Report Written By: Robert E. Wilson

Date: June 19, 2012

A. Project Number and Title: R/CE-30-NYCT, "Summer synoptic weather variability as the control of the seasonal evolution of hypoxia in Long Island Sound".

B. Project Personnel:

Robert Wilson (SoMAS): Principal Investigator Brian Colle (SoMAS): Co-Investigator Dan Codiga (URI): Co-Investigator Jindong Wang (SoMAS): NYSG Scholar Sean Bratton (SoMAS): NYSG Scholar

C. Project Results:

C1. Meeting the Objectives:

Objective 1: The stated objective is to define the variability in summertime extra-cyclone frequency and tracks.

- Bratton (2011) used LISICOS buoy temperature and bottom DO data were in conjunction with La Guardia (LGA) and NDBC buoy 44022 meteorological data to identify wind speed and directional criteria preferred for water column mixing. He found that winds from 30°-110° with speeds greater than 4 m/s were the most effective for mixing.
- Using these criteria, he developed a climatology for synoptic disturbances using NCEP/NCAR Reanalysis data, based on the above wind criteria. He categorized these events based on relevant location and type of the synoptic system in terms of three groups; high pressure patterns, low pressure patterns, or hybrid patterns (**Figures 1-3**).





Figure 2. Mean (contoured) and anomalies (filled contours) NCEP/NCAR SLP (hPa) for all **low pressure** group mixing events for 1950-2009.



SLP (hPa) for all hybrid group mixing events for 1950-2009.

 In addition to defining the mean and anomaly patterns, SLP and 500-hPa geopotential heights were used for daily lag periods -4 to 0 days prior to the start of a mixing event to determine the synoptic evolution of low and high pressure patterns that produced mixing events.

- The connection between seasonal bottom DO and mixing event metrics including, frequency, spacing, and duration was evaluated to help explain whether mixing events are able to help explain the recent (20-30 year) trends in seasonal bottom DO.
- It was determined that high pressure patterns, including what were defined as Pre-High and Extended High patterns, result in the highest percentage of total mixing events (76.3%).
- They display an increasing trend suggesting that the frequency of anticyclones is a significant factor in determining the frequency and trend of mixing events.
- It was found that mixing events are an important factor influencing both the inter-annual fluctuations in bottom DO and the duration of hypoxic events; they are not, however, able to explain the 20-30 year trends in DO and hypoxia trends evident in these datasets.

Objective 2: The stated objective is to define surface heat and momentum fluxes associated with summer cyclones.

- This objective is of course partially met by the accomplishments under **Objective 1** described above.
- Wilson et al. (2012) analyzed the relationship between LGA winds and inter-annual variations in summertime hypoxia duration and hypoxia areal extent estimates available from CTDEP. They found a significant relationship by which hypoxia duration is negatively correlated with the percent of July/August winds from the NE (Figure 4). They also showed that the direction histogram for July/August winds at LGA is characterized by three distinctive directional peaks whose relative strength exhibits inter-annual variability (Figure 5). The predominant direction is from the SSW is associated with summertime ridge and trough system. The other dominant directional peak in the histogram is for winds from the NE, with a secondary peak for winds from the NW.



Figure 4. Correlation and p-values between CTDEP hypoxia duration and percent of LGA July/August winds from different directions for 1991-2009.

- To compliment these analyses Wilson et al. (2012a) determined that synoptic period variations in summer LGA July/August winds are associated predominantly with clockwise (negative frequencies) rotating wind vectors (Figure 6). This clockwise rotational tendency can be interpreted in terms of the winds produced by either cyclonic or ant-cyclonic systems propagating towards the east and centered to the north of the Sound. This polarization requires that in Figure 5, the directional peak for winds from the NE would be associated with an anti-cyclonic high pressure system, and the peak for winds from the NW would be associated with an a cyclonic low pressure system.
- This lead Wilson et al. (2012) to the conclusion that anti-cyclonic high pressure systems are the predominant mixing agent.



Figure 5. Directional histogram for July/August winds at LGA.

Figure 6. Rotary spectrum for July/August winds at LGA.



- Analyses of current structure from moored ADCPs in the western Sound (Wilson et al., 2012) revealed a clear directional response to wind forcing which was, however, spatially variable. The relationship between wind induced current shear, stratification and vertical mixing was interpreted in terms of simple <u>longitudinal straining</u> whereby an axial wind stress can modify the shear in axial currents.
- Hindcast simulations using ROMS (Wilson and Wang, 2012) did confirm importance of longitudinal straining. Figures 7 and 8 show results from PCA: first mode is characterized by a vertically sheared axial current with principal component highly correlated with axial winds. These simulations also pointed to the importance of <u>lateral straining</u> in the wider sections of the west-central Sound. In this case a lateral wind stress can produce a significant lateral tilt of isopycnals and thereby modify stratification (Figures 9 and 10).



Objective 4: The stated objective is to evaluate dependence of hypoxia on cyclone characteristics and frequency.

- This objective is of course partially met by the accomplishments under **Objective 1** described above.
- Codiga (2012) analyzed LISICOS buoy data in the western Sound with the objective of establishing event-based metrics for summertime hypoxia. Basically, a hypoxia event was characterized by its duration (days) and event-mean oxygen deficit (mg/l) which are combined to produce a deficit-duration metric (mg/l days) (**Figure 11**).

- Using this same basic concept Codiga (2012) evaluated the functionality of an event-based metric for summertime stratification events. A stratification event was characterized by its duration (days) and event-mean temperature stratification surplus (°C) which are combined to produce a surplus-duration metric (°C days).
- He found, however, that the timing, duration, and intensity of stratification events are not closely linked to those of hypoxic events
- He determined that event duration, event-mean deficit, and deficit-duration are good metrics for hypoxic impacts on living resources.
- Season-cumulative hypoxia deficit-duration reached at least 55 mg l⁻¹ dy (a lower bound due to data gaps) in western LIS, which was more than 2 time the typical value (~25 mg/ldy) in deep Narragansett Bay



Figure 11. Example of deficit-duration calculation for LISICOS Execution Rocks buoy data in 2008 (from Codiga, 2012).

C2. Scientific Abstract: Long term observations of hypoxia duration, hypoxia areal extent, and hypoxic volume in western and west central Long Island Sound are analyzed to determine the dependence on wind forcing. Results show that inter-annual variations in the wind directional statistics over the western sound account for a major fraction of the variance in hypoxia duration, areal extent and hypoxic volume. Analyses of current structure from moored ADCPs revealed a clear directional response to wind forcing which can be interpreted in terms of longitudinal straining. ROMS hindcast simulations confirm importance of longitudinal straining but also point to importance of lateral straining in the widening west-central Sound. An analysis of LISICOS buoy temperature and bottom DO data in the western Sound in conjunction with LGA and NDBC buoy data lead to the identification of wind speed and directional criteria preferred for water

column mixing. Based on these criteria, a climatology for synoptic disturbances was developed from NCEP/NCAR Reanalysis data which included a categorization of events in terms of three groups; high pressure patterns, low pressure patterns, or hybrid patterns. It was determined that high pressure were associated with the highest percentage of mixing events (>76%). This was consistent with the results of simple rotary spectral analysis of LGA winds. The application of metrics based on event duration, event-mean oxygen deficit, and deficit-duration using LISICOS buoy temperature and bottom DO data in the western Sound was successful, and it was concluded that these metrics should be useful for evaluating hypoxic impacts on living resources.

- **C3. Problems Encountered:** Codiga's planned analysis of LISICOS data involved 7-9 years at 2 main sites and 1-2 years at 3 additional sites which would afford a description of spatial patterns and inter-annual variability. But, because of the limited data he was able to obtain, his analysis involved only 2 sites which overlapped for 2 years: EXRX: 2006 (partial), 2008, 2009, and WLIS: 2008, 2009, 2010.
- **C4.** New Research Directions: One new research direction, which was not pursued during the project but which has since been pursued relates to the interaction of wind-induced and tidal mixing. Results of this new research initiative will be presented at the Physics of Estuaries and Coastal Seas Symposium (PECS) 12-16 August 2012 in New York.
- **C5. Interactions:** Project results were recently presented at the Long Island Sound STAC synthesis meeting on 10 February, 2012.

C6. Presentations and Publications:

Publications:

- Bratton, S.D. 2011. Synoptic flow patterns that influence wind-induced mixing and the temporal evolution of hypoxia over western Long Island Sound. Masters Thesis, School of Marine and Atmospheric Sciences, Stony Brook University, pp 125.
- Codiga, D.L. 2012. Hypoxia and Stratification Western Long Island Sound Characterized Using Event-Based Metrics. Final Technical Report, pp 53. (Attached)
- O'Donnell, J., R. E. Wilson, K. Lwiza, M. Whitney, W. F. Bohlen and D. Codiga. 2011. The Physical Oceanography of Long Island Sound. Springer. (*In Press*).
- Wilson, R.E., Wang, J and S. Bratton. 2012. Evidence for directional wind response in controlling inter-annual variations in duration, areal extent and volume of summertime hypoxia in western Long Island Sound. (Prepared for Submission to Journal of Geophysical Research in July 2012, Manuscript Attached).
- Wilson, R.E. and J.Wang. 2012. Simulations of wind driven circulation in Long Island Sound and relationship to stratification and vertical. *(Manuscript in Preparation).*

Presentations: Physics of Estuaries and Coastal Seas Symposium (PECS) 12-16 August 2012, New York. Oral Presentation. **Interaction of wind and tidal straining in** western Long Island Sound, Robert Wilson, School of Marine and Atmospheric Sciences, Stony Brook University.

Abstract: Both O'Donnell et al. (2008) and Wilson et al. (2008) have suggested that wind straining of the density field plays an important role in controlling summertime hypoxia in western Long Island Sound by modulating vertical mixing. Observations from moored ADCPs and 3D model results in western Long Island Sound are analyzed to define the relative influence of longitudinal and lateral wind straining on water column stratification, including the contributions from the advection of non-uniform horizontal density gradients. Analyses emphasize the interaction between straining due to synoptic period winds and that due to semidiurnal tidal currents with tidal monthly variations. One important aspect of this interaction is the influence of wind straining with surface intensified shear on bottom boundary layer growth during flood tides.

D. Accomplishments:

D1. Impacts & Effects:

D2. Scholar(s) & Student(s) Status:

Jindong Wang was a Sea Grant Scholar on this project who participated in ROMS simulations. He has defended his PhD dissertation Flow kinematics and dynamics controlling tracer movement and shallow-water wave propagation in the Hudson River and submitted it to the Graduate School. His dissertation acknowledges support from this project. Jindong has held a position with NOAA/NOS in Silver Spring, MD as an estuarine modeler since January 2011. His contact information is:

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Sean Bratton was a Sea Grant Scholar on this project who participated in the analysis of LISICOS and NCAR/NCEP data. He has defended his Masters thesis Synoptic flow patterns that influence wind-Induced mixing and the temporal evolution of hypoxia over western Long Island Sound and submitted it to the Graduate School. His thesis acknowledges support from this project.

- **D3.** Volunteers: Provide information about any volunteers (citizens or students) who worked on the project. Indicate their activity and amount of time (hours) they participated.
- **D4. Patents:** Describe patents awarded or pending, including number and date, and licenses granted.
- E. Stakeholder Summary: Results from analyses of long term observations show that interannual variations in summertime wind directional statistics over the western Sound account for a significant fraction of the variance in hypoxia duration, areal extent and hypoxic volume. Results also show that inter-annual variability in summertime wind direction is increasing. It has been determined that summertime high pressure systems are the synoptic disturbance which is most effective in producing water column ventilation. One important message is that TMDL definitions should/must accommodate variations in physical forcing such as but certainly not limited to wind direction and wind

speed. Additionally, metrics such as duration, deficit, and deficit-duration should prove useful for evaluating and quantifying hypoxic impacts on living resources.

F. Pictorial: Provide any additional images/photos of personnel at work, in the field or laboratory, equipment being used, field sites, organism(s) of study or links to websites, etc. Please include proper photo credits and a caption with date, location, names of people, and activity. These images are useful to document your project in future NYSG publications, websites and presentations.

Hypoxia and Stratification in Western Long Island Sound Characterized Using Event-Based Metrics

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Funded by Long Island Sound Study, Connecticut Sea Grant and New York Sea Grant Award R/CE-30-NYCT "Summer Synoptic Weather Variability as the Control of the Seasonal Evolution of Hypoxia" Subcontract from Stony Brook University

> Final Report February 8, 2012

Summary

This analysis is part of a larger study to investigate the role of summer synoptic weather variability on the seasonal evolution of hypoxia in western Long Island Sound (LIS) through its influence on stratification and mixing. Because hypoxia is known to occur each summer as a series of events of durations from days to weeks, event-based metrics have been used here to characterize hypoxia and stratification, based on time series observations from buoys. Only a small subset of the data planned for the analysis was made available (two sites, 3 years at one and less than 3 at the other, 2 years overlapping), so the scope of the study and its potential findings were severely limited. Nonetheless, the patterns identified and conclusions made should provide valuable context to other analyses involving more sites and longer multi-year durations. Records from 2006 (partial), 2008, and 2009 at the Execution Rocks site (EXRX), and from 2008, 2009, and 2010 at the Western LIS site (WLIS) were treated. Event characteristics were identified using the moving window trigger algorithm (Codiga 2008) with dissolved oxygen (DO) threshold of 2.9 mg l-1, stratification threshold of 2 °C vertical temperature difference between sensors, minimum event duration 1 day, and trigger duration 9 hours.

In a typical summer, at the near-bottom sensors at both sites, there are up to 5-6 hypoxic events, each with duration about 5-15 dy (range 2 to 40 dy). Event-mean deficits (amount by which DO level is below the threshold, on average, during the event) range from ~0.2-2.5 mg l⁻¹ and are typically 0.8-1.0 mg l⁻¹. The deficit-duration (product of event-mean deficit and event duration) for individual events ranges from ~2-40 mg l⁻¹ dy. Season-cumulative deficit-duration reached at least 55 mg l⁻¹ dy, twice that typical of near-bottom sensors in deep parts of Narragansett Bay (Codiga et al. 2009). No events occurred at EXRX or WLIS shallow sensors, nor the EXRX mid-depth sensor; at WLIS mid-depth there were some events but they were less frequent and less intense compared to the deep sensor. Events at WLIS were similar in duration to those at EXRX but had smaller event-mean deficit and thus smaller deficit-durations. During periods when hypoxic events are more frequent and more intense at one site, the same appears true at the other; however, there is not a high degree of synchronicity of individual event timing at the two sites. To the extent they could be assessed, inter-annual variations of hypoxic conditions were similar at the two sites.

For the chosen threshold, events in stratification are more numerous, and occur during a larger fraction of the time during a given summer, compared to hypoxic events. Two other contrasts with hypoxic event characteristics include the fact that stratification event intensities increase leading up to mid-summer and subsequently taper off, and that stratification events did not occur later than early September. At EXRX, stratification was generally stronger between the shallow and mid-depth sensors, as compared to between the mid-depth and deep sensors; at WLIS this was true in one year but the other two years saw similar stratification between both sensor pairs. Individual stratification events had durations of up to 50 dy, event-mean surpluses (amount by which stratification exceeded the threshold, on average, during the event) of up to several degrees, and surplus-durations (product of event-mean surplus and event duration) of up to about 130 °C dy.

No clear relationship between the timing and severity of individual stratification events and hypoxic events was apparent. The small number of years treated made it difficult to discern a relationship between inter-annual variations in hypoxia and in stratification. An exploratory investigation of processes likely to influence stratification at weather-band timescales (including surface heat flux, various aspects of wind conditions, river flow, sea level differences, and spring/neap tidal conditions) demonstrated that numerous processes contribute, and relationships among them are complex.

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1 Introduction

The characteristics of hypoxia (defined, generally, as dissolved oxygen (DO) concentrations low enough to impact living resources) in western Long Island Sound (LIS), and associated driving factors such as stratification, have been examined closely from a number of different perspectives (e.g., Wilson et al. 2008, and many others). Hypoxic conditions are recognized to occur typically as a series of events, lasting days to weeks, alternating with periods that are not hypoxic. However, the analysis of time series observations with sampling interval on the order of hours, using metrics characterizing individual hypoxic events (defined as periods during which DO is lower than a specified threshold level, for a minimum duration on the order of days), deserves more attention.

Here, we present results of such an analysis applying the "moving window trigger" method and including use of the "deficit-duration" metric (Codiga 2008; Codiga et al. 2009). In addition to DO, depth differences in temperature are treated, as a proxy for stratification; the quality of the salinity records was inadequate to warrant its inclusion, thus the originally intended analyses of density and density stratification were not possible. To help discern processes shaping hypoxic events, a number of auxiliary variables from associated processes are also presented, including wind parameters, solar irradiation and surface heat flux, river flow, sea level and its gradient, and spring-neap tidal cycles. The overall context for the analysis is an investigation of the relationship between synoptic weather variability and the seasonal evolution of oxygen levels as a sequence of individual hypoxic events; the present report is the result of an effort that is a subset of a larger project, and intended to be of use in corroborating findings of colleagues Bob Wilson and Brian Colle with respect to analyses of synoptic weather event characteristics and associated evolution of stratification and mixing conditions based on numerical simulations.

2 Sources and methods

2.1 Buoy records

The primary observations treated are time series records of oxygen concentration and temperature, collected by University of Connecticut over the past ~9 years, from sensors mounted on buoys. The buoy sites are shown in Figure 1 and the sensor depths and years of data are listed in Table 1. The sensors were YSI sondes and collected salinity measurements as well as oxygen and temperature, but as noted above the quality of the salinity records was inadequate to warrant its inclusion. In addition, despite oft-repeated inquiries to UConn (Frank Bohlen) and

frequent follow-ups over a period of close to two years, only a relatively small subset of usable records (Table 1) was provided, among all those that were indicated to be available (Table 1). Data files from some other deployments were provided, but they were not useful because no quality control measures, needed to eliminate and/or correct obviously errant sections of data, had been applied to them. Quality control steps are apparently still underway at UConn, were not planned as part of this project as they lie well outside its scope, and would in any case be difficult to carry out successfully for non-UConn personnel who did not deploy and recover the sensors. As a result the only records analyzed here are from the Execution Rocks (EXRX) station in 2006 (partial), 2008, and 2009, and from the Western Long Island Sound (WLIS) station in 2008, 2009, and 2010.

The DO records, with 15-minute resolution, from May 1 through Oct 31 of each year when hypoxia generally occurs, are subjected to the moving window trigger analysis (Codiga 2008). The threshold value used is 2.9 mg 1^{-1} , the minimum event duration is 1 day, and the trigger duration is 9 hours. These are the same values as used in an analysis of hypoxia in Narragansett Bay (NB) by Codiga et al. (2009), where the basis for them is explained in detail. They are used here, despite that 2.9 mg 1^{-1} may not be a commonly used threshold for defining hypoxia in LIS, in order to facilitate the direct comparisons with NB conditions that are made below.

Stratification 'events' are defined and identified using the MWT algorithm in the same way as are hypoxic events. Throughout this analysis, temperature differences (ΔT in °C) are treated as the proxy for stratification, given the lack of useful salinity observations (see above). The threshold level defining a stratification event is $\Delta T = 2$ °C, and the same minimum event duration (1 day) and trigger duration (9 hours) as for the hypoxia analysis are used. Events are computed based on the temperature difference between the shallow and deep sensor, as well as the difference between the mid-depth and deep sensors. Stratification events are characterized by their duration, just as for hypoxia events, but in contrast to hypoxic events the other two metrics to characterize stratification events are the event-mean surplus (in °C) of temperature difference (as opposed to the event-mean deficit, for hypoxic events) and the surplus-duration (in °C dy) of temperature difference (as opposed to the deficit-duration, for hypoxic events).

Where presented together with auxiliary variables, DO and temperature observations have been subjected to the same low-pass filter and 12-hr sub-sampling (described next).

2.2 Auxiliary time series

To investigate potential processes bearing on hypoxic event timing and severity, several auxiliary parameters are used. This section explains these parameters and their sources. Because the focus of the analysis is the evolution of hypoxic events on timescales longer than a tidal period, all auxiliary variables are subjected to a 25-hr halfwidth triangular weight low-pass filter, which removes tidal variability, and sub-sampled to a common 12-hr resolution grid.

Winds, and variables needed for computation of air-sea heat flux, are from the North American Regional Reanalysis (Mesinger et al. 2006), a high quality operational dataassimilative meteorological model run in hindcast mode. The model has 32-km grid resolution, thus the grid point used (in west-central LIS, Figure 1) is representative of conditions in western LIS; given its grid spacing the model is not expected to capture highly localized effects, but comparisons of model winds with local wind observations demonstrate good agreement of weather-band variability. The model output is used instead of observations because (a) unlike direct wind observations, it is available gap-free (3-hr resolution) from all years treated, and (b) for certain variables needed to compute the heat flux, observations are generally not available.

Wind speed cubed is used as a proxy for available wind mixing energy. This is based on an open ocean formulation, e.g, Niiler and Kraus (1977), which is likely not directly applicable but is nonetheless an appropriate standard approach as a first step towards assessing the role of wind mixing.

The wind component toward northeast (45°T) is used as an indicator of along-axis winds. This is a reasonable choice, given the geometry of western LIS; a local bathymetric channel is oriented at 42°T (Wilson et al. 2008), while the along-axis direction was treated as 52°T by O'Donnell et al. (2008).

Solar irradiation is the downwelled shortwave radiation flux parameter of N.A.R.R.

The net air-sea heat flux (positive from air to sea) was computed by the standard formulation, using the following N.A.R.R. variables, as the sum of the downwelled shortwave radiation flux, downwelled longwave radiation flux, sensible heat flux and latent heat flux, less the upwelled shortwave radiation flux and the longwave radiation flux.

The collective river volume transport to LIS were computed from USGS records. To account for ungauged area, the collective transport was computed as the sum of the Connecticut River input and twice the inputs from the Housatonic, Naugatuck, Quinnipiac, Yantic, Quinnebaug, and Shetucket Rivers (the latter three comprising the Thames River), following the approaches of Riley (1952) and Gay et al. (2004).

As a very crude indicator of subtidal currents, the observed difference in sea level between Kings Point and Bridgeport (Figure 1) is used. The observations were downloaded from the NOAA website and an inverse barometer correction applied using the N.A.R.R. atmospheric pressure.

For the main variations in tidal mixing, which are thought to occur on the spring-neap cycle, the tidal range cubed is used as a crude proxy; according to theory the available tidal mixing is proportional to the cube of the tidal current speed, and in many systems the tidal current speed is proportional to the tidal range. Predicted tidal heights at Kings Point (Figure 1) were obtained from NOAA. The tidal range was computed by differencing the higher high tide and lower low tide each day.

3 Results: Hypoxic events

The MWT results for hypoxic events relative to threshold 2.9 mg 1^{-1} , at the two available stations in the available years (three at one station and less than three at the other), are summarized collectively in a timeline plot (Figure 2). No hypoxic events occurred at the shallow or mid-depth EXRX sensors, nor at the shallow depth WLIS sensor, in any of the years analyzed (these records are therefore omitted from Figure 2).

At the deep EXRX sensor, at least one event occurred in all three years treated. During the partial year of sampling in 2006 there was one event of duration 10.8 dy, event-mean deficit 1.49 mg l^{-1} , and deficit-duration 15.6 mg l^{-1} dy. In 2008 there were 4 events (the second of which was ended by a significant gap in sampling) for which the duration, event-mean deficit, and deficit-duration were comparable to the 2006 event. In 2009 there were 4 events which, compared to the events in 2006 and 2008, generally had similar durations but event-mean deficits (mean 0.85 mg l^{-1}) and therefore deficit-durations (mean 6.4 mg l^{-1} dy) that were about half as large.

At the WLIS site the event-mean deficits were generally smaller than those at EXRX. At the deep sensor, events occurred in all 3 years. In 2008 there were three events (durations of 4.8, 41.3, and 6.1 dy) that were separated by relatively short durations of non-hypoxic conditions between events. Consequently, conditions were hypoxic nearly continuously from about mid-July through mid-September. The average event-mean deficit was 0.71 mg 1^{-1} and the deficit-durations were 3.1, 35.1, and 3.4 mg 1^{-1} dy, for a season-cumulative deficit-duration of 41.6 mg 1^{-1} dy. In 2009, there

were two events that had similar event-mean deficits to the events in 2008, with durations of 4.8 and 8.7 dy and deficit-durations of 3.1 and 6.2 mg l^{-1} dy. In 2010 there were four events, each of relatively short duration (1.7 to 4.3 dy), relatively low event-mean deficit (0.23 to 0.63 mg l^{-1}), and relatively small deficit-duration (0.35 to 2.21 mg l^{-1} dy). At the WLIS mid-depth sensor, relative to the deep sensor in a given year, events were less common and generally less intense: there were 3 events in 2008, no events in 2009, and one event in 2010; these events had durations of about 1-3 dy, event-mean deficits of about 0.5-1.3 mg l^{-1} , and deficit-durations of about 1-2.5 mg l^{-1} dy.

The small number of stations and relatively few, non-overlapping years treated makes it difficult to see patterns and draw conclusions based on this analysis alone. However it is hoped that the present results can give valuable context to other analyses of datasets that span more sites and a longer multi-year duration.

In addition, even with the limited data treated, there is clear evidence for certain characteristics of hypoxia. First, hypoxic events appear more concentrated at depth at EXRX, where none occurred at the mid-depth or shallow sensors, than at WLIS where there were events at the mid-depth sensor in 2 of the 3 years treated. Second, at WLIS, events at the deep sensor are more common and more intense than at the mid-depth sensor. Third, inter-annual variability is pronounced, with 2006 and 2008 having more events, of longer durations and higher deficit-durations, than 2009 and 2010 (the least hypoxic year treated). Finally, during the two years (2008 and 2009) for which there are data at both EXRX and WLIS stations, there is some indication that events at the two deep sensors occur during similar periods (events at different locations that overlap in time; called spatial synchronicity by Codiga et al (2009)). For example, in 2008 hypoxia was sustained from about mid-July to mid-Sept at WLIS and it appears that the same could well have been true at EXRX, although a conclusive result is precluded by a significant missing-data gap; in 2009, events began at EXRX earlier (mid-July) than at WLIS (mid-August), but at both sites they ended in late August.

The season-cumulative deficit-duration at deep sensors is a useful metric. At EXRX it was 15.6, 55.4, and 25.6 mg l^{-1} dy in 2006, 2008, and 2009; at WLIS is was 41.6, 9.3, and 4.1 mg l^{-1} dy in 2008, 2009, and 2010 respectively. Significant data gaps (at EXRX in 2006 and 2008, and at WLIS in 2008) preclude effective direct year-to-year comparisons; they also suggest that if there were no data gaps the cumulative totals for the 2006 and 2008 EXRX records would be substantially higher, in particular that the 2008 value would greatly exceed 55.4 mg l^{-1} dy. However, comparisons of the general level of season-cumulative deficit-duration at the EXRX

and WLIS deep sensors (from 4.1 to at least 55.4 mg l^{-1} dy) can nonetheless be made to other systems. For example, based on a 6-year analysis of sites in the deeper portions of NB, season-cumulative deficit-durations at deep sensors ranged from zero to a maximum of about 40 mg l^{-1} dy, and typically are less than about 20 mg l^{-1} dy (Codiga et al. 2009). This comparison suggests that living resources in western LIS are subjected to more severe hypoxia conditions than in NB, and provides a meaningful metric to quantify the difference in severity.

Detailed information about the hypoxic events that Figure 2 summarizes is provided in Section 7, and presented in Figure 9 to Figure 34.

4 Results: Stratification events

Results (Figure 3) indicate that stratification events relative to the $\Delta T = 2$ °C threshold are common, with event-mean surplus values that tend to increase until about mid-June and decrease after about mid-August. They also suggest that, in contrast to hypoxic events (Figure 2), stratification events are not as likely to occur later than the start of September. For some records, events for the shallow and deep sensor ("Sh-Dp", Figure 3) temperature difference are synchronous with events for the mid-depth and deep sensors ("Md-Dp"), an indication that stratification is occurring across most of the water column; For other records the Sh-Dp events are more common and more severe, indicating stratification is concentrated in the upper water column.

At EXRX, events for Sh-Dp tend to be more common and more severe than for Md-Dp in all three years treated. This is consistent with temperature gradients that are concentrated more shallow than the mid-depth sensor (sensor depths are in Table 1), such as when there is a shallow thermocline. In 2006 the earliest good data starts in mid-August, there was only one very minor Sh-Dp event (duration 3.0 dy, event-mean surplus 0.51 °C, surplus-duration 1.1 °C dy), and there were no Md-Dp events. In 2008, four Sh-Dp events occupied nearly all the time from late May to late August; the longest has a duration of 47.9 dy, an event-mean surplus of 2.25 °C, and a surplus-duration of 103.8 °C dy. In that same year there are two Md-Dp events, separated by nearly a week with stratification weaker than the threshold, with durations 20.0 and 14.8 dy, event-mean surpluses 1.27 and 0.79 °C, and surplus-durations 23.0 and 9.7 °C dy. In 2009 conditions were similar to 2008 except that the number of events was higher and they generally had shorter durations and were separated by longer periods of non-event stratification.

At WLIS year-to-year variability in the range of depths where stratification occurs can be substantial: the Sh-Dp and Md-Dp results were very similar to each other during 2008 and 2009, but in 2010 the Sh-Dp results were similar to prior years while there were no Md-Dp events. Compared to EXRX results the WLIS events tend to be longer and more severe. In 2008 one event (for both Sh-Dp and Md-Dp) during July and most of August lasted 48.3 dy with event-mean surplus-duration of 2.75 °C and surplus-duration 132.6 °C dy, and because of a sampling gap, these are lower bounds. In 2009, Sh-Dp and Md-Dp events were similar to each other and numerous with only short breaks between them, such that non-event time amounted collectively to a total of only about 10 dy between May 1 and the end of August, and the largest individual event had duration 41.5 dy, event-mean surplus 3.14 °C, and surplus-duration 129.8 °C dy. In 2010, Sh-Dp events had characteristics comparable to those of 2008 and 2009 but there were no Md-Dp events.

The two years when both EXRX and WLIS were treated (2008, 2009) show divergent results for how similar the conditions at the two sites were to each other. In 2008 a large data gap limis conclusions but there is evidence that stratification events were persistent and intense at both EXRX and WLIS. In contrast, in 2009 stratification events at EXRX were relatively few and weaker than typical, while at WLIS they were more common and intense than in any other year.

5 Results: Relating hypoxic events, stratification events, and auxiliary parameters

Relationships between the timing and severity of hypoxia and stratification can be gauged by comparing the summary timelines of hypoxic events (Figure 2) and stratification events (Figure 3). A direct and close link between the timing and/or severity of hypoxic events and those of stratification events is not apparent. Hypoxic events tend to be shorter, and occupy a smaller fraction of the time from May through October, compared to stratification events. Stratification events tend to have more of an increase and decrease in their intensity prior to and after mid-summer, respectively.

The small number of years treated limits conclusions related to inter-annual variations. However, it is interesting to note that the years when hypoxic events were more common and/or more intense (2006, 2008) did not correspond in a simple way to years when stratification events were the most common and/or intense (2008, 2009).

These findings are based on a specific set of MWT event definition parameters (thresholds of 2.9 mg l^{-1} for hypoxia and 2 °C for temperature stratification; for both, minimum event duration

of 1 dy and trigger duration of 9 hr). While sensitivity of individual event characteristics to these parameters is to be expected, the general patterns deduced, for example regarding variability between sites and among individual years, should be only modestly affected by choice of different values in comparable ranges.

To help expose potential relationships of hypoxia and stratification events to auxiliary parameters, a series of plots is presented in which the buoy records are shown together with them (Figure 4 to Figure 8). The period included is from May 1 through Oct 31 because this spans the occurrence of hypoxic events. Because the N.A.R.R. meteorological model product was not yet available for all of 2010 at the time of this analysis, that year is not included.

Before describing characteristics of the plots, a detailed description of the contents of each of the five frames, from top to bottom, in each plot is given as follows.

- In the first frame:
 - In red with the left axis, the DO time series are presented. The deep record is solid, the middle record is dashed, and the shallow record is dotted. The threshold level is marked as a horizontal dash-dot line. Each hypoxic event identified by the MWT algorithm, for the deep sensor, is marked at the base of this frame—as well as at the bases of the other four frames below.
 - In green with the right axis, the depth-differenced temperature time series are presented. The differences between sensor pairs are the deeper sensor less the shallower sensor, hence most of the values are negative as the shallower waters are typically warmer. A dash-dot horizontal line marks zero. The solid line is the deep sensor less the mid-depth sensor. The dashed line is the deep sensor less the shallow sensor.
- In the second frame:
 - In blue with the left axis are the incoming solar irradiation (downwelled shortwave) as a solid line, and the net air-sea heat flux (positive downward) as a dashed line. A dash-dot horizontal line marks zero.
 - In green with the right axis, the temperature time series are presented. The solid curve is the deep sensor, the dashed curve is the middle sensor, and the dotted curve is the shallow sensor.

- In the third frame:
 - o In black with the left axis, the wind speed cubed is presented.
 - In the upper one-third portion of the frame, the vector wind (north up on the page, east rightward) is presented. The northward scale vector is at the far left.
 - In magenta with the right axis, the collective river inputs to LIS is presented.
- In the fourth frame:
 - In black with the left axis, the wind speed in the direction toward northeast is presented. A dash-dot horizontal line marks zero.
 - In blue with the right axis, the sea level difference between Kings Point and Bridgeport (Kings Point less Bridgeport) is presented. A dash-dot horizontal line marks zero. (The individual sea level records for the two stations are presented in frame five.)
- In the fifth frame:
 - In green with the left axis, the cube of the predicted Kings Point tidal range is presented.
 - In blue with the right axis, the observed sea level records (adjusted for the inverse barometer effect) at Kings Point and at Bridgeport are presented.

The relationships between auxiliary parameters and hypoxic or stratification events are clearly complex, and deserving of a more careful and quantitative exploration that is well beyond the scope of the present effort. What follows are some introductory observations about certain aspects of them, with emphasis on potential relations of auxiliary parameters to deep oxygen and Md-Dp temperature stratification at the 1-10 day weather-band timescale.

First consider the Md-Dp stratification (solid green curve, top frames). A feature of the seasonal cycle is the falloff to zero stratification associated with the transition from positive to negative net heat flux (dashed blue, second frame) in late August or September. Weather-band variations are energetic and apparently influenced by variability in the net heat flux and river flow (magenta, third frame) as well as wind events (wind speed cubed, black in third frame; northeastward wind, black in fourth frame). However, no simple relationships are obviously evident that suggest a dominant influence of one of these factors over the others. There are periods when stratification increases in association with high river flow but other increases occur

when river flow is weak. There are extreme wind events that destroy stratification but a systematic response of stratification to variations in the northeastward wind is not clear. Weather-band variations in the sea level difference between Kings Point and Bridgeport (blue, fourth frame) appears inversely related to the northeastward wind component, and thus (as just noted) not directly linked to stratification variations. Finally, there may be a weak indication that periods of stronger stratification are less likely to occur during and shortly after times of high tidal range cubed (green, fifth frame) in association with spring tide conditions.

The connections between hypoxic events (red lines at bases of all five frames) and auxiliary parameters are at least as unclear as those just described for stratification events. Hypoxic events generally begin to occur later in the season than stratification events, after temperatures have reached a certain level. The termination of individual hypoxic events can be associated with a variety of different weather-band variations in heat flux, river flow, and wind conditions (with associated sea level differences). In general, hypoxic events appear to be more common during neap tide conditions than during spring tides. However, there are neap tides when hypoxia does not occur, and while they appear to be the exception, there are hypoxic events that persist through spring tide conditions (for example, at EXRX during a strong spring tide in late August 2009, and at WLIS during a mild spring tide in early August 2008).

6 Conclusions

The small number of records obtained, and their significant gaps in coverage, severely limit conclusions as compared to what was planned for this analysis presuming all 7-9 years of records would be obtained and be of good quality. Nonetheless there are some apparent patterns and they can be summarized as follows.

At the EXRX and WLIS sites (Figure 1) in each year treated (Table 1) there were up to 5-6 hypoxic events (Figure 2), as defined using MWT threshold 2.9 mg Γ^{-1} with minimum event duration 1 dy and trigger duration 9 hr. At EXRX the events were limited to the deepest sensor only and at WLIS they were most prominent at the deepest sensor but also occurred, to a lesser extent, at the mid-depth sensor. Based on two years when both sites were sampled, events at EXRX did not show particularly strong overlap in timing with those at WLIS, but there was a loose association with more frequent and more severe events occurring at EXRX during periods when they were more frequent and more severe at WLIS. Inter-annual variations were substantial and generally similar at the two sites. Hypoxia at the deep sensors is more severe at EXRX,

where the season-cumulative deficit-durations are in the range of about 15 to at least 55 mg l⁻¹ dy (and likely significantly higher, given that data gaps apparently lessened this peak value significantly). At WLIS, events were slightly less common and less intense, with season-cumulate deficit-durations in the range of about 4 to 42 mg l⁻¹ dy. These season-cumulative deficit-duration ranges are larger, particularly at EXRX, than those in the deeper portions of Narragansett Bay where a six-year analysis indicated they reach maxima of 40 mg l⁻¹ dy and are typically less than about 25 mg l⁻¹ dy (Codiga et al. 2009).

Events in stratification (Figure 3) were investigated, using MWT threshold of 2 °C, based on temperature differences (salinity data did not meet quality control standards) between the shallow and deep sensors (Sh-Dp) and between the mid-depth and deep sensors (Md-Dp). Stratification events are more intense during mid-summer as compared to earlier and later, and tend to occur during a larger fraction of the time during a given year than do hypoxic events. At EXRX stratification during the years treated here tended to be concentrated in the upper water column whereas this was true only during one year at WLIS. Season-cumulative surplus-durations reached maxima of about 130 °C dy. The numbers and intensities of stratification events at EXRX and WLIS in a given year were similar to each other in one year and quite different in another.

Auxiliary parameters representing various processes potentially important to hypoxia and stratification were investigated (Figure 4 to Figure 8): heat flux across the air-sea interface, various aspects of wind conditions, river flow, sea level difference between nearby stations, and spring-neap tidal phase. Relationships are evident but complex, and no simple patterns were observed of strong links between weather-band variability in stratification or hypoxia and that of a particular auxiliary parameter. Further analysis would be fruitful.

7 Appendix: Details of hypoxic events in oxygen timeseries

For completeness, and for reference, details regarding the hypoxic events (that have been summarized by Figure 2 and discussed above) are presented in a sequence of standard plots (Figure 9 to Figure 34). For each site, sensor depth, and available year of data, there is a figure showing the "entire time series" record from May 1 through October 31, with all events for that year (if any) marked. The EXRX site results are presented, followed by the WLIS site results. For each site, and year, the results from the deep, middle, then shallow sensors are presented, in

that order. For sensors at which event(s) occurred, an additional plot is included, showing the individual event(s) on an expanded scale, immediately following the "entire time series" figure.

Features of the "entire time series" plots are as follows. Black dots indicate raw data values; vertical dashed black lines indicate the first and last date/time of the record between May 1 and October 31. Red dots indicate values that were interpolated to fill short gaps. Red vertical lines, with red circles at each point between them at mid-height on the plot y-axis, indicate the start and end of missing data gaps. The horizontal black line indicates the threshold value. Sub-threshold values within a given event have their black dot circled with a color (green, magenta, cyan, or blue). A vertical line of the same color marks the start and end time of the event; the line at the event start is dashed if the event is gap-begun, and the line at the event end is dashed if the event is gap-ended.

Features of "individual event" plots are the same as just described for the "entire time series" plots, except that the horizontal axis limits are chosen to focus on a single event. Where multiple frames showing individual events appear on the same page, the horizontal axes have the same scale, so the relative event durations are evident visually. The heading of each event frame shows the deficit-duration for that event.

References

- Codiga, D.L. 2008. A moving window trigger algorithm to identify and characterize hypoxic events using time series oberservations, with application to Narragansett Bay, GSO Technical Report 2008-01, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI, 110pp. ftp://po.gso.uri.edu/pub/downloads/codiga/chrp/mwt/TechRptMWTCodigaMar08.pdf.
- Codiga, D.L., H.E. Stoffel, C.F. Deacutis, S. Kiernan, C. Oviatt. 2009. Narragansett Bay Hypoxic Event Characteristics Based on Fixed-Site Monitoring Network Time Series: Intermittency, Geographic Distribution, Spatial Synchronicity, and Inter-Annual Variability. *Estuaries and Coasts* 32(4), p621 DOI 610.1007/s12237-12009-19165-12239.
- Gay, P., J. O'Donnell, C.A. Edwards. 2004. Exchange between Long Island Sound and adjacent waters. J. Geophys. Res.-Oceans 109, doi:10.1029/2004JC002319.
- Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P.C. Shafran, W. Ebisuzaki, D. Jovic, J. Woollen, E. Rogers, E.H. Berbery, M.B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, W. Shi. 2006. North American Regional Reanalysis. *Bull. Am. Met. Soc.* 87(3), 343-360.
- Niiler, P.P., E.B. Kraus. 1977. One dimensional models of the upper ocean. In: Kraus, E.B. (Ed.), Modeling and prediction of the upper layers of the ocean, Permagon, New York, pp. 323.
- O'Donnell, J., H.G. Dam, W.F. Bohlen, W. Fitzgerald, P. Gay, A.E. Houk, D. Cohen, M. Howard-Strobel. 2008. Intermittent ventilation in the hypoxic zone of western Long Island Sound during the summer of 2004. J. Geophys. Res 113, C09025, doi:09010.01029/02007JC004716.
- Riley, G.A. 1952. Hydrography of the Long Island and Block Island Sounds. *Bulletin of the Bingham Oceanographic Collection* 3, Article 3.
- Wilson, R.E., R.L. Swanson, H.A. Crowley. 2008. Perspectives on long-term variations in hypoxic conditions in western Long Island Sound. J. Geophys. Res 113, C12011, doi:12010.11029/12007JC004693.

Site, bathymetric depth	Average Sensor Depths (Shallow, Middle, Deep)	Years collected	Years obtained from UConn for this analysis
Execution Rocks 22.5 m	0.1 m, 5.3 m, 15.8 m	2004-2010	2006 (partial), 2008, 2009
Western LIS 18.3 m	0.2 m, 8.4 m, 15.6 m	2002-2010	2008, 2009, 2010
Flux Buoy 1 12.8	0.2 m, 4.4 m, 9.2 m	Late 2005 to 2006	None
Flux Buoy 2 16.5 m	0.2 m, 4.4 m, 14.2 m		None
Flux Buoy 3 11.9 m	0.2 m, 4.7 m, 10.1 m		None

Table 1. Time series record characteristics.



Figure 1. Region map.

EXRX = Execution Rocks oxygen/temperature buoy site; WLIS = Western Long Island Sound oxygen/temperature site; F1-F3 = Flux Buoys 1-3; BP = Bridgeport sea level station; KP = Kings Point sea level station; NARR = North American Regional Reanalysis gridpoint.





Figure 2. Summary timelines of hypoxic events (rel 2.9 mg l⁻¹) at all available stations and years. Rectangles depict individual hypoxic events. The width of the rectangle indicates the event duration, the height of the rectangle indicates the event-mean deficit (see legend at top), and the area of the rectangle indicates the deficit-duration of the event. Black horizontal lines denote periods when data are available and passed QC standards. Asterisks (example 2008 EXRX Deep, end of second event) indicate events that started or ended when data were missing, so the event start/end time is unknown. Data from EXRX shallow and middle depth sensors, and WLIS shallow sensor, are not shown because no events occurred. Results in this figure summarize the details presented in Figure 9 to Figure 34.



Figure 3. Summary timelines, stratification (ΔT) events (rel 2°C), all available stations and years. Plotted as in Figure 2. Sh-Dp indicates the temperature difference between the shallowest and deepest sensors. Md-Dp indicates the temperature difference between the mid-depth and deepest sensors.



Figure 4. DO, hypoxic events, temperature, and auxiliary parameters: EXRX, 2006. See text for detailed legend.



Figure 5. DO, hypoxic events, temperature, and auxiliary parameters: EXRX, 2008. See text for detailed legend.



Figure 6. DO, hypoxic events, temperature, and auxiliary parameters: EXRX, 2009. See text for detailed legend.



Figure 7. DO, hypoxic events, temperature, and auxiliary parameters: WLIS, 2008. See text for detailed legend.



Figure 8. DO, hypoxic events, temperature, and auxiliary parameters: WLIS, 2009. See text for detailed legend.



Figure 9. MWT results, DO: EXRX, 2006, deep. Entire time series.



Figure 10. MWT results, DO: EXRX, 2006, deep. Individual events.



Figure 11. MWT results, DO: EXRX, 2006, middle. Entire time series.



Figure 12. MWT results, DO: EXRX, 2006, shallow. Entire time series.



Figure 13. MWT results, DO: EXRX, 2008, deep. Entire time series.



Figure 14. MWT results, DO: EXRX, 2008, deep. Individual events.



Figure 15. MWT results, DO: EXRX, 2008, middle. Entire time series.



Figure 16. MWT results, DO: EXRX, 2008, shallow. Entire time series.



Figure 17. MWT results, DO: EXRX, 2009, deep. Entire time series.



Figure 18. MWT results, DO: EXRX, 2009, deep. Individual events.



Figure 19. MWT results, DO: EXRX, 2009, middle. Entire time series.



Figure 20. MWT results, DO: EXRX, 2009, shallow. Entire time series.



Figure 21. MWT results, DO: WLIS, 2008, deep. Entire time series.



Figure 22. MWT results, DO: WLIS, 2008, deep. Individual events.



Figure 23. MWT results, DO: WLIS, 2008, middle. Entire time series.



WESTERN LONG ISLAND SOUND-2008-Mid Event 1: Duration 2.5 days; Deficit-Duration 2.1 mg/l-days

Figure 24. MWT results, DO: WLIS, 2008, middle. Individual events.



Figure 25. MWT results, DO: WLIS, 2008, shallow. Entire time series.



Figure 26. MWT results, DO: WLIS, 2009, deep. Entire time series.



Figure 27. MWT results, DO: WLIS, 2009, deep. Individual events.



Figure 28. MWT results, DO: WLIS, 2009, middle. Entire time series.



Figure 29. MWT results, DO: WLIS, 2009, shallow. Entire time series.



Figure 30. MWT results, DO: WLIS, 2010, deep. Entire time series.



Figure 31. MWT results, DO: WLIS, 2010, deep. Individual events.



Figure 32. MWT results, DO: WLIS, 2010, middle. Entire time series.



Figure 33. MWT results, DO: WLIS, 2010, middle. Individual events.



Figure 34. MWT results, DO: WLIS, 2010, shallow. Entire time series.