Title: Timescales for determining Temperature and Dissolved Oxygen Trends in the Long Island Sound (LIS) Estuary

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Abstract

Long-term time series represent a critical part of the oceanographic community's efforts to discern natural and anthropogenically forced variations in the environment. They provide regular measurements of climate relevant indicators including temperature, oxygen concentrations, and salinity. When evaluating time series, it is essential to isolate long-term trends from autocorrelation in data and noise due to natural variability. Herein we apply a statistical approach, well-established in atmospheric time series, to key parameters in the U.S. east coast's Long Island Sound estuary (LIS). Analysis shows that the LIS time series (established in the early 1990s) is sufficiently long to detect significant trends in physical-chemical parameters including temperature (T) and dissolved oxygen (DO). Over the last two decades, overall (combined surface and deep) LIS T has increased at an average rate of 0.08 ± 0.03 °C yr^{-1} while overall DO has dropped at an average rate of 0.03 ± 0.01 mg $L^{-1}yr^{-1}$ since 1994 at the 95% confidence level. This trend is notably faster than the global open ocean T trend (0.01°C yr^{-1}), as might be expected for a shallower estuarine system. T and DO trends were always significant for the existing time series using four month data increments. Rates of change of DO and T in LIS are strongly correlated and the rate of decrease of DO concentrations is consistent with the expected reduced solubility of DO at these higher temperatures. Thus, changes in T alone, across decadal timescales can account for between 33 to 100% of the observed decrease in DO. This has significant implications for other dissolved gases and the long-term management of LIS hypoxia.

Key Words: Time Series, Long Island Sound, Dissolved Oxygen, Temperature Trends, Hypoxia, Climate

Conflict of Interest: none

1. **Introduction**

Long-term time series (LTTS) are just emerging in the oceanographic community relative to atmospheric and terrestrial systems. Among the oldest lasting time series for multi-parameter hydrographic and oceanographic data are Hydrostation "S," which was started in the early 1950s in Bermuda and the pier data from Woods Hole which started in 1886, (Windsor 2003, Michaels and Knap 1996, Nixon et al., 2004). Oceanographic monitoring stations have historically collected data which includes air and water temperatures, salinity, wind speeds, and wave heights; parameters which arise from their origins as meteorological data sets (Karl and Lukas 1996). In the last decade, as instrumentation has evolved, time series have expanded to include pCO_2, pH, and other chemical and biological parameters (Windsor, 2003). These data sets capture monthly, seasonal, annual, and decadal changes in ocean chemical, physical, and biological systems. They also represent a recent ability to track decadal trends in key parameters in the midst of a changing climate, where trends are defined as significant shifts in the mean (Chatfield, 2013). However, evaluating trends on such long time scales requires an assessment of the minimal time required to confirm a significant change within the "noise" of natural variability in seasonal, interannual, and decadal fluxes (including both large and small scale physical phenomena).

Tiao *et al.* (1990) and Weatherhead *et al.* (1998) provide a comprehensive methodology to calculate the amount of time necessary for a significant detection of a trend at a given confidence level. This method has been successfully applied to atmospheric data (Tiao *et al.* (1990), Weatherhead *et al*., 1998) and recently to the open ocean by Henson *et al.* (2016). The method emphasizes the need to analyze trends and spatial correlations in the context of autocorrelation in the data. The method combines the magnitude of the trend, the noise in the data, and normalizes the data by autocorrelation to yield n*, the number of years required in a time series to confirm a linear trend at a specific significance level. The major advantage of the n* method is that it does not have intrinsic requirements in terms of total observation time (Tiao *et al*., 1990, Hirsch *et al*., 2010). This makes the approach adaptable for application in a broader range of time series to identify the adequacy of the resolution and to identify additional resolution where needed to achieve a given statistical confidence. This study uses the Tiao *et al*. (1990) method in the U.S. East Coast's Long Island Sound (LIS) estuary inspired by Henson *et al.* (2016) though results are expected to differ from these open ocean estimates (as coastal systems likely respond differently due to the significant influence of local weather patterns). LIS provides a suitable example because of its long history as an urban estuary, its recurring issues with hypoxia, and because it has been monitored for over 20 years, through the Long Island Sound Study and the Connecticut Department of Energy and Environmental Protection (CT DEEP) (Wolfe *et al*., 1991, Kaputa and Olsen, 2000, UConn_2016_DEEP_LIS_Data, LISS Biennial Report, 2004).

Long Island Sound is a partially mixed estuary (Turekian *et al*., 1994). It is 185 km long and 30 km wide near the center though it narrows at both the eastern and western ends and opens to the Atlantic Ocean primarily at the eastern end. The eastern end contains a deep swift channel and is guarded by several small islands, including Fisher's Island and Plum Island. The western end opens to the Atlantic via the East River. LIS is separated into three distinct sections by a series of irregular sills; the deeper, well scoured eastern basin (90 m average depth) and the shallower central and western basins (40 m average depth). The western basin experiences recurring hypoxia annually. This low oxygen deep water zone has expanded spatially over the last 60 years despite nitrogen mitigation strategies (LISS CCMP, 1994). The extent of LIS hypoxia is expected to be impacted by a combination of anthropogenic nutrient inputs and physical mixing conditions. Dissolved oxygen (DO) in marine systems is also expected to decrease as the result of increasing global average temperatures (Matear and Hirst, 2003) and reductions in DO have been detected in rivers (Jassby and Van Nieuwenhuyse, 2005) and estuaries of other temperate coastal regions over the last three decades. Physical shifts in large scale atmospheric and current patterns (i.e the North Atlantic Oscillation (NAO)) as well as local shifts in water masses can also drive these local trends as has been suggested in other regions (Gilbert *et al*. 2005). These trends are of particular interest in estuaries since they are linked to possible broadening and intensification of existing seasonal hypoxia and anoxia events. In LIS these trends are particularly important as the ability to predict the extent of hypoxia is poorly constrained and remains a priority.

Since 1991, LIS has been monitored on a monthly basis at 48 stations along its axis for a series of parameters, including nutrients, DO, temperature (T), and salinity (S) both in the surface and at depth (Lee and Lwiza, 2008). In this analysis the Tiao *et al*. (1990) method was applied to DO, T, and S from these data sets. Three stations were chosen along the west-east axis of LIS allowing an assessment across the inland western shore, the central estuary, and the eastern mouth of the estuary bordering the adjacent Mid-Atlantic Bight continental shelf.

2. **<u>Methods</u>**

2.1 Trend Detection

This study uses the approach of (Tiao *et al*., 1990 and Weatherhead *et al.*, 1998) adapted by Henson *et al.* (2016). Briefly, the method evaluates the magnitude of a linear trend and the noise in a time series to calculate how many years of observations are necessary before a trend can be distinguished from observations and a target confidence interval. The data is fit to a linear trend,

$$Y_t=\mu+\omega X_t+N_t \qquad (1)$$

where Y_t is the time series data (ie temperature at time t), μ is the y-intercept, ω is the magnitude (slope) of the trend, X_t is time and N_t is the noise of the data which depends on the variability (both natural and analytical), autocorrelation (seasonal and interannual cycles), and the length of the data period (Tiao *et al.*, 1990, Weatherhead *et al.*, 1998, Henson *et al.*, 2016). In effect it is a linear trend plus noise.

In equation 2 the standard deviation of the noise, $\sigma_{n,}$ is scaled by the target confidence level (a coefficient of 3.3 for 95% confidence) and normalized to the slope, ω. This right term is then corrected by the first order auto-correlation coefficient term Φ, used to represent autocorrelations in the data series that result from lag terms due to persistent weather conditions and natural temporal patterns, including possible long-term and/or climatic forcing mechanisms (i.e. the NAO). Oscillating phenomena such as the NAO are captured in the autocorrelation coefficient and contribute by extending the value of n* and thus the required observational period. The precision of trend estimates depends critically on the magnitude of Φ.

$$n^* = \left(\frac{3.3\ \sigma_n}{|\omega|}\sqrt{\frac{1+\phi}{1-\phi}}\right)^{2/3} \qquad (2)$$

The parameters are combined to determine n*, the amount of time required to establish the trend (i.e. years). A significant limitation of this method is that it assumes a linear trend, and therefore does not account for non-linear rates of change. Although the trend that is identified is significant over a period of n*, projections to future rates of change should be made conservatively and become less accurate for every additional n* years projected. The best results for the n* estimations are reached when additional sources of instrument or measurement error are minimal, or can be calculated with enough accuracy to be removed. When not accountable, any additional sources of error contribute to overall noise and increase the amount of required observation time estimated as n* (Tiao *et al*., 1990). In this case the remarkable consistency in methodology, instrumentation, and calibration of the CT DEEP data for T, DO, and salinity program over its entire time period minimizes this source of error. The method requires that the data points be grouped into evenly-spaced temporal bins and the additional parameters are calculated according to these bins.

2.2 Application to the Long Island Sound

The monitoring program in the Long Island Sound has a fairly large number of stations which are scattered along both the length and breadth of the Sound and are sampled almost monthly by the Connecticut Department of Energy and Environmental Protection (DEEP). For this analysis, three observing stations were chosen along the central west-east axis of the LIS: A4, H4, and M3. A4 is located in the western end of the LIS at 73º 44' 3" W, 40º 52.35' 21" N with an average depth of 32.6m and has been sampled since December 1994. H4 is near the center of the LIS with a depth of 23.7m, located at 72º 56' 2.4" W, 41º 6' 6" N, and has been sampled since June 1994. The final station is M3 which is located at the eastern end of LIS and correspondingly has a much deeper average depth of 72.6m, at 72º 3' 12" W, 41º 14' 13.8" N. It has been sampled since January 1991 (Figure 1). LIS is roughly 6, 30, and 19 km wide at stations A4, H4, and M3 respectively.

The original DEEP station names have been preserved in this study to facilitate future comparisons.

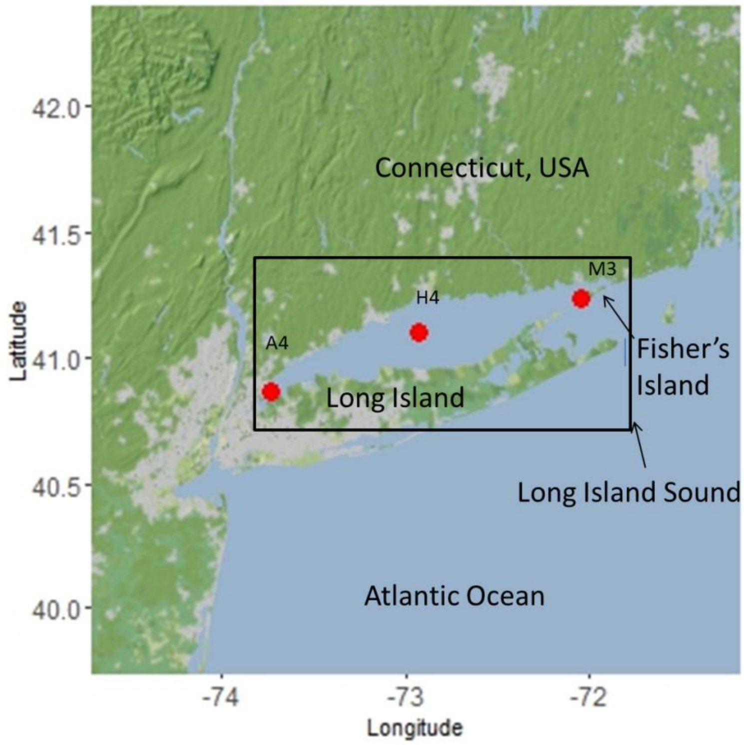

Fig. 1 Selected stations monitored (approximately monthly) year-round by DEEP in the Long Island Sound

Three parameters were selected for this analysis and both bottom and surface measurements were included; T as a major physical control and climate indicator, DO due to the pervasive seasonal hypoxia events in LIS and as a representative dissolved gas, and finally S was chosen as a relatively conservative variable with reasonably accurate and reliable time series that was expected to vary on much longer timescales due to the large fraction of saline continental shelf water in LIS and low residence time of freshwater (between 3 to 6 months) (Vlahos and Whitney, 2017).

Data were retrieved from the DEEP Water Quality Monitoring Database for the four stations and time series were plotted for surface and bottom T, DO, and S (ftp://nopp.dms.uconn.edu/pub/). Noise was defined as the standard deviation of the bin (Weatherhead *et al.* 1998) and two month, four month (Feb-May, June-Sept, Oct-Jan) and yearly bins were compared. The binned averages of the parameters were plotted over time and fit to a linear model to give the slope of the trend (Figure 2).

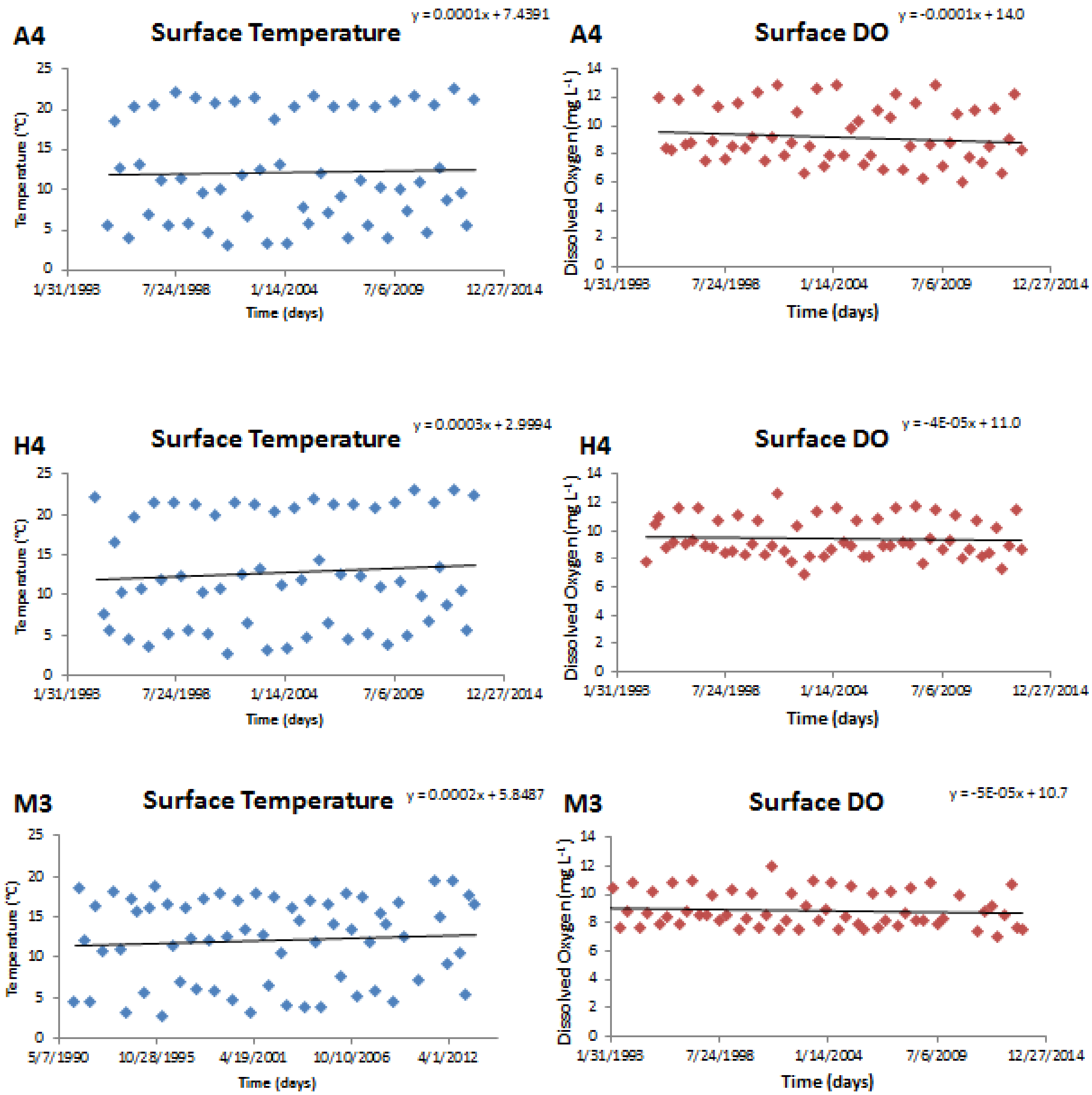

Fig. 2 Surface Temperature and Dissolved Oxygen (4 month) plotted against time for all three stations. A4 is located at the western end of the Sound, H4 near the center, and M3 at the eastern end of the Sound. X-axis is noted in calendar dates in order to more accurately depict the timing and overlap of collected data and slopes shown on graphs are day^{-1}.

3. **Results and Discussion**

3.1 *Quality Control and Sampling Bias*

Due to the sampling scheme of the DEEP data set (water samples taken at discrete times with 2-4 weeks between cruises) steps were taken to assess and mitigate bias due to frequency of sampling and time of day of sampling. In order to ensure that the lower frequency at which the DEEP data set was collected was reasonably representative of the Sound, the data set was compared to a shorter, higher frequency data set. The University of Connecticut maintains a series of buoy stations throughout the Sound, the Long Island Sound Integrated Coastal Observing System (LISICOS). These buoys were instituted in 2006 and collect surface temperature data every fifteen minutes. The LISICOS time series were binned in increments equal to those in this study (2 month, 4 month, and annual). Figure 3 is a plot of the T values derived from both time series from 2007 to 2013, where the two time series overlap. There is remarkable agreement in both data sets (1:1) with a slight tendency in the DEEP data set to yield lower temperatures which would bias towards lower rates of temperature change though this effect is expected to be minor. Based on this assessment, the DEEP data was deemed temporally representative of the Sound. This was consistent for both 2 and 4 month bins, although the annual bins were too small a sample size to resolve.

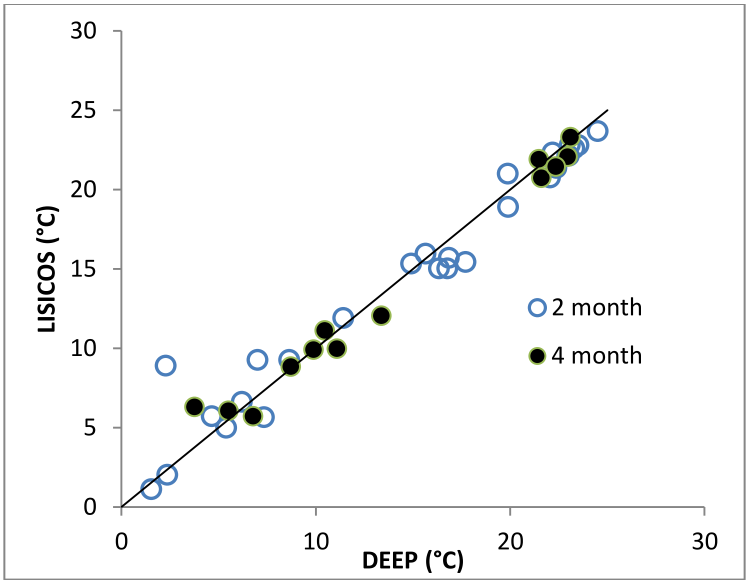

Fig. 3. LISICOS data versus CT DEEP surface data shows a one to one ratio.

Shifts in time of day of sampling were also investigated as a second source of sampling bias (i.e. warming or cooling biases or diurnal DO differences). The time of day at station over the entire time series was plotted to detect shifts in sample collection for the three stations (Figure 4). Generally, the DEEP time series is consistent in its time on station. The westernmost station, A4, had an average sampling time of 12:04 pm and the standard deviation was 68 minutes over 20 years. The station time shows an average shift from noon to 11:40 am (about 20 minutes) over the span of 1994 to 2013. The easternmost station is similarly consistent with an average sampling time at 9:40 am and a standard deviation of about 90 minutes. The shift between 1991 and 2013 is 40 minutes earlier in the day. The central station (H4) shows the most significant shift in sampling time over the sampling period of about 115 minutes; moving from before noon (11:15 am) to early afternoon (1:10 pm) equivalent to a warming bias of about +0.18°C derived from the higher resolution LISICOS time series. This correction was applied to the trend analysis of the central LIS surface waters as a linear correction over time. The shift in DO cannot be determined using the LISICOS data set, though it would be expected that any bias due to the shift in sampling time from 11am to 1pm would be in the positive direction for DO in the central Sound (H4) due to primary production.

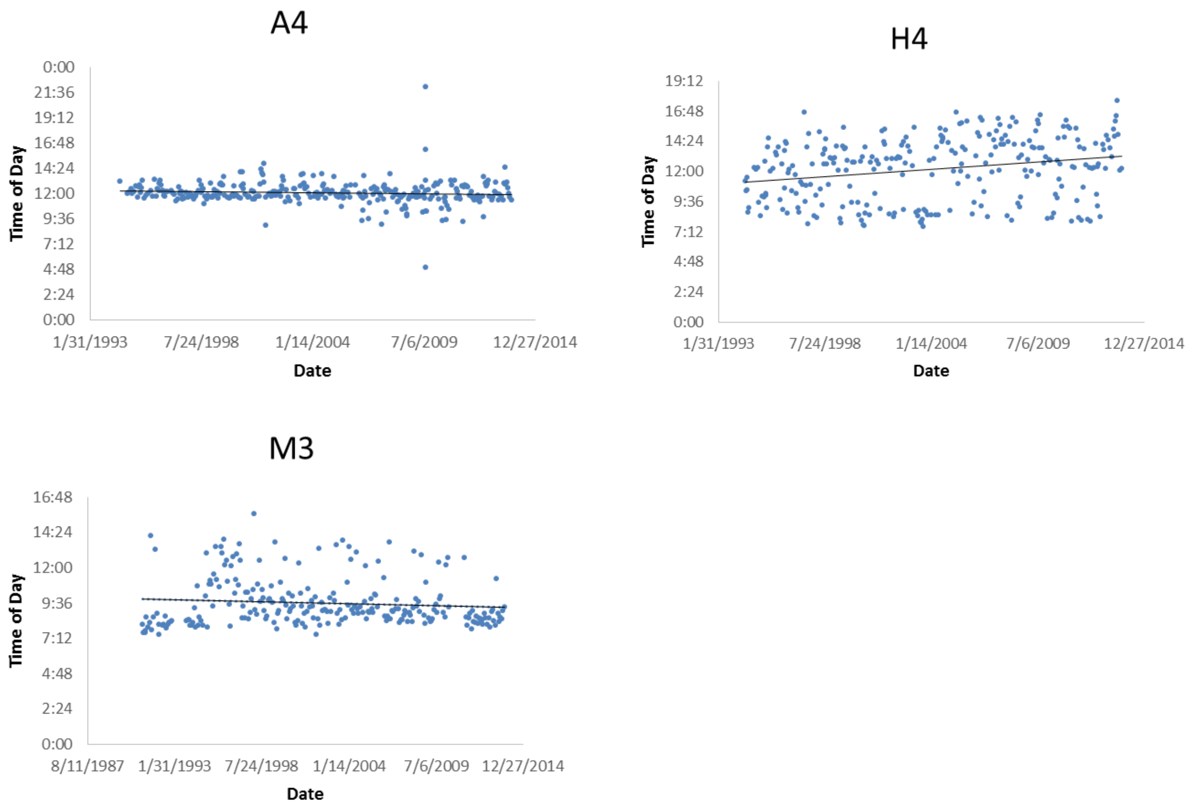

Fig. 4 Time of day of sampling at each station.

As the analysis is focused on trends and not absolute values, consistency in the station sampling time over the entire decadal time series minimizes sampling bias by minimizing noise due to diurnal variations (Tyler *et al*., 2009). If the amplitude of the diurnal cycle does not change, then these trends are representative of an overall T change in LIS; however, if the diurnal cycle is shifting (i.e. a larger amplitude in the daily cycle), this could bias results. Comparison of averages obtained during different fixed times of day from the higher frequency LISICOS time series did not indicate a change in diurnal amplitude for T and DO in the 2006 to 2013 period and thus this was not considered to be a source of bias in trend analysis.

3.2 *Autocorrelation*

An important component in environmental time series is the intrinsic autocorrelation in data that must be accounted for. Large autocorrelation leads to greater uncertainty in the predicted trends and therefore a longer period required for the confirmation of a trend at a given significance level. The autocorrelation coefficients in the analysis are summarized in Tables S.2 and S.3. Generally the greatest autocorrelation (0.53 to 0.37) occurs in the shortest, two month bins as would be expected in a marine time series where environmental conditions persist longer in the water than in the atmosphere above. 4 month bins yield negative autocorrelation coefficients which are consistent with noise in the data from seasonal cycling. Finally the annual bins yield slightly lower autocorrelation coefficients (between 0.41 and 0.17). The results are an increase in n*, the time required to confirm trends, in the two month and annual bins and a slight reduction in n* for the 4 month bins (due to negative autocorrelation coefficients).

3.3 *Time Required for a Significant Trend, n**

The Tiao *et al.* (1990) method identifies the amount of time necessary for the confident detection of a trend in a time series, with the caveat that the trend is assumed to be linear. Linear trends are helpful for detecting overall increases or decreases in target parameters. Application of the Tiao *et al.* (1990) method results in a series of n* values which are specific to each variable, bin size, and station within the Sound (Table S.1). These represent the number of years that each trend already shown in the available data must persist in order to be considered significant.

LIS n* values for the three parameters appear to be driven primarily by the magnitude of the trend rather than the standard deviation (noise) or autocorrelation components (Table S.2, S.3). For example, a greater standard deviation for the surface (0.60) than bottom T (0.53) of the annual A4 bins would indicate that the surface T should take longer to be resolved based on equation 2, but the relatively large magnitude of the trend (0.04 $^{o}Cy^{-1}$) overwhelms this such that the bottom T trend (0.01 $^{o}Cy^{-1}$) yields a smaller signal to noise ratio and thus a greater n* than the surface T. Consistently in all bin versions of this analysis and for all parameters, the slope of the trend (ω) is the dominant driving factor in determining n*.

3.4 *Salinity*

As expected, S had the highest n* values for almost every bin size and station. All but two n* values are beyond the current observational period. On average it takes several decades for a significant change in S to be confirmed across LIS. This is primarily driven by the small ω value, corresponding to a small rate of change, in equation 2. Trends for S are smaller than the corresponding T and DO trends, as salinity operates on relatively longer timescales. There are two trends that are significant within the existing time series, for the 4 month (seasonal bins) of central and eastern LIS surface waters. Both predict a modest freshening of 0.011 and 0.037 g/kg/year in surface waters. This is consistent with long-term trends of increased precipitation and base river discharge from eastern Connecticut and a large portion of New England into LIS mainly via the Connecticut River which represents 70% of the freshwater input to LIS (Hodgekins and Dudley, 2011, Lee and Lwiza, 2008). The Tiao *et al.* method predicts that additional freshening trends across LIS may be confirmable by the year 2070 in surface waters.

3.5 *Temperature*

All station trends predict an increase in T in both surface and deep waters independent of bin size or location (Figure 5). Warming surface T trends in the western sound (at station A4) require an average of 19 ± 5 years to be significant at the 95% confidence level and the increase in T over this period is 0.04°C yr^{-1} for 4 month bins. The western bottom water T trends are the only non-confirmable trends and require 5-20 more years beyond the current available time series to confirm an average warming trend of 0.04 ± 0.03°C yr^{-1}.

Surface T at the central LIS is the quickest to show a significant trend with an n* of only 11 years in 4 month bins. Regardless of binning, this station (H4) shows detectable T trends in less than twenty years (11 ± 3 years on average), making the current data set adequate for confidently identifying an upward trend in both surface and bottom waters. The trend for surface waters and bottom waters is 0.10°C yr^{-1} and 0.07 °C yr^{-1}, respectively.

Finally, the Eastern LIS time series at station M3 yields a warming trend of 0.04 ± 0.02°C yr^{-1} over 23 ± 12 years of observations in surface waters. The 4 month bins lead to the lowest n* values consistently at this site of 12 ± 2 years (0.09 ± 0.03°C yr^{-1}). 4 month bins in the bottom waters at M3 have a warming trend of 0.11°C yr^{-1}. This is consistent with Central LIS bottom water warming rates.

Averaging the 4 month bin rates of change gives an overall warming trend of 0.08 ±0.03°C yr^{-1}. This average covers the entire length of the Sound and both surface and bottom water trends are included. The 4 month bins are used for this overall rate as they consistently give significant trends.

Current average global circulation models and observations over the past century predict ocean temperature increases at approximately 0.1- 0.2° C per decade (0.01- 0.02 °C yr^{-1}) (IPCC, 2007, EPA, 2016, NOAA, 2014).These predictions range slightly according to latitude from 0.004 to 0.016 °C yr^{-1}(Deser *et al*., 2010) . However, under warming climate conditions, in shallow estuaries, influenced by their proximity to land and freshwater inputs including groundwaters, warming would be more pronounced. Thus we are not surprised to see a larger rate of change in LIS. This is due to the accelerated warming of land and shallow surface waters relative to open ocean waters surrounded by a vast ocean heat sink. Warming trends in other temperate estuaries have been summarized in Table 1 for comparison to this study. Trends are consistent though warming rates have been markedly increasing over the last two decades which corresponds to the period of this analysis. Seekell (2007) found that since 1946 the Hudson River Estuary has warmed steadily at a rate of 0.01 °C yr^{-1} though between 1977 and 2006 the rates have doubled to 0.02 °C yr^{-1}. Warming rates in the Delaware Estuary and Narragansett Bay also show accelerated warming over shorter, more recent time series, compared to longer timescales. In other regions like the San Francisco Estuary shorter, more recent time series show even greater rate increases over longer time series.

Method	Location	Trend (°C/yr)	Time Period	Reference
Linear Regression	Long Island Sound-Bridgeport CT	0.064	1964-1993	Cook *et al*. 1998
Linear Regression	Long Island Sound-Bridgeport CT	0.129	1986-1991	Cook *et al*. 1998
Kendall Test/Linear Regression	Hudson River Estuary	0.015	1946-2006	Seekell and Pace, 2011
Kendall Test/Sen Slope Estimator	Hudson River Estuary	0.022	1977-2006	Seekell 2007
Linear Regression	Narragansett Bay	0.054	1960-1994	Cook *et al*. 1998
Linear Regression	Narragansett Bay	0.133	1986-1991	Cook *et al*. 1998
Temperature Anomalies	Chesapeake Bay	0.02	1949-2002	Preston, 2004
3 Models	Delaware Estuary	0.02-0.04	2010-2100	Kreeger *et al*. 2010
Linear Regression	Delaware Bay	0.018	1960-1993	Cook *et al*. 1998
Linear Regression	Delaware Bay	0.343	1986-1991	Cook *et al*. 1998
Kendall Test/Thiel-Sen Slope	California Delta-Rio Vista	0.014	1983-2007	Jassby 2008
Kendall Test/Thiel Sen Slope	California Delta-Rio Vista	0.092	1996-2005	Jassby 2008
Kendall Test/Thiel Sen Slope	California Delta-Stockton	0.011	1983-2007	Jassby 2008
Kendall Test/Thiel Sen Slope	California Delta-Stockton	0.043	1996-2005	Jassby 2008
N*	Long Island Sound	0.08	1991-2013	

Table 1. Comparison of rates of change of temperature in various estuaries across the United States

The warming rates obtained in this study are consistent with rates obtained in other coastal regions over the same time periods and greater than rates based on longer time scales. Whether this recent accelerated warming persists remains to be seen. Extrapolating to the next few decades requires caution in that, though the rates are significant, the time series itself is short and there is no way to confirm that slopes will not shift. However, based on these data, the estimate for LIS temperature change by 2050 is an increase of 2 ± 1 °C.

3.6 *Dissolved Oxygen*

DO trends are consistently negative over all stations and depths (Figure 5). A detectable net decrease in oxygen is consistent with the increase in temperature over the same time period. At the western end of the Sound, changes in surface DO are detectable in the shortest amount of time; an average of 12 ± 2 years for all bin sizes. The 4 month bins are significant in the least amount of time with bottom waters yielding a decreasing trend of -0.03 mg L^{-1} yr^{-1} significant in only 11 years of the time series. Surface waters show a significant trend even sooner with an n* of 9 years and a trend of -0.04 mg L^{-1} yr^{-1}. All the western LIS bins have significant surface DO trends that average to -0.05 ± 0.02 mg L^{-1} yr^{-1}.

The central LIS, (H4), has a fairly similar range of n*, 15 ± 3years on average for surface DO and a wider spread of 20 ± 17 years for bottom DO. All three bins have significant trends for surface DO averaging at -0.02 ± 0.01mg L^{-1} yr^{-1}. The bottom water 4 month bins are within the LTTS window and yield significant rates of bottom DO decreases at -0.03 mg L^{-1} yr^{-1}.

The eastern Sound at Station M3 takes a noticeably longer time to confirm a significant trend with average n* of 45 ± 26 years. In fact, the only significant trends for Station M3 are from the 4 month bin which is -0.02 mg L^{-1} yr^{-1} for both surface and bottom DO. One possible explanation for the longer time period to confirm a significant trend is the increased mixing that station M3 experiences due to its position behind Fisher's Island resulting in periods where flow reversals occur and dynamics vary considerably leading to higher variations (noise) and smaller trends (Schmalz and Devine, 2003).

Open Ocean DO trends from 1960 to 2010 reported by Stramma et al., (2012) show an overall global upper ocean (defined as roughly 300m) decrease of -0.002 $mgL^{-1}y^{-1}$ with regional rates between -0.03 $mgL^{-1}y^{-1}$ and +0.02 $mgL^{-1}y^{-1}$. The overall decrease in LIS DO reported in this study remarkably falls within the range at -0.03 ±0.01 mg $L^{-1}y^{-1}$. As the LIS is significantly shallower (average depth 30m) the rates of DO decrease are reasonable.

Over the last 5 decades there has also been a 2% decline in open ocean DO and global models predict an additional 1 to 7% decrease in total ocean dissolved oxygen inventories by 2100 (Schmidtko et al., 2017). Coastal zone DO inventories are likely to be on the upper end of these estimates or higher due to shorter response times to various factors including T, increased nutrient flux and/or increased carbon remineralization. Our DO inventories in LIS over the past 2 decades have decreased on the order of 6% or 3% per decade. A cumulative decrease in DO of 1.0 ± 0.3 mg L^{-1} is predicted by 2050 based on this analysis.

3.7 Overall Rates of Change

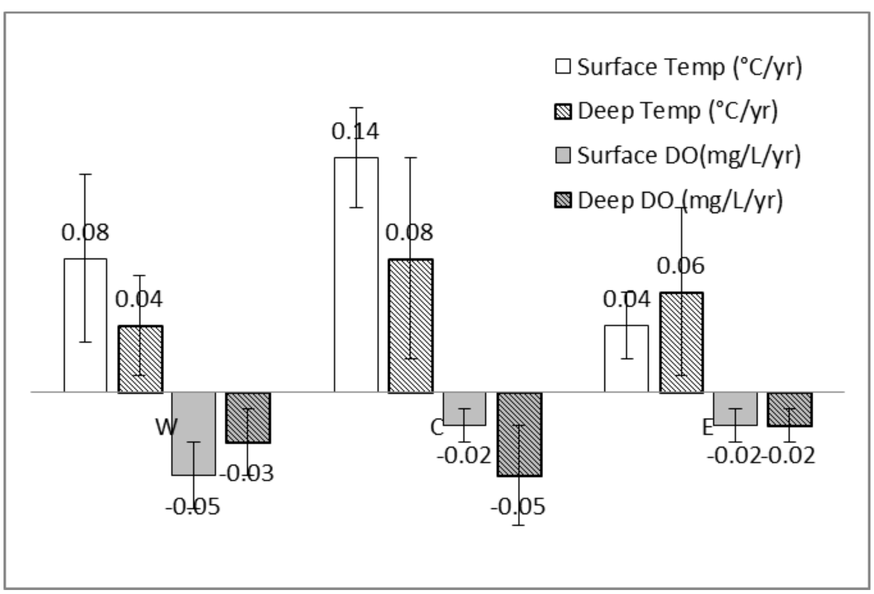

Fig 5. Average trends in temperature and dissolved oxygen from east to west.

Application of the n* method to LIS indicates that both T and DO measurements have reached or are close to reaching the time scales necessary to confirm significant trends. There is a consistent upward trend in both surface and deep T in the Long Island Sound which is present regardless of location, binning, and averaging. There is no clear west to east trend in surface water T (Figure 5). DO trends are consistently decreasing, indicating a loss of standing oxygen stocks which is independent of the recurring hypoxia events. Of particular interest is the fact that oxygen loss is enhanced in the Western and Central bottom waters of the Sound; the portions of the Sound which are subject to hypoxia.

3.8 *Correlation of DO and T*

Based on the ratio of the DO to T rates in this study of 0.03 ± 0.01 $mgL^{-1}yr^{-1}$ s and 08 ± 0.03 °C yr^{-1} the rate of change of DO to T is -0.4 ± 0.2 mgL^{-1} $°C^{-1}$. The solubility change of DO in seawater based on standard solubility curves between 0 and 20 °C and a salinity of 30 g/kg is approximately -0.21 mg L^{-1} $°C^{-1}$. The ratio in this study was between 0.2 and 0.6 and therefore overlaps with the expected change due to standard solubility. It is possible therefore that temperature can account for between 33 and 100 % of the decrease in DO. It is also plausible that DO reductions are compounded by other factors such as nutrient loads and changes in physical forcings that could contribute to the upper estimates of this ratio.

DO and T are both independent parameters in the DEEP time series and the agreement between their rates of change is remarkable and indicates that T trends could be used to predict maximum DO concentrations in LIS. This is in agreement with previous studies of hypoxia in LIS which indicate a correlation between T and bottom DO (Lee and Lwiza, 2008). The negative correlation of DO and T implies sensitivity of DO stocks to large scale climate oscillations such as El Nino and the NAO which can have significant effects on inter-annual temperature differences.

Note, however, that the general downward trend of the NAO index over the period of interest (namely 1991 to 2013) would normally be associated with a cooling trend as strongly positive NAO indices are associated with warmer temperatures across the eastern coast of the United States (NOAA, 2017, Taylor and Stevens, 1998).

This is an important result for the long-term management of LIS which has been increasingly concerned with attempts to understand and ameliorate the spreading hypoxia, particularly in the western to central LIS where it occurs annually. Warming water will generally deplete the standing stock of dissolved oxygen as solubility, and thus the capacity of the water to contain dissolved oxygen, is reduced. Such solubility reductions with temperature are true for many gases including CO_2, CH_4, and N_2. These results indicate that regardless of nitrogen mitigation strategies there will be lower average DO standing stocks stored in LIS waters which may tend to exacerbate the occurrence of seasonal hypoxia once additional limitations of stratification and increased respiration rates are compounded.

4. <u>Conclusions</u>

To our knowledge, this paper represents the first application of the Tiao *et al.* method to LTTS in a coastal estuarine system. It confirms a warming trend of 0.08 ± 0.03 °C yr^{-1} across LIS and a decrease in DO of -0.03 ± 0.01 mg L^{-1} yr^{-1} over the 1991 to 2013 period. The correlation between the rate of change in T and the rate of change in DO implies that long-term processes operating on decadal timescales control these trends and that the decrease in LIS DO can be accounted for solely through increases in T on these timescales though the range of uncertainty allows for other factors to influence DO. This may contribute to LIS hypoxia events over time and may have similar implications for reduced DO in other coastal and estuarine systems. An additional important implication of this work is the influence of this warming on other dissolved gas solubilities in semi-enclosed estuaries for gases such as CO_2, CH_4, and N_2 that are highly sensitive to temperature and may follow similar reductions in standing stock.

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Highlights

- Examines rates of change of temp and dissolved oxygen in LIS from 1991 to 2013
- Temperature has increased at a rate of at least 0.08 ± 0.03 °C yr^{-1}
- Dissolved oxygen has decreased at a rate of 0.03 ± 0.01 $mgL^{-1}yr^{-1}$
- Temperature increase is sufficient to account for the decrease in dissolved oxygen