FLORIDA COASTAL TEMPERATURE TRENDS: COMPARING INDEPENDENT DATASETS

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Abstract: *Linear least-squares temperature trends were investigated for coastal sites and near-shore areas around Florida. Land air temperature data are from the Historical Climatology Network, littoral water temperature data are from Coast and Geodetic Survey tide gauges, and near-shore pelagic marine air temperatures and sea surface temperatures are from the Combined Ocean-Atmosphere Data Set (38 independent time-series in all). Over the last 160 years or so, Florida coastal air and water temperatures seem to have increased at a rate of about 0.2 to 0.4°C per century, but the statistical significance is uncertain. No single dataset is consistent with any one other (r^2 = 0.1 between trend pairs), and there is no geographic organization to temperature change as an indicator of Florida's coastal marine climate variability.*

Key Words: Coastal Florida climate change, Florida air and water temperature trends, Florida temperature data comparisons

Surface temperatures (T) are central to understanding Earth's climate and weather, albeit on vastly different time (t) and space scales. Linear temperature trends ($\partial T/\partial t$) are widely used to quantify the rate at which temperature changes as a function of time (*e.g.* IPCC, 2002). Accordingly, linear least-squares trend parameters from three independent sources are computed herein for 19 land sites and eight 2° × 2° latitude × longitude areas around the Florida coast from Pensacola to Key West to Fernandina Beach. These temperatures are used to intercompare results between datasets and to assess the viability of using any one dataset to estimate statewide coastal temperature change.

In the USA, the Historical Climatology Network (HCN) has been the premier source of land air temperature (LAT) data for assessing climate change (*e.g.* Karl et al., 1990). The HCN provides information on the surface air temperatures and other variables at inland and coastal sites that are, for the most part, not influenced by urbanization (*e.g.* Peterson et al., 1997). The HCN however does not include coastal marine data, in particular sea surface temperature (SST) and marine air temperature (MAT).

A parallel climatological effort is the development of the Combined Ocean-Atmosphere Data Set (COADS) by Woodruff and co-workers (1998) that includes pelagic and coastal SST and MAT along with other maritime surface variables primarily from volunteer observing ships. COADS itself would benefit by including coastal climate observations such as those from the

C-MAN (coastal-marine automated network) of the National Oceanic and Atmospheric Administration (NOAA), and shallow-water SST from the tide gauge network of the NOAA National Ocean Service and of a predecessor NOAA agency – C&GS, the United States Coast and Geodetic Survey.

Temperature observations from one source often give different results compared with those from other independent sources (*e.g.* Jones et al., 1986). The southern USA for example shows generalized cooling trends in SST from coastal C&GS tide gauges but LAT warming trends from juxtaposed HCN sites (Maul et al., 2001). Is this because of changing measurement techniques, or a changing environment, or intra-regional variability, etc.? The three independent sets of data (HCN, COADS, and C&GS) are often juxtaposed in the coastal zone, and this provides the opportunity to intercompare their linear trends.

While individual temperatures and associated linear trends are expected to vary over short geographic distances in Florida (Moulin, 2005), the broader issue is: "Can the temperature trend be resolved by considering the ensemble?" (Maul and Sims, 2005). To avoid the problem of lags and leads in time-series analysis, only long-term linear least-squares trends are compared in the final analysis. Estimating the average statewide coastal temperature trend and intercomparing these trends from separate databases are the foci of this study.

METHODS—For coastal Florida, temperature trends and the standard error (SE) of the trends are calculated independently for the HCN, C&GS, and COADS data. Oftentimes the HCN station is not at the exact same location as the C&GS tide gauge (Fig. 1). On the other-hand, COADS are from ships at sea, and are compartmentalized into $2^\circ \times 2^\circ$ latitude $\times$ longitude boxes as shown in Fig. 1 ($1^\circ \times 1^\circ$ latitude/longitude COADS boxes are available from 1960–2002 but not for years prior to 1960). In attempting to intercompare trends from each source, co-located sites are used in so far as practicable.

COADS provides near-shore pelagic SST and near-surface MAT, among other maritime variables. HCN provides coastal LAT for this purpose, and the C&GS tide gauges provide shallow-water SST. Ten sites in coastal Florida were found where multidecade-long trends from HCN and COADS could be calculated and compared. Nine sites allowed comparisons of SST from COADS and SST from the C&GS tide gauges. In all cases (Tables 1 and 2 below) the linear trends $\pm$ SE are reported in degrees Celsius per century (°C/century).

Monthly mean COADS data were converted to annual means for comparison with the annual means in the LAT and C&GS databases. This often shortened the record length (N) because many years did not have 12 full months. For example, in the offing of Key West for the period 1890–2002 the trend $\pm$ SE for COADS SST using annual means (N = 113) was +0.9 $\pm$ 0.1°C/century, and using monthly means (N = 1319) it was +1.0 $\pm$ 0.2°C/century. For MAT, the parameters are +0.3 $\pm$ 0.1°C/century using annual means (N = 113), and +0.4 $\pm$ 0.2°C/century using monthly means (N = 1320). Although these annual means tend to give slightly lower trends, within the 95% Confidence Interval (using the $\pm$ 2 SE rule), the annual/monthly trend-pairs are not significantly different.

Figure 2[a] is a plot of COADS sea surface temperature (upper plot - diamonds) and marine air temperature (lower plot - squares) surrounding Key West, Florida (*q.v.* Fig. 1). The average MAT = 25.50°C and average SST = 26.52°C. Although the data extends back to the early 1840's, much is missing especially during the American Civil War – typical of many such time-series in the region. Note the MAT data during 1940–1945 with the well-known peak (IPCC, 2002) due to daytime sampling bias throughout World War II. Also note that there is no statistically significant change in variance as a function of decade in these data.

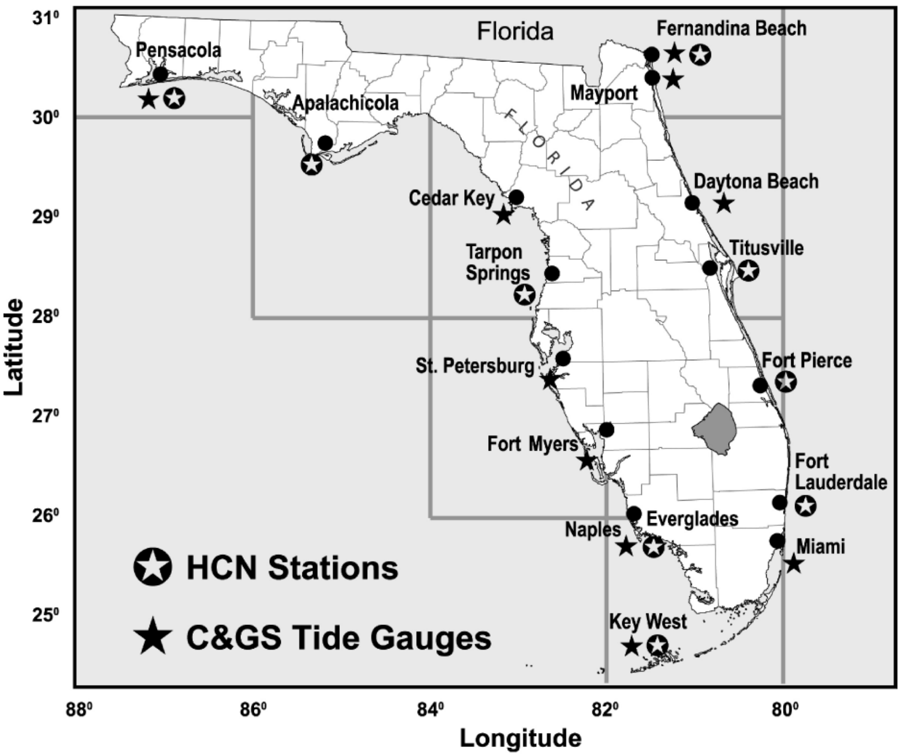


FIG. 1. Locations of the HCN (Historical Climatology Network) and C&GS (Coast and Geodetic Survey) tide gauge sties used in this study. The eight COADS 2° × 2° latitude/longitude boxes are shown in the pelagic areas offshore.

TABLE 1. Linear least-squares trends (°C/century) of land air temperatures (LAT) from the Historical Climatology Network (HCN), and the Combined Ocean-Atmosphere Data Set (COADS) marine air temperatures (MAT).

Station	Years	HCN LAT Trend	HCN ± SE	COADS MAT Trend	COADS ± SE
Fernandina Beach	1892–2000	+0.4	±0.2	+0.5	±0.5
Titusville	1912–2000	+0.0	±0.2	+0.7	±0.4
Fort Pierce	1840–2000	−0.1	±0.2	+0.0	±0.3
Fort Lauderdale	1914–2000	−0.0	±0.2	+0.7	±0.4
Key West	1834–2000	+0.4	±0.1	−0.0	±0.2
Everglades	1928–2000	−0.7	±0.4	+0.4	±0.4
Fort Myers	1892–2000	+1.4	±0.2	+0.2	±0.3
Tarpon Springs	1885–2000	+0.6	±0.2	+0.3	±0.4
Apalachicola	1904–2000	+0.1	±0.2	−0.6	±0.4
Pensacola	1880–2000	+0.2	±0.2	+0.5	±0.8

TABLE 2. Linear least-squares trends (°C/century) of pelagic sea surface temperatures (SST) from the Combined Ocean-Atmosphere Data Set (COADS), and littoral SST from the Coast and Geodetic Survey (C&GS) tide gauges.

Station	Years	C&GS SST Trend	C&GS ± SE	COADS SST Trend	COADS ± SE
Fernandina Beach	1944–1987	−1.3	±0.8	+0.1	±1.3
Mayport	1944–1993	+0.2	±0.6	+0.1	±1.0
Daytona Beach	1927–1970	−2.9	±1.7	+0.0	±0.8
Miami	1940–1991	+0.9	±0.7	+0.1	±0.5
Key West	1926–1994	−0.0	±0.3	+0.7	±0.4
Naples	1969–1991	+3.3	±2.3	+0.7	±3.1
St. Petersburg	1948–1986	+0.2	±1.2	+0.4	±1.5
Cedar Key	1922–1985	+0.7	±0.7	+0.1	±1.0
Pensacola	1924–1971	−0.4	±0.8	−0.4	±0.8

The pelagic SST and MAT time-series shown (Fig. 2a) are dominated by interannual variability, and it is difficult to assess how well the water temperature and the air temperature co-vary. In Figure 2[b], the COADS SST and the MAT in the offing of Key West are plotted against each other; there are N = 121 pairs in the analysis. The coefficient of determination (r^2) between SST and MAT, $r^2 = 0.44$, demonstrates only a modest degree of covariance between them. For lags and leads of ±2 years, r^2 varies as: 0.24 (−2 years), 0.20 (−1 year), 0.44 (0 years), 0.17 (+1 year), and 0.15 (+2 years), demonstrating that the maximum covariance is as shown (Fig. 2b) The zero-lag slope (α) of the regression, $\alpha = 0.71$, suggests that MAT and SST are changing at different rates, and the 95% Confidence Interval (CI) for the slope, $0.56 \leq \alpha \leq 0.85$, agues that the slope is significantly different from unity. These and other rates of change are discussed in the following section.

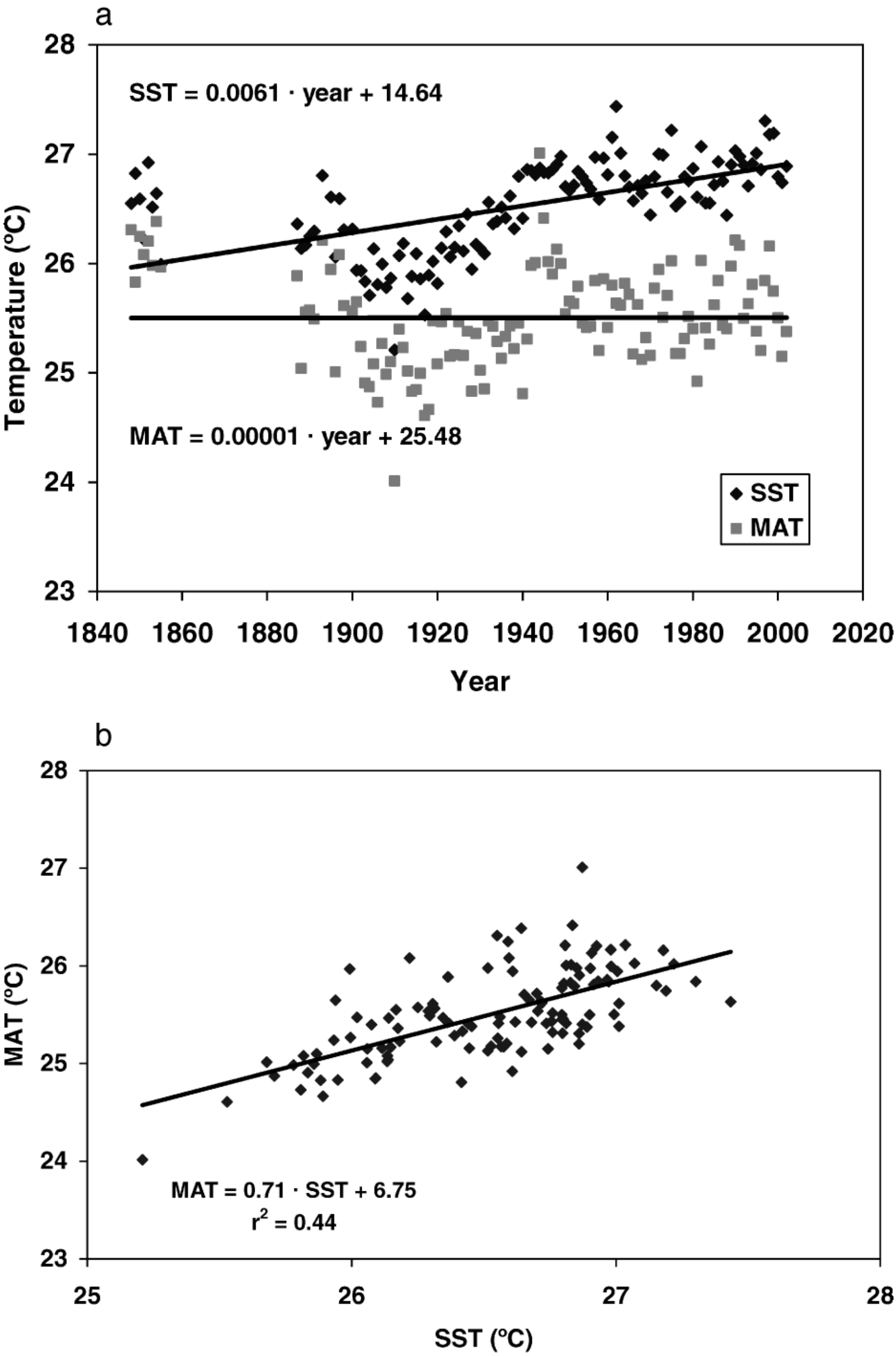
RESULTS—Table 1 summarizes the linear least-squares trends of land air temperatures (LAT) from the Historical Climatology Network (HCN), and the Combined Ocean-Atmosphere Data Set (COADS) marine air temperatures (MAT). The standard error (± SE) of each trend line is also listed. The mean and standard deviation of the HCN LAT trend column is +0.2 ± 0.5°C/century, and that of the COADS MAT column is +0.3 ± 0.4°C/century. While these two summary statistics are in good agreement, the coefficient of determination between the ten LAT and MAT trend pairs is $r^2 = 0.01$. Thus there is essentially no correlation between paired LAT trend and MAT trend around Florida's coastal zone.

Similarly, Table 2 summarizes the linear least squares trends of SST from the C&GS tide gauges and the SST from juxtaposed COADS 2° × 2° squares, with the relevant SE column to the right, respectively. The mean and standard

→

Fig. 2[a]. Annual mean sea surface temperature (SST + 5°C offset - upper) and annual mean marine air temperature (MAT - lower) for the COADS 2° × 2° latitude/longitude square in the offing of Key West, Florida (1848–2002). Trends shown by the inset equations are °C per year.

Fig. 2[b]. Annual mean sea surface temperature (SST) versus annual mean marine air temperature (MAT) for the COADS 2° × 2° latitude × longitude square in the offing of Key West, Florida (1848–2002).


a
SST = 0.0061 · year + 14.64
MAT = 0.00001 · year + 25.48
SST
MAT
Temperature (°C)
Year
28
27
26
25
24
23
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
b
MAT = 0.71 · SST + 6.75
r² = 0.44
MAT (°C)
SST (°C)
25
26
27
28

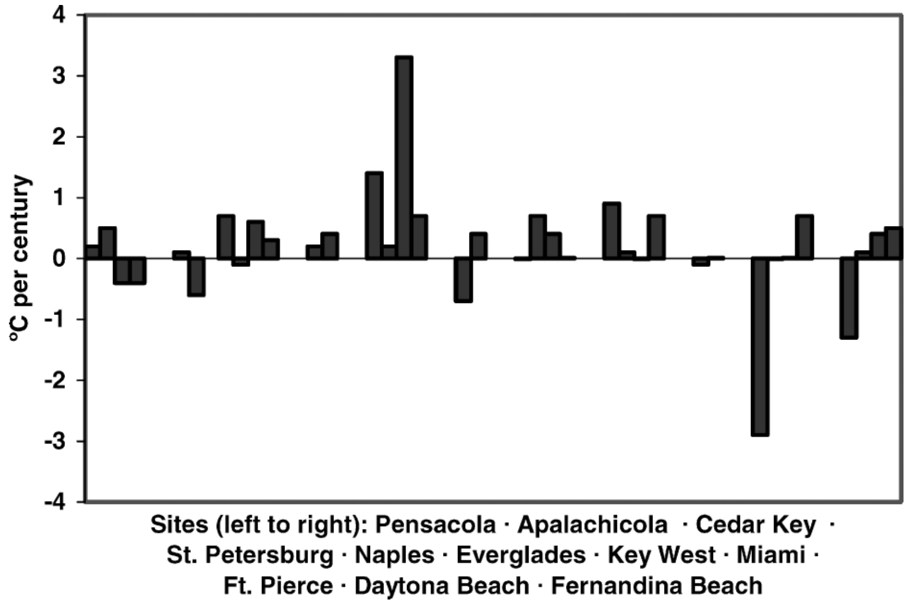


FIG. 3. Temperature trends (°C/century) from the COADS, C&GS tide gauges, and the HCN. Each site is organized as in Tables 1 and 2: left-to-right COADS SST, C&GS SST (where available), HCN LAT, and COADS MAT. Plotted west to east around the Florida peninsula, the leftmost site is Pensacola, and rightmost site is Fernandina Beach.

deviation of the C&GS SST trends is +0.1 ± 1.7°C/century and that of the COADS SST trends is +0.2 ± 0.4°C/century. The correlation of SST trend pairs from COADS pelagic data and from the littoral C&GS tide gauge data is negative and has a coefficient of determination $r^2 = 0.25$. Thus there is weak inverse correlation between SST paired trends.

Figure 3 geographically displays a subset of the trends from Tables 1 and 2. Figure 3 is organized from west to east, with Pensacola on the left, progressing along the Florida peninsula past Key West to Fernandina Beach on the right (*q.v.* Fig. 1). Each bar-graph depicts the trend of the full length of each record and excludes the subset of COADS SST equal in length to the C&GS tide gauge SST data. Little geographic organization to the trends is noticeable, but widely differing positive and negative trends at the same or nearby stations are obvious.

DISCUSSION—C&GS tide gauge SST data are from point measurements as are LAT surface air observations from the HCN on land. The COADS data are from volunteer observing ships operating within a 2° × 2° latitude × longitude area (*q.v.* Fig. 1). Certainly there is an ambiguity when comparing point-measurements with areally-averaged ones. While it is expected that the mean values in littoral water and coastal water would be different, the trends should at least have consistent signs, positive or negative, as climate change

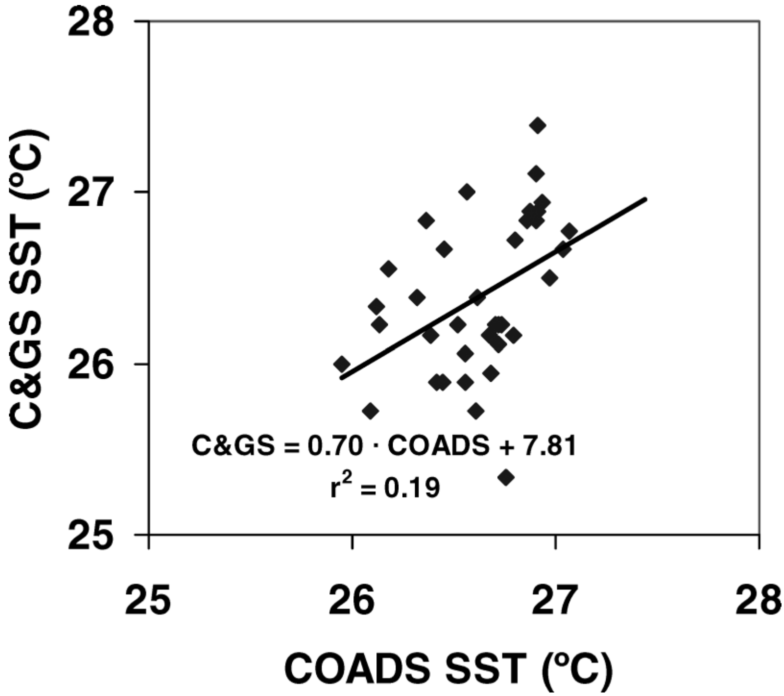


FIG. 4. Average shallow-water (littoral) C&GS tide gauge sea surface temperatures *vs.* average COADS (pelagic) sea surface temperatures in the offing of Key West, Florida (1926–1994).

occurs within a region. Consistency is clearly not the case with these data. In many instances the SE is larger than the trend, implying that the trend is not statistically different from zero (the 95% CI of the individual trend is approximately given by $\pm$ 2 SE), and the null hypothesis of no temperature change cannot be rejected.

A plot between SST from COADS and SST from the C&GS tide gauge at Key West is shown in Fig. 4 as an example. The slope (α) between Key West COADS SST and C&GS tide gauge SST (N = 36) is $\alpha = 0.70$ and $r^2 = 0.19$. Not only is the correlation low, but the 95% CI of the slope is $0.2 \leq \alpha \leq 1.2$. Again, these independent data show little organized relationships, and as with the results in Figure 2[b], COADS SST is increasing more rapidly than juxtaposed independent data.

The LAT data presented in Figure 5 (an ensemble of all HCN stations to be discussed below) has an appearance of periodicity as Enfield and others (2001) have concluded. If an equation of the form

$$T = A \cdot \sin\left(\frac{2\pi}{P} \cdot t - \phi\right) \tag{1}$$

where T is temperature, A is amplitude, P is period, t is time, and ϕ is phase,

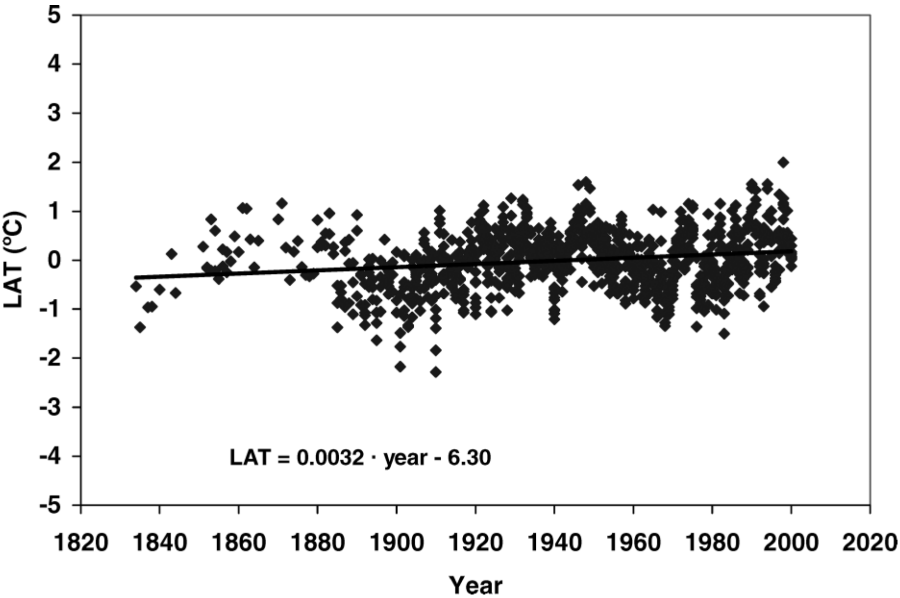


FIG. 5. Ensemble of N = 10 Florida LAT stations minus the 30-year norm of 1951–1980. The 30-year norm for each HCN station was computed, and then the ensemble was plotted and summary statistics calculated. Interannual variability is noticeable (*e.g.* Enfield et al., 2001).

describes the periodicity, then a linear least-squares fit can have a trend depending on the period, phase, and epoch of the time-series. For example, if P = 65 years, ϕ = 178.8 radians (chosen so that the sine crosses zero from minus to plus at t = 1850, and the epoch is 1834–2000, the calculated trend will be +0.28°C/century – an artifact of periodicity and epoch.

To reiterate, the average and standard deviation of the COADS SST trends (N = 9) is +0.2 ± 0.4°C/century, COADS MAT trends (N = 10) is +0.3 ± 0.4°C/century, C&GS SST trends (N = 9) is +0.1 ± 1.7°C/century, and HCN LAT trends (N = 10) is +0.2 ± 0.5°C/century. The summary statistics (N = 38) are: average trend is +0.2°C/century with a standard deviation about the average of ± 0.9°C/century and a standard error of the average of ± 0.1°C/century. These averages tend to distill a potpourri of trends down to a few parameters, but the results obtained herein (*cf.* Fig. 3) is a testament to the complexity encountered, which may be compounded by cyclic behavior.

Ensemble analyses—Using an average of the trends from Tables 1 and 2 may not be the optimal method of estimating temperature change in the coastal zone of Florida. Why should pelagic COADS SST and MAT, for example, have different trends (α = 0.71; Fig. 2[b])? Similarly, why is the C&GS tide gauge SST standard deviation so much larger than the HCN land air temperature standard deviation? Application of Student's t-test leads to the conclusion that these differences are not statistically significant at the 95% CI,

TABLE 3. Linear least-squares trends (°C/century) from blended annual ensembles of Florida sites/areas as departures from the 1951–1980 norm.

Source	Variable	Dates	Number (N)	Trend	SE
COADS	SST	1848–2002	618	+0.9	±0.1
COADS	SST	1922–1994	476	+0.7	±0.1
C&GS	SST	1922–1994	162	+0.1	±0.2
HCN	LAT	1834–2000	948	+0.3	±0.1
COADS	MAT	1848–2002	637	+0.3	±0.1

nor is the N = 38 statistic (+0.2 ± 0.9°C/century) significantly different from the null hypothesis.

An alternative method is to take all time-series from a given database (*e.g.* the HCN), subtract a 30-year norm, blend the records, and analyze the temperature anomalies. Figure 5 is an example of calculating the 1951–1980 norm (*e.g.* Jones et al., 1986) independently in each LAT record, subtracting the respective norm, concatenating the N = 10 time-series, and then calculating the common statistics. The trend and standard error of the LAT ensemble is +0.3 ± 0.1°C/century and the 95% CI of the trend is $+0.2 \leq \partial T/\partial t \leq 0.4$°C/century. Similarly, (Table 3) the trends and SE for the COADS SST, C&GS SST, and COADS MAT are calculated.

In Table 3 a slightly different pattern emerges with all ensemble datasets having positive trends. The difference between the 1922–1994 COADS SST trend (+0.7 ± 0.1°C/century) and the C&GS SST trend (+0.1 ± 0.2°C/century) is statistically significant at the 95% CI. The LAT trend (+0.3 ± 0.1°C/century) and the MAT trend (+0.3 ± 0.1°C/century) are identical. The average and standard deviation of the four independent ensemble trend anomalies is +0.4 ± 0.3°C/century, approximately the same average as that from the N = 38 trends summarized in Tables 1 and 2 but with a lower standard deviation due to using N = 4 independent datasets.

The ensemble of all Florida coastal COADS marine air temperatures (not shown) have less warming compared to the sea surface temperatures ($\alpha = 0.76$ between them; N = 616), and yet $r^2 = 0.84$ – a much larger correlation than the Key West example (Fig. 2[b]). Is $\alpha = 0.76$ in part due to larger steel ships in the late 20th century as compared to the smaller mostly wooden vessels 100 years earlier? The atmospheric dry adiabatic lapse rate is 10°C per kilometer, and if on average, the air temperature sensors are 10 meters higher on a modern ship's superstructure as compared to those a century ago, the MAT record would show a −0.1°C/century cooling, all other things being equal. Similarly, with the large enginerooms of modern ships, and perhaps indiscriminate placement of engine intake thermometers, a substantial warming in COADS SST is quite conceivable when compared to bucket temperatures of the 19th century.

For the C&GS SSTs, most of the extra-region trends are positive (Maul et al., 2001) whereas for the southern United States, they tend to be zero or

TABLE 4. Comparison of the ensemble of HCN, C&GS, COADS SST, and COADS MAT linear trends (°C/century) in the offing of Florida for different record lengths and time-frames.

Years	Number (N)	Ensemble Trend	Standard Error
1821–2002	2366	+0.4	±0.1
1850–2002	2355	+0.4	±0.1
1875–2002	2318	+0.5	±0.1
1900–2002	2224	+0.5	±0.1
1925–2002	1853	+0.2	±0.1
1950–2002	1307	+0.5	±0.1
1975–2002	678	+1.2	±0.3

slightly negative. As with the HCN data, urbanization could be affecting the C&GS temperatures, yet the ensemble LAT trend is three times larger than the tide gauge SST trend, but this is not statistically significant at the 95% CI. The growth of coastal communities should affect water temperatures and air temperatures in a similar fashion over the long-term unless operating conditions (measurement location, operator competence, localized heat sources, etc.) are causing unknown effects.

In Table 2 the C&GS SST trends are compared with COADS SST trends over the same epoch. All other trends have been calculated over the entire record-length. For the most part the HCN and COADS MAT data are more than a century in length, yet the trends are often quite different. The effect of record length and epoch is investigated for the ensemble (*cf.* Fig. 5), and is summarized in Table 4, where all four ensembles from Table 3 have been blended into a common time-series (not shown).

Trends for various epochs calculated in Table 4 illustrate several important points: First, the summary ensemble trend (N = 2355 annual values of COADS + HCN + C&GS) for 1821–2002 (+0.4°C/century) is identical to the average of the four independent trends (*cf.* Table 3). Second, as is well known (Hanson and Maul, 1993), linear trends are sensitive to the epoch and record length (Eqn. 1, et seq.). Third, the fact that the trends are quite variable (and perhaps cyclical – Enfield et al., 2001) makes it difficult to chose an epoch from which to draw more general conclusions. The Intergovernmental Panel on Climate Change (IPCC, 2002) tends to quote century-long data series, but Table 4 and Eqn. 1 make it clear that such a choice is arbitrary too.

CONCLUSIONS—Using three independent sources of temperature, linear trends in the Florida coastal zone are shown to vary widely between and within datasets. The average and standard deviation of N = 38 independent stations/areas is +0.2 ± 0.9°C/century, and for the N = 4 ensemble anomalies from the 1951–1980 norm it is +0.4 ± 0.3°C/century. In either case, these independent data, using two separate analytic approaches, show no statistically significant warming or cooling of temperatures around the Florida's coastal zone at the 95% CI (*i.e.* the null hypothesis – no change – cannot be rejected). However using a blended ensemble of all data, a statistically significant change of 0.4 ±

0.1°C/century is calculated, but one which is dominated by one of the datasets – COADS sea surface temperatures.

Given that the data quality from all three sources used herein is most likely comparable (and in fact is perhaps the best that is available), reporting any firm conclusions presents a quandary. Clearly the size and construction of volunteer observing ships has changed markedly over the time-frame that COADS covers. Certainly the micro-environment in which HCN stations are embedded has changed; Key West is a classic example of a land air temperature station that moved 14 times over its lifetime with no metadata (Hanson and Maul, 1993). At C&GS tide gauges, water temperatures are not the primary purpose of the measurements, and when tide gauges are moved or replaced, the emphasis is on vertical position control not temperature; NOS did not conduct any overlap temperatures series when replacing the C&GS tide gauges with NGWLM systems (Moulin, 2005). Comparing areally averaged and point-source values adds additional uncertainty. Finally, linear trends in cyclical data may be an artifact of the period and epoch (Eqn. 1). Given all these issues, perhaps it is not unexpected that results herein are mixed.

Probably this study has raised more questions than answers. That may be disconcerting, but the history of science is rich in observations not fitting convention, and it is a proud heritage. The fact remains, using three independent databases and two separate statistical techniques, a tidy result is not forthcoming. For the Florida coastal zone, the most plausible conclusion is that air and sea temperature change during the past century is minimal.

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