NYSG Completion Report R/CE-33-NYCT

Report Written By: Nickitas Georgas, Co-PIs and students **Date: 05/27/2016**

A. Project Number and Title:

New York Sea Grant project number: R/CE-33-NYCT

Project Title: Analyzing history to project and manage the future: Simulating the effects of climate on Long Island Sound's physical environment and living marine resources.

B. Project Personnel:

Principal Investigators:

1. Nickitas Georgas. Principal Investigator. Stevens Institute of Technology. Davidson Laboratory.
2. Penelope Howell. Co-Principal Investigator. Connecticut Department of Energy and Environmental Protection. Marine Fisheries Division.
3. Vincent Saba. Co-Principal Investigator. National Oceanic and Atmospheric Administration. National Marine Fisheries Service.
4. Alan Blumberg. Co-Principal Investigator. Stevens Institute of Technology. Davidson Laboratory.
5. Philip Orton. Co-Principal Investigator. Stevens Institute of Technology. Davidson Laboratory.

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Part-Time Staff

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Part-Time Graduate Student Research Assistants

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11. Bin Wen. Stevens Institute of Technology. Ocean Engineering.

C. Project Results: Complete the following sub-sections to discuss your results as they relate to the project's objectives:

C1. Meeting the Objectives:

The project had the following objectives:

1) ***To address the paucity of physical environmental data*** during Long Island Sound's (LIS) observed warming trend and accompanying fisheries shift by running a hindcast of the LIS circulation using the New York Harbor Observing and Prediction

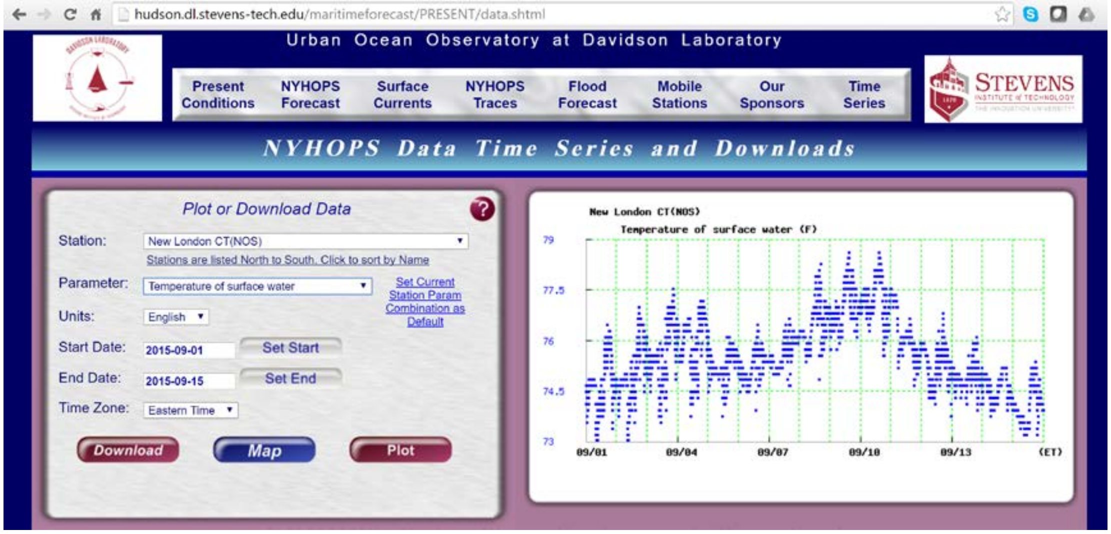
System (NYHOPS), an operational, comprehensive, high-resolution, three-dimensional, numerical model.

2) ***To explore and understand climate-forced links between the physical and ecological environment*** of the Sound by studying the statistical correlations of historic ecological data (mainly fish trawl survey data) to the physical environmental data from the NYHOPS model with a goal to explain the recent ecological regime changes and,

3) ***To project the impacts of climate change and variability*** on the Sound's ecosystem and its living marine resources, by forcing NYHOPS with Intergovernmental Panel for Climate Change (IPCC)-class global climate models.

Below, we provide a summary of how the project team addressed the objectives, with supplemental information provided in Appendices and later sections:

I. **Catalogued and made accessible supporting secondary physical data:** We worked on collecting and cataloguing the various sources of secondary data needed to accomplish the objectives. Stevens Institute of Technology's databases were expanded to accommodate the new secondary data, including real-time updates for real-time stations. A website was setup to make these time series of observations from in-situ station sources easily accessible and downloadable (http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml), including the ability to plot a time series based on a selected date range and to show station location on a map (Figure 1). Latest real-time observations can also be viewed on Google Earth (see section F).


hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml

Station: New London CT(NOS)

Parameter: Temperature of surface water

Units: English

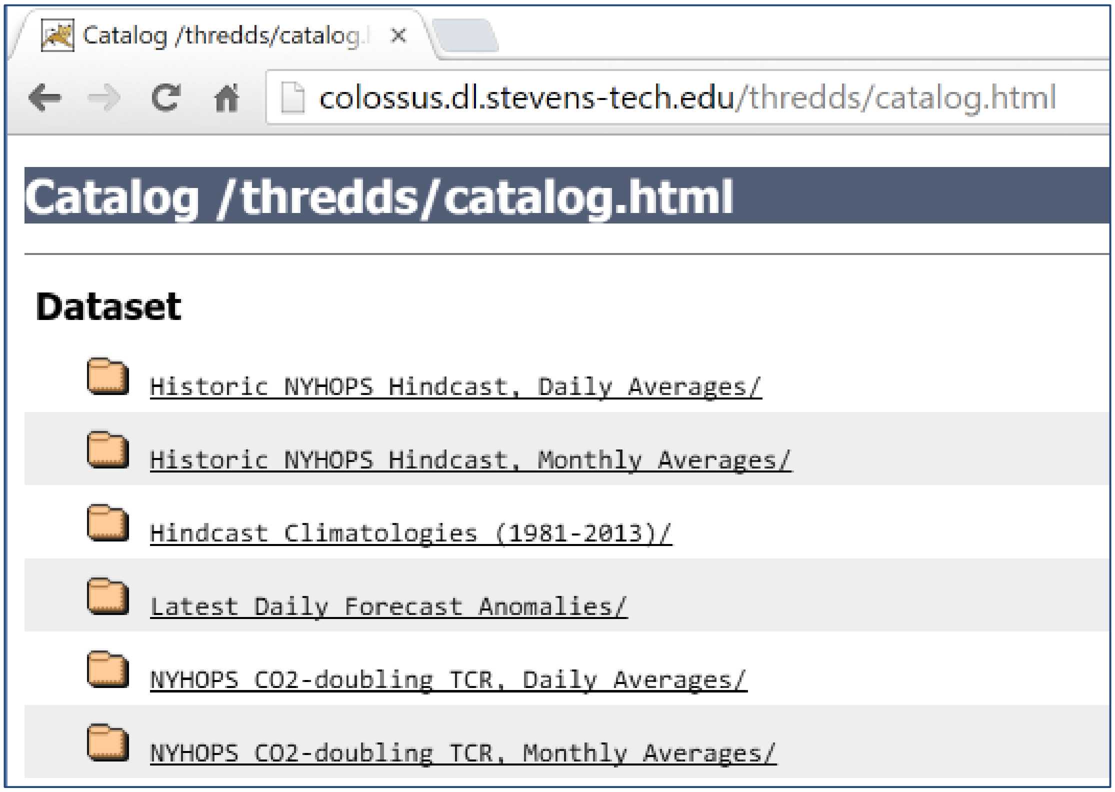
Start Date: 2015-09-01

End Date: 2015-09-15

Time Zone: Eastern Time

Figure 1. Extended Data Time Series and Download page.

II. **Constructed and validated a multi-decadal hindcast simulation of Long Island Sound's physical environment using the NYHOPS model):** We constructed and validated a multi-decadal hindcast numerical simulation performed using The New York Harbor Observing and Prediction System (NYHOPS) three-dimensional Operational Forecasting System (www.stevens.edu/NYHOPS). These model runs resulted in a contiguous three-dimensional hydrodynamic dataset for Long Island Sound's physical space, in terms of gridded time series for surface waves, total water levels, currents, water temperature, and salinity fields, as well as surface meteorological variables such as air temperature, relative humidity, cloud cover, barometric pressure, and wind velocities. After extensive model validation and debiasing (see Appendix A), a THREDDS Data Server (http://colossus.dl.stevens-tech.edu/thredds/catalog.html) was setup to serve the NYHOPS model's results in NetCDF format over the web using the OPENDAP protocol, enabling free access to daily averaged or monthly averaged time series for all the gridded hindcast physical variables in or over Long Island Sound (Figure 2). Simulated climatologies (mean simulated climate conditions averaged over the three decades of the NYHOPS hindcast period) for three-dimensional water temperatures and salinities, were also generated, and included in THREDDS. These open-access datasets are already in high demand by scientists, engineers, and managers doing work in Long Island Sound and beyond (see section D).



Catalog /thredds/catalog.html

Dataset

- Historic NYHOPS Hindcast, Daily Averages/
- Historic NYHOPS Hindcast, Monthly Averages/
- Hindcast Climatologies (1981-2013)/
- Latest Daily Forecast Anomalies/
- NYHOPS CO2-doubling TCR, Daily Averages/
- NYHOPS CO2-doubling TCR, Monthly Averages/

Figure 2. The open-access Colossus THREDDS Data Server and the Long Island Sound datasets.

Long Island Sound Forcing in the NYHOPS hindcast simulation: The completed multi-decadal high-resolution three-dimensional hindcast for Long Island Sound was based on the New York Harbor Observing and Prediction System (NYHOPS) model (www.stevens.edu/NYHOPS; Georgas et al. 2007; Blumberg and Georgas 2008; Georgas 2010; Georgas and Blumberg 2010; DiLiberto et al. 2011; Orton et al. 2012; Wilkin and Hunter 2013; Georgas et al. 2014). Meteorological forcing to Long Island Sound in NYHOPS was based on 3-hourly gridded data from the North American Regional Reanalysis (NARR, Messinger et al. 2006) of the US National Centers for Environmental Prediction (NCEP). NARR has been shown to have good skill for regional climate studies (Choi et al. 2012). Distributed hydrologic forcing to NYHOPS was based on daily United States Geologic Survey (USGS) records (Jiang et al. 2013) with comparable but expanded results to other regional published studies (Seekell and Pace 2011; Kaushal et al. 2010). With regard to offshore boundary conditions for NYHOPS at the Mid-Atlantic Bight shelf break, hourly subtidal water levels from a larger-scale model ran for the same period using NARR were added to tides, while temperature and salinity profiles were primarily based on the Simple Ocean Data Assimilation (SODA) datasets (Carton and Giese 2008).

In the construction of the three dimensional NYHOPS hindcast, great care was put into creating high-fidelity boundary conditions for hydrodynamic forces included in the NYHOPS model, to complement the surface meteorological forcing provided by NARR. For example, in order to get a representation of surface waves and subtidal forcing at NYHOPS' offshore boundary at the Mid-Atlantic continental shelf break, we constructed, run, and utilized a new, much larger scale, Western North Atlantic hydrodynamic model (SNAP: Stevens North Atlantic Predictions model; see section F and Georgas 2014) into which we nested the regional NYHOPS model. Thus, we also completed a 34 year hourly hindcast of offshore waves and tidal residuals for the SNAP domain, spanning from Cape Hatteras to Nova Scotia that includes Long Island Sound, albeit with a lower resolution (5km) that NYHOPS (~500m). The SNAP model results were used to provide offshore boundary conditions to the NYHOPS's hindcast at the shelf break for waves and storm surges. The SNAP dataset can be used for nesting other coastal models in the Mid-Atlantic and Northeast US Regions that require multi-decadal offshore boundary conditions. The skill of the SNAP model was assessed against observed records of water levels and waves at several stations (see previous report and Georgas 2014).

Also, as part of our work to create high-fidelity boundary forcing to the NYHOPS hindcast, we completed a fluvial temperature study for rivers with long temperature time series across the Mid-Atlantic that was required for the assignment of daily temperatures to our riverine discharges in the NYHOPS hindcast (NYHOPS includes an extensive hydrologic input network). We presented the earlier part of that work at the annual Mid-Atlantic Bight Oceanography and Meteorology Meeting (MABPOM 2013) and wrote a paper report for that part of the work. Our work indicates that river flows, river temperatures, and associated thermal inputs to Mid-Atlantic waters have increased similarly to the regional air temperature trends linked to global warming, with some changes in the positive rate values between different watersheds (Figures 3-4). We created complete time series of estimated river temperatures from 1979 to 2013 that were used in the high-resolution NYHOPS hindcast for Long Island Sound.

Further, to provide offshore temperature and salinity profiles at the continental shelf break to NYHOPS for the hindcast, monthly data from the Simple Ocean Data Assimilation (SODA) climatology for water temperature and salinity were acquired beginning in 1959 on a global 0.5 degree geographic resolution grid with 40 depth levels in the vertical (Carton and Giese 2008). Note that the SODA-based monthly time series also showed temperatures in Long Island Sound increasing, with differences between the Western and Eastern Sound. A weak but statistically significant one-month-lagged positive correlation of LIS water temperatures from SODA with the North Atlantic Oscillation (NAO) index was initially found (Georgas

2014). Yet the SODA resolution was poor, only 2-3 boxes for LIS, so the robustness of this correlation was questioned. The SODA datasets were only used to provide an offshore boundary condition in the NYHOPS hindcast at the continental shelf break. There were some issues we identified with the continuity and versioning of the provided SODA datasets that required significant effort in order to create a consistent monthly climatological dataset for the complete NYHOPS hindcast period of 1979-2013. A unified set of NYHOPS boundary conditions was created using SODA version 2.1.6 from 1979-1999, then SODA version 2.2.4 from 2000-2010, then results from a ROMS model run (Wilkin and Hunter 2013) generated at Rutgers University nested within a global HYCOM model for 2011-2012, and finally HYCOM global model results for 2013 (Chassignet et al. 2009). To decrease climatologically-relevant discrepancies between the last two datasets and SODA, bias correction for the last two datasets was performed both for the T/S means and their range. The native ROMS results for 2011-2012 were bias-corrected based on mean and range anomalies between the SODA version 2.2.4 datasets and the ROMS-with HYCOM datasets for the common years of 2005-2008. HYCOM for 2013 was similarly bias-corrected based on the same debiasing factors. The assumption is that if the ROMS and HYCOM models were biased compared to SODA years 2005-2008 (shifted and inflated/deflated), they would continue being biased in a similar fashion in subsequent years. This assumption was validated by comparing the debiased datasets against SODA 2.2.4 for the last two SODA years, 2009-2010. Both means and ranges were significantly closer to SODA after debiasing.

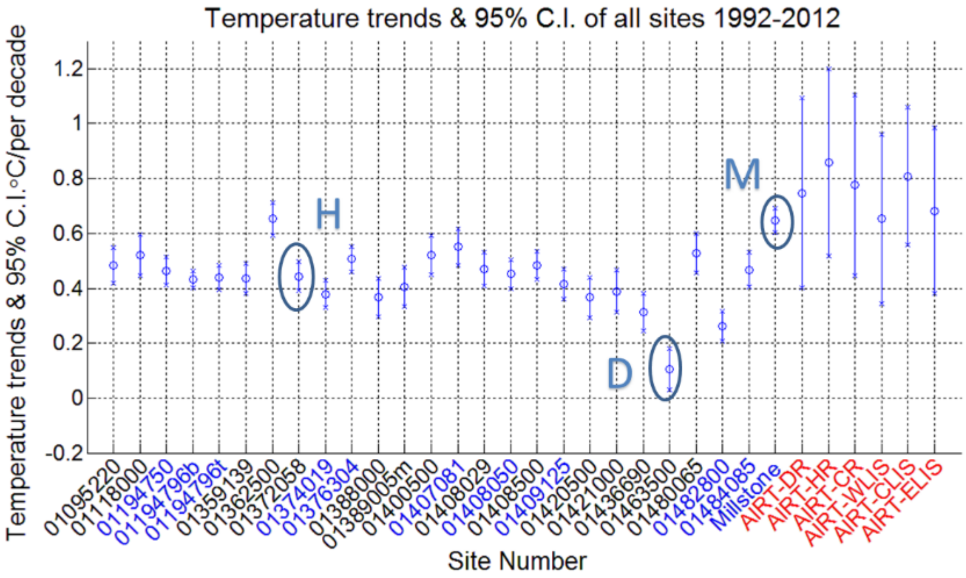


Figure 3. Temperature trends and 95% confidence intervals of different USGS HUC-08 stations from year 1992-2012. Labels H, D and M highlight Hudson River, Delaware River, and Millstone (DRS data). AIRT-DR, -HR, -CR stand for spatially averaged 2-meter-above-surface NARR air temperature for Delaware, Hudson, and Connecticut River watersheds, respectively. AIRT-WLIS, -CLIS, -ELIS stand for spatially averaged 2-meter-above-surface NARR air temperature for west, central, and east Long Island Sound regions, respectively.

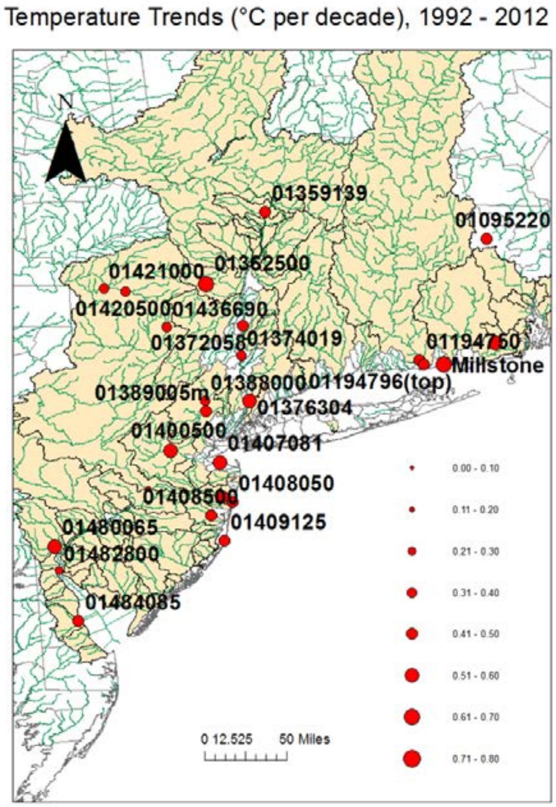


Figure 4. Linear temperature trends of different stations shown in the Mid-Atlantic Region map.

Hindcast validation against observations: The NYHOPS model's application to hindcast total water level, and 3D water temperature and salinity conditions in its region over three decades was validated extensively against observations from the National Ocean Service (NOS) and the United States Geological Survey (USGS), the New York City Department of Environmental Protection (NYC DEP), and the Connecticut Department of Energy and Environmental Protection (CT DEEP), as well as an observations-based monthly three dimensional temperature and salinity climatology dataset called MOCHA version2 created by Rutgers University (http://tds.marine.rutgers.edu/thredds/catalog/other/climatology/mocha/catalog.html; Fleming and Wilkin 2010). A comprehensive graphical validation is included in Appendix A, using methods from Georgas and Blumberg (2010).

The model's grand-mean temperature and salinity bias against CT DEEP observations in the Sound was found to be 0.18°C warmer for temperature, and 1.31psu saltier for salinity; these biases were assumed constant in time and space and were removed from the model's raw results. NYHOPS Hindcast results were overall excellent: the average Index of Agreement (Willmott skill) for storm surge (tidal departure) alone against NOS hourly observations was 0.93, (9cm Root-Mean-Square-Error, RMSE, 90% of errors less than 15cm), for water temperature it was 0.99 (1.1°C RMSE, 99% of errors less than 3°C), and for salinity it was 0.86 (1.8psu RMSE, 96% of all errors less than 3.5psu).

The model's dynamics were able to capture more variability than the observation-based MOCHA v2 climatology as evident in relative Brier Skill Scores (BSS) that were positive: 0.48 for temperature and 0.8 for salinity Sound-wide. The only exception was for salinity in the Sound's Eastern Basin, where the period-average relative BSS was -0.29, indicating that the MOCHA v2 climatology had higher skill than the NYHOPS model there. Even for that region's salinity however, the model's total RMSE was only 1psu, of which the remaining bias was 0.6psu, the average Index of agreement 0.77, and the model's results were less than 3.5psu away from observed more than 99% of the time. As a comparison, the proposed NOS standard for simulated salinity from numerical hydrodynamic models is 90% of the time errors should be within 3.5psu.

Further, the model's skill in simulating water temperature, validated against historic data from the Long Island Sound (LIS) bottom trawl survey, did not drift over the years, a significant and encouraging finding for multi-decadal model applications used to identify and research climatic trends and causalities. The validation revealed residual biases in some areas with regard to salinity, for example in small tributaries that receive urban discharges from the NYC drainage network, guiding targeted research for further model refinements in the future. For water levels, model results were excellent overall, though model errors against hourly observations increased as expected (e.g. DiLiberto et al. 2011) during major storm surge events and hurricanes (Figure 5), in part due to the resolution in time (3hrly) and space (36km) of the NARR dataset used to provide winds and barometric pressure to the NYHOPS model. Interestingly, the residual water level errors during significant storm surge events appeared to decrease toward the last years of the simulation, even though these included some of the highest storm surge peaks in the region's history during Hurricanes Irene and Sandy. This may in part be due to a presumed increase of the number of observations fed into NARR during the reanalysis process in later years compared to the beginning of the NARR record in 1979 (Figure 5 & Appendix A).

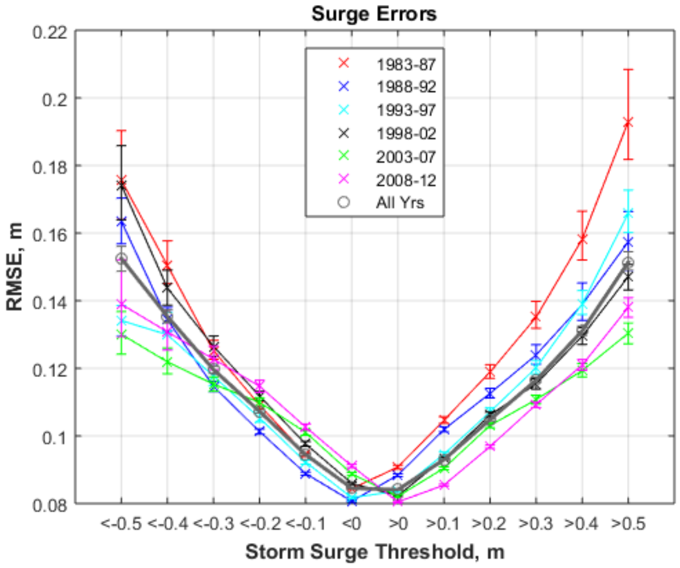


Figure 5. Root-Mean-Square errors as a function of storm surge threshold for positive and negative surges between different 5-year periods in the NYHOPS hindcast.

III. **Explored trends in LIS physical environment in the hindcast period:** NYHOPS model results were used to quantify average water temperature, salinity, and stratification trends for LIS in the hindcast period. Graphical results, trends, anomalies, and computed climatologies are included in Appendix B. The project found that statistically significant warming and freshening trends (Figures 6-7), non-stationary trends in volumetric fluxes across the western and eastern basins of the Sound (Figure 8), and an associated statistically significant increase in stratification (Figures 6-7) to have all occurred within the hindcast period.

Based on the NYHOPS hindcast, in the Long Island Sound basin, surface air temperatures, contributing river temperatures, and receiving LIS-basin-wide water temperatures (0.34±0.08°C per decade) have all seen significant increases between 1981 and 2013; more so on the shallower north shore and western Sound than the south shore. During the same period, based on USGS discharge data, major freshwater river inflows to the Sound increased: the Connecticut River at Thompsonville by 17%, the Housatonic at Stevenson by 21%, and the Hudson at Green Island by 33%. This has led to the Sound overall becoming somewhat fresher (a statistically significant trend of 0.12±0.05psu/decade), especially near river mouths at the surface, increasing stratification and changing long term volumetric transport fluxes in the basin in a statistically significant, nonstationary way.

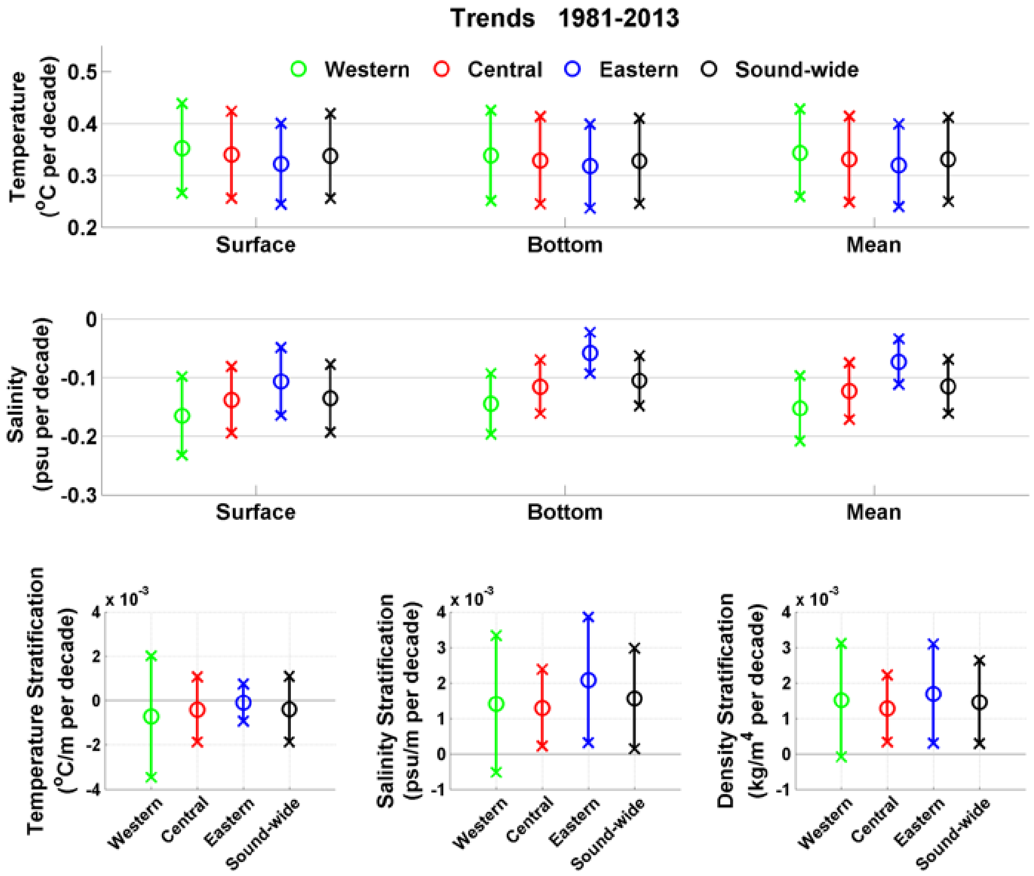


Figure 6. Decadal-averaged trends in water temperature (top), salinity (middle), and stratification (bottom), for the 3 LIS basins, and the whole Sound within the 1981-2013 NYHOPS Hindcast period.

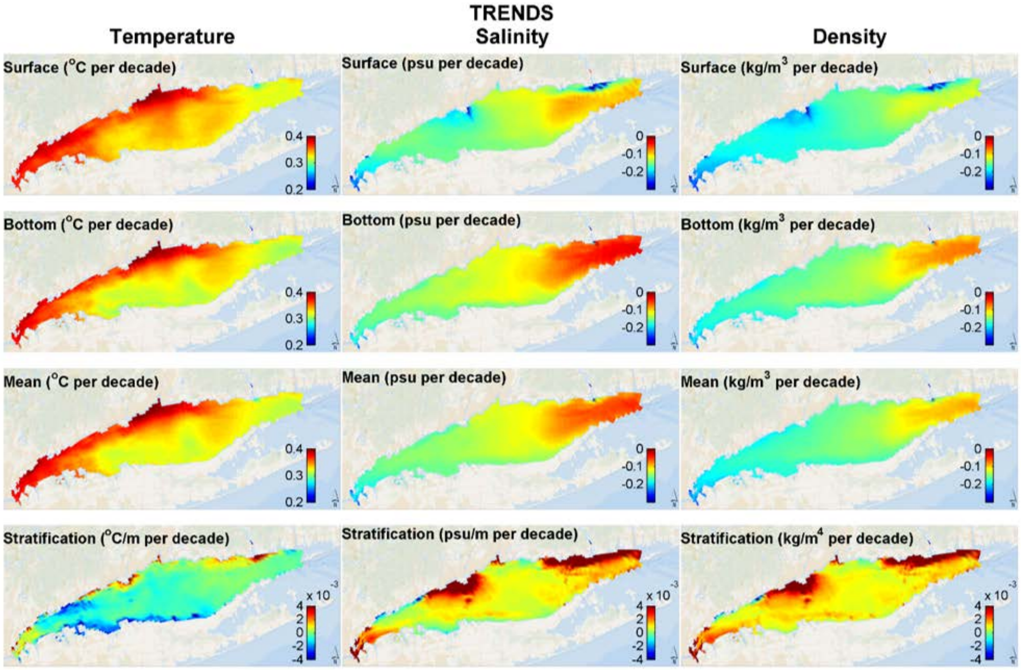


Figure 7. Spatial map of locally computed decadal-averaged trends in water temperature (left), salinity (center), density (right), and stratification (bottom) within the 1981-2013 NYHOPS Hindcast period.

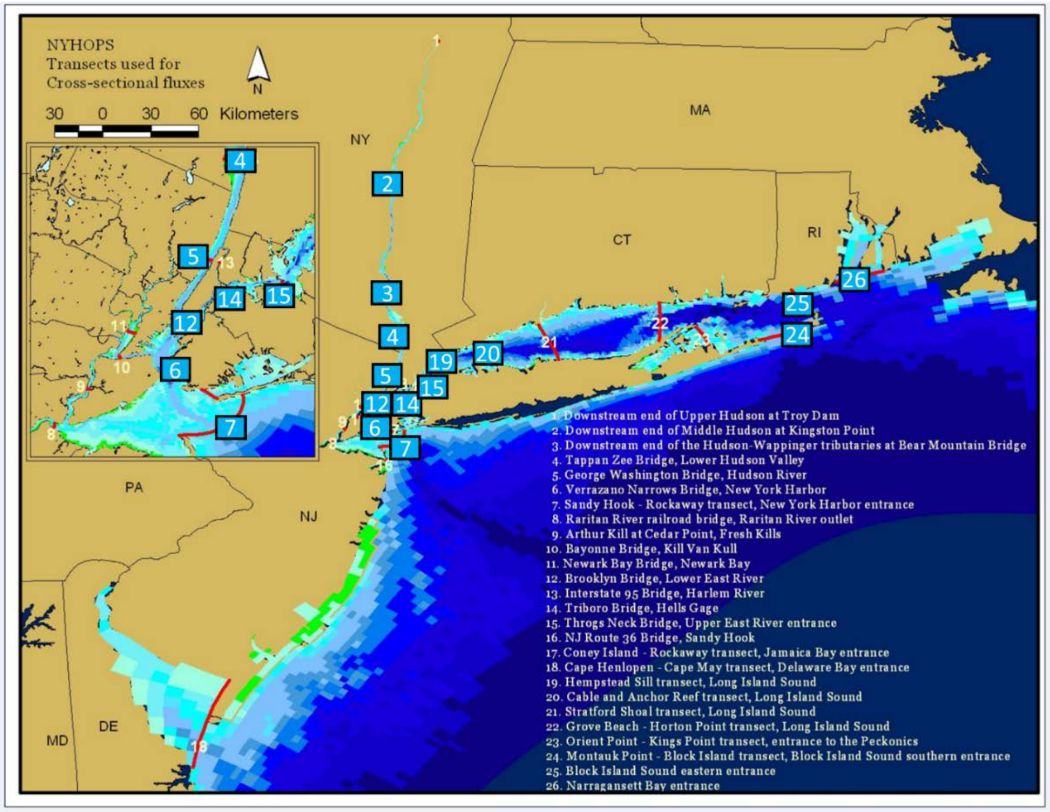


Figure 8. Transects with statistically significant trends in volumetric fluxes (squares).

IV. Thermal Habitat Trends Based on Model Bottom Temperature Estimates and Associations with Fish Abundance:

Methods: Based on analyses done previously (Howell and Auster 2012), a subset of cold-temperate and warm-temperate species were identified that were frequent enough in CT DEEP LIS Trawl Survey (LISTS) data to show a trend from 1984-2008, regardless of direction or significance of slope, and were not subject to a directed fishery (see Gottschall et al. 2000 for complete methods). Six species in each temperature guild met these criteria (Table 1). LISTS catch data (kg/tow) for years 1992-2014 of each set of six species were summed for each tow and totals transformed to natural log+1 to normalize the distribution; zero catch tows were included. Bottom temperature recorded for each tow was truncated to its integer value and few tows without temperature data were omitted. Spring (April-June) and fall (September-October) survey data were analyzed separately. Analyses of variance (ANOVA, General Linear Model procedure, SAS 2014) were run for each season and guild, and least square mean weight computed for each temperature interval. ANOVAs were run on 5-year segments (1992-96; 2000-04; 2005-09; 2010-14; note that temperature data in 1997-99 were not complete) to determine if the abundance-temperature relationship was similar throughout the 23-year time series). LISTS sampling frequencies are designed to be proportional to the area of each survey strata (four depth strata and three sediment types) and therefore no weighting or scaling by strata area was necessary. Resulting mean guild abundance for each 1°C temperature interval was fitted to a two-order polynomial and the fitted values were rescaled from 0 to 1 to generate Habitat Suitability Indices (HSI) similar to procedures described in Manderson (2014). Warm-temperate species abundance was truncated to temperature intervals above 6°C to improve the fit to their very low abundance below 8°C.

Habitat Suitability Indices (HSI) for spring and fall abundances of cold and warm temperate fish guilds were merged with bottom temperature means generated from the NYHOPS Hindcast for Long Island Sound for each CT DEEP LISTS sample grid each day for years 1979-2013. HSI values of 0.8 and 0.3 were chosen as lower threshold values of preferred and exclusionary habitat, respectively. Annual frequency tables were then created for HSI levels equal to or above 0.8 and equal to or below 0.3 for each 0.1°C temperature interval in the NYHOPS output matrix. Frequencies are presented as a percent of total area (i.e. total survey grids) times total days in each season each year, and referred to as percent area*days.

A differing but comparable analysis was done for American lobster abundance trends. Because lobster are heavily harvested and experienced a Sound-wide die-off in the middle of the temperature time series used here, a preferred temperature range (12-18°C), documented in developmental studies (MacKenzie 1988, Annis et al. 2013) and adult behavioral studies (Crossin et al. 1998, Jury and Watson 2000) was used in place of LIS Trawl Survey catch data. Straightforward assignment was made of annual area*days that were below, within, and above this preferred temperature range. Research done with LIS lobsters following the 1999 die off showed that the animals go into respiratory stress at temperatures above 20°C (Powers et al. 2004, Dove et al. 2005), and die if held at high temperature for a long duration. Therefore annual percent frequency of area*days above this stress threshold temperature were also calculated.

Table 1: Species by common and taxonomic name selected from cold and warm temperate guilds and their contribution to the total guild catch.

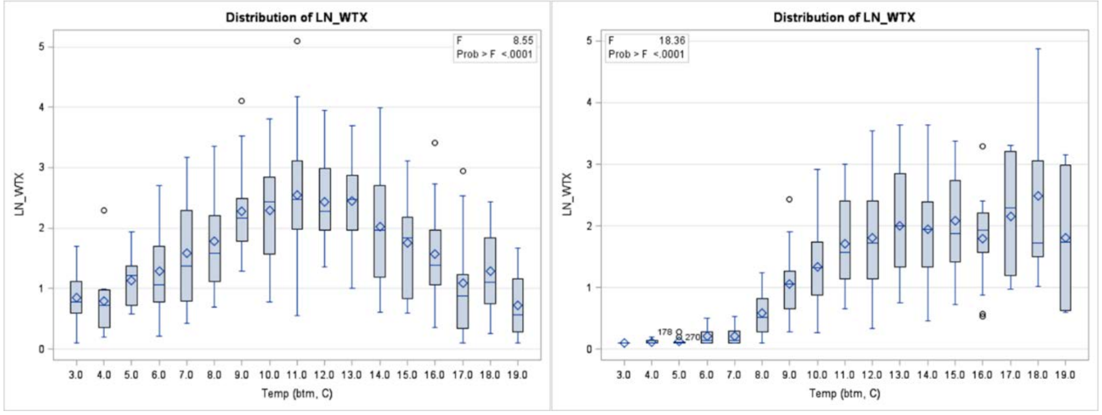
Cold Temperate Guild	
fourbeard rockling	*Enchelyopus cimbrius*
fourspot flounder	*Paralichthys oblongus*
longhorn sculpin	*Myoxocephalus octodecemspinosus*
ocean pout	*Macrozoarces americanus*
sea raven	*Hemitripterus americanus*
windowpane flounder	*Scophthalmus aquosus*
Warm Temperate Guild	
hogchoker flounder	*Trinectes maculatus*
northern kingfish	*Menticirrhus saxatilis*
northern puffer	*Sphoeroides maculatus*
northern searobin	*Prionotus carolinus*
smallmouth flounder	*Etropus microstomus*
striped searobin	*Prionotus evolans*

Percent Contributed by the Selected Six Species to Total Guild Annual Spring Catch, 1992-2014

By Number	Minimum	Maximum	Median
Cold Temperate	9%	22%	15%
Warm Temperate	1%	24%	9%
By Weight			
Cold Temperate	8%	16%	10%
Warm Temperate	1%	11%	3%

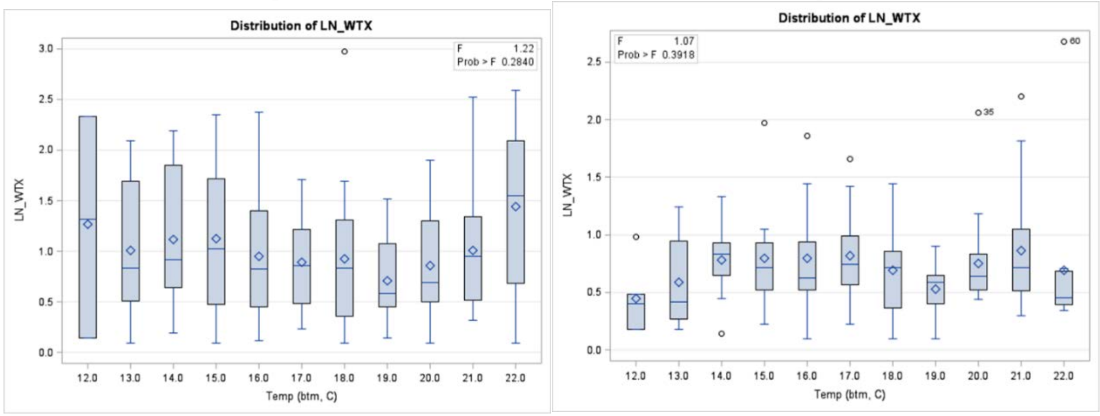
Results: ANOVA and least square mean weight results for each season and guild in 5-year segments showed that the relationship between abundance and temperature was consistent for both guilds in spring (Figure 9) but not in fall (Figure 10). Therefore, the 23-year time series of mean spring abundance for each guild were fitted to a two-order polynomial and Habitat Suitability Indices for each 1°C generated (Figure 11). The maximum HSI value for the cold guild occurred at 11.3°C, and for the warm guild at 16.4°C.

Resulting percent area*day frequencies showed that on average 59% of total spring area*days had preferred temperatures (HSI=>0.8) for the cold temperate fish guild (Figure 12). There was no trend from 1980 to 2013 (linear regression R^2=0.02, p=0.45). For the warm temperate fish guild, on average 31% of total spring area*days had preferred temperature. There was a significant upward trend (linear regression R^2=0.15, p=0.013) from 1980 to 2013.


Cold Temperate Guild

Warm Temperate Guild

Figure 9: Spring abundance of cold temperate guild and warm temperate guild, 1992-2014. The 75th and 25th quartile of mean natural log weight (kg) per sample (LN_WTX) are shown at the upper and low edge of the box, the median at center line, and the mean at the diamond. Vertical lines show maximum and minimum observations up to 1.5 interquartile range (IQR), and circles are outlier observations beyond 1.5 IQR. The cold temperate guild fit with $R^2 = 0.34$, $P<0.0001$ and CV = 42.3; the warm temperate guild fit with $R^2= 0.54$, $P<0.0001$ and CV= 50.7. Note the very low warm guild abundance below 8°C; refit of guild abundance from 6-19°C only gave $R^2= 0.47$, $P<0.0001$ and CV = 48.7.


Cold Temperate Guild

Warm Temperate Guild

Figure 10: Fall abundance of cold temperate guild and warm temperate guild, 1992-2014. The 75th and 25th quartile of mean natural log weight (kg) per sample (LN_WTX) are shown at the upper and low edge of the box, the median at center line, and the mean at the diamond. Vertical lines show maximum and minimum observations up to 1.5 interquartile range (IQR), and circles are outlier observations beyond 1.5 IQR. The cold temperate guild fit with $R^2= 0.07$, $P=0.39$ and CV = 56.8; the warm temperate guild fit with $R^2= 0.08$, $P=0.28$ and CV= 64.5.

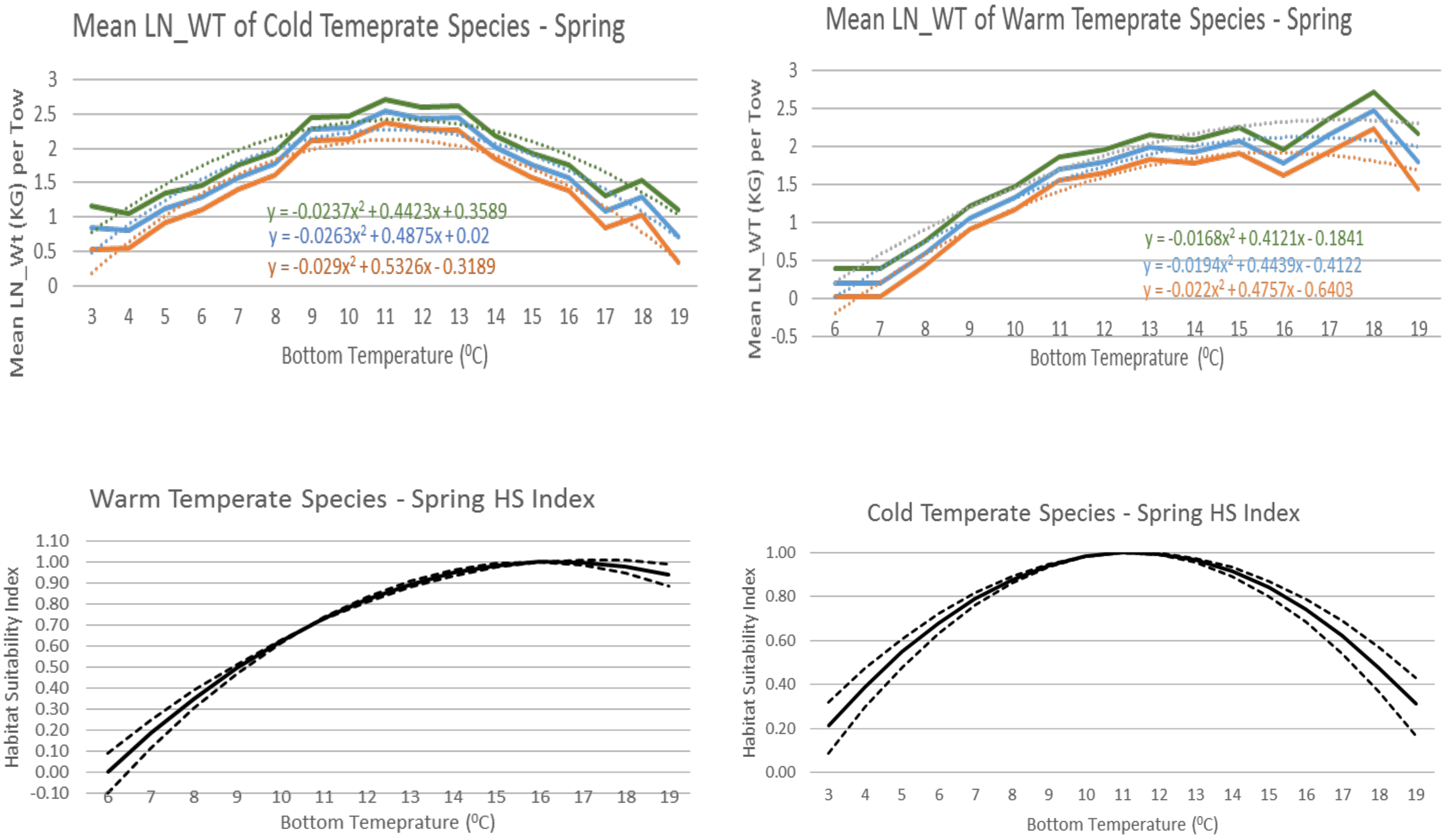


Figure 11: Mean spring cold and warm temperate guild abundance by temperature, fitted to a second-order polynomial, and fitted values rescaled from 0 to 1 to generate Habitat Suitability Indices (HSI). Observed least square mean natural log weight (kg) per sample (LN_WT) are shown (solid lines with +/- standard errors) with polynomial fits (dotted lines). HS Indices (solid line) are shown with standard errors (dashed lines). Note that the warm temperate species abundance was truncated at 6°C to better fit low abundance below 8°C.

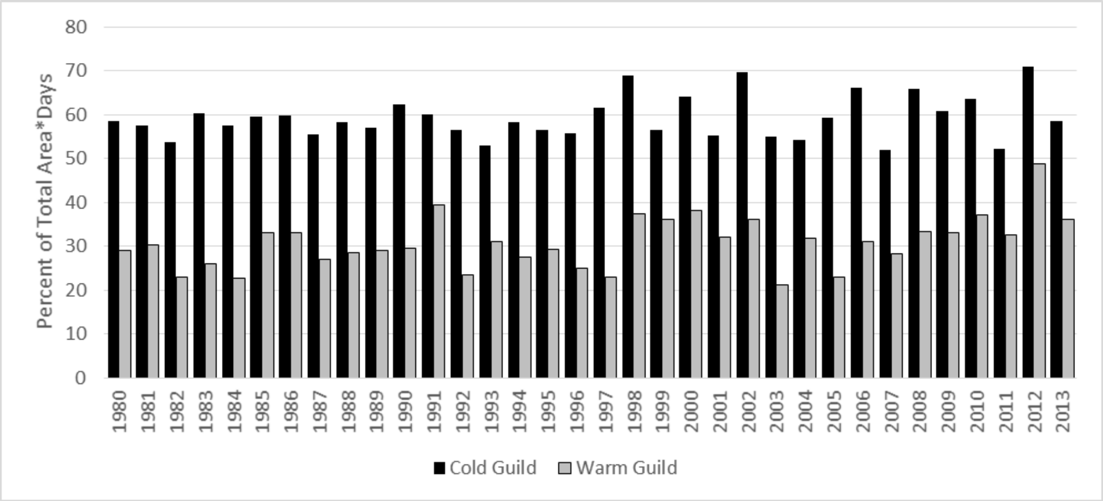
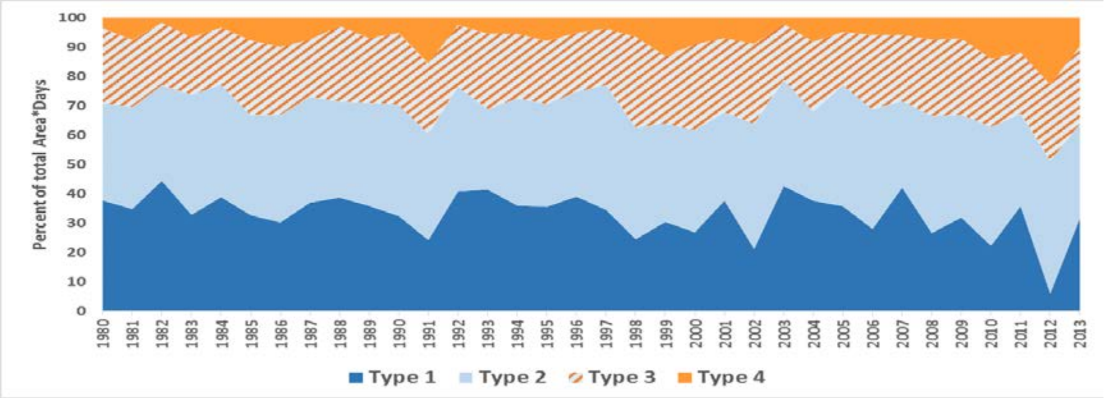


Figure 12: Percent of total spring area*days (LIST Survey area * total days April-June) with Habitat Suitability Index (HSI) equal to or greater than 0.8 for the cold and warm temperate guilds, 1980-2013.

Looking further into the annual trends in HSI by guild, each year's area*days were divided into four types (Figure 13): percent of total spring area*days where (1) both guilds' HSI<0.8 (preferred for neither), (2) cold guild HSI>0.8 and warm guild HSI<0.8 (ideal for cold species only), (3) both guilds' HSI>0.8 (preferred for both), and (4) where warm guild HSI>0.8 and col guild HSI<0.8 (preferred for warm species only). The two 'exclusionary types' (2 and 4) revealed a lack of trend in Type 2 and an increasing trend in Type 4 in the last few years (Figure 14). Additionally, even though the percent of spring area*days unsuitable for the warm guild fish (HSI <0.3) is far greater than for cold guild fish, the former is declining (R^2=0.15, p=0.013) while the latter is increasing (R^2=0.19, p=0.006), especially in the last few years.



Type 1 =Area*day with Cold HSI<0.8 and Warm HSI<0.8 (preferred for neither guild)
Type 2 =Area*day with Cold HSI>0.8 and Warm HSI<0.8 (preferred for cold guild only)
Type 3 =Area*day with Cold HSI>0.8 and Warm HSI>0.8 (preferred for both guilds)
Type 4 =Area*day with Cold HSI<0.8 and Warm HSI>0.8 (preferred for warm guild only)

Figure 13: Percent of total spring area*days preferred for cold and warm temperate guilds, 1980-2013.

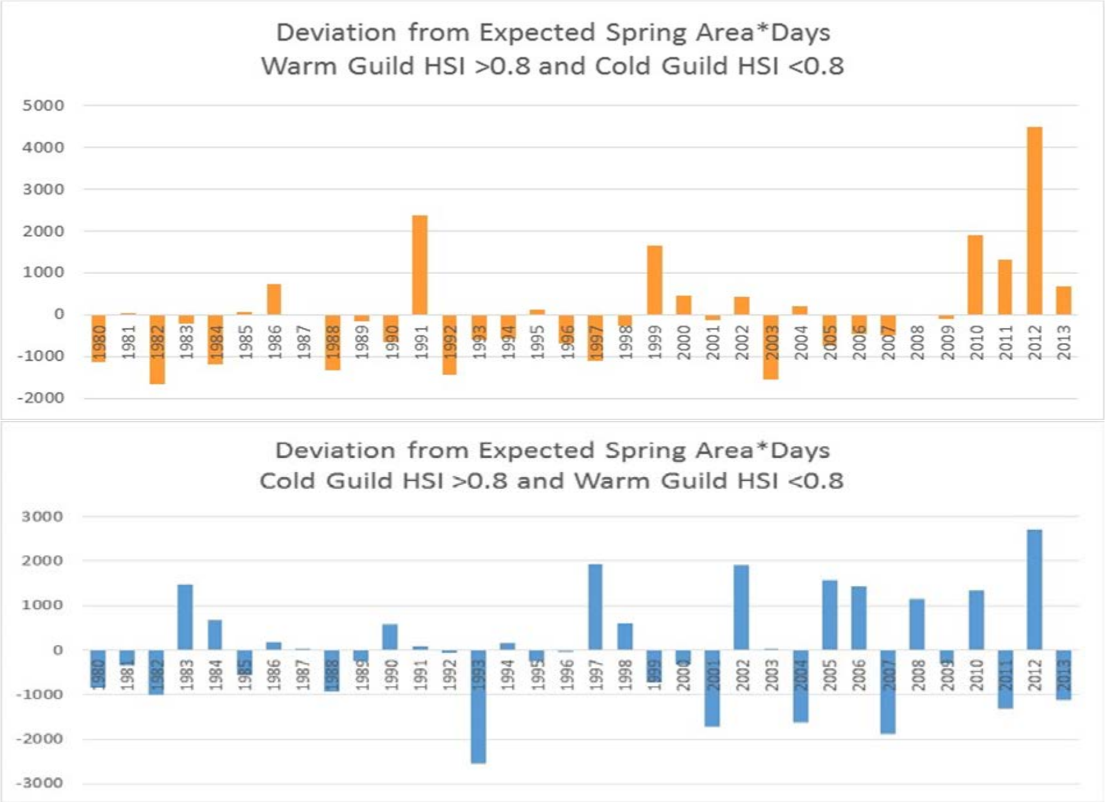


Figure 14: Deviation from expected time series mean of area*days preferred for the cold temperate guild only and preferred for the warm temperate guild only, 1980-2013. The warm guild has a significant positive trend (R^2=0.15, p=0.01); the cold guild does not (R^2=0.02, p=0.45).

Habitat suitability for lobster was completed by assignment of annual area*days that were below, within, and above their preferred temperature range (Figure 15). Resulting frequencies show that the percent of annual area*days within the preferred range has only been above the time-series median value three of the last 12 years (Figure 16). In contrast, the annual frequency of area*days above the 20°C stress threshold has increased in recent years and was below the time-series median only twice is the last 15 years (Figure 17). These data also show that 1999 was the first year that stressful temperatures were wide spread in area as well as of long duration. This finding corroborates the previous conclusion that rising water temperature was the primary cause of the lobster die off that year.

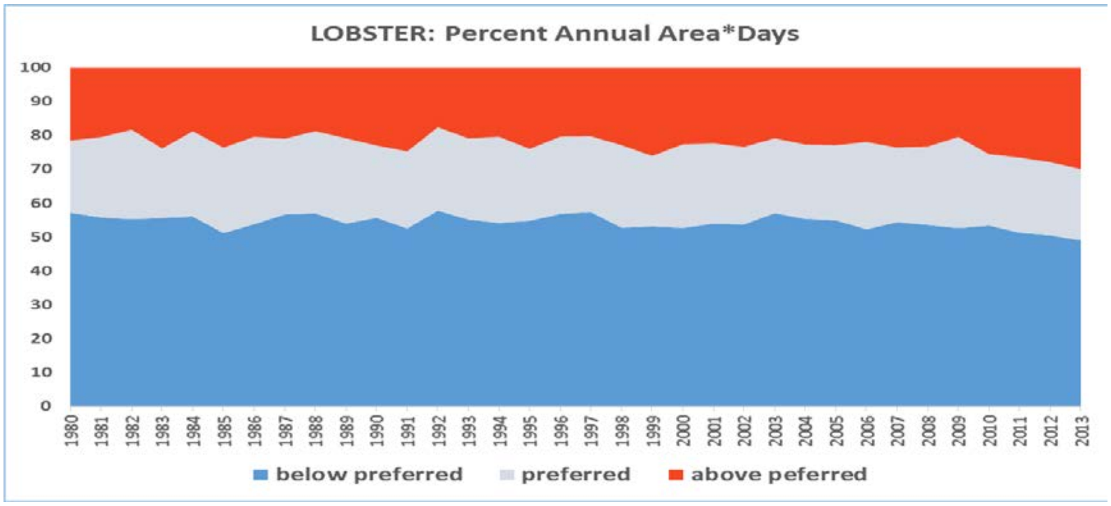


Figure 15: Percent of annual area*days in three categories of suitability for American lobster, 1980-2013. The preferred category includes area*days with bottom water temperature of 8-12°C.

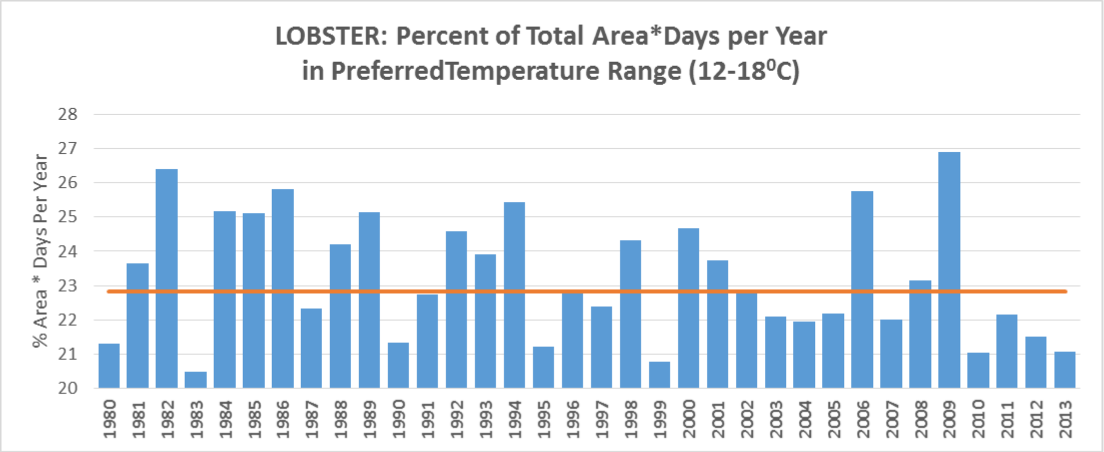


Figure 16: Percent annual area*days with bottom water temperature in preferred range (8-12°C), 1980-2013. Median value (22.8%) is shown.

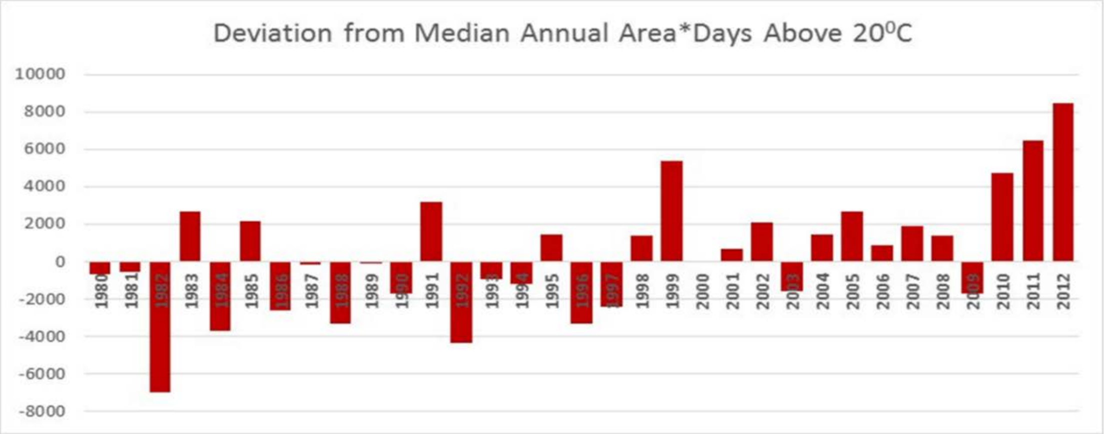


Figure 17: Deviation from the time series median of area*days above the lobster stress threshold of 20°C, 1980-2012.

V. Identified Climate Teleconnections through exploratory analysis of correlations between climate and fisheries in LIS:

Long Island Sound Climate Drivers: Climate indicators related to Long Island Sound (LIS) water and air temperature variability were investigated. In the first year of the project, statistical links of LIS climate to the neighboring North Atlantic Ocean and its Oscillation (NAO) were investigated, but correlations were found to be quite weak for LIS (somewhat stronger for the Mid-Atlantic Bight; Georgas 2014). Similarly for the Gulf Stream Index, at least in the present era. Atmospheric influences on LIS bottom temperature was quantified using spectral analysis. Figure 18 shows the percent of bottom temperature variability that can be explained by air temperature alone, as a function of time. It was found that air temperature dominates the variability of bottom temperature at all times so that other mechanisms such as oceanic advection play only a minor role. The implication of the result is that historical LIS water temperature variability as pertains to LMR thermal habitat can be understood by investigating the atmospheric mechanisms that drive it.

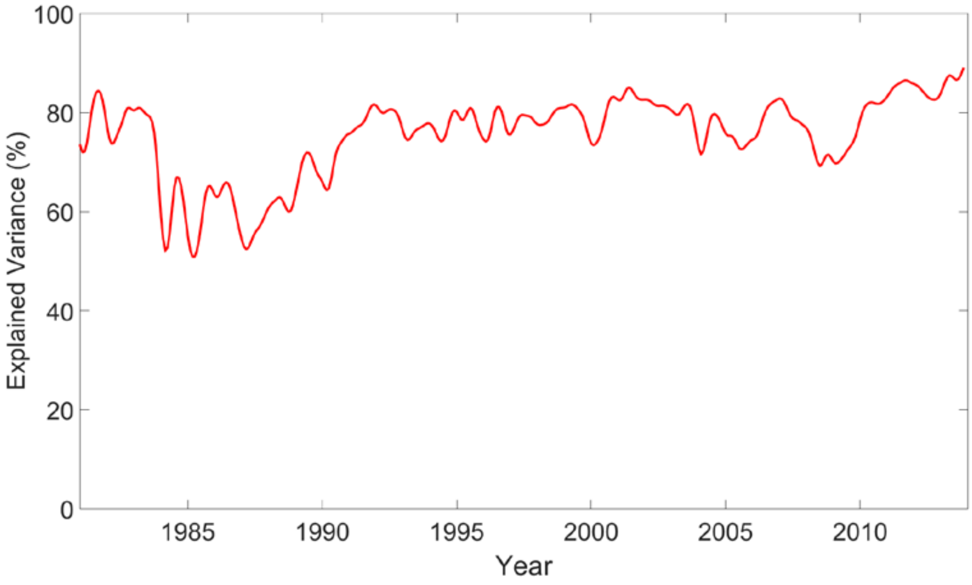


Figure 18. Percent of LIS bottom water temperature variability explained by 2m-above-surface air temperature as a function of time during the NYHOPS hindcast. All values are statistically significant at the 5% level.

Investigators then looked in the meteorologically upstream region of the western United States and Pacific Ocean for LIS climate drivers. Climate indices for the Alaskan High (AH, a new index found in this study to be important during winters), the Pacific Decadal Oscillation (PDO), and the East Pacific/North Pacific (EP/NP) patterns were found to be strongly correlated with LIS air and water temperature anomalies during most seasons and their relationships with annual water temperature anomalies was also found to be strong (Table 2). A bivariate North Pacific (BNP) index combining the PDO and AH indices was found to be capable of explaining the biennial and decadal variability of LIS water temperature.

Table 2. Pearson correlation between various climate indices and anomaly time series for LIS air, surface, and bottom temperature from 1981 to 2013 for winter, spring, summer, fall, and annual mean. Bold entries are statistically significant at the 5% level.

	DJF	**MAM**	**JJA**	**SON**	**Annual**
Air Temperature					
EP/NP	**-0.65**	**-0.51**	**-0.43**	**-0.47**	**-0.58**
NPGO	0.16	0.32	0.29	0.13	**0.35**
PDO	**-0.44**	**-0.37**	**-0.34**	**-0.62**	**-0.54**
BNP	**-0.77**	**-0.60**	**-0.63**	**-0.61**	**-0.74**
AH	**-0.67**	**-0.48**	**-0.68**	**-0.41**	**-0.62**
NAO	0.23	-0.07	-0.15	0.17	-0.32
Surface Temperature					
EP/NP	**-0.66**	-0.31	**-0.40**	-0.26	**-0.55**
NPGO	0.09	**0.50**	**0.54**	0.16	**0.45**
PDO	**-0.36**	**-0.48**	**-0.60**	**-0.46**	**-0.53**
BNP	**-0.72**	**-0.44**	**-0.69**	**-0.30**	**-0.63**
AH	**-0.66**	-0.23	**-0.52**	-0.09	**-0.48**
NAO	0.27	-0.07	**-0.34**	0.27	-0.25
Bottom Temperature					
EP/NP	**-0.65**	-0.23	-0.25	-0.29	**-0.51**
NPGO	0.07	**0.48**	**0.46**	**0.16**	0.43
PDO	**-0.36**	**-0.47**	**-0.59**	**-0.48**	**-0.52**
BNP	**-0.71**	**-0.37**	**-0.59**	**-0.33**	**-0.61**
AH	**-0.65**	-0.15	**-0.37**	-0.11	**-0.46**
NAO	0.26	-0.10	**-0.35**	0.28	-0.24

Shown in Figure 19 are 4-month running means of the time series for LIS air temperature, surface water temperature, and bottom temperature anomalies (dotted lines). The European (ERA) reanalysis was used here as a similar but different dataset to the NCEP NARR used to force the NYHOPS Hindcast. For all three time series, the most salient features are the prominent anomalous warm event in 2002 and 2012. Other notable events are the warm periods in 1991 and 1999 and cold periods in 1981, 1982, and 2011. It is also noted that the time series for air temperature from the ERA reanalysis is strongly correlated with the time series for both surface and bottom temperature from the NYHOPS hindcast. The result suggests that atmospheric processes associated with changes in air temperature are the primary mechanisms governing LIS water temperature variability. Another notable feature of Figure 19 is that all three time series have an upward trend, with colder-than-normal conditions being more frequent earlier in the record and warmer-than-normal conditions being more frequent later in the record.

The 4-month running mean of the BNP-component of the LIS air temperature time series together with the 4-month running mean of the full air time series are shown in Figure 19a. The small difference between the two time series suggests that the influence of the BNP index on air temperature anomalies was strong. For example, for 2012 the anomalies associated with the BNP index approached 1.0℃ and the anomaly associated with the complete time series was 2.3℃. Thus, according to the definition of the BNP index, the PDO and AH pattern contributed largely to the warmer-than-normal conditions in 2012. A similar interpretation holds for the warm periods of 1991, 1999, 2002, and late 2010. Colder-than-normal periods also appear to have been largely related to the PDO and AH patterns.

A similar analysis was conducted with water temperature from the NYHOPS Hindcast. The results provide evidence that the 2012 ocean heat wave was related to the PDO and AH patterns. Other warm periods such as 1999 were also related to the AH and PDO patterns. Note that the water temperature anomalies prior to approximately 1987 were not as strongly linked to the BNP index. This was also seen in scale-averaged wavelet coherence tests with coherence being also small during the 1979 to 1987 period. The wavelet output spectrum analysis together with the strong air temperature-water temperature relationship suggests that the anomalous cold or warm events were driven by changes in the North Pacific that led to changes in air temperature and resulting heat fluxes across the LIS.

18-26% of the total temperature increase during the NYHOPS hindcast period was found to be statistically associated with a warming trend linked to an upward trend in the Bivariate North Pacific (BNP) index during the same years (Figure 19). This is a very important finding, because it implies that, if the Bivariate North Pacific (BNP) index were to change phase, that part of the warming signal to Long Island Sound may be reversible, which in turn would appear as a future amelioration in the exacerbated local rate of warming in LIS. Indeed, since the beginning of 2014, the PDO index appears to have shifted from the negative (warm LIS) phase it was for over a decade to consistently positive numbers.

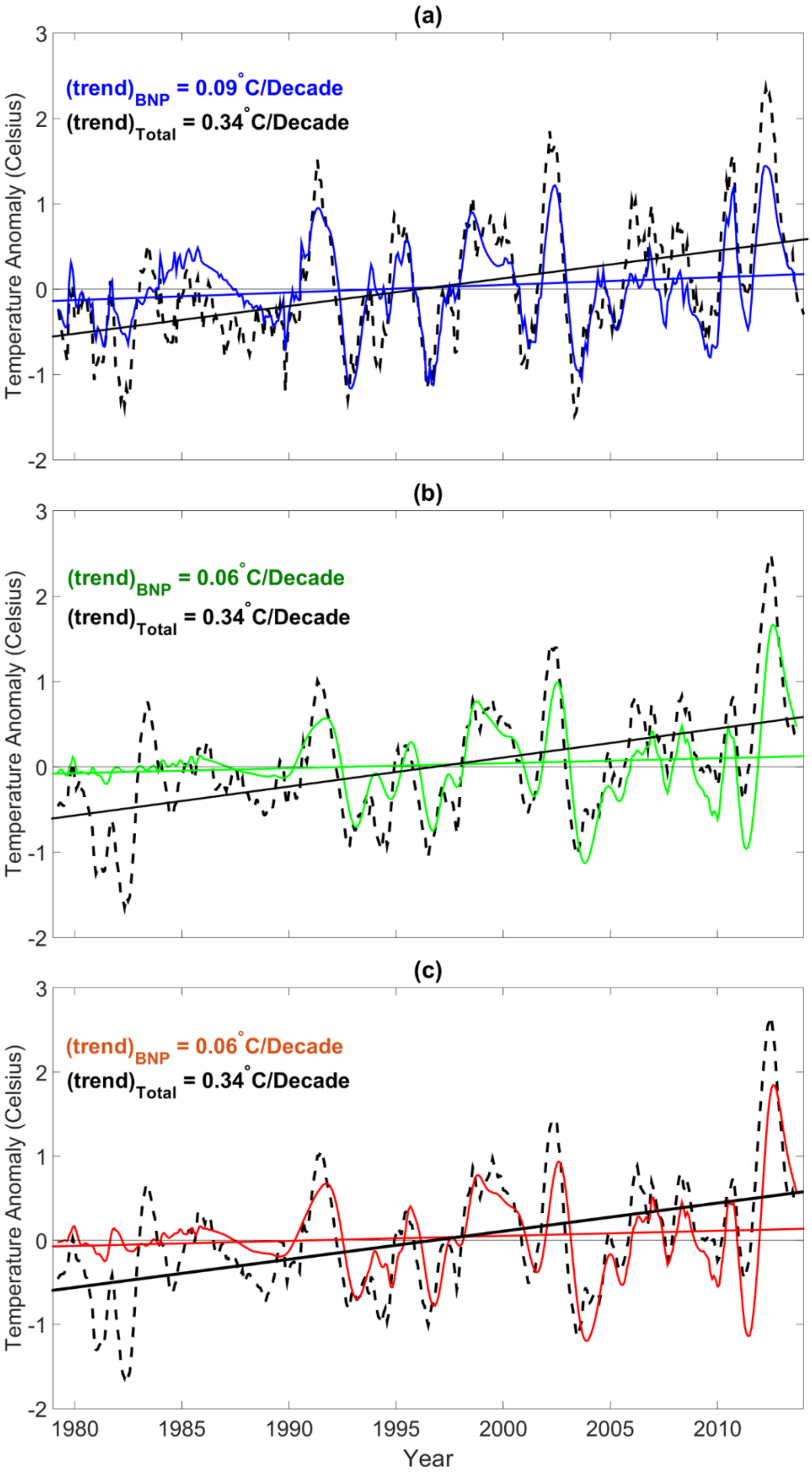


Figure 19. (a) 4-month running mean of LIS air temperature anomalies (dotted line) and the BNP component of the time series (see Section 4.7). (b) Same as (a) but for LIS surface water temperature anomalies. (c) Same as (a) but for LIS bottom water temperature anomalies.

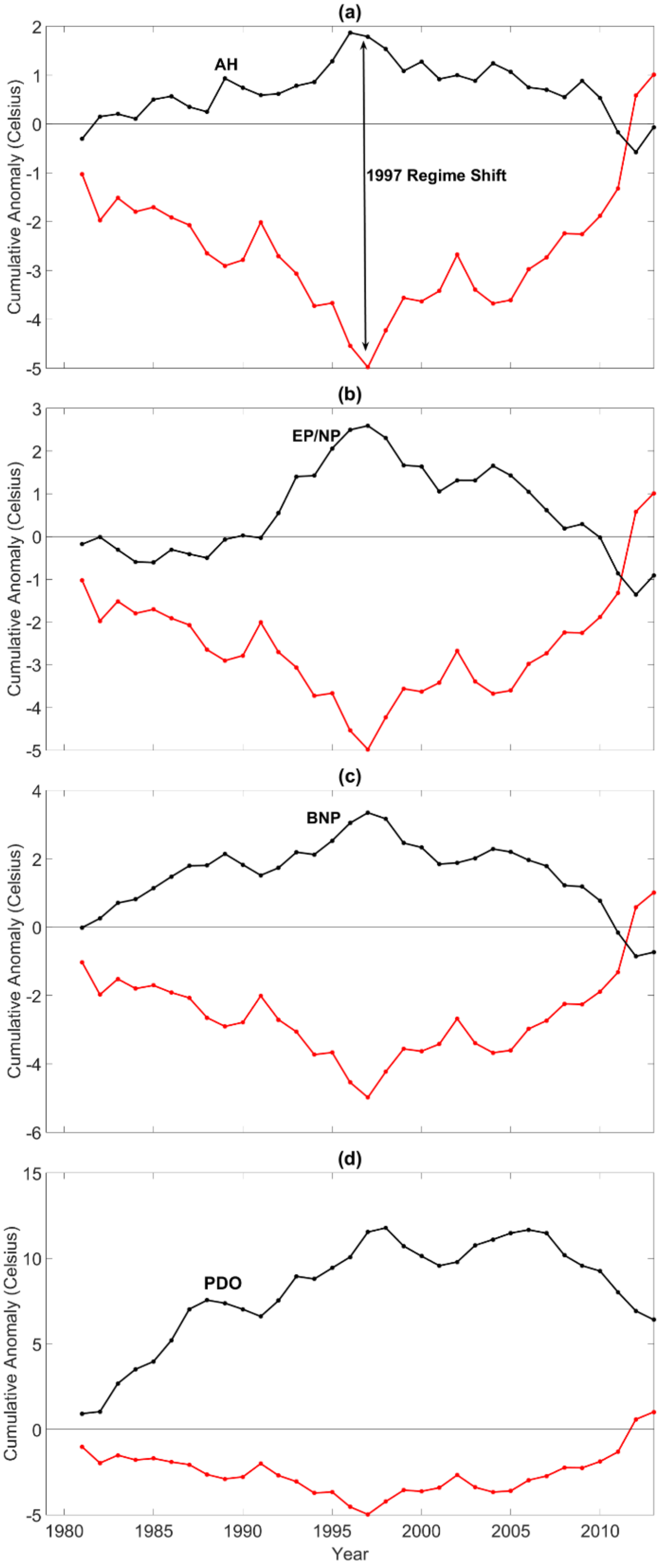


Figure 20. Cumulative sum of annual mean anomalies for the (a) AH, (b) EP/NP, and (c) BNP indices. The cumulative sum of the annual mean LIS surface water temperature are shown in red in each panel.

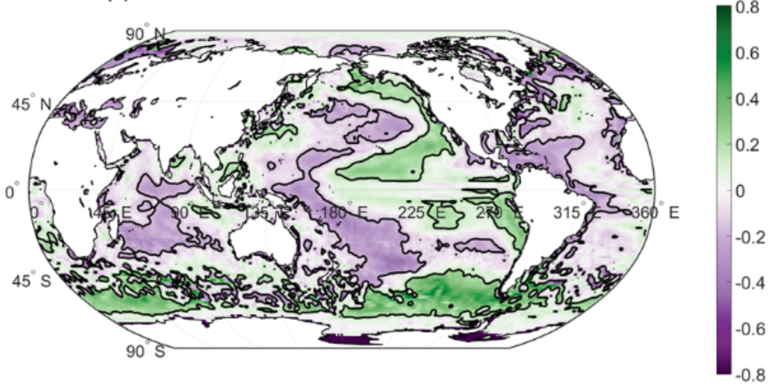
Regime changes associated with North Pacific indices were illustrated by conducting a cumulative deviation analysis of annual mean climate indices and temperature anomalies. For both air (not shown) and surface water temperature (Figure 20), negative anomalies were preferred from 1981 to 1997. Similarly, for the AH and BNP indices, positive indices were preferred from 1981 to 1997 but for the EP/NP index there was no preference from 1981 to 1990. At 1997, an inflection occurred and positive water temperature anomalies were preferred for subsequent years. Remarkably, around 1997 all three indices appear to have undergone a regime shift and negative indices were preferred from 1997 to 2013. Thus, an apparent regime shift in the AH, EP/NP, BNP patterns in 1997 was found to have coincided with a regime shift in LIS water temperatures.

Using a recently developed wavelet output spectrum analysis, LIS water temperature anomalies were found to have responded largely to 300-hPa streamfunction anomalies over the western equatorial Pacific and Alaska and the pattern of response was consistent with a Rossby wave train emanating from the western equatorial Pacific (Schulte et al, in preparation). The results suggest that periods of warmer-than-normal conditions or colder-than-normal conditions, and associated regime shifts, are related to preferential expressions of phases for the AH, EP/NP, and BNP patterns. The results furthermore suggest that some of the apparent warming trend of LIS water temperature time series since 1997 may be due to natural variability if it is assumed that anthropogenic influences do not project onto those patterns.

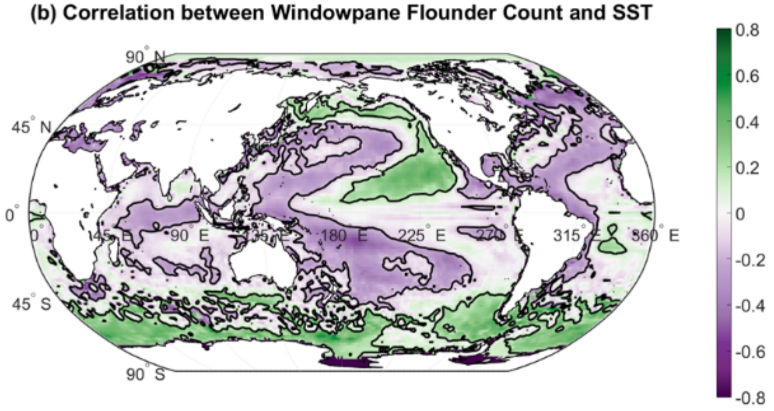
Correlations of climate drivers to fisheries: The annually, but also seasonally, averaged LIS water temperature simulated in the NYHOPS model hindcast was found to have statistically-significantly correlation to the PDO (Table 2 above). On the annual scale, a moderate association between the two time series was identified (r = -0.52, Table 2, equal for both Pearson and Spearman tests) and thus the PDO index alone was found to explain 31% of the annually averaged surface to bottom water temperature variability across the LIS simulated in the NYHOPS hindcast. The cumulative deviation plot shown in Figure 20 indicates that periods of persistently positive PDO indices coincided with persistent negative water temperature anomalies from 1981 to 1997. In 1997, a PDO regime shift occurred: more negative PDO phases were preferred and a preference for positive Long Island Sound water temperature anomalies was also identified. Figure 20 suggests that part of the warming across the LIS, from 2006 to 2013, was related to the Pacific regime shift. The physical mechanism connecting PDO to LIS water temperature was established by correlating the PDO index with 500-hPa geopotential height (Schulte et al, in preparation; see Georgas et al 2016).

To determine if any global sea surface temperature (SST) patterns were related to fish species counts, counts for the Lobster, Smallmouthed flounder, and Windowpane flounder received from CT DEEP were correlated with global sea surface temperatures (Figure 21). The counts for all three species were correlated with SST in the North Pacific, with a region of positive correlation coefficients being located along the west coast of the United States for Lobster and Windowpane Flounder, and a similar region of correlation coefficients of opposite sign being located along the west coast for the Smallmouthed flounder. A region of correlation coefficients of opposite sign was found in the central North Pacific Ocean for all three species. It is noted that the pattern of correlation coefficients again resembles the PDO and North Pacific Gyre Oscillation (NPGO; http://www.o3d.org/npgo/) patterns.

(a) Correlation between Lobster Count and SST



(b) Correlation between Windowpane Flounder Count and SST



(c) Correlation between Smallmouthed Flounder Count and SST

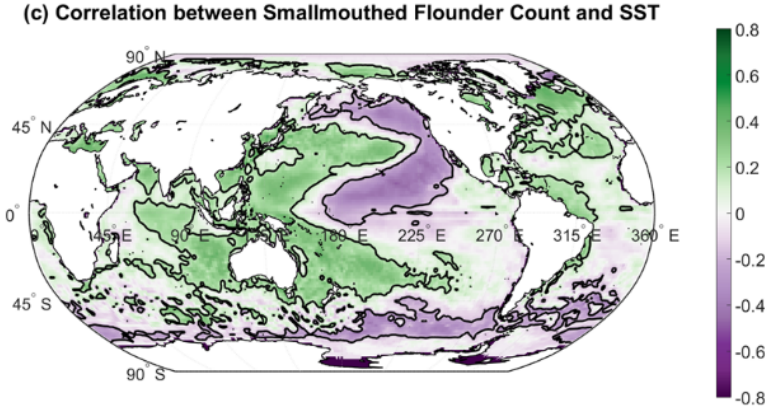


Figure 21. Correlation between sea surface temperature anomalies and counts for (a) Lobster, (b) Windowpane flounder, (c) Smallmouthed Flounder from 1985 to 2014. Contours enclose regions of 5% statistical significance.

The results above motivated the correlation analysis of fish guild counts (as defined in the previous section IV) with indices for the PDO and NPGO. The correlation between the seasonally averaged PDO index and guild count for the Spring April-June) was computed (Figure 22). It was found that the spring warm guild counts most strongly correlated ($r = -0.78$) with the summer (June-August) PDO index of the previous year (Figure 22a). Inspection of Figure 22a shows that the PDO-warm guild count relationship was found to be nonlinear. The PDO index of the previous summer was also found to be correlated with the Spring cold guild count but the relationship was found to be much weaker, with $r = -0.48$ (Figure 22b). A correlations analysis for the cold guild counts determined that the fall (September-October) cold guild count was most strongly correlated with the summer PDO index of the same year but the relationship was weaker than the PDO-Spring warm guild count relationship (Figure 23a). A similar analysis showed that fall cold guild count was also correlated with the summer PDO index of the same year and the relationship was rather weak (Figure 23b). The strong correlations to climate indices found for some species and guilds pave the way to climate outlooks (seasonal forecasts) for fisheries.

An example forecast is shown in Figure 22. The 2015 mean summer PDO index was calculated and the historical relationship between the summer PDO index and the spring warm guild count was used to forecast the spring warm guild count for spring 2016. The forecast indicates that there will be a below normal fish abundance for the warm guild in the spring. A similar forecast was made for the spring cold guild and the forecast suggests that the abundance of the cold guild will be above normal for the spring. However, the wide confidence interval shown in Figure 22 suggests that cold guild forecast is uncertain but that there is high confidence in the warm guild forecast.

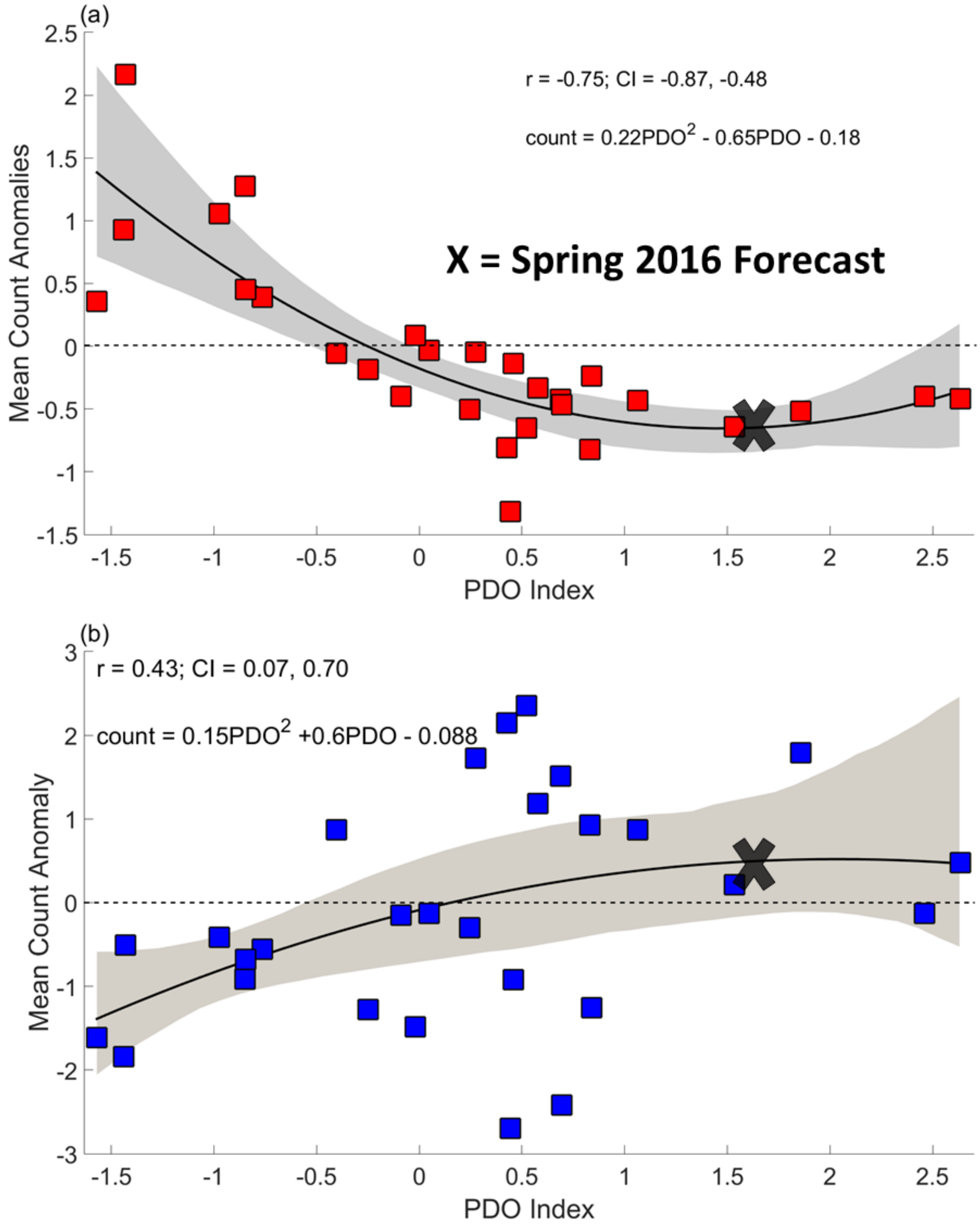


Figure 22. (a) Spring warm guild counts anomalies plotted as a function of the previous summer PDO index from 1985 to 2014. Black curve represents the best fit second-order polynomial and graying shading represents the 95% confidence interval. (b) Same as (a) but for the spring cold guild.

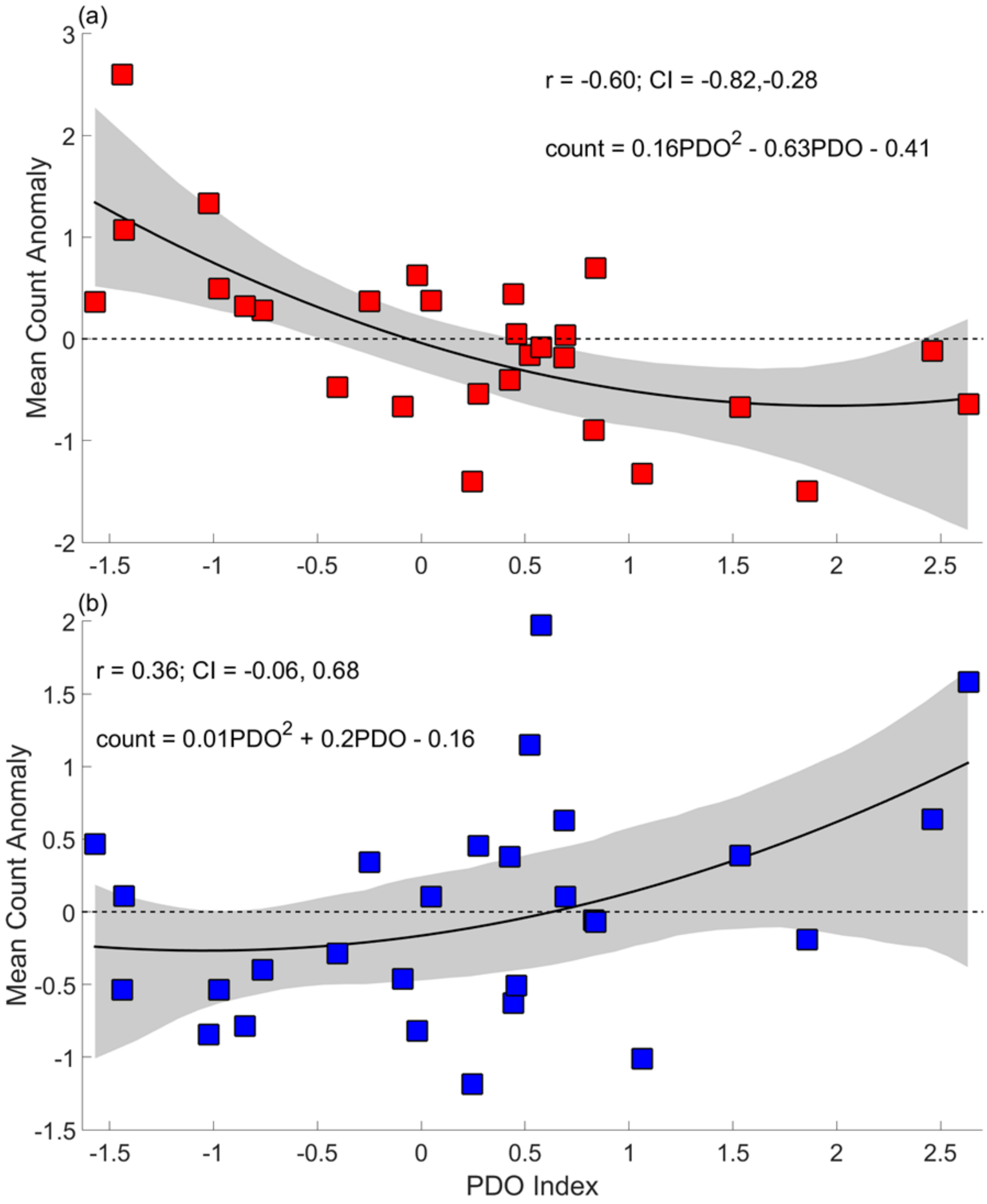


Figure 23. (a) Same as Figure 22a but for fall warm guild and the summer PDO of the same year. (b) Same as (a) but for the fall cold guild.

Salinity Analysis: Salinity is an important estuarine parameter that is related to the stratification and ecology of estuaries. It is important to understand the stratification of estuaries because strong stratification can prevent vertical mixing and promote hypoxia events that threaten fish species. For the Long Island Sound (LIS), changes in salinity and stratification are mainly related to freshwater discharge from, for example, the Connecticut, Housatonic, and Thames Rivers. Freshwater discharge primarily responds to fluctuations in precipitation but is also related to temperature because higher temperatures are associated with increased evapotranspiration.

The strong link between atmospheric conditions and freshwater discharge suggests that a better understanding of LIS salinity variability can be obtained through a better understanding of atmospheric mechanisms. However, the atmosphere is complex, evolving rapidly and changing on an array of timescales, so that such an approach may be formidable. A simplified approach is to relate indices describing a discrete set of atmospheric patterns to LIS salinity, greatly reducing the dimensions of the problem. One such atmospheric pattern is the Eastern North American mean sea level (MSLP) dipole (Schulte et al., 2015; ENA) pattern, which describes concurrent fluctuations in MSLP between two regions across the eastern United States shown in Figure 24. A positive ENA phase is associated with an anticyclone situated east of Maine and a cyclone situated over the Southeast US. Together, the anticyclone and cyclone operate synergistically to drive a surface flow from the more humid ocean during the cool season onto land. The result is increased precipitation. In previous work, the index quantifying the evolution of the ENA pattern was found to be strongly correlated with streamflow for the Susquehanna, Delaware, and Hudson rivers and is thus adopted for the salinity analysis.

Figure 25 shows the results of a lag correlation analysis between the monthly ENA index and NYHOPS model hindcast monthly surface salinity anomalies. Weak, but statistically significant anti-correlation coefficients were found when the salinity anomalies led by 1 to 2 months (Figures 25a and 25b). Correlation coefficients of larger magnitude were found at lag = 0 months, especially in the region of the Hudson River freshwater plume. The strongest relationships were found when the ENA index led by one month (Figure 25d). For example, correlation coefficients were found to approach –0.5 in the Delaware Bay and -0.35 in the Long Island Sound and in the region corresponding to the Hudson River freshwater plume. Panels **(e)** and **(f)** of Figure 25 show that the influence of anomalous ENA events can persist for 2 to 3 months.

The annually averaged ENA index was also correlated with the mean annual bottom salinity anomalies in the NYHOPS hindcast across the LIS. A strong correlation was found (r = -0.59) and the ENA index was found to explain approximately 35% of the mean annual salinity variability from 1981 to 2013. The cumulative deviation plot shown in Figure 26b indicates that periods of higher-than-normal LIS salinity were accompanied by periods of preferred negative ENA regimes (positive inverse ENA regimes) with the converse also being true. For example, LIS bottom salinity was anomalously low in 1997 and 1998 and during those years the ENA index was anomalously positive.

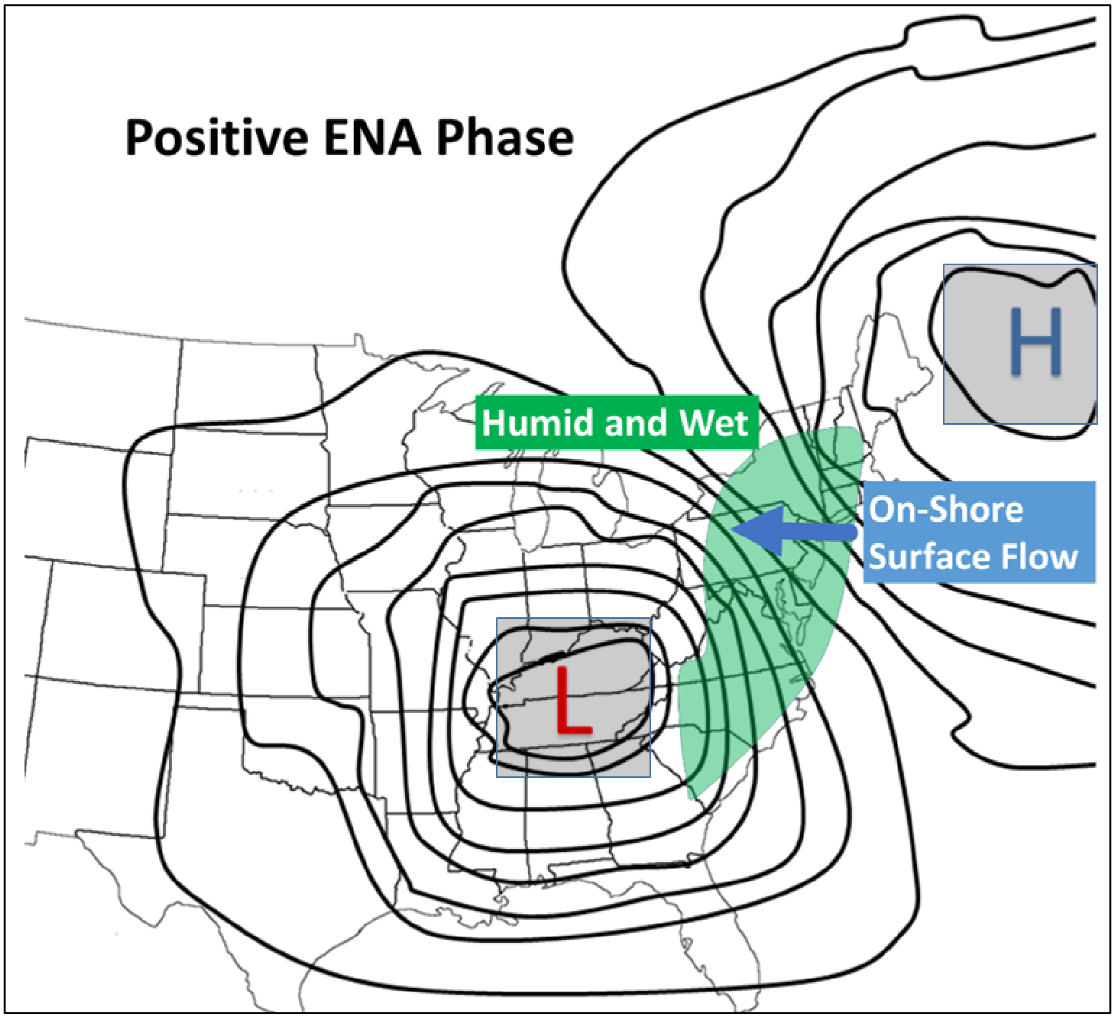


Figure 24. A schematic showing the atmospheric conditions accompanying the positive ENA phase during the months of October through April. The L and H denote the location of negative and positive MSLP anomalies or low and high pressure systems, respectively. Contours represent isobars and green shading shows the region of enhanced precipitation resulting from the transport of warm moist air from the ocean onto land. Gray shading represents the domain on which the ENA index is calculated. The ENA index is calculated by averaging MSLP anomalies in the gray boxes, dividing the resulting time series by their respective standard deviations, and then subtracting the time series for the high pressure box from that of the low pressure box.

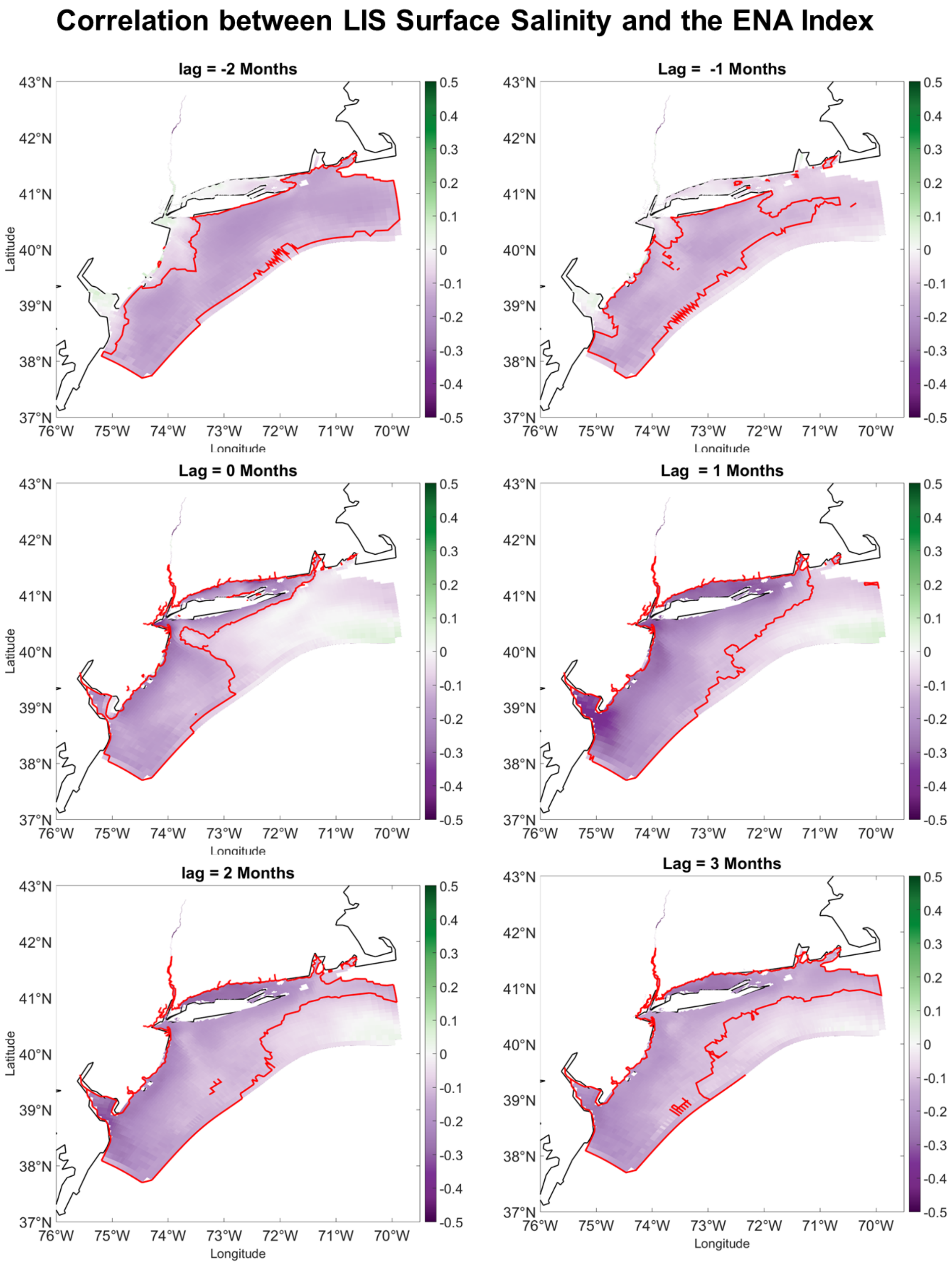


Figure 25. Lag correlation analysis between the ENA index and LIS surface salinity anomalies. Negative lags indicate that LIS surface salinity leads and positive lags indicate that the ENA index leads. Red contours enclose regions of 5% statistical significance.

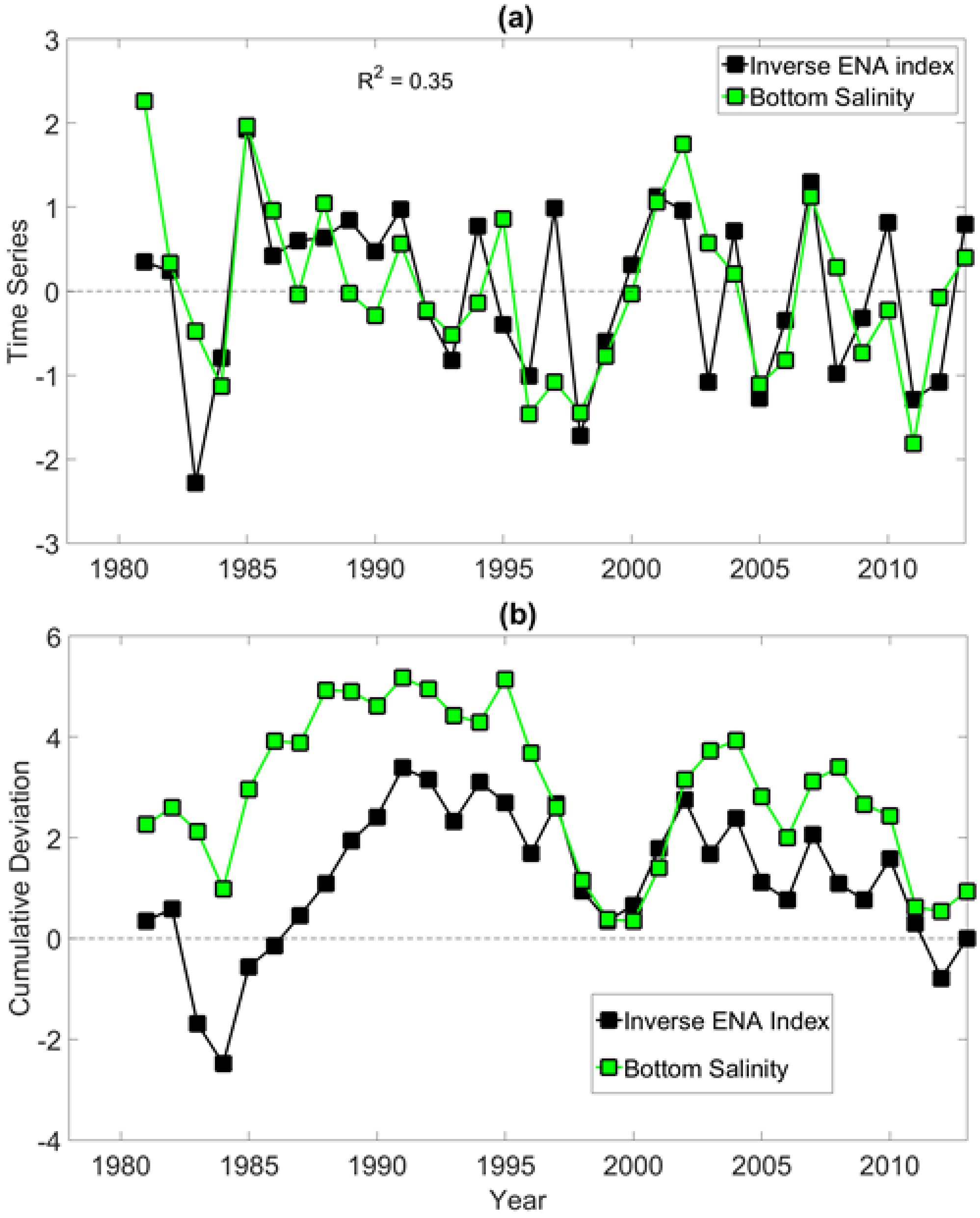


Figure 26. (a) Mean annual LIS surface salinity anomalies and the mean annual inverse ENA index, where the inverse was used to facilitate comparison. (b) The cumulative deviation of the LIS surface salinity anomalies and the inverse ENA index. The value at each point represents the cumulative sum of all annual anomalies from 1981 to that point, inclusively.

VI. **Coupled NYHOPS to the GFDL CM 2.6 climate model and ran a 2xCO2 21st century Transient Climate Response for Long Island Sound:** Turning next into the long-term future, a future climate change / Transient Climate Response (TCR) scenario for Long Island Sound was studied by dynamically downscaling a "CO2-doubling" TCR (1% annual CO2 increase each year for 80 years) projection from a state-of-the-art global climate model (NOAA GFDL's CM2.6), by using the global climate model to force a regional NYHOPS simulation. The goal was to create a methodology for such dynamic downscaling, and enhance our understanding of local impacts and sensitivities to global climate change; especially its potential effects on water temperatures and thermal habitat for Living Marine Resources (LMR). The global climate model used was the latest GFDL's CM2.6 model (Saba et al 2016), a model in the family of Climate Models considered in the International Panel on Climate Change (IPCC) Assessments Reports Four and Five (AR4 and AR5). CM2.6 resolves the atmosphere on a 0.5 degree global grid, and the global ocean on a 0.1 degree global grid.

Monthly NYHOPS forcing functions for the CO2-doubling TCR scenario were generated from GFDL's CM2.6 monthly model output, by

a) taking the monthly difference ("delta") of these forcing functions between a 2xCO2 CM2.6 run minus a baseline CM2.6 run, and, after spatial interpolation to the NYHOPS grid, and,
b) adding these deltas (monthly anomaly fields) to the respective monthly climatological fields of the NYHOPS forcing functions that were created by monthly-averaging the modeled fields from the NYHOPS 1981-2013 hindcast.

Since it takes about 70 years at the 1% annual rate to reach CO2 doubling, the NYHOPS model was run from years +58 to +80. The most significant change in the CM2.6-based NYHOPS 2xCO2 TCR surface forcing functions compared to the NYHOPS historic 1981-2013 hindcast was the increase in near surface air temperature – on the order of +2.6 °C compared to hindcast climatology NYHOPS-region-wide – with higher increases in the winter months in LIS, and lower in the summer months. The other significant change in forcing for the NYHOPS TCR was the CM2.6 model prediction of 3 °C or greater year-round increase in water temperatures at the continental shelf break consistent with a predicted northward motion of the warmer and saltier Gulf Stream over the next century under that scenario (Figure 27). More details in the NYHOPS TCR setup are discussed in Appendix C. Appendix D graphically summarizes results.

After the NYHOPS TCR run was completed, the warming response of LIS to the assigned atmospheric and oceanic forcing appeared to be overestimated, an annual mean of +3.8 °C compared to the NYHOPS historic 1981-2013 baseline; But up to +5 °C in December and January (Figure 28). As shown in Appendix C, it was reasoned that this higher than expected increase in water temperatures is most likely due to the way wind forcing was applied in the NYHOPS TCR simulation: monthly-averaged values deduced from GFDL CM2.6 anomalies, unlike the 3hourly forcing based on NARR used in the NYHOPS Hindcast. This apparently led to non-linear under-estimation of the sensible and latent heat fluxes in the TCR due to lack of wind variability, especially in the winter cool season; in effect dumping the cooling effect of winds. It is recommended that future projections using dynamic downscaling of global models one way or another consider day-to-day wind variability in the forcing.

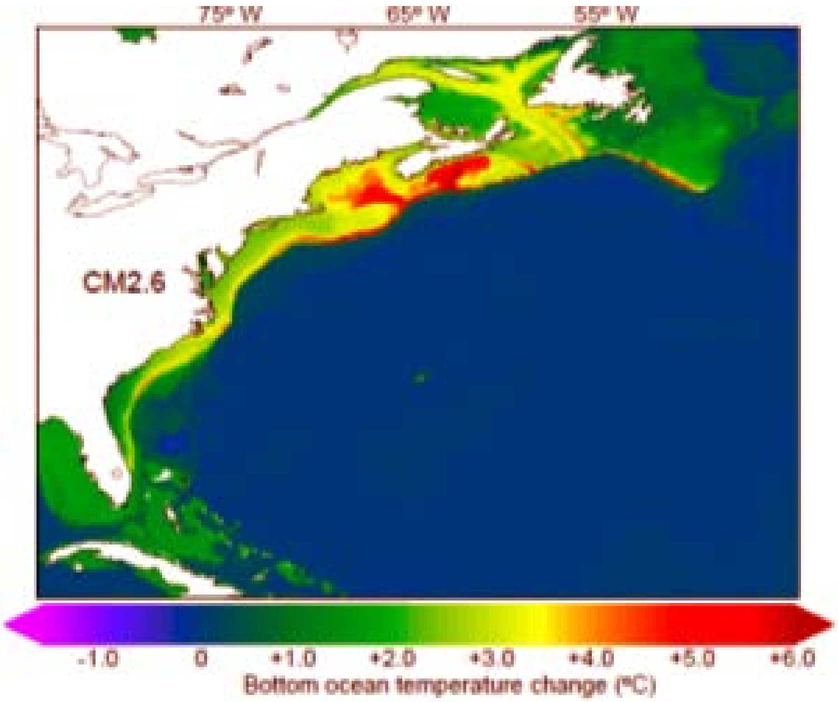
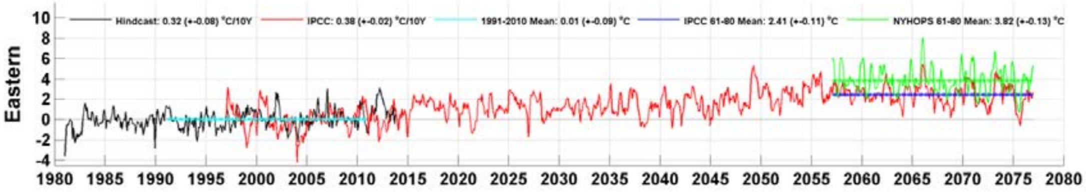
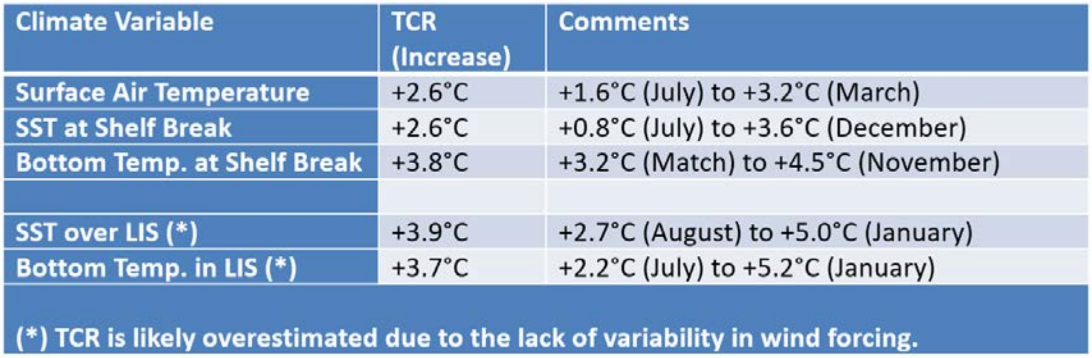


Figure 27. Bottom water temperature change (anomaly from baseline conditions) predicted by the NOAA GFDL CM2.6 model after 70 years of 1% annual CO2 increase (CO2 doubling).





Climate Variable	TCR (Increase)	Comments
Surface Air Temperature	+2.6°C	+1.6°C (July) to +3.2°C (March)
SST at Shelf Break	+2.6°C	+0.8°C (July) to +3.6°C (December)
Bottom Temp. at Shelf Break	+3.8°C	+3.2°C (Match) to +4.5°C (November)
SST over LIS (*)	+3.9°C	+2.7°C (August) to +5.0°C (January)
Bottom Temp. in LIS (*)	+3.7°C	+2.2°C (July) to +5.2°C (January)

(*) TCR is likely overestimated due to the lack of variability in wind forcing.

Figure 28. Top: Simulated temperature trends for the eastern basin of Long Island Sound ("IPCC" notes the NOAA GFDL model). Bottom: Simulated Transient Climate Response from the 2xCO2 NYHOPS TCR.

VII. Fishery Projections based on the 2xCO2 NYHOPS TCR: As abovementioned, and as explained in Appendix C, sensitivity analyses have shown that additional forcing factors (principally, day-to-day wind variability) are needed to generate more realistic projections into the next century. NYHOPS 2xCO2 TCR projected effects presented here may be considered as upper estimates for possible changes in habitat availability within Long Island Sound due to bottom water temperature increase for the two fish guilds and American lobster under a CO2-doubling scenario and, importantly, timeframe.

Habitat suitability indices for the cold and warm temperate fish guilds were applied to the projected bottom water temperatures averaged over 20 years around the double-CO2 year +70. As with the NYHOPS Hindcast simulation, output was summarized to create bottom temperature means for each CT DEEP LISTS sample grid. Annual frequency tables were then created for HSI levels equal to or above 0.8 and equal to or below 0.3 for each 0.1°C temperature interval in output matrix.

Resulting TCR projected frequencies showed that spring area*days with preferred temperatures (HSI=>0.8) for the cold temperate fish guild increased approximately 10% (Figure 29). This increase would come from a large decline in the area*days with low temperatures below 7°C, compensating for an increase in area*days with high temperatures above 19°C. For the warm temperate fish guild, projected spring area*days with preferred temperature increased approximately 20%.

Dividing TCR projected area*days into the four types examined in the hindcast (Figure 30), large change was seen in the percent of total spring area*days where a) both guilds' HSI<0.8 (type 1, preferred for neither) – which declined three-fold – and, b) where cold guild HSI<0.8 (type 4, preferred for warm species only) – which increased three-fold – from the hindcast to the TCR projection. Smaller increases were seen in the percent area*days where cold guild HSI>0.8 and warm guild HSI<0.8 (type 2, preferred for cold species only) and area*days where both guilds' HSI>0.8 (type 3, preferred for both guilds).

To examine how spring area*days unsuitable (HSI<0.3) for both guilds may change, TCR-projected values were compared to values for 1980-1999 and 2000-2013. For the cold guild, the percentage increased negligibly in the TCR projection (from, <1% to 2.3%), while the percentage for the warm guild decreased to less than half hindcast values in the projection (from 40% in 1980-1999, to 35% in 2000-2013; to 13% in the TCR). Such changes would greatly increase the probability of competition between the two guilds in time and space.

TCR-projected change in annual area*days with preferred temperature for lobster changed very little in the TCR projection from hindcast years (Figure 31). This result was due to the fact that annual area*days with temperatures below the preferred range declined, adding to area*days in the preferred range almost at the same rate as area*days with temperatures above the preferred range increased. Importantly however, area*days with temperatures equal or above this species' stress threshold of 20°C increased from 17-19% of total annual area*days in 1980-2012 to 31% in the TCR projection.

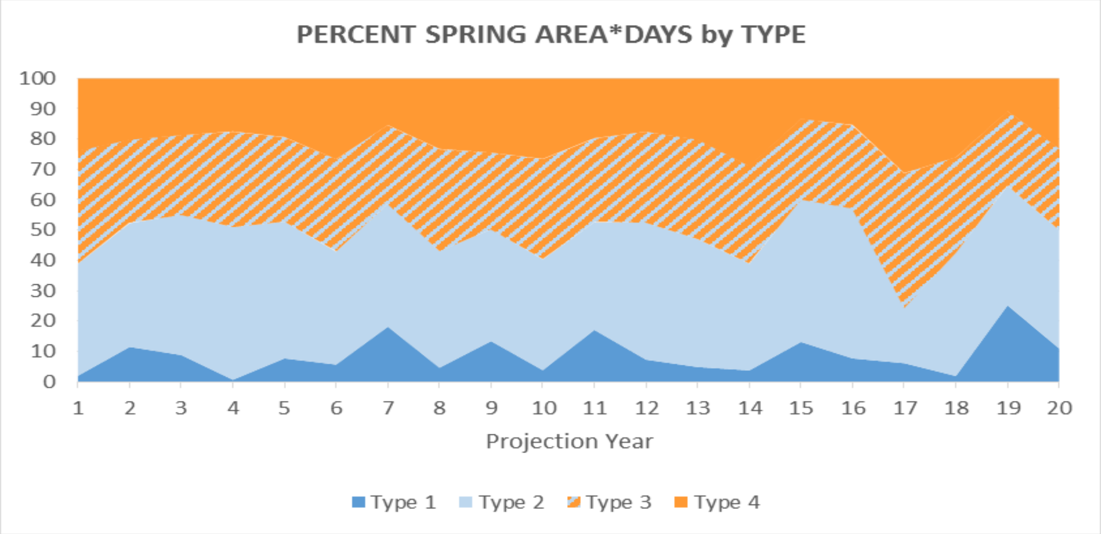


Figure 29: TCR projected percent spring area*days below, above and within preferred bottom temperature ranges for cold and warm temperate fish guilds.
Type 1 = preferred for neither guild; Type 2 = preferred for cold guild only; Type 3 = preferred for both guilds; Type 4 = preferred for warm guild only.

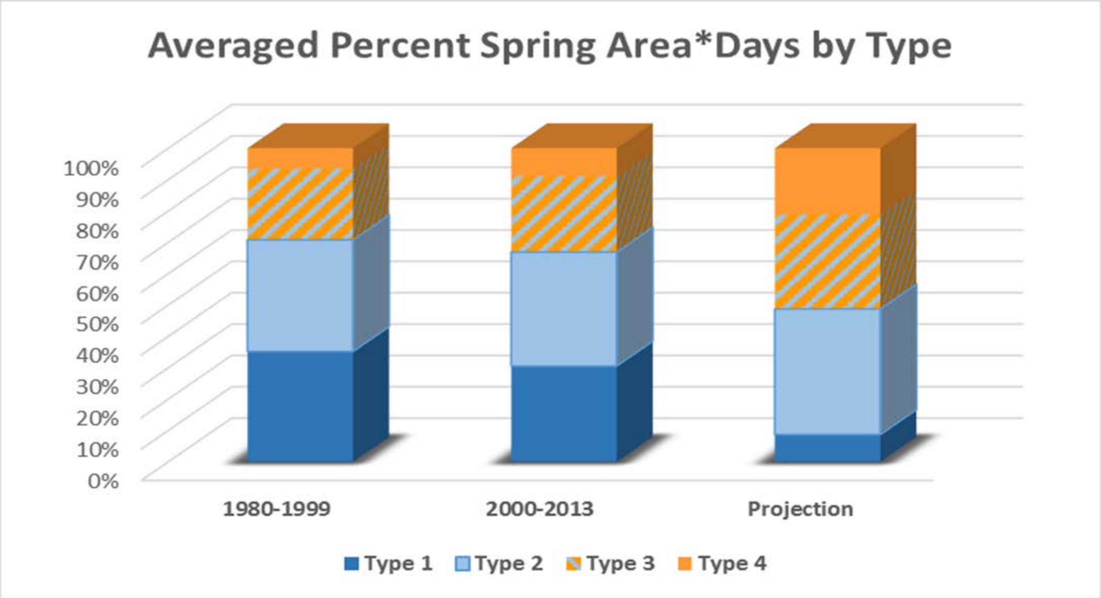


Figure 30: Percent spring area*days below, above and within preferred bottom temperature ranges for cold and warm temperate fish guilds, 1980-2013, compared to a 20-year projection. See text for description of the projection conditions. In the projection, very cold area*days (type 1, preferred for neither guild) show a large decline while area*days preferred for the cold guild only (type 2) increases slightly. Percent area*days preferred for the warm guild only (type 4) increases 3-fold in the projection, and percent area*days preferred for both guilds (type 3) increases by a third, increasing the probability of competition between the two guilds.

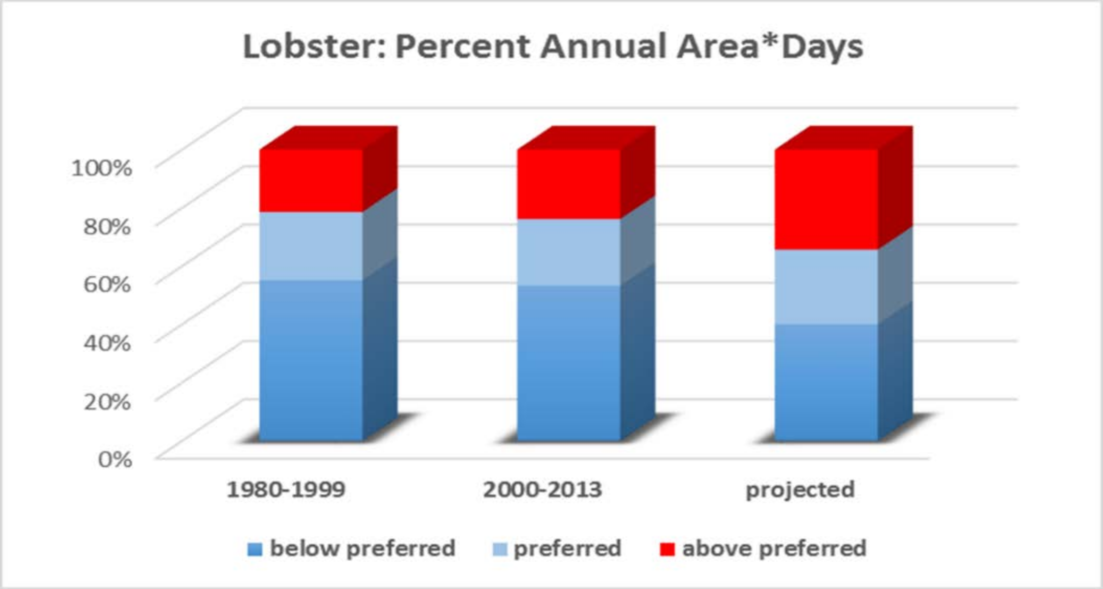


Figure 31: Percent annual area*days with bottom water temperature preferred for American lobster, above and below the preferred range, 1980-2013, compared to a 20-year TCR projection. See text for description of the projection conditions.

C2. Scientific Abstract [Public]:

Augmenting a sparse observation record through numerical simulations conducted with the New York Harbor Observing and Prediction system (NYHOPS) model, this work used exploratory statistical analyses to understand the controls of observed trends in the physical ecospace of Long Island Sound and how such processes affect LIS fish stocks. Based on extensively validated numerical model results, the project evaluated conditions over the past three and a half decades and identified warming and freshening trends in Long Island Sound, and increase in stratification. Correlations of temperature and salinity data and model results to climate indices were then used, along with wavelet analysis, to research how global climate contributes to long-term and inter-annual variability in the LIS physical environment. Climate variability in Long Island Sound was found to be significantly related to climate modes of the Pacific Ocean through the local translation of cross-continental atmospheric forcing. The Pacific Decadal Oscillation, in particular, extends beyond being a LIS climate driver, to found correlations to fish abundance during the CT DEEP spring survey, perhaps through thermal habitat controls. The strong correlations to climate indices found for some species and guilds during this research pave the way to climate outlooks (seasonal forecasts) for fisheries. Thermal Habitat Suitability Indices created through correlations and ANOVA from survey data were applied using the NYHOPS hindcast bottom temperatures to deduce historic trends in two LIS fish groups: one warm- and one cold-temperate guild. Statistically significant positive trends were found for suitable thermal habitat for the warm guild and unsuitable thermal habitat for the cold guild, supporting previous studies that have hinted that the recent warming of the Sound has cold temperate fisheries moving out and warm temperature fisheries moving in. The research also suggests that in 1997 a regime shift occurred in Pacific Ocean climate modes: more negative PDO (as well as East Pacific /

North Pacific Oscillation) phases were preferred and a preference for positive Long Island Sound water temperature anomalies was also identified. A similar analysis was done for lobster that identified 1999 as an outlier thermal habitat year supporting the theory that warm temperatures were the primary cause for that year's historic die-off; 2012 was an even warmer outlier year. The project also attempted to use the NYHOPS model to project the changes that the LIS marine physical space and ecosystem would undergo if subject to a Transient Climate Response (TCR) scenario of continuous annual increases in CO2-equivalent emissions amounting to 1% per annum over this century. There is enough evidence presented to argue that LIS managers will need to consider the likelihood of substantial and widespread climate-driven changes to the LIS management areas they are in charge of, both due to global climate change and due to the manifestation of climate modes onto the local climate phases. Significant advances were made here to increase confidence in future projections under multiple climate change scenarios, and in creating regression models to make long-lead predictions for Long Island Sound's climate and fisheries that could inform stock assessments.

C3. Problems Encountered:

Due to the comprehensive nature of the inter-disciplinary modeling and statistical analyses that were carried forward in the course of the research, an issue the research team and the Principal Investigator in particular had to grapple with was that of time management. As with any research endeavor, the entire research team's efforts were driven by a strong desire to do the best its members could to provide the highest quality science products it could, in the time provided. In this case, it was harder than usual to make decisions on "scope limitations:" how best to deal for example with gaps in some historic datasets in a scientifically defensible way without compromising the value of the work measured by the skill of numerical model results; models that, once setup, take months to run and provide the results needed for their skill to be assessed in its entirety (the "one chance to get it right" issue). However, and given the awarded no-cost extension the project received, the team strongly believes it succeeded in progressing the state of science in all of its diverse research objectives. Once the high-quality model results became available, exploratory analyses with management implications quickly and robustly advanced, continue to this day, and will undoubtedly grow in the future. The project not only was successful in creating datasets that are already in high demand, but also new practical methodologies through valuable interactions and collaborations with managers and agencies. The research team is thus very grateful for the opportunity it received through this funding cycle to generate meaningful and applied research products for Long Island Sound.

C4. New Research Directions:

The project resulted in exciting new directions for modeling and climate research, primarily due to the interdisciplinary strengths of the team that was assembled here.

With regard to numerical modeling, the model's skill in simulating water temperature, validated against historic data from the Long Island Sound (LIS) bottom trawl survey and the NYCDEP Harbor Survey, has not drifted over the years, a significant and encouraging finding for future multi-decadal model applications used to identify climatic trends and drivers. This hindcast presents a great baseline dataset for future multi-decadal sensitivity studies in Long Island Sound and beyond, and presents an enormous opportunity for coupling to multi-decadal investigations on shifts to eutrophication dynamics, pathogens, or other fate and transport related research. The accomplished first-ever dynamic downscaling of a Transient Climate Response of Long Island Sound to a climate future of double effective CO2 concentrations, provides guidance for improved dynamic climate projection methods based on downscaled models, as well as shows that this kind of modeling can be accomplished in the future for multiple climate change scenarios.

Some of the most exciting and promising results of the research are with regard to a new climate teleconnections research direction (e.g. the links of the Pacific climate oscillations to that of Long Island Sound temperatures and fisheries). This novel direction has a strong potential to enhance our understanding of global climate forcing to local physical and ecosystem responses and can lead into potential for climate outlooks (medium range or seasonal outlooks for habitat parameters and LMR) hypothesized and tested with the exploratory statistical analyses that has been outlined fist in this work. The strong correlations to climate indices found for some species and guilds during this research pave the way to climate outlooks (seasonal forecasts) for fisheries.

C5. Interactions:

In April 2013, by invitation from the Long Island Sound Study, we made a presentation at the 22nd Annual Long Island Sound Summit at Iona College (http://www.nhregister.com/general-news/20130427/long-island-sound-summit-focuses-on-ways-to-address-new-normal-issues-brought-to-light-by-sandy-video). The presentation's title was "Sandy and the big "climate change" picture." Slides are available here: http://www.slideshare.net/rebeccakaplan16/sandy-and-the-big-climate-change-picture-nickitas-georgas. A video excerpt was posted by the hosts here: http://www.youtube.com/watch?v=XHdJ6pyeVb0. We held a project meeting after the presentation. The presentation's impact was quite large, was followed with an interview by an NPR reporter, was shared with members of Northeast Utilities and the International Association of Emergency Managers, and spawned thought and information sharing with, among others, the Cities of Bridgeport, Stamford, and New York with regard to resilience against the threat of coastal storms under projected climate change. Throughout the first year of this project we continued engagement with New York City through the New York City Panel on Climate Change II and the NOAA Consortium for Climate Risk in the Urban Northeast, and contributed research on flooding for the City of Stamford and New York City. We were invited and attended the release of Mayor M. Bloomberg's "Plan for a Stronger More Resilient New York" as we contributed research to New York City's Special Initiative for Rebuilding and Resiliency (SIRR) including projections of the flooding in Western Long Island Sound and the East River were Sandy to have hit at a different tidal stage (http://www.prweb.com/releases/2013/6/prweb10829630.htm."). On September 25 3013, again by invitation, we presented our work on Changing Climate Patterns and Adaptation Strategies to SoundWaters (http://www.soundwaters.org/get-involved/business-the-environment/). That presentation was followed by a meeting on the project's Quality Assurance Control Plan with EPA staff. On October 17, 2013, we presented at the Mid-Atlantic Bight Meteorology and Oceanography Meeting our work in quantifying historic trends of river water temperatures in the North-East that is used as inputs in our hindcast for the Sound's receiving water model. In the meantime, as members of the Open Ocean Study Group and the Mid-Atlantic Regional Association of Coastal Ocean Observing Systems (MARACOOS) Fisheries Group, we were involved in synergistic research on the Butterfish stock assessment with colleagues from NMFS and partner academic institutions. At the one year anniversary of Sandy (October 29 2013) we convened a special event at Stevens Institute of Technology with notable speakers from the National Oceanic and Atmospheric Administration, the U.S. Coast Guard, the U.S. Army Corps of Engineers, Northeastern University and Stevens' Davidson Laboratory – focused on bolstering urban coastal infrastructure resilience to flooding from storm surge, as well as related social and policy issues (http://www.stevens.edu/news/sandy). During the second year of the project, we also worked with NYC DEP to use the NYHOPS model to forecast fate and transport of pathogens in the Harbor to inform waterbody and beach wet weather advisories and were able to work with their data to further validate the model as seen in Appendix A. Georgas was invited to give a talk at the North Atlantic Regional Team Meeting in August 2015 on fisheries-supporting simulations for the region. Two talks with results from the work were presented at the joint meeting of the Mid-Atlantic Bight Physical Oceanography and Meteorology and Mid-Atlantic Chapter of the American Chapter of the American Fisheries Society in October 2015. In January 2016, after meeting at EPA Region 2 Headquarters to synthesize the work, the team presented its findings in front of the LISS Management Committee. In February, Georgas was invited to present on the work at SOMAS Stony Brook University, followed by a research team presentation at UCONN in front of the LISS Science and Technical Advisory Committee. The work has generated tremendous interest, and we anticipate that the release of this report, and the publication of the associated manuscripts that are in preparation, will too. Finally, throughout the project period, we continued providing operational 72hr forecasts with the NYHOPS model, updated 4 times daily, to the US Coast Guard's SAR office, NOAA OR&R, and the NWS.

C6. Presentations and Publications:

Publications (published only):

Georgas, N., Orton, P., Blumberg, A., Cohen, L., Zarrilli, D., and L. Yin. 2014. *The impact of tidal phase on Hurricane Sandy's flooding around New York City and Long Island Sound.* Journal of Extreme Events. Vol 01, Issue 01, 1450006 (2014). DOI: 10.1142/S2345737614500067. 32pp.

Presentations:

Georgas, N., Howell, P., Saba, V., Schulte, J., Blumberg, A.F., Orton, P., Yin, L., Jiang, Y., and Y. Wang. 2016. *Analyzing History to Project and Manage the Future: Simulating the Effects of Climate on Long Island Sound's Physical Environment and Living Marine Resources*. Long Island Sound Study Science and Technical Advisory Committee Meeting. UCONN Groton, CT, February 19 2016. Invited Talk. Presented by Nickitas Georgas, Justin Schulte, and Penelope Howell.

Georgas, N. 2016. *Novel numerical modeling applications for short- and long-term environmental forecasting: From Coastal Events to Fisheries Outlooks*. SOMAS

Seminar Series. SUNY Stony Brook, NY, February 3 2016. Invited Talk. Presented by Nickitas Georgas. <Online link: https://www.youtube.com/watch?v=mjAYbaArw14>

Georgas, N., Howell, P., Saba, V., Schulte, J., Blumberg, A.F., Orton, P., Yin, L., Jiang, Y., and Y. Wang. 2016. *Analyzing History to Project and Manage the Future: Simulating the Effects of Climate on Long Island Sound's Physical Environment and Living Marine Resources: Year 2*. Long Island Sound Study Management Committee Meeting. Housatonic Community College, Bridgeport, CT, January 20 2016. Invited Talk. Presented by Nickitas Georgas and Penelope Howell. <Online link: http://www.stevens.edu/ses/documents/fileadmin/documents/pdf/LISStalk_Georgas_et_al_Final.pdf>

Georgas, N., Howell, P., Saba, V., Schulte, J., Blumberg, A.F., Orton, P., Yin, L., Jiang, Y., and Y. Wang. 2015. *Climate links to Long Island Sound fisheries: Anomalies, trends, and teleconnections based on a 34 year NYHOPS physical model hindcast analysis*. Mid Atlantic Chapter of the American Fisheries Society 2015. Cape May Conference Center, Cape May, NJ, October 29 2015. Presented by Nickitas Georgas. <Online link: http://maracoos.org/sites/macoora/files/downloads/presentations/2015/mabpom/mabpom2015georgas.pdf>

Schulte, J., Georgas, N., Blumberg, A.F., Orton, P., Saba, V., Howell, P., Yin, L., Wang, Y., and Y. Jiang. 2015. *Meteorological and Climate Forcing of Temperature and Salinity Variability in the Long Island Sound*. Mid-Atlantic Bight Physical Oceanography and Meteorology Meeting (MABPOM) 2015. Cape May Conference Center, Cape May, NJ, October 28 2015. Presented by Justin Schulte. <Online link: http://maracoos.org/sites/macoora/files/downloads/presentations/2015/mabpom/mabpom2015schulte1.pdf>

Georgas, N. 2015. *Identifying opportunities and challenges in LIS/MAB estuaries: State of Linking Models And Processes in LIS/MAB*. NOAA North Atlantic Regional Team Meeting. Norrie Point Environmental Center, Norrie Point, NY, August 27 2015. Invited Talk. Presented by Nickitas Georgas.

Georgas, N. 2015. *Developing the Tools for Science, Navigation and Emergency Response: New York Harbor Observing & Prediction System (NYHOPS)*. 2015 Hudson River Symposium. New Paltz, NY, May 06 2015. Invited Talk. Presented by Nickitas Georgas. <Online link: http://www.hres.org/joomla/download/2015%20FINAL%20Symposium%20Program.pdf >

Schmidt, A., Georgas, N., Manderson, J., Kohut, J. and A. Gangopadhyay. 2014. A simple bias correction to improve bottom temperature estimation. 17th Biennial Ocean Sciences Meeting. Hawaii Convention Center, Honolulu, HI, February 24 2014. Poster. Presented by A. Schmidt. <Online link: http://www.sgmeet.com/osm2014/viewabstract.asp?AbstractID=16098>

Georgas, N., Orton, P., Howell, P., Saba, V., Blumberg, A.F., and L. Yin. 2013. *Sandy and the big "climate change" picture*. 22nd Annual Long Island Sound Citizens

Summit. Long Island Sound Study. Iona College, New Rochelle, NY, April 26 2013. Invited Talk. Presented by Nickitas Georgas. <Online link: http://www.slideshare.net/rebeccakaplan16/sandy-and-the-big-climate-change-picture-nickitas-georgas>

Georgas, N. 2013. *Changing Patterns: Adapting to Local Impact of Weather Events*. SoundWaters Business and the Environment Speaker Series, University of Connecticut, Stamford, CT, September 25 2013. Invited Talk. Presented by Nickitas Georgas.

Jiang, Y., and N. Georgas. 2013. *Recent trends of river water temperature in the Mid-Atlantic*. 38th Mid-Atlantic Bight Physical Oceanography and Meteorology Meeting. University of Rhode Island, Narragansett, RI, October 17 2013. Presented by Yu Jiang. <Online link: http://www.po.gso.uri.edu/~dave/MABPOM2013_presentations/jiangMABPOM2013.pdf>

D. Accomplishments:

D1.

Impacts & Effects: The project generated new knowledge that will inform Long Island Sound Science for years to come. The results of the NYHOPS hindcast, and the online archive created, are already in demand by researchers and consultants in the field. We have been contacted specifically by researchers from both the University of Connecticut and Stony Brook (we can provide names) that want to use the results of the hindcast to provide forcing to their local Long Island Sound embayment models to answer scientific and applied questions for regional and local funding agencies. Being able to gain access and quickly view and animate short-term forecast anomalies (compared to the generated hindcast daily climatologies) for surface to bottom Long Island Sound properties is very powerful and useful. NYC DEP has learned of the NYHOPS hindcast and its quality and has an interest in using its results to address Long Term Control Plans and studies. Our colleagues in the Mid-Atlantic Regional Associations' Fisheries Subcommittee and NYS DEC, long interested in the NYHOPS operational forecasts for fish sampling, are interested in the exploratory research done on the NYHOPS hindcast as it could inform stock assessments in the future. Further, the novel exploratory statistical techniques that were applied in this study to investigate and prove teleconnections between climate modes, the regional environment, and fisheries abundance can be applied not only to create long-lead predictions (outlooks) in the future for temperatures, salinities, and fisheries, but to other parameters and even different science fields. CT DEEP Marine Fisheries Division staff will use the TCR temperature data set, in conjunction with local tagging studies, to estimate increasing habitat suitability in LIS for blue crab (*Callinectes sapidus*) as a potential new opportunity for commercial and recreational harvest in LIS.

D2. Student(s) Status:

Name: Yu Jiang. **Time period supported:** Fall Semester 2013 to December 2014. **Degree Program:** Master of Engineering in Ocean Engineering. **Graduation Date:** May 2015.

Name: Yifan Wang**. Time period supported:** September-October 2015**. Degree Program:** Master of Engineering in Ocean Engineering**. Graduation Date:** May 2016**.**

Name: Larry Yin**. Time period supported:** January 2015 to October 2015**. Degree Program:** Doctor of Philosophy in Ocean Engineering**. Anticipated Graduation Date:** Summer 2017**.**

Name: Bin Wen**. Time period supported:** February 2014**. Degree Program:** Doctor of Philosophy in Ocean Engineering**. Anticipated Graduation Date:** Summer 2017**.**

Name: Dr. Justin Schulte**. Time period supported:** September-October 2015**.** Post-Doctoral.

D3. Volunteers: N/A

D4. Patents: N/A

E. Stakeholder Summary [Public]:

Fisheries management has traditionally sought to reduce harvesting levels in response to low stock biomass, in its goal to maintain long-term fishery productivity (Mahon 2008). More recently, accounting for non-stationary environmental forcing has started being considered in stock assessment and management (Manderson et al 2014) with the realization that a failure to account for shifts in climate that can alter population dynamics can lead to stock collapse as with the Gulf of Maine cod fishery (Pershing et al 2015). This progress has been facilitated by new population dynamics models that consider temperature-dependencies and an improved understanding in climate-fisheries teleconnections brought about through advanced in environmental modeling.

Over the last few decades, the LIS ecosystem has undergone profound changes. Large-scale temperature increase and changes in circulation have been hinted as the most important factors associated with shifts in the mean center of biomass in Northeast fisheries (Nye et al 2009, Howell and Auster 2012, Pershing et al 2015). Yet, understanding what controls the observed trends in the physical ecospace and how such processes affect LIS stocks was limited due to the paucity of available physical environment data within LIS. This project used a multi-disciplinary approach to address this deficiency through a collaboration of numerical modelers, LIS fishery trawl survey researchers, and fishery biologists from the NOAA NMFS Northeast Fisheries Science Center residing at NOAA GFDL. A website was setup to make time series of observations from in-situ station sources easily accessible and downloadable (http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml), including the ability to plot a time series based on a selected date range and to show station location on a map. The project evaluated conditions and identified warming and freshening trends in Long Island Sound's over the past three decades, and researched how global climate contributes to long-term and inter-annual variability in the LIS physical environment and its Living Marine Resources, especially through found climate teleconnections between the Pacific Ocean and LIS. It also attempted to project the changes the LIS marine physical space and ecosystem would undergo if subject to a Transient Climate Response

(TCR) scenario of continuous annual increases in CO2-equivalent emissions amounting to 1% per annum over this century. Although this is only one climate change scenario, and the research team has identified a need for future research in improving the dynamic downscaling methodology used to making such future projections, and thus has limited confidence as to the extent of the magnitude of the changes it projected by the end of this century under the 1%/annum CO2 TCR, there is enough evidence presented to raise significant concern, and argue that LIS managers will need to consider the likelihood of substantial and widespread climate-driven changes to the LIS management areas they are in charge of. Significant advances were made here to increase confidence in future projections under multiple scenarios.

Since 1976, every year, including 2015, has had an average global temperature warmer than the long-term average. Over the 1979-2013 period, global temperature warmed at an average of 0.26 °C per decade over land and 0.10 °C per decade over the global ocean (NCDC 2016). The recently signed Paris Agreement (UN 2015), adopted by 195 countries, has a long-term goal of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels, and aims to limit the increase to 1.5 °C, as doing so is expected to significantly reduce risks and the impacts of climate change. Regionally, the Northeast shelf waters are warming as deduced by the Sea Surface Temperature (SST) satellite record. Pershing et al (2015) reported that SST rose by 0.30 °C per decade between 1982 and 2013 in the Gulf of Maine. However, the only long term observation record for water temperatures within Long Island Sound near Millstone CT (DRS 2015) has measured a much more rapid increase in LIS water temperatures that the global average: an alarming 0.44 °C per decade between 1979 and 2013, over 4 times higher than the global average rate. For coastal CT, surface air temperatures for the same time period increased by 0.33 °C per decade; that rate was double if only the 1992-2012 period was considered, but has decreased somewhat since, to 0.28 °C per decade (1979-2015; NCDC 2016).

Through the comprehensively-forced, validated multi-decadal simulation for Long Island Sound's physical environment performed for this project using Stevens Institute of Technology's NYHOPS hindcast model these temperature increases have been confirmed and have been found to be statistically significant in the present work. After extensive model validation and debiasing (see section C2 and Appendices), an online THREDDS Data Server (http://colossus.dl.stevens-tech.edu/thredds/catalog.html) was setup to serve the NYHOPS model's results in NetCDF format over the web using the OPENDAP protocol, enabling open access to daily averaged or monthly averaged time series for all the gridded hindcast physical variables in or over Long Island Sound. Simulated climatologies (mean simulated climate conditions averaged over the three decades of the NYHOPS hindcast period) for two- and three-dimensional fields such as water temperatures and salinities, were also generated, and included in THREDDS. These open-access datasets are already in high demand by scientists, engineers, and managers doing work in Long Island Sound and beyond. Included on the same THREDDS server, is a "daily anomaly" dataset, comparing the latest operational forecast of the NYHOPS model to the 1981-2013 debiased daily climatology, so that interested parties can see how different yesterday and the next 3 days are predicted to be from the climatological average, enabling near-term tracking of anomalous patterns in Long Island Sound.

Visualization is easy with off-the-shelf free software, such as NASA's Panoply, accessing the datasets over the web.

Based on the NYHOPS hindcast, in the Long Island Sound basin, surface air temperatures, contributing river temperatures, and receiving LIS-basin-wide water temperatures (0.34±0.08°C per decade) have all seen significant increases between 1981 and 2013; more so on the shallower north shore and western Sound than the south shore. During the same period, based on USGS discharge data, major freshwater river inflows to the Sound increased: the Connecticut River at Thompsonville by 17%, the Housatonic at Stevenson by 21%, and the Hudson at Green Island by 33%. This has led to the Sound overall becoming somewhat fresher (a statistically significant trend of 0.12±0.05psu/decade), especially near river mouths at the surface, increasing stratification and changing long term volumetric transport fluxes in the basin in a statistically significant, nonstationary way.

Analysis of Variance and Trend analyses were used to explain patterns in two groups of non-directed fisheries: cold-temperate and warm-temperate fish guilds; as well as Long Island Sound lobster. Thermal habitat suitability indices (HSI; water-temperature-to-fish-abundance relationships), were first defined based on CT DEEP data. Then, thermal habitat (area*days of preferred temperature ranges) over the past three decades were estimated from temperatures provided by the NYHOPS model hindcast results. In creating HSI, the relationship between abundance and temperature was found to be consistent for both guilds in spring surveys but not fall surveys. Habitat Suitability Indices were thus constructed only for spring surveys. Merging these HSI with the NYHOPS predictions for bottom temperature, a statistically significant upward trend was found in the total area*days with temperatures preferred by the warm-temperate fish guild between 1980 and 2013. No such trend was found for the cold-temperate guild. Further, and using total area*days within specific thermal ranges as a descriptor of habitat quality, it was found that unsuitable habitat for cold species is declining, while the unsuitable habitat for warm species is increasing, especially in the last few years. These results help explain the observed shift in cold-temperate species abundance increasing in the CT DEEP trawl surveys. Statistical analyses for lobster showed that – due to the warming experienced over the 34 years of the NYHOPS hindcast – thermal habitat preferable to lobster was above the time series median only three of the last 12 years, while habitat above the 20 °C thermal stress threshold was below the time-series median only twice in the last 15 years. The results point to an increase of stress in the Sound's lobster population due to environmental factors during the last, warmer period of the hindcast.

Through spectral analysis of the validated NYHOPS hindcast, the present research finds that the Sound, from its surface to its bottom, is primarily forced through surface heat flux exchanges with the overlying atmosphere: 50% to 90% of the month to month bottom temperature signal was found to be associated with the near-surface air temperature signal (coming from the North American Regional Reanalysis in the hindcast), leaving other factors such as advection of North Atlantic ocean waters modulated by Atlantic climate indices in a secondary role. Therefore, and unlike other deep regional basins like the Gulf of Maine or the outer Mid-Atlantic Bight shelf which have been found to also correlate to changes in the Gulf Stream position (Pershing et al

2015), the North Atlantic Oscillation (Marsh et al 1999), and anomalous ocean currents (Chen et al 2015), the LIS water temperatures in the monthly to multi-annual time scales primarily associate with atmospheric rather than regional oceanic forcing. However, the present research is inconclusive whether, longer-term, the slow northward movement of the Gulf Stream over the next centuries predicted by climate models may play a significant role in the future climate of LIS.

A number of exploratory statistical analysis using regression and wavelet theory were used to identify climate teleconnections to Long Island Sound's temperatures first, and then to fisheries. Correlation analysis between LIS surface water temperature and global Sea Surface Temperatures (SST) first revealed that LIS positive water temperature anomalies during the hindcast period were related to pacific SST patters that resembled the Pacific Decadal Oscillation (PDO) but were unrelated to the El-Nino Southern Oscillation (ENSO). Therefore, a climate teleconnection between the Pacific Ocean and the Long Island Sound was investigated and then established through correlation between air and NYHOPS-hindcast water temperatures and climate indices. A strong correlation (r=-0.53) between hindcast annual LIS bottom water temperatures and the Pacific Decadal Oscillation index was found. Lagged correlations between PDO and fish-guild abundance were also found to be statistically significant, and strong (up to r=-0.75 between the previous summer PDO index and next spring's mean warm-guild anomalies). The evidence suggests a remote climate forcing that projects Pacific Ocean climate modes onto Long Island Sound fisheries: planetary Rossby waves originating in the Pacific that modulate LIS's temperature and thus thermal habitat. The found teleconnections can be the foundation for developing regression models that should enable long-lead predictions for regional LIS climate, habitat, and species abundance. In other words, the strong correlations to climate indices found for some species and guilds during this research pave the way to climate outlooks (seasonal forecasts) for fisheries.

Through wavelet output spectrum analysis it was also found that the significant warming of Long Island Sound between 1981 and 2013 was in part (18-26%) due to Pacific Ocean influences. The research suggest that a PDO-related regime shift occurred in 1997: more negative PDO phases were preferred since, and a preference for positive Long Island Sound water temperature anomalies was also identified. This finding suggested that if the PDO phase changed sign, as it appears to have done since 2013, the regional warming trend should decrease, as it since has. Thus, some of the apparent warming trend of LIS water temperature time series may be due to natural variability, assuming that anthropogenic influences do not project onto these patterns. Similar investigations were conducted for salinity, where a significant correlation (r=-0.57) was found between the annual NYHOPS-hindcast bottom salinity in LIS and the annually-averaged Eastern North American mean sea level dipole pattern (ENA Index; Schulte et al 2015), again leading the way for long-lead predictions.

Turning next into the long-term future, a future climate change / Transient Climate Response (TCR) scenario for Long Island Sound was studied by dynamically downscaling a "CO2-doubling" TCR (1% annual CO2 increase each year for 80 years) projection from a state-of-the-art global climate model (NOAA GFDL's CM2.6), by using the global climate model to force a regional NYHOPS simulation. The goal was to create a methodology for such dynamic downscaling, and enhance our understanding of local impacts and sensitivities to global climate change; especially its potential effects on water temperatures and thermal habitat for Living Marine Resources (LMR). Since it takes about 70 years at the 1% annual rate to reach CO2 doubling, the NYHOPS model was run from years +58 to +80. The most significant changes in the NYHOPS 2xCO2 TCR surface forcing functions compared to the NYHOPS historic 1981-2013 hindcast was the increase in near surface air temperature, on the order of +2.6 °C compared to hindcast climatology, NYHOPS-region-wide, with higher increases in the winter months in LIS, and lower in the summer months. The other significant change in forcing for the NYHOPS TCR is the CM2.6 model prediction of +3 °C or greater year-round increase in water temperatures at the continental shelf break consistent with a predicted northward motion of the warmer and saltier Gulf Stream over the next century. After the model TCR run was completed, it was found that the temperature response of LIS to the assigned atmospheric forcing was higher than the PIs expected, an annual mean of +3.8 °C compared to the NYHOPS historic 1981-2013 baseline (but up to +5 °C in December and January). It is hypothesized that this higher than expected increase in water temperatures is most likely due to the way wind forcing was applied in the NYHOPS TCR simulation, as monthly-averaged values deduced from GFDL CM2.6 (unlike the 3hourly forcing based on NARR used in the NYHOPS Hindcast). This led to non-linear under-estimation of the sensible and latent heat fluxes in the TCR due to lack of wind variability, especially in the winter cool season. It is recommended that future projections using dynamic downscaling of global models consider day-to-day wind variability in the forcing.

Finally, based on the LIS water temperatures simulated in the NYHOPS TCR, calculations of preferred habitat for the cold-temperate fish guild during spring was projected to increase by 10% after CO2-doubling compared to the NYHOPS Hindcast period: as waters were simulated to warm significantly, more available area*days were found to be within the range of 7 to 19°C preferred by the cold guild. The warm-guild also was simulated to see an increase in area*days of about 20% as its HSI was found not to have a strong upper temperature bound. Further analyses also suggested an expected increase in competition in both time and space among the two fish guilds under a warming 2xCO2 scenario for Long Island Sound. For lobster, TCR projected change in preferred temperature days (8 to 12°C) compared to hindcast years was almost null. However, and as expected, days above the 20°C stress threshold were projected to increase significantly under the TCR, to 31% of total available area*days, compared to 18% in the 1981-2013 hindcast.

F. Pictorial:

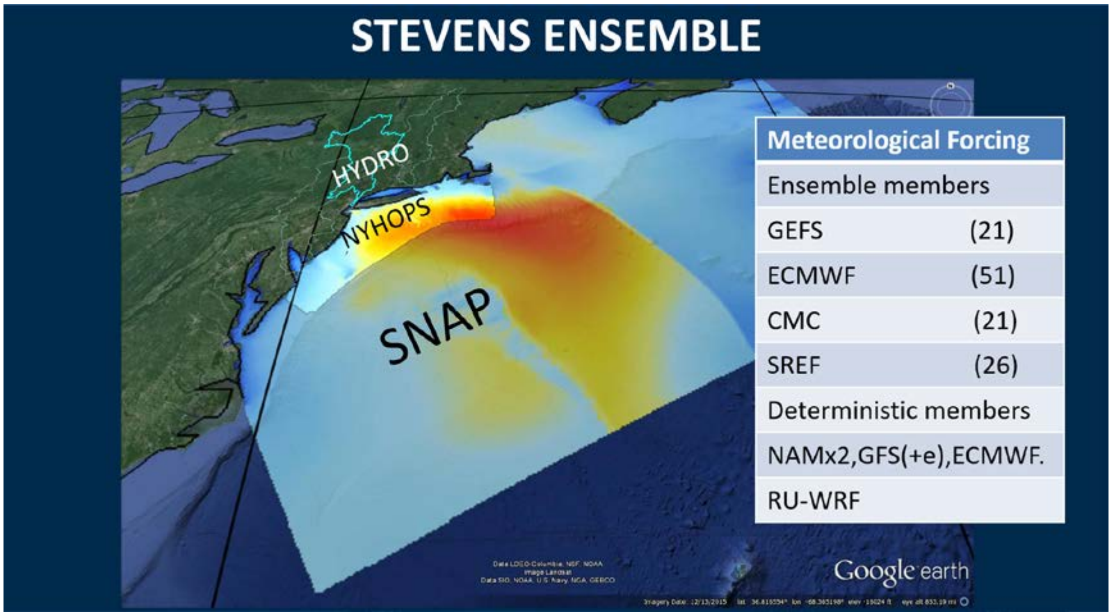
NYHOPS model website: http://hudson.dl.stevens-tech.edu/maritimeforecast/

NYHOPS model predictions in Google Earth format:
http://hudson.dl.stevens-tech.edu/maritimeforecast/google/gcmplt.kml

Latest real-time observations in the NYHOPS system in Google Earth format:
http://hudson.dl.stevens-tech.edu/maritimeforecast/google/Stevens_Database.kmz

Display interface and data download page for NYHOPS stations that include Long Island Sound: http://hudson.dl.stevens-tech.edu/maritimeforecast/PRESENT/data.shtml

NYHOPS THREDDS Server for remotely accessing the hindcast, TCR, and operational forecast datasets: http://colossus.dl.stevens-tech.edu/thredds/catalog.html



Meteorological Forcing	
Ensemble members	
GEFS	(21)
ECMWF	(51)
CMC	(21)
SREF	(26)
Deterministic members	
NAMx2,GFS(+e),ECMWF.	
RU-WRF	

The operational NYHOPS forecast model is now ran as an ensemble prediction system embedded into SNAP, and merged with an upstream hydrologic ensemble forecasting system.

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Appendices:

A. NYHOPS Historic Hindcast Validation

B. NYHOPS Historic Hindcast Results

C. NYHOPS TCR Description and Discussion

D. NYHOPS TCR Results