TEMPERATURE

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1.   OVERVIEW

Changes in air and water temperatures have profound and cascading impacts on the ecosystem and public health within the Narragansett Bay watershed. Recent and projected future increases in temperature represent an important stressor for some components of the ecosystem and have wide-ranging ecological, social, and economic implications. Air temperature in the Narragansett Bay region warmed over the last century (1905-2015) mostly as a result of global climate change, but also on a local scale through the "heat island" effect of urbanization. From 1960 to 2015, regional air temperatures increased by 1.4-1.6°C (2.5-3.0°F). Water temperatures in the Bay also warmed by 1.4-1.6°C, from 1960 to 2012, because of rising air temperatures, urbanization, and modification of water flow patterns by impoundments and other structures.

Climate projections for the Narragansett Bay region suggest that average air temperature will increase approximately 2-6°C (5-10°F) from present levels over the next 100 years depending on the greenhouse gas emission rate. Local studies show that for every 1°C (1.8°F) increase in air temperature, the water temperature in rivers increases 0.6-0.8°C (1.1-1.4°F). The warmer air and river temperatures will lead to higher estuarine water temperatures. In turn, the warming air, river, and estuarine water temperatures will have important effects on biological communities (such as phytoplankton, benthic habitat, seagrasses, fish, and stream invertebrates) and physical conditions (such as dissolved oxygen) in the Bay.

2.   INTRODUCTION

Temperature is an easily measured parameter that strongly influences public health and environmental conditions on global and local scales, making it an important indicator. Many organizations routinely monitor air and water temperatures in Narragansett Bay and its watershed, such as the National Oceanic and Atmospheric Administration (NOAA), the University of Rhode Island's Graduate School of Oceanography (GSO), and the United States Geological Survey (USGS).

Local air and water temperature trends have been measured and studied for over a century. In an analysis of air temperature data from the Providence station of the National Weather Bureau, Pilson (2008) found an overall increase of approximately 0.94°C (1.7°F) between 1905 and 2005. The Narragansett Bay Estuary Program's 2009 status and trends report stated that the Bay's annual average surface water temperature increased by 1°C (1.8°F) from 1959 to 2007 (NBEP 2009). Other studies that analyzed water temperature records from the URI-GSO fish trawl and phytoplankton surveys, NOAA tide gauge at Newport, and the Brenton Reef lightship (no longer active) found a similar increase of 0.91-1.2°C (1.6-2.2°F) between 1960 and 2005, with the majority of the warming occurring since 1970 (Nixon et al. 2009, Smith et al. 2010). The trends observed in the Narragansett Bay watershed are consistent with those in other coastal locations (e.g., Figure 1; Woods Hole, MA) and appear to have accelerated since the 1960s (Nixon et al. 2004, Oviatt 2004, Pilson 2008).
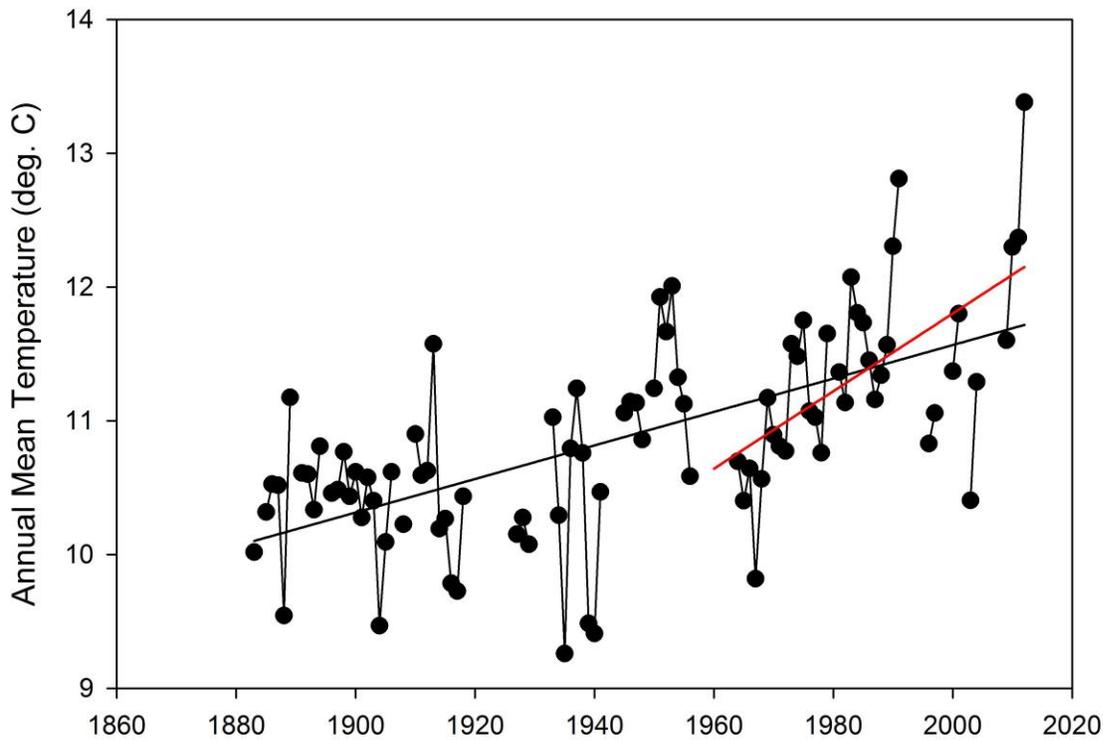
Figure 1. Annual average water temperatures at Woods Hole, Massachusetts, from 1880-2015. Black line is a linear regression for the entire time period: Temperature (°C) = 0.013(year) – 13.49 (r^2 = 0.40; p > 0.0001). Red line is a linear regression for 1960-2015: Temperature (°C) = 0.029(year) – 46.31 (r^2 = 0.34; p = 0.0001). Data provided by J. Manning (NOAA).

Increases in river water temperatures appear to be driven primarily by rising air temperatures (Morrill et al. 2005, Seekell and Pace 2011). In Massachusetts, Morrill and colleagues (2005) analyzed water temperature changes in three rivers and concluded that the rivers had a temperature increase of 0.6-0.8°C (1.1-1.4°F) for every 1°C (1.8°F) increase in air temperature. This implies that stream temperatures will likely increase 2-3°C (3.6-5.4°F) if air temperature increases 3-5°C (5.4-9.0°F) over the next century (Morrill et al. 2005). Data from the Hudson River in New York support the conclusions of Morrill and colleagues, as the river has warmed 0.95°C (1.7°F) from 1946-2008, driven by warming air temperatures (Seekell and Pace 2011).

According to climate models produced through the Intergovernmental Panel on Climate Change (IPCC) and the Climate System Research Center at the University of Massachusetts, urban development throughout the Narragansett Bay watershed is projected to magnify climate change and the impact of rising temperatures on human and environmental health (IPCC 2000, Bradley et al. 2016, USEPA 2016). Urbanization has been shown to raise water and air temperatures through an increase in impervious surfaces (heat island effect and heated runoff), and the regulation and impoundment of freshwater (Mohan et al. 2013). While this accelerated warming from urban landscapes is occurring year round, wintertime air and water temperatures are warming the most rapidly.

The trends in winter temperatures, globally and locally within the Narragansett Bay watershed, are significant because they have many effects on ecological processes. For example, warmer winters have

changed the timing of the winter-spring phytoplankton bloom, which then affects food supply for zooplankton and other species (Oviatt 2004, Nixon et al. 2009, Smith et al. 2010; see "Chlorophyll" chapter). Many of the indicators presented in other chapters of this report are influenced by warming air and water temperatures, including biological (phytoplankton, benthic habitat, seagrasses, fish communities, stream invertebrates), physical (dissolved oxygen), and public health (bacterial levels at recreational beaches and in shellfish harvest areas) indicators.

3. **METHODS**

To analyze air and water temperature trends in Narragansett Bay and its watershed, we used datasets obtained from several sources: NOAA's National Climate Data Center for air temperature, Fulweiler and colleagues (2015) for estuarine water temperature, and the USGS and the Narragansett Bay Commission for riverine water temperature (Table 1).

The NOAA air temperature datasets spanned a period of 110 years (1895-2015) for Rhode Island and 66 years (1949-2015) for Massachusetts. The Rhode Island data were collected at T. F. Green Airport in Warwick. The Massachusetts data were collected in Worcester. We analyzed the complete datasets using linear regressions to quantify the trends. We also performed linear regressions only on the data from 1960 and later because other studies have suggested that temperatures began to rise more quickly after approximately 1960 (Pilson 2008; Figure 1). That year is also, coincidently, when estuarine water temperature records started to be collected continuously in Narragansett Bay (Fulweiler et al. 2015), and focusing on the years after 1960 enabled us to compare air and estuarine water temperatures.

For estuarine water temperature, we used data for a 50-year period (1960-2010) that had been compiled by Fulweiler and colleagues (2015) from three sources: the University of Rhode Island Graduate School of Oceanography (GSO) phytoplankton surveys, the GSO fish trawl surveys, and the NOAA station at Newport, Rhode Island.

Because continuous multi-decade datasets for river and stream water temperatures in the watershed were not available, we used three datasets that covered shorter time periods. Data from the USGS station in Millville, Massachusetts, in the Narragansett Bay watershed covered two periods: 1969-1981 and 2011-2014. Data provided by the USGS for 12 rivers and streams in the Scituate Reservoir region of Rhode Island included 2001-2006 and 2010-2013. Data collected by the Narragansett Bay Commission spanned 2007-2015. We did not analyze trends in the river and stream datasets because the length of the records was not sufficient.

Table 1. Sources of temperature data, including length of record and sampling frequency.

Data Source	Length of Record	Sampling Frequency
Air Temperature		
NOAA Climate at a Glance (RI)	1895-2015 (110 years)	Daily
NOAA Climate at a Glance (MA)	1949-2015 (66 years)	Daily
Estuarine Water Temperature		
GSO phytoplankton survey	1960-2010 (50 years)	Weekly
GSO fish trawl survey	1960-2010 (50 years)	Weekly
NOAA tide station - Newport	1960-2010 (50 years)	Daily until 1996; 15 minutes from 1996 to 2010
River/Stream Water Temperature		
USGS – Millville, MA	1969-1981 and 2011-2014	Daily

| USGS – Scituate Reservoir Region | 2001-2006 and 2010-2013 | Daily |
| Narragansett Bay Commission – RI and MA rivers | 2007-2015 | Bi-weekly |

4.   STATUS, TRENDS, AND PROJECTIONS

Status and Trends

Air temperature records from Massachusetts and Rhode Island showed that temperature increased by 1.7°C (3.3°F) over the entire period at an average rate of 0.16°C (0.3°F) per decade (Figures 2 and 3). Starting in the 1960s, air temperature appeared to increase at a faster rate of 0.28-0.33°C (0.5-0.6°F) per decade (Figures 2 and 3) for a total increase in air temperature of 1.4-1.6°C (2.5-3.0°F) since 1960.
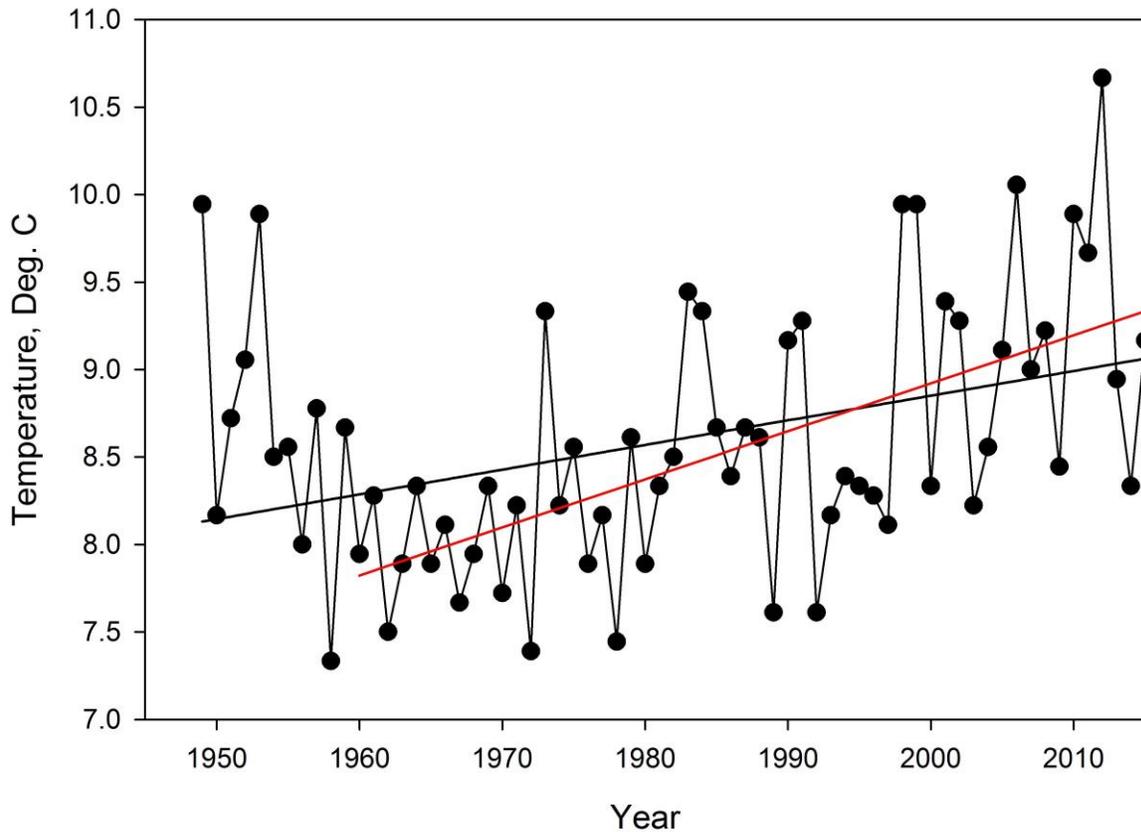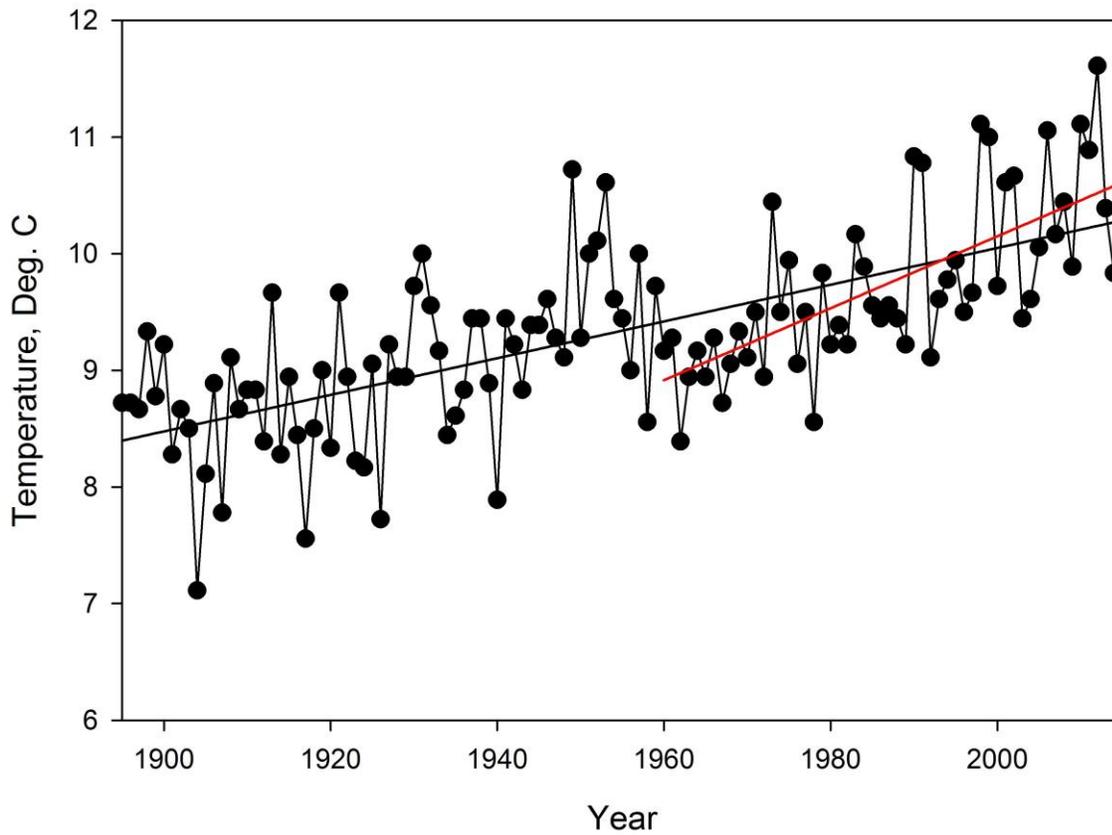

Figure 2: Annual mean air temperatures at Worcester, Massachusetts, from 1949-2015 (NOAA Climate at a Glance). Black line is regression for the entire dataset: Temperature (deg. C) = 0.014(year) – 19.40 (r2 = 0.14; p = 0.002). Red line is regression for dataset from 1960 to 2015: Temperature (deg. C) = 0.023(year) – 46.03 (r2 = 0.37; p < 0.0001).

Figure 3: Annual mean air temperatures at Warwick, Rhode Island, from 1845-2015 (NOAA Climate at a Glance). Black line is regression for the entire dataset: Temperature (deg. C) = 0.016(year) – 21.43 (r2 = 0.47; p < 0.0001). Red line is regression for dataset from 1960 to 2015: Temperature (deg. C) = 0.031(year) – 51.52 (r2 = 0.49; p < 0.0001).
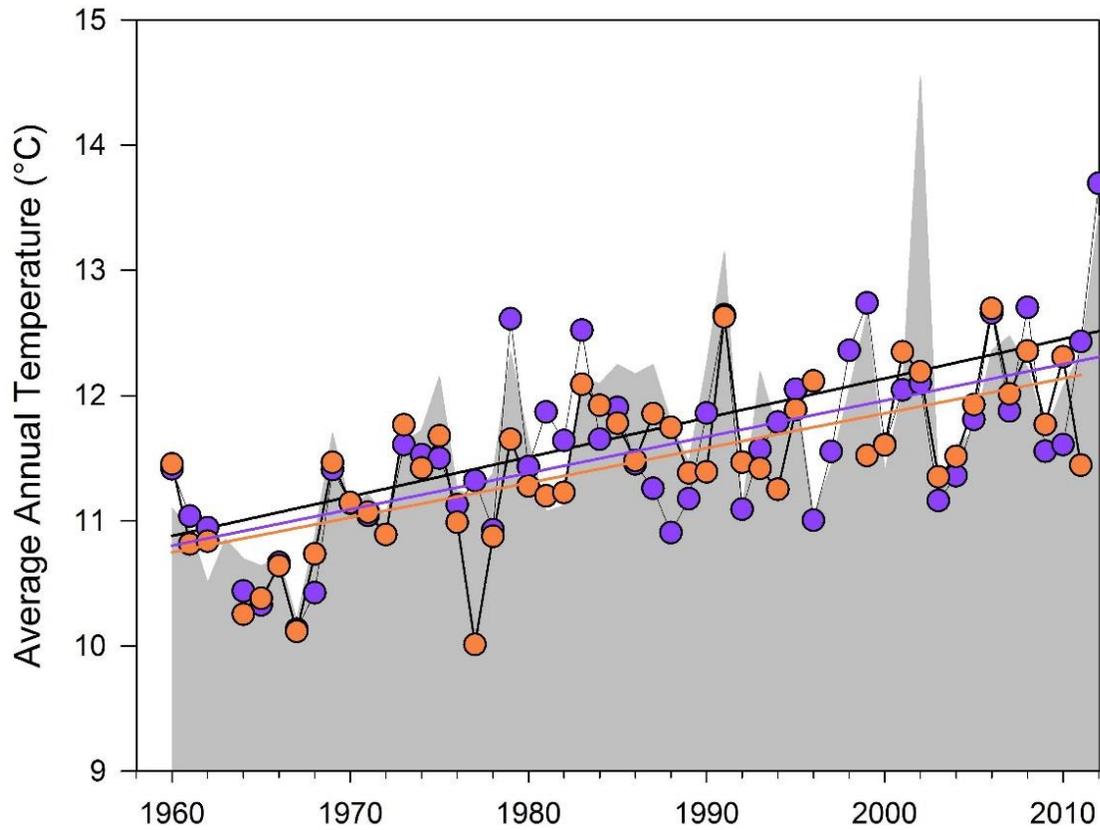
Figure 4. Annual mean surface water temperatures in Narragansett Bay from 1960-2010, including datasets from three sources: URI GSO phytoplankton survey (orange circles and line), URI GSO fish survey (purple circles and line), and NOAA station at Newport (gray shaded area and black line). Figure based on Fulweiler et al. (2015).

In Narragansett Bay, the annual average temperature of estuarine waters increased 1.4-1.6°C (2.5-2.9°F) from 1960-2010 (Figure 4).

River and stream water temperatures measured by the USGS in Rhode Island averaged 11°C (52°F) (Figure 5), while temperatures measured by the USGS at Millville, MA, (Figure 6) and by the Narragansett Bay Commission at multiple sites in the Narragansett Bay watershed averaged 13°C (55°F) (Figure 7).
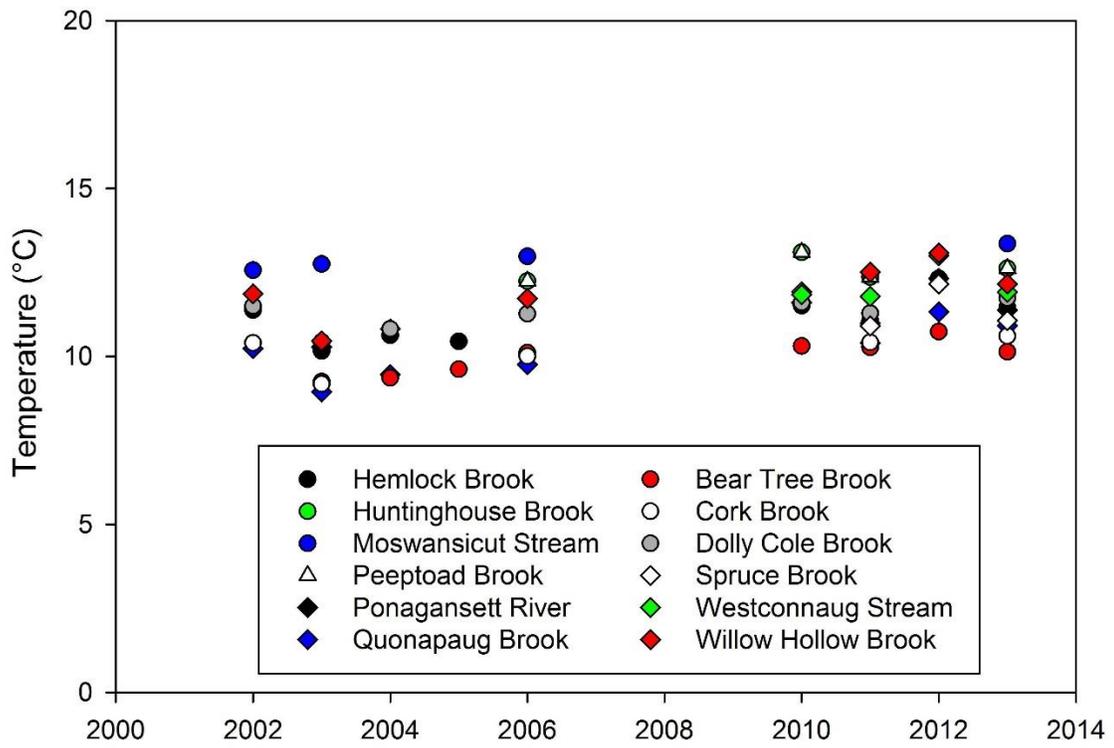
Figure 5. Annual mean river/stream water temperatures in the Scituate Reservoir region (RI) from 2002-2006 and 2010-2013. Data were collected by the USGS.
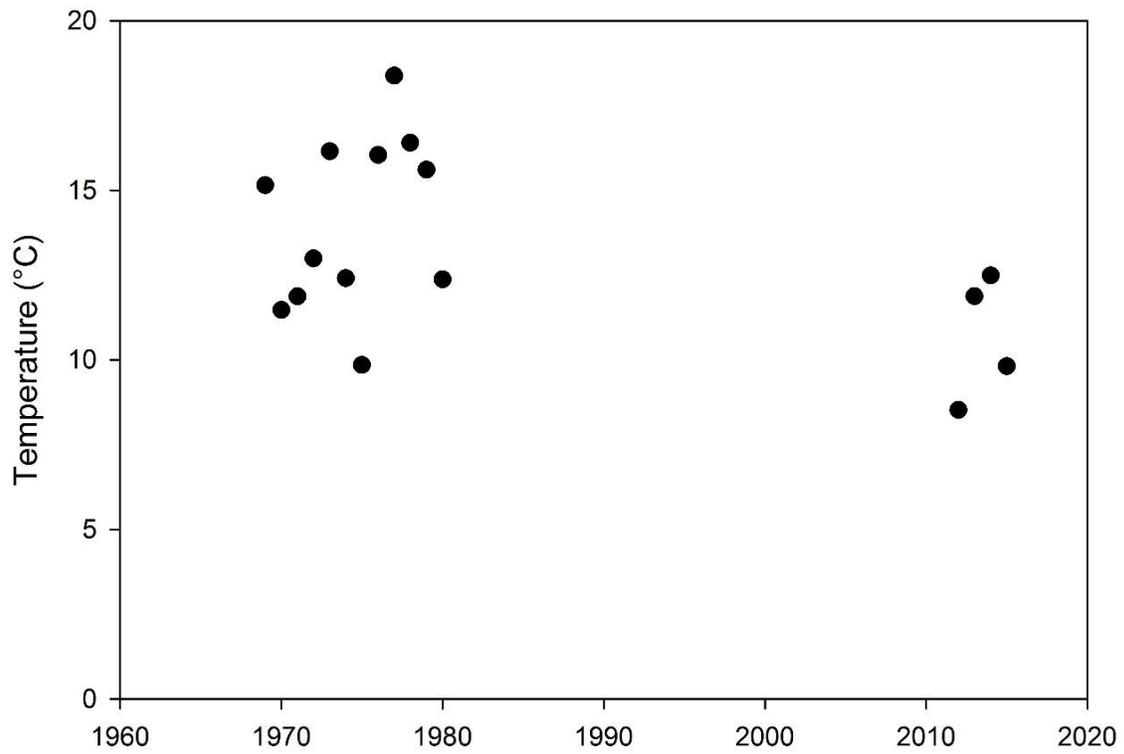
Figure 6. Annual average river/stream water temperatures at Millville, MA, from 1969-1981 and 2011-2014. Data were collected by the USGS.
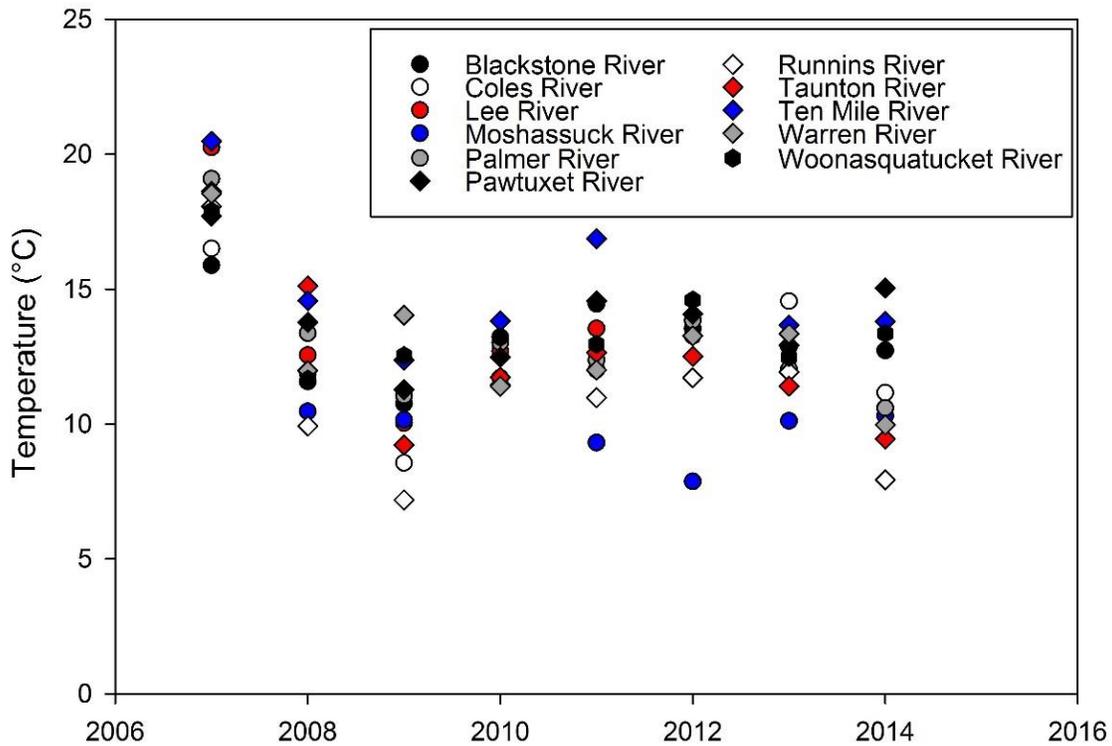
Figure 7. Annual mean river/stream water temperatures from 2007-2014 in 11 rivers and streams discharging to Narragansett Bay. Data were collected by Narragansett Bay Commission.

Projections

In 2000, the Intergovernmental Panel on Climate Change published the Special Report on Emissions Scenarios (SRES) with global temperature and precipitation climate projections for 2100 (IPCC 2000). The projections were produced through a multi-model system that encompassed several emission scenarios based on a series of societal designs (IPCC 2000) (Figure 8; Table 2). All scenarios were considered to be possible outcomes of future societies, and each scenario produced a different level of emissions. According to the projections, global temperature could potentially increase by 0.6°C to 4°C (1.1-7.2°F) by 2100 dependent on the greenhouse gas emission rates over the next century (Table 2) (IPCC 2000).

On a regional scale, the University of Massachusetts Climate System Research Center produced climate model projections for individual states in the Northeast (Bradley et al. 2016). Similar to the SRES, Bradley et al. (2016) used two emission rates to project potential changes in air temperature for Rhode Island and Massachusetts. Because the temperature projections for Rhode Island and Massachusetts were comparable, we include only the Rhode Island projection in this report (Figure 9). Under the lower emission scenario, temperature would increase by 2.0-3.0°C (3.6-5.4°F) by 2100 (Figure 9). However, the lower emission scenario is possible only if substantial efforts are made to mitigate greenhouse gas emission rates during future development so that emission rates are comparable to emission rates in 2000 (Bradley et al. 2016). Current greenhouse gas emissions are tracking along the higher emission rate scenario, which is projected to cause a local temperature increase of 4.0-6.1°C (7.2-11°F) by 2100 (Figure 9) (Bradley et al. 2016).

The projected temperature increase by 2100 is expected to create a climate in New England like that of present-day Virginia, with a milder three-season cycle. The warmest recent winters in southern New England will become the coldest experienced in 2100, and the warmest recent summers will be cool in comparison to the summers experienced in 2100 (Bradley et al. 2016). By 2100, the average winter temperature in Rhode Island is projected to be approaching 50°F, and the summer mean temperature will be just below 90°F (Figure 9) (Bradley et al. 2016).

The projected increase in air temperature carries implications for marine and freshwater systems globally and locally. According to Sheaman and Lentz (2009), average seawater temperatures near the coast tend to follow, with a time lag, trends in air temperature. Coastal seawater temperatures are affected primarily by the sea-air interface and by currents that flow along the continental shelf, meaning that local waters are highly influenced by regional air temperature shifts and by the warming of currents flowing from the Arctic (Shearman and Lentz 2009). Freshwater systems are affected similarly by regional air temperature shifts (Morrill et al. 2005, Seekell and Pace 2011).

Table 2. Summary of projected temperature increases based on seven scenarios of greenhouse gas emissions (IPCC 2000).*

Case	Temperature Increase (°C at 2090-2099 relative to 1980-1999)	
	Best estimate	**Likely range**
Constant Year 2000 concentrations	0.6	0.3 – 0.9
B1 scenario[1]	1.8	1.1 – 2.9
A1T scenario[2]	2.4	1.4 – 3.8
B2 scenario[3]	2.4	1.4 – 3.8
A1B scenario[4]	2.8	1.7 – 4.4
A2 scenario[5]	3.4	2.0 – 5.4
A1FI scenario[6]	4.0	2.4 – 6.4

*All scenarios are considered to be possible outcomes of future societies and each scenario produces a different level of emissions.

1: A convergent world with a global population that peaks in mid-century and declines thereafter, with rapid change in economic structures toward a service and information economy. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives (IPCC 2000).

2: A world defined by the technological emphasis: non-fossil energy.

3: A world in which the emphasis is on local solutions to economic, social and environmental sustainability. The global population is continuously growing with intermediate levels of economic development, and less rapid and diverse (IPCC 2000).

4: A world defined by the technological emphasis: a balance between non-fossil and fossil intensive energy.

5: A very heterogeneous world that places value on self-reliance and preservation of local identities. Economic development is regional and technological change is fragmented and slow (IPCC 2000).

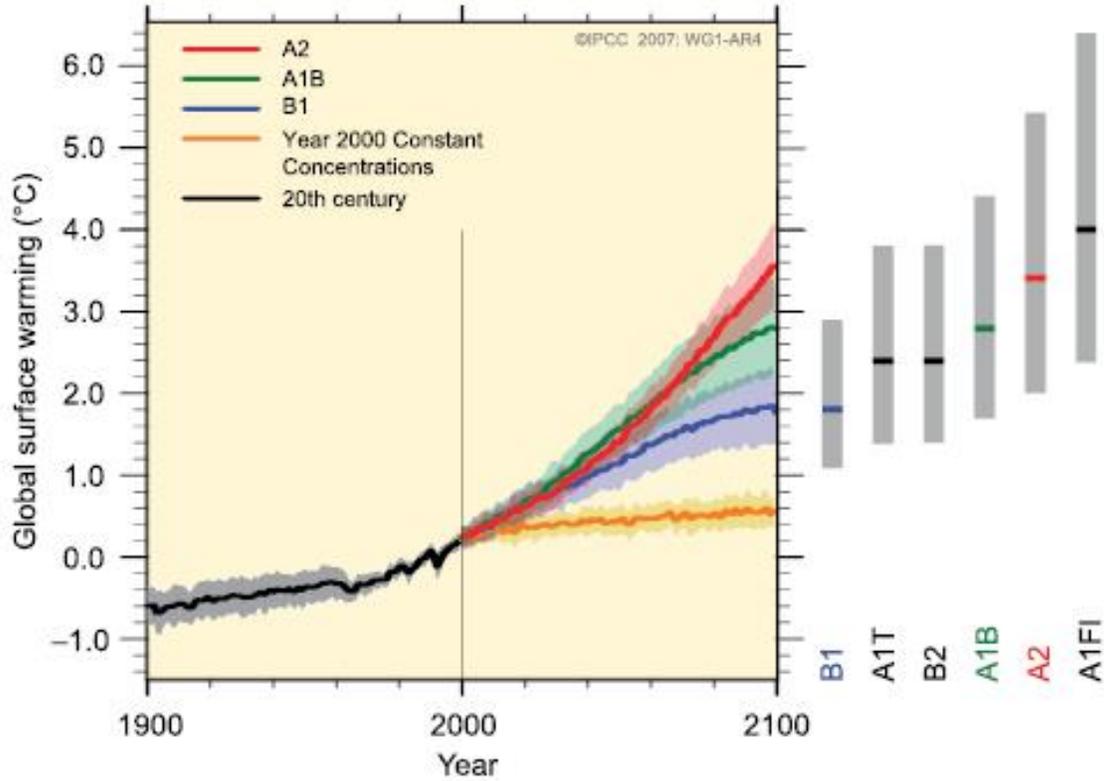6: A world defined by the technological emphasis: fossil intensive energy.

Figure 8: Summary of projected air temperature increases from 2000 to 2100 for seven scenarios of greenhouse gas emissions (IPCC 2000). Black line represents global temperature between 1900 and 2000; gray indicates standard deviation. Colored lines represent model projections for different scenarios. For IPCC scenario descriptions, see Table 2 footnotes.
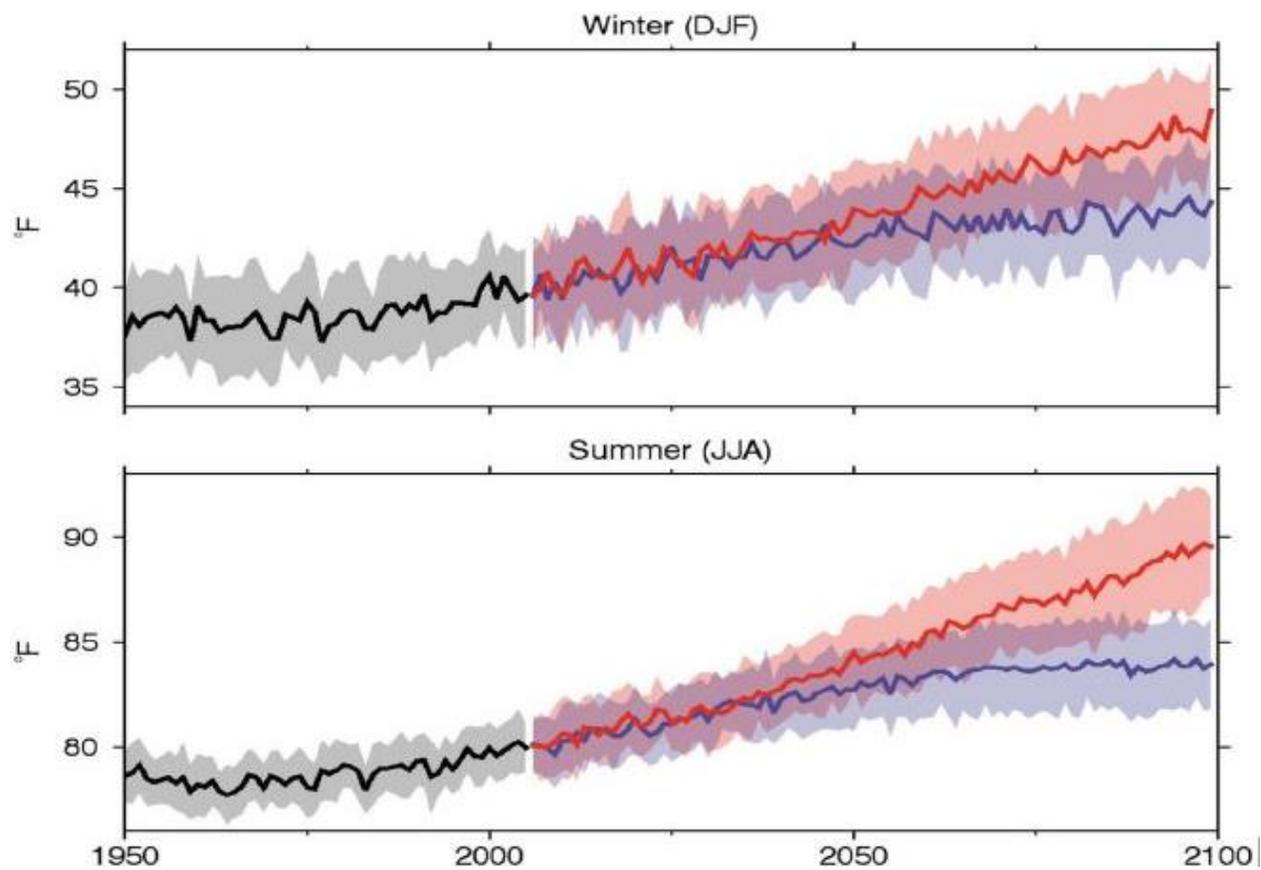
Figure 9: Seasonal air temperature projections for Rhode Island until 2100. Results are from a USGS climate model (Bradley et al. 2016). Black line represents air temperature data collected in Rhode Island from 1950 to 2015. Red temperature projection is for higher greenhouse gas emission rates that are comparable to present-day consumption. Blue temperature projection is for a lower emission rate that would be a result of reducing present-day emission rates through the introduction of energy-efficient technologies (Bradley et al. 2016). Shaded areas indicate standard deviations.

5.   DISCUSSION

Narragansett Bay has experienced substantial increases in air and water temperatures in recent decades, and projected future warming will likely lead to greater impacts on human health and ecological processes.

Regional climate change projections suggest an increase in air temperature of 2.8-5.6°C (5.0-10.0°F) between 1950 and 2100 (Figure 9; Bradley et al. 2016). At the lower end of this projection, based on lower greenhouse gas emission rates, warming would occur at a rate similar to the trend observed in the NOAA data for recent years (Figures 2 and 3). However, the higher emission scenario is more likely based on current trends in global economic development. According to that projection, temperatures would increase at a rate nearly double the rate in the NOAA data.

Estuarine water temperatures in Narragansett Bay showed trends similar to those observed at Woods Hole, MA (Figure 1). The 1960s were known to be a colder-than-normal decade, so an increase from that point forward is expected. If the temperature trend from the 1960-2012 data continues,

Narragansett Bay's estuarine water temperature may increase at a rate of 0.027-0.032°C (0.05-0.06°F) per year for a total of 2.7-3.2°C (5-6°F) over the next 100 years (Figure 4). Winter temperatures are expected to increase by 0.032-0.040°C (0.06-0.07°F) per year based on the data. This could lead to an increase of 3.2-4.0°C over the next 100 years (Figure 9). If higher greenhouse gas emission rates occur, the estuarine waters may warm faster than the current trend, meaning an increase of approximately 4.0°C (7°F) or greater by 2100.

In Narragansett Bay and its watershed, rising air and water temperatures are affecting biological communities, physical conditions, and bacterial levels at beaches and in shellfishing areas (see chapters on "Chlorophyll", "Seagrass", "Estuarine Fish", "Freshwater Fish", "Stream Invertebrates", "Dissolved Oxygen", "Marine Beaches", and "Shellfishing").

In biological communities, species often rely on environmental cues, specifically temperature, to regulate lifecycle functions from reproduction to feeding. Increases in temperature affect when specific functions occur, which in turn can affect the whole ecosystem. For example, as waters have warmed and days have become cloudier, the winter-spring diatom bloom has been delayed and diminished because of grazing pressure (brought on by warmer temperatures) or decreased light (from cloudier days) (Oviatt 2004, Nixon et al. 2009; see "Chlorophyll" chapter). The lack of a winter-spring bloom has decreased the amount of food for benthic organisms, diminishing the connection between the water column and benthos in Narragansett Bay. Similarly, the freshwater systems within the Narragansett Bay watershed are experiencing a decrease in invertebrate populations, with temperature changes identified as a contributing factor (see "Stream Invertebrates" chapter).

Increasing water temperatures are causing a shift in fish communities within Narragansett Bay (Oviatt 2004, Oviatt et al. 2003; see "Estuarine Fish" and "Freshwater Fish" chapters). Currently, Narragansett Bay is a boundary area between northern boreal and southern warmer marine and estuarine species. The warming trends could shift this boundary northward, changing the species that are present in the Bay (Nixon et al. 2009, Smith et al. 2010). The trends could be reflected similarly in terrestrial and freshwater aquatic systems (Brooks 2009, Matthews 2004). For estuarine fish, multiple studies have documented a decrease in cold-water demersal species and an increase in warm-water pelagic species. Similarly, as air and river/stream temperatures warm, environmental managers are concerned that cold-water fish habitat in freshwater streams, now common in the Narragansett Bay watershed, may decline. Cold-water habitats could be replaced by warm-water habitats, decreasing the amount of habitat suitable for brook trout and altering the ecosystem as cold-water species give way to warm-water species.

Seagrasses in Narragansett Bay can become stressed if water temperatures exceed 25-30°C (72-86°F) for extended periods, potentially leading to decreases in these important plants (Short and Neckles 1999, Bintz et al. 2003; see "Seagrasses" chapter). Warmer waters can also shift seagrasses' reproduction from root and rhizome growth to exclusively seed propagation, which increases the vulnerability of the population.

A major concern for environmental managers is the impact of rising temperatures on oxygen solubility in water. When dissolved oxygen levels decline, hypoxic conditions can result, causing stress or death to benthic organisms (see "Dissolved Oxygen" chapter). Because less oxygen dissolves in warmer water, climate change could cause hypoxia to become a more widespread problem. Fish, crabs, and other mobile species can leave the hypoxic area, but sessile species cannot. Low oxygen levels also affect the sediment-water interface, changing the types of species that can thrive there.

Projected increases in water temperature will affect pathogens in Narragansett Bay. The state monitors marine beaches and commercial shellfishing areas for pathogens that are harmful to humans, using the bacteria *Enterococci* and fecal coliform as pathogenic indicators (see "Marine Beaches" and "Shellfish Areas" chapters). Beaches are closed for all recreational activity when bacterial counts exceed standardized values. Shellfishing areas tend to be closed based on precipitation amount, which is correlated with pathogen loading. Because warmer water promotes bacterial growth, monitored beaches may experience more closures, and shellfishing areas may be closed outside of heavy rainfall events due to high background bacterial counts.

Environmental management and research groups are tracking the impacts of changing temperature trends on the biological and physical indicators of the Narragansett Bay. The rising temperatures are projected to have a variety of impacts on the integrity of the Bay and its watershed, and many of these impacts are not yet well understood. Further research into these issues will help regulatory agencies implement management practices as effectively as possible.

6.   DATA GAPS AND RESEARCH NEEDS

The river/stream temperature monitoring network in the Narragansett Bay watershed should be upgraded. While it may be challenging from an economic perspective, maintaining a continuous record of temperature is feasible and essential to documenting long-term temperature trends and to understanding changes to aquatic communities. As Morrill and colleagues (2005) observed, as air temperature increases, river and stream temperatures will also increase. The ratio of the increase between the two within the Narragansett Bay watershed is unknown, but would be a useful metric. Using that correlation, managers could use the NOAA air temperature data to estimate changes in stream temperatures in order to protect cold-water fish habitats.

Adding a long-term data collection site in the enclosed basins within Narragansett Bay—such as Greenwich Cove, Warwick Cove, or Palmer River—would provide valuable information. Rising temperatures are likely to affect these shallow and highly urbanized basins before the rest of the bay. The physical and biological responses to this warming could act as a model of "early warming" for the rest of the Bay.

While correlating temperature changes with ecological changes is an important initial step in understanding the effects of climate change, experiments using mesocosms are needed to determine how the Narragansett Bay ecosystem will be affected by climate change. Latitudinal gradient studies would also be beneficial to predict future ecosystem and species shifts resulting from changing temperature trends.

A more sophisticated trends analysis is needed for air and water temperature datasets from Narragansett Bay. While we and other researchers (e.g. Nixon et al. 2004, Oviatt 2004, Pilson 2008) used 1960 as a start date for regressions, that was an arbitrary date and the perception of a recent acceleration in warming may be a consequence of using that date. More in-depth trends analysis of the datasets could determine whether this trend is meaningful and potentially identify other significant trends.

7.   ACKNOWLEDGEMENTS

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