# Potential impact of climate change on bivalves in the tidal freshwater region of the Delaware River

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## Executive Summary

Bivalve shellfish perform numerous ecosystem services but are under threat from a variety of stressors. Climate change will alter the environmental conditions that bivalve shellfish are sensitive to, so restoration efforts should consider how the future climate will evolve. Here, climate model projections and statistical water quality models are used to estimate future changes in temperature, salinity, dissolved oxygen, and pH in the tidal freshwater region of the Delaware Estuary that are expected to result from increases in greenhouse gases and the associated climate change. Projections from eight regional climate models utilizing a medium-high emissions scenario are presented for the time period 2041-2070 during the summer, when bivalve growth rates are highest. Water temperature throughout the tidal freshwater region is expected to increase by 2.7 to 3.5 °C (95% confidence range). Near Reedy Island, where the current annual mean salinity is 4.4, salinity is expected to increase by 1.1 to 2.1 in summer as a result of streamflow declines and sea-level rise. However, in most of the tidal freshwater region, which is just upstream of Reedy Island, mean salinity change is expected to be very small, with the mean position of the 0.5 isohaline (which defines the seaward extent of the tidal freshwater region) projected to move landward by only 4 km. The combined effects of a decrease in solubility and an increase in respiration (both resulting from warming) lead to an oxygen concentration decrease of about 20 mmol $m^{-3}$ near Ben Franklin Bridge (the site of the lowest oxygen concentrations), which is a decline of approximately 13%. pH is expected to decline by 0.08 as a result of increased temperature, respiration, and atmospheric $CO_2$. The projected changes are expected have negative impacts on bivalves in the region, preferentially natives. The greatest concern regards the oxygen decline, which will increase the hypoxic stress that bivalves are currently experiencing during summer. Future research should consider changes in variability (e.g., changes in drought frequency and tidal range) as well as laboratory and field experiments to better quantify the impact of environmental conditions on bivalves in the tidal freshwater region.

## 1. Introduction

Bivalve shellfish perform numerous ecosystem services in aquatic systems, such as filtration, sediment stabilization, and habitat construction. The Delaware River System (including the river, estuary, and watershed) is home to about 60 species of bivalves and, as in many highly populated areas, these bivalves have substantially declined in numbers and extent as a result of a variety of stressors, including dam building, water quality impairments, habitat degradation, overfishing, and disease (Kreeger and Kraeuter, 2010). Though there have been reductions in some stressors (including an increase in dissolved oxygen levels), restoration efforts, such as reseeding and shell planting, are needed to re-establish vibrant bivalve communities.

The focus of this proposal is on the unique tidal freshwater region of the Delaware River, which extends from Trenton, NJ, the head-of-tide, to around Wilmington, DE, the approximate mean location of the 0.5 isohaline[1]. Climate change is a potential challenge to the successful restoration of bivalve communities because they are sensitive to temperature, salinity, sea level, flow, and water quality, all of which are likely to continue to change as a result of increases in greenhouse gases. Kreeger and Cole (2010) surveyed shellfish experts to identify the potential threats that a changing climate pose for bivalves in the Delaware River System. Increases in sea level and salinity were the major concern for tidal freshwater bivalves. It has been suggested that other climate-related changes will significantly affect bivalves in the future, such as acidification resulting from the invasion of anthropogenic carbon dioxide (Miller et al., 2009; Kreeger and Cole, 2010) and declining dissolved oxygen levels due to reduced solubility and increased respiration (Sparks and Strayer, 1998; Chen et al., 2001).

This proposal had three main objectives:

- Objective 1: To use a state-of-the art hydrodynamic model of the Delaware Estuary and projections of sea level, streamflow, and possibly other changes in climate resulting from increases in greenhouse gases to estimate the future change in extent and temperature of the tidal freshwater region of the Delaware River;
- Objective 2: To estimate the accompanying changes in pH and dissolved oxygen using a simple box model calibrated to historical data; and
- Objective 3: To work with an expert on bivalves in the Delaware River System to translate the projected changes in salinity, temperature, pH, and dissolved oxygen concentration to changes in the potential habitat of bivalves in upper portion of the Delaware Estuary.

## 2. Methodology

To achieve Objective 1, we used projections from the North American Regional Climate Change Assessment Program (NARRCAP; Mearns et al., 2009; Mearns et al., 2012), which uses eight combinations of regional climate models of relatively high spatial resolution (50 km) embedded in Global Climate Models (GCMs) of coarser resolution. These models simulated the historical climate of North America for the period 1971-2000 and projected the climate over the same domain for the period 2041-2070 under the A2 emissions scenario (Nakićenović and Swart, 2000), which is in the mid-to-upper range of emissions scenarios used by the Intergovernmental

[1] Salinity is reported in practical salinity units (psu). 1 psu is very nearly equal to 1 part per thousand.

Panel on Climate Change for their Fourth Assessment Report. We used projections of surface air temperature and runoff from the NARCCAP models. Temperature was averaged over the Delaware River Basin (DRB); because temperature change in estuaries generally follows regional temperature change (e.g., Preston, 2004), we assumed the change in water temperature of the tidal freshwater portion of the Delaware Estuary was the same as the change in air temperature over the DRB. Changes in streamflow were determined by spatially integrating (over the watershed of the DRB draining to Trenton, NJ) the runoff output of the land-surface component of the NARCCAP models. Probability distributions of projected changes in temperature and streamflow were generated using the technique of Tebaldi et al. (2005), which weights models according to their simulations of the past and their convergence towards other models in the future.

Though we have been working on a three-dimensional model of the Delaware Estuary and have given presentations on it (see Appendix B), the model was not sufficiently developed for use in climate-change applications. We therefore used a statistical approach for determining salinity change in the upper Delaware Estuary resulting from changes in streamflow and sea level (Ross et al., 2015); the statistical model was trained using long-term (1950-present) records of salinity from the United States Geological Survey (USGS) and the Haskin Shellfish Research Laboratory. The statistical models include non-parametric terms and are robust against autocorrelated and heteroscedastic errors. After using the models to remove the influence of streamflow and seasonal effects on salinity, several locations in the estuary show significant upward trends in salinity. Insignificant trends were found at locations that are normally upstream of the salt front. Downstream of the salt front, the models indicate a positive correlation between rising sea levels and increasing residual salinity, with salinity rising from 2.5 to 4.4 per meter of sea-level rise. These results are consistent with results from one-dimensional (1D) and dynamical models; in this report, we also present some results from our own implementation of Savenije's (1993) 1D model.

To estimate the sea level increase by the mid-21$^{st}$ century, we used the global projections of Rahmstorf (2007) for 2055, augmented by a subsidence term determined from the difference between historical rates of global sea-level rise and local sea-level rise.

To achieve Objective 2, we constructed a dissolved oxygen budget of the upper portion of the Delaware Estuary using dissolved oxygen concentration data from USGS stations located at Reedy Island, Ben Franklin Bridge, and Trenton (Tomaso and Najjar, 2015). From this analysis, we determined how net oxygen consumption and respiration have changed from 1970 to the present at monthly resolution. A relationship between temperature and respiration was determined, which we combined with warming projections to estimate future changes in respiration. The analysis also showed that respiration and oxygen levels were tightly linked, which then allowed us to determine future oxygen change in the estuary. To account for the impact of warming on oxygen via solubility effects only, we used the known temperature dependence of the oxygen saturation concentration (Garcia and Gordon, 1992). Changes in pH due to respiration were determined from a statistical correlation with oxygen. pH changes resulting from increasing temperature and atmospheric $CO_2$ concentration were also estimated using the known equilibrium constants of the carbonate system.

To achieve Objective 3, we consulted with a specialist on bivalves in the Delaware Estuary, Dr. Danielle Kreeger, who is the Science Director at the Partnership for the Delaware Estuary (PDE). Bivalves have highest growth rates in the summer and this is therefore the time period that we focused our analysis on.

## 3. Results

### *3.1. Projected changes in temperature, streamflow, sea level, and salinity*

Projected changes in winter (December-February) and summer (June-August) from the NARCCAP models are shown for temperature in Figure 1 and for streamflow in Figure 2. The best estimates of warming (and corresponding 95% confidence intervals) are 2.68 (2.62, 2.87) °C in the winter and 3.06 (2.66, 3.48) °C in the summer. For most models, streamflow increases in the winter and decreases in the summer. The most likely change in summer is -41 (-52.9, -2.7) $m^3 s^{-1}$, which is a decline of 19% (mean summer flow is 218 $m^3 s^{-1}$).

Global sea level, according to the model of Rahmstorf (2007), is expected to increase by about 0.34 m by 2055 (with respect to a 1990 baseline), a result that is very insensitive to the emissions scenario. Sea-level rise at Philadelphia during the second half of the $20^{th}$ century was 2.7 mm $yr^{-1}$ (Zervas, 2001) whereas the global average rate during this time was 1.8 mm $yr^{-1}$ (Church et al., 2004). We estimate the subsidence rate for the upper Delaware Estuary to be the difference of these two rates, or 0.9 mm $yr^{-1}$. Thus from 1990 to 2055, we estimate a subsidence contribution to sea-level rise of 0.06 m, giving a relative sea-level rise of 0.34 m + 0.06 m = 0.40 m.

We estimated salinity change at two locations in the Delaware Estuary: Ben Franklin Bridge (mean salinity 0.12) and Reedy Island (mean salinity 0.44). We focus on these sites because both are data-rich, the Reedy Island station is closest to the mean position of the tidal freshwater boundary (salinity ~0.5, which is about 10 km upstream of Reedy Island, on average), and the Ben Franklin Bridge station is closest to the location of the historically lowest oxygen concentrations. Statistical and 1D models were used. We note that the statistical models showed significant relationships between salinity and streamflow at both locations (Ross et al., 2015). A significant linear relationship between salinity and sea level was found at Reedy Island (3.3 $m^{-1}$) but not at Ben Franklin Bridge. Figure 3 shows salinity calculations conducted by Ross et al. (2015). They found that the 1D model of Savenije (1993) reproduced the average salinity along the main axis of the estuary (Figure 3a). Statistical and 1D approaches to estimating the sensitivity to sea level agree well at most locations throughout the estuary (Figure 3b). In particular, a 1-m sea-level rise is predicted to increase salinity at Reedy Island by slightly more than 3 and to have little effect upstream of Chester, including Ben Franklin Bridge. Streamflow changes are expected to have significant effects on salinity only in the central portion of the Bay (with the 1D model exhibiting more sensitivity) whereas little change is seen at Chester and upstream locations (Figure 3c).

The actual projected changes in salinity at Ben Franklin Bridge and Reedy Island resulting from streamflow change by 2041-2070 using the statistical models combined with NARCCAP streamflow projections are shown in Figure 4. The overwhelming majority of models projects salinity declines in winter and salinity increases in summer. However, the salinity changes at Ben Franklin Bridge are extremely small. The effect of sea-level rise on salinity at Reedy Island by 2055 (with respect to 1990) was, using the statistical model, 0.40 m × 3.3 $m^{-1}$ = 1.3, larger in magnitude than the streamflow-induced changes in salinity. In winter, streamflow and sea-level effects cancel to some extent, with estimated increases between 0.4 and 1.7, whereas in summer they work together, increasing salinity by 1.1 to 2.1 (Figure 5). According to the 1D model, the 0.5 isohaline moves landward by 3.8 and 9.3 km for sea-level rises of 0.4 and 1 m, respectively.

### *3.2. Projected changes in oxygen and pH*

We considered changes in oxygen concentration due to the impact of warming on the saturation concentration and on respiration. We focus our analysis at Ben Franklin Bridge, which is where oxygen concentrations are typically lowest (Figure 6). A warming of 3 °C in the summer (from the present mean temperature of 26 °C to a future mean temperature of 29 °C) will cause the saturation concentration to decrease by 5.2% or 13.2 mmol $m^{-3}$. The impact of temperature on respiration was estimated using results from Tomaso and Najjar (2015). They constructed an oxygen budget (or box model) in the upper Delaware Estuary by directly computing lateral advection and exchange with the atmosphere and then determined net oxygen consumption as a residual term in the budget. Primary production data were combined with the net oxygen consumption rates to estimate respiration. A climatology of respiration was computed for two time periods in two regions (or boxes) of the upper estuary: between Trenton and Ben Franklin Bridge (Box 1) and between Ben Franklin Bridge and Reedy Island (Box 2); see Figure 7. The relationship between climatological respiration and temperature is shown in Figure 8. Slopes are generally weaker in Box 1 than in Box 2 and in the earlier period than in the later period. Figure 9 shows net oxygen consumption in Boxes 1 and 2 and oxygen concentration at Ben Franklin Bridge. Both are shown as anomalies (departures from the mean annual cycle). It is clear that as oxygen consumption increases, dissolved oxygen concentration decreases. An increase in oxygen consumption by 1 mol $m^{-2}$ $mon^{-1}$ corresponds to an oxygen concentration decline of about 20 mmol $m^{-3}$. We used the slope of the line in Figure 8 for Box 1 during the later period (which is more representative of future water quality conditions than the earlier one is, due to wastewater treatment improvements): 0.14 mol $m^{-2}$ $mon^{-1}$ $°C^{-1}$. A warming of 3 °C thus results in a respiration increase of 0.42 mol $m^{-2}$ $mon^{-1}$, which leads to a decline in oxygen concentration of 8.4 mmol $m^{-3}$. Thus, the combined effects of a decrease in solubility and an increase in respiration lead to an oxygen concentration decline of about 20 mmol $m^{-3}$ at Ben Franklin Bridge.

Summer oxygen concentrations at Ben Franklin Bridge during summer are typically 100 mmol $m^{-3}$ below the saturation level of approximately 250 mmol $m^{-3}$ (Figure 6). Thus typical summer concentrations are 150 mmol $m^{-3}$. We estimate that conditions in 2041-2070 will be more like 130 mmol $m^{-3}$, an approximately 13% decline.

pH change at Ben Franklin Bridge was estimated using the correlation between pH and oxygen concentration. pH has increased with time at Ben Franklin Bridge, most likely as a result of declining net oxygen consumption. From the 1970s to the 2000s, summer pH levels at Ben Franklin Bridge increased from roughly 6.5 to 7.0. At the same time, summer oxygen levels at this location increased by about 50 to 150 mmol $m^{-3}$. Thus, an oxygen decline of 10 mmol $m^{-3}$ resulting from increased respiration corresponds to a pH decline of about 0.05. Warming itself will also lead to a pH decline. The mean summer pH at Ben Franklin Bridge for 1995-2014 is 6.984. The mean alkalinity at Ben Franklin Bridge is 672 meq $m^{-3}$, which was estimated by linearly regressing alkalinity vs. salinity (data from Sharp et al., 2009) and the using the fit to compute alkalinity at zero salinity. We used the CO2SYS program (Lewis et al., 1998) to compute the concentration of dissolved inorganic carbon (DIC), which, like alkalinity is unaffected by temperature change. Holding these values of alkalinity and DIC constant, CO2SYS was then used again to compute the pH decline of 0.0155 resulting from temperature increasing from 26 to 29 °C. Finally, the atmospheric $CO_2$ increase under the A2 emissions scenario is expected to be 167 ppm, which is expected to cause pH to decline. To calculate the pH change CO2SYS was used to compute the mean summer partial pressure of CO2 in the water (4605 ppm). When this is increased by 167 ppm, holding alkalinity constant, CO2SYS estimates a pH decline of 0.0155, the same as the temperature-induced decline. Thus, we expect a total pH decline at Ben Franklin Bridge of approximately 0.05 + 0.0155 + 0.0155 = 0.08.

### *3.3. Impact on bivalves*

Bivalves in the tidal freshwater region of the Delaware Estuary include six native species, all freshwater mussels, and two non-native species (Table 1). Only one of the native species, *E. complanata*, has a secure status in Pennsylvania. Another native species, *L. ochracea*, was, until recently, thought to be extirpated in the commonwealth. Recent surveys by the PDE and collaborators have found much greater mussel biodiversity in the tidal freshwater region than in the non-tidal region, which it shares many species with (Kreeger and Kraeuter, 2010). This discovery suggests that the tidal freshwater region may serve as the only remaining genetic broodstock for many natives in the Delaware River System.

Several studies have been conducted regarding the impacts of temperature, salinity, and dissolved oxygen on freshwater bivalves (McMahon, 1979; Sparks and Strayer, 1998; Chen et al., 2001; Verbrugge et al., 2003; Haag and Warren, 2008; Spooner and Vaughn, 2008; Galbraith et al., 2012; Gruttersa et al., 2012), which provide a basis for estimating the potential impacts of climate change on freshwater bivalves in the tidal Delaware River.

The low salinity tolerance of native bivalves (Table 1) suggests that increases in salinity associated with sea-level rise will have a negative impact on these organisms. Therefore, non-native species, which have a greater salinity tolerance (Table 1), may have a competitive advantage in the future. However, changes in mean salinity are expected to be very small in all except the very downstream portion of the tidal freshwater region. Thus, salinity increase does not seem like a dramatic threat at this time. We caution, however, that our analysis focuses on changes in mean conditions and hence does not consider salinity change associated with increases in extreme drought, increases in tidal range, etc.

Warming is expected to have negative impacts on freshwater mussels, such as *E. complanata*, by, for example, increasing oxygen consumption (Chen et al., 2001). Verbrugge et al. (2003), in a study in the Rhine River, found that warming had a negative impact on native species but not non-natives, like the Asian clam, which is present in the Delaware Estuary (Table 1). Galbraith et al. (2012) conducted laboratory experiments with three freshwater mussels, including *E. complanata* and *S. undulatas* (both native to the Delaware Estuary, Table 1) to look at the effect of temperature acclimation on maximum temperature tolerance. They found that acclimation increases temperature tolerance.

Negative impacts of dissolved oxygen declines have been documented in several studies. Chen et al. (2001) found increasing oxygen consumption with declining oxygen concentration. Sparks and Strayer (1998) found that bivalves exhibited increased stress behavior under low dissolved oxygen, including “extending their siphons, gaping, and surfacing more often than clams exposed to higher concentrations of oxygen.” Some synergistic effects with temperature were found. For example, in the study of Galbraith et al. (2012), temperature tolerance could be developed with preconditioning only under relatively high dissolved oxygen concentrations. Kahn et al. (2014) argued that, based on the existing literature, “a safe level that would avoid chronic stress would be 6 mg $l^{-1}$ or greater in bottom waters over a 24-hour daily averaging period. This translates to nearly 190 mmol $m^{-3}$, which is well above current summer levels near Ben Franklin Bridge (~150 mmol $m^{-3}$).

We are unaware of any literature documenting the impact of pH changes on freshwater bivalves. However, the projected pH decline is small (0.08), suggesting a modest impact.

In summary, projected changes in temperature, salinity, and dissolved oxygen resulting from climate change are expected to worsen conditions for freshwater bivalves (particularly natives) in the tidal Delaware River. Oxygen seems to be of greatest concern because bivalves are still stressed there, even after decades of improved water quality.

## 4. Conclusions

We have estimated future changes in temperature, salinity, dissolved oxygen, and pH resulting from increases in greenhouse gases for the tidal freshwater region of the Delaware Estuary and discussed potential impacts of these changes on bivalves in this region. Focusing on the summer period, when bivalve growth rates are highest, projections by the middle of the 21st century are for increases in temperature and salinity and decreases in dissolved oxygen and pH. Sea-level rise and streamflow declines are responsible for the salinity increases, which are limited to the very downstream portion of the tidal freshwater region. The oxygen decline results from warming-induced changes in oxygen solubility and respiration. The pH decline results mainly from increases in respiration and to a lesser extent increases in temperature, respiration, and atmospheric $CO_2$.

The projected changes are expected to have negative impacts on bivalves in the region, preferentially natives. There is some evidence for temperature acclimation and the salinity increase may be of limited spatial extent. The greatest concern regards the oxygen decline, which will increase the hypoxic stress that bivalves are currently experiencing during summer.

## 5. Additional research indicated

There are two large areas of uncertainty in projecting future impacts of climate change on bivalves in the tidal freshwater region of the Delaware Estuary. First, the projections of environmental change (temperature, salinity, oxygen, and pH) are for mean conditions. Projections need to include changes in variability, particularly extreme events, which bivalves are more likely to be affected by in the future. For example, summer droughts are likely to place high stress on bivalves by increasing temperature and salinity and decreasing oxygen and pH to extreme levels. In addition, sea-level rise is likely to see an increase in tidal range (Walters, 1992; Zhong et al., 2008), which could increase salinity extremes and possibly lead to exposure of mudflats at low tide, which bivalves are intolerant of. A second area of uncertainty is the combined impact of multiple stressors on bivalves. There is very little research on the synergistic effects of climate change (e.g., combined effects of temperature and salinity). Furthermore, studies that address acidification impacts on freshwater bivalves would be useful.

## Appendix A: Staff, Students Supported, Outreach/Extension

### a. Staff

i. Number of individuals: 1 (Raymond Najjar)

ii. Number of full-time employees (as part of the grant): 1

iii. Number of full-time employees (as part of match): 0

### b. Students Supported

i. Number of Undergraduate Students: 0

ii. Number of Graduate Students: 2

iii. Number of Ph.D. Students: 2

iv. Degrees Awarded (please indicate level): 2 Masters

Support was provided for Daniel Tomaso and Andrew Ross, who completed their Masters degrees with support from this project. References for their theses are:

Tomaso, D., 2013. Seasonal and interannual variability of the upper Delaware Estuary dissolved oxygen and dissolved inorganic carbon budgets, Masters Thesis. Department of Meteorology, The Pennsylvania State University, 32 pp.

Ross, A.C., 2013. Influences on salinity variability and change in the Delaware Estuary, Masters Thesis. Department of Meteorology, The Pennsylvania State University, 53 pp.

### c. Outreach/Extension

i. Number of meetings, workshops, or conferences, and number of attendees: Seven presentations were given at four meetings. Number of attendees at these meetings ranged from tens (Science of Source Water) to thousands (Ocean Sciences Meeting). The presentation given were:

Najjar, R., 2013. Climate change and the Delaware River Basin. Science of Source Water Workshop, Pinchot Institute for Conservation, Delaware Valley Regional Planning Commission, Philadelphia, PA, August 21, 2013.

Tomaso, D., Najjar, R.G., 2013. Estimates of net community production in the Upper Delaware Estuary. Delaware Estuary Science & Environmental Summit 2013, Cape May, NJ, January 27-30, 2013.

Najjar, R.G., Ross, A., Kreeger, D., Kilham, S., 2013. Historical climate change and variability in the Delaware River Basin. Delaware Estuary Science & Environmental Summit 2013, Cape May, NJ, January 27-30, 2013.

Ross, A., Najjar, R.G., 2013. Influence on subtidal salinity variability and change in the Delaware Estuary. Delaware Estuary Science & Environmental Summit 2013, Cape May, NJ, January 27-30, 2013.

Tomaso, D., Najjar, R.G., 2013. Seasonal and interannual variability of the Upper Delaware Estuary dissolved oxygen budget. Mid-Atlantic Bight Physical Oceanography and Meteorology Conference, University of Rhode Island, Narragansett, RI, October 17-18, 2013.

Tomaso, D., Najjar, R.G., 2014. Seasonal and interannual variability of the Upper Delaware Estuary dissolved oxygen budget. Ocean Sciences Meeting, Honolulu, Hawaii, February 23-28, 2014.

Ross, A.C., Li, M., Najjar, R.G., Herrmann, M., 2014. High-resolution simulations of Chesapeake and Delaware Bays under past and future climates. Ocean Sciences Meeting, Honolulu, Hawaii, February 23-28, 2014.

ii. Number of public or professional presentations, and number of attendees: none

## Appendix B: Impact Statement

**Title:** Climate change likely to place additional stress on bivalve shellfish of the tidal freshwater region of the Delaware Estuary

**Recap:** A study sponsored by Pennsylvania Sea Grant suggests that temperature, salinity, oxygen, and pH levels in the tidal freshwater region of the Delaware Estuary will become less favorable for bivalve shellfish in the future as a result of climate change.

**Relevance:** Bivalve shellfish in the tidal freshwater portion of the Delaware Estuary provide numerous benefits, such as water filtration and habitat construction. These bivalves have substantially declined in numbers and extent as a result of water quality impairments, habitat degradation, overfishing, and disease. Climate change is a potential challenge to the successful restoration of bivalve shellfish communities because these organisms are sensitive to temperature, salinity, dissolved oxygen, and pH, all of which are likely to continue to change as a result of increases in greenhouse gases.

**Response:** Climate and statistical water quality models were used to estimate future changes in temperature, salinity, dissolved oxygen, and pH in the tidal freshwater region of the Delaware Estuary. Implications for bivalve shellfish communities were discussed.

**Results:** Increases in greenhouse gases are projected to increase temperature and salinity and decrease dissolved oxygen and pH in the tidal freshwater region of the Delaware Estuary. These changes are expected to place additional stress on bivalve shellfish communities and pose an additional challenge to restoration efforts.

Table 1. Bivalves of the tidal freshwater region of the Delaware Estuary. After Kreeger and Krauter (2010).

| **Scientific Name** | **Common Name** | **Relative abundance** | **Pennsylvania Conservation Status** | **Salinity range** |
|---|---|---|---|---|
| | | | | |
| **Native** | | | | |
| Elliptio complanata | Eastern Elliptio | locally abundant | Secure | 0 |
| Lampsilis cariosa | Yellow lampmussel | uncommon | Vulnerable | 0 |
| Leptodea ochracea | Tidewater mucket | rare | Extirpated? | 0 |
| Ligumia nasuta | Eastern pondmussel | locally common | Critically imperiled | 0 |
| Pyganodon cataracta | Eastern floater | locally common | Vulnerable | 0 |
| Strophitus undulatus | Squawfoot | rare | Apparently secure | 0 |
| | | | | |
| **Non-native** | | | | |
| Corbicula fluminae | Asian clam | abundant | NA | 0-2 |
| Rangia cuneata | Atlantic rangia | abundant | NA | 0-10 |

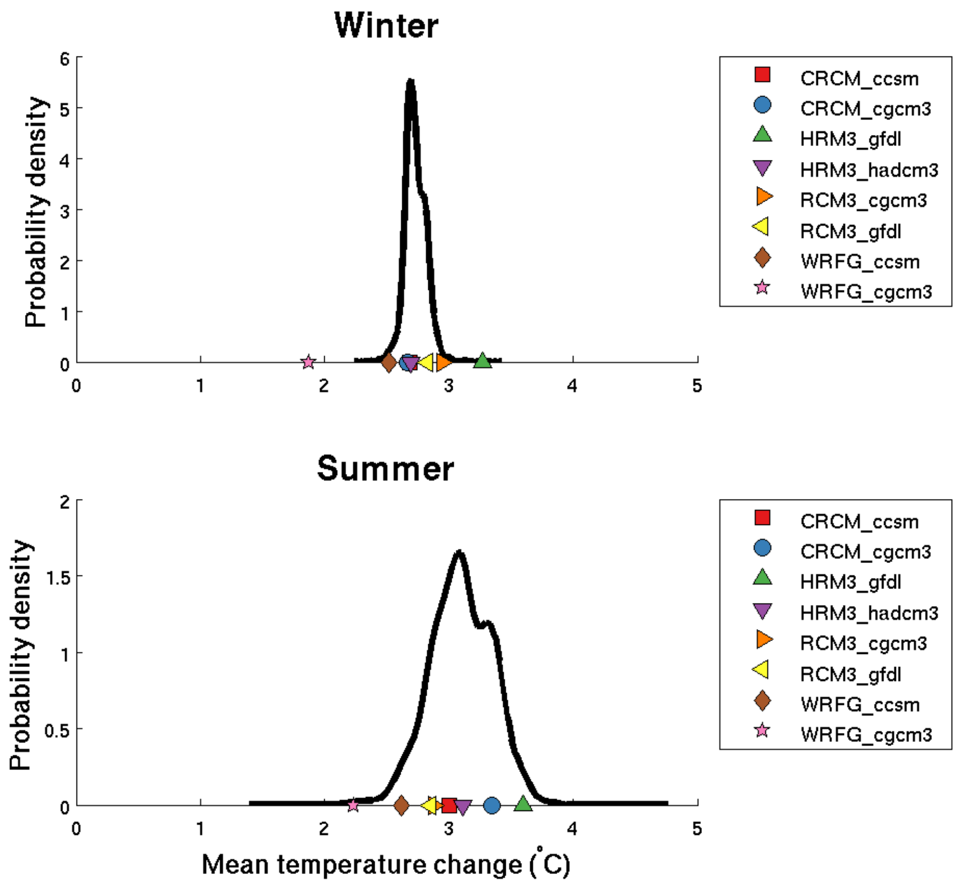


Fig. 1. Projected temperature change as of 2041-2070 by the eight NARCCAP models (symbols) and probability distribution (line) for winter (December-February) and summer (June-August).

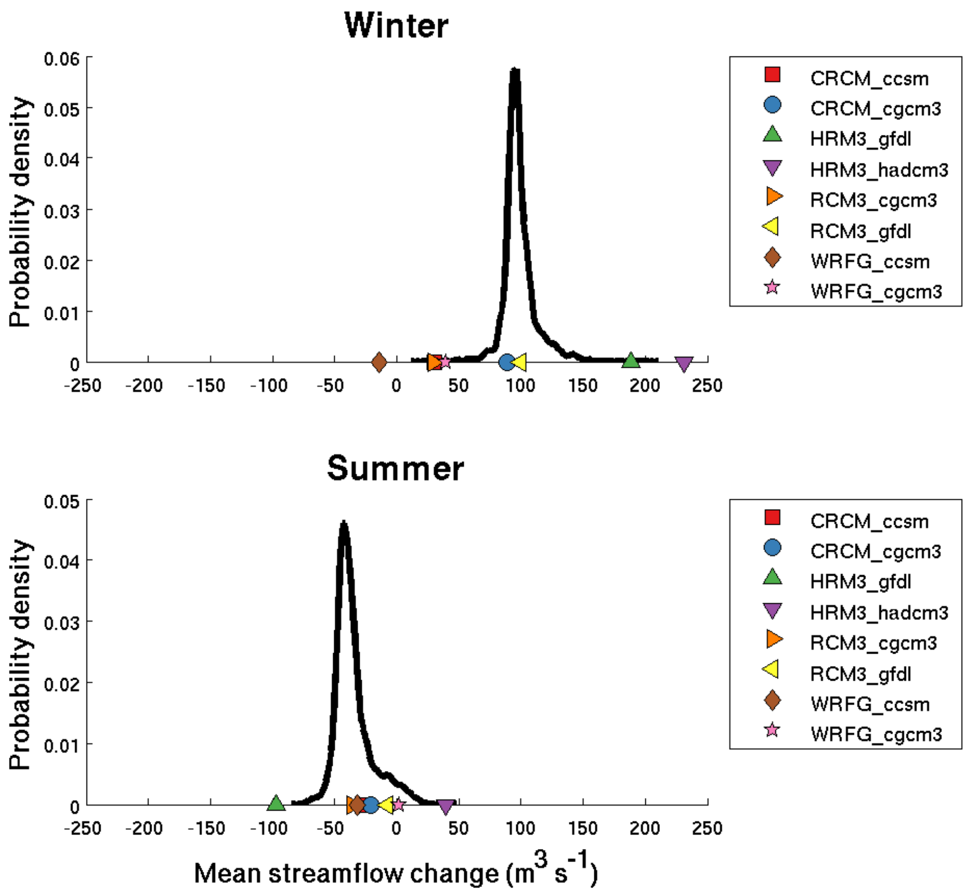


Fig. 2. Projected streamflow change as of 2041-2070 by the eight NARCCAP models (symbols) and probability distribution (line) for winter (December-February) and summer (June-August). For reference, the annual mean streamflow of the Delaware River at Trenton is 365 $m^3 s^{-1}$ (1970-2014).

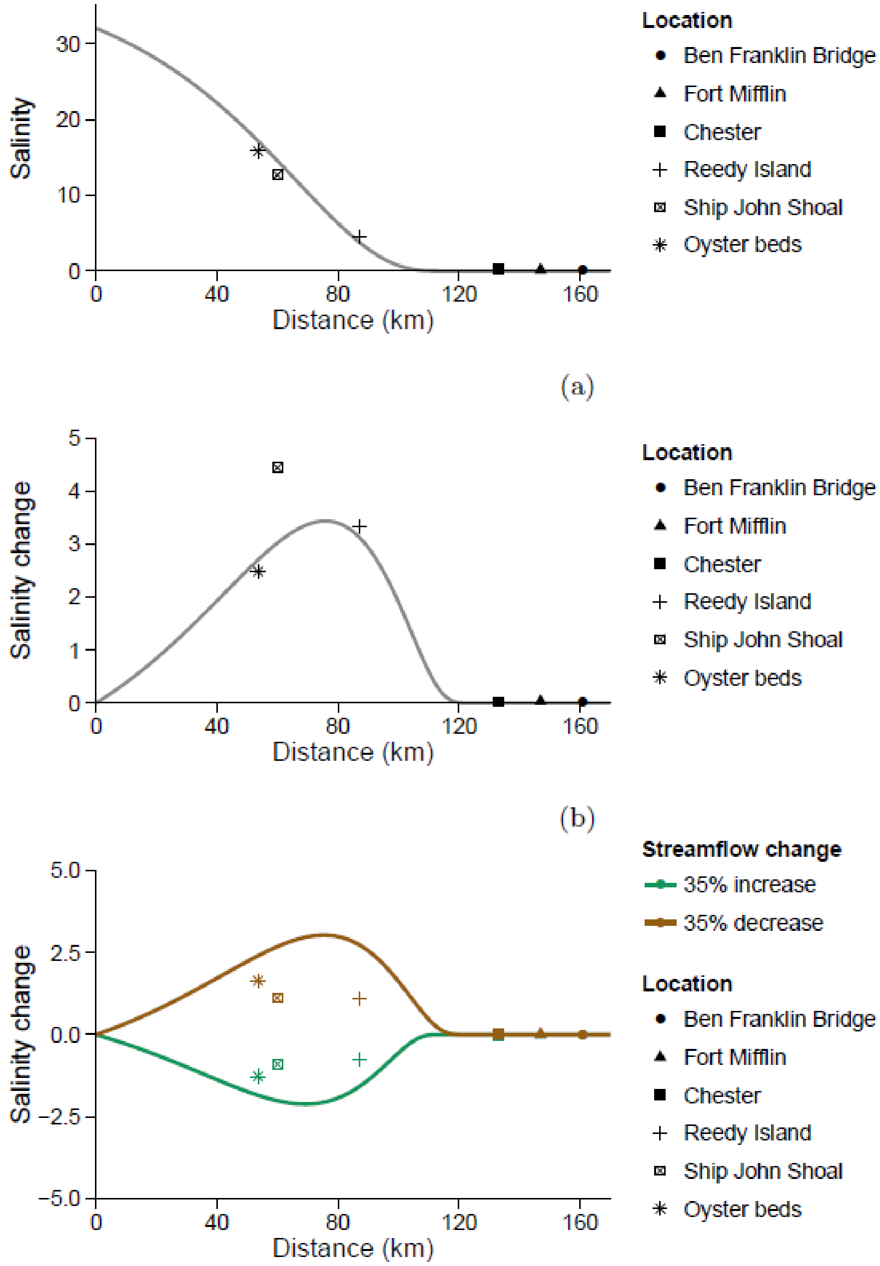


Fig. 3. (a) Comparison between observed salinity and salinity predicted by the 1D model of Savenije (1993). The shapes are the observed salinity and the lines denote the 1D model predictions. The distance for the oyster beds is determined by the mean distance weighted by number of observations. (b) Projections of salinity change in response to 1 m of sea-level rise under current mean streamflow. Solid lines are from the 1D model of Savenije (1993). Shapes are from the statistical models. (c) Projections of salinity change in response to a 35% increase or decrease in streamflow under current mean sea levels. Solid lines are from the Savenije (1993) 1D model. Shapes are from the statistical models. Reproduced from Ross et al. (2015).

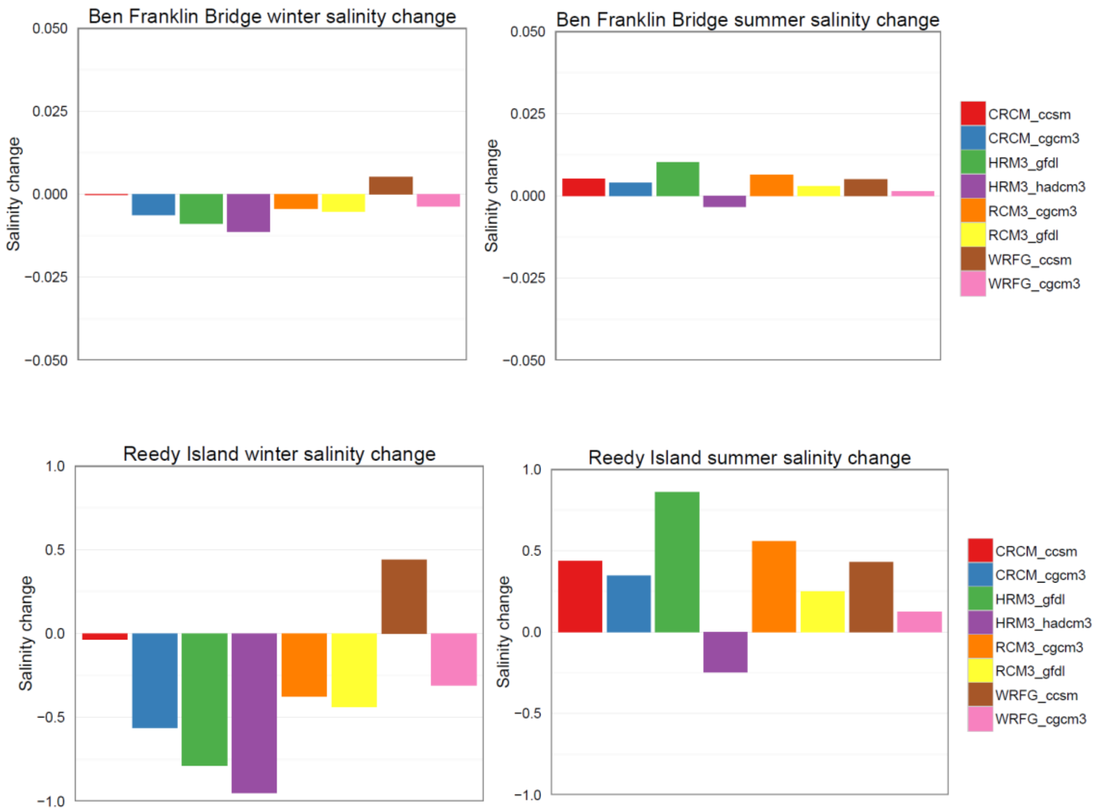


Fig. 4. Projected streamflow-induced salinity change by 2041-2070 at Ben Franklin Bridge (top) and Reedy Island (bottom) during winter (left) and summer (right).

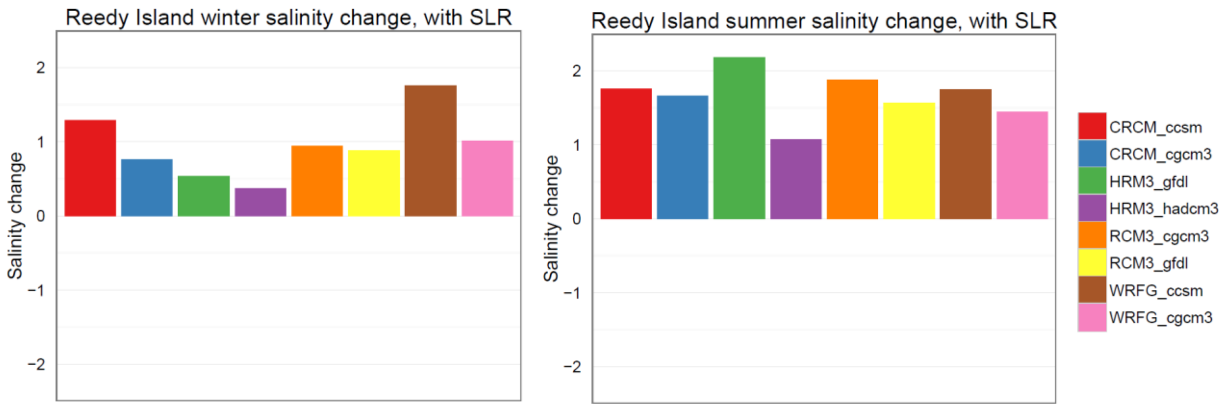


Fig. 5. Projected salinity change by 2041-2070 at Reedy Island during winter (left) and summer (right) due to the combined effects of changes in streamflow and sea level.

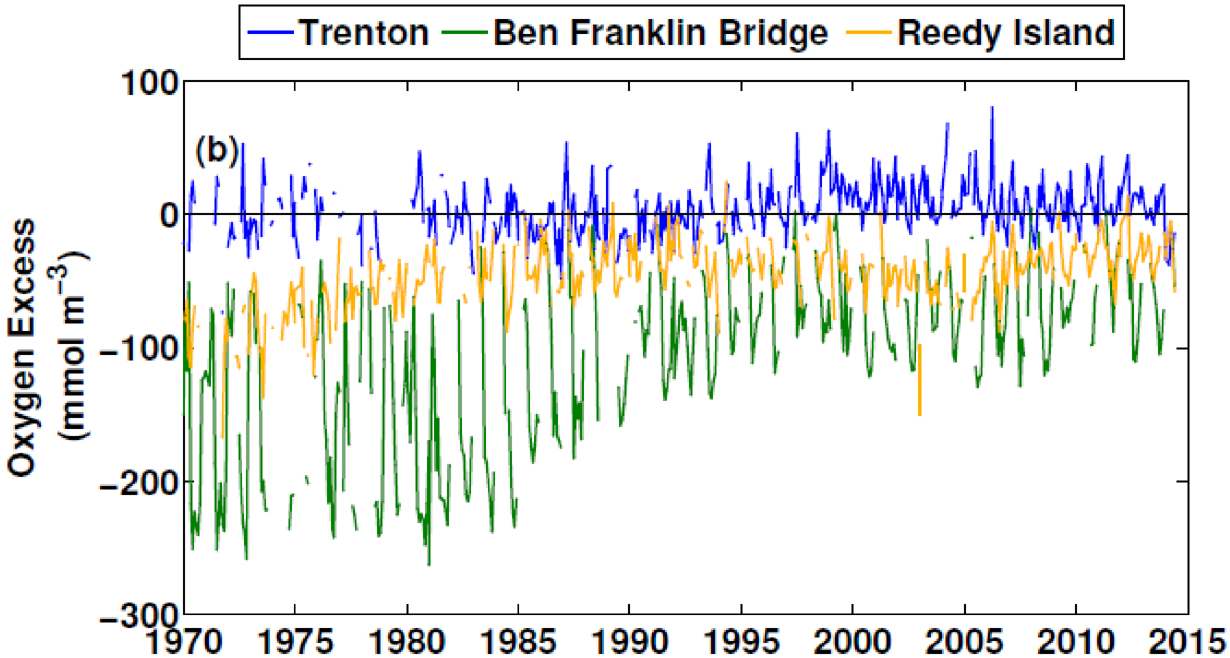


Fig. 6. Trenton, Ben Franklin Bridge, and Reedy Island monthly means of dissolved oxygen excess (the departure from the saturation concentration). Data are from USGS. Reproduced from Tomaso and Najjar (2015).

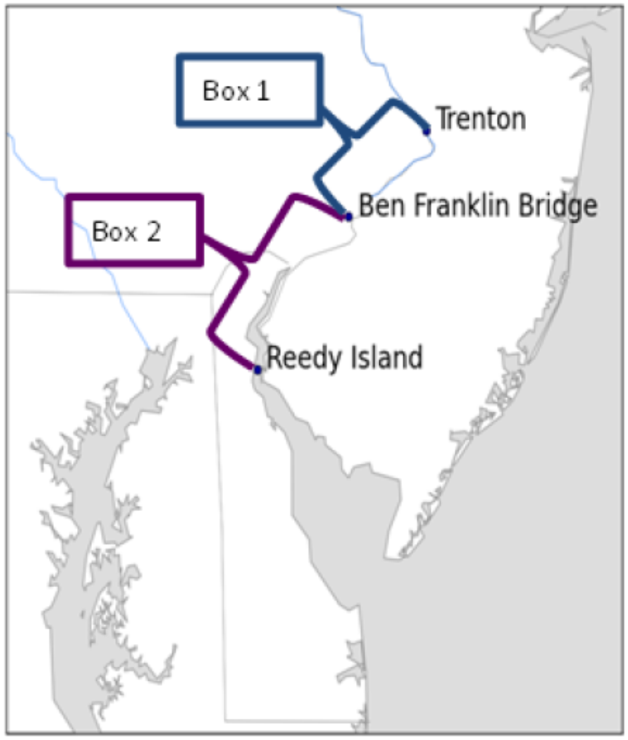


Fig. 7. Map showing the study area of the oxygen budget study of Tomaso and Najjar (2015), including locations of the three USGS stations in the upper Delaware Estuary and the two boxes (1 = tidal freshwater and 2 = oligohaline) for which oxygen budgets are constructed.

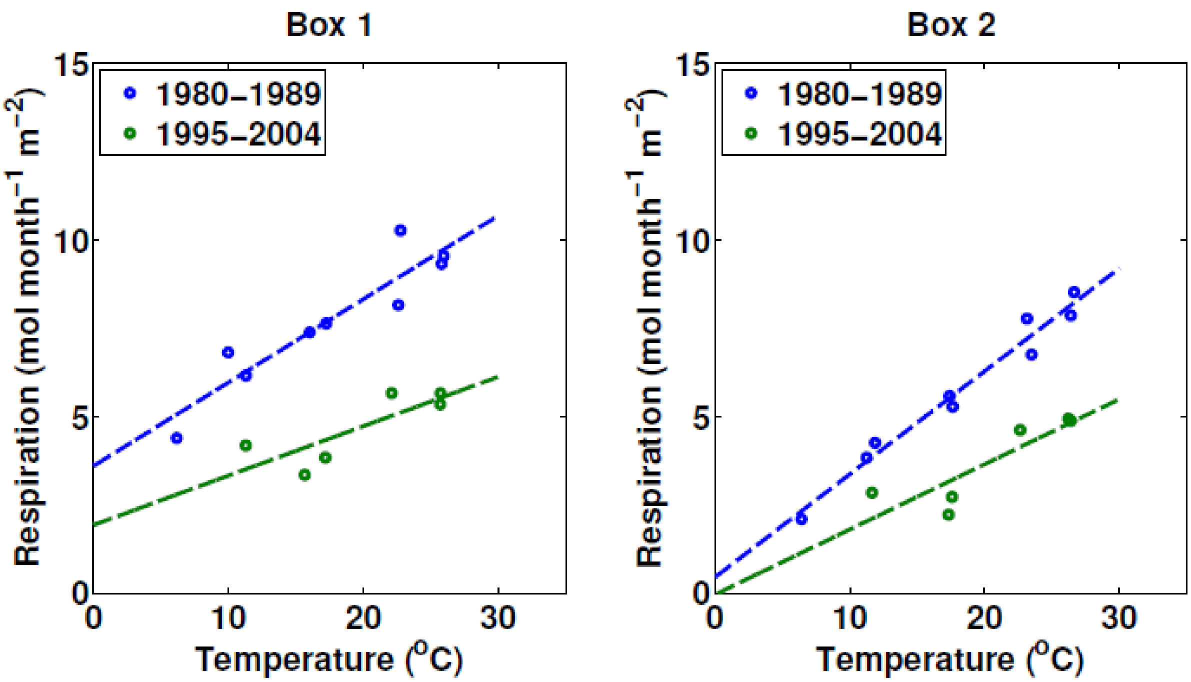


Fig. 8. Monthly averages of respiration over two time periods in Boxes 1 and 2 (1 = tidal freshwater and 2 = oligohaline) plotted versus climatological water temperature for the corresponding months. All linear fits are significant at the 95% confidence level. Reproduced from Tomaso and Najjar (2015).

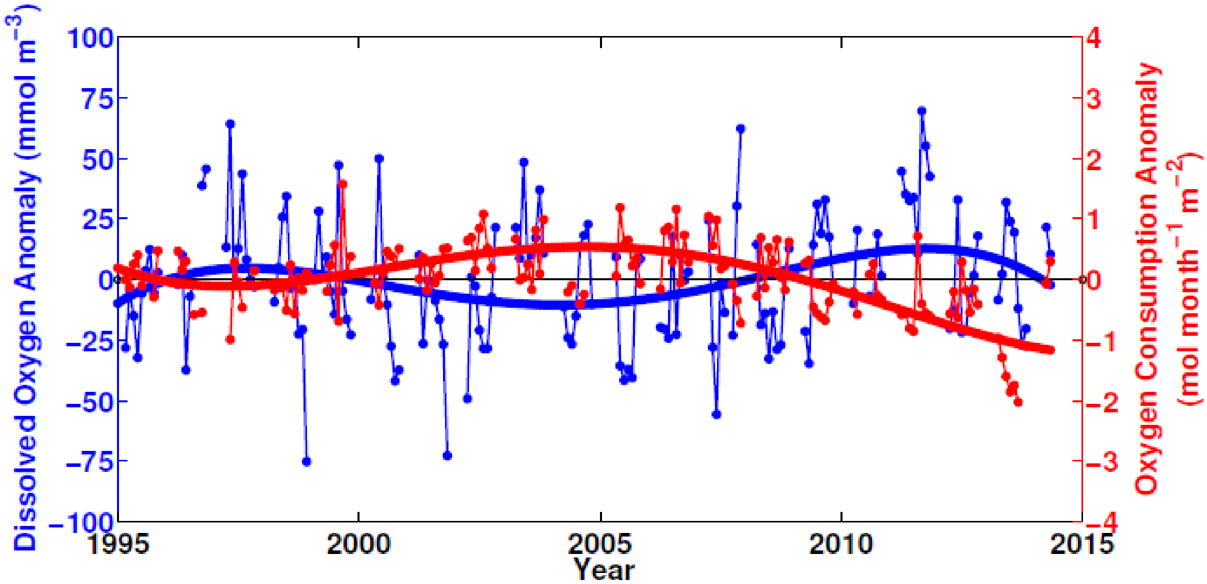


Fig. 9. Anomalies of the dissolved oxygen concentration at Ben Franklin Bridge (blue) and the net oxygen consumption rate averaged over Boxes 1 and 2 (red) from 1995 to 2014. The points are monthly values and the smooth lines are fourth-order polynomial fits. Reproduced from Tomaso and Najjar (2015).

## References


Chen, L.-Y., Heath, A.G., Neves, R.J., 2001. Comparison of oxygen consumption in freshwater mussels (Unionidae) from different habitats during declining dissolved oxygen concentration. Hydrobiologia 450, 209-214.

Church, J.A., White, N.J., Coleman, R., Lambeck, K., Mitrovica, J.X., 2004. Estimates of the regional distribution of sea level rise over the 1950-2000 period. Journal of Climate 17, 2609-2625.

Galbraith, H.S., Blakeslee, C.J., Lellis, W.A., 2012. Recent thermal history influences thermal tolerance in freshwater mussel species (Bivalvia: Unionoida). Freshwater Science 31, 83-92.

Garcia, H.E., Gordon, L.I., 1992. Oxygen solubility in seawater: Better fitting equations. Limnology and Oceanography 37, 1307-1312.

Guttersa, B.M.C., Verhofstada, M.J.J.M., van der Veldeab, G., Rajagopala, S., Leuvenc, R.S.E.W., 2012. A comparative study of byssogenesis on zebra and quagga mussels: the effects of water temperature, salinity and light–dark cycle. Biofouling: The Journal of Bioadhesion and Biofilm Research 28, 121-129.

Haag, W.R., Warren, M.L., 2008. Effects of severe drought on freshwater mussel assemblages. Transactions of the American Fisheries Society 137, 1165-1178.

Kahn, D., Kreeger, D.A., Mohler, J., Silldorff, E., Kilham, S., Eldridge, W., 2014. Dissolved oxygen standards to protect aquatic life in the tidal freshwater Delaware River, A brief of the Science and Technical Advisory Committee, Partnership for the Delaware Estuary, 21 pp.

Kreeger, D., Cole, P., 2010. Appendix P: Comprehensive bivalve shellfish survey results. In: D. Kreeger, J. Adkins, P. Cole, R. Najjar, D. Velinsky, P. Conolly, J. Kraeuter (Editors), Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning. Partnership for the Delaware Estuary, PDE Report No. 10-01, Wilmington, Delaware, USA.

Kreeger, D., Kraeuter, J., 2010. Appendix N: Ecologically significant bivalve mollusks of the Delaware Estuary. In: D. Kreeger, J. Adkins, P. Cole, R. Najjar, D. Velinsky, P. Conolly, J. Kraeuter (Editors), Climate Change and the Delaware Estuary: Three Case Studies in Vulnerability Assessment and Adaptation Planning. Partnership for the Delaware Estuary, PDE Report No. 10-01, Wilmington, Delaware, USA.

Lewis, E., Wallace, D., Allison, L., 1998. Program developed for $CO_2$ system calculations. Brookhaven National Laboratory and Oak Ridge National Laboratory, US Department of Energy, 21 pp.

McMahon, R.F., 1979. Response to temperature and hypoxia in the oxygen consumption of the introduced Asiatic freshwater clam Corbicula fluminea (Müller). Comparative Biochemistry and Physiology Part A: Physiology 63, 383-388.

Mearns, L.O., Arritt, R., Biner, S.b., Bukovsky, M.S., McGinnis, S., Sain, S., Caya, D., Correia Jr, J., Flory, D., Gutowski, W., 2012. The North American Regional Climate Change Assessment Program: Overview of Phase I results. Bulletin of the American Meteorological Society 93, 1337-1362.

Mearns, L.O., Gutowski, W.J., Jones, R., Leung, L.-Y., McGinnis, S., Nunes, A.M.B., Qian, Y., 2009. A regional climate change assessment program for North America. EOS, Transactions of the American Geophysical Union 90, 311-312.

Miller, A.W., Reynolds, A.C., Sobrino, C., Riedel, G.F., 2009. Shellfish face uncertain future in high $CO_2$ world: Influence of acidification on oyster larvae calcification and growth in estuaries. PLoS ONE 4, 1-8.

Nakićenović, N., Swart, R., 2000. Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

Preston, B.L., 2004. Observed winter warming of the Chesapeake Bay estuary (1949-2002): Implications for ecosystem management. Environmental Management 34, 125-139.

Rahmstorf, S., 2007. A semi-empirical approach to projecting future sea-level rise. Science 315, 368-370.

Ross, A.C., Najjar, R.G., Li, M., Mann, M.E., Ford, S.E., Katz, B., 2015. Sea-level rise and other influences on decadal-scale variations of salinity in a coastal plain estuary. Estuarine Coastal and Shelf Science, In press.

Savenije, H.H.G., 1993. Predictive model for salt intrusion in estuaries. Journal of Hydrology 148, 203-218.

Sharp, J.H., Yoshiyama, K., Parker, A.E., Schwartz, M.C., Curless, S.E., Beauregard, A.Y., Ossolinski, J.E., Davis, A.R., 2009. A biogeochemical view of estuarine eutrophication: Seasonal and spatial trends and correlations in the Delaware Estuary. Estuaries and Coasts 32, 1023-1043.

Sparks, B.L., Strayer, D.L., 1998. Effects of low dissolved oxygen on juvenile Elliptio complanata (Bivalvia:Unionidae). Journal of the North American Benthological Society 17, 129-134.

Spooner, D., Vaughn, C., 2008. A trait-based approach to species' roles in stream ecosystems: climate change, community structure, and material cycling. Oecologia 158, 307-317.

Tebaldi, C., Smith, R.L., Nychka, D., Mearns, L.O., 2005. Quantifying uncertainty in projections of regional climate change: A Bayesian approach to the analysis of multimodel ensembles. Journal of Climate 18, 1524-1540.

Tomaso, D., Najjar, R., 2015. Seasonal and interannual variations in the dissolved oxygen budget of an urbanized tidal river: The Upper Delaware Estuary. Journal of Geophysical Research: Biogeosciences, in revision.

Verbrugge, L.N.H., Schipper, A.M., Huijbregts, M.A.J., Van der Velde, G., Leuven, R.S.E.W., 2003. Sensitivity of native and non-native mollusc species to changing river water temperature and salinity. Biological Invasions 14, 1187-1199.

Walters, R.A., 1992. A three-dimensional, finite element model for coastal and estuarine circulation. Continental Shelf Research 12, 83-102.

Zervas, C., 2001. Sea level variations of the United States, 1854-1999, NOAA Technical Report NOS CO-OPS 36. National Ocean Service, Silver Spring, MD, 66 pp.

Zhong, L., Li, M., Foreman, M.G.G., 2008. Resonance and sea level variability in Chesapeake Bay. Continental Shelf Research 28, 2565-2573.