hydrographic profile was determined from its latitude, longitude, and the National Geophysical Data Center bathymetry. A profile was acceptable if there were more than five samples, the minimum separation between samples was less than 20 m, and density inversions between adjacent samples were less than 0.05 kg m^{-3}. Profiles for which the deepest sample exceeded the water depth by more than 10 m were assumed to have incorrect positions and were also excluded. Most of the profiles were taken between 1960 and 1998. There are about half as many acceptable profiles in winter compared to summer. Half the profiles are from the Georges Bank region (regions 6 and 7; Figure 2), one third from the New England shelf (regions 4 and 5), and the remaining sixth from the southern MAB (regions 1–3).

[6] Over the MAB shelf and slope, salinity typically increases with depth, therefore a profile is identified as having a salinity intrusion if the salinity decreases with depth by dS between adjacent samples. Since the salinity decrease occurs in the lower portion of the intrusion (Figure 1), this identifies near-surface and middepth salinity maxima, but not salinity maxima at the bottom associated with the onshore displacement of the foot of the shelf-slope front [e.g., *Lentz et al.*, 2003]. The number of intrusions depends on the choice of dS. For example, 19% of the profiles had intrusions for dS = 0.05, 11% for dS = 0.1, and 6% for dS = 0.2. However, the patterns described are not sensitive to the choice of dS in this range. In the following analyses dS = 0.1.

[7] The maximum salinity of the intrusion S_m is defined as the maximum salinity above the depth at which the salinity decrease exceeds dS and z_m is the depth of S_m (Figure 3). To determine the depth of the top (z_t) and bottom (z_b) of the intrusion, the minimum salinity S_{min} above or below z_m was found. Then, for example, the bottom of the intrusion, z_b, is defined as the depth below z_m where $S_m - S(z = z_b) = 0.95(S_m - S_{min})$. Similarly, the top of the intrusion, z_t, is defined as the depth above z_m where $S_m - S(z = z_t) = 0.95(S_m - S_{min})$, where S_{min} is the salinity minimum above z_m in this case. The value of 0.95 was chosen to avoid slight minima far above or below the intrusion when the salinity is almost vertically uniform above or below the intrusion. The intrusion thickness is defined as $\delta = z_b - z_t$ and the salinity anomaly of the intrusion as $\Delta S = S_m - S_b$, where $S_b = S(z = z_b)$. The maximum buoyancy frequency N_{max} and the depth of N_{max} were determined from the corresponding density profiles, where

$$N^2 = -\frac{g}{\rho_o}\frac{\partial \rho}{\partial z},$$

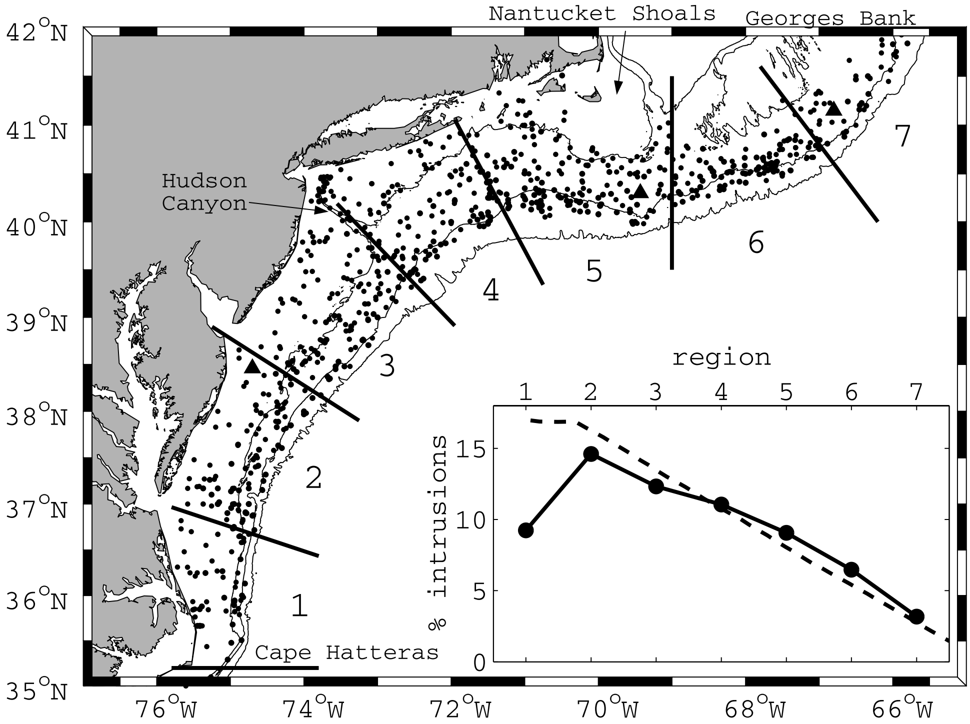

Figure 2. Distribution of salty intrusions over the shelf (water depths less than 150 m) between Cape Hatteras and the northeast peak of Georges Bank. The locations of three NDBC meteorological buoys (triangles) and the 50, 100, and 1000-m isobaths are shown. The area was subdivided into seven regions to characterize along-shelf variations in the percentage of hydrographic profiles with intrusions (inset, solid line). A prediction of the along-shelf variation (dashed line) based on a one-dimensional channel model (section 4.3) is also shown, assuming a decay time for intrusions of 90 days and a generation rate of 5×10^{-3} intrusions per kilometer per day.

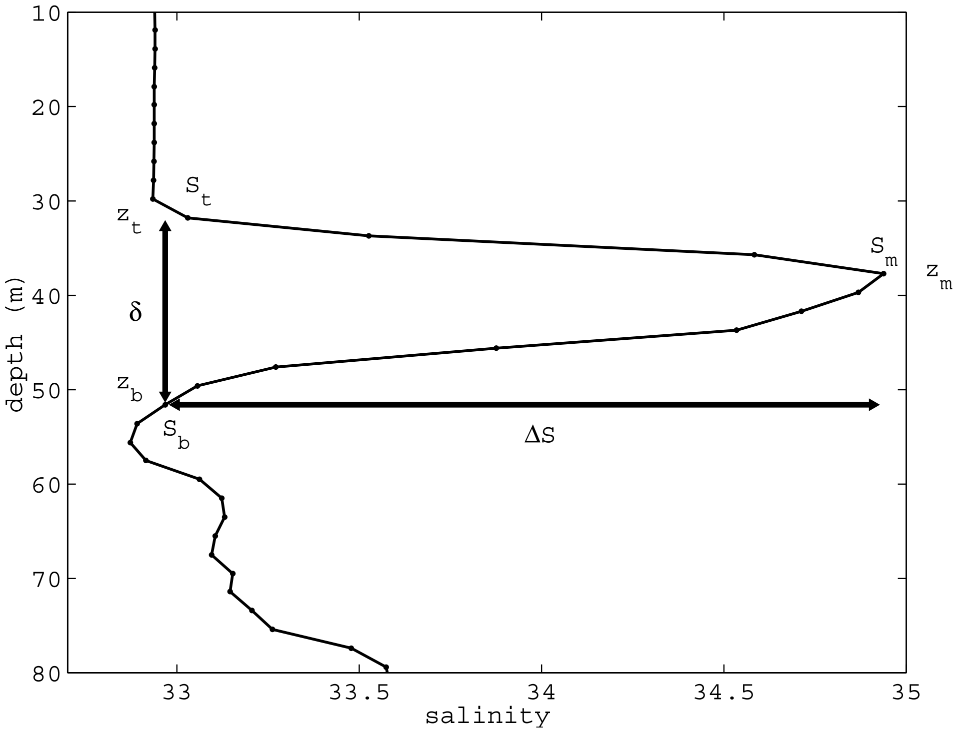

Figure 3. Example of a salinity profile with an intrusion showing the various features that are estimated: the maximum salinity of the intrusion, S_m, the ambient salinity above, S_t, and below, S_b, the intrusion, the intrusion thickness, δ, and the intrusion salinity anomaly, ΔS.

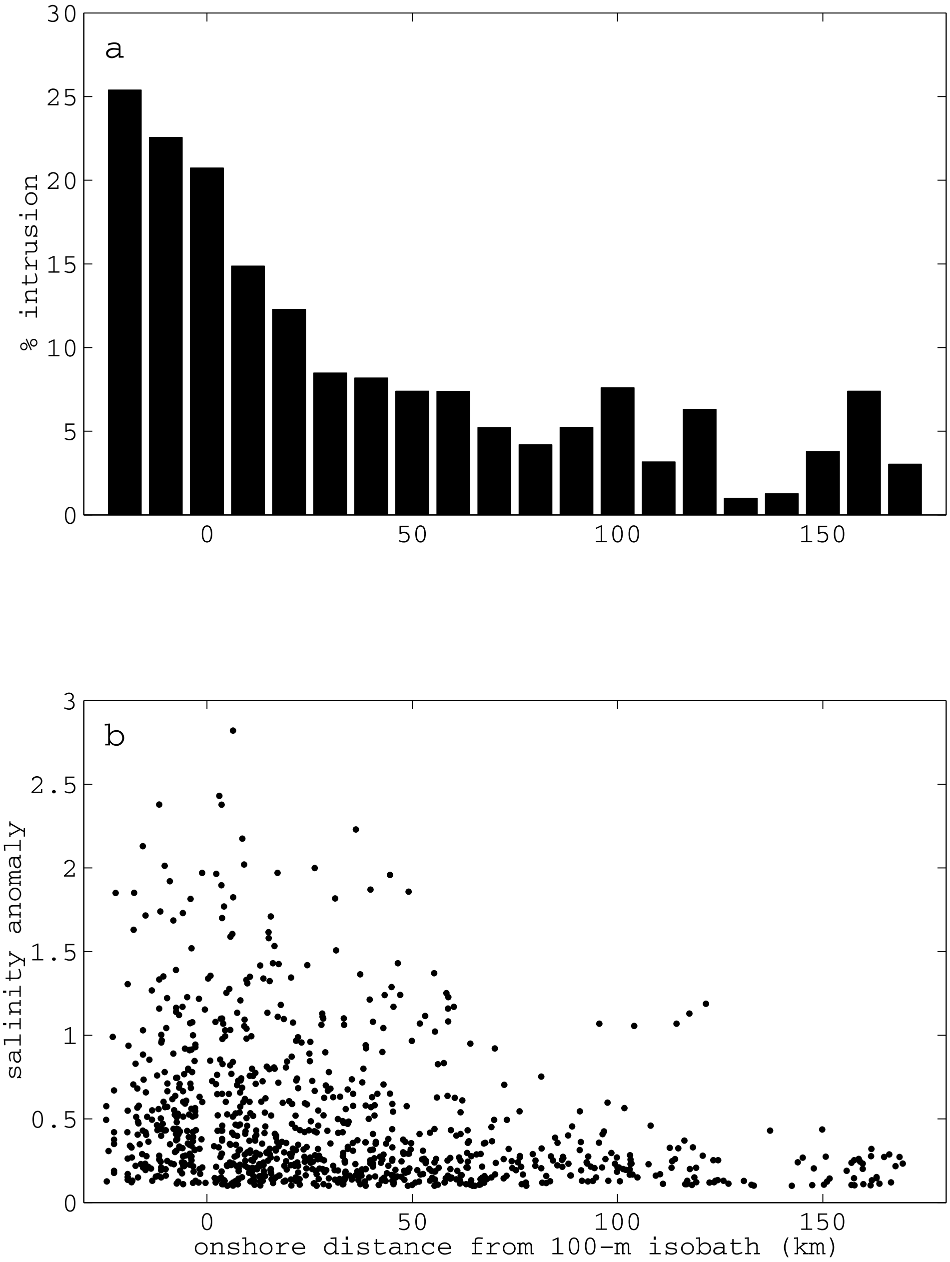

Figure 4. (a) Percentage of hydrographic profiles with salty intrusions and (b) salinity anomaly as a function of onshore distance from the 100-m isobath.

and the vertical density gradient was estimated using a finite difference between samples.

3. Results

[8] Salty intrusions are found over the shelf throughout the MAB, with the exception of the tidally mixed regions over Georges Bank and Nantucket Shoals (Figure 2). The percentage of shelf profiles with intrusions increases at a roughly constant rate from northeast Georges Bank (3%) to Chesapeake Bay (15%) and then decreases between Chesapeake Bay and Cape Hatteras (Figure 2 inset). Intrusions are observed across the entire shelf (Figure 2), but are most common near the shelf break (Figure 4a). The most notable association with a bathymetric feature is a high percentage of intrusions near the head of Hudson Canyon. (This is the cause of the small peak in the histogram centered at 160 km onshore of the 100-m isobath in Figure 4a.)

[9] Intrusions primarily occur during the summer, July–September, and are rarely observed from December through April (Figure 5a). Intrusions tend to occur at or near the depth of the maximum stratification and to a lesser extent near the surface (Figure 6) (see *Gawarkiewicz et al.* [1996] for a detailed description of a near-surface intrusion). The correlation between the intrusion depth and the depth of maximum stratification is 0.52 (significant at the 99.9% confidence level for nonzero correlation). The regression slope is 0.98 ± 0.1 and the intercept is approximately zero (-0.9 ± 3.5 m) indicating intrusions tend to be centered on

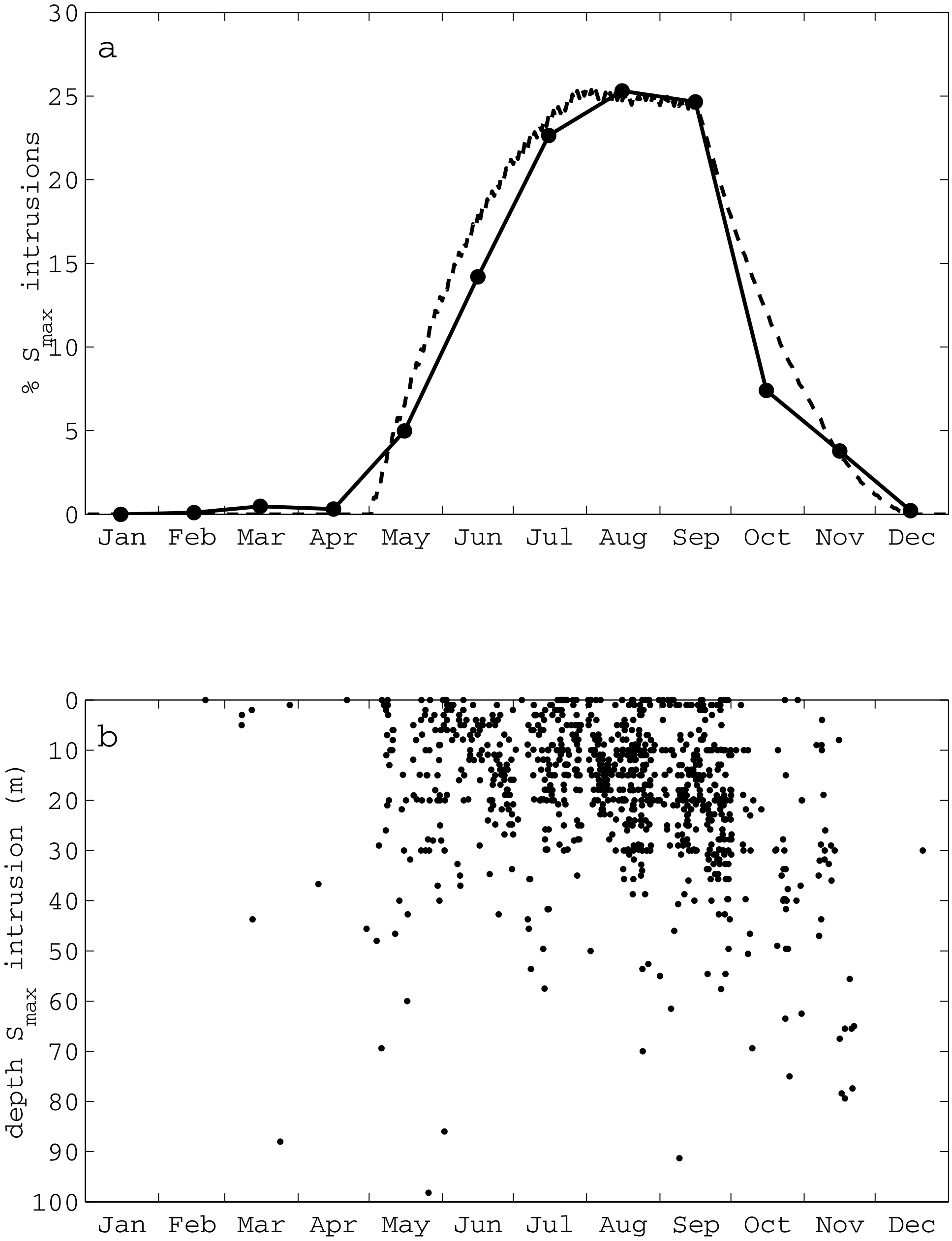

Figure 5. (a) Seasonal variation in percentage of hydrographic profiles with salty intrusions over the shelf and (b) the depth of intrusions as a function of time of year. A prediction of the seasonal variation (dashed line) based on a simple channel model (section 4.3), assuming a decay time for intrusions of 90 days and a generation rate of 5 $\times$ 10^{-3} intrusions per kilometer per day from May through mid-September is also shown in Figure 5b.

the seasonal pycnocline (thermocline). As a result, intrusions are concentrated in the upper 30 m of the water column during the spring and summer when the seasonal pycnocline is shallow (Figure 5b). As the depth of the seasonal pycnocline increases in the fall there is a corresponding increase in the depth of the intrusions.

[10] The majority of the intrusions over the shelf have temperature-salinity (T-S) characteristics that lie in the sparsely populated region of T-S space between shelf water having salinities of 32–33.5 and slope or Gulf Stream water having salinities of 35–36 (Figure 7). This is consistent with the intrusions being mixtures of shelf and slope (or Gulf Stream) water. About 70% of the intrusions have a salinity anomaly less than 0.5, while about 10% are greater than 1. The largest observed salinity anomaly is 2.8. (The percentages depend on the choice of *dS*. For *dS* = 0.05, about 85% of the intrusions are less than 0.5 and only 5% are greater than 1.) Intrusions with large salinity anomalies tend to be located near the shelf break (Figure 4b). Histograms of salinity anomaly for the south-

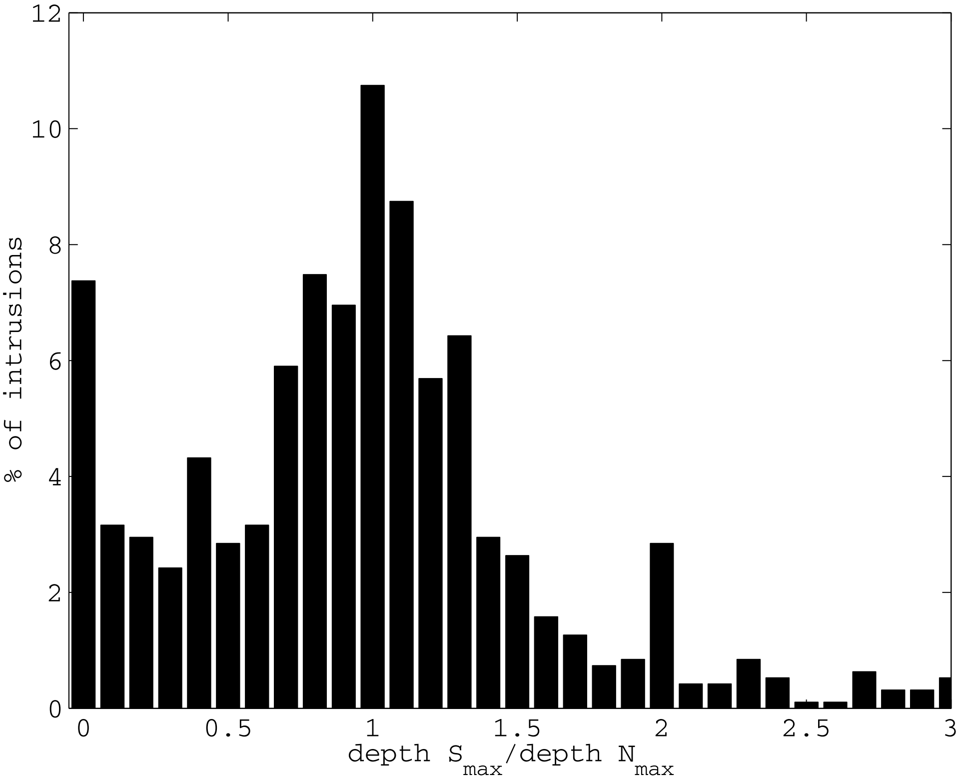

Figure 6. Histogram of the ratio of the intrusion depth and the depth of maximum stratification. There are peaks at zero (near-surface intrusions) and at one (pycnocline intrusions).

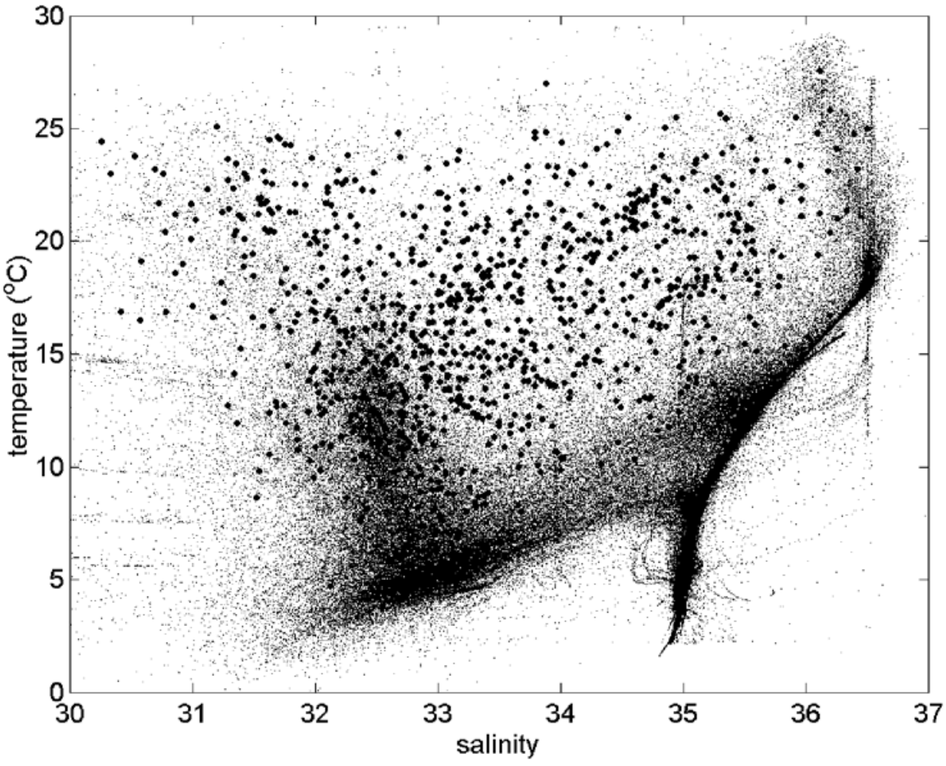

Figure 7. Temperature-salinity diagram for all hydrographic casts (decimated by a factor of 10) (small dots) and for salty intrusions (large dots). Note that most of the intrusions lie in the sparsely populated region between shelf water (high density of points at salinities between 32 and 33.5) and slope or Gulf Stream water (high density of points at salinities between 35 and 36).

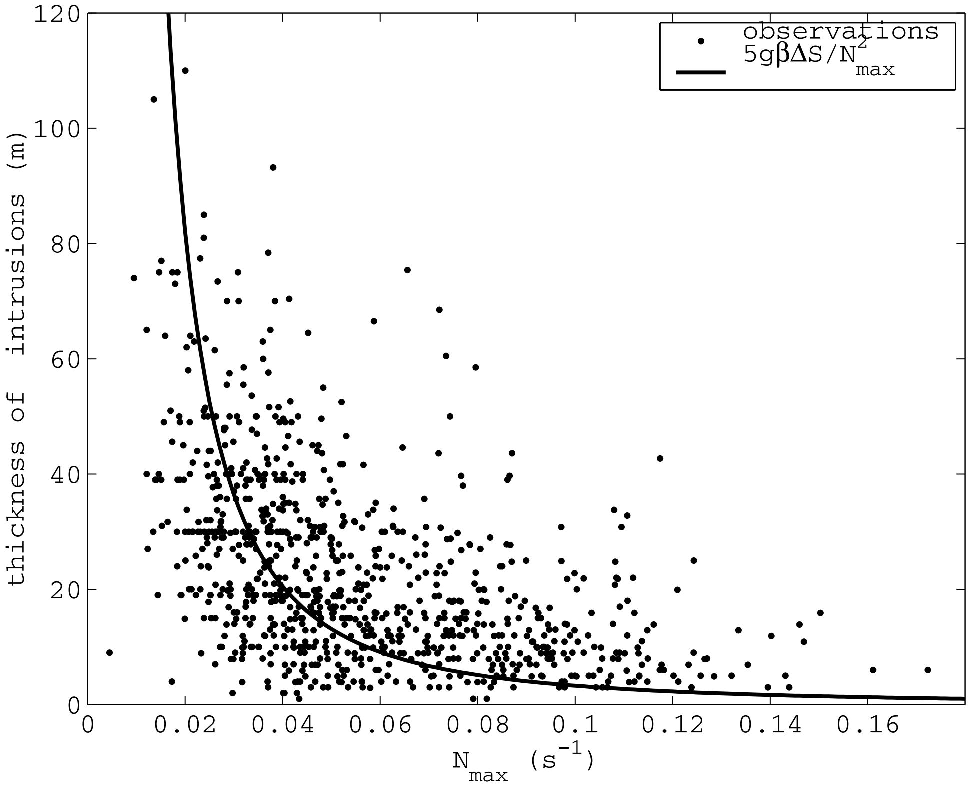

Figure 8. Dependence of intrusion thickness on maximum stratification (N_{max}). The line is an estimate of the dependence of intrusion thickness on N for double-diffusively driven lateral intrusions [*Ruddick and Turner*, 1979].

ern and northern portions of the MAB are nearly identical, suggesting that there is not an along-shelf variation in the salinity anomaly distributions. Most intrusions are less than 30 m thick (Figure 8). The thickness of intrusions depends on the strength of the stratification, with thinner intrusions during stronger stratification. Thus intrusions tend to be thinner in summer when the seasonal thermocline is strongest and thicker in fall as the seasonal thermocline weakens. The thickest intrusions tend to be near the shelf break.

[11] These observations provide little information on two important features of the intrusions, the horizontal scale and the decay timescale. Previous observations and surveys within the NODC archive indicate that the horizontal scale of intrusions is order 10 km; however, there are not enough observations to determine the distribution. Little is known about the decay timescale of intrusions. Moored observations and a few surveys suggest intrusions last at least a few days [*Flagg et al.*, 1994]. The presence of slope water intrusions near the coast [*Churchill*, 1985] (also Figure 2) suggests that at least some intrusions must persist for more than 10 days, given the shelf width of about 100 km and assuming sustained, middepth cross-shelf velocities do not exceed 10 km d^{-1}.

4. Discussion

4.1. Wind Forcing

[12] It has been hypothesized that salty intrusions in the MAB are caused by upwelling favorable winds [*Boicourt and Hacker*, 1976; *Churchill*, 1985; *Flagg et al.*, 1994]. To test this hypothesis the summer distributions of cross-shelf and along-shelf winds for times when profiles contained intrusions are compared to the distributions for all summer profiles for which there was wind data (Figure 9). Observations from the summer period, July–September, were used because the frequency of intrusions was maximum and relatively constant during this period (Figure 5a). (Choosing a longer period, such as the whole year, would result in artificial differences because of intrusions being more common during the summer than at other times of the year, and hence the winds during intrusions being more characteristic of the summer than the entire year.) Wind observations from three National Data Buoy Center (NDBC) buoys, located on the southern flank of Georges Bank, the New England shelf south of Cape Cod, and offshore of Delaware (Figure 2), were used to characterize the winds in the Georges Bank region (regions 6 and 7; along-shelf defined as toward 60°T), the New England shelf (regions 4 and 5; along-shelf eastward), and the southern MAB (regions 1 to 3; along-shelf toward 30°T), respectively. The summer wind distributions during salinity intrusions are essentially the same as the overall summer wind distribution suggesting that intrusions do not preferentially occur during certain wind conditions (Figure 9). Results are similar for each of the three regions considered separately and if the wind is lagged relative to the time of the profiles by 0.5 or 1 day. This result does not preclude the possibility that intrusions are generated during certain wind conditions, such as upwelling, and then persist for periods long

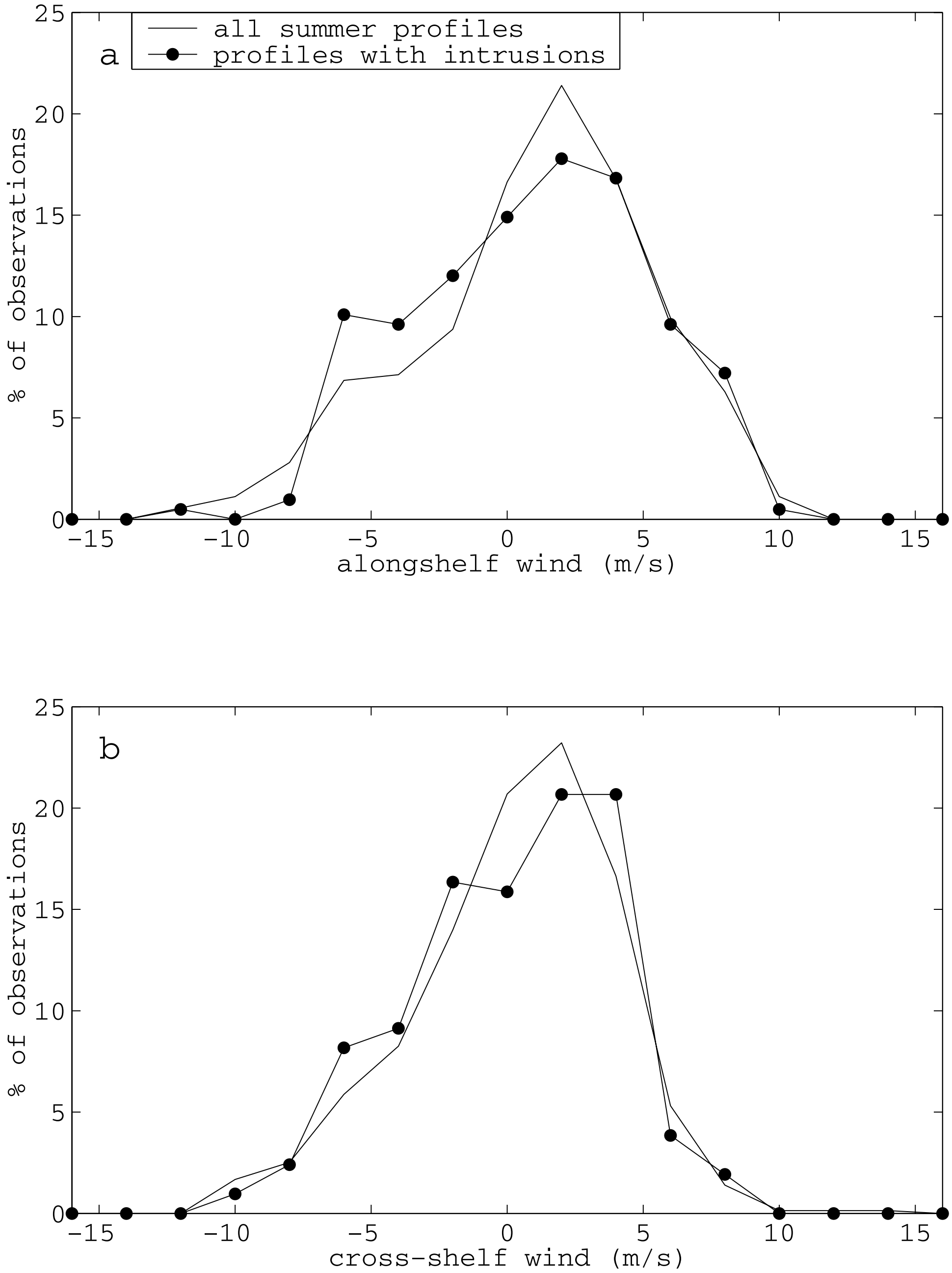

Figure 9. Distributions of (a) along-shelf and (b) cross-shelf winds during summer (July–September) for all hydrographic profiles (line) and only times when salty intrusions were observed (dots).

compare to the timescale of wind forcing (typically a few days).

4.2. Double-Diffusively Driven Intrusions

[13] Double diffusion may be important in both the generation and decay of salty intrusions. Double diffusion can force lateral intrusions at temperature-salinity fronts [*Stern*, 1967; *Schmitt*, 1994] and this has been suggested as a generation mechanism for salty intrusions associated with the shelf-slope front along the east coast of North America [*Voorhis et al.*, 1976; *Horne*, 1978; *Houghton and Marra*, 1983]. *Ruddick and Turner* [1979] argued that the thickness d of a double-diffusively driven lateral intrusion should scale as

$$d \approx g\beta\Delta S_f / N^2 \quad (1)$$

where g is gravitational acceleration, $\beta = (1/\rho)(\partial\rho/\partial S)$ is the haline contraction coefficient, ΔS_f is the salinity difference across the front, and N is the buoyancy frequency. The observed intrusion thicknesses exhibit a dependence on N^2_{max} that is similar to (1) with a proportionality constant of 5 assuming a salinity difference across the shelf-slope front of ΔS_f = 2 and $\beta = 7.6 \times 10^{-4}$ (Figure 8). Subsequent

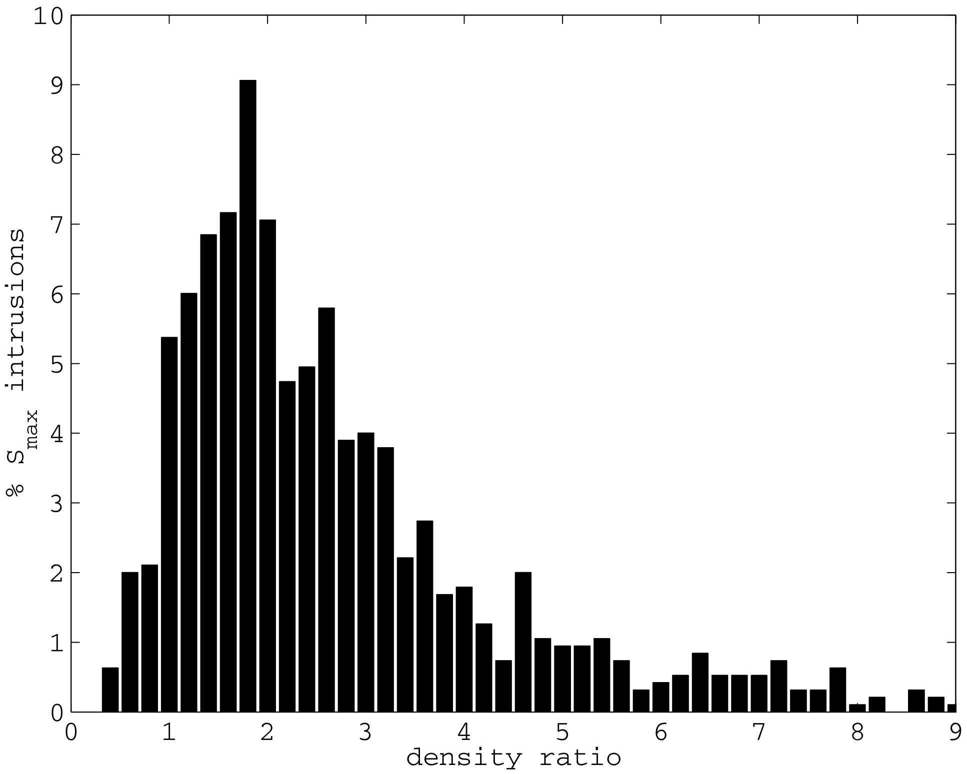

Figure 10. Distribution of density ratio in the lower half of salty intrusions. Density ratios between 1 and 2 suggest vigorous double diffusion.

studies have argued that (1) is only valid for fronts that are narrow relative to the local deformation radius [*Yoshida et al.*, 1989] and that the dependence of d on N is different if the front is wide relative to the deformation radius [*Toole and Georgi*, 1981]. The observed intrusion thicknesses are not consistent with the vertical-scale dependence on N for the case of a wide front [*Toole and Georgi*, 1981]. This result is consistent with recent high-resolution SeaSoar surveys indicating the shelf-slope front width is roughly the deformation radius (C. A. Linder et al., Seasonal characteristics of bottom boundary layer detachment at the shelf break front in the Middle Atlantic Bight, submitted to *Journal of Geophysical Research*, 2003).

[14] The similarity between (1) and the observed thickness dependence on N^2 (Figure 8) suggests double diffusion is a plausible forcing mechanism. However, growth rates for these instabilities are slow and it is unclear how the intrusions move large distances across-shelf if this is the forcing mechanism. If the intrusions decay slowly (see below), then they may be advected cross-shelf by the variable cross-shelf circulation due, for example, to wind forcing. Given that there are several other plausible forcing mechanisms for these intrusions, including warm-core rings and frontal instabilities, more work is needed to identify the generation mechanisms.

[15] The bottom of the salty intrusions should be double-diffusively unstable since warm, salty water overlays cooler, fresher water [*Voorhis et al.*, 1976; *Posmentier and Houghton*, 1978]. A histogram of the density ratio in the lower portion of the intrusions has a peak between 1 and 2 (Figure 10), which is the range of density ratio corresponding to vigorous double diffusive instabilities. The density ratio is estimated as $\alpha\Delta T/\beta\Delta S$, where ΔS and ΔT are the salinity and temperature differences between z_m and z_b (Figure 3), and α is the thermal expansion coefficient. The density ratios suggest there should be, at least initially, substantial exchange between the intrusion and the surrounding water due to double diffusion. The vertical diffusion coefficient estimated from recent dye release studies both over the New England shelf and in an open ocean salt fingering region are order 10^{-4} m^2 s^{-1} or less (J. Ledwell, personal communication, 2003). Assuming Fickian diffusion and an intrusion thickness of 20 m (Figure 8), the exponential decay timescale is 46 days suggesting that intrusions may last for several months.

4.3. Along-Shelf Distribution and Entrainment of Slope Water

[16] Two unanticipated results of this analysis are the small percentage of intrusions at the northeastern end of Georges Bank and the increase in the percentage of salty intrusions from Georges Bank to Chesapeake Bay (Figure 2 inset). The cause of this distribution is not known. The increase in the percentage of intrusions from Georges Bank to Chesapeake Bay may be related to the position of the Gulf Stream, which gets farther from the slope as it flows northwestward from Cape Hatteras [*Drinkwater et al.*, 1994]. The small percentage of intrusions at the northeastern end of Georges Bank may be due to the break in the shelf-slope front at the Northeast Channel (between Georges Bank and the Scotian Shelf) and that intrusions do not form in the Gulf of Maine because of the difference in water properties.

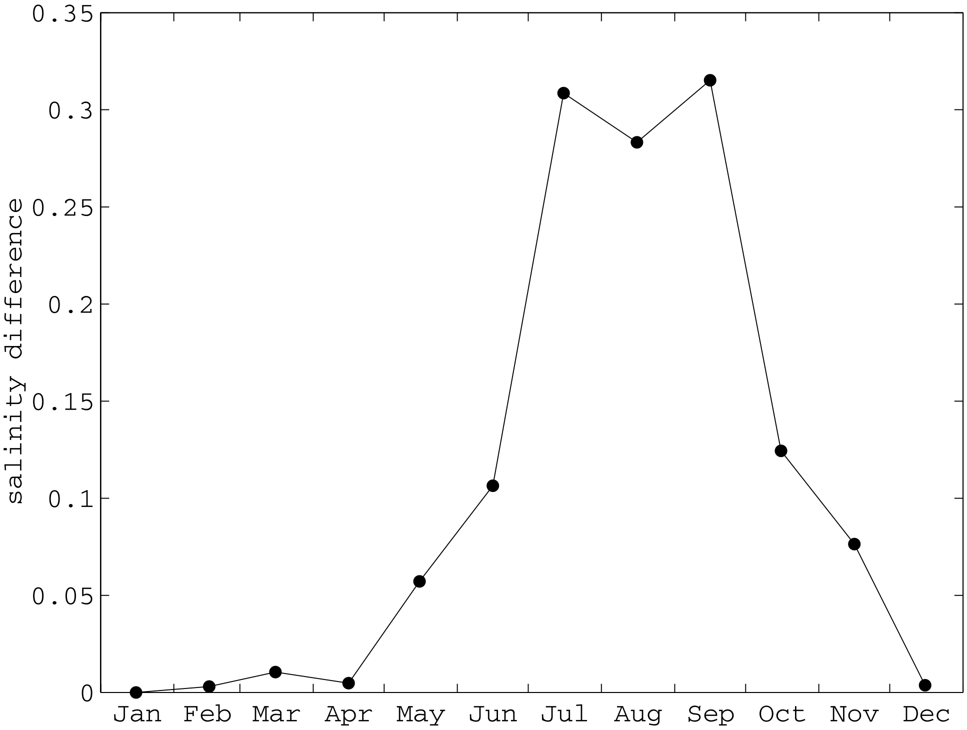

Figure 11. The difference between monthly average salinities over the Middle Atlantic Bight shelf including and excluding salty intrusions, indicating that on average the shelf is at least 0.3 saltier in summer because of intrusions.

[17] To investigate the along-shelf variation, and to determine what can be learned about the rate at which intrusions are generated and decay, a one-dimensional channel model is considered. The channel is assumed to have a constant along-channel flow u, there are no intrusions at the upstream end of the channel ($x = 0$ corresponding to the northeastern peak of Georges Bank), and there is a prescribed generation of intrusions $G(x)$ (at the shelf-slope front) that may vary along the channel and on seasonal timescales. A constant along-channel flow of $u = 10$ km d^{-1} is assumed on the basis of drifter and moored current observations [*Lozier and Gawarkiewicz*, 2001; *Beardsley and Boicourt*, 1981]. Intrusions are assumed to persist for a fixed decay timescale t_d, after which they disappear from the channel. To facilitate comparisons with the observations, the channel is assumed to have a width $W = 100$ km, and intrusions are assumed to have a cross-sectional area of $A_i = 100$ km^2 (i.e., a length scale of 10 km) on the basis of previous observations. Thus, for a channel length $L = 1000$ km the percentage of the channel covered by intrusions is $Pc = 100nA_i/(LW) = 0.1n$, where n is the number of intrusions in the channel. This simple model was implemented numerically.

[18] If the generation rate of intrusions does not vary along the channel, i.e., $G = G_o$, then the steady state solution is

$$n = \begin{cases} G_o t_d x/\lambda & x < \lambda \\ G_o t_d & x \geq \lambda \end{cases}$$

where $\lambda = ut_d$ is an along-channel decay length scale. For $x > \lambda$ the decay of intrusions equals the generation rate and hence the number of intrusions is constant. The solution matches the observed along-shelf distribution (Figure 2 inset) provided λ is 900 km or more (roughly the distance over which the observed increase is linear, Figure 2), which implies t_d is 90 days or longer. In this case, intrusions are generated along the shelf-slope front, are swept along-shelf and leave the MAB south of Chesapeake Bay before they completely mix with the surrounding shelf water (decay). Thus intrusions may not be very effective in exchanging water properties between the shelf and slope regions because of the relatively long decay time. If $t_d = 90$ days, then a generation rate of 5×10^{-3} km^{-1} d^{-1} (5 intrusions generated per day along a 1000 km stretch of the shelf-slope front) yields a distribution similar to what is observed (Figure 2 inset). A decay timescale of 90 days is consistent with the order of magnitude estimate of 46 days assuming a vertical diffusion coefficient of 10^{-4} m^2 s^{-1}. Choosing $t_d = 90$ days also yields the appropriate timescale for both the spring increase and the fall decrease in the number of intrusions (Figure 5), if the generation of intrusions begins in May and ends in mid-September. Another plausible possibility is that there is a constant generation of intrusions at the shelf-slope front throughout the year, but the decay timescale varies seasonally because of changes in the vertical mixing over the shelf. The decay timescale is long in summer and short in winter, when the water column is well mixed so that intrusions mix as rapidly as they form. While this general scenario provides a particularly simple explanation for both the seasonal variation and the along-shelf distribution, it is certainly not unique; there are other, equally plausible models. For example, the along-shelf distribution is also consistent with a generation rate that increases toward the south ($G(x) = ax$) and a decay timescale that is much shorter than 90 days. To match the seasonal evolution (Figure 5), the generation rate must gradually increase in the spring and gradually decrease in the fall in this scenario. Further work is needed to determine the generation and decay rates of salty intrusions and the associated processes.

[19] The impact of intrusions on the salt content of the shelf depends on the generation and decay rates of the intrusions. As a lower bound, monthly averages of the MAB salinity were computed using all the hydrographic profiles and using only hydrographic profiles that did not include intrusions. The difference is an indication of how much intrusions contribute to the average salinity of the MAB (Figure 11). The difference in the monthly averaged salinities is 0.3 in summer and negligible in winter, as expected from the seasonal variation in intrusions (Figure 5). The summer difference could be substantially larger, since this estimate does not account for any mixing between the intrusions and the surrounding shelf water.

5. Summary

[20] Salty intrusions are present in 11% of the historical hydrographic profiles over the continental shelf (water depths <150 m) from Cape Hatteras to Georges Bank. Intrusions occur primarily in summer and are concentrated near the seasonal pycnocline. Intrusions are typically less than 30 m thick with salinity anomalies of less than 0.5. The percentage of intrusions increases linearly from Georges Bank (3%) to Chesapeake Bay (15%) consistent with an along-shelf accumulation associated with a decay timescale of 90 days, a constant generation of intrusions along the shelf-slope front, and an along-shelf flow of 10 km d^{-1}. The decay timescale of 90 days is also consistent with the seasonal variation in the number of intrusions. However, the observed characteristics are also consistent with other scenarios, such as a generation rate that increases toward the south, a shorter decay timescale, and a gradual increase in spring and decrease in fall in the generation rate. Intrusions did not preferentially occur during certain wind conditions suggesting upwelling favorable winds are not the generation mechanism. Intrusion thickness increased as the stratification decreased in a manner consistent with double-diffusively driven lateral intrusions, suggesting this may be an important generation mechanism. The presence of salty intrusions increases the average salinity over the Middle Atlantic Bight shelf in summer by at least 0.3, and possibly much more depending on how rapidly intrusions mix with the surrounding water. Further work is needed to determine the primary generation mechanism of salty intrusions and how rapidly salty intrusions mix with the surrounding shelf water and by what processes.

[21] **Acknowledgments.** This study benefited from numerous discussions with Glen Gawarkiewicz. Comments and suggestions from Dave Chapman, Charlie Flagg, Rich Garvine, Bob Pickart, and John Toole are also appreciated. This work was funded by the Office of Naval Research (CODE 322) and the Woods Hole Oceanographic Institution, Coastal Ocean Institute and Rinehart Coastal Research Center. This is WHOI contribution number 10904.

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