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A 1,000-year, annually-resolved record of hurricane activity from Boston, Massachusetts

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[1] The annually-laminated (i.e., varved) sediment record from the Lower Mystic Lake (near Boston, MA), contains a series of anomalous graded beds deposited by strong flooding events that have affected the basin over the last millennium. From the historic portion of the record, 10 out of 11 of the most prominent graded beds correspond with years in which category 2–3 hurricanes are known to have struck the Boston area. Thus, we conclude that the graded beds represent deposition related to intense hurricane precipitation combined with wind-driven vegetation disturbance that exposes fresh, loose sediment. The hurricane signal shows strong, centennial-scale variations in frequency with a period of increased activity between the 12th–16th centuries, and decreased activity during the 11th and 17th–19th centuries. These frequency changes are consistent with other paleoclimate indicators from the tropical North Atlantic, in particular, sea surface temperature variations. **Citation:** Besonen, M. R., R. S. Bradley, M. Mudelsee, M. B. Abbott, and P. Francus (2008), A 1,000-year, annually-resolved record of hurricane activity from Boston, Massachusetts, *Geophys. Res. Lett.*, *35*, L14705, doi:10.1029/2008GL033950.

1. Introduction

[2] The natural variability of hurricane activity on centennial and longer timescales is poorly known because instrumental records extend back just ~130 years, and aircraft reconnaissance and satellite observations only began in the mid-1940's [*Landsea*, 2007]. Interest is heightened in light of studies suggesting that hurricane activity may increase due to anthropogenic global warming [*Emanuel*, 1987; *Broccoli and Manabe*, 1990; *Knutson et al.*, 1998], and, more recently, that such an increase is already perceptible [*Emanuel*, 2005; *Webster et al.*, 2005; *Mann and Emanuel*, 2006; *Santer et al.*, 2006]. By examining natural archives that preserve signatures of hurricane activity, we can provide longer-term perspectives about its variability [*Liu*, 2004; *Nott*, 2004]. From the North Atlantic basin, work has focused primarily on producing low-resolution records based on storm surge overwash deposits encountered in coastal marshes and lagoons [*Liu*, 2004; *Nott*, 2004; *Donnelly and Woodruff*, 2007]. However, recently, development has begun on a second generation of annually-resolvable records that provide a much more precise picture of past hurricane activity [*Miller et al.*, 2006; *Frappier et al.*, 2007]. Here we detail a ~1000 year long, annually-resolved (i.e., varved) lake sediment record from Boston, Massachusetts, in which anomalous graded beds, related to intense hurricane precipitation and vegetation disturbance, have accumulated over the last millennium.

2. Study Location and Methods Summary

[3] Lower Mystic Lake ("LML") is a low elevation (~1 m a.s.l.), fresh water lake situated between Medford and Arlington, MA (~10 km from downtown Boston; lat. N42° 25.6′, lon. W71° 8.8′). The lake has a maximum depth of 24 m, and was formerly confluent with the Upper Mystic Lake until the mid-1860's when a 3 m high dam was built between the two [*Besonen*, 2006]. The LML has a total watershed area of ~95 km^2, and drains to Boston Harbor via the Mystic River (Figure 1a). Prior to the construction of Cradock Dam in 1908 (Figure 1a), the river was estuarine, and marine water regularly reached the lake via the river channel during high spring tides and periods of low outflow. The denser seawater sank to the lake bottom resulting in a water column that is chemically stratified (i.e., meromictic) (Figure 1b). This stratification drove the bottom waters to anoxia, thereby protecting the sediments from bioturbution, and allowing the lake to accumulate a finely laminated record of sedimentation (Figure 1c) over the last millennium [*Besonen*, 2006].

[4] Multiple overlapping piston, gravity, percussion, and freeze cores were retrieved from the lake, and split and photographed in the lab. As the sediments are laminated, correlations from core to core were clear and obvious, and stratigraphic defects were easily identified. Overlapping sediment blocks were extracted from cores with the fewest defects, embedded in epoxy resin, and used to produce petrographic thin sections and X-ray densitometry slabs (2 mm thick). The thin sections and X-ray slabs were cut from orthogonal angles of orientation allowing us to actively identify and correct concealed/blind defects that would otherwise be invisible from a single perspective [*Besonen*, 2006]. A master, composite sequence of stratigraphy was constructed from high resolution imagery of observations made via petrographic microscopy, back scattered electron microscopy (BSEM), and X-ray densitometry. Analyses of ^{137}Cs and ^{210}Pb activity were performed on freeze core subsamples at EAWAG (Swiss Federal Institute of Aquatic Science and Technology, Zurich). AMS ^{14}C dating on terrestrial macrofossils was performed at the NSF-Arizona,

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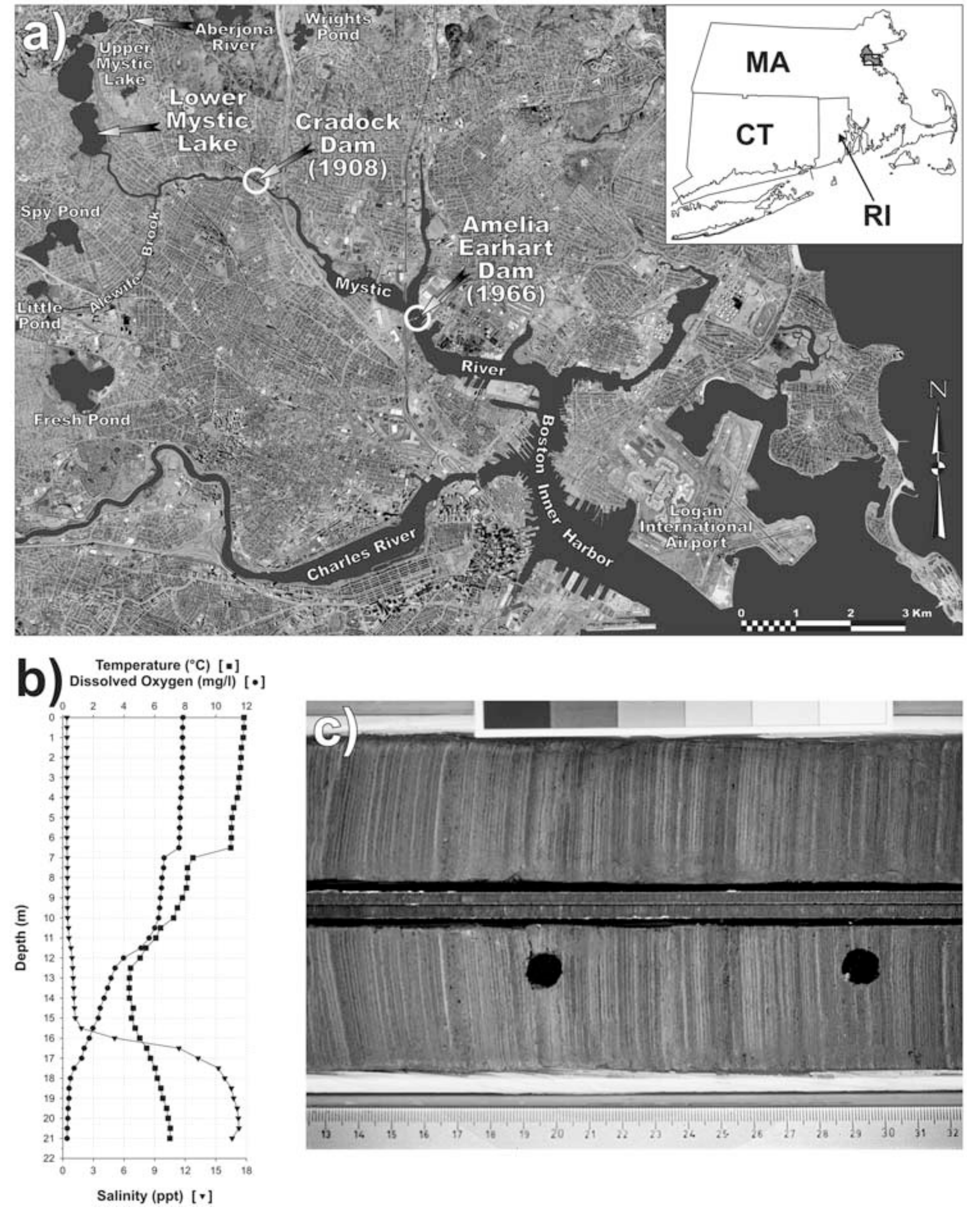

Figure 1. (a) Location map of LML and surrounding area. The shaded area in the inset map shows the complete Mystic River drainage system with the portion feeding LML reaching ~95 km^2. (b) Profiles of temperature, dissolved oxygen, and salinity in the LML water column in May 2002. (c) Example of LML laminated stratigraphy. A split sediment core shows the mm-scale, siliciclastic-biogenic varves that compose the LML record. The finely laminated stratigraphy is occasionally interrupted by anomalous graded beds, choked with organic detritus, such as the 0.75 cm thick example (AD 1520 varve) which can be seen at the 17 cm depth mark. The two holes in the bottom core half are locations where 1 cc samples were extracted for analysis.

CAMS-Lawrence Livermore National Laboratory, and University of California—Irvine facilities, and results were calibrated to calendar years using Calib v5.01 software [*Stuiver and Reimer*, 1993] with the INTCAL04 calibration data set.

3. Results and Discussion

3.1. LML Sedimentary Record and Varve Chronology

[5] The LML has accumulated at least ~12 m of sediment since deglaciation with the majority of it being a massive gyttja. However, the last ~2.5 m consists of mm-scale siliciclastic/biogenic sedimentary couplets that reflect the seasonal cycle of sedimentation in the lake, and accumulate on an annual basis. The general character of the laminated sedimentation is consistent throughout the record until around ~1870 when the sediments become sapropelic rather abruptly tracking explosive population growth and industrialization in the watershed [*Besonen*, 2006]. Combined with permanent alteration of the lake's natural hydraulic regime due to dam building in the mid-1860's as mentioned above, the post-1870 portion of the record shows strong anthropogenic disturbance and dramatically altered sedimentation dynamics.

[6] Proof that the siliciclastic/biogenic couplets accumulate on an annual basis is provided by the distribution of frustules of the diatom genus *Cyclotella*. As this diatom blooms once per year in the lake [*Chesebrough and Screpetis*, 1975], and it was found in concentration between adjacent siliciclastic laminae in high resolution (0.5 micron/pixel) BSEM imagery [*Besonen*, 2006], this confirms the annual rhythm of couplet deposition. Thus, the couplets are true varves, and serve as a robust, high resolution chronometer of sedimentation in the lake. Based on this observation, we constructed a varve chronology which extends back to 1011, and is presented as a thickness time series in Figure 2a.

[7] Multiple line of evidence provide strong, independent confirmation of the accuracy and precision of the varve chronology over the last ~400 years [*Besonen*, 2006]. Analysis of ^{137}Cs and ^{210}Pb activities confirmed the varve count, and placed the maximum Cesium concentration exactly within the 1963/64 varves as expected, and demonstrated a five half-life reduction in lead activity down core that precisely corresponds with the varve chronology. Six radiocarbon dates show excellent agreement with the varve chronology (see auxiliary material).[1] Additional confirmation of the chronology comes from changing pollen assemblages related to European settlement which began several km downstream from the lake in 1630. Pollen analysis shows no evidence of human disturbance in varves from 1595–1599, just prior to colonial settlement. A small amount of rye (*Secale*) pollen indicative of colonial agriculture was found in varves from 1643–1646, but otherwise the assemblage was similar to that from 1595–1599. And varves from 1730–1735 contain ragweed (*Ambrosia*), European weed (*Rumex*), and grass pollen, indicating a more open landscape resulting from colonial settlement. Finally, the record preserves a series of distinct sedimentary beds that show precise correspondence with the majority of known historic hurricanes which have affected the Boston area, as discussed below.

[8] Collectively, the excellent concordance between these multiple lines of evidence provides strong independent confirmation of the varve chronology, back to the beginning of the 17th century. We estimate that the possible chronological error within this portion of the record is negligible because we were able to actively account for even concealed/blind stratigraphic defects during construction of the master, composite chronology, and because of the very strong correspondence between the distinct sedimentary beds and known historical hurricanes. While there is no *a priori* reason to assume the chronology is not equally reliable prior to the early 17th century, the lack of a historical record precludes a similar level of verification.

3.2. Graded Beds Indicative of Hurricane Strikes

[9] Of particular significance within the LML record are unusually thick laminae, within which coarse sediments and terrestrial, organic detritus are overlain by progressively finer sediments (i.e., graded beds). These range in thickness, but the largest ones produce prominent outliers in the varve thickness time series plot (Figure 2a). The beds represent occasional, anomalous flooding events that have affected the basin, and are not a part of the regular seasonal cycle of deposition [*Besonen*, 2006]. These beds are not storm surge deposits carried into the lake via the river channel given that 1.) some of the highest water levels ever recorded in Boston Harbor (1723, 1743, and 1851) are not registered, 2.) the graded beds contain no microfossils which might suggest a marine origin (i.e., foraminiferal tests), and 3.) the post-1908 portion of the record also contains graded beds, but the Cradock Dam blocked marine water incursions by this time (Figure 1a). Thus, the graded beds must originate from flooding events in the watershed.

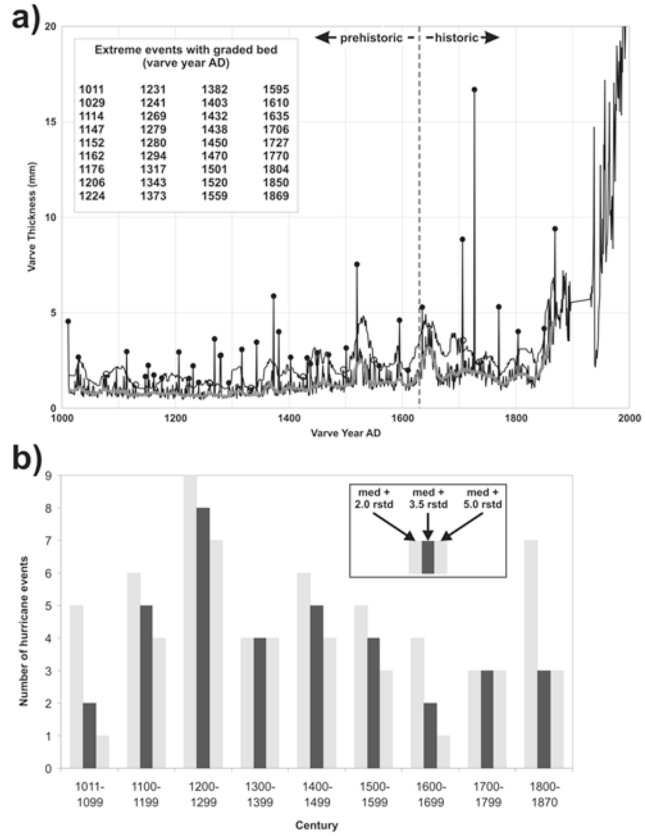

Figure 2. (a) LML varve thickness time series plot and identified extreme events. In the plot, actual varve thicknesses (mm) are plotted by the lower black line. The thickened gray line shows a robust estimate of the time dependent background thickness based on median smoothing with a 17 year window. The upper black line represents the med +3.5 rstd threshold, and varves with thicknesses which fall above this TDV are considered extremes (total of 47 observed). Of the 47 identified extreme events, the 36 which contain a graded bed are marked by filled black circles and listed in the inset table, and the 11 which do not contain a graded bed are marked by open black circles. The dashed vertical line at 1630 indicates the prehistoric/historic boundary for the region. (b) Frequency of hurricane-related deposits in the LML record grouped by century. The darker central bars represent the number of extreme events identified using a TDV of med +3.5 rstd. The flanking light gray bars represent the number of identified extremes using TDVs of med +2.0 rstd. (left) and med +5.0 rstd. (right). Note that given our analysis range (1011–1870), the first and last columns do not span a full century.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL033950.

[10] Several mechanisms produce watershed flooding events in New England including 1.) strong spring snow melts (i.e., freshets), and intense precipitation events related to either 2.) common extratropical systems such as Nor'easters, or 3.) infrequent tropical systems such as hurricanes. Thus, we examined the historical record to identify the probable mechanism responsible for the LML graded beds. We confined our analysis to the period prior to 1870 given the significant anthropogenic interference and altered sedimentation dynamics as discussed above.

[11] No relationship was noted with the freshets or extratropical systems. However, we did note a very strong correspondence with known historical hurricanes—10 of the 11 prominent graded beds deposited between 1630 and 1870 fall during years in which hurricanes are known to have struck the Boston area [*Ludlum*, 1963]. In support of this clear relationship, we interpret that the hurricane mechanism (vs. the other two) is more likely to produce the graded beds even with smaller amounts of precipitation because hurricanes are often accompanied by damaging winds which disturb vegetation and uproot trees to mobilize a supply of fresh, loose sediment. Such disturbance was aptly described by William Bradford of Plymouth Plantation (~55 km SE of Boston) who witnessed the 1635 hurricane, "This year . . . was such a mighty storm of wind and rain as none living in these parts, either English or Indians, ever saw. . . . It blew down many hundred thousands of trees, turning up the stronger by the roots and breaking the higher pine trees off in the middle."

3.3. Statistical Identification of Extreme Events Based on Varve Thickness

[12] The LML record itself shows some low frequency, background trends in sedimentation that must be accounted for to objectively identify the extremes in the varve thickness time series (Figure 2a). For example, there is a slow, general increase in varve thickness up to 1870 that is probably related to compaction of the sediments. There are also some short-lived trends such as a period of increased varve thickness between 1630 and 1670 which probably represents an increase in sediment flux related to initial land clearing following European settlement. Thus, to account for these trends, and objectively identify those varves with graded beds that actually represented extremes, we used CLIM-X-DETECT software [*Mudelsee*, 2006] to examine the thickness time series.

[13] CLIM-X-DETECT estimates the time-dependent background by median smoothing ("running median", med), and then calculates time-dependent variability ("robust standard deviation", rstd) based on scaling the median of absolute distances to the median [*Mudelsee*, 2006]. The running median (med) is a robust background estimator which is not biased by the presence of extremes in a record, and analogously, the running median of absolute distances to the median (mad) is a robust variability estimator. A normal distribution has a rstd equal to mad/0.6745. The user must specify a threshold detection value (TDV) that best differentiates the extremes of interest versus other extremes in the record.

[14] We examined the LML record using a range of TDVs from med +2.0 rstd up to med +5.0 rstd in increments of 0.5 rstd. Using the 1630–1870 portion of the historical records as a guideline, we determined the best compromise between over-/under-sensitivity was provided by a TDV of med +3.5 rstd. At this value, nine of the varves were identified as extreme events based on thickness alone. Two of the events (1707 and 1736) are varves which do not contain a graded bed, and are simply thicker than usual, for unknown reasons. However, the remaining seven events (1635, 1706, 1727, 1770, 1804, 1850, and 1869) are all varves that contain a graded bed, and correspond to a year in which a hurricane is known to have struck the Boston area [*Ludlum*, 1963]. We note that this choice of TDV is conservative as it was large enough to exclude the only varve with a prominent graded bed that does not correspond with a known hurricane year (1649). However, it did so at the expense of excluding three other varves that do include graded beds, and also correspond with hurricane years (1849, 1858, and 1861).

[15] In summary, using guidance provided by the historical portion of the record, we recognize hurricane-related events in the LML varve thickness time series based on two conditions: 1.) the varve must reach or exceed a thickness TDV defined by med +3.5 rstd, and 2.) the varve must also contain a graded bed. Using these criteria, 36 hurricane-related events (7 historic, 29 prehistoric) were recognized the LML record from 1011–1870.

3.4. Calibration of the Record

[16] As our analysis of the hurricane signal in the LML record is only available up to 1870, before instrumental records of storm intensity and associated daily rainfall are common, we cannot establish a direct link between the thickness of a graded bed, and the intensity of the storm that produced it. A few, sparse meteorological observations exist for some of the hurricanes, but as point measurements they do not necessarily provide a comprehensive picture of the effect of a particular storm on LML's ~95 km^2 watershed. Furthermore, as discussed above, the hurricane signal is also clearly related to mobilization of fresh, loose sediment by vegetation disturbance and tree blow down, so simply relating varve thickness to a single parameter like rainfall amount is not sufficient.

[17] Fortunately, estimates of the Saffir-Simpson scale intensity for many historical New England hurricanes are available. Of the seven hurricane events identified in the LML record between 1630–1870, two of the storms (1635 and 1869 [September]) were estimated to have been of category 3 intensity, three (1727, 1770, and 1804) of category 2 intensity, and one (1850 [July]) of category 1 intensity (1706 was not considered) [*Boose et al.*, 2001]. We thus interpret the varves with a graded bed as the result of both heavy rainfall amounts and landscape disturbance due to hurricanes of category 2–3 intensity.

[18] By analogy, the 29 prehistoric extremes identified by the same criteria should serve as proxy evidence for similar category 2–3 intensity hurricanes that struck the Boston area, but during prehistoric times.

3.5. Centennial-Scale Changes in Hurricane Frequency and Possible Climate Link

[19] Hurricane frequency, as recorded at LML, has not been constant over the last millennium (Figure 2b); the 12th–16th centuries had a significantly higher level of

hurricane activity (up to 8 extreme events occurring per century) compared to the 11th and 17th–19th centuries when only 2–3 per century was the norm. As the number of identified extreme events is obviously sensitive to the TDV, we note that when lower and higher TDVs are used, the same general trends are noted (Figure 2b).

[20] We emphasize that a record from a single point such as the LML cannot be used to infer total basin hurricane statistics; however, there are consistent related signals. A number of proxy records point to cooler Caribbean and tropical Atlantic SSTs (sea surface temperatures) from the 16th to 19th centuries, in areas critical for hurricane formation [*Keigwin*, 1996; *Winter et al.*, 2000; *Watanabe et al.*, 2001; *Haase-Schramm et al.*, 2003, 2005]. Coral records from the Caribbean indicate that SSTs in that area were 1.0–2.5°C lower than recent decades from ~1500 to the early 19th century and $\delta^{18}O$ in foraminifera from the Sargasso Sea (33.6°N, 57.6°W) also provides evidence that ~400 years ago SSTs were 1°C colder than today [*Keigwin*, 1996]. Thus, in areas where hurricanes generally intensify, conditions were less favorable for hurricane development during the last few centuries than in the late 20th century. The Sargasso Sea record also indicates that SSTs were ~1°C warmer ~1000 years ago, which would have favored the intensification of hurricanes entering that region. Furthermore, there is evidence that the eastern Pacific was relatively cool in High Medieval time (1100–1200) with persistent La Niña-like SSTs [*Graham et al.*, 2007]. Such conditions favor hurricane development in the Atlantic Basin by limiting wind shear aloft [*Goldenberg et al.*, 2001]. Hence, the frequency changes noted in the LML record are consistent with other paleoclimate evidence from regions where hurricanes develop and intensify.

[21] We note that conclusions about frequency changes reached from the LML record differ from those reached by studies based on lower resolution records from nearby areas. For example, a study from Long Island [*Scileppi and Donnelly*, 2007] concluded that activity had significantly increased over the last 300 years with reduced activity during the earlier part of the millennium.

4. Conclusions

[22] The LML sedimentary record provides a well-controlled and annually-resolved record of category 2–3 hurricane activity in the Boston area over the last millennium. The hurricane signal shows centennial-scale variations in frequency with a period of increased activity between the 12th–16th centuries, and decreased activity during the 11th and 17th–19th centuries. We recognize that the LML record is a single point source record representative for the greater Boston area, and hurricanes that passed a few hundred km to the east or west may not have produced the very heavy rainfall amounts and vegetation disturbance in the lake watershed necessary to produce a strong signal within the LML sediments. Nevertheless, we also note that clear evidence of a secular change in hurricane frequency identified in the LML record is consistent with other lines of evidence that conditions for the development of hurricanes have changed on centennial timescales. Hence, it appears that hurricane activity was more frequent in the first half of the last millennium when tropical Atlantic SSTs were warmer and eastern equatorial Pacific SSTs were cooler than in subsequent centuries.

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