The Mid-Atlantic Autumn Cold Pool during GliderPalooza-2013

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ABSTRACT

During the autumn of 2013 the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) - under the auspices of the NOAA Integrated Ocean Observing System (IOOS) – coordinated the shelf deployments of nine ocean gliders between Nova Scotia and Georgia in an exercise called GliderPalooza 2013. This paper describes the use of four of those gliders to map the September 2013 Cold Pool in the – the Middle Atlantic Bight (MAB). The Cold Pool is a swath of distinctive, highly-variable, bottom-trapped, cold water mass found during summer over the mid and outer continental shelf between Cape Cod and Cape Hatteras; and a dominant component of the summer MAB habitat. During September, three of the gliders each occupied a pair of cross-shelf transects extending beyond the shelfbreak south of the New England, off New Jersey, and off Maryland respectively; while the fourth patrolled inside of the 30m isobath off New Jersey. The spatially variable Cold Pool was defined at each cross-shelf glider transect in terms of its *temperature departure (TD)* relative its particular section-minimum temperature T_{min}; or for TD < 4^oC. We found that the loci of T_{min}s or Cold Pool core, was just inshore and offshore of the shelfbreak in the eastern and western MAB, respectively. The inshore Cold Pool boundary varied between the 20m and 40m isobath alongshelf, while the offshore boundary generally was beyond the shelfbreak in association with the shelfbreak front.

I. Introduction

The Cold Pool is a distinctive, highly-variable, bottom-trapped, cold water mass 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). The Cold Pool is a very important component of the summer MAB habitat. Malone et al. (1983) and Flagg et al. (1994) have shown that the Cold Pool presence affects phytoplankton productivity. Sullivan et al. (2005); and Weinberg (2005) have shown that the Cold pool 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

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May through September lifetime (Ketchum and Corwin, 1964; Boicourt and Hacker, 1976; Beardsley et al., 1976; Beardsley and Boicourt, 1981). Cold Pool water mass characteristics are initially defined with the late May onset of MAB stratification which isolates the remnant winter water to the lower half of the water column - earlier in the slightly warmer southwestern MAB and later in the in the slightly colder northwestern MAB. Once defined, the distinctive Cold Pool goes through a complex evolution during the rest of its spring/summer/fall lifetime. For example, during late spring a patch of minimum temperature Cold Pool water forms in the northeastern end of the MAB due to a May through June inflow of very cold waters from the Gulf of Maine (GoM)/Georges Bank (GB) region (Ou and Houghton, 1982). This distinctive cold patch embedded in the Cold pool is advected by the general southwestward along-shelf flow (~5 km/d) to regions off of New Jersey and Delaware by late August.

During this summer phase, the whole Cold Pool is warmed at a rate of about 1^{o}C/month (Brown et. al., 2015) by turbulent heat and salt fluxes from above and through its lateral boundaries (Houghton et al, 1982; Lentz et al., 2003; 2010). Small-scale turbulent vertical heat exchange processes in the seasonal pycnocline warm the summer Cold Pool waters from above. Also operating are larger-scale lateral exchange processes all along the shelf break front (SBF). For example, Linder et al. (2004) report on episodic exchanges associated with warm/salty intrusions by way of mid-level and bottom boundary layer. Although Gulf Stream Warm core rings are frequent in this region, their dynamic role(s) in these episodic exchanges is unclear. On the inner shelf intermittent summer-upwelling also erode the Cold Pool. However, the relative importance of these competing Cold Pool warming processes has not yet to be determined. During autumn, the inevitable energetic autumn storm mix the MAB water column well enough to erase the cold water distinctiveness the Cold Pool; 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). In this paper, we describe our new insights about the MAB Cold Pool due to the unprecedented spatial resolution of glider observations.

II. Measuring the Cold Pool

GLIDERPALOOZA 2013: During September and October 2013, the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) - under the auspices of the NOAA Integrated Ocean Observing System (IOOS) – coordinated the shelf deployments of 9 ocean gliders between Nova Scotia and Georgia in an exercise called GliderPalooza 2013. This exercise was a natural follow-up of an earlier application of the MARACOOS Slocum glider network described by Schofield et al. (2010). Here we focus on the glider operations in the Middle Atlantic Bight (MAB; see Figure 1) in which gliders named Blue, RU-23, RU-22, and RU-28.Three of those gliders measured the Cold Pool in the MAB as it had never been measured before. Each of those gliders sliced through the Cold Pool at least twice during their month-long missions. A fourth glider patrolled the landward edge of the Cold Pool in the vicinity of the New

Jersey coast. These glider data were assimilated into an application of the Regional Ocean Model System (ROMS; Zhang et al., 2010 a & b) which produced hindcast, nowcast, and forecast maps of the Cold Pool between September and October.

All of the gliders sliced through the Cold Pool twice, helping to test the hypothesis that triangular patterns are particularly effective for data-assimilation numerical modeling of MAB flow. Glider Blue was directed along leg-1 - from its deployment location just west of Martha's Vineyard offshore towards the southeast (MAB; Figure 1). After making the turn toward the west at the eastern vertex of the triangle, glider Blue continued into deeper water as it encountered the shelf-break front (SBF). About midway along the base of the triangle (leg-2), Blue reached its deepest water (~ 120m) which thereafter began to shallow through its second turn toward the northeast which carried it along leg-3 back to its deployment site. With our interest in the defining the extent of the Cold Pool, we found it convenient to define an outbound transect (see Transect-1; green in Figure 1) and an inbound transect (Transect-2; blue in Figure 1). During this mission Blue provided order 2000 profiles per transect with nominal CTD measurement resolutions of 0.15 m in the vertical and 125m laterally.

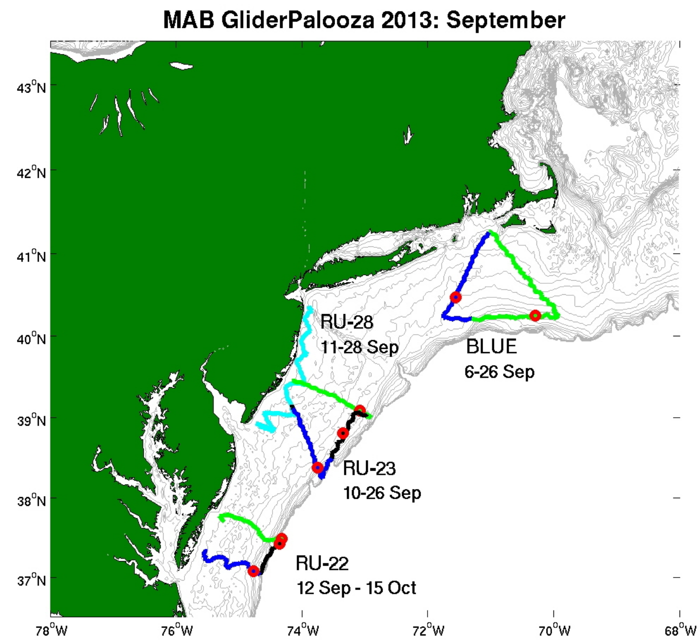

Figure 1 The Mid-Atlantic Bight (MAB) trajectories of four gliders operated by MARACOOS during GliderPalooza-2013. The glider Blue triangle was defined by an outgoing Transect-1 (green) and an incoming Transect-2 (blue). Glider RU-23's triangular trajectory off of New Jersey was defined by 3 legs, namely outgoing Leg-1 (green), along-shelf Leg-2 (black), and incoming Leg -3 (blue). Glider RU-22 "box" trajectory off of Maryland was defined by 3 legs similar to the RU-23 legs. Glider RU-28 had a zig-zag trajectory (cyan) along coastal New Jersey coast. The red dots locate the segment minimum temperatures, while the dates of each mission are indicated.

Glider RU-23, which was deployed off of the New Jersey coast, had more of a right triangular trajectory. Its outgoing leg-1 (green in Figure 1) extended beyond the SBF. RU-23 was directed back along leg-1 for a few 10s of kilometers before turning southwestward along leg-2. This leg-2 trajectory (black in Figure 1) took RU-23 through the SBF a third time, and finally a fourth time after turning north-northwestward for its inshore leg-3 (blue in Figure 1). Glider RU-22, which was deployed off the eastern shore of Maryland in the southwest sector of the MAB, had a more classic "box" trajectory. Like the cross-shelf trajectories of the other MAB gliders, the RU-22 pair of cross-shelf transects (leg-1 green; and leg-3 blue in Figure 1) extended seaward of the shelfbreak front.

At the same time, Glider RU-28 was zig-zagging its way between the 10m and 30m isobaths as it worked its way southwestward along the New Jersey coastline. The state of New Jersey funded Glider RU-28's primary mission, which was to measure oxygen in New Jersey coastal waters – waters that are prone to anoxic conditions during the summer. However, Glider RU-28, which was outfitted with the same suite of sensors as the other gliders, also provided valuable information as it patrolled the landward edge of the Cold Pool. This particular mission is an excellent example of the multipurpose applications of MARACOOS's ocean observing technologies.

Measuring the Cold Pool:
During September 2013, all of the glider-derived temperature sections indicated the presence of a distinctive Cold Pool. For example, both of glider Blue's transects (see Figure 2) showed a cold water core - with minimum temperatures of about 10°C which were capped by a very warm upper layer in the 18°C to range 24°C range and adjacent to offshore warmer waters in the 12°C to 18°C range. Glider Blue's outgoing *transect minimum temperature* (T_{min}) of 10.202°C was located at a depth of about 60m in about 95m of water. On the ingoing transect, T_{min} was a slightly warmer 10.412°C and also at 60m depth, but it was in only 70m of water. The warm water at about 200 km milepost of Transect-2 suggests to us that the local Cold Pool water may have been displaced into shallower depths and warmed by a cross-isobath mixing event. An encounter with an anti-cyclonic Gulf Stream warm core ring as described by Gawarkiewicz et al. (2012) and which according to satellite SST information was in the vicinity, might explain the distinctive asymmetry of the Cold Pool core. Future analysis of the full suite of glider-derived data including that from gliders RU-23 and RU-22 will be used to test that hypothesis. Although those sections are not presented, the information on their T_{min} diagnostic for the local Cold Pool core (see Table 1).

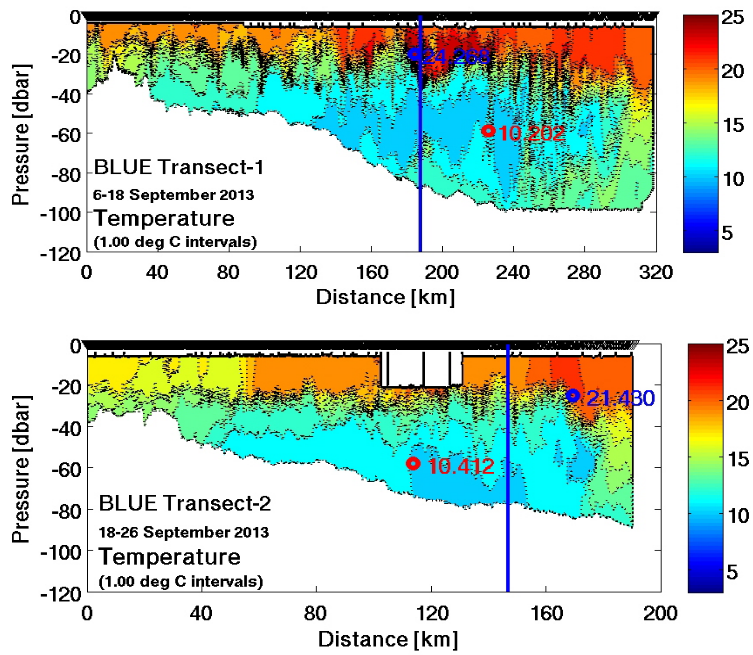

Figure 2 Each of glider Blue's two September 2013 temperature sections - (*above)* Transect-1 and *(below)* Transect-2 - are defined by profiles stretching from about 2m below the surface to a few meters above the bottom. The *section minimum temperatures* - T_{min} (red) and *section maximum temperatures* - T_{max} (blue) are located. The vertical blue lines locate the respective eastern and western vertices of the triangular trajectory.

The glider Blue, RU-23, and RU-28 transects were measured in the same time period. The RU-22 outgoing cross-shelf leg-1 coincided with the ingoing legs of the other gliders; while its along-shelf leg-2 and ingoing leg-3 were about 2 weeks later. These simultaneous measurements enable us to draw some conclusions about the Cold Pool structure. In particular, we find that the Cold Pool core, which we define as the along-shelf loci of *section minimum temperatures* T_{min}, tends to be located about midway between the bottom of the seasonal thermocline and the local bottom; and near the shelf break (Figure 1). More specifically these simultaneous measurements (see Table 1) show that, the Cold Pool core varies in depth from 50m to 60m below a seasonal pycnocline at about 30m depth and bottom depths that vary between 70m and 100m. Now we know from previous research (e.g., Brown et al., 2015) that the Cold Pool in general is warming at a rate of about $1^{o}C$/mo but it has significant alongshelf temperature gradients. In particular we find that in September 2013 that T_{min} exhibits a mid-MAB minimum with New Jersey are at T_{min}s ~9.5°C in contrast to T_{min}s south of the New England to the northeast of ~10.3°C and off of Maryland to the southwest of ~9.8+°C. These findings are consistent with the conclusions of Ou and Houghton (1982) about the down-shelf advection of early season cold water from the northeastern MAB. Our finding of the Tmin proximity to the shelf break and the shelf break front jet suggests where the Ou and Houghton (1982) down-shelf advection is likely to be concentrated.

Table 1 Individual GliderPalooza-2013 glider section temperature maxima T_{max} (highlighted in red) and minima T_{min} (blue) Also T_{min}-associated depths, date/times, latitudes and longitudes are given (in blue). (Note: Glider Blue's trajectory has been partitioned into Transect-1 (in the Leg-1 column) and Transect-2 (below Leg-3).

		Leg-1	*Leg-2*	*Leg-3*
BLUE	**Leg Dates**	6-16 Sep		16-26 Sep
Figure 2	**T_{max} (°C)**	*24.268*		*21.430*
	T_{min} (°C)	*10.202*		*10.412*
	Depth (m)	59		59
	Date	Sep 14		Sep 21
	Time (UTC)	0921		0109
	N Lat	40.2527		40.4731
	W Lon	70.2896		71.5605
RU-23	**Leg Dates**	10-15 Sep	15-20 Sep	20-26 Sep
Figure 3	**T_{max} (°C)**	*23.505*	*24.880*	*22.826*
	T_{min} (°C)	*9.485*	*9.470*	*9.789*
	Depth (m)	48	48	54
	Date	Sep 15	Sep 18	Sep 21
	Time (UTC)	0328	0751	1839
	N Lat	39.0849	38.8113	38.3846
	W Lon	73.0821	73.3450	73.7533
RU-22	**Leg Dates**	12-26 Sep	26 Sep-4 Oct	4-16 Oct
Figure 3	**T_{max} (°C)**	*22.100*	*21.809*	*22.509*
	T_{min} (°C)	*9.839*	*9.848*	*10.124*
	Depth (m)	55	59	49
	Date	Sep 25	Sep 26	Oct 1
	Time (UTC)	2356	2318	2233
	N Lat	37.486	37.428	37.084
	W Lon	74.325	74.358	74.764

Mapping the Cold Pool: How well did this quartet of GliderPalooza gliders define the Cold Pool in September 2013? To better define the geographic extent of the MAB 2013 Cold Pool, we constructed sections of *temperature departure (TD)* relative to the relevant T_{min} - following Brown et al. (2015). We find that, despite the different temperature minima T_{min} found for each section (see Table 1), the TDs in the six cross-shelf sections considered here all have standard deviations of about 4°C. Thus we choose limits on the TD scale (right in Figure 3) ranging from 0°C (or $T = T_{min}$) ranging up to 4°C. This choice means that all TDs > 4°C (there are many) are auburn – a construct that visually defines that section's Cold Pool distribution.

For example in the case of glider Blue sections, the inshore boundaries of the Cold Pool in both transects are at the 35 m isobath near the inshore vertex of the triangle. Given that triangular trajectory, the relevant seaward boundary of Transect-1 is depicted in the Transect-2 TD section (below in Figure 3) - or at about 300 along-trajectory kilometers. The seaward boundary of Transect-2 is at the 170 km section milepost. Similar presentations of the RU-23 Leg-3 and RU-22 Leg-1 sections (Figure 4), which were occupied nearly at the same time, reveal the inshore and offshore extents of the local Cool Pool at their respective sections. Note that the more southern RU-22 Leg-1 section reveals a Cold pool that extends over the slope much more than the other sections.

The TD transect information from Blue, RU-23, and RU-22 on the extent of the Cold Pool (as defined here) is used to construct the September 2013 Cold Pool map in Figure 5. In this construction, the bold dashes on the glider transects - the landward and seaward boundaries of the Cold Pool irrespective of the timing differences - are connected by thinner dashed lines - our estimate of the Cold Pool boundaries. This approach leads to some inconsistencies

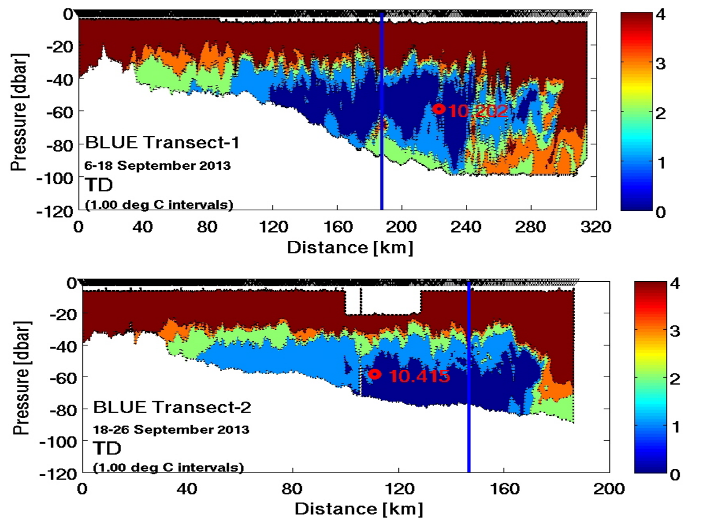

Figure 3 Glider Blue's *temperature departure* (TD) sections for the (*above)* 6-16 September Transect-1 and (*below)* 16-26 September Transect-2; with section minimum temperatures T_{min} located. The along-glider path distances are relative to the respective inshore reference stations to the left. The vertical blue lines locate the respective eastern and western vertices along the base of the glider Blue's triangular trajectory.

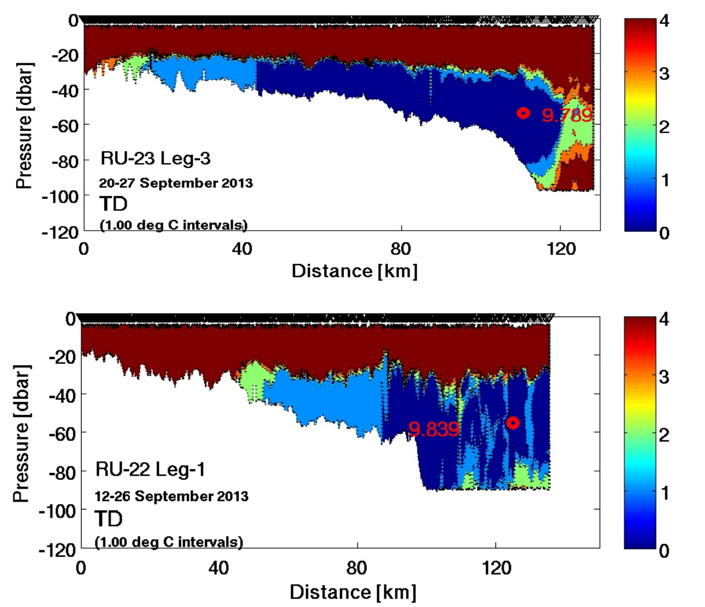

Figure 4 Temperature Departure (TD) sections for the (*above)* 20-27 Sep. *Leg-3* of RU-23 and *(below)* 12-26 Sep. Leg-1 of RU-22; with section minimum temperatures T_{min} located in each of the legs. The along-glider path distances are relative to the respective inshore reference stations to the left.

because of Cold Pool time variability and measurement timing. For example, while the RU-22 Leg-1 information is in the September time frame of the rest of the glider measurements, RU-22 Leg-3 information indicating an offshore-directed Cold Pool is from about 2 weeks later in October.

A more explicit indication of the time variability of the inshore Cold Pool boundary is given by an RU-23 Leg-3 versus RU-28 comparison. The landward extent of the Cold Pool is indicated in the composite TD section of the zig-zag trajectory of glider RU-28 in Figure 6. In particular, we see the Cold Pool encroaching to about the 20m isobath along the northeastern coast of New Jersey (zig-zags #1 and #2 in Figure 6). From Figure 1, note that the northern leg of zig-zag #5 is an extension of RU-23's Leg-3. Also note in that the RU-23 Leg-3 TD section in Figure 4 shows that the landward edge of the Cold Pool was at about the 30m isobath and did not reach the 20m isobath. This RU-23 Leg-3 versus RU-28 zig-zag #5 discrepancy suggests that there is significant time variability in the landward edge of the Cold Pool. In fact, RU-28 was on that part of its trajectory measuring temperatures around 11.9°C in and around 24 September, while RU-23 was in the vicinity measuring temperatures around 2°C higher 3 days later on 27 September. This kind of temperature variability can have profound effects on the biology in the vicinity.

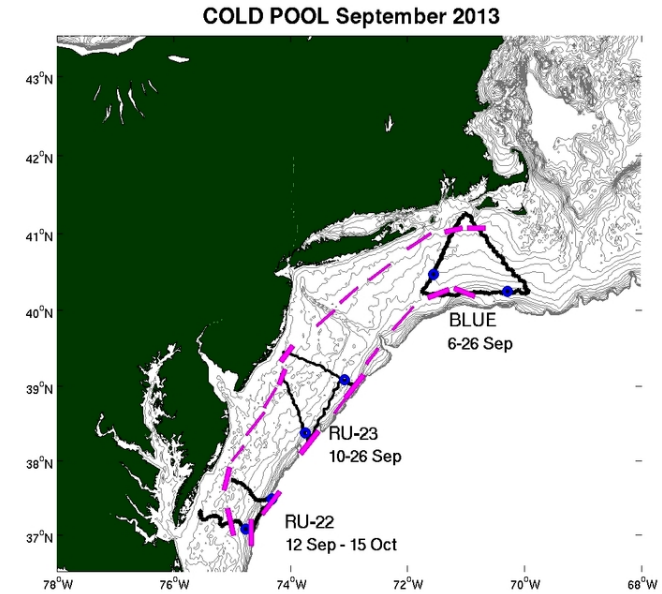

Figure 5 GliderPalooza-2013 ocean glider mapping of the extent of the 6-26 September Mid-Atlantic Bight Cold Pool.

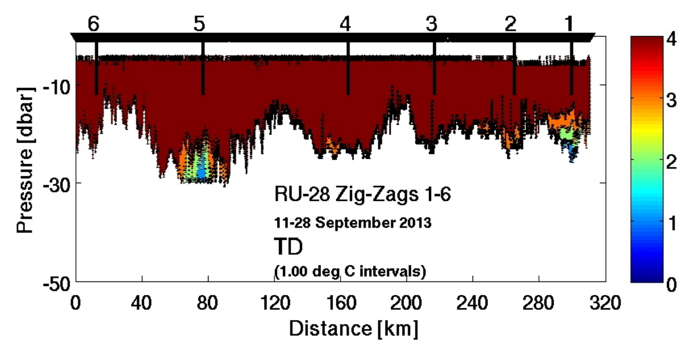

Figure 6 The inner shelf ocean glider RU-28 composite TD section (based on the RU-23 Leg-3 T_{min}= 9.789°C) occupied 16-26 September 2013. The blue lines mark the 6 most seaward extents of the glider RU-28's zig-zag trajectory - running right-to-left from northeast to southwest along coastal New Jersey.

Obviously glider observations alone cannot monitor such significant Cold Pool time-variability everywhere in the region. To address the issue, MARACOOS is combining the glider observations with numerical data-assimilation coastal ocean models. In particular, the EspressoV2 model (Zhang et al., 2010 a; b), which is assimilating a wide variety of data types including available ocean glider data in near real-time, is delivering nowcasts and forecasts. An example of a MAB bottom temperature forecast for 27 May 2013 (Figure 7) indicates that the coldest Cold Pool water (6^{o}C-8^{o}C) in this early part of the season is concentrated in the northeast end of the MAB. This is the water mass that advects southwestward – warming as it goes – to locals off of New Jersey, Delaware and Maryland by September. In the future, it is this modeling technology – with crucial assistance by the insitu measurements of a glider network - that will provide weekly nowcast/forecast maps of the Cold Pool disposition maps that will be extremely useful to marine resource managers.

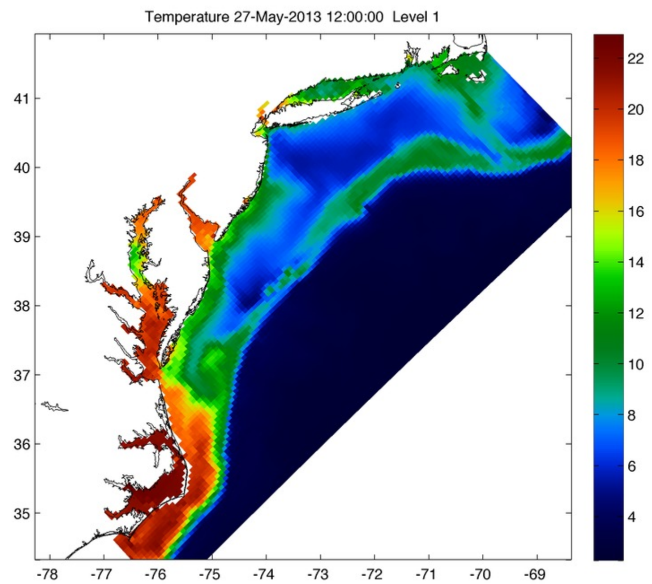

Figure 7 The EspressoV2 bottom temperature forecast for the MAB on May 27, 2013. The color-coded bottom temperatures illustrate the extent of the Cold Pool; and highlight a particularly cold patch south of Long Island, NY.

Discussion

The tantalizing coverage and resolution afforded by GliderPalooza 2013, while gratifying, spur questions about Cold Pool behavior and long-term change that are not resolved by this data set. Of interest is are that the NOAA New England Fisheries Center survey results show that the MAB bottom temperatures increased over the past few decades (Richardson et al, 2010; personal communication). The lack of temperatures in the 6-7C range from 2013 is clearly not an indication of long-term change, but these were common, not only in Bigelow's (1933) early work, but also in later surveys (1970-1980; Beardsley et al., 1976; Boicourt and Hacker, 1976). The NEFC results also suggested a possible decrease in Cold Pool penetration to the southern reaches of the MAB. The relative north-south constancy of Tmin in GliderPalooza 2013 may indicate continued penetration of this feature to the south, but this question needs further examination.

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