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Assessment of Near 0°C Temperature and Precipitation Characteristics across Canada

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Abstract. The 0°C temperature threshold is critical to many meteorological and hydrological processes driven by melting and freezing in the atmosphere, surface and sub-surface and by the associated precipitation varying between rain, freezing rain, wet snow and snow. This threshold, linked with freeze-thaw, is especially important in cold regions such as Canada. This study develops a Canada-wide perspective on near 0°C conditions with a particular focus on the occurrence of its associated precipitation. Since this analysis requires hourly values of surface temperature and precipitation type observations, it was limited to 92 stations over the 1981-2011 period. In addition, nine stations representative of various climatic regions are selected for further analysis. Near 0°C conditions are defined as periods when the surface temperature is between -2°C and 2°C. Near 0°C conditions occur often across all regions of the country although the annual number of days and hours and the duration of these events varies dramatically. Various forms of precipitation (including rain, freezing rain, wet snow and ice pellets) are sometimes linked with these temperatures with highest fractions tending to occur in Atlantic Canada. Trends of most temperature-based and precipitation-based indicators show little or no change despite a systematic warming in annual temperatures. Over the annual cycle, near 0°C temperatures and precipitation often exhibit a pattern with short durations near summer driven by the diurnal cycle, while longer durations tend to occur more towards winter associated with storms. There is also a tendency for near 0°C temperatures to occur more often than expected relative to other temperature windows; due at least in part to diabatic cooling and heating occurring with melting and freezing, respectively, in the atmosphere and at the surface.

1 Introduction

In cold regions such as Canada, numerous environmental processes and socio-economic activities are significantly impacted by temperatures near 0°C. At larger spatial and temporal scales, the seasonal arrival and retreat of 0°C temperatures influence snow melt/accumulation, hydrologic processes (spring freshet, freshwater ice duration that affects open-water evaporation, flooding), permafrost thaw and related slumping, transportation (e.g., ice roads), growing season length, and animal hibernation (e.g., Bonsal and Prowse, 2003). At smaller scales, periodic transitional episodes from below to above 0°C (or vice versa) can have adverse effects including mid-winter ice-jams and related flooding, animal starvation, freeze-thaw damage to infrastructure, unseasonal frosts, and recreation impacts (skiing, avalanches). Furthermore, if these periods are associated with precipitation (e.g., freezing rain/ice-storms), severe and sometimes life-threatening impacts are possible including damaged electrical transmission infrastructure, air traffic disruptions and hazardous road conditions.

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Many regions of the country have experienced major impacts from near 0°C events. For example, a prolonged period of freezing rain, drizzle, and ice pellets severely affected a region stretching from southeastern Ontario to southwestern Quebec, as well as northeastern United States in early January 1998 (Henson et al., 2007; Henson et al., 2011). Some areas experienced in excess of 100 mm of freezing precipitation. Transportation was shut down and damage to the electrical infrastructure, trees and farms was catastrophic. There were an estimated 47 fatalities in Canada and the United States and $4 billion U.S. in total losses (Lecomte et al., 1998; Kerry et al., 1999; Milton and Bourque, 1999; Klaassen et al., 2003). More recently, ice storms over northeast New Brunswick in January 2017 (McFadden and Theriault, 2018) and the Fraser Valley of British Columbia in December 2017 (Mendoza and Schmunk, 2017) severely impacted electrical power grids, snapping poles, downing lines and leaving thousands of people without electricity for days.

There have been previous Canadian studies related to aspects of the 0°C temperature threshold including associated precipitation. At large scales, Bonsal and Prowse (2003) assessed 20th century trends and variability in spring and autumn 0°C dates across the country and found significant trends toward earlier springs (particularly in western areas) but little change during autumn. Regionally, Stewart and Yiu (1993) examined near 0°C conditions including their horizontal scales and associated precipitation over southern Ontario. In terms of associated precipitation, MacKay and Thompson (1969) published the first climatology of freezing precipitation and this was later updated by Stuart and Isaac (1999). Many case study analyses of heavy precipitation and/or freezing rain events have been carried out to investigate storm structure and associated precipitation production mechanisms (for example, Henson et al., 2007; Henson et al., 2011). As well, two recent articles, one focused on western and northern Canada (Kochtubajda et al., 2017) and one on eastern regions (Bresson et al., 2017), have collectively documented some of the hazardous freezing conditions occurring within the country.

A number of studies have examined climatological characteristics of freezing precipitation across North America, Europe and Asia (see for example, Carriere et al., 2000; Cortinas, 2000; Changnon, 2003; Houston and Changnon, 2007; Groisman et al., 2016; Kämäräinen et al., 2016). These investigations used a variety of observational and model datasets, found wide variations in its occurrence and, in some cases, related these findings to contributing factors such as mountain barriers and coastlines. A recent study in Europe also identified the impacts of extreme weather on critical infrastructure (Groenemeijer et al., 2017). One of the results of interviews with infrastructure and emergency managers was that the impacts of freezing precipitation, snowfall, snow loading and snow storms were of most concern.

Although studies have assessed various aspects of the 0°C conditions, there has been no Canada-wide assessment describing characteristics and trends in their historical occurrence. Preliminary assessment in the frequency of near 0°C temperatures across Canada (Fig. 1) shows that, with the exception of Vancouver, there is a relatively high frequency of these temperatures in all regions of the country despite wide-ranging climates. Given the aforementioned importance of this threshold, additional information is necessary to better understand its spatial and temporal characteristics across the country. This includes the associated precipitation that often results in the greatest impacts.

The objective of this study is therefore to develop a Canada-wide perspective on near 0°C conditions with a particular focus on its associated precipitation types. Data and methods are described first, followed by an assessment of climatology and trends in key identified variables. Next, representative stations are examined in more depth followed by a discussion of several critical near 0°C features and by concluding remarks.

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2 Data and methods

2.1 Data

A combination of automated systems and human observations comprise Environment and Climate Change Canada's (ECCC) surface weather networks. These measurements are subject to subsequent manual and automated quality control procedures and are available from ECCC's National Climate Data and Information Archive at various temporal scales ranging from hourly to annual (http://www.climate.weatheroffice.ec.gc.ca). Since this study focuses on the identification of conditions near 0°C at the surface along with associated precipitation, hourly surface temperature and precipitation type observations across Canada were retrieved from the archive.

Selecting appropriate stations is fraught with several complicating issues including missing values and changes to the observing program. The initial period considered was 1953-2016, with the criterion of a minimum 25 years of record. Although 227 stations satisfied this criterion for both surface temperature and precipitation type information, many were not operating 24 hours a day whereas others changed their daily observing practices over the period of interest (for example, from 24 hours per day to fewer or vice versa). It was therefore decided that only stations operating 24 hours a day would be used, and these had to have at least 90% hourly dry bulb temperature data availability (equivalent to an average requirement of 21 hours per day).

Consequently, to maximize the number of stations but still maintain a sufficiently long period for climatological studies, the 31 year period of 1981-2011 was chosen. This latter date was influenced by the dramatic drop in the number of stations archiving information after 2012 (Mekis et al., 2018). This resulted in 92 stations being used for analyses (Fig. 2) that provide reasonable coverage over the country. For these stations, 12 weather (precipitation) types are considered: rain, rain showers, drizzle, freezing rain, freezing drizzle, snow, snow grains, ice crystals, ice pellets, ice pellet showers, snow showers and snow pellets. Precipitation intensity is characterized using four distinct values ranging from absent to 'heavy', but, for the purposes of this study, only the presence or absence of precipitation types was considered (Environment Canada, 2015).

In addition to the Canada-wide analysis, nine representative stations were chosen for further analysis (Fig. 2). These stations, having high quality consistent observing practices, represent contrasting climatic conditions across the country.

2.2 Methods

This analysis identified key near 0°C characteristics and threshold events during the study period. There is no obvious, physically-based criterion that can be used to characterize conditions near 0°C. To provide a reasonable (dry bulb) temperature (defined as T) window straddling 0°C, these conditions were defined as $-2 \leq T \leq 2$°C throughout the paper.

Four temperature-based indices were calculated from this information (Table 1). They are the average number of days per year having temperatures in this range; average number of hours per year with temperature in this range; average number of events per year; and annual maximum duration of the events within the study period. The event is defined as the number of consecutive hourly observations within the $-2 \leq T \leq 2$°C range. Note that to be considered a single event, there could be no more than three continuous hours of missing data.

The first set of indicators are associated with the near 0°C condition without the assurance of any precipitation occurrence. To assess precipitation during near 0°C conditions, further indicators combining the temperature and precipitation type conditions were computed (Table 1). These include the annual average hours with any of the 12 aforementioned precipitation type conditions;

the annual average hours with only freezing rain; the percentage of time in which any precipitation (from the 12 types) occurred; and the percentage of time that freezing rain alone occurred. Freezing rain is highlighted since its occurrence often results in major impacts.

To characterize these variables, the 1981-2011 average was determined for each station and mapped across the country. In addition, nonparametric linear trends were estimated using the approach by Sen (1968) with statistical significance based on the nonparametric Kendall's test (Kendall, 1955). This test is less sensitive to the non-normality of the data distribution, and less affected by missing values and outliers as compared to the frequently used least squares method. Since serial correlation is often present in climatological time series, the method also involves an iterative procedure that takes into account the first lag autocorrelation (Zhang et al., 2000). Given the aforementioned aspect of missing data, it was decided that, for trend computation, a minimum of 90% of the values (29 out of 31 years) was required.

In addition to the temperature and precipitation type occurrence information, hourly sky cover was also extracted over the nine representative stations. This information was only examined for the longest duration near 0°C conditions at these stations.

3 Climatology and Trends

3.1 The 31-Year Climatology for 1981-2011

Figure 3a shows the average number of days per year when temperature was between -2°C and +2°C. There are distinct regional patterns with the largest values (120 to 200 days) concentrated in three main areas. Highest occurrences are found in interior British Columbia and southern Alberta extending into southern Saskatchewan with maximum values within or on the leeward side of the western cordillera. It is likely that factors such as chinooks contribute to these high occurrences by occasionally bring warm air into the region that, during the cold season, results in temperatures near 0°C. The second region with high values is in Atlantic Canada where temperatures often fluctuate around 0°C during the cold season due to the Maritime influence. Southern Ontario also has a relatively high number of occurrences likely due to its more southerly location and resultant influxes of warmer southern air masses during the cold season. Mid-range values (80 to 120 days) occur in the continental interior stretching from the Yukon through central Canada to Quebec and Labrador. This area is colder than the previously mentioned regions with less incursions of warm air during cold season. Lowest (40 to 80) values are in the North due to even fewer warm air incursions. Low values also occur in southwestern British Columbia where temperatures seldom dip below 0°C.

The preceding indicates that, on average, near 0°C conditions can occur over 50% of the days in regions with the highest values in Fig. 3a. Even in the most northerly locations, such conditions occur approximately once per week on average.

Figure 3b shows the average number of hours per year with temperatures between -2°C and +2°C. Overall the distribution is similar to that of Fig. 3a but some differences are apparent. The same three general regions of high values still occur but the western one is more localized and does not extend east of the Canadian Rockies. This may indicate that such conditions are short-lived so they show up in the number of days but not in an extended number of hours.

High values near northern coastal British Columbia are also evident. This northern British Columbia station next to the ocean may share many characteristics to ones in the Atlantic region. Note that northern coastal British Columbia maximum values (1800 - 2000 hours) represent approximately 80 days per year. In contrast, here are now three general areas of low values. The northern

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region is split into two with one being in the far North and the second being in northern British Columbia and Alberta as well as in the Yukon and western Nunavut. This latter region experiences warm summer conditions when temperatures seldom reach this low and cold winter conditions when temperatures seldom reach this high. Stations to the east more often experience near 0°C temperatures in the warm season.

Figure 3c shows the average number of events per year. Spatial patterns are similar to those in Fig. 3a with maximum values in the west extending into southern Saskatchewan. High values are observed within the previously mentioned areas of southern Ontario and the Atlantic region, but also occur on the north shore of Lake Superior. The number of events in Atlantic Canada is comparable to the eastern Prairies even though there are far more hours in the Atlantic region. The number of events at some stations in southern Ontario is also comparable to the number in the southern Northwest Territories even though, again, there are far more hours in southern Ontario.

The maximum duration of the annual events lengths in hours, characterizing the occasional persistence of such events, is shown in Figure 3d. The pattern differs from those in Figs. 3a-c with longest durations in the Atlantic region and some interior stations in British Columbia including the northern coastal region. Other large values occur near coastlines in the North. These values range up to 130 h or ~5 days. Lowest maximum durations occur in the lee of the Rocky Mountains as well as in southern British Columbia. This may be related to the occurrence of chinooks within which temperatures can quickly pass from below to above 0°C (Brinkman and Ashwell 1968).

Figs 4a to 4d provide climatologies of precipitation types associated with near 0°C conditions. First, Fig. 4a shows the average annual number of hours with any of the 12 reported precipitation types listed in Table 1. Maximum values (up to 800 hours) are primarily concentrated in the eastern half of the country although as with the number of hours in Fig 3b, northern coastal British Columbia again is associated with high values. Such precipitation types are rare in most of western Canada (except northern coastal British Columbia) with the lowest value occurring on Vancouver Island. The magnitude of variation is enormous. There is more than an order of magnitude difference between the lowest and highest values across the country. There is even a huge variation between the two farthest north stations.

Figure 4b shows the percentage of near 0°C conditions with associated precipitation types, where the number hour reported any 12 weather type events are divided with all hours with near 0°C conditions. The pattern is quite similar to that in Fig. 4a but with a few exceptions. Highest values are again in eastern Canada and northern coastal British Columbia. The map reveals that over 40% of near 0°C conditions are associated with precipitation types in these regions but it is only of order 10 to 20% in western Canada.

Figure 4c shows the average annual number of hours of freezing rain with temperatures near 0°C. Maximum values by far are in the Atlantic region and there is a regional maximum near Montreal. Small values occur in other regions of the country, especially in the North and much of the west. In fact, freezing rain is rarely ever reported on the western side of the Prairies and North.

Figure 4d shows the percentage of near 0°C hours with freezing rain. The pattern is similar to that in Fig. 4c. This includes highest values in the Atlantic region with a secondary maximum near Montreal. One isolated, high value does occur near Vancouver however.

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3.2 Trends

Figure 5a shows trends in the number of days with temperatures near 0°C over the 1981-2011 period. The majority of stations are characterized by a non-significant decrease with few having a non-significant increase (mainly in central Alberta and parts of British Columbia). Only two stations exhibited significant change; Toronto and the most northerly station Eureka which experienced a decrease of 27 and 19 days over the 31 year period respectively.

Figure 5b shows trends in the annual number of hours with near 0°C conditions. As in Fig. 5a, most stations experienced a decrease over the 1981-2011 period. This is most pronounced over southern Ontario but also over other large areas of the country. Newfoundland, several stations in the North, as well as southern British Columbia experienced increases. Significant decrease were observed in many southern Ontario stations and again in Eureka. Only one station (western Newfoundland) showed a significant increase. The maximum changes with over 300 hours over the 31-year period (the equivalent of over 12 days) were found in three locations in Ontario, namely Toronto, Wiarton which is north of Toronto, and London in the extreme southwestern part of the province.

Figure 5c shows trends in annual number of events with near 0°C conditions. The pattern is similar to those in Figs. 5a and 5b, however, both increase and decreases are often observed in the same general areas. One exception is southern Ontario which again shows consistent decreases. Only Toronto, Eureka, Sioux Lookout in northwestern Ontario, and Montreal show statistically significant change with the decrease of 36, 31, 20 and 16 number of events, respectively, over the 31 year period.

Figure 5d shows trends of the maximum duration. There is a mix of decreasing and increasing patterns as well as many stations showing little change. Southern Ontario is completely characterized by decreases while other regions have a mixed pattern. Stations experiencing a statistically significant change are scattered across the country and exhibit both increases and decreases. Only four locations show significant change, decreasing in Toronto and Eureka with 25 and 18 hours per event and increasing in Yarmouth in Nova Scotia and Thompson in Manitoba with 34 and 19 hour per event, respectively.

4 Representative stations

The preceding analyses have illustrated Canada-wide conditions but it is also critical to examine individual stations in more detail. To address this, nine stations representing contrasting climatic conditions were chosen (Fig. 1).

An important characteristic of near 0°C conditions is the duration of events. As shown in Figure 6, this distribution shows wide variation at each of the selected stations as well as between stations. For example, almost half of the events at Calgary were less than 2 hours but at Cambridge Bay this value was 7 hours; 90% of the events at Calgary were less than 12 hours but at Cambridge Bay this value was 43 hours. In parallel, Calgary experienced the largest number of events; Cambridge Bay the least.

Figure 7 shows the distribution in the occurrence of the 12 precipitation types included in this study at the 9 stations over the 1981-2011 period. Snow dominates at all stations, except at St. John’s, and it is most prevalent over Whitehorse and Calgary. Freezing rain is minimal at most western stations but steadily increases eastward. There is also a large variation in precipitation type occurrences between the two northern stations with, for example, drizzle and freezing drizzle being minimal at Whitehorse but not at Cambridge Bay.

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As discussed in Sect. 3.2, many stations exhibited some change but few were statistically significant (Table 2). This characteristic is also prevalent for the 9 case studies with only two experiencing significant change. In particular, Toronto showed significant decreases in all 4 temperature-related indicators while Montreal had a decrease in the number of events per year.

The trend summary for the 12 weather types is shown in Table 3. Only Churchill exhibited a statistically significant trend (decrease) in the occurrence of any of these 12 types (last column). This arises from 5 significant decreasing types, namely rain showers, drizzle, freezing drizzle, ice pellets and snow showers. St. John's experienced five significant changes (in rain showers, freezing drizzle, snow, snow grains and snow showers precipitation types) but, due to the shift from snow grains and snow showers to snow, the overall changes for all types are not significant.

Patterns on sub-annual time scales are also examined. As shown in Figure 8, there is a strong dependence of average near 0°C occurrences on average monthly temperature over the 1981-2011 period; this pattern is largely independent of station. Largest occurrences naturally take place when average temperatures are close to 0°C. By ±10°C, values have fallen to of order 25-35% of those at the peaks. Although rare, near 0°C conditions sometimes occurred with average monthly temperatures with more than 20°C away from the 0°C line. The five coldest differences occurred at Churchill and Cambridge Bay, and the five warmest ones occurred at Toronto, Winnipeg and Montreal.

Further insight can be gained by examining the even shorter time scales. Figure 9 shows annual cycles of near 0°C and associated precipitation type occurrences at four of the nine representative stations. Near 0°C conditions do not occur during summer at all southern stations but they can occur in any other month. In contrast, these conditions only occur in summer at Cambridge Bay. The most frequent occurrence can be seen at St John's.

Furthermore, the occurrence of any precipitation type tends to take place towards the 'winter' side at southern stations, although there are exceptions. Such occurrences on the 'winter' side are probably linked with storms passing over the stations with associated precipitation, whereas occurrences on the 'summer' side normally just reflect the diurnal cycle.

It is evident that there is large inter-annual variability and this can mask expected systematic trends. For example, it would be expected that, with overall warming, the onset for near 0°C would occur later in autumn and earlier in spring. Although not shown, these patterns were generally not statistically significant. Only Toronto (Fig. 5c) shows both of these trends to be statistically significant. Whitehorse shows significant earlier spring cessation and St. John's shows significant later autumn onset (Fig. 9d). Cambridge Bay experiences near 0°C conditions in every 'warm season' month (Fig. 9b) so the onset of near 0°C in the spring and its cessation in the autumn were considered; neither showed statistically significant trends. No analysis was conducted for Churchill because near 0°C conditions occurred in every month.

5 Characterizations and interpretations

5.1 Country-wide patterns and governing factors

The Canada-wide plots exhibit a number of patterns in the indicators. First, there are three general regions in terms of high occurrences of near 0°C conditions. These are in central British Columbia and sometimes stretching to Saskatchewan, southern Ontario and the Atlantic region. The size of the regions vary with indicator. Regions with generally low occurrences are in the north, where such temperatures are not often reached, and in the lower southwestern part of British Columbia, where temperatures

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seldom reach 0°C. In terms of duration, highest values tend to be in the Atlantic region, eastern Northern region as well as northern coastal British Columbia. Lowest values are in southwestern British Columbia and stations just east of the Rocky Mountains in Alberta.

There are numerous factors contributing to these patterns. One is the proximity to coastlines. Many of the oceans surrounding Canada are close 0°C, especially in the cold season (Phillips, 1990), and this acts to maintain station temperatures near this value. For some stations in the North and the Atlantic region, the development and melting of sea ice also acts to maintain temperatures near 0°C; inland stations must experience a similar effect from lake ice. Most stations are similarly affected by melting and freezing of snow on the surface. Many stations are also affected by frozen soil; its freezing in the autumn and its melting in the spring would again act to maintain temperatures near 0°C (Oke, 1987).

Mountains can also be a contributor to near 0°C conditions. Circulations such as chinooks (American Meteorological Society, 2012) and valley/mountain flows are continually shifting temperatures and these can pass through 0°C in the cold season (Longley, 1967). Chinooks are common at Calgary. Longley (1967) found an average of 27 days per season (December-February) over the 1931-1965 period whereas Nkemdirim (1996) found 50 per season (November-February) over the 1951-1990 period. Associated temperature changes are typically rapid and are sometimes associated with several passes through near 0°C in a day (Brinkman and Ashwell 1968). Temperature changes with chinooks at Calgary vary between approximately 0.6°C/h and 8.3°C/h with an average of 2.1°C/h. During chinook episodes, large temperature swings can also occur. For example, at Calgary on Feb. 16, 1965, there were 4 near 0°C events (two 1-h periods, one 2-h, and one 5-hour). Weather conditions were precipitation-free this day.

These chinook effects undoubtedly contribute to the findings at Calgary. As shown in Sects. 3 and 4, it experiences many days and events with near 0°C conditions but relatively few hours since the events are short and it also experiences few hours of associated precipitation.

Long duration periods of near 0°C conditions were further examined by identifying the longest duration events at the 9 representative stations (Table 4). The longest period was in Cambridge Bay (197 hours) and the shortest in Vancouver (68 hours) which is still almost 3 days. These events occurred in every season with the longest being in June (Cambridge Bay). Using the hourly observations at these stations, it is evident that all the events were dominated by cloudy conditions, which were often accompanied with precipitation. Such sky cover would contribute to reducing temperature swings associated with daytime heating and nighttime cooling. Many of the mainly or completely clear reports were linked with temperatures initially passing into or finally passing out of these long duration near 0°C conditions.

There are also patterns with the occurrence of the associated precipitation types. The country is almost split in two between west (low values) and east (high values) (Fig. 4). One exception in the west is northern coastal British Columbia (Terrace near the coast and nearby Smithers more inland). Some Northern stations, particularly in the eastern portion, experience more occurrences than do many in British Columbia and the Prairies.

The fractional occurrence of precipitation types (Fig. 7) can generally be explained as follows. In some of the western regions (such as Calgary and Whitehorse), the atmosphere is normally dry which means that melting of snow aloft is reduced since the wet bulb temperature is lowered. Over the temperature window studied here of 2°C, more of the snow will not have melted. In contrast, the Atlantic region is buffeted by large storms coming from the south. These vigorous storms almost always mean surface

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temperatures pass from below to above 0°C with near saturated conditions; they also have strong warm air advection aloft which often leads to inversions and freezing rain.

5.2 Enhanced occurrence of near 0°C conditions

As shown in Fig. 1, near 0°C conditions are prominent in several of the representative stations. At four locations, this is the most common temperature band despite wide variations in their whole span of temperature as well as geographic location. These stations are Whitehorse, Churchill, Toronto and St. John's. As well, there is a secondary peak near 0°C at Winnipeg. Cambridge Bay and Montreal did not display dramatic change near 0°C although there is a jump in occurrence from colder temperatures. At Vancouver and Calgary, no obvious enhancement is apparent.

The enhanced occurrence of near 0°C conditions is similar to the pattern found in Japan by Fujibe (2001). This study attributed the enhancement to the melting of falling snow, which cooled temperatures towards 0°C. This is likely occurring in Canada but other factors are also critical as discussed in Sect. 5.1. For example, the only mention of the role played by snowcover by Fujibe (2001) was as a factor leading to stable atmospheric conditions, which would reduce mixing that acts to eliminate isothermal layers near 0°C but there was no mention of the cooling effect of the melting snowpack itself.

5.3 Factors affecting change

A question that arises is whether the observed warming over most Canada during the last few decades (Vincent et al., 2015, 2018), has impacted the occurrence of near 0°C conditions. Results from this study indicate a general lack of statistically significant change in the frequency and maximum duration of near 0°C conditions (Sect. 3.2). This is consistent with the Canada-wide assessment of annual freeze-thaw days (defined as the number of days with daily minimum temperature ≤ 0°C and daily maximum temperature ≥ 0°C) for the period 1948-2016 that found a slight decrease in these events when averaged over the entire country (Vincent et al., 2018). However, regional differences were apparent including minor increases in the Prairies and Ontario. The lack of significant change also holds for the four temperature indicators in this study including the onset and cessation of near 0°C conditions. The major exception is Toronto with significant declines in all four temperature indicators as well as in the onset and cessation of near 0°C conditions. Montreal only showed significant declines in the number of near 0°C events, Whitehorse shows significantly earlier spring cessation; St. John's shows significantly later autumn onset. Several stations illustrated significant change (increase and/or decrease) in the occurrence of at least one precipitation type but only Churchill experienced a significant decrease in the occurrence of any precipitation type.

It is not surprising that significant trends are not always evident. This may simply reflect a relatively short observational period (31 years) for stations with large inter-annual variability. As well, and as discussed in Sect. 5.1 and 5.2, many factors contribute to the occurrence of near 0°C conditions and these can counter each other. At many stations, temperatures in mid-winter are far below 0°C. Even with warming, that is still largely the case. For such stations, overall warming simply leads to a shift in near 0°C timing towards winter so the total number of occurrences does not necessarily change. In contrast, some stations, such as in southern Ontario (for example, Toronto), are normally not far below 0°C in mid-winter. With overall warming, these stations experience a shift in near 0°C occurrence towards winter but more instances of mid-winter temperatures above 2°C will occur, so they should experience an overall decrease in near 0°C occurrences. In addition, the factors contributing to near 0°C conditions would continue to be active despite warming. Snowcover and sea ice formed and melted; ground frozen and thawed. One exception may again be in southern Ontario where the ground may not have frozen as much or be covered by as much snow (Vincent et al., 2015); these factors may have contributed to some of this region's significant decreases in occurrence-related indicators.

These findings represent a basis for examining how near 0°C conditions may change in the future. Some studies of future freezing rain conditions have been carried out over North America (e.g., Lambert and Hansen, 2011; Jeong et al. 2019) and southern Quebec (Matte et al., 2018) but none has focused specifically on near 0°C conditions.

One can anticipate more indications of significant trends in near 0°C conditions. Even though this is not generally apparent so far, there should eventually be, for example, widespread delays in occurrence in autumn and earlier cessation in spring at southern locations. But the total number of occurrence may be countered by warmer mid-winters, although at locations such as in Toronto, temperatures mid-winter may be substantially more often sustained above 2°C (and thus no longer as often near 0°C). This latter factor may not occur for a long time at locations such as Winnipeg, where temperatures are normally far below 0°C in mid-winter. Such expected changes would be expected to affect the occurrence of the near 0°C conditions shown in Fig. 1. For example, these conditions should become less prominent at Toronto but not necessarily at stations such as Winnipeg.

6 Concluding remarks

Temperatures near 0°C represent an important issue all across Canada. A comprehensive characterization of near 0°C conditions and the occurrence of associated precipitation types has been carried out. To accomplish this, the study had to carefully address which stations had good quality hourly data for a sufficient period; 92 location were finally used for the 1981-2011 period. The period's last year 2011 was determined by the shrinking manual observation program required for the precipitation type observations. The analysis was completed for four temperature related indicators, 12 precipitation types and four combined temperature and precipitation type indicators. With the $-2 \leq T \leq 2$°C criterion, important insight was gained from the 31 year climatological and trend assessments for all locations and from in depth analysis of the nine case study locations. Key findings include:

- The entire country is characterized by highly variable near 0°C occurrences, events, durations, and associated precipitation types that have been quantified for the first time.
- There are systematic preferred regions in the occurrence of near 0°C conditions and the associated precipitation types that can be explained by large to regional scale conditions. Stations near oceans, for example, tend to have the largest values due to the moderating effects of near 0°C oceanic temperatures.
- A distinctive pattern related to the occurrence of several precipitation-related indicators is an east-west divide roughly down the center of the country. This is likely the reflection of moisture access with eastern regions being subject to more moisture from warmer sub-tropical oceanic sources whereas much of western Canada does not have this moisture source.
- As expected, the monthly near 0°C occurrences peak when average monthly temperatures are near 0°C and there is a sharp fall off as averages move away from this value although there are rare occurrences at much colder or warmer temperatures.
- The occurrence of near 0°C values is influenced by numerous factors including the solar heating and the annual temperature cycle. As well, snowcover, precipitation, ground conditions and sea ice can be important; all of these simultaneously melt and freeze with effects always being to tip temperatures towards 0°C. In addition, ocean temperatures near Canada tend to often be near 0°C during the cold season especially.

- The longest duration events are associated with prolonged cloud cover.
- The aforementioned processes lead to near 0°C temperatures often being the most common occurring temperatures during the year. This observation is evident over wide geographic and climatic areas.
- Even though surface temperatures have generally increased over the 1981-2011 period, occurrences of near 0°C conditions have not trended in a similar fashion. This arises at least in part because increased temperatures in the warm season lead to fewer conditions but this is largely balanced by more in the cold season. In addition, the processes acting to maintain near 0°C conditions have generally continued to occur even as overall temperatures have increased. One exception is Toronto, which always had cold season temperatures not too far below 0°C.

Although this analysis has provided valuable insight regarding near 0°C temperatures across Canada, further research is required to obtain a better understanding of these conditions. For example, this study did not address the directional change in near 0°C occurrence, which impacts whether the region is going from a cold-to-warm state or vice versa. Cold-to-warm versus warm-to-cold would be linked with the two branches of the diurnal cycle as well as with warm and cold fronts, respectively; these factors should affect duration and precipitation types. In addition, near 0°C conditions are closely related to freeze-thaw cycles that can have numerous economic and environmental impacts. This is also a critical area of future research. This study can be considered a first step in the better understanding of near 0°C conditions and associated precipitation across Canada.

Data availability. The dataset used in this article is available through Environment Climate Change Canada.

Author Contribution. EM was the lead author who obtained and analyzed most of the data as well as writing several sections of the article. RES wrote several sections and carried out some of the analyses. JMT and ZL carried out analyses and contributed to the manuscript. BK and BRB contributed to the manuscript. All authors contributed scientifically by providing comments and suggestions.

Competing interests. There are no competing interests.

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Tables

Table 1: Table of indicators in the -2 ≤ T ≤ 2°C range.

DEFINITIONS	UNIT
Temperature related	
Annual number of days with $-2^oC \leq T_{drybulb} \leq +2^oC$	days
Annual number of hours with $-2^oC \leq T_{drybulb} \leq +2^oC$	hours
Annual number of independent events (continuous hours) with $-2^oC \leq T_{drybulb} \leq +2^oC$	events
Annual Maximum Lengths with $2^oC \leq T_{drybulb} \leq +2^oC$	hours
Precipitation types related (occurences; 12e): Annual number of hours with	
... Rain	hours
... Rain Showers	hours
... Drizzle	hours
... Freezing Rain	hours
... Freezing Drizzle	hours
... Snow	hours
... Snow Grains	hours
... Ice Crystals	hours
... Ice Pellets	hours
... Ice Pellet Showers	hours
... Snow Showers	hours
... Snow Pellets	hours
... all 12 weather types above	hours
Combination of temperature and precipitation type	
Annual number of hours with freezing rain and $-2^oC \leq T_{drybulb} \leq +2^oC$	hours
Annual number of hours with any of the 12 precip types and $-2^oC \leq T_{drybulb} \leq +2^oC$	hours
The fraction of [$-2^oC \leq T_{drybulb} \leq +2^oC$] conditions associated with Freezing Rain	%
The fraction of [$-2^oC \leq T_{drybulb} \leq +2^oC$] conditions with any of the 12 precip types	%

Table 2: Near 0°C trends based on surface temperature for the 1981-2011 period (minimum 90% of data). Average (Aver) trend values over the 1981-2011 period. An arrow indicates a statistically significant (sign) increase (pointed up) or decrease (pointed down). Stations are arranged from west to east.

	Number of Hours		Number of Days		Number of Events		Maximum Duration	
	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign
Whitehorse	100.4	no	-10.3	no	-18.5	no	22.9	no
Vancouver	7.2	no	1.8	no	3.1	no	-5.2	no
Calgary	46.1	no	-2.6	no	-16.9	no	-6.3	no
Cambridge Bay	-110.2	no	-2.0	no	0.0	no	-36.6	no
Winnipeg	0.0	no	-8.9	no	9.3	no	8.9	no
Churchill	-143.6	no	-3.1	no	0.8	no	-27.9	no
Toronto	-316.9	↓	-26.9	↓	-35.8	↓	-25.4	↓
Montreal	-69.0	no	-10.3	no	-15.5	↓	6.2	no
St. John's	90.4	no	-3.6	no	-15.5	no	7.0	no

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Table 3: Near 0°C trends based on 12 precipitation type occurrence information for the 1981-2011 period (minimum 10 years). Average (Aver) trend values over the 1981-2011 period are shown. An arrow indicates a statistically significant (sign) increase (pointed up) or decrease (pointed down) and the last columns refers to the average trend of any of the 12 precipitation (precip) types and whether these are statistically significant. Stations are arranged from west to east.

	Rain		Rain Showers		Drizzle		Freezing Rain		Freezing Drizzle		Snow		Snow Grains		Ice Crystal		Ice Pellets		Ice Pellet Showers		Snow Showers		Snow Pellets		All 12 Prec Types	
	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign	Aver	Sign
Whitehorse	-1.8	no	5.6	↑	-1.0	no	-	n/a	-	n/a	-45.1	no	-	n/a	-	n/a	-	n/a	-	n/a	24.8	no	-1.7	no	-6.7	no
Vancouver	-8.2	no	3.4	no	0.0	no	-	n/a	-	n/a	-6.4	no	-	n/a	-	n/a	-	n/a	-	n/a	-10.4	no	-	n/a	-10.9	no
Calgary	5.2	no	-3.2	no	0.0	no	-	n/a	0.0	no	44.4	no	0.0	no	-	n/a	-	n/a	-	n/a	-69.3	↓	-2.6	no	-5.2	no
Cambridge Bay	7.6	no	30.2	↑	-18.6	no	0.0	no	-5.9	no	16.4	no	-2.1	no	-	n/a	-4.0	↓	-	n/a	78.1	↑	-0.8	no	85.6	no
Winnipeg	-0.6	no	0.0	no	-5.4	no	0.0	no	-1.1	no	-10.5	no	1.1	no	-	n/a	0.4	no	-	n/a	8.5	no	0.0	no	8.1	no
Churchill	-1.1	no	-9.4	↓	-70.6	↓	0.0	no	-20.7	↓	12.7	no	-17.5	no	0.0	no	-7.8	↓	-	n/a	-54.9	↓	-2.8	no	-144.5	↓
Toronto	-13.5	no	-6.7	no	-21.7	↓	-3.9	no	-4.4	no	-9.7	no	1.3	no	-	n/a	-2.2	no	0.0	no	-14.2	no	-4.6	no	-95.6	no
Montreal	0.0	no	-4.9	no	-6.9	no	-7.4	no	-8.9	↓	0.0	no	-11.3	no	-	n/a	-2.8	no	0.0	no	-17.7	no	-3.3	no	-24.8	no
St. John's	15.5	no	-48.1	↓	-31.0	no	-18.9	no	-66.6	↓	112.7	↑	-20.8	↓	-	n/a	-0.1	no	0.0	no	-14.6	↓	-3.9	no	-51.1	no

Table 4: The longest duration events at the 9 representative stations. Columns indicate maximum duration, start time, and hours (and fraction of duration) with mainly or completely clear skies. Times are UTC.

Station	Duration	Start Time	Mainly/Completely Clear	
	(h)	(YYYY-MM-DD-HH)	(h)	(%)
Whitehorse	110	1998-10-06-21	3.0	2.7
Vancouver	68	2005-01-06-04	1.0	1.5
Calgary	73	2003-05-05-10	0.0	0.0
Cambridge Bay	197	1987-06-11-08	3.0	1.5
Winnipeg	128	1983-03-01-15	0.0	0.0
Churchill	141	1986-10-18-12	1.0	0.1
Toronto	158	1986-12-26-16	0.0	0.0
Montreal	114	2007-12-24-12	8.0	7.0
St. John’s	148	1983-04-01-06	14.0	9.5

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480 **Figures**

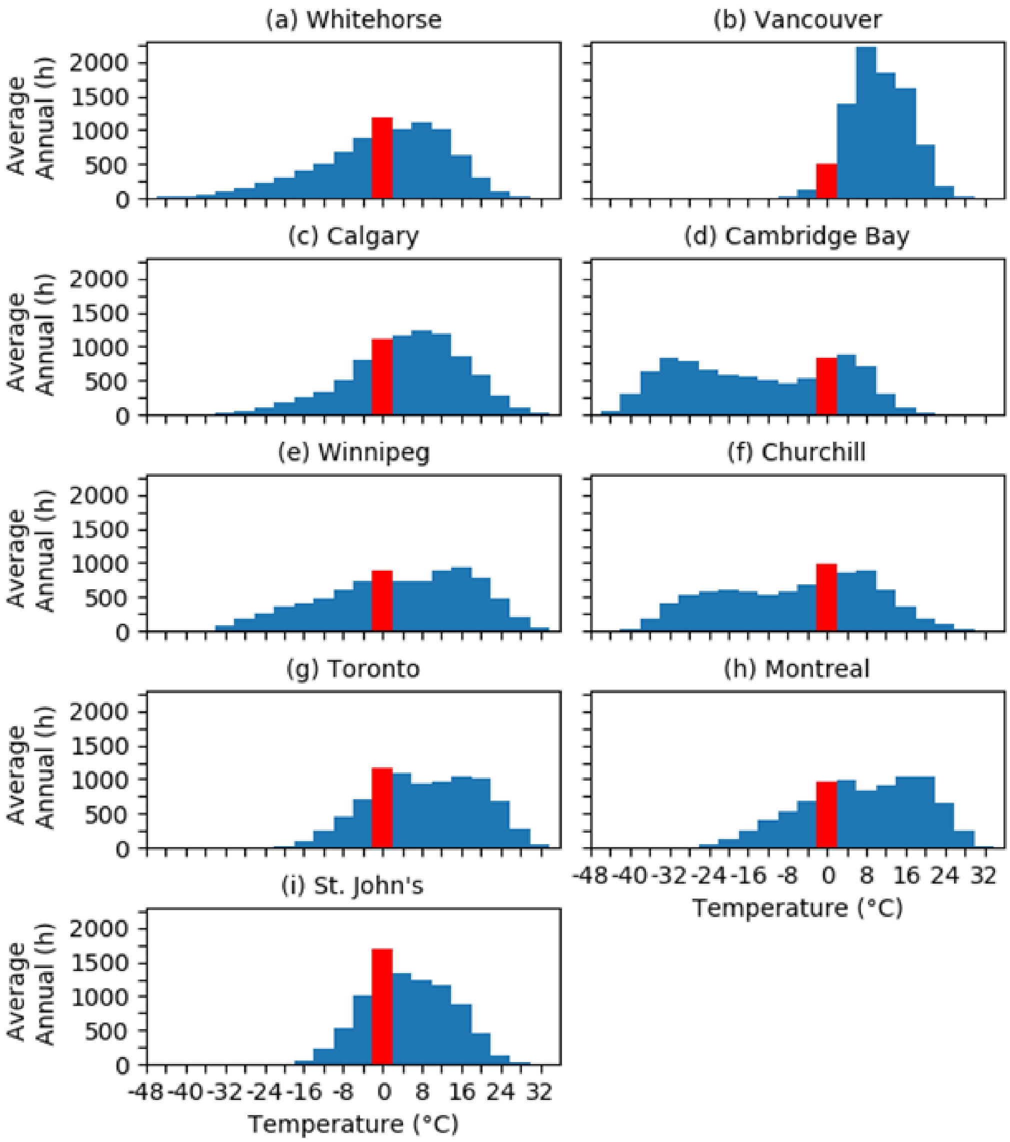

Figure 1: The average annual temperature distribution from 1981 to 2011 for 9 representative stations across Canada as shown in Fig. 2. The red bar identifies near 0°C temperatures defined as -2 ≤ T ≤ 2°C. Stations are arranged from west to east. Details on the temperature data are in Sect. 2.

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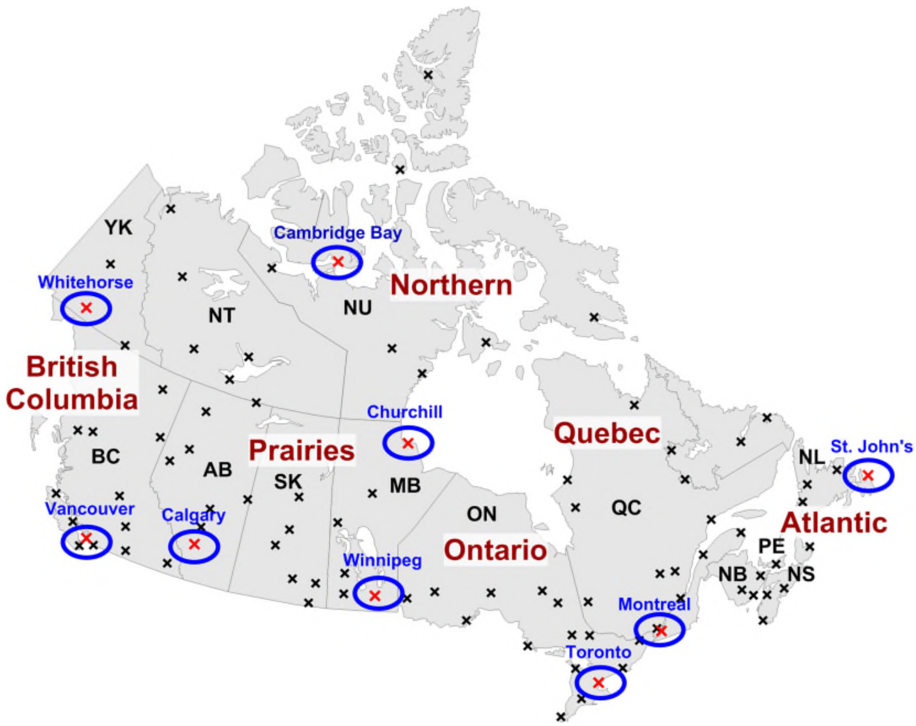

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Figure 2: The 92 stations used in the analysis (see text for details). Blue ellipses and red crosses show the 9 representative stations across Canada. British Columbia region includes all stations in British Columbia (BC); Prairies region - all stations in Alberta (AB), Saskatchewan (SK) and Manitoba (MB); Ontario region - all stations in Ontario (ON); Quebec region - all stations in Quebec (QC); Atlantic region - all stations in New Brunswick (NB), Prince Edward Island (PE), Nova Scotia (NS), Newfoundland and Labrador (NL-
490 L); and Northern region - all stations in Yukon (YK), Northwest Territories (NT) and Nunavut (NU).

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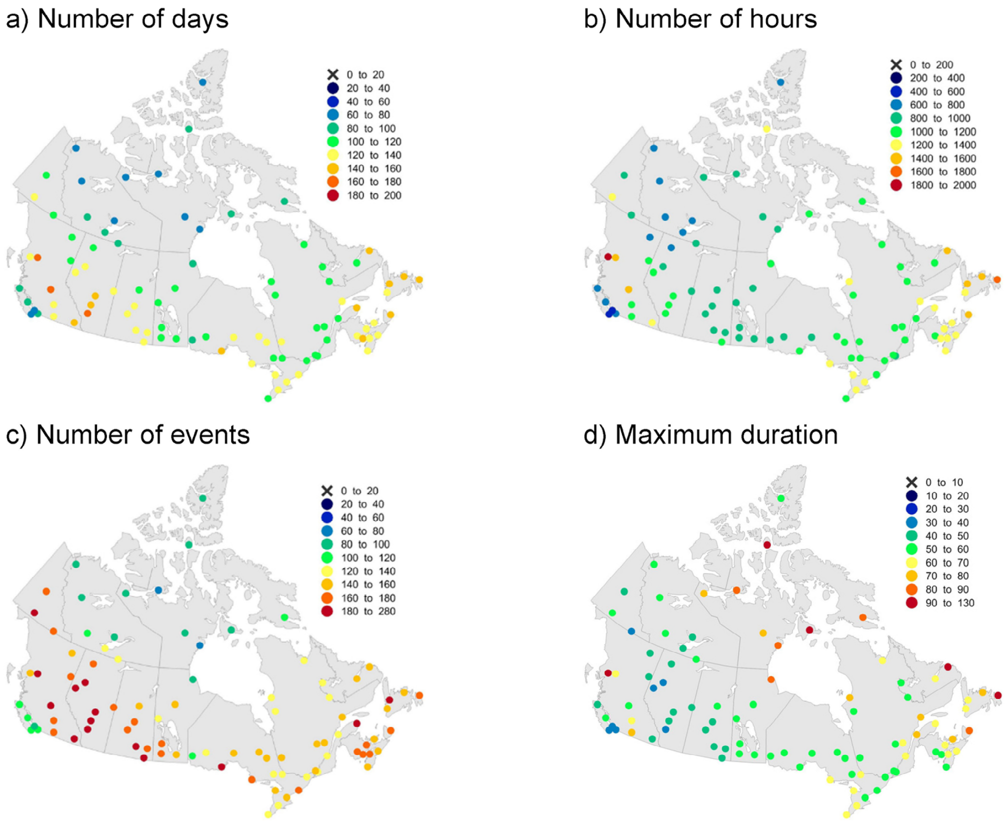

Figure 3: Average near 0°C ($-2 \leq T \leq 2$°C) conditions over the 1981-2011 period for (a) number of days per year, (b) number of hours per year, (c) number of events per year, and the (d) annual maximum (max) duration of events.

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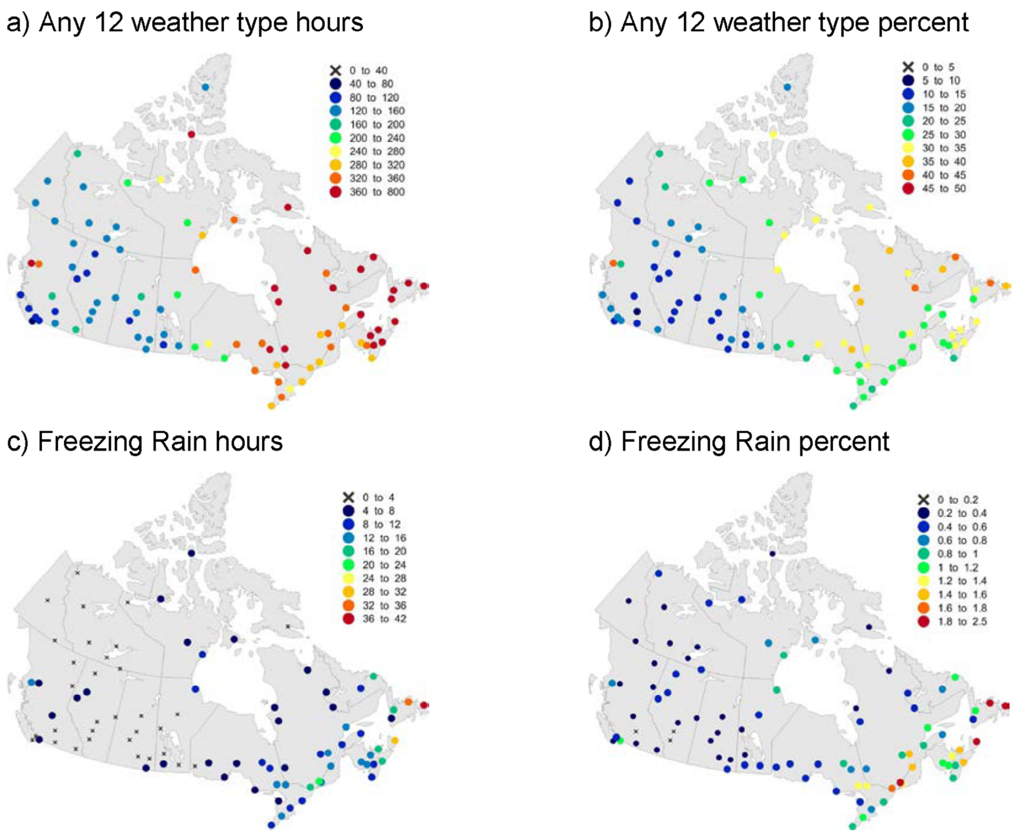

495 **Figure 4: Precipitation type occurrences during near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period, where (a) average annual number of hours with reported precipitation types (any of the 12), (b) percentage of near 0°C conditions associated with reported precipitation types (any of the 12), (c) average annual number of hours with freezing rain, and (d) percentage of near 0°C conditions associated with freezing rain.**

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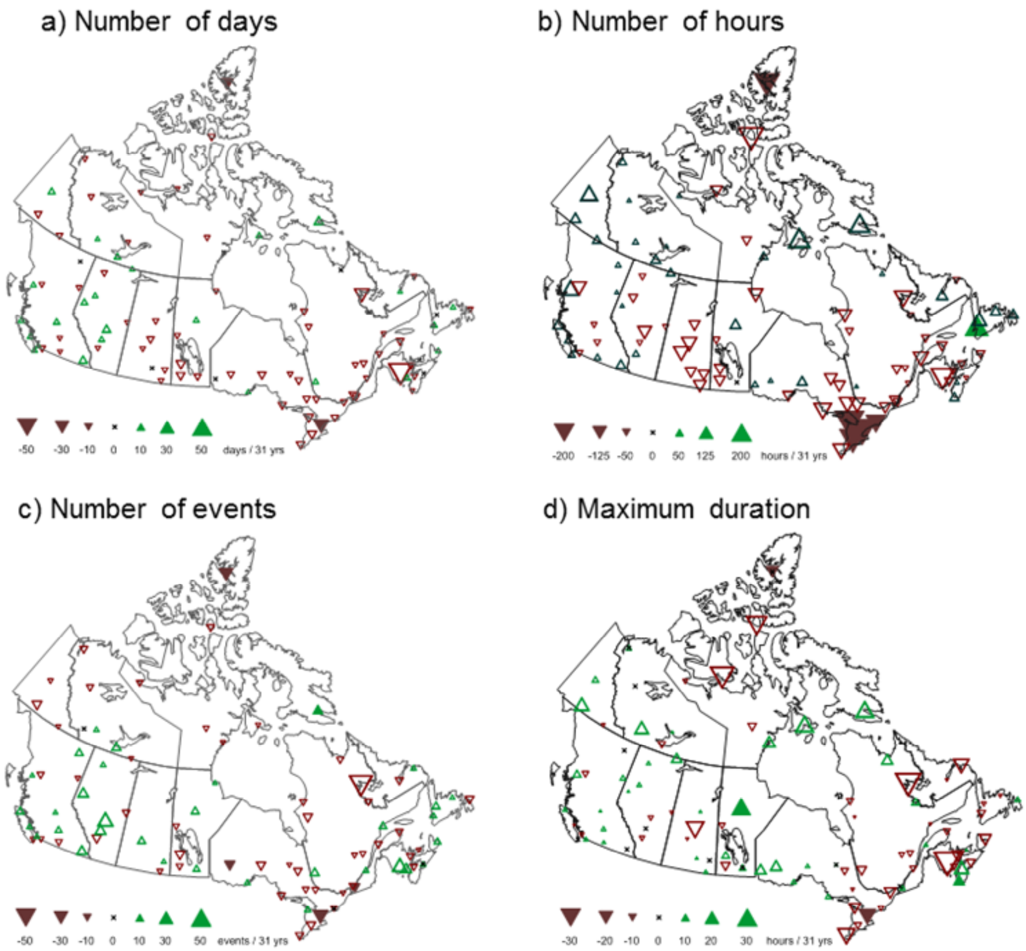

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Figure 5: Trends in near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period. (a) annual average number of days, (b) annual average hours, (c) annual number of events, and (d) annual maximum duration. A solid triangle indicates statistical significance.

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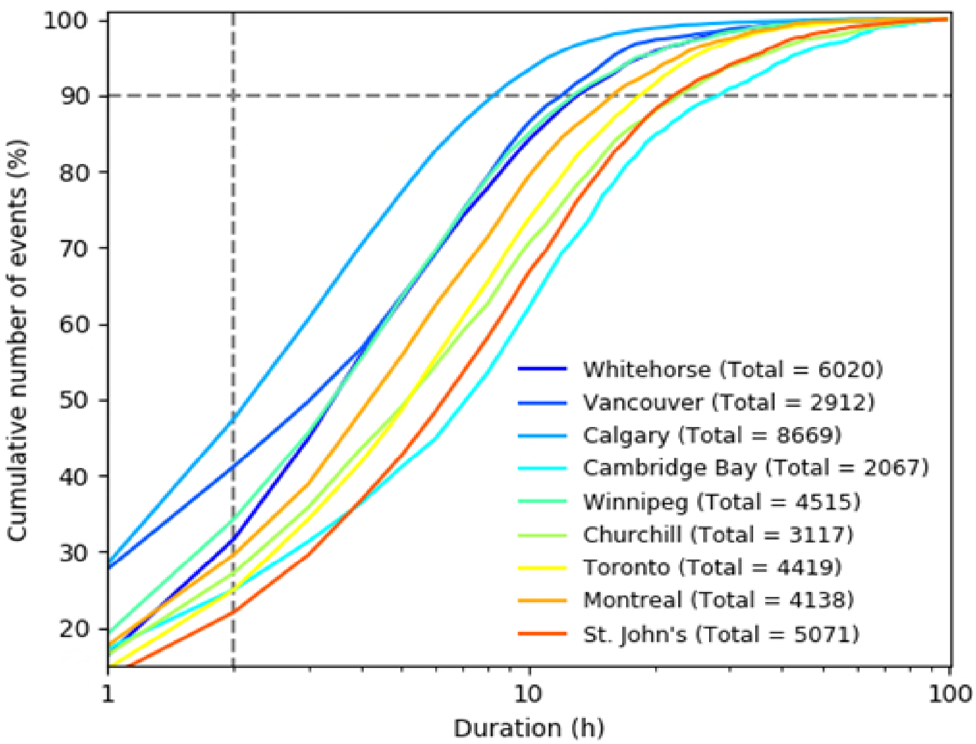

505 **Figure 6: Cumulative distribution of events (%) as a function of duration (h) of near 0°C (-2 ≤ T ≤ 2°C) events at the 9 representative stations across Canada over the 1981-2011 period arranged from west to east. The total number of events is also indicated and duration is plotted on a logarithmic scale.**

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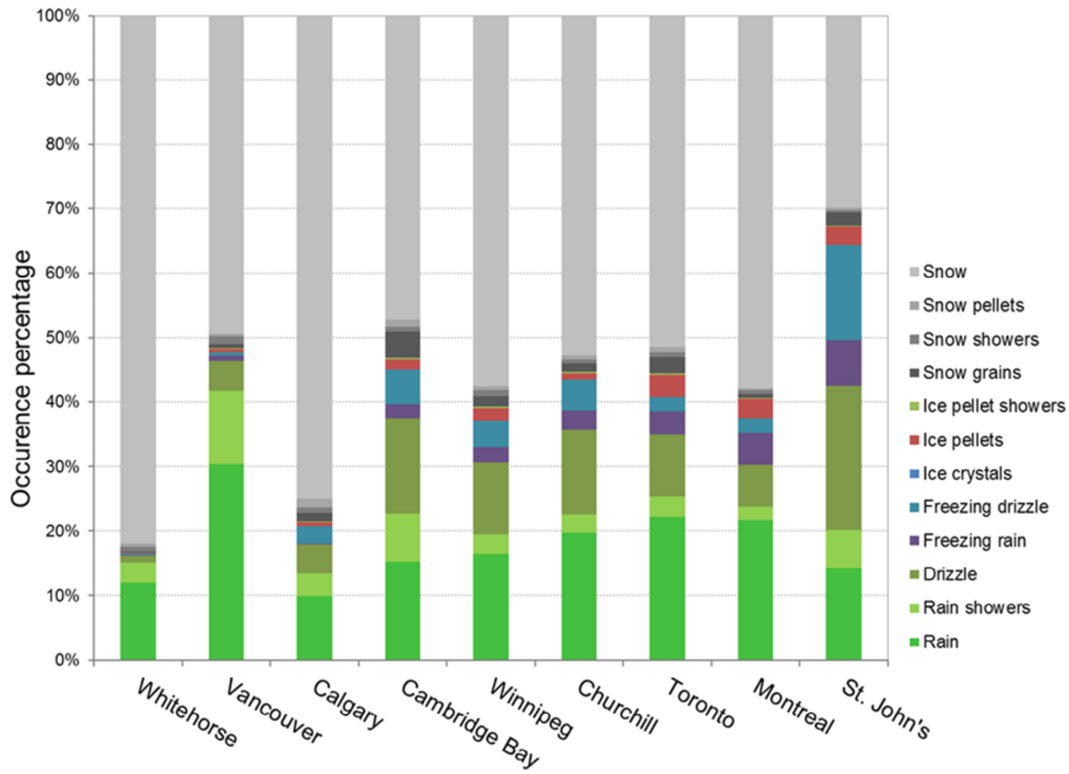

Figure 7: The distribution of precipitation type occurrence with near 0°C conditions at each of the 9 stations over the 1981-2011 period. Stations are arranged from west to east.

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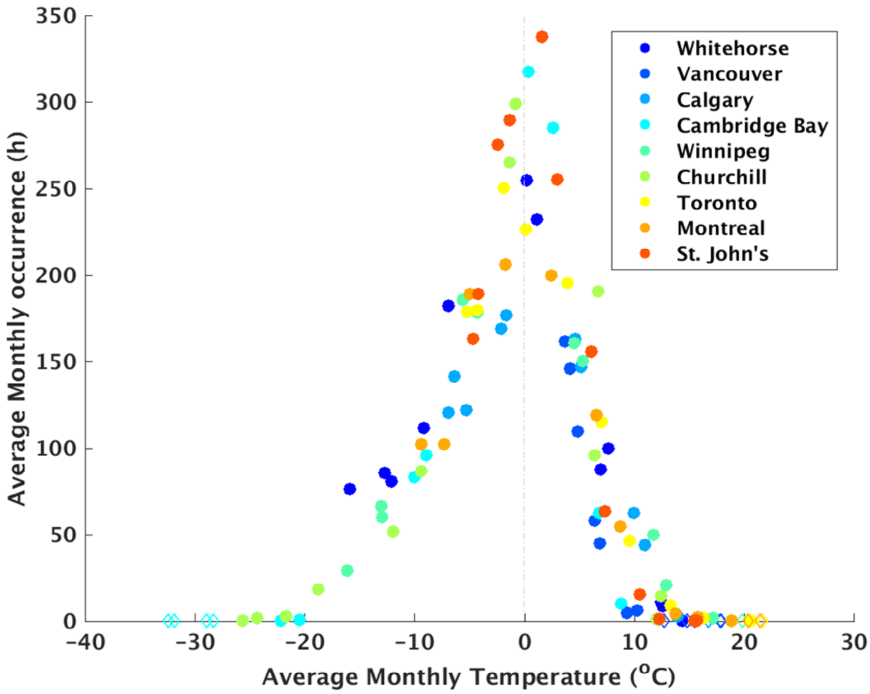

Figure 8: Average monthly occurrence (hours) of near 0°C conditions as a function of average monthly temperature for the nine representative stations over the 1981-2011 period. The open diamond symbol indicates no occurrence.

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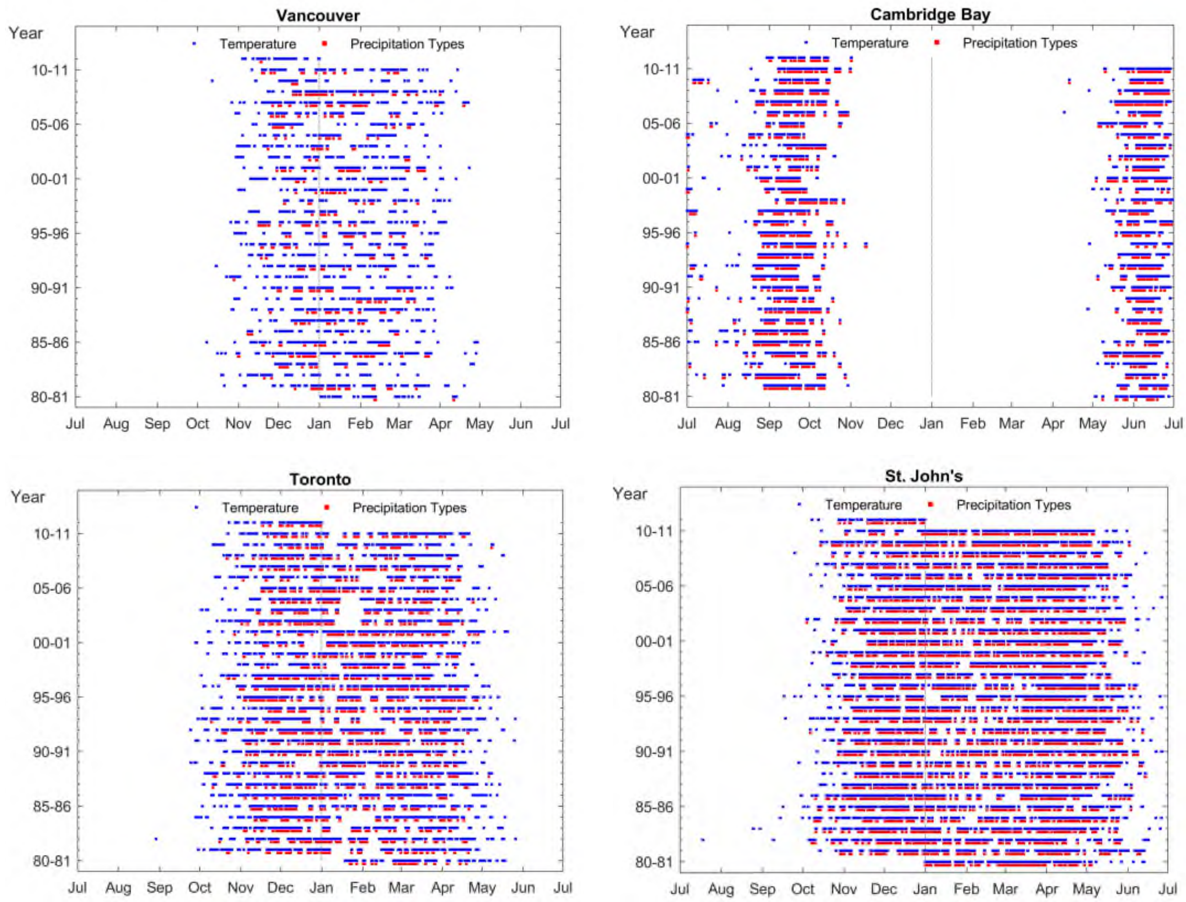

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Figure 9: The occurrence of near 0°C conditions and any (of the 12) associated precipitation types at (a) Vancouver, (b) Cambridge Bay (c) Toronto and (d) St. John's over the 1981-2011 period. Blue and red bars indicate hourly occurrences of temperature and associated precipitation types (any of the 12), respectively. The vertical, dashed line indicates January 1.