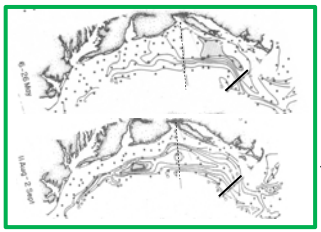
Historical Evidence of the Mid Atlantic *Cold Patch*

The Mid- Atlantic Bight (MAB) Cold Pool is defined each year when the surface stratification is established in May. During May-June, its volume grows as cold water pours into the MAB across the NSFE79 line at an estimated rate of about 5 cm/s. With the onset of summer, the Cold Pool begins to erode: *upwards* through mixing with the warm surface layer; *laterally* through cross-shelf mixing at the Shelf-Slope Front (SSF) and tidal mixing near the coast. Autumn storms obliterate the temperature distinctiveness of the Cold Pool at various times in the autumn – depending on storm frequency.

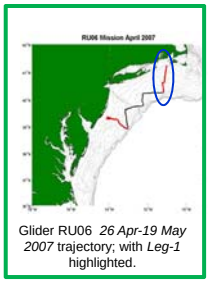


Cold Patch in the late May 1979 bottom temperatures in the Mid-Atlantic Bight (MAB) (based on NMFS data according to Houghton et al., 1982)

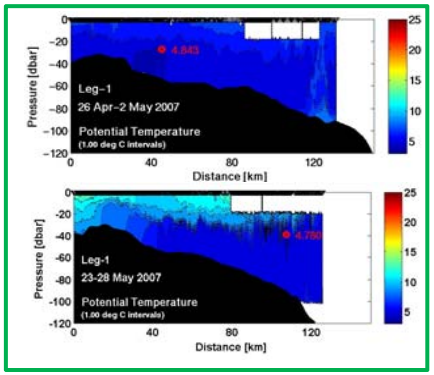
August 1979 evidence of the warming and along-shelf advection of the ***Cold Patch*** .

The Nantucket Shoals Flux Experiment (NSFE) transect (solid) and the Oleander Line (dashed) are also located.

Cold Patch Formation

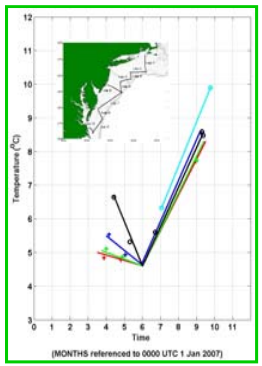


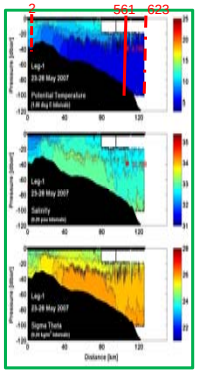
Glider RU06 *26 Apr-19 May 2007* trajectory; with *Leg-1* highlighted.

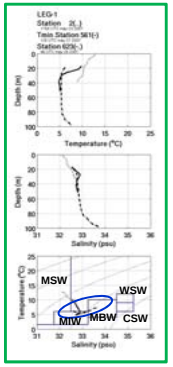


2007Glider Measurements: Southern NE Bight Transect

SNEB temperature sections for ***(upper)*** 26 Apr-2 May and ***(lower)*** 23-28 May 2007 transects. Temperature (°C) legends are to the right. Note that the indicated transect-minimum temperature (red) – a proxy for the core of the Cold Pool - decreases between early and late May. We missed data as the glider was restricted as it transited a principal shipping lane. (*after Brown et al., 2015*)







Transect Temperature Minimum Evolution

The 2007 transect minimum temperature T_{min} versus time for Leg-1 (**red+**), Leg-2 (**grn+**), Leg-4(**blu+**) and Leg-6 (**blk o)** and Leg-8 (**cayan o**).

T_{min} evidence from throughout the entire Mid Atlantic Bight indicates that the Cold Pool April-June 2007 cooling is followed by a July to October 2007average warming rate of 1.05°C.per month.

"Cold Patch" T-S Signature

The 23-28 May 2007 Leg1 *(left)* temperature (T), salinity (S) and sigma-theta sections and the *(right)* inshore (…), T_{min} (-), and offshore profiles.

The T_{min} *(top left panel)* locates the center of Cold Pool water at this across-shelf transect. This evidence indicates that that the *Cold Patch, with it's distinctive T-S signature* - is forming at this time. The T-S profiles overlay a framework of the *Brown and Irish (1993)* Gulf of Maine (GoM) water masses; consisting of GoM Surface Water (MSW), Intermediate Water (MIW), Bottom Water (MBW) and Cold Slope Water (CSW) and Warm Slope Water (WSW). The "tail" on the *Cold Patch, T-S signature indicates the slope water contributions, which we hypothesize happened through mixing processes in the GoM.*

On Origins of the Cold Water Inflows to the Mid-Atlantic Bight Cold Pool in Late Spring

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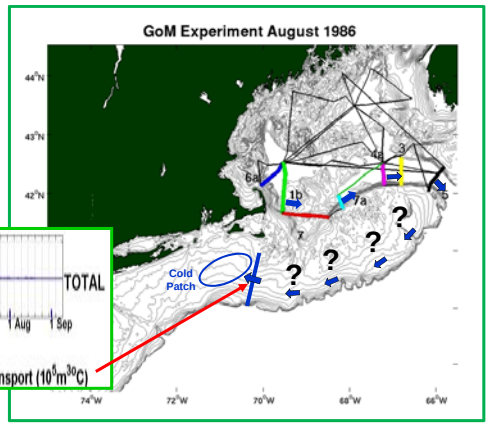
ABSTRACT During late spring each year, after the Mid Atlantic Bight (MAB) Cold Pool has been defined by vernal restratification, there is a continuing flow of even colder water from the Georges Bank/Gulf of Maine (GB/GoM) region the northeastern end of the MAB. The cold inflow water forms a distinctive minimum temperature "cold patch" that is subsequently advected southwestward down the shelf during the summer. An explicit reanalysis of the Nantucket Shoals Flux Experiment (NSFE) data shows a westward temperature transport of sub-10°C water, which peaks at about 600 x 10^5 m^3 °C in early April 1979 and exponentially decays to near zero by the end of June. This evidence begs the question about the origins of the springtime cold water inflow to the MAB Cold Pool. Between 2007 and 2012, the Mid Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) ocean gliders conducted a series of along-shelf zigzag trajectory hydrographic surveys that included full cross-shelf transects off of Massachusetts (Leg-1) and New Jersey (Leg-2). These data have been used to locate the transect temperature minima TT_{min} or core of the Cold Pool water mass; as well as define the extent of the MAB Cold Pool in 2007, 2013, and 2014. The T-S diagram signatures from the Leg-1 TT_{min} and most seaward stations are very similar to the T-S signatures hydrographic transects that intersect the north slope of Georges Bank. The latter evidence suggests the western GoM as the origin of the MAB Cold Pool's "cold patch" water. Results of an integrated analysis of the MARACOOS glider-inferred transports and high frequency radar surface current maps in terms of the variability of cold water inflow structure to the MAB will be discussed.

Cold Patch Water Origins ?

We know that sub-10°C water flows into the eastern MAB below the strengthening thermo-pycnocline between April and July.



Cold Water Transport from the Near East

Total temperature transport of water with T< 10°C (in $10^5 m^3$-°C) normal to the 1979 NSFE mooring array. Positive is toward the MAB. Results derived from 1979 New England Shelf Flux Experiment (NSFE) data (Beardsley et al., 1985, and Ramp et al., 1988) shows a substantial transport of sub-10°C water toward the MAB between April and June.

Cold Water Mass Tracking Map

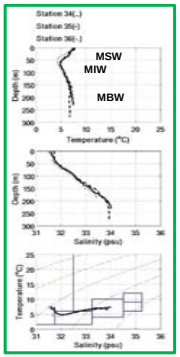
This map locates the 1979-80 Nantucket Shoals Flux Experiment (NSFE) transect (-) and the August 1986 RIM hydrographic transects: Leg-6a (blue), Leg-1b (green), Leg-7 (red), Leg-7a (cyan/green), Leg-4a (maroon), Leg-3 (yellow), and Leg-5 (**black**) (Brown and Irish, 1993).

Westward Cold Water Transport – A Cold Patch Formation Contributor -

As seen above, the westward transport of the sub-10°C waters effectively ceased by the end of June 1979; a very likely contributor to the distinctive patch of minimum temperature – the Cold Patch - in the eastern end of the MAB.

Gulf of Maine Cold Water Origins

All of this begs the question about the origins of the springtime cold water inflow to the MAB Cold Pool. One possibility is that Gulf of Maine Intermediate Water (MIW) escapes the GoM to feed the MAB Cold Pool (Brown and Irish, 1993; Hopkins and Garfield, 1979). Another possibility is that the MAB Cold Pool Water derives more directly from the Scotian Shelf via a pathway south flank of Georges Bank. Here we focus on the pathway originating in the *western Gulf of Maine*.

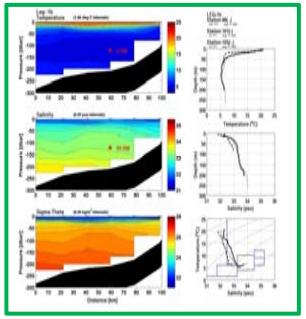


This distinctive T-S signature Is typical for Wilkinson Basin (WB) in May

The 4-5 May 1998 T, S, and T-S profiles for the northern (..), middle(-), and southern (.-) transect. 1a *(see map above).* The T-S signature indicates a newly forming MSW layer above the MIW *remnant winter water layer* above the MBW layer which derives through mixing between MIW and in this case probably Cold Slope Water

WB cold water - *trapped below the developing thermo-pycnocline* - is on the move.

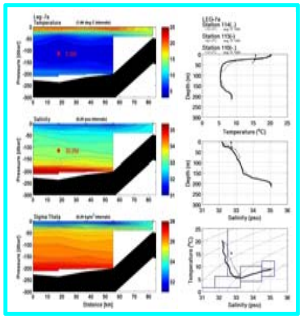
Where does it go?



MIW/MBW Cold Water Mass Tracking

Aug 1986 *RIM* **transect 1b** ***(GB - right)***

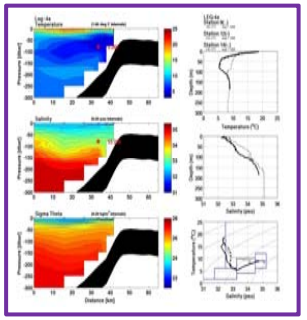
(left) T, S, and density anomaly sections, with T_{min} and corresponding salinity located; **(right)** T and S profiles and T-S diagrams for stations 98 (l), 101 (T_{min}), and 103 (r)



MIW/MBW Cold Water Mass Tracking

Aug 1986 *RIM* **transect 7a** ***(GB - right)***

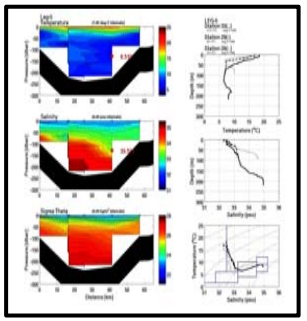
(left) T, S, and density anomaly sections, with T_{min} and corresponding salinity located; **(right)** T and S profiles and T-S diagrams for stations 114 (l), 115 (T_{min}), & 110 (r)



MIW/MBW Cold Water Mass Tracking

Aug 1986 *RIM* **transect 4a** ***(GB - right)***

(left) T, S, and density anomaly sections, with T_{min} and corresponding salinity located; **(right)** T and S profiles and T-S diagrams for stations 9 (left), 12 (T_{min}), and 14 (right)



MIW/MBW Cold Water Mass Tracking

Aug 1986 *RIM* **transect 5** ***(GB - right)***

(left) T, S, and density anomaly sections, with T_{min} and corresponding salinity located; **(right)** T and S profiles and T-S diagrams for stations 33 (left), 29 (T_{min}), & 28 (right)

Summary of Conclusions

- Glider transect minimum temperature measurements in the eastern Mid Atlantic Bight (MAB) are consistent with the formation of a Cold Patch during the May – June establishment of the MAB Cold Pool.
- Cold Patch water has a distinctive T-S signature that indicates s significant slope water component leading to our hypothesis of Gulf of Maine (GoM) origins.
- Nantucket Shoals Flux Experiment (NSFE) time series measurements indicate that April-July very cold water transports consistent with Cold Patch formation.
- Historical GoM hydrography shows that the well known Georges Bank (GB) north flank flows carry water with the distinctive GoM T-S signature that grows stronger as it flows around the eastern tip of GB to the southern flank of GB.
- Next steps include using existing GLOBEC data and newly-available Ocean Observatory Initiative (OOI) Pioneer Array data to determine the (1) relative amounts of GB/GoM water that reach the eastern MAB in spring and (2) kinematics and dynamics of the Cold Patch formation.

References

Beardsley, R.C., D.C. Chapman, K.H. Brink, S.R. Ramp, R. Schlitz, 1985. The Nantucket Shoals Flux Experiment (NSFE79). Part I: A basic description of the current and temperature variability. *J. Phys. Oceanogr.*, 15, 713-748.

Brown, W.S., and J.D. Irish, 1993. The annual variation of water mass structure in the Gulf of Maine, *Journal of Marine Research*, 51, 53-107.

Brown, W.S., O. Schofield, S. Glenn, J. Kohu, & W. Boicourt, 2015. The Evolution of the Mid-Atlantic Bight Cold Pool Based on Ocean Glider Observations *SMAST Technical Report 15-03-01, pp 35.*

http://www.smast.umassd.edu/OCEANOL/reports/MAB/coldPool_2007_fromGliders_SMASTreport_submit_10mar15.pdf

Hopkins, T.S. and N. Garfield III, 1979. Gulf of Maine Intermediate Water, *J. Marine Res.*, 37, 103-139.

Houghton, R., R. Schlitz, R.C. Beardsley, B. Butman, and J. L. Chamberlin 1982. The Middle Atlantic Bight cold pool: Evolution of the temperature structure during summer 1979. *J. Phys. Oceanogr*, 12, 1019-1029..

Ramp, S.R, W.S. Brown and R.C Beardsley, 1988. The Nantucket shoals flux experiment (NSFE79). Part 3: The along-shelf transport of volume, heat, salt and nitrogen," *J. Geophys. Res.*, 93(C11), 14,039-14,054.

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