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The Mid-Atlantic Bight Cold Pool, Part-1: Glider Observations

W. Brown
School for Marine Science and Technology
University of Massachusetts Dartmouth
706 S Rodney French Blvd.
New Bedford, MA 02744

O. Schofield, S. Glenn, & J. Kohut
Coastal Ocean Observation Lab
Rutgers, State University of New Jersey
71 Dudley Rd.
New Brunswick, NJ 08901

W. Boicourt
Center for Environmental Science
University of Maryland
PO Box 775
Cambridge, MD 21613

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 Middle 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 10ºC Cold Pool in terms of its distribution and water properties. Here we highlight July through October 2007 general warming and salting of the Cold Pool at rates of approximately 1ºC per month and 0.06 psu per month. The nominal 100m lateral resolution of the glider measurements enabled us to define the footprint of the 10ºC Cold Pool. Assuming a 30m upper layer depth, we estimated Cold Pool volumes varying from 4099 km^3 in summer 2007 to 2391 km^3 in autumn 2007. The deployment three-glider fleet view of the September 2013 gave a different view of the MAB Cold Pool during a time it was strongly influenced by the impingement of a Gulf Stream warm core ring. The warm-core-ring salting and warming effects prompted us to stretch our definition of Cold Pool TS properties to include those effects. We found that, whereas the autumn 10ºC Cold Pool volume was 1138 km^3, the autumn 12ºC Cold Pool volume was 4093 km^3.

I. Introduction

The Cold Pool is a distinctive, highly-variable, bottom-trapped, cold water mass remnant local and remote winter water found during summer over the mid and outer continental shelf between Cape Cod and Cape Hatteras – a region known as the Middle Atlantic Bight (MAB) (Figure 1). 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 et al. (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 Ou and Houghton (1982) present an contour map of the NMFS May 1979 bottom temperatures (Figure 1) which has a patch of the coldest waters (or *"cold patch"*) within the Cold Pool. They also 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. Lentz's (2017) analysis of more than 50,000 hydrographic profile minimum temperatures 1955-2014 climatology suggests that the *"cold patch"* is formed locally.

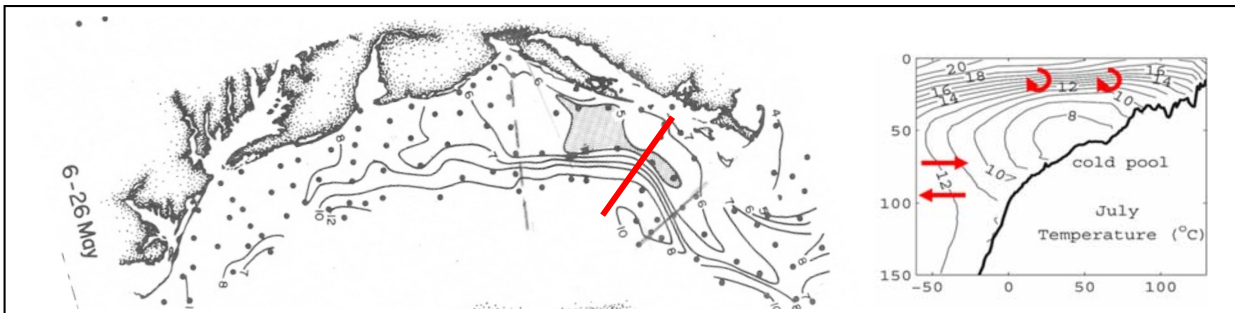


Figure 1 *(Left)* Distribution of the May 6-26, 1979 Cold Pool bottom temperatures in the Mid-Atlantic Bight. (Ou and Houghton, 1982; based on NMFS MARMAP data). *(Right)* A 1955-2014 climatological July cross-section of the Cold Pool (located south of New England by the red bar in left figure) with indicated turbulent exchanges with the upper layer and slope sea seaward of the shelf-break front (after Lentz, 2017).

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; Lentz et al., 2003; 2010). Candidate across-SBF exchange processes result in episodic warm/salty intrusions into CPW by way of the interior and bottom boundary layers (Linder et al., 1994). Interactions between Gulf Stream Warm Core Rings (WCR) and the SBF undoubtedly contribute to such exchanges.

The cooling of northeast MAB Cold Pool waters ceases in July, which is followed by a general warming of all the still distinct Cold Pool through September. Then during autumn, the inevitable energetic autumn 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.

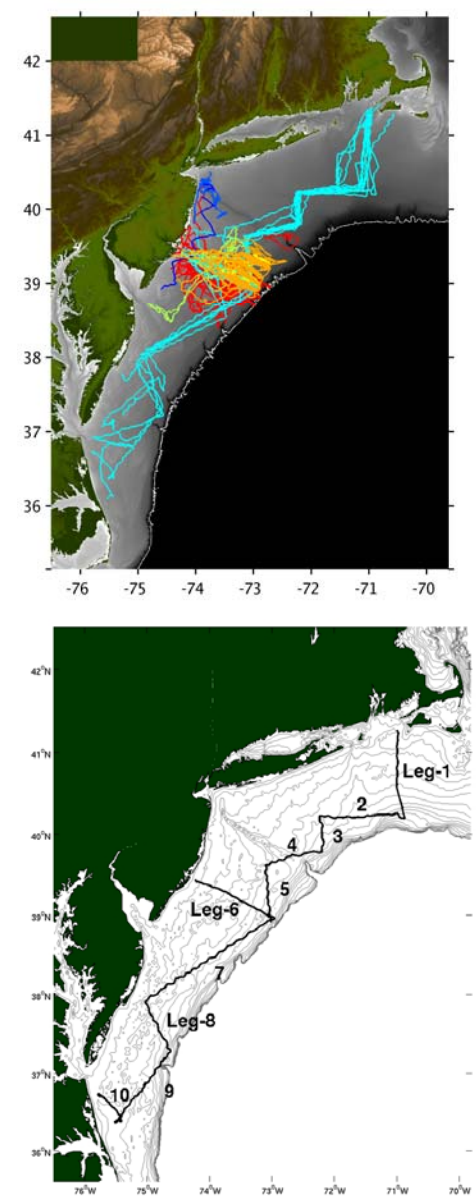


Figure 2 ***(Above)*** MARACOOS glider trajectories for missions between 2003 through 2011 feature repeat cross-shelf transects (yellow), a set of zigzag transects along the outer-shelf (cyan) and along the inner-shelf (dark blue) (Schofield et al., 2010). ***(Below)*** Transects are defined for this paper in terms of the May and July 2007 glider trajectories. Three of the key transects (Legs-1, -6 and -8) are highlighted.

II. Measuring the Cold Pool

Historical Glider Data: 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; (b) cross-shelf series of zig-zags from Massachusetts to New Jersey called the Northern Line (Legs 1-6); and (c) cross-shelf series of zig-zags from New Jersey to Maryland called the Southern Line (Legs 6-10 – Figures 2). The 2007 suite of cross-shelf zig-zag glider slices are used to construct a "glider's eye view" of the evolving 2007 Cold Pool. 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 (see Figure 2).

Our objective is to use the zig-zag glider slices to estimate the extent and properties of the MAB Cold Pool during each of the glider missions. A typical zig-zag run takes a typical 100m 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), conductivity (C) (or derived salinity S), and an estimated glider inter-surfacing segment-averaged velocity (V). Some of the gliders also measured oxygen and the optical trio of chlorophyll-a florescence, colored dissolved organic matter, and optical backscatter.

Pre-Cold Pool - Late Winter/Early Spring: The pre-2007 Cold Pool Water (CPW) is documented by the 13 March - 12 April 2007 glider measurements whose statistics are summarized in Table A1 of Appendix A. Cross-self glider transects (not shown) exhibit the vertically well-mixed "winter water". The cross-shelf Leg-1 south of Massachusetts exhibits the coldest transect minimum temperature, T_{min} = 2.87°C (with an associated salinity, S_{Tmin}, of 32.80 psu). The Leg-6 transect off New Jersey is considerably warmer with a T_{min} = 4.94°C and saltier with a S_{Tmin} = 33.08 psu.

Proto-Cold Pool – Mid-Spring: By the 26 April – 19 May 2007 glider RU06 survey, Leg-1 and Leg-6 transect T_{min}s have warmed relative to March (see Figure 3). However, the vernal warming of the upper layer off New Jersey has only begun to isolate the 2007 Cold Pool. This early expression of the Cold Pool in Leg-6, with a T_{min} = 6.65°C, (Figure 3) distinguishes it from the still homogeneous cold waters of Leg-1. The Leg-6 minus Leg-1 T_{min} difference of 1.81°C is typical of long-shelf temperature gradients between these two sub-regions of the MAB.

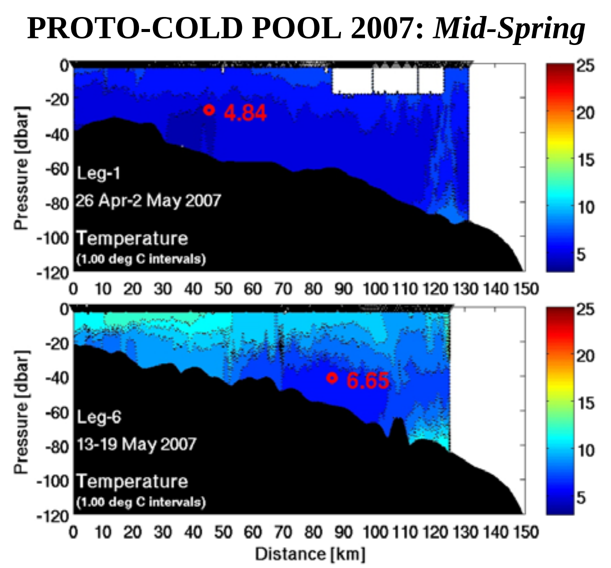


Figure 3 The 26 April – 19 May 2007 glider RU06: ***(upper)*** Leg-1 temperature section, with section-minimum temperatures indicated, and ***(lower)*** the same for Leg-6, with temperature (°C) legends to the right.

Cold Pool 2007 – Late Spring: By the late May (23 May - 15 June 2007) glider RU17 survey (Figure 4), the upper layer south of New England (Leg-1) had warmed and freshened enough to distinguish it from the emerging Cold Pool in the lower layer. Thus, the Cold Pool Water was defined throughout the MAB for 2007. Note that despite this milestone, the T_{min}s were colder than those in April; for Leg-1, 4.78°C versus 4.84°C; for Leg-6, 5.32°C versus 6.65°C (see Table 1). The much-reduced Leg-6 minus Leg-1 T_{min} difference of 0.54°C, was evidence of the regional advection of a *cold patch* embedded in the northeastern MAB Cold Pool.

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 (*$T < 12^oC$*), the means and standard deviations of *temperature departures* ($T_D = T - T_{min}$) and associated *salinity departures* ($S_D = S - S_{Tmin}$) are presented (see Appendix A for further discussion of this topic).

2007 Survey Month	Leg	Date	T_{min} (ºC)	T_D Mean (ºC)	T_D Std Dev (ºC)	S_{Tmin} (psu)	S_D Mean (psu)	S_D Std Dev (psu)
MAY	**Leg-1**	May 27	4.780	3.17	2.18	32.739	0.09	0.24
	Leg-6	June 11	5.319	3.15	1.66	33.006	0.15	0.16
		Ave.	***5.050***	***3.16***	***1.92***	***32.873***	***0.12***	***0.20***
JUL	**Leg-6**	July 24	5.603	2.84	1.70	32.961	-0.02	0.37
	Leg-8	Aug 03	6.331	3.32	1.56	33.028	0.28	0.25
		Ave.	***5.967***	***3.08***	***1.63***	***32.995***	**0.13**	***0.28***
		SUM. AVE.	***5.509***	***3.12***	***1.78***	***32.934***	***0.13***	***0.24***
SEP	**Leg-1**	Sep 30	7.711	2.06	1.12	33.006	-0.04	0.32
	Leg-6	Oct 13	8.478	0.90	0.91	32.967	0.05	0.18
		Ave.	***8.095***	***1.48***	***1.02***	***32.987***	***0.01***	***0.25***
OCT	**Leg-6**	Oct 10	8.588	0.91	0.94	33.057	0.06	0.20
	Leg-8	Oct 25	9.902	0.62	0.55	33.201	0.33	0.23
		Ave.	***9.245***	***0.77***	***0.75***	***33.129***	***0.20***	***0.22***
		AUT. AVE.	***8.670***	***1.13***	***0.89***	***33.058***	***0.11***	***0.24***

Cold Pool – Summer: By the 18 Jul – 4 Aug 2007 glider RU01 survey of the southwestern MAB (Figure 5/Table 1), the Cold Pool was well established. For example, a comparison of the mid-July Leg-6 (Figure 5) with the mid-June Leg-6 (Figure 4) shows significant warming of the upper layer and only a slight warming of the still very cold Cold Pool. The latter finding is consistent with the down-shelf translation of *cold patch*. The downward intrusions in the strong vertical stratification (in Figure 5-lower) appear to be a signature of a strong internal tide (though highly aliased by the gliders very slow speed). With reference to Table 1, the southwestern MAB (Legs 6 & 8) T_{min}-associated salinities are about 0.10 psu greater than those in the northeastern MAB (Legs 1 & 6). The salinity difference is the likely signature of intrusion(s) of higher salinity (and warmer) water across the SBF as the Cold Pool Water is advected by the SBF jet. What do the September glider measurements show?

Eastern MAB* COLD POOL 2007: *Spring

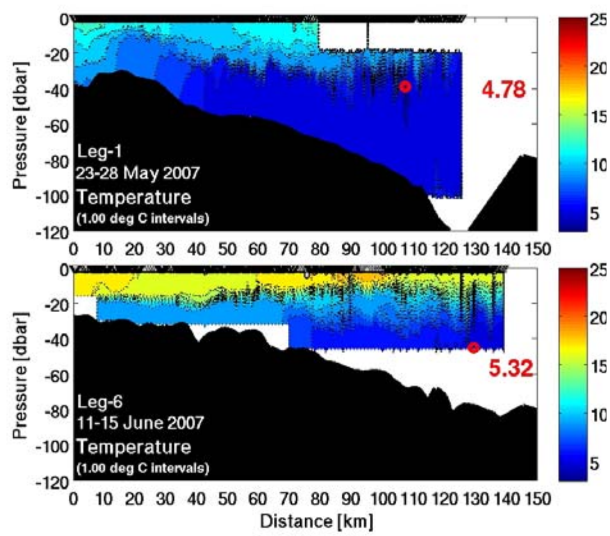


Figure 4 The 23 May - 15 June 2007 *glider RU17 (upper)* Leg-1 temperature section, with section-minimum temperatures indicated, and *(lower)* the same for Leg-6, with temperature (ºC) legends to the right.

Cold Pool – Autumn: By the 5-26 Oct 2007 glider RU06 survey of the southwestern MAB (Figure 6/Table 1), like the northeastern MAB (Figure 7/Table 1), there is still a distinct Cold Pool and it was warmer than during summer in both regions. However, the upper layer(s) cooled and continued to cool. Conversely the Cold Pool continued to warm through October and into November (Table A1).

"Cold Pool"-Winter: By the 28 November-19 December 2007 glider RU01 survey of the northeastern MAB (Figure 8/Table 1), the distinctiveness of the 2007 Cold Pool was totally erased; presumably by the seasonal storm-generated mixing. This mixing-induced homogenization of the water column led to a Leg-1 T_{min} of about 10°C near the surface of the inner shelf. Off New Jersey (Leg-6), winter cooling has begun inshore. These glider measurements captured the beginning of the winter 2007-08 cooling phase of the MAB waters.

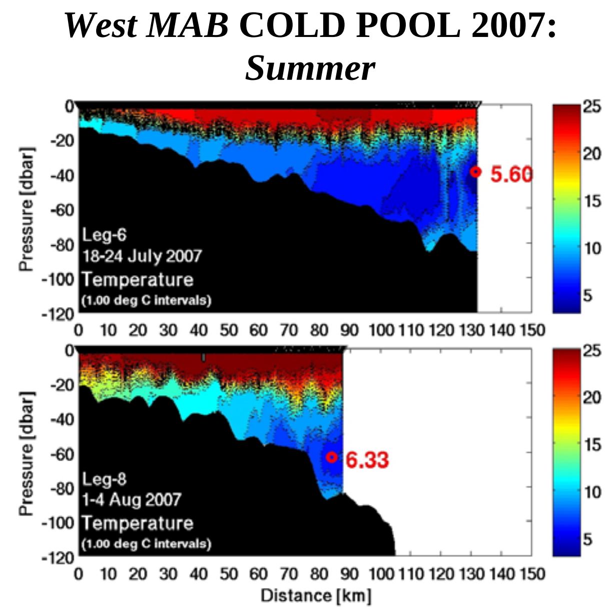


Figure 5 ***(left)*** The 18 Jul – 4 Aug 2007*glider RU01* ***(upper)*** Leg-6 temperature section, with section-minimum temperatures indicated, and ***(lower)*** the same for Leg-8, with temperature (°C) legends to the right.

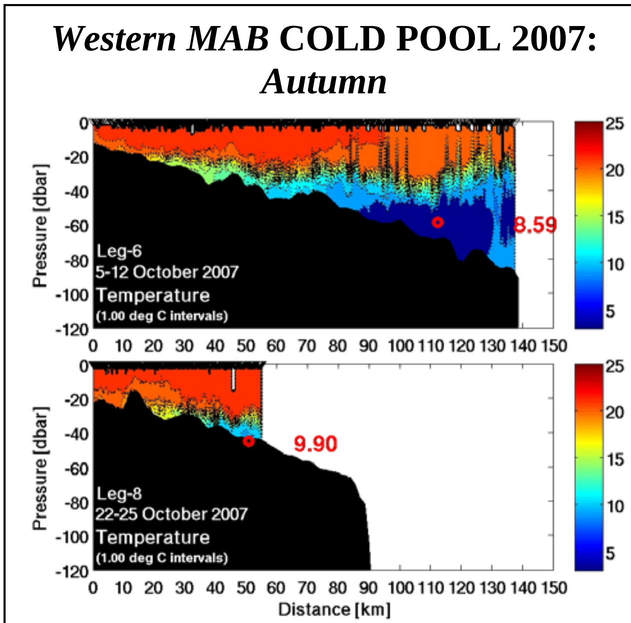


Figure 6 ***(left)*** The 5-26 Oct 2007*glider RU06* ***(upper)*** Leg-6 temperature section, with section-minimum temperatures indicated, and ***(lower)*** the same for Leg-8, with temperature (°C) legends to the right.

III. Cold Pool Water Mass Analysis

This March through November 2007 series of zig-zag glider surveys represents the most complete set of hydrographic measurements of a clearly evolving MAB Cold Pool to date. We now analyze this high-resolution data set in terms of Cold Pool 2007 water mass properties and their evolution.

We start by noting that successive glider transect T_{min}/S_{Tmin}s define the of the location of the thermal core of the Cold Pool. The loci of T_{min}/S_{Tmin}s in Figures 9 show that, throughout the MAB, the Cold Pool core is near, if not in the shelf-break front (SBF) in both summer and autumn 2007. Thus, the Cold Pool is an important part of the hydrography that geostrophically-supports the SBF jet; which is one of the fastest long-shelf flows in the MAB. The fact that T_{min} is usually 10m to 20m above the bottom is consistent with the location of the SBF jet. The geographic proximity to the SBF strongly suggests that the SBF jet advects some of the coldest water of the Cold Pool southwestward along the outer shelf.

Eastern MAB* COLD POOL 2007: *Autumn

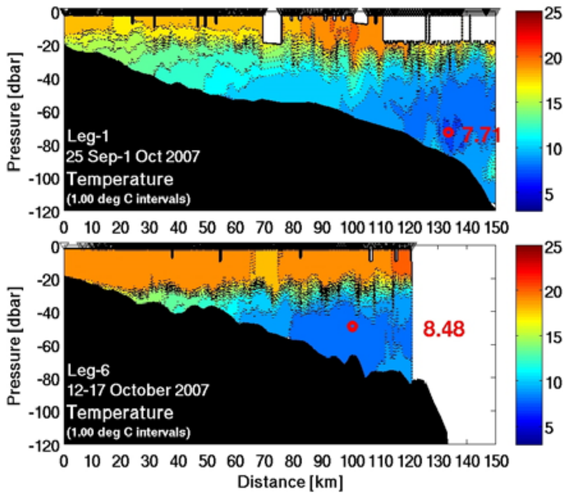


Figure 7 The 25 Sep - 17 Oct 2007*glider RU05* ***(upper)*** Leg-1 temperature section, with section-minimum temperatures indicated, and ***(lower right)*** the same for Leg-6, with temperature (°C) legends to the right.

COLD POOL 2007 Gone: *Winter*

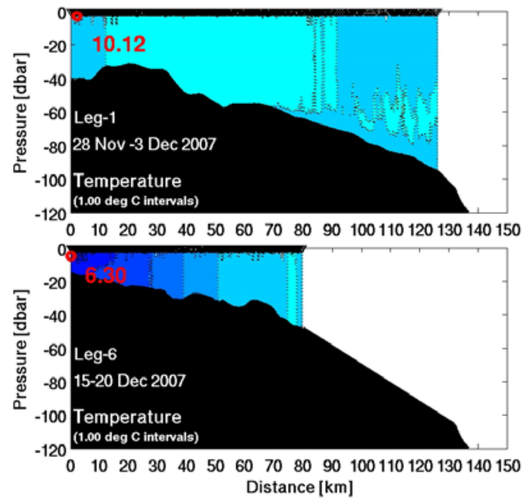


Figure 8 The 28 November- 19 December 2007*glider RU01* ***(upper)*** Leg-1 temperature section, with section-minimum temperatures indicated, and ***(lower)*** the same for Leg-6, with temperature (°C) legends to the right.

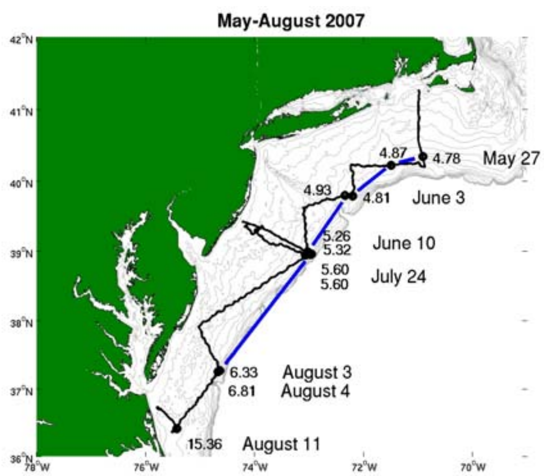


Figure 9a A composite of glider trajectories in the northeastern MAB *(RU17)* and the southwestern MAB *(RU01)*, respectively during *summer* 2007 (May-June and July-August). The section-minimum temperatures T_{min} (o) and dates are located. Note the repeat Leg-6 surveys.

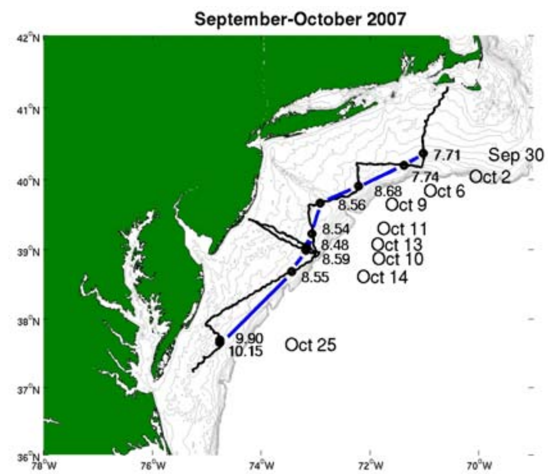


Figure 9b A composite of glider trajectories in the northeastern MAB *(RU05)* and the southwestern MAB *(RU06))*, respectively during *autumn* 2007 (Sep.-Oct and October). The section-minimum temperatures T_{min} (o) and dates are located. Note the repeat Leg-6 surveys.

The set of T_{min}s is an excellent proxy for MAB water temperatures that eventually become Cold Pool waters. Between March and April 2007, the T_{min}s of Leg-1 and Leg-6 – two of more-complete cross-shelf transects - warmed about 2°C (see Figure 10; Table 1). That was followed by a dramatic ~1.5°C cooling of the Leg-6 waters and a lesser cooling along the other transects during May. Our observations are consistent with Lentz (2017), who attributes the springtime cooling of parts of the MAB to the southwestward advection of a colder patch of the Cold Pool from the region of Hudson Canyon. Near the end of May 2007, the Cold Pool defined for the year was throughout the whole MAB.

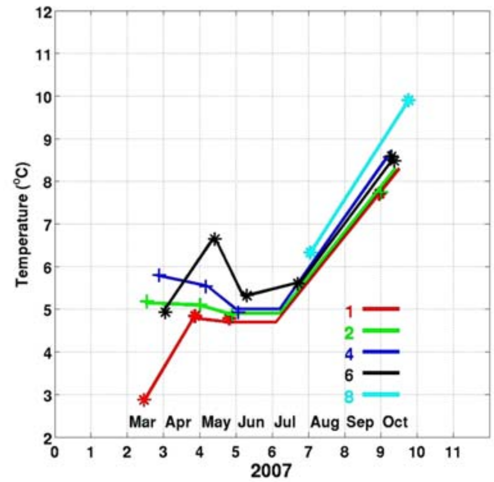


Figure 10 The 2007 section-minimum temperature T_{min} versus time for Legs-1 (red *), 2 (green +), 4 (blue +), 6 (black *) and 8 (cyan *). The visual fits to these T_{min}s show Apr-May 2007 cooling rates, which range from the larger at Leg-6 and to the smaller at Leg-1, followed by a shelf-wide average June-October 2007 warming rate of 1.05°C/month.

The lowered Cold Pool temperatures persisted in the northeastern MAB into early July. Then the MAB-wide Cold Pool Waters (CPW) began to warm at a rate of about 1°C/month. (Estimates of the warming rates in Table A1 in Appendix A highlight the contrast between the *Spring* (Apr-May) cooling and *Summer-NE* (May-October) warming in the northeastern segment of the MAB Cold Pool). The summer warming of the MAB Cold Pool (see Figure 10 & Table 2) is 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 is addressed in the Brown and Arena (2019) part-2 of this paper.

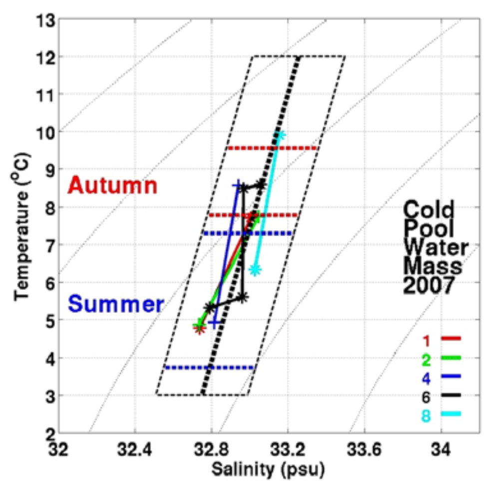


Figure 11 T_{min} versus S_{Tmin} observations for the Legs-1 (red*; color-coded lower right), 2 (green+), 4 (blue+), 6 (black*), and 8 (cyan*). The statistical definition of 2007 Cold Pool Water (CPW; black dashed trapezoid) is based on the average 2007 section T_{min}-S_{Tmin} relation (bold dashed), which is a linear fit to the May-October 2007 observations. The summer (blue dash) and autumn sub-season definitions are indicated.

The 2007 time-space variable TS water properties of the Cold Pool are defined between 3°C and 12°C in terms of a suite of T_{min}-S_{Tmin} curves (see Figure 11) for several of the main transects. A fit to the observations represents the average 2007 T_{min}-S_{Tmin} relation (bold dashed black line Figure 11). This T_{min}-S_{Tmin} relation shows that warmer Cold Pool core waters are more saline. The trend toward higher temperatures during the summer is due to differing combinations of the several ocean processes mentioned above. However, the trend of the T_{min}-S_{Tmin} relation toward higher salinities is only consistent with significant exchange across the SBF between the Cold Pool and Slope Sea waters. We have chosen to define the average 2007 Cold Pool waters in terms of ±1 standard deviation of the variability of the *salinity departures* from S_{Tmin} as described next.

Table 2. The 2007 Cold Pool Water warming rates (WR in °C/30.25day-month) and salting rates (SR in psu/month) for different Parts of the MAB are given for *Summer–I (May-Oct)* and *Summer–II (July-October),* (see Appendix A for further discussion).

2007 Survey Month	Leg	Warming Rates (°C/mo)	T_{min} (°C)	Salting Rates (psu/mo)	S_{Tmin} (psu)	Date 2007
MAY	Leg-1		4.780		32.739	May 27
SEP	Leg-1		7.711		33.006	Sep 30
		Leg-1 Sum–I WR	***0.705***	***Leg-1 Sum–I SR***	***0.066***	
MAY	Leg-6		5.319		33.006	June 11
SEP	Leg-6		8.478		32.967	Oct 13
		Leg-6 Sum–I WR	***0.771***	***Leg-6 Sum–I SR)***	***0.051***	
		AVE. Sum–I WR	***0.738***	***AVE. Sum–I SR***	***0.058***	
JUL	Leg-6		5.603		32.961	July 24
OCT	Leg-6		8.588		33.057	Oct 10
		Leg-6 Sum–IIWR	***1.159***	***Leg-6 Sum–II SR***	***0.037***	
JUL	Leg-8		6.331		33.028	Aug 03
OCT	Leg-8		9.902		33.201	Oct 25
		Leg-8 Sum–II WR	***1.301***	***Leg-8 Sum–II SR***	***0.046***	
		AVE. Sum–II WR	***1.195***	***AVE. Sum–II SR***	***0.069***	
		WR AVE.	***0.967***	***SR AVE.***	***0.063***	

The sub-thermocline water properties are strongly influenced by Cold Pool core water properties (T_{min}/S_{Tmin}) through mixing. Thus, for each parcel of sub-thermocline water (i.e., with temperature < 12°C), we computed the departure of parcel temperature from $T_{min} \Rightarrow T_D$; and the departure of parcel salinity from $S_{Tmin} \Rightarrow S_D$. The basic statistics of these T_D/S_D quantities are summarized in Table 1 and discussed further in Appendix A. The trapezoid width is a constant ± S_D standard deviation (1σ ~ 0.24 psu; see Table 1) of all sub-12°C waters. The 2007 *summer* (blue dashed) and *autumn* (red dashed) CPW temperature bounds (average $T_{min} \pm T_D$ σ sub-12°C waters are shown. In contrast to the salinities, the T_D statistics are seasonal - reflecting the warming noted before. Thus, we use a sliding average $T_{min} \pm T_D$ 1σ window to define the Cold Pool Water (CPW) mass in the region of a specific cross-shelf section with a specified T_{min}.

T-S relations of Leg-6 profiles from *summer (July)* and *autumn 2007(October)* in Figure 12 show the seasonality in the Cold Pool water masses that is demonstrated above. The T_{min} profile have the Cold Pool water defined above in them. Interestingly, the most landward (red) profile of the Leg-6 transect in both seasons have T-S relations that indicate that they are mixing products involving pure Cold Pool water. We explore the structure of the Cold Pool water mass further in the next section.

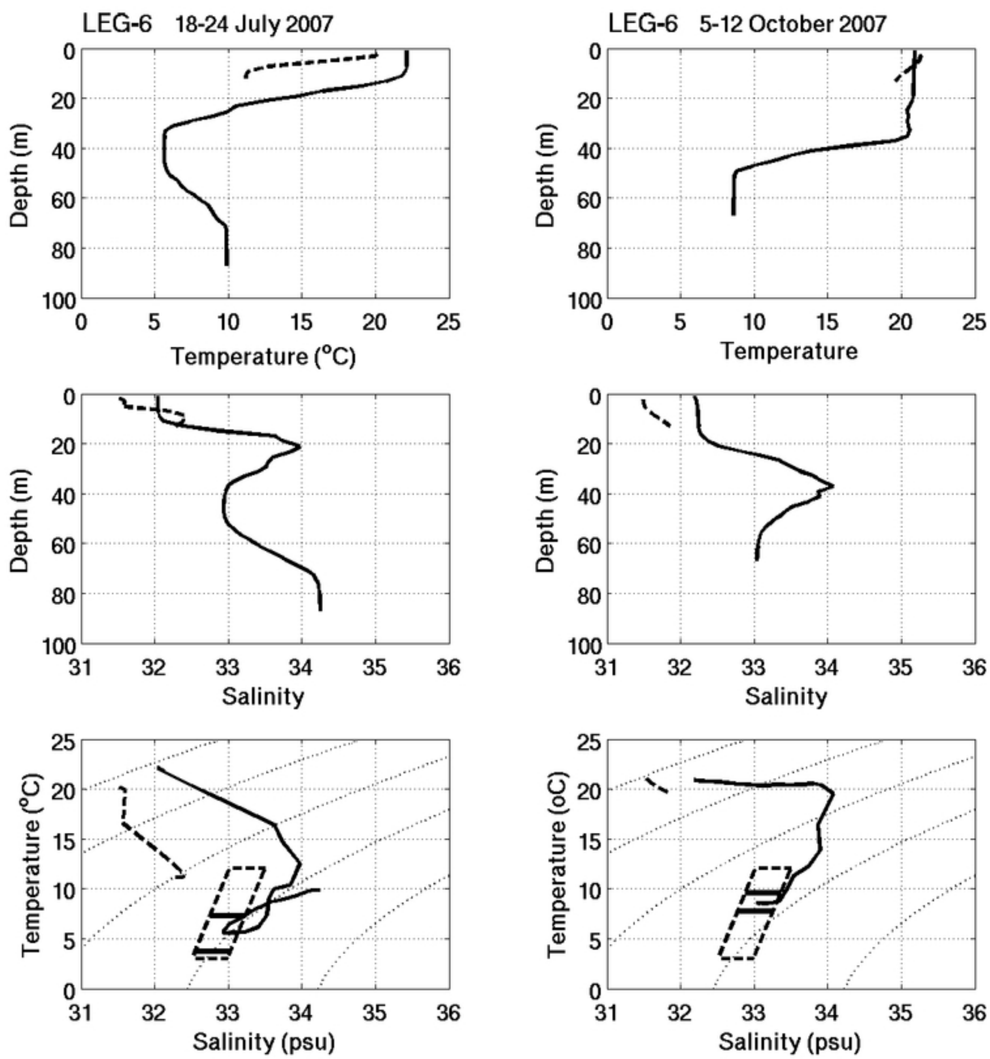


Figure 12 ***(left)*** Leg-6 July 2007 *summer* profiles of *(top)* temperature, *(middle)* salinity and *(bottom)* T-S relationship. Each panel features the T_{min} profile (solid) and most landward (dashed) profile of the section. ***(right)*** Same for Leg-6 October 2007 *autumn* profiles. The respective *summer* and *autumn* 2007 Cold Pool Water (CPW) mass definitions (solid trapezoids) are embedded in the 2007 CPW definition (dashed trapezoid).

IV. Cold Pool Water Mass Structure: 2007

Glider measurements were used to estimate the oceanographic extent of the MAB Cold Pool for *summer 2007*, *autumn* 2007 and *September 2013*. A common approach is to define the Cold Pool by a specific isothermal surface most frequently the 10°C surface – as we have done here. (See Appendix A for an alternative approach). Once the Cold Pool is distinguishable throughout the MAB (usually in May), the thermocline contains the 10°C isothermal surface (or the "ceiling" of the Cold Pool). The task here was to define inshore and offshore Cold Pool boundaries of the intersection using glider measurements. The shoreward edge of the Cold Pool is defined by the10°C isotherm/bottom intersections. But sometimes gliders just did not go far enough seaward to pierce the shelf-break front, SBF, which surely contains the 10°C isotherm (Linder et al., 2004). In this case, we set the seaward boundary of the Cold Pool at the 100m isobath - the nominal location of the SBF. This approach enabled us to estimate the extent of the *footprint* of the Cold Pool on the seafloor for different seasons and years as described next.

Summer 2007 10°C Cold Pool: The *summer (*mid-May through mid-August) *2007* sub-10°C Cold Pool Water (CPW) footprint was constructed from a composite of (a) glider RU17 measurements in the northeastern MAB and (b) glider RU01 in the southwestern MAB. With reference to Figure 13, the 10°C isotherm in the northeastern MAB during May-June appears to have intersected bottom just slightly inshore of the beginnings of the Leg-1 and Leg-6 glider measurements; and some inshore distance for all the other legs of the glider trajectory. In the southwestern MAB, the 10°C isotherm intersects the bottom on all legs (see Figure 14). The Leg-6 T_{min}s of the two surveys, despite being more a month apart, differed by only 0.28°C (see Figure 9). The *summer 2007 10°C* CPW footprint covers most of the northeast MAB and about half of the southwest MAB. The fact that the CPW mass narrows significantly is evidence that the CPW leaves the shelf offshore of the mouth of Chesapeake Bay. Assuming an upper layer average depth of 30m, the *summer 2007 10°C CPW footprint* in Figure 15 has an estimated volume of 4099 km^3; and represents is a reasonable *10°C* Cold Pool extent for this season.

Autumn 2007 10°C Cold Pool: The *autumn 2007 sub-10°C* CPW footprint (Figure 16) was constructed from glider *RU05 and RU06* surveys (see Brown et al., 2015). Gliders RU05 and RU06 occupied the New Jersey transect (Leg-6) within a week of each other and found very similar T_{min}s and 10°C isotherm/bottom intersection locations. The *autumn 2007* CPW footprint is the same general shape as is its *summer* counterpart, with its apparent off-shelf escape route offshore of the Maryland coast. The *autumn 2007 10°C* CPW is about 3°C warmer and 0.1 psu saltier than the *summer 2007 CPW*. However, the *autumn 2007 10°C* CPW footprint has only 58% of the *summer 2007* volume. Given the significant salting of the T_{min}-waters during the summer, lead us to conclude that a significant amount of the CPWs are lost through lateral exchange across the SBF as it moves southwestward. This could explain the narrowing of the Cold Pool footprint in the southwestern MAB.

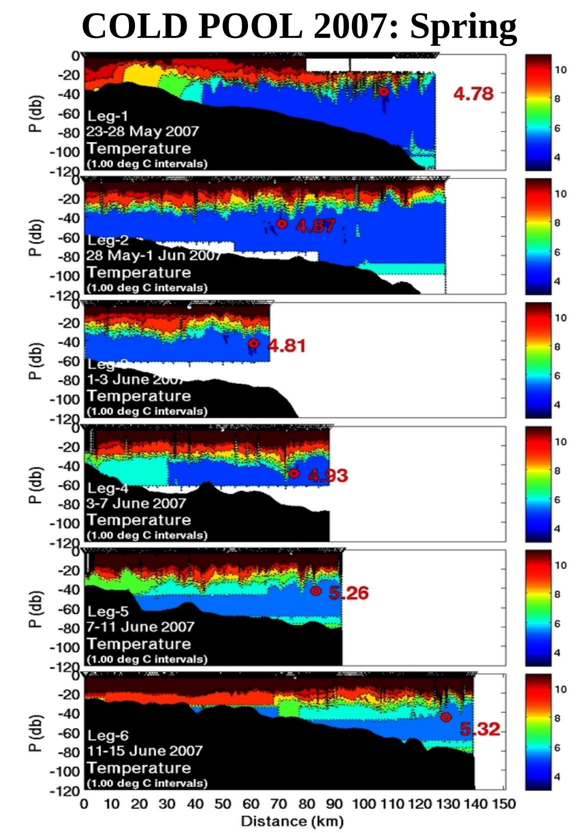


Figure 13 The May-June 2007 *glider RU17* temperature sections in the northeastern MAB. (*Top-to-bottom panels*) Legs-1, -2, -4, -5 and -6, respectively. The orange-red boundary is the 10°C isotherm.

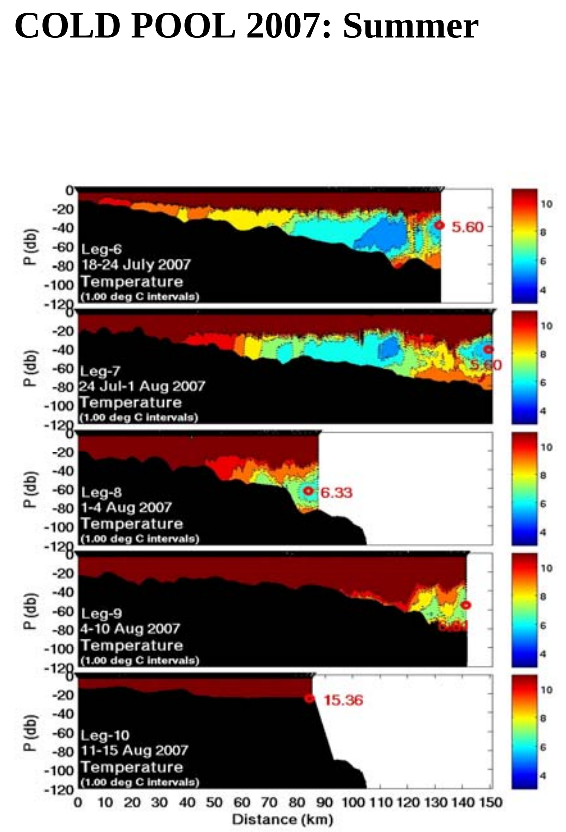


Figure 14 The Jul.-Aug. 2007 *glider RU01* temperature sections in the southwestern MAB. (*Top-to-bottom panels*) Legs-6 through -10, respectively. The orange-red boundary is the 10°C isotherm.

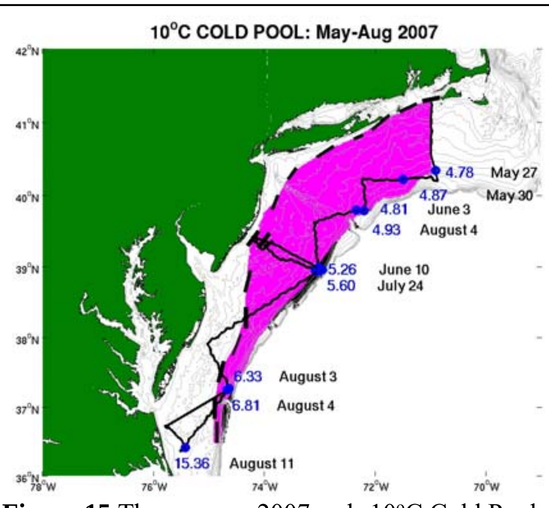


Figure 15 The *summer* 2007, sub-10°C Cold Pool Water (CPW) footprint (pink) is defined by *glider RU17/RU01* survey measurements. The section-minimum temperatures (blue o) - defining the Cold Pool core - are located.

Estimated Cold Pool Volume => 4099 km³

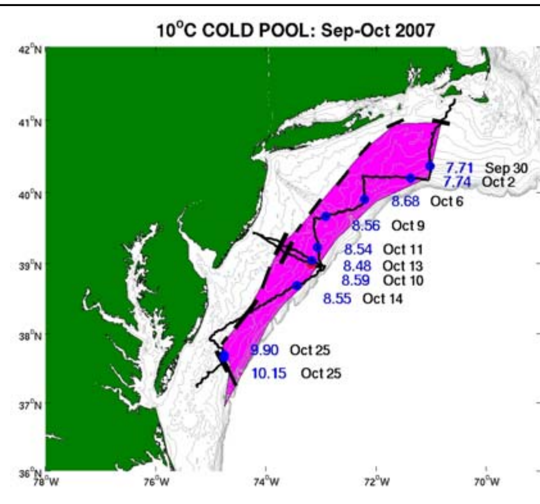


Figure 16 The *autumn* 2007, sub-10°C CPW footprint (pink) is defined by *glider RU05/RU06* survey measurements. The section-minimum temperatures (blue o) - defining the Cold Pool core - are located.

Estimated Cold Pool Volume => 2391 km³

The shape of the late May to early August or *summer 2007 10°C* Cold Pool Water (CPW) footprint is generally consistent with the Lentz (2017) monthly climatologies of the profile minimum temperatures (Figure 17). The distinct narrowing of this CPW footprint toward the shelf-break off Maryland is similar in both depictions. However, the seaward edge of the *summer 2007* CPW appears to be colder than the Lentz (2017) climatologies.

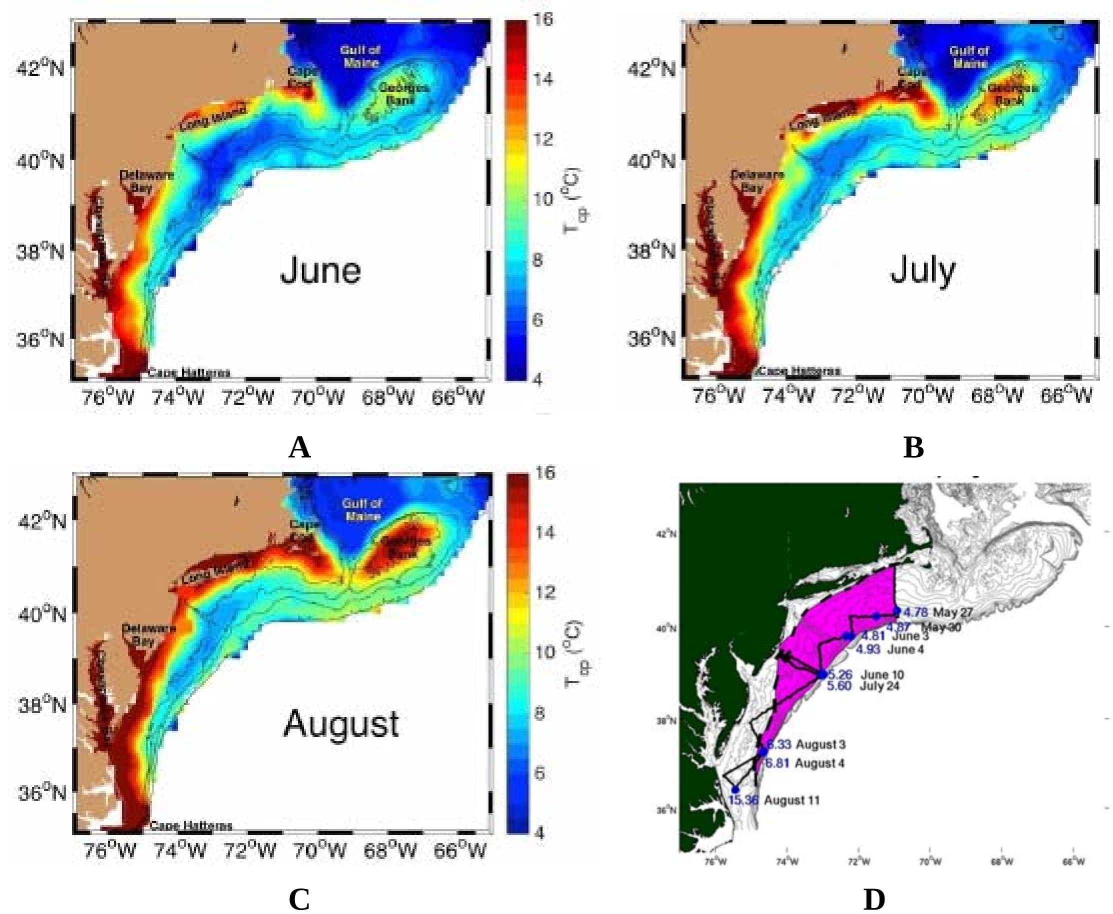
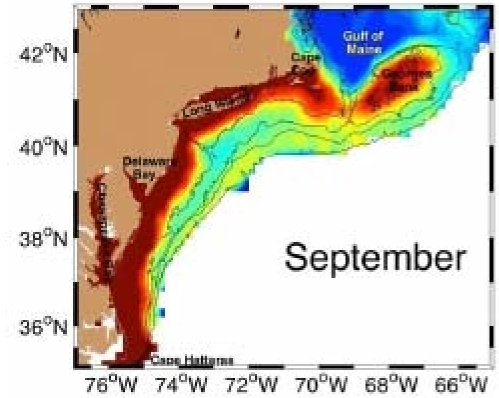
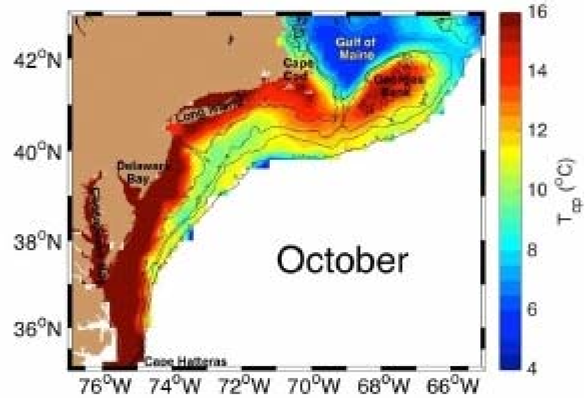


Figure 17 Comparison of the (*panel D*) late May to early August 2007 sub-10°C Cold Pool footprint derived from glider measurements with the Lentz (2017) monthly 1955-2014 climatologies of hydrographic profile minimum temperatures for (*panel A*) June, (*panel* B) July, (*panel* C) August. The climatological 10°C isotherm is in the green band.

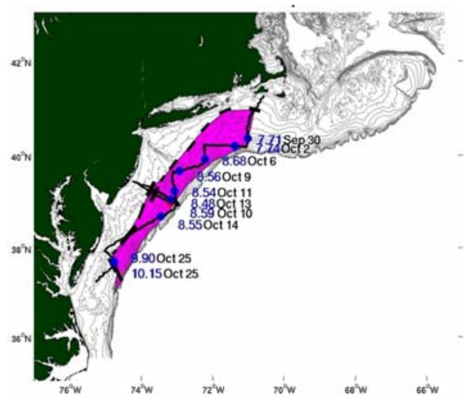
The shape of the late September-October or *autumn 2007 10°C* Cold Pool Water (CPW) footprint is generally consistent with the Lentz (2017) September and October profile minimum temperature climatologies (Figure 18). In particular, the northeastern edge of the *autumn 2007* 10°C CPW footprint is similar to that in the Lentz (2017) October climatology.



A



B



C

Figure 18 Comparison of the (*panel C*) late September-October 2007 sub-10ºC Cold Pool footprint derived from glider measurements with the Lentz (2017) monthly 1955-2014 climatologies of hydrographic profile minimum temperatures for (*panel A*) September and (*panel B*) October. The climatological 10ºC isotherm is in the green band.

V. Cold Pool Water Mass Structure: September2013

September 2013 Cold Pool: 10ºC: In 2013, MARACOOS organized a 9-glider deployment consisting of operations all along the American coastal ocean between Nova Scotia and Florida - *GliderPalooza 2013*. Here we focus on a four-glider subset of missions in the MAB (see Figure 19). The gliders Blue, RU-23 and RU-22 missions were conducted on the mid to outer shelf almost at the same time in September and October. Glider RU-28 patrolled the inner shelf in water depths less than 30m along the NJ coast. The three outer shelf gliders also tested the hypothesis that triangular glider patterns were most effective for data-assimilation numerical ocean modeling of MAB dynamics and kinematics.

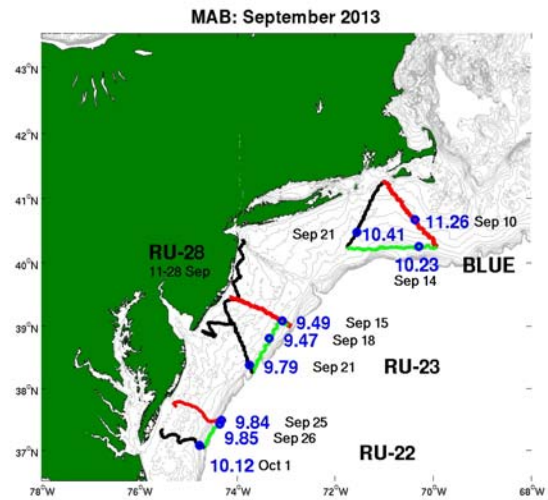


Figure 19 The MAB trajectories of *gliders BLUE, RU23, RU22, and RU28*. The glider Blue triangle in the Southern New England Bight consists of Legs -1 (red), -2 (grn), and -3 (blk); as was the *glider RU23* trajectory off NJ; as was the *glider RU22* trajectory east of Maryland. The *glider RU28* trajectory (blk) is the one just off the NJ coast. The Leg-T_{min}/dates are indicated.

Glider Blue followed a near-equilateral triangular trajectory and sliced through the Cold Pool twice in the Southern New England Bight (SNEB; see Figure 19). Glider Blue penetrated the shelf-break front (SBF) twice during its Leg-2. Glider RU-23 followed a right triangular trajectory off New Jersey (NJ) and sliced through the Cold Pool and SBF twice – nearly at the same time as glider Blue. A week or so later, glider RU22 trajectory, followed a near rectangular trajectory off Maryland (MD) and sliced through the Cold Pool and SBF twice. We noted the fact that the RU23 off NJ (see transect T_{min}s Figure 19; Table B1 in Appendix B) measured clearly colder temperatures of than either the gliders to the north and south got our attention.

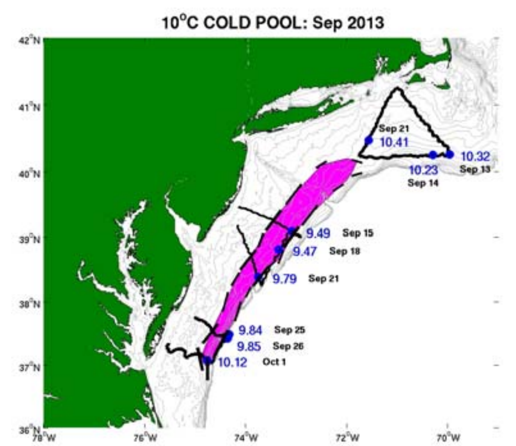


Figure 20 The Sep 2013 sub-10ºC MAB Cold Pool (pink) is defined by glider measurements: *glider Blue* in the northeast, *glider RU23* in mid-shelf and *glider RU22* in the southwest. The inshore and seaward edges of the Cold Pool is defined by 10ºC isotherm/bottom intersections (black). The section-minimum temperature T_{min} (blue o) are located.
Estimated Cold Pool Volume of 1138 km³.

The 2013 Cold Pool was clearly warmer than the *autumn* 2007 Cold Pool, as evidenced by the lack of sub-10ºC Cold Pool waters in the Southern New England Bight (SNEB) end of the MAB (see Figure 20). Still the glider Blue measurements showed a warmed Cold Pool structure (see Appendix B). The Cold Pool had been warmed (and salted) by a Gulf Stream water core ring, which impinged on the SNEB region during August-September 2013. The fact that

Gulf Stream water core rings are frequent visitors to the edge of the MAB - locally warming and salting Cold Pool properties - forced us to revise our definition of Cold Pool Water properties (see Figure 21). This, in turn, prompted us to explore the extent of a sub-12°C Cold Pool for the whole MAB.

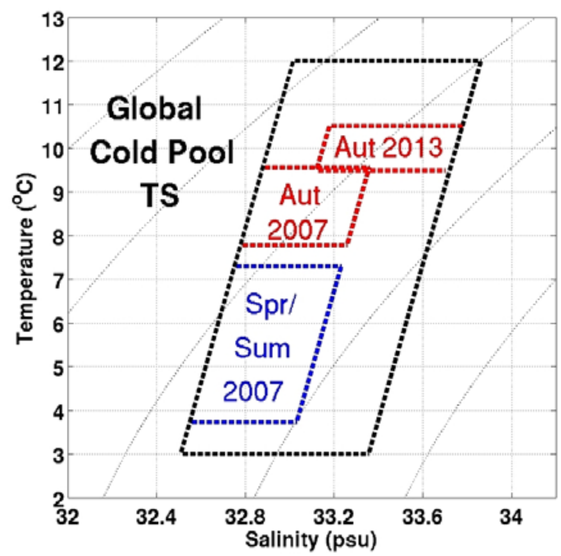


Figure 21 The "global" definition of the Cold Pool water mass (blk dashed) includes seasonal sub-definitions: Spring/Summer 2007, Autumn 2007 and Autumn 2013.

Given the proximity of the Cold Pool core (i.e., T_{min}s) to the SBF jet flow, much of the coldest waters of the Cold Pool must be advected from the northeast toward the southwest (Linder et al., 2004).

The geography of the September 2013, sub-12°C Cold Pool (see Figure 22) was derived from the glider measurements as described in Appendix B. The sub-12°C Cold Pool footprint is considerably more voluminous (4093 km^3) than the sub-10°C Cold Pool (1138 km^3).

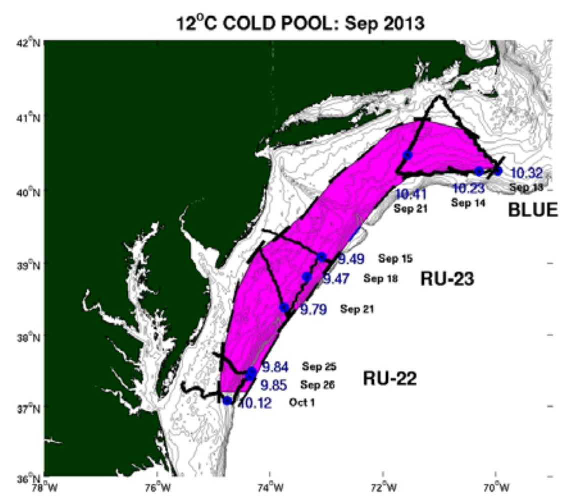


Figure 22 The sub-12°C MAB Cold Pool (pink) for September 2013 is defined by the trio of glider measurements: *glider Blue* in the northeast, *glider RU23* in mid-shelf and *glider RU22* in the southwest. The section-minimum temperatures T_{min} (blue o) are located.
Estimated Cold Pool Volume => 4093 km^3

The TS diagram of the glider Blue's T_{min} profiles in the SNEB region in Figure 23 intersects the Cold Pool water mass definition and the inshore water properties are seen to be a product of lateral mixing with Cold Pool waters. Figure 23 also suggests that the deepest Cold Pool waters mix with warm slope water (WSW), which has been strongly influenced by the Gulf Stream.

The TS diagram of the glider RU-23's T_{min} profiles off New Jersey region in Figure 24 intersects the Cold Pool water mass definition and the inshore water properties are seen to be a product of lateral mixing with Cold Pool waters. While the TS signature of NJ Cold Pool waters point toward possible mixtures with WSW, it is less clear as it is in the SNEB region.

VI. 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 have used the glider water property measurements – particularly temperature – to define an important, evolving habitat feature of the Mid-Atlantic Bight.

We document the details of the establishment of the Cold Pool – most robustly off New England and New Jersey in May 2007. We explore the time-space evolution of the Cold Pool with a series of single glider zig-zag missions with series of transects down the shelf northeast to southwest in 2007. The glider transect minimum temperatures T_{min}s define the core of the 2007 Cold Pool, which parallels the outer shelf near the Shelf-Break Front (SBF; Figure 9). These glider measurements show that the Cold Pool waters warm at the rate of about 1^{o}C per month and salt at the rate of from July for the rest of the summer into October. They also showed We were able to define 2007 Cold Pool waters in TS space by

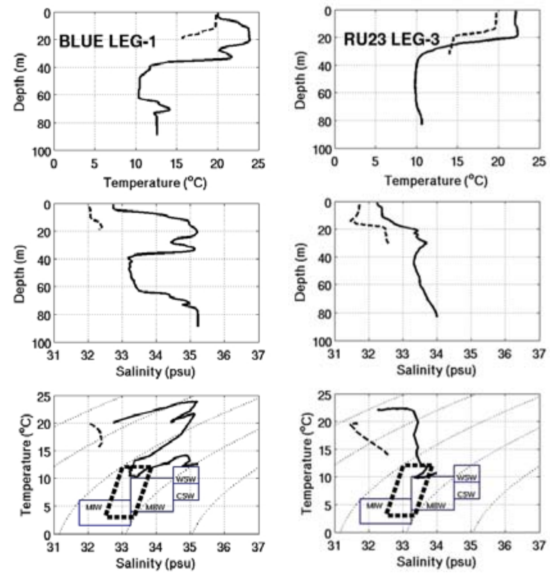


Figure 23 The September 2013 *(top)* temperature, *(middle)* salinity and *(bottom)* T-S relations for the T_{min} (solid) and most shoreward (dashed) profiles of for ***(left)*** SNEB Leg-1 and ***(right)*** NJ Leg-3. The “global” Cold Pool water mass is defined (dashed trapezoid). The Brown and Irish (1993) definitions of Maine Intermediate Water MIW, Maine Bottom Water MBW, and Warm Slope Water WSW and Cold Slope Water CSW.

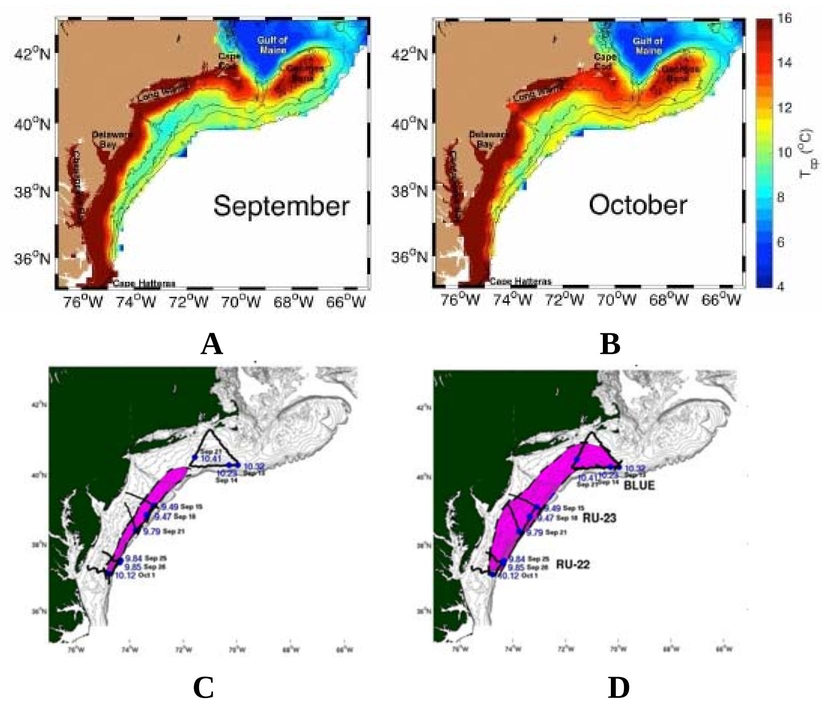


Figure 24 The 1955-2014 monthly climatological average of the hydrographic profile minimum temperatures *(T_{cp})* in (A) September and (B) October are compared with the (C) sub-10^{o}C Cold Pool and (D) sub-12^{o}C Cold Pool footprints derived from gliders *BLUE, RU23 and RU22* measurements in September and October 2013. In the Lentz (2017) climatology, the 10^{o}C isotherm is in the green band and the 12^{o}C isotherm is in the orange band.

combining the results from the 2007 glider surveys (without GS warm core rings) Then the Cold Pool loses its distinctiveness – a casualty of autumn storm mixing- and becomes homogenized in preparation for winter cooling.

We explored the inter-annual variability through a comparison of the September-October 2007 MAB 10ºC Cold Pool Waters (CPW) with its 2013 counterpart measured by a nearly simultaneous trio of glider missions (Figure 19). The comparison clearly showed how the 2013 MAB waters in the northeastern sector were warmed and salted by the impingement of a Gulf Stream Warm Core Ring (GS-WCR).

Our *summer* 2007 *sub-10ºC Cold Pool* footprint (using only glider measurements) decreases from almost full shelf width south of New England to a very narrow strip off Maryland (Figures 15 & 16). Assuming a thermocline depth of 30m throughout the region, we estimated the summer 2007 Cold Pool volume to be 4099 km^3. This compared to an estimated volume of 2391 km^3 *autumn* 2007 (see Figure 16). The latter compared to estimated volume of a *sub-10ºC Cold Pool* of 1138 km^3 in September 2013 (Figure 20). We attribute this volume loss to the 2013 warming effects of the impingement Gulf Stream warm core ring.

We defined TS properties of Cold Pool waters by combining the results from the 2007 glider surveys (without GS warm core rings) and 2013 surveys (with GS warm core ring; Figure 21). The 2007 series of glider measurements document the approximate 1^{O}C per month Cold Pool warming and 0.06 psu per month Cold Pool salting during summer into the autumn. These results suggest that a quantitative water mass analysis – beyond the scope of this effort – could lead to cross-SBF mixing rates. In Part-2, Brown & Arena (2019) consider how the temperature budget can be used for estimates of cross-SBF mixing.

Appendix A: Temperature Departure (TD)

An alternate approach to defining the Cold Pool is to use the statistics of the departures of sub-thermocline water temperature from T_{min} and salinity from S_{Tmin} in a transect located at a down-shelf "*s*" (see Table A1).

Table A1 Transect minimum temperatures (T_{min}), associated salinities (S_{Tmin}), T_{min}/S_{Tmin} depths, and T_{min}/S_{Tmin} 2007 dates. The 2007 warming rates (WR in ºC/30.25day-month) for each section are given for the northeastern MAB *Spring (Apr-May)*, *Summer–I (May-Oct)* and *Fall (Oct-Dec);* and for the southwestern MAB in *Summer–II (July-October)*, respectively. The salting rates (SR in psu/month) are also given.

2007	**LEG=>**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
SPR											
Mar-Apr	**T_{min} (ºC)**	**2.872**	***5.186***	***6.121***	***5.803***	***6.261***	***4.929***				
	S (psu)	32.801	*33.074*	*33.362*	*33.598*	*33.696*	*33.083*				
	depth (m)	75	1	55	33	43	257				
	date	Mar16	Mar 19	Mar 20	Mar 29	Mar 29	Apr 3				
Apr-May	**T_{min} (ºC)**	**4.843**	***5.107***	***5.231***	***5.532***	***6.052***	**6.648**				
	S (psu)	32.815	*32.712*	*32.913*	*33.087*	*33.087*	33.272				
	depth (m)	27	45	39	49	41	41				
	date	Apr 28	May 2	May 6	May 7	May 11	May 15				
Spring	*WR (ºC/mo)*	*-0.064*	***-0.166***	***-0.272***	***-0.466***	***-0.560***	***-0.956***				
	COLD	***POOL***	***Start***								
May-Jun	**T_{min}**	**4.780**	**4.866**	**4.810**	**4.931**	**5.258**	**5.319**				
Fig. 4	S (psu)	32.739	32.736	32.781	32.816	32.763	32.753				
	depth (m)	39	47	43	49	43	37				
	date	May 27	May 30	Jun 3	Jun 4	Jun 10	Jun 11				
SUM											
Jul-Aug	**T_{min}**						**5.603**	**5.597**	**6.331**	**6.806**	**15.361**
Fig. 5	S (psu)						32.961	32.930	33.028	33.033	33.555
	depth (m)						39	41	63	55	25
	date						Jul 24	Jul 24	Aug 3	Aug 4	Aug 11
Sep-Oct	**T_{min}**	**7.711**	**7.741**	**8.679**	**8.562**	**8.535**	**8.478**				
Fig. 7	S (psu)	33.006	33.047	33.128	32.942	32.947	32.967				
	depth (m)	73	65	75	51	73	49				
	date	Sep 30	Oct 2	Oct 6	Oct 9	Oct 11	Oct 13				
October	**T_{min}**						**8.588**	**8.554**	**9.902**	**10.147**	
Fig. 6	S (psu)						33.057	33.201	33.153	33.311	
	depth (m)						59	45	45	47	
	date						Oct 10	Oct 14	Oct 25	Oct 25	
FALL	***COLD***	***POOL***	***End***								
Dec	**T_{min}**	**10.063**	**10.008**	***10.159***	***10.088***	***10.160***	**6.299**				
Fig. 8	S (psu)	34.288	*34.345*	*32.642*	*32.703*	*32.384*	30.988				
	depth (m)	99	99	1	1	1	5				
	date	Dec 3	Dec 3	Dec 9	Dec 10	Dec 13	Dec 19				

We compute respective temperature departure (T_D) according to

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

and salinity departures (SD) according to

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

where T^t/S^t is any temperature/salinity pair in the transect with T_{min}/S_{Tmin}, *"x"* is an inshore coordinate referenced to the location of the most offshore transect station, and *"z"* is upward. A T_D/S_D is computed for sub-thermocline water parcels with temperatures less than 12°C. The *mean* and *standard deviations* for all the T_D/S_Ds of a selected subset of the transects are presented in Table 1 (main text). The T_D *standard deviations* range from a minimum of 0.55°C for the October Leg-8 to a maximum of 2.18°C for the May Leg-1; with a May-October 2007 average of 1.33°C.

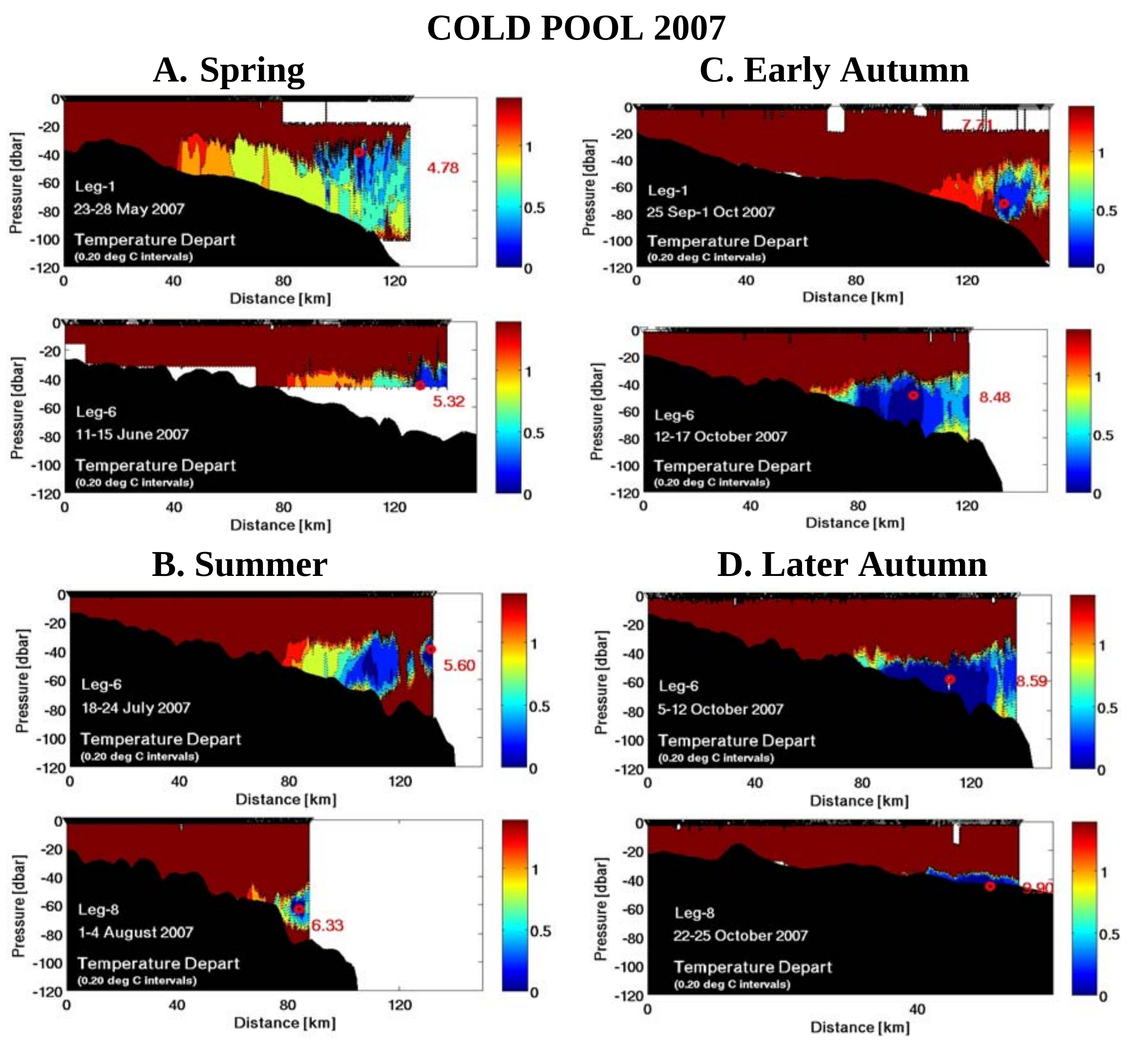


Figure A1. The 2007 glider-derived temperature departure TD sections for *(upper left)* spring (May-June) RU17 Legs 1 and 6 in the northeastern MAB; *(lower left)* summer (July-Aug.) RU01 Legs 6 and 9 in the southwestern MAB; *(upper right)* early autumn (Sep-Oct) RU05 Legs 1 and 6 in the northeastern MAB; and *(lower right)* later autumn (Oct.) RU06 Legs 6 and 8 in the southwestern MAB. The colored-coded contours have been forced to saturate at the $T_D = 1.33°C$ isopleth – the red-auburn boundary.

Cold Pool 2007 waters are defined as those waters with T_Ds less than an annual average standard deviation or *1.33*ºC. Transect plots of contoured T_Ds, with limits of 0ºC < T_D < 1.33ºC (see Figures A1-A & B) silhouette Cold Pool waters and enable us to determine the inshore boundaries of the spring/summer Cold Pool. For example, we see on the Leg-1 spring and summer sections (Figures A1-A & B) that the 1.33ºC T_D contour intersects the seafloor near the 40m isobath, while on the Leg-6 section the intersection is closer to the 40m isobath. During autumn (Figures A1-C & D), the 1.33ºC T_D contour bottom closer to the 40m isobath on all four legs of the 2-glider survey. We use these *1.33*ºC T_D contour/seafloor intersections to mark the inshore extent of the summer 2007Cold Pool (by the T_D definition) (bold red bars in Figure A2). The dashed red lines represent the approximate T_D-defined inshore extent of the summer 2007 Cold Pool. The extent of the 10ºC isotherm-defined Cold Pool is also presented in Figure A2. In the northeastern MAB, there is a considerable difference in these Cold Pool definitions; in the southwestern MAB the difference is considerably less. Both results show that the Cold Pool near-bottom extent narrows considerably offshore of Maryland. This narrowing implies that Cold Pool waters are exiting the shelf in the southwestern sector of the MAB. We assume that the outer edge of the 2007 Cold Pool is approximated by the shelf-break at about the 100m isobath.

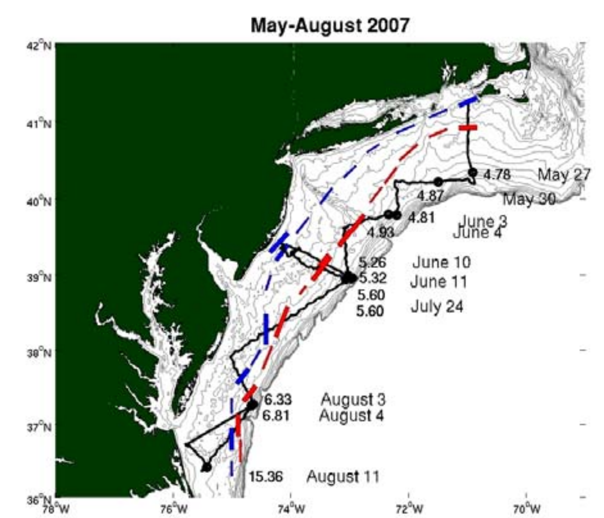


Figure A2 A composite of two glider survey trajectories: (a) RU17 May-June 2007 in the northeastern MAB and (b) RU01 July-August 2007 in the southwestern MAB locates each section-minimum temperature T_{min} (o) value/date. The inner edge of the Cold Pool is defined in terms of the 1.33ºC T_D isopleth/seafloor intersection (red) or the 10ºC isotherm (blue). For the 2007, glider observations, the seaward edge is approximated by the shelf-break isobath (~100m) – the average location of the Shelf-Break Front.

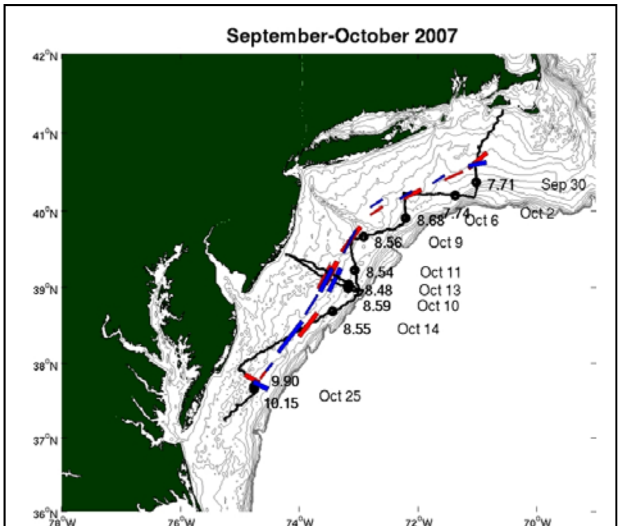


Figure A3 A composite of two glider survey trajectories: (a) RU05 Sep.-Oct. 2007 in the northeastern MAB and (b) RU06 Oct. 2007 in the southwestern MAB locates each section-minimum temperature T_{min} (o) value/date. The inner edge of the Cold Pool is defined in terms of the intersection of the 1.33ºC TD isopleth (red) or the 10ºC isotherm (blue) with the seafloor. The seaward edge is approximated by the shelf-break isobath (~100m) – the average location of the Shelf Break Front.

Autumn 2007 Cold Pool: TD

The September - October 2007 glider T_D transects (see Brown et al., 2015) enable us to construct a map of the autumn 2007 CPW (Figure A3) that is distinctly warmer and thus narrower than the summer 2007 Cold Pool. Also, in contrast to summer 2007, the 1.33ºC T_D and the 10ºC isotherm coincide. The inshore extent of this warmer autumn 2007 CPW is like the Spring/Summer 2007 CPW in the northeastern sector of the MAB. However, while we have fewer transects than for spring/summer 2007, the CPW inshore boundary in the southwestern sector of the MAB is further offshore; and may even indicate an offshelf exit pathway.

Appendix B: Geography of the 12°C Cold Pool in September 2013

At the inshore end of glider Blue's Leg-1 temperature section (see Figure B1), the 12°C isotherm intersects with the bottom near the 40m isobath. At the inshore end of glider Blue's Leg-3 section, the 12°C isotherm intersects with the bottom near the 45m isobath. At the Leg-3 end of glider Blue's Leg-2 section, the 12°C isotherm also intersects the bottom at 85m. At the Leg-1 end of glider Blue's Leg-2 section, the 12°C isotherm extends 20-30 km beyond the shelf break in the westward direction.

At the inshore and seaward ends of glider RU-23's Leg-1 temperature section (see Figure B2), the 12°C isotherm intersects with the bottom near the 25m and 82m isobaths, respectively. The same is true for the 12°C isotherm/bottom intersections on RU-23's Leg-3 section.

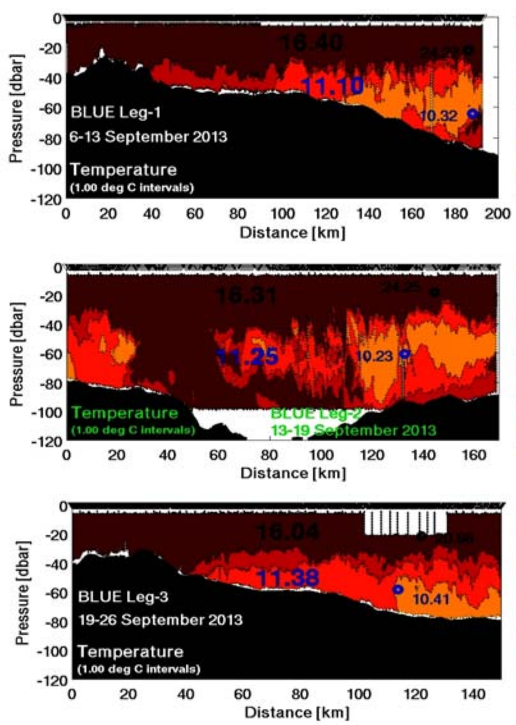


Figure B1 *(upper)* glider Blue's Leg-1 temperature (°C) section. *(middle)*The same for Leg-2 & *(lower)* The same for Leg-3. The 12°C isotherm is at the red/auburn interface. The sub-12°C average temperature (larger font) is indicated and the Leg-minimum temperature is located.

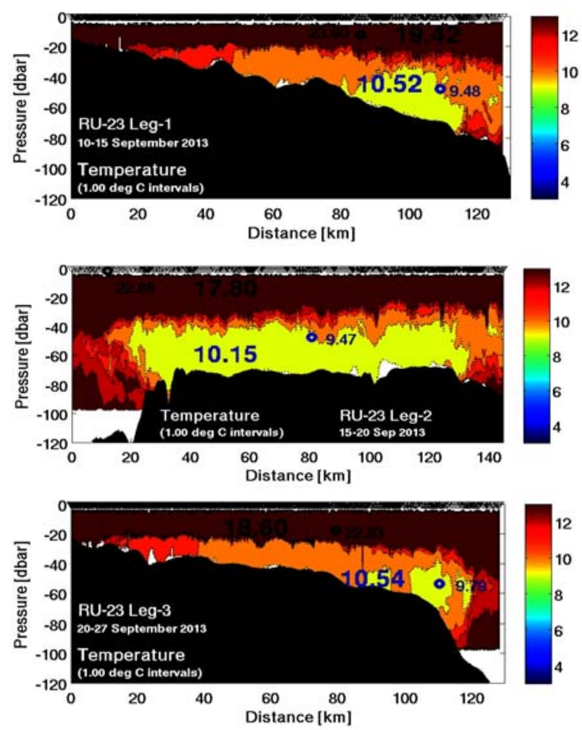


Figure B2 *(upper)* glider RU23's Leg-1 temperature (°C) section. *(middle)*The same for Leg-2 & *(lower)* The same for Leg-3. The 12°C isotherm is at the red/auburn interface. The sub-12°C average temperature (larger font) is indicated and the Leg-minimum temperature is located.

The inshore 12°C isotherm/bottom intersections for both of glider RU-22's Legs-1 and -3 temperature sections (see Figure B3), occur near the 35m isobath. The footprint of the sub-12°C Cold Pool is presented in Figure 22 (main text).

September-October 2013 Cold Pool: TD

The T_D/S_D quantities have been computed for gliders Blue, RU-23 and RU-22 data gathered in the context of GliderPalooza 2013 (see main text). The transect T_{min}s/S_{Tmin}s have been processed as described above and are presented in Table B1.

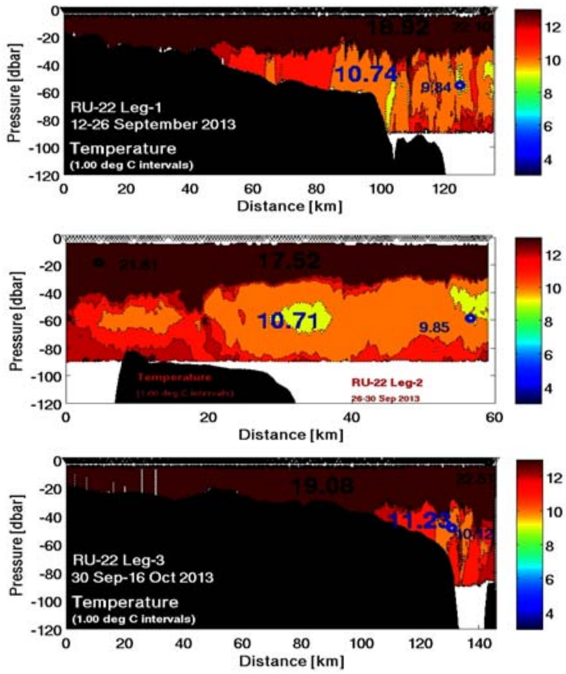


Figure B3 *(upper)* glider RU22's Leg-1 temperature (°C) section. *(middle)*The same for Leg2 & *(lower)* The same for Leg3. The 12°C isotherm is at the red/auburn interface. The sub-12°C average temperature (larger font) is indicated and the Leg-minimum temperature is located.

Table B1 The *2013* section-minimum temperatures T_{min}, associated salinities S_{Tmin}, and the average temperatures of the upper and lower layers (super- and sub-12°C waters) are presented. The means and standard deviations of *temperature departures* (T_D=T-T_{min}) and associated *salinity departures* (S_D=S-S_{Tmin}) for water *temperatures less than 12°C* are also presented.

Glider ID	Sec. ID	Dates Sep 2013	Lower Ave. T(°C)	Upper Ave. T(°C)	T_{min} (°C)	T_D Mean (°C)	T_D Std Dev (°C)	S_{Tmin} (psu)	S_D Mean (psu)	S_D Std Dev (psu)
BLUE	**Leg-1**	06-13	11.11	16.40	10.317	0.791	0.423	33.332	- 0.112	0.265
	Leg-3	19-26	11.38	16.04	10.412	0.971	0.394	33.449	0.035	0.254
		Ave.	***11.25***	***16.22***	***10.365***	***0.881***	***0.409***	***33.391***	***- 0.077***	***0.260***
RU-23	**Leg-1**	10-15	10.54	19.42	9.485	1.054	0.666	33.483	-0.216	0.286
	Leg-3	20-27	10.55	18.60	9.789	0.757	0.558	33.465	-0.250	0.294
		Ave.	***10.55***	***19.01***	***9.637***	***0.906***	***0.612***	***33.474***	***-0.233***	***0.290***
RU-22	**Leg-1**	12-26	10.75	18.92	9.839	0.909	0.536	33.345	0.015	0.285
	Leg-3	S30-O16	11.23	19.08	10.124	1.105	0.490	33.427	0.107	0.364
		Ave.	***10.99***	***19.00***	***9.982***	***1.007***	***0.513***	***33.386***	***0.061***	***0.325***
	Globe	***AVE.***	***10.97***	***18.08***	***9.995***	***0.931***	***0.511***	***33.417***	***-0.083***	***0.292***
BLUE	**Leg-2**	13-19	11.24	16.31	10.231	1.012	0.423	33.381	0.320	0.444
RU-23	**Leg-2**	15-20	10.15	17.80	9.470	0.679	0.608	33.433	0.125	0.223
RU-22	**Leg-2**	26-30	10.72	17.52	9.848	0.868	0.537	33.361	0.242	0.280

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