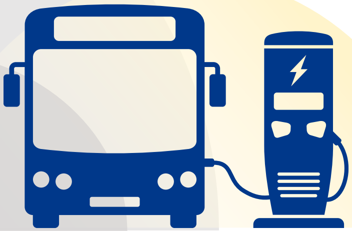
CLIMATE CHANGE AND RESILIENCE ASSESSMENT REPORT

12/8/2023



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1 INTRODUCTION

Cities, communities, businesses, and individuals are facing new and intensifying challenges from extreme weather events, increasing air temperatures, and changes in precipitation intensities and flooding as a result of climate change. The City of Stratford (City) has chosen to be proactive in response to these changes. The City has transformed their thinking, begun to look at their transportation systems differently, and engaged HDR to provide decision support for their resilient actions as part of the Infrastructure Canada's Zero Emission Transit Fund (ZETF) Applicant Guide, Annex A and the companion GHG + Plus Guidance Modules Battery Electric Buses (BEBs) in support of Transit Agency capital funding applications for BEBs.

In accordance with the Intergovernmental Panel on Climate Change (IPCC 2021), Environment and Climate Change Canada (ECCC) defines resilience as the capacity of Stratford's social, economic, and environmental systems:

1. To cope with a hazardous event or trend or disturbance

2. To respond or reorganize in ways that maintains their essential function, identity, and structure,

3. To maintain Stratford's capacity for adaptation, learning, and transformation.

The goal of this study is to provide for the decision support necessary to create dynamic, adaptive systems that protect human health, economic security, and environmental well-being.

2 PROJECT DESCRIPTION

This report is written to specifically address and quantify risks associated with the impacts of climate change to Stratford's transit infrastructure. While many of the current policies and initiatives are concerned with climate change mitigation (reduction of greenhouse gases), this report concentrates on how climate change may impact the potential implementation of Battery Electric Buses (BEBs). Additionally, it addresses the commitment the City has made to taking action by developing mitigation and adaptation strategies for the near-term and long-term assessment of greenhouse gas reductions and infrastructure vulnerability.

This step-by-step analysis utilizes historic climate trends to set the baseline for understanding projected future climate trends so that the current transit system vulnerabilities can be correlated to those that are anticipated to change at future time scales due to climate change. Once the climate data was collected, analyzed, and understood, it was used to identify the infrastructure vulnerability to these climate changes as part of a vulnerability assessment, which was derived in accordance with the instructions provided by Infrastructure Canada's ZETF Applicant Guide. This assessment allows for the development of risk identification and risk analysis as per the Applicant Guide.

As per the ZETF Applicant Guide, definitive boundaries were set within Stratford based on the extent of the transit system which included bus routes, rail lines, bus stops, and in the interest of logistical planning, transit facilities (**Figures 1 and 2**). This analysis is primarily concentrated on the bus routes, stops, and support facilities specific to addressing the protocol as described in the ZETF Applicant Guide. It makes considerations for potential climate risks expected during planned operation and maintenance phases of the project.

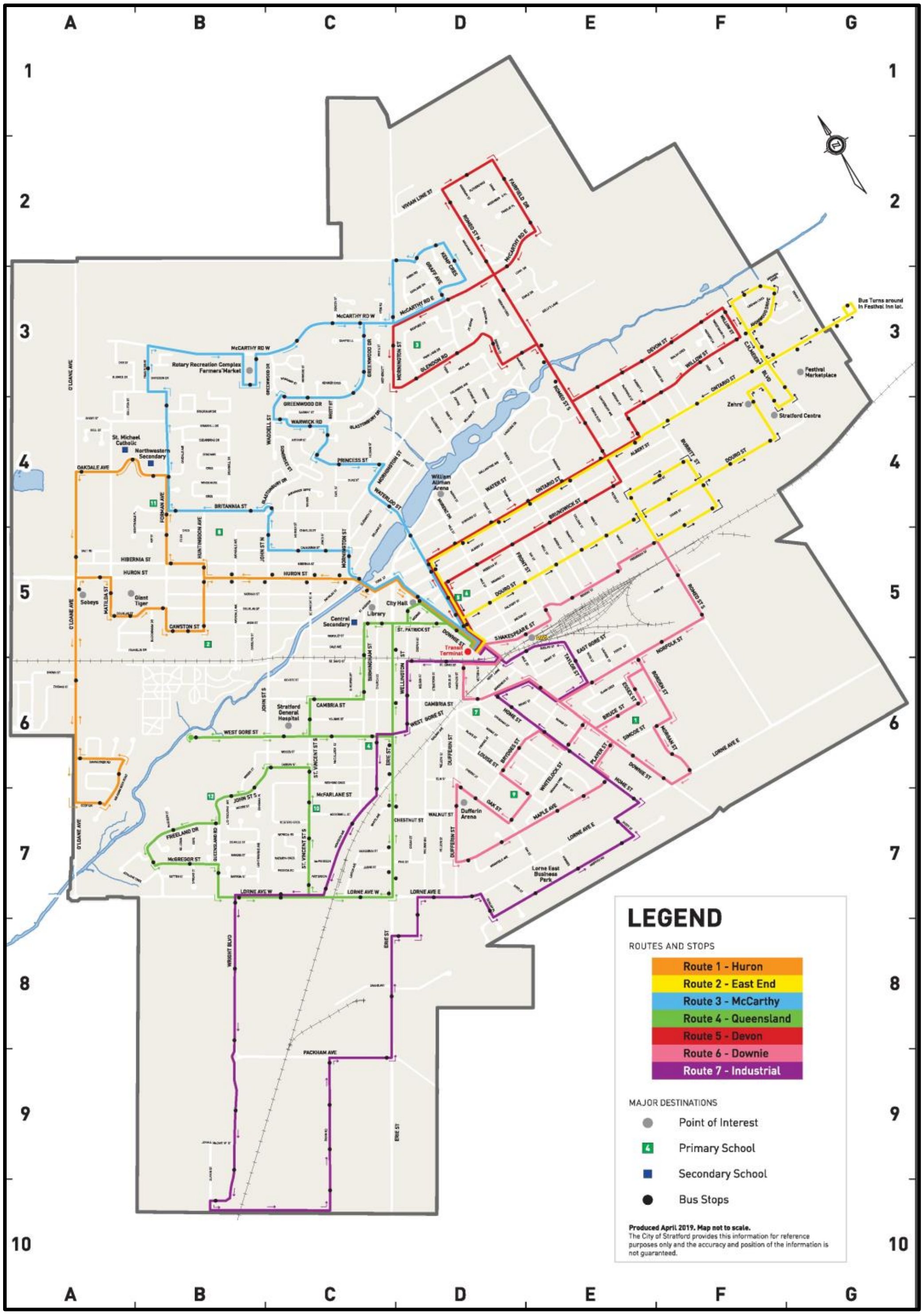


Figure 1. Stratford route map with water courses across Stratford.

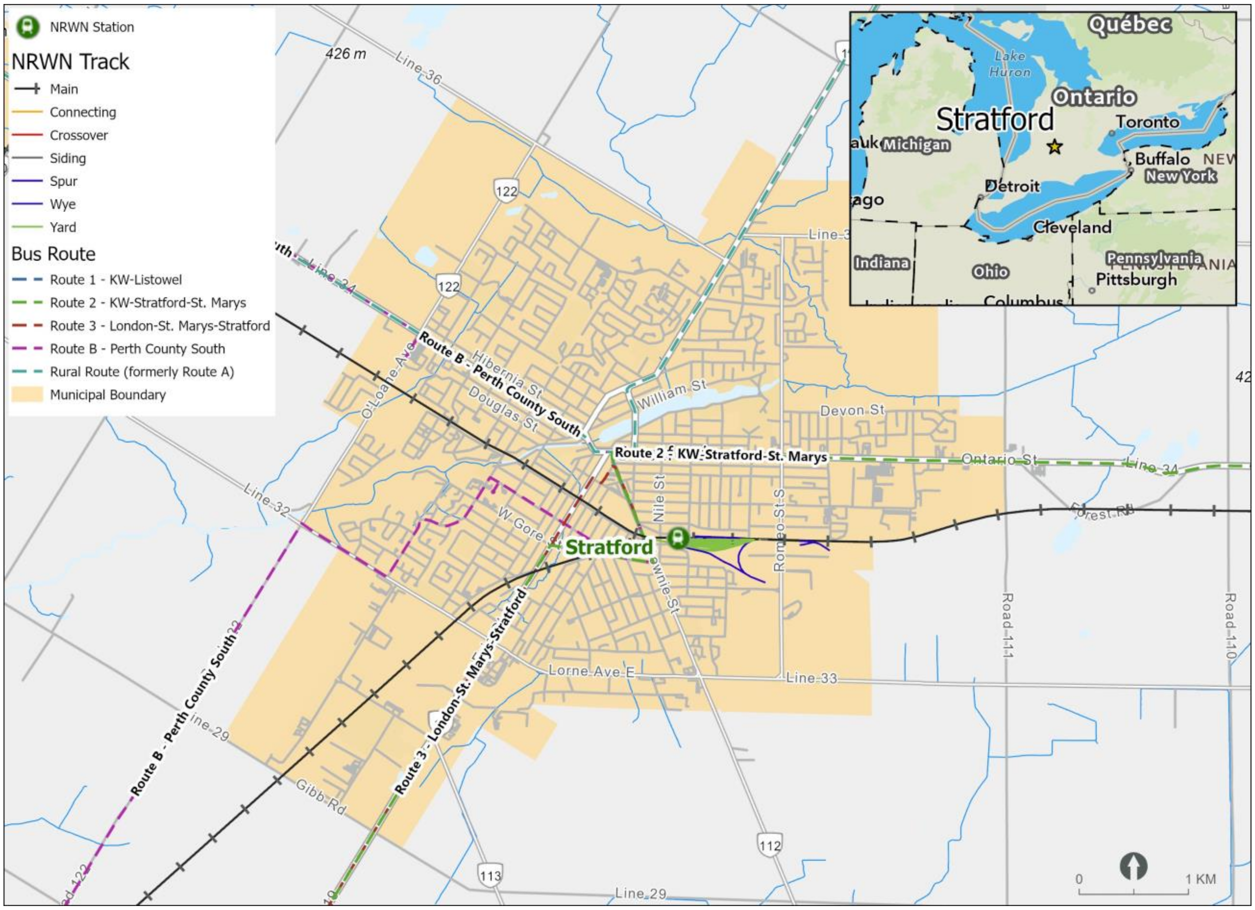


Figure 2. Map of NRWN rail lines and Stratford Bus routes and facilities.

3 HISTORIC CLIMATE TRENDS AND FUTURE PREDICTIONS

The first step in assessing the potential impacts of climate change is to understand the interactions of historical climate conditions within a geographical area of interest, (i.e., where your project will be located), both in terms of trends in key climate variables and records of extreme events. Understanding this historical record can help identify areas of vulnerability and provide a baseline of climate conditions to compare against projected future changes in the climate.

While the expected lifespan of a zero-emission bus is approximately 12 years, the Canadian Government sees this program as an important step in meeting their 2050 zero emissions target. Thus, although the asset life of the zero-emission buses is relatively short, all facilities and longer-term assets are expected to have a lifespan beyond the year 2050. This report will identify and quantify risk associated with climate change out to the year 2100, so that the continued operation and maintenance of these facilities will be covered as old buses are retired and new buses are acquired.

Historic climate trends are critical to setting a relationship between observed changes in the climate and projected changes in the future climate. They represent the “here and now” of climate hazards and how those hazards have changed over time in the observed record. This section investigates current climate trends, as well as their extrapolations into the future so that those extrapolations can be compared with future climate scenarios for the following environmental parameters.

3.1 IDENTIFY CLIMATE TRENDS AND POTENTIAL IMPACTS OF CHANGES IN AIR TEMPERATURE

Increasing air temperatures are anticipated to be an outcome of climate change on a global scale, throughout Canada, and specific to Stratford (Government of Canada 2019). While these increasing air temperatures are expected to have a significant impact on the health and mobility of the users of Stratford’s transit infrastructure, only the potential for air temperature extremes, primarily extreme heat, are likely to have an impact on system infrastructure.

3.1.1 OBSERVED AIR TEMPERATURE TRENDS

While the meteorological reporting station in Stratford has a period of record (POR) dating back to the early 1900’s, the reliability of the data fell off around 2005 and therefore, was not used for the historic climate analysis. Instead, the historical climate data from the Prairie Climate Centre’s (PCC) Climate Atlas of Canada for the Stratford Municipality was used for the 1950-2020 period (PCC 2019). **Figure 3** identifies a trend showing overall increases in both average annual maximum temperatures and average annual minimum air temperatures, but, more importantly, shows a dramatic shift (inflection) in these graphs around the year 1980. This same pattern regularly shows up in the analysis of average annual air temperatures across North America and is particularly pronounced as it pertains to nighttime low temperature annual averages.

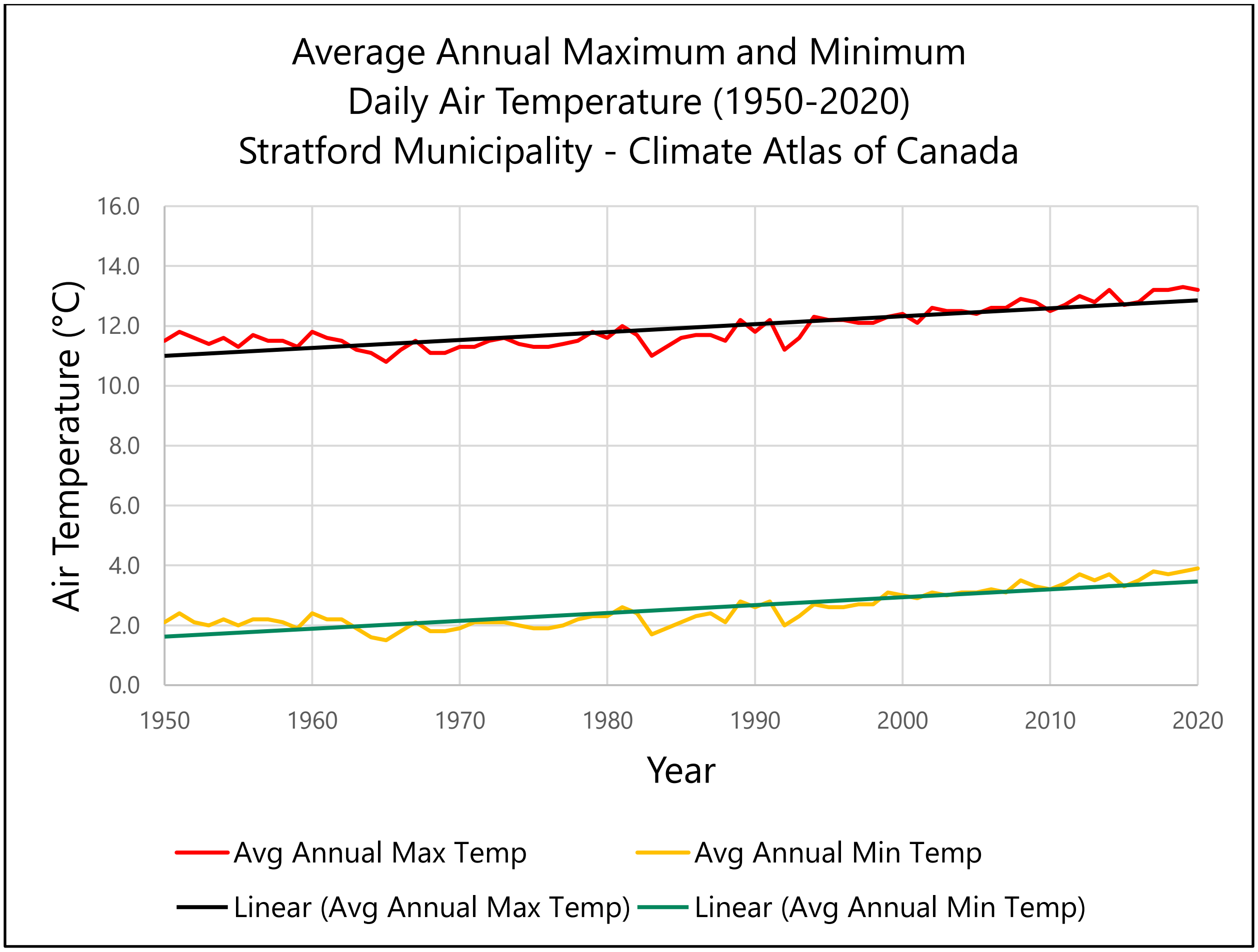


Figure 3. Average annual maximum and minimum Daily Air Temperatures using historic data from the PCC *Climate Atlas of Canada* (1950-2020). Trendlines in black and green. Source: PCC 2019

As will be discussed in relation to changes in the other environmental parameters in this study, decisions made in regard to climate resilient actions should consider observed climate trends as equally as they do projected climate trends. In order to better understand these decisions, it is necessary to provide a "What if?" scenario along the lines of, "What if the current (last 30-40 years) climate trends were to continue into the future?".

Figure 4 shows the graphs of the current average annual maximum and minimum temperature trends (1950-2020) extrapolated out to the year 2100. This graph indicates that if the current trend continues through the year 2100, the average annual maximum air temperature will rise to 15˚C and the average annual minimum air temperature will rise to 5.6˚C. These extrapolations should be compared with the projected air temperature trends in Section 3.1.2. Increasing air temperatures, as will be seen in the next section on climate projections, are expected to have a significant impact on both human health for system users, and the longevity of system infrastructure.

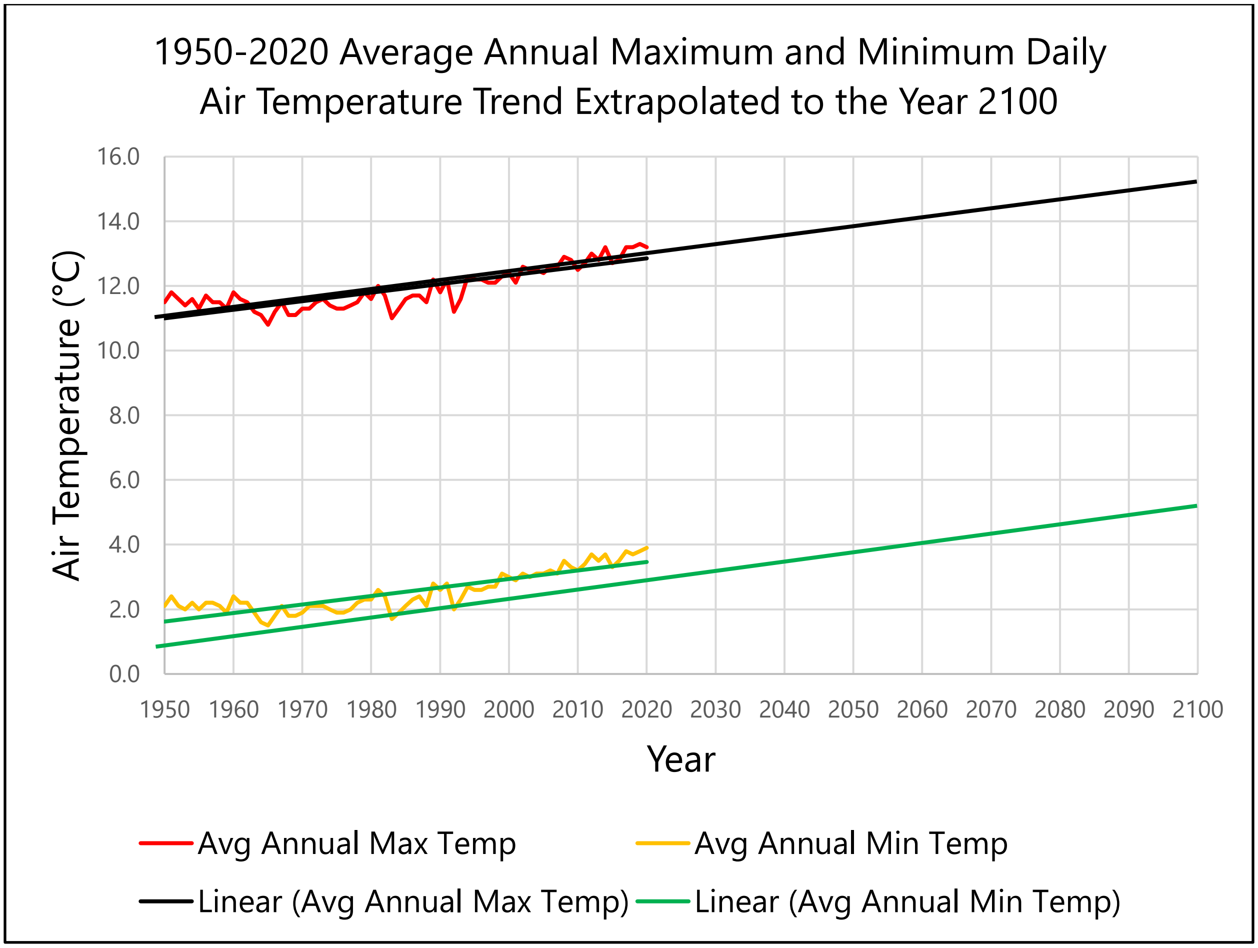


Figure 4. Average annual maximum and minimum daily air temperatures at Stratford (1950-2020) extrapolated to the year 2100. Trendlines in black and green. Source: PCC 2019

Periods of extreme heat, or colloquially known as heat waves, are expected to be a consequence of climate change (Government of Canada 2019). A heat wave occurs when at least three days in a row reach or exceed 30 °C. **Figure 5** shows the average annual number of heat waves from 1950-2020 using data from the *Climate Atlas of Canada*. This chart shows a dramatic increase in the number of heat waves starting in the 1990's. **Figure 6** shows a graph of the historic climate trend in annual daily maximum air temperatures using the historic data from the *Climate Atlas of Canada*. The increasing trend in these values throughout the entire period of record is a phenomenon which is, generally, attributable to the Urban Heat Island effect, wherein the changes in land use from rural to urban create a situation where daytime radiation is absorbed by the increasingly urban landscape and held in-place. It is also the reason for the noted increase in nighttime temperatures shown in **Figure 3**.

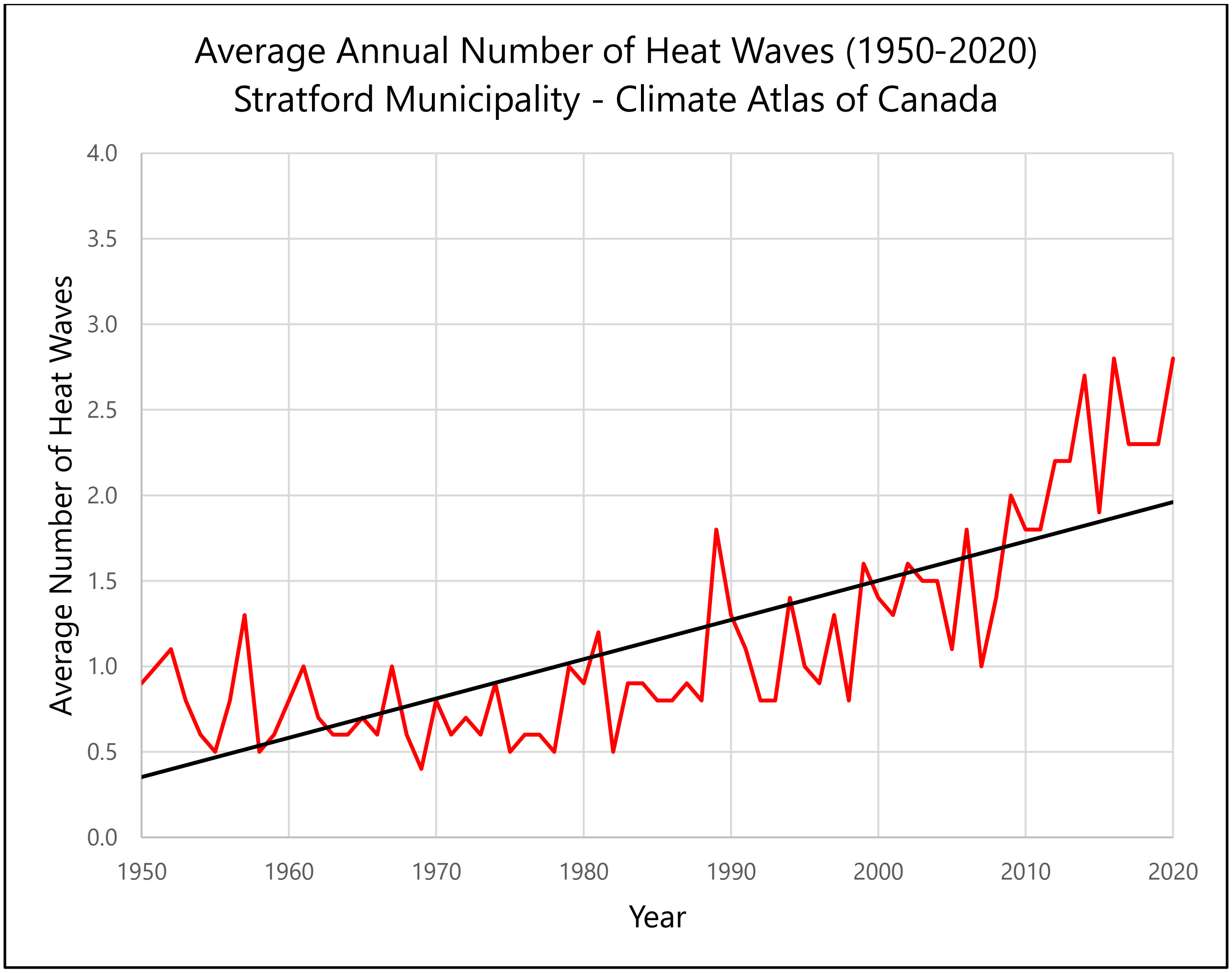


Figure 5. Average annual number of heat waves from 1950-2020. Source: PCC 2019

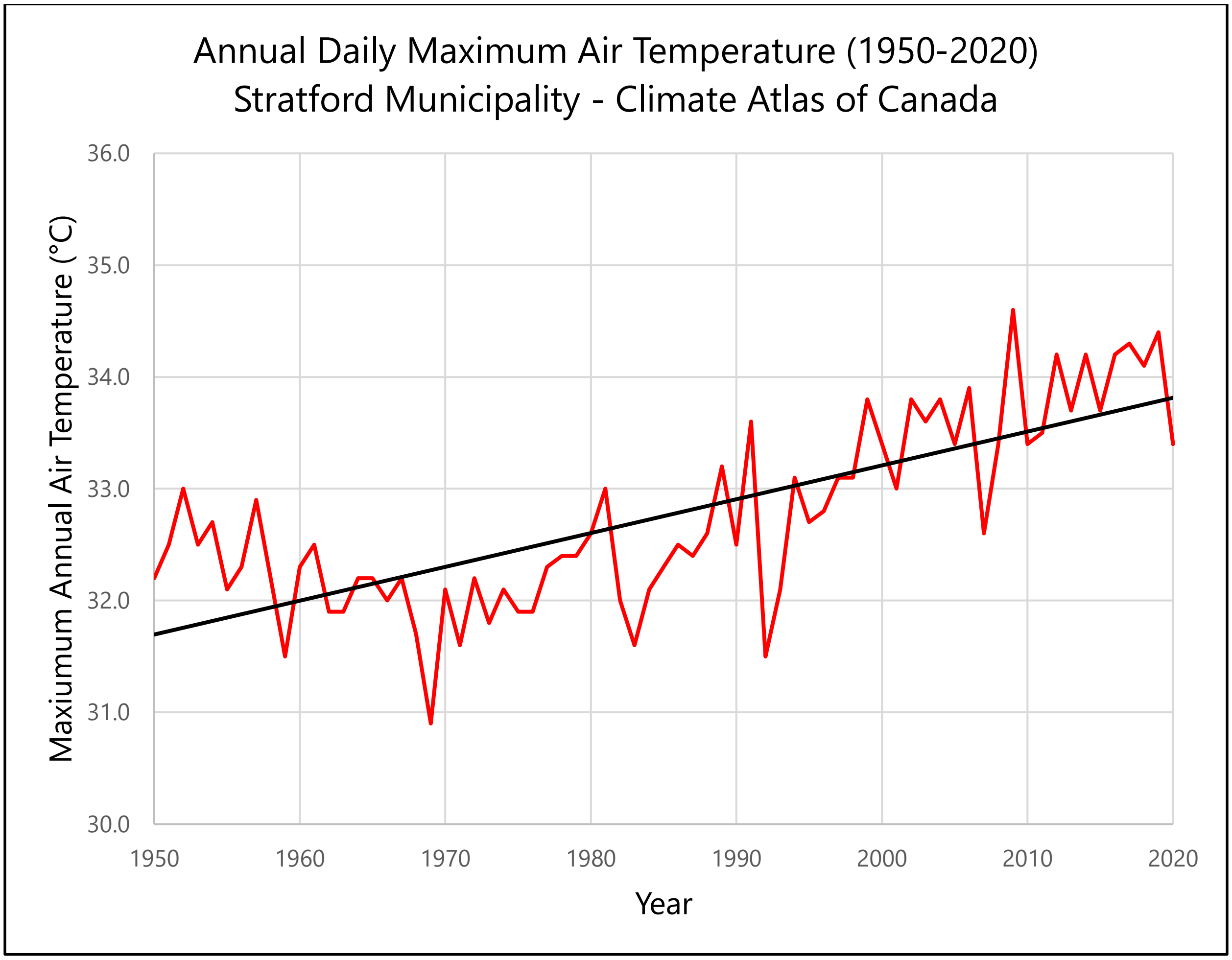


Figure 6. Annual daily maximum air temperature at Stratford (1950-2020). Trendline in black. Source: PCC 2019

3.1.2 PROJECTED AIR TEMPERATURES

One of the most profound findings of PCC is the fact that through analysis of the observed climate record, Canada is warming at a rate that is more than twice the global rate. This is primarily a consequence of phenomenon called "Arctic amplification", or the result of changes in a land area's, particularly the Canadian Arctic's, albedo. Basically, this equates to less snow and sea ice which equals more radiative absorption, and, thus, more warming.

Future changes in air temperatures are expected to have a much greater impact on human health and behavior (system demand) than on transportation system infrastructure; however, the following climate projections and understanding of the potential impacts to the human condition are provided for consideration as part of the resiliency equation for Stratford. The downscaled climate data provided by the PCC, specific to Stratford and this portion of Ontario, were used to quantify expected changes in air temperature at future time scales.

Figure 7 shows the projected annual average maximum temperatures expected in Stratford for the years 2000-2100. As of the year 2000, the annual average maximum temperature was 12.4˚C. **Table 1** shows the anticipated annual average maximum air temperature projections for the year 2035, 2050, 2075, and 2100 based on Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios. RCP 4.5 is a "Low Carbon" emissions scenario, in which emissions peak around 2040 and then decline to 2100. RCP 8.5 is a "High Carbon" emissions scenario which is the highest baseline emissions scenario in which emissions continue to rise throughout the 21st century (Cal-Adapt 2023). **Figure 4**, the extrapolation of the current trend in annual average maximum air temperature, is in surprisingly good agreement with the RCP 8.5 projected trend just a few degrees warmer.

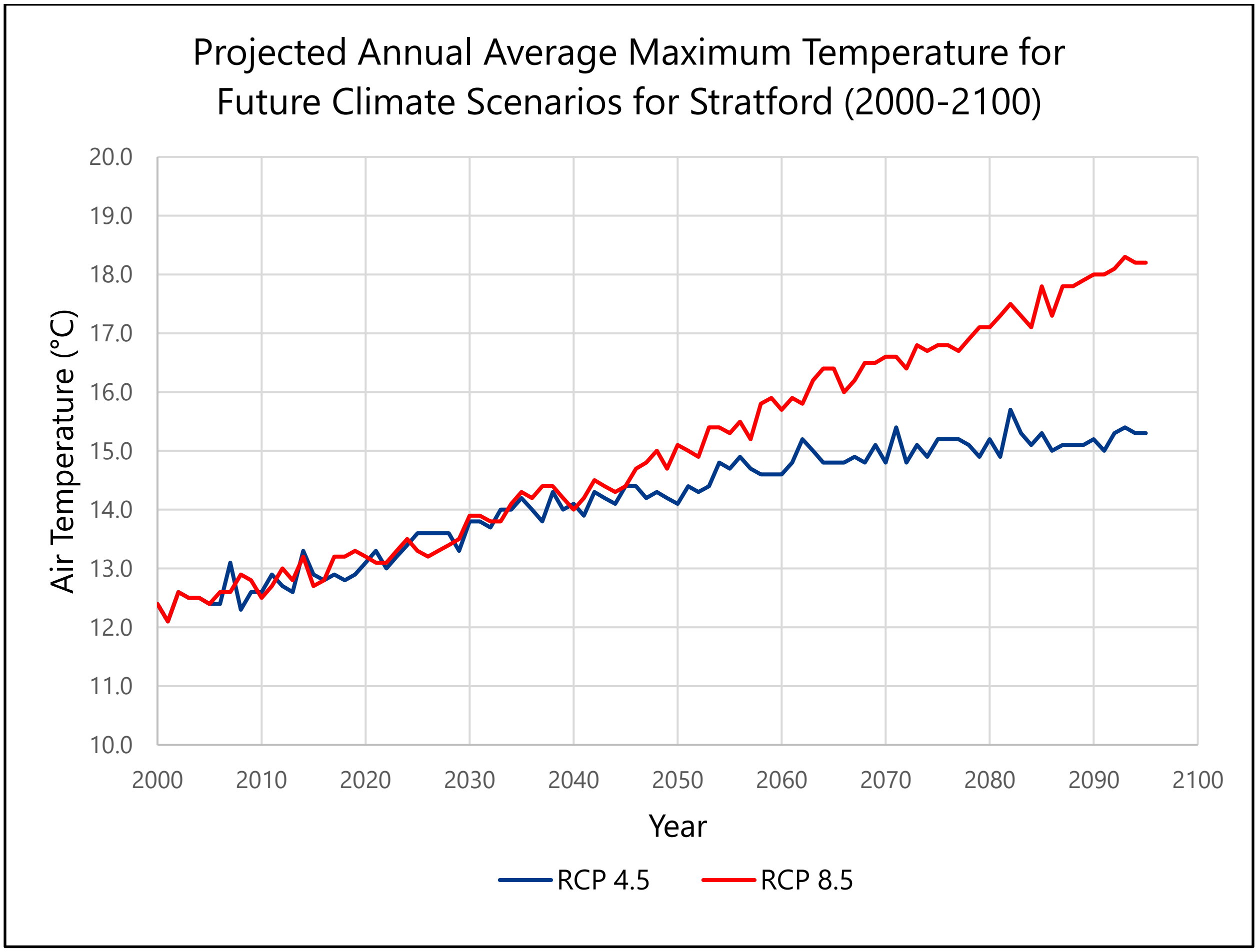


Figure 7. Projections of future annual average maximum air temperatures downscaled for Stratford to the year 2100. Source: PCC 2019

Table 1. Projected annual average maximum air temperatures for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (˚C)	RCP 8.5 (˚C)
2035	14.2	14.3
2050	14.1	15.1
2075	15.2	16.8
2100	15.3	18.2

Figure 8 shows the projected changes in annual average minimum air temperatures for Stratford under the two future climate scenarios. **Table 2** provides a quantification of these projections for future time scales. The projected changes in annual average air temperatures under the RCP 8.5 are also in fairly close alignment with those predicted in the extrapolation of the observed data for this parameter in **Figure 4**, albeit a few degrees warmer.

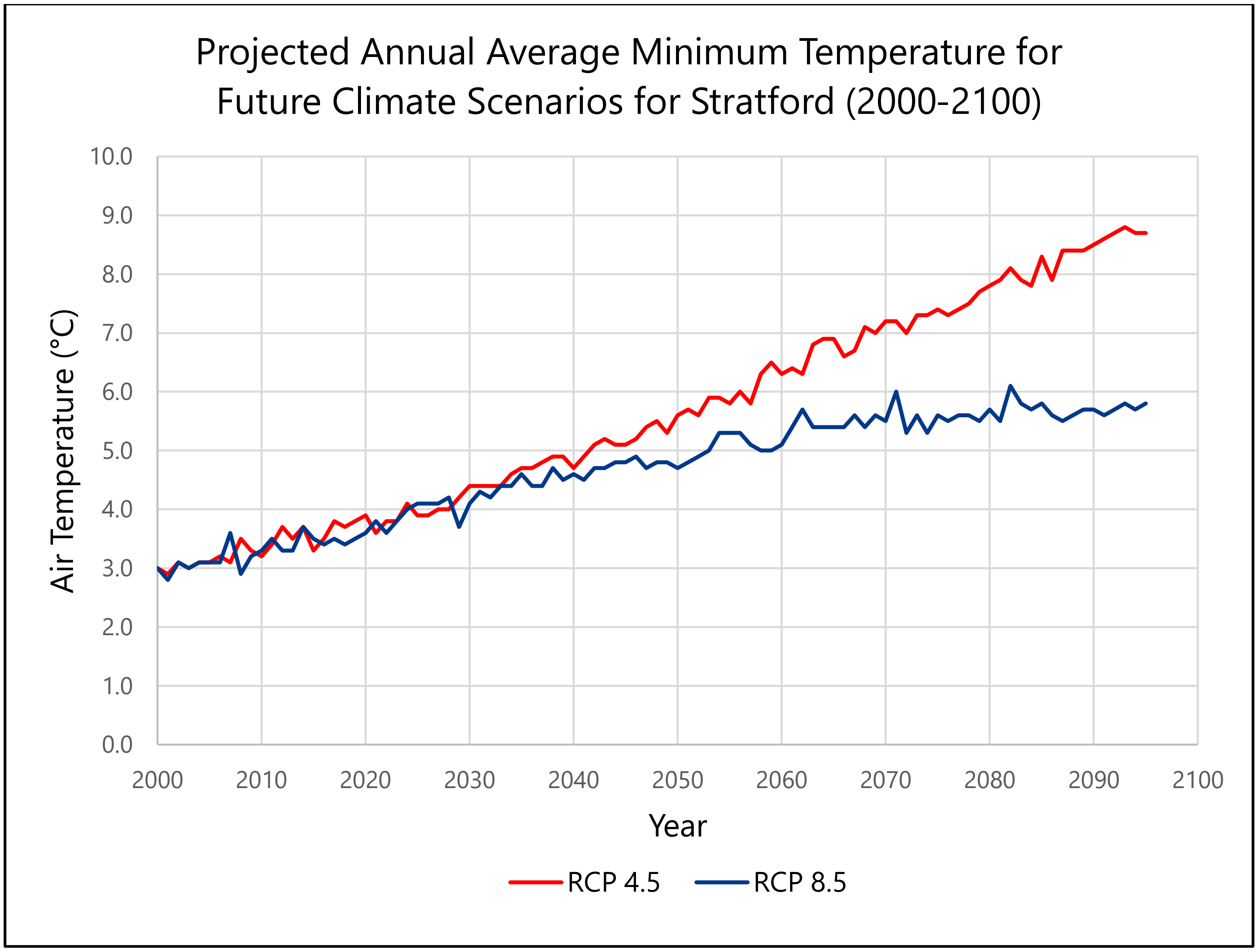


Figure 8. Projections of future annual average minimum air temperatures for Stratford to the year 2100. Source: PCC 2019

Table 2. Projected annual average minimum air temperatures for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (˚C)	RCP 8.5 (˚C)
2035	4.6	4.7
2050	4.7	5.6
2075	5.6	7.4
2100	5.8	8.7

As stated earlier in this section, air temperatures are expected to have a significant impact on human behavior as the residents of Stratford interact with the transportation system. This will be particularly true on very hot days equal to or greater than 30˚C. **Figure 9** shows the projected number of very hot days expected in conjunction with the two future climate scenarios used for this analysis. **Table 3** quantifies these number of days at future time scales. While the increasing number of very hot days is only expected to have a nominal impact on infrastructure, primarily as a result of thermal expansion within components of the system, it may prove, along with changes in precipitation and other weather phenomenon, to become a major factor for changes in system demand. A recent study in Berlin, Germany (Nissen, K.M. et al. 2020) showed public transit ridership and road traffic decreasing 5 percent on very hot days (>28ºC), while ridership increased as much as 30% on very cold days (<-5 ºC) during a time when road traffic decreased. This report showed a decrease in ridership on buses and light rail during days with precipitation and an even greater decrease during times of heavy rain. The impact of precipitation on the number of drivers was difficult to quantify but there is a strong correlation between traffic accidents and precipitation.

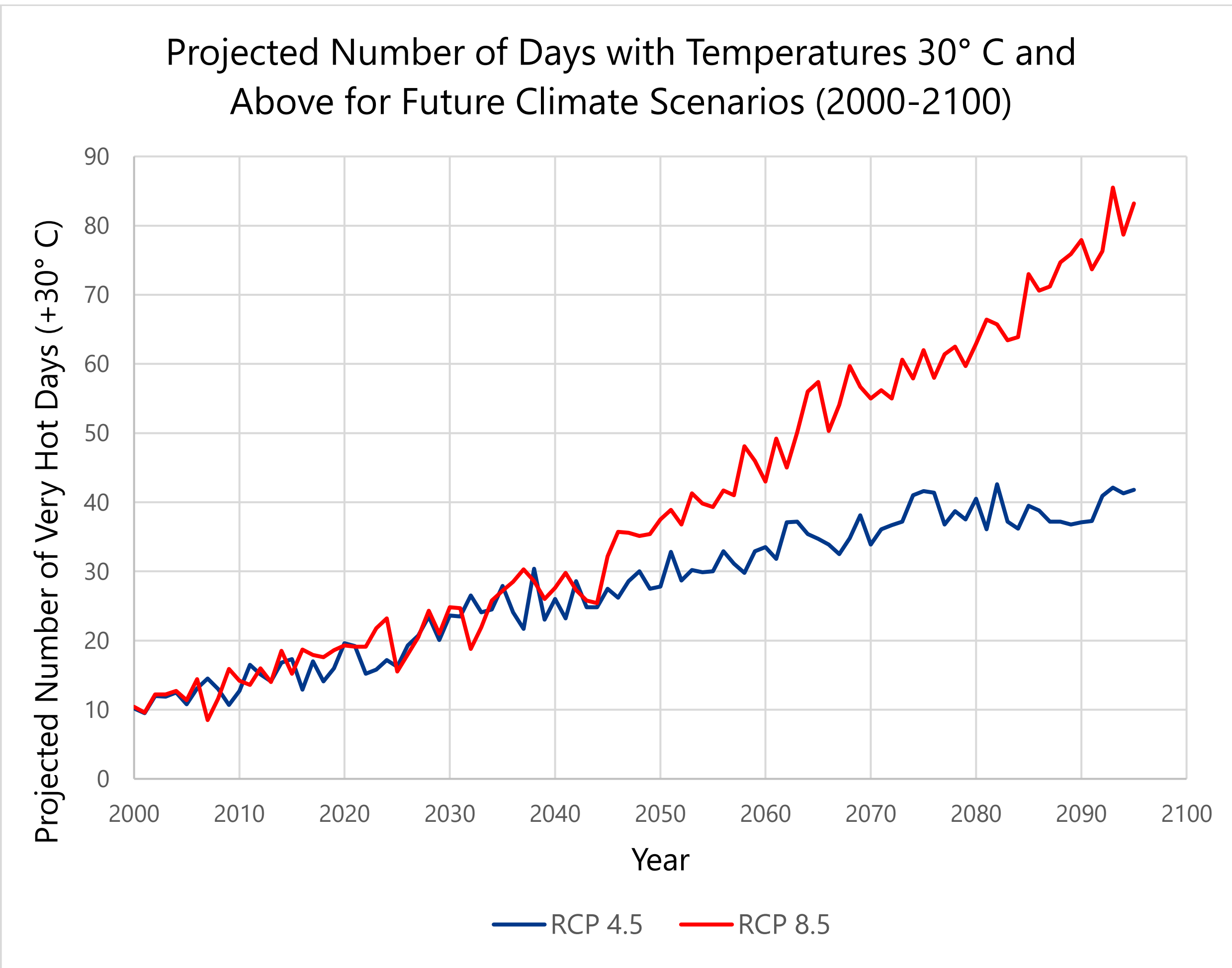


Figure 9. Projected number of very hot days (≥30˚C) for Stratford to the year 2100. Source: PCC 2019

Table 3. Projected number of days with air temperatures greater than or equal to 30˚C for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (# days)	RCP 8.5 (# days)
2035	27.9	27.2
2050	27.8	37.5
2075	41.6	62.0
2100	41.8	83.2

While the increasing number of days of air temperatures greater than or equal to 30˚C are expected to have a greater impact on system users, the most extreme air temperatures could cause infrastructure problems or failure through thermal expansion (i.e. asphalt buckling). **Figure 10** shows the anticipated increase in maximum temperatures in Stratford under both future climate scenarios. **Table 4** quantifies these maximum temperatures at future time scales.

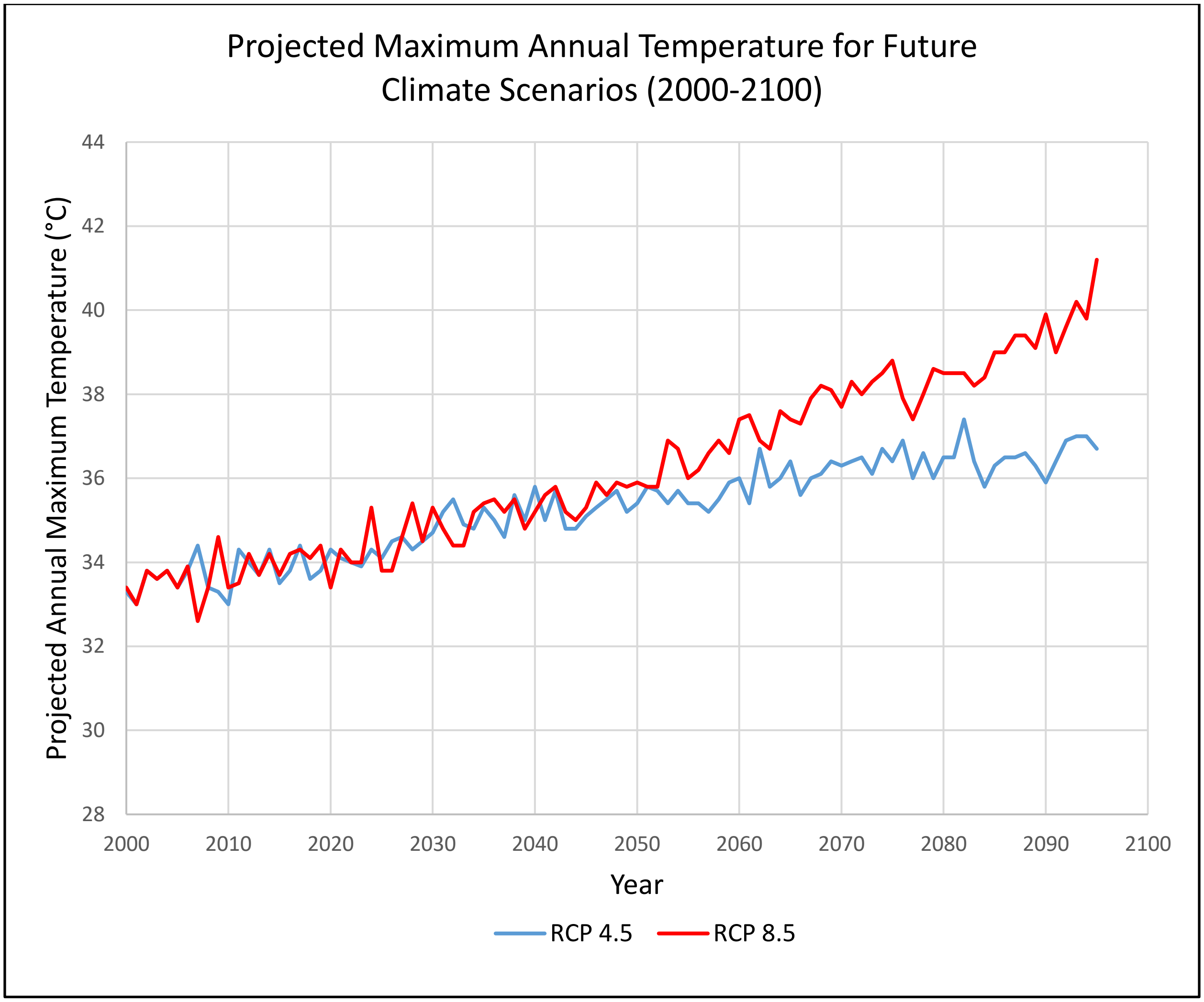


Figure 10. Projected maximum annual air temperature for Stratford to the year 2100. Source: PCC 2019

Table 4. Projected annual maximum air temperature for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (Max T ˚C)	RCP 8.5 (Max T˚ C)
2035	35.3	35.4
2050	35.4	35.9
2075	36.4	38.8
2100	36.7	41.2

One of the most important components of future air temperatures expected to impact the transportation infrastructure of Stratford relates to the freeze-thaw cycles within Perth County. Changes in the freeze-thaw cycles could destabilize the ground underneath transportation infrastructure and cause undue heaving, subsidence, or movement to roadbeds and foundations. A freeze-thaw cycle occurs when the daily maximum temperature is higher than 0˚C and the daily minimum temperature is less than or equal to -1˚C. The minimum temperature of -1˚C is used as the threshold for freezing to raise the likelihood that water actually froze at the surface. Although the freeze-thaw cycle parameter is only partially correlated to the depth of frozen ground, it is a good proxy for it. **Figure 11** shows the number of days of freeze-thaw cycles for both future climate scenarios. This finding is in concert with the projection of future average minimum air temperatures for this region, which show that significant warming is expected during the next 80 years.

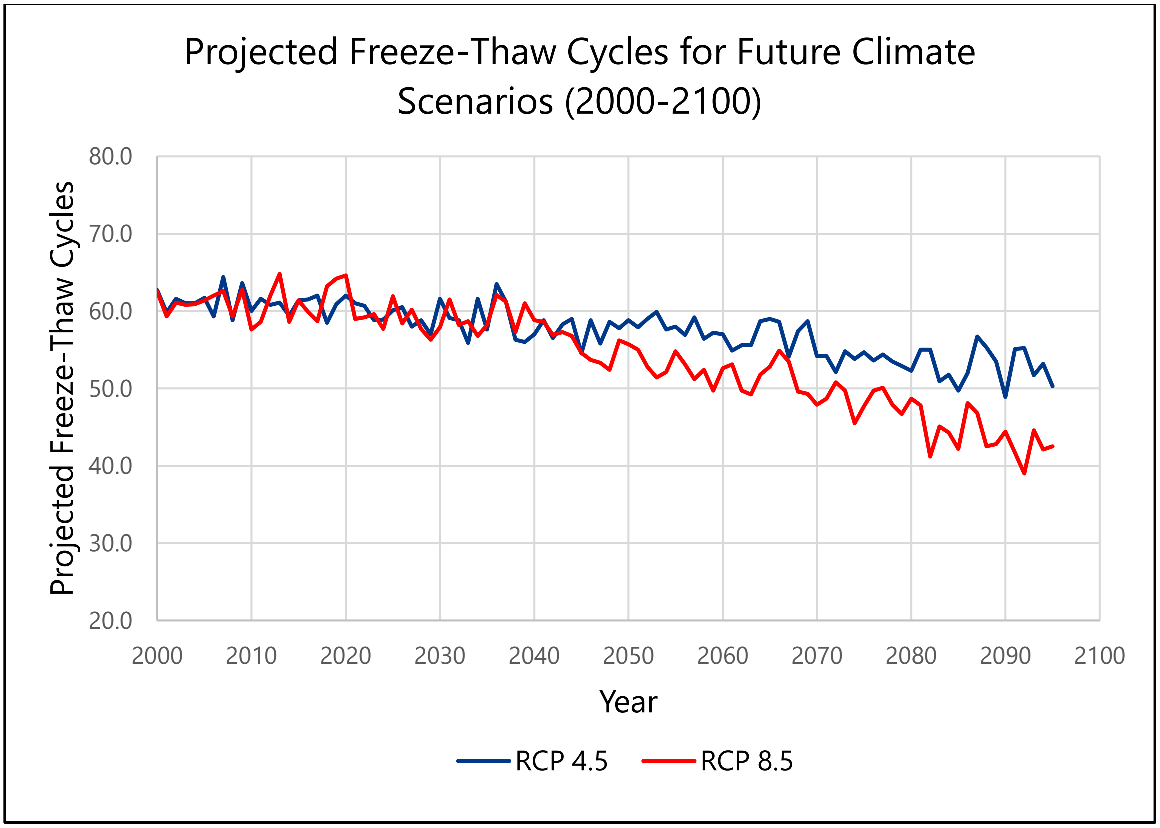


Figure 11. Projected freeze-thaw cycles for Stratford to the year 2100. Source: PCC 2019

Table 5. Projected freeze-thaw cycles for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (# days)	RCP 8.5 (# days)
2035	57.6	58.2
2050	58.8	55.7
2075	54.7	47.7
2100	50.3	42.5

3.1.3 POTENTIAL SYSTEM IMPACTS OF CHANGES IN AIR TEMPERATURE

Observed air temperature trends and projected temperature trends show a long-term increase in air temperatures that is expected to continue through the end of the century. The impacts to the Stratford and surrounding communities will be primarily related to the health and welfare of the riders rather than the infrastructure and operations related to the program under the ZETF Applicant Guidelines. As noted in the observed trend in **Figure 6** and the projected trend in **Figure 7,** increasing air temperatures are expected to lead to an increased number of days with air temperatures in Stratford exceeding 30˚C-- a temperature at which human health problems, especially for the aged and those with disabilities, begin to occur. This additional need for cooling within the zero emission buses may place an additional strain on power consumption and reduce battery life on very hot days.

As identified in **Figure 10,** annual maximum temperatures in Stratford are expected to reach 37˚C regularly by the year 2060 under the RCP 8.5 scenario. While buses should not experience any impacts from this kind of heat, road deformation/buckling, or rail buckling usually begins to occur at this temperature. Fortunately, a secondary impact of increasing air temperatures, particularly nighttime air temperatures (**Figures 4 and 8)**, is that there is expected to be a reduction in the number of freeze-thaw days in Stratford. This should reduce the threat of ground heaving and pavement deterioration in the Stratford area. Risk associated with these impacts will be quantified in Section 4.

3.2 IDENTIFY CLIMATE TRENDS AND POTENTIAL IMPACTS OF CHANGES IN PRECIPITATION

Changes in annual precipitation and increases in short-duration, high-intensity rainfall events are impacting transit infrastructure throughout North America.

3.2.1 OBSERVED PRECIPITATION TRENDS

As noted in the previous section regarding changes in air temperatures, as the annual average air temperatures increase, so does the atmosphere's ability to hold and release moisture. This is physically related to the Clausius-Clapeyron equation wherein, as the temperature increases, the atmosphere's ability to hold moisture increases approximately 6.3 percent per degree C. **Figure 12** shows the changes in annual maximum 24-hour precipitation at Stratford using the PCC *Climate Atlas of Canada* historical data (1950-2020). This upward trend over the 70-year POR is something that has been observed in many locations across North America.

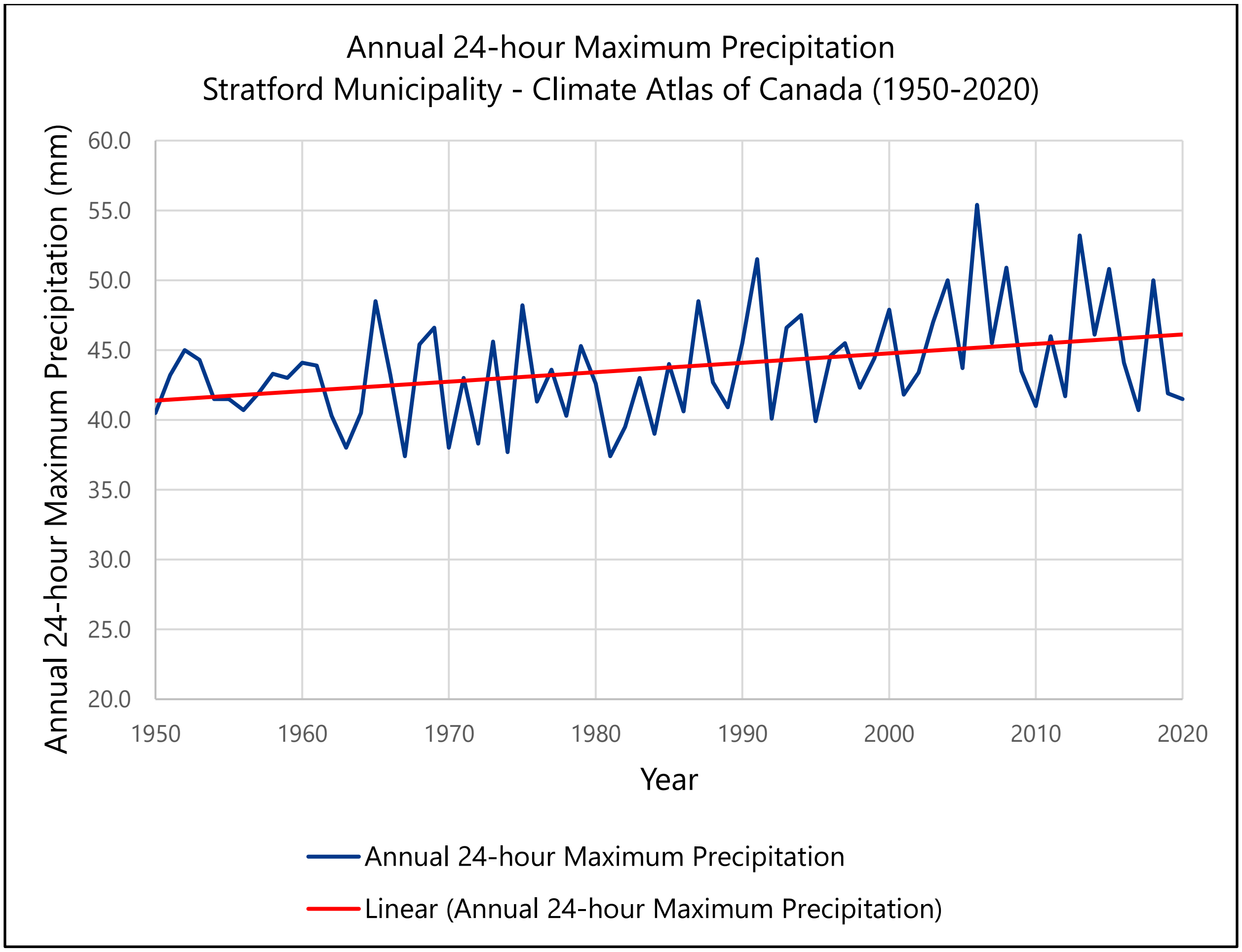


Figure 12. Annual 24-hour maximum precipitation at Stratford (1950-2020). Trendline in red. Source: PCC 2019

The same principle of a warmer environment producing more precipitation is very apparent in the record for annual precipitation in Stratford as well. **Figure 13** clearly indicates that the total annual precipitation in Stratford is steadily increasing. This has many implications regarding the stability of infrastructure in saturated soils as well as to changes in runoff during extreme storm events. These topics will be covered during the discussion of potential impacts in the following sections.

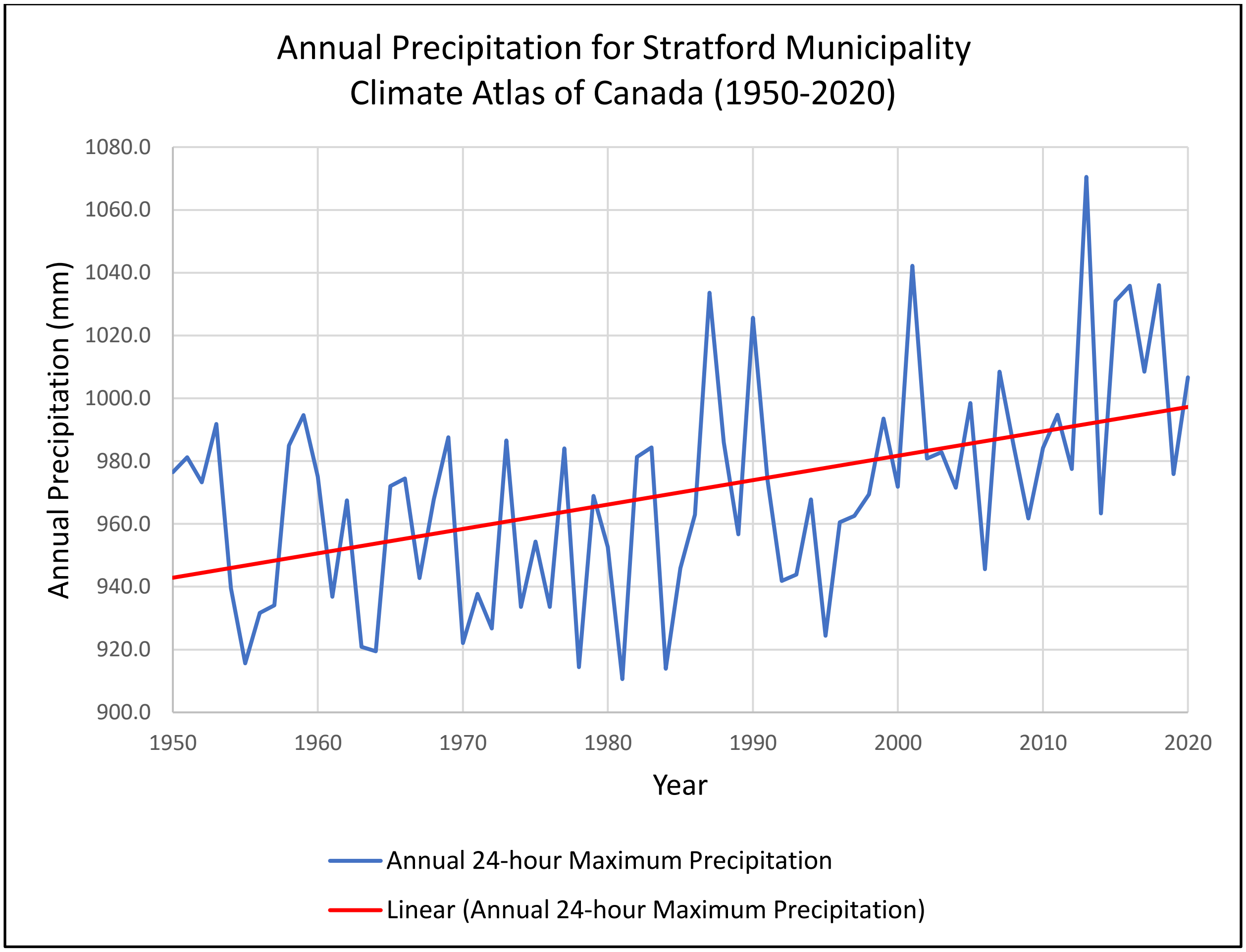


Figure 13. Annual precipitation at Stratford (1950-2020). Trendline in red. Source: PCC 2019

3.2.1 PROJECTED PRECIPITATION TRENDS

As noted in the previous section, the atmosphere's ability to hold and release moisture is expected to increase with increasing air temperatures. A projection of this increase on an annual basis can be seen in **Figure 14** for both RCP 4.5 and RCP 8.5. While these increases in annual precipitation in Stratford are significant, one of the more important factors that may result of this increase in annual precipitation is the increasing likelihood that the ground may be saturated before a significant precipitation event, which would result in a higher likelihood of flooding.

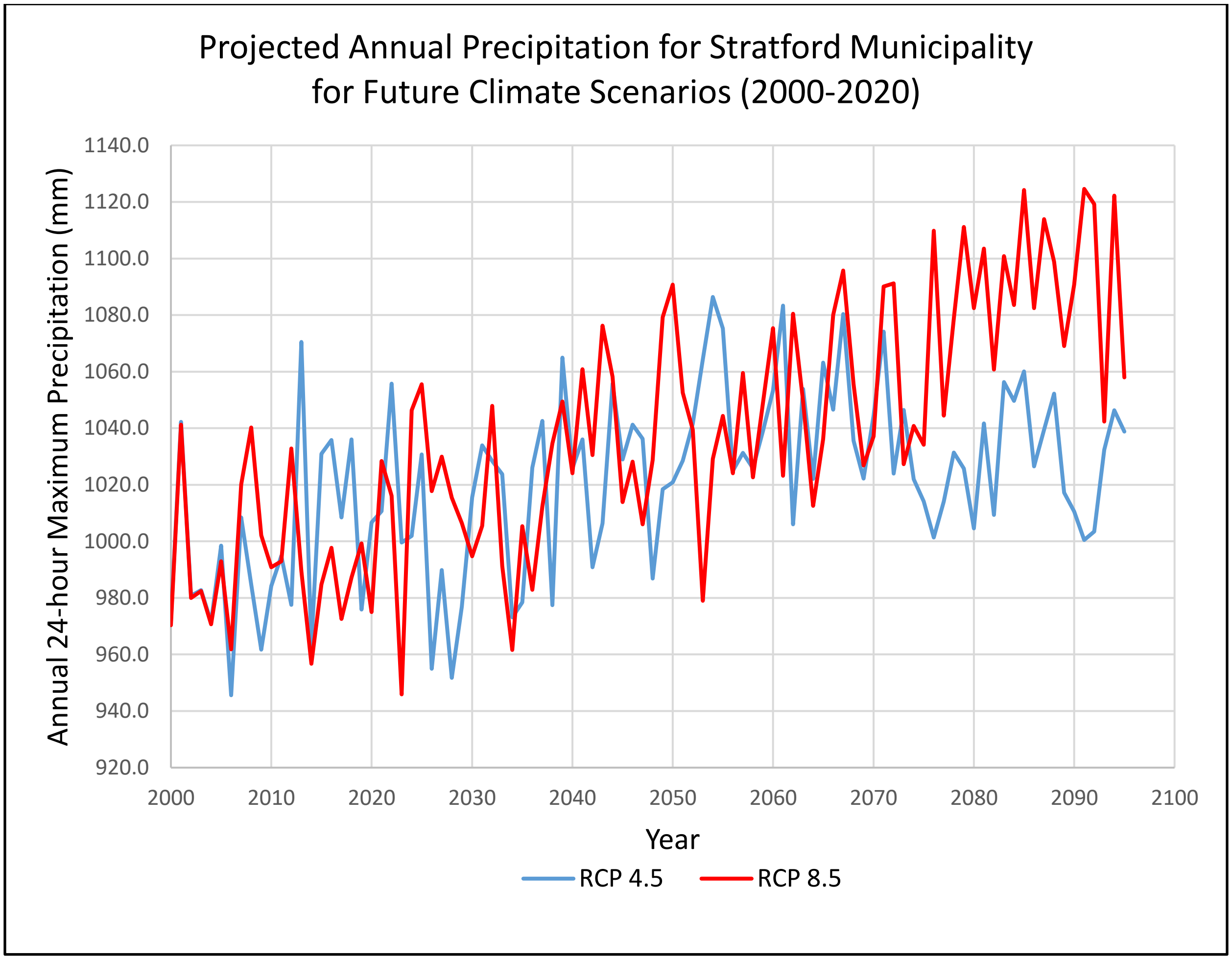


Figure 14. Projected changes in annual precipitation for Stratford to the year 2100. Source: PCC 2019

Table 6. Projected changes in annual precipitation for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (mm)	RCP 8.5 (mm)
2035	978.4	1005.4
2050	1020.9	1090.8
2075	1014.1	1034.2
2100	1038.8	1058.0

Figure 15 shows the projected annual number of days of heavy precipitation, which is quantified as days with greater than 20mm of precipitation. Although this 20mm benchmark may only emulate an event that could cause nuisance flooding, it also provides an understanding of the potential of extremely heavy precipitation events in excess of a 10-year return frequency or greater. Storms of this nature can produce significant flooding.

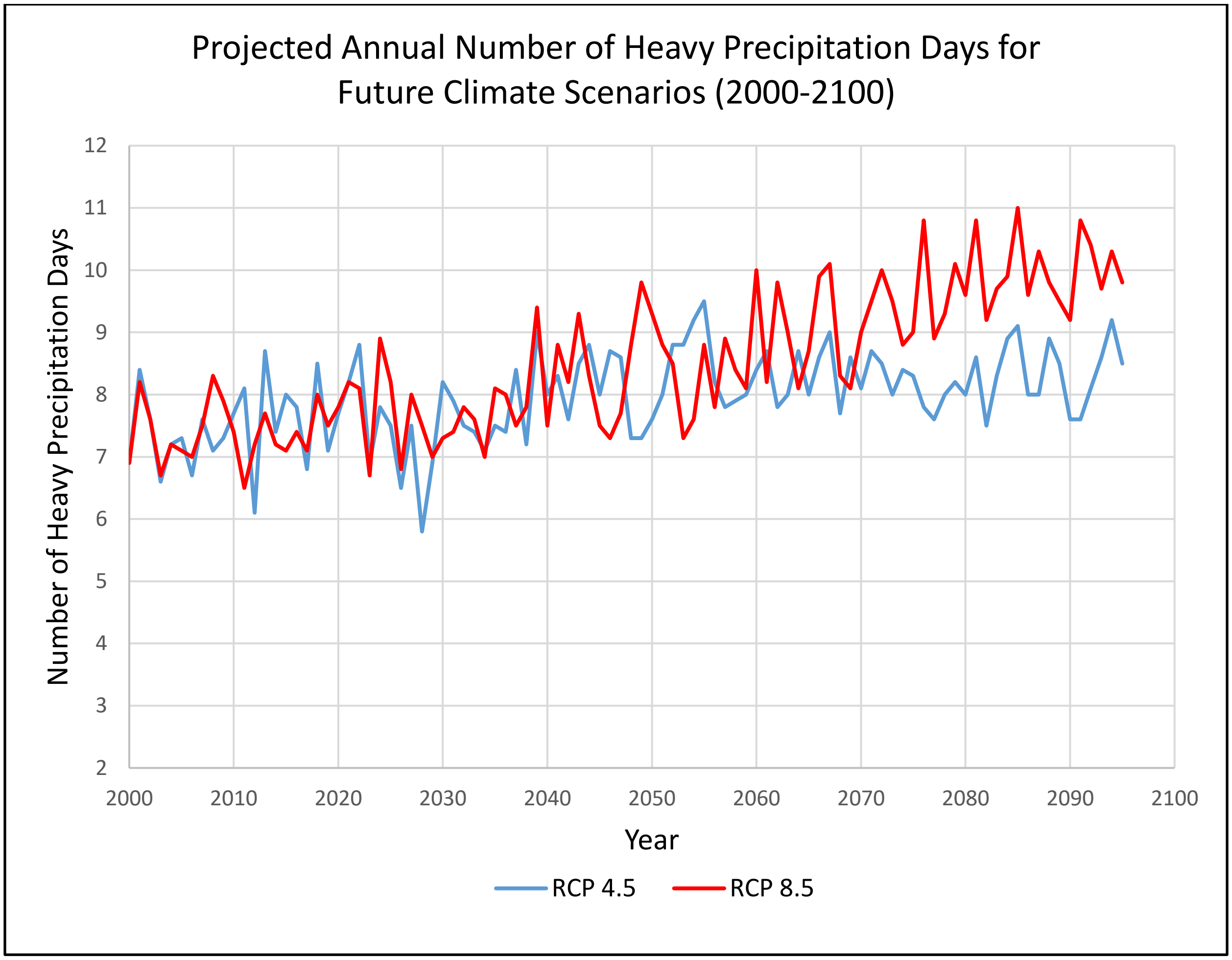


Figure 15. Projected changes in the annual number of heavy precipitation (>20mm) days for Stratford to the year 2100. Source: PCC 2019

Table 7. Projected changes in the annual number of days with heavy precipitation (20mm+) for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (days)	RCP 8.5 (days)
2035	7.5	8.1
2050	7.6	9.3
2075	8.3	9.0
2100	8.5	9.8

The increase in 24-hour (daily) precipitation intensities are important to understanding the potential change in flooding within Stratford and the surrounding communities, but the changes in multi-day storm event precipitation may, potentially, be even more important to an understanding of future flooding. **Figure 16** identifies the projected change in annual maximum 3-day precipitation as a result of the two different climate scenarios. **Table 8** provides a quantification of these projections at future time scales.

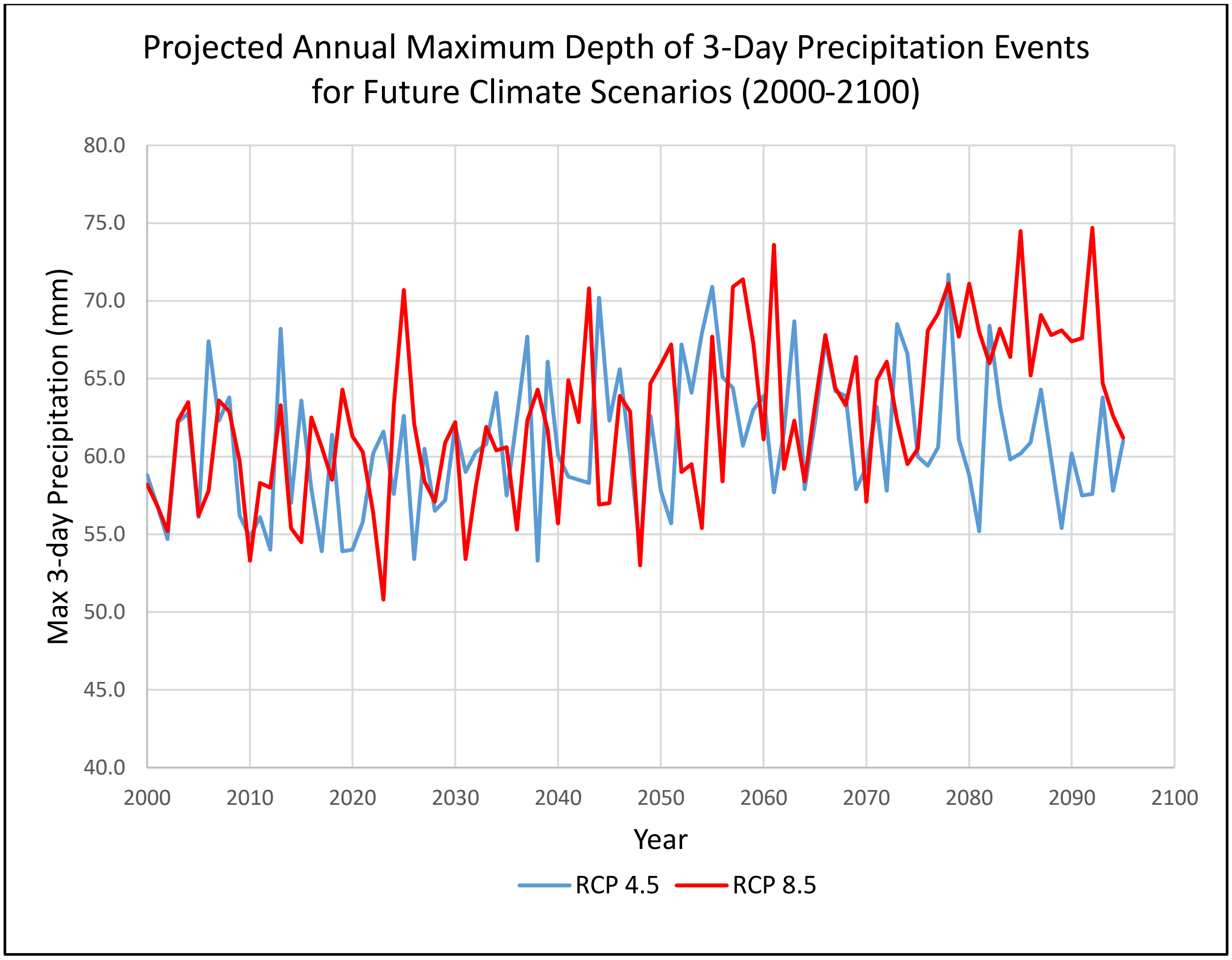


Figure 16. Projected change in annual maximum 3-day precipitation events for Stratford to the year 2100. Source: PCC 2019

Table 8. Projected changes in annual maximum 3-day precipitation events for Stratford at future time scales.

Future Scenarios		
Year	RCP 4.5 (mm)	RCP 8.5 (mm)
2035	57.5	60.6
2050	57.8	65.9
2075	60.0	60.5
2100	61.0	61.2

3.2.2 POTENTIAL SYSTEM IMPACTS OF CHANGES IN PRECIPITATION

As evidenced by many recent short-duration, high-intensity storms over North America during the last several years, increasing air temperatures are leading to increases in precipitation intensities and resultant flooding. The observed record (**Figure 12)** does show that this has been the case for Stratford and the projected increase in annual and heavy precipitation **(Figures 14, 15, and 16)** shows a significant increase is anticipated in the future. These increases are expected to lead to an increase in the number and magnitude of stream/river and stormwater flooding throughout Ontario and the Stratford communities. As seen in **Figures 1 and 2,** there are many streams and tributaries that flow across or near the rail lines, bus routes, stops, and facilities in this region.

One secondary consequence of the increase in annual precipitation is increased ground saturation. When coupled with short-duration, high-intensity rainfall events, this can lead to flash flooding in Stratford. Risks associated with these impacts will be quantified in Section 4.

3.3 OBSERVED AND PROJECTED EXTREME FLOODING POTENTIAL

The flood of record for the Thames River watershed (which also impacted the Avon River at/above Stratford) occurred from the storm in April 1937. This event was the most destructive of life and property where an estimated 1,100 homes were ruined and property damage ran to $3,000,000. While London was the hardest hit from this event, the heavy rainfall led to a flood on the Avon River that greatly impacted and undermined the dam of Lake Victoria at the center of the city. The floods were the result of nearly 150 mm (6 inches) of rain falling on Southwestern Ontario in five days, combined with spring runoff from the melting snows.

3.3.1 OBSERVED FLOODING EVENTS AND TRENDS

The most significant source of flooding is heavy rainfall from local convective storms and strong large-scale continental storm systems that include storm systems that drop large amounts of rainfall on already snow-covered ground. Heavy rainfall still impacts Stratford and the Upper Thames River watershed to this day. An example of these larger events occurred on September 22, 2021. The approximately 30-hour rainfall event produced around 80mm over Stratford (67mm in 24hours) and a maximum of 135mm over Woodstock to the south/southeast according to the NOAA National Severe Storms Laboratory (NSSL) Multi-Radar / Multi-Sensor (MRMS) rainfall estimates (**Figure 17**). This heavy rainfall event produced waters that flooded many roads and walkways including the Avondale Cemetery and the Stratford Golf and Country Club (Beacon Herald Staff 2021).

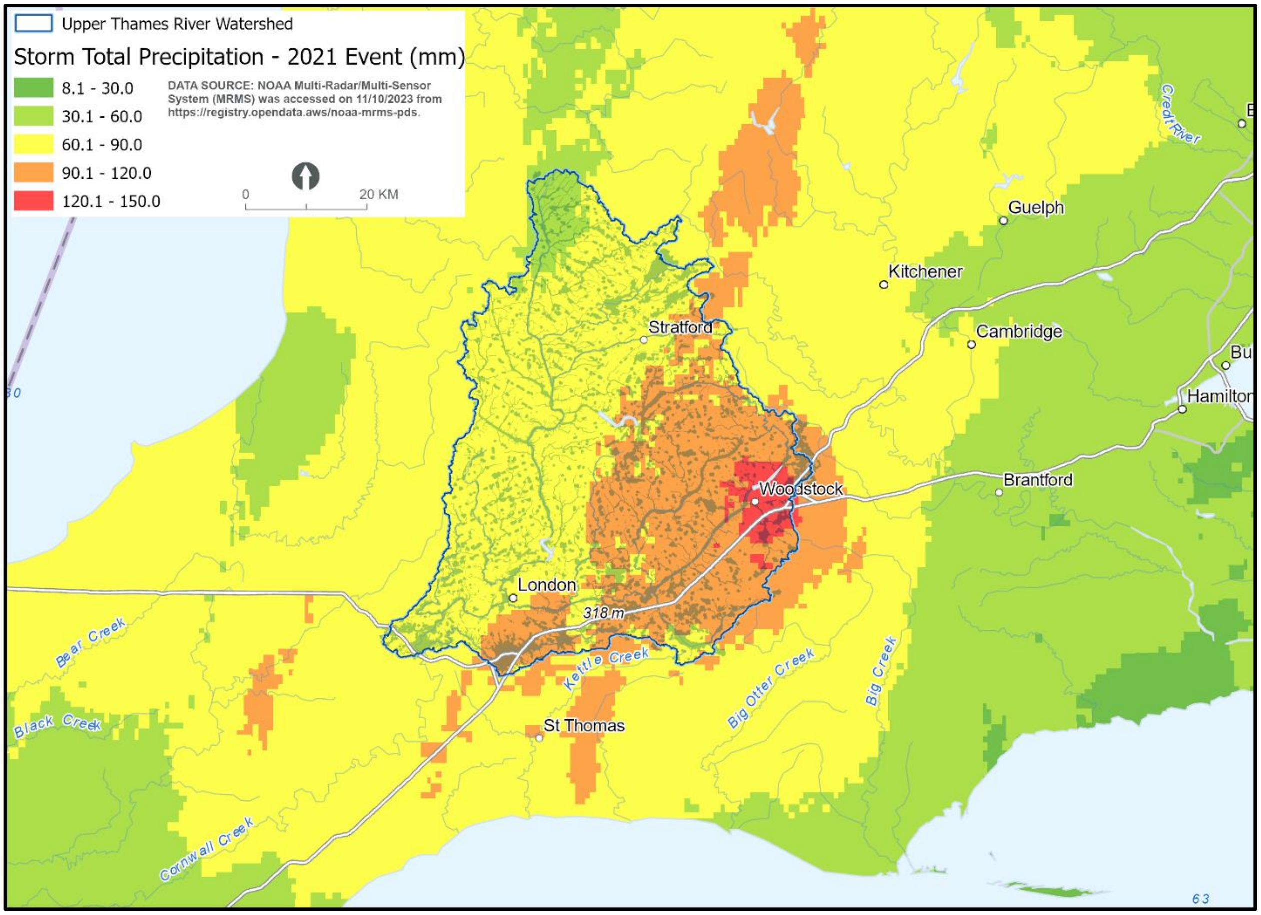


Figure 17. MRMS depiction of the estimated rainfall from the September 2021 heavy rainfall event. Source: NSSL 2011

3.3.2 POTENTIAL IMPACTS OF CHANGES IN FLOODING EVENTS

As discussed in Section 3.2.3, increases in heavy precipitation events are expected to occur throughout the remainder of this century in Stratford. These events and the increase in the number and intensity of severe storms (Section 3.4), are expected to significantly impact stream and river crossings across Stratford and Perth County. This would indicate that the rainfall flooding event of 2021 could occur more frequently in the future.

3.4 ADDITIONAL OBSERVED AND PROJECTED CLIMATE-RELATED HAZARDS AND IMPACTS

Much like the potential for extreme flooding events, the projection of the likelihood of future severe weather events needs to be handled as a qualification rather than a quantification. Projected increases in air temperature and atmospheric moisture lend themselves to the understanding of the potential for future severe storms. The changes in these parameters form the foundation for increasing convective activity, and, as a result, increases in the various hazards related to convective storm events.

3.4.1 OBSERVED AND PROJECTED TORNADOES, LIGHTNING, AND SEVERE THUNDERSTORMS

In a recent article (Sills et al. 2020) in the Bulletin of the American Meteorological Society (BAMS), the Northern Tornadoes Project produced an extensive climatology of tornadic activity in Canada. **Figure 15** shows that during the years 2017-2019 the great majority of strong tornadoes (>=EF1, enhanced Fujita scale) occurred in Ontario and Quebec, particularly in the southern areas of these two provinces. According to this data, Stratford is already a likely location for tornadic activity as evidenced by the cluster of tornadoes near Stratford shown in the map in **Figure 18** and within the dashed line related to tornado frequency. As the atmosphere warms, the potential for an increase in the frequency and intensity of severe storms are expected to also increase. Climate change is like giving steroids to the atmosphere. It provides the vehicle for an increase in the differential between warm and cold air masses, which is at the root of most severe storm events. This increasing threat is expected to be spatially equal across the domain of this portion of southwestern Ontario, but the increase in the likelihood of severe weather has a potentially higher level of consequences for intersections where traffic is managed by signals and for transit stations with exposed areas.

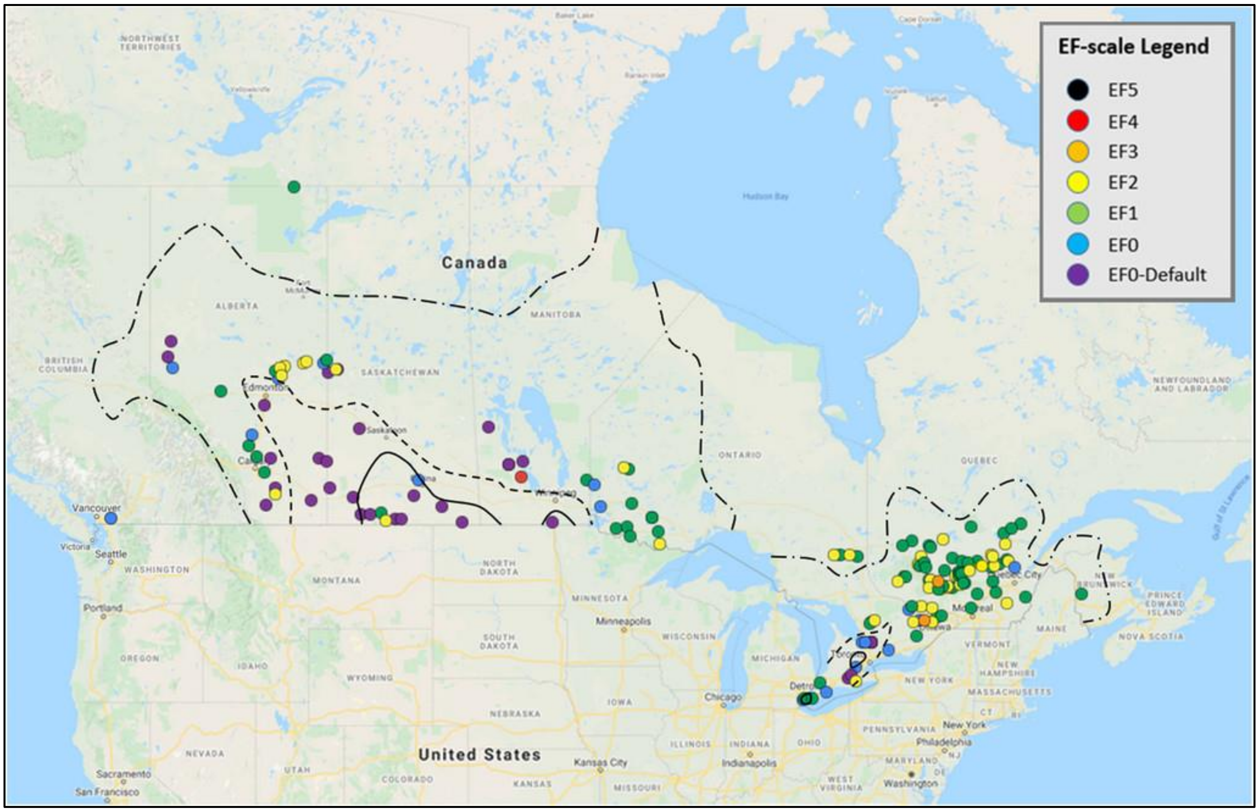


Figure 18. All 2017-2019 tornadoes reported in Canada by EF scale. Smoothed contours of average annual tornado frequency in tornadoes per 10,000km^2 per year: dash–dotted = 0.1, dashed = 1.0, and solid = 2.0.

Weather phenomena are the one of the biggest causes of power outages in Canada, but lightning tops that list in almost all locations for momentary outages (outages lasting less than one minute). These momentary outages can be extremely disruptive to a system such as Stratford's. Additionally, lightning strikes, even near misses, can produce an Electro-Magnetic Pulse (EMP) that can knockout sensitive electronics. The following section provides an understanding of current threat of lightning in the vicinity of Stratford.

Figure 19 shows the annual average number of cloud-to-ground lightning strikes on a per sq. km basis in the vicinity of Stratford. Fortunately, Stratford is in a location that is just outside a higher area of lightning activity but still can see an average number of lightning strikes of approximately 1.98 per sq. km per year.

Lightning detection is done through a remote sensing system developed by the Vaisala Corporation, which provides lightning detection data for a large portion of North America through the U.S. National Lightning Detection Network (NLDN). It is capable of sensing the magnitude and locating cloud-to-ground lightning at extreme distances and, therefore, can provide lightning strike detection and information evenly across the much of Ontario.

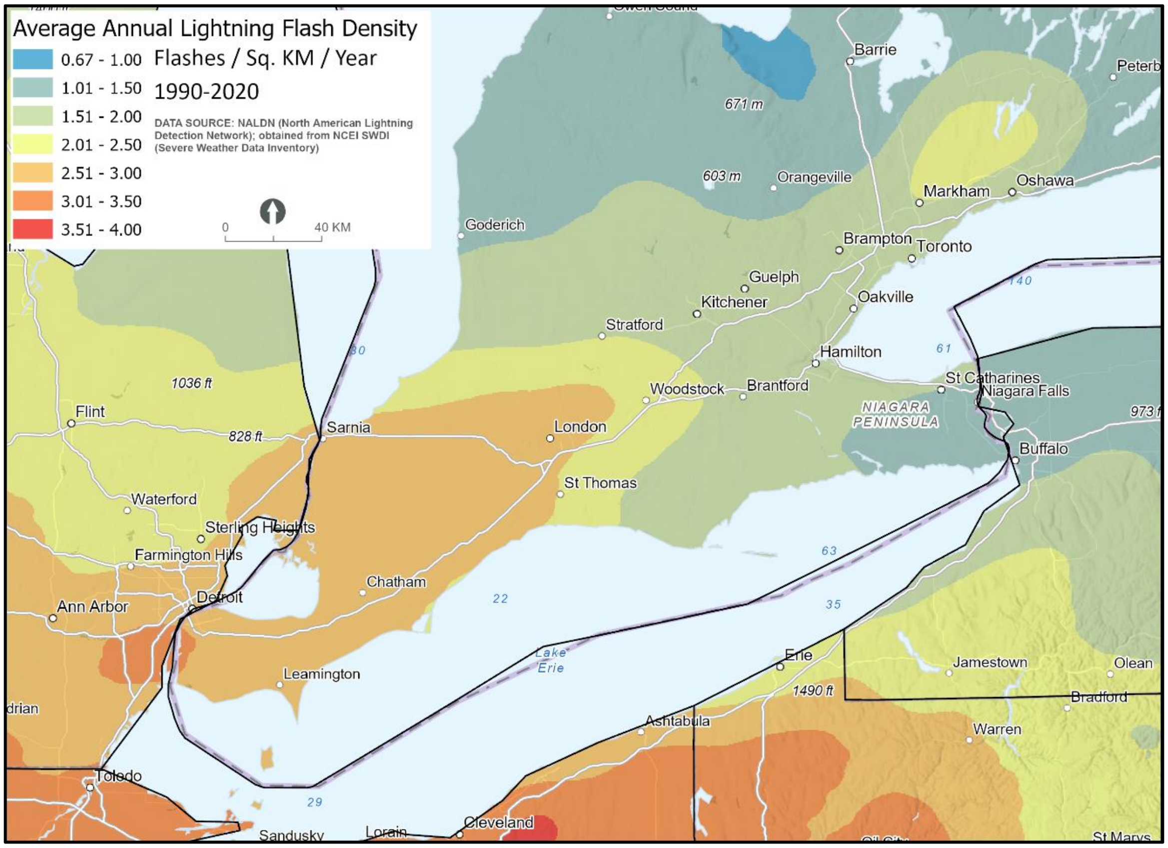


Figure 19. Average annual lightning flash density (cloud-to-ground) in the vicinity of Stratford during the period 1990-2020.

As noted in the prior section, climate projections indicate an enhancement in atmospheric moisture, warming, and instability. These are all the ingredients that produce thunderstorms, and of course, lightning. A published research paper in the Scientific American publication (Thompson 2014) reported that lightning rates are expected to increase 12 percent for every 1.0.C rise in air temperature. Using the projected air temperature changes in **Tables 1 and 2**, **Table 9** represents the percent increase in the average annual number of lightning strikes per sq. km in Stratford at future time scales.

Table 9. Projected increase from current flash density for RCP 4.5 and RCP 8.5 climate scenarios based on 12% increase in flash density per ºC in air temperature at future time scales.

Projected Increase from Current (2020) Flash Density (strikes per year per sq.km) for RCP 4.5 and RCP 8.5 Climate Scenarios		
Year	RCP 4.5	RCP 8.5
2035	2.10	2.11
2050	2.09	2.21
2070	2.22	2.41
2100	2.23	2.58

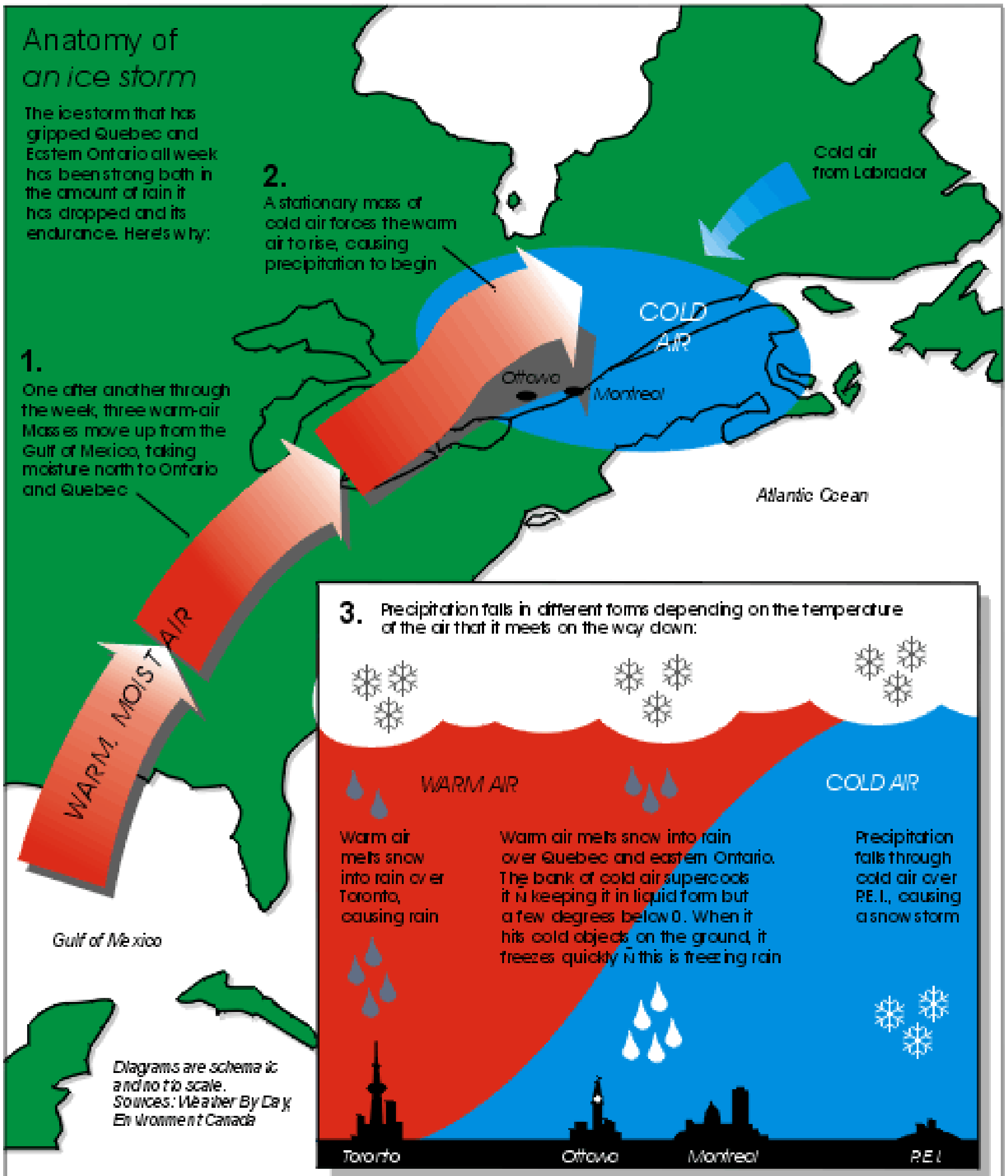
In addition to an increase in the frequency of lightning, there is a strong likelihood of an increase in the intensity of lightning at future time scales as well. A typical cloud-to-ground lightning strike generates 300 million volts, 30,000 amps, and is approximately 50,000ºF. The mechanisms that create lightning within a thunderstorm are driven by the frictional forces of both liquid and frozen water particles coming in contact with each other to create a static charge. Thus, it follows that if thunderstorms are likely to become more powerful and the atmosphere will be able to hold more moisture, then greater frictional forces are expected to occur as well. An increase in the power (amperage) of lightning could lead to a situation where lightning protection could be over-powered and damage may result.

3.4.2 OBSERVED AND PROJECTED ICE STORMS AND WINTER STORMS

In order to develop an understanding of the historic likelihood of an ice storm or what is classified as winter weather in this portion of Ontario, the criteria for these events were based on the criteria for public weather alerts as defined by Environmental Canada. An ice storm (freezing rain) becomes a hazard event when it poses a threat to infrastructure or property; or when the event lasts for two hours or more. A winter storm is classified as a storm that has 25cm or more of snowfall in a 24-hour period or a storm which is combined with other cold weather precipitation types such as freezing rain, strong winds, blowing snow and/or extreme cold.

Figure 20 shows the anatomy of an ice storm as a result of freezing rain. This graphic provides an understanding of the atmospheric conditions to that can produce an ice storm over this portion of Ontario so that projected changes in these atmospheric conditions can have some context on their impacts on changes in ice storms over the region. Ice storms, particularly ice storms that cause damage to infrastructure, are a rare event in Stratford. Consequently, winter storm events that involve heavy snowfall (>=25cm/day) are occurring on average about once every 4 years (approximately 27 heavy snowfall events 1900-2006) in Stratford. **Figure 21** shows a graph of the annual daily maximum snowfall in

Stratford from 1900-2006 (Stratford WWTP Meteorological reporting station), which identifies a general downward trend in this parameter. **Figure 22**, a graph of annual snowfall in Stratford 1900-2006 shows an overall increasing trend in annual snowfall for the entire period of record, however, it's easy to see the highly variable yet decreasing totals in annual snowfall since around 1980.



CARL NEUSTAEDTER/The Globe and Mail

Figure 20. The anatomy of an ice storm based on the extreme ice storm event of January 1998.

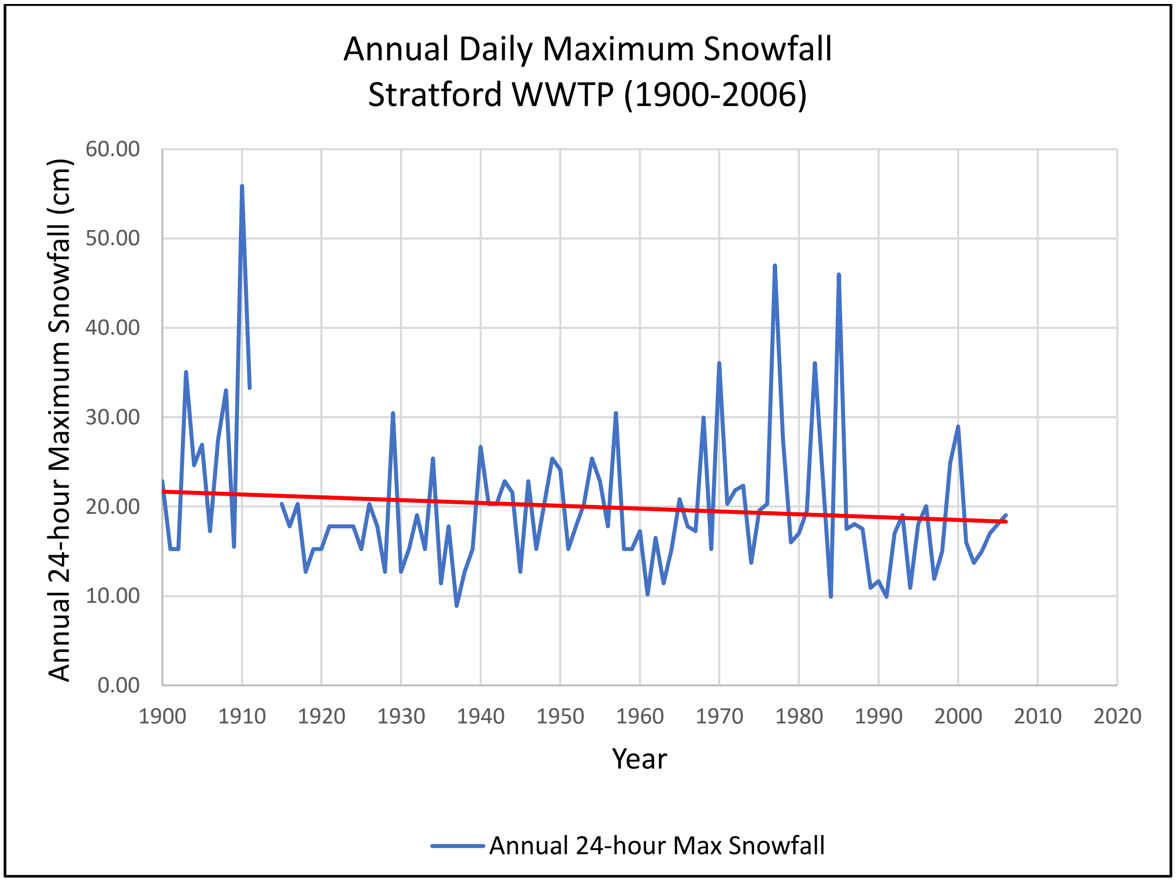


Figure 21. Annual daily maximum snowfall in Stratford (1900-2006). Red line is the long-term climatic trend. Source: NCEI n.d.

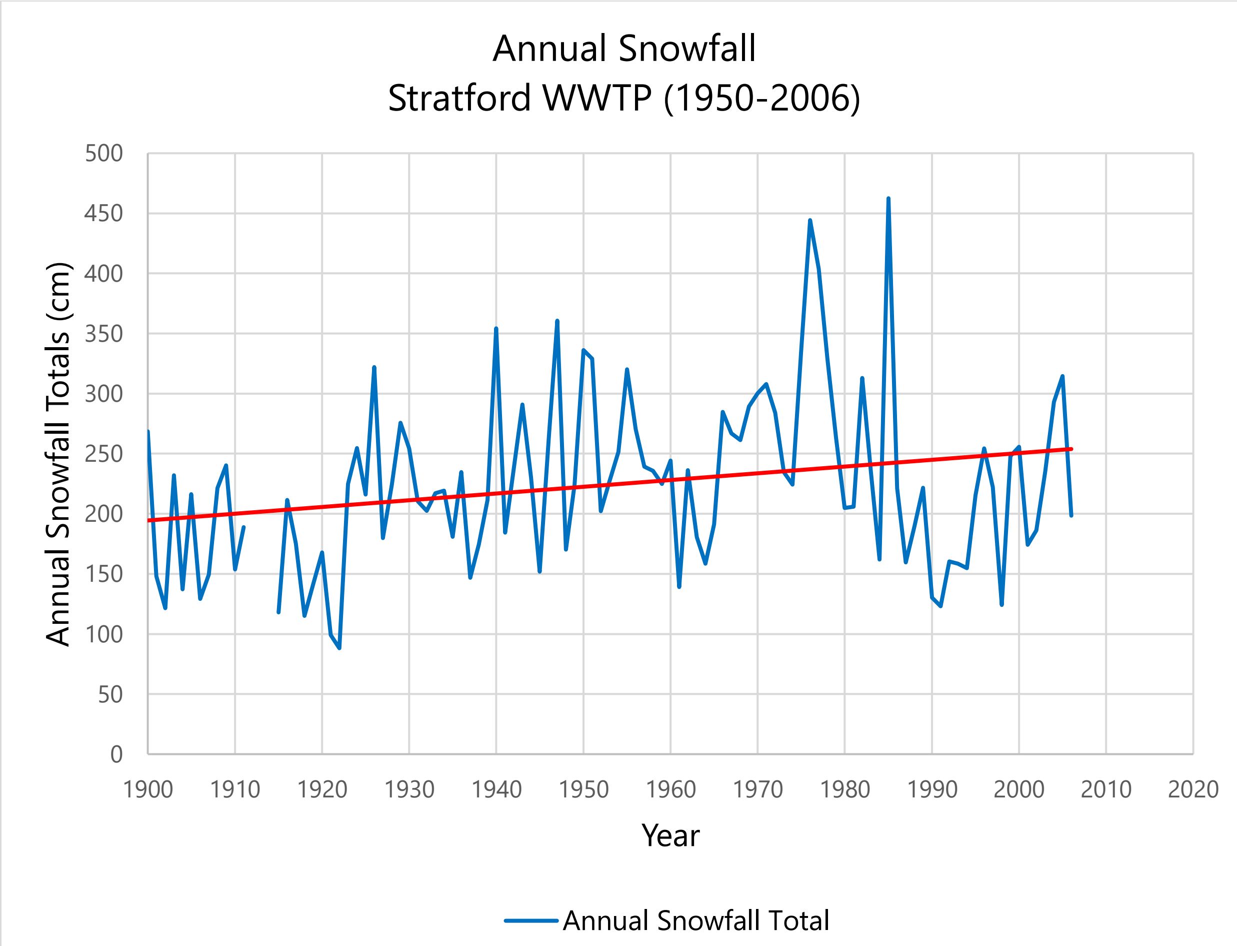


Figure 22. Annual cumulative snowfall for Stratford (1900-2006). Red line is the trend for the entire period of record. Source: NCEI n.d.

3.4.3 POTENTIAL SYSTEM IMPACTS DUE TO CHANGES IN TORNADOES, LIGHTNING, AND SEVERE THUNDERSTORMS

Climate changes in air temperature and precipitation are expected to lead to changes in extreme weather events in Stratford and Perth County. While these events already have the capacity to impact transportation operations and infrastructure, projected changes in the magnitude and intensity of extreme storms are expected to increase the risk of these hazards impacting the system. Increases in the frequency and magnitude of tornadic activity are expected in concert with increases in the frequency and intensity of lightning as a result of severe thunderstorms. Both of these hazards are expected to have a significant impact on the electrical grid that will supply power to the zero emissions facilities and system components. Additionally, the severe thunderstorms that can result in tornadoes and episodes of cloud-to-ground lightning are expected to be accompanied by short-duration, high-intensity precipitation. Thus, the impacts of the increase in convective thunderstorms can be expected systemwide.

4 RISKS ASSOCIATED WITH CLIMATE CHANGE IMPACTS AND SYSTEM VULNERABILITIES

The potential changes in climate parameters described in the previous sections for parameters such as changes in air temperature and extreme storms are generally applicable to this entire portion of Ontario's transit infrastructure and specifically applicable to the Zero Emissions Transit program with impacts being highly dependent on infrastructure design and condition. While hydrologic and hydraulic modeling of these future precipitation events would produce the most definitive quantification of the likely spatial extent of future floods as a result of increased precipitation intensities and likelihood of rain-on-snow events, this study utilized the percentage increase in future precipitation as a proxy for increases in flood extent for the region.

As per the ZETF GHG+ PLUS Guidance Modules, a risk analysis of the system must identify the magnitude of the consequences of an event and its likelihood of occurring (likelihood X consequences = risk). **Table 10** provides estimates for the likelihood of climate impacts and **Table 11** provides estimates for the consequences of those impacts. In each of these tables, the different levels of likelihood and consequences applied to each climate event are scored from 1 to 5 and totaled for each category of event. Likelihood scores for chronic or cumulative event occurrences are not scored. Risk represents the product of likelihood and consequences. **Table 12** provides an overall *relative* risk ranking for the Stratford Zero Emission Transit (SZET) system based on this analysis of current and future climate risk. This relative risk ranking provides a prioritization of climate threats to the SZET system. An accounting of the anticipated risks to specific assets within the system will be detailed in Section 5 (Risk Treatment and Adaptation).

Table 10. Likelihood of climate impacts for Stratford due to changes in climate events.

	Likelihood					
Probability Range/ Type of Event	**Very Low**	**Low**	**Moderate**	**High**	**Very High**	**Total**
Event(s)	**Not Likely to occur in the next 50 years (1)**	**Likely to occur once between 30 and 50 years (2)**	**Likely to occur once between 10 and 30 years (3)**	**Likely to occur at least once a decade (4)**	**Likely to occur once or more annually (5)**	**Score**
Stream/River flooding		X	X	X	X	14
Extreme Short-Duration Precipitation		X	X	X		9
Stormwater flooding		X	X	X	X	14
Ext. Annual Precipitation		X	X	X		9
Tornadoes		X	X	X	X	14
Extreme Heat		X	X	X	X	14
Severe Thunderstorms		X	X	X		9
Ice/Winter Storms			X	X		7
Lightning		X	X	X	X	14
On-going / Cumulative Occurrence	**Not likely to become critical/ beneficial in period**	**Likely to become critical in 30-50 years**	**Likely to become critical in 10-30 years**	**Likely to become critical in a decade**	**Will become critical within several years**	
Heat deformation		X	X	X		
Freeze-thaw Cycles		X	X	X	X	

Table 11. Consequences of climate impacts for Stratford due to changes in climate events.

Consequences													
		People				Economic			Environment				Total
Event	Factor Degree	Health & Safety	Displacement	Loss of Livelihood	Reputation	Infrastructure Damage	Financial Impact on Proponent	Financial Impact on Stakeholders	Air	Water	Land	Eco-system	Score
Stream/River Flooding	Very Low (1)												
	Low (2)								X				
	Moderate (3)												
	High (4)	X	X	X	X	X					X	X	
	Very High (5)						X	X		X			45
Extreme Short-Duration Precipitation	Very Low (1)												
	Low (2)								X				
	Moderate (3)				X						X	X	
	High (4)	X	X	X		X							
	Very High (5)						X	X		X			42
Urban Stormwater Flooding	Very Low (1)												
	Low (2)								X				
	Moderate (3)		X				X	X					
	High (4)	X		X						X	X	X	
	Very High (5)				X	X							41
Extreme Annual Precipitation	Very Low (1)												
	Low (2)				X				X				
	Moderate (3)	X		X									
	High (4)		X			X	X	X			X	X	
	Very High (5)									X			39
Tornadoes	Very Low (1)								X				
	Low (2)									X			
	Moderate (3)				X						X	X	
	High (4)		X				X	X					
	Very High (5)	X		X		X							39
Day with Extreme Heat (>=30˚C)	Very Low (1)												
	Low (2)		X	X							X		
	Moderate (3)				X	X	X	X					
	High (4)								X	X			
	Very High (5)	X										X	38
Severe Thunderstorms	Very Low (1)												
	Low (2)								X				
	Moderate (3)		X	X	X		X	X		X	X	X	
	High (4)					X							
	Very High (5)	X											35
Ice/Winter Storms	Very Low (1)												
	Low (2)								X				
	Moderate (3)		X	X	X		X	X		X	X	X	
	High (4)	X				X							
	Very High (5)												34
Lightning	Very Low (1)								X	X			
	Low (2)		X		X						X	X	
	Moderate (3)			X			X	X					
	High (4)					X							
	Very High (5)	X											28

Table 12. Risk scoring for each climate hazard/event.

Event(s)	Likelihood Score	Consequences Score	Risk (Likelihood X Consequences)
Stream/River flooding	14	45	630
Extreme Short-Duration Precipitation	9	42	378
Stormwater flooding	14	41	574
Ext. Annual Precipitation	9	39	351
Tornadoes	14	39	546
Extreme Heat	14	38	532
Severe Thunderstorms	9	35	315
Ice/Winter Storms	7	34	238
Lightning	14	28	392

5 RISK TREATMENT AND ADAPTATION

As per the ZETF guidance, after the climate risks are identified and quantified, risk treatments and adaptation measures are to be recommended. The following sections pertain to potential resilient solutions to the aforementioned climate hazards that may lead to adaptive measures for the Stratford system.

5.1 EXTREME HEAT AND HEAT WAVES

As identified in the previous climate analysis, extreme heat and heat waves are expected to increase within the Stratford service region over the coming decades. Changes in air temperatures have the biggest impact on the human condition rather than the infrastructure itself, so mitigating the impacts of these changes will first be about addressing the bus station/bus stop/bus maintenance facility/bus storage facility exposure to extreme heat. Increasing available shade, whether through the planting of trees or cover structures is the simplest and least costly remedy for these extreme heat days. Additionally, there is expected to be an increase in the need for air conditioning in bus stations and within the buses themselves. This is very important when it comes to the use of energy to produce air conditioning on zero emissions buses. It will be important to “build-in” the need for increased energy load on the buses due to the need for air conditioning.

Although extreme heat will have the biggest impact on the human condition and operations, there is the potential at the more distant future time scales to produce air temperatures hot enough to deform metal structures and asphalt surfaces. This is the very extreme case and probably not expected prior to the year

2035 but may need to become a component of current decision making when it comes to materials to be used for design or redesign.

A tertiary concern that needs to be addressed or adapted to is the logistical issue of power availability. If extreme heat or a multi-day heat waves is impacting Stratford, the load on the power grid could conceivably produce reduced power availability (i.e. brown-out) for the bus system. Many transit agencies within North America are currently dealing with this issue through the use of renewable energy alternatives and the installation of more robust generator backups (i.e. power generation capabilities and fuel storage).

5.2 EXTREME SHORT-DURATION PRECIPITATION AND URBAN STREAM FLOODING

Although the observed trend doesn't show a significant increase in short-duration, high-intensity storms, the projected trends do. These increasing heavy precipitation events are expected to temporally disrupt egress along roads/bus lines, particularly in the lowest elevations of the city near the Avon River. Recommendations for adaptation to such events is the same for Stratford as it is for stormwater in the entire region; a stormwater system capacity assessment should be undertaken to identify system vulnerabilities and assess future needs as a result of these types of events.

Figure 23 shows the rail lines and bus routes within the city. As with the increase in annual precipitation in Section 5.3, extreme short-duration precipitation events in the future are likely to overtax the present-day drainage systems in the city near where these rail lines and bus routes cross urban streams, the Avon River, and any low-lying flood prone area in the city. It is recommended stormwater and riverine hydrologic and hydraulic modeling be performed using climate projections for future storm scenarios to determine at-risk locations.

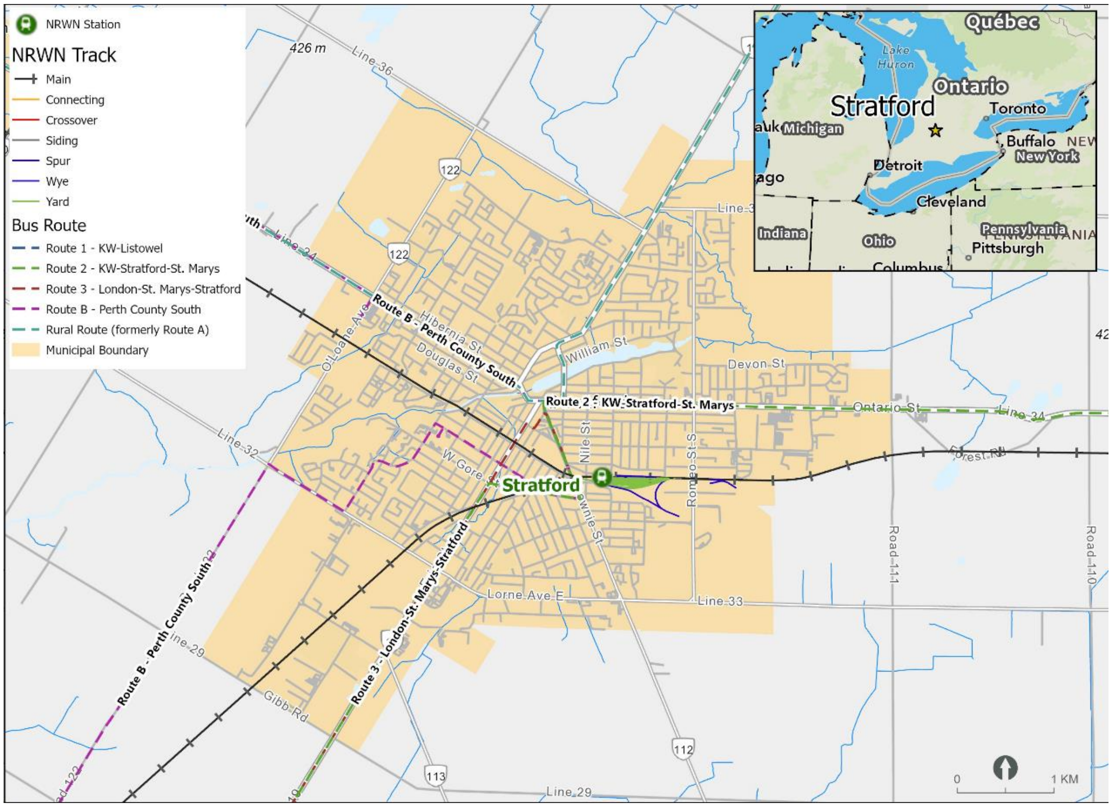


Figure 23. NRWN rail lines and bus routes through the City of Stratford, ON.

5.3 EXTREME ANNUAL PRECIPITATION

As noted in both the analysis of observed annual precipitation and projected trends, increasing precipitation will make for reduced ground stability (i.e. road deformation, sink holes, pot holes, etc.) in the future. Increased annual precipitation can make for increased groundwater levels which lead to ground instability under roads and foundations. This may point to a need for dewatering of locations prone to ground destabilization in wet weather.

5.4 TORNADOES, LIGHTNING, SEVERE THUNDERSTORMS

The anticipated increase in convective activity as a result of a warming environment is expected to produce an increase in the number and intensity of tornadoes, the frequency and magnitude of lightning, and the heavy precipitation, wind and hail associated with severe thunderstorms.

As noted in the previous section, the number of tornadoes and their associated intensity is expected to increase at future time scales. While the need for tornado shelters is already apparent in the region, it is recommended that a more robust response and recovery methodology through asset management be investigated. These events are capable of producing catastrophic damage and are particularly damaging to power delivery infrastructure. Planning for mitigation often becomes a discussion of only response and recover rather than hardening.

The anticipated increase in the frequency and magnitude of lightning points to the need for a lightning protection that is appropriately sized and focused toward protecting the electrical grid for Stratford transit facilities. Due to the anticipated increase in the strength of severe thunderstorms, it is recommended that a thorough inspection of any infrastructure that could become airborne should be undertaken and remediation actions implemented. The Derecho wind event in the northern plains of the U.S. on May 12th, 2022, which had embedded areas of straight-line winds of 130 to 160 kmh, could be used as a benchmark for redesign and retrofitting of structures that could become airborne.

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