REVIEW

Projected changes to air temperature, sea-level rise, and storms for the Gulf of Maine region in 2050

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A scientific scenario paper was prepared ahead of the Gulf of Maine (GOM) 2050 International Symposium to review and summarize possible weather-related and sea-level changes within the GOM as a result of climate change. It is projected that the GOM will experience warming temperatures, continued sea-level rise, and changes to storm characteristics and related elements such as precipitation and waves in the intermediate term, by approximately 2050. Coastal communities within the GOM region are particularly vulnerable to the anticipated impacts of climate change. This article aims to provide context on some of the consequential impacts that may occur from the changes projected within the area.

Introduction

The recent release of collaborative national climate assessments such as the "Canada's Changing Climate Report (CCCR)" (Bush and Lemmen, 2019) and the "Climate Science Special Report (CSSR)" (U.S. Global Change Research Program, 2017, 2018) has provided a scientifically informed overview of the current state and projected changes to the environment as a result of climate change. This knowledge and information provides the foundation needed for decision makers to consider the possible impacts on coastal environments, infrastructures, and people.

The Gulf of Maine (GOM) is a coastal and ocean basin in the North Atlantic Ocean. Its waters include the Bay of Fundy, the Northeast Channel, and Georges Bank, while its coastal area extends along the Canadian provinces of Nova Scotia and New Brunswick and down the northeastern United States of Maine, New Hampshire, and Massachusetts to the tip of Cape Cod. This scenario article will outline how changes to air temperature, sea-level rise, and storms are likely to alter the conditions for regions within the GOM in the intermediate term, by approximately 2050. The results embedded are those of the referenced authors as this review was used to help guide discussions at the GOM 2050 International Symposium in November 2019.

Over the past three decades, the Intergovernmental Panel on Climate Change (IPCC), an international body responsible for assessing the science related to climate change, has conducted global-scale scientific assessments of climate change. Projections of future climate change are driven by a range of potential forcing scenarios of greenhouse gas (GHG) and aerosol emissions. These scenarios are based on assumptions about how fossil fuel consumption and land use will change in the coming years. Because future emissions are difficult to predict, it is necessary to use plausible scenarios, ranging from low to high emission scenarios, to project future climate change. Recent climate change projections, that is, climate model projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) described in the IPCC Fifth Assessment Report (IPCC, 2013a, 2014), are based on a suite of future forcing scenarios called Representative Concentration Pathways (RCPs). The RCPs are identified by a number indicating the change in radiative forcing caused by GHGs and other external drivers by the end of century (van Vuuren et al., 2011). The national climate assessments summarized in the American CSSR and the Canadian CCCR present climate scenario results for this standard suite of RCP scenarios. The information presented in this paper is based primarily on data within the CSSR, the CCCR, and multi-model ensemble percentile results from 29 CMIP5 global climate models (GCMs) with a focus on the GOM region (1 × 1° grid resolution). Similar to the CCCR, in this article, we will refer to climate scenarios based on RCP2.6 as "low emission scenarios," those based on RCP4.5 and RCP6 as "medium emission scenarios," and those based on RCP8.5 as "high emission scenarios."

It should be noted that more recently the CanLEADv1 (Canadian Large Ensembles Adjusted Data set version 1) has become available. This data set includes bias-adjusted regional climate model output based on the CanRCM4

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Up to mid-century, the estimated change in temperature, sea level and storm behavior varies relatively little between the low, medium and high emission scenarios. This lack of variability provides a strong basis for short-term adaptation planning. Post 2050, there is a significant increase in uncertainty and growing separation of projections from the different emission scenarios. For purposes of long-term planning and mitigation efforts, the range in future temperature and sea level that need to be considered will largely depend on the risk tolerance of stakeholders.

(Canadian Regional Climate Model) large ensemble data set (Cannon et al., 2015; Cannon et al., 2018). Further computational analysis is required to produce results specific to the GOM for the 2050 period (data available on the open data catalogue: https://open.canada.ca/data/en/dataset/a97edbc1-7fda-4ebc-b135-691505d9a595). Future studies using these results could provide the finer spatial detail (0.5° resolution) needed by decision makers to distinguish the more complex projections of climate parameters including temperature, precipitation, pressure, and wind speed, between coastal and inland areas within the domain.

Temperature projections
Under all emission scenarios, annual average air temperatures are projected to rise throughout the next century. All of these scenarios suggest similar projected warming in the near term but show a growing separation between results for the low emission scenario and high emission scenario beginning mid-century (IPCC, 2014).

Due to varying local climate processes and feedbacks, the rates of warming are not globally uniform and tend to vary from one region to another. GOM-specific output from the CMIP5 multi-model ensemble is given in **Table 1** and **Figure 1**.

Projected changes to average and extreme temperatures
Table 2 summarizes the projected changes in other temperature indices specific to the regions within the GOM by mid-century. Note that the range of values for each index represents not only the variations within the low to high emission scenarios but also their geographical variation within the GOM region.

Based on CMIP5 GCMs, the median of the multi-model ensemble projections shows that the annual mean temperature average across the GOM region is expected to rise +1.4 °C to +2.7 °C by mid-century (**Table 1**). To put this into perspective, consider that such an increase in the annual mean temperature would be comparable to the hottest year in historical record for the contiguous United States (1.8 °C [3.2 °F] in 2012; NOAA, 2013). Given such a rise in annual temperatures, recent record-setting temperature years could be the norm in the GOM region by mid-century.

Over the northern part of the GOM region in particular, warming over the winter months is expected to be slightly greater than the warming during the summer months (Zhang et al., 2019). This differentiation of annual warming is reflected in other temperature indices, most notably in degree days (**Table 2**). Heating degree days (the annual sum of daily mean temperature below 18 °C) and cooling degree days (the annual sum of daily mean temperature above 18 °C) are indicators of building cooling and heating demand used for energy utility and planning. Degree days are also indicators of the amount of heat available for crop growth. The projected change in the number of heating degree days is considerably greater than the change in cooling degree days, which is a reflection of the higher projected warming trend in winter compared to summer.

Throughout the GOM region, the growing season for warm-season crops is expected to lengthen by 2–4 weeks by mid-century. A longer growing season and warmer winters provide a longer period for plant growth and productivity of beneficial plants (such as crops and forests). However, these warmer temperatures present challenges including increased weed and pest pressure, as well as an extended period of vulnerability to frost damage due to accelerated leaf-out and bud development (Rigby and Porporto, 2008; Wolfe et al., 2018).

With warmer annual average temperatures and fewer cold extremes, a shorter and less pronounced cold season is expected, along with less early-winter snowfall and earlier snowmelt, resulting in changes to the seasonal hydrological cycle and stream flows throughout the GOM region (Notaro et al., 2014; Demaria et al., 2016; Contosta et al., 2017).

More frequent and intense heat events are projected throughout the coming decades, while the frequency and intensity of cold waves are projected to decrease throughout the GOM region (Thibeault et al., 2014). Highest daily maximum temperatures are expected to become hotter by mid-century, with a projected rise of 1.9 °C to 4.4 °C (**Table 2**). By the 2050s, under a high emission scenario, the annual highest daily temperature that would currently be attained once every 50 years is projected to occur every 3 or 4 years (Zhang et al., 2019).

Implications of warmer average temperatures and extremes
There are numerous potential implications associated with a local climate that has higher average temperatures with hotter and more frequent extremes. The following short list of potential impacts is summarized and discussed in further detail within the latest Canadian and American national climate change reports (Lemmen et al., 2014; Savard et al., 2016; Dupigny-Giroux et al., 2018; Zhang et al., 2019).

· More frequent drought conditions due to increased rates of surface evaporation and loss of water from plants caused by higher temperatures.
· Earlier and longer fire seasons due to hotter and drier conditions.
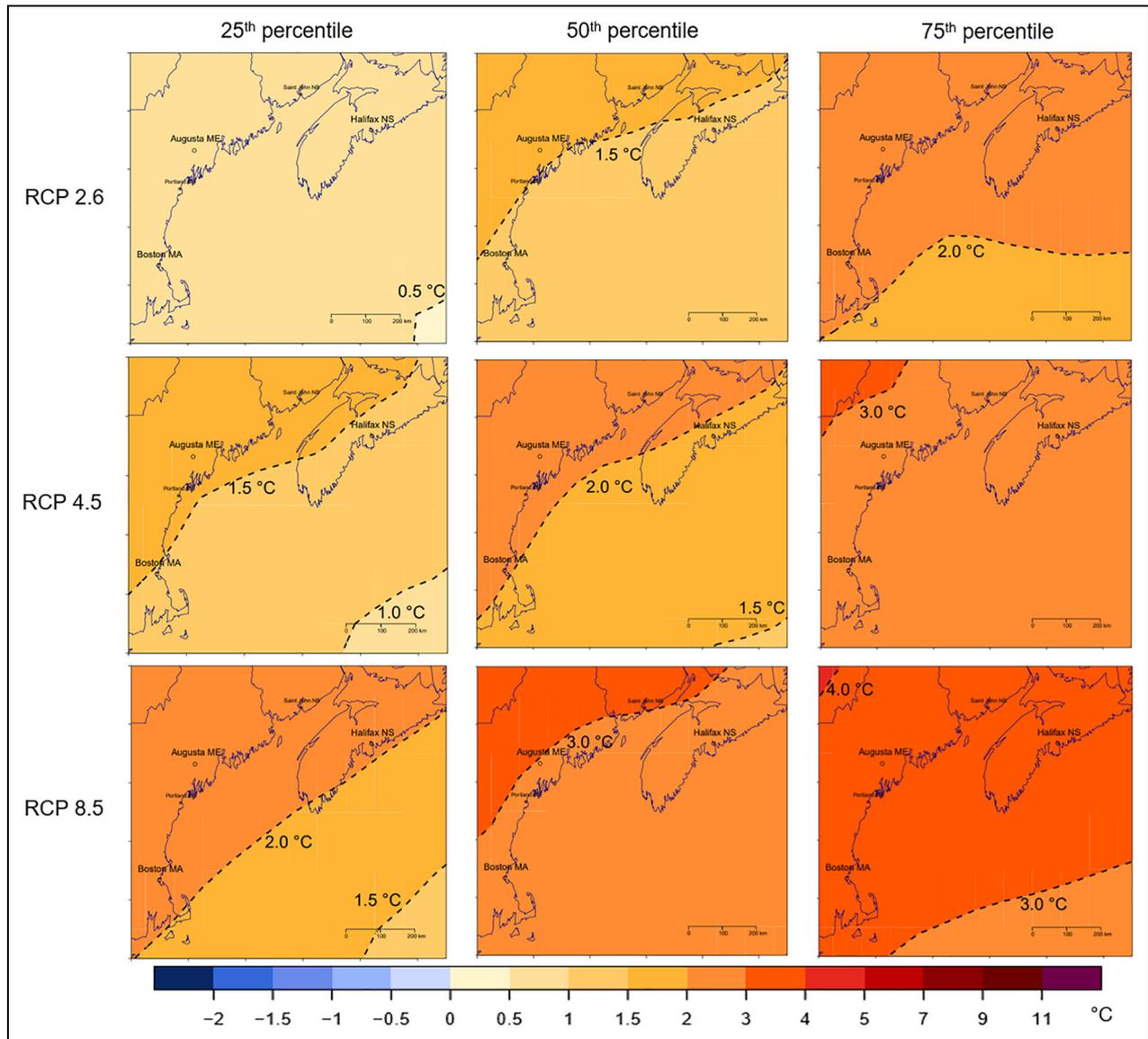
Figure 1. Spatial depiction of projected changes (relative to 1986–2005) in annual mean air temperature. Based on CMIP5 multi-model ensemble results for the GOM region (1 × 1° grid resolution) for 2046–2065 for three scenarios (RCP2.6, RCP4.5, and RCP8.5) and for three percentiles (25th, 50th, and 75th). DOI: https://doi.org/10.1525/elementa.2021.00059.f1

Table 1. Projected changes in annual temperature by mid-century in the GOM.[a] DOI: https://doi.org/10.1525/elementa.2021.00059.t1

Climate Scenario	Median Projected Annual Temperature Change[a] in °C (25th, 75th Percentile)
RCP2.6	1.4 (0.8, 2.1)
RCP4.5	1.9 (1.4, 2.6)
RCP8.5	2.7 (2.0, 3.4)

[a]Projections for 2046–2065 relative to 1986–2005 based on CMIP5 multi-model ensemble results for the GOM (1 × 1° grid resolution) provided by ECCC, Climate Research Division.

· Increases in associated health-related impacts such as heat stroke and exhaustion, and costs associated with more frequent and severe heat-related events.
· Increased weed and pest pressure due to a longer growing season and warmer winters.
· An extended period of spring frost risk to vulnerable agricultural sectors such as fruit crops, due to warmer spring temperatures causing early season leaf-out and spring development.
· A decline in freshwater quality due to more frequent algal blooms in warmer surface waters of large lakes.

Table 2. Summary of projected changes in various temperature indices.[a] DOI: https://doi.org/10.1525/elementa.2021.00059.t2

Index	Projected Change (GOM)
Cooling degree days	+50 °C to +300 °C
Heating degree days	−400 °C to −1300 °C
Number of growing season days (warm-season crops)	+18 to +29
Highest daily maximum temperature	+1.9 °C to +4.4 °C
Lowest daily minimum temperature	+3.8 °C to +5.5 °C
Annual number of "hot" days[b]	+2 to +20

[a]From recent American climate assessments (relative to 1976–2005) and Canadian climate assessments (relative to 1986–2005) for the GOM region (Kunkel et al., 2013; Vose et al., 2017; Dupigny-Giroux et al., 2018; Zhang et al., 2019).

[b]"Hot" days are defined by the CCCR as greater than 30 °C.

· Earlier river ice breakup and freshet flow in spring due to earlier peaks in spring snowmelt.
· Changes to hydrological power production due to changes in timing of spring streamflow.

· Impacts to winter recreation industries due to warmer (and shorter) winter conditions.
· Impacts to rural industries such as logging and maple syrup production due to warmer winter and spring conditions.
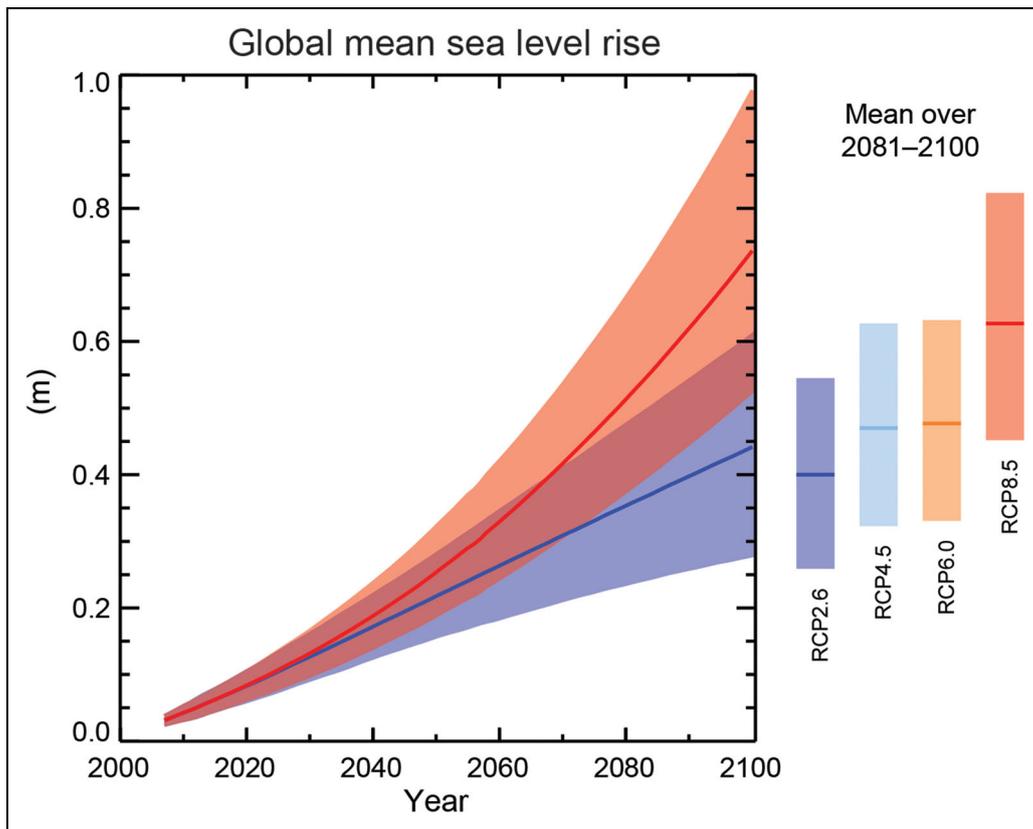
Sea-level rise projections
Global sea-level rise
Global sea-level rise is one of the most significant consequences of increasing global temperatures and is primarily driven by two factors: (1) thermal expansion of a warming ocean and (2) increased melting of mountain glaciers, icecaps, and the Antarctic and Greenland ice sheets (IPCC, 2014, n.d.).

Global mean sea-level change is referenced to the center of the Earth and is commonly discussed in terms of "absolute" sea level. Up to 2050, uncertainty in climate change-driven future sea level is relatively small, and absolute sea-level projections using low to high emission scenarios suggest a rise of 15–35 cm by mid-century as depicted in **Figure 2** (IPCC, 2013b; Sweet et al., 2017a; Greenan et al., 2018).

Beyond 2050, a major source of uncertainty in projections of global sea level is the stability of the Antarctic Ice

Figure 2. Projected change in global mean sea levels due to climate change. Projections of global mean sea-level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean over the period 2081–2100 for all RCP scenarios are given as colored vertical bars, with the corresponding median value given as a horizontal line (IPCC, 2013b, Figure SPM.9). DOI: https://doi.org/10.1525/elementa.2021.00059.f2

Sheet (AIS). Current climate models are not yet able to adequately capture the dynamic process of AIS instability; thus, the global mean sea-level rise projections in **Figure 2** do not capture the low-probability, high-impact scenario of accelerated AIS melt. In September 2019, the IPCC released a Special Report which focused on climate change impacts on the world's oceans and cryosphere (IPCC, n.d.). This report highlights that, since the IPCC Fifth Assessment Report in 2014, there have been numerous research efforts that have focused on better understanding the dynamic processes affecting the AIS and providing improved estimates of the contribution of Antarctica to global sea-level rise. These research endeavors indicate that under higher GHG emission scenarios, there is the potential for even more rapid global sea-level rise after mid-century due to the instability of the AIS (DeConto and Pollard, 2016; Wilson et al., 2018). For a high emission scenario, DeConto and Pollard (2016) concluded that AIS instability could contribute an additional 91 cm (3 ft.) to global sea-level rise by 2100.

Relative sea-level rise

Changes to sea level are not uniform globally. Locally, the sea-level change that is experienced relative to land is of most concern to coastal planners and is known as "relative" sea-level change. In addition to the global sea-level change estimates, projected changes to relative sea level at a coastal site depend on the following:

1) Local vertical motion of the ground

The primary cause of vertical land motion across North America is glacial isostatic adjustment, which causes surface uplift or subsidence due to the delayed effects of the last continental glaciation. Within the GOM region, locations along the Canadian coastline to the Canada–U.S. border tend to be sinking, while U.S. locations along the Maine and Massachusetts coasts have very small uplift rates (Craymer et al., 2011).

Subsidence caused by human activity has also been identified as an important factor in vertical land motion in many parts of the world, delta regions in particular.

Table 3. Summary of mean relative sea-level rise projections for 2050 (relative to 1995).[a] DOI: https://doi.org/10.1525/elementa.2021.00059.t3

Tide Gauge Locations	Projections of Relative Sea-Level Rise by 2050
Halifax, NS	24–32 cm (0.79–1.0 ft.)
Yarmouth, NS	
Saint John, NB	19–27 cm (0.62–0.89 ft.)
Eastport, ME	
Portland, ME	
Boston, MA	

[a]For a selection of tide gauge station locations within the GOM region (James et al., 2014; Zhai et al., 2014, 2015).

Within the GOM region, this process of anthropogenic subsidence has not been recognized as a significant contributor to vertical land motion and has not been taken into account in projections of relative sea-level rise herein.

2) Spatial variations in the redistribution of glacial meltwater in the global oceans

Geographically distinct patterns of sea-level variability around the world due to changes in water storage on Earth's continents and in the mass of ice sheets are known as sea-level fingerprints and have been discussed in detail by Mitrovica et al. (2011). As ice melts and reduces the mass of glaciers and ice caps, the load and gravitational pull on the underlying land surface are reduced. Ocean waters nearby move away, thus causing sea level to rise faster far away from the melting ice.

3) Regional changes to sea level due to dynamic oceanographic effects and global circulation patterns

Changes to atmosphere–ocean dynamic factors such as ocean currents and winds can lead to changes in the sea surface height and therefore changes in local relative sea level (Hughes et al., 2009). For much of the East Coast region, including the GOM, a projected slowing of the Gulf Stream could contribute 10–20 cm to sea-level rise by 2100 due to dynamic oceanographic effects including a significant decline of ocean density contrast across the Gulf Stream (Yin, 2012; Yin and Goddard, 2013).

Table 3 summarizes projected mean relative sea-level change by 2050 (relative to 1995) for a selection of tide gauge station locations within the GOM region. These values are based on projections of sea-level change from the IPCC's Fifth Assessment Report (IPCC, 2014) for the medium and high emissions scenarios, with the addition of contributions from vertical land motion, variation in meltwater distribution, and dynamic oceanographic factors (James et al., 2014; Zhai et al., 2014, 2015).

It should be noted that a few studies suggest that in a high emission scenario that considers accelerated AIS melt, while the probability is small, an additional 50 cm or more is possible in addition to these 2050 mean relative sea-level rise estimates (Han et al., 2016; Sweet et al., 2017b). Recent research by Wake et al. (2019) along the New Hampshire coast also investigated contributors to local relative sea-level rise and probabilities associated with future relative sea-level rise projections. Their projections are consistent with the National Climate Report (Sweet et al., 2017a, 2017b) and also highlight the low-probability, high-impact, extreme scenario. Their work suggests that along the New Hampshire coast for the medium emission scenario, there is a 1-in-100 chance that relative sea-level rise will exceed 61 cm (2.0 ft) by 2050, and a 1-in-1000 chance that relative sea-level rise will exceed 88 cm (2.9 ft) by 2050.

Coastal flooding

Regardless of the uncertainties in the exact magnitude, a rise in sea level in the coming decades is inevitable. Given the rising sea levels, the number of floods each year from tidal forcing alone that cause minor impacts (also called "nuisance floods") will also increase in depth and frequency, turning it from a rare event into a recurrent and potentially damaging problem due to road closures, overwhelmed storm drains, and compromises to infrastructures (Sweet et al., 2014; Moftakhari et al., 2015; Ray and Foster, 2016).

The Bay of Fundy within the GOM is home of the world's largest tides due to its shape which enhances the natural period of oscillation or tidal resonance. Within the Bay of Fundy, significant flooding only tends to occur when high water events coincide with the 1–2 h that the tide is near its maximum. Extreme Sea Level (ESL) events are caused by a combination of processes such as storm surges, waves, and tides, and ultimately have significant coastal impacts (IPCC, n.d.). The highest tides of the year, commonly known as King Tides, occur during perigean (moon is closest to Earth) spring tides (moon and sun aligned). Exceptionally, high King Tides occur when perigean spring tides optimally coincide with other astronomical occurrences of declination and other orbital positions of the earth, sun and moon. In many coastal locations, tide levels are at their highest when these astronomical factors peak simultaneously every 18.7 years in what is termed a lunar nodal cycle (Talke et al., 2018). Within the Bay of Fundy itself, some studies suggest that the occurrence of strongest tide levels coincides closer to the 18.03-year Saros cycle in which perigean spring tides peak simultaneously with a select group of astronomical factors as described by Desplanque and Mossman (2004). The most recent nodal cycle (and Saros cycle) peaked in 2016 and caused extensive minor flooding all along the Eastern Seaboard even in the absence of a significant weather system. Awareness of the coastal impacts from King Tides is important because it demonstrates what average water levels might look like in the future based on sea-level rise projections. Numerous King Tides Projects, in which participants snap and share images of King Tides, have been established locally (Gulf of Maine King Tides Project: http://gulfofmaine.kingtides.net/) and worldwide to help citizens understand how sea-level rise will impact their local community.

ESL events and coastal flooding often occur if a King Tide coincides with a storm (Wood, 1986). Mid-latitude and tropical storms often cause an abnormal rise in water level above the predicted tide (referred to as a storm surge) due primarily to changes in atmospheric pressure and the effect of winds pushing water onshore. A storm surge coinciding with a King Tide, particularly at high tide in the Bay of Fundy, often results in a damaging ESL event, which can extend further inland and lead to more extensive flooding. Several major coastal flooding events of the past in the GOM region have resulted from mid-latitude storms striking the area close to a King Tide (i.e., the Saxby Gale, Desplanque and Mossman, 1999, the Ash Wednesday Storm of 1962, Cooperman and Rosendal, 1962, the

Northeastern U.S. Blizzard of 1978, U.S. ACE, 1979, and Winter Storm Grayson 2018, LeComte, 2019). It is of particular interest that future nodal and Saros cycles, producing exceptionally high King Tides, will peak again in the mid-2030s and again in the early 2050s.

As sea levels continue to rise under all emissions scenarios, ESL events will become more frequent. Research suggests that "once per century" ESLs are projected to occur at least once per year in the GOM by 2050 even under low emission scenarios (Oppenheimer et al., n.d.). For purposes of coastal adaptation and mitigation, it is vital that risk tolerance assessments consider contributions from extreme weather events to future sea levels.

Implications of sea-level rise for the GOM

The potential impacts associated with sea-level rise are numerous and can be specific to a local community or municipality. The following is a short set of some of the more significant challenges that sea-level rise will bring to coastal regions, the GOM in particular (Bush et al., 2014; Atkinson et al., 2016; Savard et al., 2016; Greenan et al., 2018; Sweet et al., 2017a):

- Accelerated erosion and more frequent and severe flooding will impact:
- coastal farmland, housing, or recreation areas
- coastal infrastructure used for fisheries, such as ports, wharves, piers, and fish plants
- tourism infrastructure (e.g., wharves and coastal properties) and cultural resources
- existing and proposed coastal export terminals
- Flooding of wetlands and ecosystem changes that will affect the flora and fauna, causing the loss of habitat for fish, birds, plants, and many other species
- Flooding of highways causing isolation of coastal communities.
- Loss of areas providing physical protection (e.g., wetlands and dykes)
- Increased permanent inundation due to higher average water levels
- Increased saltwater intrusion within coastal rivers and aquifers

Storm projections

As mentioned above, air temperatures are projected to continue to rise into 2050. These increasing temperatures have implications on many aspects of storms including their development. Changes in the frequencies and intensities of storms by 2050 are difficult to predict due to the nature of these events, the varying results within the scientific literature, and the uncertainties associated with characterizing them for the initial stages of climate modeling (Greenan et al., 2018). One of the largest factors when considering storm track projections begins with the global atmospheric circulation pattern. For example, the

North Atlantic Oscillation (NAO), which represents the pressure pattern between the Subtropical (Azores) High and the Subpolar (Arctic) Low, significantly influences the path and intensity of storms that would affect the GOM region. However, while the NAO and other large-scale atmospheric patterns such as the El Niño–Southern Oscillation (ENSO) have significant effects on climate variability, they are not captured to the accuracy needed in order to resolve regional-level questions such as storm projections with high confidence (Shepherd, 2014). One trend of storms that has been consistently projected, although still with low confidence, is the continued northward push of storm tracks (Collins et al., 2013). This change to storm tracks has consequential effects on weather elements of the storm such as a shift in the precipitation and wind patterns for a given location.

Although the level of detail and confidence for storm projections is limited and more analysis is needed (Colle et al., 2015), a general overview of the information found in the scientific literature pertaining to high-impact storms, such as winter storms and tropical storms, is given below.

Winter storms

Projections of Atlantic Extratropical Cyclones based on a method whereby the seven best models within a subset of 15 CMIP5 GCMs were used to evaluate storm behavior in the western Atlantic during the "cool season" (November–March; Colle et al., 2013). The results for the mid-century (2039–2068) period show fewer and weaker storms offshore of the Northeast U.S. coast, including the area off Cape Hatteras, NC, where East Coast winter storm tracks often originate. However, projections for inland areas of the Northeast U.S. seaboard show more storms, including a peak at year 2050 in more intense storms (<980 mb). These results show differences between projected storm traits along inland and offshore areas of the coast within the GOM region. These differences reiterate the need for downscaling the GCMs to achieve the finer spatial resolution needed to understand the regional impacts of these storms. More intense storms could result in dangerous (and costly) conditions for ocean transport and coastal infrastructure being less useable due to increased wave action, as well as produce more damage from the wind-driven waves and storm surge possibly severe enough to cut off access to coastal communities (Savard et al., 2016). Increase in storm-driven winds and wave action would also result in a proportional increase in demand for environmental response and search and rescue services (Shackell et al., 2013).

When considering changes to precipitation phase, increasing temperatures imply that more wintertime precipitation will fall as rain than snow. The projected higher temperatures, combined with the northward shift of storm tracks and associated rain–snow boundary to higher latitudes, further suggest a changing proportion of solid to liquid phase precipitation for snow-dominated areas. Statistically downscaled CMIP5 model output for a high emission scenario shows this evolution of liquid dominated precipitation by the end of the 21st century for the eastern US (Ning et al., 2015), including areas within the

GOM. Similar uncertainties exist with model initialization as stated above, as there have been changes in monitoring procedures and locations over time making the observations of snowfall amounts in particular subject to variability. Also, climate model computations of precipitation have an inherent level of uncertainty due to the nature of these events, especially for snow (Easterling et al., 2017). However, with the potential for less snow occurrence and a shorter snow season, there are possible implications on water resources, ecosystems, and the economy (Ning et al., 2015). Further to that, with more precipitation during the winter season falling as rain, there will be an increase of rain-on-snow events which can have an impact on snow loads resulting in compromised infrastructures like rooftops (Federal Emergency Management Agency, 2013) and cause damage to roadways including extensive washouts (Rapaport et al., 2017). An earlier spring snowmelt can also result in major inland flooding, as has been the case for rivers within the GOM (Kunkel et al., 2013).

Tropical cyclones

Tropical cyclones (storms and hurricanes) are a crucial component when considering the likelihood of more extreme weather events in the coming decades as they are often accompanied by higher extreme precipitation, winds, waves, and storm surge, causing significant damage especially to coastal sectors such as the GOM. Globally, projected changes of tropical cyclone systems, including the waves associated with them, combined with rising mean sea levels, could result in higher ESL events (Collins et al., 2019). There is a lack of consistent projections of tropical cyclones for the GOM region by the intermediate term (2050), and regional downscaling of the GCMs would be needed to decipher their unique characteristics within the domain. However, with increasing sea surface temperatures (SSTs) as a result of increasing air temperatures (Loder and Wang, 2015), and these SSTs being a key parameter for the strength of tropical cyclones, models are in general agreement that there will be an increase in the intensity of these storms (Collins et al., 2019). It is also suggested that there will be more tropical cyclones in the Atlantic basin within the very intense category (Knutson et al., 2013). This possibility is notable from an impact perspective because of the significant winds and waves that these storms produce. Category 4 and 5 storms are defined by the Saffir-Simpson Hurricane Wind Scale as having sustained winds of 114135 knots (210–249 km/h) and greater than 135 knots (249 km/h), respectively. Although hurricanes of these categories do not occur as often, they cause a disproportionate amount of damage as has been shown by historical analyses of U.S. hurricane damage with category 4 and 5 hurricanes accounting for approximately half of the damage (Pielke et al., 2008). These more severe storms would threaten human health and safety (Berry et al., 2014) and cause damage to infrastructure, which in turn would elevate insurance costs and lead to effects on the tourism industry (Kovacs and Thistlethwaite, 2014). Storm-related disruptions, in general, can also cause a loss of productivity to the transportation sector with a consequential economic impact.

Table 4. Projected changes in annual precipitation by mid-century in the GOM. DOI: https://doi.org/10.1525/elementa.2021.00059.t4

Climate Scenario	Median Projected Annual Precipitation Change[a] in % (25th, 75th Percentiles)
RCP2.6	2.2 (–5.2, 10.4)
RCP4.5	4.1 (–3.6, 12.2)
RCP8.5	4.6 (–3.2, 13.2)

[a]Projections for 2046–2065 relative to 1986–2005 based on CMIP5 multi-model ensemble results for the GOM (1 × 1° grid resolution) provided by ECCC, Climate Research Division.

Precipitation

Changing precipitation patterns are important to consider when thinking about implications for the future as they can have many consequential impacts. A projection of storm tracks northward would result in a general shift of precipitation patterns. Regional-level precipitation patterns are more difficult to project than temperature because they are affected by the global circulation pattern as well as temperature, which dictates how much moisture the atmosphere can hold (Shepherd, 2014). However, with increasing water vapor (Santer et al., 2006) and higher temperatures, there is confidence in trends toward increases in extreme precipitation events, but it is unclear if this is the main driver for the increase and more research is needed to clearly link the two (Kunkel et al., 2013). Specifically, for the GOM region, there is high confidence that the observed increases in extreme precipitation events will continue throughout the United States, including in the northeast where the largest increases have occurred. Projected change in the 20-year return period (i.e., 1 in 20 probability of occurring each year) amount for daily precipitation shows increases greater than 10% for the Northeast United States for the low emission scenario by mid-century (Easterling et al., 2017). In Canada, while the observational trends have not been as consistent, projections for all regions show increases in the annual maximum daily precipitation by mid-century, with Atlantic Canada (which includes the Canadian side of the GOM) having an approximate 8% increase in the 20-year return period by mid-century (Zhang et al., 2019). This information is of interest to municipal planners who are concerned with the management of stormwater as extreme precipitation events can cause flooding, erosion, and damage to infrastructure such as roads and buildings. However, quantifying these trends is difficult due to the small-scale nature of systems causing extreme precipitation events. Therefore, even if model downscaling is conducted for a region, the projected amounts of precipitation from extreme events should still be considered with less confidence (Zhang et al., 2019).

Projected changes in annual precipitation for the GOM for the mid-century period (2046–2065) relative to 1986–2005 as given by the CMIP5 multi-model ensemble results are shown in **Table 4**. The results are for three scenarios (RCP2.6, RCP4.5, and RCP8.5) and for three percentiles (25th, 50th, and 75th) showing the range of uncertainties. The median values spanning the low (RCP2.6) to high (RCP8.5) emission scenarios suggest a 2.2%–4.6% increase in annual precipitation for the area.

Seasonal projections

Tables 5 and **6** give the projected seasonal changes (relative to 1986–2005) in temperature and precipitation, respectively, from the CMIP5 multi-model ensemble results for the GOM region (1 × 1° grid resolution) for 2046–2065. There is no notable seasonal difference in temperatures for the GOM depicted in these results. All three emission scenarios show similar ranges of temperature warming (**Table 5**) with median ensemble values of +1.3 °C to +2.8 °C from the low emission (RCP2.6) scenario to the high (RCP8.5). The change in precipitation (**Table 6**) appears to be larger for the winter months, with median values of 3.0% (RCP2.6) to 6.8% (RCP8.5). However, it should be noted that there is less confidence in seasonal precipitation projections than annual projections (Zhang et al., 2019).

Implications of storms for the GOM

There are many possible consequential impacts as a result of changing storm patterns. The list below is a selection of the possibilities for various sectors within the GOM (Forbes et al., 2004; Federal Emergency Management Agency,

Table 5. Projected changes in seasonal temperature by mid-century.[a] DOI: https://doi.org/10.1525/elementa.2021.00059.t5

Season	Median Projected Temperature Change[a] in °C (25th, 75th Percentiles)		
	RCP2.6	RCP4.5	RCP8.5
Winter (December–February)	1.4 (0.3, 2.5)	2.1 (1.1, 3.0)	2.7 (1.7, 3.7)
Spring (March–May)	1.3 (0.5, 2.3)	1.7 (0.9, 2.7)	2.4 (1.5, 3.4)
Summer (June–August)	1.4 (0.7, 2.2)	1.9 (1.2, 2.7)	2.7 (2.0, 3.5)
Fall (September–November)	1.5 (0.8, 2.3)	2.0 (1.3, 2.7)	2.8 (2.0, 3.6)

[a]Projections for 2046–2065 relative to 1986–2005 based on CMIP5 multi-model ensemble results for the GOM (1 × 1° grid resolution) provided by ECCC, Climate Research Division.

Table 6. Projected changes in seasonal precipitation by mid-century.[a] DOI: https://doi.org/10.1525/elementa.2021.00059.t6

Season	Median Projected Precipitation Change[a] in % (25th, 75th Percentiles)		
	RCP2.6	RCP4.5	RCP8.5
Winter (December–February)	3.0 (−10.5, 17.9)	5.0 (−8.2, 19.4)	6.8 (−6.6, 22.1)
Spring (March–May)	2.8 (−11.1, 18.0)	4.4 (−9.8, 20.2)	5.4 (−9.6, 21.6)
Summer (June–August)	0.3 (−14.2, 17.1)	2.3 (−13.7, 19.9)	1.1 (−15.0, 19.6)
Fall (Sep.–Nov.)	−1.1 (−15.3, 15.1)	1.6 (−12.6, 17.2)	0.9 (−14.5, 17.0)

[a]Projections for 2046–2065 relative to 1986–2005 based on CMIP5 multi-model ensemble results for the GOM (1 × 1° grid resolution) provided by ECCC, Climate Research Division.

2013; Shackell et al., 2013; Savard et al., 2016; Rapaport et al., 2017; Oppenheimer et al., n.d.):

· More intense storms could result in dangerous conditions for ocean transport and coastal infrastructure may become less usable due to increased wave action.
· Increased damage to coastal infrastructure due to larger storm surge and waves from more intense storms, including the potential for coastal communities to become inaccessible.
· Increase in storm-driven winds and wave action would result in a proportional increase in demand for environmental response and search and rescue services.
· Potential for less snow occurrence and a shorter snow season leads to possible effects on water resources, ecosystems, and the economy.
· More winter season rain could increase rain-on-snow events which can have an impact on snow loads resulting in compromised infrastructures like rooftops and cause damage to roadways including extensive washouts.
· Earlier spring snowmelt could result in major inland flooding and overflowing rivers.
· Potential for more intense tropical cyclones accompanied by higher extremes in rainfall, storm surge, and peak winds may produce more severe impacts, threaten human health and safety, and cause damage to infrastructure. This in turn would elevate insurance costs and have effects on the tourism industry.
· Storm-related disruptions can cause a loss of productivity to the transportation sector with a consequential economic impact.
· Extreme precipitation events can cause flooding, erosion, and damage to infrastructure such as roads and buildings.

· Average storms that reoccur in the same area can result in destabilization of the coast within small dunes.

Summary

In the coming decades, the coastal communities within the GOM region will not be exempt from experiencing the projected impacts of climate change (Tables S-1, S-2, and S-3 summarize the potential impacts by element). Warming air temperatures are likely to result in more frequent droughts and extended fire seasons and will ultimately have impacts not only on the health of GOM people and ecosystems but also on the local economy, particularly in the agricultural, hydro production, and recreation sectors. The projected rise in local sea levels and more frequent ESL events will result in coastal erosion and more frequent and severe flooding, causing an increase in disruptions and damage to communities, infrastructure, and ecosystems in the GOM region. Although less certain, a warmer climate in the GOM could also bring about a potential shift in storm tracks, both winter and tropical, which could lead to changes in local precipitation and wind patterns. There is a general agreement between climate models in the estimated changes in temperature, sea level, and storm behavior in the GOM over the next three decades, irrespective of the emission scenario. The consequences of today's emission controls will be felt more acutely after mid-century.

There are many recent and ongoing initiatives within the GOM that focus on addressing climate change resilience, adaptation, and education (some of which are highlighted in Text S-1). Presentations and discussions from the GOM 2050 International Symposium highlighted the need for tools that stakeholders can use to provide guidance for their decision making and planning based on their risk tolerance to help mitigate these impacts. This aspect needs to be better communicated to motivate cross discipline coordination and break down research silos (Collins et al., 2019).

Data accessibility statement

The CMIP5 data used in this manuscript can be downloaded from the ECCC Climate Scenarios website: https://climate-change.canada.ca/climate-data/#/cmip5-data.

Supplemental files

Table S-1. Short list of potential climate change impacts in the Gulf of Maine due to changing air temperatures.

Table S-2. Short list of potential climate change impacts in the Gulf of Maine due to changing sea level.

Table S-3. Short list of potential climate change impacts in the Gulf of Maine due to changing storm factors.

Text S-1. Initiatives with a focus on addressing climate change resilience, adaptation, and education within the Gulf of Maine.

Competing interests

The authors have no competing interests to declare.

Author contributions

WA contributed to conception and coordinated the manuscript production. Author co-leads LC and TT conducted the review of existing research within the domain of interest (Gulf of Maine) for the projected time period (mid-century, approximately 2050). BT and RR produced multi-model ensemble scenarios for temperature and precipitation for the domain of interest. LC and TT interpreted all data sets used in the manuscript to provide context to build a scenario paper. All coauthors contributed to multiple drafts and a final revision of the manuscript.

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