Near 0°C surface temperature and precipitation type patterns across Canada

Eva Mekis[1], Ronald E. Stewart[2], Julie M. Theriault[3], Bohdan Kochtubajda[4], Barrie R. Bonsal[5] and Zhuo Liu[2]

[1]Meteorological Research Division, Environment and Climate Change Canada, Toronto, M3H5T4, Canada
[2]Department of Environment and Geography, University of Manitoba, Winnipeg, R3T2N2, Canada
[3]Centre ESCER, Department of Earth and Atmospheric Sciences, Université du Québec à Montréal, H2X3Y7, Canada
[4]Meteorological Service of Canada, Environment and Climate Change Canada, Edmonton, T6B1K5, Canada
[5]Watershed Hydrology and Ecology Research Division, Environment and Climate Change Canada, Saskatoon, S7N3H5, Canada

Correspondence to: Eva Mekis (eva.mekis@canada.ca)

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 is especially important in cold regions such as Canada because it is linked with freeze-thaw, snowmelt and permafrost. This study develops a Canada-wide perspective on near 0°C conditions using hourly surface temperature and precipitation type observations from 92 climate stations for the period 1981 to 2011. 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 types of precipitation (for example rain, freezing rain, wet snow and ice pellets) sometimes occur with these temperatures. The near 0°C conditions and the reported precipitation type occurrences tends to be higher in Atlantic Canada, although high values also occur in other regions. Trends of most temperature-based and precipitation-based indicators show little or no change despite a systematic warming in annual surface temperatures over Canada. 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 surface temperatures to occur more often than expected relative to other temperature windows at some stations; 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, both 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, 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 (e.g., Beltaos et al., 2006; Lindenschmidt et al., 2016), freeze-thaw damage to infrastructure (e.g., Kraatz et al., 2019), unseasonal frosts (e.g., McKenney et al., 2014), and recreation impacts (skiing, avalanches) (e.g., Moen and Fredman, 2007; Laute and Beylich, 2018). Furthermore, if these periods are associated with precipitation (e.g., freezing rain/ice-storms), severe

35   and sometimes life-threatening impacts are possible including damaged electrical transmission infrastructure, air traffic disruptions and hazardous road conditions. If near 0°C occurrences change, this will have subsequent impacts on all these issues.

Many regions of Canada 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

40   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

45   people without electricity for days.

Near 0°C conditions occur over many areas of the world. Over land areas, even high terrain experiences such conditions. Some of the most critical questions associated with our changing climate are associated with temperature change and the hydrological cycle. This certainly applies to the future occurrence of near 0°C conditions and its associated precipitation.

There naturally continues to be many studies documenting global, regional and local surface temperatures ranging from climate

50   change synthesis reports (Intergovernmental Panel on Climate Change, 2013) to studies of temperature at individual weather stations. Many of these of course include 0°C but few have focused on this temperature, although, for example, Wexler et al. (1954), Fujibe (2001) and Takeuchi et al. (2002) all showed that melting and/or freezing can affect its occurrence and/or duration.

In contrast, several studies have examined the varying precipitation types near 0°C. Examples of studies examining the occurrence of rain and snow in relation to temperature and, in some cases, relative humidity include U.S. Army Corps of Engineers (1956),

55   Auer (1974), Matsuo and Sasyo (1981a,b), Matsuo et al. (1981) and Kienzle (2008). In general, these studies found a steady increase in the probability of rain as temperatures increase from near 0°C to higher values and they also pointed out that lower atmospheric moisture generally leads to higher temperatures needed for rain to occur. Dai (2008) built on this work to examine global distributions of rain and snow although freezing rain was just included within the snow category in this study. Sims and Liu (2015) developed an algorithm for use with remotely sensed observations to discriminate different types of surface precipitation;

60   they emphasized the importance of atmospheric moisture. Jennings et al. (2018) examined the threshold temperature at which rain and snowfall with equal frequency, mapped this parameter over the Northern Hemisphere, and illustrated its strong dependence on atmospheric humidity. Overall, many of these studies illustrated that the variation in atmospheric moisture directly affects the temperature threshold needed for rain to occur with lower values acting to increase required temperatures. In addition, atmospheric humidity can also influence the characteristics of the melting particles and consequently the threshold. For example, under saturated

65   conditions aloft with rising air, cloud droplets can be produced and later be captured by falling precipitation particles. The ensuing rimed, more dense particles require greater fall distances and/or higher temperatures to melt (Stewart et al., 2019).

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.

70   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 for Canada and this was later updated by Stuart and Isaac (1999) and Wang (2006). 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). 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 freezing precipitation occurrence and, in some cases, related these findings to contributing factors such as mountain barriers and coastlines. A recent study also identified the impacts of extreme weather on critical infrastructure in Europe (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. A preliminary assessment of near 0°C surface temperatures across Canada (Fig. 1) shows that they occur at stations at which average annual surface temperatures range between below, near, and substantially above 0°C. Given the aforementioned importance of this threshold, additional information is necessary to better understand its spatial and temporal characteristics across Canada. This includes the associated precipitation that often results in the greatest impacts.

The objective of this study is therefore to quantify and improve understanding of near 0°C conditions temperature and precipitation type patterns across Canada. Data and methods are described first, followed by an assessment of climatology and trends in key identified variables. Next, selected stations are examined in more depth followed by a discussion of several critical near 0°C features and by concluding remarks.

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 Historical Climate Data portal at various temporal scales ranging from hourly to annual (http://www.climate.weatheroffice.ec.gc.ca, ECCC, 2019a). Since this study focuses on the identification of conditions near 0°C at the surface along with associated precipitation, hourly surface temperature and the manual precipitation type observations across Canada were retrieved from the archive.

Selecting appropriate stations for further analysis was determined by data availability and 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 hourly surface temperature and precipitation type information, many were not operating 24 hours a day whereas others changed their 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 surface dry

bulb temperature data availability (equivalent to an average requirement of 21 hours per day). For precipitation type observations, the only condition was the existence of the program during the study period.

Consequently, to maximize the number of stations but still maintain a sufficiently long period for climatological studies, the 31
110 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, the following 12 manual weather (precipitation) type observations 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. Reporting was carried out according to World Meteorological Organization standards that are described
115 in the Manual of Surface Weather Observation Standards (MANOBS https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manobs-surface-observations.html, ECCC, 2019b). Precipitation intensity is characterized using four distinct values based on visibility or the rate of rainfall ranging from absent to 'heavy', but, for the purposes of this study, only the presence or absence of precipitation types was considered. Definitions are described in American Meteorological Society (2018), ECCC (2019b) and WMO (2017).

120 Canada is a vast country with many different climatic regions (Gullett et al., 1992) and ecozones (Zhang et al., 2001). For easier evaluation of the results, similar to Vincent et al. (2018), the country was divided into six broad regions based on the 13 provincial/territorial boundaries (Fig. 2). In addition to the Canada-wide analysis, nine stations were chosen for further analysis (Fig. 2). These stations, having high quality consistent observing practices, represent contrasting climatic conditions across the country.

125 **2.2 Methods**

This analysis identified key near 0°C characteristics and threshold events during the study period. There is no precise, physically based criterion that can be used to characterize conditions near 0°C although we did want to focus on conditions in which embedded change in precipitation types is common. We note that WMO Solid Precipitation Intercomparison Experiment (SPICE) broke down precipitation into three categories based on surface temperature (T) with those being snow < -2°C, mixed precipitation -2°C ≤ T ≤
130 2°C, and rain > 2°C (Nitu et al., 2018); this approach was similar to that used by Yang et. (1995, 1998). As well, Matsuo et al. (1981) found that almost all of the precipitation near rain-snow transitions in Japan is rain if the surface temperature is ≳ 2°C and relative humidity is ≳ 90% and we also note that Kochtubajda et al. (2017) found that 75% of freezing rain across the Canadian Prairies and northern Canada fell at surface temperatures ≳ -2°C. To provide a reasonable symmetric temperature window straddling 0°C with embedded large fractions of overall occurrences of varying precipitation types, we defined near 0°C conditions
135 as -2 ≤ T ≤ 2°C throughout the paper.

A total of 21 indicators were considered (Table 1). The first four indicators are associated with the near 0°C temperature condition (measured as hourly surface dry bulb temperature) without any consideration of precipitation. They are the number of days per year; number of hours per year; 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 ≤ T ≤ 2°C range. Note that to be considered a
140 single event, there could be no more than three continuous hours of missing data. To assess precipitation during near 0°C conditions, a further thirteen precipitation type indicators were computed. In addition, the combination of temperature and precipitation type provides an additional four indicators. 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, these rather

145   than other frozen precipitation, 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. The assessment of the trend can be challenging for time series with low occurrences and repetitive (tied) values (Frei and Schar, 2001 and Keim and Cruise, 1998) such as the annual number of days with certain precipitation types. The Chi-square test was applied to the data to determine whether the data is following normal or Poisson distribution. Depending on the results, two different

150   approaches were used to estimate the trends. For the data with normal distribution (most of the surface temperature related indicators), the estimated magnitude of the trend is based on the slope estimator of Sen (1968), and the statistical significance of the trend is based on the nonparametric Kendall's tau-test (Kendal, 1955). This same approach was recently used to assess trends in Canada's climate (Vincent et al., 2015) and in surface temperature and precipitation indices (Vincent et al., 2018). 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

155   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). For the data following the parametric Poisson distribution (mainly the precipitation type indicators), the logistic model was applied to transform the time-series (McCullagh and Nelder, 1989). This case only the direction (positive and negative trends) and the significance of the fitted curve were used in the analysis. The statistical significance of the trends were assessed at the 5% level. Given the aforementioned aspect

160   of missing data and similar to earlier works (Mekis et al., 2015; Vincent et al., 2018), the trends were calculated if there were at least 90% of the values (29 out of 31 years) were available, otherwise the trends were set to missing.

In addition to the temperature and precipitation type occurrence information, hourly sky cover was also extracted over the nine representative stations. Sky conditions are reported in units of octas according to World Meteorological Organization standards that are described in the Manual of Surface Weather Observation Standards (ECCC, 2019b). If multiple cloud layers are observed,

165   then the octas of the layers are summed. This information was only examined for the longest duration near 0°C conditions at these stations.

The average annual surface temperature contour lines was computed from the 1981-2010 climate normal period (http://climate.weather.gc.ca/climate_normals/index_e.html, ECCC, 2019c). Kriging with a linear Variogram model and a grid spacing of 50 km was applied to create the interpolated surface temperature map from the 1619 stations for Canada.

170   **3 Climatology and Trends**

3.1 The 31-Year Climatology for 1981-2011

Figure 3a shows the number of days per year when surface temperatures were between -2°C and +2°C. In relation to the average annual 0°C surface temperature line, it is apparent that high values generally occur at stations that are near or above 0°C. There are distinct regional patterns with the largest values (120 to 200 days) concentrated in three main areas. Highest occurrences are

175   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. 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

180 and Labrador. This area is colder than the previously mentioned regions with fewer incursions of warm air during the 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 to values 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.

185 Figure 3b shows the average number of hours per year with surface temperatures between -2°C and +2°C. Unlike the number of days in Fig. 3a, the number of hours shows less dependence on the location of the average annual 0°C surface temperature line. Overall, the spatial distribution is similar to that of Fig. 3a, but 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 east of the Canadian Rockies so they show up in the number of days but not as an extended number

190 of hours. High values are even more pronounced in Fig. 3b than in Fig. 3a at one northern coastal British Columbia station (Terrace) where maximum values of 1800-2000 hours represent approximately 80 days per year. This northern British Columbia station near 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 to Fig 3a, there are now three distinct areas of low values (< 800 hours) in the average number of hours near 0°C (Fig. 3b). These areas are the far North; southwestern British

195 Columbia; and northern British Columbia, and the Northwest Territories. This latter region experiences warm summer conditions when temperatures seldom reach this low and cold winter conditions when temperatures seldom reach this high.

Figure 3c shows the average number of events per year. Similar to Fig. 3a, almost all high values occur at stations with average annual surface temperatures near or above 0°C. Spatial patterns are also similar to those in Fig. 3a with maximum values (180-280) in the west extending into southern Saskatchewan. High values are observed within the previously mentioned area of the

200 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 (120 - 140) is also comparable to the number in the southern Northwest Territories even though, again, there are far more hours in southern Ontario.

The annual maximum duration of events, characterizing the occasional persistence of such events, is shown in Fig. 3d. Maximum

205 duration of events tend to show little dependence on the average annual 0°C surface temperature line across the entire country. The spatial 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 hours or ~5 days. Lowest maximum durations (10 - 20 hours) occur in the lee of the Rocky Mountains as well as in southern British Columbia.

210 Figures 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. There is no strong dependence in the occurrence of any weather type in relation to the position of the average annual 0°C surface temperature line. 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

215 (except northern coastal British Columbia) with the lowest value (40 - 80 hours) occurring on Vancouver Island. 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 (120 - 160 hours and 360-800 hours).

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. As in Fig. 4a, there is little dependence on average 220 annual surface temperature. The spatial 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 - 20% in western Canada.

Figure 4c shows the average annual number of hours of freezing rain with surface temperatures near 0°C. In contrast to Figs. 4a-b, highest values of freezing rain primarily occur at stations with average annual surface temperature above 0°C. Maximum values 225 by far are in the Atlantic region (36 - 42 hours) and there is a regional maximum near Montreal (20 - 24 hours). Low values (0 - 4 hours) occur in other regions of the country, especially in the North and much of the west. In fact, freezing rain is rarely reported on the western side of the Prairies and North.

Figure 4d shows the percentage of near 0°C hours with freezing rain. Consistent with the freezing rain hours in Fig. 4c, highest values of freezing rain percent also tend to occur at stations with average annual surface temperature above 0°C. The spatial pattern 230 is also similar to that in Fig. 4c. This includes highest values (1.8 - 2.5%) being in the Atlantic region with a secondary maximum near Montreal. One isolated, high value (1.0 - 1.2%) does occur near Vancouver however.

3.2 Trends

Figure 5a shows trends in the number of days with temperatures near 0°C over the 1981-2011 period significant at 5% level. There is no apparent relationship in these trends to the average annual 0°C surface temperature line. The majority of stations are 235 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, there is no simple relationship to the average annual 0°C surface temperature line, although more decreasing trends are evident in areas above 0°C. Most stations 240 also 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 245 extreme southwestern part of the province.

Figure 5c shows trends in annual number of events with near 0°C conditions. No apparent pattern in relation to the 0°C surface temperature line was found. 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, 20 250 and 16 number of events, respectively, over the 31 year period.

Figure 5d shows trends of the maximum duration. As in Figs. 5a-c, there is no simple relation to average annual surface temperature. 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 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 Selected 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). Annual average frequencies for the four surface temperature and 13 precipitation type related indicators are available in Table 2 and 3 at each case study locations. The greatest annual number of days and number of hours with near 0°C conditions occurred at St John's with 155 days and 1744 hours respectively. The maximum annual number of independent event occurred at Calgary (280 events) while the maximum duration are the coaster stations St John's, Cambridge Bay and Churchill (91, 89 and 84 hours respectively). This is consistent with regional patterns shown in Figs. 3 and 4.

An important characteristic of near 0°C conditions is the duration of events is studied further. As shown in Fig. 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 fewest.

While Table 3 contains the average number of hours of the 12 precipitation types, Fig. 7 shows the distribution in the occurrence based on the same input 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.

As discussed in Sect. 3.2, many stations exhibited some change but few were significant (Fig. 8 and 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. These regional patterns are also somewhat reflected in dependence on average annual surface temperature; high values generally occur at stations with near or above 0°C conditions, although long durations also often occur at stations with below 0°C conditions.

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 five 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. The average monthly occurrences of near 0°C conditions were calculated and these values were compared with average monthly surface temperatures. As shown in Fig. 9a, there is a strong dependence of

average near 0°C occurrences on average monthly surface 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 with higher values generally associated with lower temperatures. Although rare, near 0°C conditions sometimes occurred with average monthly surface temperatures with more than 20°C away from the 0°C line (Fig. 9b). 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 shorter time scales. For example, Fig. 10 shows annual cycles of near 0°C conditions and associated precipitation type occurrences at four stations (Vancouver, Cambridge Bay, Toronto and St. John's) chosen to illustrate a range of variation. Near 0°C conditions do not occur during summer at all southern stations (Figs. 10a, c, d) but they can occur in any other month. In contrast, these conditions only occur in summer at Cambridge Bay (Fig. 10b). The most frequent occurrence can be seen at St John's (Fig. 10d). 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 would be expected that, with overall warming (Bush and Lemmen, 2019), the onset for near 0°C would occur later in autumn and earlier in spring. As shown in Table 3 and Fig. 10c, both of these trends are significant at only one location, Toronto. Whitehorse shows significant earlier spring cessation (Table 4) and St. John's shows significant later autumn onset (Fig. 10d and Table 4). Cambridge Bay experiences near 0°C conditions in every 'warm season' month (Fig. 10b and Table 4) 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 (Table 4).

It is recognized that there are four pathways through which surface temperatures enter and leave near 0°C conditions (Fig. 11). These pathways are events (1) from above to below, (2) from below to above, (3) from above back to above, and (4) from below back to below. As shown in Fig. 11, pathway 3 is most common at all selected stations, Calgary experiences this pathway more than anywhere else (94 events/year), and this pathway dominates at Vancouver. Except for Vancouver and Calgary, the least common pathways are 1 and 2 (which have very similar values at all stations) with the overall lowest value being at Cambridge Bay (< 4 events/year).

Pathways with the highest and lowest fractions of any type of precipitation vary. The highest fractional occurrence of any precipitation is associated with pathway 1 at St. John's (88%), and this pathway is also associated with the highest fraction at Calgary and Cambridge Bay. Pathway 3 is associated with the highest fraction at Vancouver; pathway 4 is associated with the highest fraction at the remaining five stations. The lowest fractional occurrence is associated with pathway 2 at Calgary (19%), and this pathway is associated with the lowest fraction at all stations. St. John's experiences the maximum occurrence of freezing rain for all pathways. The pathway most often associated with freezing rain events varies between stations. For example, it is pathway 1 at Churchill; pathway 2 at Toronto, Montreal and St. John's; and pathway 4 at Winnipeg.

5 Characterizations and interpretations

5.1 Canada-wide patterns and governing factors

The Canada-wide plots exhibit a number of patterns in the temperature indicators. First, there are three general regions in terms of high occurrences of near 0°C conditions (Fig. 3a-c). These are in central British Columbia and sometimes stretching to Saskatchewan, southern Ontario and the Atlantic region. The size of the regions varies 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 seldom reach 0°C. In terms of duration (Fig. 3d), 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. These regional patterns are also somewhat reflected in dependence on the average annual 0°C surface temperature line with higher values generally occur at stations near or above 0°C. However, long durations also often occur at stations with below 0°C conditions.

There are numerous factors contributing to these patterns. One is the proximity to coastlines. Many of the oceans surrounding Canada are close to 0°C, especially in the cold season (Phillips, 1990; Larouche and Galbraith, 2016), and this acts to maintain station temperatures near this value. For some stations in the North and Atlantic regions, the development and melting of sea ice also must acts to maintain temperatures near 0°C; inland stations in close proximity to large lakes likely experience a similar effect from the development and melting of lake ice. For example, Larouche and Galbraith (2016) showed that water temperatures in parts of the Great Lakes, are close to 0°C during the cold season. Most stations are similarly affected by melting and freezing of snow on the surface (Takeuchi et al., 2002).

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 during chinooks can be dramatic. Nkemdirim (1997) pointed out that temperature increases of more than 25°C in less than 24 hours are typical, and Gough (2008) indicated that the largest observed temperature change at Calgary was associated with a 4-hour event in 1883 during which the temperature increased 30°C (from -17°C to +13°C). During chinook episodes, large temperature swings can also occur. For example, Brinkman and Ashwell (1968) showed that, at Calgary on Feb. 16, 1965, there were 4 near 0°C events (two 1-h periods, one 2-h, and one 5-hour) and no precipitation at all.

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 based on surface temperature were further examined by identifying the longest periods at the selected stations (Table 5). The longest period was found 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). An analysis of the hourly sky conditions during these events was carried out by identifying the associated frequency of clear or mainly clear sky conditions (≤ 2 octas of clouds). All of the events were dominated by cloudy conditions that were sometimes accompanied with persistent precipitation (Table 5). Such sky conditions would contribute to reducing temperature swings associated with daytime heating and nighttime cooling (see, for example, Ahrens et al., 2015). 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. Canada is almost split in two between west (low values) and east (high values) (Fig. 4). This is likely a reflection of moisture access with eastern regions receiving warm, humid tropical and subtropical air much more often than western regions and, in association, raising temperatures through 0°C (Hare, 1997). 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 regional patterns related to the occurrence of any precipitation type are not directly reflected in dependence on the average annual 0°C surface temperature line. This is not the case for freezing rain where high values generally occur at stations with above 0°C conditions.

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 (Matsuo et al., 1981). In contrast, the Atlantic region is subject to large storms coming from the south as discussed by, for example, Stewart et al. (1987) and Stewart et al. (1995a). These vigorous storms almost always associated with surface temperatures passing from below to above 0°C with near saturated conditions (Stewart and Patenaude, 1988); they also associated with strong warm air advection aloft which often leads to inversions and freezing rain (Stewart et al., 1987).

An examination of the four pathways through which surface temperatures enter and leave near 0°C conditions revealed additional patterns (Fig. 11). Regardless of whether the average annual surface temperature is above, near or below 0°C, the pathway associated with initially above 0°C temperatures and back again (pathway 3) is associated with the most number of events at all nine selected stations. In contrast, this most common pathway is associated with a variable fraction of precipitation occurrence from low values, perhaps simply reflecting the diurnal cycle, to high values, possibly reflecting the passage of weather systems. Freezing rain is most likely in events with temperatures passing from below to above 0°C (pathway 2) at several locations; this pathway follows the temperature evolution during the passage of a warm front, which commonly leads to freezing rain (see, for example, Stewart et al., 1995b).

5.2 Enhanced occurrence of near 0°C conditions

As shown in Fig. 1, near 0°C conditions are prominent in several of the selected stations. At four locations, this is the most common temperature band despite wide variations in their whole span of temperature, average annual 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 surface temperatures towards 0°C, as previously noted by, for example, Wexler et al. (1954). But other factors are also critical as discussed in Sect. 5.1. For example, the only mention by Fujibe (2001) of the role played by snowcover 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 on the atmosphere of the melting snowpack and refreezing of meltwater (Takeuchi et al., 2002). As well, the freezing of freezing rain drops at the surface acts to raise

temperatures towards 0°C (Stewart, 1985); rain reaching the surface that subsequently freezes with lowering temperatures would have the same effect.

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, delayed onset of near 0°C conditions in the autumn, and earlier spring cessation of these conditions (Table 2 and Table 4).. Montreal only showed significant declines in the number of near 0°C events (Table 2); Whitehorse showed significantly earlier spring cessation and St. John's showed later autumn onset (Table 4). 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 (Table 3).

It is not surprising that significant trends are not always evident. This may simply reflect a relatively short observational period (31 years). 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 (Table 4), even with the recent warming. 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 (Table 4). With the observed overall warming, these stations experience a shift in timing of near 0°C occurrence towards winter but more instances of mid-winter temperatures above 2°C will probably also occur, so they would likely experience an overall decrease in near 0°C occurrences. In addition, the melting and freezing factors contributing to near 0°C conditions would continue to be active despite warming (Sect. 5.1). One exception may again be southern Ontario where the ground has not covered by as much snow (Vincent et al., 2015; Bush and Lemmen, 2019).

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 occurrences may be countered by warmer mid-winters, although at locations such as in Toronto (Table 4), mid-winter temperatures 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 (Table 4). Such 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 locations 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:

- Canada 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.
- 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 daily, radiatively-driven temperature variation and the annual temperature cycle. As well, precipitation, snowcover, and sea/lake ice can be important; all of these can melt and freeze with effects always being to tip temperatures towards 0°C. In addition, sea surface temperatures around Canada tend to be near 0°C during the cold season especially near some of Canada's coastlines (Larouche and Galbraith, 2016). This is especially evident in Atlantic Canada and the Arctic; parts of the Great Lakes have comparable values in some seasons as well. When such conditions occur, SSTs are generally slightly above 0°C although in some small areas they are below. SST values near 0°C would act to bring the temperature of the overlying air towards similar values.
- The longest duration events at the 9 selected stations are associated with persistent cloud conditions which act to reduce diurnally-driven temperature swings.
  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.
- Four pathways into and out of near 0°C conditions occur. At all of the nine selected stations across Canada, the pathway in which surface temperatures never becomes lower than -2°C is associated with the most number of events, and the one in which surface temperatures pass from below to above 0°C is associated with the lowest fraction of events with any precipitation except at Vancouver

465   •   Even though surface temperatures have generally increased over the 1981-2011 period (Bush and Lemmen, 2019), the 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 470   0°C.

    •   There has been no significant change in the frequency of occurrence of any of the 12 precipitation types or of freezing rain at most stations. However, the period of 31 years is relatively short to detect statistically significant changes. Using different selection criteria and period, Wang (2006) found that some areas of Canada experienced an increasing trend of freezing rain events over the 1953-2004 period.

475 Although our -2 ≤ T ≤ 2°C window for defining near 0°C conditions is justified as discussed in Sect. 2.2, it is recognized that other surface temperature windows could have been used. Overall findings would undoubtedly be similar, although quantitative values would change. For example, although not shown, near 0°C conditions largely exhibit the same occurrence patterns at the selected stations (Fig. 1) whether a -1 ≤ T ≤ 1°C window or a -3 ≤ T ≤ 3°C window is used instead. As well, a narrower (wider) surface temperature window would lead to smaller (larger) fractions of precipitation type occurrences simply being rain and snow. Future 480 research should nonetheless thoroughly investigate the implications of applying different definitions to the study of near 0°C conditions. Related to trend computation, this study followed the statistical approach used in several recent Canadian studies (Vincent et al., 2015; Vincent et al., 2018), but the use of "significance/non-significance" terms for trends analysis can be restrictive. Additional research is needed to examine the strengths and probabilities of each relationships as discussed by, for example, Wasserstein et al. (2019).

485 The findings of this study may be applicable to many other regions. On examining a global map of the location of the average annual 0°C isotherm (Ahrens et al., 2016), one can appreciate that it slices through large expanses of land; areas at least occasionally passing through 0°C will be massive. The recent WMO international project focusing on solid precipitation measurement (Nitu et al., 2018), utilized observational sites across North America, Europe and Asia and concerned, in part, with the -2°C ≤ T ≤ 2°C so called "mixed" precipitation range examined here. And, Dai (2008) and Jennings et al. (2018) illustrated rain/snow issues over 490 many regions of the world. Given the importance of near 0°C conditions and the large areas of the world subject to them, analyses carried out in this study should be conducted elsewhere.

In summary, this study can be considered an important step in the better understanding of near 0°C conditions and associated precipitation types across Canada and possibly many other regions.

495 *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.

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Tables

Table 1: Table of indicators in the -2 ≤ T ≤ 2°C range. The "T" refers to hourly surface dry bulb temperature. Definitions were obtained from American Meteorological Society (2018), ECCC (2019b) and WMO (2017).

DEFINITIONS	UNIT
Surface temperature related	
Annual number of days with -2°C ≤ T ≤ +2°C	days
Annual number of hours with -2°C ≤ T ≤ +2°C	hours
Annual number of independent events (continuous hours) with -2°C ≤ T ≤ +2°C	events
Annual Maximum Lengths with 2°C ≤ T ≤ +2°C	hours
Precipitation types related (occurences): Annual number of hours with	
... **Rain**: Liquid water drops having diameters > 0.5 mm	hours
... **Rain Showers:** Rainfall where intensity can be variable and may change rapidly	hours
... **Drizzle:** Liquid water droplets having diameters between 100 nm and 0.5 mm	hours
... **Freezing Rain:** Rain that freezes upon contact forming a layer if ice on the ground or on exposed objects	hours
... **Freezing Drizzle:** Drizzle that freezes upon contact forming a layer if ice on the ground or on exposed objects	hours
... **Snow:** Precipitation of ice crystals singly or agglomerated into snowflakes	hours
... **Snow Grains:** Very small opaque white particles of ice having diameters < 1mm	hours
... **Ice Crystals:** Crystalline forms in which ice appears including hexagonal columns, hexagonal platelets, dendritic crystals, ice needles and combinations of these forms.	hours
... **Ice Pellets:** Transparent ice particles usually spheroidal or irregular and rarely conical having diameters < 5 mm.	hours
... **Ice Pellet Showers:** Ice pellets falling where intensity can be variable and may change rapidly	hours
... **Snow Showers:** Snowfall where intensity can be variable and may change rapidly	hours
... **Snow Pellets:** White and opaque ice particles, generally conical or rounded having diameters as large as 5 mm	hours
... **all 12** precipitation types above	hours
Combination of surface temperature and precipitation type	
Annual number of hours with freezing rain and -2°C ≤ T ≤ +2°C	hours
Annual number of hours with any of the 12 precipitation types and -2°C ≤ T ≤ +2°C	hours
The fraction of [-2°C ≤ T ≤ +2°C] conditions associated with Freezing Rain	%
The fraction of [-2°C ≤ T ≤ +2°C] conditions with any of the 12 precipitation types	%

Table 2: Average annual frequencies of the selected near 0°C indicators along (in brackets) with the 31 year trend values based on hourly surface temperature over the 1981-2011 period (minimum 90% of data). The numbers in bold indicate significant changes at 5% level.

	Whitehorse	Vancouver	Calgary	Cambridge Bay	Winnipeg	Churchill	Toronto	Montreal	St. John's	Units
Number of Days	139.5 (100.4)	62.3 (7.2)	161.0 (46.1)	67.9 (-110.2)	108.7 (0)	92.6 (-143.6)	121.6 **(-316.9)**	107.0 (-69)	155.0 (90.4)	days
Number of Hours	1229.9 (-10.3)	530.3 (1.8)	1149.1 (-2.6)	854.3 (-2)	902.3 (-8.9)	1025.7 (-3.1)	1201.8 **(-26.9)**	979.5 (-10.3)	1744.5 (-3.6)	hours
Number of Events	194.3 (-18.5)	93.9 (3.1)	279.8 (-16.9)	66.5 (0)	145.8 (9.3)	99.7 (0.8)	142.1 **(-35.8)**	133.7 **(-15.5)**	163.6 (-15.5)	events
Maximum Duration	58.3 (22.9)	37.2 (-5.2)	39.5 (-6.3)	89.5 (-36.6)	53.8 (8.9)	84.1 (-27.9)	58.0 **(-25.4)**	52.2 (6.2)	91.0 (7)	hours

Table 3: Average number of hours with the 12 different precipitation type occurrences along in bracket with the indication of changes over the 1981-2011 period. ">" indicates statistically significant increasing change; "<" indicates statistically significant decreasing change; "no" indicates no significant change; "rare" indicates that the given precipitation type rarely occurs and the change is not computed; "n/a" indicates that there is not enough data to compute the change. The statistical significance of the trends were assessed at 5% level.

	Whitehorse	Vancouver	Calgary	Cambridge Bay	Winnipeg	Churchill	Toronto	Montreal	St. John's	Units
Rain	16.3 (no)	25.2 (no)	12.7 (no)	29.9 (no)	23.1 (no)	60.7 (no)	49.9 (no)	56.3 (no)	83.9 (no)	hours
Rain Showers	4.2 **(>)**	9.6 (no)	4.6 (no)	15.1 **(>)**	4.1 (no)	9.1 **(<)**	6.8 (no)	5.7 (no)	34.5 **(<)**	hours
Drizzle	2.0 (no)	3.7 (no)	6.5 (no)	30.2 (no)	15.1 (no)	41.8 **(<)**	21.4 **(<)**	16.2 (no)	132.2 (no)	hours
Freezing Rain	n/a	2.2 (rare)	n/a	4.9 (no)	3.6 (no)	10.0 (no)	8.3 (no)	13.4 (no)	41.0 (no)	hours
Freezing Drizzle	n/a	n/a	4.2 (no)	10.9 (no)	5.9 (no)	15.3 **(<)**	5.2 (no)	6.3 **(<)**	85.7 **(<)**	hours
Snow	111.8 (no)	41.2 (no)	96.2 (no)	91.9 (no)	79.6 (no)	163.3 (no)	115.1 (no)	152.0 (no)	173.2 **(>)**	hours
Snow Grains	n/a	1.4 (rare)	1.8 (no)	8.6 (no)	2.8 (no)	5.7 (no)	6.0 (no)	2.4 (no)	12.8 **(<)**	hours
Ice Crystal	n/a	n/a	0.0 (rare)	n/a	n/a	0.1 (no)	n/a	n/a	n/a	hours
Ice Pellets	n/a	n/a	2.4 (rare)	4.5 **(<)**	3.6 (no)	3.9 **(<)**	7.6 (no)	7.9 (no)	16.8 (no)	hours
Ice Pellet Showers	n/a	n/a	n/a	n/a	0.8 (rare)	1.9 (rare)	0.9 (no)	0.9 (no)	1.2 (no)	hours
Snow Showers	29.1 (no)	16.7 (no)	36.5 **(<)**	68.6 **(>)**	11.9 (no)	44.4 **(<)**	53.3 (no)	40.2 (no)	174.2 **(<)**	hours
Snow Pellets	0.9 (no)	n/a	2.5 (no)	3.4 (no)	1.5 (no)	2.6 (no)	2.7 (no)	1.5 (no)	3.0 (no)	hours
Any of the 12 types	154.7 (no)	85.6 (no)	151.6 (no)	250.5 (no)	136.3 (no)	323.2 **(<)**	252.6 (no)	276.2 (no)	686.1 (no)	hours

700 **Table 4: Average monthly surface temperatures (°C) and trends (days/31 years) of the onset of near 0°C conditions in autumn and cessation in spring for the period 1981-2011. For Cambridge Bay (*), average monthly values refer to June, July and August and trends refer to the cessation of near 0°C conditions in autumn and onset in spring. No calculations were carried out at Churchill. Average monthly surface temperatures were obtained for the 1981-2010 period from ECCC (2019c). The numbers in bold indicate trends significant at the 5% level.**

Station	Average Monthly Temperature (°C)			Autumn Onset Trend (days/31 years)	Spring Cessation Trend (days/31 years)
	December	January	February		
Whitehorse	-12.5	-15.2	-12.7	6.4	**-11.8**
Vancouver	3.6	4.1	4.9	8.3	-4.1
Calgary	-6.8	-7.1	-5.4	5.4	1.1
Cambridge Bay*	2.7	8.9	6.8	23.8	0.2
Winnipeg	-13.2	-16.4	-13.2	4	-2.4
Churchill	-21.9	-26	-24.5	-	-
Toronto	-2.2	-5.5	-4.5	**25.1**	**-15.4**
Montreal	-5.4	-9.7	-7.7	9.6	-0.8
St. John's	-1.5	-4.5	-4.9	**32.3**	-10.9

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Table 5: The longest duration events at the 9 selected stations. Columns indicate maximum duration, start time, and hours (and fraction of duration) with mainly or completely clear sky conditions, hours with any of the 12 reported precipitation types (and fraction of duration). Times are local standard.

Station	Duration	Start Time	Mainly/Completely Clear		Precipitation	
	(h)	(YYYY-MM-DD-HH)	(h)	(%)	(h)	(%)
Whitehorse	110	1998-10-06-21	3.0	2.7	12.0	10.9
Vancouver	68	2005-01-06-04	1.0	1.5	44.0	64.7
Calgary	73	2003-05-05-10	0.0	0.0	60.0	82.2
Cambridge Bay	197	1987-06-11-08	3.0	1.5	63.0	32.0
Winnipeg	128	1983-03-01-15	0.0	0.0	106.0	82.8
Churchill	141	1986-10-18-12	1.0	0.1	98.0	69.5
Toronto	158	1986-12-26-16	0.0	0.0	13.0	8.2
Montreal	114	2007-12-24-12	8.0	7.0	34.0	29.8
St. John's	148	1983-04-01-06	14.0	9.5	75.0	50.7

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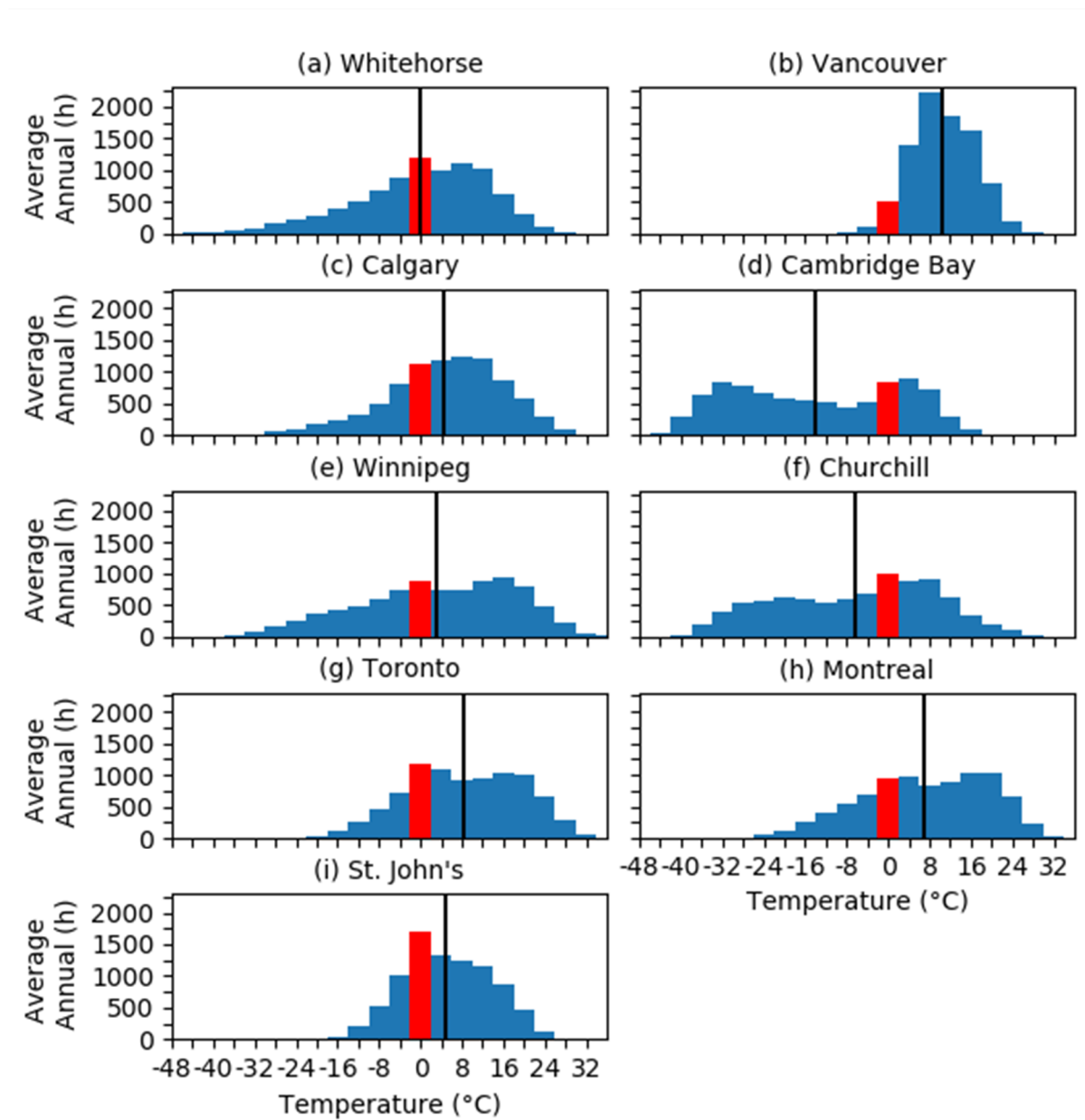
Figures

Figure 1: The average annual surface temperature distribution (4°C bins) from 1981 to 2011 for 9 representative stations across Canada
715 **as shown in Fig. 2. The vertical black line indicates the average annual surface temperature using information from ECCC (2019a). The red bar identifies near 0°C surface temperatures defined as -2 ≤ T ≤ 2°C. Stations are arranged from west to east. Details on the temperature data are in Sect. 2.**
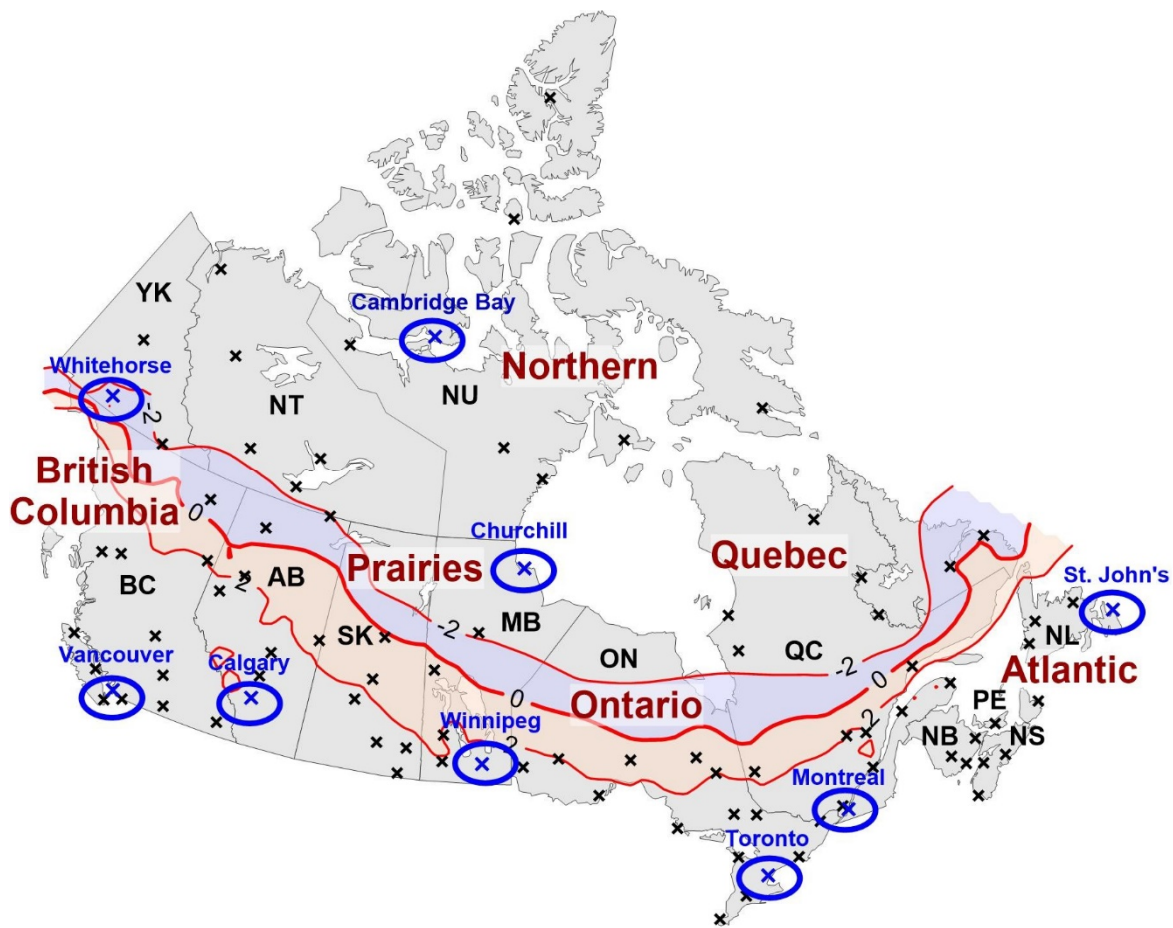
Figure 2: The 92 stations used in the analysis (see text for details). Blue ellipses and red crosses show the 9 representative stations across Canada. British Columbia region includes all stations in British Columbia (BC); Prairies region - all stations in Alberta (AB), Saskatchewan (SK) and Manitoba (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-L); and Northern region - all stations in Yukon (YK), Northwest Territories (NT) and Nunavut (NU). The average annual 0°C, -2°C and 2°C surface temperature lines, computed from 1981-2010 climate normals of 1619 locations (ECCC, 2019c), are also shown.
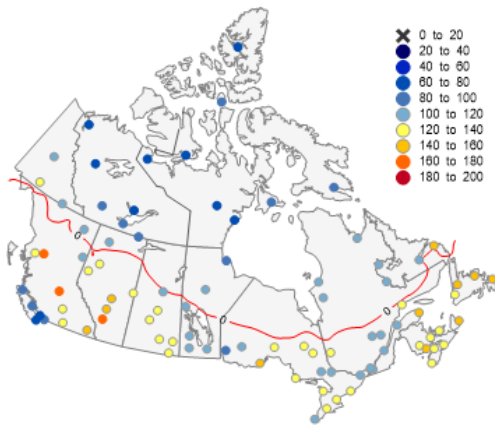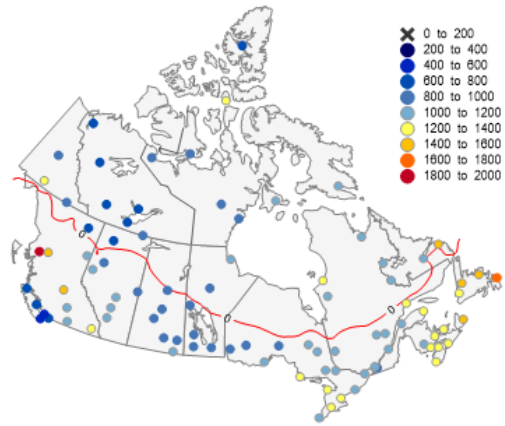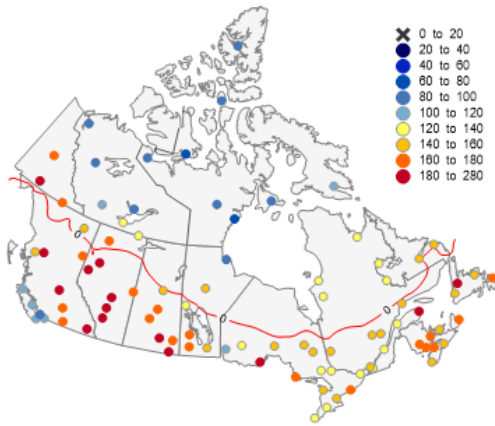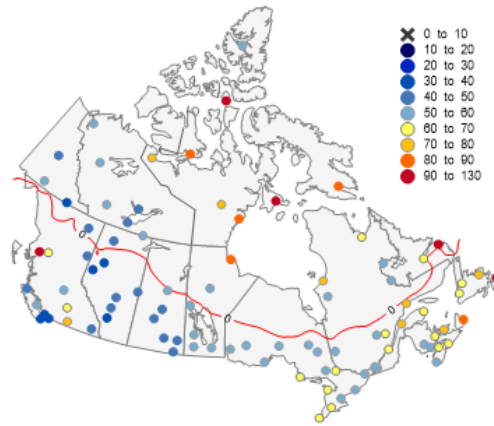
Figure 3: Average near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period for (a) number of days per year, (b) number of hours per year, (c) number of events per year, and the (d) annual maximum (max) duration of events. The red line indicates the annual average 0°C surface temperature computed from 1981-2010 climate normals (ECCC, 2019c).

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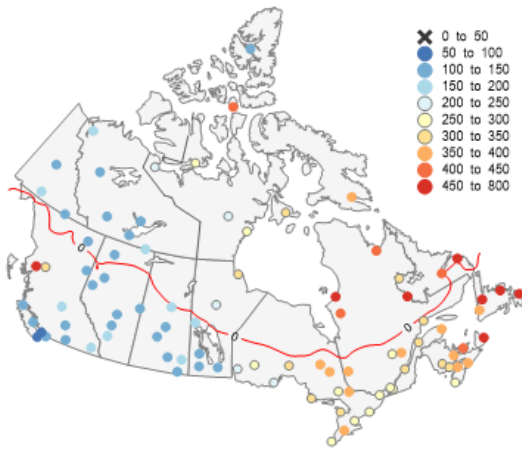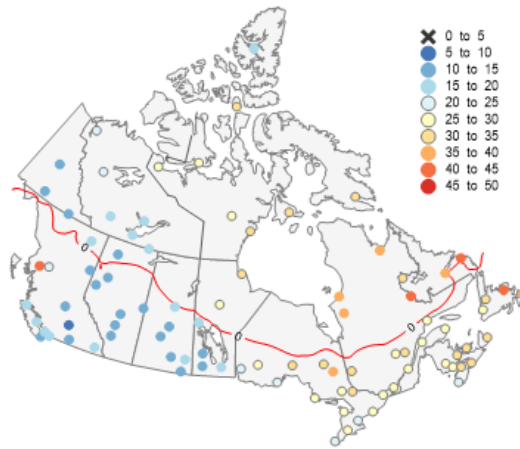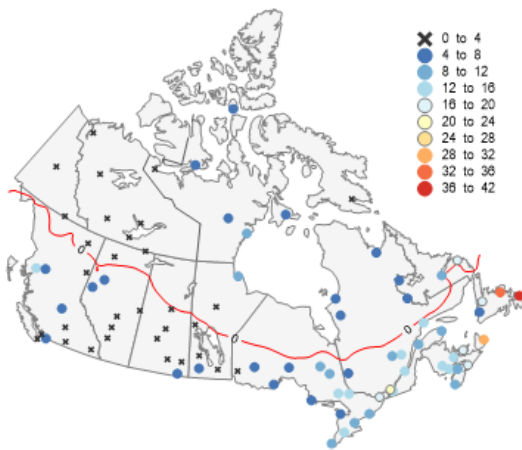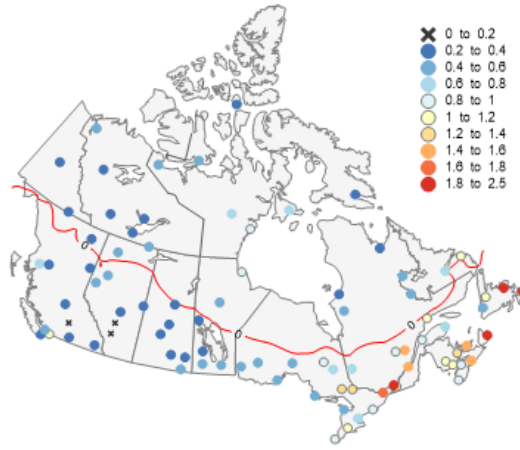
Figure 4: Precipitation type occurrences during near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period, where (a) average annual number of hours with reported precipitation types (any of the 12), (b) percentage of near 0°C conditions associated with reported precipitation types (any of the 12), (c) average annual number of hours with freezing rain, and (d) percentage of near 0°C conditions associated with freezing rain. The red line indicates the annual average 0°C surface temperature computed from 1981-2010 climate
735 **normals (ECCC, 2019c).**
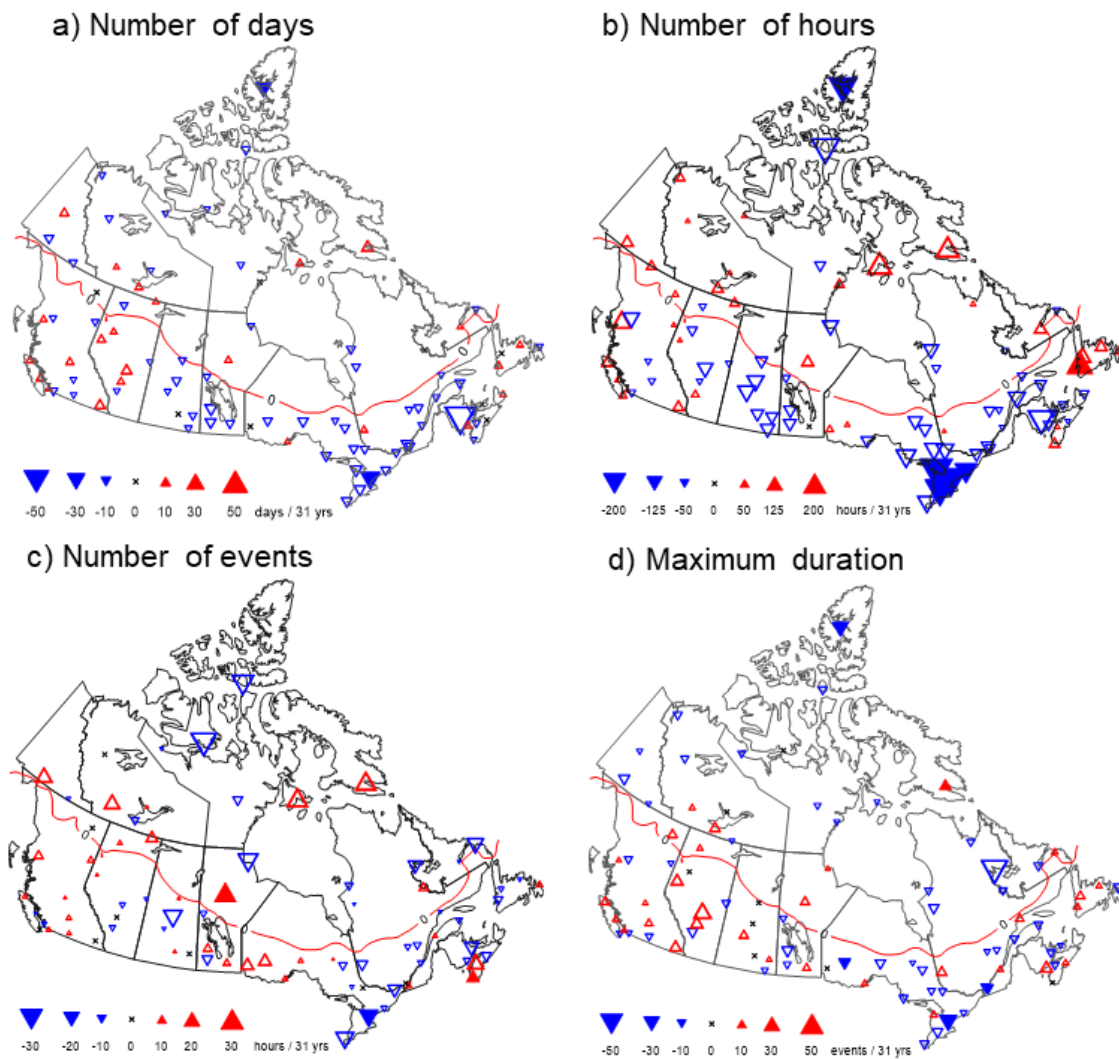
Figure 5: Trends in near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period. (a) annual average number of days, (b) annual average hours, (c) annual number of events, and (d) annual maximum duration. A solid triangle indicates statistical significance at 5% level. The red line indicates the annual average 0°C surface temperature computed from 1981-2010 climate normals (ECCC, 2019c).
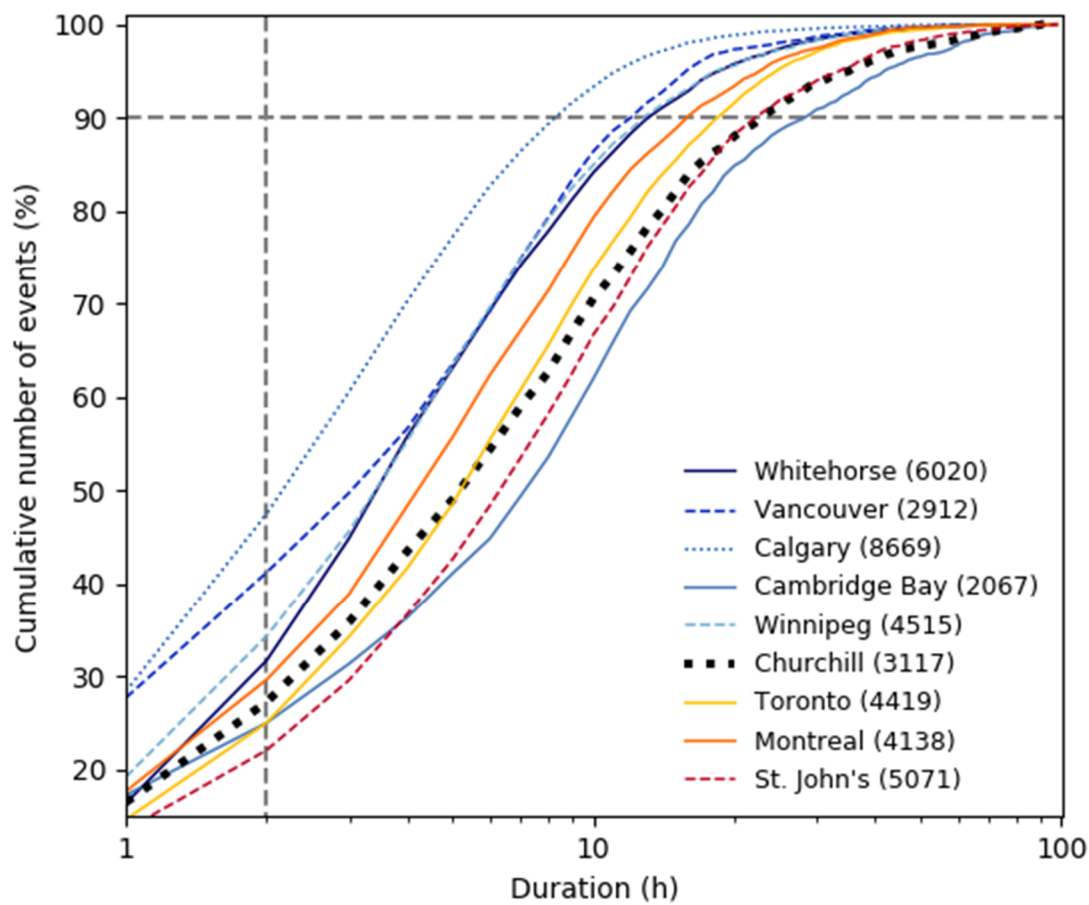
Figure 6: Cumulative distribution of events (%) as a function of duration (h) of near 0°C (-2 ≤ T ≤ 2°C) events at the 9 representative stations across Canada over the 1981-2011 period arranged from west to east. The total number of events is shown in brackets and duration is plotted on a logarithmic scale.

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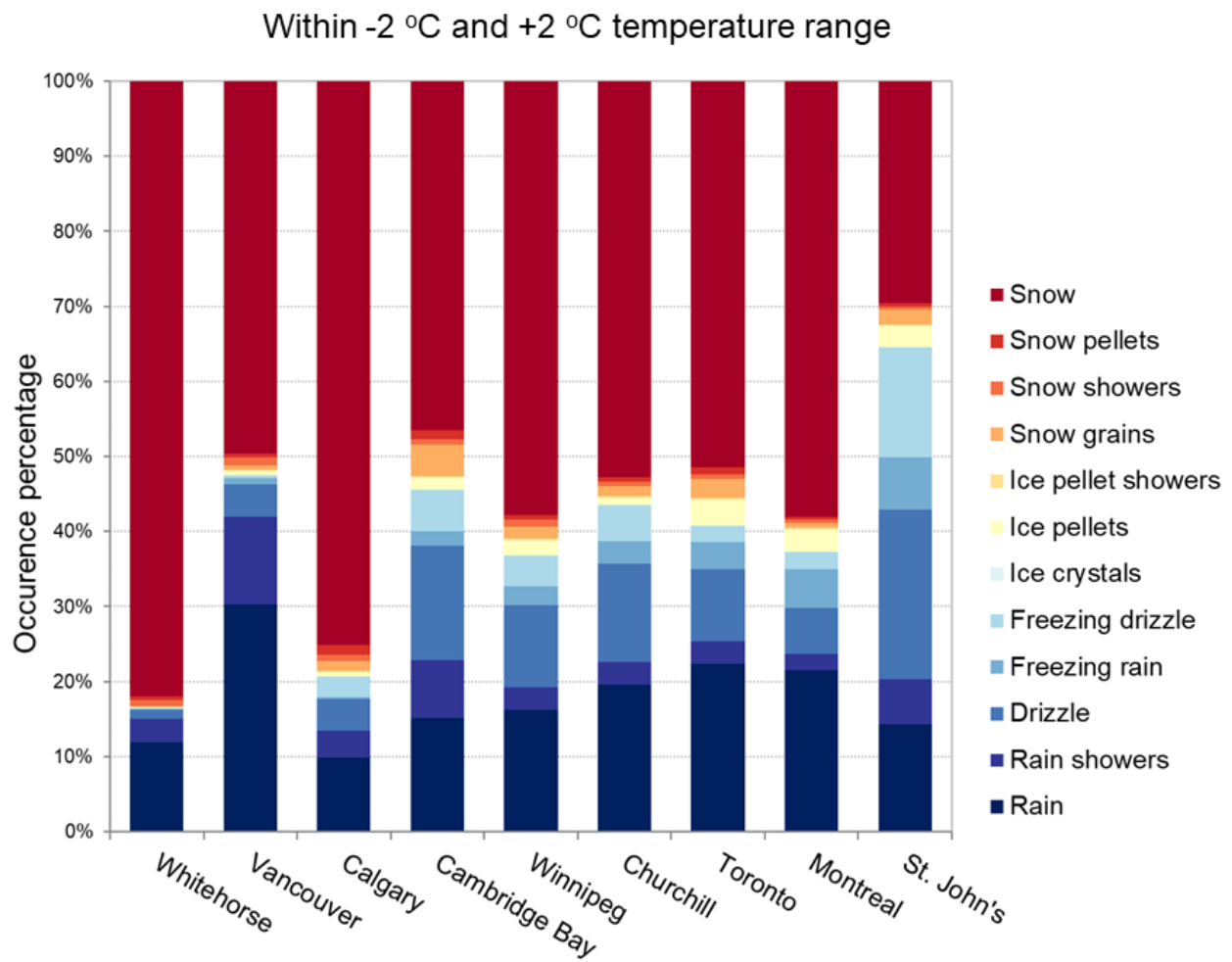
Figure 7: The distribution of precipitation type occurrence with near 0°C conditions at each of the 9 stations over the 1981-2011 period. Stations are arranged from west to east.
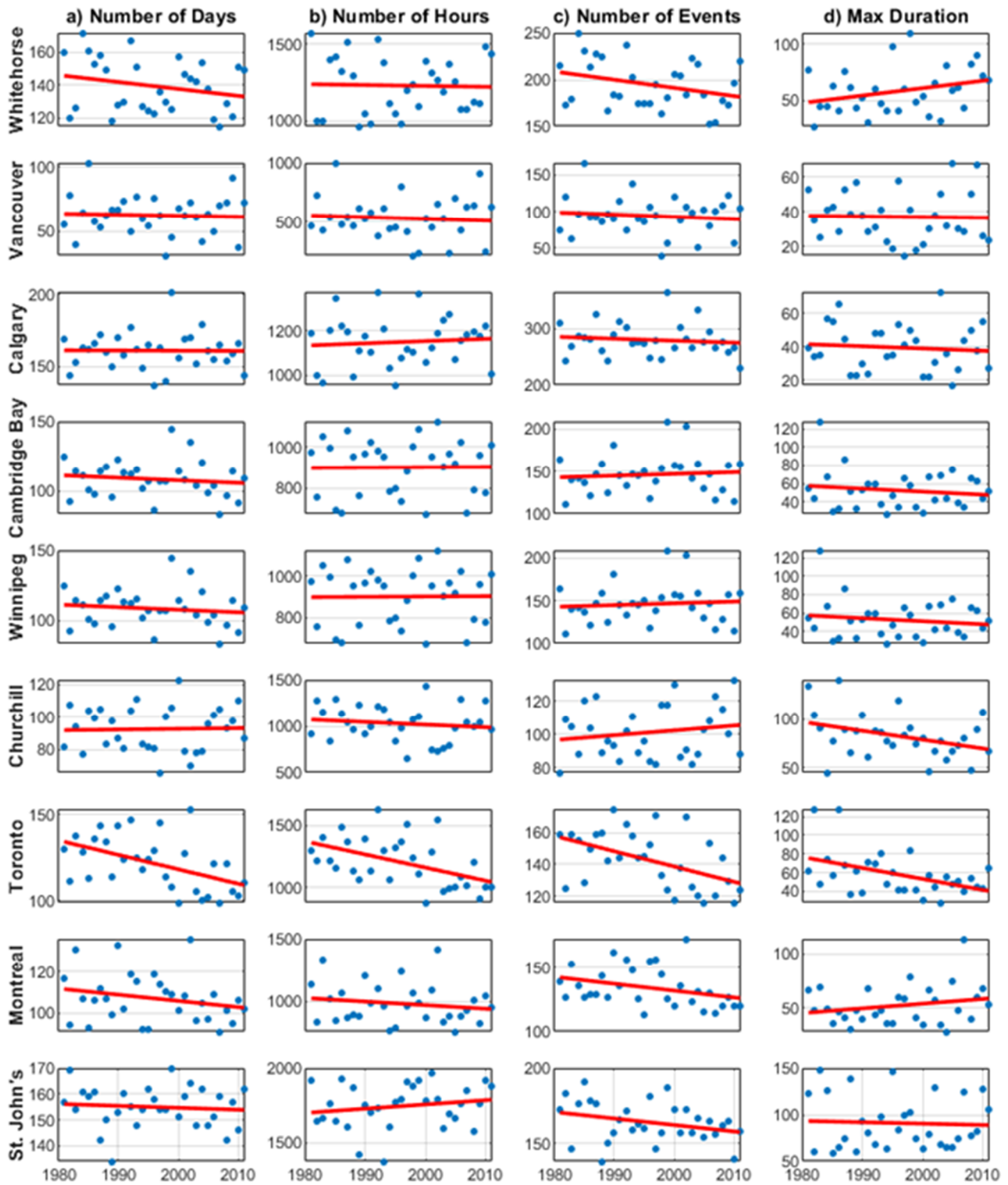
Figure 8: The 1981-2011 values of average (a) annual number of days, (b) annual number of hours, (c) annual number of events and (d) annual maximum duration (in hours) during near 0°C (-2 ≤ T ≤ 2°C) conditions for the nine selected locations in Canada. Linear trend lines are superimposed in red.
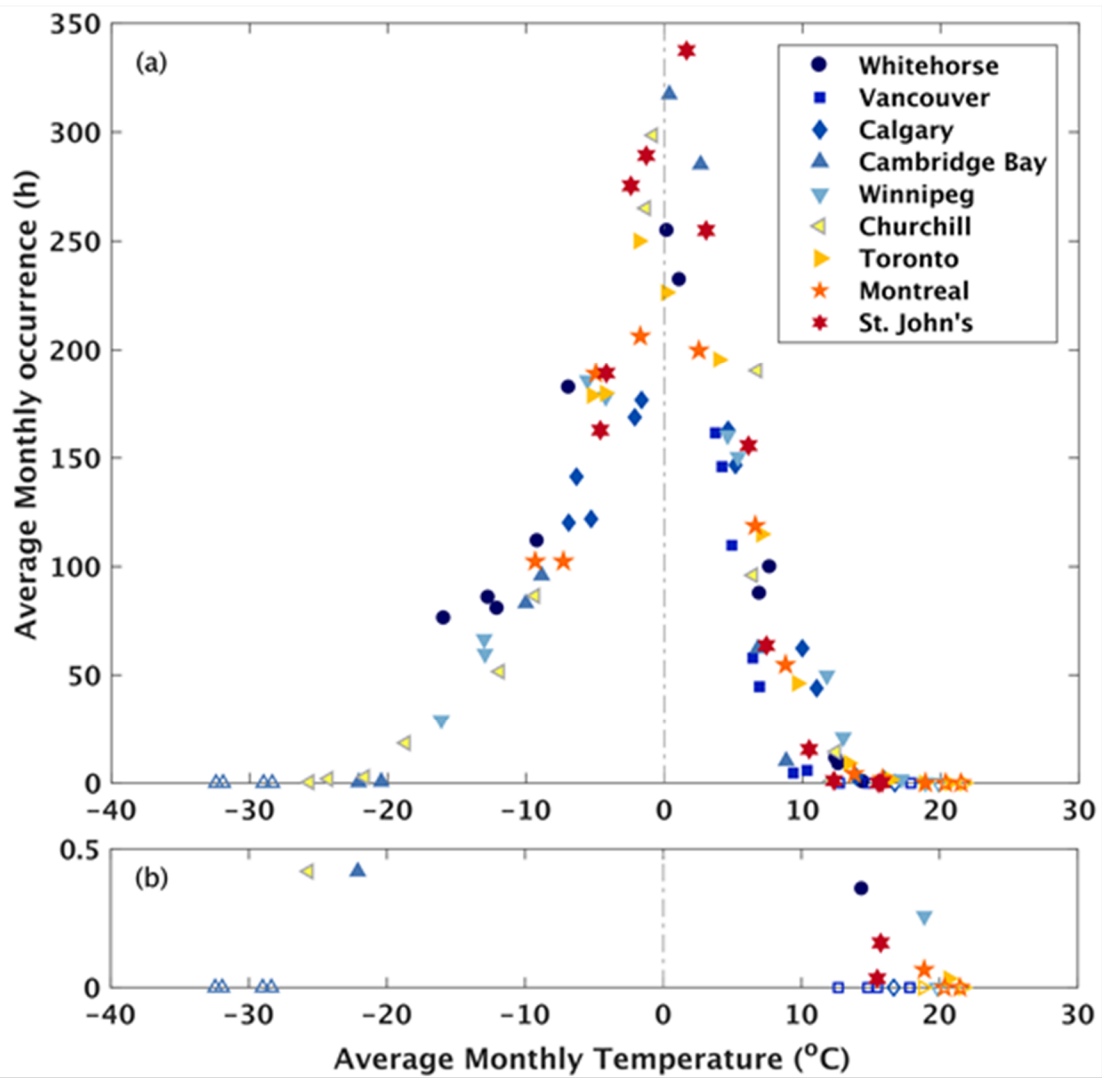
Figure 9: a) Average monthly occurrence (hours) of near 0°C conditions as a function of average monthly surface temperature for the nine selected stations over the 1981-2011 period. Filled symbols indicate occurrence and open or unfilled symbols indicate no occurrence.
755   **b) An expanded view to better illustrate low values of average monthly occurrence.**
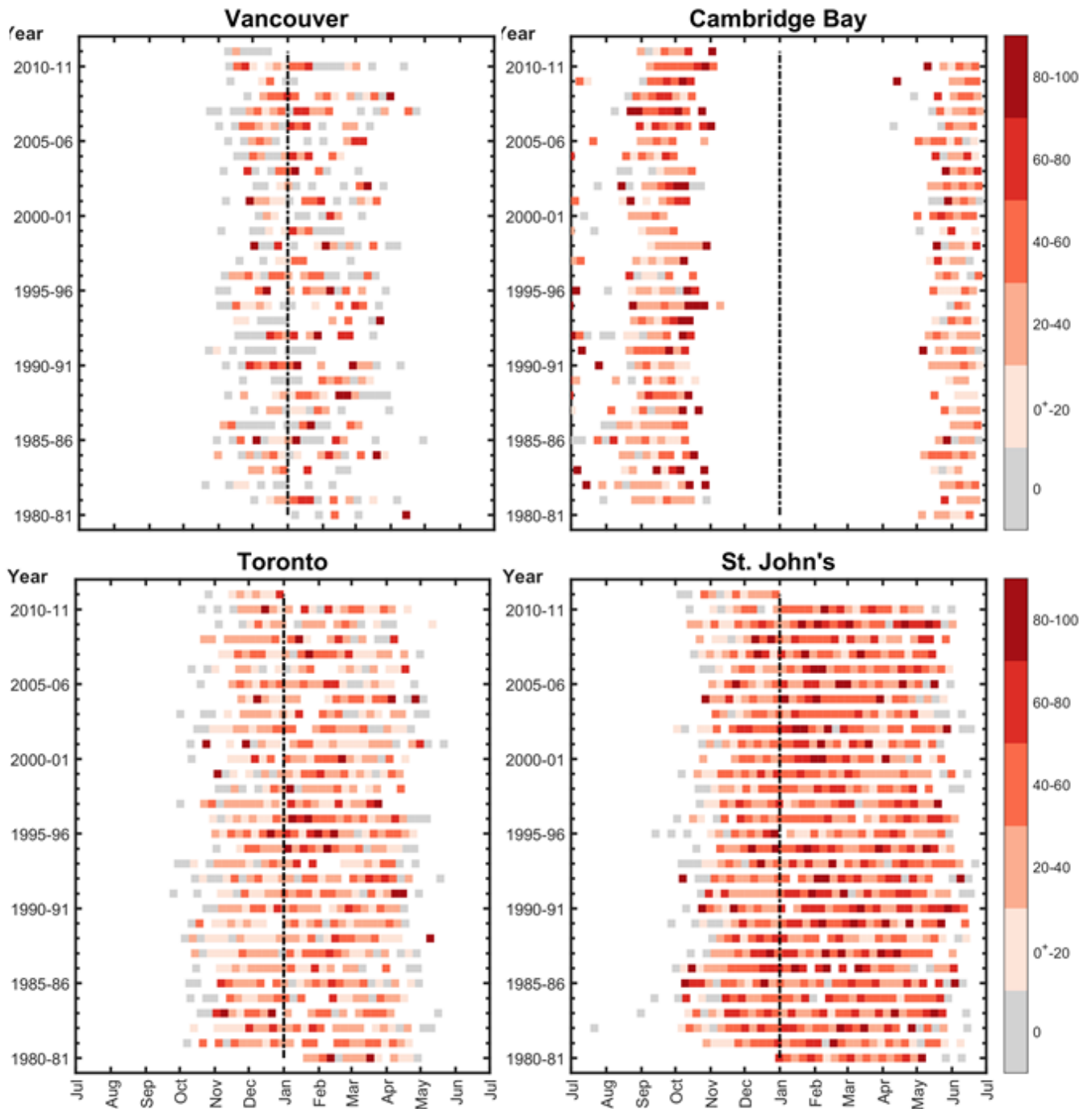
Figure 10: The occurrence of near 0°C conditions and any (of the 12) associated precipitation types at (a) Vancouver, (b) Cambridge Bay (c) Toronto and (d) St. John's over the 1981-2011 period. Shading refers to the weekly fraction (%) of near 0°C hours with (or without) precipitation, the '0+ symbol' refers to at least one hour of precipitation whereas the gray '0' means no precipitation even if the near 0°C criterion was met. Blank areas indicate no occurrence of near 0°C conditions. The vertical, dashed line indicates January 1.

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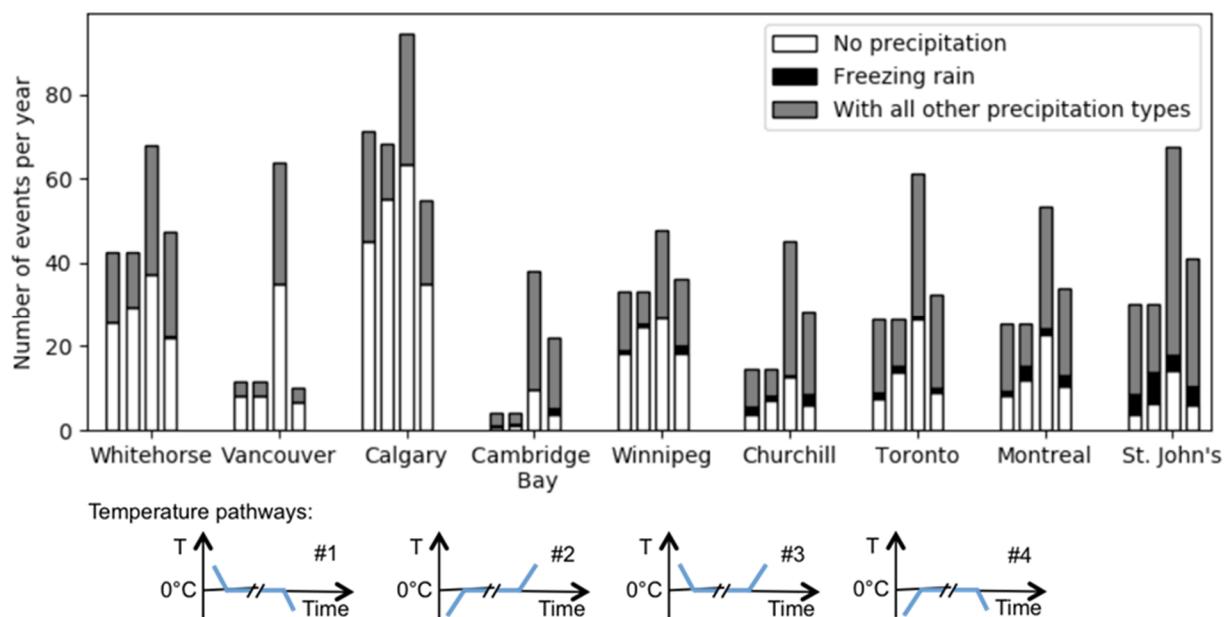
Figure 11: Average annual number of near 0°C events at the 9 selected stations organized by surface temperature pathways. The four pathways are shown schematically below the figure. They are represented by bars at each station from pathway 1 to 4 (left to right). No shading refers to the occurrence of near 0°C conditions, dark shading refers to the occurrence of freezing rain near 0°C, and light grey refers to the occurrence of all other types of precipitation near 0°C.

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