DID THE ZEBRA MUSSEL (*DREISSENA POLYMORPHA*) ALTER THE THERMAL BALANCE OF THE HUDSON RIVER?

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ABSTRACT

The ecological effects of the zebra mussel (*Dreissena polymorpha*) invasion on the Hudson River have been well documented. Higher bivalve filtration rates after the invasion increased water clarity. This should have decreased water surface albedo and may have lead to changes in water temperature. This study used the equilibrium temperature concept to explore potential changes in water temperature due to change in albedo. Equilibrium temperature is the water temperature at which the sum of energy fluxes across the water surface equals zero. Equilibrium temperature is a function of meteorological and hydrological conditions including albedo. We calculated equilibrium temperature for the Hudson River for observed conditions and for modeled conditions where the influence of zebra mussel filtration was removed. Changes in albedo due to zebra mussel filtration were small and the resulting changes in equilibrium and water temperature were negligible. The equilibrium temperature concept may be useful for further exploration of drivers of a known warming trend.

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INTRODUCTION

Climate change due to global warming is likely to profoundly alter estuaries (Scavia et al. 2002). Critical physical factors such as the timing and volume of freshwater inflows will change and lead to shifts in water residence time, salinity, and mixing that determine or influence many properties of estuaries (Knowles and Cayan 2002; Scavia et al. 2002). Warming may also increase nitrogen fluxes resulting in eutrophication (Howarth et al. 2006). Warming will alter biological communities and ecological interactions within estuaries leading to likely changes in resource species (Oviatt 2004; Meynecke et al. 2006; Mackenzie et al. 2007). In addition to climate induced warming, many systems are also being invaded by exotic species. In 1992 the zebra mussel (*Dreissena polymorpha*) invaded the Hudson River. Impacts on macrozoobenthos (Strayer et al. 1998), native bivalves (Strayer and Malcom 2007), phytoplankton (Roditi et al. 1996; Caraco et al. 1997), zooplankton (Pace et al. 1998), fish assemblages (Strayer et al. 2004), dissolved oxygen (Caraco et al. 2000) cyanobacteria (Fernald et al. 2007) and sediments (Strayer and Malcom 2006) have been documented. Strayer et al. (1999) and Caraco et al. (2000) suggested that zebra mussels have likely increased water clarity in the Hudson. This is because the zebra mussel population has a higher filtration rate than exerted previously by native bivalves and as a consequence achieve greater removal of particles from the water column. The water surface albedo of clear water is less than that of turbid water (Rosenberg et al. 1983). Increasing water clarity should alter the thermal balance of the river, warming it by allowing more incoming solar radiation to enter the water. This could contribute to the known warming trend in the Hudson that has accelerated in years since the zebra mussel invasion (Pace and Seekell 2009). Changing temperature during spring and early summer months could change reproductive timing and success of fish species. It also may impact the development of some species and their ecological interactions as they undergo ontogenetic shifts in diet and predator susceptibility (Mehner et al. 1996; Tetzlaff et al. 2005). Warmer summer months could lead to further constraints on thermally suitable habitat for species during what are already the warmest months of the year (Mohseni et al. 2003).

Equilibrium temperature is the water temperature at which the sum of all energy fluxes across the water surface equals zero (Mohseni and Stefan 1999; Bogan et al. 2003; Caissie et al. 2005). It is a function of meteorological and hydrological conditions including albedo (Mohseni and Stefan 1999; Bogan et al. 2003; Caissie et al. 2005). At coarse temporal scales river water temperatures closely track equilibrium temperature (Bogan et al. 2003). This study uses the equilibrium temperature concept to test the hypothesis that changes in water temperature are a result of the zebra mussel invasion. The equilibrium temperature approach better accounts for the major drivers of water temperature than simple regression models but has more manageable data requirements than full energy budgets. Albedo is an important component of equilibrium temperature and thus modeling albedo is an important part of this exercise. Albedo was calculated based on observed conditions. Albedo without zebra mussel filtration was then estimated. These values were used to calculate observed and potential (without zebra mussel filtration) equilibrium temperature time series to test for an effect of mussels on temperature.

METHODS

Data

Meteorological data from 1989-2007 were obtained from a long term environmental monitoring site in Millbrook NY (Long W 073.741447°, Lat N 41.785823°, elevation 128m) (Cary Institute of Ecosystem Studies 2008). This is the closest weather station to the Hudson River sampling sites that records all of the necessary meteorological parameters over the period of time examined. Photosynthetically active radiation (μmol s^{-1} m^{-2}) was measured with a Licor Model LI-190SB sensor 2 m (1989-2002) and 2.5 m (2002-2007) above the ground. Incoming shortwave radiation (W m^{-2}) was measured with an Eppley Model 8-48 sensor 2 m (1989-2002) and 2.5 m (2002-2007) above the ground. Relative humidity was measured with a Phys Chem Corp. PCRC-11 or PCRC-55 (1989-1997) and a Campbell Scientific HMP45C (1997-2007) sensor 1.6 m above the ground inside a motor aspirated shield. Air temperature (°C) was measured with a Campbell Scientific Model 107 or 207 (1989-1998) and HMP45C (1998-2007) sensor 1.6 m above the ground inside a motor aspirated shield. Wind speed (km h^{-1}) was measured with a Campbell Scientific Model 014A sensor (1989-2002), Met One Instruments Model 50.5 solid state sensor, and Climatronic Corp sonimometer on a 10 m tower. All measurements were taken over a flat, mowed grass surface. Solar angle was calculated using the standard equations (see Allen et al. 1998).

Hudson River data from 1989-2007 were collected off of Kingston NY (Long W 74.004088° Lat 41.928877°) bi-weekly during the ice free season (typically April to

November). This portion of the river is well mixed and turbid with suitable substrate and salinity for zebra mussels (Caraco et al. 1997). Photosynthetically active radiation (PAR)(µmol s^{-1} m^{-2})(L_z) was measured with a Licor LI-193SA spherical quantum sensor. Zebra mussel filtration was estimated from a geographically stratified (to include multiple bottom surface types) sample and regression model based on abundance and size (Strayer et al. 2006). Water temperature was measured at a USGS station just south of Poughkeepsie. Water flow was measured as freshwater inputs into the lower Hudson over the gauging station at the Federal dam in Troy. Inorganic seston was calculated the product of total seston and 1 - organic seston mg L^{-1} / total seston mg L^{-1}. Seston was collected and measured from water samples with glass fiber filters. The organic composition was determined by combustion.

Light Extinction Coefficient

The light extinction coefficient k (m^{-1}) was calculated based on irradiance profiles obtained with the quantum sensor. Light extinction is calculated as the regression coefficient of the natural log of L_z at 0.5m, 1m, and 2m relative to irradiance at 0.5m. This can be used as a proxy for water clarity (Caraco et al. 1997). A multiple regression model of k as a function of zebra mussel filtration, inorganic seston, calendar day, and water flow was used (Table 1). To estimate k in a zebra mussel free scenario filtration is set to zero.

Table 1. Parameter estimates for a multiple regression model of the light extinction coefficient.

Parameter	Coefficient	Std. Error	Std. Coef.	P
Constant	-0.834	0.084	0	-
Inorganic Seston	-0.05	0.003	-0.624	< 0.001
Julian Day	$-8.18*10^{-4}$	$3*10^{-4}$	-0.089	0.005
Zebra Mussel Filtration	0.019	0.008	0.068	0.021
Water Flow	$-1.37*10^{-4}$	$1.4*10^{-5}$	-0.371	< 0.001

Cloud Cover

Cloud cover is an important component of equilibrium temperature and surface albedo. Clouds non-selectively refract incoming solar radiation. Consequently, diffuse radiation increases with cloud cover. This decreases water temperatures and increases albedo. Cloud cover is difficult to measure and is rarely recorded (Lhomme et al. 2007). Cloud cover was estimated using the proxy given by Lhomme et al. (2007) and Lenters et al. (2005) to estimate fractional cloud cover (f_c). Here f_c is the ratio of the of incoming solar radiation (H_s) for each daylight hour to potential incoming solar radiation on a cloud free day ($H_{s,0}$)(equation 1). To eliminate time of day effects the sum of H_s and $H_{s,0}$ for each daylight hour were used to find daily cloud cover.

[1] $$f_c = \frac{H_s}{H_{s,0}}$$

Albedo

There are several components of surface water albedo (α) (Nunez et al. 1972). Incident radiation can be reflected at the water surface, backscattered by particulates in the water or reflected off of the river bed. All components are rarely measured (Nunez et al. 1972). Albedo was calculated after Caraco et al. (1997) as a ratio of irradiance in the air (L_{air})(μmol s^{-1} m^{-2}) and irradiance at the surface (L_0)(μmol s^{-1} m^{-2})(equation 2).

[2] $$\alpha = 1 - \frac{L_{air}}{L_0}$$

The sensor only measures in the 400-700 nm range; thus, it is necessary to assume that all wavelengths reflect equally on the water surface. Because L_0 was only measured between 1989 and 1993 albedo was calculated for the rest of the series with an empirical model of L_0. L_0 cannot be estimated from the light extinction coefficient and irradiance measurements at a known depth (L_z) because turbulence in the upper 0.5 m of the water column alters the light extinction relationship (Wetzel 2001). This approach generally over estimates surface irradiance values. In clear sky conditions (no diffuse radiation) on a flat surface albedo is a function of the solar angle (Wetzel 2001). However this condition rarely occurs at the study site. An ordinary least squares regression with solar angle, L_{air}, k, and inorganic seston (mg L^{-1}) as predictors explained over 97% of variance in L_0 ($\log_e$ transformed) (Table 2). Solar angle and L_{air} were $\log_e$ transformed.

Table 2. Parameter estimates for an empirical model of L_0.

Parameter	Coefficient	Std. Error	Std. Coef.	P	VIF
Intercept	-0.15	0.37	0.00	---	---
Solar Angle	-0.35	0.07	-0.11	<0.001	1.16
L_{air} (Log_e)	1.11	0.03	0.94	<0.001	1.19
Inorganic Seston	-0.01	0.005	-0.08	0.056	3.90
K	-0.11	0.05	-0.08	0.046	3.92

Albedo varies with time of day because of changing solar angle. On a typical summer day albedo has a maximum value near dawn, decreases to a minimum at noon and then increases again in the afternoon (Figure 1). To eliminate the time of day effect from the analysis the sum of L_0 and sum of L_{air} for each daylight hour were used to calculate daily albedo.

Equilibrium Temperature

Equilibrium temperature is the water temperature at which the sum of energy fluxes across the water surface equals zero (Mohseni and Stefan 1999; Bogan et al. 2003). At the coarse time scales (one day or greater) this is expressed as

[3] $H_s + H_l - H_e = 0$

where H_l is net long wave radiation (MJ m^{-2} day^{-1}) and H_e is evaporative heat flux (MJ m^{-2} day^{-1})(Caissie et al. 2005; Bogan et al. 2003). Convective heat flux is not accounted for because it has been found to be insignificant in water temperature modeling (Caissie et al. 2005). The equilibrium temperature can be expressed in linear form as a function of meteorological conditions (Mohseni and Stefan 1999). A simple approximation is presented by Caissie et al. (2005) as

[4] $T_e = B_1 H_s + B_2 T_a + B_3 T_d + B_4$

where T_e is equilibrium temperature (°C), T_a is air temperature (°C), and T_d is the dew point temperature (°C). The coefficient B_1 adjusts incoming solar radiation (H_s) for shading (assumed to be zero) and albedo. The product of B_1 and H_s represents the radiation that enters the water body. Coefficient B_2 is atmospheric long wave radiation which is a linear function of T_a. Coefficient B_3 represents the amount of energy able exit the water body through evaporative heat flux at the dew point T_d. The coefficient B_4 is long wave radiation from the water degraded by atmospheric emissivity (a function of air water vapor pressure and cloud cover) and water surface emissivity (see Mohseni and Stefan 1999 and Caissie et al. 2005 for derivation of the coefficients).

Modeling Approach

Equilibrium temperature was first calculated using observed meteorological and light extinction data. Equilibrium temperature was then recalculated with observed meteorological data but with modeled light extinction data where the influence of zebra mussel filtration was removed. This alters albedo, changing the amount of solar energy entering the water and thus the equilibrium temperature. The impact of zebra mussel filtration on Hudson River equilibrium temperature was assessed by comparing the results of the two calculations.

RESULTS

The observed light extinction in the Hudson varies with time of year (Cole et al. 1992). The median light extinction coefficient was -1.79 m^{-1} with a minimum of -7.94 m^{-1} and a maximum of -0.84 m^{-1}. The modeled light extinction coefficients were similar to the observed. Fit was evaluated by root mean square error (RMSE). RMSE is the standard deviation of difference between observed and estimated values. The RMSE of modeled light extinction coefficients was 0.33 m^{-1}. The mean difference between the observed light extinction coefficient and the light extinction coefficient with zebra mussel filtration set to zero is 0.066 m^{-1} (standard deviation 0.045). The portion of the light extinction coefficient attributed to zebra mussel filtration varies cyclically over time (Figure 2).

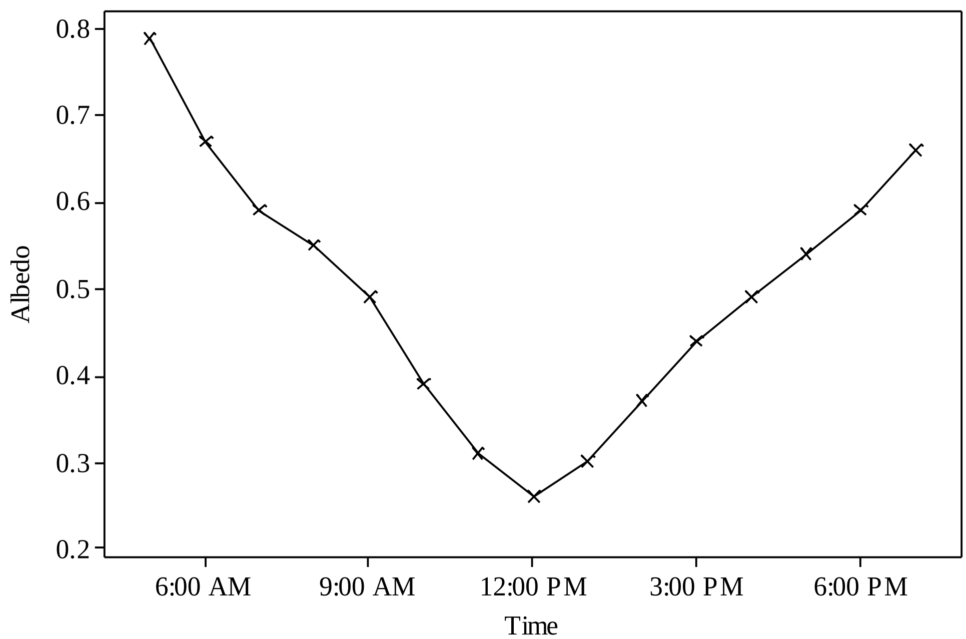

Figure 1. Hudson River albedo over the course of a typical summer day. Solar angle is largely responsible for the time of day effect (Rosenberg et al. 1983)

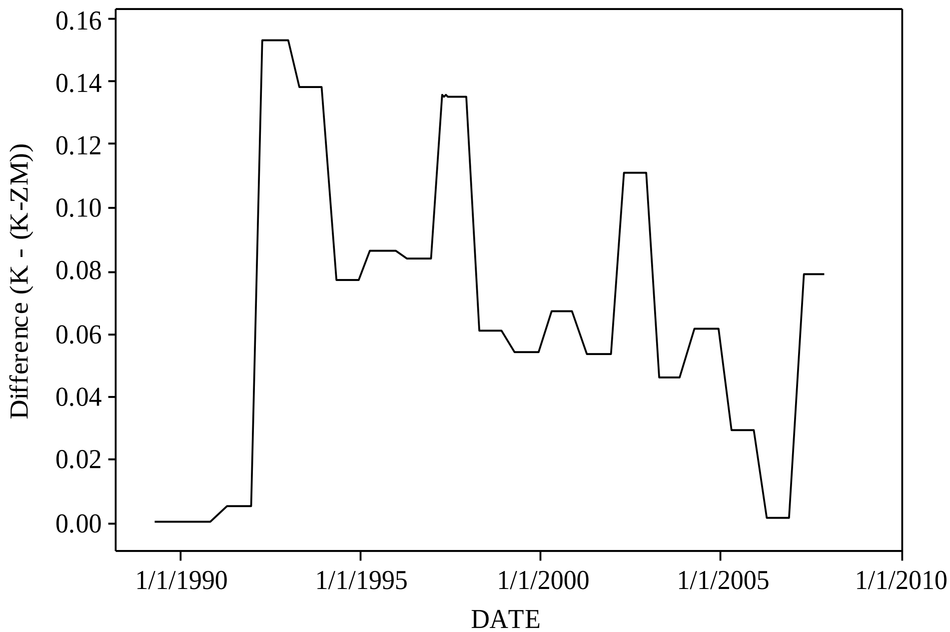

Figure 2. The difference in light extinction coefficient between observed and minus zebra mussel calculations. This difference is attributed to zebra mussel filtration. This portion of the light extinction coefficient follows the same 2-4 year cycle as the Hudson River zebra mussel population (Strayer and Malcom 2006).

Albedo varied greatly over the study period due to time of year, cloud cover and humidity. The median albedo was 0.455. Observed albedo ranged from 0.325 to 0.668. The modeled albedo closely tracked the observed albedo with a RMSE of 0.02161. The mean difference between modeled albedo and albedo minus the influence of zebra mussel filtration is 0.004234 with a standard deviation of 0.003. The change in albedo attributed to zebra mussel filtration follows the same two to four year cycle as the portion of the light extinction coefficient attributed to zebra mussel filtration (Figure 3). However, the difference between observed albedo and albedo minus zebra mussel filtration is negligible. Consequently it is not necessary to calculate equilibrium temperature for the scenario without zebra mussels because any difference would be well within measurement error and routine environmental variability.

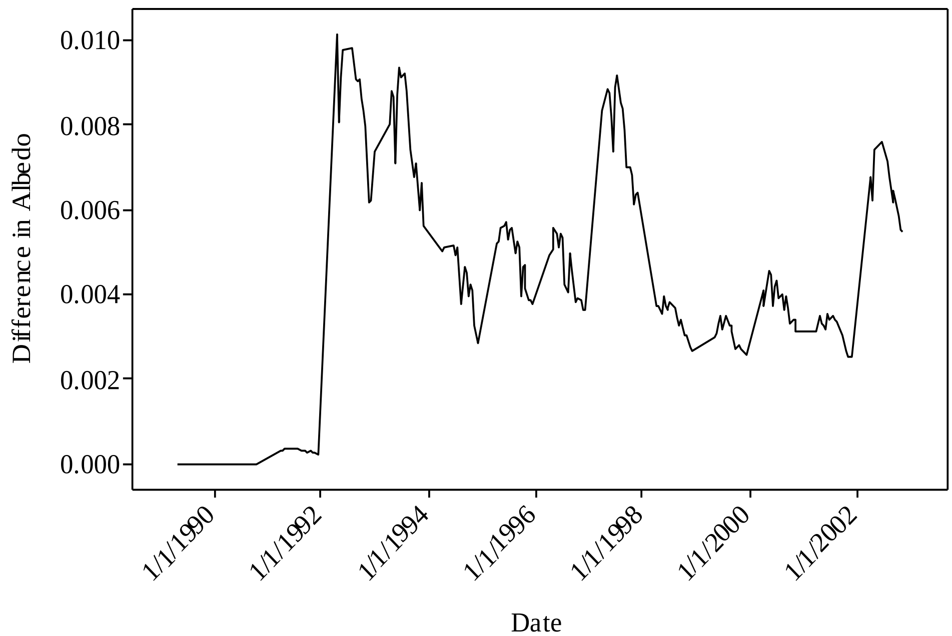

Figure 3. The difference in albedo between the observed data and a zebra mussel free scenario. The value is the change in albedo which is attributed to zebra mussel filtration. It follows the same cycle as the light extinction coefficient (figure 2) and the zebra mussel population cycle (Strayer and Malcom 2006).

The average air temperature over the period was 13.89°C (SD 6.86°C). Air temperature was roughly normally distributed with a minimum of -2.02°C and the maximum was 26.73°C. The mean equilibrium temperature was 18.74°C (standard deviation 13.73°C). Equilibrium temperature also roughly follows a normal distribution with a minimum of -10.76°C and maximum of 51.19°C. The upper extreme seems unreasonable. This could be due to the use of a relatively short time interval. At weekly or monthly time intervals the equilibrium temperature is expected to more reasonable. Water temperature roughly followed a heavy tailed normal distribution with a mean of 16.74°C, a minimum of 1.00°C and a maximum of 28.00°C. It should be noted that these values are based off of a biweekly sampling scheme during the ice free season and do not represent annual mean temperatures. Temperature trends were not tested for because it data were not collected at the equally spaced intervals generally necessary for trend analysis (Hirsch et al. 1991).

There was a linear relationship between equilibrium and water temperature. The ordinary least squares regression slope of the relationship is 0.35 (standard error 0.026). Equilibrium temperature explains 48.8% of variance in water temperature. Air temperature and equilibrium temperature also have a linear relationship with a least squares regression slope of 1.67 (standard error 0.079). Air temperature explains 69.7% of the variance in equilibrium temperature. Air temperature explained 68.4% of variance in water temperature. The slope of the relationship between air and water temperature was 0.83 (standard error 0.04). However, the air temperature/water temperature relationship begins to depart from linearity above approximately 20°C and below approximately 5°C.

DISCUSSION

The light extinction coefficient was difficult to model using the available data. While both light extinction and albedo changes attributed to zebra mussel filtration follow the two to four year cycle of the zebra mussel abundance (and hence filtration rates), the models did not resolve the change in light extinction found by Caraco et al. (1997. Standardized coefficients showed that zebra mussel filtration was unimportant relative to other parameters in the light extinction model. Light extinction, in turn, had relatively little impact in the albedo model. The small change in light extinction coefficient due to zebra mussel filtration results in a trivial changes in albedo and equilibrium temperature. The simple models used in this study are unable to show any zebra mussel induced changes in water temperature.

An alternative approach for assessing the influence of zebra mussel filtration may be to de-trend the influence of flow on water temperature and regress the residuals on zebra mussel filtration. Light extinction is jointly controlled by grazing and water flow (Strayer et al. 2008). Removing the influence of flow may make any zebra mussel dependent signal more apparent. This approach could be hampered by the relatively small number of zebra mussel samples.

While it does not find temperature changes due to increased filtration, this exercise does demonstrate the utility of the equilibrium temperature concept. The Hudson River is known to be warming (Ashizawa and Cole 1994). The relatively simple equilibrium temperature calculations may give more insight into the processes controlling water temperature. The impacts of changing cloud cover, thermal pollution, and relative humidity may be evaluated in ways that more simplistic air/water temperature regressions cannot.

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NOTATION

f_c	fractional cloud cover, dimensionless
H_s	incoming solar radiation, W m^{-2}
$H_{s,0}$	potential incoming solar radiation with a cloudless sky, W m^{-2}
H_l	net long wave radiation, MJ m^{-2} day^{-1}
H_e	evaporative heat flux, MJ m^{-2} day^{-1}
H_c	convective heat transfer, MJ m^{-2} day^{-1}
α	water surface albedo, dimensionless
L_{air}	irradiance in the air, µmol s^{-1} m^{-2}
L_0	irradiance at null depth, µmol s^{-1} m^{-2}
T_e	equilibrium temperature, °C
T_a	air temperature, °C
T_d	dew point temperature, °C

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