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Mid-Atlantic Bight cold pool based on ocean glider observations

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ABSTRACT

During summer, distinctive, bottom-trapped, cold water mass of remnant local and remote winter water called Cold Pool Water (CPW) resides as a swath over the mid to outer continental shelf throughout much of the Mid-Atlantic Bight (MAB). This evolving CPW is important because it strongly influences the ecosystem, including several important fisheries. Thus, there is a priority to better understand the relevant ocean processes and develop CPW forecast capability. Over the past decade, repeated high-resolution Slocum glider measurements of ocean water properties along a New Jersey cross-shelf transect have helped to define the variability of the CPW structure off New Jersey. More recently the Mid-Atlantic Regional Association Coastal Ocean Observing System-supported ocean gliders have occupied a series of along-shelf zigzag trajectories from Massachusetts to New Jersey and New Jersey to Maryland. The comprehensive set of March through November 2007 glider measurements has been used to define the annual evolution of the 10 °C Cold Pool in terms of its distribution and water properties. The rather steady warming at the rate of 1 °C per month July through October 2007 is reflected in the 2007 CPW temperature (T) and salinity (S) properties. We describe how a three-glider fleet view of the September 2013 Cold Pool (a) confirmed the Lentz (2017) CPW cold patch and (b) the impingement of a Gulf Stream warm core ring warmed and salted the 2013 CPW. The Gulf Sream 2013 event forced our extension of the CPW T and S properties.

1. Introduction

The Cold Pool is a distinctive, highly-variable, bottom-trapped, cold water mass remnant of the local and remote winter water. It is found during summer over the mid and outer continental shelf between Cape Cod and Cape Hatteras – a region known as the Mid-Atlantic Bight (MAB).

The Cold Pool is an important element in the MAB habitat according to Malone et al. (1983) and Flagg et al. (1994), who have shown that it affects phytoplankton productivity; and Sullivan et al. (2005) and Weinberg (2005) who have shown that it affects the behavior and recruitment of pelagic and demersal fish on the shelf.

The distribution and characteristics of this Cold Pool water mass evolves significantly during its May through October lifetime (Ketchum and Corwin, 1964; Boicourt and Hacker, 1976; Beardsley et al., 1976; Beardsley and Boicourt, 1981). Lentz (2003) present the annual evolution of a MAB-averaged cross-shelf section of the climatological temperature. This sequence shows that well-mixed winter shelf waters cool between January and March. The May section shows how the vernal onset of temperature- and fresh water-induced stratification creates a bottom-trapped, Cold Pool water mass with minimum temperatures dependent on the severity of the previous winter's local cooling.

Once formed, this distinctive Cold Pool goes through a complex evolution during the rest of the spring and throughout the summer. For example, during May–June the northeastern MAB Cold Pool gets colder due to continued inflow of winter water from the Gulf of Maine/Georges Bank (GoM/GB) region (Brown and Irish, 1993; Hopkins and Garfield, 1979; Ramp et al., 1988). The Lentz (2017) map of the NMFS May 1979 data reveals a patch of the coldest waters (or *"cold patch"*) within the Cold Pool. Ou and Houghton (1982) note that locations of the *"cold patch"* during the summer 1979 is consistent with the well-documented general 5 cm/s (~5 km/day) southwestward along-shelf MAB flow.

During the summer, the Cold Pool Water mass (CPW) is warmed by turbulent processes acting on its surface (Chen et al., 2014) and along its inshore boundary (Kohut et al., 2004). The CPW is also heated and salted by a complex array of turbulent processes along its offshore boundary which is the shelf-break front (SBF) (Houghton et al., 1982; 2010). Candidate

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across-SBF exchange processes result in episodic warm/salty intrusions into CPW by way of the interior and bottom boundary layers (Linder et al., 2004). Interactions between Gulf Stream Warm Core Rings (WCR) and the SBF undoubtedly contribute to such exchanges.

The cooling of northeast MAB CPW ceases in July, which is followed by a general warming of all the still distinct Cold Pool through September (Lentz, 2017). Then during autumn (primarily in October), the inevitable energetic storms mix the MAB water column well enough to erase the distinctiveness the Cold Pool by November, when and the following year's annual Cold Pool evolution cycle begins anew.

The mysteries of the Cold Pool and its importance to the MAB ecosystem prompt us to seek answers regarding these erosion processes. Such answers are now within our reach because of the newly available technologies, including ocean gliders, remote high frequency radar-derived surface current mapping, modern data-assimilation coastal ocean numerical models, and the development of the Integrated Ocean Observing System (IOOS; Bassett et al., 2010) and the Ocean Observatory Initiative (OOI): Pioneer Array. This paper describes what we have learned about the MAB Cold Pool from primarily glider observations.

2. Measuring the Cold Pool

Rutgers University researchers began deploying Teledyne/Webb Research (TWR) Slocum ocean gliders on the Mid-Atlantic Bight shelf in 2003 (Schofield et al., 2010). This earlier effort evolved into the effort of the Mid Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) to deploy ongoing series of Slocum glider missions along a (a) cross-shelf transect off New Jersey called the Endurance Line (Fig. 1; Leg-6); (b) cross-shelf series of zigzags from Massachusetts to New Jersey in the northeastern part of MAB (NE-MAB; Legs 1–6); and (c) the southwestern part of MAB (SW-MAB; Legs 6–10) is series of cross-shelf zigzags from New Jersey to Maryland. The following description of the different phases of the Cold Pool is based primarily on glider measurements from the most extensive cross-shelf transects represented by Legs 1, 6, and 8, respectively.

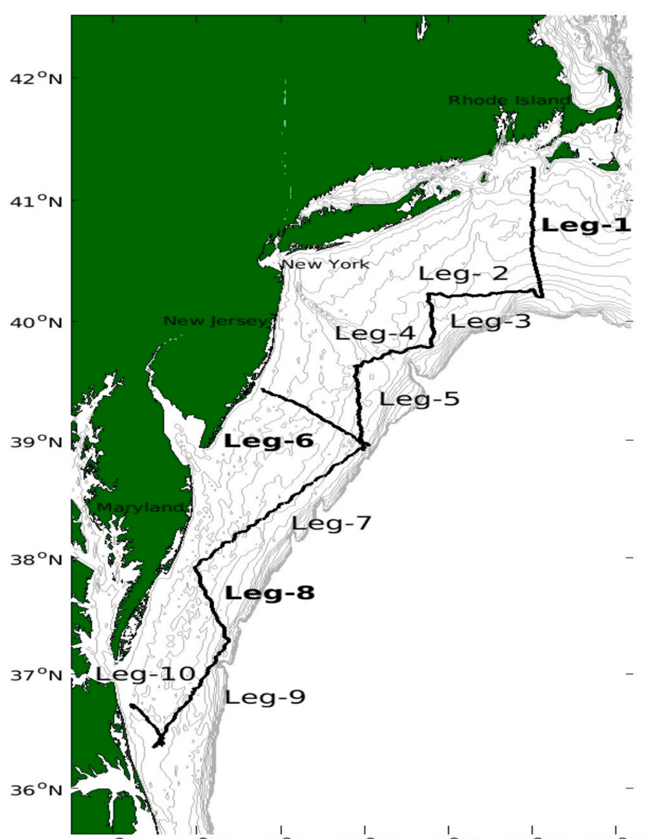

Fig. 1. The definition of the transect sections in this paper in terms of a composite of the May 2007 glider trajectory in the northeastern MAB (NE-MAB; Legs 1–6) and July 2007 in the southwestern MAB (SW-MAB; Legs 6–10). Leg-1, Leg-6 and Leg-8 are emboldened. Some of the MAB states are identified.

The Slocum glider sawtooths its way through the ocean (Schofield et al., 2010) with an average horizontal speed of about 0.25 m/s (½ kt.). A glider slant (27° rel. to horizontal) shelf profile consists of depths of about 3 m–3 m above the bottom. On the shelf, these Slocum gliders make about 20 sawtooth pairs of profiles in 3 h - our typical time between surfacings. We use the zigzag glider slices to estimate the extent and properties of the MAB Cold Pool during each of the glider missions. A typical zigzag run takes a typical 100 m Slocum glider (at ~25 km/day) about 3–4 weeks to transit from Massachusetts to New Jersey. All the gliders considered here measured a standard suite of measurements including pressure (P), temperature (T), pumped conductivity (C) (or derived salinity S), and an estimated glider inter-surfacing segment-averaged ocean velocity (V).

2.1. *Pre-cold pool – Late Winter/Early Spring*

The glider measurements between 13 March and 12 April 2007 define the MAB winter water mass, which is the basis for the 2007 Cold Pool Water (CPW). The cross-self glider transects show the expected vertically well-mixed "winter water". Leg-1 south of Massachusetts exhibits the coldest transect minimum temperature (T_{min}) at 2.87 °C (Table 1). The salinity at the Leg-1 T_{min} (S_{Tmin}) is 32.80 Practical Salinity Units (psu; see Appendix A for the way to covert those psu salinities into the more modern Absolute Salinity S_A). The Leg-6 transect off New Jersey is somewhat warmer with a T_{min} at 4.94 °C and saltier with a S_{Tmin} at 33.08 psu than the Leg-1 counterparts. The individual transect temperature minima T_{min} is a good proxy for the properties and location of the *core of the Cold Pool* of that section.

2.2. *Proto-cold pool – Mid-Spring*

Vernal warming of the MAB upper layer leads to the first definition of the 2007 Cold Pool off of New Jersey. This is shown by the 13–19 May 2007 Leg-6 glider measurements (Fig. 2) which contrast with the Leg-1 still well-mixed structure. However, both transect T_{min}s have warmed relative to the March T_{min}s. The along-shelf gradients in the Leg-1 versus Leg-6 water properties are typical of what we see even after the development of 2007 Cold Pool throughout the MAB as presented next.

2.3. *Cold pool 2007 established – Spring 2007*

The 23–27 May 2007 glider measurements (Fig. 3) show a surface layer that has warmed and freshened enough to isolate and thus define the 2007 Cold Pool Water throughout the MAB. However, note that T_{min} in both transects is somewhat cooler than that seen in April (and thus throughout the MAB). The along-MAB temperature gradients, with the Leg-6 waters generally warmer than the Leg-1 waters at corresponding depths define the cold patch in the northeastern MAB. We speculate that the cooler temperatures are due to the inflow of colder "upstream" waters from the Gulf of Maine/Georges Bank region.

2.4. *Cold pool – Summer 2007*

The 18–24 July Leg-6 reveals an increasingly distinct Cold Pool with a transect T_{min} of 5.60 °C (Fig. 4-upper). It compares well with the 11–15 June Leg-6 T_{min} of 5.32 °C (Fig. 3) and consistent with the expected translation of the temperature minimum patch. The 18–24 July Leg-6 S_{Tmin} compares well with the 11–15 June Leg-6 S_{Tmin} (Table 1) being only about 0.3 psu greater than its Leg-1 counterpart. The salinity difference is likely the signature of intrusion(s) of high salinity/warmer

Table 1
The 2007 section-minimum temperatures T_{min} and associated salinities S_{Tmin} are presented for a representative set of sections. For sub-thermocline waters (T < 10 °C), the means and standard deviations of *temperature departures* ($T_D = T - T_{min}$) and associated *salinity departures* ($S_D = S - S_{Tmin}$) are presented.

2007 Survey Month	Leg	Date	T_{min} (°C)	T_D Mean (°C)	T_D Std Dev (°C)	S_{Tmin} (PSU)	S_D Mean (PSU)	S_D Std Dev (PSU)
MAR	**Leg-1**	Mar16	2.872	1.70	0.81	32.801	0.23	0.16
	Leg-6	Apr 03	4.929	1.83	1.16	33.083	0.52	0.40
		Ave.	***3.901***	***1.77***	***0.99***	***32.942***	***0.38***	***0.28***
APR	**Leg-1**	Apr 28	4.843	1.30	0.82	32.815	0.01	0.24
	Leg-6	May 15	6.648	1.76	1.02	33.272	−0.00	0.23
		Ave.	***5.746***	***1.53***	***0.92***	***33.044***	***0.01***	***0.24***
		SPR. AVE.	***4.824***	***1.63***	***0.96***	***32.993***	***0.20***	***0.26***
MAY	**Leg-1**	May 27	4.780	3.17	2.18	32.739	0.09	0.24
	Leg-6	June 11	5.319	2.14	1.87	33.006	0.13	0.18
		Ave.	***5.050***	***2.66***	***2.03***	***32.873***	***0.11***	***0.21***
JUL	**Leg-6**	July 24	5.603	2.04	1.47	32.961	0.08	0.25
	Leg-8	Aug 03	6.331	2.10	1.10	33.028	0.22	0.21
		Ave.	***5.967***	***2.07***	***1.29***	***32.995***	***0.15***	***0.23***
		SUM. AVE.	***5.509***	***2.37***	***1.66***	***32.934***	***0.13***	***0.22***
SEP	**Leg-1**	Sep 30	7.711	1.24	0.54	33.006	0.03	0.28
	Leg-6	Oct 13	8.478	0.49	0.39	32.967	0.06	0.17
		Ave.	***8.095***	***0.87***	***0.47***	***32.987***	***0.05***	***0.23***
OCT	**Leg-6**	Oct 10	8.588	0.41	0.37	33.057	0.07	0.19
	Leg-8	Oct 25	9.902	0.04	0.03	33.201	0.07	0.08
		Ave.	***9.245***	***0.23***	***0.20***	***33.129***	***0.07***	***0.14***
		AUT. AVE.	***8.670***	***0.55***	***0.34***	***33.058***	***0.06***	***0.19***
		ASSA. AVE.	6.334	***1.52***	***0.99***	32.995	***0.13***	***0.22***

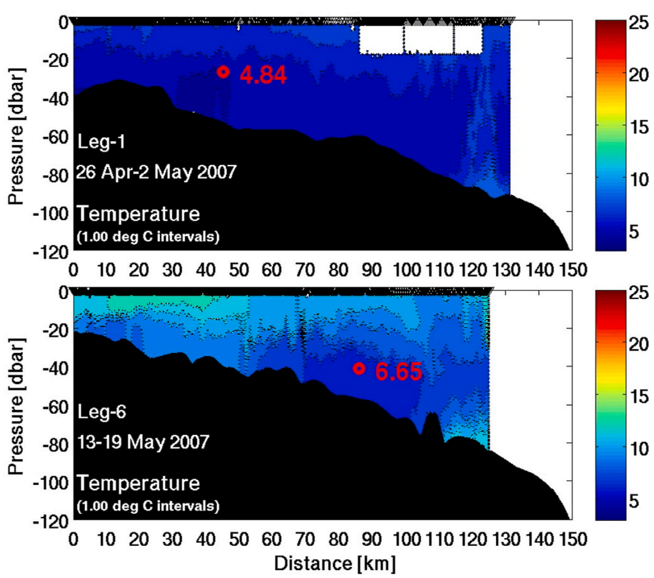

Fig. 2. NE-MAB PROTO-COLD POOL 2007: *Mid-Spring.* The 26 April–19 May 2007 glider RU06: *(upper)* Leg-1 temperature section, with section-minimum temperatures indicated (red). *(lower)* The same for Leg-6, with temperature (°C) legends to the right. (The missing data is due to our glider piloting, while crossing the east-west New York shipping lanes.)

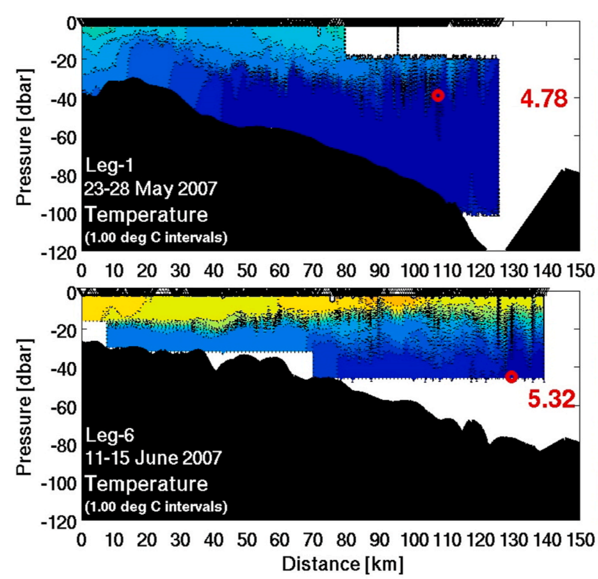

Fig. 3. NE-*MAB* COLD POOL 2007: *Spring.* The 23 May–15 June 2007 *glider RU17 (upper)* Leg-1 temperature section, with section-minimum temperatures indicated (red), and *(lower)* the same for Leg-6, with temperature (°C) legends to the right.

water intrusion across the shelf-break front. Repeated intrusions such as this are thought to be one of the mechanisms that warms/salts the seaward extremes of the Cold Pool during the summer (Gawarkiweiz et al., 2018). The strong vertical stratification with its downward intrusions (Fig. 4-lower) appears to be supporting a strong internal tide. Spatial glider measurements of the internal tide will always be aliased.

2.5. Cold pool – Autumn 2007

Glider measurements in the northeast MAB (Fig. 5) and southwest MAB (Fig. 6) define a still distinct Cold Pool that is even warmer than summer Cold Pool. The warming of T_{min} continues into late autumn (Fig. 7; Table 1); presumably by atmospheric cooling-induced mixing of the water column of the warm upper and cool lower layers. The winter cooling (to come) is forecast by the Leg-6 T_{min}, which in the New Jersey inshore.

There is mid-December evidence (Fig. 7) of the water column is beginning to cool. These measurements capture the beginning of the winter 2007–08 cooling phase of the MAB waters. After more atmospheric cooling of the coastal ocean in January through March, that water mass becomes part of the 2008 Cold Pool.

3. An evolving Cold Pool

This 2007 series of zigzag glider runs provide the most complete view of an annual realization of a clearly evolving MAB Cold Pool to date. With this high-resolution picture of an evolving Cold Pool, we now focus on the more complete set of Cold Pool water mass properties and their evolution. The *thermal cores* of the 2007 Cold Pool for both summer

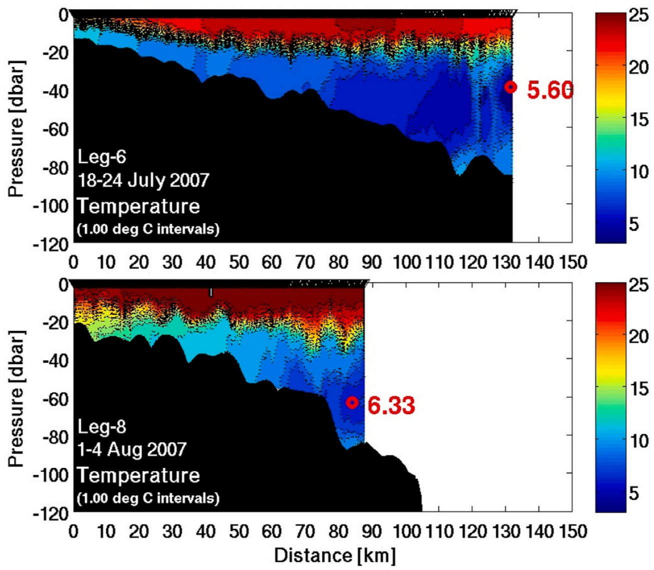

Fig. 4. *SW-MAB* COLD POOL 2007: *Summer*. The 18 July–4 August 2007 *glider RU01 (upper)* Leg-6 temperature section, with section-minimum temperatures indicated (red), and *(lower)* the same for Leg-8, with temperature (°C) legends to the right.

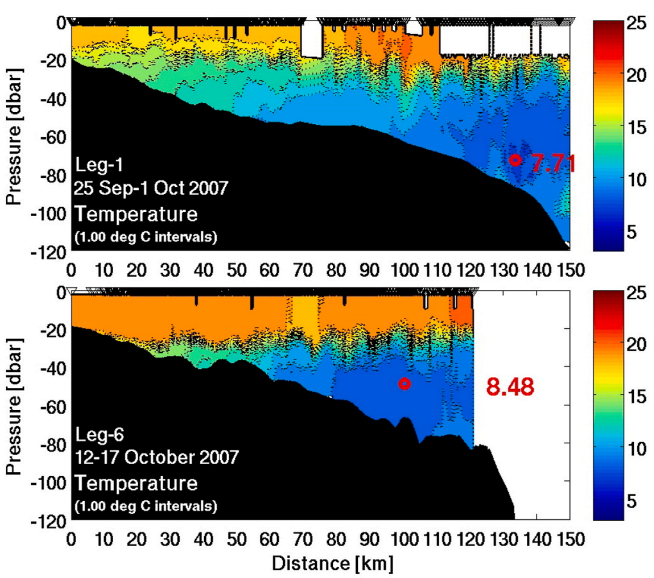

Fig. 5. *NE-MAB* COLD POOL 2007: *Autumn*. The 25 September–17 October 2007 *glider RU05 (upper)* Leg-1 temperature section, with section-minimum temperatures indicated (red), and *(lower)* the same for Leg-6, with temperature (°C) legends to the right.

and autumn are defined by the section temperature minimums T_{min}s, as we can see in Figs. 8 and 9. The locations of the T_{min} show that the Cold Pool core is near, if not in the shelf-break front (SBF) during both seasons. Thus, the Cold Pool hydrography geostrophically supports the SBF jet, which are exemplified by some of the fastest along-shelf flows. The fact that T_{min}s are usually 10 m–20 m above the bottom is consistent with the location of the SBF jet. Thus, the SBF jet advects the outer part of the Cold Pool generally from northeast to southwest along the outer shelf.

The section minimum temperature T_{min} is an excellent proxy for the seasonal variability of Cold Pool temperature at different sections of the MAB. For example, the T_{min} of Leg-1 and Leg-6 (two of more complete

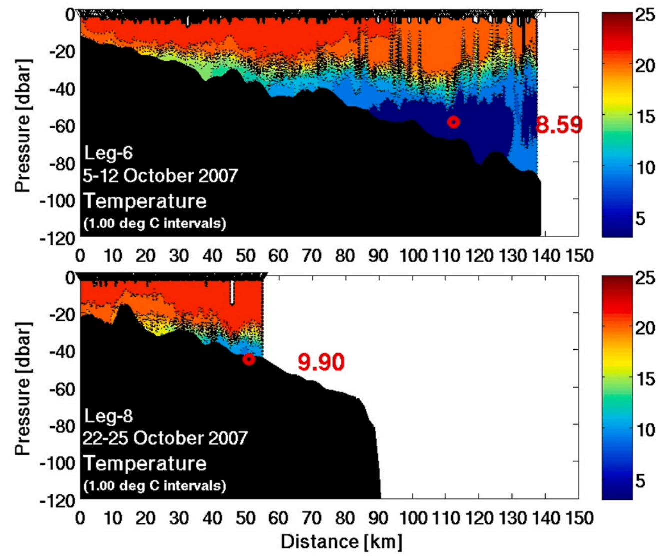

Fig. 6. *SW-MAB* COLD POOL 2007: *Autumn*. The 7–26 October 2007 *glider RU06 (upper)* Leg-6 temperature section, with section-minimum temperatures indicated (red), and *(lower)* the same for Leg-8, with temperature (°C) legends to the right.

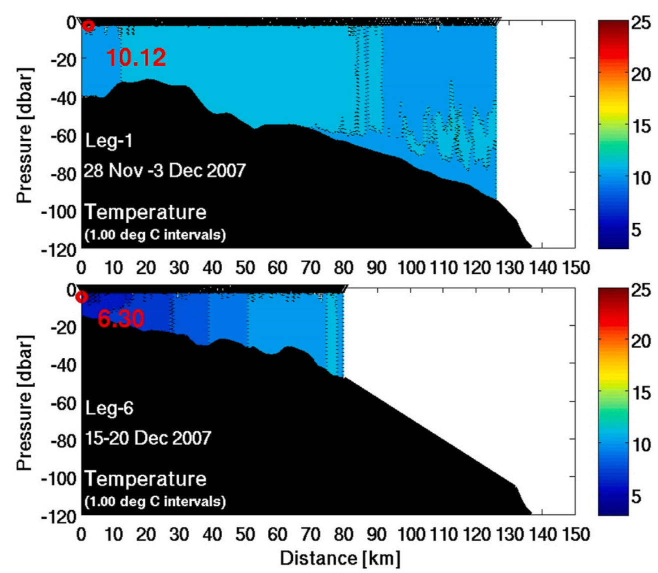

Fig. 7. NE-COLD POOL 2007: *Late Autumn*. The 28 Nov.–20 Dec. 2007*glider RU01 (upper)* Leg-1 temperature section, with section-minimum temperatures indicated (red), and *(lower)* the same for Leg-6, with temperature (°C) legends to the right.

cross-shelf transects) warmed between March and April 2007 (Table 1). This *warming phase* was followed during May by a dramatic cooling of the Leg-6 waters. The fact that the Legs-1 through −4 tends to support the Lentz (2017) argument that a cold patch centered on the Hudson Valley is responsible for this observation. Consequently, the substantial Leg-6 T_{min} minus Leg-1 T_{min} difference of 2.0 °C at the beginning of May decreased rapidly to 0.7 °C by mid-June. The 2007 Cold Pool was established throughout the MAB at this time.

In early July, the MAB-wide Cold Pool Waters (CPW) began to warm at about a rate of ~1 °C/month. Estimates of the warming rates highlight the contrast between the *Spring* (Apr–May) cooling and *Summer* (May–October) warming in the northeastern segment of the MAB (NE-MAB) Cold Pool. The summer warming of the MAB Cold Pool (Fig. 10) could be

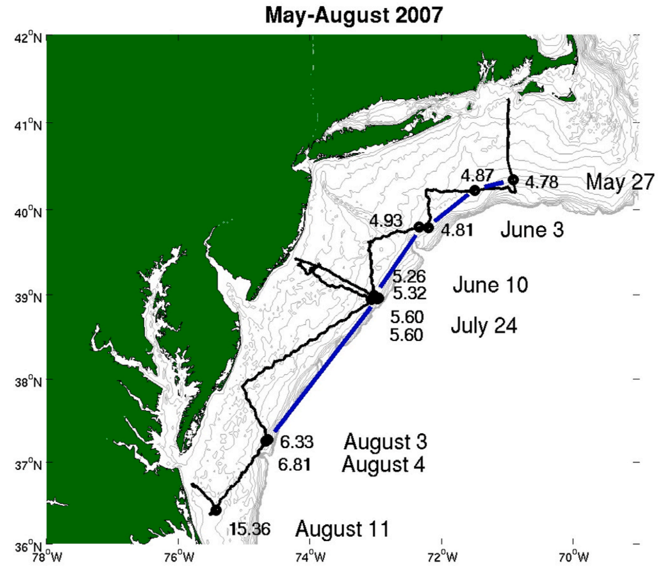

Fig. 8. The composite of the glider trajectories in the northeastern (NE) MAB *(RU17)* and the southwestern (SW) MAB *(RU01)* during the *summer* 2007. The section-minimum temperatures T_{min} (o) are highlighted by the blue line. The dates are located according to their alongshelf location of the gliders.

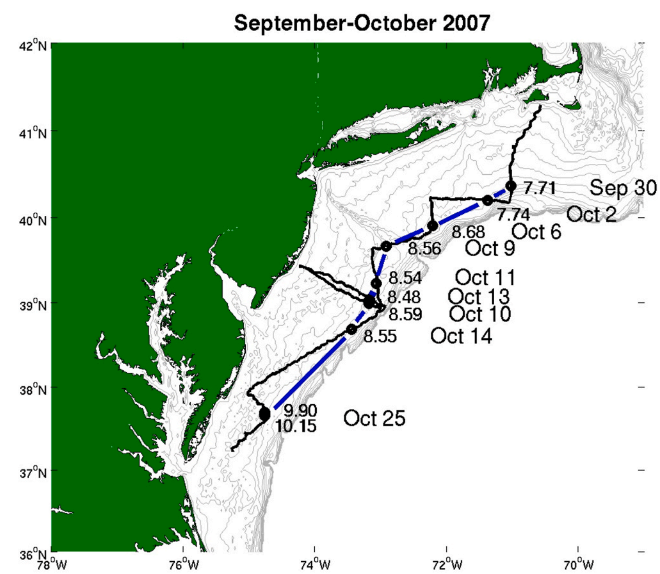

Fig. 9. The composite of the glider trajectories in *autumn* 2007: NE MAB *(RU05)* and SW MAB *(RU06)*. The section-minimum temperatures T_{min} (o) are highlighted by the blue line. The dates are located according to their alongshelf location of the gliders.

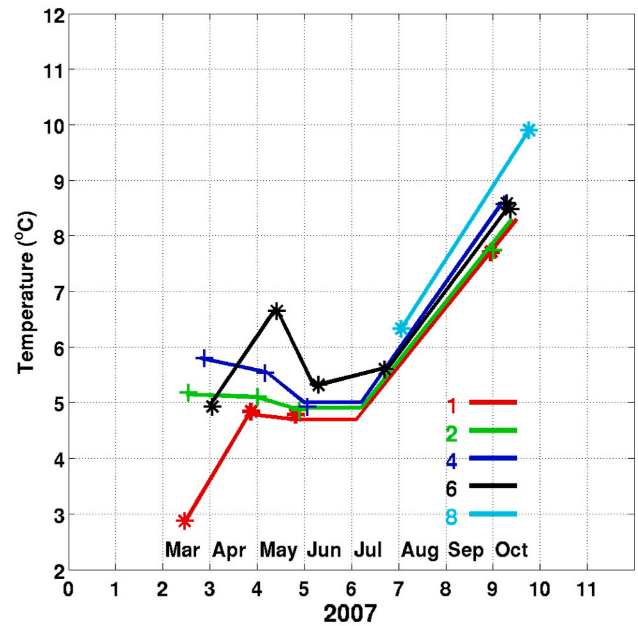

Fig. 10. The 2007 section-minimum temperature T_{min} versus time for Legs-1 (red *), 2 (green +), 4 (blue +), 6 (black *) and 8 (cyan *). Note that the Apr.–May 2007 cooling rates, which range from largest at Leg-6 and smallest at Leg-1, are followed by a shelf-wide average Jun.–Oct. 2007 warming rate of 1.05 °C/month.

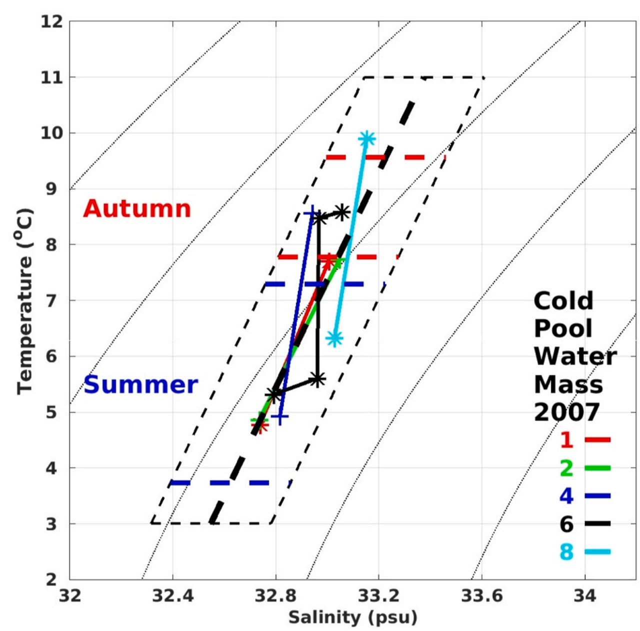

Fig. 11. A statistical definition of 2007 Cold Pool Water properties (CPW; black dashed trapezoid) is based on the average 2007 section T_{min}–S_{Tmin} relation (bold dashed line); which is a linear statistical fit to the May–October 2007 T_{min}/S_{Tmin} observations for the Legs-1 (red*), 2 (green+), 4 (blue+), 6 (black*), and 8 (cyan*). The trapezoid width is a constant $\pm$ S_D standard deviation (σ) of all sub-10 °C waters (see main text). The 2007 summer (blue dashed) and autumn (red dashed) CPW temperature bounds are shown.

due to several processes including turbulent transport of heat from the (a) surface layer above, (b) offshore waters beyond the shelf-break front (SBF), and (c) landward boundary via upwelling/downwelling exchange. The question of which of these processes dominate during the different phases of the Cold Pool evolution will be addressed below.

The 2007 T_{min}/S_{Tmin} are used to define the Cold Pool's TS water properties between 3 °C and 11 °C (Fig. 11) for several representative transects. A linear fit to the observed T_{min}/S_{Tmin} represents the average 2007 T_{min}–S_{Tmin} relationship (Fig. 11; bold dashed line). This T_{min}–S_{Tmin} relationship shows as the Cold Pool core waters warm their salinity increases. The trend toward higher temperatures during the summer could be due to the processes mentioned above. However, the trend of this T_{min}–S_{Tmin} relationship toward higher salinities is only consistent with exchange between the Cold Pool and Slope Sea water across the SBF.

Sub-thermocline Cold Pool water properties through mixing with other adjacent water masses (e.g., Slope Sea and MAB shelf waters). The extents of the Cold Pool Water properties on a specific transect T^t and S^t in Fig. 11 were determined by the statistics of their respective departure properties T_D/S_D computed according to:

$$T_D\ (x, s, z) = T^t\ (x, s, z) - T_{min}(s)$$

and

$$S_D\ (x, s, z) = S^t\ (x, s, z) - S_{Tmin}\ (s),$$

where T^t/S^t is any temperature/salinity pair in the transect with respect to T_{min} (s)/S_{Tmin} (s); "*x*" is an inshore coordinate referenced to the alongshore location of the "s" and "*z*" is upward.

Thus, for measured sub-thermocline water temperatures (<10 °C), we computed the departure of temperatures from T_{min} (T_D); and salinities from the corresponding S_{Tmin} (S_D). Note in Table 1 that the S_D standard deviations are virtually constant throughout the summer (1σ ~ 0.24 psu). That is the basis for the dashed lines on either side of the average T_{min}–S_{Tmin} relationship in Fig. 11. In contrast to the salinities, the T_D statistics are seasonal – reflecting the warming noted before. Thus, we use a average T_{min} ± T_D 1σ window to define the Cold Pool Water (CPW) mass in the region of a specific cross-shelf section with a specified T_{min}. Examples of the temperature boundaries ± 1σ relative the average T_{min} for the respective *summer* and *autumn 2007* are given in Fig. 11.

4. Cold Pool 2007 Water masses

A few glider measured-transects can be used to define the seasonal cycle of the bathymetric extent of properties of the 2007 MAB Cold Pool. We determine the footprint of the of the *summer* 2007, sub-10 °C Cold Pool from a composite of measurements by (a) glider RU17 in the northeastern MAB during *late May-early June* and (b) glider RU01 in the southwestern MAB during *late July–early August*. The traditional approach in defining the Cold Pool extent is to use the 10 °C isotherm. Following this approach, we locate the inshore intersection of the 10 °C isotherm with the bottom – "the bottoming" – in each temperature section.

In addition, we built a model for estimating the Cold Pool volume. We wrote a Matlab program to estimate the Cold Pool (CP) volume using real estimated bathymetry. The inputs are the glider-measured/estimated geometry of the sub-10 °C (or sub-12 °C based glider missions) Cold Pool and the uniform-thickness warm layer above the Cold Pool. Then, we ran the estimation model, with a various warm layer thicknesses (based glider measurements) for the different cases. For each case, the CP volume mean ± one standard deviation are given.

4.1. Summer 2007 Cold Pool: 10 °C isotherm

Both the RU17 and the RU01 glider missions just did not go far enough offshore to pierce the Shelf-Break Front (SBF; Linder et al., 2004). However, the SBF hovers around the 100 m isobath, and contains the 10 °C isotherm. Therefore, we assume that the seaward boundary of the 2007 10 °C Cold Pool to coincides with 100 m isobath. We built a crude model to estimate the Cold Pool volume (4119 ± 9 km^3) and the bottom footprint of the *summer 2007 sub-10 °C Cold Pool* map (Fig. 12). The error involved with the assumption stated above was small.

4.2. Autumn 2007 Cold Pool: 10 °C isotherm

We construct a map of the *autumn 2007 sub-10 °C Cold* map (Fig. 13) following the above approach with the September/October 2007 glider RU05 and RU06 transects (see Brown et al., 2015). Note that gliders RU05 and RU06 occupied the New Jersey transect - Leg-6 - within a week of each other and measured very similar 10 °C isotherm bottoming locations and T_{min}s. The footprint of the *autumn 2007* Cold Pool is clearly smaller, about 3 °C warmer and 0.1 psu saltier than the *summer 2007 CPW*. The *autumn 2007* Cold Pool does not go inshore, as much as its *summer* counterpart. However, it does indicate an off-shelf escape

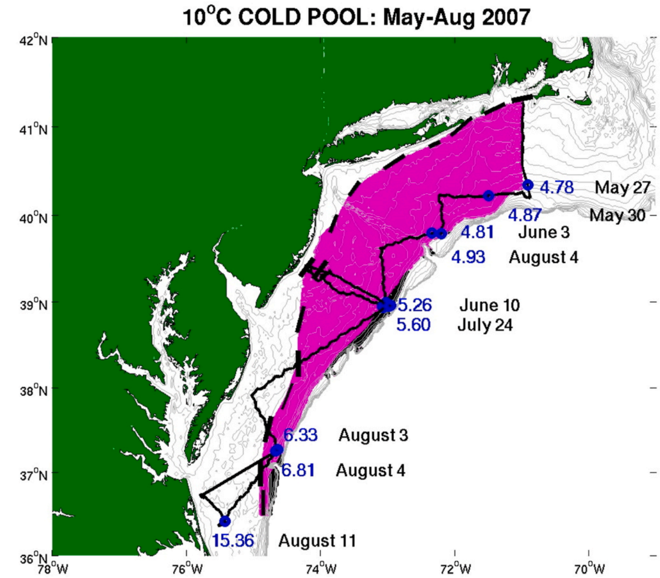

Fig. 12. The *summer* 2007, sub-10 °C Cold Pool Water (CPW) footprint (pink) is defined by *glider RU17/RU01* survey measurements. The section-minimum temperatures (blue o) – defining the Cold Pool core – are located. Estimated CPW Volume = 4119 ± 9 km^3.

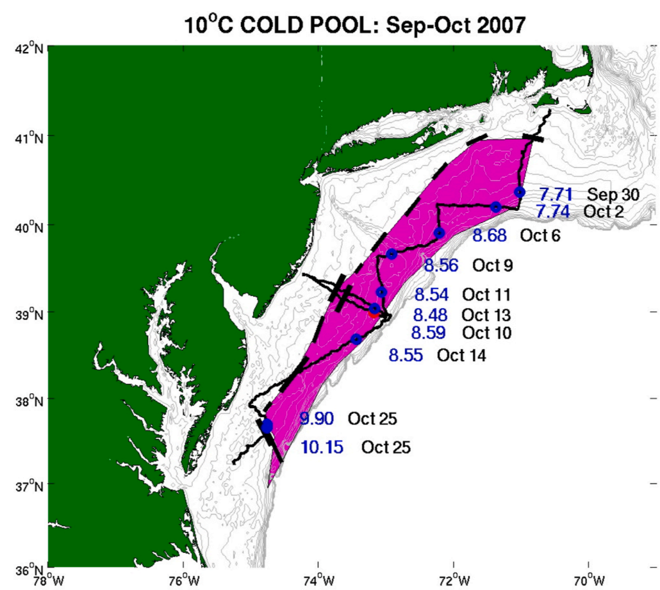

Fig. 13. The *autumn* 2007, sub-10 °C CPW footprint (pink) is defined by *glider RU05/RU06* survey measurements. The section-minimum temperatures (blue o) – defining the Cold Pool core – are located. Estimated CPW Volume = 2310 ± 45 km^3.

route offshore of the mouth of the Chesapeake Bay. We have assumed a uniform depth of 30 m for the thermocline, which contains the 10 °C isotherm and estimated the volume of the autumn 2007, sub-10 °C Cold Pool to be 2310 ± 45 km^3.

4.3. September 2013 Cold Pool: 10 °C isotherm

MARACOOS organized a 9-glider deployment consisting of glider operations all along the American coastal ocean between Nova Scotia and Florida – *GliderPalooza 2013*. We focus on a three-glider subset of missions in the Mid-Atlantic Bight (MAB) consisting of the almost simultaneous glider Blue, RU-23 and RU-22 missions (Fig. 14). The

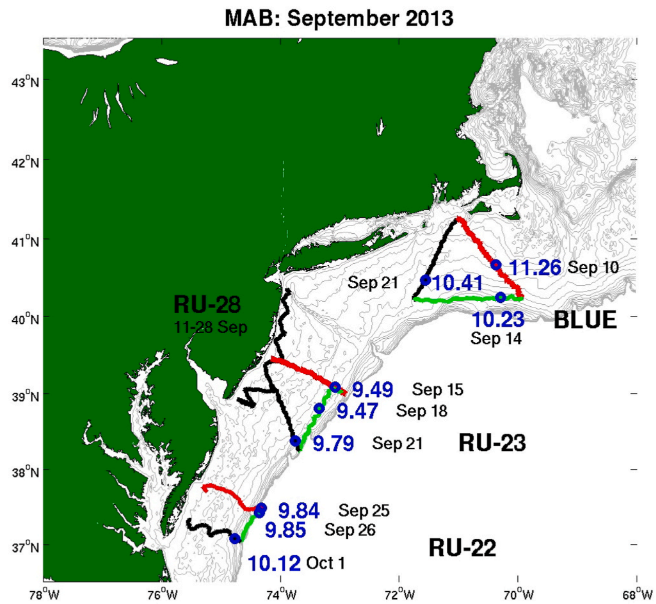

Fig. 14. The MAB trajectories of *gliders BLUE, RU-23, RU-22, and RU-28*. The glider Blue triangle in the Southern New England Bight consists of Legs-1 (red), -2 (green), and -3 (black); as was the *glider RU-23* trajectory off New Jersey (NJ); as was the *glider RU-22* trajectory east of Maryland (MD). The *glider RU-28* trajectory (blk), inside of the 30 m isobath, completed the triangle in the NJ region. The Leg-T_{min}/dates are indicated.

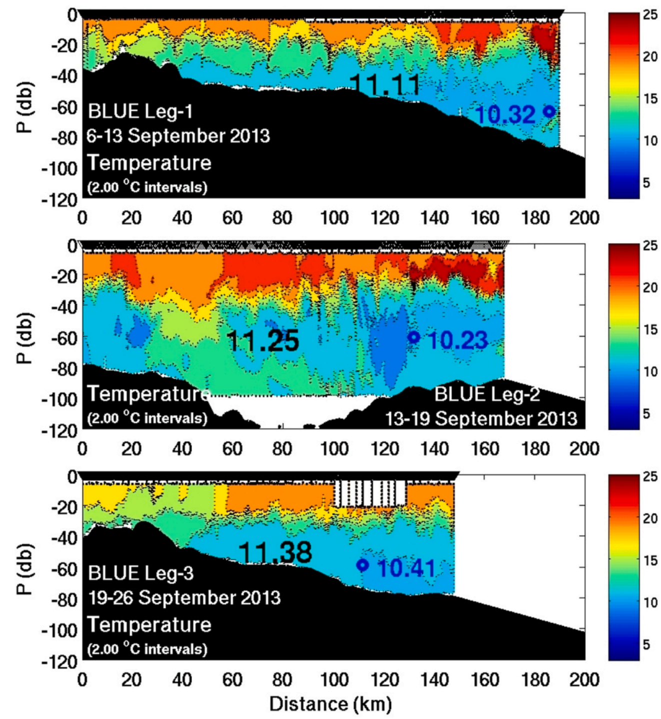

Fig. 15. Glider Blue's temperature (T°C) sections for *(upper)* Leg-1; (*middle*) Leg-2; and *(lower)* Leg-3 are presented. Section minimum temperatures T_{min} (blue) are located and the average lower-layer temperatures ≤12 °C (black) are indicated. The missing data in Leg-3's upper layer is because we restricted the glider's maximum depth to 17 db in the New York's east-west shipping lanes except for surfacing (lines).

September 2013 Cold Pool was warmer than the autumn 2007 Cold Pool.

Glider Blue's conducted its mission in the Southern New England Bight just south of Rhode Island (SNEB). The near-equilateral triangular trajectory sliced through the cold water (a redefined Cold Pool – see below) twice (Fig. 14). During glider Blue's east-west Leg-2 penetrated the shelf-break front (SBF) once. The middle panel of the three-leg display of glider Blue's contoured temperatures (Fig. 15) shows the measuring temperatures above 12 °C (green).

Almost simultaneously, glider RU23 penetrated beyond the SBF as it sliced through the Cold Pool twice (Fig. 15). This coldest patch of Cold Pool water in the New Jersey sector of the MAB. RU-28 patrolled the inner shelf in water depths less than 30 m along the NJ coast at the same time. These gliders also tested the hypothesis that triangular patterns are particularly effective for data-assimilation numerical modeling of MAB flow with a general 5 km/day southwestward flow.

A week or so later, glider RU22 was deployed at an inshore site off Maryland. RU22 sliced through the Cold Pool and SBF twice (with a non-triangular trajectory). Notice that the glider RU23 section minimum temperatures (Figs. 14 and 16) were clearly colder than those of either gliders Blue to the north and RU22 to the south.

The September 2013 glider Blue leg T_{min}s are greater than sub-10 °C (in the SNEB region of the MAB) were warmer than the 10 °C waters in September–October 2007. The gliders in the NJ and MD measured leg T_{min}s were sub-10 °C. So, the Sep.–Oct. 2013 sub-10 °C Cold Pool footprint (Fig. 17) is smaller than its autumn 2007 counterpart. The sub-10 °C CPW volume 1132 ± 47 km^3 is about half as much as the comparable Cold Pool volume in Sep.–Oct. 2007 (2310 ± 46 km^3).

We have concluded that the Cold Pool waters were being warmed by the cross-SBF mixing with the warmer/saltier waters of the Sep. 2013 Gulf Stream warm core ring (GS-WCR; Fig. 18). Gulf Stream water core rings influence the MAB in all seasons; systematically warming and salting Cold Pool properties.

The influence of the GS-WCR on the Cold Pool temperature prompted us to reconsider using a sub-10 °C definition for Cold Pool. Based on the observations described below, we expanded the "typical" Cold Pool

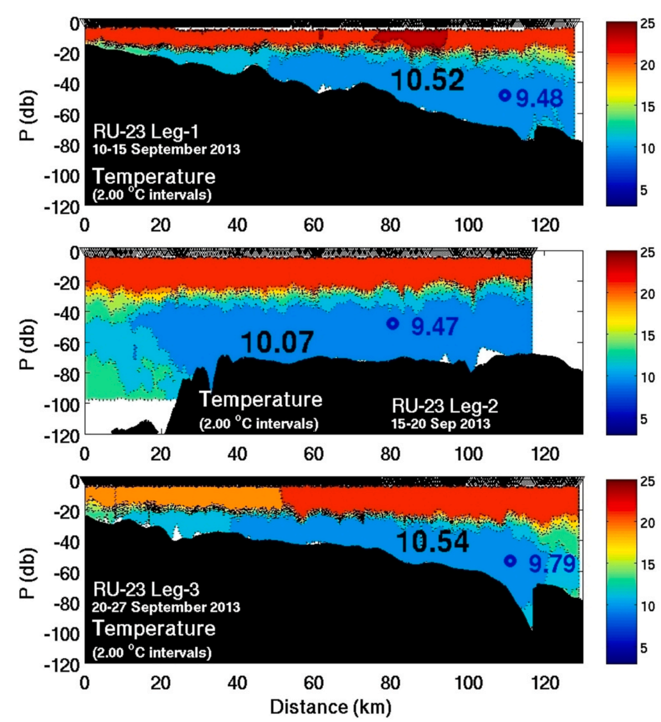

Fig. 16. Glider RU23's temperature (T°C) sections for *(upper)* Leg-1; *(middle)* Leg-2; and *(lower)* Leg-3 are presented. The blue lines at the ends of Legs1 & 2 mark "duplicate" sections. Section minimum temperatures T_{min} (blue) are located and the average lower-layer temperature T ≤ 12 °C (black) is indicated.

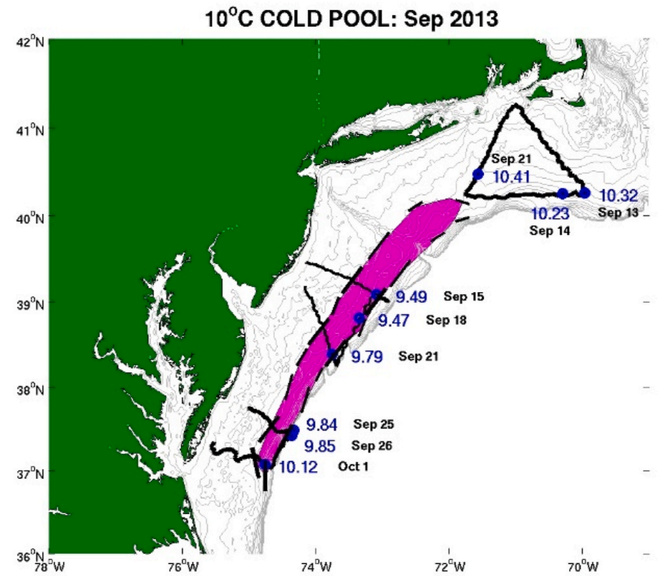

Fig. 17. The sub-10 °C MAB Cold Pool (pink) for September 2013 is defined by the trio of glider measurements: *glider Blue* in the northeast MAB, *glider RU23* in mid-shelf MAB and *glider RU22* in the southwest MAB. The section-minimum temperatures T_{min} (blue o) are located. *Estimated CPW Volume* = 1132 ± 47 km^3.

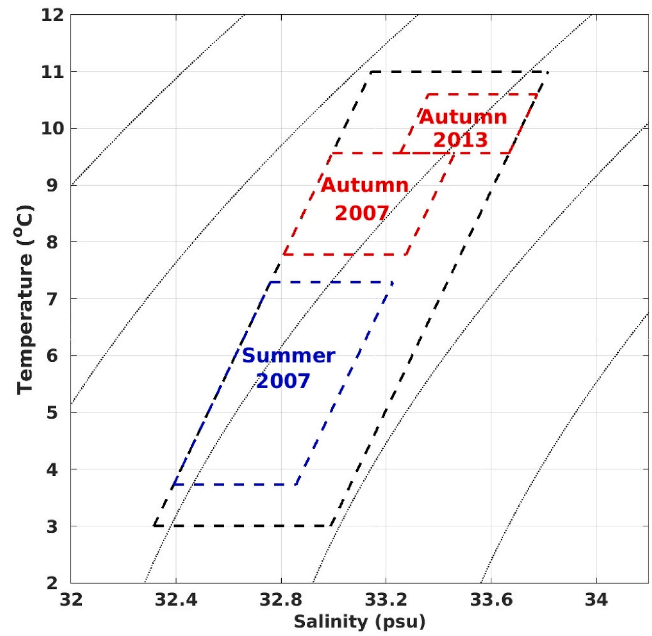

Fig. 19. The "global" definition of the Cold Pool water mass (blk dashed) includes seasonal sub-definitions: Spring/Summer 2007, Autumn 2007 and Autumn 2013.

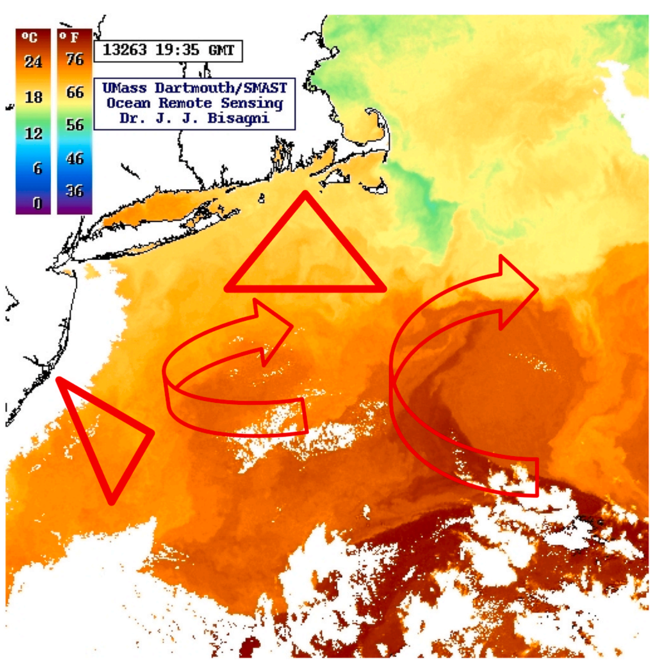

Fig. 18. A NOAA-18 AVHRR SST image of a warm ring and streamer that are influencing the MAB region on Sep. 20, 2013. The anti-cyclonic circulation around Gulf Stream warm core ring and streamer are indicated.

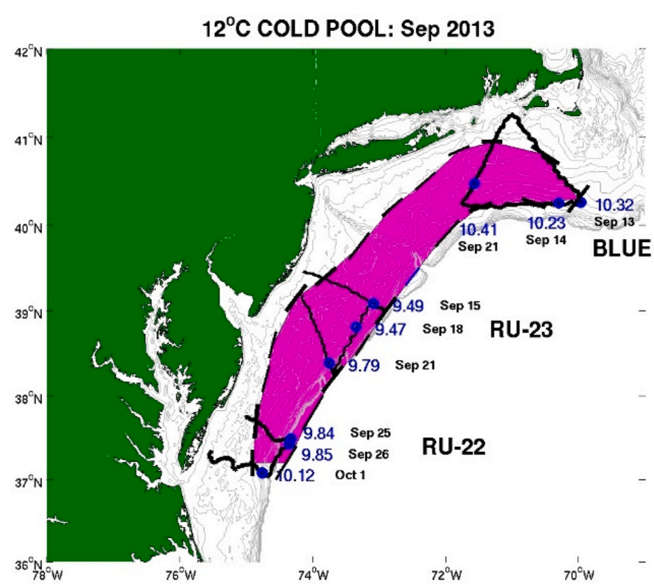

Fig. 20. The sub-12 °C MAB Cold Pool (pink) for September 2013 is defined by the trio of glider measurements: Blue (SNEB sector), RU23 (NJ sector) and RU22 (MD sector). The section-minimum temperatures T_{min} (blue o) are located.

water mass properties to higher salinities (Fig. 19). Rather we used a sub-12 °C definition for the CPW for the 2013 season. All MAB glider-derived temperature sections during Sep. 2013 displayed a distinctive sub-12 °C Cold Pool (Figs. 15 and 16). This sub-12 °C definition of CPW properties, allowed us to define the 2013 CPW mass shown in Fig. 20. The CPW "footprint" is shown in Fig. 20 is associated with an estimated the CPW mass volume to be 4109 ± 15 km^3.

Estimated CPW Volume = 4109 ± 15 km^3

The extent of the sub-12 °C CPW is shown in Fig. 20. Embolden short lines mark where the glider's measurements indicated the 12 °C isotherm intersected with bottom on the inshore end of the leg. The seaward end of the 12 °C isotherm is assumed to in the SBF, which is assumed to run along the 100 m isobath. The details for the SNEB (Blue), NJ (RU23) and MD (RU22) are presented next.

4.3.1. *SNEB region*

At the inshore end of glider Blue's Leg-1 temperature section (Fig. 15), the 12 °C isotherm intersects with the bottom near the 40 m isobath. Glider Blue measurements along Leg-2 indicate seaward end of the 12 °C isotherm extends 20–30 km beyond the shelf-break in the westward direction. At the Blue's Leg-2 near the western end, we see the Cold Pool water extension of Leg-3 and the signature (Fig. 15 -green) of the SBF at about 100 m isobath. Within the SBF, the 12 °C isotherm intersects with the bottom near the 85 m isobath. At the Leg-3 seaward end of glider Blue's Leg-2 section, the 12 °C isotherm intersects the bottom at 45 m.

4.3.2. NJ region

At the inshore end of Leg-1 temperature section (Fig. 16), the 12 °C isotherm intersects with the bottom near the 25 m isobath. Glider RU-23 did not go far enough to cross the SBF on Leg-1. Most of Leg-2 is less 80 m and the temperature data indicates the Cold Pool Water extends seaward. It is toward the southwestern end of Leg-2 that it deeper 80 m and the 12 °C isotherm in SBF intersects with the bottom near the 85 m isobath. At the seaward end of Leg-3, we also see the 12 °C isotherm in SBF intersects with the bottom near the 85 m isobath. At the inshore end of Leg-3 section, the 12 °C isotherm/bottom intersection occurs at a depth of about 30 m.

4.3.3. MD region

At the inshore ends of temperature sections of Leg-1 and Leg-3, the 12 °C isotherm with the bottom near the 35 m isobath (not shown). The seaward temperature data (not presented) is consistent with a at least part of the Cold Pool is leaving shelf here.

The September 2013 glider-measured water properties are consistent with our Cold Pool water mass definition. For both the SNEB and NJ regions, the T_{min} station T/S profiles intersect our Cold Pool water mass definition (Fig. 21). The SNEB/Blue region of the TS diagram suggests that the deepest Cold Pool waters mix with warm slope water (WSW). Also, the TS diagram information indicates that inshore water properties are strongly influenced by lateral mixing with Cold Pool waters (Fig. 21). These results suggest that a quantitative water mass analysis – beyond the scope of this effort – could lead to cross-SBF mixing rates.

5. Summary of results

A series of Slocum glider observation missions in 2007 and 2013 have been used to define the time-space variable Cold Pool between Cape Cod and Cape Hatteras. We describe the time-space evolution of the 2007 Cold Pool in terms of a spring/autumn series of *single glider* zig-zag missions with from northeast to southwest down the shelf. The Cold Pool was defined by the thermocline at the bottom of warm upper layer, which varied spatially from 25 to 45 m.We used the 2007 glider water property measurements to define sub-10 °C Cold Pool – an important, evolving habitat feature of the Mid-Atlantic Bight (MAB). Based on the 2007 glider measurements, we found that a trapezoidal T–S definition of Cold Pool Water, highlighted by an increased about 1 °C warming/mon. and 0.11 psu salting/month after June (Fig. 11). This all happened to Cold Pool, while the MAB water were flowing southwestward at an average velocity of 5 km/day.

The 2007 glider measurements show that the core of the Cold Pool (defined by the transect minimum temperatures – T_{min}) hugs the outer shelf in the vicinity of the well-known Shelf-Break Front (SBF; Figs. 8 and 9). The Cold Pool salts due to exchanges with Slope Sea waters as the Cold Pool waters flow from northeast to southwest along the MAB. The vertical mixing caused by autumn storms gradually erase the temperature distinctiveness of the Cold Pool. The vertical mixing late November–early December 2007 produce the vertically well mixed temperature profiles in Fig. 7. The intense winter cooling is hinted at in the inshore profiles of Leg-6 of Fig. 7.

Our early summer 2007 mapping, based on only two zigzag glider measurements of a *sub-10 °C waters,* ranging from full shelf-width CPW in the SNEB region to a very narrow strip southwestward in locations off Maryland (Fig. 12). We estimated the summer 2007 Cold Pool volume to be 4119 ± 9 km^3. The warming of CPWs in the MAB continued throughout summer leading to a decrease in CPW volume. This reduced autumn 2007 estimated volume of 2310 ± 46 km^3 (Fig. 13). This loss of sub-10 °C CPW volume is associated with increased salinity (Table 1) and is consistent with the southwestward average flow 5 km per day.

During September–October 2013, we have also explored the Mid-Atlantic Cold Pool with the contemporaneous *trio of glider* missions highlighted in Fig. 14. With that set of nearly simultaneous glider measurements, we showed that the *September 2013* Cold Pool in the NJ region was colder than in 2007 than the rest of 2013 Cold Pool.

We also showed that the SNEB region the *2013 Cold Pool* was warmer than the 2007 Cold Pool in this region. That warming of the SNEB region of the Cold Pool was probably due to the influence of a nearby Gulf Stream Warm Core Ring (Fig. 18). This led us to widen of the trapezoidal T–S definition of Cold Pool Water properties -salinity in particular (Fig. 19). We changed from the sub-10 °C cold Pool definition to a 12 °C definition for the 2013 Cold Pool. This resulted in a *sub-12°C* 2013 Cold Pool has an estimated volume of 4109 ± 15 km^3 (Fig. 20).

The September/October 2013 glider measurements (as well as in October 2007) document the autumn Cold Pool 2013, during which the Cold Pool loses its distinctiveness due to storm mixing. [Of course, the SNEB region 2013 Cold Pool water properties are consistent with our redefined trapezoid of Cold Pool water properties (Fig. 21)]. All three sub-regions – SNEB, NJ and MD – exhibited inshore water properties that reflected mixtures with the local Cold Pool waters. The T_{min} T–S relationships indicated deeper water properties that hinted at slope water influence. The possibility CPW origins of "upstream" from the Gulf of Maine is explored in Appendix B. The inter-annual variability of Cold Pool Waters was explored through glider measurements of autumn

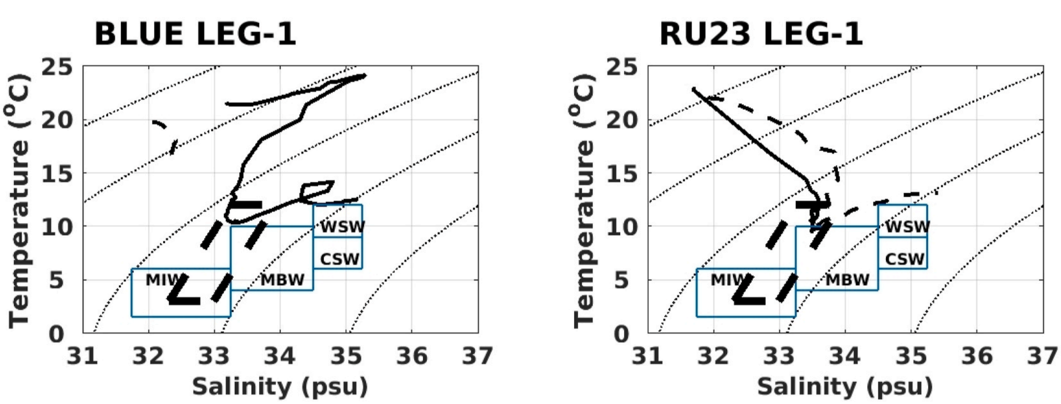

Fig. 21. The (left) SNEB region glider Blue Leg-1 and (right) NJ region glider RU23 Leg-1 T–S relations for the T_{min} station (solid) and most shoreward station (dashed) for the September 2013 measurements. The global Cold Pool water mass is defined by the dashed trapezoid. The rectangular boxes define the Brown and Irish (1993) Gulf of Maine water masses – MIW and MBW and the warm (WSW) and cold slope water (CSW).

2013. The nearly simultaneous 2013 trio of glider measurements (Fig. 14) were used to show how the 2013 MAB Cold Pool Waters in the northeastern sector were warmed and salted by the impingement of a Gulf Stream Warm Core Ring. However, these results suggest that a quantitative water mass analysis – beyond the scope of this effort – could lead to cross shelfbreak front mixing rates.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Covert Practical Salinity to Absolute Salinity (S_A)

We expressed salinities in this paper as PSS-78 Practical Salinities (S_P); with units as psu). Pawlowicz (2013) maintains that “However, for all purposes S_A (Absolute Salinity) according to the TEOS-10 definition is required”. Determining S_A from S_P requires the following.

(1) For waters in the “Neptuian” range (i.e., $2 < S_P < 42$; -2 °C < ITS-10 temperature <35 °C), a Reference Salinity S_R on the Reference Composition Salinity Scale (Millero et al., 2008) be estimated as

$$S_R \Big/ \left(\mathrm{g\,kg^{-1}}\right) = \frac{35.16504}{35} \times S_P$$

The Reference Salinity is the mass fraction of solute in an artificial seawater with a precisely defined Reference Composition.

(2) “Because the composition of seawater is not exactly constant, this Reference Salinity is not exactly as the same as the actual Absolute Salinity. Instead, they differ by a small correction factor δS_A:

$$S_A = S_R + \delta S_A.$$

This correction factor is usually, but always positive.” It can be large as 0.02 g/kg in the open ocean, and as 0.09 g/kg in some coastal areas. Pawlowicz (2013) recommends estimate $\delta S_A = 0$ for coastal regimes such as we have here and states in ignoring this correction is roughly equivalent to using the PSS78/EOS80 approach.

Appendix B. Cold Pool Water Origins

We have used the New England Shelf Flux Experiment (NSFE) data (Ramp et al., 1988) to characterize the inflow variability to the Mid Atlantic Bight (MAB) Cold Pool through a section south of Nantucket during spring/summer 1979. The multi-mooring array configuration is shown Fig. B1. The variability of the westward transport of waters of less than 10 °C through the NSFE (N1–N4) section in Fig. B2 shows that the sub-10 °C water inflow ceased by the end of June 1979.

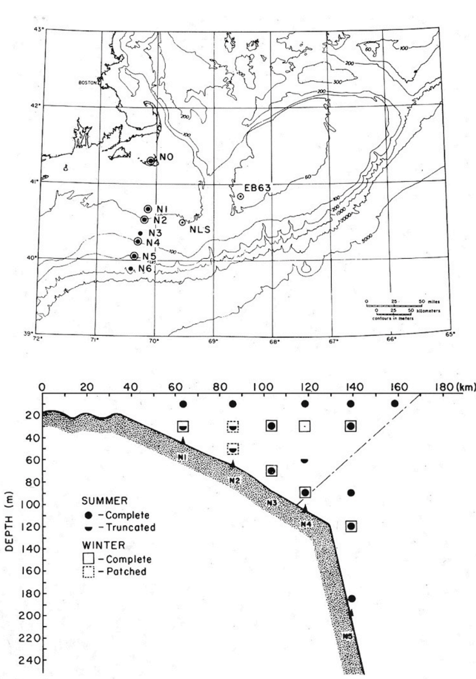

Fig. B1. *(upper)* A map the NSFE mooring array: N1 (depth = *46m*), N2 (*66m*), N3 (*88m*), N4 (*105m*), N5 (*196m*) and N6 (*250m*). *(lower)* The temperature and current measurements making up the year long NSFE. The focus of our interest in the “summer” measurements. (from Ramp et al., 1988).

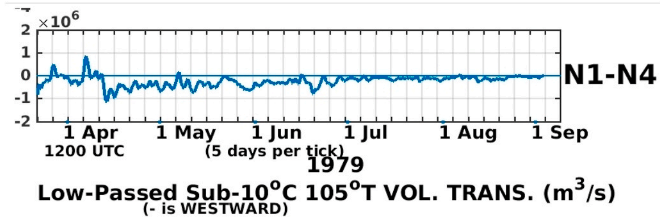

Fig. B2. The major portion of the volume transport of sub-10 °C waters (in 10^6 m^3/s) (spans moorings N1 and N4) normal (105°T) to the 1979 NSFE mooring array. Negative transport is toward the MAB (185°T).

This typical April–June process leaves a distinctive pocket of very cold water that is advected west and southwestward along the MAB. This cold water pocket feeds the evolving Cold Pool, which warms from July onward … as described above in the main text.

What is the origins of the springtime cold water inflow to the MAB Cold Pool? One possibility is that Gulf of Maine Intermediate Water (MIW) escape to feed the MAB Cold Pool. Another possibility is that the Cold Water derives from the Scotian Shelf via the south flank of Georges Bank. We explore both of those possibilities below.

This study tracks MIW outflow from Wilkinson Basin through the set of hydrographic transects (henceforth RIM) from the Gulf of Maine 1986–87 Experiment (Fig. B3 – Brown and Irish, 1993). In particular, note the similar-looking T–S diagrams of the T_{min} stations in each of the transects. The corresponding T–S diagram is shown in Fig. B4. It indicates the presence of Maine Bottom Water (MBW), which Brown and Irish (1993) and others have shown is a mixture between Maine Intermediate Water (MIW characterized by T_{min}) and Slope Water after its entry into the Gulf of Maine (GoM) through the Northeast Channel (NEC). From this evidence, we conclude that significant amounts of MIW, which we know is produced in Wilkinson Basin in the western GoM, is flowing out of the Gulf at a depth in and around 100 m - below the minimum depth of the sill in the great South Channel.

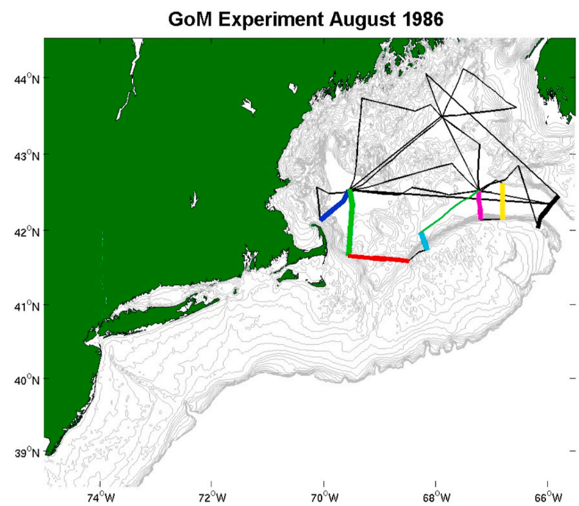

Fig. B3. Composite of the August 1986 Hydrographic Survey Color-Coded RIM Transects: Leg-6a (blue), Leg-1b (green), Leg-7 (red), Leg-7a (cyan/green), Leg-4a (maroon), Leg-3 (yellow), and Leg-5 (black).

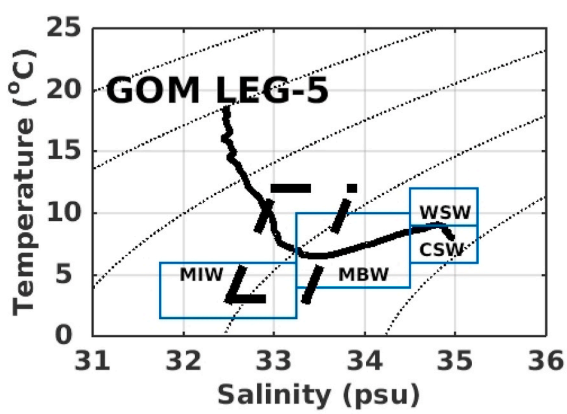

Fig. B4. The T–S diagram for the T_{min} station of the Aug 1986 RIM transect 5 (in Fig. B-3 – black). The global Cold Pool water mass properties is defined (dashed trapezoid). The rectangular boxes define the Brown and Irish (1993) Gulf of Maine water masses – MIW and MBW and the warm (WSW) and cold slope water (CSW).

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