

# The Middle Atlantic Bight Cold Pool is warming and shrinking: Indices from in situ autumn seafloor temperatures

Kevin D. Friedland<sup>1</sup>  | Travis Miles<sup>2</sup>  | Andrew G. Goode<sup>3</sup>  | Eric N. Powell<sup>4</sup>  | Damian C. Brady<sup>3</sup> 

<sup>1</sup>Northeast Fisheries Science Center, Narragansett, Rhode Island, USA

<sup>2</sup>Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey, USA

<sup>3</sup>School of Marine Sciences, University of Maine, Orono, Maine, USA

<sup>4</sup>Gulf Coast Research Laboratory, University of Southern Mississippi, Ocean Springs, Mississippi, USA

## Correspondence

Kevin Friedland, National Marine Fisheries Service, 28 Tarzwell Dr., Narragansett, RI 02882, USA.

Email: kevin.friedland@noaa.gov

## Funding information

USDA ARS

## Abstract

The Cold Pool feature of the Middle Atlantic Bight (MAB) is a body of cold bottom water that develops in the spring and persists through the summer-autumn months. It is maintained by northerly currents and can be traced back to Arctic water masses. The Cold Pool provides habitat for many boreal species at latitudes far south of their normal range and plays an important role in the population dynamics of lower and upper trophic level organisms. Here, we describe changes in the extent and thermal properties of the Cold Pool using both observations and models. Two indices are developed based on a gridded, interpolated bottom temperature dataset; the first is a mean temperature indicator, and the second is a spatial extent indicator. The temperature indicator showed a significant increasing trend over the study period 1968–2019 and a single change point in 2008. Similarly, the area indicator declined significantly, also displaying a change point in 2008. Cold Pool maximum temperature and minimum size were observed in 2017, which is also known as a heatwave year in the MAB. The indices presented here support the view of a rapidly warming Cold Pool that is being limited in its spatial extent. Changes in Cold Pool hydrography will likely affect boreal species distributions and total ecosystem productivity.

## KEYWORDS

climate change, Cold Pool, ecosystem, regime shift, temperature

## 1 | INTRODUCTION

The Cold Pool refers to the formation of cold bottom water that develops in the spring and persists during the summer and into the early autumn months over the US Northeast continental shelf (NES) ecosystem, primary focused in the Middle Atlantic Bight (MAB) subregion of the NES (Chen et al., 2018; Houghton et al., 1982; Lentz, 2017). The cold water that forms the Cold Pool originates from local winter water and is partly impacted by the contribution of upstream Gulf of Maine and Scotian Shelf waters (Chen et al., 2018; Houghton et al., 1982). Though the Cold Pool is sensitive to vertical mixing, its spatial dynamics can also be altered by horizontal advection (Lentz, 2017) and wind mixing (Roarty et al., 2020). The interplay

between regional bathymetry and tidal forcing concentrates the coldest waters along the New York Bight (Lentz, 2017). Though the Cold Pool is most fully developed during summer, its formation and persistence is reflected in its spring and fall properties, respectively, which will affect any phenological dependencies within the ecosystem.

The impacts of changing thermal conditions in the NES can pose added challenges to organisms that rely on the thermal gradients of the Cold Pool and the resultant thermal habitats created. The Cold Pool tends to have a distinct nutrient profile (Marra et al., 1990), bacterial fauna, and nutrient cycling regime (Hoarfrost et al., 2019) compared with surrounding waters, attributable to source water characteristics. The Cold Pool appears to play a basin scale function in contributing to the nutrient budget of North Atlantic surface waters

(Wood et al., 1996) and local scale spatial dynamics of phytoplankton production of the MAB (Xu et al., 2020). Cold Pool variability also affects higher trophic levels. For example, yellowtail flounder, *Limanda ferruginea*, recruitment dynamics (Sullivan et al., 2005) were shown to be better predicted with the incorporation of the Cold Pool's environmental variability (Miller et al., 2016). The Cold Pool influences fish migration patterns (Secor et al., 2019), including the movement of striped bass, *Morone saxatilis*, and Atlantic sturgeon, *Acipenser oxyrinchus* (Rothermel et al., 2020).

The autumn extent of the Cold Pool appears to play specific roles in the distribution and ecology of regional shellfish taxa. The inshore and southern extent of the cold pool marks the boundary between cool temperate and boreal faunas, the latter of which extends much farther south than the normal latitudinal limit due to the cold bottom water maintained in the Cold Pool. Among this boreal fauna is the ocean quahog *Arctica islandica* (Morton, 2011), the longest living noncolonial marine species and the sea scallop *Placopecten magellanicus* (MacDonald & Thompson, 1986), supporting the second most valuable fishery in the U.S. The ecotone between the two faunas is well documented by the overlap of the cool temperate Atlantic surfclam, *Spisula solidissima*, and ocean quahog along much of the MAB to the Georges Bank (Powell et al., 2020). This critical cool temperate-boreal boundary is maintained by the autumn breakdown of the cold pool, which determines the timing and duration of temperatures above  $\sim 15^{\circ}\text{C}$  in the autumn. Mortality events in surfclams have been linked to earlier than normal breakdown of the Cold Pool that is associated with the mixing of warm water to the bottom (Narváez et al., 2015). In ocean quahogs, reproductive condition increases from early summer through the autumn, with the heaviest spawning coinciding with Cold Pool breakdown in the autumn (Jones, 1981; R. Mann, 1982). The Cold Pool also plays a role in the reproductive phenology of the whelk, *Buccinum undatum*, on the NES (Borsetti et al., 2020). Collectively, the autumn transitional state of the Cold Pool plays a preeminent role in establishing the structure of the benthic community over much of the MAB.

As with any water mass, the Cold Pool has volumetric properties that have been represented by univariate time series indices. The observation-based time series constructed in Miller et al. (2016) was calculated from bottom temperature anomalies for September and October with date of collection correction based on a harmonic estimate of seasonal temperature cycles (Mountain et al., 2004). This index provides a depiction of the Cold Pool for the period 1973–2011 and suggests an increasing temperature trend indicative of warming within the Cold Pool. This observation-based index provides a contrast to the approach taken by Chen and Curchitser (2020) who provided indices of the Cold Pool based on model reconstruction for the period 1958–2007. The model-based approach allows the computation of multiple spatial and temporal indices, supporting the contention that the Cold Pool has increased in temperature and decreased in persistence and size (Chen & Curchitser, 2020).

Here, we develop indicators of the Cold Pool using a long-term time series not used in any previous depictions to describe both its core temperature and spatial extent during the ecologically important autumn period. While recognizing the limitations of describing the

Cold Pool based on autumn temperatures, we advocate for the value of an independent depiction of the Cold Pool that may contribute to an ensemble characterization of this important ecosystem feature. In addition to testing for trends in our indicators, we also investigate whether change points occurred in the Cold Pool time series.

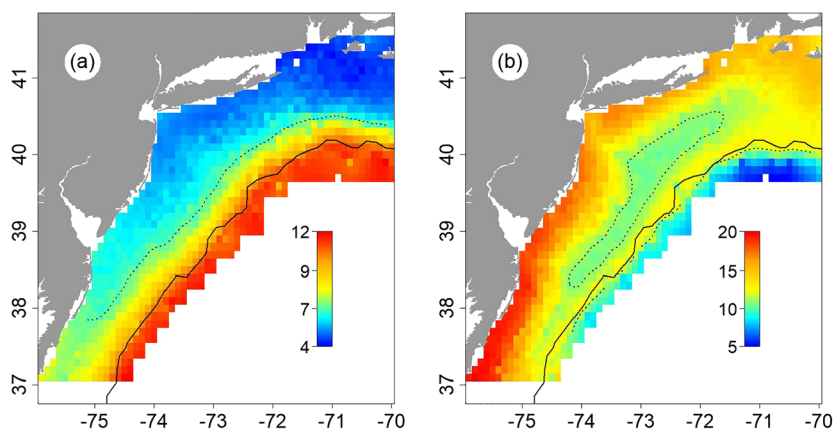
## 2 | METHODS

Two indicators representing change in the MAB Cold Pool were developed from autumn time frame bottom temperature gridded data fields. These fields originated from an analysis of temperature trends for this ecosystem during spring and autumn months (see Friedland et al., 2020 for details on the estimation procedure); they are used here without modification. Briefly, the bottom temperatures were based on multiple observational data sources and were interpolated onto a  $0.1^{\circ}$  grid to represent thermal conditions in spring based on a standardized day of the year of April 3 and in autumn based on standardized day of the year of October 11th (see data availability statement). The bivariate relationships between day of year and temperature were overwhelmingly linear and have been widely used to standardize multiyear surveys (Friedland et al., 2020). However, we should note that there were a few instances where destratification caused nonlinear changes in temperature during the time periods around April 3 and October 11 but did not affect overall trends. We based our analysis on a subportion of the full NES grid bounded by  $37^{\circ}\text{N}$  and  $70^{\circ}\text{W}$  and landward and depth constraints. The spring temperature fields suggested that the Cold Pool was not formed by early April (Figure 1a). However, the Cold Pool feature was evident in the autumn temperature field (Figure 1b); hence, the indicators were developed from autumn data only. The first indicator we developed was based on the temperature over the mean location of the Cold Pool extent. The mean extent was the area bounded by the  $11^{\circ}\text{C}$  isotherm based on temperature contours of the mean temperature field in the portion of the shelf shallower than 150-m depth (Figure 1b). The  $11^{\circ}\text{C}$  isotherm provided the largest discrete area of the MAB that did not have any boundary conditions; lower thresholds were increasingly smaller index areas and higher temperatures had extents outside the study area. For each year, the mean of the temperatures within this shape was calculated as the indicator. The second indicator was the area of the seabed with a bottom temperature less than  $13^{\circ}\text{C}$  within the subportion areas of the grid and constrained to portions of the shelf less than 150-m depth. This threshold produces a time series of areas all greater than zero.

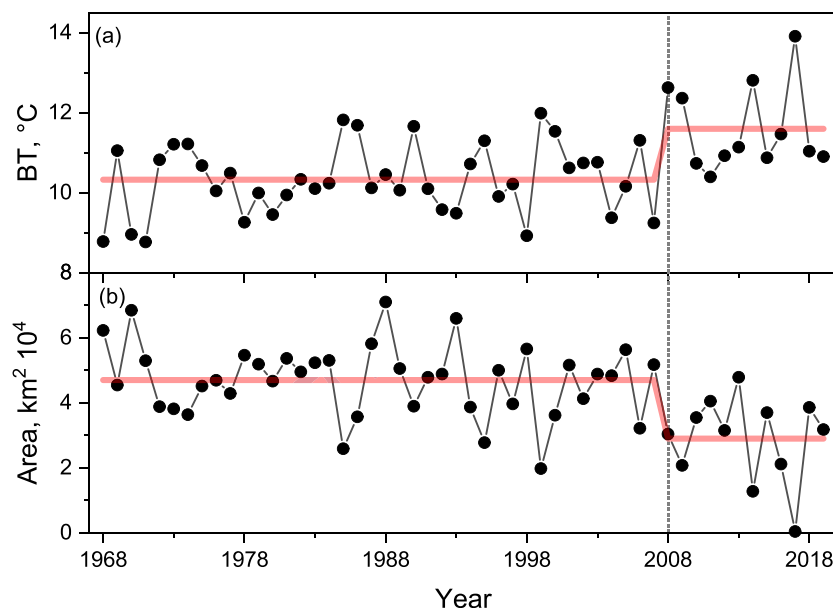
Trend in the Cold Pool indices was estimated using a Mann–Kendall nonparametric statistical test. Kendall's tau was calculated as a two-tailed test (H. B. Mann, 1945), and the Theil–Sen slope associated with each test was estimated using the R package “zyp” (version 0.10-1.1). In addition, we used the Yue and Pilon method to perform Mann–Kendall tests with a correction for autocorrelation (Yue et al., 2002).

We identified time series change points or potential regime shifts in the data using a sequential averaging algorithm called STARS or

**FIGURE 1** Map of the US Northeast Shelf study area with mean spring (a) and autumn (b) bottom temperature ( $^{\circ}\text{C}$ ) plotted as color map. Dotted line marks the  $11^{\circ}\text{C}$  contour and solid line marks the 150-m depth contour



**FIGURE 2** Cold Pool indices with regime means shown as red lines based on the mean temperature of the core area of the Cold Pool (a) and the size of the Cold Pool based on a threshold temperature of  $13^{\circ}\text{C}$ . Dotted line marks 2008



“sequential *t*-test analysis of regime shifts” (Rodionov, 2004, 2006; Thomson & Emery, 2014). The STARS algorithm parameters were specified a priori to detect change in thermal regime (alpha level  $\alpha = 0.05$ ; the length criteria = 10; Huber weight = 1). We applied change point detection to time series of the temperature and area indices, which provided a determination of the year in which a change point occurred and the magnitude of the change designated by the change in regime means, which is consistent with the terminology associated with the STARS algorithm.

### 3 | RESULTS

The Cold Pool indicators we calculated indicate long-term change in the temperature and extent of the Cold Pool and present the possibility of a distinct change point in Cold Pool dynamics in 2008. The temperature-based Cold Pool indicator had a long-term trend over the study period of  $0.029^{\circ}\text{C year}^{-1}$  ( $p < 0.01$ ) representing an overall warming of  $1.5^{\circ}\text{C}$  during the study period (Figure 2a). A change point in the temperature indicator was identified in 2008 with a change in

regime means from  $10.3^{\circ}\text{C}$  to  $11.6^{\circ}\text{C}$ , suggesting a change in temperature of  $1.3^{\circ}\text{C}$  based on the difference of regime means. The area-based indicator also had a significant long-term trend of  $-397 \text{ km}^2 \text{ year}^{-1}$  ( $p < 0.01$ ), representing a  $20,654\text{-km}^2$  reduction in the area of the Cold Pool over the study period (Figure 2b). A change point in the area indicator was also identified in 2008 with a change in regime means from approximately  $47,000$  to  $29,000 \text{ km}^2$ , suggesting a reduction in area of  $18,000 \text{ km}^2$  based on the difference of regime means. Since these time series are associated with step changes, long-term change based on trend analysis may be unreliable; hence, changes suggested by the regime means calculations were a 12% increase for the temperature index over the study period and 38% decline for the area-based index.

### 4 | DISCUSSION

The Cold Pool indicators developed here support previous observations that the feature has changed significantly in recent decades and also represent an updated view since the most recent estimates of

Cold Pool change used model output that ended in 2007 and observational data ending in 2011 (Chen & Curchitser, 2020; Miller et al., 2016). Our indicators of cold temperature and areal extent agree with reports of warming of the Cold Pool from these analyses and produce robust trend estimates owing to controls on time series autocorrelation. Our extended time series suggests the emergence of important features, a change point in Cold Pool temperature and size around the year 2008 and minimization of the Cold Pool in 2017. The change point in 2008 appears to be related to thermal change throughout the ecosystem (Friedland et al., 2020) and to the changing advection of Labrador slope water due to variation in Gulf Stream position and its upstream effects on the Labrador current (Brickman et al., 2018; Friedland et al., 2020; Gonçalves Neto et al., 2021). The extreme Cold Pool statistics in the year 2017 would appear to be the product of the heat wave observed in the same year (Gawarkiewicz et al., 2019). We expect that both annual features may have had distinct ecosystem impacts. To put the change in areal extent of the Cold Pool into perspective, the Cold Pool by our index occupied approximately one third of the area of the MAB at the beginning of the study period. However, in recent years, the Cold Pool only represents approximately 20% of the MAB with an overall reduction of >23,000 km<sup>2</sup> during the autumn time period. This result indicates either a broad reduction in Cold Pool extent or a change in timing of Cold Pool breakdown, with breakdown occurring prior to the autumn surveys.

The metrics developed here are complementary to other estimates of long-term trends in Cold Pool characteristics, including model-based approaches. Maximum vertical temperature gradients between the Cold Pool and overlying surface waters are typically reached in July and August (Castelao et al., 2010; Lentz, 2017). During autumn, a gradual reduction of surface heat flux, combined with intermittent tropical and extratropical storm events, erodes stratification and mixes the Cold Pool throughout the full water column (Forsyth et al., 2018). The episodic nature of the termination of the Cold Pool adds uncertainty to estimates of interannual Cold Pool characteristics derived from our early October observational data. However, significant challenges also exist in model-based metrics that rely on uncertain initial, boundary, and forcing inputs as well as similar observational datasets for validation and assimilation. We contend that the Cold Pool features we observed can serve an intrinsic value of contributing to an ensemble with other estimates (Kumar et al., 2014; Zhang et al., 2007) and perhaps reveal some features beyond the ability of other methods to resolve. We also suggest that there may be other proxy measures of the Cold Pool to explore, including those based on the change in the distribution of specific taxonomic groups, like boreal species.

Changes to thermogeography have widespread implications to patterns of biogeography (Adey & Steneck, 2001), and similar thermal shifts in the NES have resulted in significant changes to trophic structure and dynamics. The Gulf of Maine is an example of how similar thermal shifts affect ecosystems. The copepod *Calanus finmarchicus* is one of the predominant food sources of the NES and is especially sensitive to thermal shifts at the southern extent of its geographic range.

Abrupt increases in temperature decrease the survival of diapausing *C. finmarchicus* (Melle et al., 2014) and impact the food availability to other species later in the year (Sorochan et al., 2019). Such changes have been related to reduced survival of larval lobster (Carloni et al., 2018) and the distribution and calving rate of the endangered North Atlantic right whale, *Eubalaena glacialis* (Pace et al., 2017; Record et al., 2019). The American lobster, *Homarus americanus*, has undergone variable impacts across the NES due to these thermal shifts. At the southern extent of the NES, the onset of epizootic shell disease is more rapid and severe at higher temperatures (Castro et al., 2006; Steneck et al., 2011) contributing to recent reductions in reproductive potential and settlement (Wahle et al., 2015). In the Gulf of Maine, however, rapid expansion of suitable thermal recruitment habitats (Goode et al., 2019; Le Bris et al., 2018) attributable to a thermal regime shift starting in 2008 (Friedland et al., 2020) accelerated the population expansion of lobster northeastward.

The transition in bottom temperature in the Gulf of Maine around 2008 has attracted attention due to its connection with valuable resources like lobster; however, there is evidence that the change point in the Cold Pool may also have been impactful to Middle Atlantic species. Other taxa, including predatory fishes such as the black sea bass, *Centropristis striata*, with a distributional focus in the MAB, have become more abundant poleward (Nye et al., 2009) as thermal conditions favor overwintering survival of juveniles (Younes et al., 2020). Friedland et al. (2019) identified 2009 as a year with a cluster of change points in distributional indices for NES species including black sea bass; the change in extent of the Cold Pool could also be related to this change in distribution. Increased abundance of these predatory fishes may act as new top-down controls to crustacean species (McMahan & Grabowski, 2019) that have been relaxed since the functional reduction of demersal species due to overfishing (Steneck & Wahle, 2013) and limited ability to recover due to ocean warming (Pershing et al., 2015), hence providing an additional feedback on MAB lobster populations.

Perhaps most important is the impact of Cold Pool retraction on the sedentary biomass dominants of the Mid-Atlantic, including surfclams and ocean quahogs. The Cold Pool extends the habitat of the ocean quahog (and associated boreal species) farther south than any other location in its circumboreal range dramatically expanding the boundary between the boreal and cold temperate faunas. Instability and contraction of the inshore Cold Pool boundary has resulted in the interaction of these two communities, not heretofore typically observed, with two disparate outcomes. Simultaneous occurrence, likely engaging competitive interactions, is exemplified by the overlap of the offshore range boundary of surfclams (Timbs et al., 2019) with the inshore range boundary of ocean quahogs that now extends along the entirety of the Long Island to Delmarva continental shelf (Powell et al., 2020). This overlap coupled with the ability of ocean quahogs to estivate for long periods to avoid lethal temperatures results in the competitive overlap of these two species, the effects of which on their population dynamics remain undetermined. Farther north, Powell et al. (2019) documented the development of transient multiple stable states, these being the separate nonoverlapping

occupation of the same depth range by mytilid mussels and surfclams in a habitat not occupied by surfclams prior to 2004. These observations confirm that dynamic changes in the areal extent of the Cold Pool are driving unprecedented changes in the community structure of the Mid-Atlantic continental shelf benthos with the potential for a future catastrophic reorganization of the community structure of this benthos over much of this region. Projections of future shifts in the Cold Pool, both timing and extent, are sorely needed.

## ACKNOWLEDGMENTS

We thank C. Melrose and P. Fratantoni for comments on an early draft of the paper. Funding for Dr. Brady was provided by the USDA ARS nonassistance cooperative agreement (58-8030-0-004).

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

## AUTHOR CONTRIBUTION

K.F. conducted statistical analyses, produced figures, and drafted sections of the manuscript. T.M., A.G., E.P., and D. B provided sections of the manuscript. All authors provided comments and suggestions on revisions.

## DATA AVAILABILITY STATEMENT

The source data for the bottom temperature estimates were the database of NES water column properties observations available online ([ftp://ftp.nefsc.noaa.gov/pub/hydro/matlab\\_files/yearly/](ftp://ftp.nefsc.noaa.gov/pub/hydro/matlab_files/yearly/)) and the World Ocean Database holdings available [https://www.nodc.noaa.gov/OC5/WOD/pr\\_wod.html](https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html) website.

## ORCID

Kevin D. Friedland  <https://orcid.org/0000-0003-3887-0186>

Travis Miles  <https://orcid.org/0000-0003-1992-0248>

Andrew G. Goode  <https://orcid.org/0000-0001-9801-3501>

Eric N. Powell  <https://orcid.org/0000-0001-9467-0248>

Damian C. Brady  <https://orcid.org/0000-0001-9640-2968>

## REFERENCES

- Adey, W. H., & Steneck, R. S. (2001). Thermogeography over time creates biogeographic regions: A temperature/space/time-integrated model and an abundance-weighted test for benthic marine algae. *Journal of Phycology*, 37(5), 677–698. <https://doi.org/10.1046/j.1529-8817.2001.00176.x>
- Borsetti, S., Munroe, D., Rudders, D., & Chang, J.-H. (2020). Timing of the reproductive cycle of waved whelk, *Buccinum undatum*, on the U.S. Mid-Atlantic Bight. *Helgoland Marine Research*, 74(1), 5. <https://doi.org/10.1186/s10152-020-00537-6>
- Brickman, D., Hebert, D., & Wang, Z. (2018). Mechanism for the recent ocean warming events on the Scotian Shelf of eastern Canada. *Continental Shelf Research*, 156, 11–22. <https://doi.org/10.1016/j.csr.2018.01.001>
- Carloni, J. T., Wahle, R., Geoghegan, P., & Bjorkstedt, E. (2018). Bridging the spawner-recruit disconnect: Trends in American lobster recruitment linked to the pelagic food web. *Bulletin of Marine Science*, 94(3), 719–735. <https://doi.org/10.5343/bms.2017.1150>
- Castelao, R., Glenn, S., & Schofield, O. (2010). Temperature, salinity, and density variability in the central Middle Atlantic Bight. *Journal of Geophysical Research: Oceans*, 115(C10). <https://doi.org/10.1029/2009JC006082>
- Castro, K. M., Factor, J. R., Angell, T., & Landers, D. F. (2006). The conceptual approach to lobster shell disease revisited. *Journal of Crustacean Biology*, 26(4), 646–660. <https://doi.org/10.1651/S-2761a.1>
- Chen, Z., & Curchitser, E. N. (2020). Interannual variability of the Mid-Atlantic Bight cold pool. *Journal of Geophysical Research: Oceans*, 125(8), e2020JC016445. <https://doi.org/10.1029/2020JC016445>
- Chen, Z. M., Curchitser, E., Chant, R., & Kang, D. J. (2018). Seasonal variability of the cold pool over the Mid-Atlantic Bight continental shelf. *Journal of Geophysical Research-Oceans*, 123(11), 8203–8226. <https://doi.org/10.1029/2018jc014148>
- Forsyth, J., Gawarkiewicz, G., Andres, M., & Chen, K. (2018). The inter-annual variability of the breakdown of fall stratification on the New Jersey shelf. *Journal of Geophysical Research-Oceans*, 123(9), 6503–6520. <https://doi.org/10.1029/2018jc014049>
- Friedland, K. D., McManus, M. C., Morse, R. E., & Link, J. S. (2019). Event scale and persistent drivers of fish and macroinvertebrate distributions on the Northeast US Shelf. *ICES Journal of Marine Science*, 76(5), 1316–1334. <https://doi.org/10.1093/icesjms/tsy167>
- Friedland, K. D., Morse, R. E., Manning, J. P., Melrose, D. C., Miles, T., Goode, A. G., Brady, D. C., Kohut, J. T., & Powell, E. N. (2020). Trends and change points in surface and bottom thermal environments of the US Northeast Continental Shelf Ecosystem. *Fisheries Oceanography*, 29(5), 396–414. <https://doi.org/10.1111/fog.12485>
- Gawarkiewicz, G., Chen, K., Forsyth, J., Bahr, F., Mercer, A. M., Ellertson, A., Fratantoni, P., Seim, H., Haines, S., & Han, L. (2019). Characteristics of an advective marine heatwave in the middle Atlantic bight in early 2017. *Frontiers in Marine Science*, 6, 1–14. <https://doi.org/10.3389/fmars.2019.00712>
- Gonçalves Neto, A., Langan, J. A., & Palter, J. B. (2021). Changes in the Gulf Stream preceded rapid warming of the Northwest Atlantic Shelf. *Communications Earth & Environment*, 2(1), 1–10. <https://doi.org/10.1038/s43247-021-00143-5>
- Goode, A. G., Brady, D. C., Steneck, R. S., & Wahle, R. A. (2019). The brighter side of climate change: How local oceanography amplified a lobster boom in the Gulf of Maine. *Global Change Biology*, 25(11), 3906–3917. <https://doi.org/10.1111/gcb.14778>
- Hoarfrost, A., Balmonte, J. P., Ghobrial, S., Ziervogel, K., Bane, J., Gawarkiewicz, G., & Arnosti, C. (2019). Gulf stream ring water intrusion on the Mid-Atlantic Bight continental shelf break affects microbially driven carbon cycling. *Frontiers in Marine Science*, 6. <https://doi.org/10.3389/fmars.2019.00394>
- Houghton, R. W., Schlitz, R., Beardsley, R. C., Butman, B., & Chamberlin, J. L. (1982). The Middle Atlantic Bight Cold Pool: Evolution of the temperature structure during summer 1979. *Journal of Physical Oceanography*, 12(10), 1019–1029. [https://doi.org/10.1175/1520-0485\(1982\)012<1019:TMABCP>2.0.CO;2](https://doi.org/10.1175/1520-0485(1982)012<1019:TMABCP>2.0.CO;2)
- Jones, D. S. (1981). Reproductive cycles of the Atlantic surf clam *Spisula solidissima*, and the ocean quahog *Arctica islandica* off New Jersey. *Journal of Shellfish Research (USA)*, 1, 23–32.
- Kumar, S., Dirmeyer, P. A., & Kinter, J. L. (2014). Usefulness of ensemble forecasts from NCEP climate forecast system in sub-seasonal to intra-annual forecasting. *Geophysical Research Letters*, 41(10), 3586–3593. <https://doi.org/10.1002/2014GL059586>
- Le Bris, A., Mills, K. E., Wahle, R. A., Chen, Y., Alexander, M. A., Allyn, A. J., Schuetz, J. G., Scott, J. D., & Pershing, A. J. (2018). Climate vulnerability and resilience in the most valuable North American fishery. *Proceedings of the National Academy of Sciences of the United States of America*, 115(8), 1831–1836. <https://doi.org/10.1073/pnas.1711221115>
- Lentz, S. J. (2017). Seasonal warming of the Middle Atlantic Bight Cold Pool. *Journal of Geophysical Research: Oceans*, 122(2), 941–954. <https://doi.org/10.1002/2016JC012201>



- MacDonald, B. A., & Thompson, R. J. (1986). Influence of temperature and food availability on the ecological energetics of the giant scallop *Placopecten magellanicus*. *Marine Biology*, 93(1), 37–48. <https://doi.org/10.1007/BF00428653>
- Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, 13, 245–259. <https://doi.org/10.2307/1907187>
- Mann, R. (1982). The seasonal cycle of gonadal development in Arctic *islandica* from the southern New England shelf [Ocean quahog]. *Fishery Bulletin United States, National Marine Fisheries Service*, 80(2), 315–326.
- Marra, J., Houghton, R. W., & Garside, C. (1990). Phytoplankton growth at the shelf-break front in the Middle Atlantic Bight. *Journal of Marine Research*, 48, 851–868. <https://doi.org/10.1357/002224090784988665>
- McMahan, M. D., & Grabowski, J. H. (2019). Nonconsumptive effects of a range-expanding predator on juvenile lobster (*Homarus americanus*) population dynamics. *Ecosphere*, 10(10), e02867. <https://doi.org/10.1002/ecs2.2867>
- Melle, W., Runge, J., Head, E., Plourde, S., Castellani, C., Licandro, P., Pierson, J., Jonasdottir, S., Johnson, C., Broms, C., Debes, H., Falkenhaus, T., Gaard, E., Gislason, A., Heath, M., Niehoff, B., Nielsen, T. G., Pepin, P., Stenevik, E. K., & Chust, G. (2014). The North Atlantic Ocean as habitat for *Calanus finmarchicus*: Environmental factors and life history traits. *Progress in Oceanography*, 129, 244–284. <https://doi.org/10.1016/j.pocean.2014.04.026>
- Miller, T. J., Hare, J. A., & Alade, L. A. (2016). A state-space approach to incorporating environmental effects on recruitment in an age-structured assessment model with an application to southern New England yellowtail flounder. *Canadian Journal of Fisheries and Aquatic Sciences*, 73(8), 1261–1270. <https://doi.org/10.1139/cjfas-2015-0339>
- Morton, B. (2011). The biology and functional morphology of Arctic *islandica* (Bivalvia: Arctiidae)—A gerontophilic living fossil. *Marine Biology Research*, 7(6), 540–553. <https://doi.org/10.1080/17451000.2010.535833>
- Mountain, D. G., Taylor, M. H., & Bascuñán, C. (2004). Revised procedures for calculating regional average water properties for Northeast Fisheries Science Center cruises. *NEFSC Reference Document*, 04–08.
- Narváez, D. A., Munroe, D. M., Hofmann, E. E., Klinck, J. M., Powell, E. N., Mann, R., & Curchitser, E. (2015). Long-term dynamics in Atlantic surfclam (*Spisula solidissima*) populations: The role of bottom water temperature. *Journal of Marine Systems*, 141, 136–148. <https://doi.org/10.1016/j.jmarsys.2014.08.007>
- Nye, J. A., Link, J. S., Hare, J. A., & Overholtz, W. J. (2009). Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. *Marine Ecology-Progress Series*, 393, 111–129. <https://doi.org/10.3354/Meps08220>
- Pace, R. M., Corkeron, P. J., & Kraus, S. D. (2017). State-space mark-recapture estimates reveal a recent decline in abundance of North Atlantic right whales. *Ecology and Evolution*, 7(21), 8730–8741. <https://doi.org/10.1002/ece3.3406>
- Pershing, A. J., Alexander, M. A., Hernandez, C. M., Kerr, L. A., Le Bris, A., Mills, K. E., Nye, J. A., Record, N. R., Scannell, H. A., Scott, J. D., Sherwood, G. D., & Thomass, A. C. (2015). Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. *Science*, 350(6262), 809–812. <https://doi.org/10.1126/science.aac9819>
- Powell, E. N., Ewing, A. M., & Kuykendall, K. M. (2020). Ocean quahogs (*Arctica islandica*) and Atlantic surfclams (*Spisula solidissima*) on the Mid-Atlantic Bight continental shelf and Georges Bank: The death assemblage as a recorder of climate change and the reorganization of the continental shelf benthos. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 537, 109205. <https://doi.org/10.1016/j.palaeo.2019.05.027>
- Powell, E. N., Mann, R., Kuykendall, K. M., Long, M. C., & Timbs, J. R. (2019). The intermingling of benthic macroinvertebrate communities during a period of shifting range: The “East of Nantucket” Atlantic Surfclam Survey and the existence of transient multiple stable states. *Marine Ecology*, 40(4), e12546. <https://doi.org/10.1111/maec.12546>
- Record, N., Kenney, R., Balch, W., Davies, K., Pershing, A., Johnson, C., Stamieszkin, K., Ji, R., Feng, Z., Kraus, S., Kenney, R., Hudak, C., Mayo, C., Chen, C., Salisbury, J., & Thompson, C. (2019). Rapid climate-driven circulation changes threaten conservation of endangered north Atlantic right whales. *Oceanography*, 32(2). <https://doi.org/10.5670/oceanog.2019.201>
- Roarty, H., Glenn, S., Brodie, J., Nazzaro, L., Smith, M., Handel, E., Kohut, J., Updyke, T., Atkinson, L., Boicourt, W., Brown, W., Seim, H., Muglia, M., Wang, H., & Gong, D. (2020). Annual and seasonal surface circulation over the Mid-Atlantic Bight continental shelf derived from a decade of high frequency radar observations. *Journal of Geophysical Research: Oceans*, 125(11), e2020JC016368. <https://doi.org/10.1029/2020JC016368>
- Rodionov, S. N. (2004). A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, 31(9), 1–4. <https://doi.org/10.1029/2004gl019448>
- Rodionov, S. N. (2006). Use of prewhitening in climate regime shift detection. *Geophysical Research Letters*, 33(12), 1–4. <https://doi.org/10.1029/2006gl025904>
- Rothermel, E. R., Balazik, M. T., Best, J. E., Breece, M. W., Fox, D. A., Gahagan, B. I., Haulsee, D. E., Higgs, A. L., O'Brien, M. H. P., Oliver, M. J., Park, I. A., & Secor, D. H. (2020). Comparative migration ecology of striped bass and Atlantic sturgeon in the US Southern Mid-Atlantic Bight flyway. *PLoS ONE*, 15(6), e0234442. <https://doi.org/10.1371/journal.pone.0234442>
- Secor, D. H., Zhang, F., O'Brien, M. H. P., & Li, M. (2019). Ocean destratification and fish evacuation caused by a Mid-Atlantic tropical storm. *ICES Journal of Marine Science*, 76(2), 573–584. <https://doi.org/10.1093/icesjms/fsx241>
- Sorochan, K. A., Plourde, S., Morse, R., Pepin, P., Runge, J., Thompson, C., & Johnson, C. L. (2019). North Atlantic right whale (*Eubalaena glacialis*) and its food: (II) Interannual variations in biomass of *Calanus* spp. on western North Atlantic shelves. *Journal of Plankton Research*, 41(5), 687–708. <https://doi.org/10.1093/plankt/fbz044>
- Steneck, R. S., Hughes, T. P., Cinner, J. E., Adger, W. N., Arnold, S. N., Berkes, F., Boudreau, S. A., Brown, K., Folke, C., Gunderson, L., Olsson, P., Scheffer, M., Stephenson, E., Walker, B., Wilson, J., & Worm, B. (2011). Creation of a gilded trap by the high economic value of the Maine lobster fishery. *Conservation Biology*, 25(5), 904–912. <https://doi.org/10.1111/j.1523-1739.2011.01717.x>
- Steneck, R. S., & Wahle, R. A. (2013). American lobster dynamics in a brave new ocean. *Canadian Journal of Fisheries and Aquatic Sciences*, 70(11), 1612–1624. <https://doi.org/10.1139/cjfas-2013-0094>
- Sullivan, M. C., Cowen, R. K., & Steves, B. P. (2005). Evidence for atmosphere–ocean forcing of yellowtail flounder (*Limanda ferruginea*) recruitment in the Middle Atlantic Bight. *Fisheries Oceanography*, 14(5), 386–399. <https://doi.org/10.1111/j.1365-2419.2005.00343.x>
- Thomson, R. E., & Emery, W. J. (2014). Chapter 5—Time series analysis methods. In R. E. Thomson & W. J. Emery (Eds.), *Data Analysis Methods in Physical Oceanography* (Third Edition) (pp. 425–591). Elsevier. <https://doi.org/10.1016/B978-0-12-387782-6.00005-3>
- Timbs, J. R., Powell, E. N., & Mann, R. (2019). Changes in the spatial distribution and anatomy of a range shift for the Atlantic surfclam *Spisula solidissima* in the Mid-Atlantic Bight and on Georges Bank. *Marine Ecology Progress Series*, 620, 77–97. <https://doi.org/10.3354/meps12964>
- Wahle, R. A., Dellinger, L., Olszewski, S., & Jekielek, P. (2015). American lobster nurseries of southern New England receding in the face of climate change. *ICES Journal of Marine Science*, 72, 69–78. <https://doi.org/10.1093/icesjms/fsv093>
- Wood, A. M., Sherry, N. D., & Huyer, A. (1996). Mixing of chlorophyll from the Middle Atlantic Bight cold pool into the Gulf Stream at Cape

- Hatteras in July 1993. *Journal of Geophysical Research: Oceans*, 101(C9), 20579–20593. <https://doi.org/10.1029/96JC01135>
- Xu, Y., Miles, T., & Schofield, O. (2020). Physical processes controlling chlorophyll-a variability on the Mid-Atlantic Bight along northeast United States. *Journal of Marine Systems*, 103433, <https://doi.org/10.1016/j.jmarsys.2020.103433>
- Younes, A. F., Cerrato, R. M., & Nye, J. A. (2020). Overwintering survivorship and growth of young-of-the-year black sea bass *Centropristis striata*. *PLoS ONE*, 15(8). <https://doi.org/10.1371/journal.pone.0236705>, e0236705
- Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, 16(9), 1807–1829. <https://doi.org/10.1002/hyp.1095>
- Zhang, S., Harrison, M. J., Rosati, A., & Wittenberg, A. (2007). System design and evaluation of coupled ensemble data assimilation for global oceanic climate studies. *Monthly Weather Review*, 135(10), 3541–3564. <https://doi.org/10.1175/Mwr3466.1>

**How to cite this article:** Friedland, K. D., Miles, T., Goode, A. G., Powell, E. N., & Brady, D. C. (2022). The Middle Atlantic Bight Cold Pool is warming and shrinking: Indices from in situ autumn seafloor temperatures. *Fisheries Oceanography*, 31(2), 217–223. <https://doi.org/10.1111/fog.12573>