Impact of Urbanization on the Nature of Precipitation at Toronto, Ontario, Canada

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ABSTRACT: A newly developed precipitation phase metric is used to detect the impact of urbanization on the nature of precipitation at Toronto, Ontario, Canada, by contrasting the relative amounts of rain and snow. A total of 162 years of observed precipitation data were analyzed to classify the nature of winter-season precipitation for the city of Toronto. In addition, shorter records were examined for nearby climate stations in less-urbanized areas in and near Toronto. For Toronto, all winters from 1849 to 2010 as well as three climate normal periods (1961–90, 1971–2000, and 1981–2010) were thus categorized for the Toronto climate record. The results show that Toronto winters have become increasingly “rainy” across these time periods in a statistically significant fashion, consistent with a warming climate. Toronto was compared with the other less urban sites to tease out the impacts of the urban heat island from larger-scale warming. This yielded an estimate of 19%–27% of the Toronto shift in precipitation type (from snow to rain) that can be attributed to urbanization for coincident time periods. Other regions characterized by similar climates and urbanization with temperatures near the freezing point are likely to experience similar climatic changes expressed as a change in the phase of winter-season precipitation.

KEYWORDS: Anthropogenic effects/forcing; Climate change; Climate variability; Freezing precipitation; Hydrology; Snow cover

1. Introduction

What does it mean for a winter to be “snowy”? In the scientific literature, several metrics of “snowiness” exist (Hewer and Gough 2020). These include the direct measurement of snowfall, that is, the measurement of precipitation that is intercepted at Earth’s surface in the form of snow (Groisman and Easterling 1994; Ueda et al. 2015); snow cover, that is, the spatial extent of snow that remains as ground cover (Farmer et al. 2009; Fernandes et al. 2014); and snow depth, that is, the thickness of the snow on the ground (Hong and Ye 2014). In addition, derived metrics such as the fraction of total precipitation that fell as snow and the fraction of precipitation days that recorded snow are used (Hewer and Gough 2020). In this work, the ratio of snow to rain, introduced as a new metric, precipitation phase index (PPI), by Hewer and Gough (2020), is used to assess factors affecting local climate change. In particular, “snowiness” was contrasted with “raininess,” where months in which there was more rain than snow were not considered to be snowy even if the amount of snow was substantial. In this sense, we take a two-dimensional variable, precipitation, that can vary in quantity and quality (phase of water—rain or snow) and focus on the latter as the metric of change. Others have used a snow-to-rain ratio metric. Hamlet et al. (2019) examined the nature of climate change for the state of Indiana and projected a reduction of the snow-to-rain ratio due increasing temperatures. Lapp et al. (2005), Wipf et al. (2009), Huang et al. (2018), and Dong et al. (2019) indicated that a reduced

snow-to-rain ratio was an important factor in snowmelt and runoff in alpine environments. Berghuijs et al. (2014) used a snow-to-rain ratio that was deduced using a temperature formula in order to disaggregate precipitation into rainfall and snowfall. Hewer and Gough (2020) found the variations of the PPI were significantly linked to variations in winter maximum temperature of the day.

An urban bias does exist in the climate record that is reflective of the proximity of climate stations to populated centers (Seto and Shepherd 2009). The urban bias has been estimated to range from negligible to substantial. Hansen et al. (2001) and Peterson (2003) in an examination of contiguous American climate stations indicate that the urban effect is small or negligible, consistent with Jones et al. (1990). At the other end of the spectrum, Scafetta and Ouyang (2019) used a temperature analysis to estimate that up to 50% of the warming in Chinese cities since the 1940s is the result of uncorrected urbanization bias. However, this is at odds with Li et al. (2004) who found the urbanization effect to be much smaller (less than 10%) than background change in regional temperatures in the period from 1954 to 2001. Jin et al. (2018) use a different method to estimate that urbanization accounts for 18% of the overall warming in China from 1961 to 2012.

In this work we use the newly created ratio PPI (Hewer and Gough 2020), from observations of rainfall and snowfall, to detect subtle shifts as a result of environmental change—both urbanization and larger-scale regional change. Johnson and Shepherd (2018) have examined the impact of urbanization on varying forms of precipitation by creating a 21-yr climatology of precipitation affecting urban areas in the eastern United States. They found a discernible melting shift in precipitation with proximity to urban centers.

a. Climate of Toronto

The site description of Toronto, Ontario, Canada, and its climate are fully described in Gough et al. (2014). Part of that

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FIG. 1. Location of climate stations: Albion Field Station, Toronto Pearson Airport, Toronto, Toronto Island Airport, and Trenton Airport.

description is adapted here for the readers' convenience. Toronto is Canada's largest urban area and is situated on the northwest shore of Lake Ontario (43.7°N, 79.4°W) (Tam and Gough 2012), one of the Laurentian Great Lakes (Hewer and Gough 2019). The city is located in southern Ontario, a transition zone between polar and tropical air masses, spawning midlatitude cyclones and considerable weather variation (Angel and Isard 1998; Gough et al. 2002; Gough 2008; Anderson et al. 2018). These cyclones are common in the midlatitudes and have a significant impact on climate variability (Gough 2008; Tam and Gough 2012; Anderson et al. 2018). Toronto has a humid, continental climate with warm to hot summers, cold winters with snow, no dry seasons, and a wide range in annual temperatures, modified by the presence of Lake Ontario (Scott and Huff 1996; Leathers and Ellis 1996; Gough and Rosanov 2001; Ellis and Johnson 2004; Hewer and Gough 2019). From 1849 to 2010, Toronto has had an average annual snowfall of 105 cm and a median value of 104 cm, ranging from 28 cm in 1932 to 223 cm in 1873. Of the top 10 highest snow accumulation years, only one has occurred since 1950, that is, 1999 (Gough 2000; Fassnacht et al. 2004). For the climatological winter months of December, January, and February the average aggregate rainfall is 89 mm, with a median of 81 mm. The rainfall ranges from 12.7 mm in 1921 to 206.1 mm in 1891.

As a result of urbanization and larger-scale warming, Toronto's climate has been changing (Munn et al. 1969; Gough and Rosanov 2001; Mohsin and Gough 2010, 2012; Gough and Sokappadu 2016; Anderson and Gough 2017). Urbanization in Toronto has produced a well-established heat island with the downtown core on average being warmer than rural counterparts by about 3°C with some seasonal variation (Mohsin and Gough 2012). Mohsin and Gough (2010) using temperature

data estimate that the warming experienced since 1840 is at least 30% attributable to the evolving heat island and the balance to wider spread regional warming. The impact on the winter season has been detected in a number of studies (Ho and Gough 2006; Mohsin and Gough 2014; Gough et al. 2014; Allen et al. 2015; Anderson and Gough 2017). Climate change projections indicate that the climate of Toronto will continue to warm (Mohsin and Gough 2014) with fewer cold extremes, including fewer extreme cold weather alerts (Gough et al. 2014) and less Lake Ontario ice coverage (Hewer and Gough 2019).

Toronto has experienced considerable urbanization during the period of climate data collection (from 1840 to present). The data were collected at the University of Toronto beginning in 1840 when Toronto had a population of less than 50 000 people (Gough 2020). The University of Toronto location was at the northern fringe of the municipality. The population has since grown to over 2 500 000 by 2001 and the urban sprawl has expanded beyond the city boundaries to a more generalized urban sprawl extending along the Lake Ontario shoreline from Oshawa to Hamilton (Fig. 1). Gough (2020) examined this climate record in detail and concluded that from the 1840s to the 1860s the climate station data from the University of Toronto station was consistent with a rural station during a time when the population was less than 65 000. However, from the 1870s to 1890s as Toronto grew in population to 100 000 and beyond, the thermal signature was that of a peri-urban climate (i.e., a climate that is characteristic of the boundary between urban and rural locations), consistent with expansion of the city to the university grounds and beyond (Gough 2020). This characteristic subsided in the following decades as Toronto reached a million inhabitants by the 1930s and the University of Toronto climate station represented the center of a large

TABLE 1. List of climate stations.

Station	Lat	Lon	Duration	Landscape
Toronto	43.67°N	79.40°W	1849–2010	Urban
Toronto Island Airport	43.63°N	79.40°W	1958–94	Coastal
Toronto Pearson Airport	43.68°N	79.63°W	1954–2010	Peri-urban
Albion Field Station	43.92°N	79.83°W	1970–2001	Rural
Trenton Airport	44.12°N	77.53°W	1954–2010	Rural

urban landscape. Similar but delayed behavior was detected at Toronto Pearson International Airport, a location 30 km to the west of the University of Toronto at the edge of the City of Toronto. Peri-urban characteristics had shifted to this location by the 1960s.

b. Research objectives

In this work, a newly developed metric of classifying winter-season precipitation, PPI (Hewer and Gough 2020), is used to revisit the nature of the precipitation climatology of Toronto and to detect the influence of urbanization on this record. The basis of the new metric is not the absolute amount of snowfall or rainfall (quantity) but rather the phase of the precipitation (quality), focusing on the relative amounts of snow and rain within given time periods. To compare snow with rain, snow is converted into rain using a 10:1 ratio that is typically used in Canada, although we recognize that this ratio varies depending on snow type and ambient temperature (Wang et al. 2017). Since snow is measured in centimeters and rain is measured in millimeters, the factor of 10 is captured in the units and a direct comparison of archived data is used. Hewer and Gough (2020) introduced the following four categories. “Very snowy” are years in which each of the months of December, January, and February (the climatological winter) within a given winter had more snow than rain. “Snowy” indicates that two of the three months have a dominant snow/rain ratio. When two of three months are dominated by rain, this is labeled “rainy.” If all three months were dominated by rain, “very rainy” is the designation. This new metric is compared with a ratio generated by pooling all three months and is also compared with absolute snowfall. In addition to the examination of the Toronto data that was begun in Hewer and Gough (2020), four additional climate stations of varying urbanization are analyzed to determine the relative impact of urbanization on the snow/rain dominance. The latter method follows the tradition of pairing urban stations with rural or less-urban stations to assess the thermal impact of urbanization. This methodological approach has been questioned (Mohsin and Gough 2012; Debbage and Shepherd 2015). Mohsin and Gough (2012) found that the magnitude of Toronto’s urban heat island was dependent on the characteristics of the chosen rural stations. Debbage and Shepherd (2015) in examining 50 urban areas in the United States found that urban density and form were key to the magnitude of the urban heat island. Tam et al. (2015), based on Gough (2008), proposed a new method of assessing the thermal impact of urbanization using a day-to-day temperature variability that produced a clear thermal signature that was not dependent on a rural station selection. This has

been applied to Chinese cities (Gough and Hu 2016), Toronto (Anderson et al. 2018), coastal cities (Gough and Shi 2020), and peri-urban landscapes (Gough 2020). However, a corollary precipitation metric has yet to be developed, and thus we rely on the more traditional comparisons of locations of varying urbanization.

2. Data and analysis

a. Data

The snowfall and rainfall data for five climate stations in and around Toronto are used (Table 1; Fig. 1). Toronto data have been collected since 1841, although only data from 1849 to 2010 were used because of missing data in the very early record. In addition to this time series, we also examine three sets of climate normals, 1961–90, 1970–2000, and 1980–2010. These climate normals aggregate climate data by month over each 30-yr period and are often used to establish baseline climate conditions within the study of regional climatic change and for assessing climate change impacts. Snowfall was recorded using a snow gauge, and rainfall was recorded with a rain gauge. The data were collected on the grounds of the Saint George campus of the University of Toronto. However, the weather station was moved several times during this time period. All locations are within 1 km and essentially at the same elevation. Although the movement of the station may influence the total amounts of rainfall and snowfall recorded, it is unlikely that the phase of the precipitation changed as a result of the location changes. The data from the other four climate stations varied in collection periods and were used to compare with Toronto during concurrent time periods. Wang et al. (2017) identifies some systemic instrumentation issues with the measurement of rain and snow. The most significant of these is undercatchment by rain and snow gauges, particularly snow gauges. Homogenized datasets are available from Environment Canada that provide corrections to the measured data. Corrections for snow undercatchment range from 5% to 25%. One station, Toronto, was accessed from the homogenized dataset for comparison with the uncorrected data.

The landscape classifications of these stations are informed by Anderson et al. (2018), Gough (2020), and Gough and Shi (2020). In Anderson et al. (2018), which built on the work of Tam et al. (2015) and Gough and Hu (2016), urban and rural landscapes are distinguished by using a day-to-day temperature variability introduced by Gough (2008) and applied to climate stations in the Toronto region. The day-to-day temperature variability of the maximum temperature of the day is compared with the day-to-day temperature variability minimum

temperature of the day. For urban locations, the maximum temperature variation tends to exceed that of the minimum, and vice versa for rural locations, thus providing a way to identify a station as either rural or urban. In Gough (2020) a related metric that examined the nature of warm-to-cold daily transitions generated a metric that identified climate stations located at the boundary between urban and rural locations, that is, peri-urban landscapes. Gough and Shi (2020) were able to provide a nuanced measure of continentality that is based on the day-to-day variation of the minimum temperature of the day. Using the results of these studies, the stations used in this study can be appropriately classified.

Winter is climatologically defined as consisting of the months of December, January, and February within this region; thus, these months were used in this analysis. However, we acknowledge that snow does fall in other months of the year in Toronto, particularly in the months of November and March, as well as other months, episodically. Yet, on average, all of these other months experience precipitation much more often as rain than snow, being characterized with monthly mean temperatures that are above the freezing point (0°C).

b. Analysis

A snowfall-to-rainfall ratio was calculated for each of the winter months for all of the years spanning from 1849 to 2013 following Hewer and Gough (2020). The Toronto record is remarkably complete, such that no months were omitted because of missing data (Allen et al. 2015), other than those prior to 1849. Each year was binned into four PPI categories: very rainy, rainy, snowy, and very snowy. As noted above, very rainy occurred when all three months had rain dominance and rainy occurred when two of three were dominated by rain. Similarly, very snowy occurred when all three months were dominated by snow and snowy occurred when two of three months were dominated by snow rather than rain. To generate a time series, very snowy was assigned a value of 1, snowy was assigned a value of 2, rainy was assigned a value of 3, and very rainy was assigned a value of 4. In this we differed from Hewer and Gough (2020) who used -3 , -1 , 1 , and 3 to correspond to the same categories. A time series analysis was done to determine if there is a statistically significant change in any of the categories over time. Linear regression analysis was used. All time series were tested for normality using the Shapiro–Wilk test. The time series was tested for autocorrelation. As in Hewer and Gough (2020), no autocorrelation was detected for PPI. We repeat the categorization analysis for one homogenized climate dataset (Toronto).

In addition, the snow and rain data of the three winter months were pooled, and a determination of snowy or rainy was made depending on which of the two dominated in the seasonal aggregate over these three months. This aggregate was compared with the four-category analysis (in which case very rainy and rainy were binned together as were very snowy and snowy). A time series analysis was also done on both records. The metrics that depend on relative amounts of snow and rain were compared with ranking winters according to absolute snowfall (total of snowfall over the three winter months).

To explore the second research objective, the impact of urbanization on snowiness, we examine climate data from four additional nearby stations (Table 1, Fig. 1). These stations are rural (Albion Field Station and Trenton Airport), peri-urban (Toronto Pearson Airport), and coastal (Toronto Island Airport). These landscape assessments are based on Anderson et al. (2018), Gough (2020), and Gough and Shi (2020). To assess the differences between the stations, we do a series of pairwise comparisons. For identical assessments of raininess or snowiness (using the four categories) a value of 0 is assigned; when comparison sites are less rainy or more snowy or they switch from rainy to snowy by one category, a value of 1 is assigned; if they switch by two categories, a value of 2 is assigned; and if they switch by three categories, a value of 3 is assigned. If the comparison site is more rainy or less snowy or switches from snowy to rainy, corresponding negative values are assigned. For a given time series comparison, the positive and negative values are summed and divided by the number of years in the time series to generate a snow-to-rain index (SRI):

$$\text{SRI} = (\sum_N S_+ - \sum_N S_-)/N, \quad (1)$$

where S_+ is the sum of scores above zero, S_- is the absolute value of the sum of scores below zero, and N is the number of years in the time series. The division by the number of years in the time series enables time series of different durations to be compared. If the index is 0, the two time series in general have the same degree of snowiness and raininess (the negative values cancel the positive values). An index value of 1 indicates that on average the comparison site is “snowier” by one category; likewise a score of -1 indicates “rainier” by one category. In general, this corresponds in the first case to a colder station and in the second to a warmer climate record.

The inclusion of the additional stations provides an opportunity to address the research objective of teasing out the relative impacts of urbanization and regional warming. We begin by assuming that the two rural stations, Albion Field Station and Trenton, have little to no urban influences and any net shifts in precipitation types are a result of regional climate change. As indicated by Gough (2020) there is evidence that Trenton may display some peri-urban characteristics. To do this comparison time series of precipitation type were created for Toronto and these two stations. As done in the previous analysis, very snowy was assigned a value of 1, snowy was assigned a value of 2, rainy was assigned a value of 3, and very rainy was assigned a value of 4. For the respective overlap periods, the net trend (slope) was determined. The difference in the slopes for Toronto and the other two stations is an estimate of Toronto urbanization, assuming that regional change is affecting all stations in the same manner. Thus, taking a ratio of the difference and the Toronto slope provides the fraction of the changes in Toronto attributable to urbanization.

3. Results and discussion

a. Snow-to-rain ratio categorization

We begin by examining climate normal data for Toronto for three overlapping time periods: 1961–90, 1971–2000,

TABLE 2. Categorization of winter precipitation using climate normal data for 1961–90, 1971–2000, and 1981–2010. The snow-to-rain ratio is calculated for each month (December, January, and February) of the three normal periods.

	1961–90	1971–2000	1981–2010
December	0.76	0.76	0.63
January	1.56	1.31	1.28
February	1.13	1.02	0.91
Monthly	Snowy	Snowy	Rainy
Aggregate	Snowy	Rainy	Rainy

and 1981–2010. For each of the winter months (December, January, February) for the three sets of normals we calculate the snow-to-rain ratio. These ratios are reported in Table 2. The winters are assessed in two ways. First, a monthly analysis is done as described in section 2b. For 1961–90 two of the three winter months are above one (snowy) and one is below one (rainy) and thus the winter season for this normal period is deemed snowy. Similarly, for 1971–2000, the winter season is also deemed snowy but

for the most recent normal period, 1981–2010, the winter shifts to rainy. The change came in the month of February that switched from snowy to rainy, joining December in this category. Binning the rain and snow data over the three months allows for an aggregate winter analysis. In this case, the labeling is the same for the 1961–90 (snowy) and 1981–2010 (rainy) but 1971–2000 shifts to rainy, suggesting that the less dominant snow in January and February fail to dominate the rains of December.

In Table 3, the results of the categorization of each year from 1849 to 2010 in one of four categories—very snowy, snowy, rainy, and very rainy—on the basis of the snow-to-rain ratio for each of the three winter months (December, January, and February). Of these years there are 27 very snowy years, 69 snowy years, 55 rainy years, and 11 very rainy years. Thus, winter precipitation in Toronto over this time period has been snow dominant (96 years for snow and 66 years for rain). We now split the record in half, before and after 1929 (the median year). For 1929 and before there were 54 either snowy or very snowy years and 27 rainy or very rainy years. In contrast, after 1929 the numbers were 41 and 40, respectively, a substantial reduction in snow-dominant winters in the latter part of the

TABLE 3. Categorization of each year from 1849 to 2013 into the four categories: very snowy (labeled *snowy*), snowy, rainy, and very rainy (labeled *rainy*).

Year	Category	Year	Category	Year	Category	Year	Category	Year	Category
1849	Rainy	1882	<i>Rainy</i>	1915	Snowy	1948	<i>Snowy</i>	1981	Rainy
1850	Snowy	1883	<i>Snowy</i>	1916	Snowy	1949	Rainy	1982	Snowy
1851	Rainy	1884	<i>Snowy</i>	1917	<i>Snowy</i>	1950	Rainy	1983	<i>Rainy</i>
1852	Snowy	1885	Rainy	1918	Snowy	1951	<i>Rainy</i>	1984	Snowy
1853	Snowy	1886	Rainy	1919	<i>Rainy</i>	1952	Snowy	1985	Snowy
1854	Snowy	1887	<i>Snowy</i>	1920	<i>Snowy</i>	1953	Rainy	1986	<i>Snowy</i>
1855	<i>Snowy</i>	1888	Rainy	1921	Snowy	1954	Snowy	1987	Rainy
1856	<i>Snowy</i>	1889	Snowy	1922	Rainy	1955	Snowy	1988	Rainy
1857	Rainy	1890	<i>Rainy</i>	1923	<i>Snowy</i>	1956	<i>Snowy</i>	1989	Rainy
1858	Rainy	1891	Rainy	1924	Snowy	1957	Snowy	1990	Rainy
1859	Snowy	1892	Snowy	1925	Rainy	1958	Rainy	1991	Snowy
1860	<i>Snowy</i>	1893	Snowy	1926	<i>Snowy</i>	1959	Snowy	1992	Rainy
1861	Snowy	1894	Rainy	1927	<i>Snowy</i>	1960	Snowy	1993	Snowy
1862	<i>Snowy</i>	1895	Snowy	1928	<i>Rainy</i>	1961	Snowy	1994	Snowy
1863	Snowy	1896	Snowy	1929	Rainy	1962	Rainy	1995	Rainy
1864	Snowy	1897	Snowy	1930	Rainy	1963	Snowy	1996	Rainy
1865	<i>Snowy</i>	1898	Rainy	1931	<i>Snowy</i>	1964	Snowy	1997	Rainy
1866	Snowy	1899	Rainy	1932	<i>Rainy</i>	1965	Rainy	1998	<i>Rainy</i>
1867	Snowy	1900	Rainy	1933	<i>Rainy</i>	1966	Rainy	1999	Rainy
1868	Snowy	1901	Snowy	1934	Snowy	1967	Snowy	2000	Snowy
1869	<i>Snowy</i>	1902	Rainy	1935	Snowy	1968	<i>Rainy</i>	2001	Rainy
1870	Rainy	1903	Rainy	1936	<i>Snowy</i>	1969	Snowy	2002	Rainy
1871	Snowy	1904	Snowy	1937	<i>Rainy</i>	1970	<i>Snowy</i>	2003	Snowy
1872	<i>Snowy</i>	1905	Snowy	1938	Snowy	1971	Snowy	2004	Snowy
1873	<i>Snowy</i>	1906	<i>Rainy</i>	1939	<i>Snowy</i>	1972	Snowy	2005	Rainy
1874	Snowy	1907	Rainy	1940	Rainy	1973	Rainy	2006	Rainy
1875	<i>Snowy</i>	1908	Snowy	1941	Snowy	1974	Snowy	2007	Rainy
1876	Snowy	1909	Snowy	1942	Rainy	1975	Rainy	2008	Snowy
1877	<i>Snowy</i>	1910	Snowy	1943	Rainy	1976	Snowy	2009	Snowy
1878	Rainy	1911	Snowy	1944	Rainy	1977	Snowy	2010	Rainy
1879	Snowy	1912	Snowy	1945	<i>Snowy</i>	1978	Snowy		
1880	Rainy	1913	Rainy	1946	Snowy	1979	Rainy		
1881	Snowy	1914	<i>Snowy</i>	1947	Snowy	1980	Rainy		

record consistent with the climate normal analysis. If we look at the extremes before 1929, there were 19 very snowy years and 5 very rainy years, but after 1929 these changed to 7 and 6, respectively. We also note that in last 23 years of the record (1987–2010) there has been only one very rainy year (1998) and no very snowy years. We repeated the analysis for the homogenized Toronto climate dataset. Since the greatest adjustment was the increase in snowfall due to undercatchment issues with the instrumentation, the homogenized data tended to be more snowy, with a shift of 6% of the years from rainy to snowy relative to the raw data. We opt to use the raw data for all five stations for the sake of consistency of the intercomparison while acknowledging for all stations there may be an underestimate of “snowiness” due to instrumentation undercatchment.

b. Comparison with aggregate winter analysis

We now compare the characterizing of winter precipitation using monthly snow-to-rain ratios with a snow-to-rain ratio using the aggregated snow and rain data summed over the three months. For this analysis the results are binary, either snowy or rainy depending on whether the ratio is above or below 1, respectively. For comparison with the monthly analysis, very snowy and snowy are binned together as being snowy; and very rainy and rainy are binned together as being rainy. In direct comparison, 126 years are categorized in the same way, but 36 years are not. This typically occurs when the precipitation of one month dominates the overall precipitation of that entire winter season. For example, 1999 was characterized by the monthly method as rainy but in the aggregate was labeled as snowy. This was a result of both December and February being dominated by rain but January experiencing extremely large snowfall (Gough 2000). In 2008, the opposite occurred with December and January being snowy and February experiencing very heavy rains. Thus, the monthly analysis deemed that winter was snowy, but the aggregate categorized it as rainy. Overall, the aggregate analysis had two fewer rainy years.

To examine the temporal trends in the data for these two methods, we count the number of rainy and snowy years per decade and plot these in Figs. 2a and 2b, for both the monthly and aggregate methods, respectively. The snowiness of Toronto's winters is declining (blue) and the raininess is increasing (red). In both cases, the trends are statistically significant, with p values less than 0.05 for all trends. The monthly analysis suggests that the shift toward to raininess is occurring at a faster rate, a nuance that is obscured in the aggregate analysis.

c. Comparison with absolute snowfall

In Table 4, the years from 1849 to 2010 are ranked by absolute snowfall (sum of December, January, and February) from highest to lowest. Numbers in *italics* indicate those years identified as very snowy and snowy and numbers in upright font indicate those identified as very rainy and rainy. Numbers in boldface indicate either very snowy or very rainy. The first eight years correspond as expected as snowy, with four of these very snowy, and the last six years as rainy, with six as very rainy, also as expected. However, the intervening 147 years are a mix of snowy and rainy years. For example, 1999 had the ninth-heaviest snowfall. As noted in the previous section, most of this

FIG. 2. (a) Classification of winter precipitation using (a) monthly data and (b) seasonally aggregated data. The data are aggregated by decade, where the data point for 1960 reflects the aggregate value from 1951 to 1960, etc. Snowy winter counts are in blue, and rainy winter counts are in red.

snow fell during January 1999, although rain dominated December 1998 and February 1999 (Gough 2000). However, in aggregating the three winter months, winter 1999 is identified as snowy. A similar story was true for 1987, the 20th-heaviest snowfall year. At the other end of the spectrum, 1938 was the 10th-rainiest winter. Snow dominated in December 1937 and January 1938, but there were heavy rains in February 1938. The median value is for 1982 (103.7). Above this there are 16 years of 81 years that are labeled rainy (20%). Below the median, 30 years are labeled snowy of 81 (37%). So, in general terms, years with high snowfall are snowy and years with low snowfall are rainy, although there is considerable variability, with snowfall ranging from 80 to 125 cm. We also examined the data as a time series. Snowfall is decreasing over time at a highly statistically significant rate ($p < 0.001$). However, the corresponding rainfall is not changing in a statistically significant fashion.

d. Comparison with nearby locations

We now turn to the additional stations analyzed to reveal the impact of urbanization. For these, four time series were analyzed by month and each year designated as very snowy, snowy, rainy, and very rainy in the same manner as was done for

TABLE 4. Years between 1849 and 2010 are ranked from highest absolute snowfall (cm) to lowest absolute snowfall. Years identified as “snowy” and “very snowy” are in italics and boldface italics, respectively. Years identified as “rainy” and “very rainy” are in upright font and boldface upright font, respectively.

Year	Snow	Year	Snow	Year	Snow	Year	Snow	Year	Snow
1873	223.1	1875	133.6	1889	<i>112.7</i>	1958	91.9	1991	73.0
1871	<i>210.2</i>	1946	<i>130.0</i>	1956	111.3	1955	<i>91.2</i>	1922	72.4
1867	<i>180.5</i>	1915	<i>129.9</i>	1911	<i>110.7</i>	1980	91.1	1878	70.4
1945	168.8	1923	129.3	1935	<i>109.9</i>	1972	<i>89.9</i>	1989	70.2
1860	165.5	1874	<i>128.7</i>	1947	<i>109.9</i>	1859	<i>89.5</i>	1921	<i>69.0</i>
1869	165.4	1898	127.6	1864	<i>109.4</i>	1997	89.4	2002	66.2
1908	<i>165.4</i>	1909	<i>127.5</i>	1993	<i>108.4</i>	1932	88.9	1890	65.4
1861	<i>162.3</i>	1857	126.8	1876	<i>107.3</i>	1954	<i>88.8</i>	1872	65.1
1999	162.2	1943	126.0	1894	107.2	1990	88.6	1986	64.8
1924	<i>160.9</i>	1920	125.7	1964	<i>107.2</i>	1983	88.3	1981	64.7
1887	159.5	1984	<i>125.6</i>	1895	<i>107.1</i>	2007	87.9	1913	63.6
1978	<i>157.2</i>	1900	125.3	1970	106.2	1881	87.8	1897	<i>63.4</i>
1868	<i>155.3</i>	1914	<i>123.7</i>	1992	105.4	1892	<i>87.1</i>	1995	62.4
1852	<i>154.3</i>	1950	123.6	1891	104.9	1888	86.4	1919	62.0
1884	150.1	1870	123.5	1925	104.4	1880	86.4	2000	<i>62.0</i>
1865	149.5	1976	<i>123.3</i>	1982	<i>103.7</i>	1973	86.1	1942	61.9
1971	<i>149.0</i>	1886	122.7	1961	<i>103.6</i>	1901	85.5	1944	59.0
1855	148.8	1854	<i>121.4</i>	1903	103.0	2003	<i>84.6</i>	1962	58.7
1918	<i>147.7</i>	2004	<i>120.7</i>	1853	<i>102.3</i>	1979	84.5	1938	<i>57.8</i>
1987	146.2	1904	<i>120.4</i>	1858	101.3	1957	<i>84.1</i>	1951	53.3
1862	145.8	1905	<i>120.4</i>	1851	101.0	1934	82.9	2010	53.3
1883	145.4	1948	<i>120.3</i>	2001	99.0	1866	<i>82.4</i>	1988	52.2
1893	<i>143.7</i>	1885	119.8	1927	97.8	2005	82.0	1998	51.4
1910	<i>141.8</i>	1930	118.8	1931	97.8	1968	81.4	1975	45.9
1896	<i>141.1</i>	1974	<i>118.2</i>	1985	<i>97.6</i>	1941	81.2	1882	44.8
2009	<i>140.5</i>	1879	<i>117.4</i>	1850	<i>97.4</i>	1969	<i>81.1</i>	1953	44.5
1977	<i>140.2</i>	1959	<i>117.1</i>	2008	96.6	1963	<i>78.0</i>	1928	39.7
1939	136.3	1936	117.0	1907	96.2	1996	77.6	1906	35.8
1952	<i>136.2</i>	1912	<i>116.4</i>	1949	92.4	2006	77.4	1937	33.7
1863	<i>134.6</i>	1916	<i>115.4</i>	1849	94.8	1967	<i>77.1</i>	1933	28.3
1966	134.6	1960	<i>115.3</i>	1917	93.0	1940	76.6		
1856	134.4	1926	114.8	1965	92.9	1929	75.3		
1877	133.9	1902	114.3	1994	<i>92.4</i>	1899	73.7		

Toronto. These stations were compared in a pairwise fashion with Toronto and with each other, calculating the SRI [Eq. (1)] for each comparison. These index values are reported in Table 5. The climate stations listed in the vertical columns represent the comparators. Thus, there is a negative asymmetry in the matrix of reported values. For example, following the row labeled Toronto, we see a negative value for Toronto Island Airport and positive values for the remainder of the stations (Toronto Pearson Airport, Albion Field Station, and Trenton Airport). The negative value for Toronto Island means that it is on average “rainier” or less snowy than Toronto, and the opposite is true for Pearson, Albion, and Trenton. As we move down the table to the next entry, Toronto Island, all other stations are less rainy or snowier than that site, and so on for the rest of the rows. The results presented in Table 5 present a coherent picture of the relative climates of the stations selected. The “rainiest” station is Toronto Island Airport, a climate station located on an island in Lake Ontario. The relative “coastal” climate generated from the proximity to the thermal inertia of Lake Ontario results in the greater dominance of rain relative to the other sites. We note that this

difference is clearly discernible in comparing with Toronto, which is a station less than 4 km away but inland from the lake. Pearson is located in a peri-urban environment on the edge of the metropolitan Toronto area. It is influenced by urban surface modification but does not experience the same heat island as the Toronto station (Gough and Rosanov 2001; Mohsin and Gough 2010; Anderson et al. 2018; Gough 2020). Thus, a positive value of SRI, indicating a less rainy, snowier climate is indicated. The two stations labeled rural, Albion and Trenton, have larger positive SRI values, indicating that the two stations are largely, although not completely in the case of Trenton (Gough 2020), free of the urban effects found at Toronto and Pearson and the lake effect found at Toronto Island. This is illustrated in Fig. 3, a satellite image of the Trenton site and its surroundings. The climate station is located at the airport. The airport is located east of the small city of Trenton. North of the airport is agricultural land. South of the airport is the Bay of Quinte, a narrow body of water that flows into Lake Ontario. The two most dissimilar stations are Toronto Island and Albion with a value of 0.440 followed by the Toronto Island and Trenton comparison (0.405). The small difference between

TABLE 5. SRI comparison of the five climate stations Toronto, Toronto Island Airport, Toronto Pearson Airport, Albion Field Station, and Trenton Airport.

	Toronto	Toronto Island Airport	Toronto Pearson Airport	Albion Field Station	Trenton Airport
Toronto	—	−0.135	0.117	0.188	0.164
Toronto Island Airport	0.135	—	0.324	0.440	0.405
Toronto Pearson Airport	−0.117	−0.324	—	0.156	0.083
Albion Field Station	−0.188	−0.440	−0.156	—	−0.125
Trenton Airport	−0.164	−0.405	−0.083	0.125	—

Albion and Trenton is likely the nascent peri-urban climate at Trenton (Gough 2020). Overall, the SRI values present a matrix of consistency despite the varying periods for the pairwise comparisons, ranging from 61 years for the Toronto–Trenton comparison to 25 years for the Toronto Island–Albion comparison.

e. Estimate of urbanization effect on Toronto's climate

All time series were found to be normally distributed (Shapiro–Wilk test) except Albion Field Station (likely because of its relatively short record), and thus we do not use this station in the linear regression analysis and instead use Trenton as the sole rural station. An estimate of the fraction of urbanization is generated for the Toronto precipitation record by comparing Toronto with Trenton for the period 1954–2010 using the time series generated from very snowy to very rainy (1–4). Comparing the slopes of the time series generated by linear regression, we estimate that 19% of the Toronto slope (Table 6) is attributable to urbanization. Mohsin and Gough (2010) found that the UHI for Toronto has become saturated and is not increasing, particularly since 2000. To explore this finding, we redid the Trenton–Toronto comparison for the time period 1954–2000. This yielded an attribution of 27%, suggesting that the urbanization effect of Toronto was stronger

in the past (before 2000). Last, we used Pearson as the “urban” station and compared it with Trenton, for the period 1954–2010. This yielded a difference of 10%, somewhat lower than the value for the Trenton–Toronto comparison (19% for the same time period), suggesting that Pearson exhibits some characteristics of an urban location, which is a conclusion also drawn by Anderson et al. (2018) and Gough (2020).

4. Conclusions

In this work, we used a newly introduced method for characterizing the snowiness of a winter season on the basis of the nature of the precipitation (Hewer and Gough 2020). Rather than using absolute snowfall, we used a comparative measure examining the snow-to-rain ratio for winter months (December, January, and February). A snow-to-rain ratio was calculated for these three months for each of the years in the Toronto record, 1849–2010, as well as for three climate normal periods: 1961–90, 1971–2000, and 1981–2010. Years were characterized as very snowy if all three of the monthly ratios were snow dominant, snowy if two of three months were snow dominant, rainy if two of three months were rain dominant, and very rainy if all three months were rain dominant. This metric was compared with a

FIG. 3. Trenton climate station located at the Trenton Airport. Scale: 1:80 000.

TABLE 6. Impact of urbanization. The urban, rural, and delta columns report the average rate of change of precipitation categorization (yr^{-1}). A positive value represents a shift from snowiness to raininess.

	Period	Urban (yr^{-1})	Rural (yr^{-1})	Delta (yr^{-1})	Percentage
Trenton – Toronto	1954–2010	0.0158	0.0128	0.0030	19%
Trenton – Toronto	1954–2000	0.0191	0.0141	0.0050	27%
Trenton – Pearson	1954–2010	0.0141	0.0128	0.0014	10%

similar metric in which all three months of snow and rain data were aggregated to create one seasonal value, and then the respective year was labeled either snowy or rainy. Then, this metric was compared with characterizing snowy winters by total snowfall amount (for the three months). To assess the influence of urbanization and regional environmental change, we expanded the analysis to four additional climate stations in and near Toronto (Toronto Island Airport, Toronto Pearson Airport, Albion Field Station, and Trenton Airport).

The use of the traditional measures of snowiness, for example, total snowfall, may be obscuring what is occurring in Toronto. Although total snowfall is decreasing in a statistically significant fashion for Toronto, there is not a corresponding statistically significant increase in rainfall (total precipitation is decreasing). The use of a relative measure of snowiness using a snow-to-rain ratio better captures the nature of changing patterns of winter precipitation in Toronto. For both the monthly and aggregate seasonal snow-to-rain ratios the substantial increase in the raininess of Toronto's winters (coupled with the decrease in snowiness) becomes apparent.

Historically, Toronto has been characterized by snowy winters. This work confirms that this was certainly the case for the early part of Toronto's historical climate record, as also shown in Hewer and Gough (2020). As a result of the enhancement of an urban heat island effect and regional warming resulting from global climatic change, Toronto's climate has been warming (Mohsin and Gough 2010; Anderson and Gough 2017; Hewer and Gough 2019). This work shows how regional climatic change in Toronto is further detectable by measuring changes in the form of winter-season precipitation, from snow to rain. This is consistent with the work of Johnson and Shepherd (2018), who found that proximity to urban centers affected the phase of the hydrometeors, particularly during mixed precipitation events.

The analysis of the additional climate stations was performed using a newly developed comparison metric, the snow-to-rain index, that assessed the difference between and among stations. Rainier conditions were found for the coastal station (Toronto Island Airport) and snowier conditions at the peri-urban (Toronto Pearson Airport) and rural stations (Albion Field Station and Trenton Airport) as expected. This analysis enabled the determination of the relative influence of urbanization and regional climate change on the shifting precipitation of Toronto, yielding an estimate of between 19% and 27% for urbanization using Trenton Airport as the rural station for two different time periods. The range of values is attributable to the time period chosen for the comparison and suggests that the Toronto UHI has become saturated as has been suggested

elsewhere (Mohsin and Gough 2010). The results are consistent with Mohsin and Gough (2010) who generated an estimate of the influence of urbanization of at least 30% based on the temperature record and consistent with other estimates in the literature (e.g., Jin et al. 2018). A comparison of Pearson and Trenton indicated that Pearson has some urban characteristics also consistent with previous work (Anderson et al. 2018; Gough 2020). This novel approach to assessing the impact of urbanization can add to the existing tool kit for such determination, estimates that have been largely dependent on temperature analysis.

Because of Toronto's midlatitude geographic location, and especially because it is one of Canada's more southerly cities, it is susceptible to climatic changes in the form of winter-season precipitation because average winter temperatures are situated near the freezing point (0°C). Since global climate change and the local urban heat island effect have been causing regional warming, the local climate that previously was below the freezing point may now be above the freezing point, causing winter precipitation more frequently to fall as rain rather than snow. Teasing out the impact of urbanization using precipitation phase change and by the intercomparison of sites of varying landscapes is an important tool that could be applied to other locations.

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