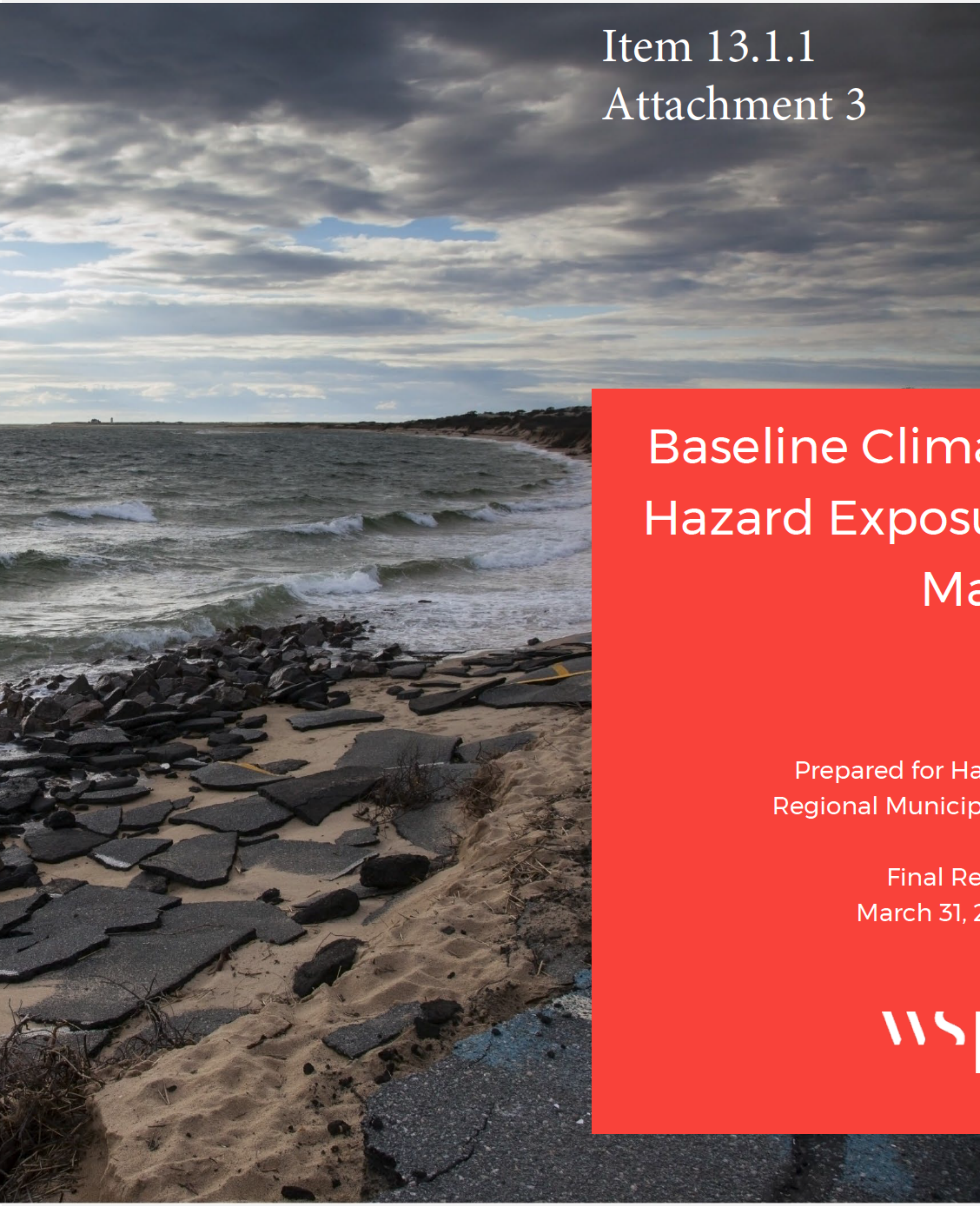
Item 13.1.1
Attachment 3



Baseline Climate Hazard Exposure Maps

Prepared for Halifax Regional Municipality

Final Report
March 31, 2023

WSP

Baseline Climate Hazard Exposure Maps for Halifax Regional Municipality

Final Report

Halifax Regional Municipality

Final

Project No.: 211-10974-01
Date: March 31, 2023

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March 31, 2023

Final

Halifax Regional Municipality
PO Box 1749, Halifax, Nova Scotia B3J 3A5

Attention: Emma Bocking, Environmental Specialist

Dear Emma:

Subject: Final Report - Baseline Climate Hazard Exposure Maps for Halifax Regional Municipality

Client ref.: 21-1113 Engineering, Environmental, Landscape Architecture, Surveying, Architectural, Interior Design, Project Management, Traffic and Transportation, Transportation Demands Management, and Real Estate Appraisal and Evaluation Services

WSP is pleased to provide the final report and maps for the **Baseline Climate Hazard Exposure Maps for Halifax Regional Municipality** project. This report describes the methodology and results from the assessment of exposure to six climate hazards over three time periods.

Thank you for the opportunity to support Halifax Regional Municipality in advancing its climate resilience work.

Kind regards,

[redacted]

[redacted]

Christina Schwantes, MEM
Advisor, Climate Risk and Resilience

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Revision History

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FINAL

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March 31, 2023

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March 31, 2023

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Appendices

1 EXECUTIVE SUMMARY

The purpose of this project is to create baseline climate hazard exposure maps to enable Halifax Regional Municipality (HRM) staff to make strategic, data-informed, and climate-aligned decisions around critical infrastructure prioritization, emergency management, and planning. Six climate hazards were assessed over three time periods: recent past (historical: 1991-2020), near-term future (2050: 2021-2050), and long-term future (2100: 2071-2100). The hazards are:

— Extreme heat
— Meteorological drought
— Extreme rainfall
— Extreme snowfall
— Extreme wind
— Changing winter temperatures

Projections were obtained for a set of climate indicators for each hazard and were assessed using Representative Concentration Pathway (RCP) 8.5. Projections were obtained from an ensemble of 27 statistically downscaled climate models (Pacific Climate Impacts Consortium) as well as the CanRCM4 regional climate model from the North American CORDEX Program (Mearns, 2017), which is a climate model focusing on extreme wind.

The projections for each climate indicator were normalized on a five-point scale and then averaged to provide a relative hazard exposure score from lowest (1) to highest (5) for all communities within the HRM boundary in each of the time periods assessed.

The outputs of the analysis are a set of climate projections and associated maps (Appendix B) that include extreme values for multiple indicators of six climate hazards. The GIS maps and accompanying spatial data for each climate indicator have also been provided to HRM. These spatial data show how climate hazards evolve over time and are intended to be used by HRM as inputs for further assessments and to inform decision making related to climate change across the municipality.

The next steps HRM should consider following this assessment include:

— Compile a hazard exposure database to centralize climate hazard data and contributing indicators in GIS. Ensure that the database supports comparison with other hazard studies completed to date (i.e., flooding) and future studies of other hazards (i.e., wildfire).

- Complete a spatial climate vulnerability and risk assessment to understand the sensitivity, adaptive capacity, and overall risk associated with multiple climate hazards in different communities across HRM. This study should leverage existing, community-level infrastructure, environmental, and sociodemographic data. The results can inform tailored resilience measures that address drivers of vulnerability and risk in each community.
- Supplement hazard maps with additional, detailed spatial studies to identify geographic, atmospheric and environmental features that may influence climate hazards at the local scale such as the urban heat island effect.
- Use the spatial hazard exposure maps to inform the Hazards, Risks, and Vulnerability Assessment (HRVA) process and mainstream climate adaptation into emergency management and planning, infrastructure prioritization, and long-range planning and development strategies.

2 PROJECT OVERVIEW

In 2020, Halifax Regional Municipality (HRM) adopted a comprehensive climate change plan (HalifACT 2050: Acting on Climate Together). HRM has also completed an Adaptation Baseline Report, and a Hazards, Risks, and Vulnerability Assessment (HRVA) process to respond to the climate crisis and prepare for a resilient and healthy future in Atlantic Canada.

HalifACT 2050 identifies actions for HRM to illustrate spatial data on a variety of climate hazards to enable both municipal staff and the broader community to mainstream climate thinking and action to influence decision making processes as it pertains to the four pillars of emergency management and identify critical resources, infrastructure, and services across the Region.

WSP created a set of baseline climate hazard exposure maps and related GIS data for the entire regional municipality (the Baseline Climate Hazard Exposure Maps project, henceforth referred to as “the project”). The data will help HRM understand future changes in climate and extreme weather conditions for six climate hazards. The outputs of this project include this report and accompanying spatial data that can be used by HRM as inputs for future risk and vulnerability assessments, mainstreaming climate change into decision-making, and capacity building for climate adaptation, which are core areas of action in HalifACT. This study is intended to complement ongoing work by another consultant to develop spatial pluvial, fluvial, and coastal flood hazard maps for the entire municipality.

Three time horizons were considered for this project as requested by HRM to understand climate hazards over the recent past (historical: 1991-2020), near-term future (2050: 2021-2050), and long-term future (2100: 2071-2100). See Box 1 for information on why each time horizon is assessed over a 30-year period. These time horizons align with other work completed by HRM and with best practices used for climate adaptation. The project assessed the following climate hazards:

- Extreme heat
- Meteorological drought
- Extreme rainfall
- Extreme snowfall
- Extreme wind
- Changing winter temperatures

Box 1: Weather vs. Climate

Weather describes the atmospheric conditions at a specific location and time. Climate is an average of weather conditions over a long period of time (usually a 30-year period). Climate indicators represent the average intensity or frequency of weather events over the 30 years in question. Climate indicators represent average or extreme values of weather variables. They can be averaged over time and space to help describe a variety of climate conditions, including season-over-season variability and extreme events.

3 METHODOLOGY

The following sections outline the steps taken by WSP to prepare the climate hazard exposure maps including the selection and sourcing of climate indicator data, the analysis of data to develop hazard exposure maps, and the assumptions and limitations associated with the use of the data.

3.1 Due Diligence and Data Assessment

An initial selection of climate hazards was provided by HRM. These hazards were then reviewed by WSP's climate science team to identify opportunities and constraints based on the availability and quality of climate projection data. A high-level scan and review of climate change adaptation and risk mapping projects across Canada was completed to find existing best practices for mapping exposure to climate hazards. Table 3-1 presents the primary content reviewed to inform the study methodology. Academic studies and scientific literature were also consulted to understand approaches for regional scale exposure mapping and limitations for mapping complex climate hazards that do not have readily available climate projections (such as wind and storm activity), and are listed in the Bibliography of this report.

Table 3-1: Document Review

Region/Community of study	Title of Reference
The City of Calgary	Community Climate Risk Index (WSP, 2021)
Region of Durham	Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region (Ontario Climate Consortium, 2020)
Region of Peel	Climate Trends and Future Projections in the Region of Peel (Ontario Climate Consortium et al., 2016)
City of Moncton	Climate Change Adaptation and Flood Management Strategy (City of Moncton, 2013)
Vancouver Coastal Health Authority	Mapping spatial patterns in vulnerability to climate change-related health hazards (Jessica Yu et al., 2020)

Region/Community of study	Title of Reference
Town of Bridgewater	Municipal Climate Change Action Plan (Town of Bridgewater, 2013)
District of Yarmouth	Municipal Climate Change Action Plan: Thriving Amidst Uncertainty (District of Yarmouth, 2013)

Through the literature scan and climate science review, the list of climate hazards and indicators was refined and agreed upon with HRM in the Methodology Memo for Indicator Development (see Appendix D). Climate indicator selection is discussed further in the following sections.

Beyond the climate hazard review, HRM also provided a set of spatial data for review and inclusion in the study. This included HRM community/neighbourhood boundaries and various infrastructure, landscape and demographic data which can provide context to the climate hazard maps.

3.2 Climate Indicator Selection

For the six climate hazards included in this project, WSP conducted background research to identify the most relevant climate indicators for the HRM context. Climate indicators are used to quantify climate hazards and demonstrate trends and evolution over time. For example, the number of days above 30°C is one climate indicator for extreme heat. By quantifying the number of days above 30°C in the recent past, near-term future, and long-term future, it becomes possible to interpret the trend and evolution of extreme heat. To understand how and why climate hazards are changing in the Halifax region, multiple indicators were selected for each hazard. The following criteria were used to select specific climate indicators:

- The indicators are relevant to the climate hazard
- The indicators represent the most relevant climate change impacts in terms of physical risk to infrastructure, people, and the natural environment
- The indicators are used and applied in similar climate change work at other Canadian municipalities
- There is sufficient development and modelling in the scientific literature

The outcome of this step was a collection of climate indicators that support the overall characterization of a given climate hazard. The climate hazards are described by their supporting indicators in the following tables along with justification for their inclusion.

Table 3-2: Extreme Heat Indicators

Indicator	Description/Relevance
Number of days > +30°C	This indicator is a measure of the number of days with a maximum daily temperature above 30°C. Relevant for impacts on people in alignment with heat warnings and days that mechanical cooling becomes critical to maintain indoor air quality/comfort.
Cooling degree days (accumulated number of degrees Celsius when a given day's mean temperature is above 18°C)	Cooling degree days are days where the mean temperature is greater than 18°C. The indicator considers the intensity of heat by measuring the number of degrees above the 18°C threshold each day. Relevant to understand demand for mechanical cooling.
Highest maximum temperature	The highest annual temperature. Relevant for impacts on human health and safety, potential heat stress on plants/natural environment, and impacts to temperature-sensitive assets (e.g., softening and deformation of asphalt).
Length of hot season (season where 30°C temperatures occur)	Indicator of the length of the summer season, measuring the number of days from first occurrence of a +30℃ day to the last occurrence during the summer season. Relevant for human health, environmental impact, and demand for mechanical cooling.

Table 3-3: Meteorological Drought Indicators

Indicator	Description/Relevance
Number of drought days (preceding 2-week water deficit)	A meteorological drought episode is a period longer than 2 weeks where the water budget (i.e., Precipitation - Evapotranspiration value) falls below the 10th percentile. Relevant for agricultural and environmental impacts with some indication of irrigation demand and water supply.
Total summer precipitation (mm) (June to August)	Total precipitation accumulating between June and August. Relevant for drought which tends to be most impactful during the late summer and fall and is influenced strongly by precipitation in the preceding months.
Total precipitation in winter and spring (mm) (December to May)	Total precipitation accumulating between December and May. Relevant for drought which tends to be most impactful during the late summer and fall and is influenced strongly by precipitation in the preceding months.

Table 3-4: Extreme Rainfall Indicators

Indicator	Description/Relevance
Heavy precipitation days (> 20 mm)	The annual average number of days where precipitation exceeds 20 mm. Relevant to inform occurrences of localized flooding and operational impacts related to heavy rain (e.g., road closures, traffic impacts).
Annual maximum 1-day precipitation	The average amount of precipitation to fall on the wettest day of the year. Relevant to understand extreme rain events and related water damage/disruptions.
Annual maximum 5-day precipitation	The average amount of precipitation to fall on the wettest 5 consecutive days of the year. Relevant to inform the impact of sustained rain events.

Table 3-5: Extreme Snowfall Indicators

Indicator	Description/Relevance
Heavy snowfall days (>10 cm)	The annual average number of days where precipitation falls below 0°C and exceeds 10 mm snow water equivalent. Relevant for winter operations and cold weather emergency response.
Annual maximum 1-day snowfall	The average amount of precipitation (with temperature below 0°C) to fall on the wettest day of the winter. Relevant to inform the impact of extreme snowfall events.
Annual maximum 5-day snowfall	The average amount of precipitation (with temperature below 0°C) to fall on the wettest 5 consecutive days of the winter. Relevant to inform the impact of sustained snowfall events.

Table 3-6: Extreme Wind Indicators

Indicator	Description/Relevance
Average wind speed (km/h)	The average wind speed measured over a year. Provides an indication of general changes in wind condition at a coarse scale (approximately 25 km x 25 km spatial resolution).
Maximum wind speed (km/h)	The highest wind speed recorded over a year. Provides an indication of potential for physical damage to infrastructure and the natural environment at a coarse scale (approximately 25 km x 25 km spatial resolution).

Table 3-7: Changing Winter Temperatures Indicators

Indicator	Description/Relevance
Maximum winter temperature (December to February)	The highest temperature between December and February. Relevant to understand the extreme scenario for increases in winter temperatures.
Winter number of freeze-thaw cycles (December to February)	Number of freeze-thaw cycles, where the minimum temperature is equal to or below -2°C and the maximum temperature is above 2°C within a 24-hour period. Relevant to the degradation of infrastructure and operational management of ice accumulation and snowmelt during winter months.
Annual number of freeze-thaw cycles (October to September) ***Not used for mapping**	Number of freeze-thaw cycles, where the minimum temperature is equal to or below -2°C and the maximum temperature is above 2°C. Relevant to the degradation of infrastructure and operational management of ice accumulation and snowmelt.
Icing days (daily maximum temperature < 0°C) ***Not used for mapping**	Number of days where the daily maximum temperature is below 0°C. Relevant to inform the length of the winter season.

Winter temperature indicators suggest that there will be a general increase in both average and extreme temperatures over the winter season with greater fluctuations between high and low temperatures.

Some of the indicators for this climate hazard trend in opposite directions, making it challenging to represent the full range of hazard exposure. For instance, winter freeze-thaw cycles are expected to increase while annual freeze-thaw cycles are expected to decrease in both the near-term and long-term horizons. Additionally, the number of icing days is expected to decrease while the maximum winter temperature is expected to increase. To avoid indicator exposure ratings cancelling each other out, the list of indicators was shortened to capture only the changes related to winter freeze-thaw cycles and maximum winter temperatures in the hazard exposure maps. While warmer winter temperatures may present both challenges and opportunities, greater fluctuation in temperatures can damage infrastructure over time and may require changes to winter maintenance procedures.

Data for annual freeze-thaw cycles and icing days have still been provided to HRM for their own reference and analysis.

3.3 Climate Projections and Exposure Analysis

3.3.1 Climate Projections

HRM selected three-time horizons to assess changes in climate indicators and hazards over time and to inform current and future planning efforts: the recent past (historical: 1991-2020), near-term future (2050: 2021-2050), and long-term future (2100: 2071-2100).

Representative concentration pathway (RCP) 8.5 was used to assess all climate hazards. RCP 8.5 is a high carbon emission scenario with a strong increase in global temperature (4.5 – 5.0°C) by the end of the 21st century (Taylor et al., 2012). This emission scenario was chosen to provide a conservative estimate of future climate change (greater magnitude of climate change) and to align with other studies and data used by HRM. Newer climate models are now available and will eventually replace the models used to develop RCP scenarios. Future updates to the hazard exposure maps should consider using the latest generation of climate models.

The climate models used for this assessment are widely used to study climate change within Canada, and are the same models used by Environment and Climate Change Canada (ECCC) for climate projections. Two main climate change data sets were used. The first data set is from the Pacific Climate Impacts Consortium (PCIC, 2019), which relies on an ensemble of 27 statistically downscaled climate models. The second data set is the CanRCM4 regional climate model from the North American CORDEX Program (Mearns, 2017), which is a climate model focusing on extreme wind.

Because these climate models are at a global scale, it is necessary to downscale the spatial resolution. Downscaling is a process of “re-gridding” data to represent climate conditions at the regional or sub-regional scale. All PCIC data was downscaled to a spatial resolution of approximately 10 km by 10 km. The CORDEX data for extreme wind has been projected over a 25 km by 25 km grid, which is a coarser spatial resolution than the PCIC data. For each climate indicator at each time horizon, values were computed for the grid cells that cover the entirety of HRM.

3.3.2 Climate Hazard Exposure Analysis

The climate hazards considered in this assessment have the potential to impact people, infrastructure, and the environment in any and all locations across HRM. For instance, high temperatures could occur across the whole province of Nova Scotia, but some areas may experience higher temperatures than others. Exposure to a given climate hazard is expressed quantitatively for all contributing climate indicators for each grid cell within the HRM boundary.

Hazard exposure describes the relative magnitude of exposure to a climate hazard across HRM and uses a five-point scale from lowest (1) to highest (5). As a relative scale, it is calibrated over the entire range of values within the dataset for a given climate indicator. It can highlight, for example, the areas that experience the greatest relative change in exposure. For each indicator, the following process was used to create a unique scale:

— Identified the full range of values present within the data for each indicator across all three time horizons
— Defined a relative scale for the entire range of values and divided this scale into five equal segments, allowing numerical ranges for all climate indicators to be represented on a five point scale from lowest (1) to highest (5)

An example of the scaling approach for annual maximum temperature, which is one indicator for extreme heat, is provided in Table 3-8. For this indicator, the minimum and maximum values represent the value of the 90th percentile (the extreme high value).

Table 3-8: Indicator Scaling for Annual Maximum Temperature

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Highest maximum temperature	°C	30.18	39.92	30 – 40	30 – 31.9	1
					32 – 33.9	2
					34 – 35.9	3
					36 – 37.9	4
					38 – 40	5

For each time horizon, the range of values represent the 90th percentile value, which was selected to capture worst-case events rather than average events. The only exception is for precipitation-related drought indicators, where the worst-case is represented by the 10th percentile value (the extreme low value). Professional judgement has been applied to calibrate the individual scores across the range of values. These extreme values represent climate events that occur infrequently (10 percent of the time) but are more likely to cause problems for people, infrastructure, or the natural environment. Assessing changes in extreme values across the three time horizons allows for comparison of low likelihood but potentially high consequence events. Understanding these rare but impactful events will allow HRM to effectively prepare for future extreme events.

Using the previously computed projections for each grid cell, a hazard exposure score was assigned for each indicator based on the grid cell value, relative to the five-point scale. Recall that climate hazards are expressed as one or more climate indicators. Thus, the hazard exposure score for a climate hazard is the average of all contributing indicator exposure scores. This process resulted in a hazard exposure score for each grid cell in each time horizon for the six climate hazards considered. The hazard exposure scores were translated into a colour scale based on their rating (e.g., from lowest to highest) to allow for visual assessment across all grid cells in HRM. Geospatial outputs are provided in the geodatabase that accompanies this report.

All indicator data ranges, and associated scales are provided in Appendix A. Descriptions of each indicator file used to produce the GIS maps are provided in Appendix C – Data Dictionary.

3.4 Climate Hazard Exposure Mapping

WSP selected a sample of community layers provided by HRM and included these visual elements on the hazard exposure maps to situate visually how hazard exposure varies across the region.

- Community boundaries
- Locations of select communities

WSP also indicated HRM's nine unique regions on each map based on an image from the Discover Halifax website. A geospatial layer of the regions did not exist at the time of this project.

The intent of this study is to serve as a baseline for future assessments and decision-making. Thus, the sample layers are for demonstration only. Additional geospatial layers may be added by HRM to match their analysis needs.

3.5 Assumptions & Limitations

The assumptions and limitations of this project reflect that:

- The climate data were produced by a set of computational models that have been tested and validated by the international scientific community through different studies. However, the models remain prone to present biases and uncertainties. Those are, to some extent, related to computational limitations and the current incapacity of modelling all climate processes. This means that projections can be used to inform what future conditions may look like within HRM but may not accurately represent in detail site-specific conditions or outlier events that may be influenced by many complex factors that can not be completely represented in a climate model.
- WSP has selected climate indicators to characterize a given climate hazard based on a review of similar studies completed by other municipalities, relevant literature, and professional expertise. The list of climate indicators selected is not exhaustive and can only represent some of the main challenges that may be posed to the municipality from changing climate hazards.
- For climate indicators related to wind, climate projections are only available at a coarse spatial resolution. These climate projections can only provide an estimate of the percentage increase in strong wind conditions and have limited utility for informing location-specific exposure which are highly influenced by topography and local weather patterns that occur at a finer scale than can be captured by global climate models. Confidence is low for wind projections compared to other indicators.
- For climate indicators related to extreme heat, the climate projections do not take into consideration land cover conditions that may affect solar gain such as the urban heat island effect. As a result, the values for extreme temperatures may be over or underestimated in some locations. A more detailed analysis that considers the albedo of different land surface types and actual surface temperature observations can provide additional useful information about extreme heat exposure within the municipality. Urban area growth projections may also influence future heat island affect and would be valuable to consider.
- Climate science is an evolving discipline. This project aligns with the fifth generation of climate models (that is, CMIP5[2] and RCPs). New methods and data are continuously being made publicly available. WSP recommends that HRM revisit this work in the near future using the latest generation of climate models (CMIP6[3] and SSPs, Shared Socioeconomic Pathways).
- Preliminary hazard maps are presented at a broad scale (HRM boundary) and do not present detailed sub-neighbourhood information. As all data layers created for this assessment are provided to HRM, further analysis can be completed at a finer spatial scale (i.e., the neighborhood/community scale).

[2] CMIP5 refers to the Coupled Model Intercomparison Project Phase 5
[3] CMIP6 refers to the Coupled Model Intercomparison Project Phase 6

- The GIS climate hazard exposure layers created for this assessment are intended to inform high level strategic decision making about climate change and support further assessments of vulnerability and risk. The layers are not intended to be used for detailed design, code development, or any activities requiring detailed, site-specific information.

4 RESULTS

This section describes the results of the exposure analysis for each of the six climate hazards. The evolution of each hazard over the three time horizons is discussed, and key trends are highlighted along with examples from selected climate indicators.

All maps are provided in PDF in Appendix B. The GIS maps and accompanying spatial data for each climate indicator have also been provided to HRM in a shared folder. A description of each folder and indicator used in GIS is provided in Appendix C – Data Dictionary.

4.1 Extreme Heat

Extreme heat events may represent a sudden or prolonged period of intense hot weather that may have adverse impacts to human health and/or put strain on infrastructure systems like mechanical cooling systems and the natural environment. Map 1 (see Appendix B) shows that hazard exposure to extreme heat is projected to increase through the near-term future and into the long-term future. In the recent past, the hazard exposure scores ranged from 1 (lowest) to 2 (low). The hazard exposure scores range from 2 (low) to 3 (moderate) by the near-term future and 3 (moderate) to 5 (highest) by the long-term future. This suggests that the occurrence and duration of extreme heat events will increase over time. Changes in extreme heat exposure are evident for all regions by the near-term horizon, but the greatest increases for all indicators will be experienced in the long-term.

The increase in extreme heat exposure is driven by increases in several indicators (see Appendix A). The number of hot days (> 30 °C) is one indicator for extreme heat. For the three time periods, the number of hot days (> 30 °C) evolves in the following way:

- Recent past (hazard exposure score of 1 to 2): one to 30 hot days per year
- Near-term future (hazard exposure score of 2 to 3): 31 to 45 days per year
- Long-term future (hazard exposure score of 3 to 5): 45 to 70 hot days per year

The indicator evolution shows an increase in intensity (magnitude) as well as the variability of occurrence. This trend is true for all extreme heat indicators except the length of the hot season, which increases in magnitude but maintains a stable variability of approximately 50 days (20 to 70 days in the recent past; 80 to 126 days by long-term future).

The increase in exposure to extreme heat is greater for some areas than others. Inland areas generally show higher exposure to heat than coastal areas with more northern coastal areas showing the lowest exposure values in all time horizons. Coastal areas remain cooler than inland areas due to the temperature moderating effects of the ocean. However, coastal areas may also be impacted by increased humidity which has not been considered in this assessment and could be considered in future studies.

4.2 Meteorological Drought

Meteorological drought is defined as a prolonged period of dry weather that may result in a lack of soil moisture and socio-economic impacts related to a lack of water availability. It occurs as a result of low precipitation over a prolonged period. Drought may have the potential to limit water supply with implications for human use, agriculture, and water supply infrastructure. Map 2 (see Appendix B) shows that hazard exposure to meteorological drought is projected to increase through the near-term and into the long-term future. In the recent past and into the near-term, the hazard exposure scores range from 2 to 4. In the long-term, the hazard exposure scores range from 3 to 5. This suggests that the minimum amount of precipitation to fall over the winter, spring, and summer will decrease and there may be longer stretches of dry periods.

The increase in meteorological drought exposure is driven by increases in several indicators (see Appendix A). Drought days (days with a preceding 2-week water deficit) is one indicator for meteorological drought. For the three time periods, the indicator evolves in the following way:

- Recent past (hazard exposure score of 2 to 4): 28 to 52 drought days per year
- Near-term future (hazard exposure score of 2 to 4): 28 to 52 drought days per year
- Long-term future (hazard exposure score of 3 to 5): 36 to 60 drought days per year

In general, coastal areas show a lower hazard exposure than inland areas and northern areas lower than southern areas. For example, the hazard exposure score for Sheet Harbour increases only from 2 to 3 over all time periods while inland areas near Upper Sackville increase from 3 to 4. Drought is projected to increase by the long-term future with roughly two thirds of the region experiencing a hazard exposure rating of 4 and the first occurrence of a rating of 5 in the furthest inland sections of the region.

Spatial variability in drought exposure may be related to several climatic and geographic factors that influence precipitation and evaporation. Inland areas can generally be expected to be dryer than coastal areas. Differences in vegetation cover may also play a role in determining water deficits and these landcover changes may not be captured well by the global climate models. It is also important to note that exposure to meteorological drought does not consider water availability and storage which will significantly influence the social and economic consequences of drought. Water availability and storage is an important factor to determine overall drought risk and should be considered in future studies.

4.3 Extreme Rainfall

Extreme precipitation events deliver a large amount of rainfall in a short period of time, which may contribute to flooding or infrastructure damage. Map 3 (see Appendix B) shows that hazard exposure to extreme rainfall is projected to increase through the near-term future and into the long-term future. In the recent past, the hazard exposure scores ranged from 1 to 3. In the near-term the hazard exposure scores range from 1 to 4 and in the long-term from 4 to 5. This suggests that the amount of rainfall in the near-term future is comparable to current conditions. In the long-term, HRM will experience different extreme rainfall conditions than in the recent past with more frequent and intense rainfall events.

The increase in exposure to extreme rainfall is driven by increases in several indicators (see Appendix A). Heavy precipitation days (> 20 mm) is one indicator for extreme rainfall. For the three time periods, the indicator evolves in the following way:

- Recent past (hazard exposure score of 2): two to three days of heavy precipitation per year
- Near-term future (hazard exposure score of 3): four to five days of heavy precipitation per year
- Long-term future (hazard exposure score of 4 to 5): six to nine days of heavy precipitation per year

The increase in hazard exposure to extreme rainfall is greater for some areas than others. For example, the hazard exposure score for Halifax and Dartmouth is 3 in the baseline period. In the near-term future, while the hazard exposure score remains 3 for Dartmouth, the hazard exposure score for Halifax increases to 4. In the long-term future, the hazard exposure score for both Halifax and Dartmouth is 5. Overall, these two communities experience a two point increase from the recent past compared to the long-term future, which represents an increase of about 14 mm of rain (annual maximum 1-day precipitation). By comparison, Sheet Harbour shows a three point increase of 2 to 5 over the same time period (from 2 to 3 and 5), which represents an increase of about 21 mm of rain (annual maximum 1-day precipitation).

Regional and local differences in precipitation may be due to several factors including, temperature, proximity to water, topography, prevailing winds, and vegetation cover (Stevens, 2010). Topography is a major driver of precipitation, with areas on the windward side of higher terrain generally experiencing greater precipitation than areas on leeward slops. Proximity to the coast may also be a factor with coastal areas generally receiving higher rainfall amounts than inland areas. Both of these factors may explain the higher exposure scores in the regions near Halifax and Sheet Harbour.

4.4 Extreme Snowfall

Heavy snowfall may lead to rapid accumulation of snow which can damage utility lines and trees, and cause disruption to transportation systems and infrastructure, and pose a risk to human health and safety. Map 4 (see Appendix B) shows that hazard exposure to extreme snowfall is projected to remain approximately stable through the near-term future and decrease in the long-term future. In the recent past, the hazard exposure scores ranged from 3 to 5. In the near-term, the hazard exposure scores range from 2 to 5 and in the long-term from 2 to 3. This suggests that the amount of snowfall in the near-term future is comparable to current conditions. In the long-term future, extreme snowfall events are projected to be less heavy and less frequent as more winter precipitation is expected to fall as rain.

The overall decrease in hazard exposure is driven by decreases in several indicators (see Appendix A). Heavy snowfall days (> 10 cm) is one indicator for extreme snowfall. For the three time periods, the indicator evolves in the following way:

- Recent past (hazard exposure score of 3 to 5): 34 to 40 days of heavy snowfall
- Near-term future (hazard exposure score of 2 to 5): 32 to 40 days of heavy snowfall
- Long-term future (hazard exposure score of 2 to 3): 32 to 36 days of heavy snowfall

The decrease in hazard exposure for extreme snowfall is greater for some areas than others. For example, the hazard exposure score for Otter Lake was 5 in the recent past. In the near- and long-term futures, the hazard exposure decreases to 4 and 3, respectively. This is a two point decrease from the recent past as compared to the long-term future, which represents a decrease of about 8 mm snow water equivalent (SWE)[4] (indicator: annual maximum 1-day snowfall). By comparison, Musquodoboit Harbour shows only a one point decrease over the same time period (from 3 to 3 and 2), which represents a decrease of about 4 mm (SWE) (indicator: annual maximum 1-day snowfall).

Similar to extreme rainfall, spatial differences in extreme snowfall are likely due to differences in topography with higher elevation areas northwest of Halifax and northeast

[4] Snow water equivalent (SWE) is a measure of the water volume present in precipitation that falls below 0°C. SWE is used by climate models as it is not possible to project actual snowfall depths due to the many factors that affect snow density. SWE provides a consistent estimate of the water content within snow. A generic conversion ratio of 1:10 can be used to convert mm of SWE to cm of snow, though this will vary at time.

of Sheet Harbour. These areas show decreasing hazard exposure over time but will likely experience more snow than lower elevation areas due to the cooler temperatures that can be expected over higher terrain.

4.5 Extreme Wind

Extreme wind can be a widespread or highly localized event that may cause damage to built infrastructure or the natural environment and pose a risk to human health and safety. Map 5 (see Appendix B) shows that hazard exposure to extreme wind is projected to remain approximately stable through the near-term future and into the long-term future. In the recent past, near-term, and long-term, the hazard exposure scores range from 1 to 5. This suggests that wind speeds in the near- and long-term futures are comparable to current conditions.

The overall stability in hazard exposure is driven by stability in two indicators. Maximum daily wind speed (m/s) is one indicator for extreme wind. For the three time periods, the indicator remains largely unchanged, with hazard exposure scores of 1 to 5 representing wind speeds of 50 to 125 km/h. While the hazard exposure remains similar for the same regions over time, the hazard exposure varies across regions (regardless of time period). The indicator evolves spatially in the following way:

- Coastal (hazard exposure score of 5 in all time periods): 110 to 125 km/h maximum wind speed
- Inland (hazard exposure score of 1 to 2 in all time periods): 50 to 80 km/h maximum wind speed

Extreme wind is a complex climate variable to model and as a result only coarse projections over large areas are available. These climate projections can only provide an estimate of the percentage increase in strong wind conditions and have limited utility for informing location-specific exposure. The confidence in wind projections is low compared to other indicators. This is because there is a lack of historical wind gauge data to validate models and trends over time. Additionally, wind is highly influenced by local topography and may vary greatly over fine spatial scales.

4.6 Changing Winter Temperatures

Several temperature indicators can inform risk related to winter conditions that are expected to shift with climate change and may cause impacts to infrastructure, transportation systems, municipal services, and the environment. Warming winter temperatures and greater fluctuations in winter temperature pose challenges for municipal operations like snow and ice removal and may accelerate damage to infrastructure, due to repeated freeze-thaw cycles, excessive ice build up, or rapid snow melt.

Map 6 (see Appendix B) shows that hazard exposure to changing winter temperatures is projected to increase through the near-term future and into the long-term future. In the recent past, the hazard exposure scores ranged from 2 to 3. In the near-term, the hazard exposure scores range from 3 to 4 and in the long-term from 4 to 5. This suggests that winter temperatures in the near- and long-term futures will be different than current conditions. In both time horizons, winters are projected to be warmer with more freeze-thaw cycles.

The overall increase in hazard exposure is driven by increases in two indicators (see Appendix A). Maximum winter temperatures (°C) are one indicator for changing winter temperatures. For the three time periods, the indicator evolves in the following way:

- Recent past (hazard exposure score of 2 to 3): maximum winter temperatures of 12°C to 16°C
- Near-term future (hazard exposure score of 3 to 4): maximum winter temperatures of 14°C to 18°C
- Long-term future (hazard exposure score of 4 to 5): maximum winter temperatures of 16°C to 20°C

The increase in hazard exposure of changing winter temperatures is greater for some areas than others. For example, the hazard exposure score for Milford was 2 in the recent past. In the near- and long-term futures, the hazard exposure increases to 3 and 5, respectively. This is a three-point increase from recent past as compared to the long-term future, which represents an increase of about nine winter freeze-thaw cycles. By comparison, Halifax and Dartmouth experience only a two-point increase over the same time period (from 2 to 2 and 4), which represents an increase of about six winter freeze-thaw cycles.

Spatial differences in hazard exposure to changing winter temperatures is somewhat sporadic, but a general trend can be observed over the three time periods with inland areas generally showing higher exposure than coastal areas, especially by the end of the century. This can likely be attributed to the temperature moderating effect of the ocean. Inland areas can be expected to show a greater increase in winter temperatures over time and more variability in daily and seasonal temperature (Stevens, 2010).

5 CONCLUSION & RECOMMENDATIONS

WSP has developed climate hazard exposure projections and maps for six climate hazards over three time periods. Based on the analysis, exposure to all climate hazards will increase into the near- and long-term future, except for extreme snowfall which will decrease.

The spatial data produced for this project can serve to improve HRM's understanding of how various climate hazards and indicators are projected to evolve in different areas of the municipality. Specifically, the spatial data can be used to support the HRVA process which is used by HRM to support climate action planning (HalifACT), business continuity planning, emergency management and planning. The spatial data may also be used to advance core areas of action under HalifACT, including risk and vulnerability assessments (Actions 15 and 16) and capacity building for climate adaptation (Actions 31, 32, and 33).

The following recommendations describe how HRM may use the results of this study to further improve its understanding of how climate change may impact the municipality, inform decision making, and advance various action areas from HalifACT.

1 **Build a comprehensive database of future climate hazard maps**

To further build capacity for climate adaptation, it is recommended to use the recently completed flood hazard maps together with the hazards assessed in this study. Considering multiple climate hazards will allow HRM to identify high exposure areas for further study, compare how hazard exposure varies spatially across the municipality, and understand compounding events, impacts, and risk. Areas that are exposed to overlapping hazards could be prioritized for more detailed assessment of vulnerabilities and risks. Future hazard mapping could be developed for other hazards such as wildfire, which should be completed using a comparable approach to this project.

Updates to the hazard exposure maps should consider using the latest generation of climate models (CMIP6[5] and Shared Socioeconomic Pathways).

2 **Conduct a spatial climate hazard vulnerability and risk assessment**

A spatial climate hazard vulnerability and risk assessment should be conducted to evaluate the sensitivity and adaptive capacity of built, social, and natural systems in communities across HRM. The study should evaluate vulnerability

[5] CMIP6 refers to the Coupled Model Intercomparison Project Phase 6

and risk associated with multiple climate hazards, particularly those with higher exposure: extreme heat, meteorological drought, extreme rainfall, and changing winter temperatures. Climate hazards should be considered along with critical resources, infrastructure and services within the community to understand the impacts of climate change to these key community services.

Vulnerability can be assessed by analyzing built indicators such as asset condition; sociodemographic information such as population, income and age; and characteristics of natural systems such as health and species. The study time periods should include the near-term future (2050: 2021-2050) and long-term future (2100: 2071-2100) and factor in projected population growth to help demonstrate how vulnerability and risk may evolve across a growing region. Community-level risk should also be assessed to understand the likelihood and potential consequences of climate change impacts related to different hazards.

Assessing vulnerability and risk will help identify “hotspots” across the municipality and help HRM understand the drivers of vulnerability and risk in different areas. The assessment can support the mainstreaming of climate information into decision-making and inform the monitoring and reporting on climate action and impact. HRM can use results to develop targeted community adaptation actions, prioritize infrastructure investments, and plan emergency response measures in the most vulnerable or high-risk communities (see Recommendation 4). Spatial climate hazard vulnerability and risk assessments can also provide valuable insight for avoiding maladaptation and/or leveraging co-benefits associated with retrofit projects, renewable energy programming, electrification of transportation, net-zero standards for buildings, and sustainable financing strategies.

3 Detailed studies to enhance hazard mapping for critical infrastructure and areas of concern

This study provides a high-level understanding of the trend and magnitudes of change that can be expected for a variety of climate hazards in HRM. However, there are limitations to the spatial extent of downscaled climate data which can not accurately represent site-specific or micro-climactic conditions. For instance, a detailed analysis that considers the albedo of different land surface types and actual surface temperature observations can provide additional useful information about extreme heat exposure. Urban area growth projections may also influence future heat island affect and would be valuable to consider. Therefore, it is recommended to build on the baseline climate hazard maps with more in-depth spatial analyses that considers geographic, atmospheric and environmental features that may influence hazards at a finer spatial scale.

In-depth studies may be prudent for areas of concern identified in the HRVA process. Studies should be selected depending on HRM's information needs, and should reflect climate hazards to which HRM is most exposed and vulnerable, as determined by a vulnerability and risk assessment.

4 **Use the climate hazard exposure maps to mainstream climate adaptation into emergency management and planning, asset management planning, infrastructure and service investment, and long-range planning and development strategies under the HVRA process**

The spatial mapping layers may be used in the HRVA process to identify critical infrastructure, update emergency plans, identify areas of concern where risk mitigation measures are appropriate, provide technical information and data for projects and business units, and collaborate with agencies to develop recovery and community resilience plans.

It is recommended that HRM develops prescriptive and prioritized adaptation measures to address key climate-related risks and vulnerabilities to its assets, operations and services. Alongside action identification, HRM should assess the investment requirements for both capital and operational municipal budgets to increase resilience.

Examples of how the data can be used for emergency management and planning, infrastructure prioritization, and long range planning and development are expanded below.

Emergency management and planning: HRM can identify areas that are most exposed to climate hazards, and plan emergency preparedness and response measures in affected communities. For example, the maps can help identify areas that are exposed to extreme heat and have a high concentration of vulnerable populations, suggesting heat-related health risks. The maps could also help identify areas exposed to extreme wind with vulnerable tree canopies, where emergency access could become blocked during storm events. By identifying areas that may require support or resources to help communities adapt and respond to extreme events, interventions can be tailored to the unique context of each community or multi-community area. This will help HRM continue advancing the objectives and action areas within HalifACT.

Infrastructure prioritization: Critical infrastructure and assets that are most exposed to climate hazards should be prioritized for further risk assessment, with climate adaptation interventions if needed. It is also recommended to consider infrastructure vulnerability indicators such as asset age or condition to improve HRM's understanding of risk across the community. Layering on sociodemographic indicators of vulnerability can further help HRM identify vulnerable communities where infrastructure adaptation should be prioritized.

Long range planning and development strategies: HRM should focus development in lower hazard areas as much as possible and implement plans and policies that limit risk to communities and infrastructure in exposed areas. After identifying areas of concern, the maps can also be used to identify and prioritize resilience measures for incorporation in community and/or area development plans. For example, a community exposed to extreme heat or drought may benefit from improved access to air conditioned spaces and/or shade structures, green or blue infrastructure or xeriscaping. Using vulnerability indicators in conjunction with exposure maps can add depth to the analysis and allow for even more tailored actions. Community profiles can be developed to inform planning teams about the top climate hazards and vulnerabilities in each community during planning processes and enhance community awareness and education on climate change.

It is recommended to complete a vulnerability and risk assessment (see Recommendation #2) to further inform emergency management, planning and infrastructure prioritization.

GLOSSARY

Adaptive capacity: The potential or ability of a system, region, or community to adapt to the effects or impacts of climate change. Enhancement of adaptive capacity represents a practical means of coping with changes and uncertainties in climate, including variability and extremes (IPCC, 2001).

Cooling degree-days (CDD): Measure of how hot the temperature is or will be during a given year. This is used as a measure of energy use required to cool and maintain comfortable indoor temperatures. Annual cooling degree days are equal to the number of degrees Celsius a given day's mean temperature is above 18°C, compounded throughout the year. For example, if the daily mean temperature is 21°C, the CDD value for that day is equal to 3. If the daily mean temperature is below 18 °C, the CDD value for that day is set to zero. The sum of each day's CDD is added together to create an annual total. There are no units associated with CDDs.

Climate: The weather conditions prevailing in an area in general over a long period, typically a minimum of 30 years. Climate differs from weather in that weather reflects short term (minute, hourly, daily, weekly, seasonal) conditions of the atmosphere and does not denote the long-term trends.

Climate change: Any significant long-term change in the expected patterns of average weather of a region over a significant period of time, usually averaged to a minimum of 30 years.

Climate Indicator: A climate indicator is a quantitative parameter that explains how type of weather condition will evolve over time. The maximum temperature recorded each year is an example of an indicator used to understand extreme heat.

Downscaling: The process of converting climate model output to a finer spatial resolution (Government of Canada, 2022).

Exposure: Presence of people, livelihoods, assets, services, resources or infrastructure in place in a specific region that could be adversely affected by climate change.

Freeze-thaw cycle: Number of days where maximum temperature is above 0°C and the minimum temperature is below 0°C. Under these conditions, it is likely that some water at the surface was both liquid and solid at some point during the day.

Global climate model (GCM): Complex computer programs commonly used to simulate the atmosphere or ocean of the earth and project climate trends on a global scale. The mathematical models are based on general circulation of the planetary atmosphere and apply thermodynamics to calculate radiation and latent heat in order to establish a global mass and energy balance.

Hazard: in the context of this study, a hazard is a set of climate conditions that may cause adverse effects on infrastructure, people, or the environment. A climate hazard may be influenced or explained by multiple climate indicators.

Hazard exposure: The relative magnitude of exposure to a climate hazard across space based on the values of all contributing climate indicators.

Intergovernmental Panel on Climate Change (IPCC): An intergovernmental body of the United Nations charged with advancing scientific knowledge about anthropogenic climate change.

Regional climate model (RCM): Complex configurations of computer code representing different parts of the climate system (atmosphere, ocean, land surface, ice, ecosystems, etc.) used to simulate Earth's climate for a particular region. An RCM can have higher spatial resolution as it models a much smaller area than a global climate model (GCM), which simulates the climate globally (Government of Canada, 2022).

Representative concentration pathways (RCP): A greenhouse gas concentration trajectory scenario adopted by the International Panel on Climate Change (IPCC). The four scenarios (RCP2.6, RCP4.5, RCP6, and RCP8.5) represent the range of possible climate policy outcomes for the 21st century. RCP2.6, the most optimistic scenario, assumes aggressive mitigation while RCP8.5 is the "business-as-usual" scenario with little or late change.

Resilience: The ability of a system to absorb disturbances while maintaining the same basic structure and ways of functioning.

Risk: The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social, and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence (*Annex I: Glossary*, 2018).

Snow Water Equivalent (SWE): Number of millimetres of precipitation once all types of precipitation (snow, rain, hail, etc.) have been converted to liquid precipitation. The usual equivalent is 1 centimetre of snow equals 1 millimetre of rain, but the calculation might differ depending on the type of snow and its density.

Scenario: A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Scenarios are used as inputs into climate models to determine future climate projections.

Shared socioeconomic pathway (SSP): Pathways that describe possible socio-economic conditions, land-use changes, and other human-caused climate drivers that influence greenhouse gas emissions. SSP-based scenarios were used in the most recent set of climate model experiments, known as the Sixth Phase of the Coupled Model Intercomparison Project, or CMIP6. SSP scenarios further refine the previous greenhouse gas concentration scenarios known as Representative Concentration Pathways (ClimateData.ca, n.d.).

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of changing climate, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2001).

Water budget: An accounting of all the water that flows into and out of an area. Water budget typically takes into account precipitation, evaporation, and evapotranspiration.

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APPENDIX

A Indicator Scales

APPENDIX

The following six tables present the data ranges and scales used for each climate hazard and indicator. In each table, the indicator is provided long with the units, minimum and maximum value, the overall range of values considered for the maps. The range of values was then divided into 5 sub-ranges and associated with a hazard exposure score. In some instances, the overall range of values is lower and/or higher than the minimum and/or maximum values for logical consistency.

Indicator Scaling for Extreme Heat

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Number of days > +30℃	days	1	70	1 – 70	0 – 15	1
					16 – 30	2
					31 – 45	3
					46 – 60	4
					≥ 61	5
Length of hot season (season where 30°C temperatures occur)	days	19	126	10 – 130	0 – 30	1
					31 – 60	2
					61 – 90	3
					91 – 120	4
					≥ 120	5
Highest maximum temperature	°C	30.2	39.9	30 – 40	30 – 31.9	1
					32 – 33.9	2
					34 – 35.9	3
					36 – 37.9	4
					38 – 40	5
Cooling degree days	°C	100	856	50 – 900	0 – 180	1
					181 – 360	2
					361 – 540	3
					541 – 720	4
					≥ 720	5

APPENDIX

Indicator Scaling for Meteorological Drought

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Total precipitation in winter and spring (December to May)	mm	563	724	580 – 730	580 – 60.9	5
					61 – 639.9	4
					640 – 669.9	3
					670 – 699.9	2
					≥ 700	1
Total summer precipitation (mm) (June to August)	mm	172	218	170 – 220	170 – 179.9	5
					180 – 189.9	4
					190 – 199.9	3
					200 – 209.9	2
					≥ 210	1
Number of drought days (preceding 2-week water deficit)	days	24	58	20 – 60	20 – 27.9	1
					28 – 35.9	2
					36 – 43.9	3
					44 – 51.9	4
					52 – 60	5

Indicator Scaling for Extreme Rainfall

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Annual Maximum 1-day Precipitation	mm	78	109	75 – 110	75 – 81.9	1
					82 – 88.9	2
					89 – 95.9	3
					96 – 102-9	4
					103 – 110	5
Annual Maximum 5-day Precipitation	mm	136	180	135 – 180	135 – 143.9	1
					144 – 152.9	2
					153 – 161.9	3
					162 – 170.9	4
					171 – 180	5
Heavy Precipitation Days (> 20 mm)	days	1	8	0 – 9	0 – 1	1
					2 – 3	2
					4 – 5	3
					6 – 7	4
					8 – 9	5

APPENDIX

Indicator Scaling for Extreme Snowfall

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Heavy Snowfall Days (>10 cm)	days	50	68	30 – 40	30 – 31.9	1
					32 – 33.9	2
					34 – 35.9	3
					36 – 37.9	4
					38 – 40	5
Annual Maximum 1-day Snowfall	mm SWE	73	95	50 – 70	50 – 53.9	1
					54 – 57.9	2
					58 – 61.9	3
					62 – 65.9	4
					66 – 70	5
Annual Maximum 5-day Snowfall	mm SWE	30	40	70 – 100	70 – 75.9	1
					76 – 81.9	2
					82 – 87.9	3
					88 – 93.9	4
					94 – 100	5

Indicator Scaling for Extreme Wind

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Maximum wind speed	km/h	50	122	50 – 125	50-64.9	1
					65-79.9	2
					80-94.9	3
					95-109.9	4
					110-125	5
Average wind speed	km/h	10.8	32.4	3 – 10	10-14.9	1
					15-19.9	2
					20-24.9	3
					25-29.9	4
					30-35	5

APPENDIX

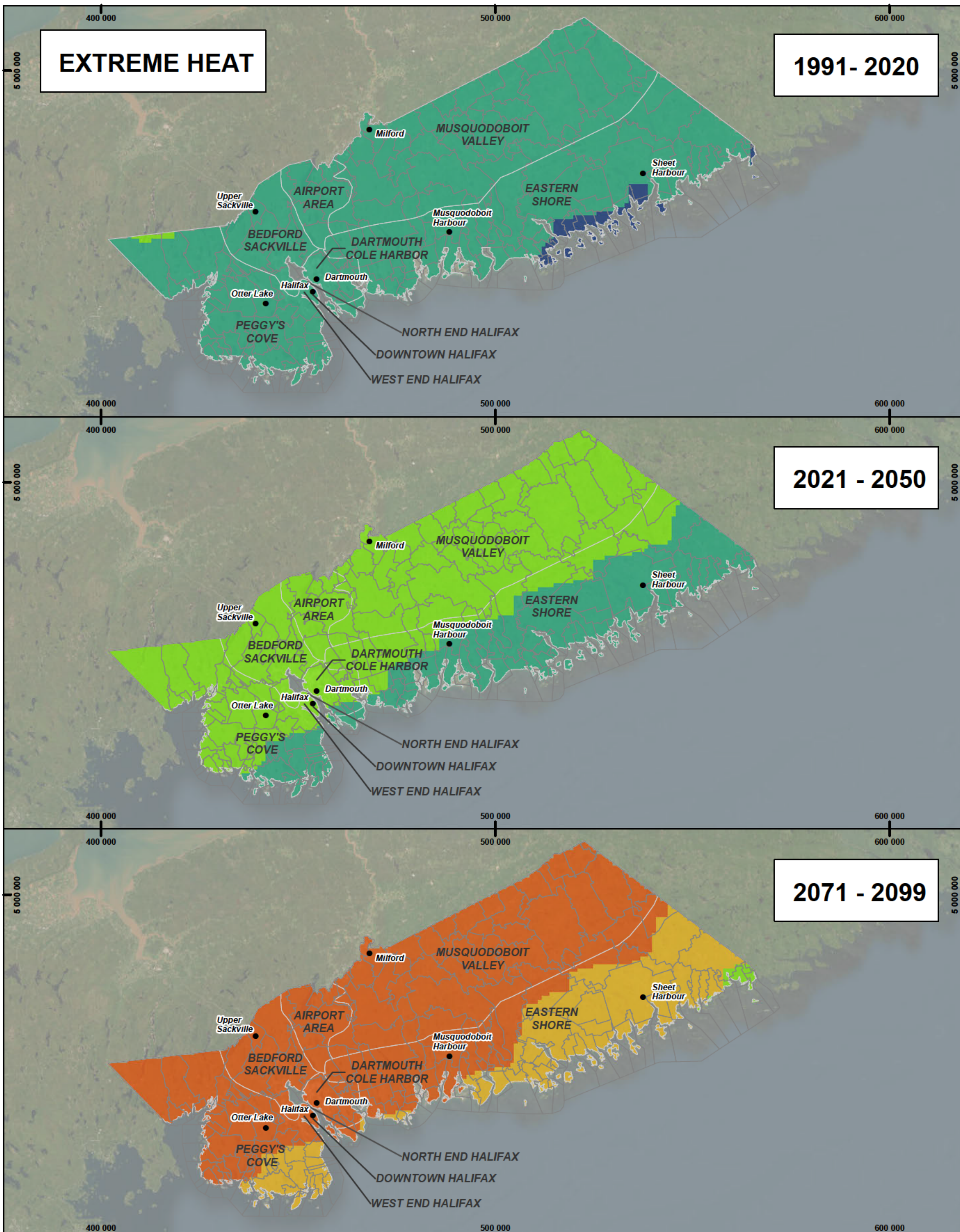
Indicator Scaling for Changing Winter Temperatures

Indicator	Units	Minimum Value	Maximum Value	Range	Scale	Score
Winter number of freeze-thaw cycles (December to February)	cycles	25	38	25 – 40	25 – 27.9	1
					28 – 30.9	2
					31 – 33.9	3
					34 – 36.9	4
					37 – 40	5
Maximum winter temperature (December to February)	°C	13	19	10 – 20	10 – 11.9	1
					12 – 13.9	2
					14 – 15.9	3
					16 – 17.9	4
					18 – 20	5
Annual number of freeze-thaw cycles (October to September)*	cycles	42	64	40 – 65	40-44.9	~~1~~
					45-49.9	~~2~~
					50-54.9	~~3~~
					55-59.9	4
					60-65	~~5~~
Icing days*	days	18	70	15 – 75	15-26.9	~~1~~
					27-38.9	~~2~~
					39-50.9	~~3~~
					51-62.9	4
					63-75	~~5~~

*Note: “annual freeze-thaw cycles (October to September)” and “icing days” have not been included in the averaged hazard score presented in the Changing Winter Temperature Map. The raw data layers are provided to HRM for reference and analysis.

APPENDIX

B Maps



HALIFAX

Baseline Climate Hazard Exposure Maps

Map 1
Extreme Heat

0 10 20 km

Sources :
- Cooling Degree Days (above 18°C)
- Number of days between the first and last occurrence of 30°C
- Number of days when the maximum temperature is above 30°C
- Highest maximum temperature
Extracted from RCP8.5 Pacific Climate Impacts Consortium

UTM, Zone_20N, NAD83

2023-03-24

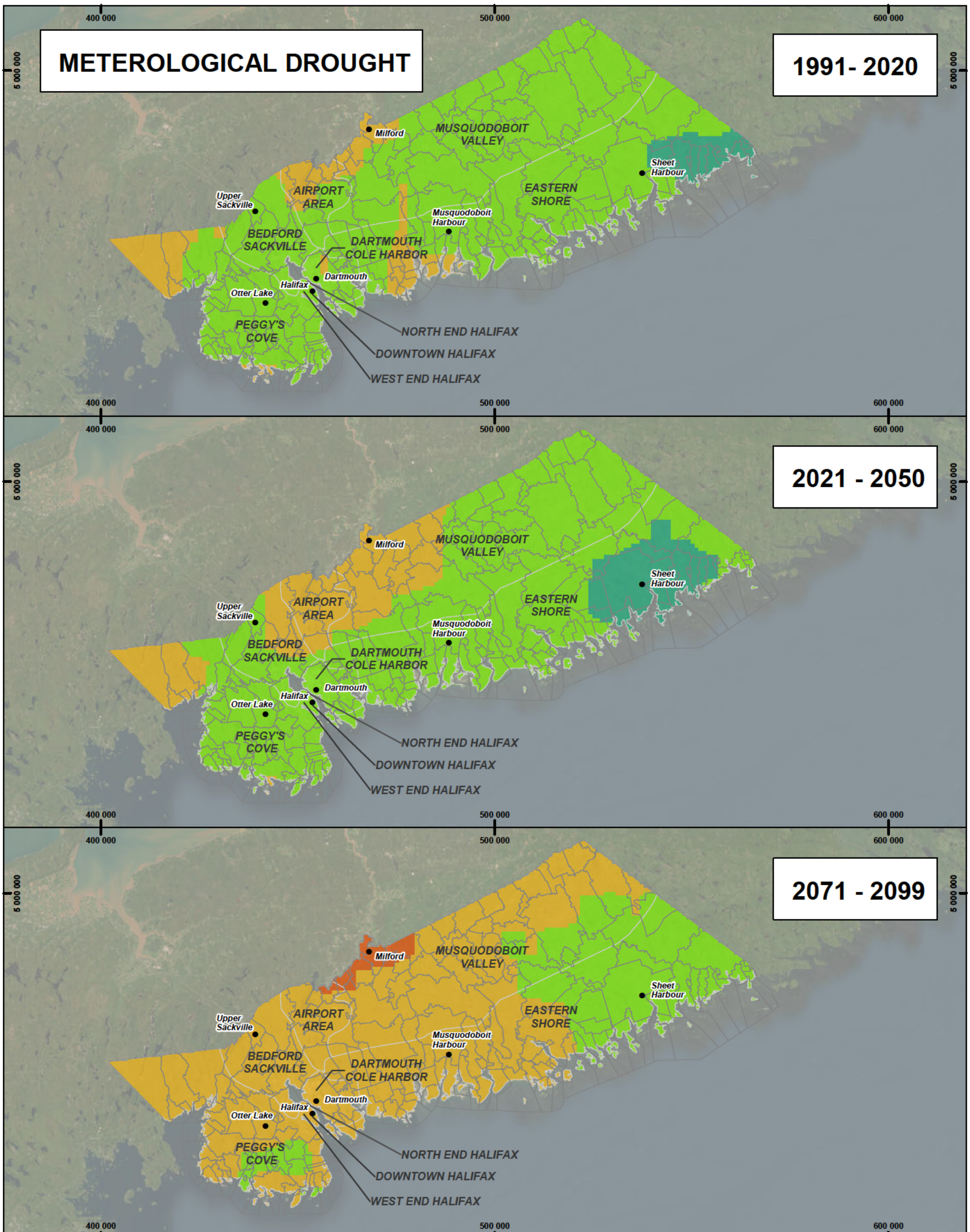
Preparation: Charles Cuell
Drawing: Félix-Antoine Audet
Validation: Daniel Tse / Jay Maloney
WSP_Climate_exposure_Heat_M1_230324.mxd

Exposure Score -- Exposure Rating

- 1 -- Lowest
- 2 -- Low
- 3 -- Moderate
- 4 -- High
- 5 -- Highest

HRM Limits and Localisation

- City / Town
- Community Boundaries
- EASTERN SHORE — HRM Region



HALIFAX

Baseline Climate Hazard Exposure Maps

Map 2
Meteorological Drought

0 10 20 km

Sources :
- *Number of days when the accumulated moisture balance is less than the 10th percentile for that day (baseline calculated over 1981-2010)*
- *Number of days when the accumulated moisture balance is less than the 10th percentile for that day (baseline calculated over 1981-2010)*
- *Total precipitation Summer (10th percentile)*
- *Total precipitation Dec-May (10th percentile)*

Extracted from RCP8.5 Pacific Climate Impacts Consortium

UTM, Zone_20N, NAD83

2023-03-24

Preparation: Charles Cuell
Drawing: Félix-Antoine Audet
Validation: Daniel Tse / Jay Maloney
WSP_Climate_exposure_Drought_M2_230324.mxd

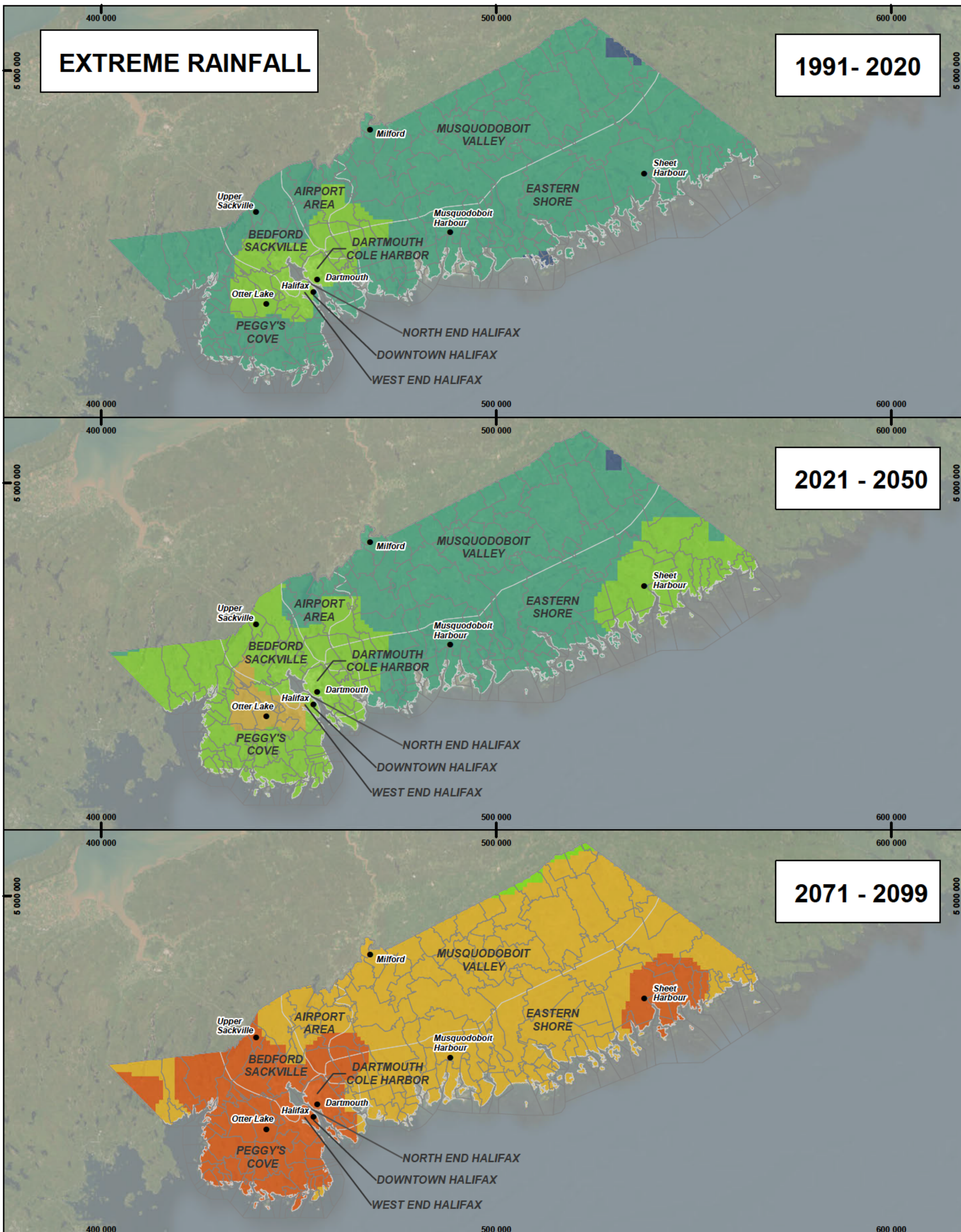
wsp

Exposure Score -- Exposure Rating

- 1 -- Lowest
- 2 -- Low
- 3 -- Moderate
- 4 -- High
- 5 -- Highest

HRM Limits and Localisation

- City / Town
- Community Boundaries
- EASTERN SHORE — HRM Region



HALIFAX

Baseline Climate Hazard Exposure Maps

Map 3
Extreme Rainfall

0 10 20 km

Sources :
- *Number of days when liquid precipitation was higher than 20 mm*
- *Maximum amount of liquid precipitation for a single day*
- *Maximum amount of liquid precipitation accumulated over five consecutive days*

Extracted from RCP8.5 Pacific Climate Impacts Consortium

UTM, Zone_20N, NAD83

2023-03-24

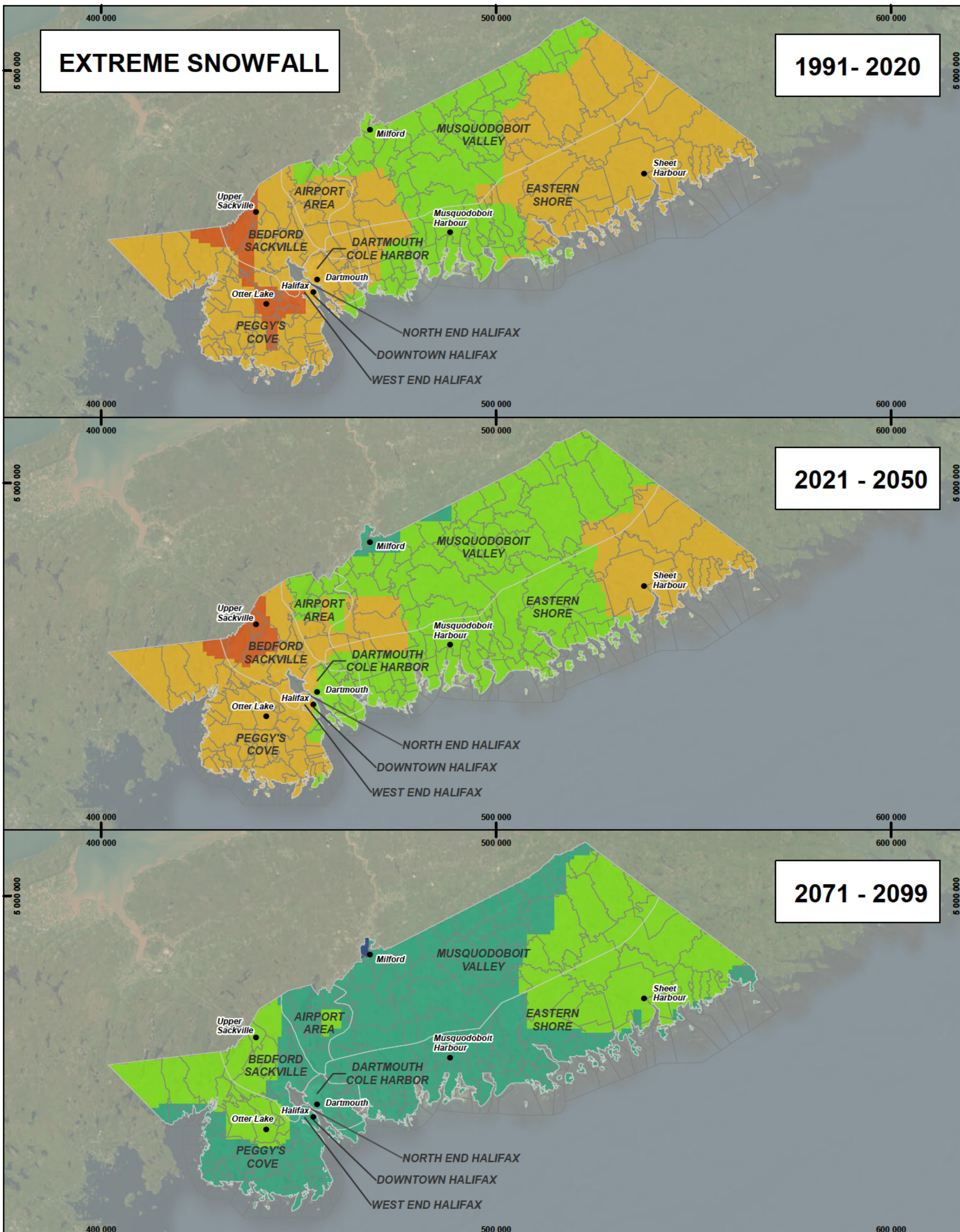
Preparation: Charles Cuell
Drawing: Félix-Antoine Audet
Validation: Daniel Tse / Jay Maloney
WSP_Climate_exposure_Rainfall_M3_230324.mxd

Exposure Score -- Exposure Rating

- 1 -- Lowest
- 2 -- Low
- 3 -- Moderate
- 4 -- High
- 5 -- Highest

HRM Limits and Localisation

- City / Town
- Community Boundaries
- *EASTERN SHORE* HRM Region



HALIFAX

Baseline Climate Hazard Exposure Maps

Map 4
Extreme Snowfall

0 10 20 km

Sources :
- Number of days when solid precipitation was above 10 mm snow water equivalent (approx. 10 cm snow depth)
- Maximum amount of solid precipitation (snow water equivalent) for 1 day
- Maximum amount of solid precipitation (snow water equivalent) accumulated over five days
Extracted from RCP8.5 Pacific Climate Impacts Consortium

UTM, Zone_20N, NAD83

2023-03-24

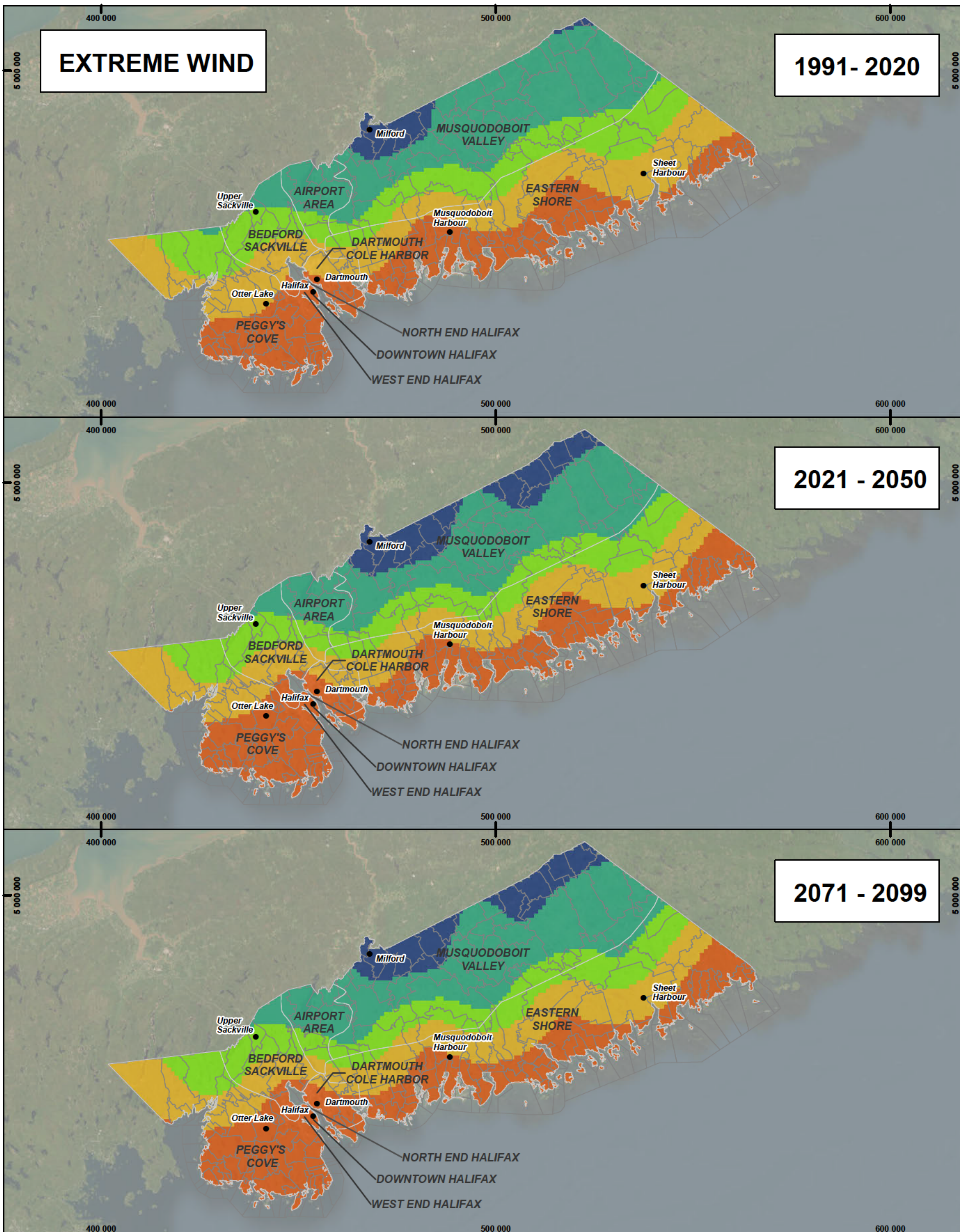
Preparation: Charles Cuell
Drawing: Félix-Antoine Audet
Validation: Daniel Tse / Jay Maloney
WSP_Climate_exposure_Snowfall_M4_230324.mxd

Exposure Score -- Exposure Rating

- 1 -- Lowest
- 2 -- Low
- 3 -- Moderate
- 4 -- High
- 5 -- Highest

HRM Limits and Localisation

- City / Town
- Community Boundaries
- EASTERN SHORE — HRM Region



HALIFAX

Baseline Climate Hazard Exposure Maps

Map 5
Extreme Wind

0 10 20 km

Sources :
- Maximum wind speed
- Average wind speed for days where wind was above 3.6 km/h
Extracted from CanRCM4 Canadian Centre for Climate Modelling and Analysis

UTM, Zone_20N, NAD83

2023-03-24

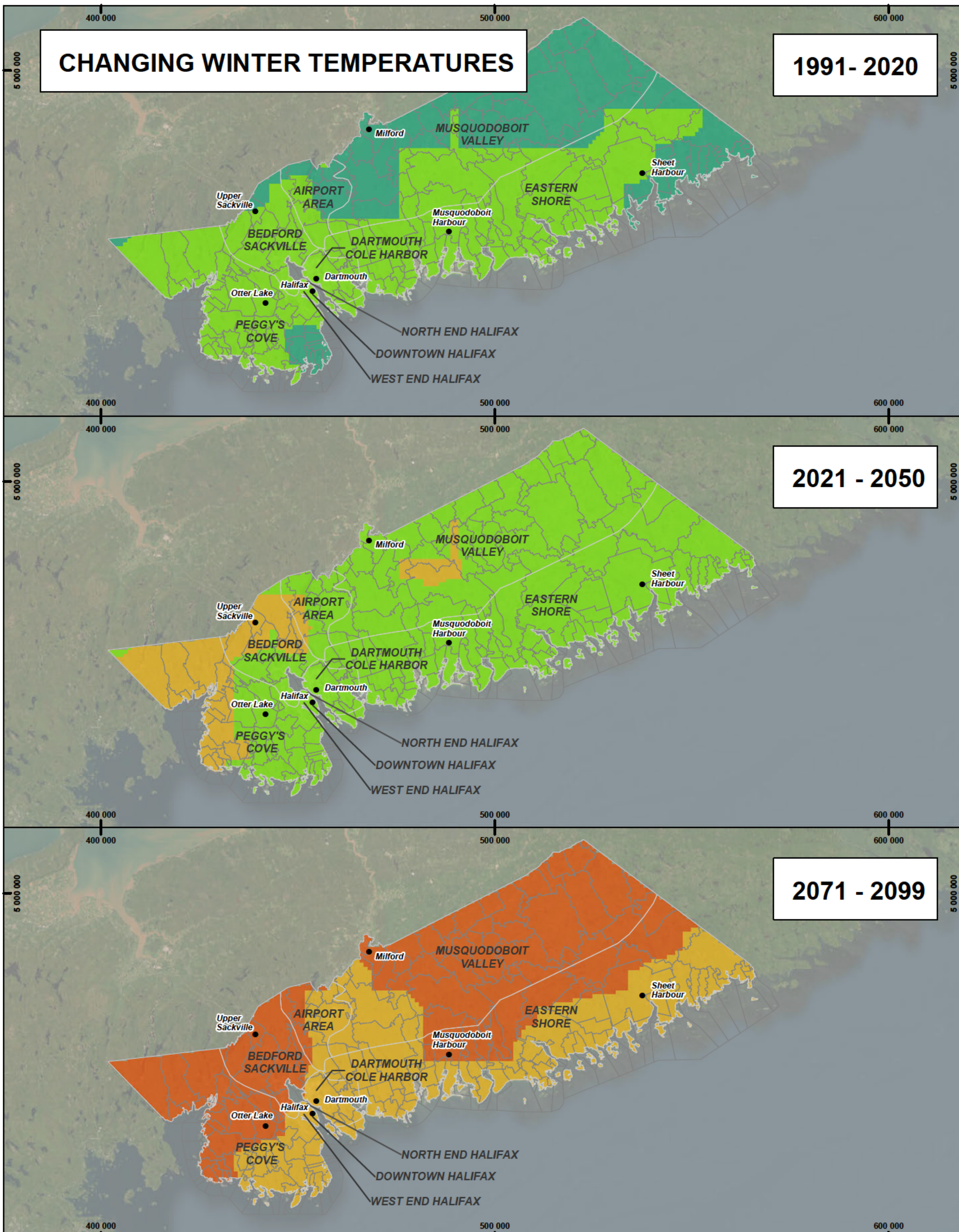
Preparation: Charles Cuell
Drawing: Félix-Antoine Audet
Validation: Daniel Tse / Jay Maloney
WSP_Climate_exposure_Wind_M5_230324.mxd

Exposure Score -- Exposure Rating

- 1 -- Lowest
- 2 -- Low
- 3 -- Moderate
- 4 -- High
- 5 -- Highest

HRM Limits and Localisation

- City / Town
- Community Boundaries
- EASTERN SHORE — HRM Region



HALIFAX

Baseline Climate Hazard Exposure Maps

Map 6
Changing Winter Temperatures

0 10 20 km

Sources :
- Number of days when minimum temperature is less than -2°C and maximum temperature is greater than 2°C.
- Highest maximum temperature
Extracted from RCP8.5 Pacific Climate Impacts Consortium
Note: this map considers the following two indicators only:
- Winter number of freeze thaw cycles (December to February)
- Maximum winter temperature (December to February)

UTM, Zone_20N, NAD83

2023-03-24

Preparation: Charles Cuell
Drawing: Félix-Antoine Audet
Validation: Daniel Tse / Jay Maloney
WSP_Climate_exposure_Changing_Winter_M6_230324.mxd

Exposure Score -- Exposure Rating

- 1 -- Lowest
- 2 -- Low
- 3 -- Moderate
- 4 -- High
- 5 -- Highest

HRM Limits and Localisation

- City / Town
- Community Boundaries
- EASTERN SHORE — HRM Region

APPENDIX

C Data Dictionary

(see Excel file *“WSP-HRM Baseline Hazard Maps_Appendix C - Data Dictionary”* in shared folder)

APPENDIX

D Methodology Memo

MEMO

TO:	Emma Bocking, Environmental Specialist, Halifax Regional Municipality
FROM:	Christina Schwantes, MEM, Climate Change Risk and Resilience, WSP Canada
SUBJECT:	Task 4 – Methodology Memo for Indicator Development
PROJECT:	Baseline Climate Hazard Exposure Maps for Halifax Regional Municipality
REFERENCE:	WSP Ref.: 211-10974-01 HRM Ref.: 2070892962
DATE:	February 21, 2023

WSP is working with Halifax Regional Municipality (HRM) to create a set of baseline climate exposure maps and related GIS data for the entire geographic area of HRM. This memo has been prepared to document, explain, and dialogue with HRM about the structure and characterization of climate change hazards and indicators for the Baseline Climate Hazard Exposure Maps project.

The representative concentration pathway (RCP) 8.5 is used to assess all climate hazards. This is considered a high-carbon emission scenario with a strong increase of the global temperature (4.5 – 5.0°C) by the end of the 21st century (Taylor et al., 2012). This emission scenario was chosen to provide a conservative estimate of future climate change (more climate change) and to align with other studies and data used by HRM. Newer climate models are now available and will one day replace the models used to develop RCP scenarios. This means that hazard exposure maps will need to be updated in the future.

Three-time horizons are considered for this project as requested by HRM to understand climate hazards over the recent past (historical: 1991-2020), near-term future (2050: 2021-205), and long-term future (2100: 2071-2100). See Box 1 on the following page for information on why each time horizon is assessed over a 30-year period. These time horizons align with other work completed by HRM and with typical best practices used for climate adaptation. The time horizons are considered for the following climate hazards:

— Extreme Heat
— Meteorological Drought
— Extreme Rainfall
— Extreme Snowfall
— Extreme Wind
— Changing Winter Temperatures

A high-level scan of existing best practices for assessing and mapping exposure to climate hazards was completed by reviewing climate change adaptation and risk mapping projects at municipalities across Canada. Consideration was also given to academic studies to identify and map climate hazards at a regional scale. Scientific literature was primarily used to understand approaches and limitations to map complex climate hazards like wind and storm activity that do not have readily available climate projections. Table 1 presents the primary content reviewed to inform the study methodology.

Box 1: Weather vs. Climate

Weather describes the atmospheric conditions at a specific moment in time in the past or present. Climate is a probabilistic description of typical or average atmospheric conditions or events experienced in a region over a 30-year period. Climate indicators represent the average intensity or frequency of weather events over the 30 years in question. Climate indicators can inform extreme weather events by looking at the variability in the data to understand the range of events that contribute to the climate average.

Table 1: Document Review

Region/Community of study	Title of Reference
City of Calgary	Community Climate Risk Index (WSP, 2021)
Region of Durham	Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region (Ontario Climate Consortium, 2020)
Region of Peel	Climate Trends and Future Projections in the Region of Peel (Ontario Climate Consortium et al., 2016)
City of Moncton	Climate Change Adaptation and Flood Management Strategy (City of Moncton, 2013)
Vancouver Costal Health Authority	Mapping spatial patterns in vulnerability to climate change-related health hazards (Jessica Yu et al., 2020)

METHODOLOGY

WSP has developed a four-step methodology to complete climate hazard exposure mapping (and associated spatial data) for the entire regional municipality.

Step 1: Definition of Climate Hazards and Indicators

For the six climate hazards included in this project, we conducted background research to identify the most relevant climate indicators for the HRM context. The following criteria was followed when selecting specific climate indicators:

- Representativeness of the most relevant climate change impacts in terms of physical risk to infrastructure, people, and the natural environment.
- Use and application in similar climate change work at other Canadian municipalities; and
- Development and modelling in the scientific literature.

The outcome of Step 1 is a collection of climate indicators that support the overall characterization of a given climate hazard. The full list of climate hazards and supporting indicators are presented in Appendix A.

Step 2: Indicator Assessment and Hazard Mapping

2a – climate data and projections

Two climate change data sets will be used to complete this assessment. The first data set comes from the Pacific Climate Impacts Consortium (PCIC, 2019), which relies on an ensemble of global climate models. The second data set is the CanRCM4 regional climate model via the North American CORDEX Program (Mearns, 2017), which is specifically used for extreme wind projections. Because these climate models are global, it is necessary to downscale the data to smaller spatial resolutions. Downscaling results in the development of gridded data that represents the climate conditions at a regional or sub-regional scale. Information on the spatial resolution of the climate data sources is available in Appendix 1. For each climate indicator, values will be computed for each grid cells to cover the entirety of HRM for the three-time horizons considered in this study.

2b – climate hazard exposure

Exposure to a given climate hazard will be expressed quantitatively for each contributing climate indicators for each grid cell within the HRM boundary. Hazard exposure will be represented on a five-point scale from Very Low (1) to Very High (5). The scale will be calibrated based on the range of values present within the data for each climate indicator as follows:

- Compare the range of values in the historical period against the 2050s and 2100s.
- Define a relative scale for the entire range of values and divide this scale into 5 equal segments. This would enable five numerical ranges of exposure to be labeled as Very Low (1) to Very High (5)

Using the previously computed projections for each grid cells, a relative exposure score is assigned based on where the value for a given grid falls within the five-point exposure scale. Subsequently, the exposure scores for all climate indicators contributing to a given climate hazard are averaged, providing an overall exposure score for each grid cell in each time horizon.

Averaged hazard exposure scores are then presented on a colour scale to allow for visual assessment of the hazard exposures across all grid cells in HRM. Individual indicators can also be mapped to show the actual values rather than the relative score used to assess exposure.

Step 3: Visualization of Climate Hazards

Once the climate hazard and indicator layers have been developed, WSP will select a sample set of asset, landscape, and demographic layers which have been provided by HRM. This mapping exercise will be used to help HRM visualize how exposure may vary across climate hazards and HRM assets, landscape, and demography. We understand that HRM will use the exposure layers in their own processes and systems for later assessments, including infrastructure vulnerability and risk analysis. The outcome Step 3 is a series of maps that display select HRM assets, landscape, and demography overtop of the climate hazard and indicator layers. These maps may be included in the draft/final report.

Step 4: Interpretation and Reporting of Exposure

Drawing on the outcomes of Step 3 (the exposure map series), WSP will interpret at a high-level the hazard exposure for select asset, landscape, demography data (as supplied and agreed upon by HRM). This interpretation will be qualitative only, highlighting areas where heightened exposure spatially intersects with HRM assets, landscape, or demography of interest. The interpretation may inform high-level discussion and recommendations in the draft/final report on possible next steps for HRM. For example, we may provide high-level suggestions on how HRM may use the hazard layers as input in future risk and vulnerability assessments and which areas or regions may be priorities. Step 4 may be treated as a validation exercise for if the climate hazard and indicator layers enable salient information about exposure for subsequent risk and vulnerability analysis.

ASSESSMENT LIMITATIONS

The method outlined in this document has been developed to support strategic prioritization of climate hazard exposure across HRM. Due to data limitations, it is recommended that the outcomes are not applied to inform detailed design decisions. Details on these limitations include:

- The climate data is produced by a set of computational models that have been tested and validated by the international scientific community through different studies. However, the models remain prone to present biases and uncertainties. Those are, to some extent, related to computational limitations and the current incapacity of modelling all climate processes. This means that projections can be used to inform what future conditions may look like within HRM but may not accurately represent in detail site specific conditions or outlier events.
- For climate indicators related to wind, climate projections are only available at a coarse special resolution and can not represent the values associated with changing wind conditions. These climate projections may can only provide an estimate of the percentage increase in strong wind conditions and have limited utility for informing location-specific exposure. Confidence is low for wind projections compared to other indicators.
- WSP have selected climate indicators to characterize a given climate hazard based on professional expertise. The list of climate indicators selected is not exhaustive and can only represent some of the main challenges that may be posed to the municipality from changing climate hazards.
- Climate science is a fast-evolving discipline and evergreen field. This project aligns with the fifth generation of climate models (that is, CMIP5[1] and RCPs). New methods and data are continuously being made publicly available. We recommend that HRM revisit this work in the near future using the latest generation of climate models (CMIP6[2] and SSPs, Shared Socioeconomic Pathways).
- Data and GIS layers have been provided by HRM for visualizing climate hazards relative to a variety of community features. This includes asset, landscape, and demography data. WSP has selected assets based on professional judgement to provide useful visualization of the hazard exposure. This is not intended to place any weight on the importance of a given data layer and it is assumed that HRM will use the exposure data to perform their own analysis that considers asset criticality and vulnerability
- These GIS data layers will be created for the sole purpose of the Baseline Climate Hazard Exposure Maps project and to inform with high level strategic decision making about climate planning. It is not intended be used for detailed design, code development, or any activities requiring detailed, site-specific information.

NEXT STEPS

This memo presents to HRM our recommendation on how to structure and characterize the most salient, representative climate exposure layers that consider subsequent decision-making about climate risk and vulnerability.

[1] CMIP5 refers to the Coupled Model Intercomparison Project Phase 5
[2] CMIP6 refers to the Coupled Model Intercomparison Project Phase 6

Our work schedule and timeline have assumed a review period from February 13 to February 17 (inclusive) for review and feedback. This memo will not be formally resubmitted as a standalone deliverable. Rather, revisions will be incorporated directly into the draft report (forthcoming in late February).

Once comments have been received and revisions are addressed, WSP will:

- Analyse, generate, and map the GIS exposure layers
- Package and delivery the GIS data
- Write and submit a technical report.

APPENDIX A: HAZARDS AND INDICATORS

1.1. EXTREME HEAT

Extreme heat events may represent a sudden or prolonged period of intense hot weather that may have adverse impacts to human health and/or put strain on infrastructure systems like mechanical cooling system and the natural environment.

Indicator	Description/Relevance	Data Source	Resolution
Number of days > +30°C	This indicator is a measure of the number of days with a maximum daily temperature above 30°C. Relevant for impacts on people in alignment with heat warnings and days that mechanical cooling becomes critical to maintain indoor air quality/comfort.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Cooling degree days (accumulated number of degrees Celsius a given day's mean temperature is above 18°C)	Cooling degree days is a measure of the number of days where temperature is greater than 18°C. The indicator also considers the intensity of heat by measuring the number of degrees above the 18°C threshold each day Relevant to understand demand for mechanical cooling.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Highest maximum temperature	The highest annual temperature. Relevant for Impacts on human health and safety, potential heat stress on plants/natural environment, and impacts to temperature-sensitive assets (e.g., softening and deformation of asphalt).	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Length of hot season (season where 30°C temperatures occur)	Indicator of the length of the summer season measuring the number of days from first occurrence of +30°C day to the last occurrence during the summer season. Relevant for human and environmental impact.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km

1.2. METEOROLOGICAL DROUGHT

Drought is defined as a prolonged period of dry weather that may result in a lack of soil moisture and socio-economic impacts related to a lack of water availability. The drought indicators presented here represent only metrological drought and do not consider aspects of drought mitigation related to natural or built structures for water storage.

Indicator	Description/Relevance	Data Source	Resolution
Number of drought days (preceding 2-week water deficit)	A meteorological drought episode is a period longer than 2 weeks where the water budget (i.e., Precipitation-Evapotranspiration value) falls below the 10th percentile. Relevant for agricultural and environmental impacts with some indication of irrigation demand and water supply.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Total summer precipitation (mm) (June to August)	Total precipitation accumulating between June and August. Drought tends to be most impactful during the late summer and fall and is influenced strongly by precipitation in the preceding months.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Total precipitation in winter and spring (mm) (December to May)	Average precipitation accumulating between December and May. Drought tends to be most impactful during the late summer and fall and is influenced strongly by precipitation in the preceding months.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km

1.3. EXTREME RAINFALL

Extreme precipitation events deliver a large amount of rainfall in a short period of time, which may contribute to flooding or infrastructure damage at varying scales.

Indicator	Description/Relevance	Data Source	Resolution
Heavy Precipitation Days (> 20 mm)	The annual average number of days where precipitation exceeds 20 mm. Relevant to inform occurrences of localized flooding and operational impacts related to heavy rain (e.g., road closures, traffic impacts).	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Annual Maximum 1-day Precipitation	The average amount of precipitation to fall on the wettest day of the year. Relevant to understand extreme rain events and related water damage/disruptions.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Annual Maximum 5-day Precipitation	The average amount of precipitation to fall on the wettest 5 consecutive days of the year. Relevant to inform the impact of sustained rain events.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km

1.4. EXTREME SNOWFALL

Heavy winter storms may lead to rapid accumulation of snow which can damage utility lines and trees, and cause disruption to transportation infrastructure, thus posing risks to human health and safety.

Indicator	Description/Relevance	Data Source	Resolution
Heavy Snowfall Days (>10 cm)	The annual average number of days where precipitation falls below 0°C and exceeds 10 cm. Relevant for winter operations and cold weather emergency response.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Annual Maximum 1-day Snowfall	The average amount of precipitation (with temperature below 0°C) to fall on the wettest day of the winter. Relevant to inform the impact of extreme snowfall events.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Annual Maximum 5-day Snowfall	The average amount of precipitation (with temperature below 0°C) to fall on the wettest 5 consecutive days of the winter. Relevant to inform the impact of sustained snowfall events.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km

1.5. EXTREME WIND

Extreme wind can be a widespread or highly localized event that may cause damage to built infrastructure or the natural environment and pose a risk to human health and safety. Wind is a complex climate variable to model and as a result only coarse projections are available to characterise changes in wind conditions over large areas. Additionally, the confidence in wind projections is low compared to other indicators.

Indicator	Description/Relevance	Data Source	Resolution
Average wind speed	The average wind speed measured over a year. Provides an indication of general changes in wind condition at a coarse scale (approximately 25 km x 25 km spatial resolution).	CanRCM4 (2012) CMIP5 model output	25 km × 25 km (approximately)
Maximum wind speed	The highest wind speed recorded over a year. Provide an indication of potential for physical damage to infrastructure and the natural environment at a coarse scale (approximately 25 km x 25 km spatial resolution).	CanRCM4 (2012) CMIP5 model output	25 km × 25 km (approximately)

1.6. CHANGING WINTER TEMPERATURES

Changing winter conditions represent a variety of temperature conditions that are expected to shift with climate change and may cause problems for infrastructure and urban living. Warming winter temperatures and greater fluctuations in winter temperature pose challenges for municipal operations like snow and ice removal and may accelerate damage to infrastructure due to repeated freezing-thawing and from excessive ice build up.

Indicator	Description/Relevance	Data Source	Resolution
Winter number of freeze-thaw cycles (December to February)	Number of freeze thaw cycles, where the minimum temperature is equal to or below -2°C and the maximum temperature is above 2°C. Relevant to the degradation of infrastructure and operational management of ice accumulation and snowmelt.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Annual number of freeze-thaw cycles (October to September)	Number of freeze thaw cycles, where the minimum temperature is equal to or below -2°C and the maximum temperature is above 2°C. Relevant to the degradation of infrastructure and operational management of ice accumulation and snowmelt.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Icing days	Number of days where the daily maximum temperature is below 0°C. Relevant to inform the length of the winter season.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km
Maximum winter temperature (December to February)	The highest temperature between December and February. Relevant to understand the extreme scenario for increases in winter temperatures.	PCIC (2019) downscaled climate model ensemble	10 km × 10 km

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