PRECIPITATION

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1. OVERVIEW

Changing global and regional precipitation patterns have cascading impacts on environmental quality and human health in Narragansett Bay and its watershed. Global climate change is the primary cause behind these precipitation changes. The changing patterns are stressing and will continue to stress ecosystem condition indicators such as water clarity, dissolved oxygen, chlorophyll, and water quality, as well as public health indicators including beach and shellfish closures.

Regionally, precipitation as rainfall has increased by 0.4 to 0.7 inches per decade since 1895, with a 71 percent increase in the frequency of intense storms since 1965. Local projections include increased volume of annual precipitation, greater frequency and intensity of precipitation events, and a changing seasonality in which winter precipitation is increased (as rain) and summer precipitation is limited (prompting drought and drought-like conditions).

2. INTRODUCTION

Precipitation patterns provide insight into how water delivery to the Narragansett Bay watershed will change, leading to potential impacts on environmental, physical, and public health in the region. By understanding changes to precipitation patterns, managers can create more effective climate change adaptation policies as new conditions arise.

A number of recent analyses based on precipitation data from the National Oceanic and Atmospheric Administration (NOAA), the National Weather Service, and the United States Geological Survey found an increase in the average annual volume of precipitation in Rhode Island and Massachusetts, severity of tropical cyclones in the North Atlantic, and extreme precipitation events (EEA 2011, RI CCC 2012, RI EC4 STAB 2016, UNH 2016). Several analyses have been completed for the region, showing an increase of 0.305 centimeter per year (0.1 inch per year, or 1 inch per decade) in precipitation from 1905 to 2005 (Pilson 2008, Smith et al. 2010, Heffner et al. 2012, UNH 2016).

The increased frequency of intense precipitation events has become the norm, with a 71 percent increase of heavy precipitation events from 1958 to 2010 in Rhode Island and Massachusetts (Melillo et al. 2014, CRSC 2016). The increased precipitation can potentially affect organic and inorganic pollution levels from runoff, urban flooding, and wastewater treatment flow and overflow. Although there is a trend of increasing annual precipitation, these data sources also reveal that shifts in seasonality of precipitation lead to longer periods of drought and drought-like conditions in summer (EEA 2011).

In this chapter, we analyze the status, recent trends, and future projections of precipitation patterns. We discuss the effects on physical conditions of the Bay, including water clarity, dissolved oxygen, chlorophyll, and water quality, as well as the impacts on human health, such as beach or shellfishing closures.

3.   METHODS

NOAA has collected precipitation data nationally since the 1800s. We analyzed data from two NOAA stations: Providence, Rhode Island (1895 to 2015) and Worcester, Massachusetts (1948 to 2015). Precipitation, temperature, and the Palmer Drought Severity Index data were obtained from NOAA's Climate at a Glance report (NOAA 2016). This source was selected due to the longevity and extensiveness of the data set.

The Palmer Drought Severity Index is a measurement of the relative dryness of an area on a standardized scale of -10 to +10 calculated from temperature and precipitation data. This parameter assumes the precipitation is readily available to be evaporated or transpired by plants, and it does not account for snow or ice, which experience delayed runoff (Dai et al. 2016).

4.   STATUS, TRENDS, AND PROJECTIONS

Status and Trends
The status of rainfall in the Narragansett Bay watershed is based on data from 2015, the most recent full year of data provided by NOAA. In 2015, both Massachusetts and Rhode Island received about 40 inches of precipitation. The long-term annual averages of the entire datasets were 45.9 inches for Rhode Island and 46.9 inches for Massachusetts (Figures 1 and 2).

We examined trends in precipitation from the beginning of local annual precipitation records. Regional precipitation patterns have been variable, but the annual average amount of precipitation has increased steadily. Rhode Island's annual average of precipitation increased 0.40 inches per decade since 1895, and Massachusetts' average precipitation increased 0.73 inches per decade since 1948 (Figures 1 and 2). A more recent trend for Rhode Island was an increase of 1 inch per decade since the 1940s. The largest periods of drought were in the 1940s and 1960s. In the 1970s, precipitation in Rhode Island and Massachusetts shifted from being generally below to generally above the long-term average (Figures 1 and 2). This pattern has continued despite some recent years of below-average precipitation.

Despite the recent years of droughts and drought-like conditions, the Palmer Drought Severity Index agrees with the precipitation data, showing that wetter years have become more common. The Palmer Drought Severity Index has increased 0.03 per decade in Rhode Island and 0.07 per decade in Massachusetts (Figures 3 and 4).
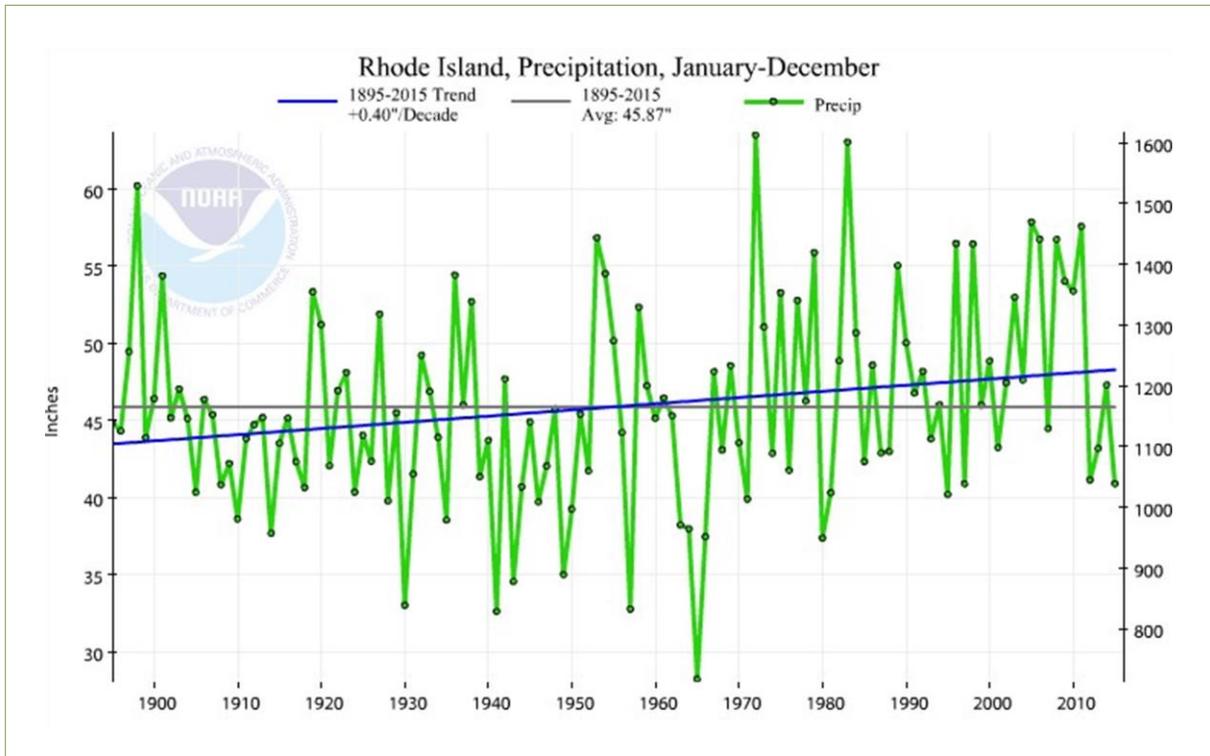
Figure 1. Annual precipitation at Providence, Rhode Island. Blue line is the trend in the data. Grey line is the average annual precipitation over the entire dataset. Source: National Oceanic and Atmospheric Administration Climate at a Glance (December 2016).
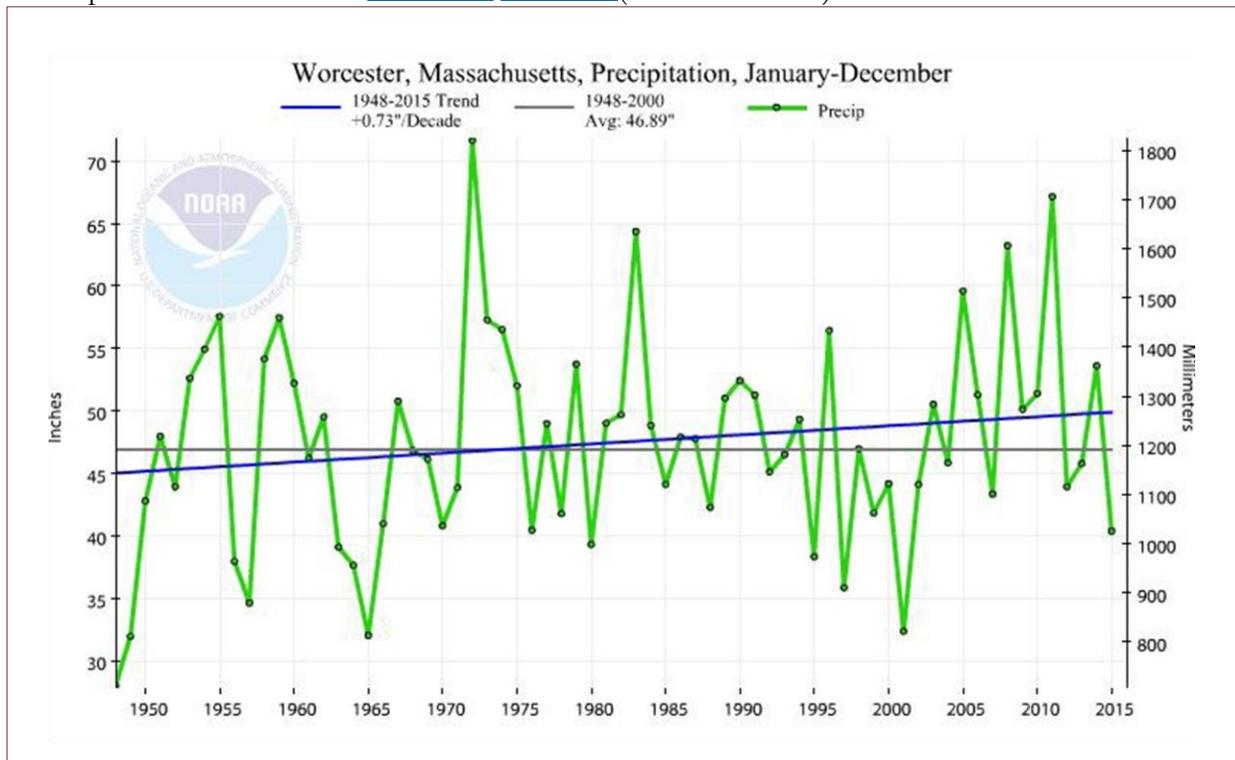

Figure 2. Annual precipitation at Worcester, Massachusetts. Blue line is the trend in the data. Grey

line is the average annual precipitation over the entire dataset. Source: National Oceanic and Atmospheric Administration Climate at a Glance (December 2016).
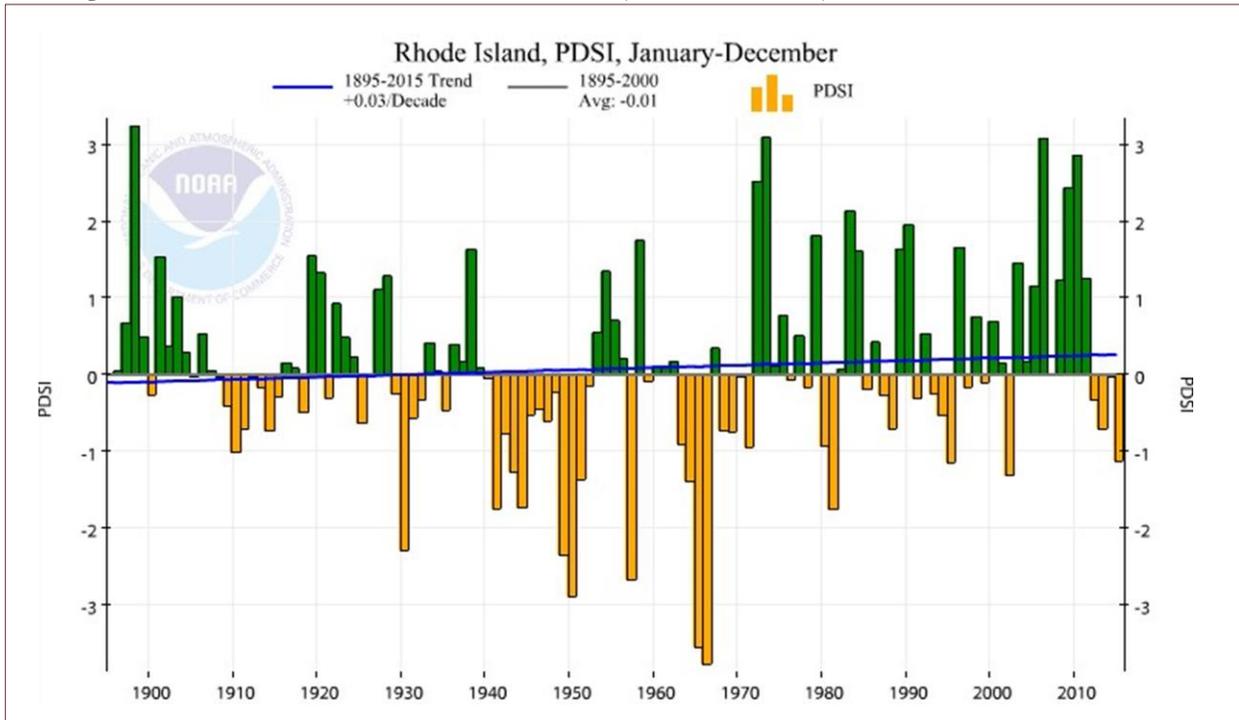

Figure 3. Annual Palmer Drought Severity Index (PDSI) for Rhode Island. Blue line is the trend in the data. Yellow bars indicate drier years. Green bars indicate moister years. Source: National Oceanic and Atmospheric Administration Climate at a Glance (December 2016).
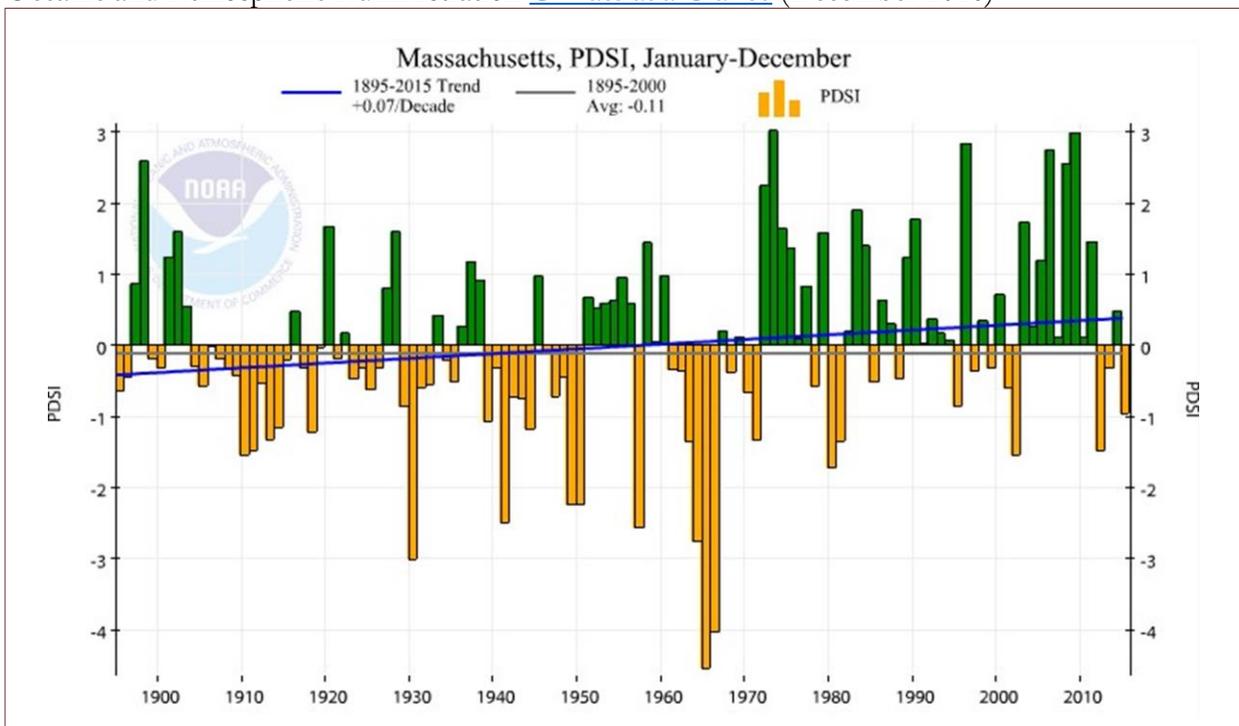

Figure 4. Annual Palmer Drought Severity Index for Massachusetts. Blue line is the trend in the data.

Yellow bars indicate drier years. Green bars indicate moister years. Source: National Oceanic and Atmospheric Administration Climate at a Glance (December 2016).

Projections

The Intergovernmental Panel on Climate Change (IPCC) published precipitation projections for 2100 based on a multi-model project (IPCC 2000 and 2013). The Special Report on Emissions Scenarios encompassed various greenhouse gas emission rates based on potential societal activities. To ensure accuracy, the IPCC overlaid the outputs of all emission scenarios and only published projections that were supported by at least 66 percent of the model outputs. The projections were reported as deviations from 1990–1999 precipitation rates (Figure 5). At high latitudes above 45°N an increased volume of precipitation is very likely, while in subtropical regions precipitation is likely to decrease as much as 20 percent. The seasonality of weather events will also be impacted, with winter months bringing additional precipitation (blue), and summer months bringing decreased precipitation volume (red) as compared to past regional averages (Figure 5). The frequency and intensity of severe precipitation events, such as hurricanes, are projected to increase along with the average volume of precipitation (IPCC 2000). The geographical distribution of these weather events is also projected to deviate from current patterns. In addition, it is projected that extratropical storms will be more likely to move toward the poles (IPCC 2000).

On a more local scale, the University of Massachusetts Climate System Research Center produced climate model projections for Rhode Island and Massachusetts, as well as other states in New England and the Midwest (Bradley et al. 2016). The precipitation projections were based on two greenhouse gas emission rates, similar to the IPCC Special Report on Emissions Scenarios model. The lower emission rate scenario will occur only if there are substantial efforts to mitigate greenhouse gas emission rates during future economic development (Bradley et al. 2016). Current greenhouse gas emissions compare with the higher emission rate scenario (Bradley et al. 2016). In the study, both emission rates resulted in similar findings regarding precipitation. The projections showed an increase by 2100 from 3 millimeters per day to 4 millimeters per day (0.12 to 0.16 inches per day) (Figures 6 and 8). The overall amount of winter precipitation is projected to increase, but warming temperatures will cause more rain and less snowfall (Figures 7 and 9). These changing precipitation patterns and rising temperatures will create a climate in New England that in 2100 is similar to present-day Virginia with a three-season cycle (Bradley et al. 2016).
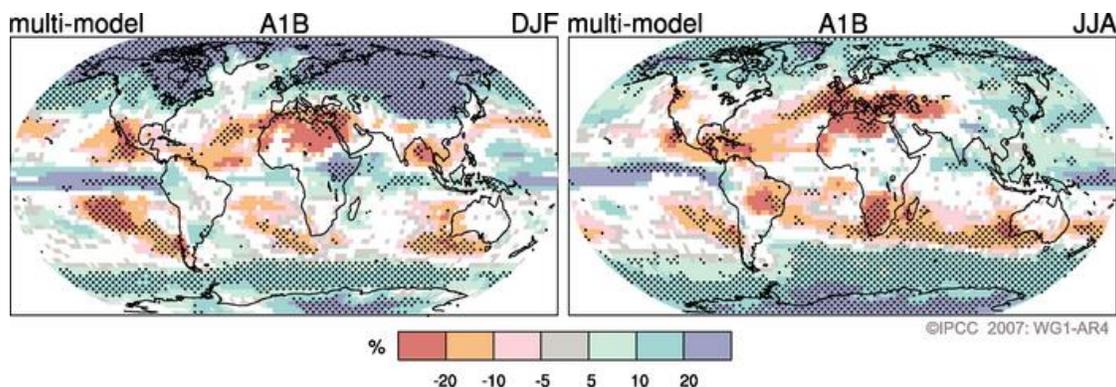

Figure 5: Projected precipitation patterns in 2100 produced through a multi-model process by the International Panel on Climate Change (IPCC 2000). The scale is in reference to deviation from

1990-1999 precipitation rates. The left image displays December to February (DJF) trends, and the June to August (JJA) trends are displayed on the right (IPCC 2000). White areas on the map indicate areas where less than 66 percent of models predicted the same precipitation trend, so the projection was removed from the graphic (IPCC 2000). Stippling represents areas where more than 90 percent of the climate models had the same projection for precipitation rates (IPCC 2000).
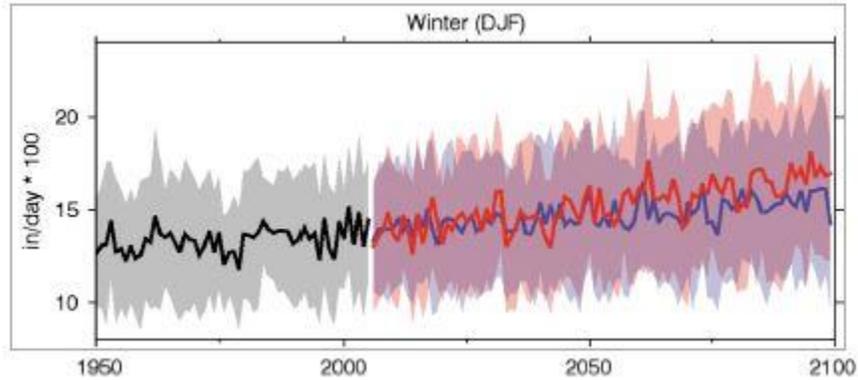

Figure 6: Climate model projection of the winter (December–February) total precipitation in Rhode Island until the year 2100. The black line represents precipitation data collected in Rhode Island between 1950 and 2015. The red line is the temperature projection under a scenario of high greenhouse gas emission rates that are comparable to present-day emissions. The blue line is the temperature projection under a scenario of lower emission rates 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 deviation.
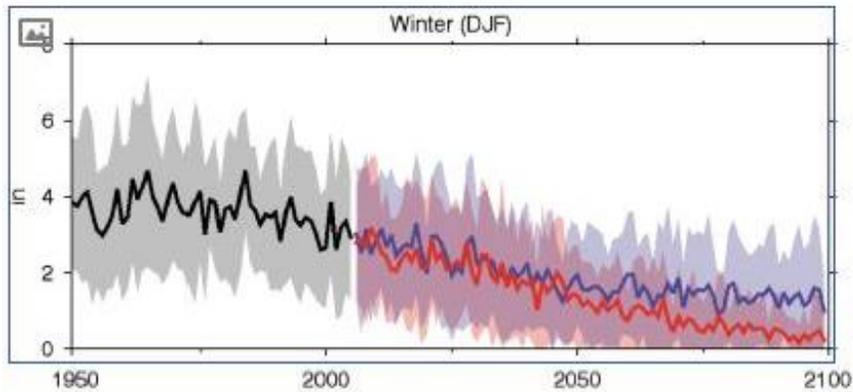

Figure 7: Climate model projection of the winter (December–February) annual snowfall in Rhode Island until the year 2100. The black line represents precipitation data collected in Rhode Island between 1950 and 2015. The red line is the projection under a scenario of high greenhouse gas emission rates that are comparable to present-day emissions. The blue line is the projection under a scenario of lower emission rates 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 deviation.
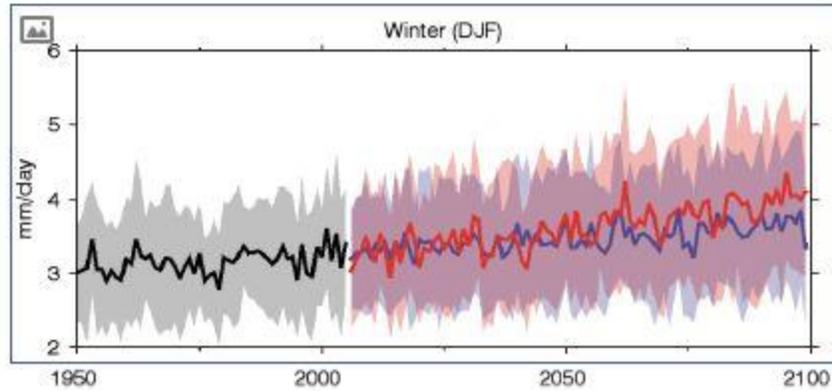
Figure 8: Climate model projection of the winter (December–February) total precipitation in Massachusetts until the year 2100. The black line represents precipitation data collected in Massachusetts between 1950 and 2015. The red line is the projection under a scenario of high greenhouse gas emission rates that are comparable to present-day emissions. The blue line is the projection under a scenario of lower emission rates 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 deviation.
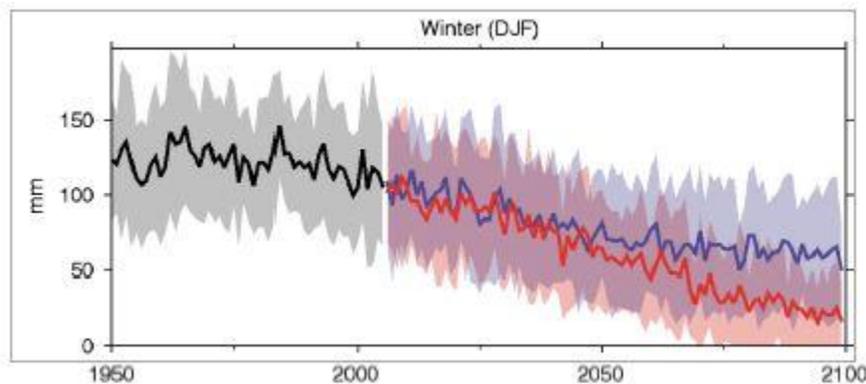
Figure 9: Climate model projection of the winter (December–February) annual snowfall in Massachusetts until the year 2100. The grey sector represents precipitation data collected in Massachusetts between 1950 and 2015. The red line is the projection under a scenario of high greenhouse gas emission rates that are comparable to present-day emissions. The blue line is the projection under a scenario of lower emission rates 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 deviation.

5.   DISCUSSION

Climate change is altering the intensity, frequency, and seasonality of local precipitation patterns. These trends directly impact the Narragansett Bay watershed, changing physical conditions including water clarity, dissolved oxygen concentrations, and water quality; biological parameters such as chlorophyll; and human health through beach and shellfishing closures. These impacts have already been observed regionally and will be magnified as precipitation patterns continue to change.

Current climate models project that total volume of precipitation will increase by 1 to 3 inches per decade locally (Figures 6 and 8) and that seasonality of precipitation will continue to change, leading to greater effects on the overall health of Narragansett Bay (Bradley et al. 2016). Rhode Island and Massachusetts have received at least 40 inches of rain annually since 1980, and the annual amount of precipitation has increased between 0.5 to 1 inch per decade (Figures 1 and 2; Pilson 2008, Vallee and Giuliano 2014, UNH 2016). The local increase in precipitation is due to large, slow-moving storm systems, multiple events in a short period of time, and the increase in frequency and intensity of rain events (Vallee and Giuliano 2014). The projected increased intensity and frequency of precipitation events in places with aging infrastructure, urbanization, and poor soil quality is expected to promote flooding (see "Sea Level" chapter). This will increase pressure on local wastewater treatment facilities, causing more overflow events and introducing excess nutrients and pathogens into the rivers and the downstream estuarine waters (Melillo et al. 2014, USEPA 2016; see "Wastewater Infrastructure" chapter). This increased runoff and overflow into the Narragansett Bay watershed is expected to have cascading negative impacts on the overall health of the watershed.

The observed and projected intense flooding and overflow events will degrade the physical, biological, and human health conditions within the Narragansett Bay watershed. Water quality is degraded when a large volume of precipitation is introduced rapidly, creating turbidity within the water column. This turbidity and increased inputs of nutrients, pollutants, pathogens and sediment often decrease the clarity of the water column. Poor water clarity impacts important habitats, such as seagrasses (see "Seagrass" chapter), and is an overall indicator of poor water quality.

Increased precipitation also affects chlorophyll concentrations and primary production by phytoplankton. Primary production occurs predominantly at the surface of the water column where nutrients (i.e., from precipitation, runoff, point-source discharge, and remineralization), sunlight, and dissolved oxygen are readily available. As the increased volume of precipitation introduces additional organic and inorganic nutrients to the estuary, it is expected that primary production may increase in surface waters, prompting eutrophication. As the primary producers die and settle to the bottom, this flux of organic matter decomposes, resulting in decreased dissolved oxygen in the water column, impacting benthic and other estuarine communities.

Dissolved oxygen levels can also be affected by water column stratification. With precipitation and runoff, the freshwater rests on top of the denser, saltier water. If no mixing occurs (either wind, tidal, or storm-induced), the bottom waters will become isolated or trapped and depleted of oxygen as organic matter decomposition and respiration of organisms consume oxygen. Without mixing, or advection of new water to the region, dissolved oxygen cannot be replenished (see "Dissolved Oxygen" chapter). The increase in precipitation and intense precipitation events may lead to more stratification of the water column in Narragansett Bay, depleting dissolved oxygen in the bottom water; an analysis of stratification concluded that climate-driven changes will be due to increases of river runoff more than increases in temperature (Codiga 2012).

The physical and biological impacts of increased precipitation often prompt local beach and shell fishing closures due to the decreased water quality. Increased precipitation often brings fecal coliform or *E. coli* bacteria to rivers and estuaries. Correlations have been made between the amount of precipitation and bacterial counts at local monitored beaches (see "Marine Beaches" chapter). Similarly, precipitation amounts and correlated bacteria counts have been used to close areas approved for shellfishing (see "Shellfishing Areas" chapter). Both beaches and shellfishing areas are opened as soon as the threat to human health passes.

The impacts from increased flooding and overflow events are the most obvious results of changing precipitation patterns witnessed in the region. However, this is only one aspect of the changing patterns. Although the total volume of precipitation is projected to further increase, when and how the precipitation is falling is also changing. According to the Massachusetts Executive Office of Energy and Environmental Affairs and demonstrated in Figures 8 and 9, winter precipitation is expected to increase faster than other seasons, often falling as rain rather than snow (EEA 2011). This increase of rain events in the winter months will impact local snow pack, spring snowmelts, and peak stream flow (Trenberth 2011, EEA 2011, RI EC4 STAB 2016, USEPA 2016). Historically, this region of New England received snowfall, which immobilized the water on land. Spring temperatures reintroduced the water source into the estuary. In comparison, when rain is delivered to a watershed, the precipitation is immediately introduced into the waterways. This immediate introduction increases base flow of streams in the winter, and may reduce base flow during spring when New England would typically undergo a thawing period. Due to this change, low-flow periods are expected to occur earlier in the spring, extending the summer dry season. Therefore, the projected alteration of water delivery to the Narragansett Bay watershed will alter the timing and intensity of local low-flow periods (EEA 2011).

The projected drought and drought-like conditions are expected to increase the water temperatures in small rivers and streams, degrade reservoir and groundwater reserves, and magnify the impact of environmental pollutants (RI EC4 STAB 2016). During times of water stress, any withdrawal of water will be felt more intensely, especially if the fresh groundwater is not replaced through precipitation, but perhaps through saltwater intrusion (USEPA 2016). This can occur most commonly around estuaries so therefore is a concern for the Narragansett Bay watershed (USEPA 2016).

Periods of drought allow pollutants to build up on land. When precipitation does fall, the first flush (first pulse of water over land) contains a very high concentration of pollutants delivered to receiving waters. The high concentration of organic and inorganic pollutants associated with the first flush has the potential to magnify the negative impacts on turbidity, water clarity and quality, chlorophyll, dissolved oxygen, and human health within Narragansett Bay and its watershed. In order to prevent the impacts from an event such as the first flush, or any large flooding event, the Narragansett Bay Commission and other organizations are conducting local mitigation efforts. In Providence, a three-phase Combined Sewer Overflow Abatement Program is designed to prevent 1.1 billion gallons of untreated water and wastewater from entering Narragansett Bay annually as a result of flooding and overflow (NBC 2017). The first phase of the project was completed in 2008 and included the construction of a deep rock tunnel that contains the wastewater until the storm has passed and the treatment plant has the capacity to treat it. The second phase of the project was completed in 2014 and consists of two interceptors (Woonasquatucket and Seekonk), two sewer-separation projects, and an artificial wetlands facility that will mitigate the discharge rate from 17 sources of sewage outflow (NBC 2107). The third phase of the project, currently under review, consists of another deep rock tunnel through Pawtucket and Central Falls that feeds into the Bucklin Point Wastewater Treatment Facility (NBC 2107). The success of the first two phases of this project has allowed the Rhode Island Department of Health to investigate opening an urban beach on the Providence River estuary and adjusting the precipitation amounts that trigger a shellfish acreage closure (RIDOH 2015; see "Shellfishing Areas" chapter).

Overall, the changing precipitation patterns as a result of global climate change will likely alter the physical and biological conditions of the Bay and indirectly impact human health. The changing trends will pose new challenges for the health of the Bay and biodiversity, but with a proactive and innovative perspective, environmental management groups will work to mitigate the impacts in order to preserve the integrity of the Narragansett Bay watershed.

6. DATA GAPS AND RESEARCH NEEDS

The assessment of the Palmer Drought Severity Index conducted as part of this report is a preliminary evaluation and requires further development. Other assessments need to be evaluated—such as the Crop Moisture Index and Cornell University's effort to analyze frequency and intensity of precipitation—to be certain that the Estuary Program is using the best available information and analyses regarding changing precipitation (Figure 10). The Crop Moisture Index is a weekly measurement of short-term water needs versus available water (www.drought.gov), and Cornell University's effort to examine extreme precipitation is designed to be a critical component of engineering design and regulations for structures and facilities to withstand the precipitation. We need to explore which approach, or combination of approaches, would give the best possible picture of extreme precipitation and drought throughout the watershed.
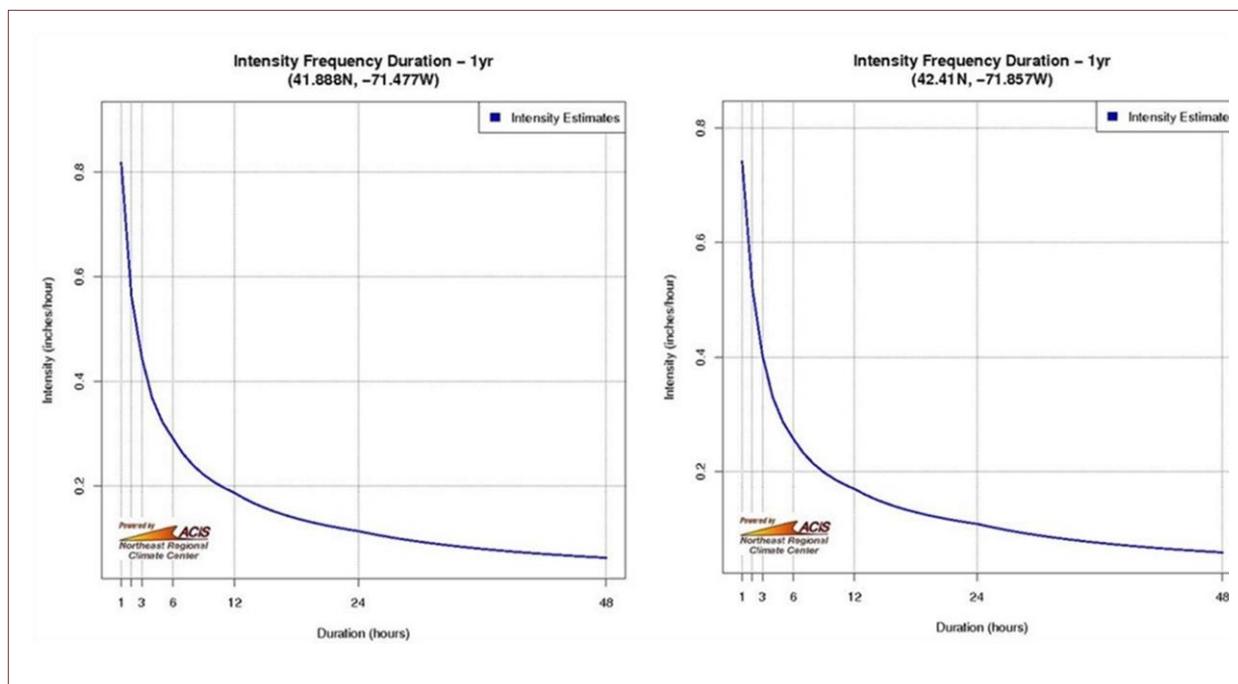

Figure 10. Precipitation intensity-frequency-duration plots for a one-year storm. Left: Providence, Rhode Island. Right: Worcester, Massachusetts. Source: Cornell University (2016)

The frequency, amount, timing (seasonality), and type (rain, snow) of precipitation influence physical, chemical, and biological processes within Narragansett Bay and its watershed. These interactions are complex, and research is needed to better understand the environmental responses to changing precipitation so that effective recommendations can be made regarding climate change adaptation strategies. Specifically, we need to know how increased precipitation affects river flows, nutrient loading, animal and plant communities, water clarity, water column stratification,

groundwater quantity and quality, and wetland processes (both freshwater and coastal wetlands), among others. We suggest development of conceptual models that highlight the many interactions, coupled with field studies and numerical ecosystem-level models.

7. ACKNOWLEDGEMENTS

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