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Seawater Temperature Trends at USA Tide Gauge Sites

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Abstract. Seawater temperatures have been measured at United States tide gauges throughout most of the 20th century. All available records have been digitized, and the longest 14 have been analyzed by linear least-square regression. The largest positive trend is from Boston MA (+3.6 ± 0.4°C per century), and the largest negative trend is at Charleston SC (−0.1 ± 0.3°C per century). No consistent latitudinal or east-coast vs. west-coast patterns are discernable, but air temperature trends are typically greater than seawater changes.

Introduction

Tidal observers at primary tide gauges of the United States Coast and Geodetic Survey (now the NOAA National Ocean Service) routinely measured seawater temperature and density. Many records extend back to the early part of the last century, the longest record extant being San Francisco (Carvalho and Maul, 1997). For the most part, these records have not been digitized nor analyzed for climatic signatures to our knowledge.

Unfortunately, many of the 81 or so USA tidal station temperature records have missing data or are too short for analysis of linear trend. Modern tide gauges typically have seawater temperature sensors reporting in their data- stream, but the traditional analog systems relied on the skill of the observer to measure, record, summarize, and report temperature and density. The missing records are probably not the fault of field observers, and may well yet be discovered in misfiled reports.

Herein, records that span most of the last 100 years are entered into spreadsheet files, and are made available. Most of the digitizing is the product of work-study students at Florida Tech. Quality control and quality assurance utilize standard methods including plots and visual outlier detection. All data were converted from Fahrenheit to Celsius.

Data Source and Processing

Data were provided as photocopies (and more recently digitized records) of the station sheets filed with each tide station folder. In most cases the data included monthly and annual mean temperatures, monthly and annual maximum and minimum temperatures, monthly and annual mean seawater density and maximum and minimum density. Almost all data on the photocopies are hand entries; monthly and annual means were mechanically calculated.

Temperatures and densities from the tidal station sheets were placed into spreadsheets manually. Plots of monthly data were made to determine errors or outliers. Finally the digitized tables were compared to the photocopies to ensure accurate copying.

As with meteorological stations, tide gauge stations are moved from time to time. The usual emphasis in sea level continuity is through benchmark checks by differential leveling. No such practice seems to have been emphasized with the seawater temperature or density observations, but considering the tradition of excellence within the U.S. Coast and Geodetic Survey since its founding by President Thomas Jefferson in 1807, it is reasonable to assume the historical information is reliable.

Quantifying the standard errors associated with these monthly or annual means is problematic. The observer traditionally visited the tide gauge on a daily basis, and recorded the data by hand on summary sheets and on the marigram itself (USC&GS, 1929). Temperature and density typically are from bucket samples and thus represent true sea surface observations. Well-designed and calibrated thermometers are usually read at least to the nearest 1°F or to the nearest 0.5°C, and estimating the number of observations per month to be 30, it seems reasonable to assume the monthly mean standard error is less than ± 0.1°C. Observer error then is probably negligible for the purposes of determining trends.

Linear trend error estimates reported below have not been adjusted for serial correlation (WMO, 1966), and thus represent an optimistic estimate. In serially correlated data, the effective sample size (N′) is often considerably less than the number of data points (N), increasing the standard error by $\sqrt{N}/\sqrt{N'}$. This additional uncertainty is an aside to the main theme reported herein.

Results

Table 1 summarizes linear trends (ΔT) at fourteen of the longest USA stations. This subset of the 81 uncovered to date all end in the 1990's and in so far as possible represent a common epoch but not necessarily a common record length. Also reported are the standard errors (SE) of the trend (± °C per century). Figure 1 shows the data.

A cursory glance at the table shows that the most complete record on the east coast USA during the 20th century is from Charleston SC and on the west coast at La Jolla CA. Carvalho and Maul (1997) reported a linear trend of +0.3°C per century for their extended analysis of San Francisco covering 1855-1993, including a data gap 1878-1920. The

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Table 1: Seawater Temperature Trends (ΔT °C·100yr^{-1}) ± Standard Error (SE ± °C·100yr^{-1}) from USA Tide Gauges

Station	Years	N	ΔT	SE
Boston	1921-1994	69	3.6	0.3
New York	1926-1994	61	1.8	0.4
Atlantic City	1911-1991	54	0.9	0.4
Baltimore	1914-1993	65	0.9	0.5
Charleston	1921-1992	70	-0.1	0.3
Mayport	1944-1993	46	0.2	0.6
Key West	1926-1994	36	0.0	0.3
Galveston	1921-1992	36	-0.1	0.5
La Jolla	1916-1996	79	0.7	0.3
Los Angeles	1923-1991	40	0.8	0.4
San Francisco	1921-1994	57	0.5	0.4
Seattle	1922-1994	41	0.0	0.4
Neah Bay	1935-1994	53	1.1	0.4
Seward	1925-1993	29	0.1	0.4

linear trend during 1921-1994 at San Francisco is +0.5 ± 0.4°C per century.

Linear trend at Boston's primary tide station (N=69) is the highest in Table 1 at +3.6 ± 0.3°C per century. At Charleston SC, a station with 70 recorded annual means, the trend is -0.1 ± 0.3°C per century, not unlike other negative trends at Key West FL, and Galveston TX. Except for Key West, perhaps the most "oceanic" site on the USA east coast is Atlantic City NJ (1911-1991) which shows a linear warming trend of +0.9 ± 0.4°C per century.

West coast sites show a similar mixture of linear temperature trends as on the east coast. Highly urbanized Seattle WA shows 0.0 ± 0.4°C per century, and nearby Neah Bay WA, a much more remote site, is +1.1 ± 0.4°C per century. The longest reportable record from Alaska is Seward (+0.1 ± 0.4°C per century); no records longer than N=19 (Honolulu, 1975-1993) are recovered in Hawaii.

Comparison with Air Temperatures

Trends from air temperature records are often more problematic than sea surface temperature. For example, Hanson and Maul (1993) analyzed the record at Key West from 1851 to 1986. They found that the station had been moved 14 times and few details of station location were kept. They cautiously chose not to attempt a trend analysis of air temperatures, but a visual inspection suggests no discernable change.

At San Francisco, Carvalho and Maul (1997) reported an air temperature trend of +1.6°C per century, a rate some three times larger than the sea surface temperature at the tide gauge. Other air temperature trend sites include Baltimore (+2.0°C per century), Boston, Charleston, and Mayport (all +0.6°C per century), and Neah Bay (+1.0°C per century). In each case except Boston (very curiously), air temperature trends are equal or higher than seawater temperature trends.

An exhaustive inquiry into air temperature trends is beyond the scope of this paper. Suffice to say that for the most part, the urban air seems to be warming faster than the nearby water. Urbanization effects in climatic records are well known, but adjusting for them in time series analysis ultimately is an issue of judgment for the investigator.

Discussion

The tide gauge sites at each of the cities reported in Table 1 were originally chosen for the purpose of observing tides. Due to the efforts of USC&GS hydrographic surveyors, the tide gauges have proven useful for long-term sea level studies as well. It is not as clear that they are equally useful for discerning climatic temperature trends.

Boston harbor for example is a semi-enclosed basin with only a small river to flush the estuary. San Francisco is near the mouth of a large bay, and Seattle is well inside Puget Sound. Each site has experienced significant population growth in the last 100 years, and yet their seawater temperature trends are all very different. Certainly, with the increase in maritime traffic and discharge of wastewater one would expect water temperatures to rise.

If projections of global warming are correct, one would also expect to find larger seawater temperature trends in northern sites, decreasing to the south. While that could be argued to be the case on the east coast of the USA based on these results, just the opposite occurs for the most part on the west coast. Clearly other factors are at work in these places.

Roemmich (1992) reports that the water temperature at the La Jolla tide gauge during the 1980s was the warmest decade

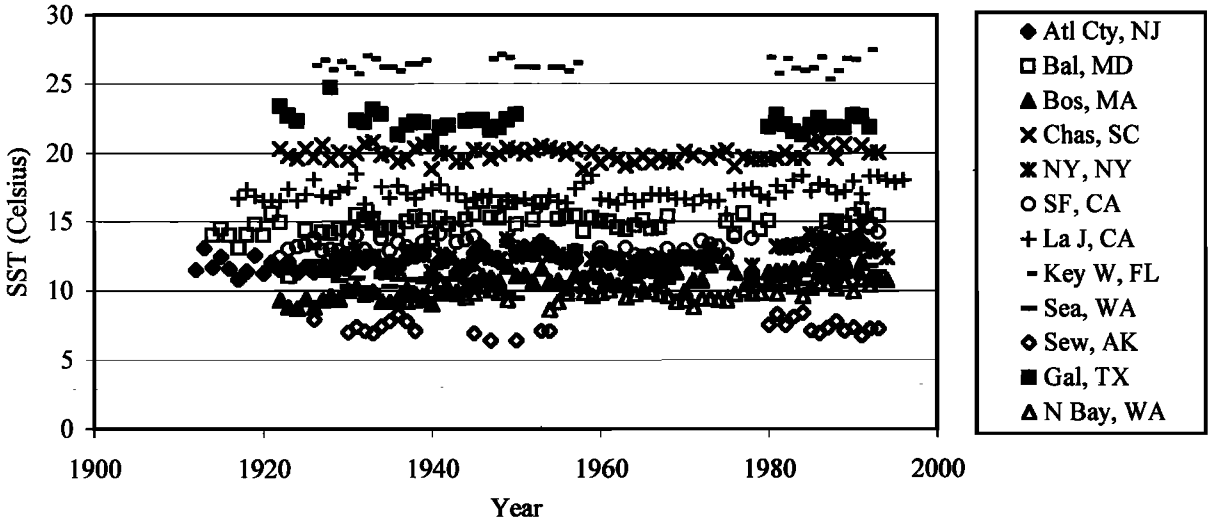

Figure 1. Time series of seawater temperatures from USA tide gauge sites.

between 1950 and 1991. Such warming toward the end of a record certainly could increase trends. Unfortunately many other records reported herein are not as complete as La Jolla. Until more of these records are found and digitized it seems inappropriate to apply techniques such as two-phase regressions to test for accelerated change.

In reviewing the methods used by the tide observers (USC&GS, 1929), it was also discovered that they were instructed to observe "outdoor air" temperature. Each monthly Temperature and Density Report (USC&GS Form 457) should have an equally complete air temperature record. It seems that this may be another rich source of temperature data not yet uncovered.

Further, it should be noted that the method of obtaining temperatures has changed with the introduction of digital systems. Seawater now is measured at the intake of the tide-gauge stilling well rather than by bucket. Modern temperatures are thus taken several meters below the surface, and in the case of a salt-wedge estuary, the submerged thermisters may be sampling a different water mass.

As noted above, often the seawater temperature summary sheets in this effort left large unexplained gaps. A search was attempted by correspondence, but little more has been uncovered. Probably the missing data exist, and a more extensive search at the National Ocean Service seems warranted. An effort to find temperature records at the water level monitoring sites of the US Army Corps of Engineers and at the US Geological Survey proved unfruitful.

Conclusions

The range of seawater temperature trends for the USA is surprisingly large, with the null and negative trends providing the most unexpected results. That numerous air temperature trends are much larger than seawater trends too is unanticipated. On the time scales investigated herein, one would expect the water temperatures to equilibrate to the air despite the 4:1 ratio of specific heats of water to air.

High quality observational records such as seawater (and apparently outdoor air) temperatures at tide gauge sites are invaluable sources of new information. They should be given equal status with the Historical Climate Network records, digitized for the public domain, and aggressively studied.

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