National Science Foundation Graduate Research Internship Program
Project Summary
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Fellow Name:	Rebecca M. Dalton
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Project Title:	Climate-induced shifts in phenology of marine ecosystems: A case study on migration patterns in *Alosa psuedoherengus*
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Graduate Program:	University Program in Ecology Nicholas School of the Environment Duke University
Partner Agency:	Northeast Climate Adaption Science Center United States Geological Survey Department of the Interior
Host/Sponsoring Researcher:	Dr. Michelle Staudinger

Title: Climate-induced shifts in phenology of marine ecosystems: A case study on migration patterns in *Alosa psuedoherengus*

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Introduction:

Over the past few decades, warming and other climatic changes have led to shifts in phenology, or the timing, of an animal or plant's life cycle events (Parmesan and Yohe 2003, Visser and Both 2005, Poloczanska et al. 2013, Reed et al. 2013, Lynch et al. 2016). As plants and animals rely on environmental cues to time physiological processes or activities critical for growth, reproduction, and survival, changes in phenology may have ecological and evolutionary consequences (Miller-Rushing et al. 2010, Rasmussen and Rudolf 2015). Phenology impacts how strongly species interact with one another (Yang and Rudolf 2010). For example, when interacting species in a community experience unequal phenological shifts in response to the same environmental cues, mismatches between trophic levels may result in disruption of food resources and habitat availability, potentially affecting fitness and population dynamics (Cushing 1990, Johansson et al. 2015).

Both individual- and species-level responses to global change drivers via phenological responses have been well studied in a diverse range of ecosystems, particularly in temperate, terrestrial regions (Parmesan and Yohe 2003). However, far less is known about aquatic and marine systems compared to terrestrial systems (Lynch et al. 2016). A recent review of empirical evidence of marine systems suggests that phenological shifts are more common in lower trophic levels, although anecdotal evidence of phenological shifts in higher trophic levels exists (Poloczanska et al. 2013).

Objectives:

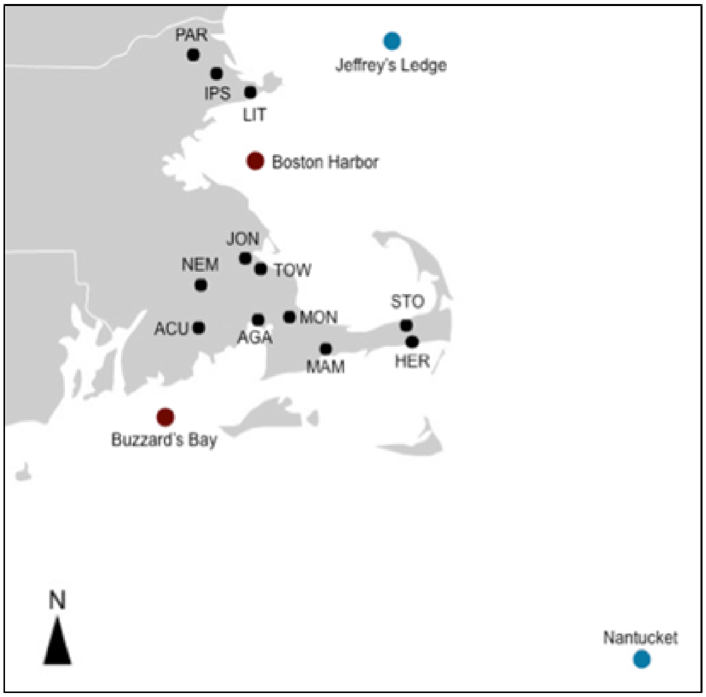
Diadromous fish are critical to ecosystems because they transport marine-derived nutrients between freshwater and ocean environments (Durbin et al. 1979). In addition, many diadromous fishes are important to coastal human communities as a source of commercially and recreational fisheries as well as culturally value to tribal nations (Mullen et al. 1986). Diadromous fishes are subject to strong seasonal cycles as they migrate between marine and freshwater habitats to spawn, potentially resulting in phenological mismatches. ***Therefore, we investigated the relationship between climate drivers and timing of migration of an anadromous fish species, Alosa psuedoherengus.*** *Alosa psuedoherengus* are well suited for this study because has been identified as highly vulnerable to climate change due to their sensitivity to predicted exposure to abiotic stressors, and complex life history (Hare et al. 2016). They are also a Regional Species of Greatest Conservation Need (RSGCN) for multiple Northeast states as well as well as of interest to federal agencies and tribal nations. In addition, long-term data on adult migrations are available since *A. psuedoherengus* are well monitored at passage points in coastal Massachusetts rivers.

We examined how climate affects timing of spawning migration in adult *A. psuedoherengus* in Massachusetts by asking the following questions: 1) has timing of spawning migration shifted as a result of warming spring temperatures, 2) is the direction and magnitude of shifts similar across spawning runs, and 3) what are the regional environmental factors which best predict movements across spawning rungs?

Methods:

Study system. *Alosa psuedoherengus* (Clupeidae) is an anadromous species of river herring found in Eastern North America, from Newfoundland, Canada to North Carolina, USA. They primarily consume zooplankton and are ecologically important, supporting higher level predators as forage fish, and are of importance historically to fisheries and native American cultures as food and bait (Mullen et al. 1986). *A. psuedoherengus* rely on a variety of habitat types for completion of their life cycle; completing their early life history in coastal freshwater ponds, spending the adult portion of their lives in marine waters of the continental shift, and stage in estuaries until they move upstream to the spawning ponds. Adults typically reach sexual maturity at four years old, and return to freshwater streams to spawn multiple times in their life. Given their complex life history cycle and sensitivity to environmental stressors, such as increased sea surface temperature, *A. psuedoherengus* are considered a highly climate vulnerable species (Hare et al. 2016). In addition, *A. psuedoherengus* has experienced significant declines in abundance in the northeastern United States as a result of habitat loss through damming of coastal rivers (Mattocks et al. 2017).

Fish counts and study location. We synthesized data from 12 coastal streams in the state of Massachusetts and organized them into a single consolidated database for this study (Fig. 1). The Massachusetts Division of Marine Fisheries (MA DMF) records the daily number of *A. pseudoharengus* passing at the 12 sampling sites using visual counts and electronic counters (Fig. 1). Daily fish counts across these sampling sites go as far back as 1990 along the coast of Massachusetts (range: 8-28 years, Fig. 1).



Stream Name	Count	Years
Parker (PAR)	C	1997 - 2017*
Ipswich (IPS)	V	1999 - 2017
Little River (LIT)	V	2000 - 2017*
Jones (JON)	V	2005 - 2017
Town Brook (TOW)	V	2010 - 2017
Nemasket (NEM)	V	1998 - 2017
Agawam (AGA)	C	2006 - 2017
Monument (MON)	C	1990 - 2017
Acushnet (ACU)	C	2005 - 2017
Stony Brook (STO)	V	2007 - 2017
Marston Mills (MAM)	V	2006 - 2017
Herring (HER)	V	2009 - 2017

Figure 1: *Locations of Alosa psuedoherengus sampling sites (black) and locations of buoys used for estuary temperatures (red) and ocean temperature (blue). Stream name and abbreviations of sampling locations, counter type (C: electronic counter, V: visual counts) and sampling years. Asterisks indicate non-continuous sampling periods.*

Phenology metrics. We calculated run initiation date, median run date, and end of run date using fish count data. We calculated run initiation date as the day of the year when 5% of the population has passed, median run date as the day of the year when 50% of the population passed our sampling site, and end of the run as the day of the year when 95% of the population passed. We used these more conservative estimates (rather than the absolute first observation) as *A. pseudoharengus* may begin to migrate upstream and return to the estuary if conditions are not adequate.

Environmental variables. *Stream temperature:* The MA DMF records daily temperature at each sampling site using HOBO® Data Loggers or a thermometer. We averaged hourly temperature records to achieve a daily temperature at each sampling site.

Estuary and Ocean Temperature: We downloaded daily estuary and ocean temperatures from the National Oceanic and Atmospheric Administration's National Data Buoy Center (http://www.ndbc.noaa.gov/). We selected two buoys, one close to the Northern sites (Boston Harbor) and one close to Southern sampling sites (Buzzard Bay) as an estimate of estuary temperature (Fig. 1). We also chose two buoys in the ocean, again in the Northern (Jeffery's Ledge) and Southern (Nantucket) portion of the region.

Spring transition date: We used spring transition date, the day of the year that ocean temperatures reach a threshold temperature, to assess how timing of spring warming in the ocean affects fish migration. We calculated spring transition date of the closest ecological regions to our sampling sites according to Friedland et al. (2015).

Stream flow: We estimated daily flow ($m^3/s/d$) using a Weather Research Forecast Hydro extension (WRF-hydro), which reproduces historical daily stream flow at *A. pseudoharengus* passage points (Salas et al. 2018).

Lunar illumination: We used daily proportion of the moon illuminated from the R Package 'lunar' (https://cran.r-project.org/web/packages/lunar/lunar.pdf).

North Atlantic Oscillation Index: We downloaded monthly North Atlantic Oscillation indices from The National Weather Service's Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml). We then averaged monthly means to achieve annual values.

Model selection. We assessed how environmental factors affect daily fish counts at all sampling sites. First, we assessed how spring transition date influences timing of *A. pseudoharengus* spawning migration. We ran a generalized linear mixed effects model (R package, 'lme4') with spring transition date as a fixed effect and location as a random effect. Secondly, we determined the direction and magnitude of phenological shifts for each stream system by running separate generalized linear models (glm) for each location. Finally, we assessed which environmental factors best predict daily fish counts using a generalized linear model (R package, 'glmmTMB') with all environmental variables as fixed effects and year and location as random effects.

We z-score standardized all environmental variables in our models. Due to over-dispersion and high number of zeroes in fish counts, we used a zero-inflated negative binomial model to assess which environmental variables best predict daily fish counts. To reduce collinearity, we removed correlated variables with variance inflation factors greater than or equal to about 2 (Table 1). We ran the models with an autoregressive structure to account for temporal autocorrelation between temperature variables (i.e. stream, ocean, estuary). We then selected the best model using a forward selection procedure. We conducted all analyses in R 3.3.3 (R Core Team, 2017).

Predictor	VIF
Julian date	1.26
Lunar illumination	1.00
Spring transition date	1.17
Yearly NAO index	1.19
Daily stream flow	1.09
Annual count	1.94

***Table 1**. Variance inflation factors (VIFs) for all predictors used in the final model.*

Preliminary Results:

Run initiation date occurs earlier when spring occurs earlier. Spring transition date (Day of year) has shifted significantly earlier over time (p_{year}<0.001), especially in recent years (≥ 2005) across our sampling sites; however, only run initiation dates showed a weakly significant relationship with earlier spring onset (R^2=21.7%, p_{std}=0.035, Fig. 2A). We did not see a significant relationship between spring transition date and median migration date or end of run date (Fig. 2B and 2C).

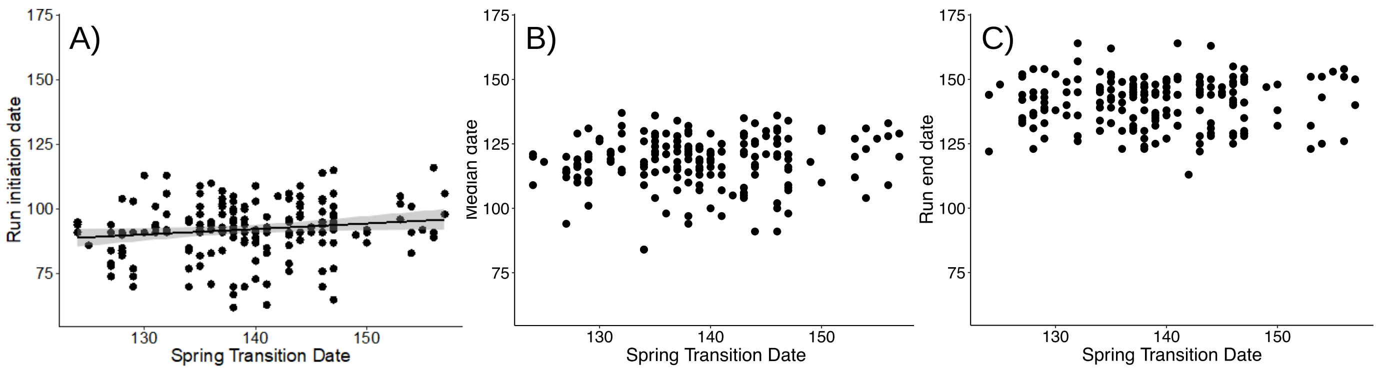


***Figure 2:** Relationship between spring transition date and A) run initiation date, B) median migration date, and C) end run date.*

The occurrence, magnitude, and the direction of phenological shifts across 12 study streams were highly variable. Some streams did not show a significant trend in run initiation, median run, or end of run dates, while others showed changes in one or more phenology metrics (Figure 3).

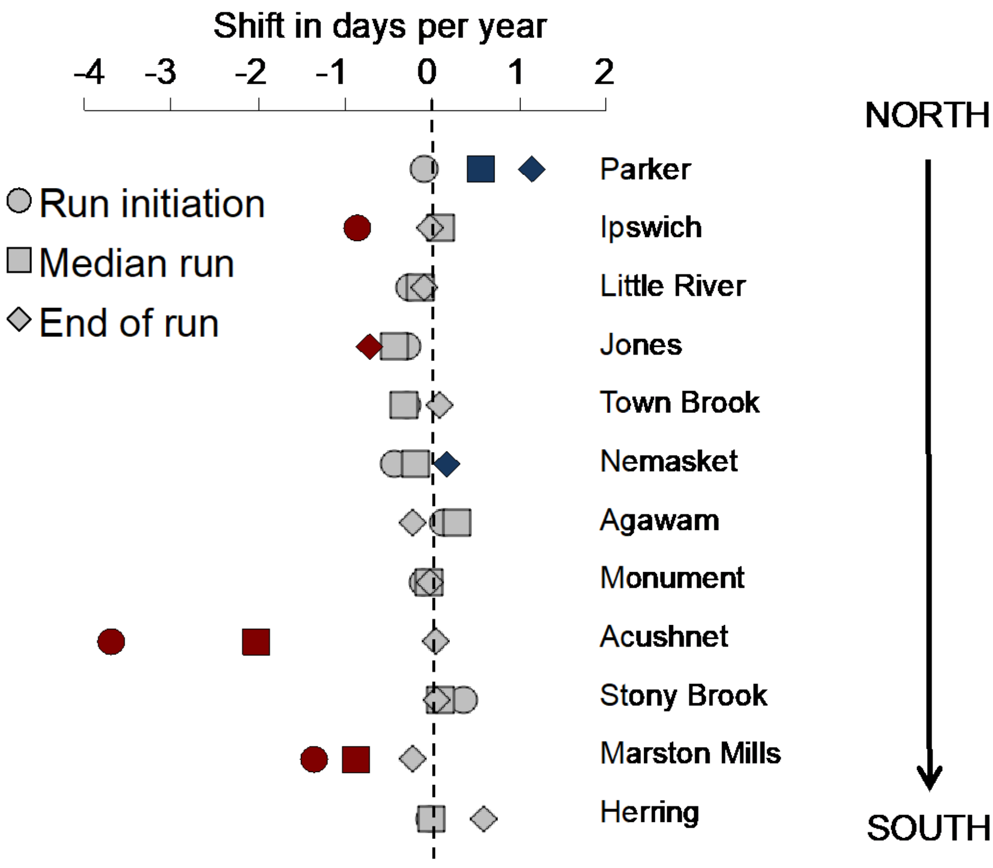


Figure 3. *Phenological shifts in Julian date of run initiation (circle), Julian date of median run date (square), and Julian date of end of run (diamond) date over time (years) in Massachusetts, USA. Streams are ordered from North to South. Red indicates a statistically significant advancement in phenology over time (days/year), blue symbols indicates a significant delay in phenology over time, and gray symbols indicate no significant shift in migration timing.*

Julian date, NAO index, stream flow, and annual count best predict daily counts. Of the seven variables included in the preliminary model, we determined six to be significant drivers of daily fish counts. We found Julian date and Julian date^2, annual NAO index, annual count, spring transition date, and daily flow to be the best regional predictors of daily fish counts (Table 2). These analyses are preliminary and analyses are still ongoing. Julian date is significantly correlated to temperature in the streams, and therefore a relationship between daily fish counts and the squared term indicates that there is a window of optimal temperatures (range of dates) when fish passage is greatest. The NAO index, which represents a regional, atmospheric process, is positively correlated to daily count. Positive values are associated with warmer temperatures and higher precipitation over New England. During warmer, wetter years, daily fish counts are often higher. Spring transition date, which is the date at which a temperature threshold is met in the ocean and spring begins, demonstrates a positive relationship with daily fish counts. Therefore, when spring occurs later in the year, fish are more likely to migrate at later dates. Finally, high daily stream flow is related with lower fish counts, suggesting that fish are less likely to migrate during high flow periods.

Factor	z	p
Lunar illumination	27.12	0.67
Spring transition date*	-2.37	0.02
Yearly NAO index*	4.69	<0.001
Daily stream flow*	-6.70	<0.001
Annual count*	7.87	<0.001
Julian date*	33.59	<0.001
Julian date^{2*}	-34.53	<0.001

Table 2. *ANOVA table for model predicting daily Alosa psuedoherengus counts across freshwater streams in Massachusetts, MA. Asterisks indicate significance predictors.*

Next Steps:

Migration is complex in *A. psuedoherengus* and our initial analyses found high variation among sites. Shifts in migration timing are inconsistent among spawning locations. For example, some stream-pond systems exhibit earlier migration, while in others, migration is occurring later or there is no detectable shift correlated with temperature. Although we did detect a relationship between regional drivers - yearly NAO index and spring transition date - these analyses are still preliminary. We are currently working on finishing the model and interpreting results. This project is ongoing. Currently, we are examining other temperature metrics, including temperature thresholds most suitable for migration based on published studies. We expect to publish this work in a scientific journal within the next year.

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PROFESSIONAL DEVELOPMENT:

The Northeast Climate Adaptation Science Center is a consortium of seven research institutions from across the Northeast and Midwest United States. These institutions include researchers with a diverse understanding of natural and human-influenced systems, and have strong relationships with natural resource managers, conservation organizations, and government agencies. The GRIP internship allowed me to: (1) learn about the difference between basic and applied research, (2) best practices for communicating with stakeholders and engaging with the public about scientific research, and (3) and build a diverse professional network of researchers and administrators at the NE CASC and UMass Amherst.

(1) I learned about the difference between basic and applied ecological research.
Although stakeholder-driven research and basic research use the same, rigorous, scientific method, the different approaches to forming questions are striking. Applied

research often involves collaborations between stakeholders, such as state agencies or land managers, and researchers at an academic or government institution. Conversely, basic research questions are often formed at the discretion and interests of researchers. My career until this point has strictly been on basic ecological research, and I was grateful for the chance to learn about and work on an applied research project. I hope to take all that I have learned about different types of research and apply to my career path after graduation and beyond.

(2) I received training in practices for communicating with stakeholders and the public. I attended weekly Northeast Climate Adaptation Science Center's Fellows meeting, which brought together graduate students, postdoctoral researchers, faculty, and staff from the NE CASC. Each week, we learned about primary research by our colleagues or best practices for engaging with the public and communicating with stakeholders. During one of our meetings, we discussed how to form and maintain relationships with stakeholders by listening to their science needs, forming personal connections, and actively including them in development and continuation of research questions. Although I do not currently work with stakeholders for my PhD research, these discussions will enhance my ability to do so in the future. In addition to stakeholder engagement, we also learned techniques for clearly communicating our scientific research to broader audiences. I have already incorporated aspects from our weekly NE CASC Fellows meeting into public talks that I have since given about my own dissertation research.

(3) I diversified my professional network of government and academic researchers. During the GRIP, I presented my internship research at the NE CASC Weekly Fellows meeting and my dissertation work at a colleague's laboratory meeting in the Biology Department at University of Massachusetts Amherst (Dr. Adler). From the Fellows meeting, I connected with another researcher who studies phenological shifts in the Rocky Mountains. We have since been in communication about a collaborative research project incorporating both of our research interests. Additionally, after presenting for Dr. Lynn Adler's research group, I now have the opportunity to apply for postdoctoral work with her in the future. She studies pollination and bee disease, and my time at the NE CASC enabled me to connect with her and discuss future opportunities. These are just two examples of how my time at the NE CASC broadened my professional network and may lead to future research projects and career opportunities.

SCIENTIFIC SKILL DEVELOPMENT:

The GRIP internship provided me with access to resources and tools necessary to broaden my understanding of statistical analyses. Through diverse learning experiences, I now have a deeper understanding of analytical methods, which is already proving to be indispensable to the completion of my own dissertation work. During the GRIP internship, I completed coursework, met with experts, and attended weekly group meetings with peers and colleagues to cultivate skills that I could use in my own dissertation and research in the future.

(1) I learned statistical techniques and skills through coursework.
Since the Northeast Climate Adaptation Science Center is hosted by the University of Massachusetts, Amherst, I had the unique opportunity to take courses during my GRIP internship. I attended a statistics course during the semester, Analysis of Environmental Data, taught by Dr. Kevin McGarigal (UMass Amherst, Department of Environmental Conservation). I learned how to critically think about project design, how to use statistical programs to analyze data, and best practices for drawing conclusions based on statistical output. After taking this course, I feel comfortable using advanced statistical analyses in R (Studio 2012). Since the completion of the internship, I have referred to notes from this course multiple times when analyzing data for my dissertation and teaching undergraduate researchers at my home institution.

(2) I fine-tuned these skills through meeting with experts.
In addition to having access to coursework, I was able to attend Quantitative Sciences Group (QSG) consultations through the Department of Environmental Conservation at University of Massachusetts, Amherst. This group meets weekly with students and faculty to provide expert advice on study design and statistical methods. I met with QSG two months into my internship. The faculty provided guidance on data preparation, model selection, and how to interpret results. Furthermore, a faculty member from this group has since become a co-author on this project as they continue to contribute substantially knowledge and expertise to our project.

In addition to meeting with statistical experts, I had the opportunity to interact with experts in hydrology, fisheries scientists, and researchers from other disciplines. For example, I learned about how hydrological models are used to predict stream flow from Dr. Marcelo Somos-Valezuela (University of La Frontera, Chile), how local habitat heterogeneity may affect fish populations from John Sheppard (MA DMF), and what type of ongoing concerns stakeholders have about river herring from Drs. Allison Roy (USGS Coop Unit), Adrian Jordaan (UMass Amherst), and their lab groups.

(3) I applied these learned skills during weekly group meetings with colleagues.
Finally, I attended laboratory meetings of both Dr. Michelle Staudinger (GRIP host, NECASC, Environmental Conservation, UMass) and Dr. Lynn Adler (Biology Department, UMass), which allowed me to garner additional statistical knowledge and improve skills learned during my coursework. Each week, we would either read primary literature articles or discuss our colleagues' current research projects, often with a focus on methods and analyses. I also learned to think critically about different types of ecosystems during Dr. Michelle Staudinger's laboratory meetings. Many of her students and collaborators work on seabirds, marine mammals, and fishes. We spent time discussing how phenology affects both marine and terrestrial systems in similar and dissimilar ways. I believe these weekly lab meetings ultimately allowed me to apply techniques learned throughout the semester to different types of ecological research.

Furthermore, I was able to build this skillset through diversification of my research program. The GRIP internship enabled me to advance my ability to use statistics and apply these techniques in totally new ecological systems, which will ultimately help me in future research endeavors and my career.

MENTORSHIP:

Mentee: I received incredible mentorship through this GRIP internship. I worked closely with Dr. Michelle Staudinger and her research group on this project. At the beginning of the semester, she asked me what my goals were. I expressed interest in learning how government research differs from academic research, how relationships with stakeholders are formed and maintained, and to learn more about potential careers in government research. In addition to working closely with me on all aspects of the research project and meeting with me frequently, she involved me in meetings with stakeholders, invited me to attend conferences with other academic and government scientists and stakeholders, and connected me with other researchers to learn about their careers. Even after the end of the internship, Dr. Staudinger is still actively mentoring me scientifically and professionally, and I look forward to our future mentee/mentor relationship.

Mentor: During the GRIP internship, I mentored an undergraduate student, Quentin Nichols. We worked together on learning how to download and explore publically available environmental data, applying basic statistical and graphing techniques to these data in R, and reading primary literature articles.

CONFERENCES ATTENDED:

- Massachusetts River Herring Network Annual Meeting. Sandwich, Massachusetts. 2 November 2017.
- 4th Annual Society for Women in Marine Science Symposium. Woods Hole, Massachusetts. 3 November 2017.

PRESENTATIONS:

- "Climate-induced phenological shifts in early blooming flowering species and adult alewife migration" Northeast Climate Science Center Fellow's Meeting. 16 October 2017.
- "Phenological shifts in adult alewife migration in Massachusetts", Duke University Biology Department Population Biology Seminar. 7 March 2018.

PUBLIC ENGAGEMENT:

- "What do fish and flowers have in common?" Early Career Climate Forum Guest Blog Post. 18 December 2017. https://eccforum.org/what-do-fish-and-flowers-have-common