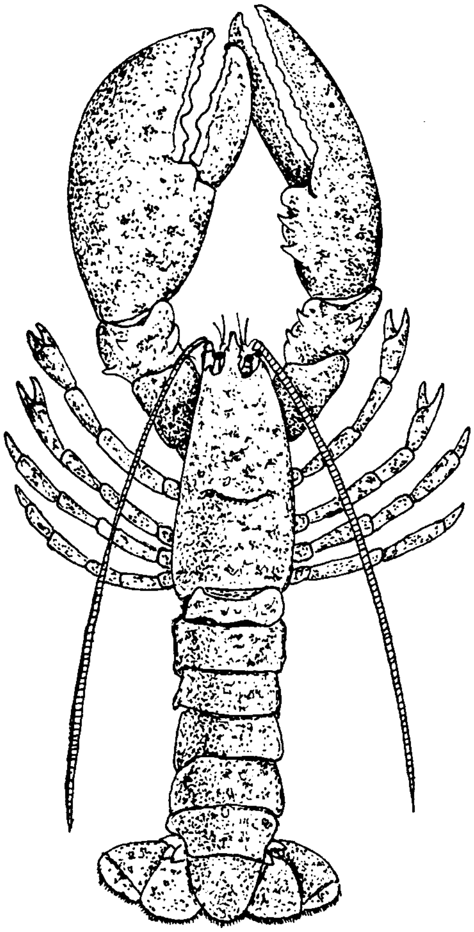
Environmental Stressors



Monitoring of Bottom Water and Sediment Conditions at Critical Stations in Western Long Island Sound

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The collapse of the lobster fishery in WLIS during September of 1999 served to raise concerns in the scientific and regulatory communities about the environmental processes that regularly occur at the bottom in WLIS. REMOTS® sediment-profile images taken immediately after the lobster die-off showed the presence of an extremely shallow (< 1 cm deep) apparent Redox Potential Discontinuity (aRPD) in the sediments underlying the majority of lobster fishing grounds in the western Sound. Such an aRPD is usually indicative of a recent hypoxic/anoxic event.

The summer of 1999 was not the first summer, however, during which WLIS experienced severe, widespread occurrences of hypoxic conditions and fisheries loss – it was simply the most widespread and the most economically-costly occurrence. One common environmental thread that runs through all of the lobster die-offs in LIS, both the massive ones and the more minor ones, is the presence of hypoxic/anoxic waters, as recorded by the CT DEP as part of their ongoing monitoring of water conditions in Western Long Island Sound. Although many other factors (e.g. paramoebas, high water temperatures, pesticide spraying, bait degradation products) may, undoubtedly, have been the ultimate cause of the death of the lobsters, bottom water hypoxia *was* recorded early during the summer of 1999 (CT DEP monitoring data), as well as during the massive die-off itself (as recorded by REMOTS®).

Hypoxia in Long Island Sound is a long-standing problem. Its main cause appears to be nitrogen enrichment from both point and non-point sources of pollution (CT DEP Bureau of Natural Resources, Marine Fisheries Office, 2000; Kaputa, N.P. & C.B. Olsen, 2000; Welsh, B.L. & F.C. Fuller,1991; Welsh, B.L, *et al.*,1994). Beginning in 1988, a comprehensive monitoring of western LIS waters for physical, chemical, and biological data has been undertaken by the CT DEP in conjunction with the USEPA in order to track, among other things, the development of hypoxic and anoxic waters. It should be noted that water samples are routinely taken as part of this analysis at approximately 1 meter off the bottom. While this provides important information, it does not necessarily reveal the environmental conditions at the sediment-water interface that benthic organisms are experiencing at any given point in time.

In the Spring of 2000, the USEPA and NEIWPCC authorized a four month study (August-November) of bottom water (< 5 cm above the bottom) and sediment chemistry at 36 sites in WLIS. The majority of these sites coincided with stations previously sampled immediately following the die-off in October of 1999. In addition to collecting REMOTS® sediment-profile images, the USEPA-NEIWPCC study also analyzed bottom waters for dissolved oxygen, hydrogen sulfide, and ammonia. Data from this study revealed that a number of stations, mainly concentrated in the western-most Sound (Western Narrows), had extremely black (i.e., anoxic/sulfidic) sediment and thin redox depths. Hypoxia (as defined by dissolved oxygen measurements) at the bottom of the water column in WLIS persisted during the summer of 2000 for a longer time period of time than in the waters present at 1 m or more above the bottom (CT DEP data). In fact, dissolved oxygen concentrations indicative of moderately severe hypoxia were observed at stations in the extreme western Sound during late August 2000. Bottom water dissolved oxygen levels increased steadily from August to November, indicative of the breakdown of thermal stratification and system wide re-aeration of the bottom waters.

In addition, measurable levels of hydrogen sulfide and ammonia were detected in bottom waters during August, September, and November indicating that the anaerobic decomposition processes occurring in the sediment at that time dominated the bottom water benthic environment. Although much valuable data was collected in this study, the timing was such that the study missed most of the months when WLIS is, in fact, most susceptible to hypoxia (June-August), as well as some of the time during which the lobster mortality occurred (September-October). The work discussed herein sought to address this lack of information, particularly as it relates to seasonal changes in sediment dissolved oxygen levels, benthic infaunal communities, and releases of hydrogen sulfide and ammonia into WLIS bottom waters.

The chemical basis of hypoxia is described in a simple manner in the paragraphs that follow.

1) Oxygen is renewed in marine surface waters in two general ways. Phytoplankton productivity in the upper water column (photic zone) introduces oxygen into water via photosynthesis. Surface wind mixing of the waters facilitates oxygen exchange with the atmosphere, renewing the oxygen content of the surface waters. Downward advection of surface waters then brings oxygen to the bottom waters. Normal average oxygen saturation for LIS waters is approximately 7 mg/l.

2) Oxygen is consumed in marine waters in several ways. The organisms that live in the marine environment consume oxygen during respiration; plant respiration in the photic zone also consumes a certain amount of oxygen although significantly less than what is produced by the phytoplankton. Finally, the sediments, depending on their organic content, consume oxygen via bacterial degradation of organic matter.

3) This last point is extremely important for sediments that have high organic carbon, such as those of Western Long Island Sound. Such sediments, in contact with oxygen, will consume oxygen via aerobic bacterial decomposition of organic matter. This effects of sediment oxygen demand can become quite large if bottom water oxygen renewal is limited by either water temperature or the existence of a stratified water column which prevents vertical mixing, ultimately setting the stage for the onset of hypoxic and perhaps even anoxic bottom waters (within 2 cm of the sediment-water-interface).

The research undertaken specifically investigated bottom water dissolved oxygen, as well as hydrogen sulfide and ammonia (two end-products of organic matter degradation that are known to negatively affect many organisms), as structuring influences on the benthic habitat quality and associated benthic communities of western Long Island Sound. It is hypothesized that long-term exposures to low oxygen, ammonia, and hydrogen sulfide may have contributed to a chronic low-level, physiologically-stressed state in the lobsters and other organisms that died in 1999, weakening their immune system, and setting them up for disease.

The results of this study are as follows:

1) The REMOTS® images reveal that the sediment surface at stations in the Eastern Narrows appeared to be oxygenated, with aRPD depths on the order of 2-4 cm. Extremely black (ie. sulfidic) sediments were more routinely observed at stations in the Western Narrows in all three REMOTS® surveys. REMOTS® photos in May revealed that all of the stations in the Western Narrows had either well-developed aRPD depths of 2-4 cm or, at least, a thin band (< 1-2 cm) of oxygenated sediment at the sediment-water interface overlying black, sulfidic sediment. The September REMOTS® photos revealed black, sulfidic sediments exposed at the sediment surface at five stations in WLIS, including one that had obvious methane bubbles present. The December REMOTS® photos revealed a thin band (1-4 cm) of oxygenated sediment overlying black, sulfidic sediments at all stations.

2) There were linear trends in the data, corresponding to depth and substrate type. Measured bottom water dissolved oxygen levels were consistently lower than those recorded by the DEP during their water column sampling of WLIS for the same time period as this study.

3) Bottom waters (within 5 cm of the bottom) at two-thirds of the sites sampled contained their highest dissolved oxygen levels in May and their second highest oxygen levels in December. Near-bottom waters (approximately 1 meter above the bottom) most likely follow the same trend, however data for May were not collected due to sampling constraints at the time.

4) Hydrogen sulfide was present in bottom waters at almost all stations sampled throughout the duration of the study, with peak levels occurring in May and October. Near-bottom water levels of hydrogen sulfide peaked in September and October and were barely present in August at all stations.

5) Ammonia was present in bottom waters at all stations during all sampling times; however, peak ammonia values were obtained from stations in the western Sound during the month of October. Near-bottom water ammonia levels also followed this exact trend.

The REMOTS® photos were similar to those obtained in WLIS in past years, with sulfidic sediments and thin aRPD depths characterizing stations in the Western Narrows, and a significant amount of small-scale spatial variability present in the observed aRPD. These images record the chemical changes that occur in the presence of hydrogen sulfide and iron and are a record of overall seasonal changes but do not capture the actual chemical variability that occurs on a weekly to monthly time scale.

Chemical data collected from this study reveals that the chemistry of the bottom waters in WLIS is very dynamic and varies dramatically over the course of a year. The variation in the ammonia and sulfide data correlates not with oxygen levels in the upper water column but with temperature and organic matter availability in the sediments themselves. Thus, a disconnect appears between water column dissolved oxygen levels and conditions at the sediment-water interface. It appears that seasonal variations in water column conditions simply lead to variations in the magnitude of the disconnect between the water column and the sediment but do not directly control processes within bottom waters. In turn, sediment processes and their end-products exert effects upon the dissolved oxygen levels at the bottom. The existence of the disconnect between the chemical environment that is experienced by benthic organisms and that which is occurring 1 meter or more above the bottom means that, for systems like Long Island Sound, it is the sedimentary environment that strongly structures the bottom waters in which benthic organisms live. The presence of the disconnect is best detected with chemical methods and does not show up as distinctly with REMOTS®, which appears to record a seasonal time averaging of benthic phenomena rather than the weekly shifts that are, apparently, present and significant to organisms living in the environment.

One of the issues central to management of the lobster fishery in western Long Island Sound is the condition of the bottom waters with respect to hypoxia. This study has documented that the sediments play a significant role in structuring bottom water chemistry in WLIS although it must be recognized that the onset of hypoxia in western Long Island Sound results from the interplay of many different factors, including air and water temperature, rainfall, currents, amount and type of organic matter, initial bottom water oxygen levels, anthropogenic inputs, and degree of stratification. The individual contribution made by any of these factors can vary from year to year. This makes it all the more necessary to know the “standing” background conditions of the sediments, sediment geochemistry, and the benthic communities in WLIS in order to be able to effectively predict how well the Sound can support a lobster fishery in any given year, as well as provide important information to be used to gain further insights into the lobster mortality event of 1999.

Literature Cited:

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Welsh, B.L. & F.C.Fuller, 1991. Mechanisms controlling summertime oxygen depletion in western Long Island Sound. *Estuaries* 14:265-278.

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Prevailing Water Column Conditions in Long Island Sound and the Relationship to Lobster Mortality Events

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Our activities have included an analysis of long term records for water column temperature, salinity and dissolved oxygen. We have used available data from NY DEP and CT DEP within Long Island Sound, and additional data from Block Island Sound. Our objective has been to describe spatial and temporal patterns in anomalies (from climatology) in these parameters and covariation between parameters.

Results provide evidence for climate variability, especially for bottom temperature, with large winter anomalies which persist for more than one year. They also provide evidence for weather induced anomalies, some associated with anomalous vertical mixing events.

We provide here an example of results from an analysis of the covariation in bottom temperature and bottom dissolved oxygen over the last decade for six CT DEP stations distribute over the length of Long Island Sound. Figures 1 through 4 show results of principal component analysis applied to these twelve series. Each series consists of monthly averaged anomalies for the period 1991 through 2002. Figure 1 shows the eigenvector for Mode l; it represents the spatial structure associated with this mode of variability.

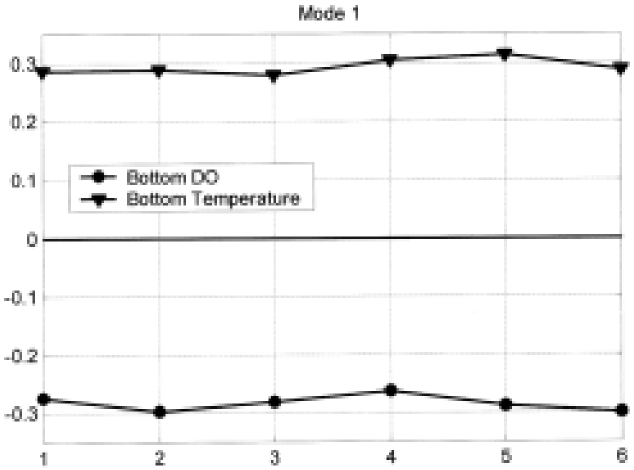


Figure 1. Eigenvector for Mode 1, representing the spatial structure associated with this mode of variability.

Mode 1 accounts for 52% of the total variance in these data. The horizontal axis in Figure 1 is series number so it can be considered distance down the axis of the Sound from west to east. Series 1 is from CT DEP station A4 in the western Sound. Series 6 is from CT DEP station M3 to the east of Mattituck sill in the far eastern Sound. Figure 1 shows that fluctuations in bottom temperature and near bottom dissolved oxygen have opposite signs with very little spatial structure over the length of the basin. It should be mentioned, however, that the series have each been normalized by their standard deviations and that there are significant spatial variations in these standard deviations.

Figure 2 shows the amplitude time series for Mode 1. It shows the strong positive winter anomalies which occurred in 1998, 1999 and 2002. It also shows a strong positive anomaly in the fall of 1999. A positive amplitude corresponds to a positive bottom temperature anomaly and a negative near bottom dissolved oxygen anomaly.

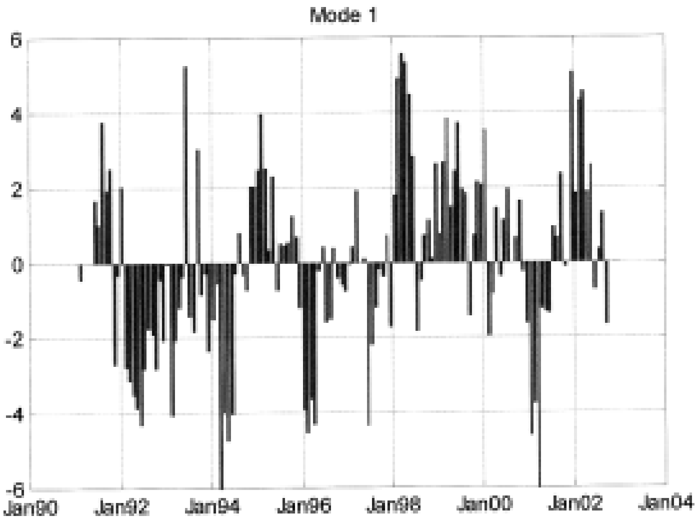


Figure 2. Amplitude time series for Mode 1. It shows the strong positive winter anomalies which occurred in 1998, 1999 and 2002. It also shows a strong positive anomaly in the fall of 1999. A positive amplitude corresponds to a positive bottom temperature anomaly and a negative near bottom dissolved oxygen anomaly.

Figure 3 shows the eigenvector for Mode 2 which accounts for 30% of the total variance in the 12 series. In contrast to Mode 1 it shows that the eigenvector components for bottom temperature and dissolved oxygen have the same sign throughout the basin. There is some longitudinal variation associated with the structure of this mode. The amplitude time series for Mode 2 (Figure 4) shows the strong positive anomalies which occurred in 1999 and 2002. For this mode a positive amplitude corresponds to positive bottom temperature bottom and dissolved oxygen anomalies. Both modes 1 and 2 are associated with positive bottom temperature anomalies in 1999 and 2002. Mode 2 exhibits very long term trends which is characteristic of the first mode results for bottom temperature alone.

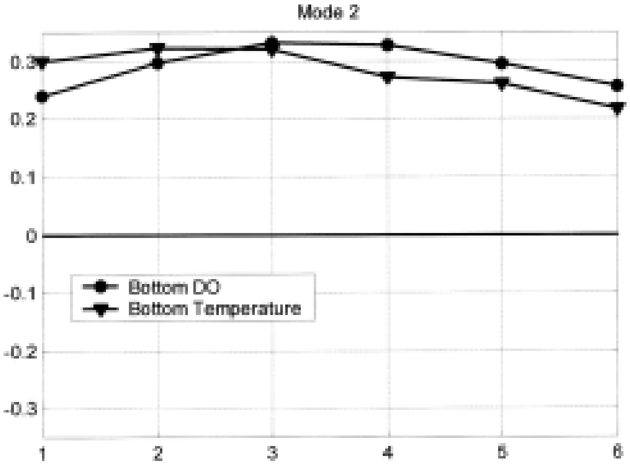
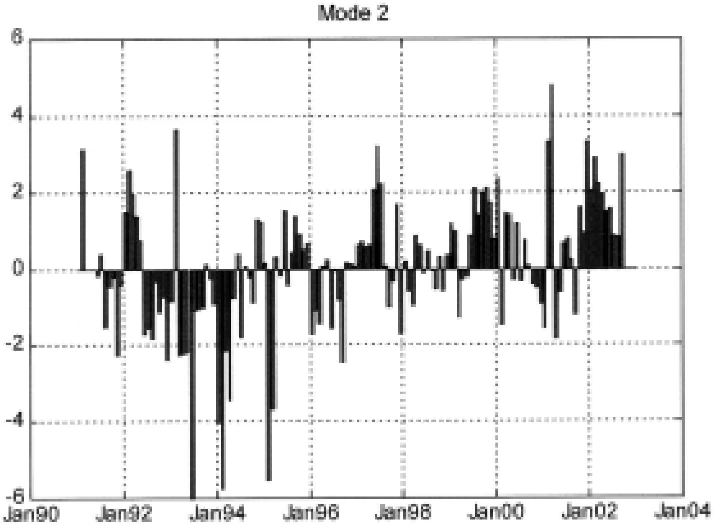


Figure 3. Eigenvector for Mode 2.

Figure 4. Amplitude time series for Mode 2.



Exposure of Lobsters to the Varied Chemical and Biological Environment of Long Island Sound

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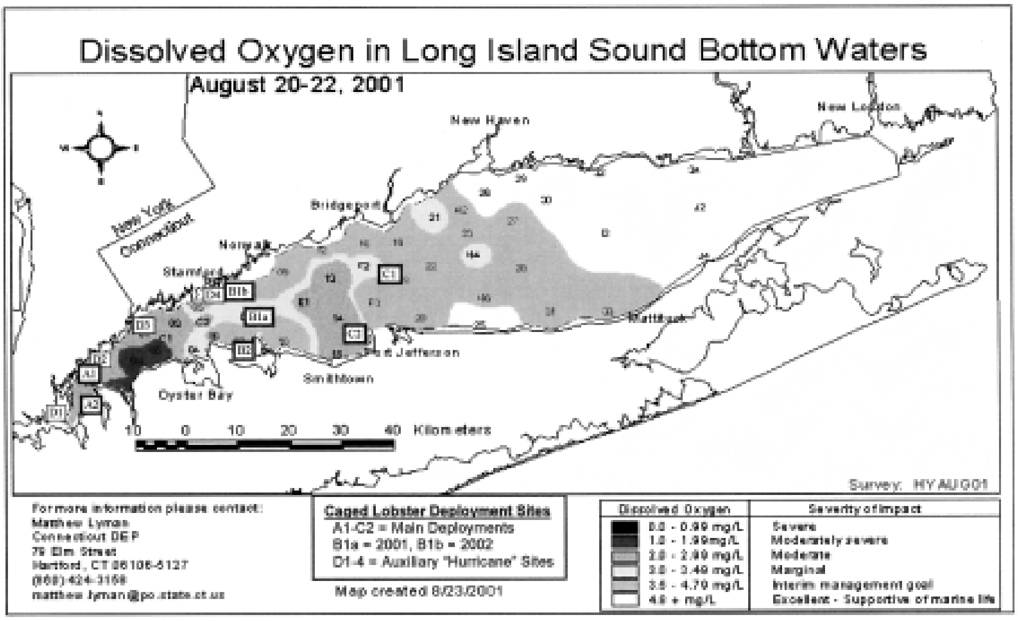
This field experiment was designed to increase understanding of the relationship between lobster health and the ambient chemical and biological environment of Long Island Sound. During the first weeks of July 2001 and 2002, we deployed between 9 and 24 chemically naive lobsters (from Atlantis Canyon) in individual cages at each of six locations in western Long Island Sound (Figure 1). The sites were selected to expose the lobsters to the west to east cultural eutrophication gradient emanating from the New York metropolis, and to either sandy or muddy sediments. Each site was equipped with a temperature recorder and up to four sites had temperature-salinity-dissolved oxygen recording instruments. At two-week intervals, divers retrieved a subset of cages from each site and collected sediment and water column samples, exchanged hydrographic instruments and fed the remaining lobsters. Samples were aliquoted for the analysis of biogeochemicals in the water column and porewaters, and trace metals and chlorinated hydrocarbons in sediments. Retrieved lobsters were sampled to assess infection by bacteria and other pathogens, lipid distribution, accumulation of metals in gills, brain, and muscle tissue, and accumulation of chlorinated hydrocarbons in hepatopancreatic tissue. An auxiliary set of caged lobsters was deployed each year at four shallow water stations along the New York-Connecticut coast to examine the role that storm activity plays in exposing lobsters to biogeochemicals from resuspended sediments.

Raw mortality among lobsters caged in the main deployment reached 37% in 2001. However, this value may have been influenced by methodological problems which were subsequently addressed in the 2002 deployment when the maximum observed mortality was only 23%. Chemical analyses of habitat and tissue samples are currently in progress with about half of the variable classes completed.

Figure 1. Locations of deployed lobster cages in western Long Island Sound.



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Environmental Change in Long Island Sound in the Recent Past: Eutrophication and Climate Change

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Goal of the research

The goal of our research is to document recent environmental changes in Long Island Sound (LIS) and their effects on the ecosystem as shown in microbiota which leave fossil evidence (photosynthesizing diatoms and dinoflagellates, and heterotrophic foraminifera and dinoflagellates), and put these into the historical perspective of the last 500-1000 years. We emphasize changes that occurred over the last 150 years, with the main anthropogenic imprint since the middle part of the 19th century, the changes that occurred over the last 30-40 years since anoxia/hypoxia in western LIS became common after the late 1960s-early 1970s, and changes in the late 1990s when the lobster die-off occurred. In order to document these environmental and biotic changes we have studied samples from sediment cores to record changes in dinoflagellate and diatom floras and benthic foraminiferal faunas, to obtain evidence for changes in water temperature and salinity (using $\delta^{18}O$ and Mg/Ca in carbonate foraminiferal shells), to document pollutant burdens, degree of bottom water oxygenation (using $\delta^{13}C$ in the calcite of foraminiferal shells), to provide evidence for changes in the magnitude of sewage input (using abundances of the bacterial spore *C. perfringens*), changes in diatom productivity (using analyses of sediment-stored biogenic silica), and changes in the storage and origin of C_{org}, and N_{org}, using C and N abundances and isotopic compositions ($\delta^{15}N$ and $\delta^{13}C$) and changes in sulfur abundances. We have also put effort into calibrating these indicators used in the core samples in the modern LIS environment through water sampling, surface sediment sampling and measurements of water column parameters (temperature, dissolved oxygen, salinity). We are working on providing age models for the sediment cores to obtain temporal records of the environmental and biotic changes.

Results

Nutrient fluxes have increased in the Sound with increased population density and changes in land use patterns. The Narrows and Western LIS have the largest inputs of effluents from wastewater treatment plants (WWTP) and there we find the most pronounced increased organic productivity as well as the resulting bottom water hypoxia/anoxia as a result of this eutrophication process.

Records of C_{org} concentrations in sediment cores show an increase from ~ 1850 on, in central LIS going from 1.2 to 2.5 % and in western LIS up to 4.5 %. A core in western LIS also shows an increase in N concentration from ~0.1 at the bottom to ~0.2 % at the top. Recalculation of C_{org} data as C_{org} accumulation rates shows that these rates have increased by a factor of 5 between 1850 and 2000. Accumulation rates of biogenic silica have increased as well by a factor of 4-5 over the last 150 years. This finding confirms and quantifies the long-held suspicion that the primary productivity and resulting flux of organic carbon to the LIS bottom waters has increased strongly as a result of eutrophication. We can, however, not conclude without further consideration that this enhanced carbon flux is the direct cause of the bottom water hypoxia/anoxia, because the carbon is covered more rapidly by sediment as the result of the higher sediment accretion rates of the last 150 years.

The records of paleo-salinity and -temperature (mean bottom water temperature over several years) show strong variations over the last millennium, with a positive correlation between temperature and salinity (warm and dry versus cool and wet). The highest temperatures occurred about 1,000 years ago (Medieval

Warm period) whereas the lowest water temperatures were reached about 200 years ago (end of Little Ice Age). The water temperatures have increased over the last 100 years. The paleo-salinity shows a narrow window between 26 and 31 ‰, with more extreme events during the 20th century. We assume that these short, low-salinity events are the result of wet periods, which, with changes in land use, resulted in more direct pulses of fresh water input into the Sound than before. The $\delta^{13}C$ values of carbonates in LIS sediment become substantially lighter over the last 200 years, the result of the oxidation of organic carbon in the bottom waters. The Nitrogen isotope signal becomes heavier by almost 2 per mille over that same period, evidence for the influx of anthropogenic nitrogen into the LIS system.

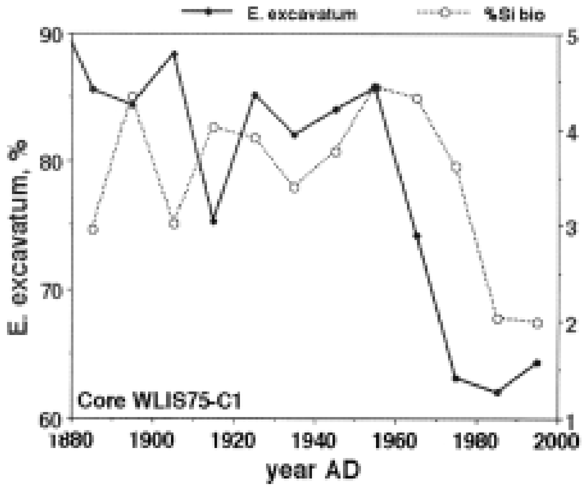
Diatom floras from a core in western LIS show a major decrease in diversity and species richness and an increase in the centric/pennate ratio (C:P; an indicator of eutrophication and increasing water turbidity) starting in the middle 19th century, when C_{org} data indicate increasing organic storage in the sediments. During the last few decades, the number of diatom valves declined as did diatom diversity, while the ratio of centric to pennate diatoms increased even more. Preliminary data on dinoflagellates show a strong east-west gradient in surface samples, with heterotrophic dinoflagellates (indicators of eutrophication) more abundant in western LIS. The heterotrophic forms increase in abundance from bottom to top in cores in western LIS.

Benthic foraminiferal faunas show the most severe changes with time in western LIS. In most cores, the total abundance of foraminifera (nr/gr bulk sediment) increased from the middle of the 19th century, but decreased again during the last ~30 years, and most prominently in the last few years. The mid 19th century increase in number of benthic foraminifera was caused by an increase in absolute and relative abundance of the diatom-consuming species, *Elphidium excavatum*. The decrease in total foraminiferal numbers in western LIS and the Narrows was caused by the decrease in numbers of *E. excavatum* during the last few decades. The decrease in relative abundance of this species was caused by an increase in abundance of the omnivorous *Ammonia beccarii*, a cosmopolitan omnivorous species which was very rare in LIS before the mid-1960s.

We speculate that the major changes in the benthic foraminiferal faunas were largely caused by the increased diatom productivity in the middle 19th century, followed by the decrease in diatom abundance in the last few decades. The increase in C:P in diatoms may be explained by increasing eutrophication and resulting increase in turbidity of the water column. The recent decrease in abundance of diatom valves and decrease in diversity could be explained by silica limitation during the spring phytoplankton bloom. The strong increase in relative abundance of the benthic foraminifer, *A. beccarii*, in western LIS at a time of decreasing abundance of the diatom-consuming species could have been caused by blooming of non-diatom phytoplankton. In the last few decades, the main primary producers in LIS may thus have changed from diatoms to organic-walled phytoplankton such as dinoflagellates, which has potentially a major impact on all LIS biota.

Conclusions

The paleo environmental records (examples shown below for core WLIS 75 –in the Narrows; cores A1C1 and A4C1 in West LIS) show clear evidence for eutrophication of the Sound since the mid-19th century, as evidenced by enhanced storage of organic carbon, biogenic silica, and nitrogen, heavier nitrogen isotopes, lighter carbon isotopes, and changes in benthic foraminiferal faunas and diatom floras. A decrease in biogenic silica and change in fauna in the last 20-30 years in the extreme western Sound may signal the onset of new changes in the LIS ecosystem. Salinity and water temperature have not moved dramatically outside their long-term range, but over the last century stronger variations in salinity seem to occur and waters have been warming. The warming with the occurrence of more extreme events in low-salinity together with the enhanced production of organic carbon is most likely the cause for the hypoxia/anoxia in western LIS. The documented changes in the LIS microfloral and faunal ecosystem may have propagated throughout the LIS ecosystem.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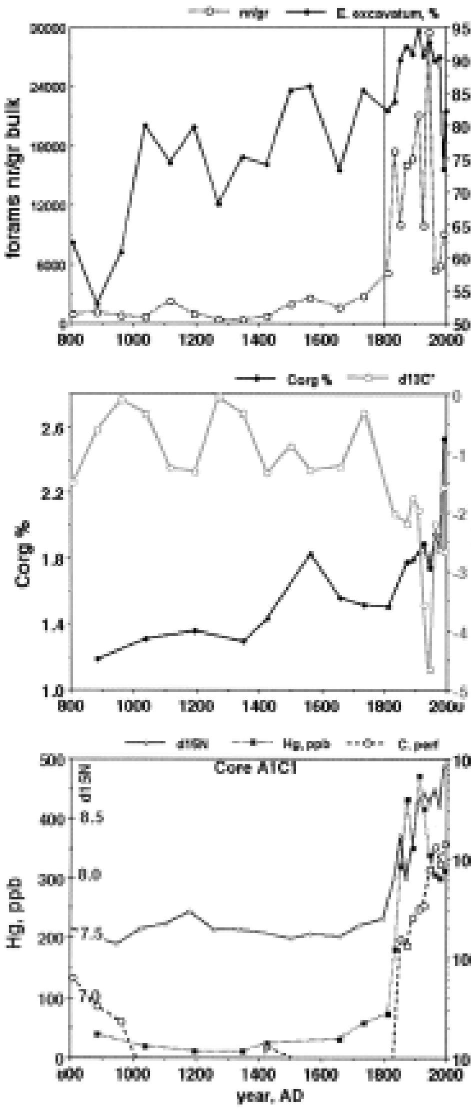
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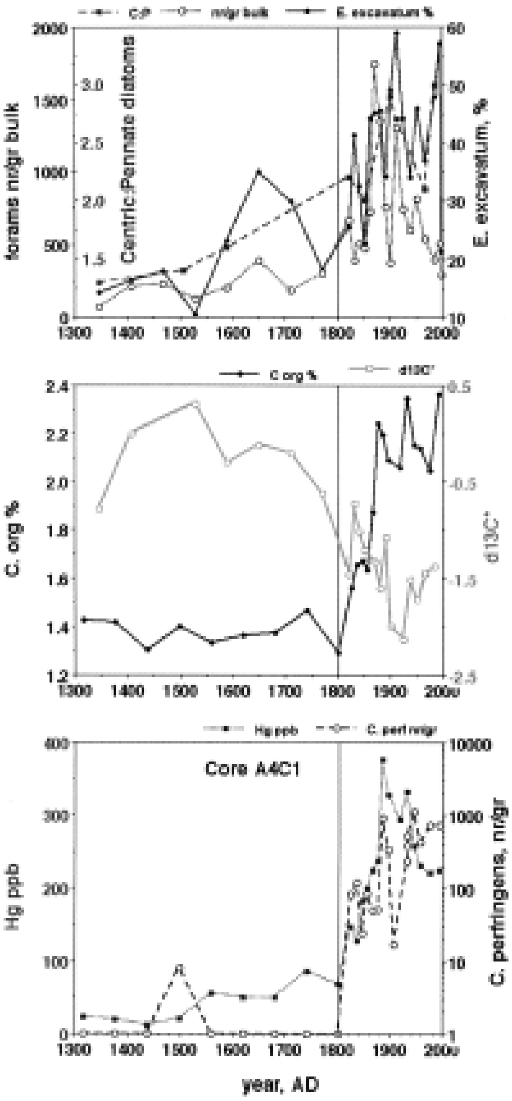
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