J. Northw. Atl. Fish. Sci., Vol. 43: 93–101 Publication (Upload) date: 3 Aug 2011

A Note on the Long-Term Sea Surface Temperature Records at Boothbay Harbor, Maine

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Drinkwater, K.F., B. Petrie. 2011. A Note on the Long-Term Sea Surface Temperature Records at Boothbay Harbor, Maine. *J. Northwest Atl. Fish. Sci.*, **43**; 93–101. doi:10.2960/J.v43.m663

Abstract

Sea surface temperature (SST) records have been collected at Boothbay Harbor, Maine, since 1905. A dramatic change in the structure of the monthly mean SST anomalies occurred around 1950. Prior to 1950, when observations were made with a bucket thermometer, there was a large range in the monthly mean temperature anomalies with warmer summers and cooler winters. After 1950, when a fixed thermistor was used, the difference between winter and summer anomalies were much reduced. We show that the primary cause of the change in the monthly anomaly patterns is related to the difference in the depth of the measurements from near surface (pre-1950) to 1.7 m below mean low water (post-1950) combined with the thermal stratification of Boothbay Harbor waters. The non-homogeneous nature of the surface temperature time series at Boothbay Harbor means that they should not be used for retrospective analyses that cover the entire period. Since 2000, the annual mean Boothbay Harbor temperatures have been much warmer than nearby sites, however the cause of this phenomenon is as yet unclear.

Keywords: sea surface temperature, monthly means, Boothbay Harbor, St. Andrews, Gulf of Maine

Introduction

The Boothbay Harbor sea surface temperature (SST) record taken at the Maine Department of Marine Resources dock (43.84ºN, 69.64ºW) on the coast of the Gulf of Maine is one of the longest continuous ocean temperature time series on the United States Atlantic seaboard and in the Northwest Atlantic. The U.S. Bureau of Commercial Fisheries began the measurements in March of 1905 and data have been collected to the present with only temporary, short-term interruptions. The Maine Department of Marine Resources took over the sampling in 1973. Annual or monthly mean SST data from Boothbay Harbor have been used to investigate the physical oceanography of the region, including large-scale aspects of the circulation (Sutcliffe *et al*., 1976) and ocean climate variability (Fogarty *et al*., 2007), as well as temperature effects on the ecology, including phytoplankton (Coleman and Brawley, 2005) and fish and shellfish (Dow, 1969, 1972, 1977a, 1977b, 1978; Sutcliffe *et al*., 1977). Many of the latter studies suggested that some biological processes, including reproduction, abundance, growth, recruitment and catch, were temperature-dependent. Such long-term records as the Boothbay Harbor temperature time series are becoming increasingly important to monitor the expected anthropogenic-induced warming (IPCC, 2007).

Whether used for comparisons with flora and fauna or to determine temperature trends, such records need to be of high quality and comparable over their lengths in spite of changes in technology, otherwise the conclusions drawn from analyses using the data may be faulty. In this note, evidence is presented of differences in the pre- and post-1950 monthly mean near surface temperature data collected at Boothbay Harbor that shows the earlier period exhibits relatively warm summer anomalies and cool winter anomalies compared to the latter period when the monthly temperature anomalies show little seasonal differences. Possible reasons for this problem are also presented. In addition, we find through comparison with nearby sites that the Boothbay Harbor SSTs from 2000 onward appear to be overestimated.

Data and Methods

The Boothbay Harbor (Fig. 1) monthly mean SSTs from March 1905 to December of 2010 were obtained from the Maine Department of Marine Resources (Lazzari,

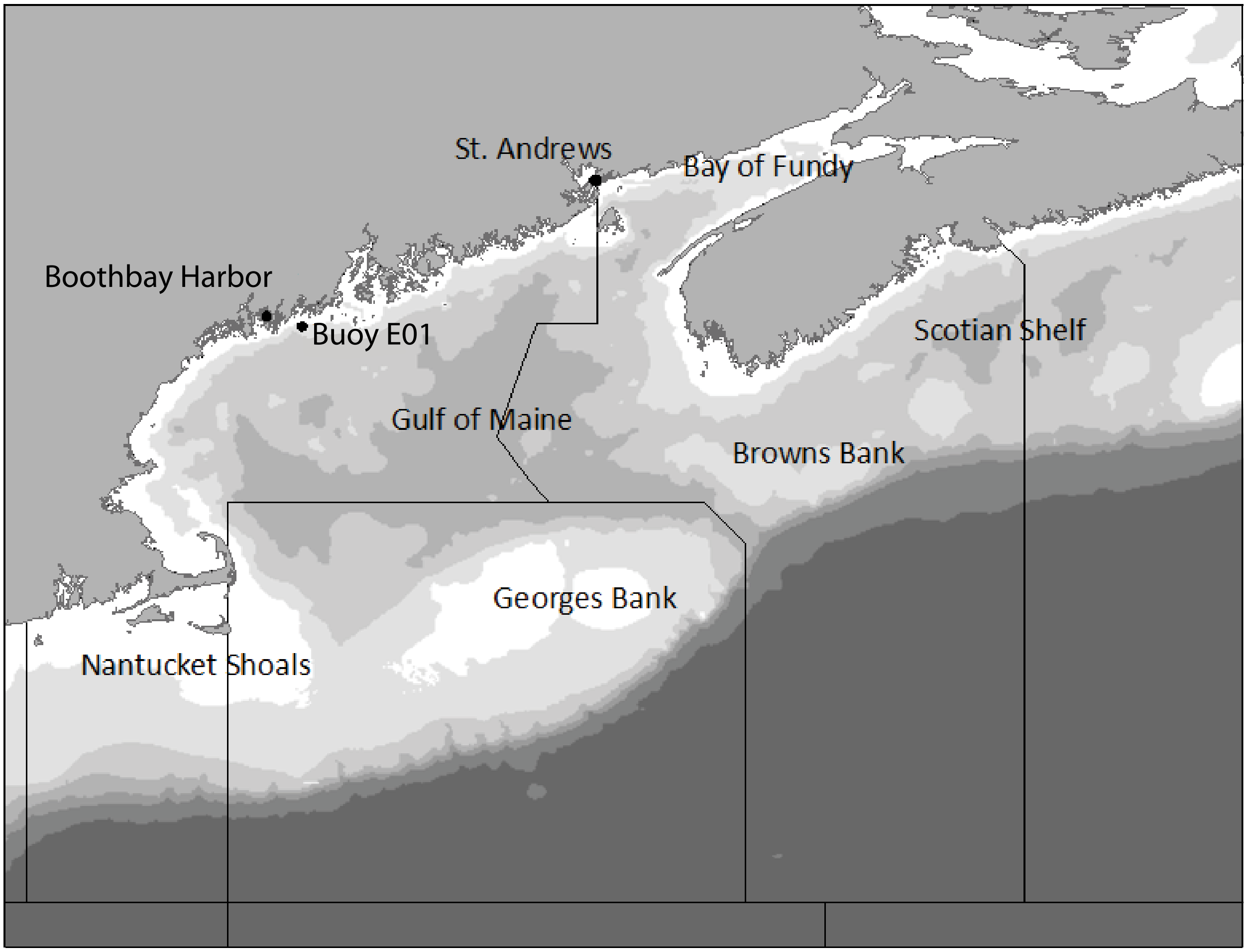

Fig. 1. Map of the Gulf of Maine and Bay of Fundy showing the location of the SST sites of Boothbay Harbor in Maine and St. Andrews in New Brunswick, as well as the location of Buoy E01.

personal communication). The only missing data were from July 1949 to September 1950. The monthly mean temperatures and a description of the methods and instrumentation used to collect the Boothbay SST data were provided in a Marine Resources internal report by Welch (1977). He noted that from its inception in March 1905 to June 1949, sea water temperatures were read three times daily (08:00, 12:00 and 17:00 local time) by inserting a thermometer into a bucket of water taken from the surface at the wharf of the Boothbay Harbor Marine Laboratory. From November 1949 through September 1950 temperatures were read using a thermometer several times a day in laboratory tanks supplied with sea water; these observations were reported to agree well with measurements taken at the surface in the Harbor. Monthly mean SST data during this period are listed in Welch (1977) and have been used to fill in these missing data. From October 1950 to present, with minor interruptions, temperatures have been continuously monitored using a thermistor located at approximately 1.7 m below mean low water at the end of the wharf. During August and September 1957, while the recorder was inoperative, temperatures were taken from a continuous recording thermometer in a laboratory tank supplied with running water. Subsequent comparisons of these temperature recordings with those measured with the thermistor at dockside showed that the two series were nearly identical (Welch, 1977).

Welch (1977) went on to state that the daily means were calculated from the average of the three observations per day during the pre-1950 era and from the 24-hourly readings after 1950. The monthly and annual means were calculated using all of the individual observations rather than by averaging all of the daily or monthly means, respectively. The accuracy of the post-1950 data was initially checked through comparison with other instruments on an infrequent and irregular basis; after 1966, a second sensor was installed and daily and monthly operational calibration checks were undertaken. It is interesting to note that Welch (1977) stated that there was no way to check the accuracy of the pre-1950 data.

To test the effect of the frequency of sampling on the monthly mean temperatures, hourly data were also obtained from the Maine Department of Marine Resources (Mark Lazzari, personal communication). Unfortunately, no hourly data were available in the period prior to 2001, so data from 2001 to 2005 were used. We also obtained the bottom temperatures (7.6 m below mean low water) at Boothbay Harbor from 1989 to 2009 (Mark Lazzari, personal communication) to examine the seasonal variability in the thermal stratification.

For long-term comparisons with Boothbay Harbor, sea surface temperature data were obtained for St. Andrews, New Brunswick (Fig. 1) from the website of the Department of Fisheries and Oceans in Ottawa, Canada (http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/climat/sst-tsm/costal-cotieres-eng.asp?id=Standrew). The St. Andrews time series began in 1921 and temperature has been measured continuously with some short gaps through to the present. These data were initially collected using bucket thermometers from the St. Andrews wharf with measurements taken twice per day, at 08:00 and 16:00 or 17:00 (Hachey, 1939). In 1986, the bucket thermometer was replaced by a thermistor mounted on the St. Andrews wharf. Interruption of the time series occurred from October 1985 to April 1986 due to wharf reconstruction (Drinkwater and Trites, 1988).

To carry out comparisons with both of the coastal sites in the recent years, we obtained SST data from the Gulf of Maine Ocean Observing System (GoMOOS) Buoy E01 (temperatures from 1 m depth, January 2002–December 2010; http://www.gomoos.org/) located 27 km offshore of Boothbay Harbor (Fig. 1).

For both Boothbay Harbor and St. Andrews, SST anomalies (deviations from the mean) were calculated for the monthly data using the 30-year reference period, 1961–1990. The monthly anomalies were then averaged to obtain the mean annual anomalies for those years when there were at least 8 monthly anomalies available. Where normalized monthly anomalies were estimated, each monthly anomaly was divided by the standard deviation for that month estimated over the years 1961–1990. Significance levels for correlations calculated during this study were based on the effective number of degrees of freedom by adjusting for autocorrelation in the time series using the method of Garrett and Toulany (1981).

Results

Based on the climatology (1961–1990), SSTs at Boothbay Harbor typically vary from a monthly mean low of slightly less than 2°C in February to a high in August of almost 16°C with an annual mean around 8.5°C (Fig. 2). In comparison, temperatures throughout the year at St. Andrews tend to be cooler, with differences between the two sites showing seasonal variability from a maximum in summer to a minimum in autumn (Fig. 2). The cooler temperatures at St. Andrews, especially in summer, are believed to be mainly associated with the higher tidal elevations in the Bay of Fundy region, which result in stronger tidal currents and hence more intense vertical mixing.

The time series of annual SST anomalies relative to 1961–1990 mean for Boothbay Harbor and St. Andrews are plotted in Fig. 3. They generally show strong similarity, which is reflected in their relatively high correlation coefficient (1921–2009; r=0.74, p<0.0001). Temperatures at both sites exhibit high annual variability but generally below average temperatures prior to the 1940s, then a relatively rapid rise to peak temperatures in the 1950s followed by a decline into the 1960s. The SSTs then rose and were above the long-term mean during the 1970s and into the 1980s, declined slightly in the late 1980s and early 1990s before rising again. Note the much higher anomalies at Boothbay Harbor compared to St. Andrews since 2000 (Fig. 3). If the comparison of the annual anomalies between the two sites is only based on 1921–1999, the correlation coefficient increases to 0.80 (p<0.0001). We shall return to the high values at Boothbay Harbor since 2000 later in the paper. The differences in the annual SST anomalies between Boothbay Harbor and St. Andrews reveal that the temperature anomalies of the former are generally of higher magnitude with higher highs and lower lows. For those years from 1921–1999 when Boothbay Harbor is colder than normal, it is about 0.2°C colder than St. Andrews; when Boothbay Harbor temperatures are warmer than normal, they are about 0.3°C warmer than St. Andrews. The higher variability at Boothbay Harbor is also reflected in its higher standard deviation of the annual anomalies (0.86°C) compared to St. Andrews (0.63°C).

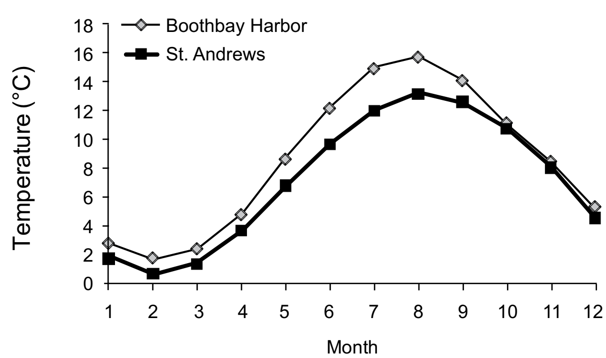

Fig. 2. The monthly mean SSTs at Boothbay Harbor and St. Andrews from 1961–1990.

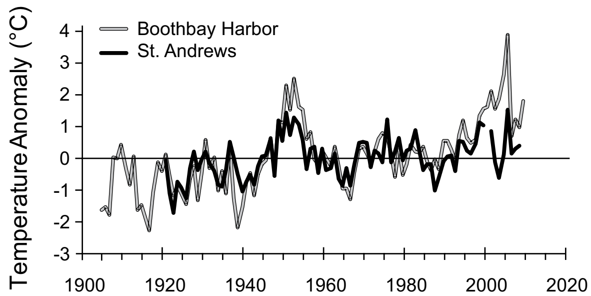

Fig. 3. The time series of the mean annual sea surface temperature anomalies for Boothbay Harbor and St. Andrews, N.B.

The time series of each of the monthly mean SST anomalies at Boothbay Harbor are plotted together in Fig. 4a. Figures 4b and 4c respectively show the plots for the cooler months (October to March), hereafter designated as winter, and warmer months (April to September), designated as summer. Of particular note is the change in the amplitude of the spread in the monthly mean anomalies (Fig. 4a). Prior to 1950, the spread between maximum and minimum monthly anomalies was relatively large but after 1950 there was a relatively low and constant spread between the monthly anomalies each year. Examining winter observations at Boothbay Harbor shows that the monthly SSTs anomalies prior to 1950 are consistently below their long term means, on average by -1.48°C (Fig. 4b), while for the summer the monthly temperature anomalies for the same period averaged +0.24°C (Fig. 4c). For the period 1950 to 1999, the means for the winter, +0.38°C, and summer, +0.32°C, temperature anomalies are very similar. It is also interesting to note that the standard deviation for Boothbay Harbor temperatures over the period 1906–1950 is 0.78°C and after 1950 is 0.75°C, only a slight difference, however, the step-like transition around 1950 adds to the variance boosting the overall (1906–1999) standard deviation to 0.86°C.

The time series of the monthly means for St. Andrews shows no significance difference in the pattern of monthly temperature anomalies pre- and post-1950 as observed for the Boothbay Harbor data or pre- and post-1986, which is the time of the switch from bucket thermometers to thermistors at this site (Fig. 5).

The difference between the two stations is further shown in the time series plot of the annual differences between the maximum and minimum monthly anomalies (Fig. 6). At Boothbay Harbor, the differences mostly range between 3-5°C pre-1950 and are about 2°C in the post-1950 years. At St. Andrews, the differences were generally less than 2°C throughout the entire record.

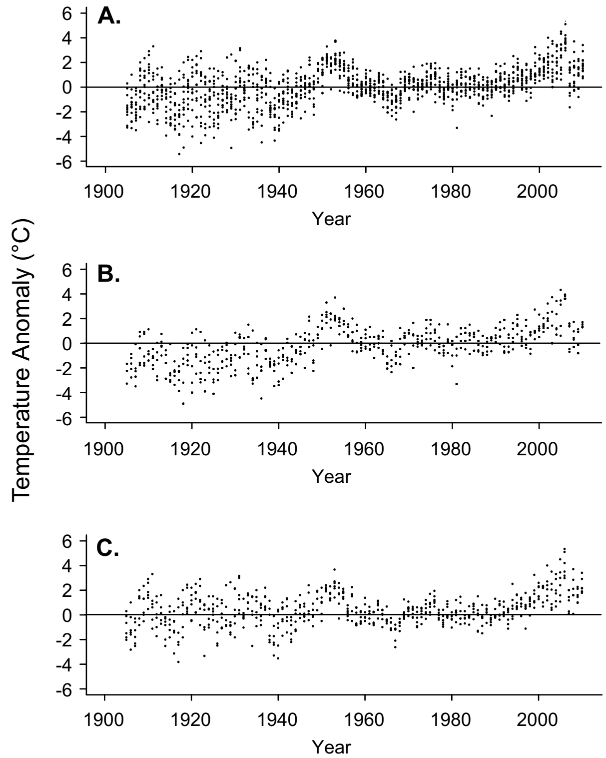

Fig. 4. The separate monthly mean temperature anomaly time series from Boothbay Harbor: (**A**) all months; (**B**) winter months (October–March); and (**C**) summer months (April–September).

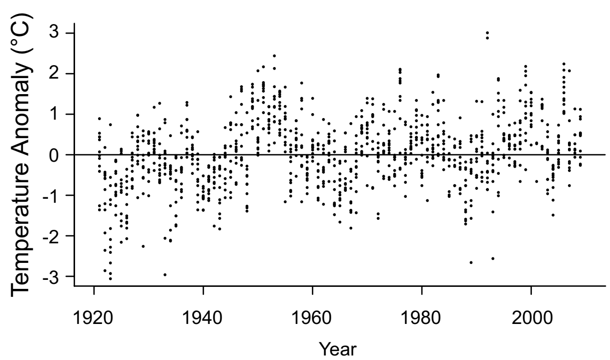

Fig. 5. The separate monthly mean temperature time series from St. Andrews, N.B., all months.

Further examination shows a distinct seasonal cycle in the average of the mean anomalies at Boothbay Harbor for the pre-1950 period with warm summer months and cold winter months (Fig. 7a). No such seasonality is detected post-1950. Only data up to 1999 were used because of the expected overestimate of the SSTs in later years. At St. Andrews the monthly mean anomalies show no strong seasonal variability in either period, being similar across months (Fig. 7b). Note that at both stations the pre-1950 average monthly anomalies tended to be colder than normal while the 1951–1999 values were warmer than normal, consistent with what was observed previously.

We now return to the data collected from 2000 onwards. Evidence that the data from Boothbay Harbor during this period were overestimated comes from comparisons with earlier Boothbay observations, records from St. Andrews and from an offshore oceanographic buoy (Fig. 1). For Boothbay Harbor in the period of 1951–1999, the monthly SSTs were approximately normally distributed for the earlier period but strongly skewed towards higher values for period 2000–2010 (Table 1). At St. Andrews, the monthly anomalies were normally distributed in both periods (note that these data only extend to 2009). For the 2000–2010 period, the average of the absolute values of the monthly normalized anomalies for Boothbay was 2.3, the median 2.0 and the maximum 7.2 (June 2006) indicating that this period was exceptionally above normal. The average of the 2001–2010 monthly normalized anomalies were all above zero, with 7 of the months more than 2 standard deviations above normal values; the absolute values of the normalized anomalies indicates that all anomalies for the months March-September were positive (Table 2). These are much higher than can be accounted for by any long-term warming. The Boothbay minus St. Andrews monthly average temperatures differences were constructed for two periods, 1951–1999 and 2000–2009. The differences for 2000–2009 were greater in all months and by as much as 2.5°C in July and August than for 1951–1999. These results raise questions concerning the reliability of the Boothbay Harbor data since 2000 as initially reported by Petrie *et al.* (2005).

Comparison of the Boothbay Harbor series with the 1 m temperature time series (January 2002–December 2010) from Buoy E01 shows that temperatures were always higher in Boothbay for April–September, with on average the highest offset in June (+3.7°C) and the highest individual monthly offset of +5.6°C in July 2004 (Fig. 8). Such large temperature differences cast doubt on the representativeness of the Boothbay series for the central Gulf of Maine, at least during much of the first decade of the 2000s.

Comparison of the thermistor-measured surface (1.7 m) and bottom (7.6 m) temperatures at Boothbay Harbor indicates that the vertical thermal gradient was greater for the 1989–1999 period than the years during the 2000s implying that vertical stratification was not the cause of the extraordinary temperatures during the later period.

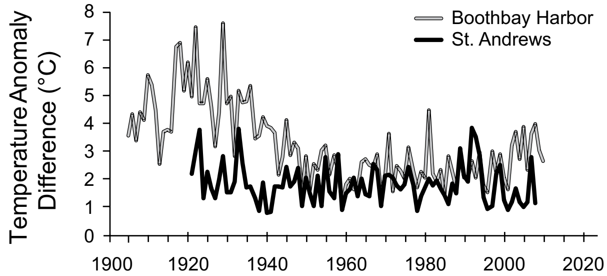

Fig. 6. The annual difference between the maximum and minimum of the monthly mean temperature anomalies for Boothbay Harbor and St. Andrews, N.B.

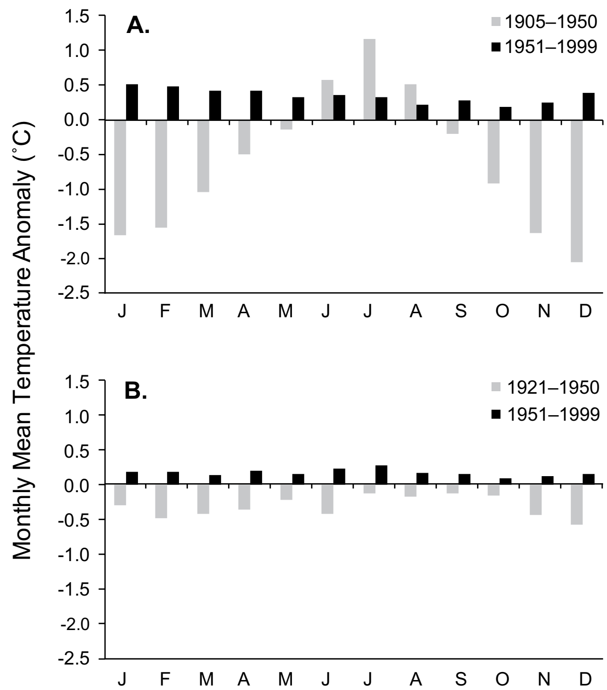

Fig. 7. The monthly mean sea surface temperature anomalies for the pre-1950 and 1950–1999 for (**A**) Boothbay Harbor and (**B**) St. Andrews.

Discussion

Examination of the long-term SST data from Boothbay Harbor has revealed a fundamental difference in the structure of the monthly mean SST anomalies with a significant change occurring around 1950. In the pre-1950 period, there was substantial spread between the temperature anomalies with the summer months exhibiting higher anomalies than the winter months. This difference in anomalies was significant, being on average almost 2°C, and the differences between the maximum and minimum monthly anomalies being around 4°-5°C and in some years exceeding 7°C. In contrast, after 1950, there was no significant difference between the summer and winter SST anomalies, and the differences between the maximum and minimum anomalies of the months was around 2°C. The general similarity in monthly temperature

Table 1. Distribution of normalized monthly temperature anomalies. Note that 9 months of data were missing between 1951 and 1999 and 16 months between 2000 and 2009 at St. Andrews.

Boothbay Harbor 1951–1999	Months within <1 SD	1 to <2SD	2 to <3SD	≥3SD
Number	356	164	48	20
Percentage	61	28	8	3
Cumulative %	61	89	97	100
2000–2010				
Number	26	37	28	41
Percentage	20	28	21	31
Cumulative %	20	48	69	100
St. Andrews 1951–99				
Number	451	116	11	1
Percentage	77.9	20.0	1.9	0.2
Cumulative %	77.9	97.9	99.8	100
2000–2009				
Number	75	26	3	0
Percentage	72	25	3	0
Cumulative %	72	97	100	0

Table 2. Average of monthly anomalies and absolute values of the monthly normalized anomalies for Boothbay Harbor, 2000–2010.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Average	1.03	1.00	1.65	2.41	2.29	3.26	3.89	4.01	3.35	2.20	1.27	1.20
Average Absolute	1.21	1.15	1.65	2.41	2.29	3.26	3.89	4.01	3.35	2.23	1.36	1.54

anomalies post-1950 meant that if the annual anomaly were colder (warmer) than normal, most of the months in that year were also colder (warmer) than normal.

What was the likely reason for the change in spread of the monthly temperature anomaly time series around 1950 at Boothbay Harbor? One possibility is that the data are real and there was an actual change in the structure of the monthly mean anomalies around 1950. This is difficult to reconcile, however, since the SST data at St. Andrews show no difference in their anomaly pattern between the pre- and post-1950. The pattern of the monthly anomalies at St. Andrews throughout the entire record was similar to those in the post-1950 period at Boothbay Harbor. We next considered the possibility that there might be a bias in taking only 3 readings a day during daylight hours prior to 1950 compared to continuous records after 1950. To test this hypothesis we used the hourly data from 2001–2005. Monthly means were estimated based first on all of the available data and then using just the data for the hours when the bucket temperatures were taken, *i.e.* 08:00, 12:00 and 17:00. While not a true test of the hypothesis as the recent hourly data are a mean over an hour and not instantaneous readings such as provided by thermometer readings, still they should provide a hint as to whether this could explain the difference in the pre- and post- 1950 pattern. The results do show a slight seasonal difference, being colder in the winter and warmer in summer, but the amplitude is much too small to account for the observed differences between winter and summer in the pre-1950 data. Also, at St. Andrews, for the years when the measurements were taken with bucket thermometers, there were only two measurements per day and no such difference in the winter and summer anomalies was

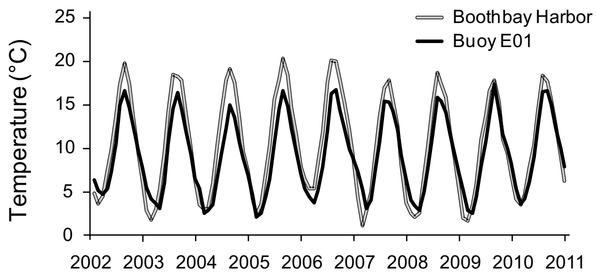

Fig. 8. Comparison of the monthly mean SSTs at Boothbay Harbor and from the offshore buoy E01.

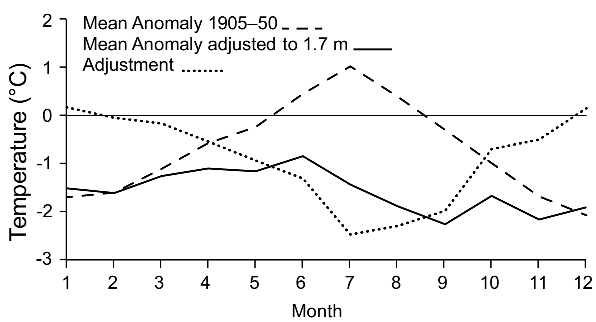

Fig. 9 Mean monthly surface temperature anomalies at Boothbay Harbor taken using the bucket thermometer for the 1905–1950 period (dashed line, see Fig. 7a) and adjusted to the thermistor depth of 1.7 m below low water (solid line) based on the monthly mean temperature gradient between 1.7 m and 7.6 m from 1989–2009 (dotted line, temperature adjustment shown).

found after the switch from the bucket thermometer to a thermistor, in contrast to Boothbay Harbor.

As noted above, there was a change in observational methods from bucket thermometer readings to continuous recordings using a thermistor attached to the wharf. There was approximately a year (July 1949 to September 1950) between these two methods when temperatures were recorded inside a laboratory from water pumped near the wharf site. The timing of the switch in instrumentation corresponds to the approximate timing of the change in pattern of the monthly means. The warmer summers and cooler winters in the pre-1950 period at Boothbay may therefore have been due to the measurement technique. Details of the precise method used in obtaining the bucket measurements, such as how long the thermometer was allowed to sit in the bucket prior to the measurement being taken or whether the bucket was shielded from the sun or the wind, are not available. However, the seasonal trend in the monthly anomalies could be accounted for if at the time of the measurements they were not shielded from the weather and if the time taken to obtain the measurement was too long. This would result in the water tending to be cooled in the winter and warmed during the summer. It would seem unlikely though that they would have not have taken care to avoid such effects. Also, no such difficulty is suggested from the St. Andrews data although the method used may not have been identical to that at Boothbay Harbor. Differences in the precision and accuracy of the bucket thermometers used between these two sites might also account for part of the observed differences between Boothbay Harbor and St. Andrews prior to 1950 but are unlikely to account for the large differences of several degrees nor could it explain the differences between the winter and summer patterns.

Another possibility is that the difference could be accounted if there was thermal stratification between the surface (bucket) and the depth of the thermistor (1.7 m below mean low water). Data at Boothbay Harbor for these two depths are unavailable to determine the near surface thermal gradient there but the offshore buoy (E01, 100 m bottom depth) collected data at 1 and 2 m. Using the available buoy data (2002–2010), the average monthly maximum difference between the two depths was 0.5ºC, typically peaking in July or August. Given that Boothbay Harbor is more sheltered than the buoy's offshore site, one might expect that the temperature difference in the top couple of meters in the former would be larger. To explore this possibility further we subtracted the Boothbay Harbor monthly mean temperatures near bottom (7.6 m) from those near surface (1.7 m) for the years with data (1989–2009). The average over all years indicated strong thermal stratification peaking in summer with a maximum difference of about 5ºC in July. If one assumes a linear thermal gradient with depth over the full water column, the difference between the surface and thermistor depth of 1.7 m below mean low water can be estimated. However, one must also account for the mean tidal range of 2.68 m, thus the thermistor was on average slightly more than 3 m (1.7 m + 1/2 of the mean tidal range) below the surface. This produces monthly mean differences in temperature between the surface and the thermistor depth from near zero in winter to a peak value of 2.6ºC in July.

The adjustments to bring the surface bucket observations to the thermistor depth of 1.7 m below mean low water are strongly and inversely correlated (r^2 = 0.81) with the mean monthly anomalies from 1905–1950 (Fig. 9). They substantially reduce the annual cycle (least squares fit of a mean + annual harmonic) from 1.4ºC to 0.5ºC. Moreover, these monthly adjusted anomalies are all negative and range from -0.8ºC (June) to -2.3ºC (September), with an average value of -1.5ºC.

This is in better agreement with the St. Andrews record (Fig. 7b) where for the 1921–1950 period all monthly anomalies were negative with an average value of -0.3ºC. From this analysis we conclude that the thermal gradient combined with the depth difference between the bucket measurements and the thermistor can account for most of the difference in the monthly mean temperature anomaly patterns between pre- and post-1950.

We considered using the St. Andrews measurements to "correct" the early Boothbay Harbor time series of monthly mean temperatures. However, since interannual variability in the thermal stratification will result in year-to-year differences in the correction that should be applied and there was no way of validating such a new dataset, we decided not to carry out this exercise.

Of more recent concern is the apparent very high temperatures recorded at Boothbay Harbor during the present decade. The SSTs appear much too warm compared to either St. Andrews or to measurements taken at a buoy located 27 km offshore. While increased stratification since 2000 has been ruled out as a possible explanation for these extreme surface temperatures, the actual cause has not been determined. This suggests that users should exercise caution in interpreting any results using these data. Constant monitoring of the site through comparisons with nearby stations to validate their reliability is recommended.

Conclusions

We conclude that differences in the pattern of mean monthly temperature anomalies at Boothbay Harbor from 1905–1950, when surface bucket observations were made, and 1951-2000, when measurements were recorded 1.7 m below mean low water, can largely be accounted for by the vertical temperature gradient. The adjustments however apply only to the period as a whole and cannot be made confidently to data from an individual year. It is important to point out that both the pre- and post-1950 data are "correct" (to within the uncertainties of the measurements) but because of the differences in the depth of the measurements and the thermal stratification, the time series are not homogeneous over the full length of the record. Because of this, studies using the monthly mean surface temperature or temperature anomaly time series from Boothbay Harbor, when used for either climate studies or in combination with biological data to explore temperature effects on the biota, should not combine data from the pre- and post-1950 periods. The temperatures at Boothbay Harbor from 2000 onwards are inconsistent with nearby stations and until an explanation is forthcoming they must be viewed with caution. The long-term temperature record at Boothbay Harbor, in spite of the non-homogenous nature of the full record and the apparent over-estimated values in recent years, should be maintained well into the future but with constant vigil to insure data are of the highest quality.

Acknowledgements

We thank Mark Lazzari of the Marine Department of Natural Resources for his kind assistance and providing the SST data from Boothbay Harbor and to Roger Pettipas for his technical assistance. Two anonymous reviewers provided valuable comments on an earlier draft, one of whom suggested we should explore the thermal stratification as a possible explanation for the difference in the temperature anomaly patterns, for which we are thankful. K.D. would like to acknowledge the supported by the Bjerknes Centre for Climate Research for the time to complete the writing of this paper.

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