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Climatic Control on Eutrophication of the Hudson River Estuary

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ABSTRACT

Eutrophication is arguably the biggest pollution problem facing estuaries globally, with extensive consequences including anoxic and hypoxic waters, reduced fishery harvests, toxic algal blooms, and loss of biotic diversity. However, estuaries vary greatly in their susceptibility to eutrophication. The Hudson River estuary receives very high levels of nutrient inputs yet in the past has shown relatively low rates of phytoplankton productivity and is generally considered to be only moderately susceptible to eutrophication. Here, we show that eutrophication and primary production in the Hudson estuary can increase dramatically in response to climatic variation and lowered freshwater discharge from the watershed. During dry summer periods in 1995 and 1997, rates of primary production were substantially higher than those measured during the 1970s, when freshwater discharge tended to be high. In the Hudson, low freshwater discharge increases water residence times and stratification and deepens the photic zone, all of which (alone or in combination) could lead to the observed increase in primary production. Our data, along with the prediction of most climate change models that freshwater discharge will be lower in the future during the summer in the northeastern US, suggest that the Hudson will become more susceptible to eutrophication. Eutrophication in an estuary is a complex process, and climate change is likely to affect each estuary differently due to interactions with nutrient loadings and physical circulation. Hence, it is essential to consider the effects of climate change in the context of individual estuarine functioning to successfully manage eutrophication in the future.

Key words: primary production; eutrophication; estuary; climate change; watershed; freshwater discharge; light limitation; photic zone; water residence time.

Estuaries are one of the most valuable ecosystem types supporting human society, with much of this value due to assimilation of nutrients (Constanza and others 1997). However, the ability of estuaries to process nutrients is not infinite and excessive nutrient inputs can lead to eutrophication, defined as excess inputs of organic matter particularly from increased primary production (Nixon 1995). Eutrophication is arguably the biggest pollution problem facing estuaries globally, with extensive consequences including anoxic and hypoxic waters, reduced fishery harvests, toxic algal blooms, and loss of biotic diversity (NRC 1993, 1996, 2000). A national assessment of estuarine eutrophication in the US has just concluded that "nearly all estuarine waters now exhibit some symptoms of eutrophication, though the scale, intensity, and impact may vary widely, and the level of nutrient input required to produce these symptoms also varies" (Bricker and others 1999). Many factors affect the susceptibility of an estuary to eutrophication, including differences in light limitation related to turbidity and mixing depth (Malone 1977; Cloern 1991, 1996;

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Lucas and others 1998), dilution of nutrient inputs (Bricker and others 1999), water residence time relative to the growth rate of phytoplankton (Wyatt and Qasim 1973; Malone 1977; Cloern and others 1983), and perhaps grazing by benthic suspension feeders (Lucas and others 1998; Meeuwig and others 1998) or zooplankton (Ingrid and others 1996).

The Hudson River estuary receives very high levels of nutrient inputs from wastewater from the 8 million people who live in the watershed and from nonpoint sources including both agricultural sources and atmospheric deposition of NO_y derived from fossil fuel combustion (Clark and others 1992; Johnson and Hetling 1995; Jaworski and others 1997). Although the nonpoint source inputs per area of watershed for the Hudson are similar to those for other rivers in the Northeast (Jaworski and others 1997), the Hudson's watershed area is large compared with the surface area of the estuary, and so the nitrogen inputs per area of estuary are among the highest in the US (Bricker and others 1999). Nonetheless, the Hudson estuary generally is considered to be only moderately susceptible to eutrophication because of light limitation and/or short water residence time (Malone 1977; Bricker and others 1999). Most previous studies of gross primary production (GPP) in the Hudson estuary occurred in the 1970s and reported rates to be fairly low, usually below 1 g C m^{-2} d^{-1} and always below 2 g C m^{-2} d^{-1} (Malone 1977; Sirois and Fredrick 1978). Estuaries generally are considered to be eutrophic when their annual rate of GPP exceeds 500 g C m^{-2} y^{-1} (Nixon 1995; NRC 2000), which corresponds to a daily rate of approximately 2–3 g C m^{-2} d^{-1} on average during the active growing season. Thus, the Hudson estuary during the 1970s was not eutrophic.

Our research in the 1990s reveals a very different pattern, with rates of GPP often far higher than observed in the 1970s. We measured GPP on a total of 25 expeditions during spring, summer, and fall of 1994, 1995, and 1997 along a 20-km-long representative stretch of the Hudson River estuary, beginning 0.25 km north of the George Washington Bridge in New York City (20 km north of the mouth of the estuary) and extending to the beginning of the Tappan Zee (40 km north of the mouth). Salinities in this portion of the estuary tend to vary between 5 and 20°/₀₀, classifying the estuary as mesohaline (Limburg and others 1986). We used a novel in situ diel O_2 technique to measure GPP, grouping data from five stations spaced along the estuary and examining how a "plane" of O_2 concentrations as a function of salinity and depth changes over a diel period (Swaney and others 1999). When corrected for atmospheric exchange, the rate of decrease in O_2 overnight provides an estimate of respiration. The change in O_2 during daylight, also corrected for atmospheric exchange, is the net result of GPP and respiration. GPP therefore can be estimated by adding the hourly rate of respiration (from the nighttime observations) to the increase in O_2 during the day. O_2 exchange between the atmosphere and the Hudson estuary is controlled largely by wind and can be estimated from wind and O_2 saturation (Marino and Howarth 1993; Clark and others 1994). Expressed per unit of phytoplankton biomass as estimated from chlorophyll concentrations, our rates of GPP measured by the in situ diel method compare favorably with estimates made earlier in the Hudson estuary by using ^{14}C uptake or O_2 changes in light and dark bottles (Malone 1977; Sirois and Fredrick 1978).

Our measured rates of GPP in the 1990s varied from near 0 to as high as 18 g C m^{-2} d^{-1} (Figure 1a). The mean rate was 3.5 g C m^{-2} d^{-1}, and the median value was 2.5 g C m^{-2} d^{-1}. Thus, during our sampling times in the 1990s, the Hudson estuary was often eutrophic and sometimes extremely so (Nixon 1995; NRC 2000). It is unlikely that the increase in GPP and eutrophication between the 1970s and the 1990s was due to an increase in nutrients, because concentrations of both inorganic nitrogen and phosphorus were already very high and unlikely to be limiting to GPP in the 1970s (Garside and others 1976; Malone 1977). Furthermore, nutrient inputs from nonpoint sources in the Hudson watershed have changed relatively little over the past two decades (Jaworski and others 1997), whereas point source inputs may actually have decreased (Clark and others 1992; Johnson and Hetling 1995).

Rates of GPP in the Hudson estuary during our cruises in the 1990s exhibited great variability, but high rates occurred only when freshwater discharge from the Hudson basin was relatively low (less than 200 m^3 s^{-1}; Figure 1A). One mechanism whereby discharge may affect GPP is the influence on water residence time. We estimate water residence times for surface waters (R) from the equation $R = V_s/\{Q[S_b/(S_b - S_a)]\}$, where V_s is the volume of surface water in the estuary, Q is the freshwater discharge into the estuary, S_b is the salinity of the bottom waters, and S_a is the salinity of surface waters (Pritchard 1969); V_s was calculated as the product of the surface area for the mesohaline estuary (29 km^2) and the mean photic zone depth (2.5 m; our unpublished data). When freshwater discharge to the Hudson is less than 200 m^3 s^{-1}, we estimate that residence times for the surface waters of the estuary are variable but frequently are greater than 2 days (Figure 1B). At discharge rates greater than 300 m^3

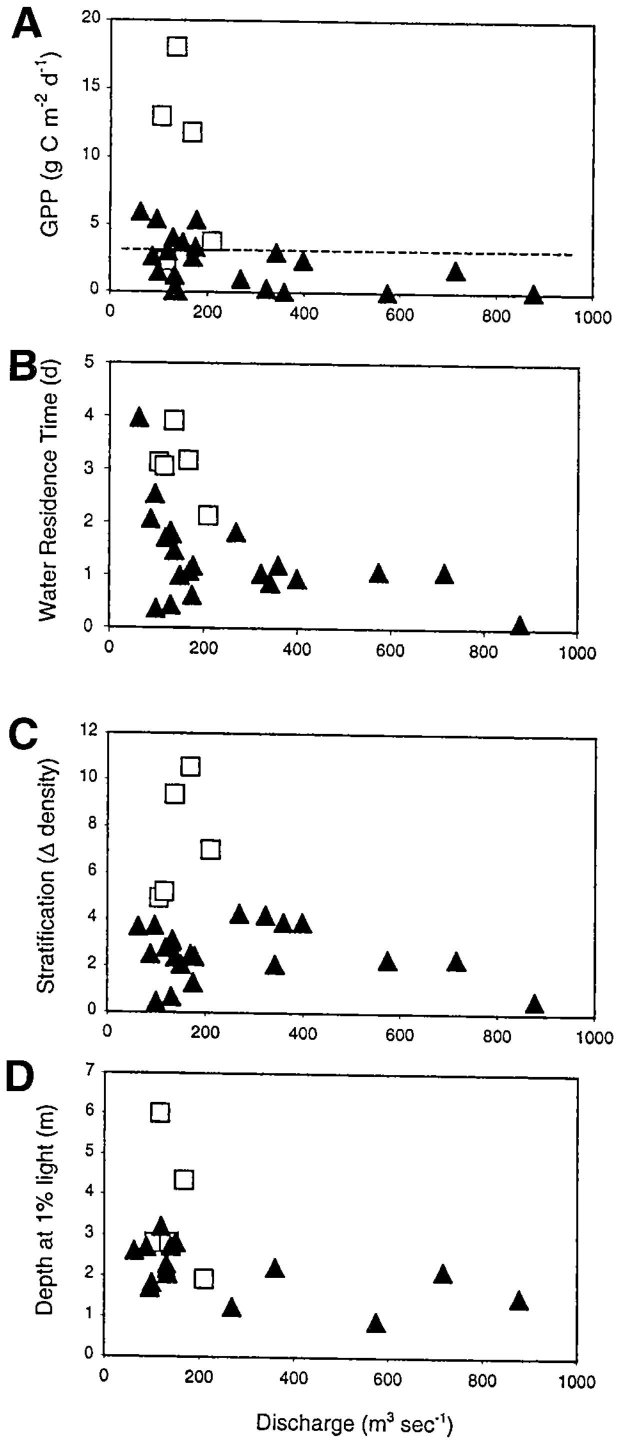

Figure 1. Relationship between freshwater discharge and GPP (**A**), water residence time (**B**), stratification (**C**), and light penetration (**D**) during 25 cruises conducted during the spring, summer, and fall of 1994, 1995, and 1997. Open symbols represent times when tidal amplitude was <1.15 m; dark symbols represent greater tides. The dashed line in (**A**) represents the approximate value for GPP above which an estuary is considered to be eutrophic (see text). Note that high rates of GPP only occur when freshwater discharge is <200 m^3 s^{-1} and are more likely when tidal amplitudes are low. Freshwater discharge data are from the USGS from their monitoring station at Green Island, NY (*http://waterdata.usgs.gov/nwis-w/US/*). Discharge at Green Island constitutes approximately 67% of the total estimated freshwater input to the Hudson estuary and is well correlated with these total inputs (Howarth et al. 1991; Swaney et al. 1996).

s^{-1}, water residence time in the estuary is less than 1 day. The maximum growth rate for phytoplankton in an estuary such as the Hudson corresponds to a doubling time of slightly less than 1 day (Malone 1977), so that when the residence time of surface waters is also less than 1 day, phytoplankton are advected out of the estuary almost as rapidly as they can grow, limiting the size of any potential bloom (Wyatt and Qasim 1973; Cloern 1996). As the residence time increases above 1 day, phytoplankton blooms become increasingly more likely.

Another mechanism whereby freshwater discharge may affect GPP in the Hudson estuary is the influence on stratification and light penetration (Figure 1C and D). Light availability can limit the growth rate of phytoplankton in an estuary (Malone 1977; Cloern 1991, 1996; Lucas and others 1998), and this is related both to stratification and to water clarity. In a deep, turbid estuary such as the Hudson, mixing of the water column tends to move phytoplankton into deeper, darker waters where light levels are too low to support photosynthesis in excess of phytoplankton respiration rates. Increased stratification reduces this mixing and keeps the phytoplankton more buoyed in surface waters where higher light levels can lead to higher rates of GPP. We can portray stratification in the Hudson estuary as the average density differences between surface waters and water at a depth of 8 m for each sampling date; densities are calculated from temperate and salinity, which we measured at each depth at each station and time by using Orion probes. In the mesohaline Hudson estuary, stratification varies from quite low to quite high when freshwater discharge is below 200 m^3 s^{-1}, and the estuary tends to have moderately low stratification when the freshwater discharge is higher (Figure 1C). Note that this contradicts the general expectation for estuaries that they are more stratified at greater freshwater discharges (Postma 1980; Moore and others 1997). As is discussed below, the variation in stratification at low discharge is related to the spring-neap tide cycle. Discharge also is related to light penetration in the Hudson (which we measured at each station during each cruise by using a

Licor spherical sensor that responds to photosynthetically active wavelengths), with sunlight tending to penetrate more deeply into the water column when discharge is low (Figure 1D). This relationship between discharge and light penetration probably occurs both because there is less resuspension of particles and because there is less input of sediment from the watershed when discharge is low (Howarth and others 1991; Swaney and others 1996). Thus, low discharge in the Hudson favors greater GPP both by increasing stratification, which tends to keep the phytoplankton higher in the photic zone, but also by increasing light penetration and deepening the photic zone.

Some of the variation we observed in rates of GPP, water residence time, stratification, and light penetration at times of low freshwater discharge is related to the spring-neap tidal cycle, as has been observed in San Francisco Bay (Cloern 1991, 1996), and to stochastic events such as wind direction, which can affect tidal amplitude in the Hudson estuary. There is a strong tendency for greater rates of GPP, longer water residence time, greater stratification, and deeper light penetration all to occur when the daily tidal amplitude is relatively small (less than 1.15 m; Figure 1; we obtained tide data from NOAA for their monitoring station at the Battery at the southern tip of Manhattan Island: http://www.opsd.nos.noaa.gov/data_res.html). There is apparently little influence of the tidal cycle on physical parameters such as stratification and water residence time when freshwater discharge is high, but when discharge is low, the tidal cycle has a pronounced effect on physical circulation and therefore on GPP.

During two of our cruises when low discharge and low tidal amplitude led to longer residence times and to greater stratification, GPP rates remained somewhat lower (but still at eutrophic rates; 2–5 g C m^{-2} d^{-1}) than observed during the major bloom events that produced rates of GPP above 10 g C m^{-2} d^{-1} (Figure 1A). The reasons for this remain unclear but were perhaps due to "top-down" control by grazing (Ingrid and others 1996; Lucas and others 1998; Meeuwig and others 1998) as commonly occurs in lakes (Carpenter and Kitchell 1993). Nonetheless, our data strongly indicate that GPP can be quite high when discharge is low, whereas we have never observed high rates of GPP when freshwater discharge is high (Figure 1A). During the summers and falls of 1995 and 1997, conditions conducive to high GPP—freshwater discharge below 200 m^{3} s^{-1} and tides below 1.15 m—occurred approximately 75% of the time (data from US Geological Survey [USGS] and NOAA web sites), and so the estuary was likely eutrophic most of the time.

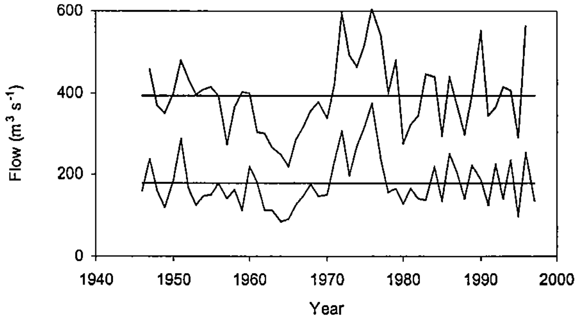

Figure 2. Average freshwater discharge to the Hudson at the USGS gauging station at Green Island, NY, obtained from their web site (*http://waterdata.usgs.gov/nwis-w/US/*). Upper curve shows annual average flows while lower curve shows average summertime flows. Horizontal lines indicate mean values for annual discharge (390 m^{3} s^{-1}) and for summertime discharge (180 m^{3} s^{-1}). Note that during our cruises in 1995 and 1997, summertime mean discharge was <150 m^{3} s^{-1}. In contrast, during previous studies in the 1970's summertime mean discharge was >200 m^{3} s^{-1}. We have only observed high rates of GPP when discharge is <200 m^{3} s^{-1}.

A comparison of freshwater discharge during the years of our cruises in comparison with the discharge during the 1970s when the previous studies of GPP were conducted is instructive. During the 1970s, average discharge during the summer tended to be well over 200 m^{-3} s^{-1} (Figure 2). This was also true for the summer of 1994 during our cruises, but in the summers of 1995 and 1997 discharge was much lower. Thus, lower freshwater discharge during some of the years of the 1990s in comparison with the 1970s provides an explanation for the higher rates of GPP we measured in the 1990s. Mean freshwater discharges observed in the 1990s tend to be near the mean for all years since 1945 (although year-to-year variation was greater in the 1990s), but summertime discharges in the 1990s were lower than in the unusually wet years of the 1970s (Figure 2) when the previous studies on GPP were conducted. During these previous studies in the 1970s, calculated residence times for surface waters in the estuary were always well below 1 day (Malone 1977).

Predicting the results of climate change in the future is fraught with difficulty, and precipitation will likely increase in some regions and decrease in others. Nonetheless, most models predict that climatic warming will lead to decreases in precipitation during the summer months in the mid-Atlantic states and the northeastern United States (Wigley

1999). Increased temperatures also will increase evapotranspiration, and so freshwater runoff during summer months is likely to decrease even more than the predicted decrease in precipitation (Moore and others 1997). Furthermore, if more precipitation in the winter occurs as rainfall rather than snow, greater wintertime discharge is likely, with less retention in snowpack and therefore further reduction of summertime discharge. If climatic change does indeed lead to lessened summertime discharge in the Hudson basin, increased eutrophication in this nutrient-rich estuary seems likely.

The response of other estuaries to reduced discharge remains somewhat uncertain and demands further study. Depending upon the nature of nutrient sources and of physical circulation in an estuary, changes in discharge might make an estuary either more or less eutrophic. In the case of the Hudson, nutrient inputs are so large that any climatic influence on these nutrient loadings is unlikely to have a major influence on eutrophication. Many other estuaries are also quite nutrient rich (Bricker and others 1999), and therefore, as with the Hudson, the major effect of climate change on eutrophication is likely to be an alteration of the physical circulation in a manner that changes the susceptibility of the estuary to eutrophication. However, most estuaries have lower nutrient loading than the Hudson, and for these systems, climate change may have a major influence on eutrophication through alteration of these nutrient inputs (in addition to changing physical circulation and the susceptibility of the estuary to eutrophication). In general, increased discharge will increase nutrient inputs from nonpoint sources, while lowered discharge will decrease nutrient inputs (Moore and others 1997).

It is more difficult to generalize the influences of climate change on physical circulation (particularly stratification) and eutrophication. Whereas we observed that the mesohaline Hudson estuary becomes more stratified as freshwater discharge decreases (Figure 1C), the more general expectation is that an estuary would become less stratified as freshwater discharge decreases (Postma 1980; Moore and others 1997). On the other hand, longer water residence times are a likely response to decreased freshwater discharge for almost all estuaries. When the residence time is short in relation to the growth rate of phytoplankton, as it is in the Hudson, any change in residence time is likely to have a major impact on GPP and eutrophication. Some estuaries such as Long Island Sound and Chesapeake Bay have relatively long residence times (months to years). However, many other estuaries have residence times as short as the Hudson (Jay and others 2000), and for these, decreased freshwater discharge may well lead to greater eutrophication. In any event, it is essential to consider the effects of climate change on estuarine functioning for the successful management of eutrophication in the future.

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