水 研 機 構 研 報，第 49 号，53 － 64，平 成 31 年
Bull. Jap. Fish. Res. Edu. Agen. No. 49，53－64，2019

Monitoring coastal acidification along the U.S. East coast: concerns for shellfish production

Matthew POACH[*1], Daphne MUNROE[*2], James VASSLIDES[*3], Ian ABRAHAMSEN[*4],
and Nicole COFFEY[*5]

Abstract: In coastal systems endangered by acidified water, it becomes paramount to understand the link between acidification and its environmental drivers. Embayments along the US Mid-Atlantic coast are particularly vulnerable to local amplification of ocean acidification due to eutrophic conditions, low alkalinity freshwater input, and episodic upwelling of acidified water. To better understand these drivers, two research studies were conducted along the coast of New Jersey, U. S. A. The first study was conducted during the summer of 2014 at the Aquaculture Innovation Center (AIC) of Rutgers University located in Cape May, NJ. The AIC is an important research hatchery that currently supports the local oyster aquaculture industry through the production of disease resistant and triploid seed oysters. The second study, which began in the summer of 2017, focused on elucidating the range of pH and aragonite saturation (Ω_{Ar}) conditions experienced in Little Egg Harbor Bay, NJ, an important shellfish farming and fishing location. At the AIC, temperature, salinity, dissolved oxygen (DO), turbidity and pH were continuously monitored at the intake pipe located in the Cape May Canal. The pH at the intake showed diurnal variations that tended to mirror the DO signal. The largest drop in pH was measured in July of 2014. This pH drop was decoupled from the DO signal. The occurrence of consistent Southwesterly winds and cooler surface water temperatures along the coast before the pH decrease indicated that upwelling was occurring. A strong shift in the winds likely pushed upwelled water inshore to the intake. The lowest pH reading coincided with a decrease in salinity due to higher river discharge and strong winds. These results show that hatcheries along the NJ coast need to be aware that upwelling and freshwater input may bring reduced pH conditions that can negatively impact shellfish production, and highlights the need for continued monitoring. Starting in May of 2017, temperature, salinity, DO, turbidity, pH and carbon dioxide partial pressure (pCO_2) were continuously monitored at a station in Little Egg Harbor off Beach Haven. Sensor temperature, salinity, pH and pCO_2 data were used to calculate Ω_{Ar}. Results indicated that DO and pH conditions are likely not detrimental to local shellfish production. There was no indication that upwelling occurred during the monitoring period so no conclusions could be reached about the potential for summertime upwelling to impact shellfish production in Little Egg Harbor.

Key words: coastal acidification, upwelling, shellfish aquaculture, hatchery

---

2018年 8 月31日受理（Accepted on August 31, 2018）

[*1] NOAA/NMFS, James J Howard Marine Sciences Laboratory, Highlands, NJ 07732, U. S. A.
[*2] Rutgers University, Haskin Shellfish Research Laboratory, Port Norris, NJ 08349, U. S. A
[*3] Barnegat Bay Partnership, Ocean County College, Toms River, NJ 08753, U. S. A.
[*4] University of Pittsburgh, Pittsburgh, PA 15260, U. S. A.
[*5] University of Delaware, Newark, DE 19716, U. S. A.
E-mail: matthew.poach@noaa.gov

Introduction

Human carbon dioxide (CO_2) emissions have raised atmospheric CO_2 levels from 180 ppmv in the 19th century to over 400 ppmv today (IPCC, 2014; Tans and Keeling, 2018). Of that CO_2 increase, ~ 1/3 has been absorbed by the oceans (Sabine *et al*., 2004) and has impacted the ocean's carbonate chemistry in a process known as ocean acidification (OA). The increase in surface water pCO_2 leads to a decrease in pH and carbonate ion concentrations (Caldeira and Berner, 1999; Caldeira and Wickett, 2003). A reduction in the carbonate ion concentration also reduces carbonate ion saturation state (Ω), which can result in an undersaturated condition for carbonate minerals. These changes in carbonate chemistry are particularly detrimental to the early developmental stages of shellfish as the larvae tend to precipitate the more-soluble aragonite-form of calcium carbonate (Barton *et al*., 2012; Waldbusser *et al*., 2015). Aragonite undersaturation has been shown in laboratory experiments to reduce survival and growth of shellfish larvae (Barton *et al*., 2012; Gazeau *et al*., 2013; Gobler *et al*., 2014; Talmage and Gobler, 2010; Waldbusser *et al*., 2013; Waldbusser and Salisbury, 2014).

While OA monitoring has historically been focused on offshore regions, commercially important bivalve aquaculture and fisheries are located in the coastal zone where the CO_2-system is impacted by the additive effects of natural and anthropogenic processes at both global and local scales (Feely *et al*., 2010; Cai, 2011; Bauer *et al*., 2013; Duarte *et al*., 2013; Breitburg *et al*., 2015). In productive estuarine environments, the system is further driven toward increasing acidity from local generation of CO_2 due to microbial decomposition of labile organic carbon and by injection of waters undersaturated with respect to carbonate via upwelling or storm events. With high rates of photosynthesis and respiration in these systems, they can be expected to experience greater fluctuations in pH and Ω compared to the open ocean. Importantly, increased respiratory CO_2-production and upwelling events that lower Ω and adversely impact estuarine chemistry may co-occur with the timing of the economically driven production of larval shellfish at hatcheries or spawning in wild populations. For example, coastal acidification has caused hatchery larval production problems costing the oyster farming industry in the U.S. Pacific Northwest over $100 million and threatening 1000's of jobs (Washington State, 2012).

Global aquaculture production is expanding and now accounts for half of world food fish and shellfish production (Naylor *et al*., 2009). Shellfish aquaculture is particular a widely practiced way of producing food in coastal areas that helps meet the needs of a rapidly growing global human population (Foley *et al*., 2011; FAO, 2016). Most commercially and recreationally important fish and shellfish species depend on estuarine ecosystem services at some point in their life cycle. An assessment of the vulnerability and adaptation of U.S. shellfisheries to ocean acidification (OA) found that the most socially vulnerable communities are spread along the U.S. East Coast and Gulf of Mexico (Ekstrom *et al*., 2015). Their analysis also found that a number of socially vulnerable communities lie adjacent to water bodies that are exposed to a high rate of OA or at least one local amplifier, indicating that these places could be at high overall vulnerability to OA.

Shellfish production was once vitally important to the economy of the state of New Jersey (Ford, 1997). From 1870 to 1930, the Barnegat Bay-Cape May area produced about 20 % of all market oysters harvested in the state. This production had declined significantly by the 1950's due to overfishing, salinity changes, and disease. The quahog fishery also saw a decline after the 1950's mainly due to pollution which caused bed closures. The decline of shellfish populations along the New Jersey coast over the last century has prompted significant efforts at their restoration. As a result of coastal acidification processes, the shellfish industry in New Jersey is likely already experiencing acidification conditions stronger than the open ocean. Since modern shellfish aquaculture production relies entirely on reliable and consistent larval production in hatcheries, understanding coastal ocean acidification (coastal OA) in the Northeast U.S. is a matter critical to the stability and sustainability of this industry. In coastal systems endangered by acidified water, it becomes paramount to understand the link between acidification and its environmental drivers.

In order to understand the carbonate chemistry experienced by coastal estuaries and their shellfish resources, two different monitoring studies were conducted, one at Rutgers University's Aquaculture Innovation Center (AIC) located in Cape May and the other at a marina in the southernmost segment of the Barnegat Bay - Little Egg Harbor Estuary complex, NJ, U.S.A. (**Fig.1**). The AIC is an important research hatchery that currently supports the New Jersey oyster aquaculture industry through the production of disease resistant and triploid seed oysters. The Barnegat Bay - Little Egg Harbor estuary is currently undergoing eutrophication (Fertig *et al.*, 2014), which may impact shellfish restoration in this estuary.

Materials and Methods

AIC: At the AIC, the carbonate chemistry of intake water was monitored during the summer of 2014. From June 15 through July 20, temperature, salinity, dissolved oxygen (DO), and pH were measured every 15 minutes at the AIC's intake pipe located in the Cape May Canal. Parameters were monitored using a YSI EXO™2 water quality sonde that was installed 1 meter off the bottom next to the intake. Probes were calibrated according to manufacturer recommendations prior to deployment. Probe calibration was also performed at the end of the deployment. After sensor retrieval, data were downloaded and subjected to quality control analysis. Quality control consisted of the identification and removal of missing or erroneous data due to sensor malfunction as well as identification and removal of outliers. Correlations between pH and other measured parameters were examined through regression analysis.

Little Egg Harbor (LEH): During the Spring of 2017, the Little Egg Harbor estuary monitoring station was installed at a bay side pier located at Morrison's Marina in Beach Haven, NJ. The installation consisted of a YSI EXO™2 water quality sonde to measure temperature, salinity, DO, and pH and a Pro-Oceanus CO_2Pro-CV™ sensor to measure pCO_2. In July, a SeaFET™ pH sensor was attached to the pCO_2 sensor. Sensors were installed ~ 1 meter off the bay bottom. YSI sensor readings were collected every 15 minutes while the pCO_2 and SeaFET™ pH sensors took a reading every 30 minutes. Sensor data was stored by a Campbell® Instruments CR-6 datalogger. Data sets were retrieved hourly through cellular telemetry to a desktop computer. Downloaded data were subjected to quality control analysis, which consisted of the identification and removal of missing or erroneous data due to sensor malfunction as well as identification and removal of outliers. The sampling line for the pCO_2 and SeaFET™ sensors fouled often compromising the data and leading to their removal in mid-August. Data recorded during an 11 day period in June and a 12 day period in July displayed a reasonable range of values for pCO_2. During those periods the pCO_2 explained 89 % of variation in pH indicating that the data was likely valid as the YSI pH and the pCO_2 sensors were independent of each other. In July the SeaFET™ pH was similar to YSI pH. As the SeaFET™ sensor shared the same sample intake as the pCO_2 sensor the similarity between the two independent pH readings provide additional support for the quality of the YSI pH data and pCO_2 data (**Fig.2**). The valid YSI pH and pCO_2 data along with their corresponding depth, salinity, and temperature data were used to calculate the aragonite saturation state (Ω_{Ar}) by the CO_2SYS_xls program (Pierrot *et al.* 2006).

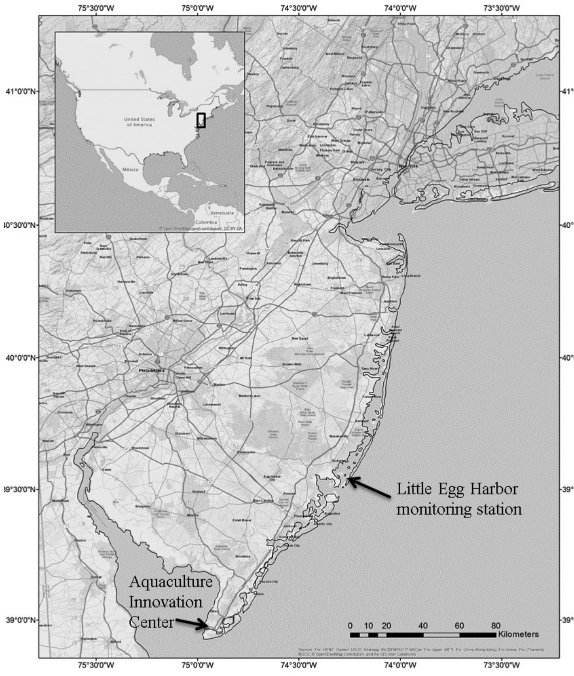

Fig. 1. Map showing the coast of New Jersey with the two monitoring sites indicated.

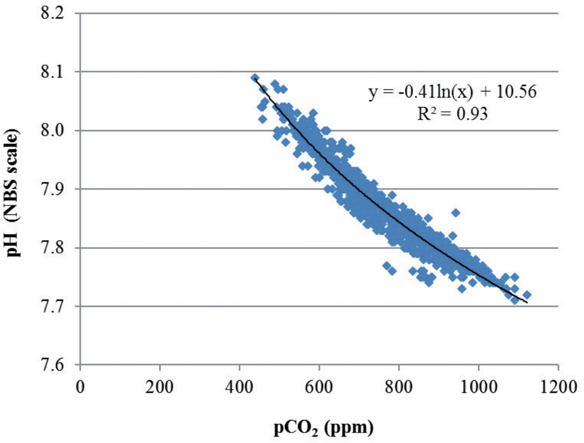

Fig. 2. Regression relationship between pCO$_2$ and YSI pH measured in the LEH estuary during June and July.

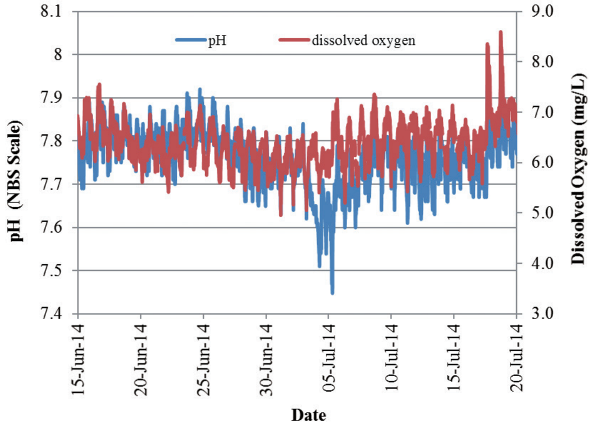

Fig. 3. The pH as measured on the NBS scale and dissolved oxygen in mg/L recorded during the study period by a YSI water quality sonde installed one meter off the bottom and next to the intake pipe for the Aquaculture Innovation Center.

Results and Discussion

AIC: From June 15th to July 20st of 2014, pH ranged from 7.45 to 7.99 while DO ranged from 4.95 to 8.60 mg/L (**Fig.3**). The coarse scale trend for pH tended to mimic that for DO. Both tended to show a general diurnal trend of increasing values during the day and decreasing values at night. These trends were expected because during the day net photosynthesis will increase both DO and pH, while net respiration during the night will decrease both. Even though pH and DO exhibited similar patterns, DO accounted for only 35 % of the variation in pH. The relationship between pH and DO noticeably diverged during July 3rd through the 5th (**Fig.3**). During this period the decreases in pH were not associated with similar decreases in DO. The lowest pH values of the study were measured during this period with the lowest value of 7.45 measured on the morning of July 5th. Low correlation between pH and DO can result from factors in the coastal environment that can affect pH without a change in DO such as the input of low pH water from either coastal upwelling or freshwater inflow. Upwelled water tends to have a pH lower than the average surface ocean pH due to higher net respiration rates in bottom water. Once this water reaches the surface it will equilibrate rather quickly with atmospheric O$_2$, while pCO$_2$ remains relatively unchanged due the slow rate of CO$_2$ degassing. Likewise, most rivers in New Jersey have low alkalinity which would lead to a different relationship between pH and O$_2$ in river water than in ocean water.

An examination of other environmental data indicated that the drop in pH observed from July 3rd through the 5th likely resulted from a combination of both coastal upwelling and freshwater input. From July 1st through the 3rd there were strong south / southwest winds (**Fig.4**), which are necessary to drive upwelling along the New Jersey coast. The premise that upwelling was occurring during this period was supported by colder sea surface temperatures along the coast on July 2nd (**Fig.5a**). Cold water along the coast on July 5th (**Fig.5b**), indicated that upwelling was still occurring even though the winds were blowing strongly out of the northeast on July 4th then out of the northwest on July 5th. This change in wind direction along with its strength is likely the reason why low pH water made it to the AIC's intake. Similar pH drops were not recorded at other dates when there were strong upwelling favorable winds. Strong southerly winds occurred between July 13th and 15th; yet during or immediately after this period, pH did not drop below 7.6. The difference between this period of southerly winds and the previous was the lack of strong northerly winds immediately after July 15th. The distinction between these two events strongly suggests that an abrupt shift to strong

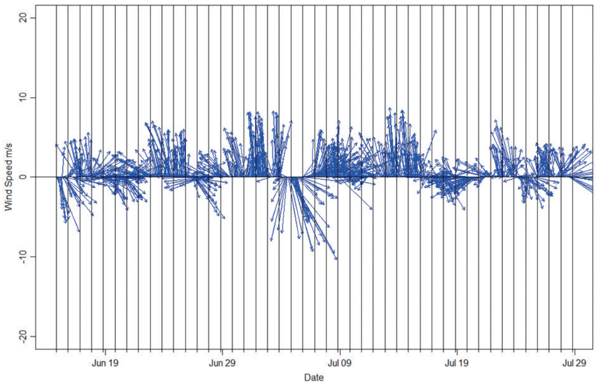

Fig. 4. Wind stick vector plot for winds during the study period as measured by the weather station located at the Cape May - Lewes ferry terminal which is adjacent to the Aquaculture Innovation Center. Arrows point in the compass direction toward which the wind is blowing (*i.e.* a northward pointing arrow indicates a south wind). Arrow heads mark the magnitude of the winds.

northerly winds following sustained southerly winds helps to push upwelled water inshore along the New Jersey coast.

While upwelling and strong northerly winds would explain the decrease in pH on July 4th; the lowest pH of 7.45 on July 5th coincided with the lowest salinity reading during the study period. Salinity dropped to a low of 21.3 ppt after an early morning high of 29.3 ppt (data not shown). This salinity decrease coincided with a high river discharge and outgoing tide. This indicates that river water likely contributed to the lowest pH reading. Along with freshwater input, upwelling and strong northerly winds were also likely contributors as there was a higher river discharge on June 15th, yet on that date salinity and pH did not drop lower than 25.9 and 7.69, respectively.

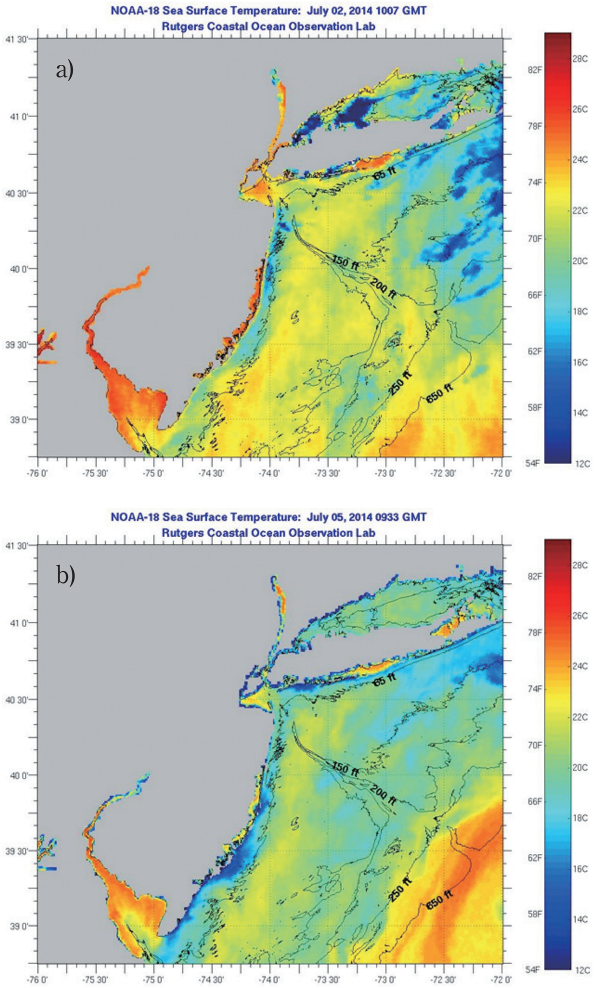

Fig. 5. Satellite AVHRR-derived images of sea surface temperature from NOAA-18 satellite for a) July 2nd at 10:07 Z and b) July 5th at 09:33 Z. (Images from Rutgers Coastal Ocean Observation Laboratory at https://marine.rutgers.edu/cool/sat_data/)

These results indicate that both upwelling and freshwater input can reduce the pH of source water for the AIC. To assess the potential for those drivers to affect shellfish production it is necessary to consider the magnitude, duration, and timing of pH decreases. During this study the pH decreased to levels that have been shown to decrease survival and to delay metamorphism of *C. virginica larvae* (Gobler and Talmage, 2014; Talmage and Gobler, 2009). It should be noted, however, that these negative effects weren't exhibited until after more than three days of constant exposure. The reduced pH event at the AIC lasted two days and was not constantly held low as intermittent increases occurred due to tidal changes. Fluctuating pH has been shown to lessen the negative effects of constantly low pH on survival of *C. virginica larvae* (Clark and Gobler, 2016; Keppel *et al.*, 2016). When only considering the pH data, the previous research suggests that the short duration of the reduced pH event along with the fluctuation in pH levels would not be stressful enough to impact oyster product in the facility (Shaw *et al.*, 2013). But the decrease in pH wasn't the only change that would have been stressful for oyster production. The decrease in pH on July 5th was also accompanied by an additional stress of a sudden decrease in salinity. While no studies have looked at the effects of short-term salinity decreases on larvae of *C. virginica*; in studies of gastropod larvae, short term salinity decreases resulted in increased mortality (Diederich *et al*., 2011; Montory *et al*., 2014; Montory *et al*., 2016). Decreased salinity has also been shown to exacerbate the negative effects of lower pH on *C. virginica* juveniles (Dickinson *et al*., 2012; Waldbusser *et al*., 2011). Even if the reduction in salinity was temporary; this additional stress may shorten the exposure time necessary for reduced pH to affect oyster larvae.

As for event timing, the AIC conducts the majority of its oyster spawning during the late winter-spring period. High river discharges accompanied by strong northerly winds are more likely to occur during that time period (Hughes, 2011; Joesoef, 2015); while upwelling is limited to the summer season. This means that freshwater input has a higher potential to impact AIC operations than upwelling. While upwelling will likely not affect spring hatchery operations, it occurs during the most sensitive time of year for natural coastal populations of shellfish. In coastal New Jersey, oysters and clams spawn during the summer. Summer is also when eutrophic systems can develop hypoxic conditions with associated acidification. These conditions can be exacerbated by upwelling as it not only transports acidified water but also nutrients that further drive eutrophication.

LEH: For June and July of 2017, YSI pH ranged from 7.71 to 8.15 while DO ranged from 4.4 to 9.57 mg/L (**Fig.6**). As with the AIC data, the coarse scale trend for pH mimicked that for DO, with increasing values during the day and decreasing values at night. Conversely, pH trends in June and July mirror the trends in pCO$_2$, which ranged from to 438 to 1122 µatm (**Fig.7**). The fluctuations in pH and pCO$_2$ produced levels that ranged from present-day averages for the open ocean to averages predicted for the open ocean at the end of the 21st century due to ocean acidification (Bopp *et al*., 2013). The paired values for YSI pH and pCO$_2$ produced values for Ω_{Ar} ranging from 0.75 to 1.87 (**Fig.8**). Most Ω_{Ar} values were between 1 and 1.5. The Ω_{Ar} dropped below 1 for an extended period on June 6th and then again on June 7th. This likely resulted from a strong east wind during both days that helped to build up water levels in the estuary.

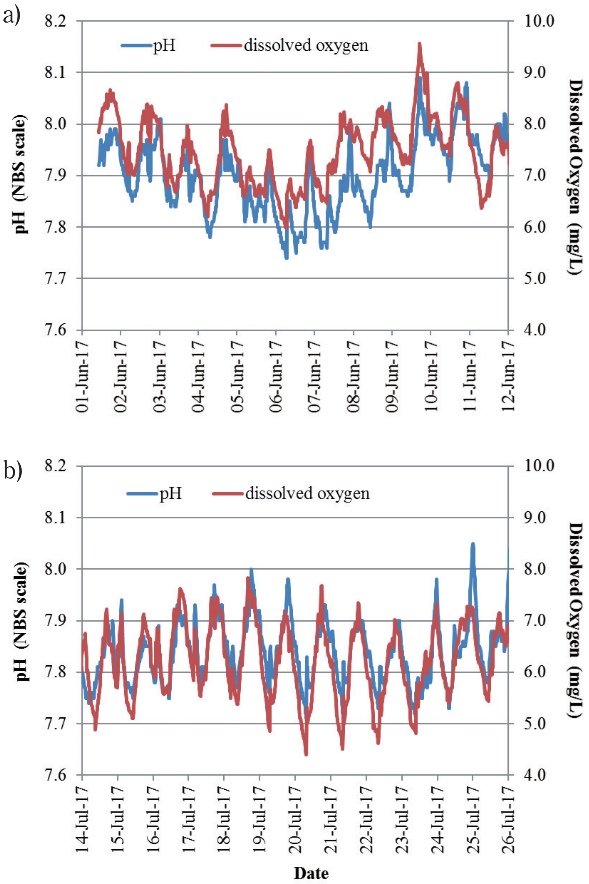

Fig. 6. Trends in pH (blue) and dissolved oxygen (red) measured at the intake to the AIC hatchery by a YSI EXO™2 water quality sonde during a) June and b) July of 2017.

These results are evidence of the dynamic environment to which estuarine organism must adapt. It is this dynamic nature that makes it difficult to predict the effects of acidification on bivalves common in Northeastern U.S. estuaries. While constant exposure to pCO$_2$ and pH levels similar to the lowest recorded here have been shown to affect the survival, metamorphosis, growth, and physiology of *Mercenaria mercenaria, Argopecten irradians*, and *Crassostrea virginica* larvae (Gobler and Talmage, 2014; Miller *et al*., 2009; Talmage and Gobler, 2009); effects were not seen when exposure periods were shorter (Boulais *et al*., 2017; Talmage and Gobler, 2009). Such shorter exposure periods may occur under fluctuating pH conditions leading to the mitigation of

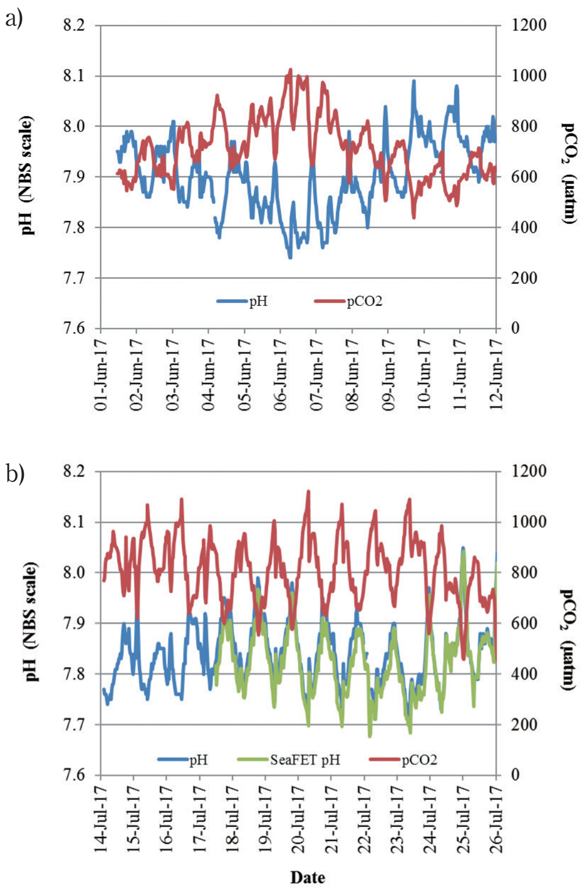

Fig. 7. Trends in pH measured by a YSI EXO™2 sonde (blue) and a SeaFET™ (green) and pCO_2 measured by a CO_2Pro-CV™ sensor in LEH estuary during a) June and b) July of 2017.

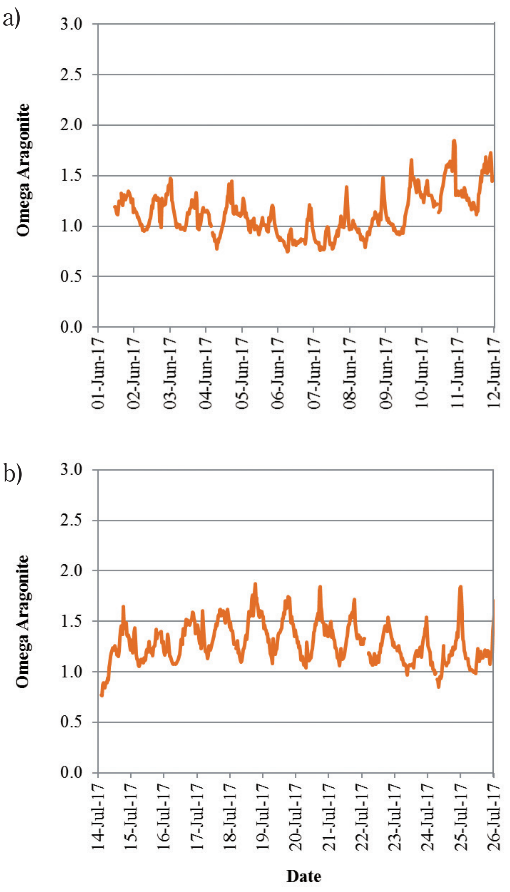

Fig. 8. Trends in aragonite saturation state, omega aragonite, measured 1 meter off the bottom in LEH estuary during a) June and b) July of 2017.

low pH impacts on bivalves (Frieder *et al.*, 2014). Very few studies of acidification effects on local bivalve species have included a fluctuating pH treatment. In studies that have included fluctuating treatments, pH was decrease to levels below the lowest pH levels recorded here (Clark and Gobler, 2016; Gobler *et al.*, 2017; Keppel *et al.*, 2016). The levels of pH and pCO_2 recorded here likely did not lead to negative impacts because Ω_{Ar} rarely dropped below 1. Still, even fluctuating pH conditions can produce negative impacts in bivalves when compared to static levels that are similar to the average of the fluctuations. In order to understand the impacts of fluctuations in pH reported for LEH, more studies need to be conducted that incorporate similar pH ranges.

The LEH is considered to be undergoing eutrophication (Fertig *et al.*, 2014). Eutrophic estuaries can experience extended periods of hypoxic and anoxic conditions in summer that also lead to depressed pH (Gobler and Baumann, 2016). Hypoxic conditions and its associated acidification have negative effects on marine organisms that are both additive and synergistic (Wallace *et al.*, 2014). Even though LEH is considered mildly eutrophic, DO levels did not drop below 4 mg/L (**Fig.6**). The DO values recorded here appear to be representative of summertime values for the Barnegat Bay – LEH system (Glibert *et al.*, 2010; NJDEP, 2014). This system is shallow and well mixed which deters the occurrence of extremely low DO levels (Glibert *et al.*, 2010). The levels of both DO and pH measured during the monitoring period indicate that this area of LEH is likely not experiencing oxygen or carbonate conditions that are detrimental to shellfish production.

The LEH monitoring site was chosen because it is near the mouth of Great Bay, which is a site of recurrent summertime upwelling (Glenn *et al*., 2004). A decrease in pH indicative of upwelled water did not occur during the June and July monitoring periods highlighted here. While it is possible for upwelling to occur and not be pushed far enough inshore to be captured at this sensor location; upwelling was not indicated in the coastal sea surface temperature data during June or July. More monitoring is necessary to determine if upwelled water has the potential to impact the LEH ecosystem. Determining if upwelling can enter LEH is important because it not only brings lower pH water but also additional nutrients to fuel productivity during the warmer more productive time of the year. These excess nutrients can exacerbate eutrophication.

Acknowledgment

The authors would like to acknowledge NOAA's Ocean Acidification Program and NOAA's Hollings Scholarship program for the support that they provided to this research. Thanks to Mike DeLuca and the AIC staff for their support with water sampling at the AIC. Gregg Sakowicz provided technical assistance and YSI calibration for which we are grateful. Thanks also to Nicole Petersen for her tireless work in troubleshooting and maintaining the LEH station. The LEH station was funded by a US EPA Clean Water Act Section 320 Grant to the Barnegat Bay Partnership (CE982123-12-2).

References

Bauer J. E., Cai W. J., Raymond P. A., Bianchi T. S., Hopkinson C. S., and Regnier P. A. G., 2013: The changing carbon cycle of the coastal ocean. *Nature*, **504**, 61-70.

Bopp L., Resplandy L., Orr J. C., Doney S. C., Dunne J. P., Gehlen M., Halloran P., Heinze C., Ilyina T., Séferian R., Tjiputra J., and Vichi M., 2013: Multiple stressors of ocean ecosystems of the 21st century: projections with CMIP5 models. *Biogeosciences*, **10**, 6225-6245.

Boulais M., Chenevert K. J., Demey A. T., Darrow E. S., Robison M. R., Roberts J. P., and Volety A., 2017: Oyster reproduction is compromised by acidification experienced seasonally in coastal regions. *Sci. Rep*., **7**, 3276. doi:10.1038/s41598-017-13480-3

Breitburg D. L., Salisbury J., Bernhard J. M., Cai W. J., Dupont S., Doney S. C., Kroeker K. J., Levin L. A., Long W. C., Milke L. M., Miller S. H., Phelan B., Passow U., Seibel B. A., Todgham A. E., and Tarrant A. M., 2015: And on top of all that… Coping with ocean acidification in the midst of many stressors. *Oceanography*, **28**, 48-61.

Cai W. J., 2011: Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration?. *Annu. Rev. Mar. Sci.*, **3**, 123-145.

Caldeira K. and Berner R., 1999: Seawater pH and atmospheric carbon dioxide. *Science*, **286**, 2043-2043.

Caldeira K. and Wickett M. E., 2003: Anthropogenic carbon and ocean pH. *Nature*, **425**, 365-365.

Clark H. R. and Gobler C. J., 2016: Diurnal fluctuations in CO_2 and dissolved oxygen concentrations do not provide a refuge from hypoxia and acidification for early-life-stage bivalves. *Mar. Ecol. Prog. Ser*., **558**, 1-14. doi:10.3354/meps11852

Dickinson G. H., Ivanina A. V., Matoo O. B., Pörtner H.O., Lannig G., Bock C., Beniash E., and Sokolova I. M., 2012: Interactive effects of salinity and elevated CO_2 levels on juvenile Eastern oysters, *Crassostrea virginica*. *J. Exp. Biol.*, **215**, 29-43. doi:10.1242/jeb.061481

Diederich C. M., Jarrett J. N., Chaparro O. R., Segura C. J., Arellano S. M., and Pechenik J. A., 2011: Low salinity stress experienced by larvae does not affect post-metamorphic growth or survival in three calyptraeid gastropods. *J. Exp. Mar. Biol. Ecol.*, **397**, 94-105.

Duarte C.M., Hendriks I. E., Moore T. S., Olsen Y. S., Steckbauer A., Ramajo L, Carstensen J., Trotter J. M., and McCulloh M., 2013: Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuaries and Coasts*, **36**, 221-236.

Feely R. A., Alin S. R., Newton J., Sabine C. L., Warner M., Devol A., Krembs C., and Maloy C., 2010: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary. *Estuar. Coast. Shelf Sci.*, **88**, 442-449.

Fertig B., Kennish M. J., Sakowicz G. P., and Reynolds L. K., 2014: Mind the data gap: identifying and assessing drivers of changing eutrophication condition. *Estuaries and Coasts*, **37**, S198-S221. doi:10.1007/s1223701397465

Foley J. A., Ramankutty N., Brauman K. A., Cassidy E. S., Gerber J. S., Johnston M., Mueller N. D., O'Connell C., Ray D. K., West P. C., Balzer C., Bennett E. M., Carpenter S. R., Hill J., Monfreda C., Polasky S., Rockström J., Sheehan J., Siebert S., Tilman G. D., and Zaks D. P. M., 2011: Solutions for a cultivated planet. *Nature*, **478**, 337-342.

FAO, 2016: The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all, Rome, 200pp.

Ford S. E., 1997: History and present status of molluscan shellfisheries from Barnegat Bay to Delaware Bay, in "The History, Present Condition, and Future of the Molluscan Fisheries of North and Central America and Europe, Vol. 1. Atlantic and Gulf Coasts" (ed. by MacKenzie Jr. C. L., Burrell Jr. V. G., Rosenfield A., and Hobart W. L.), NOAA Tech. Rept. NMFS 127, pp. 119-140.

Frieder C. A., Gonzalez J. P., Bockmon E. E., Navarro M. O., and Levin L. A., 2014: Can variable pH and low oxygen moderate ocean acidification outcomes for mussel larvae?. *Glob. Chang. Biol.*, **20**, 754-764.

Gazeau F., Parker L. M., Comeau S., Gattuso J. P., O'Connor W. A., Martin S., Portner H. O., and Ross P. M., 2013: Impacts of ocean acidification on marine shelled molluscs. *Mar. Biol.*, **160**, 2207-2245.

Glenn S., Arnone R., Bergmann T., Bissett W. P., Crowley M., Cullen J., Gryzmski J., Haidvogel D., Kohut J., Moline M., Oliver M., Orrico C., Sherrell R., Song T., Weidemann A., Chant R., and Schofield O., 2004: Biogeochemical impact of summertime coastal upwelling on the New Jersey Shelf. *J. Geophys. Res.*, **109**, C12S02. doi:10.1029/2003JC002265

Glibert P. M., Madden C. J., Boynton W., Flemer D., Heil C., and Sharp J. H., 2010: Nutrients in estuaries: a summary report of the National Estuarine Experts Workgroup (2005–2007). US EPA report 68-C-02-091 and EP-C-07-025, United States Environmental Protection Agency, Washington, D.C., 188pp.

Gobler C. J. and Talmage S. C., 2014: Physiological response and resilience of early life-stage Eastern oysters (*Crassostrea virginica*) to past, present and future ocean acidification. *Conserv. Physiol.*, **2**. doi:10.1093/conphys/cou004

Gobler C. J., DePasquale E. L., Griffith A. W., and Baumann H., 2014: Hypoxia and acidification have additive and synergistic negative effects on the growth, survival, and metamorphosis of early life stage bivalves. *PLoS One*, **9(1)**, e83648. doi:10.1371/journal.pone.0083648

Gobler C. J., Clark H. R., Griffith A. W., and Lusty M. V., 2017: Diurnal fluctuation in acidification and hypoxia reduce growth and survival of larval and juvenile bay scallops (*Argopecten irradians*) and hard clams (*Mercenaria mercenaria*). *Front. Mar. Sci.*, **3**, 282. doi:10.3389/fmars.2016.00282

Hughes C. P., 2011: The climatology of the Delaware Bay/sea breeze. M.S. thesis. School of Marine Science and Policy, University of Delaware, 129pp. [Available online at http://udspace.udel.edu/handle/19716/10659.]

IPCC, 2014: Climate Change 2014. Synthesis report, Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by Pachauri R. K. and Meyer L. A.), IPCC, Geneva, Switzerland, 151pp.

Joesoef A., Huang W.-J., Gao Y., and Cai W.-J., 2015: Air–water fluxes and sources of carbon dioxide in the Delaware Estuary: spatial and seasonal variability. *Biogeosciences*, **12**, 6085–6101. doi:10.5194/bg-12-6085-2015

Keppel A. G., Breitburg D. L., and Burrell R. B., 2016: Effects of co-varying diel-cycling hypoxia and pH on growth in the Juvenile Eastern Oyster, *Crassostrea virginica*. *PLoS One*, **11**, e0161088. doi:10.1371/journal.pone.0161088

Miller A. W., Reynolds A. C., Sobrino C., and Riedel G. F., 2009: Shellfish face uncertain future in high CO_2 world: influence of acidification on oyster larvae calcification and growth in estuaries. *PLoS One*, **4**, e5661. doi:10.1371/journal.pone.0005661

Montory J. A., Chaparro O. R., Pechenik J. A., Diederich

C. M., and Cubillos V. M., 2014: Impact of short-term salinity stress on larval development of the marine gastropod *Crepipatella fecunda* (*Calyptraeidae*). *J. Exp. Mar. Biol. Ecol.*, **458**, 39-45.

Montory J. A., Chaparro O. R., Navarro J. M., Pechenik J. A., and Cubillos V. M., 2016: Post-metamorphic impact of brief hyposaline stress on recently hatched veligers of the gastropod *Crepipatella peruviana* (*Calyptraeidae*). *Mar. Biol.*, **163**, 1-10.

Naylor R. L., Hardy R. W., Bureau D. P., Chiu A., Elliott M., Farrell A. P., Forster I., Gatlin D. M., Goldburg R., Hua K., and Nichols P. D., 2009: Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci. U.S.A*, **106**, 15103-15110. doi:10.1073/pnas.0905235106

New Jersey Dept. of Environmental Protection (NJDEP), 2014: Dissolved Oxygen Levels in Estuarine & Near Shore Waters. Environmental Trends Report, NJDEP, Office of Science. https://www.nj.gov/dep/dsr/trends/

Pierrot D., Lewis E., and Wallace D. W. R., 2006: MS Excel program developed for CO_2 system calculations, ORNL/CDIAC-105a. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi:10.3334/CDIAC/otg.CO2SYS_XLS_CDIAC105a

Sabine C. L., Feely R. A., Gruber N., Key R. M., Lee K., Bullister J. L., Wanninkhof R., Wong C. S., Wallace D. W. R., Tilbrook B., Millero F. J., Peng T.-H., Kozyr A., Ono T., and Rios A. F., 2004: The oceanic sink for anthropogenic CO_2. *Science*, **305**, 367-371.

Shaw E. C., Munday P. L., and McNeil B. I., 2013: The role of CO_2 variability and exposure time for biological impacts of ocean acidification. *Geophys. Res. Lett.*, **40**, 4685-4688. doi:10.1002/grl.50883

Talmage S. C. and Gobler C. J., 2009: The effects of elevated carbon dioxide concentrations on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*). *Limnol. Oceanogr.*, **54**, 2072-2080. doi:10.4319/lo.2009.54.6.2072

Talmage S. C. and Gobler C. J., 2010: Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. *Proc. Natl. Acad. Sci. U.S.A*, **107**, 17246-17251.

Tans P. and Keeling R., 2018: Trends in atmospheric carbon dioxide, Mauna Loa, Hawaii, Earth System Research Laboratory Global Monitoring Division, NOAA. https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html

Waldbusser G. G. and Salisbury J. E., 2014: Ocean acidification in the coastal zone from an organism's perspective: multiple system parameters, frequency domains, and habitats. *Annu. Rev. Mar. Sci.*, **6**, 221-247.

Waldbusser G. G., Brunner E. L., Haley B. A., Hales B., Langdon C. J, and Prahl F. G., 2013: A developmental and energetic basis linking larval oyster shell formation to acidification sensitivity. *Geophys. Res. Lett.*, **40**, 2171-2176. doi:10.1002/grl.50449

Waldbusser G. G., Hales B., Langdon C., Haley B. A., Schrader P., Brunner E. L., Gray M. W., Miller C. A., and Gimenez I., 2015: Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nat. Clim. Chang.*, **5**, 273-280.

Waldbusser G. C., Voigt E. P., Bergschneider H., Green M. A., and Newell R. I. E., 2011: Biocalcification in the Eastern Oyster (*Crassostrea virginica*) in relation to long-term trends in Chesapeake Bay pH. *Estuaries and Coasts*, **34**, 221-231. doi:10.1007/s12237-010-9307-0

Washington State Blue Ribbon Panel on Ocean Acidification, 2012: Ocean acidification: from knowledge to action, Washington State's strategic response (ed. by Adelsman H. and Binder L. W.), Washington Department of Ecology, Olympia, Washington. Publication no. 12-01-015.

Annotated bibliography

(1) Barton A., Hales B., Waldbusser G. G., Langdon C., and Feely R. A., 2012: The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnol. Oceanogr.*, **57**, 698-710.

The authors report results of a monitoring study designed to evaluate the response of Pacific oyster (*Crassostrea gigas*) larvae, grown at a commercial hatchery on the Oregon coast, to natural changes in carbonate chemistry associated with periodic seasonal upwelling during the summer of 2009. During the study the intake waters experienced aragonite saturation states from 0.8 to 3.2 and pH from 7.6 to 8.2. They observed significant negative relationships between aragonite saturation states at the time of spawning and subsequent growth and production of larvae over the size range of 120 to 150-mm shell length. This was one of the first studies to link failures in seed oyster production to more corrosive water from coastal upwelling.

(2) Booth J. A.T., McPhee-Shaw E. E., Chua P., Kingsley E., Denna M., Phillips R., Bograd S. J., Zeidberg L. D., and Gilly W. F., 2012: Natural intrusions of hypoxic, low pH water into nearshore marine environments on the California coast. *Cont. Shelf Res.*, **45**, 108-115.

The authors reviewed a decade-long data set to examine oxygen and pH variability on the inner shelf off of Central California. Results show regular inundation of cold, hypoxic and low pH water. The source-water for these periodic intrusions originates in the offshore, midwater environment above the local OMZ, generally between 50–100 m but occasionally deeper. Pulses of the greatest intensity arose at the onset of the spring upwelling season, and fluctuations were strongly semidiurnal and diurnal. Arrival of cold, hypoxic water on the inner shelf appears to be driven by tidal-frequency internal waves pushing deep, upwelled water into nearshore habitats. These observations are consistent with the interpretation that hypoxic water is advected shoreward from the deep, offshore environment where water masses experience a general decline of temperature, oxygen and pH with depth.

(3) Ekstrom J. A., Suatoni L., Cooley S. R., Pendleton L. H., Waldbusser G. G., Cinner J. E., Ritter J., Langdon C., van Hooidonk R., Gledhill D., Wellman K., Beck M. W., Brander L. M., Rittschof D., Doherty C., Edwards P. E. T., and Portela R., 2015: Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nat. Clim. Chang.*, **5**, 207-214. doi:10.1038/nclimate2508

Authors present a spatially explicit, multidisciplinary analysis of the vulnerability of coastal human communities in the United States to ocean acidification. Their results highlight US regions most vulnerable to ocean acidification, reasons for that vulnerability, important knowledge and information gaps, and opportunities to adapt through local actions. Results indicated that 16 of the 23 bioregions around the United States are exposed to rapid OA (reaching Ω_{Ar} 1.5 by 2050) or at least one amplifier; 10 regions are exposed to two or more threats of acidification. The marine ecosystems and shelled molluscs around the Pacific Northwest and Southern Alaska are expected to be exposed soonest to rising global OA, followed by the north-central West Coast and the Gulf of Maine in the northeast United States. Communities highly reliant on shelled molluscs in these bioregions are at risk from OA either now or in the coming decades. In addition, pockets of marine ecosystems along the East and Gulf Coasts will experience acidification earlier than global projections indicate, owing to the presence of local amplifiers such as coastal eutrophication and discharge of low-Ω_{Ar} river water. This analysis can be used to help prioritize societal responses to ocean acidification.

(4) Gobler C. J. and Baumann H., 2016: Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. *Biol. Lett.*, **12**, 20150976. doi:10.1098/rsbl.2015.0976

As climate change progresses, the effects of atmospheric CO_2 on coastal acidification will intensify; and, while hypoxia is a much studied stressor for coastal organisms, the combined effect of hypoxia and acidification has only recently become a focus for scientists. The authors conduct a meta-analysis of published research that studied the combined effects of pH and dissolved oxygen variability on marine organisms. The authors conclude that low DO is a greater stressor to most marine organisms than low pH conditions, although worse effects can occur through the synergistic interaction of the two. While most traits under concurrent low DO and low pH appeared to be additively affected, every study reviewed also found synergistic interactions in at least one instance. They also conclude that neither the occurrence nor the strength of these synergistic impacts is currently predictable, and therefore, the true threat of concurrent acidification and hypoxia to marine food webs and fisheries is still not fully understood. Addressing this knowledge gap will require an expansion of multi-stressor approaches in experimental and field studies.

(5) Wallace R. B., Baumann H., Grear J. S., Aller R. C., and Gobler C. J., 2014: Coastal ocean acidification: The other eutrophication problem. *Estuar. Coast. Shelf Sci.*, **148**, 1-13. doi:10.1016/j.ecss.2014.05.027

To assess the potential for acidification in eutrophic estuaries, the authors characterized the spatial and temporal patterns of DO, pH, pCO_2, and Ω_{Ar} in four, semi-enclosed estuarine system across the Northeast US: Narragansett Bay, Long Island Sound, Jamaica Bay, and Hempstead Bay. Multi-year monitoring datasets were assessed to define seasonal patterns in pH and DO while cruises were conducted to vertically and horizontally resolve spatial patterns of acidification during the seasonal onset, peak, and decline of hypoxia in these estuaries. They utilized three approaches for this study: 1) The analysis of monthly monitoring data across Long Island Sound; 2) Vertical measurements of water column conditions across Narragansett Bay, Long Island Sound, and Jamaica Bay; and 3) Continuous, horizontal mapping of conditions across Jamaica Bay and Hempstead Bay. Low pH conditions (< 7.4) were detected in all systems during summer and fall months concurrent with the decline in DO concentrations. While hypoxic waters and/or regions in close proximity to sewage discharge had extremely high levels of pCO_2, (> 3000 μatm), were acidic pH (< 7.0), and were undersaturated with regard to aragonite ($\Omega_{Ar} < 1$), even near-normoxic but eutrophic regions of these estuaries were often relatively acidified (pH < 7.7) during late summer and/or early fall. This study revealed that acidification is an annual feature of eutrophic estuaries across the Northeast US that co-occurs with seasonally low oxygen. The spatial and temporal dynamics of DO, pH, pCO_2, and Ω_{Ar} suggest that they are all ultimately driven by high rates of microbial respiration. The degree of acidification observed in these systems during summer are within ranges that have been shown to adversely impact a wide range of marine life.