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Increasing Frequency of Mid-Depth Salinity Maximum Intrusions in the Middle Atlantic Bight

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Key Points:

- Observations over several decades show substantial increase of frequency of middepth Salinity Maximum Intrusions
- There is significant inter-annual and month-to-month variability in the frequency and occurrence of Salinity Maximum Intrusions
- Salinity Maximum Intrusions now commonly extend up to 100 km shoreward of the shelfbreak and profiles may contain multiple intrusions

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Abstract Shelfbreak exchange processes have been studied extensively in the Middle Atlantic Bight. An important process occurring during stratified conditions is the Salinity Maximum Intrusion. These features are commonly observed at the depth of the seasonal pycnocline, and less frequently at the surface and bottom. Data collected from NOAA's National Marine Fisheries Service Ecosystem Monitoring program as well as data collected from the fishing industry in Rhode Island show that the middepth intrusions are now occurring much more frequently than was reported in a previous climatology of the intrusions (Lentz, 2003, https://doi.org/10.1029/2003JC001859). The intrusions have a greater salinity difference from ambient water and penetrate large distances shoreward of the shelf break relative to the earlier climatology. The longer term data from the Ecosystem Monitoring program indicates that the increase in frequency occurred in 2000, and thus may be linked to a recent regime shift in the annual formation rate of Warm Core Rings by the Gulf Stream. Given the increased frequency of these salty intrusions, it will be necessary to properly resolve this process in numerical simulations in order to account for salt budgets for the continental shelf and slope.

Plain Language Summary An important exchange process between waters of the continental slope and continental shelf is the Salinity Maximum Intrusion. These have been studied before but there is little information on their along-shelf scale, how they are generated, or their broad impact on shelf ecosystems. Observations from both a multi-decadal data set from the National Marine Fisheries Service as well as community science data collected by the commercial fishing industry over 5 years show that the frequency of these intrusions has increased significantly since 1998. In addition, the intrusions appear to be saltier and penetrate further onshore than previous reports. Future work is necessary to determine how the increasing frequencies of this important process may be affecting continental shelf heat and salt balances as well as broader impacts to the continental shelf ecosystem.

1. Introduction

A variety of shelfbreak exchange processes have been studied in the Middle Atlantic Bight. It has long been recognized, since Bigelow and Sears (1935), that water masses from the continental slope and deep ocean are intermittently transported onto the continental shelf to mix with the ambient water masses of the continental shelf. An important feature which facilitates cross-shelf exchange has been identified in cross-shelf hydrographic transects. The Pycnocline Salinity Maximum Intrusion is a middepth intrusion of relatively salty slope water that extends onto the continental shelf to varying degrees. Boicourt and Hacker (1976) identified these intrusions in data off Maryland, and the features were later examined in greater detail by Gordon and Aikman (1981), who coined the term Pycnocline Salinity Maximum. Gordon and Aikman (1981) estimated that the features are capable of driving an annual average onshore salt flux that is nearly half of what is needed to balance fresh water inputs in the Middle Atlantic Bight and maintain the observed mean annual salinity. The intrusions appear in vertical profiles of salinity as a local maximum, typically near the depth of the seasonal pycnocline, hence the name.

Aikman (1984) used a model based on the seasonal evolution of the mixed layer over the continental shelf and slope to examine the mismatch between mixed layer depths as a forcing mechanism for the intrusions. He found that the pycnocline over the continental shelf was shallower than that of the continental slope, resulting in a reversal of density gradients at intermediate depths. Flagg et al. (1994) described intrusions in the southern portion of the Middle Atlantic Bight using a combination of shipboard hydrography and moored instrumentation including Acoustic Doppler Current Profilers. They note that the time scales for both the onset as well as the presence of the intrusions is on the order of 1 day. The intrusions were related to upwelling favorable winds, but the cross-shelf velocities (0.1–0.2 m/s) were larger than expected from wind-driven Ekman transport. They concluded that pre-conditioning with high salinity water masses adjacent to the shelfbreak front was necessary for initiation, and that the intrusions were infrequent.

Lentz (2003) presents a climatology of Salinity Maximum Intrusions using archived hydrographic data to examine the statistics of the features observed along the shelf from Cape Hatteras, NC to Georges Bank. Between 1960 and 1998, intrusions were observed at an annual frequency of 11% during the stratified season (May–October). The features were observed more frequently in the southern portion of the Middle Atlantic Bight where the Gulf Stream is closer to the shelf. Lentz's climatology documents a number of characteristics associated with each Salinity Maximum Intrusion, including the maximum salinity within the intrusion, the depth of the maximum salinity relative to the depth of peak stratification, the salinity difference between the intrusion and the ambient water, and the density ratio underlying the intrusion. Lentz estimates that the intrusions increase the salinity on the shelf by up to 0.3 PSU, depending on the rate of decay as the intrusions mix with ambient shelf water.

In recent years, there have been significant changes to the water masses occupying the continental shelf and slope. Changes are driven by long-term warming (e.g., Forsyth et al., 2015; Loder & Wang, 2015), short term extreme events such as Marine Heat Waves (e.g., Chen et al., 2014; Gawarkiewicz et al., 2019; Mills et al., 2013), upstream influences near the Grand Banks (Holliday et al., 2020; Neto et al., 2021), and the increasing influence of Gulf Stream meanders and rings over the continental slope (Andres, 2016; Gangopadhyay et al., 2019). Cross-shelf glider observations from the Ocean Observatory Initiative Pioneer Array show a substantial increase in salinity over the upper continental slope (Gawarkiewicz et al., 2018). It is thus timely to consider whether the frequency or character of Salinity Maximum Intrusions may also be changing, particularly since decadal shifts in the salinity over the continental shelf have been attributed to offshore forcing (Wallace et al., 2018). This process may be particularly sensitive to changes in water mass properties and stratification and thus is an attractive target for investigating how larger scale changes may be affecting shelfbreak exchange processes on smaller temporal and spatial scales. We note that Ullman et al. (2014) found that bottom intrusions of warm salty water were observed to penetrate large distances shoreward associated with a northward excursion of the Gulf Stream. It is reasonable to ask if this is also occurring with middepth intrusions.

In this study, we use two data sets to examine vertical hydrographic profiles for the presence of Salinity Maximum intrusions. In Section 2, we describe the characteristics of the intrusions for comparison to the Lentz climatology. The data sources along with spatial and temporal coverage are presented in Section 3. The results are described in Section 4, showing a significant increase in the frequency of the intrusions. The possible forcing mechanisms resulting in this increase are discussed in Section 5, and the results are summarized in Section 6.

2. Characteristics of a Mid-Depth Salinity Maximum Intrusion

We define the characteristics used to identify intrusions in vertical profiles following Lentz (2003), whose study established a framework for classifying intrusions that is useful for this analysis.

Characteristics used to identify intrusions are illustrated in Figure 1, using an observed salinity profile. Here, $S_{\max}$ is the maximum salinity measured within a localized peak in the vertical profile and z_m is the corresponding depth of the salinity maximum. A local peak is only labeled an inversion if the difference between the salinity maximum and the ambient salinity (ΔS) exceeds a specified threshold, where the ambient salinity is defined as the larger of the minima either above or below the salinity maximum. Lentz (2003) required $\Delta S \geq 0.1$. The thickness of the intrusion is measured relative to the top (z_t) and bottom (z_b) of the intrusion peak, which Lentz (2003) identified as the depth at which the salinity in the peak decreases by 95% relative to the minimum salinity in the profile. It should be noted that the example provided by Lentz (2003; their Figure 2) illustrating the characteristics of an intrusion is rather simple, showing an intrusion embedded within a fairly constant ambient profile. In our experience, recent salinity profiles are more complex than the example presented by Lentz (2003). For example, intrusions are often embedded within a stratified profile (Figure 1), making it challenging to identify a representative ambient salinity and leading to unrealistic thickness and ΔS values. For this reason, we made some changes to the identification criteria as discussed next.

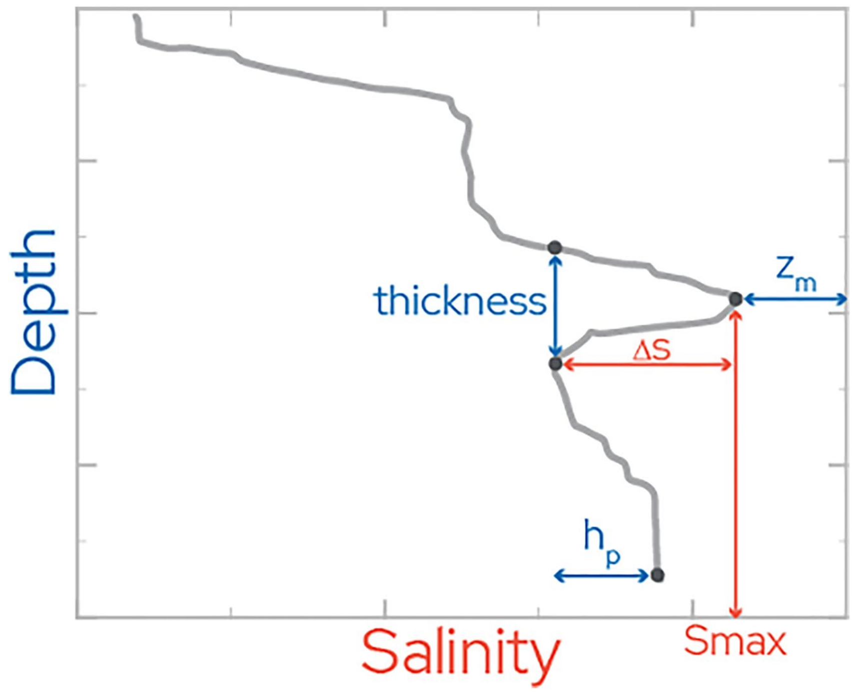

Figure 1. A sample vertical profile of salinity with depth showing the various characteristics of the intrusions. S_{max} is the maximum salinity, z_m is the depth of S_{max}, ΔS is the difference between S_{max} and the ambient salinity (minimum value from above and below), and the thickness is defined relative to the smaller of the two minima above or below the intrusion. The bottom depth of the profile is defined as h_p.

Analysis of salinity profiles collected since 1998 necessitated some changes in the calculations of intrusion characteristics. As the example profile illustrates, the layering and stratification observed in recent profiles was more complex than the example provided by Lentz (2003).

Here, a modification is made to the ΔS criterion used to identify Salinity Maximum Intrusions within a salinity profile. Applying the criteria $\Delta S \geq 0.1$ as adopted by Lentz (2003) to observations from both of the data sets examined for this analysis revealed a large number of profiles containing multiple intrusions. This resulted in considerable ambiguity when quantifying the number and character of intrusions. In order to reduce ambiguity and to ensure that this analysis is focused on the more pronounced features, we increased the threshold criterion to $\Delta S \geq 0.2$. The thickness of the intrusion was calculated relative to the straight line intersection with the larger of the minima above and below the local maximum S_{max}. In all cases, there was enough vertical separation or salinity differences between the local minima to be able to determine the most reasonable choice.

3. Data Sources and Temporal and Spatial Coverage

Two high-quality hydrographic data sets were used for this analysis, each with distinctly different spatial and temporal footprints. The NOAA Fisheries Ecosystem Monitoring Program Data set spans ~40 years, sampling the Northeast US Shelf from Cape Hatteras through the Gulf of Maine at roughly seasonal resolution. The Commercial Fisheries Research Foundation/Woods Hole Oceanographic Institution Shelf Research Fleet data set spans 5 years, sampling the New England shelf at higher temporal resolution. Both data sets are described in detail below.

3.1. The Ecosystem Monitoring Program Data Set

The Ecosystem Monitoring Program (EcoMon) has been collecting oceanographic and lower-trophic level measurements on the Northeast U.S. Shelf for decades. Run by NOAA's Northeast Fisheries Science Center, the program continues a long history of regular hydrographic and plankton sampling dating back to the 1970s. Sampling following standard protocols and using standard gear is conducted on up to six full-shelf surveys per year, spanning the continental shelf between Cape Hatteras, NC and Cape Sable, Nova Scotia inclusive of the Gulf of Maine and Georges Bank (Figure 2a). Standard EcoMon surveys typically sample at 35 fixed stations and 120 randomly distributed stations across the Mid-Atlantic Bight, Gulf of Maine and Georges Bank (Figure 2a). EcoMon sampling is also conducted on the Northeast Fisheries Science Center Groundfish Surveys, wherein hydrographic measurements are made at ~390 stations spanning the same region. Overall, the current hydrographic database includes observations from over 60,000 stations, averaging between 1,000 and 2,000 stations per year. The broad spatial coverage and relatively long uninterrupted timeseries makes EcoMon an ideal data set to examine recent changes in the character and frequency of salinity intrusions, particularly relative to the Lentz climatology. EcoMon surveys typically sample 50 profiles per year within the area sampled by the Shelf Research Fleet.

Prior to 1987, hydrographic sampling was largely accomplished through the collection of water samples at discrete depths. CTD's were gradually introduced to the surveys in the early 80s, becoming standard equipment in 1988. For this study, we examine hydrographic data collected between 1990 and 2019, limiting our analysis to the period when CTDs had been fully incorporated into EcoMon surveys so that intrusion statistics are not biased by low vertical resolution. This also allows for more direct comparison with Survey Fleet results. Data are averaged to 1 db depth bins vertically. To be consistent with the Lentz climatology and Shelf Fleet analysis, we consider here the subset of EcoMon profiles collected at stations having water depth ≤150 m within the Middle Atlantic Bight and Georges Bank regions (Figure 2a). In addition to these regional requirements, profiles must also satisfy the following criteria: (a) water depths ≥30 m, (b) samples at 5 or more depths, and (c) vertical density inversions between adjacent samples measuring less than 0.05 kg m^{-3}. In total, 21,486 EcoMon profiles met these criteria.

3.2. The Shelf Fleet Data Set

The Commercial Fisheries Research Foundation/Woods Hole Oceanographic Institution Shelf Research Fleet is a community science program that enlists fishing vessels to deploy CTD (conductivity-temperature-depth) sensors to measure hydrographic variables across the New England Shelf. Data collection began in late-2014 and continues to the present. Here, we examine profiles collected by the program between 2015 and 2019, a period of 5 years.

Samples were collected at weekly intervals from 2015 to 2017, decreasing to bi-weekly intervals from 2018 to 2019. Typically, three vessels sample across the continental shelf at a time within each sampling window. A map of the stations occupied through 2019 appears in Figure 3, where black dots show the position of stations without intrusions, while the green dots denote stations where intrusions were observed. Stations generally span the width of the shelf between the 30 and 200 m isobaths in a domain bounded by 70.5°–71.5°W and 40.0°–41.3°N, with some deeper stations present as well. Note that the distribution is not even across the shelf but reflects both the temporal and spatial patterns of active fishing.

The fishing vessels deploy RBR-Concerto CTDs equipped with wireless systems such that data can be downloaded from the deck, shortly after deployment, to an iPad provided by the Shelf Research Fleet. Data is then plotted and stored on the iPad. CTDs are rotated among vessels, and swapped out over a period of months for maintenance and calibration. The CTDs have been routinely calibrated throughout the program, both by the manufacturer and via parallel deployments on research cruises in comparison with SeaBird 911+ systems. Data were bin averaged in 1 m depth increments, consistent with the data processing from the Ecosystem Monitoring program. The Commercial Fisheries Research Foundation reports that the fishing vessels have used the hydrographic data to assist in deciding where to actively fish, which provides motivation for continued participation in the Shelf Research Fleet Program.

In total, 475 profiles were collected through 2019, with 119 collected in 2015, 112 in 2016, 105 in 2017, 81 in 2018, and 58 in 2019. The fewest number of profiles in an individual month was 3 (in October 2017 and April 2018) and the greatest number was 27 (in April 2017). Variations in monthly sampling result from a number of factors, including weather, fishing conditions, and servicing and calibration of CTDs.

The initial analysis was performed on the 5 years of the Shelf Research Fleet data, which identified a significant increase in the frequency of occurrence of the Salinity Maximum Intrusions. The collection of data from a community science activity such as the Shelf Research Fleet includes inherent biases. The data are collected in areas where the fishing activity is greatest, and are not randomly distributed as in the Ecosystem Monitoring

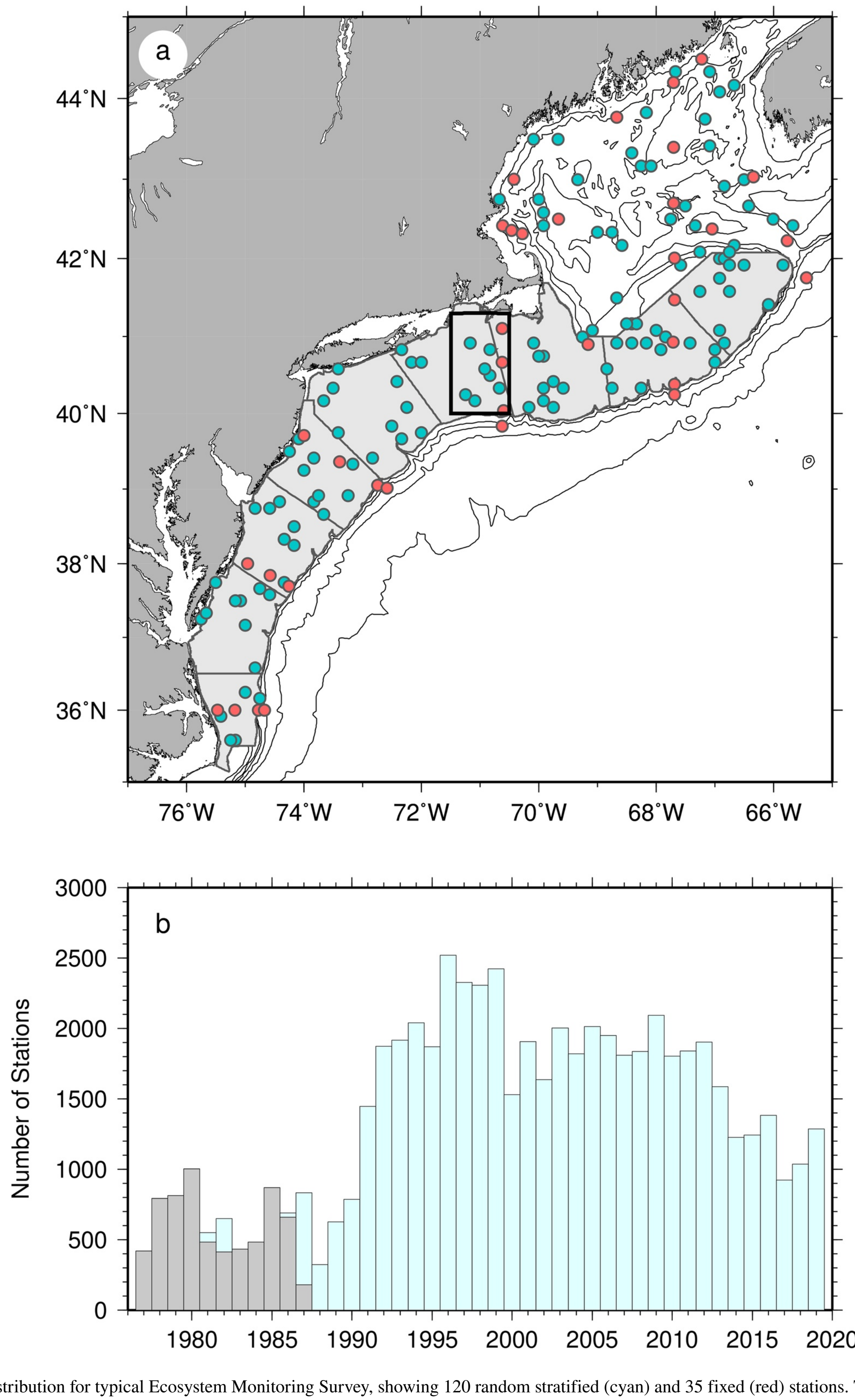

Figure 2. (a) Station distribution for typical Ecosystem Monitoring Survey, showing 120 random stratified (cyan) and 35 fixed (red) stations. The domain typically sampled by the Shelf Research Fleet is denoted by the box. Hydrographic observations collected within the gray shaded polygons are considered for this analysis. (b) Histogram showing the time history of data collections in the EcoMon database. The colored bars show the transition in sampling methodologies, shifting from collecting discrete water samples using Niskin bottles (gray) to deploying conductivity-temperature-depth (CTD) instruments to profile the water column (blue).

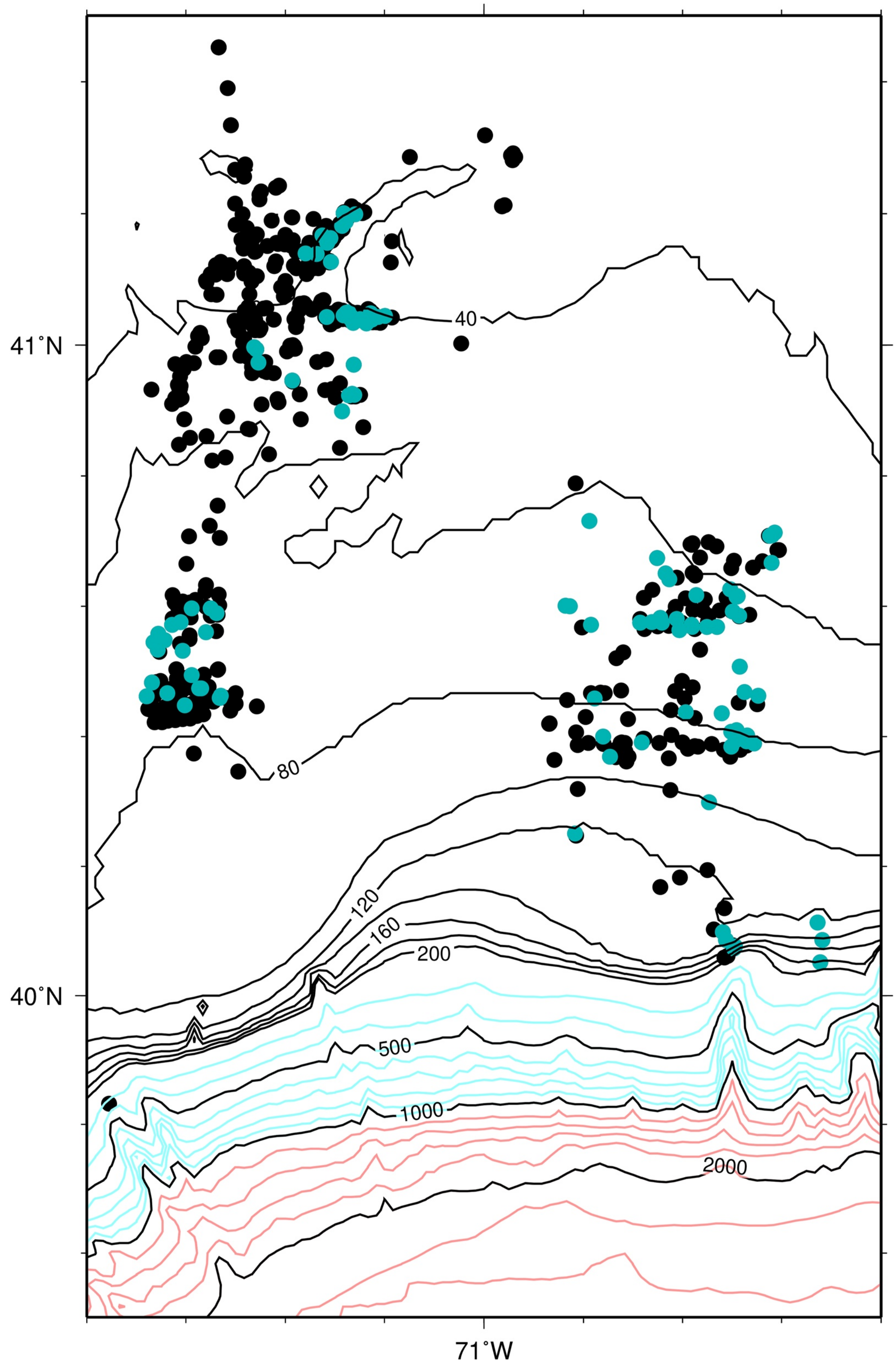

Figure 3. A map of the profiles collected by the Shelf Research Fleet between 2015 and 2019. Blackdots denote profiles with no intrusion, while the green dots denote profiles where an S_{max} intrusion was identified. The profiles generally are located between the 30 and 200 m isobaths. The black contours denote isobaths from 40 to 200 m in 20 m increments in addition to the 500, 1,000, and 2,000 m isobaths. The blue contours denote the 300–900 m isobaths in 100 m increments, and the red contours denote the 1,200–2,400 m isobaths in 200 m increments.

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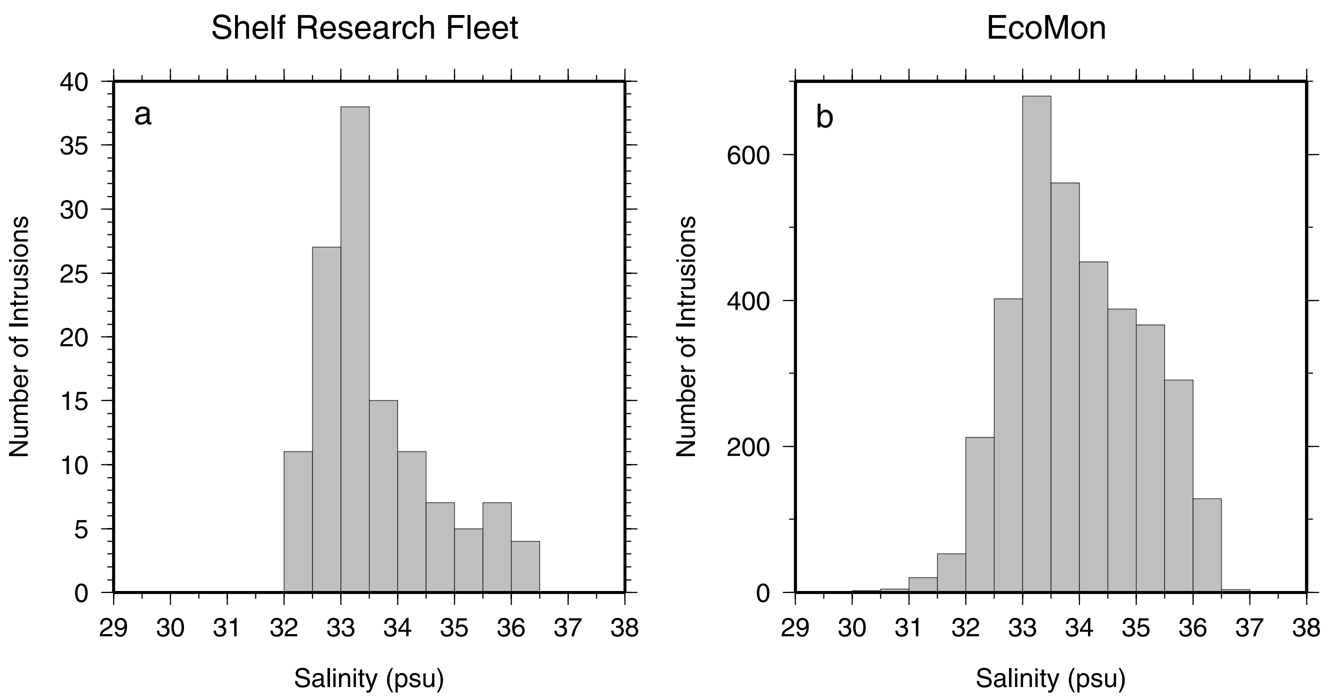

Figure 4. (a) Histogram of the peak salinity (S_{max}) associated with each intrusion identified in the Shelf Research Fleet data set from 2015 to 2019. (b) A histogram of the peak salinity (S_{max}) detected within each Salinity Maximum intrusion in the EcoMon data set.

program. However, cross-comparison of the southern New England region data from the Ecosystem Monitoring program with the Shelf Research Fleet data showed consistency in the frequency of occurrence of the intrusions as well as in the appearance of profiles with multiple intrusions.

4. Characteristics, Spatial Pattern, and Frequency of Salinity Maximum Intrusions

The characteristics of Salinity Maximum Intrusions are described for the time period 1990–2019 from EcoMon and 2015–2019 from the Shelf Research Fleet, with an emphasis on changes relative to the 1960–1998 conditions documented by the Lentz climatology. In the following, we discuss the characteristics of the intrusions as measured in each data set, as well as the temporal variability observed. Next, the frequency of the intrusions is presented. In general, there are significant differences relative to the earlier climatology.

4.1. Salinity Maximum Intrusion Characteristics

We now consider the statistics of intrusion characteristics as revealed by the two data sets. We present histograms from both the Shelf Research Fleet and EcoMon for the salinity at the intrusion peak (S_{max}), the depth of the intrusion (z_m) and its vertical position relative to the depth of peak stratification, the salinity anomaly relative to ambient conditions (ΔS), and the intrusion thickness.

The average value of the Salinity Maximum from the Shelf Research Fleet profiles is 33.60 PSU, with values ranging from 32.00 to 36.45 PSU (Figure 4a). The majority of intrusions have salinities between 33.0 and 33.5 PSU, although there is a broad spread of values between 34.0 and 36.5 PSU. The higher values tend to be observed in deeper waters over the upper continental slope. On average the intrusions on the New England shelf contain waters that are fresher than the waters found in the Shelfbreak Front (34.0 PSU) but saltier than the waters over the shelf, generally falling between 32.0 and 33.0 PSU. This is consistent with the EcoMon analysis, which finds Salinity Maximum values in the same range but with an even larger number of intrusions at higher salinities and an average of 33.9 psu (Figure 4b). As expected, intrusions having higher peak salinities (>34.5) were observed progressively closer to the shelf edge in the EcoMon data set. The temperature ranges from 13 to 21°C

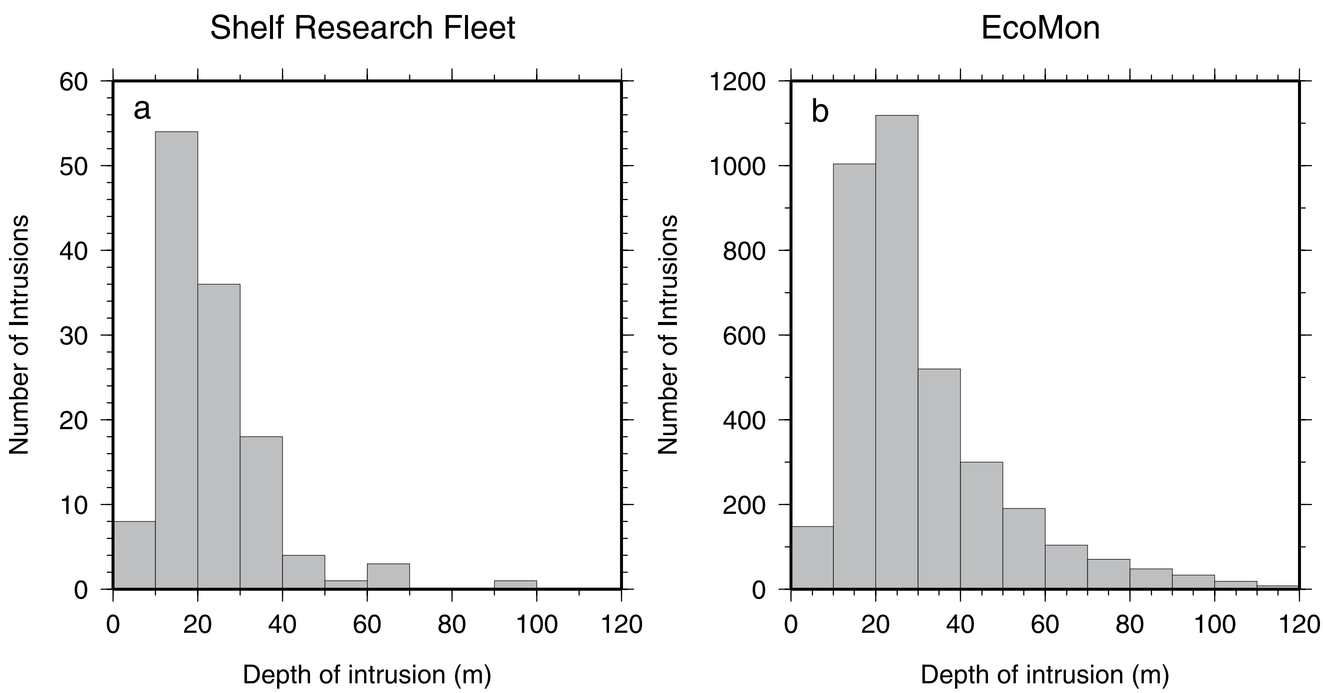

Figure 5. (a) Distribution of the intrusion depth z_m (meters) from the Shelf Research Fleet profiles. (b) Histogram of intrusion depth z_m (meters) as detected in the EcoMon database.

for most of the intrusions. The most common density range for the intrusions is between 23.5 and 24.5 σ_Θ, which is the typical range of densities for the pycnocline in the Middle Atlantic Bight.

The mean depth of intrusions observed in the Shelf Research Fleet and EcoMon databases was 22.04 and 29.8 m, respectively. Lentz (2003) notes that intrusions tend to occur in the upper 30 m of the water column, preferentially at the depth of peak stratification. The mean intrusion depth measured in both recent data sets incorporates a seasonal progression that tracks the changes in stratification, shallowing in late summer and deepening in fall.

The distribution of the depth of S_{max} is shown in Figure 5. Consistent with the earlier climatology, the majority of intrusions are observed in the 10–30 m depth range, with depths skewed somewhat deeper in the EcoMon data set. In both data sets, there is a broader distribution of deeper intrusions. These intrusions are observed in deeper waters, and generally have large values of S_{max}.

Consistent with Lentz (2003), intrusions identified in the EcoMon data set are tightly aligned with the depth of the seasonal pycnocline (Figure 6b). Interestingly, this is not the case in the Shelf Fleet data set. Here, a significant number of intrusions are observed at depths shallower than the depth of peak stratification (Figure 6a). Notably, some intrusions in the Shelf Fleet data set occurred at very shallow depths, underlying a very thin fresh surface layer. These fresh layers can occur at depths above the depth of peak stratification.

In general, the peak stratification measured in profiles with intrusions spans a broad range in both data sets, between 1 and 9×10^{-3} s^{-2}, consistent with the wide range of stratification over the stratified portion of the seasonal cycle.

The mean intrusion thickness in the Shelf Fleet data set is 15.65 and 19.76 m in the EcoMon data set. The majority of intrusions are less than 10 m thick in the Shelf Fleet data set and less than 20 m thick in the EcoMon data set, although both data sets include intrusions reaching 100 m which are mostly observed in deeper water (Figure 7).

One interesting aspect of the intrusions in both the Shelf Research Fleet and EcoMon data sets is the presence of multiple intrusions within a single profile. Individual intrusions must satisfy the criteria that $\Delta S \geq 0.2$ while being separated from other peaks by at least 5 m in the vertical. On average, 20% of the EcoMon profiles contained multiple intrusions. While a single intrusion was certainly the most common case, the EcoMon data set indicates that multiple intrusions have become more common in recent years. We observe an increase through

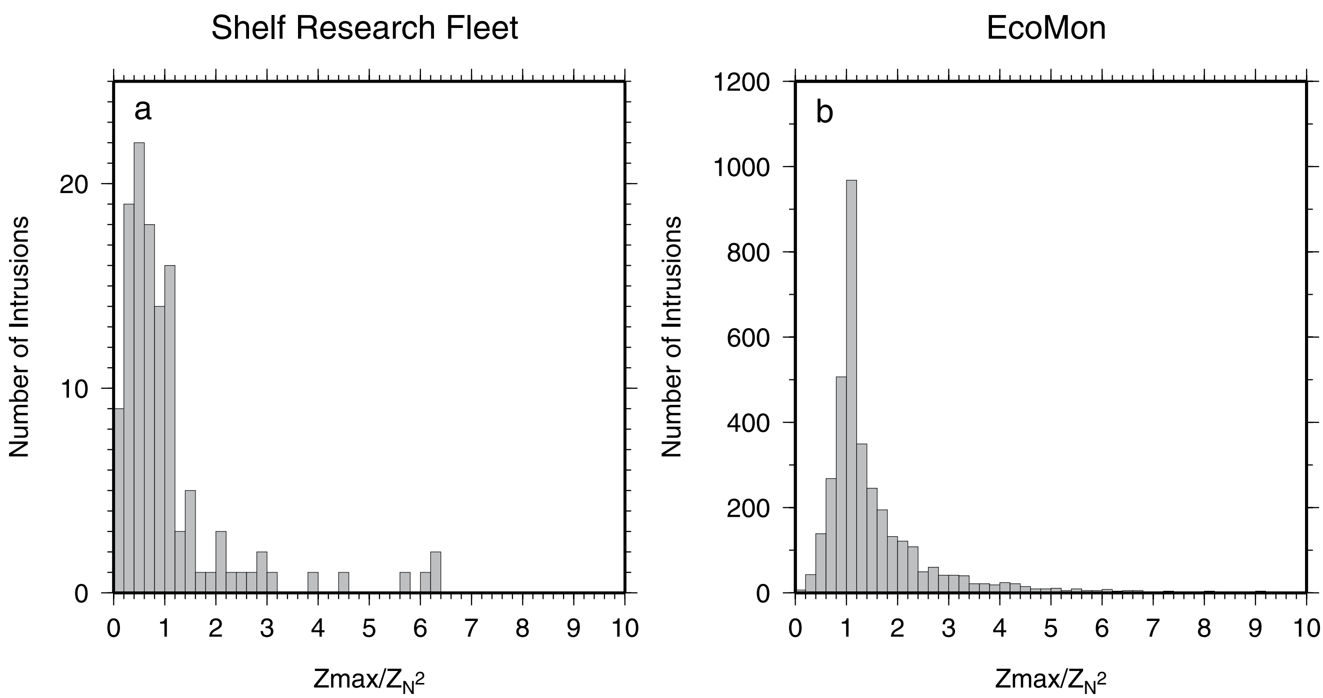

Figure 6. (a) Distribution of the ratio of the depth of S_{max} to the depth of peak stratification from the Shelf Research Fleet data set. (b) Histogram showing the ratio of intrusion depth to the depth of maximum stratification in the EcoMon data set.

the late 1990s in the percent of profiles containing more than one intrusion (Figure 8). Between 1994 and 1999, the percent of EcoMon profiles with multiple intrusions increased steadily from 0% to 20%, remaining in that range for the next two decades.

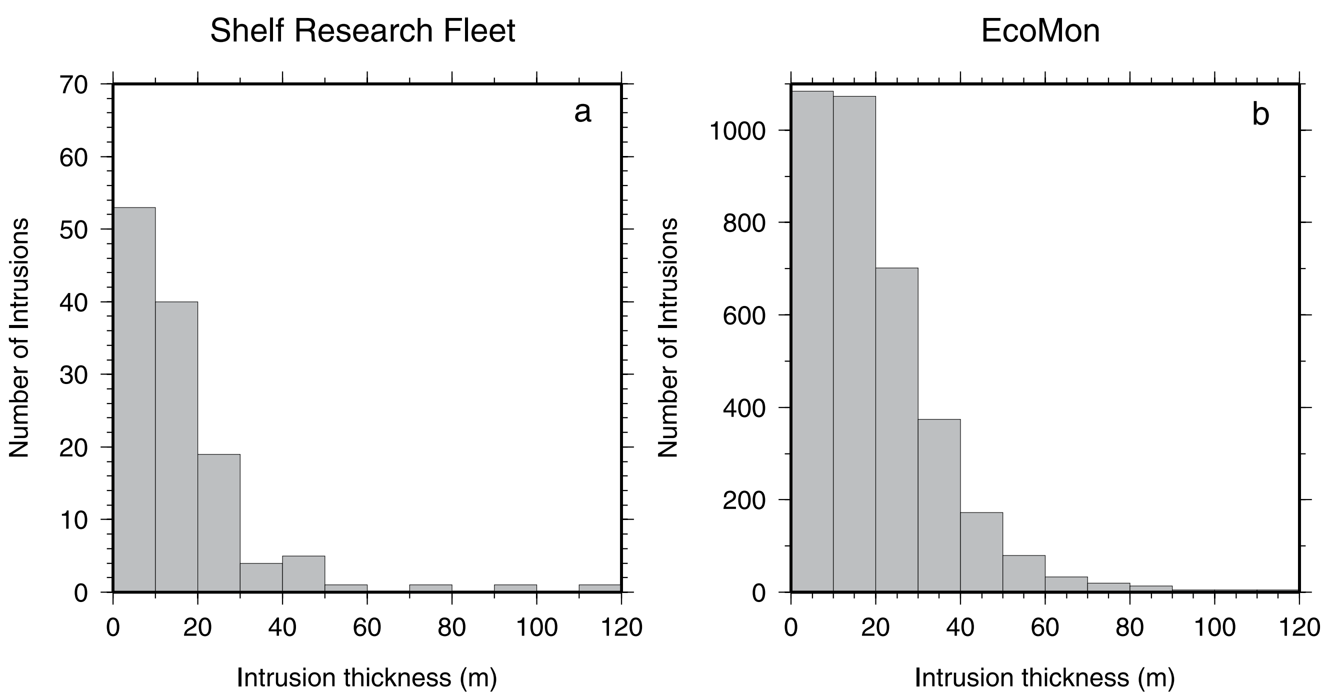

Figure 7. (a) Distribution of the thickness of S_{max} intrusions from the Shelf Research Fleet data set. The thickness is defined in Figure 1 (b) Histogram showing the thickness of intrusions in the EcoMon data set.

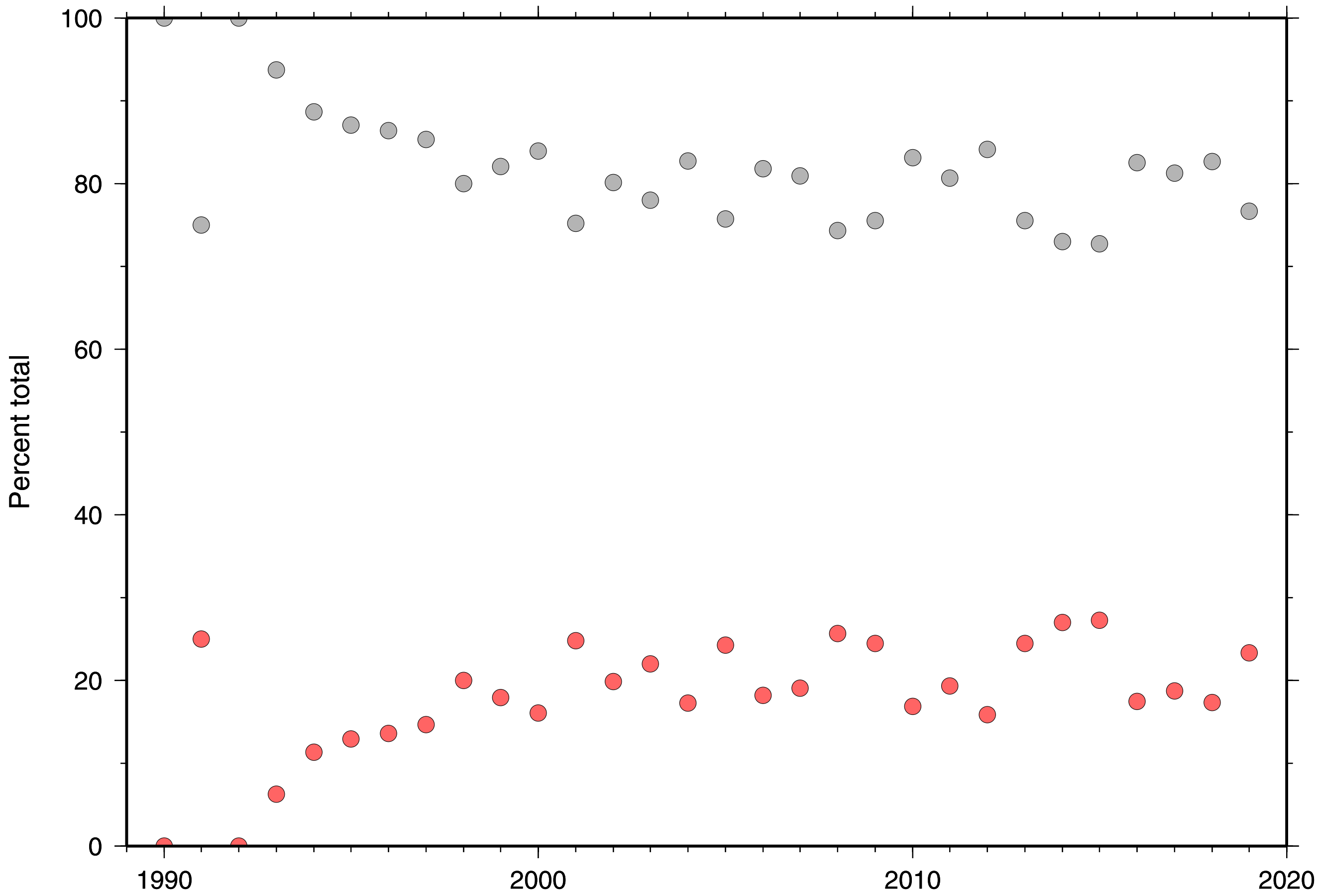

Figure 8. Percent of EcoMon profiles with intrusions per year that contain one (gray) versus multiple intrusions (red).

Between 2015 and 2019, the Shelf Research Fleet database shows that 10% of the profiles with intrusions contained multiple S_{max} features at different depths. Of these, 11 profiles contained two maxima, one profile included three maxima, and one profile included four maxima. The profile for the case with four maxima is shown in Figure 9. This suggests that the Shelf Research Fleet has observed significantly more complex layering structures than was seen by the Lentz climatology, since there is no mention of multiple intrusions in that study.

The mean ΔS from the Shelf Research Fleet data set was 0.46 PSU. The distribution was sharply peaked toward values near 0.2 PSU but had extreme values as large as 1.7 PSU.

4.2. Spatial Pattern of S_{max} Intrusions

A drastic change from the previous climatology is the increasing shoreward penetration of the intrusions. Lentz (2003) states that the intrusions are limited to within 30 km of the shelfbreak, although a limited number of intrusions did exceed 100 km shoreward of the shelfbreak. However, as Figure 2 shows, Shelf Research Fleet data shows numerous intrusions up to 100 km shoreward of the shelfbreak. The EcoMon data confirms this, with numerous intrusions extending to the 30 m isobath throughout the Middle Atlantic Bight (Figure 10a). Consistent with the previous climatology, intrusions occur more frequently in the southern portion of the Middle Atlantic Bight (Figure 10b).

A breakdown of the spatial distribution by month from the EcoMon data appears in Figure 11. This strongly suggests that the time period for maximum shoreward penetration is between July and September. Intrusions were most common at the shelf edge in early spring and fall, but prevalent across the width of the shelf during August and September when the stratification was well-developed. The shoreward limit of intrusion activity observed

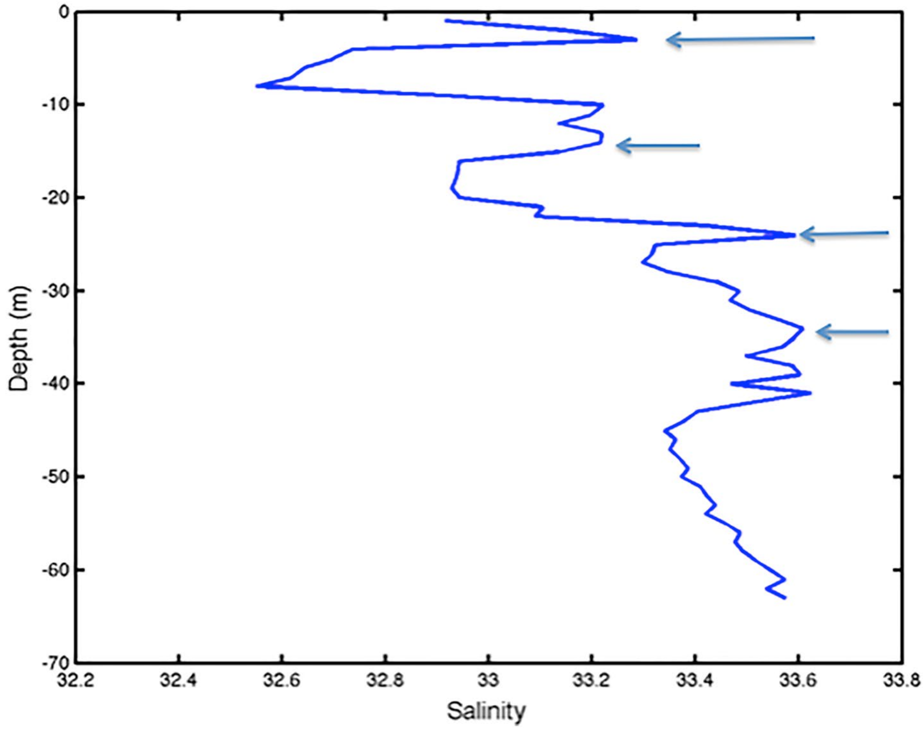

Figure 9. A profile showing four distinct S_{max} intrusions. The four local salinity maxima used in calculating the intrusion statistics are marked with arrows.

from July through September extends to the 30 m isobath, which was the minimum depth range included in the analysis.

A particularly dramatic example of an S_{max} intrusion was observed on 8 August 2018, approximately 10 nautical miles south of Martha's Vineyard. Two separate profiles recorded maximum salinity values over 36.0 PSU. While these profiles were not included in the analysis, they are a strong indicator of the remarkable shoreward penetration of high salinity water masses across the continental shelf relative to previous decades.

4.3. Frequency of Intrusions

The frequency of intrusions, which is defined as the fraction of the total profiles that contain an S_{max} intrusion, appear in Figure 12 for the Lentz climatology, the EcoMon data set, and the Shelf Research Fleet data set. We note that the Shelf Research Fleet data is much more limited in space (southern New England) and time (5 years) relative to the two other data sets.

Intrusions were observed much more frequently in both the EcoMon and Shelf Research Fleet data compared with the earlier climatology. Overall, intrusions were observed in 11% of the profiles examined by the Lentz climatology, while intrusions were present in 14% of profiles examined from EcoMon and 17.5% of the profiles from the Shelf Research Fleet data set. It is important to note that the criterion used for defining an intrusion in this analysis is double that used in the earlier climatology, increasing from $\Delta S \geq 0.1$ to ≥ 0.2. The increase in occurrence frequency would likely have been even greater under the less conservative threshold. Intrusion frequencies are largest in the southern Middle-Atlantic Bight based on the broad-scale data sets, with an abrupt transition in intrusion frequency measured in the vicinity of Southern New England (Figure 10b).

Intrusions were observed most frequently between May and November in the EcoMon data set, with 22% of profiles containing intrusions during this period. The Intrusion frequency increased from 5% in May to ~30% in July and August, peaking at 47% in September and decreasing again to 20% in October and 10% in November. The September peak is roughly equivalent to the frequency observed in the Shelf Fleet and roughly double that of

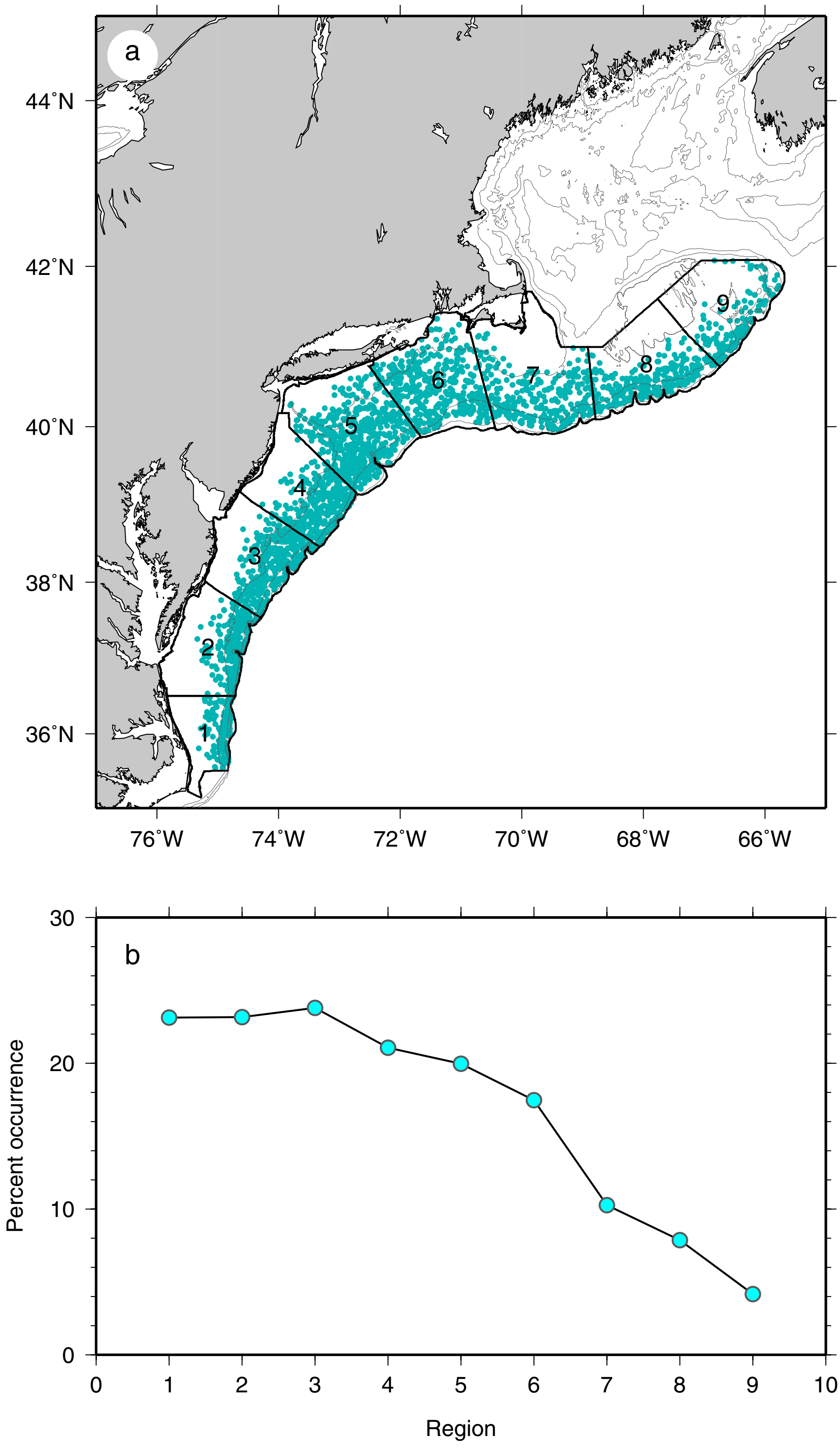

Figure 10. (a) Distribution of S_{max} intrusions identified in the EcoMon data set between 1990 and 2019 (cyan dots). The 50, 100, and 200 m isobaths are shown in gray. Regional polygons corresponding to Figure 5b are also shown. (b) Percent occurrence of S_{max} intrusions as identified from the EcoMon data set within each regional polygon shown in Figure 2a.

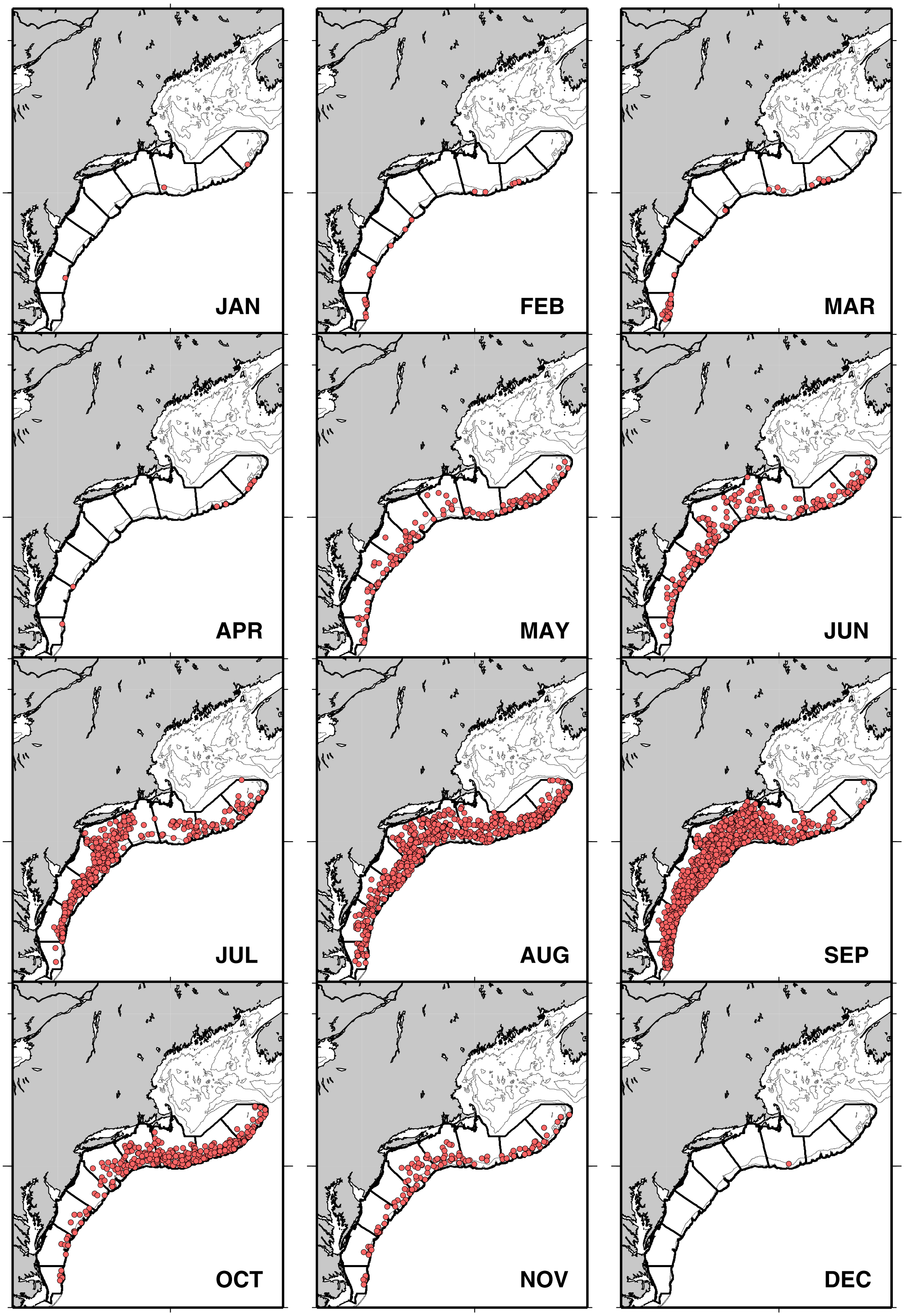

Figure 11. Monthly distribution of S_{max} intrusions as identified in the EcoMon data set between 1990 and 2019.

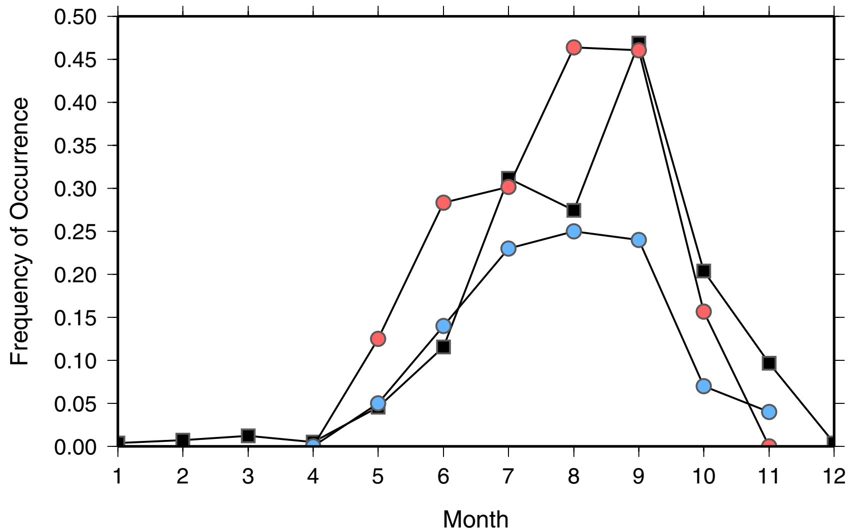

Figure 12. Monthly frequency of S_{max} intrusions from the Shelf Research Fleet (red), EcoMon (black squares), and from the Lentz climatology (blue). Intrusions were not detected in the Shelf Research Fleet data set between December and March.

the Lentz climatology for the same month. Only a very small number of intrusions were identified outside of the stratified season, consistent with the other two data sets.

Intrusions were observed between May and October in the Shelf Research Fleet data, occurring in 35.9% of profiles during the stratified portion of the year. Relative to the earlier climatology, the frequency nearly doubles at its peak, measuring 46% for the months of August and September compared to ∼25% in the climatology. The relative frequency more than doubles in May, June, and October. In November, no intrusions were detected in the Shelf Research Fleet data set, although these occur 4% of the time in the earlier climatology. It is possible that the intrusions detected in the earlier period during November occurred in the southern portion of the Middle Atlantic Bight, where closer proximity to the Gulf Stream and stronger stratification may play a role in allowing the intrusions to occur later in the seasonal cycle.

The Shelf Research Fleet results suggests that intrusions are much more prevalent in recent years compared to earlier decades. The EcoMon data set provides the opportunity to determine whether the Shelf Research Fleet sampled intrusions that are part of a gradually increasing trend or more abrupt regime shift, or whether they represent a few anomalous years. Figure 13 shows the interannual variation in the frequency of Salinity Maximum intrusions identified within the EcoMon data set. Overall, the intrusion frequency steadily increases from 1% to 20% over the first 10 years of the time series (1990–2001), before stabilizing at these higher rates. Following the transition period, the intrusion frequency fluctuates between ∼15% and 25% for the next 20 years. It is notable that the Lentz analysis ends partway through the period of transition, while the Shelf Research Fleet observations fall in the period well after the transition and include some of the highest measured intrusion years in the EcoMon record. Overall, intrusions were detected in 22% of the EcoMon profiles collected between 2015 and 2019 (the sampling period for the Shelf Research Fleet). Considering only those EcoMon profiles collected within the Shelf Research Fleet sampling region during this period, the frequency of intrusions decreases to 18.1%. This is remarkably similar to the proportion detected in the Shelf Fleet data set, indicating that the two independent data sets are consistent. By comparison, 7% of EcoMon profiles collected between 1990 and 1998 (overlapping with the earlier climatology) contained intrusions, also consistent with the statistics reported independently by Lentz (2003).

5. Discussion

5.1. Temporal Variability of Intrusion Frequency From the Shelf Research Fleet

The monthly sampling by the Shelf Research Fleet allows for consideration of both annual as well as monthly variations in the frequency of intrusions. However, the results must be interpreted with caution, as there are large variations in the number of profiles from individual months.

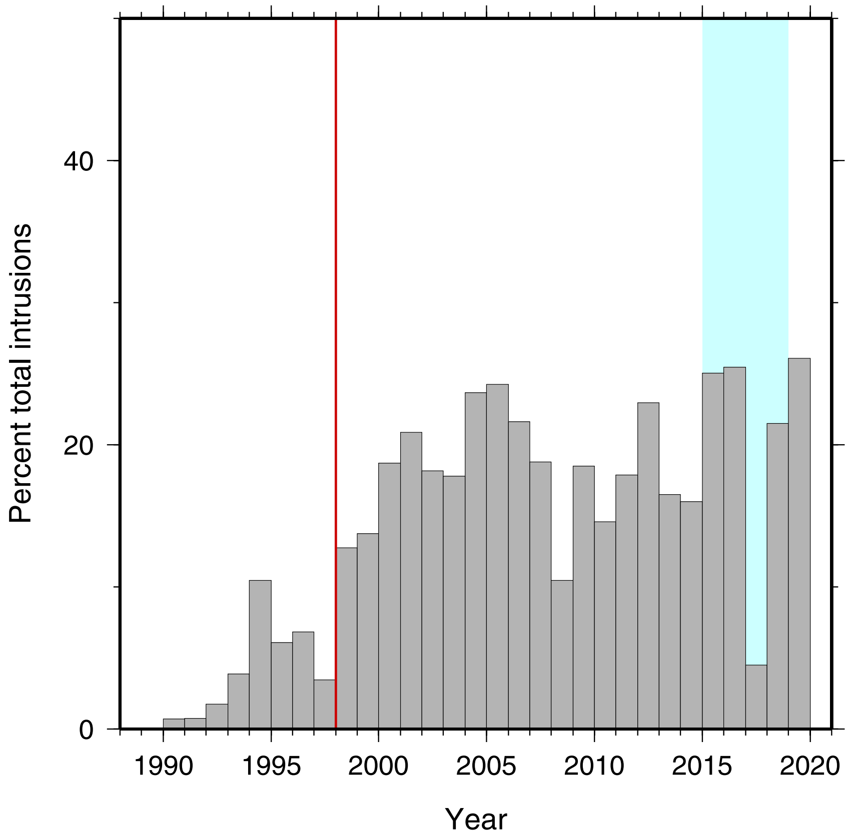

Figure 13. Proportion of profiles in the EcoMon database found to contain Salinity Maximum intrusions as a function of year (gray). The red line marks the last year in the Lentz (2003) climatology while the cyan shading denotes the period included in the Shelf Research Fleet analysis (2015–2019).

Of the 5 years, 2015 measured the highest frequency of intrusions (Figure 14). Fifty-one percent of the profiles in 2015 showed evidence of an S_{max} intrusion. In contrast, 2017 had measured the lowest frequency, with only 15% of profiles showing the presence of an S_{max} intrusion.

The monthly frequencies show that there are interesting differences from year to year in the seasonal timing of the intrusions. In 2015, frequencies were the highest of all the five years in May through August. The peak frequency in 2018 was in August, while the peak frequency in 2016, 2017, and 2019 was in September. The maximum frequency was in September 2019. Other time periods with frequencies of over half of the profiles having intrusions include June–September 2015 and August 2018.

The sharp year to year differences in monthly distribution of intrusion frequency suggests that Warm Core Rings may have become an increasingly important factor in forcing the S_{max} intrusions. Recent work (Gangopadhyay et al., 2019) has shown that a Regime Shift occurred in the number of rings formed annually by the Gulf Stream after 2000. The average number increased from 18 per year (1977–1999) to 33 per year after 2000 (2000–2017). There are big differences in the number of rings formed by the Gulf Stream from year to year during 2015–2019. For example, 28 rings were formed in 2016 and 42 in 2017. In addition, meanders in the Gulf Stream have shifted westward and increased in amplitude since the 1990s (Andres, 2016). On occasion, very large amplitude meanders come into close proximity to the shelf break (e.g., Ezer et al., 2013; Gawarkiewicz et al., 2012). This is reflected in the high salinities recently measured over the upper continental slope by gliders from the Ocean Observatories Initiative Pioneer Array (Gawarkiewicz et al., 2018). Thus, there are considerably more salty water masses over the upper continental slope near the surface. In addition, stratification during the summer has been increasing considerably, as noted by Harden et al. (2020) in observations made during June for the time period 2003–2013. Future work will examine in more detail the relationship between the proximity of Warm Core Rings and the timing and position of S_{max} intrusions using data from a climatology of rings (Gangopadhyay et al., 2020).

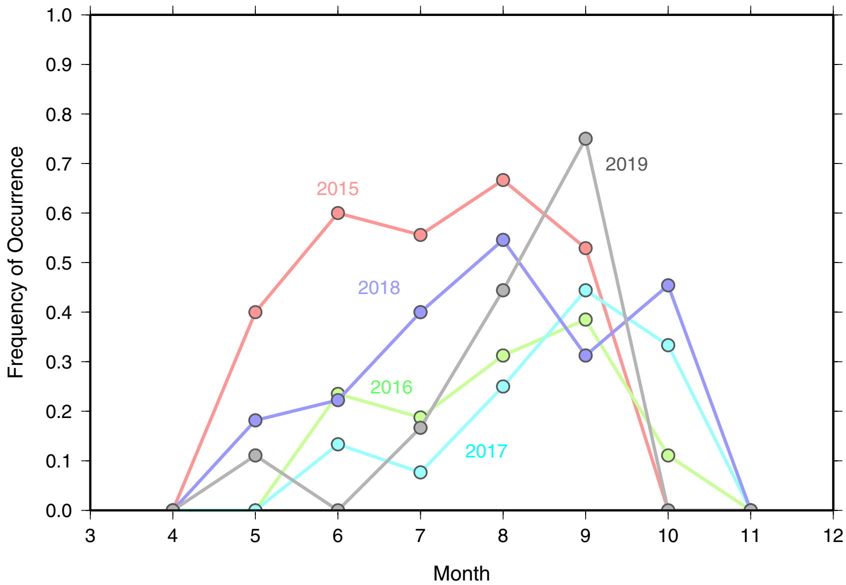

Figure 14. Monthly frequencies of S_{max} intrusions in profiles from the Shelf Research Fleet from 2015 to 2019. The different years are labeled with different colored symbols.

This study is merely suggestive that rings may play an important role in the increasing frequency of intrusions. The combination of more salty water offshore and stronger continental shelf stratification likely makes conditions more conducive to the generation of S_{max} intrusions. However, the dynamics of these intrusions including their generation remains elusive. Aikman (1984) suggested that a mis-match in pycnocline depths between the continental shelf and slope reverses density gradients at middepth and may drive geostrophic currents onshore. This remains to be tested in future observations. Concurrent velocity observations will be critical to understanding the dynamics of these intrusions.

The Shelf Research Fleet data set can be used to estimate the salinity increase in the water column resulting from the intrusions. The mean ΔS is 0.4615, and the mean thickness is 15.65 m. This results in an increase in salinity of 0.144 over the upper 50 m of the water column. The mean latitude for the intrusions is 41.7 km north of 40°20′N, which is the mean position for the foot of the Shelfbreak Front. Lentz (2003) notes that the majority of the intrusions occur within 30 km of the shelfbreak. The onshore penetration distance has increased since the previous climatology. The maximum northward position was 97 km north of the mean position of the foot of the Shelfbreak Front and was likely limited by the northward limit of the profiles that were sampled. The increased frequency and shoreward penetration of the intrusions likely contribute to the warming of the Cold Pool in recent years.

5.2. Possible Ecological Consequences

One interesting aspect of the changing nature of the characteristics of the S_{max} intrusions is the presence of multiple intrusions in individual profiles. This may result in much more complex layering of zooplankton and other organisms that serve as prey for higher trophic level predators and hence more complex predator-prey interactions. The increasing frequency of the intrusions coupled with their much greater shoreward penetration may increase both the quantity as well as the shoreward extent of organisms typically found over the upper continental slope or within Warm Core Rings. This may have particular importance for marine organisms in which different life stages may involve transport across the continental shelf, for example, Northern short-finned squid or the American eel (Rypina et al., 2014).

The cross-shelf velocity field associated with intrusions remains an outstanding critical issue for understanding the impacts of intrusions. Changes in the magnitude, structure and occurrence frequency of intrustions may very well lead to changes in the Lagrangian transport times relative to several decades ago. An illuminating study of the complex transport mechanisms in this region indicates how subtle the Lagrangian aspects of larval fish transport may be (Hare et al., 2002). Flagg et al. (1994) have shown from moored measurements that cross-shelf velocities associated with S_{max} intrusions may be as large as 0.2 m/s. Thus these intrusions may provide a significant boost to larval fish, squid, and other organisms that routinely transit the continental shelf as part of their life cycle. Implications of these changes to such an important cross-shelf transport process will be important for future study in terms of larval fish transport (Walsh et al., 2015) and in the broader context of vulnerability of Living Marine Resources to climate change impacts in the region (Hare et al., 2016). The data used in this study do not include velocity measurements, but future studies will need to address the velocity fields associated with these intrusions.

The increasing frequency of the intrusions also have implications for the onshore transport of nutrients. A recent study (Friedrichs et al., 2019) concluded that inter-annual variability of nutrient levels over the continental shelf in the Middle Atlantic Bight was primarily due to fluctuations in onshore transport of nutrients from the continental slope. Future work should also examine the role of S_{max} intrusions in onshore transport of nutrients to the continental shelf.

5.3. Future Directions

The data used for analysis in this study was not specifically directed toward resolving these intrusions, and thus a number of questions remain regarding their spatial and temporal scales. Fortunately, recent high resolution observations collected in June 2021 from the R/V Neil Armstrong as part of an NSF-funded project will provide detailed information on the spatial scales of intrusions, connection to Warm Core Rings offshore, and turbulence and mixing near the intrusions. Sampling includes shipboard velocity measurements as well as repeat profiling with a Vertical Microstructure Profiler. Multiple Autonomous Underwater Vehicles were deployed and successfully sampled within and around two separate intrusions. Analysis of these observations as well as those from a second planned cruise in 2022 will be reported in the future.

The contrast between the present state and that described by Flagg et al. (1994) is striking. Observations made in 1989 suggest that S_{max} intrusions were uncommon. Yet the EcoMon analysis (Figure 14) indicates that intrusions occur over 20% of the time in this region. Flagg et al. (1994) noted that the presence of high salinity water over the upper slope is likely a necessary pre-condition for initiation of these intrusions, and attributed their infrequent appearance to the absence of high salinity water masses over the continental slope. As observations from the OOI Pioneer Array have shown, water masses having salinities greater than 35.5 PSU are now frequently observed over the upper slope (Gawarkiewicz et al., 2018). Thus, one limiting factor noted in the past may now be relaxed, enabling the increased frequency of the intrusions.

The increasing frequency of these intrusions likely has important ramifications for the salt balance on the continental shelf in the Middle Atlantic Bight and certainly calls for an update to the salt budget estimated by Lentz (2010). However, given the uncertainty over both estimating the duration and along-shelf scales of the intrusions, which are not attainable from the data sets examined herein, we hesitate to provide even an order of magnitude estimate for the increased salt flux to the continental shelf. Observations made during the intrusion-focused field study initiated in 2021 should provide valuable input to inform such estimates. Numerical modeling of salinity intrusions has not been widely reported, and resolving this process is necessary before models can accurately address recent changes to the salt balance.

Finally, the commercial fishing industry in New England has been experiencing change and efforts are continuing to understand how recent changes in fishing outcomes may have been affected by the increasing frequency of intrusions. Regular meetings between academic scientists and commercial fishers associated with the Commercial Fisheries Research Foundation are ongoing. Ultimately a better understanding of processes such as these will help to responsibly manage Living Marine Resources in the region and contribute to efforts to improve sustainability in the seafood industry.

6. Conclusions

Analysis of two separate data sets confirms a significant increase in the frequency of occurrence of S_{max} intrusions in the Middle Atlantic Bight. While some characteristics such as the depth of the peak salinity are similar to those reported in an earlier climatology of intrusions, other characteristics such as the salinity contrast with ambient shelf water have increased. In addition, a large number of recent profiles contained multiple layered intrusions. These results are important because they show that ocean warming and increasing stratification, which have been described on larger spatial and temporal scales, have a direct impact on important shelfbreak exchange processes. Together, these changes will likely have significant implications for ecosystem dynamics, including larval transport and increased shoreward penetration of organisms originating from the upper continental slope onto the continental shelf. Furthermore, the increasing presence of the intrusions also is likely to be important to the overall salt budget for the continental shelf in the Middle Atlantic Bight. Further work is necessary to understand the dynamics of these intrusions, including process oriented field work and modeling studies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data from the CFRF/WHOI Shelf Research Fleet is publicly available at http://science.whoi.edu/users/seasoar/cfrfwhoi. This is an archive jointly held between CFRF and WHOI. Data from the EcoMon program is available at the National Centers for Environmental Information World Ocean Database accessible at www.ncei.noaa.gov/products/world-ocean-database.

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