Provincetown
Center for Coastal Studies

ANALYSIS OF TIDAL DATA FROM MEETINGHOUSE POND, CHATHAM FISH PIER AND BOSTON : WITH APPLICATION TO MANAGEMENT

by

Graham S. Giese
Department of Marine Geology

for

The Pleasant Bay Resource Management Alliance

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5 Holway Avenue
Provincetown, MA 02657
www.coastalstudies.org
(508) 487- 3623

ABSTRACT

Analysis of tidal data from Meetinghouse Pond and Boston between 2005 and 2012 and from Chatham Fish Pier between 2009 and 2012 provides insight into recent Pleasant Bay tidal patterns. Of particular interest for management are the observed trends of increasing tidal range and mean high water levels at Meetinghouse Pond between 2007 and early 2010, followed by decreasing tidal range and mean high water levels between early 2010 and early 2012. In March 2012 the tidal range was less than at any time since soon after the formation of the 2007 tidal inlet, and mean high water was lower than it had been since early 2009. Study results suggest that the increasing and decreasing mean high water levels reflect the influence of a major regional sea level anomaly, and that the recent decreasing tidal range results from a combination of the sea level anomaly and local shoaling. Both decreasing tidal range and decreasing high water levels reduce the volume of the Pleasant Bay tidal prism, which in the absence of other factors, acts to reduce water quality.

INTRODUCTION

The breaching of Nauset Beach during a severe northeasterly storm on January 2, 1987, ended a long period of growth of the barrier beach - a century of incremental southward extension - and initiated disintegration of its southern section into intertidal and subtidal shoals and integration into older and inner coastal landforms. New channels were formed as well as shoals, and a second breaching in 2007 produced another tidal inlet north of that formed in 1987 (e.g., Giese et al., 2009).

These landform changes, still ongoing today, are accompanied by pronounced changes in the hydraulics of the Pleasant Bay/Chatham Harbor estuary, and the altered tidal and wave patterns produce significant responses in the closely coupled natural ecosystems and human social systems. For this reason improved understanding of the changing tidal and wave patterns can lead to improved management of the entire coastal system.

Here we report findings of a study requested by the Pleasant Bay Alliance to compile and analyze tidal data that have been acquired at Meetinghouse Pond, at the extreme head of the Chatham Harbor/Pleasant Bay system, and at Chatham Fish Pier which lies between the two tidal inlets at the mouth of the system. During the course of the study it was determined that some pronounced changes within Pleasant Bay/Chatham Harbor are direct responses to regional tidal characteristics. To help delineate these regional influences, limited tidal data from Boston Harbor have been included in this report.

BACKGROUND

In the early 2000's, both the Pleasant Bay Alliance and the Chatham Department of Coastal Resources recognized the value of tidal information to management of the rapidly changing Pleasant Bay/Chatham Harbor estuarine system and initiated programs to monitor the system's tides.

Pleasant Bay. The Pleasant Bay Alliance requested that the Cape Cod National Seashore (CCNS) and the Provincetown Center for Coastal Studies (PCCS) monitor tides at Meetinghouse Pond in Orleans for short intervals over a period of years in order to compile information concerning changing hydrodynamic conditions that could indicate future tidal inlet changes.

Responding, in 2005, and again in 2006, CCNS's Kelly Medeiros mounted a non-vented Yellow Springs Instruments (YSI) pressure, temperature and conductivity recorder on a pier piling at the Nauset Marine East facility in East Orleans. Those deployments provided the desired data and the instrument was re-deployed in March 2007. However, on April 7, before a full 30-day time series had been obtained, Nauset Beach was again breached during a severe northeasterly storm, and the breach slowly developed into a tidal inlet.

Those events created an even more pressing need to monitor Pleasant Bay tides and therefore the CCNS tide recorder was kept active at Meetinghouse Pond until its removal was necessitated by marina reconstruction in December 2010. The tide recorder was redeployed in April 2011, following completion of a new pier. The first data set from the redeployment was successfully retrieved in June 2011, and instrument deployments have continued – with some data breaks due to instrument malfunction - to the present time.

Chatham Harbor and Boston Harbor. The Town of Chatham briefly deployed a non-vented pressure recorder at the Chatham Fish Pier, but the quality of the data was soon surpassed by installation of a state-of-the-art NOAA/NOS microprocessor-based acoustic tide recorder in 2009. That instrument remains in operation and the data are freely available to the public on the NOAA tidal website, "tidesandcurrents.noaa.gov". An instrument similar to that at Chatham is in place in Boston Harbor and those data are similarly available at the NOAA website.

CCNS	Cape Cod National Seashore
GPS	Global Positioning System
MHW	Mean High Water
MLW	Mean Low Water
MSL	Mean Sea Level
MTR	Mean Tidal Range
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
PCCS	Provincetown Center for Coastal Studies

Table 1 : Abbreviations used in the report

METHODS

The tidal patterns illustrated and discussed in this report were derived from basic tide recorder data using simple analytical/statistical methodology. The objective of the analysis was to focus attention on patterns of sea level, tide level and tidal range change within the Pleasant Bay/Chatham Harbor estuary at annual and interannual time scales. All available verified tide data from the two recorders within the system were accessed: six-minute tide levels from the NOAA/NOS tide recorder at the Chatham Fish Pier and six-minute tide level data from the CCNS recorder at Meetinghouse Pond. In addition, as mentioned above, a limited set of tide data from the NOAA/NOS tide recorder at Boston Harbor was accessed to define regional trends.

Meetinghouse Pond. A tide level data set was derived from the Meetinghouse Pond pressure, temperature and conductivity recorder by adjusting pressure measurements for water density variations using in situ temperature and conductivity measurements. Beginning in December 2008, Meetinghouse Pond water level data were corrected for the effects of atmospheric pressure using data from a HOBOS pressure recorder established at CCNS's North Atlantic Coastal Laboratory in North Truro. Earlier data have not been corrected for variations in atmospheric pressure. The derived tide level above the instrument's pressure sensor was established relative to the current vertical geodetic datum, NAVD88, by means of precision GPS surveys.

The length of each individual data set varied, most being between approximately 30 to 60 days in length. Since the instrument required removal from the water periodically for accessing the stored data and cleaning, and since that operation was most efficiently carried out at low levels of the tide, the beginning and ending of each time series occur irregularly during the months of operation.

The processed Meetinghouse Pond tide data includes 41 individual data sets, some of which were produced by combining data from multiple deployments. As stated earlier, the 2005 and 2006 deployments were brief, totaling approximately 2 months each year. The major breaks following the March 2007 deployment resulted from the piling removal and pier reconstruction in 2010 and 2011. Shorter interruptions were caused by instrument malfunction, and occasionally, sea ice in the pond.

Statistics for each data set were calculated using MATLAB software. Using the six-minute data as input, mean sea level (MSL), mean high and low water (MHW and MLW), and mean tidal range (MTR) were derived for the individual time series. Times reported for each mean or derived statistic were determined by the temporal mid-point of the respective time series.

Chatham Fish Pier and Boston. As stated above, NOAA/NOS instruments at Chatham Fish Pier and Boston acoustically measure water level damped by a stilling well and produce elevation data at six-minute intervals. The resulting tide data and monthly statistics produced by their processing were downloaded from the NOAA/NOS website. The full-month data available for Chatham Fish Pier begin with May 2009, and continue to the present time. All available data through April 2012, were used for this report. Similar tide data for Boston begin much earlier and also continue to the present. Data used for this report begin with those for January 2005, and end with those for March 2012.

Summary. All source data for this report were recorded at six-minute intervals. Data sets consisted of month-long time series in the case of Chatham Fish Pier and Boston Harbor, while at Meetinghouse Pond data sets varied in length between approximately 30 and 60 days. Statistics were derived by taking simple means of sea levels and tide levels. Levels are reported and graphed in terms of meters measured vertically with respect to NAVD88. Times are reported as local standard time.

RESULTS

To focus on the annual and interannual tidal patterns and trends of primary interest in this study, the much larger amplitude, shorter term tidal variations of sea level have been removed in most of this report by averaging higher frequency data over time periods of a month or more. However we begin with two figures illustrating the patterns produced by the original six-minute tide measurements from the three stations, Meetinghouse Pond, Chatham Fish Pier and Boston.

Figure 1 illustrates the full data sets from all three stations for a single month, March 2012, while Fig. 2 provides a close-up view of the tides on three representative days. Of significance to our study is the fact that the elevations of high water at Meetinghouse Pond and Chatham Fish Pier follow each other very closely, while the elevations of low water do not. The low water elevations at Meetinghouse Pond are distinctly truncated as compared to low water at the other two stations, both of which exhibit a pronounced fortnightly spring-neap tide pattern. The truncated pattern at Meetinghouse Pond indicates that when tides are low there, tidal flows of water toward and away from the pond are strongly influenced by the shallow bottom. This phenomenon is discussed at greater length below.

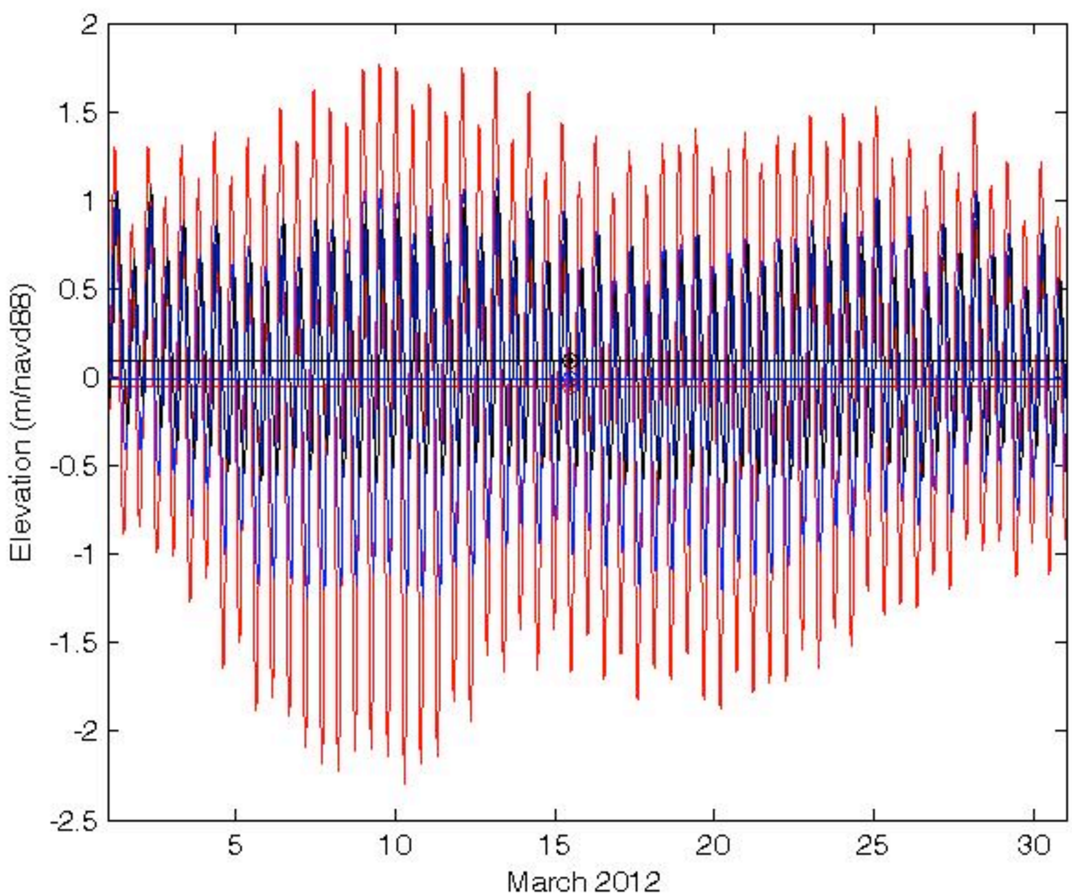
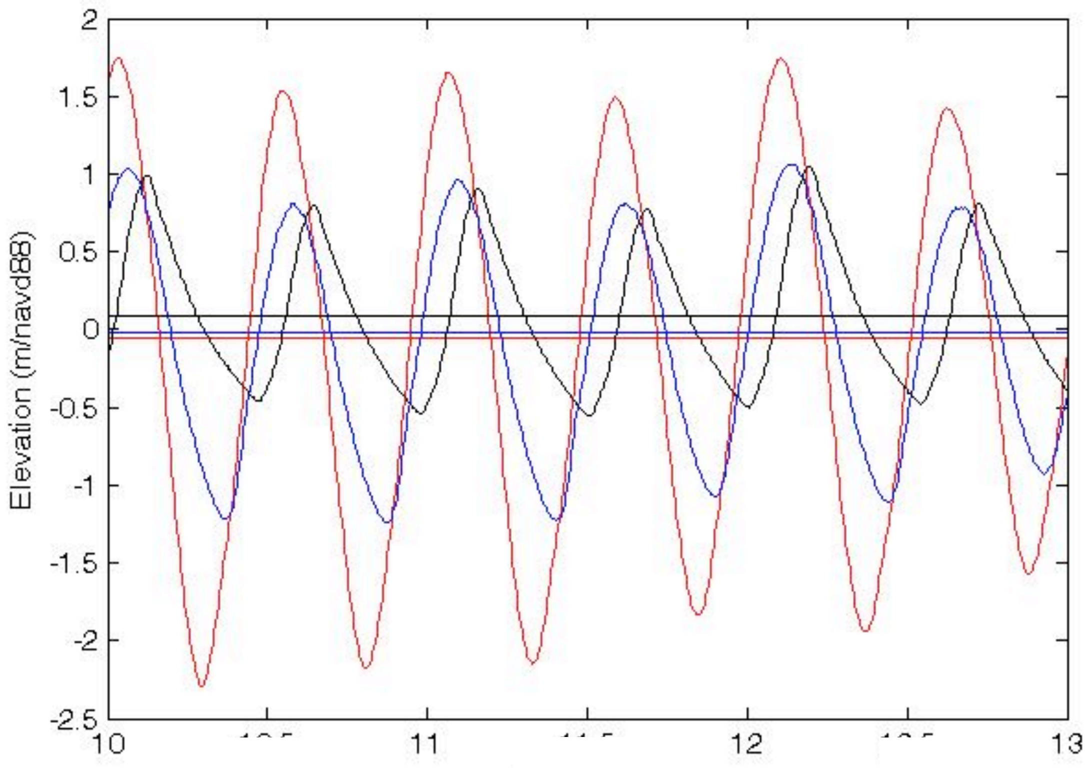


Fig. 1 : Plots of tide levels observed at six- minute intervals during March 2012, at Boston (red), Chatham Fish Pier (blue), and Meetinghouse Pond (black). The horizontal lines represent the monthly mean sea level values for each station. Note that the fortnightly variation of low water elevation is less pronounced at Meetinghouse Pond than at Boston and Chatham Fish Pier.



Days in March, 2012

Fig. 2 : Plots of tide levels observed at six- minute intervals during March 10 - 12, 2012, at Boston (red), Chatham Fish Pier (blue), and Meetinghouse Pond (black).

<u>*Chatham Fish Pier and Meetinghouse Pond viewed separately*</u>. Figure 3 illustrates the full suite of Chatham Fish Pier monthly data beginning with the installation of NOAA tide recorder and continuing through April 2012. Each dot in this and subsequent figures represents the mean value of one of the levels (sea level, high water, low water) or the tidal range. The dashed lines connecting the dots aid visualization but have no other significance.

The rhythmic high-low oscillations apparent on the plots of “levels” are produced by “seasonal” sea level changes and are common to all coastal tide records. Ignoring the seasonal oscillations, all four curves exhibit a trend of decreasing elevation over the two-year period between early 2010 and 2012. The three tide level curves show an increase-in-elevation trend during the first year of observation. Note the March, 2010, maximum on the MHW, MSL and MLW curves.

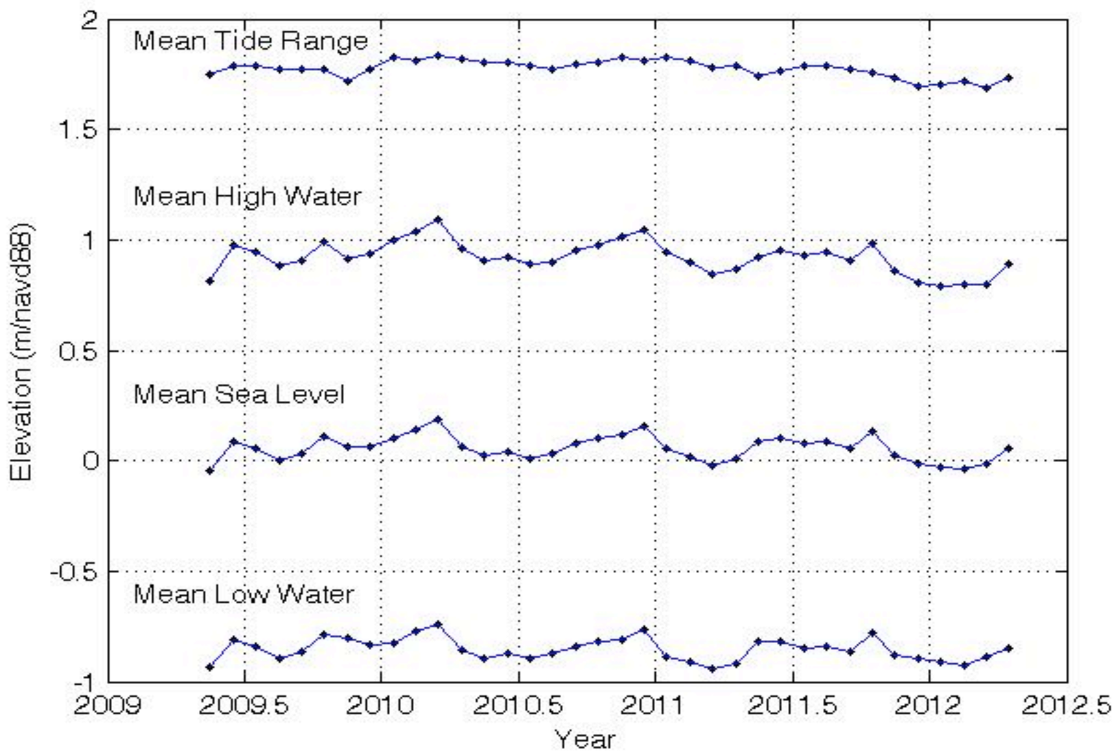


Fig. 3 : Monthly tide levels and range at Chatham Fish Pier. May 2009, is the first month for which data are available. Note the March 2010, maximum on the MHW, MTR and MLW curves.

The corresponding tide level and range results for Meetinghouse Pond are shown in Fig. 4. The time base in this figure is more than twice that of the previous figure, and the data points are centered not at mid-month, but rather at the mid-point of the individual time-series data sets.

The Meetinghouse Pond results are in some respects similar to those at Chatham Fish Pier. MHW and MTR show a decrease in elevation after early 2010, and the amount of decrease, especially in MTR, is considerably greater than at Chatham Fish Pier. Also both show a trend of increasing elevation prior to 2010, in this case going back to 2007 when continual monitoring began.

However a different trend is evident in the other two tide levels, especially in the MLW curve. Mean low water increases in elevation over the observation period. The MSL curve exhibits the same general rise of all the curves prior to 2010, following which there is just a small decrease. The fact that MSL must respond to changes in both MLW and MHW would explain this middle-of-the-road behavior.

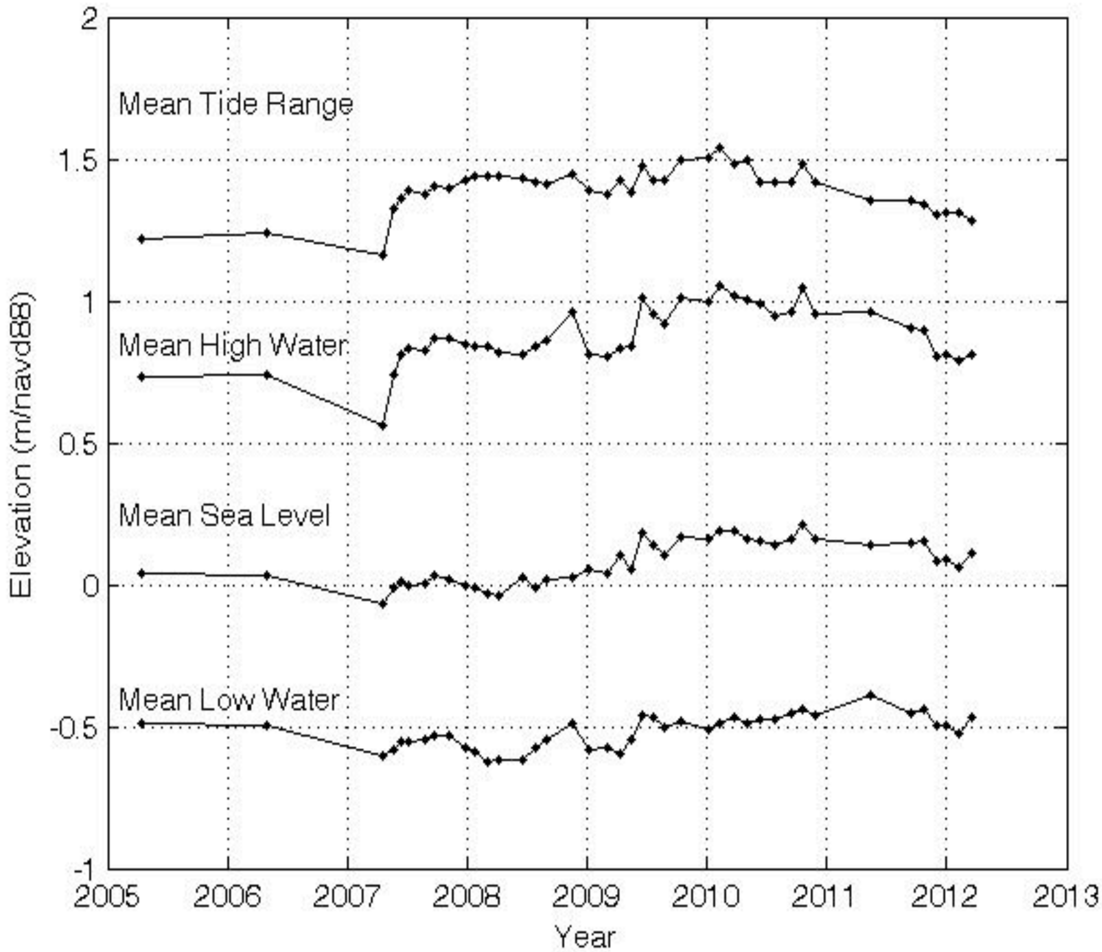


Fig. 4 : Tide levels and range at Meetinghouse Pond. Only one data set is available for each of the years 2005 and 2006. The 2007 tidal inlet formed in April 2007, near the end of the first data set for that year.

Boston added. The previous figures presented the results from Chatham Fish Pier and Meetinghouse Pond separately. Next we compare the results from each station with analogous data from Boston. Figure 5 shows monthly tidal range and levels at Boston in red, and those at Chatham Fish Pier in blue. The levels match well, in particular MSL and MHW. Note that at both Boston and Chatham Fish Pier MSL and MHW show a maximum value at March, 2010. Over the entire time series, 2005-2012, there seems to be no apparent trend, neither an increase nor decrease in elevation, for MLW at Boston. However, from 2010 to the present both MLW and MHW show a slight decrease in elevation. The individual trends are so similar that their difference, MTR, shows no apparent trend at all.

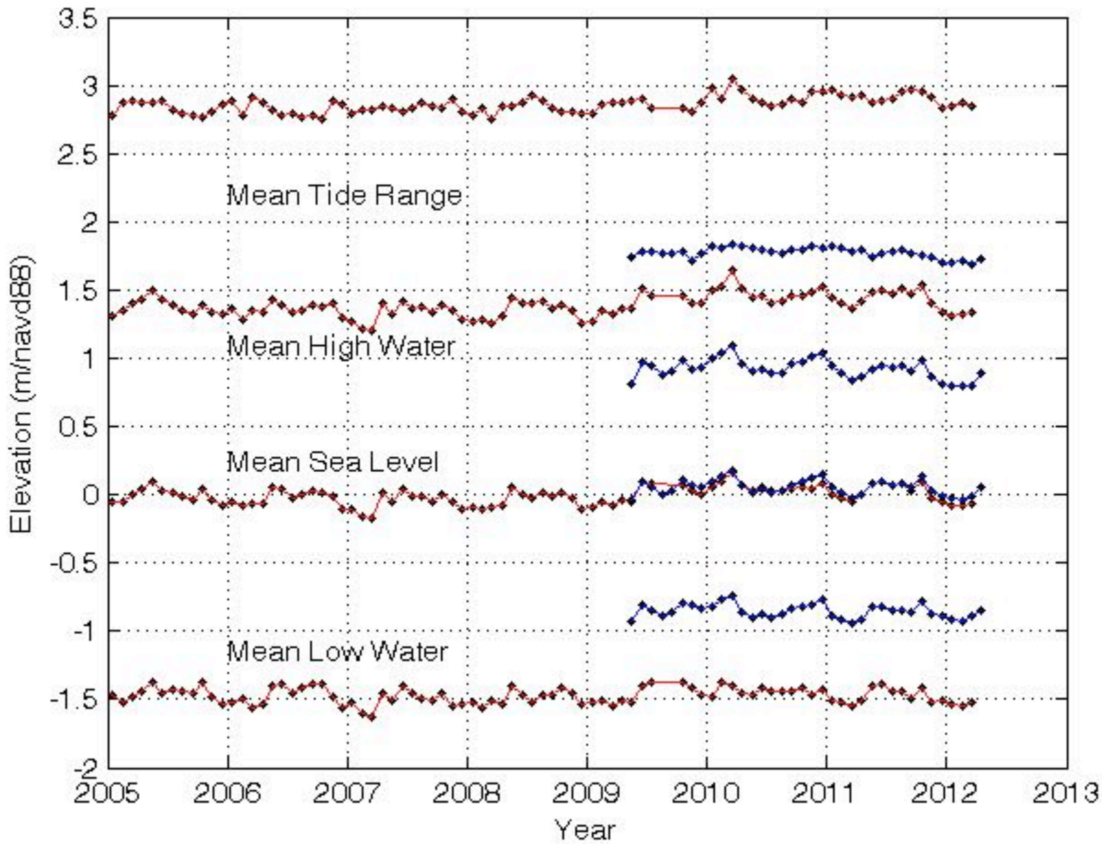


Fig. 5 : Monthly tide levels and range at Boston (red) and Chatham Fish Pier (blue). Note the similarity between the MSL patterns at the two stations; also note the decline in MTR at Chatham Fish Pier since early 2010.

Boston and Meetinghouse Pond results are compared in Fig. 6 and Fig.7, the first showing tide levels and the second tidal range. Three aspects of this comparison (involving both figures) are of primary interest here.

First we note the trend of increasing levels of MHW at both stations over the three-year period from early 2007 through early 2010, followed by a corresponding trend of decreasing MHW over the two-year period from early 2010 through early 2012. The similarity in pattern at the two stations strongly suggests that MHW at Meetinghouse Pond is the result of forcing by regional tides, and is not due to local geomorphic factors.

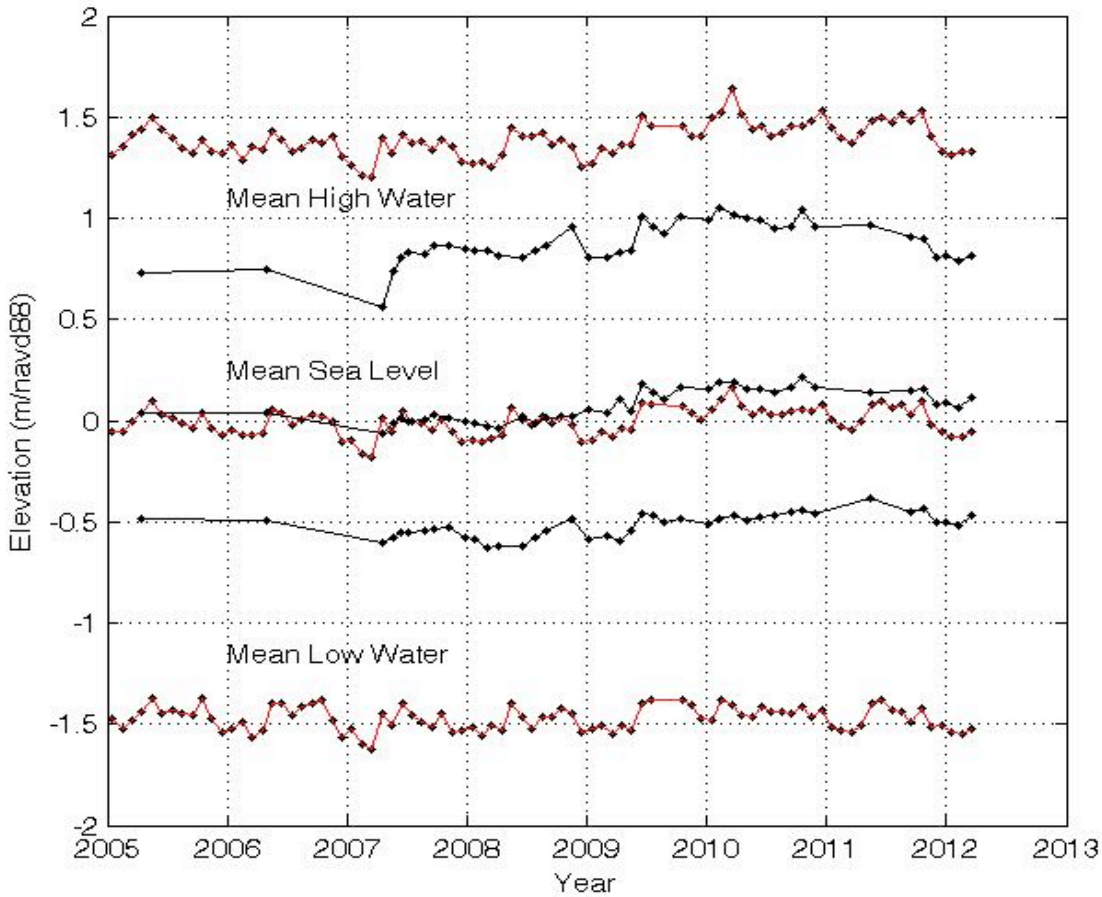


Fig. 6 : Monthly tide levels and range at Boston (red) and Meetinghouse Pond (black). Note the increase in low water levels at meetinghouse Pond beginning in 2007, and the decrease in high water levels since early 2010.

Secondly, unlike the behavior of high water, the MLW curves differ markedly. The lack of an apparent trend in low water at Boston contrasts strikingly with the rise in elevation of low water at Meetinghouse Pond since the start of continuous monitoring there in 2007. This difference in pattern suggests that the behavior of MLW at Meetinghouse Pond is not due to regional tides, but instead is the result local geomorphic factors.

The third interesting aspect of the comparison is most important for our purposes because it involves the peculiar behavior of MTR at Meetinghouse Pond. As seen in Fig. 7, following an initial burst in MTR following the opening of North Inlet in 2007, tide range increased gradually until early 2010, after which it decreased more rapidly to the present time.

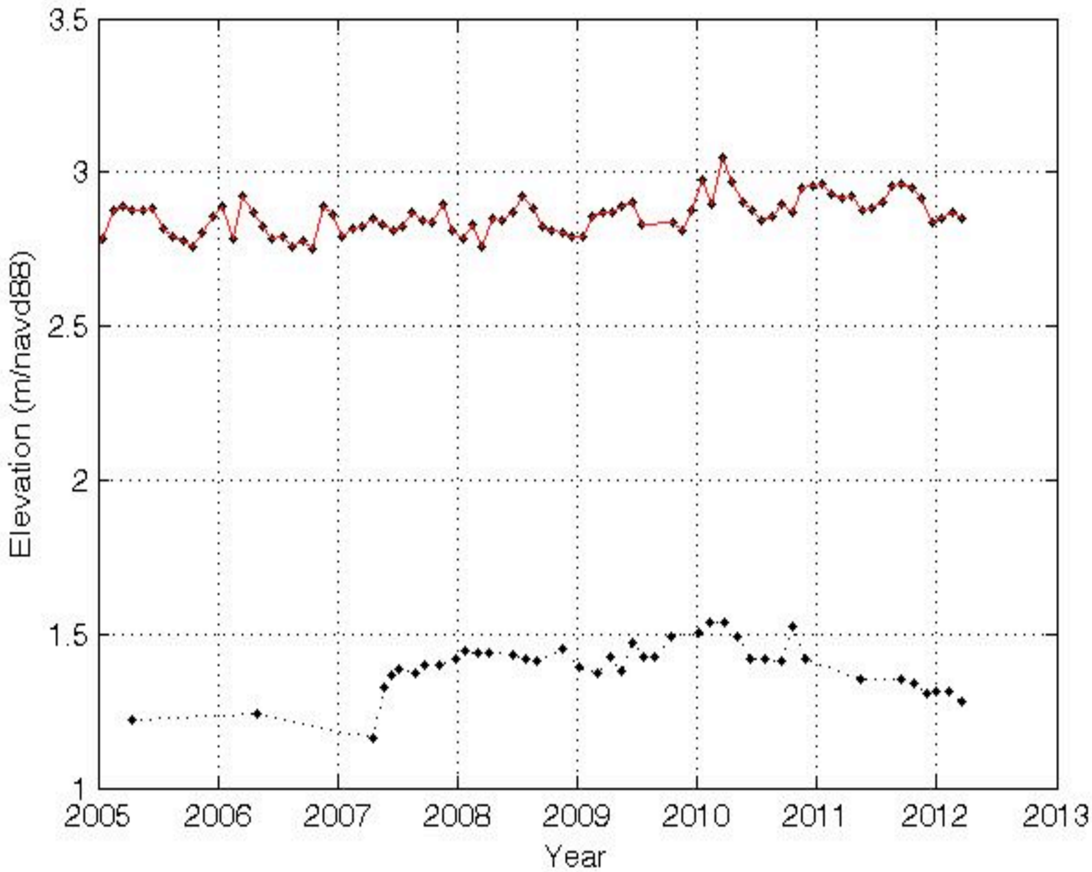


Fig. 7 : Monthly tidal range at Boston (red) and Meetinghouse Pond (black). Note the increase in tidal range at MHP from 2007 to early 2010, and the more rapid decrease in tidal range later.

Chatham Fish Pier and Meetinghouse Pond viewed together. In Fig. 8 we view the Meetinghouse Pond and Chatham Fish Pier data together. Because the Chatham Fish Pier observations began only shortly prior to the regional MSL historic high level of March, 2010, we will only discuss patterns of observations made after that date.

Mean high water (MHW), MSL, MLW and MTR all decreased gradually at Chatham Fish Pier. This pattern is similar to the regional decreasing sea level discussed above. At Meetinghouse Pond, the patterns of MHW and MSL are similar to those at Chatham Fish Pier, but the behavior of MLW was decidedly different. It continued to increase in elevation even while regional sea level was decreasing. Finally, the most rapidly changing pattern of all, the decrease in MTR at Meetinghouse Pond.

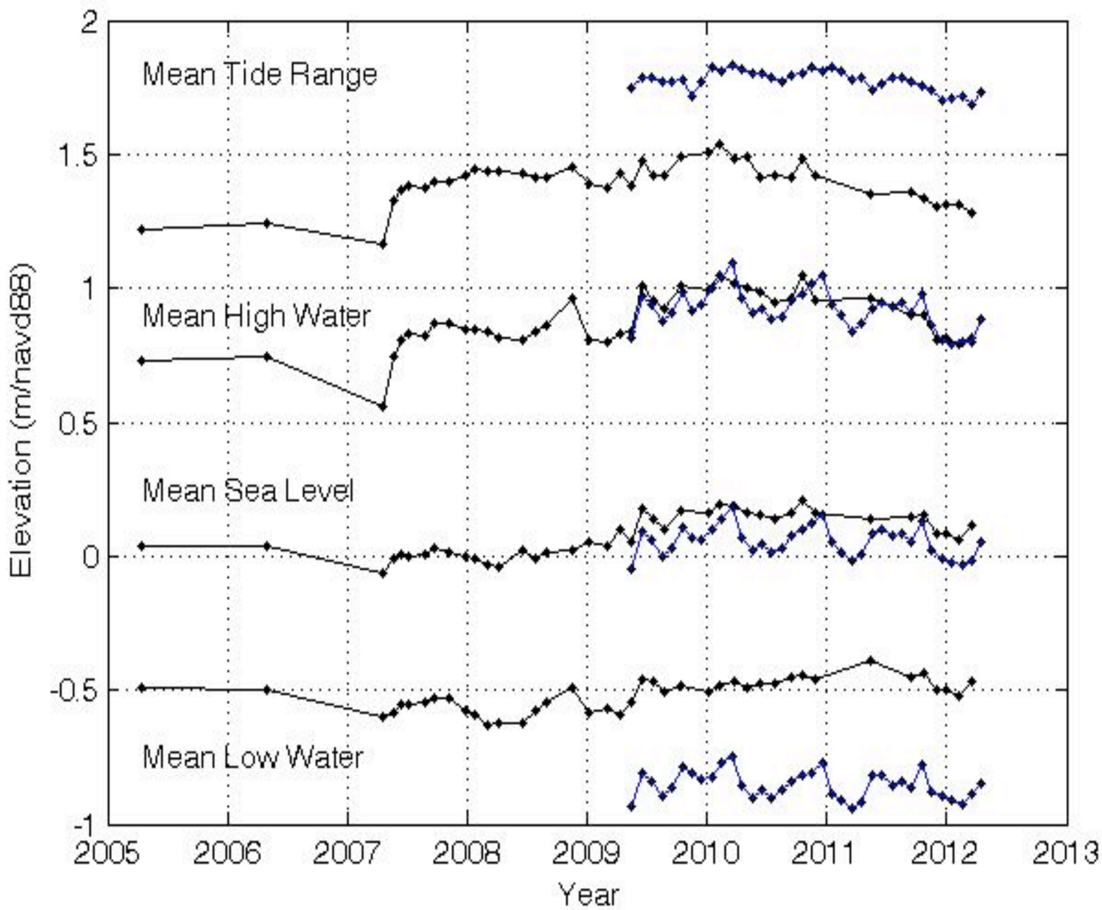


Fig. 8 : Monthly tide levels and range at Chatham Fish Pier (blue) and Meetinghouse Pond (black). Note that while tidal range decreased at both stations after early 2010, the rate of decrease was more rapid at meetinghouse Pond.

DISCUSSION

Mean low water at Meetinghouse Pond. Results of the analyses reveal several trends in Meetinghouse Pond tides that have significance for management of the Pleasant Bay/Chatham Harbor estuary. First we consider the trend of increasing MLW apparent in Fig. 4 and shown more clearly in Fig. 9a. The solid trend line in the figure represents the results of linear regression analyses of the full set of individual MLW data points beginning in April 2007, and ending in March 2012, while the dashed lines represent one standard deviation of the scatter of the data points around the trend line.

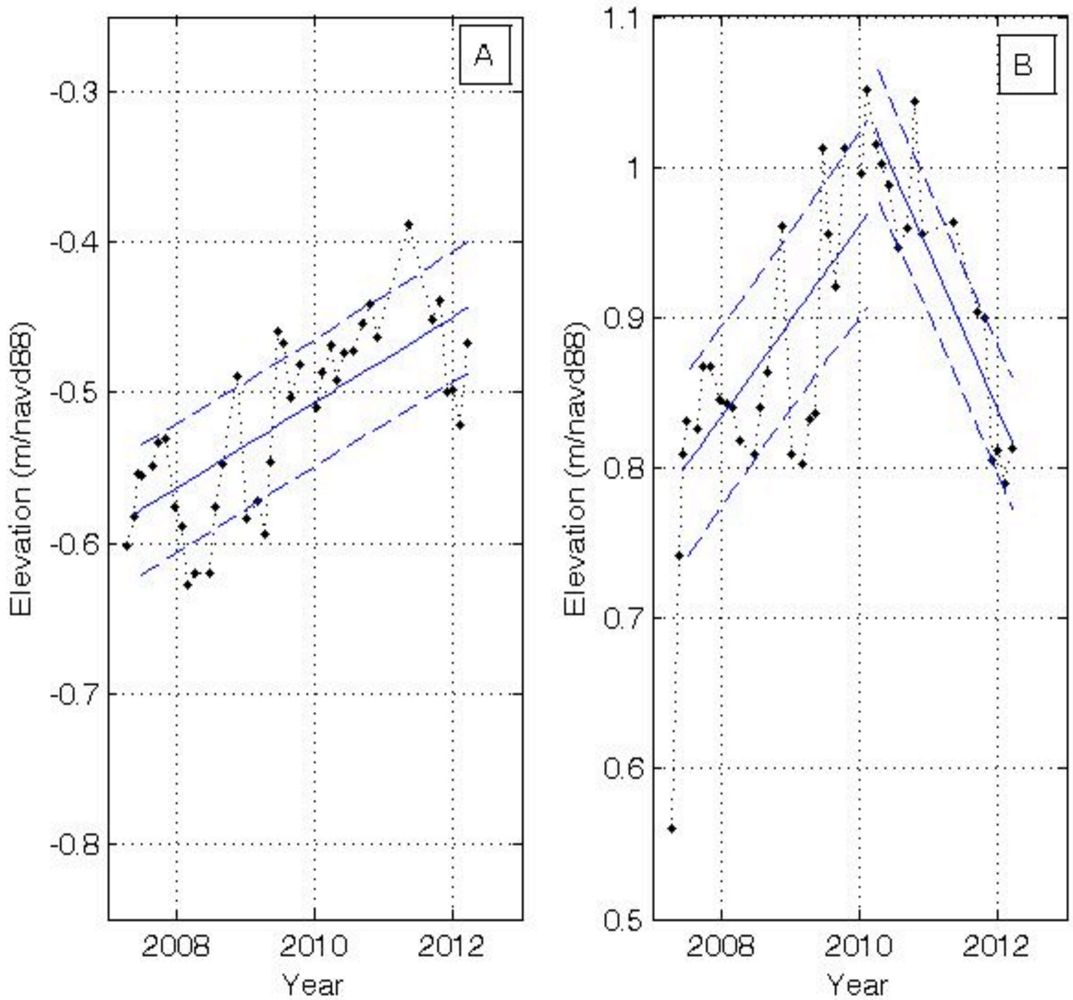


Fig. 9 : **A.** Results of linear regression analysis of the full set of Meetinghouse Pond MLW data (solid trend line), showing one standard deviation of the scatter of the data around the trend line (dashed lines). **B.** Results of similar analysis of two sub-sets of Meetinghouse Pond MHW data: May 2007 - February 2010 (left) and March 2010 - March 2012 (right).

The 5-year trend of increasing mean low water elevations at Meetinghouse Pond illustrated in Fig. 9a likely results from shoaling associated with the 2007 tidal inlet, in particular sediment deposition in the channel that lies east of Strong Island and just north of the inlet. Such shoaling has been observed and reported by the Chatham Department of Coastal Resources (Theodore Keon, personal communication). The pronounced influence of bottom boundary conditions on low water levels at Meetinghouse Pond is evident in Fig. 2 from the truncated pattern of low water levels and the large lag in the time of low water as compared to the other two stations.

Mean high water at Meetinghouse Pond. The second set of Meetinghouse Pond tidal trends of interest are those of MHW as illustrated in Fig. 9b. In the figure two trends are apparent on either side of an early 2010 maximum. Two linear regression lines were calculated, one for data between May, 2007, (the first data set following inlet formation) and February, 2010; the other between March, 2010, and March, 2012. Mean high water exhibited an upward trend during 2007, 2008 and 2009; between March, 2010, and March, 2012, it exhibited a downward trend.

To explore the similarity of this pattern to that of regional mean sea levels noted above, Fig. 10 presents results of trend lines fitted to monthly MSL data from Boston and Nantucket. Note that NOS tidal data from Boston, rather than Nantucket, were analyzed for this report to represent regional influences despite its greater distance from Pleasant Bay. There were two reasons for this. First, because the outer coast of Cape Cod and Massachusetts Bay both directly participate in the primary Gulf of Maine tidal system (e.g., Garrett, 1972), Boston harbor tidal characteristics (e.g., tidal *harmonics*) are closer to those of Pleasant Bay than are those of Nantucket. Second, NOS tidal elevations at Nantucket are referenced to Nantucket mean sea level for the 1983-2001 tidal epoch, but not to NAVD88 which is the vertical datum chosen for this study.

Nevertheless, as is evident in Fig. 10, monthly mean sea level at both Boston and Nantucket exhibited similar patterns between January, 2007, and March, 2012, with a maximum early in March, 2010. For both stations, the two regression trend lines were calculated, one for data from January, 2007, through February, 2010, and the other for data from March, 2010, through March, 2012. Sea level at both stations experienced an upward trend during 2007, 2008 and 2009, reaching a maximum in early 2010. Between early 2010 and March, 2012, both experienced a downward trend.

The similarity between the trends in Meetinghouse Pond MHW record (fig. 9b) and those in the Boston and Nantucket MSL records (Fig. 10), suggest a causal relationship between the two, i.e., regional forcing of Pleasant Bay tide level increases and decreases by similar changes in sea level. Such a MSL anomaly during this period for the entire East Coast has been reported and discussed in a recent National Ocean Service technical report (NOAA, 2009). Such anomalies in the long-term overall rise in sea level are not uncommon; in fact, multiyear to decadal scale periods of sea level rise and fall superimposed on century scale sea level acceleration are characteristic of the global record of the past 200 years (Jevrejeva et al., 2008).

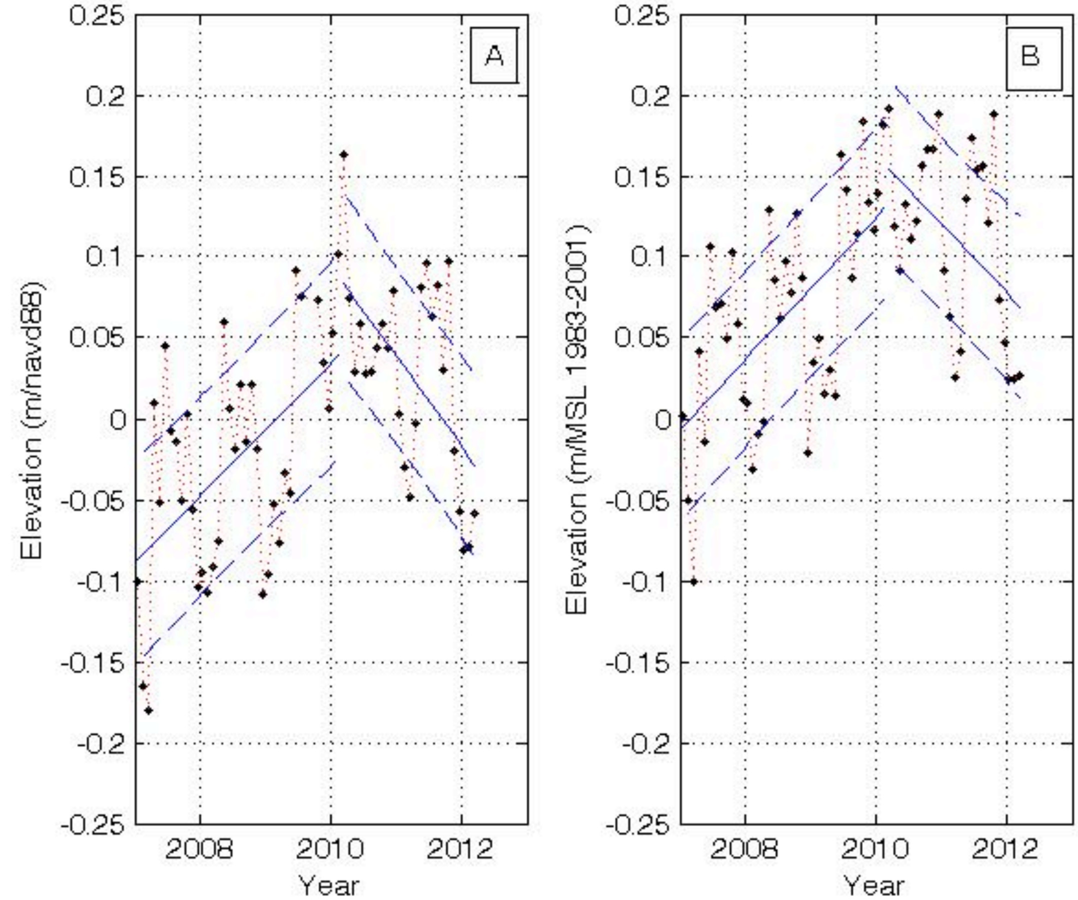


Fig. 10 : A. Results of regression analysis (solid trend lines) of two sub-sets of Boston MSL data: January 2007 - February 2010 (left) and March 2010 - March 2012 (right), showing one standard deviation of the scatter of the data around the trend lines (dashed lines). **B.** Results of similar analysis of two sub-sets of Nantucket MSL data for the same periods. Reversal in trend at both stations highlights the early 2010 regional sea level anomaly.

Mean tidal range at MHP. Finally, Fig. 11, presents the trends in MTR at Meetinghouse Pond. The data were divided into two sets and trend lines were calculated for each group as described above for Fig. 9b. During 2007, 2008 and 2009, MTR increased, while between March 2009, and March 2010, MTR decreased, eventually reaching levels not seen at Meetinghouse Pond since 2007. Consideration of these results in light of local mean high and low water patterns (Fig.9) and regional mean sea level observations (Fig.10) suggests that the pattern of MTR change at Meetinghouse Pond may reflect the regional sea level anomaly which reached a maximum in early 2010, as well as the local pattern of increasing mean low water levels.

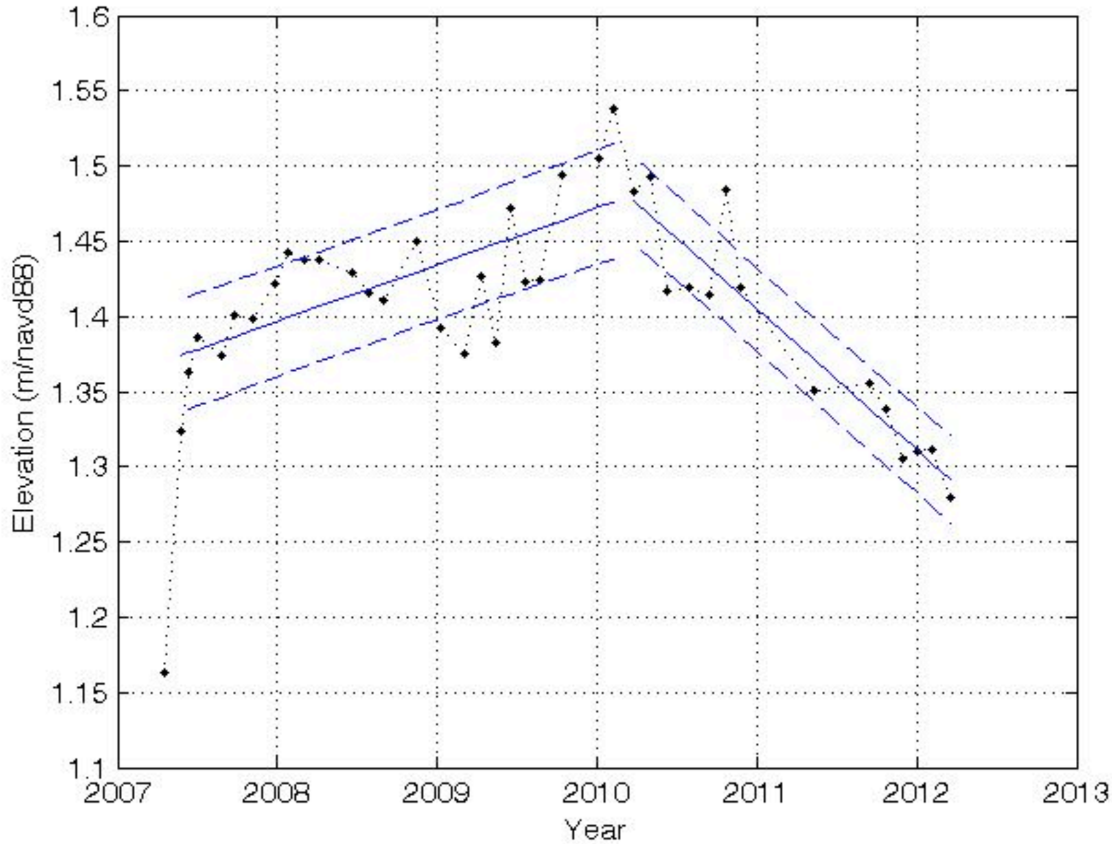


Fig. 11 : Results of linear regression analysis (solid trend lines) of two sub-sets of Meetinghouse Pond MTR data (May 2007 - February 2010 and March 2010 - March 2012), showing one standard deviation of the scatter of the data around the trends line (dashed lines). The trend of decreasing MTR began in early 2010 and by early 2012 had reached lower levels than at any time since soon after the formation of the 2007 tidal inlet

9. ACKNOWLEDGEMENTS

Many individuals and organizations contributed to this work. Kelly Medeiros of the Cape Cod National Seashore (CCNS) is responsible for the entire set of Meetinghouse Pond tidal data upon which the study is based. Over the past 7 years she has deployed and maintained NPS instruments at Meetinghouse Pond, processed the data, and maintained a complete set of files of all relevant information. Her contributions to, and enthusiastic support of, all phases of the study have made it a reality.

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