ANALYSIS OF A WARMING TREND IN WATER TEMPERATURE IN THE HUDSON RIVER ESTUARY

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Abstract. Water temperature exerts important constraints on the biological, chemical, and physical properties of aquatic ecosystems. Estuaries are subject to warming due to global climate change but few studies to date have considered trends or rates of temperature increase (or decrease) because of limited data. We analyzed temperature trends and rates of temperature change over time for the Hudson River estuary using long term data, mainly from daily measures taken at the Poughkeepsie Water Treatment Facility. Mean annual temperature in the Hudson River has warmed over 1 °C since 1946. The rate of warming is accelerating as demonstrated by increased slopes in temperature-time relationships for more recent periods. Additionally many of the warmest years in the record occurred in the last 14 years. A seasonal analysis of trends indicated significant warming for the months of April through August. The warming of the Hudson is primarily related to increasing air temperature with variation in freshwater discharge having a significant but relatively minor influence on mean annual temperatures.

INTRODUCTION

Estuaries are ecologically and economically important systems providing crucial ecosystem services (Costanza et al. 1997; Knowles and Cayan 2002). Climate change and sea level rise due to global warming are likely to profoundly alter estuaries and affect their capability of maintaining current services (Scavia et al. 2002). Climate change will influence many aspects of estuaries including physical properties such as altered volume and timing of freshwater inflows with the consequence of potentially changing water residence time and salinity (Knowles and Cayan 2002; Scavia et al. 2002). Warming may also increase nitrogen fluxes resulting in eutrophication (Howarth et al. 2006). In addition, warming will alter physical conditions, biological communities and ecological interactions within estuaries leading to likely changes in resource species (e.g. Oviatt 2004; Meynecke et al. 2006; Mackenzie et al. 2007).

Despite the significance of estuaries and threats of climate change, there are still relatively few studies on contemporary temperature change and on air-water temperature relationships. In contrast, there have been a number of analyses of freshwater systems where long-term records of stream and river temperatures (Webb 1996; Pilgrim et al. 1998; Webb et al. 2007) as well ice cover duration (Magnuson et al. 2000) indicate warming in many locales. For estuaries, discerning temperature changes may be more difficult because of limited long-term data, hydrodynamic complexity, and the influence of the large reservoir of the coastal ocean which will respond more slowly to warming. Nevertheless, there is limited evidence of warming in estuaries including an early study of the Chesapeake Bay that identified a warming trend of 0.265 °C per decade that correlated with air temperature changes (Brady 1976). A more recent study of the Chesapeake Bay used multiple temperature series derived from different stations throughout the system to examine warming trends (Preston 2004). Trends were spatially heterogeneous. Positive trends were seasonal and associated with warming during winter months. Ashizawa and Cole (1994) analyzed temperature data from the Hudson River estuary in New York. They were able to derive a temperature time series from the Poughkeepsie Water Treatment Facility largely from stored written records that extended from 1908 to 1990. They identified a significant long term warming trend of 0.12 °C per decade between 1920 and 1990. Both significant and insignificant shorter term temperature trends were described within the series. They noted that warming was more evident later then earlier in the series. They also speculated that water temperature is dependent on both air temperature and freshwater flow (discharge) to the estuary (Ashizawa and Cole 1994).

In this paper we update the temperature series used by Ashizawa and Cole (1994) and apply non-parametric time series methods to re-analyze long term temperature trends in the Hudson River focusing on the period from 1946 through 2006. This time span was selected because continuous data were available as well as additional data on air temperature and discharge to test for relationships with water temperature. We identified a significant long term warming of over 1 °C during a 61 year period. We provide analyses that indicate that the rate of warming is increasing and is driven primarily by increasing air temperature.

METHODS

Time Series Data

The main water temperature series used in this study was collected by the Poughkeepsie Water Treatment Facility (PWTF), in Poughkeepsie, New York (lat 41°43'25.81"N, long 73°56'10.66"W). We used the data assembled by Ashizawa and Cole for the period 1908 to 1990 and updated the series with temperature values collected from 1991-2006. Poughkeepsie is an ideal site for long-term water temperature data collection as it is approximately in the center of the estuary (Ashizawa and Cole 1994) where mixing is vigorous resulting in uniform temperature depth profiles (Cole et al. 1992). This location reduces the seasonal influence of upstream freshwater inputs from the Mohawk River Valley and the Adirondack Mountains as well as the tidal influence of seawater mixing into the estuary from the Atlantic Ocean on the time series (Ashizawa and Cole 1994). All water samples were collected from intake pipes located 4 meters below the low tide mark and measurements were made immediately upon sample withdrawal (Ashizawa and Cole 1994). Water collection methods varied somewhat over the 98 year period, but all temperature measurements at PWTF were made with calibrated thermometers soon after water withdrawal. There are no obvious steps in the data that indicate difference in readings related to various forms of measurement (Ashizawa and Cole 1994).

The United States Geologic Survey (USGS) stations south of Poughkeepsie (lat 41°39'03"N, long 73°56'42"W), South Dock at West Point (lat 41°23'10"N, long 73°57'20"W), and south of Hastings-on-Hudson (lat 40°59'16"N, long 73°53'15"W) provided additional water temperature data. These time series are considerably shorter then the PWTF series and are based on surface water measurements. At the two most downriver stations (West Point and Hastings-on-Hudson), occasional higher temperatures are likely due to salinity intrusions and the partial mixing that occurs (Geyer and Chant 2006) which would allow greater warming of surface waters especially during summer. These series were, therefore, only used in a regional analysis test (see below).

Historical air temperature data for Poughkeepsie, New York, were provided by the United States Historical Climatology Network (USHCN). These data were selected over other possible air temperature series because of the quality control procedures used to adjust for changes in measurement techniques, time of observation bias, variation due to station relocation, and urban warming (Easterling et al. 1996). The Poughkeepsie air temperature time series covers the past 130 years through 2005(Table 1). For the year 2006 we used the mean annual air temperature for Poughkeepsie provided in the Climatological Data Annual Summary for New York (NOAA 2006).

Discharge data were obtained from the USGS Green Island station (lat 42°45'08"N, long 73°41'22"W). This station is located at Federal Dam at Troy, New York which is the head of the estuary. Approximately 80% of the freshwater enters the estuary at this station reflecting the combined inputs of the upper Hudson and Mohawk rivers (Limburg et al. 1986). The discharge series spans from 1947 to 2006.

There were missing data in the PWTF record. Ashizawa and Cole (1994) excluded the years 1920, 1924-1929, 1938, 1940, 1943, and 1945 from their analysis of annual means due to missing values. In the more recent record (1991-2006) data were missing for the years 1993-1995 and observations were sparse in 2005 and 2006. To fill these recent gaps we used data from the nearby USGS station just south of Poughkeepsie. There were strong correlations between the monthly and annual temperature means derived from data collected at the two stations over similar time periods ($r > 0.99$). Temperatures recorded by the USGS were on average slightly lower then those recorded by PWTF. The values substituted into the series are, therefore, conservative estimates of the missing values. The PWTF data set with missing gaps filled using the USGS data provided continuous data for the years 1946-2006.

The other USGS stations also had some missing temperature data particularly for 2003 from South Dock at West Point, data from 1996 to 1999 at Hastings-on-Hudson, and a few additional months in the various series. These time periods were excluded from the analyses below.

Analysis of Trends and Relationships

Deviation from average and LOWESS (LOcally WEighted Scatterplot Smooth; Cleveland 1979) plots were made using annual mean temperature to allow qualitative visual analysis of Hudson water temperature series. A Mann-Kendall test was run on mean annual water temperature for the entire Poughkeepsie record (1908-2006) and for the time period 1946-2006 to identify significant trends. A Sen slope estimator (Sen 1968) was then used to quantify the magnitudes of identified trends. The Mann-Kendall tests and Sen Slope estimations were calculated on software made available by the Finnish Meteorological Institute and Claudia Libiseller at the University of Linköping, Sweden (Salmi et al. 2002; Libiseller 2002).

The Seasonal Kendall trend test, first presented by Hirsch et al. (1982), was used for time series analysis of monthly mean temperatures (Helsel and Hirsch 2002; Helsel and Frans 2006). Probability values were adjusted for serial correlation. The seasonal Kendall slope estimator, which is based on the Sen slope estimator was used to examine the direction and magnitude of trends. USGS software was used for the Seasonal Kendall tests and Kendall Slope Estimators (Helsel et al. 2005).

The Seasonal Kendall test was expanded upon by running Mann-Kendall tests for trend and Sen slope estimators for mean temperature by month. This analysis allowed identification of trends with monthly data through the Seasonal Kendall test and identification of seasonal trends with the Mann-Kendall test. Discharge and air temperature data were also analyzed with a seasonal Kendall test with Kendall slope estimator and Mann-Kendall test with Sen slope estimator to identify annual and monthly trends.

The nonparametric trend tests, specifically the Mann-Kendall test with Sen Slope estimator and Seasonal Kendall test with Kendall Slope estimator, are superior in this application to ordinary least squares regression for several reasons (Hirsch et al. 1982; Helsel and Hirsch 2002; Helsel et al. 2005). These methods are robust to non-normality in the data reducing type 1 error. The tests also provide more accurate estimates of magnitude of any trend by reducing the influence of outliers. Finally these methods also minimize the influence of missing data, seasonal changes, and extreme events (Hirsch et al. 1982).

A Regional Kendall test, a variant of the seasonal Kendall test put forth by Slack and Frans (2006) was run on annual data over the time span 1992-2006 where temperature data were available for four stations. The test computes a trend for the temperature series at each observation station then combines the test statistics into an overall trend for a region (Helsel and Frans 2006). This analysis provided a temperature trend for the most recent time period in the estuary for the area between South of Hastings-on-Hudson and Poughkeepsie. The Regional Kendall test was computed on software made available by the USGS (Helsel et al. 2005). An additional USGS Hudson temperature series from Albany, NY (lat 42°38'46"N, long 73°44'53"W; station number 02020006) was not included in the analysis due to low number of observations.

Various methods of modeling air temperature and water temperature relationships have been used ranging from purely empirical to more mechanistic, physically-based models. Statistical models have the advantage of simplicity and typically require few inputs. Linear regression analysis is an effective method of modeling the relations between different physical parameters and water temperature (Webb and Walling 1992; Webb and Nobilis 1997; Langan et al. 2001; Webb et al. 2003). However, water-air temperature relationships are usually only linear between approximately 0°C and 20°C (Mohseni and Stefan 1999). Non-linear logistic curves have been used across broader temperature ranges to examine relationships. (Mohseni et al. 1998). In some cases lag times have been incorporated into analyses where data over fine time scales (e.g. sub-daily to daily measurements) are available (Pilgrim et al. 1998; Webb et al. 2003). We used multiple regression to test for the influence of air temperature and discharge as drivers of water temperature. The test employed the annual means for the 1947-2006 period. Residuals were examined and tested for autocorrelation using the Durbin Watson *d* test (Gujarti 1978).

The seasonal relationship between air temperature and water temperature was examined using single and multi-segmented Kendall-Theil Robust Line (K-TRL) models. These models do not rely on the assumption of normal distribution of residuals – a typical problem with seasonal data. Software to fit the lines was provided by the USGS (Granato 2006). Two models were created, splitting the calendar year to account for the effects of hysteresis in the data. Various models were constructed and compared by root mean square error (RMSE) and nonparametric prediction error sum of squares (NPRESS) for best fit. Median absolute deviation (MAD) was also calculated for each model. The significance of the models was evaluated by calculating Kendall's tau following the methods detailed by Helsel and Hirsch (2002). Spearman's rank correlation coefficients (denoted as r) were calculated to explore the relationship between discharge, water temperature, and air temperature for the different seasonal periods identified in the K-TRL models.

RESULTS

Temperature Trends

The long term mean annual temperature of the Hudson River was 12.36 and 12.48 °C for the 1908-2006 and 1946-2006 periods, respectively. The vast majority of the deviations from the annual means fall within the range of ±1 °C. The coolest year of the record was 1922 where the mean temperature was 10.6 °C, and the warmest year was 1998 with a mean temperature of 13.8 °C. Since 1979 almost all of the years have had above average temperature (only 2 years with negative deviations), and the magnitude of temperature deviations from the mean appears to have increased especially in the last two decades (Figure 1). A LOWESS fit to the annual mean temperature data supports this interpretation indicating that annual temperature is increasing as is the rate of warming (Figure 2). The initial period of the record was warm (1908-1921) but since the early 1920s the Hudson has been warming and the LOWESS fits indicate an increase in the warming rate since the beginning of the 1980s (Figure 2).

A Mann-Kendall test confirms that there has been a significant ($p < 0.001$) long term warming trend for the entire series and for the more recent continuous period with Sen Slopes of 0.009 and 0.017 °C per year, respectively (Figure 3). Seasonal Kendal tests identified three significant trends of varying magnitudes and time spans (Fig. 4) over the 1946-2006 period. For the earliest part of the record, 1946-1992, the Sen Slope was 0.010, and this slope increased for more recent time periods (up to 0.022 for 1977-2006).

Significant long term trends were identified for the months of April through August, with nearly significant trends occurring in March and September (Figure 5). Interestingly, long term cooling trends were identified for the months of October and November, although neither was significant. These possible cooling trends are however, logically consistent with trends of increasing water flow into the estuary from the headwaters that were identified for these months. The increasing discharge in October and November were the only significant long term trend in discharge identified for the USGS Green Island time series.

The Regional Kendall test provides a means to examine if the warming relationship for the longer time series of the Hudson is evident for a number of stations. This test indicated an overall warming trend of 0.055 °C per year ($P = 0.066$) since 1992. Given the short series of data available for this test, we regard this 'regional' trend as significant in support of the trend based on the data from Poughkeepsie.

Drivers of Temperature Change

In order to evaluate the drivers of temperature change in the Hudson, we examined seasonal and annual data for air temperature and discharge in relation to the water temperature. Air temperature is increasing long-term at Poughkeepsie. The trend for mean annual temperature is significant ($p < 0.001$) with a Sen slope of 0.021. As noted above there was no trend for discharge.

On a seasonal basis two multi-segmented Kendall-Theil Robust Lines were identified as most efficient for describing the air-water temperature relationships at Poughkeepsie (both $P < 0.001$, see Table 2). The first model, representing monthly mean temperatures from January to June, illustrates the limited effect of winter air temperatures on river temperature and then the spring warming period where temperature rises rapidly during April through June (Figure 6a). The second model fits temperatures well for the July to December time period (Figure 6b). The river cools slowly as air temperatures decline from approximately 25 to 15 °C and then a more rapid autumn cooling occurs (Figure 6b). Freshwater inputs had a significant relationship with water temperature that varied seasonally (see Table 3). Freshwater input had a positive effect on the seasonal variability of winter water temperatures and a negative affect at other times of the year. The correlation of discharge and water temperature was strongest during spring warming ($r = -0.74$, $p < 0.01$) when higher discharges tended to cool the estuary.

The variation in annual mean water temperature (WT) was strongly related to annual means of air temperature (AT) and discharge (D) by the following equation:

$$[1] \qquad WT = 7.86 + 0.59\ AT - 0.002\ D$$

where $P < 0.0001$ and $r^2 = 0.59$ for the multiple regression model. Both air temperature and discharge were highly significant in the relationship with t-values of 9.17 ($P < 0.0001$) and -4.13 ($P = 0.0001$), respectively. Residuals of the relationship, however, were autocorrelated (Durbin Watson test $P < 0.05$) which leads to underestimates of variance and standard errors and compromises tests of significance. To account for this problem, we transformed the data applying the Durbin-Watson estimate of autocorrelation denoted as a to produce the transformed variables WT*, AT*, and D* (Gujarti 1978). The data were differenced by subtracting the autocorrelation estimate ($a = 0.245$) time the value of the variable in the previous year from the current year (e.g. $WT_t - aWT_{t-1}$). The transformed data were fit using least squares to produce the following equation:

$$[2]\ Wt^* = 5.29 + 0.64\ AT^* - 0.00136\ D^*$$

where $P < 0.0001$ and $r^2 = 0.58$ for the multiple regression model. Air temperature was highly significant in the relationship, $t = 8.86$ ($P < 0.0001$), while discharge was weakly significant ($t = -2.14$, $P = 0.04$). Residuals of the transformed data were not autocorrelated.

DISCUSSION

The Hudson River Estuary is warming. The deviation plot and LOWESS fit of annual means, the Mann-Kendall test of annual means, the Seasonal Kendall test of monthly means, and the Regional Kendall test of multiple stations all provide support for this conclusion. The Mann-Kendall test identified a significant long term warming trend with a magnitude of 0.017 °C per year which equates to a just over 1 °C warming of annual mean temperature over the course of the 61 year series from 1946-2006. Seasonal-Kendall tests of monthly mean estuary temperature at Poughkeepsie identified three significant trends of various time spans, with different magnitudes. As the trends become shorter and more recent the magnitude increases, such that the shortest, most recent trend has a magnitude twice that of the longest and earliest trend. This suggests that while there is not enough data to identify two significant non-overlapping trends of different magnitudes, the rate of warming in the estuary is increasing.

The significant long term warming trends identified in the spring and summer months drives the annual warming trend identified in this study. The timing of changes in temperature is of interest for several reasons. First, this pattern contrasts with a study of the Chesapeake Bay that identified warming trends occurring during winter and early spring months (Preston 2004) rather than the late spring and summer as for the Hudson. A plausible explanation is that the Chesapeake Bay estuary does not become as cold as the Hudson during winter which tends to reach a low but relatively constant temperature throughout winter. Hence, the Hudson would require a greater warming to move away from its baseline winter temperature. The Chesapeake may also approach a near maximum temperature in the summer where the vapor pressure deficit over the estuary increases with air temperature, resulting stronger evaporative cooling and lower increase in water temperature relative to increase in air temperature (see Mohseni and Stefan 1999). This affect would restrict further warming to other seasons. Second, increased temperature places potential habitat constraints on some species and provides new habitat opportunities for other species. For example, species most likely will not have cold temperature constraints of their thermal habitat during winter as temperatures are relatively unchanged over this period. However with warming coming in what are already the warmest months of the year, species could see constraints on their thermal habitat during spring when many species spawn and during summer when temperatures are warmest (Mohseni et al. 2003). Lastly, increased temperature in the late spring and summer months likely affects the development of some fish species (Tetzlaff et al. 2005) and the ecological interactions of populations as they undergo ontogenetic shifts in diet and predator susceptibility (Mehner et al. 1996). However, such changes may be difficult to resolve in ecological time series. For example, abundances of early life stages of two species of *Morone* (striped bass and white perch) in the Hudson were unrelated to variation in temperature for the period 1974-1990 (Pace et al. 1993) when there was considerable variation in annual mean temperature (Figure 2b).

Changes in air temperature appear to be driving the increase in Hudson River temperatures. The multi-segmented Kendall-Theil Robust Line method identified two significant models (see Table 2). In the first model, representing monthly mean temperature from January to June, the first segment is made up of data primarily from the first three months of the year, with the second segment derived from late spring and early summer months. In the second model the first segment is derived from autumn and early winter temperatures, while the second segment is derived from summer months. The models indicate the overall strong relationship between air temperature and water temperature while the variability in slopes for different times of the year indicate that warming air temperature will have an unequal impact on warming of the river. For instance, due to hysteresis, the major seasonal warming and cooling periods are of different slopes. The low slope of model 2 segment 2, which is derived from summer months, suggests that the estuary is approaching its maximum temperature during these months. Variability in Spearman’s rank correlation coefficients suggests a dynamic relationship between freshwater input and temperature in the estuary. A positive relationship for model 1 segment 1 is indicative of warmer winter temperatures that result in melting of snow and ice leading to greater freshwater input. Negative correlations with other models are relatively weak with the exception of model 2 segment 2 where there was a strong negative relationship.

At the annual scale air temperature is the main driver of changes in river temperature with variation in freshwater discharge playing a secondary role. Higher freshwater flows tend to cool the estuary. Discharge, however, had no trend over the record while air temperature in Poughkeepsie and in the region is increasing (Burns et al. 2007). Hence the warming trend in the Hudson is result of a warming regional climate.

One of the interesting features of the Poughkeepsie temperature record is the relatively warm temperature in the earliest part of the record. Ashizawa and Cole (1994) previously speculated that the initial warm temperatures followed by the cooling observed in the 1920s might have been driven by reforestation and restoration of cooler stream temperatures in the Adirondacks following the extensive logging of the late 19th century. This speculation is difficult to test but the early cooling is not related to the patterns of air temperature at Poughkeepsie.

Our analyses have some limitations. The initial cooling of the Hudson as noted above is unexplained. There are also missing data in the record. We substituted observations from the USGS Poughkeepsie site to fill the largest gaps in the recent PWTF data series and prior to 1946 there are discontinuous records in some cases with no reasonable options for estimating the missing data. Hence, we focused our quantitative tests on the more recent data from 1946-2006. The Seasonal Kendall and Mann-Kendall tests used for time series analyses are relatively robust to the effects of gaps in data and many of the assumptions needed to apply parametric tests (Hirsch et al. 1982). In addition, the sheer length of the time series should render the effects of missing data negligible. Hence, the basic trend described by Ashizawa and Cole (1994) of a warming Hudson is supported by our analyses. A further limitation on this study comes from the inherent uncertainties of applying statistical models rather physically-based mechanistic models particularly in relating air temperature to water temperature. Nevertheless, the statistical relationships between air and water temperature are compelling as is the relationship between water temperature and discharge. A next step would be to apply an air temperature time series to a hydrological model of the Hudson to determine if the water temperature trends and air-water relationships we present can be simulated.

In conclusion, the Hudson River Estuary is warming in response to increases in air temperature with a significant trend suggesting 1 °C annual warming over the past 61 years. The warming is occurring in the late spring and summer months, and the annual rate of warming in the estuary is increasing. The overall warming is consistent with other studies of observed temperature change (Ashizawa and Cole 1994; Preston 2004; Burns et al. 2007) and with paleoclimatic evidence of temperature change (Cronin et al. 2003). Changing temperature can alter the abundance and community structure of fish in estuarine systems (Austin 2002; Hare and Able 2007). Many ecosystem processes including major biogeochemical fluxes as well as important physical variables such as salinity and water residence time are also likely to change with warming as documented already by Howarth et al. (2006) for nitrogen loading. Long term temperature change looms as an important force for environmental change in estuarine systems, the impacts of which will become ever more evident if anthropogenic greenhouse gas emissions continue at current or greater rates. It is important that temperature monitoring programs commence or continue and that further impacts of temperature change on estuarine ecosystem structure and function be explored.

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Source of unpublished data

PWTF data were provided by Matthew Geho, Laboratory Director at the Poughkeepsie Water Treatment Facility, 3431 North Road, Poughkeepsie, NY 12601.

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APPENDIX

TABLE 1. Type, location, time span, and collecting agency of time series analyzed

Series Type	Location (Station Number)	Time Span Analyzed (full years)	Agency
Water Temperature	Poughkeepsie (NA)	1946-2006	Poughkeepsie Water Treatment Facility
Water Temperature	Below Poughkeepsie (01372058)	1993-2006	United States Geologic Survey
Water Temperature	South Dock at West Point (01374019)	1992-2006	United States Geologic Survey
Water Temperature	South of Hastings-on-the-Hudson (01376304)	1993-2006	United States Geologic Survey
Air Temperature	Poughkeepsie (306820)	1889-2005	United States Historical Climatology Network
Water Flow	Green Island (01358000)	1947-2006	United States Geologic Survey

TABLE 2. Water-Air Temperature Relationship Models at Poughkeepsie (where $\overline{Ta}$ is monthly mean air temperature and $\overline{Tw}$ is monthly mean water temperature). For Model 1 P < 0.001, residual mean square error (RSME) = 0.984, NPRESS = 333, and MAD = 0.083. For Model 2 P < 0.001, RMSE = 1.47, NPRESS = 754, and MAD = 0.311.

Model	Segment	Equation	Beginning Month	Ending Month	Constraints
1	1	$\overline{Tw} = 1.66 + 0.20 * \overline{Ta}$	January	June	$\overline{Ta} \leq 3.13$
1	2	$\overline{Tw} = -1.13 + 1.09 * \overline{Ta}$	January	June	$\overline{Ta} > 3.13$ and ≤ 21.13
2	1	$\overline{Tw} = 5.00 + 1.06 * \overline{Ta}$	July	December	$\overline{Ta} \leq 15.77$
2	2	$\overline{Tw} = 15.00 + 0.43 * \overline{Ta}$	July	December	$\overline{Ta} > 15.77$ and ≤ 24.41

TABLE 3. Spearman's rank correlation coefficients of relationship between freshwater input and water temperature at Poughkeepsie where $\overline{Ta}$ is mean monthly air temperature, $\overline{Tw}$ is mean monthly water temperature, and $\overline{Wi}$ is mean monthly freshwater input (* p < 0.05, ** p < 0.01).

Model	Segment		$\overline{Ta}$	$\overline{Wi}$	Constraints
1	1	$\overline{Tw}$	0.632**	0.42**	$\overline{Ta} \leq 3.13$
1	1	$\overline{Ta}$	--	0.625**	$\overline{Ta} \leq 3.13$
1	2	$\overline{Tw}$	0.962**	-0.742**	$\overline{Ta} > 3.13$ and ≤ 21.13
1	2	$\overline{Ta}$	--	-0.701**	$\overline{Ta} > 3.13$ and ≤ 21.13
2	1	$\overline{Tw}$	0.953**	-0.575**	$\overline{Ta} \leq 15.77$
2	1	$\overline{Ta}$	--	-0.463*	$\overline{Ta} \leq 15.77$
2	2	$\overline{Tw}$	0.632**	-0.205*	$\overline{Ta} > 15.77$ and ≤ 24.41
2	2	$\overline{Ta}$	--	0.001	$\overline{Ta} > 15.77$ and ≤ 24.41

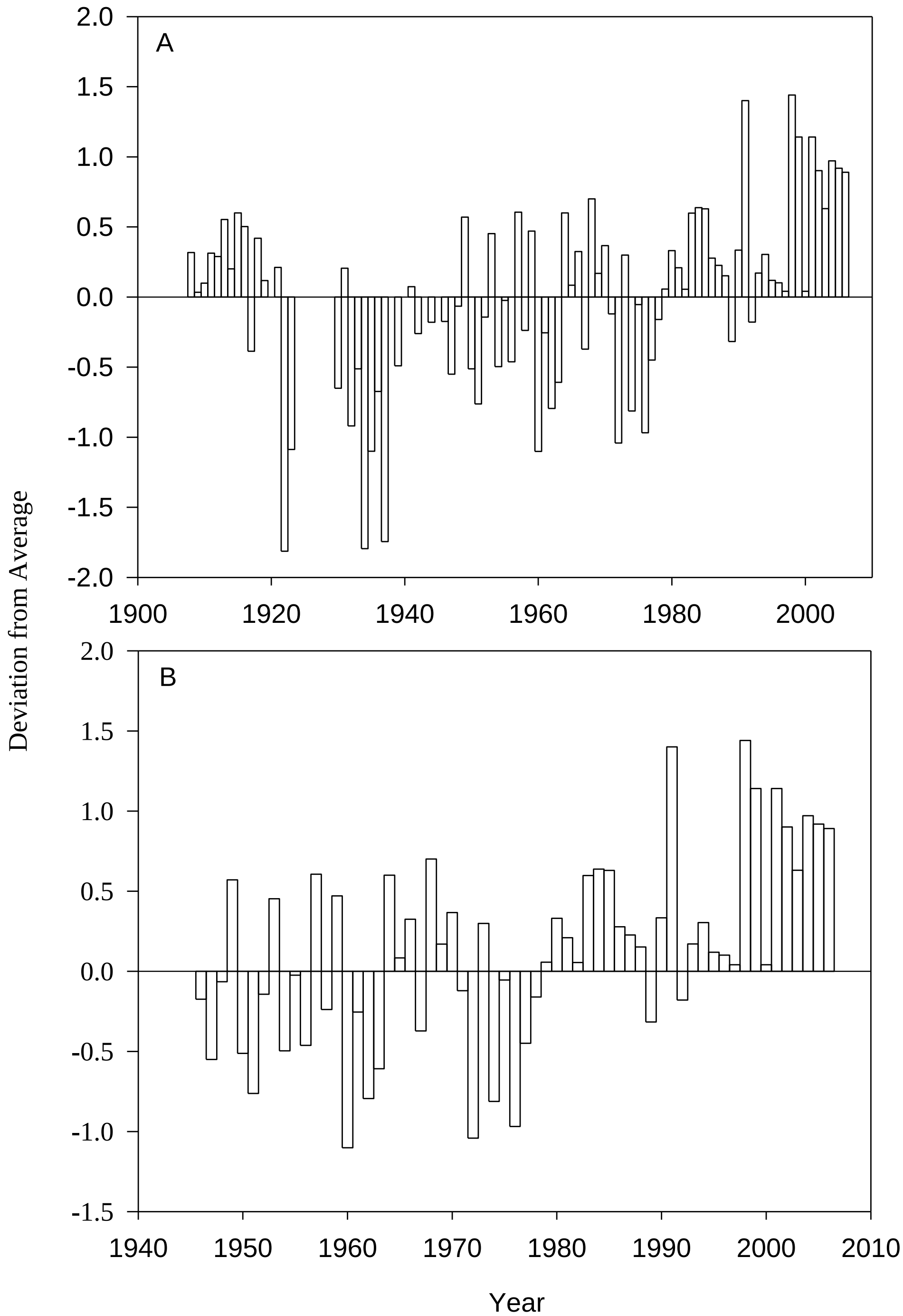


FIGURE 1. Deviation plot of annual mean water temperature in the Hudson River estuary at Poughkeepsie for: a) the entire record from 1908 to 2006 and b) for the period from 1946 to 2006 where annual data are continuous. Note the increase in the frequency of above average years in the later portions of the series.

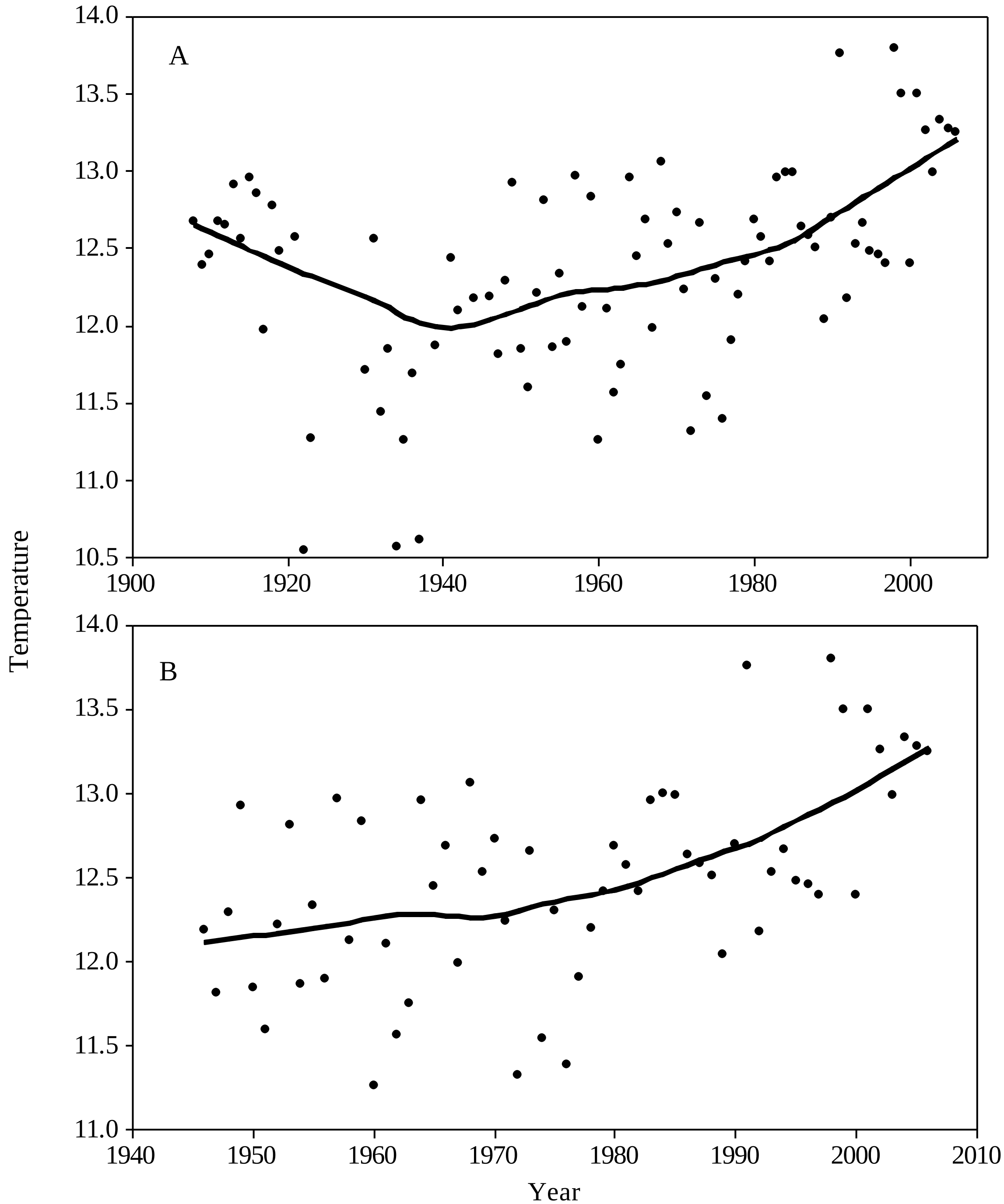


FIGURE 2. Locally Weighted Scatter Plot Smooth (LOWESS) of annual mean water temperature in the Hudson River Estuary at Poughkeepsie over the period a) 1908 to 2006 and b) 1946 to 2006 using a smoothing coefficient of .5.

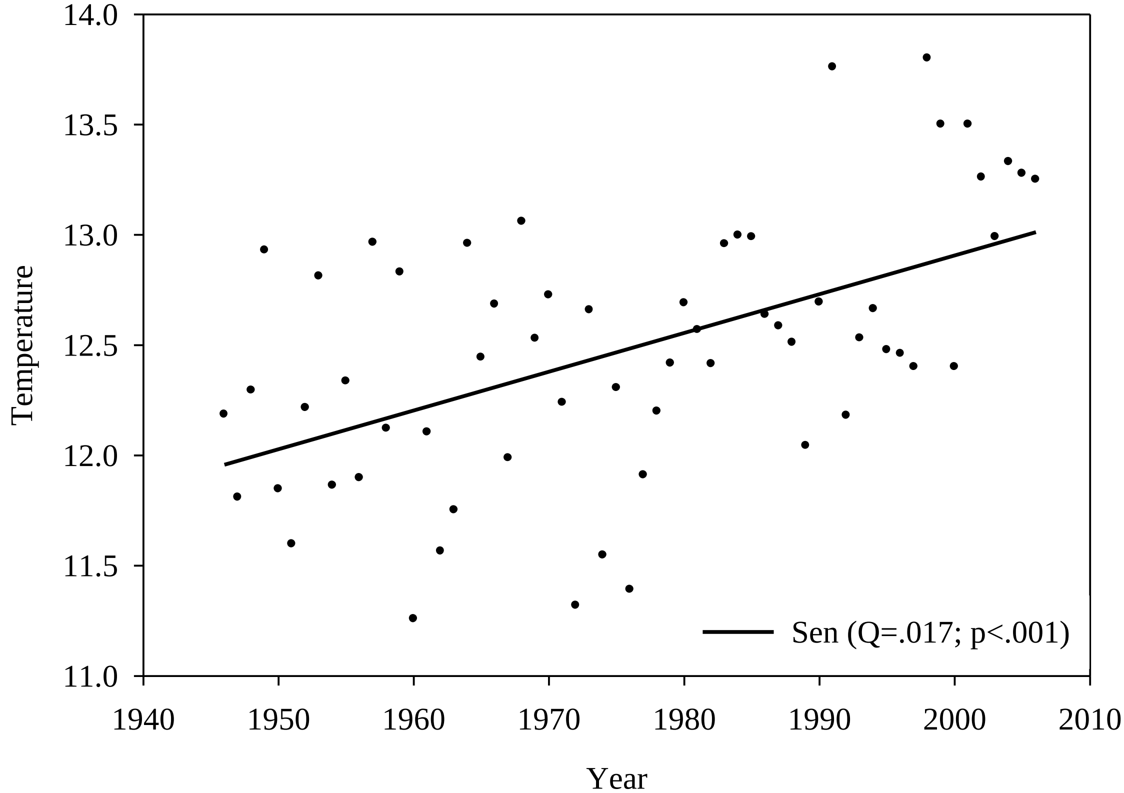


FIGURE 3. Warming trend in annual mean water temperature in the Hudson River estuary at Poughkeepsie over the period from 1946 to 2006. The trend is significant ($P < 0.001$) with a magnitude of 0.017 °C per year.

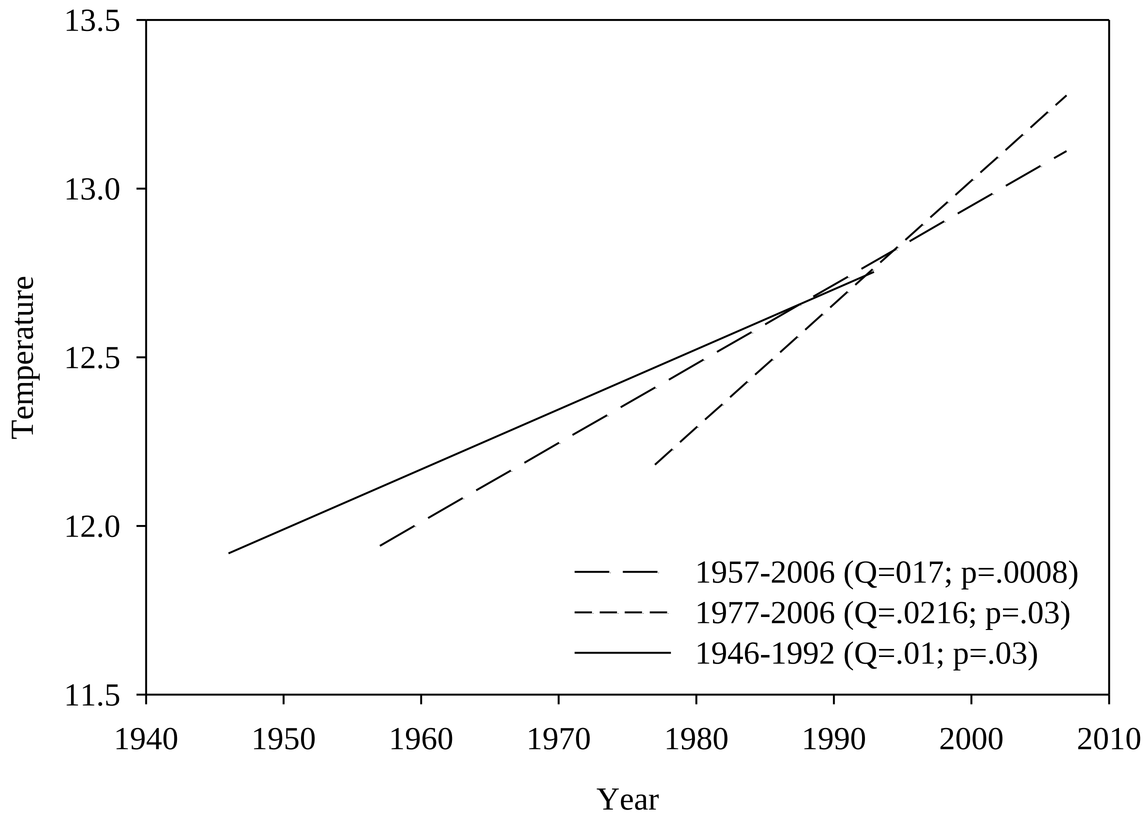


FIGURE 4. Magnitudes of several significant warming trends identified in the Hudson River Estuary at Poughkeepsie using Seasonal Kendall tests and Kendall Slope Estimators. The magnitude of the trends increases as the trend becomes shorter and more recent, suggesting that the rate of warming in the Estuary is increasing.

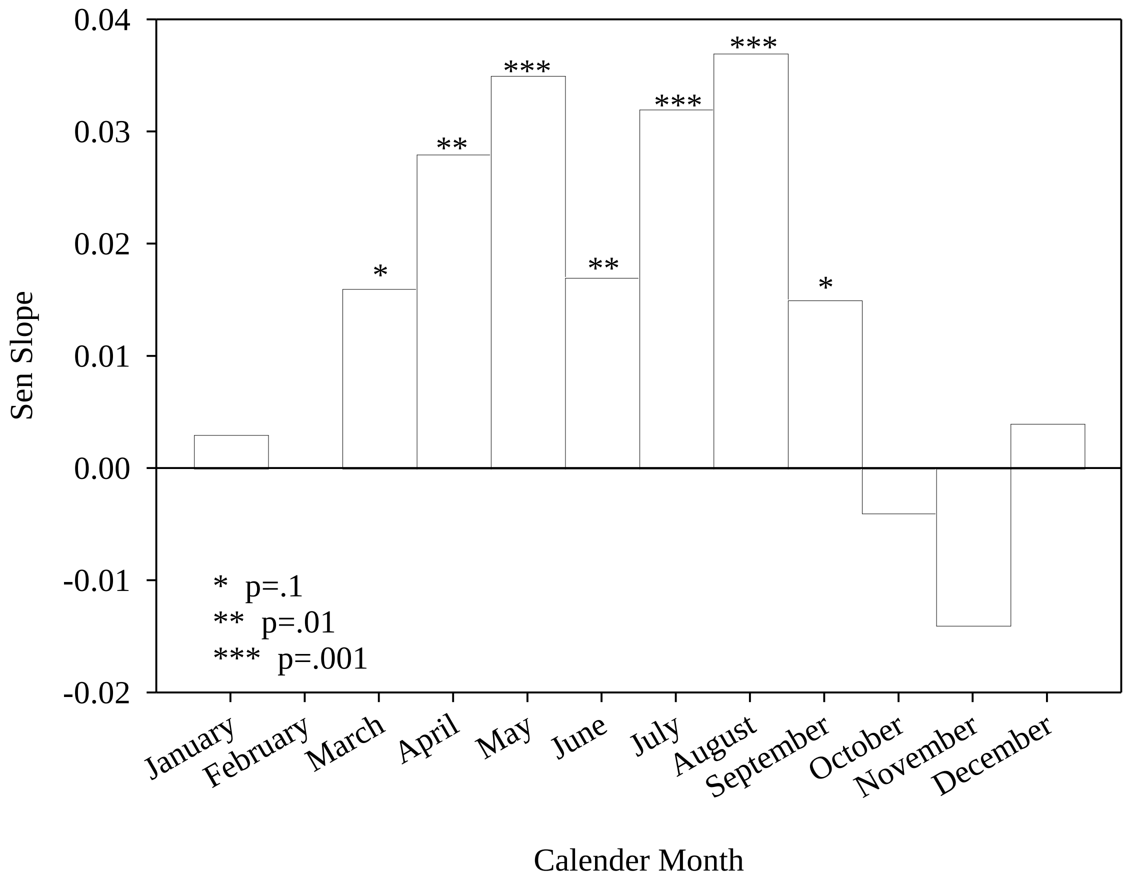
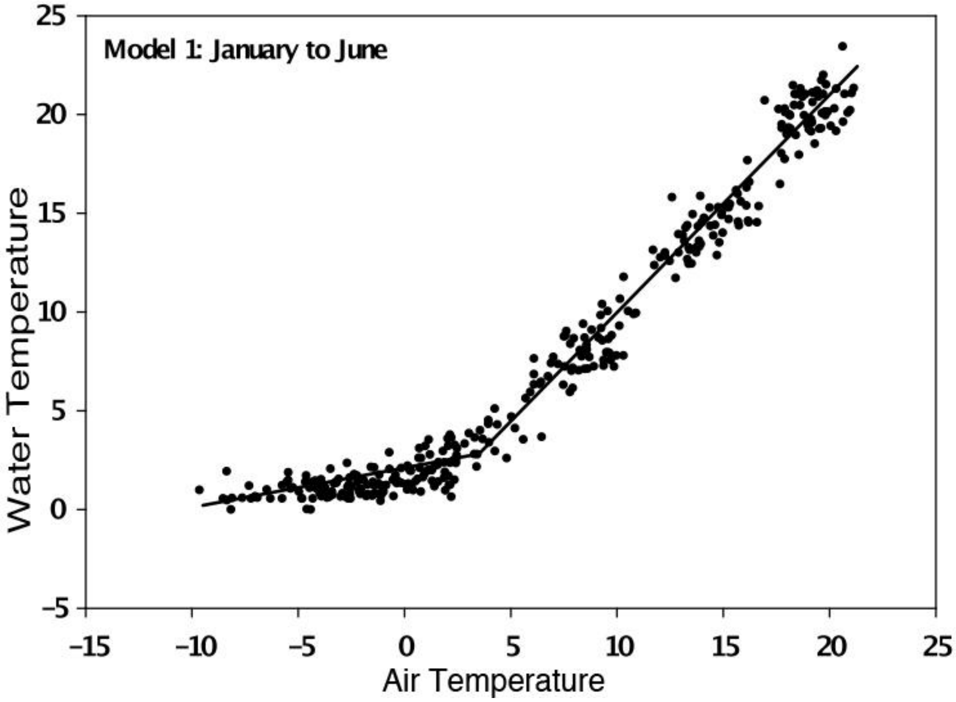


FIGURE 5. Sen Slopes of long term temperature trends (1946-2006) by month in the Hudson River estuary at Poughkeepsie. Significant trends noted by * were identified in April, May, June, July, and August.



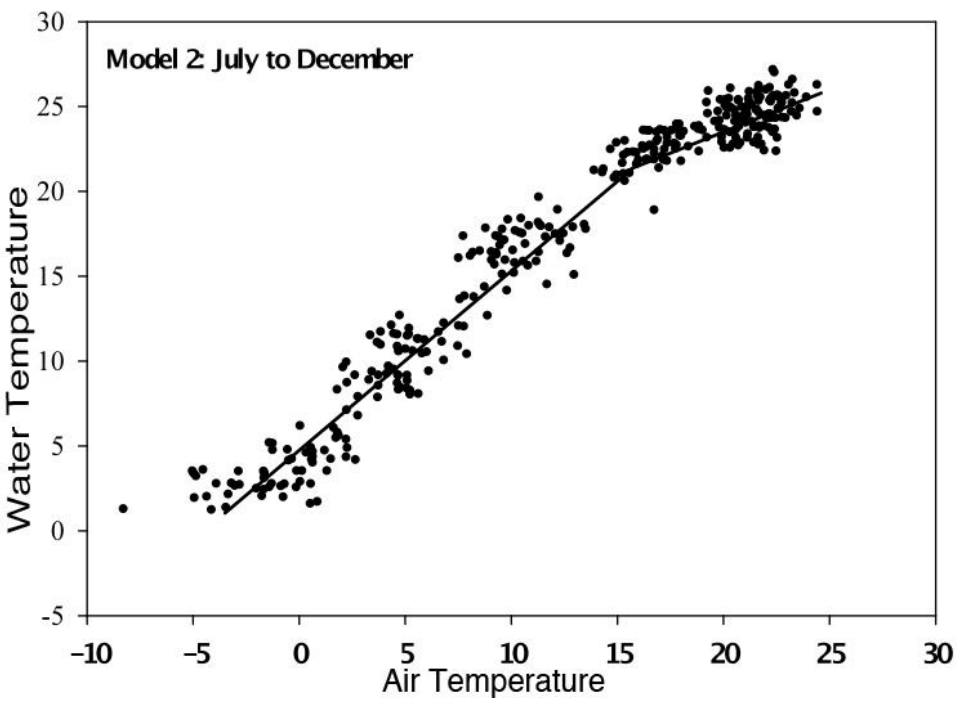


FIGURE 6. Air-water temperature relationships at Poughkeepsie. Model 1 represents temperatures between January and June. Model 2 represents temperatures between July and December.