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PAPER

Climate change drives warming in the Hudson River Estuary, New York (USA)†

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Estuaries may be subject to warming due to global climate change but few studies have considered the drivers or seasonality of warming empirically. 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. This temperature record is among the longest in the world for a river or estuary. The Hudson River has warmed 0.945 °C since 1946. Many of the warmest years in the record occurred in the last 16 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. Increasing freshwater discharge into the estuary has not mitigated the warming trend.

1 Introduction

Climate change due to global warming is likely to profoundly alter estuaries.[1–3] Critical physical factors such as the timing and volume of freshwater inflows will change and lead to shifts in water residence time, salinity, stratification, and mixing that determine or influence many of the properties of estuaries.[1,4,5] Warming may also increase nitrogen fluxes resulting in eutrophication.[6] In addition, warming will alter biological communities and ecological interactions within estuaries, likely leading to changes in resource species.[7–9]

Despite the threats of climate change to these ecosystems, there are still relatively few studies of temperature trends in estuarine and to a lesser extent coastal waters based on long-term records. Little is known about the interactions of seasonality and drivers that determine estuarine warming or cooling. Thus, there is a poor basis for understanding how recent changes in climate are affecting estuaries. Nixon *et al.* summarized many of the available studies of coastal temperature series for the United States noting that a number of long-term records had been discontinued.[10] They also presented a continuous 117 year record from Woods Hole, Massachusetts and documented a significant warming of 0.04 °C a^{-1} for the 1970 to 2002 period. Other analyses of temperature time series of approximately 50 years or greater also indicate recent increases in water temperature including for the North Sea at Helgoland,[11] the Chesapeake Bay,[2,3,12–14] and the Hudson River.[14–16] Most studies, to date, have not examined air–water temperature relationships nor complicating factors like freshwater discharge which can influence temperature variation in rivers, estuaries, and nearshore coastal waters.

In this paper we apply trend statistics to test if changes in water temperature are being driven by changes in air temperature and/or freshwater water discharge. For this analysis we updated the long-term temperature series of Ashizawa and Cole for the Hudson River estuary.[15] These authors derived a temperature time series from stored written records that extended from 1908 to 1990 for the Poughkeepsie Water Treatment Facility. They identified a significant long-term warming trend of 0.12 °C per

Environmental impact

Long-term records demonstrate warming in river, estuarine, and coastal zone waters across North America and Europe. However, few studies attempt to describe the drivers or seasonality of warming. This study applies trend statistics to identify a rapid long-term warming trend in the Hudson River estuary (New York, USA). Warming has primarily occurred in the summer months and is primarily driven by rising air temperatures in the region that are consistent with global warming. Freshwater discharge is also increasing in the Hudson and would be expected to cool the system. However, this increased discharge is unable to mitigate warming in the Hudson.

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decade between 1920 and 1990. We used the Ashizawa and Cole time series plus an additional 18 years of data that accumulated since their study. Kaushal *et al.*[14] examined annual means from this extended time series, finding a warming trend of 0.01 °C a^{-1}. However Kaushal *et al.* did not explore potential drivers or seasonality of warming. We focus most of our analysis on the period from 1946 through 2008 because continuous data were available as well as additional data on air temperature and freshwater discharge to test for relationships of these variables to water temperature.

2 Methods

A Time series data

Much of the Hudson River estuary is tidal freshwater where salinity seldom or never reaches concentrations > 0.1 ppt.[17] Over this expanse the river mixes vigorously mainly due to tidal and wind forces. Water temperatures are uniform with depth.[18] The main water temperature series used in this study was collected by the Poughkeepsie Water Treatment Facility (PWTF) at Poughkeepsie, New York (latitude 41°43′25.81″N, longitude 73°56′10.66″W). This site is located approximately at the midpoint of the 234 kilometer-long estuary within the tidal freshwater section. A map of the sampling location is available in Ashizawa and Cole.[15] We used the data assembled by Ashizawa and Cole for the period 1908 to 1990 and updated the series with temperature values collected from 1991–2008. All water samples were collected from intake pipes located 4 meters below the low tide mark.[15] Water collection methods varied somewhat over the 101 year period, but all temperature measurements at PWTF were made with calibrated thermometers immediately after water withdrawal. There are no obvious steps in the data that indicate difference in readings related to measurement.[15]

The United States Geologic Survey (USGS) station also at Poughkeepsie (latitude 41°39′03″N, longitude 73°56′42″W) provided additional water temperature data. This time series is considerably shorter (1993–2008) than the PWTF series and is based on surface water measurements.

Historical air temperature data for Poughkeepsie, New York, were retrieved from the United States Historical Climatology Network.[19] 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.[19] The Poughkeepsie air temperature time series covers the past 114 years through 2008.

Discharge rates were obtained from the USGS Green Island station (latitude 42°45′08″N, longitude 73°41′22″W). This station is located at Federal Dam at Troy, New York which is the head of the estuary. A major portion of the freshwater enters the estuary at this station reflecting the combined inputs of the upper Hudson and Mohawk rivers.[16,20] The discharge series spans from 1946 to 2008.

There were missing data in the PWTF record. Ashizawa and Cole excluded the years 1920, 1924–1929, 1938, 1940, 1943, and 1945 from their analysis of annual means due to missing values.[15] In the more recent record (1991–2008) data were missing for the years 1993–1995 and 2007–2008, and observations were sparse in 2005 and 2006. To fill these recent gaps we used data from the nearby USGS Poughkeepsie station. 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 than recorded by the PWTF. We used a linear function (eqn (1)) to adjust for the slight bias in the USGS data (T_{USGS}) substituted into the PWTF series (T_{PWTF})

$$T_{\mathrm{PWTF}} = 1.109 + 0.947 \times T_{\mathrm{USGS}} \qquad (1)$$

Daily values were averaged to get monthly mean values. The PWTF temperature series with missing values filled using the USGS data provided continuous data for the years 1946–2008. We conducted our analysis on this more recent period when data were available for air temperature, water temperature, and discharge. We do, however, present plots of annual mean temperature for both the entire series as well as the more recent continuous data with locally weighted regression for visually examination and discussion.

B Statistical analysis

The non-parametric, rank based, seasonal Kendall trend test was applied to time series of monthly mean air temperatures, monthly mean water temperatures, and monthly mean freshwater discharge rates. The seasonal Kendall test calculates the significance of a monotonic trend for each month of the year then combines the results to test for an overall trend.[21] Probability values were adjusted for serial correlation.[22] Because positive and negative monthly trends can cancel each other out when combined to test for an overall trend, we tested the monthly temperature trends for homogeny according to van Belle and Hughes.[23] We used the conditional seasonal Kendall test to test for significant annual water temperature trends when trends in air temperature and discharge are taken into account as covariates.[24] If there is still a significant warming trend in water temperature after a warming trend in air temperature is accounted for, the rising water temperature could be due to, for instance, land use change effects such as urban heat island effects or discharge of heated effluent discharge from urban areas.[14] If there is no significant warming trend after accounting for a warming trend in air temperature then warming water is consistent with the rising air temperature. Further, if there is a significant warming trend when an increasing discharge trend is taken into account, increasing discharge does not mitigate warming.

Various methods of modeling air temperature and water temperature relationships have been used ranging from purely empirical statistical models 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.[25–29] 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.[28,30] However, water–air temperature relationships are usually only linear between approximately 0 °C and 20 °C.[31] Non-linear logistic curves have been used across broader temperature ranges to examine relationships.[32] The seasonal relationship between air temperature and water temperature was examined with the nonlinear function (eqn (2)) used by Mohseni *et al.* for modeling weekly stream temperatures.[32]

$$T_w = \mu + {}^{(\alpha - \mu)}\Big/_{1 + e^{\gamma(\beta - Ta)}} \qquad (2)$$

where T_w = water temperature, μ = minimum temperature, α = maximum temperature, T_a = air temperature, γ = steepest slope of the function, β = function inflection point. Two models were created, splitting the calendar year to account for differences between the spring warming and fall cooling periods of the year.

3 Results

The long-term annual mean temperature of the Hudson River was 12.37 and 12.49 °C for the 1908–2007 and 1946–2007 periods, respectively. An annual mean was not calculated for 2008 because data were not available for all months. The vast majority of the anomalies 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). A locally weighted regression fit to the annual mean water temperature data supports this interpretation indicating that annual temperature is increasing as is the rate of warming (Fig. 1). The initial period of the record was warm (1908–1921), but since the early 1930s the Hudson has been warming, and the locally weighted regression fits indicate an increase in the warming rate since the beginning of the 1980s (Fig. 1).

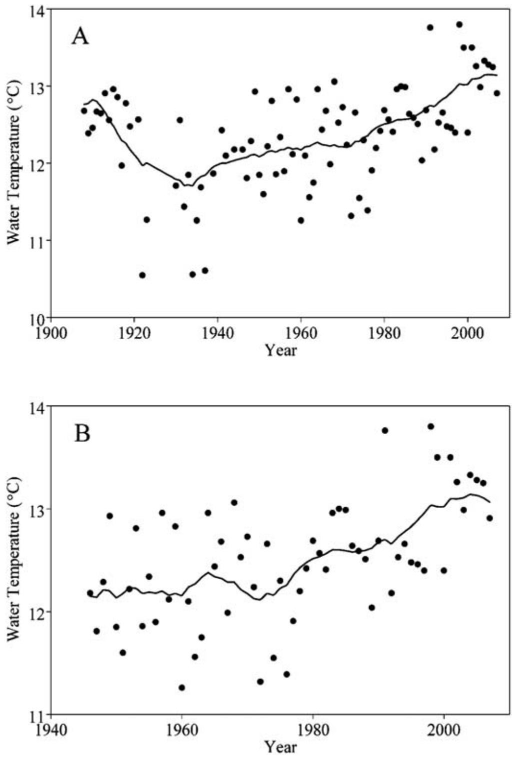

Fig. 1 Locally weighted regression of annual mean water temperature by time in the Hudson River estuary at Poughkeepsie over the period A) 1908 to 2007 (mean water temperature 12.37 °C) and B) 1946 to 2007 (mean water temperature 12.49 °C). 2008 was not included in the plots because data for the entire year were not available.

A Trend analysis

There was a significant ($p < 0.001$) overall positive trend in water temperature from 1946 to 2008 of 0.015 °C a^{-1}, 50% greater than the trend identified by Kaushal *et al.* for 1908–2007 at the same location.[14] This equates to an increase of 0.945 °C during the 63 year span. Seasonally, the water temperature trend had significant heterogeneity (p = 0.002) with the most consistent upward trends between April and August (Fig. 2A).†

There was a significant (p < 0.001) positive (0.013 °C a^{-1}) warming trend of air temperature from 1895 to 2008, a 1.5 °C increase in average air temperature over the period. The air temperature trend was homogenous (p = 0.06) (Fig. 2B). The

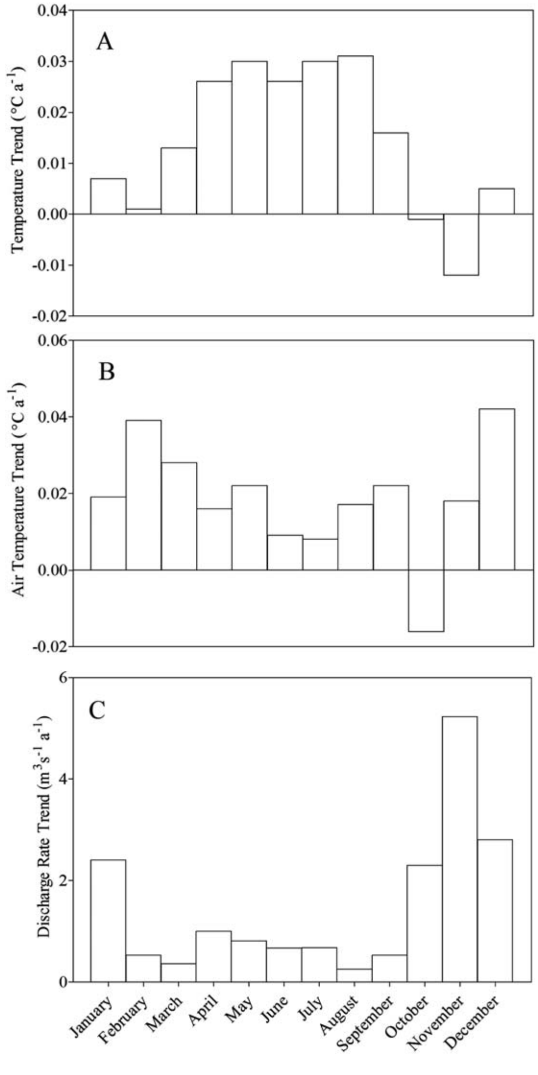

Fig. 2 A: Seasonal trends in water temperature. B: Seasonal trends in air temperature. C: Seasonal trends in freshwater discharge into the estuary.

results were identical for the period from 1908 to 2008, when water temperature was recorded. For 1946 to 2008 when discharge data was available, the homogenous (p = 0.391) air temperature trend (p < 0.001) is of greater magnitude (0.017 °C a^{-1}) than the longer time series (Fig. 2B). There was a significant (p = 0.006) positive trend in discharge of 1.62 m^3 s^{-1} per year (Fig. 2C). This is an increase of 102 m^3 s^{-1} over 63 years. Seasonally, the trend was homogenous (p = 0.114). Over the 63 year series the mean monthly discharge was 415 m^3 s^{-1} although mean discharge is seasonally variable with the highest discharge in April (900 m^3 s^{-1}) and the lowest discharge in August (172.5 m^3 s^{-1}).

In the spring and summer water temperature trends (Fig. 2) are greater than the air temperature trends but each slope is associated with a normally distributed error and 95% confidence interval. The 95% confidence intervals for air temperature and water temperature trend for each month overlap and thus are not statistically different from each other. This indicates that estimated monthly water temperature trends are consistent with the estimated monthly air temperature trends. The conditional seasonal Kendall test found a significant (p < 0.001) annual warming trend after removing the influence of trend in discharge. However, after removing the influence of air temperature trend the annual water temperature trend is no longer significant. Thus the river is warming despite an increasing freshwater discharge. The annual water temperature trend is not significantly different from what is expected given the observed increases in air temperature.

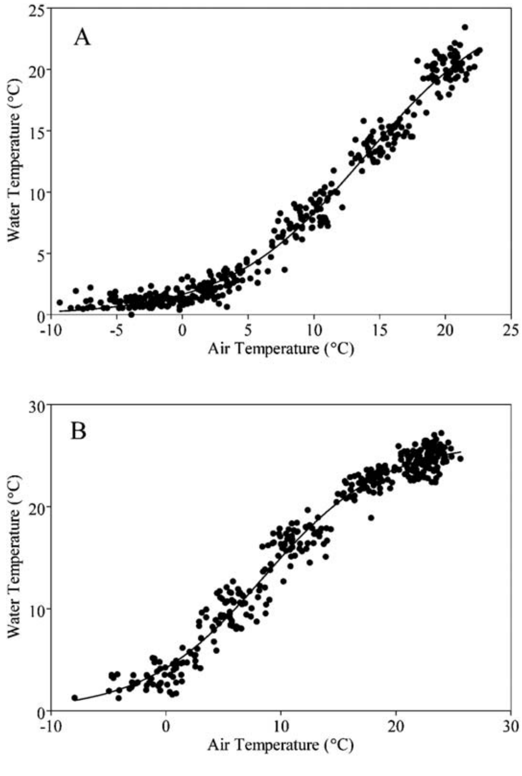

Fig. 3 The non-linear air–water temperature relationship at Poughkeepsie, New York. A: temperatures between January and June. B: temperatures between July and December.

B Non-linear regression

There was a clear non-linear seasonal relationship between monthly air temperature and water temperature (Fig. 3). 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 (Fig. 3A). The second model fits temperatures well for the July to December time period (Fig. 3B). The river cools slowly as air temperatures decline from approximately 25 to 15 °C and then below 15 °C a more rapid autumn cooling occurs (Fig. 3B). In both models air temperature explains over 97% of the variance in water temperature (Table 1). Both models do not plateau at the maximum temperatures (α in Table 1) although the second model, which includes the months of July and August, approaches this temperature.

4 Discussion

The Hudson River Estuary is warming. The trend test identified a significant long-term warming trend with a magnitude of 0.015 °C per year which equates to a 0.945 °C warming of annual mean temperature over the course of the 63 year series 1946–2008. The rate of warming is faster than previously reported annual warming trends for the Hudson[14,15] but is relatively pedestrian compared to warming reported in other estuaries.[33,34] The significant long-term warming trends identified for spring and summer drive 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 rather than the late spring and summer as for the Hudson.[13] A plausible explanation for this difference is that the Chesapeake Bay estuary does not become ice-covered like the Hudson during winter. The Hudson has a low but relatively constant temperature throughout winter and winter warming may not occur to any significant extent until ice-cover is substantially eliminated. 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 in stronger evaporative cooling and lower increase in water temperature relative to increase in air temperature.[31] This effect would tend to 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 on their thermal habitat during winter as temperatures are relatively unchanged over this period. However, the seasonal warming pattern of the

Table 1 Parameters for non-linear seasonal water–air temperature relationship models at Poughkeepsie. α is the maximum temperature of the model, β is the curve's inflection point, γ is the steepest slope of the function, and μ is the model's minimum temperature

Model	α	β	γ	μ	r^2
A: January to June	25.85	13.90	0.19	0.00	0.98
B: July to December	26.26	8.52	0.19	0.00	0.97

Hudson could lead to thermal habitats constraints during spring when many species spawn and during summer when temperatures are warmest.[35] Increased temperature in the late spring and summer months likely affects the development of some fish species[36] and the ecological interactions of populations as they undergo ontogenetic shifts in diet and predator susceptibility.[37] 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 when there was considerable variation in annual mean temperature.[38] Strayer *et al.* described a similar pattern for a larger number of fish species in the Hudson but also found growth was strongly correlated with temperature.[39] Daniels *et al.* noted from analysis of long-term records that some fish species are either substantially reduced (*Microgadus tomcod*) in abundance or apparently eliminated (*Osmerus mordax*, rainbow smelt) from the Hudson.[40] They suggest these changes are related, at least in part, to increased temperatures, particularly maximum summer temperatures in the case of tomcod. Lastly, the Hudson River has been subject to repeated invasions (at least 113) by exotic species.[41] Warming could have a synergistic affect with invasive species or it may dampen the impact of species invasion on the system.[42] In the freshwater portion of the Hudson River, zebra mussel (*Dreissena polymorpha*) grazing jointly controls the food-web with freshwater discharge.[43] Recent simulation and experimental evidence has suggested that the invasive zebra mussel may be adversely impacted by warming water temperatures, reducing grazing pressure on zooplankton due to altered size distribution and abundance of zebra mussel populations.[44–46]

Changes in air temperature are driving the increase in Hudson River temperatures. The nonlinear curves for the seasonal relationship between air and water temperature indicate maximum average water temperatures in excess of 25 °C (Table 1). Daily temperatures can exceed this value by several degrees. In the first model representing monthly mean temperature from January to June, the flat part of the curve in the left half portion of the graph is made up of data primarily from the first three months of the year while the steeper portion of the curve in right half of the graph is derived from late spring and early summer months. In the second model for temperatures from July through December, the left half of the graph is derived from autumn and early winter temperatures while the right half is derived from summer months. The models provide a good fit ($r^2 > 0.97$) for the air/water temperature relationships. The different slope at the inflection point for the major seasonal warming and cooling periods indicate that warming air temperature will have an unequal impact seasonally in warming the river. The low slope of the right half of model 2, which is derived from summer months, suggests that the estuary is approaching its maximum temperature during these months (where evaporative cooling tends to balance increased air temperature).

Air temperature is the main driver of long term annual changes in river temperature while variation in freshwater discharge is unrelated to the trend. Higher freshwater flows tend to cool the estuary. Despite increasing discharge, water temperature increased. Air temperature in Poughkeepsie and in the region is increasing due to climate change.[47–49] Hence, the warming trend in the Hudson is result of a warming regional climate. Because there is no warming trend greater than what is expected from air temperature it is unlikely that land use change or heated effluent discharge are significant in the long-term warming of the river, at least since 1946.

The proximal causes of temperature change at short time scales (*e.g.*, sub-daily) are complicated and may include interactions between numerous heat fluxes (*e.g.*, sediment-water heat flux) and other environmental factors (*e.g.*, turbity, shading, salt water inputs, and internal processes such as tidal circulation).[50] As data are averaged to courser time scales (*e.g.*, monthly) the main drivers of water temperature change to air temperature which is a good surogate for net heat flux over long periods.[28] Course temporal scale data such as those used in this analysis are driven by air temperature and are appropriate for the trend and non-linear regression analysis used here as well as for future extraplations of water temperature under climate change scenarios done elsewhere.[35] Finer scale data with other drivers may fit poorly or may be inappropriate for these methdologies.

One of the interesting features of the Poughkeepsie temperature record is the relatively warm temperature in the earliest part of the record (Fig. 1A). Ashizawa and Cole 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.[15] This speculation is difficult to test but the early cooling is not consistent with the patterns of air temperature at Poughkeepsie which was increasing during this period.† Abood *et al.* noted that the recent warming of the Hudson had "apparently returned temperatures to levels previously observed in the early 1900s."[16] However, the average value of the annual means over the most recent years (1997–2008) is over 0.5 °C warmer than the initial 10 year period of 1908–1917. Average annual temperatures >13 °C were observed only in 1968 and 1984 prior to 1998. Since 1998, eight years have had annual average temperatures >12.99 °C. Hence, the temperatures of the most recent period have been uniformly high and exceeding those of any period in the nearly 100 year record.

Our analyses have some limitations especially for the full 1908–2008 period. The initial warm period and subsequent 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 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 1946–2008. The Kendall trend 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.[21,22] In addition, the sheer length of the time series should reduce the effects of missing data. Hence, the basic trend initially described by Ashizawa and Cole of a warming Hudson is supported by our analyses.[15]

There are few long-term (>50 year) water quality time series.[10,14,15,29] Consequently, analyses of these series are generally case studies, providing conclusions for just one river, stream, or estuary. Newer, more widespread monitoring programs may demonstrate the spatial variability in trends due to heterogeneous responses to climate warming. However these widespread time series are generally short (<20 years) and the significance of trends is potentially confounded by decadal scale hydrological oscillations.[51] Our analysis is unique in that the time series is both long enough to avoid the adverse statistical effects of decadal scale hydrological oscillations, and because it includes long-term time series of covariates able to establish the drivers of tempeature change.[51]

In conclusion, the Hudson River Estuary is warming in response to increases in air temperature with a significant trend suggesting 0.945 °C annual warming over the past 63 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 water and air temperature change in the region[10,13,15,47,48] and with paleoclimatic evidence of temperature change.[52] Changing temperature can alter the abundance and community structure of fish in estuarine systems.[53,54] 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.* for nitrogen loading.[6] Long-term temperature increase 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.[3] 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. In the specific case of the Hudson River, a new monitoring program, the Hudson River Environmental Conditions Observing System, has been recently implemented using automated sensors at six sites along the river (www.HRECOS.org). This program provides freely available, high quality, high frequency environmental data. These types of programs should ultimately replace the type of measurements that we have relied on for this study where environmental data are secondary to the mission of a government agency and hence subject to changes or discontinuation. The long record of Hudson temperatures is a lucky result of the relative permanence of the city of Poughkeepsie's water treatment plant and the storage of records by its employees over nearly a century.

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References

1 D. S. Scavia, J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell, R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger and J. G. Titus, *Estuaries*, 2002, **25**, 149–164.
2 C. R. Pyke, R. G. Najjar, M. B. Adams, D. Breitburg, M. Kemp, C. Hershner, R. Howarth, M. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop and R. Wood, 2008, Climate change and the Chesapeake Bay: state-of the-science review and recommendations, *Chesapeake Bay Program Science and Technical Advisory Committee*, Annapolis, Maryland.
3 R. G. Najjar, C. R. Pyke, M. B. Adam, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M. R. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop and R. Wood, *Estuarine, Coastal Shelf Sci.*, 2010, **86**, 1–20.
4 N. Knowles and D. R. Cayan, *Geophys. Res. Lett.*, 2002, **29**, 1891–1894.
5 C. Rosenzweig, D. Karoly, M. Vicarelli, P. Neofotis, Q. Wu, G. Casassa, A. Menzel, T. L. Root, N. Estrella, B. Seguin, P. Tryjanowski, C. Liu, S. Rawlins and A. Imeson, *Nature*, 2008, **453**, 353–357.
6 R. W. Howarth, D. P. Swaney, E. W. Boyer, R. Marino, N. Jaworski and C. Goodale, *Biogeochemistry*, 2006, **79**, 163–186.
7 C. A. Oviatt, *Estuaries*, 2000, **27**, 895–904.
8 J. O. Meynecke, S. Y. Lee, N. C. Duke and J. Warnken, *Estuarine, Coastal Shelf Sci.*, 2006, **69**, 491–504.
9 B. R. Mackenzie, H. Gislason, C. Mollmann and F. W. Koster, *Global Change Biol.*, 2007, **13**, 1348–1367.
10 S. W. Nixon, S. Granger, B. A. Buckley, M. Lamont and B. Rowell, *Estuaries*, 2004, **27**, 397–404.
11 K. H. Wiltshire and B. F. J. Manly, *Helgol. Mar. Res.*, 2004, **58**, 269–273.
12 D. K. Brady, *Chesapeake Science*, 1976, **17**, 225–227.
13 B. L. Preston, *Environ. Manage.*, 2004, **34**, 125–139.
14 S. S. Kaushal, G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T Belt, D. H. Secor and R. L. Wingate, *Front. Ecol. Environ.*, 2010, **8**, 461–466.
15 D. Ashizawa and J. J. Cole, *Estuaries*, 1994, **17**, 166–171.
16 K. L. Abood, T. L. Engler, S. G. Metzger, C. V. Becker, T. J. Groninger and S. Mallavaram, *Am. Fish. Soc. Symp.*, 2006, **51**, 39–61.
17 W. R. Geyer and R. Chant, in *The Hudson River Estuary*, ed. J. S. Levinton and J. R. Waldman, Cambridge University Press, New York, pp. 24–38.
18 J. J. Cole, N. F. Caraco and B. L. Peierls, *Limnol. Oceanogr.*, 1992, **37**, 1608–1617.
19 M. J. Menne, C. N. Williams and R. S. Vose, 2009, United States Historical Climatology Network daily temperature precipitation, and snow data, *Carbon Dioxide Information Analysis Center*, Oak Ridge National Laboratory. http://cdia.ornl.gov/epubs/ndp/ushcn/ushcn.html. Accessed 14 April 2010.
20 K. E. Limburg, M. A. Moran and W. H. McDowell, 1986, *The Hudson River ecosystem, 2000*, Springer-Verlag, New York.
21 R. M. Hirsch, J. R. Slack and R. A. Smith, *Water Resour. Res.*, 1982, **18**, 107–121.
22 R. M. Hirsch and J. R. Slack, *Water Resour. Res.*, 1984, **20**, 727–732.
23 G. Van Belle and J. P. Hughes, *Water Resour. Res.*, 1984, **20**, 127–136.
24 C. Libiseller and A. Grimvall, *Environmetrics*, 2002, **13**, 71–84.
25 B. W. Webb and D. E. Walling, *Hydrol. Sci. J.*, 1992, **37**, 567–580.
26 B. W. Webb and F. Nobilis, *Hydrol. Processes*, 1997, **11**, 137–147.
27 S. J. Langan, L. Johnson, M. J. Donaghy, A. F. Yougson, D. W. Hay and C. Soulsby, *Sci. Total Environ.*, 2001, **265**, 195–207.
28 B. W. Webb, P. D. Clack and D. E. Walling, *Hydrol. Processes*, 2003, **17**, 3069–3084.
29 B. W. Webb and F. Nobilis, *Hydrol. Sci. J.*, 2007, **52**, 74–85.
30 J. M. Pilgrim, X. Fang and H. G. Stefan, *J. Am. Water Resour. Assoc.*, 1998, **34**, 1109–1121.
31 O. Mohseni and H. G. Stefan, *J. Hydrol.*, 1999, **218**, 128–141.
32 O. Mohseni, H. G. Stefan and T. R. Erickson, *Water Resour. Res.*, 1998, **34**, 2685–2692.
33 C. Koutsikopoulos, P. Beillois, C. Leroy and F. Taillefer, *Oceanologica Acta*, 1998, **21**, 335–344.
34 D. Masson and P. F. Cummins, *Cont. Shelf Res.*, 2007, **27**, 634–649.
35 O. Mohseni, H. G. Stefan and J. G. Eaton, *Climatic Change*, 2003, **59**, 389–409.
36 D. Tetzlaff, C. Soulsby, A. F. Youngson, C. Gibbins, P. J. Bacon, I. A. Malcom and S. Langn, *Hydrol. Earth Syst. Sci.*, 9, pp. 193–208.
37 T. Mehner, H. Schultz, D. Bauer, R. Herbst, H. Voigt and J. Beendorf, *Ann. Zool. Fenn.*, 1996, **33**, 353–361.

38 M. L. Pace, S. B. Baines, H. C. Cyr and J. A. Downing, *Can. J. Fish. Aquat. Sci.*, 1993, **50**, 1976–1985.
39 D. L. Strayer, K. Hattala and A. Kahnle, *Can. J. Fish. Aquat. Sci.*, 2004, **61**, 924–941.
40 R. A. Daniels, K. E. Limburg, R. E. Schmidt, D. L. Strayer and R. C. Chambers, *Am. Fish. Soc. Symp.*, 2005, **45**, 471–503.
41 E. L. Mills, D. L. Strayer, M. D. Scheuerell and J. T. Carlton, *Estuaries*, 1996, **19**, 814–823.
42 D. L. Strayer, V. T. Eviner, J. M. Jeschke and M. L. Pace, *Trends Ecol. Evol.*, 2006, **21**, 645–651.
43 D. L. Strayer, M. L. Pace, N. F. Caraco, J. J. Cole and S. E. G. Findlay, *Ecology*, 2008, **89**, 12–18.
44 E. M. Griebeler and A. Seitz, *Oecologia*, 2007, **151**, 530–543.
45 C. Viergutz, M. Kathol, H. Norf, H. Arndt and M. Weitere, *Oecologia*, 2007, **151**, 115–124.
46 M. Weitere, J. Dahlmann, C. Viergutz and H. Arndt, *Limnol. Oceanogr.*, 2008, **53**, 477–486.
47 S. C. Trombulak and R. Wolfson, *Geophys. Res. Lett.*, 2004, **31**, L19202.
48 D. A. Burns, J. Klaus and M. R. McHale, *J. Hydrol.*, 2007, **336**, 155–170.
49 R. Najjar, L. Patterson and S. Graham, *Clim. Change*, 2009, **95**, 139–168.
50 B. W Webb, D. M. Hannah, R. D. Moore, L. E. Brown and F. Nobilis, *Hydrol. Process.*, 2008, **22**, 902–918.
51 Z. Chen and S. E. Grasby, *J. Hydrol.*, 2009, **365**, 122–133.
52 T. M. Cronin, G. W. Dwyer, T. Kamiya, S. Schwede and D. A. Willard, *Global Plant. Change*, 2003, **36**, 17–29.
53 H. M. Austin, *Am. Fish. Soc. Symp.*, 2002, **32**, 155–170.
54 J. A. Hare and K. W. Able, *Fish. Oceanogr.*, 2007, **16**, 31–45.