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Analysis of a Newly Digitized Long-Term Dataset of Environmental Observations from Long Island Sound

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Analysis of a Newly Digitized Long-Term Dataset of Environmental Observations
from Long Island Sound

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B.S., University of Maine at Machias, 2014

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

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At the

University of Connecticut

2017

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Jacob Thomas Snyder

2017

APPROVAL PAGE
Masters of Science Thesis

Analysis of a Newly Digitized Long-Term Dataset of Environmental Observations
from Long Island Sound

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Abstract

Project Oceanology, a non-profit oceanographic educational organization has been collecting data including pH, oxygen, and temperature conditions as well as abundances of benthic invertebrates and near-shore fish catches since 1972 from Eastern Long Island Sound. These data had been stored solely on single-copy paper sheets and were therefore inaccessible to analysis. I digitized more than 100,000 abiotic measurements and 50,000 species abundance and size data collected over the past 45 years, and developed a web-based SQL database housed on the Long Island Sound Integrated Coastal Observing System (LISICOS) server. The database will ultimately become a searchable, downloadable, user-friendly web-based tool to aid students, researchers, and educators. Here, I examined this long-term dataset for evidence of acidification and warming in North-Eastern Long Island Sound. Furthermore, I explored decadal shifts in species abundance, diversity, and richness in relation to shifts in abiotic parameters and large-scale climate indices (e.g. AMO). I applied wavelets analysis and principal components analysis (PCA), as well as linear regression and other simpler statistical metrics. Eastern Long Island Sound has been warming ($0.45 \pm 0.281^{\circ}\text{C} \bullet \text{decade}^{-1}$) significantly faster than the global ocean, acidifying at a rate twice as fast as the global average ($-0.04 \pm 0.044 \bullet \text{decade}^{-1}$), and whole water-column dissolved oxygen concentrations are decreasing ($-0.29 \pm 0.233 \text{ mg/L} \bullet \text{decade}^{-1}$). Concomitantly, there has been no change in the abundance of warm-water adapted species, a significant decline in species richness, significant declines in lobsters, winter flounder, and significant increases in spider crab abundance. These data clearly show both the sensitivity of estuaries to climate change and the utility of a citizen-science collected data set when studying decadal variation.

Introduction

Marine Climate Change

Marine climate change driven by anthropogenic CO₂ emissions has significant effects on marine species (Fabry et al., 2008; Howell and Auster, 2012; Miller et al., 2009). A large body of work is available on global processes and open ocean marine climate change, but resolution on smaller spatial scales (i.e. coastal and estuarine) is still being developed (Baumann and Smith, 2017). Marine climate change is a syndrome comprised of three main processes; warming, acidification, and deoxygenation, which work synergistically to increase stress on organisms in the marine realm (Pörtner et al., 2005). Increased CO₂ emissions leads to warming and deoxygenation of marine habitats, while CO₂ dissolution leads to acidification (Baumann and Smith, 2017; Doney et al., 2009). In addition, eutrophication of coastal environments stimulates primary production and successive microbial respiration, which exacerbates acidification and deoxygenation (Cloern, 2001; Cloern et al., 2014; Nixon, 1995).

Ocean acidification (OA), “mankind’s other CO₂ problem” (Doney et al., 2009), refers to the process of anthropogenic CO₂ release into the atmosphere decreasing sea-surface pH by way of CO₂ dissolution into the sea surface and resultant disassociation increasing [H⁺] (Wallace et al., 2014); partially driven by increased release of CO₂ from fossil fuel combustion into the atmosphere over the past century (Orr et al., 2005). River input of allochthonous carbon, decreased alkalinity from lower salinity driven by freshwater input, high solubility of CO₂, and the terminal effects of eutrophication all strongly influence pH in estuarine systems (Doney et al., 2009; Salisbury et al., 2009; Wallace et al., 2014; Wong, 1979). Eutrophication directly effects coastal waters through increased nutrient loading, leading to phytoplankton blooms and enhanced CO₂ drawdown (Cloern et al., 2014), but results in high levels of decomposition and respiration which increases the likelihood of benthic hypoxia (Pörtner et al., 2005). Tidal stirring and the breakdown of stratification (Simpson et al., 1990) complicate estuarine pH

trends. Feely et al. (2010) have shown that estuarine stratification and limited mixing led to high rates of primary production at the surface and high rates of benthic microbial respiration, which led to significant differences in pH levels throughout the water column.

The primary consequence of increased CO₂ emissions is the Earth's increased ability to retain outgoing longwave radiation—trapped heat correlates to a greater solar insolation flux and warmer atmospheric temperatures (Ramanathan, 1981). As average atmospheric temperatures rise so will average SSTs. However, high latitudes warm faster than mid-latitudes and the tropics, and are therefore showing the greatest effects of warming (Hansen et al., 2010). Locations like Long Island Sound, a temperate estuary on the Northern end of the mid-Atlantic bight warms rapidly given both its location and unique physical and geological characteristics (Baumann and Doherty, 2013; Rice et al., 2014).

While climate change is a global issue, the sensitivity of coastal environments or the potential resilience of organisms in these coastal environments to a changing marine climate is highly localized and species specific. Estuaries are one of the most productive marine habitats (Cloern et al., 2014) and the impacts felt from climate change can be more severe than the open ocean (Lotze et al., 2006; Whitehead et al., 2009). Effects can be compounded or ameliorated by coastal processes including storm water runoff, nutrient input, intense mixing, and daily to seasonal changes in marine chemistry (Baumann and Smith, 2017; Baumann et al., 2015). When combined with high levels of biodiversity, these interactive factors make the coastal ocean highly responsive and potentially susceptible to marine climate change. However, estuaries undergo daily, monthly, seasonal, and decadal changes in seawater chemistry and biology. As a result, estuarine organisms typically exhibit high levels of plasticity (Bamber and Henderson, 1988; Janzen, 1967) and are able to withstand large and rapid fluctuations in temperature, salinity, pH, oxygen, and other abiotic factors (Anderson and Taylor, 2001; Baumann and Smith, 2017; Baumann et al., 2015; Cloern and Nichols, 1985; Duarte et al., 2013; Gillanders et al., 2011). Understanding both how these environments change and how those changes drive organismal

abundance and distributions is critical to understanding the effects of marine climate change in estuaries.

Community Responses to Marine Climate Change

Many marine species are susceptible to small- and large-scale shifts in pH, oxygen, and temperature, but estuarine species regularly experience broad ranges and can quickly adapt (Bamber and Henderson, 1988; Janzen, 1967; Madeira et al., 2012). High levels of urbanization around Long Island Sound make the estuary particularly susceptible to eutrophication. While some species appear to be adapted to changing climates, others show limited thermal and pH tolerance, manifested by shifts of marine species and assemblages (Howell and Auster, 2012; Kleisner et al., 2016; Nye et al., 2009; Pinsky et al., 2013). Many marine organisms are shifting poleward, or to deeper and colder waters (Nye et al., 2009), with rising coastal temperatures favoring warm-adapted and temperate species (Collie et al., 2008; Howell and Auster, 2012; Kleisner et al., 2016). Others have quantified climate velocities, i.e., the speed and direction of shifting isotherms in the ocean (Kleisner et al., 2016), and showed that fish species and assemblages closely track shifting climate velocities (Pinsky et al., 2013).

To study species shifts in abundance or location, long-term datasets are required. Collie et al. (2008) studied fish abundance and diversity from biweekly trawl data in Narragansett Bay between 1959 and 2005 and observed a shift from a benthic to pelagic dominated community (Fig. 1), and an increase in overall invertebrate abundance, particularly squid (*Doryteuthis pealaeii*). While they observed a SST increase of 1.6°C which was highly correlated to shifting species abundances, they did not have data on oxygen concentrations and pH, and therefore were limited in their discussion of what factors drove these changes. Studies of Long Island Sound have shown significant decreases in cold-water species and increases in warm-water species (Howell and Auster, 2012), significant decreases in American Lobster

abundance (Landers et al., 2016; Pearce and Balcom, 2005), as well as general increases in warm temperate species in the Thames River (DEEP, 2017). Commercial and recreational fish removal from

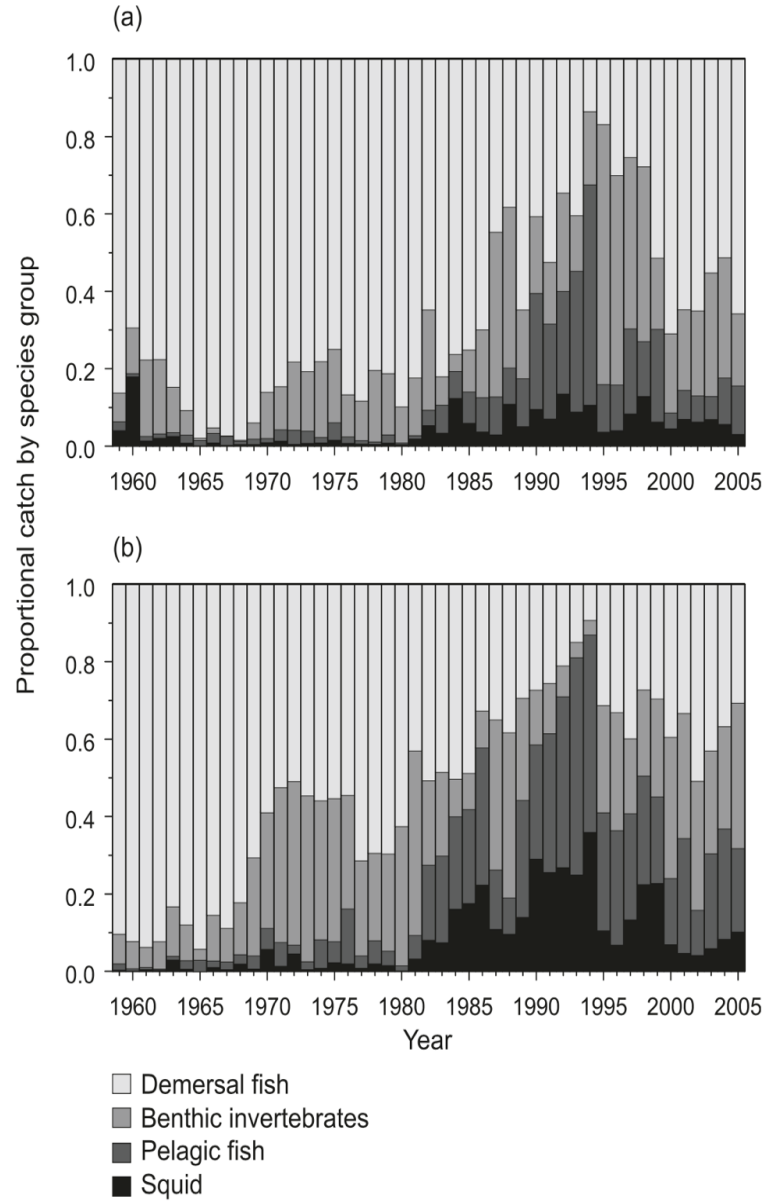


Figure 1. Shift in fish and invertebrate abundances at Narragansett Bay Station (a) and Sound Station (b). Adapted from (Collie et al., 2008).

the ocean has already depressed populations (Hutchings, 2000), and this likely exacerbates the effects of climate change.

Reduction in baseline oxygen concentrations and increases in hypoxia are stressful for many marine organisms, with vertical and lateral displacement of numerous marine species caused by benthic and whole-water column hypoxia (Breitburg, 2002; Sagasti et al., 2001). Hypoxia also effects organisms based on their activity level; mobile species tend to have a lower stress tolerance to hypoxic events than sessile organisms. Sagasti et al. (2001) showed that some sessile species actually experience predation refuges during brief hypoxic events (i.e. their predators are mobile and temporarily leave the hypoxic zone), while some mobile species can move to avoid hypoxia and in turn reduce predation on sessile organisms in those hypoxic-zones. It has also been shown that fish emigrating away from stressful O₂ conditions can concentrate on non-hypoxic refuge zones and devastate natural prey abundance (Lenihan et al., 2001). While the work cited here focused on hypoxia alone, when combined with increasing temperatures and decreasing pH the synergistic effects of these stressing factors are still largely unresolved, but may further drive shifts in species abundances and distributions.

Estuaries

Estuaries are a dynamic and integral part of the worlds' oceans— being highly productive nurseries for fish, they connect freshwater sources to the ocean (Attrill and Power, 2002; Houde and Rutherford, 1993). Coastal ecosystems provide essential ecosystem services to humans including; habitats for fish, high levels of production, and recreation. Estuaries close connection to land, however, makes them vulnerable to development, eutrophication, pollution, and removal of natural substrates (Howarth et al., 2000; Mallin et al., 2005).

Long Island Sound is a partially mixed estuary located in Southern New England, directly connected to Connecticut, New York, and Rhode Island by over 600 miles of coastline, with its watershed extending over 16,000 km² (LISS.net, Fig. 2). Seasonal and yearly marine residents include

many species of finfish and benthic invertebrates, some of which are commercially and recreationally important. Freshwater is predominantly supplied by four major rivers, with the mouth of the Thames River being the focus of this study. The Thames River is a short 24km river that flows south from Norwich CT where the Yantic and Shetucket rivers converge, and drains into eastern Long Island Sound just West of Fishers Island Sound. It has served as an important shipping and commercial port, with a US Sub Base and ferries located near the mouth.

Project Oceanology is a marine education (grades 4-12) organization based in Groton Connecticut on the University of Connecticut's Avery Point campus. It has consistently collected and stored data from the same locations for the past 45 years; standard boat-trips introduce oceanographic topics to students and the general public, with an emphasis on the Thames River Mouth. During a two-and-a-half-hour standard trip, cruise participants record temperature, salinity, pH, and oxygen data, in addition to sediment condition and species abundance from otter trawls. While this study focuses on data collected aboard a standard oceanographic trip, Project Oceanology also collects data on lobster catches, blue crabs, shellfish populations, nearshore beach surveys, beach profiles, and marsh quality.

The Value of Long-Term Data Sets

Long-term datasets (LTDS) are highly valuable for studying decadal changes, but they are scarce due to logistical and funding constraints (Keeling, 1998). LTDS are important when attempting to understand long-term and large-scale changes in abiotic variables, shifts in populations, species, and species assemblages. Large datasets are regularly collected and used to understand trends in movement and behavior (Provost and Fawcett, 2013), or can be used in concert with experimental approaches that focus on shorter time scales (Hofmann et al., 2013). When trying to understand global change, researchers need data that spans decades to centuries if possible. Big-data has been defined as

being large, complex data sets that require intense computing power to analyze (Ward and Barker, 2013). While not large enough to be a true “big-data” dataset, I use the concepts of big-data and LTDS to argue that the data used here have been A) collected in the same manner using identical or similar equipment and methods for ~45 years, B) a biologically educated instructor oversees the entire data collection process, and C) the data were quality-checked again upon digitization. Big-data emphasizes the concept that discrete point accuracy is less important when a large body of data exists—errors in one point become negligible and overall trends can be distinguished with confidence. This thesis applies the ‘big-data’ concepts to data collected by Project Oceanology to examine decadal trends in abiotic and biotic variables. To assess the validity and usefulness of this data set, this thesis applied error propagation concepts and included inherent measurement error in each calculation to accurately quantify error throughout the analysis. Here, I digitized, analyzed, and show the utility and direct applicability of data collected by citizen scientists and compared their data to other data sources collected in Southeastern New England.

Objectives & hypotheses

The objective of this study was to digitize a citizen-science collected LTDS from the Mouth of the Thames River Estuary in Eastern Long Island Sound and to examine it for long-term trends in a suite of biotic and abiotic variables. The primary problem this data-source presented is that it was previously inaccessible, as it was stored in single-copy format in filing cabinets. I hypothesized that these decadal records would show a warming trend similar or exceeding the warming rates of Long Island Sound, the US Atlantic Shelf, and the average surface ocean. I also hypothesized that waters of the Thames River Estuary would show a decrease in pH, i.e., acidification over time, at rates that were greater than coastal and global rates given the high productivity and low alkalinity of estuarine habitats. Standing oxygen

concentrations were hypothesized to decline over time in part due to warming temperatures and increases in nutrient input. Furthermore, I expected the trawl data to show increases in warm-water adapted over cold-water adapted species, driven in part by the warming of Long Island Sound waters. Finally, I hypothesized that dominant abiotic variables including pH, temperature, and dissolved oxygen were correlated to species abundances or assemblages, which would suggest that abiotic variables drive some of the biotic patterns.

Methods

Data Collection

Environmental data are regularly being collected by middle and high school students and their educators at Project Oceanology (PO) since 1972. Electronic instruments (CTD, light meters) were regularly reset to factory defaults (i.e. pseudo-calibrated, see statistical methods section for measurement error calculations), while the remainder of the tests were conducted using chemical titrations (pH, CO₂) or pieces of equipment (thermometers, hydrometers, secchi disk) that did not require calibration. Data quality and control (QA/QC) procedures included briefings on data collection methods and best-practices, on-board assistance by trained PO staff and educators, post-trip assessments of data quality by PO personnel, and data comparisons between repeated measurements by different groups during a boat trip. Approximately 5% of all data found was marked as inaccurate or untrustworthy by PO staff present on that particular trip (personal observation) and they were not used in this analysis.

Temperature, salinity, and oxygen were routinely measured in one-meter interval vertical profiles, and pH was measured at the surface, middle, and bottom of the water column. Additional

measurements of CO₂, light, water clarity and color, as well as navigation and meteorological data were recorded for educational purposes; however, these data were excluded from this thesis because of

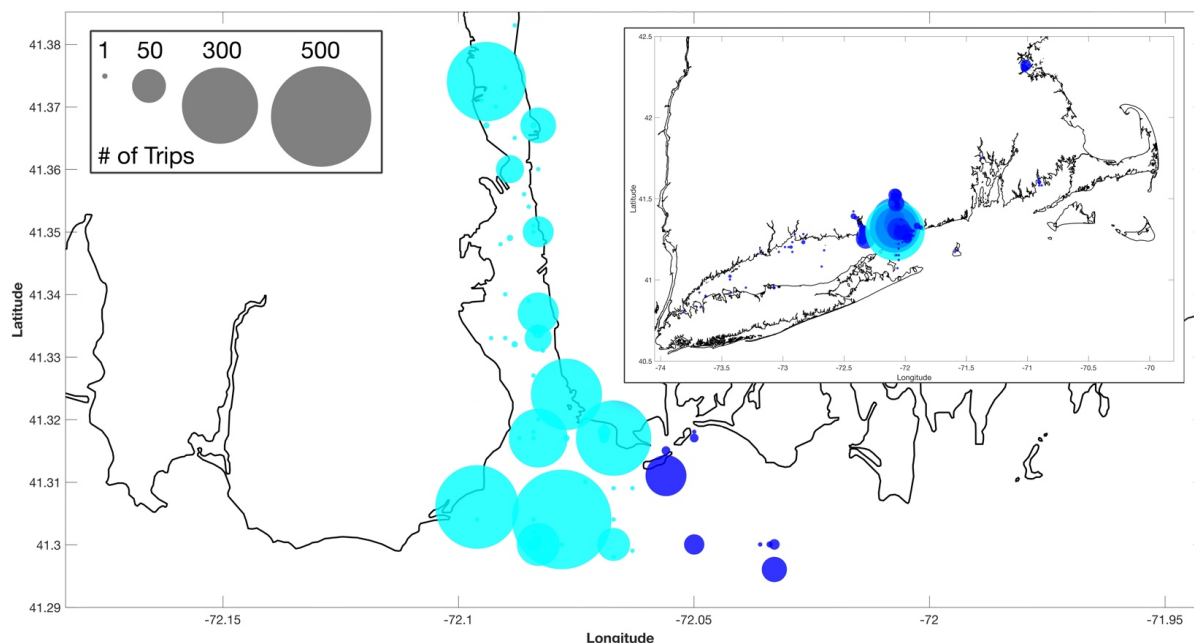


Figure 2. A total of 51 stations were spaced across Long Island Sound, the Connecticut River, Thames River, Fishers Island Sound, and Boston Harbor. Most entries included specific coordinates, and those were plotted to a regularly spaced grid, and then analyzed into groups based on nearest points. Lightly shaded circles show the focus of this thesis (TRM), while dark circles show the rest. Legend in the top left is for the Thames River Mouth, shown here in the main figure, while the inset shows the entire spread of data collection efforts.

known accuracy issues, low coverage of data, or likelihood of measurement error. For example, CO₂ has been measured via titration, with the indicating color being a light pink, and students often tend to over-titrate (personal observation). As with all citizen-science endeavors there is an increased likelihood of measurement error, and quantifying this error was an integral part of this thesis. PH measurements are made via titration with an average measurement error of ± 0.1 units. Measurement errors of dissolved oxygen (DO) and temperature were more difficult to estimate, but were conservatively assumed to be $\pm 1^\circ\text{C}$ and $\pm 1 \text{ mg} \cdot \text{L}^{-1} \text{ DO}$.

During most standard trips, an otter-trawl net was deployed (Wilcox Flat Trawl, 3m width, 12m depth, 2.5cm stretch diamond mesh, 1.25cm cod end mesh), with the standard trawl duration being 20

Station	Common Name	Latitude	Longitude	# of Trips
1	New London Ledge Light	41.304	-72.078	727
2	Hobbs Island	41.324	-72.077	786
3	Pfizer	41.337	-72.083	137
4	State Pier	41.360	-72.089	92
5	Coast Guard Academy	41.374	-72.094	412
6	Sub Base	41.388	-72.095	75
7	Dow Chemical	41.443	-72.088	17
8	Montville Power Station	41.428	-72.099	60
9	Walden Island	41.467	-72.068	14
10	Poquetanuck Cove	41.467	-72.068	63
11	Thermos	41.513	-72.077	16
12	Norwich Harbor	41.522	-72.079	59
13	Black Ledge	41.311	-72.056	106
14	Sara's Ledge	41.306	-72.096	400
15	Pine Island	41.314	-72.056	4
16	Bushy Point	41.317	-72.053	0
17	Bluff Point Sand Beach	41.320	-72.048	1
18	Newtown Beach	41.330	-72.034	0
19	Bluff Point Parking Lot	41.335	-72.034	0
20	South of Black Rock/LIS	41.300	-72.067	46
21	NL Dump Site/LIS	41.283	-72.067	57
22	CT River Mouth	41.250	-72.317	140
23	CT River, DEEP	41.313	-72.347	21
24	Sandy Point	41.330	-71.901	12
25	Faulkners Island	41.183	-72.667	1
26	Branford Buoy #35	41.233	-72.833	5
27	Milford Buoy #16	41.167	-73.033	2
28	Bridgeport Harbor	41.167	-73.183	1
29	Sheffield Island	41.017	-73.433	4
30	Piningo Bay	40.917	-73.683	3
31	Whitestone Bridge	40.800	-73.817	2
32	Matinecock Point	40.900	-73.633	1
33	Smithtown Bay	40.950	-73.300	1
34	Port Jefferson Harbor	40.950	-73.067	2
35	Roanok Shoals	41.000	-72.684	1
36	Hortons Point	41.084	-72.684	1
37	Plum Island	40.217	-71.183	1
38	Niantic Bay	41.306	-72.187	12
39	Wilderness Point	41.250	-71.983	21
40	Fishers Island Sound	41.289	-71.998	53
41	Seaflower Reef	41.296	-72.033	37
42	Selden Island	41.394	-72.419	11
43	Riverside Park	41.775	72.333	0
44	Pawtucket River, Buoy 26/27	41.749	-71.368	1
45	Mouth of Pawcatuck River	41.317	-71.871	3
46	Boston Harbor (Dorchester Bay)	42.325	-71.008	44
47	Clarks Point (New Bedford)	41.581	-70.899	6
48	Silver Eel Pond	41.259	-72.032	5
49	Eastern Fishers Island Sound	41.298	-71.933	2
50	Millstone Intake	41.308	-72.171	28
51	Millstone Discharge	41.305	-72.161	28

Table 1. A list of all stations sampled by Project Oceanology in Southeastern New England waters, including station latitude and longitude, the common name, and the number of trips conducted at each station. The station list does not follow any geographic pretext, as stations were added as they were discovered in the data.

minutes. With the help of onboard educators, students identified organisms to the lowest taxonomic level possible and for select species recorded lengths, counts, sex, as well as sex-specific sizes if applicable. Trawl data fell into two categories of effort determined by trip length and time availability—basic collection recorded the number of all species encountered, whereas the advanced collections also recorded length measurements of select species and sexes. Over the time series, basic collections were less frequent (nbasic = 82 vs. nadv = 579), but the primary focus of my analyses involved species frequency as the temporally most dense metric. Species identification was supervised by experienced PO staff using a local identification key (Weiss and Bennett, 1995). Data coverage, while widespread temporally and spatially, was concentrated at the mouth of the Thames River (Eastern LIS), as this location is closest to the PO facility and docks (~0.85nm). For my thesis, I focused on all data collected at or near the Thames River Mouth (TRM, 41°18'59"N 72°04'54"W), an area of approximately 10

square kilometers that included stations from the Coast Guard Academy just north of the I-95 bridge to just south of New London Ledge Light (Fig. 2, Table 1).

Database

PO's data were almost exclusively stored as the original paper data sheets students filled out during or after their excursions. The first step of my thesis work involved locating, collecting, and assessing the scope of these data stored in the Project Oceanology building (UConn Avery Point campus). Next, I helped design and build a web-based structured query language (SQL) database that is housed on the Long Island Sound Integrated Coastal Observing System (LISICOS) server (www.lisicos.uconn.edu). The SQL format was chosen for both its simplicity and ease of use, as well as the accessibility it provides for relational (connected) data. The web-based data entry form broadly follows the PO datasheets, allowing for all fields to be entered, but not requiring all to be filled. Valid entries required at minimum the date and location. If a trip included trawl data, trawl location was an additional required entry. Any datasheets missing these metadata (~15%) were not entered into the database. Some less routine data collections by Project Oceanology, for example lobster catches, shellfish surveys, or beach profiles were not entered into the database for reasons of sparse spatial and temporal coverage. Data were manually entered into the database by myself (80%) and two undergraduate students (20%), an estimated effort of approximately 850 hours. In total, 110,679 abiotic data points belonging to 3,096 boat trips were entered. All data were subsequently downloaded in Excel format from the database and split into biotic and abiotic data files. Temperature, DO, and pH profiles were vertically averaged for each station and event. Bottom temperature, DO (both percent saturation and concentration), and salinity values were calculated by selecting the last value in each

vertical profile. The earliest record was from April 1972, and January 1 2017 was the truncation of the time series.

Species	Scientific	Batch*	Habitat**	Mean Catch/Tow
American Lobster	<i>Homarus americanus</i>	N/A	Demersal	3.79
Black Seabass	<i>Centropristis striata</i>	WarmWater	N/A	2.69
Bluefish	<i>Pomatomus saltatrix</i>	N/A	Pelagic	N/A
Butterfish	<i>Peprilus triacanthus</i>	WarmWater	Pelagic	8.26
Cancer Crab	<i>Cancer spp.</i>	N/A	Demersal	3.19
Fourspot Flounder	<i>Paralichthyes oblongus</i>	ColdWater	Demersal	1.22
Hake Spp.	<i>Urophycis spp.</i>	ColdWater	Demersal	1.92
Herring Spp.	<i>Clupea spp.</i>	ColdWater	Pelagic	2.41
Horseshoe Crab	<i>Limulus polyphemus</i>	N/A	Demersal	1.41
Lady Crab	<i>Ovalipes ocellatus</i>	N/A	Demersal	18.39
Little Skate	<i>Raja erinacea</i>	ColdWater	Demersal	4.30
Longfin Squid	<i>Loligo paeleii</i>	N/A	Pelagic	6.73
Porgy	<i>Stenotomus chrysops</i>	WarmWater	Demersal	30.02
Sculpin Spp.	<i>Myoxocephalus spp.</i>	N/A	Demersal	1.39
Sea Robin Spp.	<i>Prionotus spp.</i>	WarmWater	Demersal	2.49
Silver Hake	<i>Merluccius bilinearis</i>	ColdWater	Demersal	3.67
Smooth Dogfish	<i>Mustelus canis</i>	WarmWater	N/A	1.50
Spider Crab	<i>Libinia emarginata</i>	N/A	Demersal	39.65
Striped Bass	<i>Morone saxatilis</i>	WarmWater	N/A	1.00
Summer Flounder	<i>Paralichthyes dentatus</i>	WarmWater	Demersal	2.83
Tautog	<i>Tautoga onitis</i>	WarmWater	Demersal	1.27
Weakfish	<i>Cynoscion regalis</i>	N/A	Pelagic	2.55
Windowpane Flounder	<i>Scopthalmus aquosus</i>	ColdWater	Demersal	3.88
Winter Flounder	<i>Pseudopleuronectes americanus</i>	ColdWater	Demersal	5.89

*Howell and Auster 2012; **Collie et al., 2008

Table 2. Species assemblages and groupings used for data analysis based on work by Howell and Auster (2012) and Collie et al. (2008). Mean catch/tow shows the average number of individuals caught per trawl, as a proxy for presence.

Trawl Data

Trawls were regularly conducted in two general locations at the mouth of the Thames River, one near Ocean Beach (station 14, 41°18'22.8" N, -72°5'45.8"W, Table 1) and the other near Black Ledge (station 13, 41°18'39"N, -72°3'20"W, Table 1). For the purposes of my thesis, those two stations were

combined given their proximity (~1nm). Trawl duration varied from 10 to 25 minutes, with the average being 19.6 minutes. 14% of trawls lacked duration information, and in those cases the calculated average of 19.6 minutes was assumed. Species abundance was expressed as catch per unit effort (CPUE), calculated as the number of each species caught per trawl minute. To assess long-term trends in species assemblages, species collected in trawls were grouped into warm-water, cold-water, demersal, benthic invertebrate, and pelagic assemblages following the definitions given in Collie et al. (2008) and Howell and Auster (2012) (Table 2). Species richness was calculated using the Margalef Diversity Index, d (Margalef, 1958),

$$d = \frac{S-1}{\ln N} \text{ (Eq. 1)}$$

where S is the number of species, and N is the total number of individuals. Discrete values were calculated for each individual trawl, and then yearly averaged monthly anomalies were used in the analysis.

Statistical Analysis

To remove intra-annual (i.e., seasonal) variability from the data for analysis, monthly anomalies were calculated by averaging the whole dataset by month ($n=12$) and then subtracting that grand mean value from each measurement. Those monthly anomalies were then averaged by month per year, and each year was averaged to arrive at a single yearly average anomaly ($n=42$)—this ensured that each month was weighted evenly in the final mean value used for statistical analysis. Given the variability in the original data-set, outliers, as defined by being greater than 2 standard deviations outside the monthly mean, were removed from both raw and calculated variables. Thus, ~50 discrete measurements were removed from each variable out of the ~1600 trips at the TRM. To ensure

appropriate error propagation from individual measured values to the final mean used for analysis, I used equation 2 to calculate the standard error (SE) of the mean, which includes the inherent measurement error. SE_{me} is the standard error that includes inherent measurement error, σ_s is the standard deviation of the sample, M^2 is the standard measurement error, and N is the total number of values.

$$SE_{me} = \frac{\sqrt{\sigma_s^2 + M^2}}{\sqrt{N}} \text{ (Eq. 2)}$$

I first used linear regression of the monthly-anomaly of each abiotic variable over time to test for general temporal trends. Wavelets analysis (Torrence and Compo, 1998) using the yearly averaged monthly anomalies was employed for analyzing decadal trends. Using wavelets analysis, yearly averages were tested for significant decadal oscillations in the data. The yearly-averaged anomalies were plotted against year, and a smoothed line was calculated using the original time series and subtracting the low-frequency variability to provide a smoothed line indicative of the longer term (greater than ten year) variability. Global and local power spectra were also calculated via wavelets analysis, and dominant trends were considered significant if they fell within the cone of influence (Torrence and Compo, 1998; Whitney, 2010). A linear regression analysis on the low-pass-filtered data for vertically averaged temperature, DO, and pH was conducted. An effective degrees of freedom analysis was run (Matlab 2017Ra) to identify the lag where the squared autocorrelation coefficient crosses a specified threshold (0.5) and divides the data length (n=42) by the lag number, to calculate the effective degrees of freedom (Table 4). This modifies both the P-value, the F-statistic, and the confidence intervals on the slope.

pH and temperature data were taken from the (2016) Millstone Annual Report and correlated to our data using linear regression to assess similarities and equivalence of long term trends. To synthesize abiotic and biotic variables principle components analysis (PCA) and Pearson correlation were used. A total of 63 variables were considered potentially important, and the PCA was condensed down to 33

variables and 176 cases. In lieu of using every single case (~1,600) and having fewer variables in the analysis given poor data overlap, the data were averaged monthly for each year, which condensed ~1600 cases down to 176, allowing for more variables to be included in the final analysis. To ensure orthogonality of the principal components, the principal components were rotated using the Varimax procedure (SPSS, IBM). PCA was followed by Pearson correlation to test for significant correlations between variables identified as related from the PCA. Given the nature of the Pearson Correlation and that it tests multiple hypotheses, a Bonferroni correction was made, and the updated alpha was 0.0026 instead of 0.05. Other studies (Collie et al., 2008; Nye et al., 2009) have shown the importance of climate oscillations such as the Atlantic Multidecadal Oscillation (AMO) when attempting to understand temperature changes and species shifts. The AMO, a basin-wide climate index based on the sea surface temperature of the North Atlantic, uses data from the NOAA Earth Systems Research Laboratory where monthly AMO time-series are calculated from regularly updated Kaplan SST data (Enfield et al., 2001). AMO was correlated to all major variables in both the PCA and Pearson correlation analyses. To examine the effects of temperature on DO concentrations I used a Loess smoothing method to show the overall trend between temperature and DO concentrations.

Results

Data Coverage

The database included 3,096 entries, with a total of 1,693 trips being conducted in the TRM. Abiotic data were collected from 1974 to 2016 at an average collection rate of 40 trips/year, with the most active year being 1998 (107 trips) and the least active being 1995 (0 trips, the only year from which no data was found). Biotic data were collected on 670 of those trips, with 99% of those trawls occurring after 1996. Therefore, my trawl analyses focused on data from 1997 to 2016. The entire PO dataset covered stations across the entire Long Island Sound (LIS), the Thames River up to Norwich Harbor, the

Connecticut River up to Hartford (Fig. 2), as well as trips to Boston Harbor. The by far densest collections occurred in the TRM, which was focus area of this study (Fig. 2).

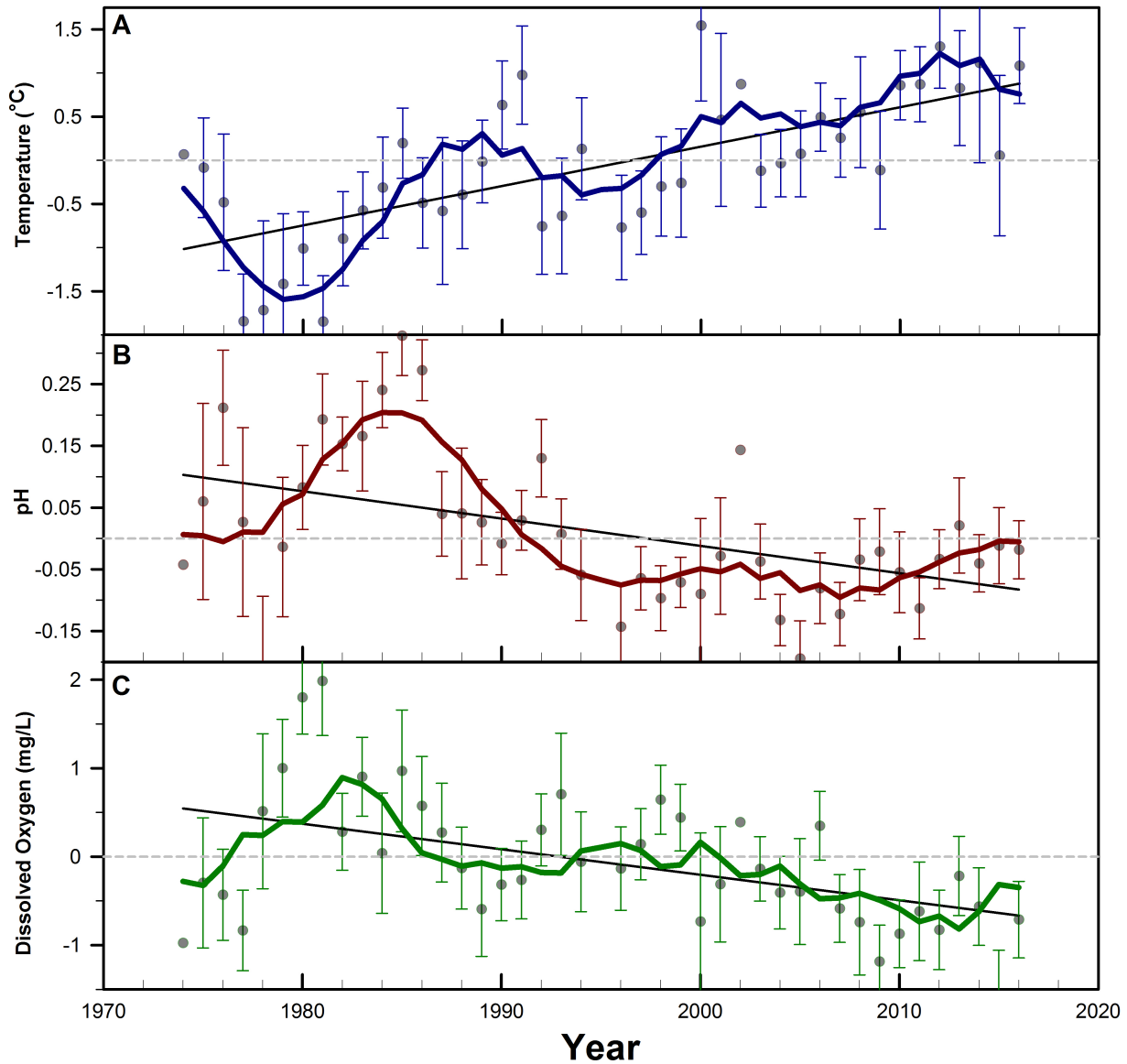


Figure 3. Time series of abiotic variables from the Mouth of the Thames River Estuary. Yearly-averaged monthly anomalies of vertically-averaged temperature (A), pH (B), and dissolved oxygen (C). Circles represent yearly anomalies, smoothed lines represent variability greater than ten years, and black lines are linear regression lines showing the overall trend in the time series. Error bars are the calculated standard measurement error (see Eq. 2).

Abiotic Data

Temperature increased significantly ($P = 0.0047$, $r^2 = 0.472$, Fig. 3) over the study period, with an overall warming trend of $0.45 \pm 0.281^\circ\text{C} \cdot \text{decade}^{-1}$. Inter-annual temperature variability was greater in the first compared to the second half of the time series. PH decreased significantly in the TRM ($P = 0.0338$, $r^2 = 0.206$) over the past 43 years at a rate of $-0.04 \pm 0.044 \text{ units} \cdot \text{decade}^{-1}$ (Fig. 3). However, pH did not decline monotonically; instead, pH first increased then sharply decreased during the 1980s and

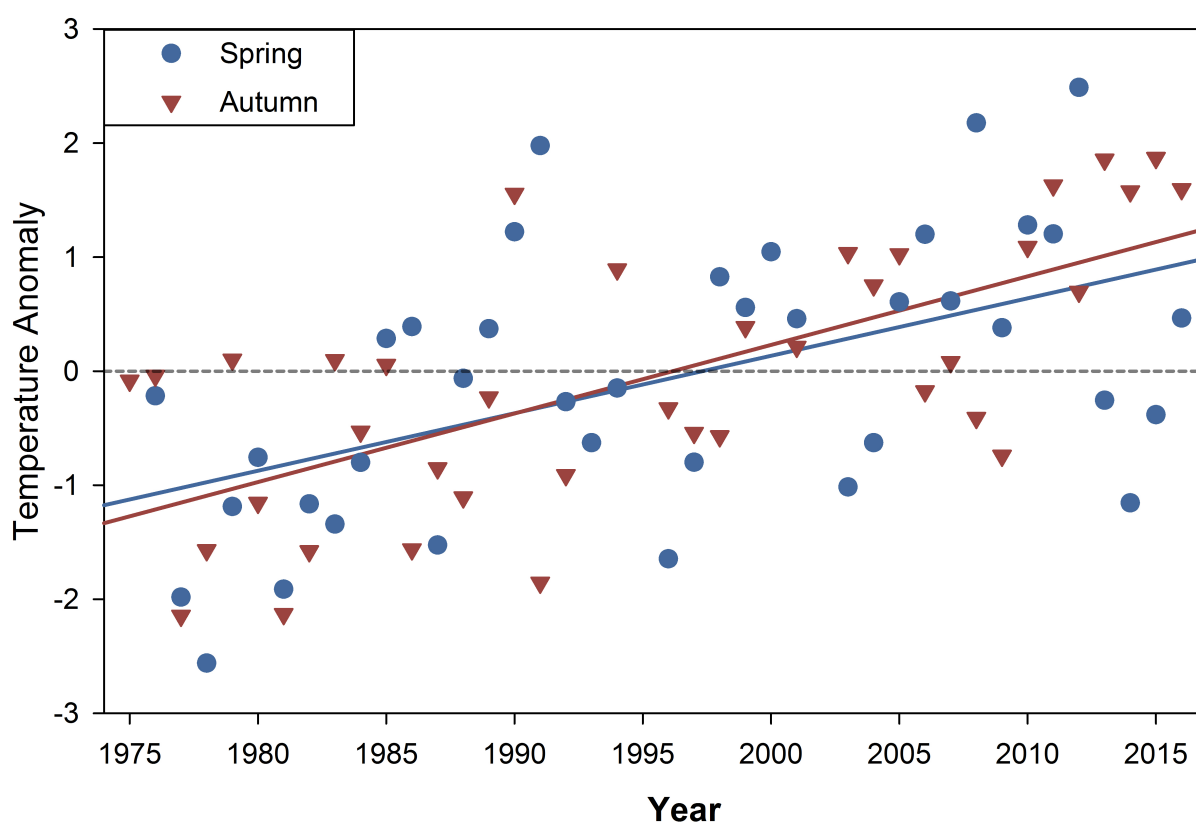


Figure 4. Spring (April, May, June) and Autumn (September & October) temperatures at the Mouth of the Thames River. Data presented are yearly averaged monthly anomalies, with both sets being linearly regressed.

the beginning of the 1990s. DO also decreased significantly at a rate of $-0.29 \pm 0.233 \text{ mg/L} \cdot \text{decade}^{-1}$ ($P = 0.0201$, $r^2 = 0.242$, Fig. 3). Patterns of variability were similar to temperature, i.e., larger variability in the first compared to the second half of the time series. All regression statistics can be found in table 4.

Nonsignificant seasonal trends were evident for temperature, with the fall warming at a slightly faster rate than the spring ($0.6^{\circ}\text{C} \cdot \text{decade}^{-1}$ and $0.5^{\circ}\text{C} \cdot \text{decade}^{-1}$, respectively; Fig. 4). PH, however, showed a seasonal trend with the pH starting higher in the late winter and early spring, decreasing during summer months, and then increasing again during late fall and into winter. No significant inter-annual or seasonal patterns were found for ammonium, nitrate, or phosphate across the time series, and there

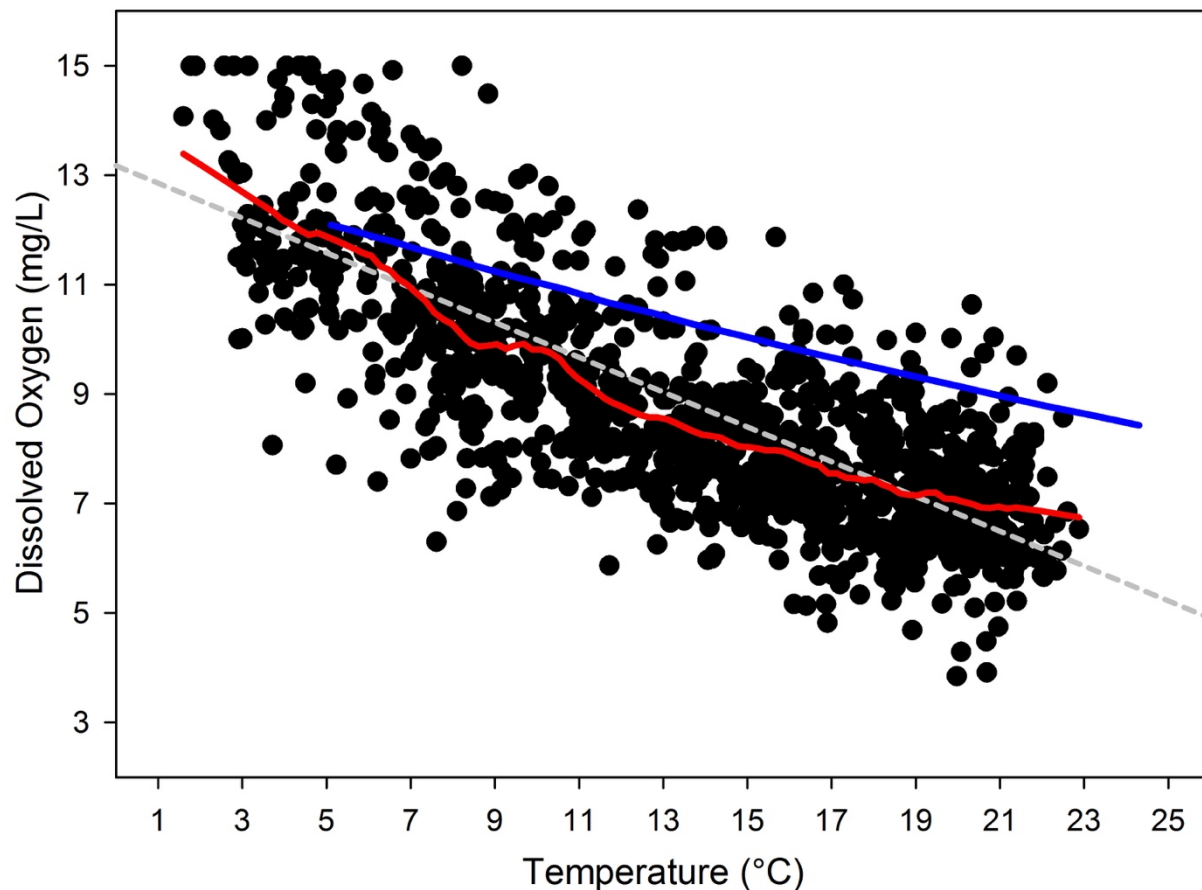


Figure 5. Temperature vs dissolved oxygen. Black dots represent a single trips' records, grey dashed line represents linear regression, and the red line represents a Loess smoothed line showing a slightly factorial trend rather than linear. The solid blue line indicates the sole effects of temperature on oxygen solubility in water, using data taken from (Walczyńska and Sobczyk, 2017).

Temperature and DO were significantly correlated (Pearson correlation, $P < 0.001$, $r^2 = 0.611$, Fig. 5), while pH was uncorrelated to temperature or DO. The decrease in DO was greater than the reduction in DO resulting from the temperature increase alone, indicating additional factors are driving

Common Name	Scientific	Presence(%)	Common Name	Scientific	Presence(%)
Spider Crab	<i>Libinia emarginata</i>	68.26	Whiting	<i>Merlangius merlangus</i>	0.89
Winter Flounder	<i>Pseudopleuronectes americanus</i>	58.87	Atlantic Silverside	<i>Menidia menidia</i>	0.75
Fluke	<i>Paralichthys dentatus</i>	43.82	Lady Crab	<i>Menidia menidia</i>	0.75
Porgy	<i>Stenotomus chrysops</i>	40.24	Jonah Crab	<i>Cancer borealis</i>	0.60
Hermit Crab	<i>Pagurus pollicaris</i>	39.64	Mud Crab		0.60
Rock Crab	<i>Cancer irroratus</i>	35.77	Scallop	<i>Argopecten irradians</i>	0.60
Squid	<i>Doryteuthis pealeii</i>	35.47	Red Goatfish	<i>Mullus auratus</i>	0.45
Lobster	<i>Homarus americanus</i>	32.49	Snail	<i>Littorina littorea</i>	0.45
Little Skate	<i>Leucoraja erinacea</i>	28.61	Tomcod	<i>Microgadus tomcod</i>	0.45
Channeled Whelk	<i>Busycotypus canaliculatus</i>	27.27	Big Eye Tuna	<i>Thunnus obesus</i>	0.30
Seastar	<i>Asterias rubens</i>	23.70	Bloodstar	<i>Henricia sanguinolenta</i>	0.30
Blue Crab	<i>Callinectes sapidus</i>	23.55	Cod	<i>Gadus morhua</i>	0.30
Windowpane Flounder	<i>Scophthalmus aquosus</i>	22.65	Eel		0.30
Small Mouth Flounder	<i>Nematops microstoma</i>	19.67	Hardshell Clam	<i>Mercenaria mercenaria</i>	0.30
Skate spp.	<i>Family Rajidae</i>	15.20	Menhaden	<i>Brevoortia tyrannus</i>	0.30
Northern Sea Robin	<i>Prionotus carolinus</i>	8.94	Monkfish	<i>Lophius americanus</i>	0.30
Butterfish	<i>Peprilus triacanthus</i>	8.64	Sea Horse	<i>Hippocampus spp.</i>	0.30
Shrimp	<i>Crangon spp.</i>	8.49	Squirrel Hake	<i>Urophycis chuss</i>	0.30
Knobbed Whelk	<i>Busycon carica</i>	7.75	Striped Bass	<i>Morone saxatilis</i>	0.30
Striped Sea Robin	<i>Prionotus evolans</i>	6.86	Anchovy	<i>Engraulis mordax</i>	0.15
Spotted Hake	<i>Urophycis regia</i>	5.96	Anenome	<i>Urticina felina</i>	0.15
Clearnose Skate	<i>Raja eglanteria</i>	5.81	Arc Clam		0.15
Black Sea Bass	<i>Centropristis striata</i>	4.62	Asian Shore Crab	<i>Hemigrapsus sanguineus</i>	0.15
Moon Snail	<i>Euspira heros</i>	4.47	Atlantic Mackerel	<i>Scomber scombrus</i>	0.15
Four-Spot Flounder	<i>Hippoglossina oblonga</i>	4.32	Blue Mussel	<i>Mytilus edulis</i>	0.15
Sea Raven	<i>Hemitripterus americanus</i>	4.32	Blue Runner	<i>Caranx crysos</i>	0.15
Rock Gunnel	<i>Pholis gunnellus</i>	3.87	Bluefish	<i>Pomatomus saltatrix</i>	0.15
Sea Robin spp.	<i>Prionotus spp.</i>	3.87	Brittle Star	<i>Ophiura ophiura</i>	0.15
Green Crab	<i>Carcinus maenas</i>	3.73	Dog Whelk	<i>Nucella lapillus</i>	0.15
Tautog	<i>Tautoga onitis</i>	3.73	Flying Gurnard	<i>Dactylopterus volitans</i>	0.15
Green Sea Urchin	<i>Strongylocentrotus droebachiensis</i>	3.13	Green Sea Turtle	<i>Chelonia mydas</i>	0.15
Hake spp.		2.68	Grubby	<i>Myoxocephalus aeneus</i>	0.15
Horseshoe Crab	<i>Limulus polyphemus</i>	2.68	Hogchoker	<i>Trinectes maculatus</i>	0.15
Sculpin	<i>Myoxocephalus spp.</i>	2.68	Moon Jelly	<i>Aurelia aurita</i>	0.15
Sulphur Sponge	<i>Cliona celata</i>	1.94	Mud Snail		0.15
White Hake	<i>Urophycis tenuis</i>	1.94	Oyster Drill	<i>Urosalpinx cinerea</i>	0.15
Cunner	<i>Tautoglabrus adspersus</i>	1.64	Perch	<i>Perca spp.</i>	0.15
Moonfish	<i>Selene setapinnis</i>	1.64	Pipefish	<i>Syngnathus fuscus</i>	0.15
Weakfish	<i>Cynoscion regalis</i>	1.64	Sandlance	<i>Ammodytes spp.</i>	0.15
Kingfish	<i>Scomberomorus cavalla</i>	1.49	Silver Perch	<i>Bairdiella chrysoura</i>	0.15
Mantis Shrimp	<i>Squilla empusa</i>	1.49	Slipper Snail	<i>Crepidula fornicata</i>	0.15
Herring	<i>Clupea harengus</i>	1.34	Spotfish	<i>Leiostomus xanthurus</i>	0.15
Mackerel	<i>Scomber scombrus</i>	1.19	Toadfish	<i>Opsanus tau</i>	0.15
File Fish	<i>Stephanolepis hispidus</i>	1.04	Transverse Ark	<i>Anadara transversa</i>	0.15
Lizard Fish	<i>Synodus saurus</i>	0.89	Triggerfish	<i>Family Balistidae</i>	0.15
Northern Puffer	<i>Sphoeroides maculatus</i>	0.89			

Table 3. Full list of species caught in benthic otter trawls, as well as presence, shown as a percent presence of total trawls. Species with a presence % of 0.15 were caught only once.

the decrease in DO. The Atlantic Meridional Oscillation index was significantly positively correlated to yearly-averaged temperature anomalies (Pearson Correlation, $P = 0.005$). TRM temperature and pH data were significantly positively correlated to temperature and pH data from Niantic Bay ($P < 0.001$ & $P = 0.005$, respectively; Fig. 6).

Biotic Data

A list of all species caught and their relative presence in the trawls can be found in Table 3. Over the entire time series (1974 – 2016), a total of 91 species were caught in the otter trawl (table 3). Of those, 65 occurred more than once. Spider crabs (*Libinia emarginata*) were the most abundant species

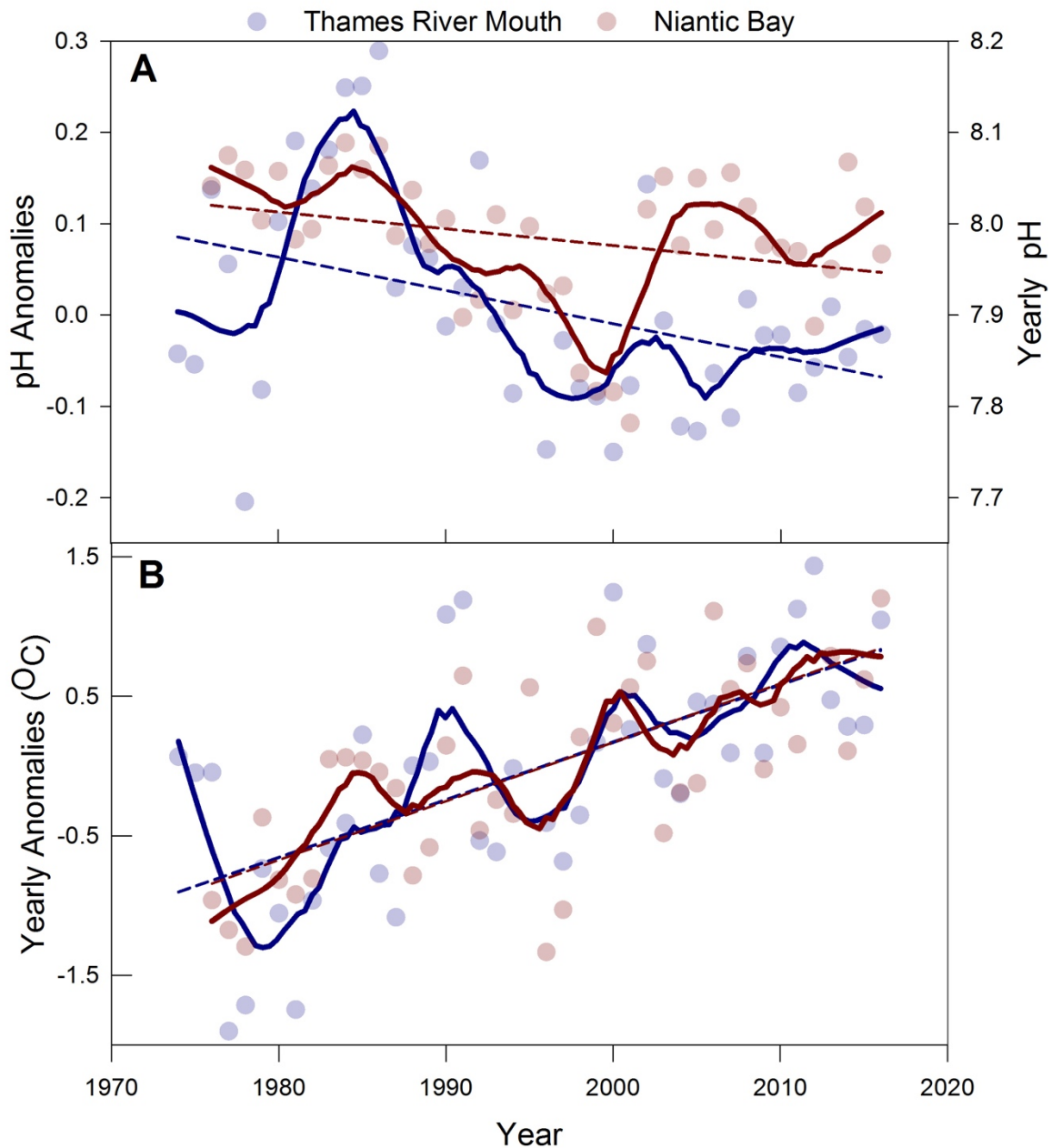


Figure 6. Data taken from the 2016 annual report by Millstone Power Station in Niantic Bay directly compared to this study's data. This study's data represented in yearly-averaged monthly anomalies (blue) and raw data from MPS in red. Scales are comparable allowing for direct comparison. Opaque circles represent raw data, thick lines represent a Loess smoothed line for the raw data, and dashed lines indicate linear regression trends.

on average, being present in 68% of the 670 trawls conducted. The 10 most present species were caught in 40% of the trawls. While lacking enough data to test for significance, I observed an overall shift in species composition through time, shown in Fig. 7. Between 1997 and 2016, the number of species caught per trawl over time did not change statistically, but species diversity declined from 1997 to 2016

Variable	N	DoF	Eff. DoF	p-value	r ²	RMSE	Rate	b ± 95% CI
pH	42	41	22	0.0338	0.206	0.0126	-0.04 • decade ⁻¹	± 0.044
Temperature	42	41	15	0.0047	0.472	0.3758	0.45°C • decade ⁻¹	± 0.281
Dissolved Oxygen	42	41	22	0.0201	0.242	0.431	-0.29 mg/L • decade ⁻¹	± 0.233
Temp*DO	1185	1184	N/A	< 0.001	0.611	N/A	-0.33 mg/L • °C ⁻¹	± 0.007
Species Richness	20	19	N/A	0.018	0.273	N/A	-0.021 • year ⁻¹	± 0.018

Table 4. Regression statistics including the number of samples (N), the degrees of freedom (DoF), the calculated effective degrees of freedom (Eff. DoF), the p-value and r² from the regression analysis, the root mean square error (RMSE) taken from the eff. DoF analysis, as well as the rate of change (slope, b) and ± 95% confidence intervals.

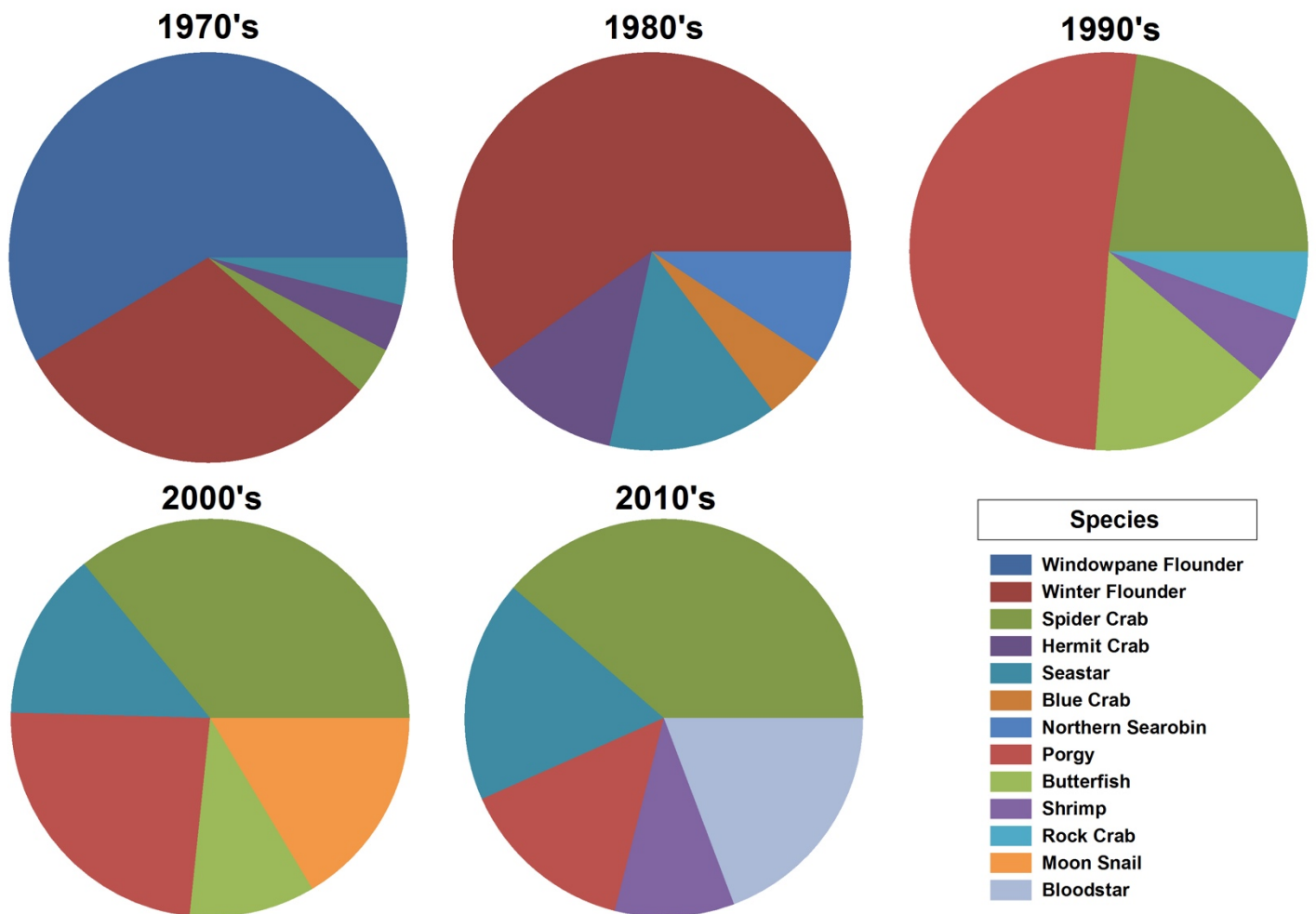


Figure 7. General species presence and abundance as shown by mean catch • trawl⁻¹, per decade. These data include data not in many analyses (10 trawls from the seventies and eighties).

(Margalef diversity index, $P = 0.018$, Fig. 8). While some species showed significant changes in abundance, trends in species assemblages were not significant. The CPUE of warm-water species remained almost constant, while the CPUE of cold-water species showed a non-significant decline (linear regression, $P = 0.218$ & $P = 0.130$, respectively). Benthic invertebrate CPUE showed a non-significant decline (1997 = 0.9064, 2016 = 0.6252), while the CPUE of pelagic species showed almost no change (1997 = 0.1812, 2016 = 0.1717). Interestingly, the demersal species assemblage CPUE showed a strong and statistically significant ($p = 0.049$) increase (1997 = 1.806, 2016 = 3.28), likely driven by a strong increase in Spider crab abundance.

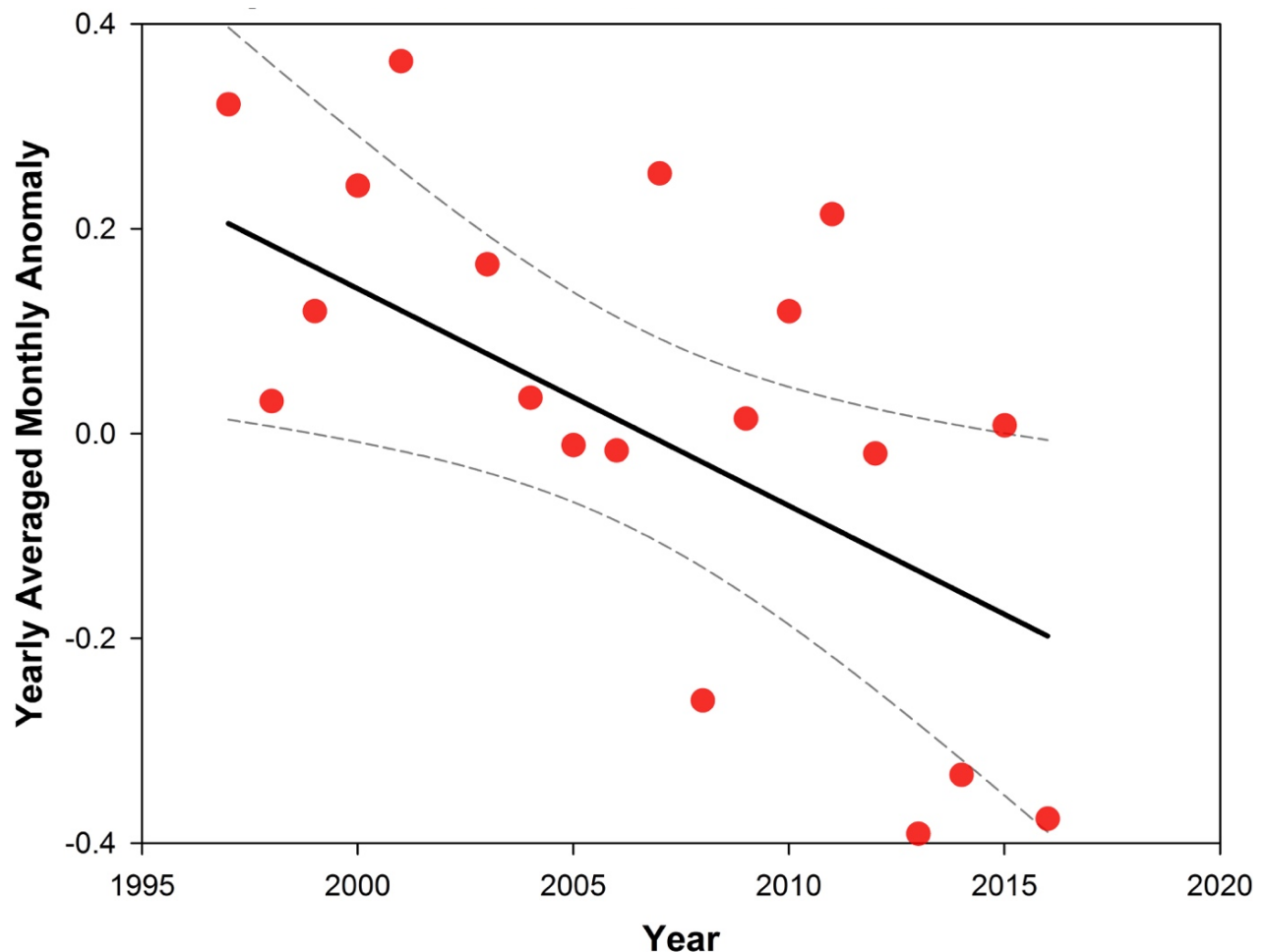


Figure 8. Yearly-averaged monthly anomalies of species richness calculated using the Margalef diversity index. Linear regression ($p=0.018$) trend shown by the line, and yearly averaged values shown by the points, and grey dashed lines indicate 95% confidence intervals.

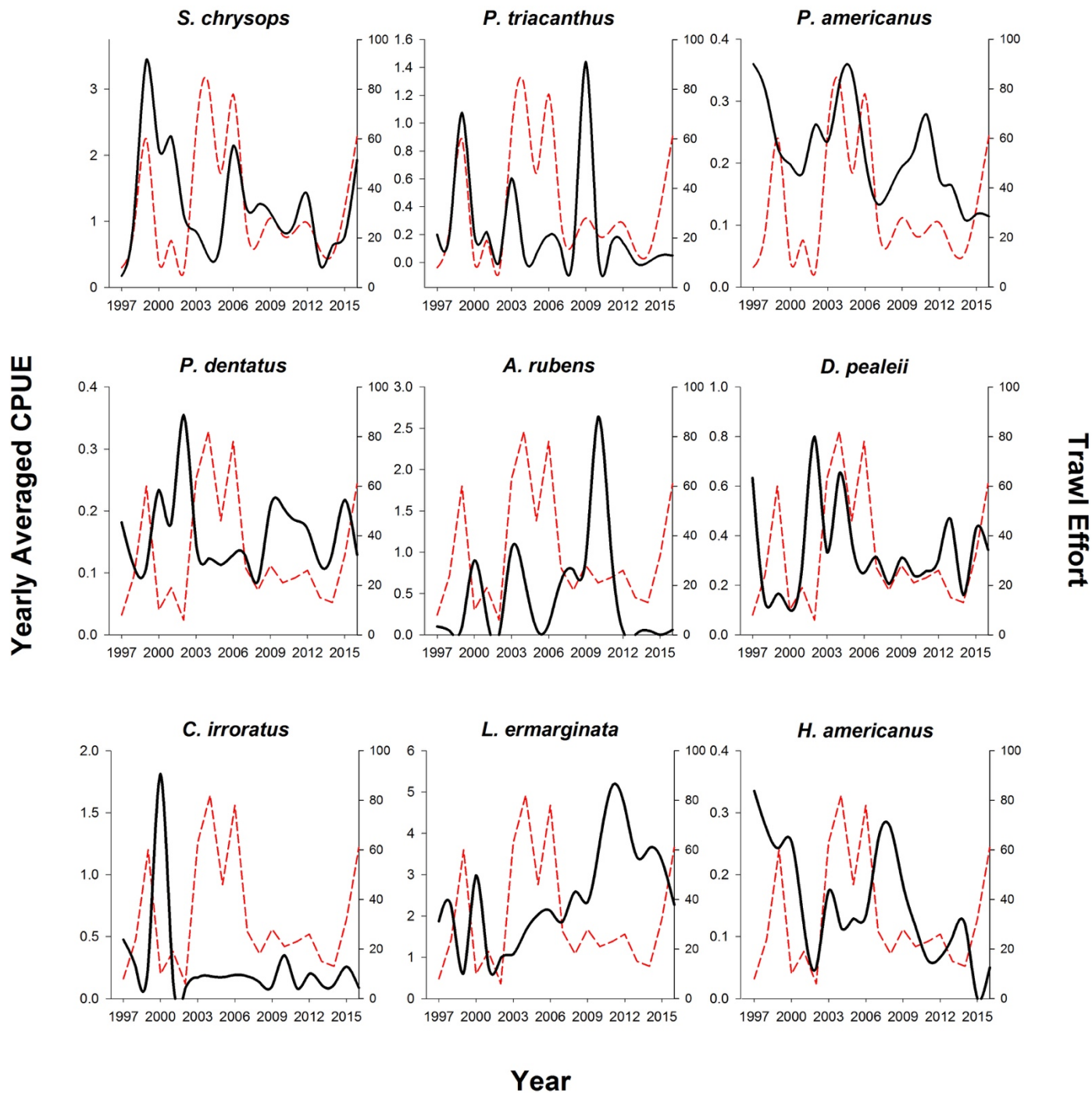


Figure 9. Yearly averaged catch-per unit effort (CPUE, #/minute caught) of nine species identified as important from the principal components analysis (i.e. *S. chrysops* & *P. triacanthus*) or of commercial and recreational importance (i.e. *H. americanus* & *D. paeleii*). Black solid lines represent yearly averaged CPUE and red lines represent mean effort (i.e. trawls/year). Dashed red lines indicate trawl effort, a metric for number of trawls per year.

time, while Spider crabs significantly increased in abundance ($P < 0.001$; Fig. 9). *H. americanus* average abundance in the late nineties was 5.12 per trawl, which decreased in the 2010s to 1.75 per trawl.

Winter flounder (*Pseudopleuronectes americanus*) abundance decreased significantly ($P = 0.001$) over

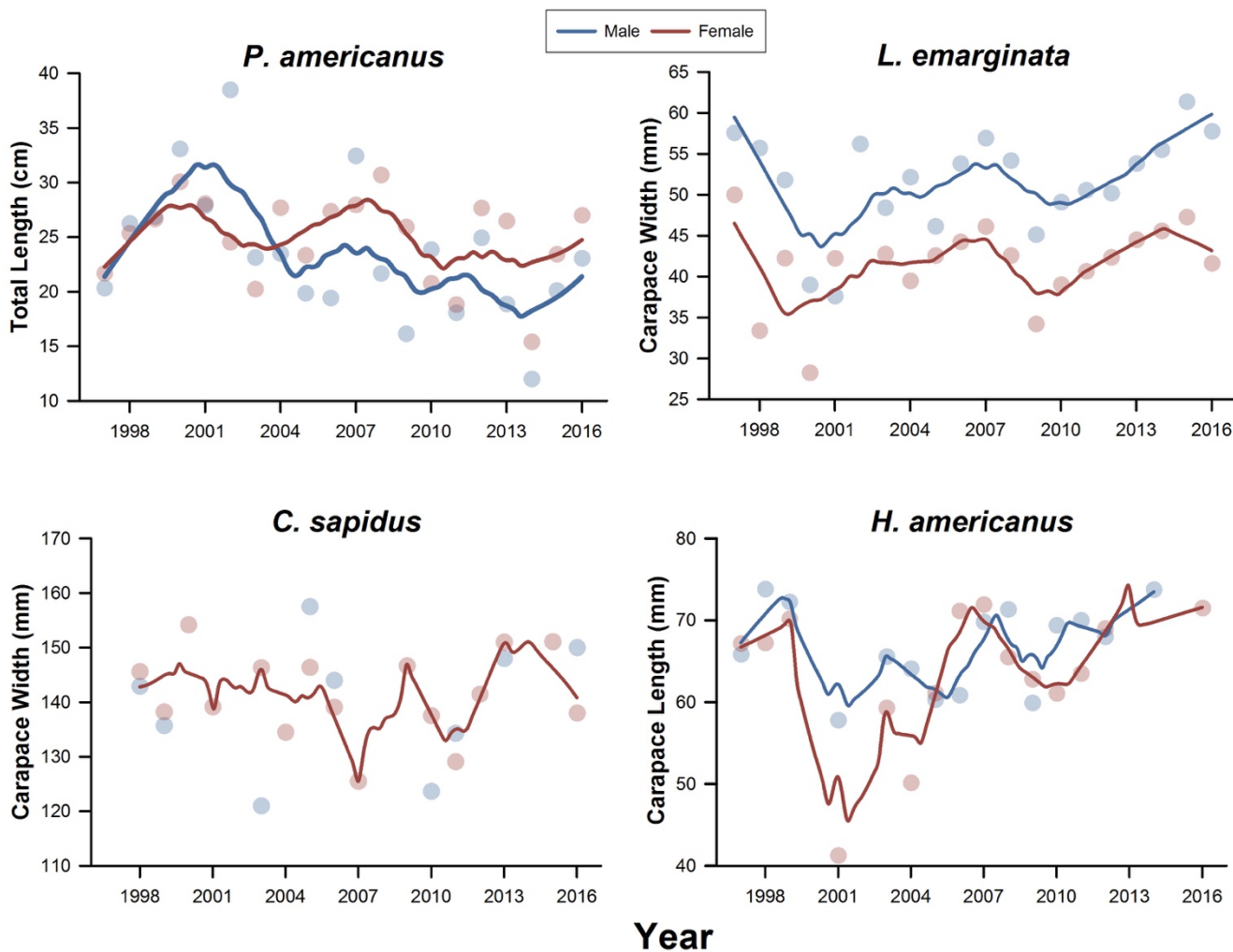


Figure 10. Male and female mean sizes (averaged yearly) for four benthic species collected, either chosen for commercial (*H. americanus* & *C. sapidus*) and recreational (*P. americanus*) significance or high data density (*L. emarginata*). Yearly averages are shaded circles, and Loess smoothed lines were processed for all except male *C. sapidus* (given their low data density). Blue colors indicate male and red colors indicate female. Size unit and portion measured are shown on each respective y-axis.

time. While not included in the analysis, two trawls in the early seventies recorded *P. americanus* catches of 49 and 145 individuals per trawl, whereas the largest catch between 1997-2016 was 26 individuals. Scup (*Stenotomus chrysops*), butterfish (*Peprilus triacanthus*), and seastar (*Asterias rubens*) abundance was highly heterogeneous and did not change significantly over time (Fig. 9).

Temporal patterns of sex-specific size differed between species (Fig. 10). *L. emarginata* was the only species with a pronounced sex dimorphism, with males being consistently larger than females throughout the time series. Blue crabs (*Callinectes sapidus*) lacked sufficient data for males, while females showed no change in size over time. *H. americanus* male and female sizes did not change over time. There were no evident trends in sex ratio (not shown).

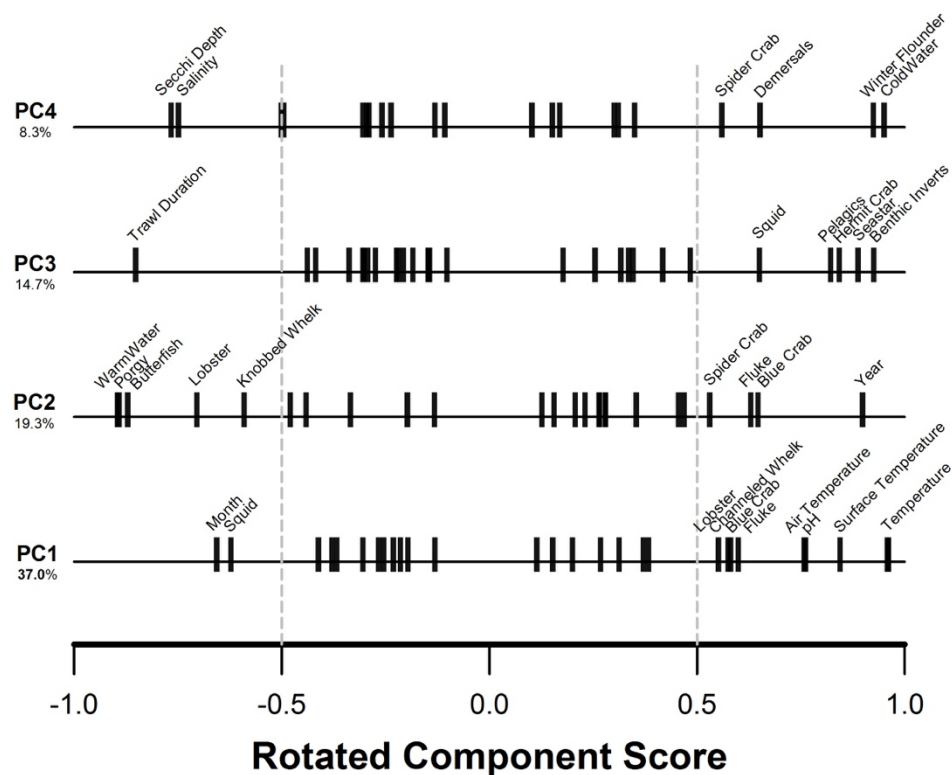


Figure 11. Principal components analysis of 33 variables and 176 cases identified 8 principal components, with the first four explaining 79.3% of the variance. Rotated (Varimax procedure, SPSS) component scores are presented here for the first four principal components, and variables with scores less than -0.5 and greater than 0.5 are considered of interest, and those closely associated are presumed correlated.

Principal Components Analysis (PCA) identified seven principal components with eigenvalues greater than 1, with the first four explaining ~79.3% of the variance in the dataset (Fig. 11). The first four principal components (PCs) were used to identify correlations between abiotic and biotic factors, which included month and squid (PC1), warm- water species and *S. chrysops* and *P. triacanthus* (PC2), benthic invertebrates and long-wristed hermit crabs (*Pagurus longicarpus*) and *A. rubens* (PC3), as well as cold-water species and *P. americanus* (PC4, Fig. 11). Significant correlations were also found between the AMO and *H. americanus* (Pearson correlation, $P = 0.001$, $r^2 = 0.117$), suggesting that some of the local trends were driven by large scale basin-wide climate indices.

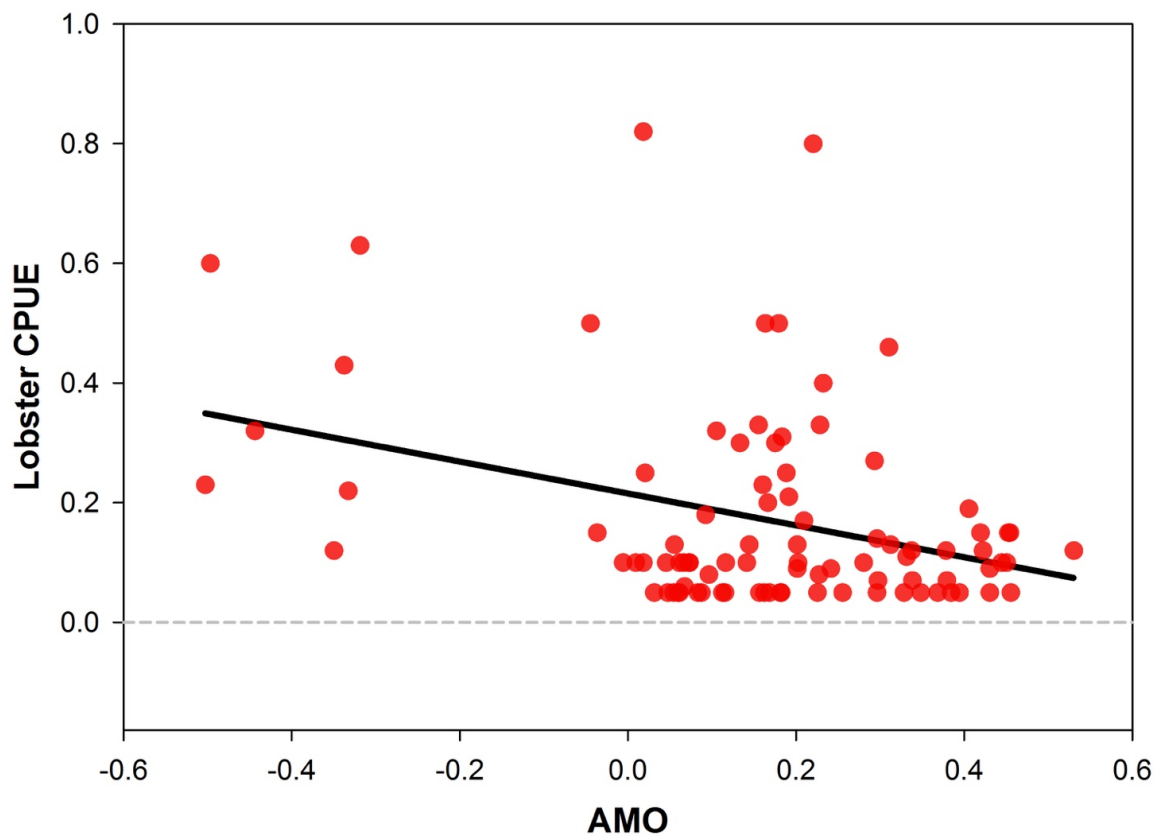


Figure 12. The Atlantic Multidecadal Oscillation (AMO) regressed against Lobster CPUE, identified as a significant correlation from a Pearson Correlation analysis ($P=0.001$).

Discussion

My thesis research analyzed decadal environmental data collected by Project Oceanology in the Thames River Estuary to test the hypotheses that nearshore waters in eastern LIS have been warming, acidifying, deoxygenating, and undergoing shifts in species abundance and diversity. The data clearly show that Eastern LIS has been experiencing rapid rates of warming, acidification, and decreasing DO concentrations. Concomitantly, warm-water species have increased in abundance and occurrence, and declines in *P. americanus*, *H. americanus*, and other commercially important species have been observed.

Marine Climate Change

Rapid yet variable declines in ocean SST and vertically-averaged temperature have been shown for the global ocean as well as coastal environments (Belkin, 2009; Nye et al., 2009; Pershing et al., 2015), but long-term data covering nearshore coastal environments are rare and therefore highly valuable. LIS is a unique estuary—it is moderately shallow, has limited freshwater input in the head and significant freshwater input near the mouth, and much of LIS experiences strong seasonal stratification (Parker and O'Reilly, 1991; Peterson and Bellantoni, 1987). Estuarine and coastal regions are subject to direct effects of currents, upwelling intensity, winds, cloudiness, and changing thermocline depths (Gómez-Gesteira et al., 2008). Projected decreases in freshwater runoff and increased residence times for global coastal regions (Howarth et al., 2000) could exacerbate seasonal stratification as warming continues. The observed TRM warming rates of $0.45^{\circ}\text{C} \bullet \text{decade}^{-1}$ are considerably faster than the global ocean rate ($0.1^{\circ}\text{C} \bullet \text{decade}^{-1}$, (Pershing et al., 2015)), but were consistent with recent work showing SST in latitudes around 42° in the North Atlantic to be warming at rates close to $\sim 0.3^{\circ}\text{C} \bullet \text{decade}^{-1}$ (Baumann and Doherty, 2013). In addition, Rice et al. (2014) have shown comparable warming

rates in LIS of approximately $0.3^{\circ}\text{C} \bullet \text{decade}^{-1}$, consistent with Baumann & Doherty (2013). While slower than average warming of the global, the TRM warming is highly consistent with the warming rates found in the Gulf of Maine (Pershing et al., 2015), one of the nearest coastal zones for which there is long term data. Other nearshore time series in LIS have shown similar warming trends: Millstone Power Station has been collecting environmental data on surface and bottom temperature, species abundances, and overall organismal health in Niantic Bay since 1976 (Landers et al., 2016). Niantic Bay is located approximately 9 km to the west of the TRM and given similar characteristics should exhibit comparable trends. Indeed, data taken from the 2016 annual report show similar warming rates of $0.51^{\circ}\text{C} \bullet \text{decade}^{-1}$, with near-identical and highly correlated short-term trends and inter-annual variability (Fig. 6).

The observed average acidification rate of the global surface ocean is $-0.018 \bullet \text{decade}^{-1}$ (Lauvset et al., 2015), whereas pH at TRM declined more than twice as fast ($-0.04 \bullet \text{decade}^{-1}$). Estuaries and coastal zones have higher rates of primary production and respiration than the average open ocean and act as CO_2 sources to the atmosphere (Baumann and Smith, 2017; Cai, 2011). While currently sinks of atmospheric CO_2 , coastal habitats are expected to increase CO_2 drawdown (Mote and Mantua, 2002), which may shift the balance and make estuaries zones of carbon sequestration. Increased CO_2 uptake may make coastal zones highly susceptible to increased atmospheric concentrations of CO_2 and resultant acidification. Niantic Bay saw acidification rates of $-0.018 \bullet \text{decade}^{-1}$, again significantly correlated with TRM data but showing a slower rate that matches global ocean change more closely. However, Niantic Bay experiences a much smaller freshwater input from the Niantic River and has reduced discharge rates when compared to the Thames River, and is therefore less likely to have high freshwater influence (and allochthonous carbon input) as the TRM.

While there are numerous factors that make estuaries susceptible, another noteworthy factor is alkalinity. Recent studies (Salisbury et al., 2009) are expanding our knowledge and resolution of data on estuarine surface alkalinity, but salinity and total alkalinity (TA) have already been shown to be positively

related (Wang et al., 2013; Wong, 1979). Estuaries and coastal zones regularly experience wide ranging pH (Baumann and Smith, 2017; Baumann et al., 2015) and alkalinities dependent upon salinity and relative freshwater input (Millero et al., 1998; Wong, 1979). Estuarine locations with high levels of freshwater input and lower salinity have lower TA and therefore have a reduced ability to buffer against CO₂ uptake and experience resultant pH declines (Salisbury et al., 2009). Additionally, biological processes can affect the alkalinity levels of surface waters— the uptake of nitrate [NO₃⁻] by phytoplankton can increase alkalinity, whereas the uptake of ammonium [NH₄⁺] can decrease alkalinity (Brewer and Goldman, 1976; Millero et al., 1998). Photosynthesis rates and resultant primary production are greater in estuarine and inter-coastal systems when compared to the open ocean, which highlights the importance of understanding community metabolism (Baumann and Smith, 2017) when considering the susceptibility of an environment to OA. However, this study detected no significant trends in NO₃⁻ or NH₄⁺ in the TRM.

While warming and acidification studies are becoming more numerous, seasonal and persistent hypoxia predates climate change research by decades. LIS is a complex estuary with unique geography and freshwater input—the head sees low levels of freshwater input and limited mixing, while the mouth sees the opposite (Parker and O'Reilly, 1991; Peterson and Bellantoni, 1987; Rolfhus and Fitzgerald, 2001). Given this unique hydrogeography, the western sound regularly experiences strong seasonal hypoxia (Anderson and Taylor, 2001; Parker and O'Reilly, 1991). Our data showed significant decreases in DO concentrations at the TRM as temperatures rose (also shown by many others, including (Dam et al., 2010), see Fig. 23). While hypoxic levels (defined as less than 2.0 mg • L⁻¹) (Diaz and Rosenberg, 1995) were observed at the TRM on short time-scales, if mean DO levels continually decrease the rate and regularity with which those daily or seasonal hypoxic levels appear is likely to increase. Another factor is freshwater input, which provides mixing by way of flushing—nearly 70% of the freshwater input into LIS comes solely from the Connecticut River (Rolfhus and Fitzgerald, 2001), which regularly mixes the sound

in conjunction with tides and wind. Potential reductions in global precipitation rates (Adams et al., 1990) and freshwater input into LIS, as well as increased seasonal stratification may further exacerbate the seasonal duration and extent of hypoxia in LIS.

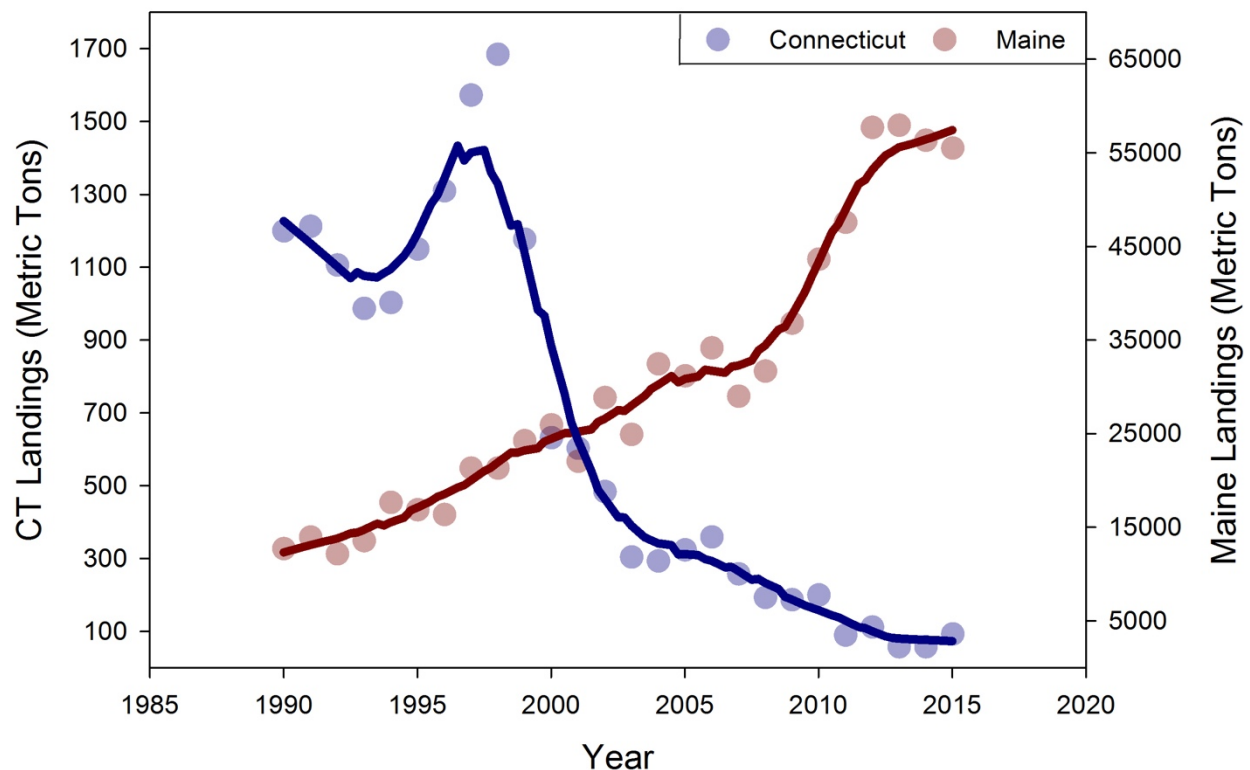


Figure 13. Lobster landings from the National Marine Fisheries Survey (NMFS) for Connecticut and Maine landings of Lobsters *H. americanus* from 1990-2015. Both scales are in metric tons, and the left scale relates to the CT landings and the right scale relates to the ME landings. **note scale differences

Shifting Species Abundances

Decreases in American lobster (*H. americanus*) abundance have been observed across southern New England since the late nineties (Collie et al., 2008; Pearce and Balcom, 2005), while increases in the Gulf of Maine started in the early 2000s (Fig. 13). Decreases in LIS lobster abundance has been attributed to high rates of shell disease (Castro and Angell, 2000), over-fishing (Landers Jr et al., 2001), and increased temperatures (Pearce and Balcom, 2005). My data showed significant declines in *H.*

americanus CPUE between 1997 and 2000, and an overall decline from 1997-2016 (Fig. 9), consistent with other studies both in LIS and in Southern New England (Collie et al., 2008; Oviatt, 2004; Pearce and Balcom, 2005). Average ocean temperature at the TRM between 1995 and 2000 was increasing rapidly after a five-year period of temperature decrease (Fig. 3). Shortly after the populations in LIS, the populations in the Gulf of Maine greatly increased (Fig. 13).

Lobsters were not the only species affected by increased temperatures in LIS and intense fishing pressure during the late nineties— Winter flounder (*P. americanus*) also showed significant declines during that same period (Fig. 9). However, the true decline of *P. americanus* in eastern LIS waters likely began decades earlier during the mid-seventies (L. Rader, personal observation). The National Marine Fisheries Service survey (Pers. Comm., National Marine Fisheries Service, Fisheries Statistics Division. [Oct. 2017]) shows strong and considerable declines from the fifties, with record lows occurring after the beginning of the 21st century. Trawls during the early seventies conducted by Project Oceanology caught over 100 *P. americanus* per trawl; this is consistent with data collected by the Coast Guard Academy via otter-trawl just north of the TRM, which showed significant declines in *P. americanus* abundance from 1974-2015 (Pers. Comm., K. Mrakovcich). Interestingly, these data also show significant declines in juvenile *P. americanus* in seine surveys conducted from 1974-2015. Niantic bay has also experienced significant declines in *P. americanus* abundance since the early seventies, with the number of trawls containing no individuals greatly increasing between 1991 and 2006 (Landers et al., 2016).

My data showed significant increases in *L. emarginata* abundance between 1997 and 2016 (Fig. 9), while other data sources show similar trends on varying time scales. Collie et al. (2008) saw increases in abundance at two stations in Narragansett Bay between 1959 and 2005. Strong increases in *L. emarginata* abundance in southern New England may have resulted from their resilience to

intermittent hypoxia (Burnett, 1979), effective use of decorative cover as a method of predator evasion (Wicksten, 1993), and their relative lack of utility as a commercial or recreational fishery.

In addition to shifts in single species abundances, other studies have noted significant regime shifts from fish species to invertebrate species in Narragansett Bay RI (Collie et al., 2008), while others have seen shifts from cold-adapted species to warm-adapted species in LIS (Howell and Auster, 2012). Our data, however, shows a moderation of both; the regime shift observed by Collie et al. (2008) was clear, but observed over a much longer period than our trawl data covered (1959 – 2005 vs. 1997-2016, respectively), and as such our time-series coverage was simply too short and too ‘late’ to observe any significant regime shifts, as the regimes might have already shifted. The shift from cold-water to warm-water dominated groups in LIS observed by Howell & Auster (2012) included more regular trawls and greater species and spatial coverage in LIS than my data. However, my data showed non-significant increases in warm-water species assemblages, and a strong correlation between vertically averaged temperature and warm-water species abundances. An increase in warm-water species abundance was driven primarily by *P. triacanthus* and *S. chrysops*, two schooling species that seasonally reside in LIS during the summer and fall months. Trawls including these two seasonal species have greatly increased in the last 20 years, and their relative abundance made them a significant contributor to the warm-water species assemblage both in our study and in others (Collie et al., 2008; Howell and Auster, 2012). Overall diversity decreased during the entirety of this time series (Fig. 8), due in part to reduced species abundances but also may be correlated to the trawling methodology of PO. Trawls regularly occur in the same location, and it is possible that species richness/diversity declined in part due to their regular trawling of the same benthic habitat.

Synthesis

Two dominant forces that drive regional and basin decadal changes in sea-surface temperature are the Atlantic Meridional Oscillation (AMO) and the North Atlantic Oscillation (NAO). These climate indices have been shown to correlate with regional changes in SST (Collie et al., 2008; Nye et al., 2009) and shifts in species assemblages and growth (Attrill and Power, 2002), and a variety of other climate-driven processes (Ottersen et al., 2001). Our yearly averaged SST anomalies showed weak but significant correlations to the AMO, indicating that local processes are, in part, influenced by large scale climatological forcing.

A more localized and dominant driver of estuarine processes (like hypoxia) is eutrophication, nutrient-rich runoff from rivers drain into an estuary, thereby greatly increasing the estuaries nutrient levels, which often results in phytoplankton blooms (Cloern, 2001; Nixon, 1995). Eutrophication as a concept is well understood, but its effects vary from estuary to estuary, given the level of urbanization (Parker and O'Reilly, 1991), the relative input of nutrient-rich waters derived from sewage treatment plants (Mallin et al., 2005) and groundwater (Makings et al., 2014), and turnover and flushing rate of those nutrients out of the estuary (Parker and O'Reilly, 1991; Rolfhus and Fitzgerald, 2001). LIS is a unique example given high levels of urbanization and nutrient input near the head from New York City and southwestern CT (Anderson and Taylor, 2001; Parker and O'Reilly, 1991) and the comparatively low rate of eutrophication in the near the mouth. This time series shows no significant increases or decreases in the nutrient input from the Thames River over time, but is limited by a lack of chlorophyll *a* analysis to corroborate nutrient data.

While I have no data showing eutrophication, it can have large effects on estuarine pH levels—excessive nutrients lead to phytoplankton blooms, which increases primary production. This increase in primary production in estuarine surface waters has been shown to mitigate the effects of OA on

carbonate chemistry (Borges and Gypens, 2010). In LIS, these phytoplankton blooms as a result of eutrophication and increased surface water temperature are a regular occurrence, often happening more than once a year (Anderson and Taylor, 2001). The net effect of these algal blooms on estuarine systems is unclear; when the phytoplankton die and fall to the bottom, their bacterial decomposition results in hypoxia and the remineralization of their organic matter, which in turn can lower the pH of bottom waters (Feely et al., 2010). The resultant decrease in pH from decomposition is often considered to be less than the increase in pH from photosynthesis (Millero et al., 1998). The beginning of a phytoplankton bloom correlates with an increased uptake of CO₂ and a local lowering of acidity, and the end of a bloom correlates to an increase in acidity from increased microbial respiration.

Large-scale shifts in species abundances in response to a changing marine climate are becoming more regular (Nye et al., 2009; Pinsky et al., 2013); many species respond either by moving into deeper waters or poleward to cooler waters, or both. While many lobsters likely died during the late nineties, it is possible that some moved out of the sound to deeper and cooler waters, including the Gulf of Maine, particularly because LIS represents the southernmost extent for the Western Atlantic *H. americanus* population. This can be inferred from Fig. 13, which shows a strong decline in lobster landings in Connecticut but a strong increase in lobster landings in Maine shortly thereafter, although no direct link (i.e. population genetics) has been shown. Lobsters, particularly *H. americanus*, have been shown to make migrations greater than 200km in some instances (Pezzack and Duggan, 1986), making climate-velocity movement a possibility. Climate velocity can also be applied to *C. sapidus*, a species that was originally dominant in southern coastal waters like Chesapeake Bay (Lipcius and Stockhausen, 2002), and has recently colonized and increase in abundance in LIS shortly after the die-offs of *H. americanus*.

Future Directions

Citizen science is an effective tool for long term monitoring and data collection, but its utility in published literature and high profile scientific endeavors is controversial given accuracy and data quality. This thesis clearly shows not only its utility in a masters' thesis and potential publications, but also the utility that a time series of this length provides. Our data shows strong positive correlations with other local scientific institutions' meticulously collected data and indicates sufficient long term accuracy. While useful, data collected in this manner is not often kept in a strict format, and therefore many hours had to be spent on organizing, decoding, and clarifying stored data. This work proves not only as a digitization and analysis of the data, but also as a secure copy in a separate location, ensuring the data will never be lost or unintentionally destroyed. The final step will be to formulate the database into a user friendly, simple, and approachable resource, with the final website to be referred to as the Project Oceanology Data System (PODS). This new website will allow for data-entry, the ability for students to see how their data compares to the dataset as a whole and where their data fits in, to download data on certain variables, and to provide graphing capabilities of the data either directly entered or already in the database. This website will not only be a resource for entry, but a resource for learning, for teaching data-analysis tools and processes, and for general use by local teachers and scientists, as well as the general public. Educators are currently using the data for lessons on data entry and analysis. The ultimate goal is to have the new interface built and running, and then to hand off the data-entry and management tasks to PO moving forwards. The intent of the online database is three-fold—to provide an easily-accesses and secure source for all PO data, to provide a data-set to be used for the purpose of long-term time-series data analysis, and for use as a reference and teaching source for PO, local educators, and other scientists/research staff.

Conclusions

My study demonstrates the value of long-term data collected by citizen science organizations like Project Oceanology for broadening our empirical evidence for pervasive and unfolding climate change in coastal waters. I show clear and strong increases in estuarine temperature, decreases in pH and DO, as well as reductions in species-specific abundances. I also show evidence of correlations to larger climate indices (i.e. AMO), as well as compare our data to other nearby sources in LIS as well as along the New England coastline. While our data does not show significant shifts from cold-water to warm-water adapted species assemblages, we did observe significant reductions in *H. americanus* and *P. americanus* abundance, both commercially and recreationally important species. While citizen-science efforts like this may have small-scale data inaccuracies, this type of time-series analysis is still valid given the large set of data and length it was collected for.

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