# Temperature trends at several sites in the upper San Francisco Estuary

Alan Jassby*

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## 1 Background

This report is a brief examination of water temperature trends in Suisun Bay and the Delta. Water temperature trends are of particular interest because the success of both desirable and undesirable species can be highly temperature-sensitive. For example, the nuisance cyanobacterium *Microcystis aeruginosa*, which has been spreading in the estuary since 1999, has a high optimum temperature over 25°C, depending on the strain (Nalewajko and Murphy, 2001). In contrast, the endangered native delta smelt *Hypomesus transpacificus* appears to have a lethal limit near 25°C (Swanson et al., 2000).

The analysis is based primarily on hourly time series data collected by the California Department of Water Resources (CDWR). CDWR and the California Department of Fish and Game (and before 1975, the U.S. Bureau of Reclamation) also collect water temperature from many sites at an approximately monthly interval. But temperature variability is very high at higher frequencies because of seasonal and daily cycles as well as tides and river flow, rendering trends difficult to detect or possibly spurious. High-frequency measurements must be used when available. Here, because of the brief duration of the study, we use only those high-frequency records that were immediately available to us. This study could therefore be expanded to additional sites and longer time spans.

## 2 Data analysis methods

Observations of water temperature and specific conductance (hourly average at 1 m depth) were collected at Antioch (1983–2007, except for 1994), Mallard (1984–2006), Rio Vista (Bridge, 1983–2006) and Stockton (Rough and Ready Island, 1983–2006) by CDWR and obtained from Dr. Anke Müller-Solger. Air temperature data were also collected, but were available only for Antioch at the time of this writing. High-frequency observations were also available from Prisoners Point, but only since 1999 and with many large gaps.

Most large spikes in the water temperature data that were obvious artifacts were removed by using only observations $> 5$ and $< 35$°C. All hourly time series were then filtered

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with a centered rolling median of width 3 to suppress smaller isolated spikes representing noise and to interpolate gaps of $\leq 2$ missing hours. Daily mean, minimum and maximum values were determined for days with no remaining gaps. The daily time series, in turn, were filtered with a centered rolling median of width 3 to interpolate gaps of $\leq 2$ missing days. Monthly medians of the daily time series were determined only for months with more than 15 non-missing daily values. Unless otherwise specified, all data analysis was conducted using R version 2.6.1 and associated packages (R Development Core Team, 2007).

Trends in the monthly series were assessed with the Seasonal Kendall test, including a correction for between-month serial correlation, using the DOS program Kendall.exe described by Helsel et al. (2005). A certain amount of missing data is allowed. In particular, the recommendation for the Seasonal Kendall test is that: (1) pairwise comparisons of the same month between years in the first and last fifths of the data should be possible for at least 50% of possible combinations; (2) the same should be true of pairwise comparisons within the middle three-fifths of the data; and (3) criteria (1) and (2) should be true for at least 80% (i.e., 10) of the months (Schertz et al., 1991).

The Seasonal Kendall test is most useful when monthly trends are all in the same direction. If some are up and some down, test results may indicate no overall trend. Although not incorrect, the test provides a limited view under these circumstances and should be supplemented with a suitable trend test for individual months. Here, we use the Mann-Kendall test for trend significance and the Theil or Sen slope estimate for trend magnitude (Helsel et al., 2005).

# 3 Trends during 1983–2007

The data coverage, as exemplified by the monthly water temperature time series, appears to be complete enough for long-term trend analysis (Figure 1). In particular, the data requirements for the Seasonal Kendall test are easily satisfied even when we require $> 15$ non-missing days to estimate a monthly median. Criteria (1) and (2) are then true for all 12 months (e.g., Antioch: Table 1). Note also that isolated spikes have been successfully removed by the filtering process (Figure 1).

There were no significant Seasonal Kendall trends in the mean, minimum or maximum daily water temperature during 1983–2007 (Table 2). The daily maximum at Antioch showed, if anything, a weakly significant *declining* trend. Jassby (2008) also found no significant long-term Seasonal Kendall trends in the discrete monitoring program temperature data. The discrete data do not provide for a powerful test, so the apparent lack of trend was not very convincing. The continuous data used here, though, support the same conclusion and give more credence to it.

The lack of an overall long-term trend as indicated by the Seasonal Kendall test does not preclude trends for individual months, as discussed above. There were, in fact, significant monthly trends at all four sites, almost all positive, according to the Mann-Kendall test. The Theil-Sen slopes ranged from $-0.09$ to $0.09$°C y$^{-1}$, or more than 2°C over 25 y (Figure 2). The trends at Stockton (RRI) are of most interest, as they happen in the biologically significant summer season when maximum temperatures may help determine species success. Although summer trends are positive at Mallard and Rio Vista, they are not as

Table 1: Number of days with complete hourly water temperature data at Antioch.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1983 | 0 | 0 | 0 | 0 | 7 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 1984 | 31 | 29 | 19 | 27 | 31 | 30 | 31 | 30 | 28 | 27 | 23 | 31 |
| 1985 | 25 | 28 | 31 | 28 | 29 | 30 | 24 | 31 | 30 | 31 | 30 | 31 |
| 1986 | 31 | 28 | 31 | 30 | 31 | 22 | 17 | 31 | 29 | 31 | 30 | 31 |
| 1987 | 31 | 27 | 31 | 29 | 31 | 25 | 25 | 11 | 18 | 31 | 30 | 31 |
| 1988 | 16 | 19 | 25 | 30 | 31 | 30 | 25 | 23 | 0 | 0 | 23 | 24 |
| 1989 | 31 | 15 | 29 | 28 | 0 | 8 | 31 | 31 | 30 | 29 | 30 | 31 |
| 1990 | 31 | 28 | 31 | 28 | 28 | 30 | 31 | 15 | 0 | 10 | 28 | 22 |
| 1991 | 30 | 28 | 30 | 30 | 31 | 29 | 31 | 31 | 30 | 31 | 30 | 31 |
| 1992 | 30 | 12 | 3 | 0 | 28 | 30 | 31 | 31 | 30 | 31 | 21 | 31 |
| 1993 | 31 | 25 | 14 | 19 | 31 | 30 | 15 | 0 | 0 | 0 | 0 | 0 |
| 1994 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1995 | 0 | 19 | 2 | 28 | 31 | 16 | 29 | 31 | 30 | 24 | 26 | 31 |
| 1996 | 31 | 25 | 31 | 30 | 25 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 1997 | 31 | 26 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 25 | 31 |
| 1998 | 31 | 28 | 31 | 30 | 31 | 4 | 23 | 31 | 30 | 31 | 30 | 31 |
| 1999 | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2000 | 31 | 29 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2001 | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2002 | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 30 |
| 2003 | 31 | 28 | 31 | 30 | 5 | 13 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2004 | 31 | 29 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2005 | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2006 | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |
| 2007 | 23 | 24 | 31 | 30 | 31 | 30 | 28 | 31 | 30 | 31 | 30 | 31 |

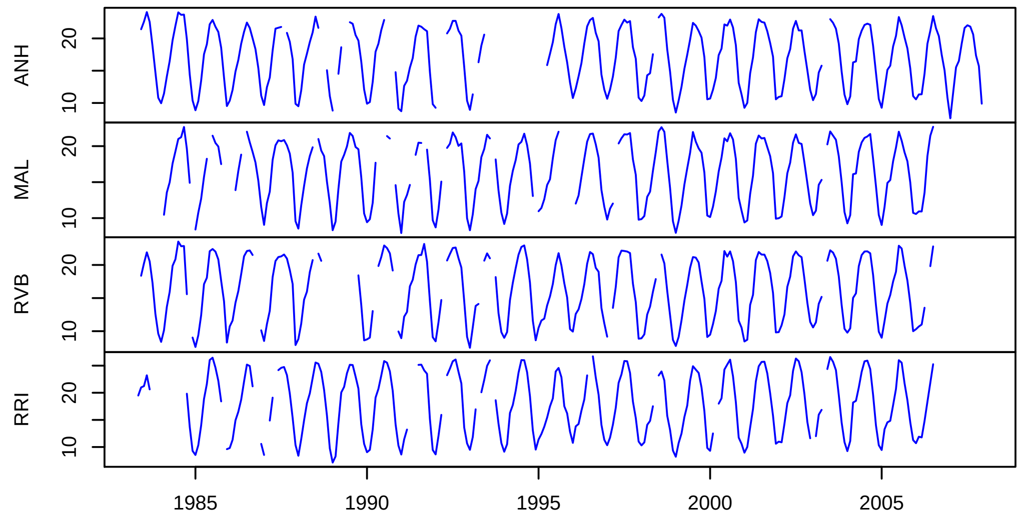


Figure 1: Monthly medians of daily mean water temperature (WT, °C) at Antioch (ANT), Mallard (MAL), Rio Vista (RVB) and Stockton (RRI).

Table 2: Seasonal Kendall trend tests on water temperature data, 1983–2007.

| | | trend, °C $y^{-1}$ | tau | $p$-value | adjusted $p$ |
|---|---|---|---|---|---|
| Antioch: | mean | -0.015 | -0.095 | 0.089 | 0.190 |
| | minimum | -0.009 | -0.060 | 0.287 | 0.399 |
| | maximum | -0.025 | -0.135 | 0.016 | 0.068 |
| Mallard: | mean | 0.004 | 0.019 | 0.759 | 0.763 |
| | minimum | 0.006 | 0.027 | 0.654 | 0.670 |
| | maximum | 0.000 | 0.007 | 0.915 | 0.911 |
| Rio Vista: | mean | 0.014 | 0.066 | 0.247 | 0.440 |
| | minimum | 0.020 | 0.076 | 0.185 | 0.395 |
| | maximum | 0.006 | 0.038 | 0.500 | 0.648 |
| Stockton: | mean | 0.011 | 0.042 | 0.470 | 0.604 |
| | minimum | 0.012 | 0.034 | 0.561 | 0.676 |
| | maximum | 0.011 | 0.034 | 0.561 | 0.669 |

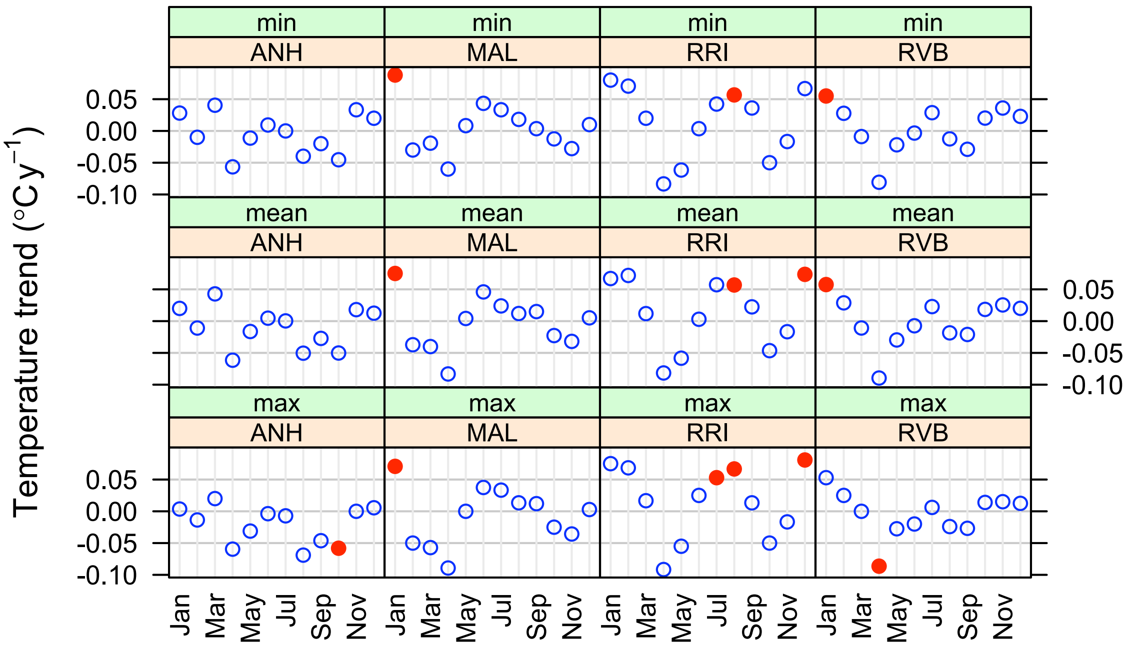


Figure 2: Trends in daily water temperature at four sites in the upper San Francisco Estuary from 1983 (1984 for MAL) through 2006 (2007 for ANH). Trends represent the Theil-Sen slope and their significance is assessed with the Mann-Kendall test. *Filled circles, $p < 0.05$.*

convincing in terms of statistical significance.

The significant water temperature trends, as one would expect, appear to be driven primarily by corresponding trends in air temperature (Figure 3). The relationship is indeed strong for all months except January (Figure 4). Maximum daily Antioch air temperature accounted for almost half the variability in maximum daily water temperature during the hot summer months. Some of the unexplained variability may simply be a consequence of using monthly summary statistics rather than higher-frequency data. The number of years is too small to investigate more complex models with these monthly summary statistics. Any further investigation should be based on the daily summaries or hourly averages.

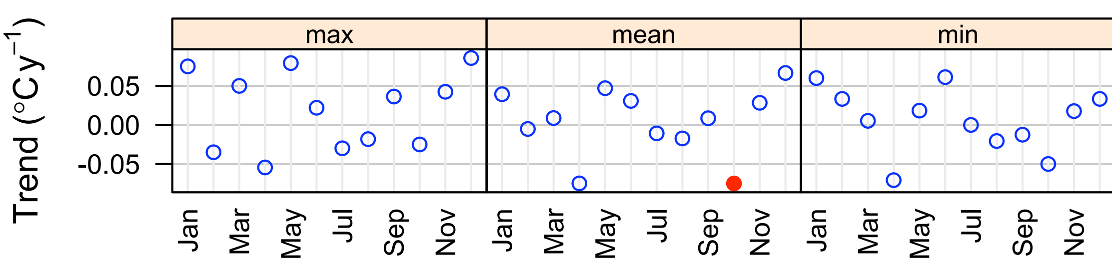


Figure 3: Trends in daily air temperature at Antioch. Trends represent the Theil-Sen slope and their significance is assessed with the Mann-Kendall test. *Filled circles, $p < 0.05$.*

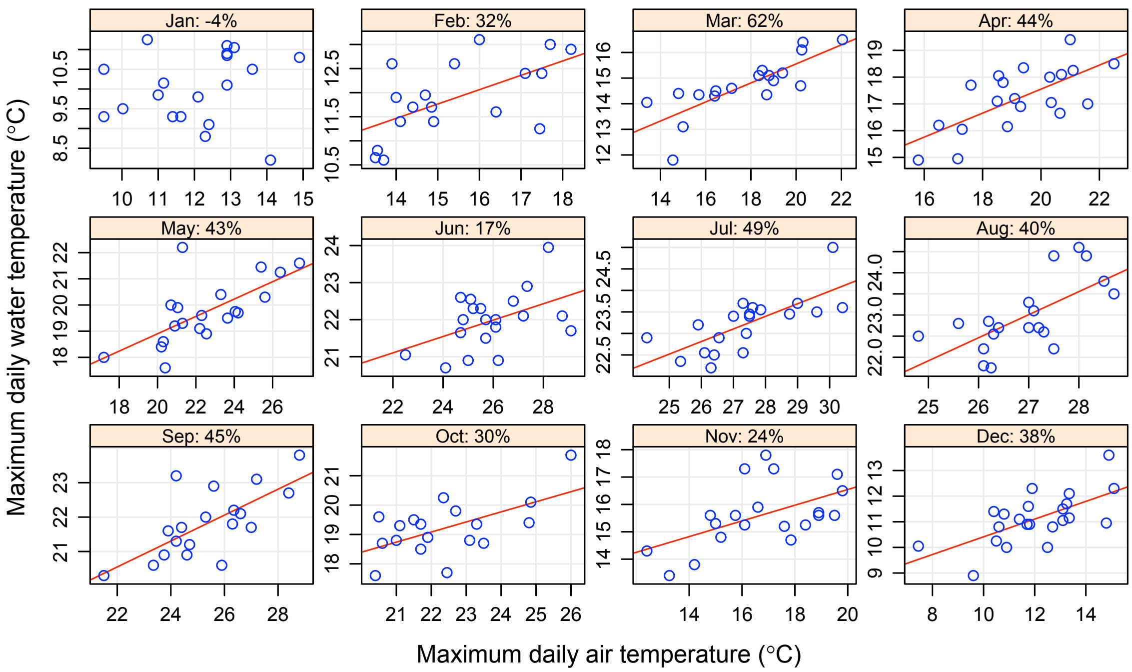


Figure 4: Relationship between maximum daily air and water temperatures at Antioch. *Lines,* linear regression lines for months when $p < 0.05$; *values following month names,* adjusted $R^2$ for linear regression.

# 4 Trends during 1996–2005

Jassby (2008) found a positive trend for Delta but not for Suisun temperatures during March–June 1996–2005, using the discrete monthly EMP monitoring data. The Regional Kendall test was used, which increases power by combining multiple stations. There are not enough continuous stations to make this a worthwhile approach for the present analysis. For the sake of comparison, we used the continuous data to estimate the monthly Mann-Kendall trends and the overall Seasonal Kendall trends for 1996–2005. The $p$-values for the latter test were not adjusted because the time period is only 10 years, in keeping with recommended procedures (Helsel et al., 2005). Although no individual monthly trends are significant—a decade-long series offers low power—the ones for Rio Vista and Stockton tend to the positive, whereas those for Suisun Bay tend to the negative (with the notable exception of Mallard in spring) (Figure 5). This tendency is substantiated by the Seasonal Kendall results, which show at least weakly significant trends for Rio Vista and Stockton but not for Antioch and Mallard (Table 3). The qualitative findings for both long-term and decadal trends in the present study are therefore consistent with those from the monthly sampling program.

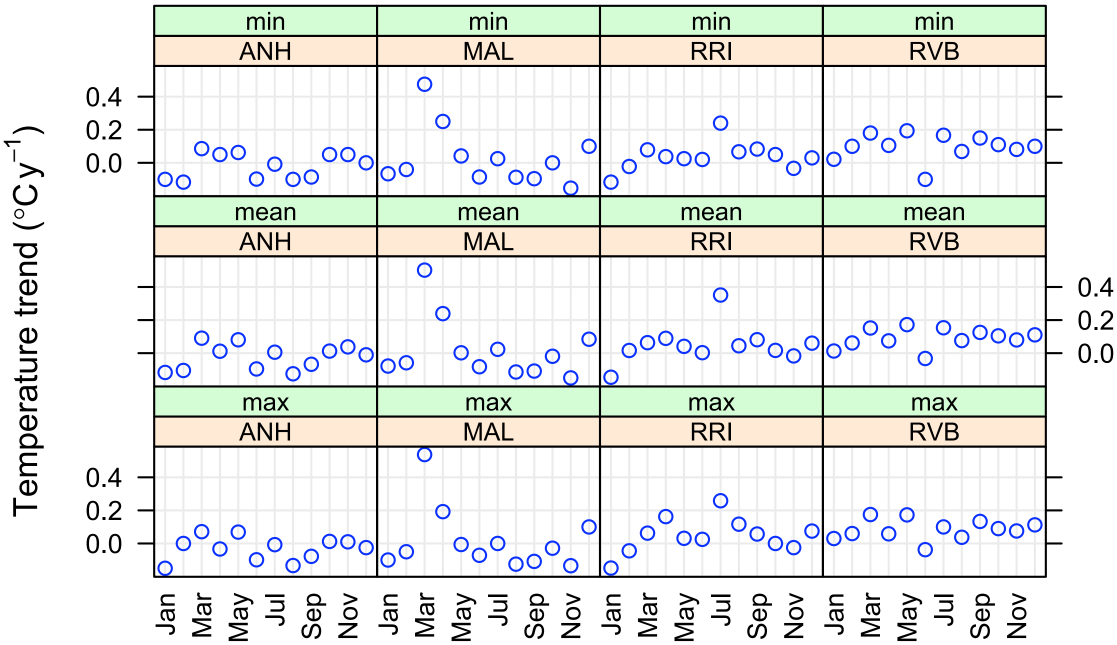


Figure 5: Trends in daily water temperature at four sites in the upper San Francisco Estuary from 1996 through 2005. Trends represent the Theil-Sen slope.

Table 3: Seasonal Kendall trend tests on water temperature data, 1996–2005.

| | | trend, °C y$^{-1}$ | tau | *p*-value |
|---|---|---|---|---|
| Antioch: | mean | −0.002 | −0.027 | 0.709 |
| | minimum | −0.004 | −0.029 | 0.688 |
| | maximum | −0.016 | −0.075 | 0.309 |
| Mallard: | mean | −0.039 | −0.037 | 0.636 |
| | minimum | −0.020 | −0.021 | 0.788 |
| | maximum | −0.039 | −0.062 | 0.422 |
| Rio Vista: | mean | 0.092 | 0.202 | 0.006 |
| | minimum | 0.103 | 0.205 | 0.006 |
| | maximum | 0.083 | 0.181 | 0.015 |
| Stockton: | mean | 0.043 | 0.130 | 0.083 |
| | minimum | 0.034 | 0.104 | 0.171 |
| | maximum | 0.044 | 0.131 | 0.082 |

# 5 Summary

1. Hourly time series data were used to assess water temperature trends at two stations in Suisun Bay and two in the Delta.

2. No overall (Seasonal Kendall) trends were detected for the period 1983–2007, consistent with previous findings from the monthly sampling program.

3. But (Mann-Kendall) trends were detected for a few individual months, the most biologically significant being elevated temperatures near Stockton in summer.

4. Air temperature accounts for about half the variability in water temperature on the basis of monthly summary statistics at Antioch.

5. Over the decade 1996-2005, positive trends in water temperature were found for Delta stations but not for Suisun Bay stations. These findings were also consistent with the earlier study using data from the monthly monitoring program.

# References


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