ORIGINAL PAPER

Examining past temperature variability in Moosonee, Thunder Bay, and Toronto, Ontario, Canada through a day-to-day variability framework

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Abstract Temperature variability in Moosonee, Thunder Bay, and Toronto, Ontario, Canada is examined through a day-to-day variability framework. Statistical measures used in this study include standard deviation (SD), day-to-day temperature variability (DTD), DTD/SD ratio (*G*), change in day-to-day variability (ΔDTD), and threshold measures of 5°C and 10°C. ΔDTD is the difference between day-to-day change in temperature maximum (DTDtmax) and day-to-day change in temperature minimum (DTDtmin). A distinct seasonal trend is reflected in DTD in Moosonee, Thunder Bay, and Toronto, where ΔDTD is greatest during spring. Monthly ΔDTD averages in Toronto, Thunder Bay, and Moosonee are affected by seasonal variation, the lake effect, and the freeze-up of nearby waterbodies. Yearly averages of ΔDTD have significantly increased over the past recent years in Moosonee and Thunder Bay; a continual increase in climate variability may be detrimental to the subsistence lifestyle of those living in these areas.

1 Introduction

Day-to-day climate variability is an important aspect in understanding how climate variability is experienced. Day-to-day temperatures can have significant implications on various societal aspects such as human health (Saez et al. 1995; Kalkstein 1991) and agriculture (Mearns et al. 1996). Understanding how day-to-day variability has evolved over the last century is of value, as it may have direct impacts on quotidian

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existence. Environmental changes and increased climate variability has affected the subsistence lifestyle of many Aboriginal communities in Canada (Turner and Clifton 2009; Pearce et al. 2010; Furgal and Seguin 2006; Laidler and Gough 2003). Dramatic day-to-day changes in climate have impacted the harvesting lifestyle and well-being of an Aboriginal community in western James Bay (Tam et al. 2011). An increase in unpredictable and dramatic weather conditions have increased the risk to injuries and death in northern Aboriginal communities in Canada (Furgal and Seguin 2006; Tam et al. 2011).

In this study, day-to-day temperature variability is examined in Toronto, Thunder Bay, and Moosonee, Ontario, Canada. This study is part of a larger initiative in assessing the significance of climate variability on both urban and rural Aboriginal populations in Ontario. In this paper, we focused specifically on examining day-to-day temperature variability in the three aforementioned locations, each of which is located in one of Ontario's ecozones: Mixedwood Plains, Boreal Shield, and Hudson Plains. Toronto is located in the Mixedwood Plains, Thunder Bay in the Boreal Shield, and Moosonee in the Hudson Plains. Each of these locations is also located by a large waterbody and in severe mid-latitude climates [(D)—Koeppen system] (Aguado and Burt 2004). Toronto, Thunder Bay, and Moosonee differ in population size and density, latitude, and subclimates (humid continental climate versus subarctic climate). A geographical comparison in climate variability of locations near large waterbodies but at different latitudes and of different size and environments will provide further insight on factors that influence day-to-day temperature variability.

1.1 Toronto, Ontario, Canada

Toronto is a large urban center located in southern Ontario, Canada, on the northwest shore of Lake Ontario (Fig. 1). The

total population of Toronto in 2010 was 5,741,400 people (Statistics Canada 2011a). Toronto is located in the Mixed-wood Plains ecozone of Ontario and in a humid continental climate (Dfb) (Atlas of Canada 2011). The Mixedwood Plains extends along the regions of the lower Great Lakes and St. Lawrence Valley in southern Ontario and Quebec. A humid continental climate is characterized by warm to hot summers, cold winters with snow, no dry seasons, and a wide range in annual temperatures (Aguado and Burt 2004). The humid continental climate, found between 40°N and 55°N, is located in the mid-latitudes. It is located along the polar front zone where polar and tropical air masses converge, thus triggering cyclonic activity and great climate variability (Strahler and Strahler 1984). As cold and warm fronts converge, the warm front is uplifted by the cold front, frequently instigating the formation of cumuliform clouds and precipitation. The passage of fronts have been found to cause noticeable rapid changes in wind direction and speed, temperature, moisture content, and cloud cover (Aguado and Burt 2004). The convergence of fronts may also lead to cyclogenesis. As mid-latitude cyclones are common in the mid-latitudes, they too have a significant impact on day-to-day climate variability (Gough 2008). Based on the Spatial Synoptic Classification system (SSC) (Kalkstein et al. 1996; Sheridan 2002), the main air masses that influenced Toronto's climate from 2000 to 2008 include the Dry Moderate (DM), Moist Polar (MP), Moist Moderate (MM), Dry Polar (DP), and Dry Moderate (DM) air masses, with DM (mild and dry) being the most prominent and MP (cool and humid) being the second-most prominent air masses to affect Toronto (Leung 2010). Toronto's climate normals are described in Table 1. From December to March, daily average temperature normals are below 0°C; and from April to November, daily average temperature normals are above 3°C (Environment Canada 2010).

1.2 Thunder Bay, Ontario, Canada

Thunder Bay is a city located adjacent to Lake Superior in Ontario, Canada (Fig. 1). The total population of Thunder Bay in 2010 was 126,700 people (Statistics Canada 2011a). Thunder Bay is located in the Boreal Shield and, like Toronto, is classified as having a humid continental climate (Atlas of Canada 2011). The Boreal Shield covers northern Saskatchewan through to Newfoundland. The region around Lake Superior, including Thunder Bay, is affected by cold arctic and continental polar air masses in the winter (Assel 1990; Scott and Huff 1996). In the summer, this region is affected by summer Pacific air masses and at times, warm, moist air masses from the Gulf of Mexico (Matheson and Munawar 1978). Climate normals of Thunder Bay are presented in Table 1. Average daily temperature normals remain below 0°C from November to March, and above 2°C from April to October (Environment Canada 2011).

1.3 Moosonee, Ontario, Canada

Moosonee is a rural town located in northern Ontario, Canada, at the southern end of James Bay (Fig. 1). In 2006, the total population of Moosonee was 2,006 people (Statistics Canada 2011b). Moosonee is located in the Hudson Plains, which extends along the regions around the Hudson–James Bay, from northeastern Manitoba to northwestern Quebec. Moosonee is classified as having a subarctic climate (Dfc) (Atlas of Canada 2011), which typically has cooler summer temperatures than humid continental climates, precipitation year-round, and harsh winters. During the winter, mean monthly temperatures may be extremely low, and the length of the season may be long, as "temperatures may remain below freezing level for up to 7 months" (Aguado and Burt 2004). The subarctic climate, ranging from 50°N to 70°N, is predominantly affected by the polar and arctic air masses. More specifically, the James Bay region is predominantly affected by Pacific, maritime tropical, and, as previously mentioned, Arctic air masses (Baldwin et al. 2000; Bryson 1966). In winter, cold arctic air masses and warmer air masses from the south converge over northern Ontario, forming precipitation (Muzik 1982). As a result of thick snow cover, the high albedo from snow causes much incoming shortwave radiation to be reflected back to the atmosphere, leading to very cold temperatures, temperature inversions, and thus very stable atmospheric conditions. During the summer, the subarctic climate region is affected by the convergence of air masses and mid-latitude cyclones moving poleward from the mid-latitudes, causing greater precipitation and greater fluctuations in temperatures to occur (Muzik 1982). Climate normals of Moosonee are described in Table 1. Daily average temperatures from May to October range from 3.4°C to 15.4°C ; and from November to April, daily average temperatures range from −4.7°C to −20.7°C (Environment Canada 2010).

2 Data

Daily temperature minimum (T_{min}) and daily temperature maximum (T_{max}) data from 1959 to 1992 for Moosonee, Thunder Bay and Toronto were obtained through Environment Canada's Climate Data and Information Archive (Environment Canada 2010; 2011). For Moosonee, temperature data were obtained from a weather station located at 51.3°N, 80.7°W (Environment Canada 2012). The Moosonee weather station was first opened in October 1932 (Environment Canada 1983a). The weather station was closed and reopened four times between 1934 and 1939, and, to our knowledge, has stayed open since May 1939 (Environment Canada 1983a). In December 1966, the Moosonee weather station was relocated 1.6 km southwest of its original position (Environment Canada 1983a). For Toronto, temperature data were obtained from a

Fig. 1 Map of study areas: Moosonee (51.3°N, 80.5°W), Thunder Bay (48.4°N, 89.3°W), and Toronto (43.7°N, 79.4°W), Ontario, Canada

weather station located at Toronto Lester B. Pearson International (Int'l) Airport (43.7°N, 79.6°W) (Environment Canada 2012). The Toronto Lester B. Pearson Int'l Airport weather station was first positioned on the airfield in November 1937 (Environment Canada 1983b). The weather station was relocated 200 m southwest of its original location in October 1939, and relocated 2.1 km south of the previous location to its current position in April 1964 (Environment Canada 1983b; Allen 2011). For Thunder Bay, temperature data were obtained

from a weather station located at Thunder Bay Airport (48.4°N, 89.3°W) (Environment Canada 2012). The Thunder Bay Airport weather station was first opened in August 1941 (Environment Canada 1983c). In January 1956, the instrument site was relocated 380 m northeast of its original position, and in June 1963, the instrument site was relocated 60 m northeast of the previous location (Environment Canada 1983c).

Temperature data of the weather stations located at Toronto Lester B. Pearson Int'l Airport and Thunder Bay Airport are

Table 1 Climate normals (1971–2000) of study areas (temperature data retrieved from Environment Canada 2010, 2011)

	Toronto	Thunder Bay	Moosonee
Highest daily T_{max}	26.8°C (August)	24.2°C (July)	22.2°C (July)
Lowest daily T_{min}	−10.5°C (January)	−21.1°C (January)	−27°C (January)
Extreme daily T_{max}	38.3°C (August 25, 1984)	40.3°C (August 7, 1983)	37.8°C (July 3, 1975)
Extreme daily T_{min}	−31.3°C (January 4, 1981)	−41.1°C (January 30, 1951)	−46.7°C (January 15, 1948)

recorded hourly. Climate records indicate that for the Moosonee weather station, temperature data were recorded at every 6 h starting at 0100 h from 1953 to 1954 (Environment Canada 2012). Between 1955 and 1971, temperature data were recorded at every 3 h starting at 0100 h (Environment Canada 2012). Between 1972 and 1976, temperature data were recorded at every hour except at 0300 h and 0400 h; temperature data were also not recorded at 0200 h in 1976 (Environment Canada 2012). Between 1978 and 1992, temperature data were recorded at every 6 h starting at 0100 h, with an additional recording at 0600 h for the years between 1978 and 1981 (Environment Canada 2012). Moosonee climate records indicate that temperature data are missing for several months of the year between 1993 and 1999 (Environment Canada 2012). Thus, the time frame from 1959 to 1992 was chosen due to temporal coincidence of available data for the three study regions.

3 Methodology: statistical measures

Statistical measures used for this study include standard deviation (SD), day-to-day variability (DTD), G, change in day-to-day variability (ΔDTD), and threshold exceedances of 5°C and 10°C. Temporal analyses were performed to illustrate how day-to-day temperature variability of Toronto, Thunder Bay, and Moosonee has evolved over the last century. Linear regression analyses and t tests were applied to assess the significance of the results.

Standard deviation is a traditional measure used to assess variation in a distribution. Though it is commonly used to examine variation from the mean, Gough (2008) found standard deviation to overestimate significant departures from the mean for orderly climates. An alternate statistical measure of variability was introduced by Karl et al. (1995). Karl et al. (1995) performed a large-scale temperature variability assessment on numerous sites located in China, Australia, USA, and the former Soviet Union using a day-to-day statistical measure. In this measure, variation is not measured using the difference from the mean but rather the difference from the previous day and is in essence the variation that is experienced. Gough (2008) applied this day-to-day variability measure on two cities in Canada, and extended the use of this measure by introducing the "DTD/SD ratio", also referred to as "G". Using this ratio, Gough (2008) classified climates as random, orderly, or oscillatory. Gough (2008) found standard deviation to be an appropriate measure of variability only if the climate is random. If the climate is orderly, then day-to-day variability would be the more appropriate measure to use, as it better represents variability that progresses through the days of the month. Gough (2008) and Gough et al. (2012) have found most climate records examined exhibited a degree of orderly behavior.

DTD is based on the absolute difference between two adjacent days (Karl et al. 1995; Gough 2008). DTD is defined as: $\sum_i |T_i - T_{i-1}|/(N-1)$ (Gough 2008). Here | | represents the absolute value, T represents daily temperature (either T_{min} or T_{max}), n is the number of days in a given month, $\sum$ is the sum over all n data elements, and i is the counter that marches through the days in a month.

G is a ratio comparing DTD to SD and is defined as: $G=$ DTD/SD. By calculating G, the type of climate can be determined. Gough (2008) found that when $G < 1$, SD overestimates variability and the climate is orderly. When $G \approx 1$, SD estimates variability similar to that of DTD and the climate is random; and when $G > 1$, SD underestimates variability and the climate is oscillatory (Gough 2008). Gough et al. (2012) elaborated on day-to-day variability and introduced ΔDTD, which measures the difference between day-to-day variability in T_{max} and day-to-day variability in T_{min}. ΔDTD is defined as: ΔDTD=DTDtmax−DTDtmin, where DTDtmax represents the day-to-day change in temperature maximum, and DTDtmin represents the day-to-day change in temperature minimum. A positive result indicates greater variability during the day; a negative result indicates greater variability during the night (Gough et al. 2012). Threshold exceedances are calculated by "counting the number of times within a given month the change of temperature from one day to the next exceeds [a given threshold]" (Gough 2008). The thresholds chosen for this study are 5°C and 10°C.

3.1 Calculating temperature variability for Moosonee, Thunder Bay, and Toronto

Using daily T_{max} data, SD and DTD were calculated for each month commencing from 1959 to the end of 1992. G is calculated for each month, and DTD monthly averages were calculated for the entire time period. This was repeated on daily T_{min} data. ΔDTD was then calculated, and yearly ΔDTD averages were calculated. The total number of day-to-day threshold exceedances of 5°C and 10°C in T_{min} and T_{max} were counted for each month, and the monthly averages were calculated. Time series and linear regression analyses were performed on monthly threshold exceedances and ΔDTD results.

4 Results and discussion

4.1 G values

For Moosonee, Thunder Bay, and Toronto, monthly averages of T_{max} G between 1959 and 1992 are shown in Fig. 2, and monthly averages of T_{min} G are shown in Fig. 3. G monthly averages of T_{max} ($p < 0.05$) and T_{min} ($p < 0.05$) are significantly different between Moosonee and Toronto, and G monthly

averages of T_{min} ($p<0.01$) are significantly different between Thunder Bay and Toronto. The G values for Moosonee, Thunder Bay, and Toronto range between approximately 0.6 and 0.9, indicating that the climates of these three locations are orderly, exhibiting clustering of data or "climate memory". In Moosonee, T_{max} G reflects a higher degree of randomness than T_{min} G throughout the year except in September, October, and February, whereas the T_{min} G results reflect a higher degree of randomness. Similarly in Thunder Bay, T_{max} G reflects a higher degree of randomness than T_{min} G throughout the year except in January, February, October, and November. Toronto's climate reflects a greater degree of orderliness than the climates of Moosonee and Thunder Bay, and unlike Moosonee and Thunder Bay, T_{max} G in Toronto reflects a higher degree of randomness than T_{min} G for all the months of the year. This is consistent with Gough et al. (2012) findings, where DTDtmax was found to have greater variability than DTDtmin due to the mitigating influence of urbanization. Results of t tests analyses on monthly G values reveal that climate variability between Moosonee and Thunder Bay is not significantly different throughout the year except in February. Climate variability in Toronto and Thunder Bay is significantly different during the summer months and November, and climate variability between Toronto and Moosonee is significantly different throughout the year except in January, June, October, and December (Table 2).

For Moosonee, Thunder Bay, and Toronto, seasonal patterns are not apparent in the T_{min} G results, whereas the T_{max} G results reflect a slight increase in randomness for the warmer seasons. This may be due to greater heat sources and fog. During the warm seasons when there is no snow cover, there is a greater influx of solar radiation at the surface, which has the potential to lead to a higher increase in temperature than other seasons. During the day, solar radiation is dissipated as latent and sensible heat, and conducted to and from the ground (Oke 1978). Surface heating occurring in the day can lead to episodic convective mixing of the atmosphere which contributes to greater daytime temperature variability. This is less likely to occur at night
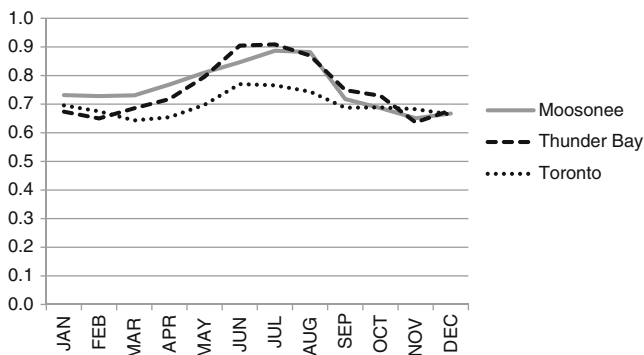
Fig. 2 Monthly averages of G (DTD/SD) for Moosonee, Thunder Bay, and Toronto, Ontario, Canada, using daily T_{max} data from 1959 to 1992
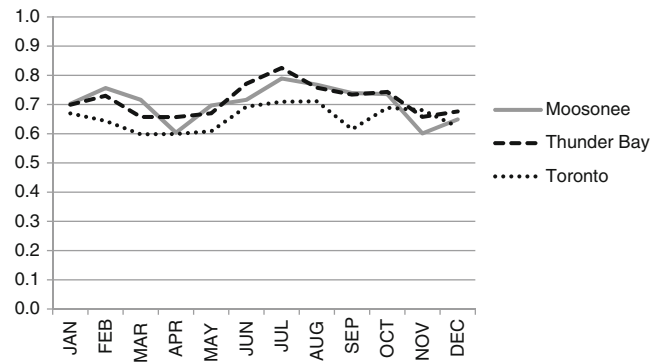
Fig. 3 Monthly averages of G (DTD/SD) for Moosonee, Thunder Bay, and Toronto, Ontario, Canada, using daily T_{min} data from 1959 to 1992

leading to reduced variability. During the evening where there is radiative cooling, condensation may occur when the air is humid and close to saturation, leading to fog formation (Oke 1978), thus releasing energy from latent heat. In this way, fog directly mitigates the drop in temperatures, reducing T_{min} variability. The fog will also reduce the longwave radiative flux thus contributing to a mitigation in temperature decrease, thereby resulting in greater variability in T_{max} than T_{min}.

4.2 Monthly averages of ΔDTD

In general, DTDtmin is found to be greater than DTDtmax during the cold months and vice versa during the warm months for Moosonee, Thunder Bay, and Toronto (Figs. 4, 5, and 6). Throughout the year, DTDtmax and DTDtmin are generally greatest in Moosonee and mildest in Toronto (Figs. 5 and 6). These differences may be due to geographical location and surrounding environment (urban vs. rural). Moosonee, a rural town located furthest north, shows the greatest temperature variability, and Toronto, an urban metropolitan center located furthest south, shows the mildest variability; Thunder Bay, located at a latitude between Moosonee and Toronto, generally reflects temperature variability in between.

For Moosonee, monthly averages of ΔDTD are lowest in March and November, and highest in May (Fig. 4). Thunder Bay reflects a similar ΔDTD trend, where monthly averages of ΔDTD peak in May, though monthly averages of ΔDTD are lowest in February. The spring months (April, May, and June) particularly in Moosonee and Thunder Bay reflect significantly higher monthly averages of ΔDTD. This timing coincides with the warming of spring and the concurrent dramatic changes in albedo due to snow melt. Monthly ΔDTD may be dramatically higher in spring due to an increase in solar radiation, spring melt, albedo changes, and night time fog formation, causing a decrease in DTDtmin concurrent with an increase in DTDtmax (Figs. 5 and 6).

Table 2 t test results on the significance of G T_{max} and T_{min} monthly values, intercomparing Toronto, Thunder Bay, and Moosonee

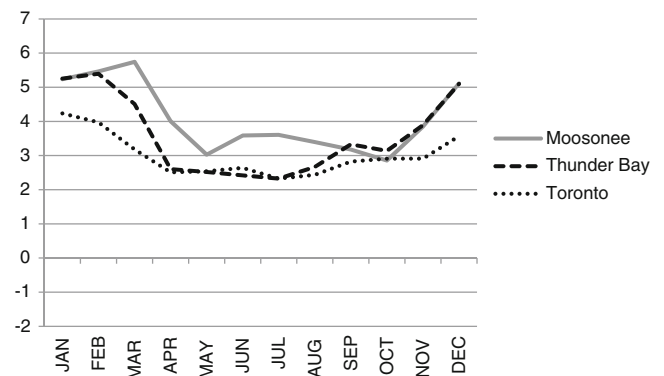|	Toronto vs. Thunder Bay		Toronto vs. Moosonee		Thunder Bay vs. Moosonee	
	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
January	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
February	n.s.	n.s.	n.s.	<0.05	<0.05	n.s.
March	n.s.	n.s.	<0.05	<0.01	n.s.	n.s.
April	n.s.	n.s.	<0.05	n.s.	n.s.	n.s.
May	n.s.	n.s.	<0.05	n.s.	n.s.	n.s.
June	<0.001	n.s.	n.s.	n.s.	n.s.	n.s.
July	<0.01	<0.01	<0.01	n.s.	n.s.	n.s.
August	<0.01	n.s.	<0.001	n.s.	n.s.	n.s.
September	n.s.	<0.01	n.s.	<0.01	n.s.	n.s.
October	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
November	<0.05	n.s.	n.s.	<0.01	n.s.	n.s.
December	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s. not significant

Moosonee's climate normals indicate that there is an average snowfall of 6.9 cm in May and an average snowfall of 0.7 cm in June, but an average snow depth of 0 cm from May to October (Environment Canada 2010). Likewise, Thunder Bay has a snow depth normal of 0 cm between May and October (Environment Canada 2011). This indicates that snow cover likely begins to melt in April and disappears by May in both Thunder Bay and Moosonee. The increase in incoming solar radiation directly increases the amount of latent and sensible heat partitioned to the surface, thus melting and sublimating the snow, dramatically altering the environment's albedo and raising air temperatures. Fresh snow has an albedo of 0.95, old snow has an albedo of 0.4, short grass has an albedo of 0.16, bare coniferous and deciduous forests have an albedo ranging from 0.05 to 0.20, and asphalt has an albedo ranging from 0.05 to 0.2 (Oke 1978). As seasonal transition from winter to spring occurs, snowmelt concurrent to a transition from fresh to old snow reduces the reflectivity of the snow, increasing the volume of heat storage. As the snowpack disappears, the albedo of the surrounding environment is

altered. Since grass, bare forests, and asphalt all have a lower albedo than snow, the reflectivity of the environment is greatly reduced and there is an increase in sensible heat storage. This corroborates with the substantial increase of ΔDTD in April in Thunder Bay and Moosonee (Fig. 4). During the day, solar radiation is largely partitioned into snowmelt or snow sublimation (Oke 1978). As snow cover is reduced and greater ground surface area is exposed, more energy is partitioned in sensible heat (raising the temperature) and subsurface heat storage. The exchanges of heat between the ground, air, and snowpack lead to greater fluctuations in temperature, particularly in T_{max}; thus, there is greater variability in DTDtmax (Fig. 6). During the evening, the temperature of the snow cools down, although the release of latent heat fusion due to the freezing of snow or deposition retards this process (Oke 1978). This source of latent heat minimizes the drop in evening temperatures, resulting in less variability in daily T_{min}. Once snow has completely melted, more energy will be available to heat the air and the surface of the surrounding area in Thunder Bay and Moosonee. An increase in solar radiation
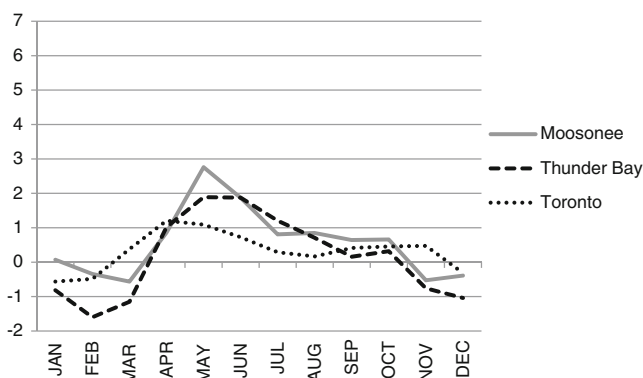
Fig. 4 Monthly averages of ΔDTD for Moosonee, Thunder Bay, and Toronto, Ontario, Canada using daily temperature data from 1959 to 1992

Fig. 5 Monthly averages of DTDtmin for Moosonee, Thunder Bay, and Toronto, Ontario, Canada using daily temperature data from 1959 to 1992
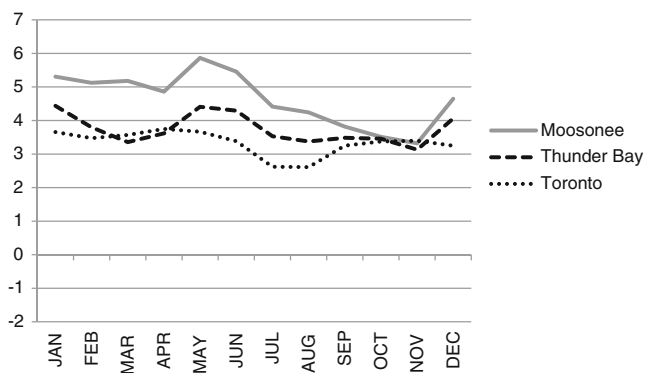
Fig. 6 Monthly averages of DTDtmax for Moosonee, Thunder Bay, and Toronto, Ontario, Canada using daily temperature data from 1959 to 1992

and uncovered ground may potentially lead to greater variability in DTDtmax. In May, the significant peak in ΔDTD (Fig. 4) occurring in Thunder Bay and Moosonee may be due to an increase in heat source, variably covered ground surface area, and fog formation. Since energy is no longer partitioned to snowmelt, more energy is freely available to be dissipated into sensible heat, which will then be conducted to and from the ground. During the evening, there is no longer a source of latent heat generated from the freezing of the snow cover; however, fog formation resulting from radiative cooling may have a similar effect in that it may reduce the drop in temperatures. The layer of fog is a source of latent heat as it emits more energy than it receives from the underlying surface (Oke 1978). This layer of fog thus reduces variability in DTDtmin (Fig. 5). A combination of an increase in DTDtmax and a decrease in DTDtmin translates to day-to-day variability that is significantly higher in May than any other month of the year in Thunder Bay and Moosonee, as shown in Figs. 4, 5, and 6.

Moosonee's monthly ΔDTD averages decrease in June and become relatively stable between July and October (Fig. 4). Ice breakup and freeze-up of James Bay may be the primary influence to the decline and linearity of monthly ΔDTD averages found during this time. The northern part of James Bay was found to break up in late June and freeze up in late November, and the northern part of Hudson Bay was found to freeze up in October (Gagnon and Gough 2005). As breakup occurs in Hudson–James Bay, water will be exposed to incoming solar radiation. The interactions of heat exchange between the atmosphere and the exposed waterbody will affect the climate of land nearby, i.e., the lake effect. The lake effect occurs during the day when land heats up at a faster rate than water, causing a shift in surface air pressure between land and water. Since water does not heat up as fast, the air pressure over water becomes greater than the air pressure over land; air over water flows towards the low pressure area, creating a lake (or sea) breeze to nearby land areas (Aguado and Burt 2004). During the evening, land cools at a faster rate than water, switching the shift in surface air pressure between land and

water. The air pressure over land becomes greater than the air pressure over water, creating a land breeze that moves towards the waters. Extreme T_{max} in Moosonee may be mitigated by the lake/land breeze effect between June and October, thus reducing dramatic temperature fluctuations (Fig. 6) (see also Muzik 1982).

Monthly ΔDTD averages of Thunder Bay may also be influenced by a large waterbody, as it is located by the shoreline northwest of Lake Superior. Of the five Great Lakes, Lake Superior is the largest; it has the lowest surface air mean temperatures and greatest mean depth and heat storage capacity (Assel et al. 2003). Lake Superior begins to freeze along the shoreline in December (Assel 1990). As mid-lake of Lake Superior is much deeper, this area has a different freeze-up regime and begins to freeze later than the shoreline, with the lowest ice areal extent occurring in the deepest part of Lake Superior (Assel 1990; Assel et al. 2003). Because of this, maximum ice areal extent occurs in February and declines from March into April (Assel 2005). Coincidentally, the lowest monthly ΔDTD average for Thunder Bay occurs in February and subsequently increases. Since ice areal extent of Lake Superior is greatest in February, this minimizes the exchange of latent heat from Lake Superior to adjacent land areas; thus, DTDtmin may be greatest during this time. As ice areal extent begins to decline from March to April, the exchange of latent heat from Lake Superior begins to increase as well, mitigating variations in DTDtmin. Furthermore, similar to Moosonee, monthly DTDtmax averages stabilize from July to October in Thunder Bay (Fig. 6); the lake/land breeze effect from Lake Superior may be most pronounced during this time (Muzik 1982; Baldwin et al. 2000).

Toronto's distribution of monthly ΔDTD averages reflects a similar shape to Moosonee's and Thunder Bay's distribution of monthly ΔDTD averages, but does not peak as high as Moosonee's ΔDTD average in May (Fig. 4). Like the climates in Moosonee and Thunder Bay, Toronto's ΔDTD in spring is likely influenced by an increase in solar radiation, changes in albedo, and spring melt, but may differ due to total snowfall and local built environment. Toronto is an urban center with a large built environment. Urbanization has been found to have a significant influence on ΔDTD (Gough et al. 2012). Urban areas in the mid-latitudes have an average albedo of 0.15, concrete walls have an albedo ranging from 0.1 to 0.35, tar and gravel roofs have an albedo ranging from 0.08 and 0.18, and, as previously mentioned, asphalt has an albedo of 0.05 to 0.2 (Oke 1978). Such factors have a significant impact on the local climate (Oke 1978). Due to the heat island effect, large storage of sensible heat retained in the built environment of urban areas mitigate the loss of outgoing energy at night (Gough et al. 2012). This results in greater day-to-day variability in T_{max} than T_{min} (Gough et al. 2012).

Toronto's monthly ΔDTD averages peak in April, a month earlier than Moosonee's and Thunder Bay's monthly ΔDTD

averages. This coincides with the seasonal transition from winter to spring occurring at an earlier time, as Toronto's climate normals show, the average snow depth is 0 cm from April to November (Environment Canada 2010). On average, Toronto receives less snow than Moosonee and Thunder Bay. From 1971 to 2000, Toronto's total snowfall normal is 115.4 cm, Thunder Bay's total snowfall normal is 187.6 cm, and Moosonee's total snowfall normal is 212.9 cm (Environment Canada 2010). Since Toronto comprises of a large built environment, the area has a lower albedo and thus less reflectivity. Because there is less snow in Toronto and thus less surface water, less incoming solar radiation is partitioned into latent heat; rather, more energy is absorbed and partitioned into sensible heat. Though there is less of an uptake of latent heat energy, snowmelt may still occur at a faster rate due to it being a smaller snowpack and the surrounding built environment, which again coincides with an earlier peak in monthly ΔDTD averages (Fig. 4). Once snow has completely melted, more solar energy will be partitioned into sensible heat, thus raising air temperatures. During the day, energy partitioned into sensible heat may be conducted to and from the ground and into heat storages found in the built environment in Toronto (e.g., concrete buildings and roads). An influx in sensible heat sources may lead to greater variability in DTDtmax. During the evening, as temperatures cool, there is a release of heat from heat storages found in the built environment (Oke 1978). This leads to higher nocturnal minimum temperatures and reduced variability in DTDtmin, in effect day time storage buffers night time heat loss. Coinciding with past research, a combination of an influx in sensible heat and Toronto's built environment may lead to greater variability in DTDtmax and reduced variability in DTDtmin (Gough et al. 2012), resulting in a peak in ΔDTD averages in April (Fig. 4). During winter, DTDtmin in Toronto is much milder than Moosonee and Thunder Bay (Fig. 5). Heat retained in the built environment may mitigate large variations in T_{min} (Gough et al. 2012), leading to a milder DTDtmin that is pronounced during the cold season.

Toronto is adjacent to Lake Ontario and thus experiences the lake/land breeze effect as well. Between July and November, Toronto's monthly ΔDTD averages stabilize (Fig. 4); the lake effect may be most pronounced during this time. Like Lake Superior, Lake Ontario is seldom completely covered by ice during the cold season (Assel et al. 2003). Assel et al. (2003) examined annual maximum ice concentration for the Great Lakes from 1963 to 2001. Lake Ontario was found to have a median annual maximum ice concentration of 21% (Assel et al. 2003). Ice formation in the Great Lakes is found to start in December to January, and reach its maximum areal extent by February to early March (Assel 1990, 1999). As Lake Ontario may not be completely frozen year-round, Toronto's climate may be impacted by the lake in most months of the year. However, it is only during the warmer months when

Toronto is free of snow cover. It is during this time when land heats up faster than Lake Ontario, causing a shift in surface air pressure between land and water. The lake breeze effect occurs, mitigating dramatic changes in T_{max} (Gough and Rozanov 2001). This may be why monthly ΔDTD averages of Toronto are notably stable between July and November (Fig. 4).
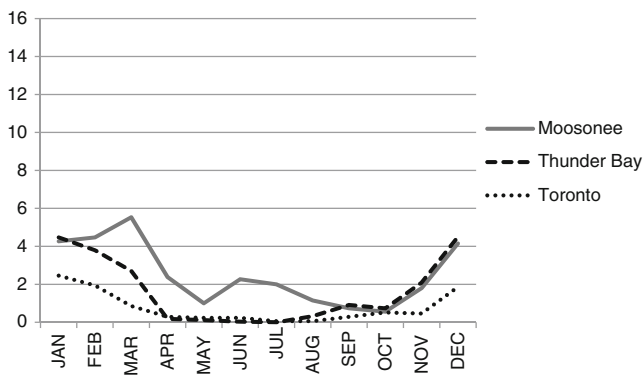
4.3 Threshold exceedances by 5°C and 10°C

Monthly averages of the number of day-to-day T_{min} threshold exceedances by 5°C and 10°C for Moosonee, Thunder Bay, and Toronto are shown in Figs. 7 and 8 (respectively), and monthly averages of the number of day-to-day T_{max} threshold exceedances of 5°C and 10°C are shown in Figs. 9 and 10 (respectively). As shown in Figs. 7, 8, 9, and 10, Moosonee experiences significantly greater amounts of day-to-day temperature variation than Toronto throughout all months in the year by this measure. Moosonee generally experiences significantly greater amounts of day-to-day temperature variation than Thunder Bay with the exception of T_{min} threshold exceedances by 5°C, where there is greater variability in Thunder Bay in January, February, and October, and the same number of threshold exceedances by 5°C occurring in November and December (Fig. 7). For Moosonee and Thunder Bay, the highest count of T_{max} threshold exceedances (5°C and 10°C) occurs in May concurrent to much lower counts of T_{min} threshold exceedances (5°C and 10°C) also occurring in May (Figs. 7, 8, 9, and 10). The combination of highest and much lower threshold exceedances of T_{max} and T_{min} (respectively) coincides to the significant peak in monthly ΔDTD occurring in Moosonee and Thunder Bay, as shown in Fig. 4. This is consistent with the finding that there is greater variability in DTDtmax and less variability in DTDtmin occurring in May in Moosonee and Thunder Bay; the combination of these two factors results in a high peak in monthly ΔDTD taking place in spring.
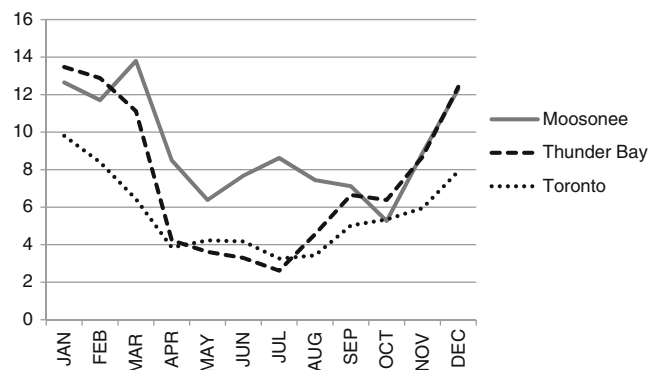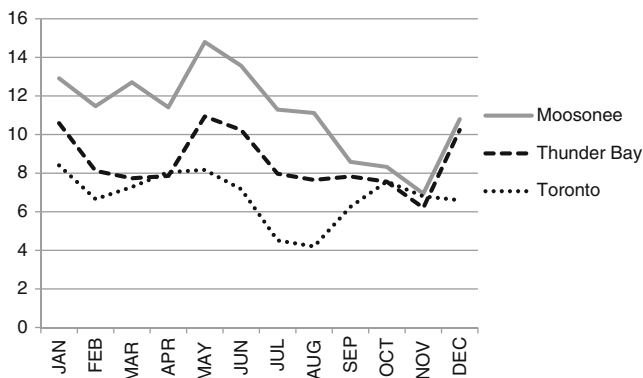

Fig. 7 Monthly averages of the total number of day-to-day T_{min} threshold exceedances by 5°C for Moosonee, Thunder Bay, and Toronto, using daily T_{min} data from 1959 to 1992
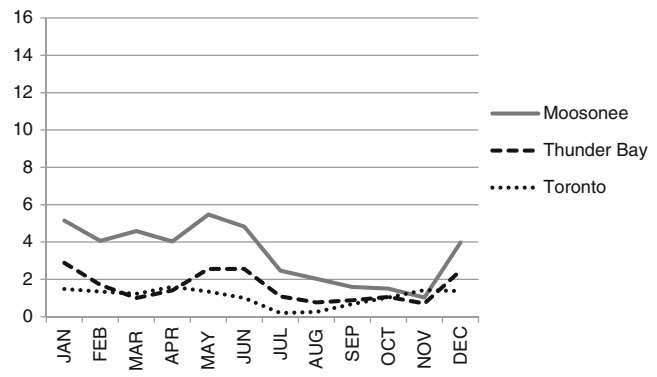
Fig. 8 Monthly averages of the total number of day-to-day T_{min} threshold exceedances by 10°C for Moosonee, Thunder Bay, and Toronto, using daily T_{min} data from 1959 to 1992

Fig. 10 Monthly averages of the total number of day-to-day T_{max} threshold exceedances by 10°C for Moosonee, Thunder Bay, and Toronto, using daily T_{max} data from 1959 to 1992

For Moosonee, T_{min} and T_{max} threshold exceedances (5°C and 10°C) are the lowest between October and November (repeated in Figs. 7, 8, 9, and 10); this may be due to the freeze-up of the Hudson–James Bay. For T_{min}, the lowest number of threshold exceedances (5°C and 10°C) occurred in October; and for T_{max}, the lowest number of threshold exceedances (5°C and 10°C) occurred in November. During this time, freeze-up of Hudson–James Bay commences (Gagnon and Gough 2005). The freezing of ice releases latent heat and consequently acts as a self-equilibrating process (Oke 1978). Because the Hudson–James Bay is a large waterbody, there will be a significant amount of latent heat directly affecting surrounding areas. This source of heat may reduce day-to-day fluctuations in T_{min} during freeze-up. Until freeze-up is complete, the release of heat acts as a self-equilibrating process, mitigating dramatic day-to-day temperature variability in Moosonee. Since more of the freezing is occurring at night, the source of latent heat may reduce variability in DTDtmin. Once freeze-up is complete, latent heat is greatly reduced and DTDtmin variability thus can increase. This coincides with Fig. 4, where ΔDTD averages are lower from November to March.

Fig. 9 Monthly averages of the total number of day-to-day T_{max} threshold exceedances by 5°C for Moosonee, Thunder Bay, and Toronto, using daily T_{max} data from 1959 to 1992

In Thunder Bay, there is a parabolic seasonal trend reflected in T_{min} threshold exceedances. T_{min} threshold exceedances of 5°C is lowest in June, and T_{min} threshold exceedances of 10°C is nearly non-existent during the summer months (Figs. 7 and 8). T_{min} threshold exceedances then increase for the colder months (Figs. 7 and 8) and T_{max} threshold exceedances stabilize from July to October (Figs. 9 and 10). The lake/land breeze effect may be most pronounced during the summer months (Muzik 1982), mitigating large variations in T_{min} at night, and large variations in T_{max} during the day. This may be because surface temperatures of Lake Superior are warmer near the shoreline than mid-lake in the summer and cooler near the shoreline than mid-lake in the winter (Bennett 1978). Since Thunder Bay is located by the shoreline of Lake Superior, it may experience the lake effect more so in the summer than winter. Furthermore, in May, the onset of spring warming increases surface temperatures, with the rate of surface warming peaking in July at a maximum of "10 degress per month" (Bennett 1978). During this time, minimum surface temperatures are higher than mean lake temperatures, allowing for heat flux exchanges between the lake and atmosphere to occur (Bennett 1978). As the rate of surface warming peaks in July, the lake effect may be most pronounced particularly at night in July, mitigating large variability in T_{min} (Baldwin et al. 2000) (Fig. 7).

Toronto has less day-to-day temperature variability than Moosonee, as shown in Figs. 7, 8, 9, and 10. For Toronto, seasonal distribution of threshold exceedances is slightly more orderly (Figs. 7, 8, 9, and 10) with winter experiencing the greatest amount of day-to-day variability. The distributions of both T_{min} threshold exceedances (5°C and 10°C) are somewhat parabolic with the warmer months reflecting a much lower count of T_{min} threshold exceedances, and the colder months reflecting a much higher count (Figs. 7 and 8). For both T_{max} threshold exceedances (5°C and 10°C), the distributions are bimodal (Figs. 9 and 10). The warmer months reflect a higher total of threshold exceedances, except in July and August, where the threshold exceedance counts significantly drop

(Figs. 9 and 10). The lake effect may be most prominent during this time, where extreme day-to-day variability of T_{max} may be mitigated by incoming lake breeze from Lake Ontario (Gough 2008).

4.4 Temporal trends in DTD and threshold exceedances

From 1959 to 1992, Toronto's DTDtmin yearly averages ($p<0.05$) significantly declined over time (slope coefficient=−0.009). This indicates that variability of DTDtmin has been gradually declining in Toronto throughout the years, which may be attributed to Toronto's urban heat island (UHI) effect (Mohsin and Gough 2010). The UHI effect is found to have a more significant effect on T_{min} than T_{max} (Mohsin and Gough 2010). As a result, a faster increase in T_{min} than T_{max} has caused a decline in diurnal temperature range (DTR) (the difference between daily T_{max} and daily T_{min}) in urban areas (Kan et al. 2007). From 1959 to 1992, Moosonee's DTDtmax yearly averages ($p<0.05$) significantly increase over time (slope coefficient=0.0108), and yearly averages of ΔDTD for Moosonee ($p<0.05$) and Thunder Bay ($p<0.05$) significantly increase over time (Moosonee slope coefficient= 0.0148, Thunder Bay slope coefficient=0.0117). This indicates that total change in temperature variability has been increasing in Moosonee and Thunder Bay, but not in Toronto. These results also indicate that the significant increase in Moosonee's yearly ΔDTD averages is due to a significant increase in DTDtmax yearly averages over time. Toronto's yearly averages of ΔDTD also increased over time, but it was not statistically significant. Furthermore, Moosonee's DTDtmin yearly averages, Toronto's DTDtmax yearly averages, and Thunder Bay's DTDtmax and DTDtmin yearly averages do not significantly change over time.

From 1959 to 1992, T_{max} threshold exceedances of 5°C significantly declined in Toronto ($p<0.05$) (slope coefficient= −0.0028). From 1959 to 1992, T_{min} threshold exceedances of 5°C significantly declined in Moosonee ($p<0.01$), Thunder Bay ($p<0.05$), and Toronto ($p<0.01$) (Moosonee slope coefficient=−0.0042; Thunder Bay slope coefficient=−0.0057; Toronto slope coefficient=−0.0041). The decline in T_{min} threshold exceedances may be connected to the decline in past global DTR. From 1950 to 1993, the global DTR decreased by 0.1°C per decade (IPCC 2007). This was mainly due to a smaller increase in T_{min} during the evenings. As DTR decreases, T_{min} threshold exceedances will be affected. In Canada, a significant decline in colder events (i.e., cold days, nights, or frost days) was observed from 1950 to 2003, as well as a significant decline in DTR from 1900 to 2003 (Vincent and Mekis 2006). It is projected that due to global warming, DTR and the number of cold extremes in winter may decrease (IPCC 2007). A decline in DTR and fewer cold extremes may contribute to a continual decline in T_{min} threshold exceedances of 5°C in Toronto, Thunder Bay, and Moosonee in the near future.

T_{min} threshold exceedances of 10°C decline over the years for Moosonee, Thunder Bay, and Toronto, but they are not statistically significant. T_{max} threshold exceedances of 5°C for Moosonee and Thunder Bay, and T_{max} threshold exceedances of 10°C for Moosonee, Thunder Bay, and Toronto show no significant change over the years.

5 Conclusion

Examining the climates of Moosonee, Thunder Bay, and Toronto through a day-to-day framework provided a detailed understanding on temperature variability, where not only day-to-day analyses delineated daily and month variation but also seasonal and yearly variance in temperature. Factors that affect day-to-day temperature variability of these three locations include seasonal variation in solar radiation, spring melt, snow cover, lake effect, freeze-up of nearby waterbodies, fog formation, and local environment (e.g., built environment, UHI). In general, climate variability is greater in Moosonee and Thunder Bay than Toronto. As yearly averages of ΔDTD have significantly increased over time in Moosonee and Thunder Bay, Aboriginal populations residing in these two locations may continue to experience the effects of increasing climate variability in the future. Unpredictable and dramatic weather conditions may continue to occur, leading to continual issues with physical health risks in hunting practices (Furgal and Seguin 2006), shorter hunting trips, and less game meat (Tam et al. 2011). In Toronto, DTD is lower in magnitude than for Moosonee's and Thunder Bay's climates. Aboriginal populations in Toronto may not experience the same effects of climate variability as would rural Aboriginal communities, but this may be primarily due to differences in lifestyle. Rural Aboriginal communities have to cope with climate variability due to their subsistence lifestyle and remote location (Ford et al. 2010), whereas urban Aboriginal communities have greater access to resources in urban cities.

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