Responses to Reviewer Comments

We combine our responses to all four reviewers into this one document. In some cases, similar comments were made by different reviewers and they can see the consistency in our responses. In a few other cases, to best address a comment by a particular reviewer, we also referred to our response to another reviewer.

Reviewer 4 responses can be found on pages 47-83 in the attached supplement file

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1	4 - 5
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Please note, following the revision we added two new figures and one new table to the originally submitted document. In order to avoid confusion the figure and table numbers in this "Response to Reviewers' Comments" document corresponds to the originally submitted paper (hence our figure numbers do match the numbers in the question).

The conversion table to the reviewed document as follows:

New Figure order:

- Fig 7
- Fig X => Fig 8
- Fig 8 => Fig 9
- Fig 9 => Fig 10
- Fig Y => Fig 11

New Table order:

- Table 3
- Table X => Table 4
- Table 4 => Table 5

Comments from the Editor

Response: Responses to the two comments are given individually below and these are followed by a new paragraph in Sect. 6 (Concluding Remarks) which includes the response to comment 1 plus part of the response to comment 2.

E1. From my perspective the questions arising around the -2 to 2°C threshold are the most important aspect of the reviewer comments. Although you have already provided rather convincing arguments for theis choice, I feel that the justification AS WELL AS a discussion of potential implications of using this threshold need yet to be a bit strengthened.

Response: We feel that our $-2 \leq T \leq 2$°C window is a reasonable choice as discussed in Sect. 2.2. But, other surface temperature windows could have been used instead although we feel that overall results would be similar. We have added this and related information to the Concluding remarks. (The new text will be inserted into Sect. 6 and combined with new text addressing comment 2 to form a single new paragraph.)

New text in Sect. 6 (Concluding remarks) starting at Line 355 in the original submission: "This study has provided important insight on near 0°C conditions and associated precipitation type occurrences across Canada but further research could be carried out. Although our $-2 \leq T \leq 2$°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 $-1 \leq T \leq 1$°C window or a $-3 \leq T \leq 3$°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 research should nonetheless thoroughly investigate the implications of applying different definitions to the study of near 0°C conditions."

E2. A further point I would like to point you to is the discussion around statistical significance levels. There has been, already for a while, been quite some discussion in the statistics community about the (non-)usefulness of the term "significance", which culminated in a very recent paper by Wasserstein et al. (2019), suggesting, amongst others, to completely drop the binary use of "significance"/"non-significance" and instead only report effect strength and probability for any relationship.

Reference: Wasserstein, R. L., Schirm, A. L., & Lazar, N. A. (2019). Moving to a world beyond "p< 0.05". The American Statistician, 73:1-19.

Response: Thank you for pointing this out. Since this study was initiated over two years ago, we have followed the "statistical significance" approach used in our past studies (Vincent et al., 2015; Vincent et al., 2018; first author was co-author on both) to show if trends are "important" (or not). The applied method is now clearly mentioned and described. We also added that different statistical approach could have been used in the concluding remarks. We prefer to keep the paper with the statistical significance now, but we will certainly consider a different approach to report the strength and probability of the trends in our future works. New text will be inserted into Sect. 2.2 and Sect. 6 (this will be combined with new text addressing comment 1 to form a single new paragraph).

New text in Sect. 2.2 (Methods) starting at Line 114: "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)."

New text in Sect. 6 (Concluding Remarks) starting at Line 355: "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).”

New reference:

Wasserstein, R. L., Schirm, A. L. and Lazar, N. A.: Moving to a world beyond “p< 0.05”. The American Statistician. 73, 1-19, 2019.

New paragraph in Sect. 6 (Concluding Remarks) starting at Line 355: This paragraph combines the new text addressing comment 1 as well as part of the new text addressing comment 2.

“This study has provided important insight on near 0°C conditions and associated precipitation type occurrences across Canada but further research could be carried out. Although our $-2 \leq T \leq 2$°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 $-1 \leq T \leq 1$°C window or a $-3 \leq T \leq 3$°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 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).”

Reviewer 1

This is a comprehensive assessment of the weather conditions across Canada around 0 Celsius. It deserves to be published with minor corrections. I have only two suggestions:

Comment 1: Freezing precipitation occurrence (for both rain and drizzle) is not symmetric around 0 Celsius and happen rarely with positive near surface air temperatures. Please, test/address this issue in your analyses.

Response: This same comment was made later in regards to Reviewer 2, Major Point #2 and Lines 95-98 and the same response is used here. We agree that there is no precise, physically based criterion that can be used to characterize conditions near 0°C. We did want to focus on conditions within which many changes in precipitation types are embedded. We have now included several references that point out that substantial fractions of some precipitation types occur within our chosen temperature window and we also indicate that we wanted a simple symmetric temperature window straddling 0°C. We also deleted the dash between the words "physically" and "based" following a comment by another reviewer.

New/Revised Text: "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 ≤ 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 temperature symmetric window straddling 0°C with embedded large fractions of overall occurrences of varying precipitation types, we defined surface near 0°C conditions as -2°C ≤ T ≤ 2°C throughout the paper."

New References:

Matsuo, T., Sasyo, Y. and Sato, Y.: Relationship between types of precipitation on the ground and surface meteorological elements, Journal of the Meteorological Society of Japan. Ser. II, 59(4), 462–476, doi:10.2151/jmsj1965.59.4_462, 1981.

Nitu, R., Roulet, Y.A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, G.W., Lejeune, Y., Leppänen, L., Mekis, E.,Panel, J.M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Nishimura, K. and Senese, A.: WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012-2015), World Meteorological Organization Instruments and Observing Methods Report No. 131, Geneva, 2018.

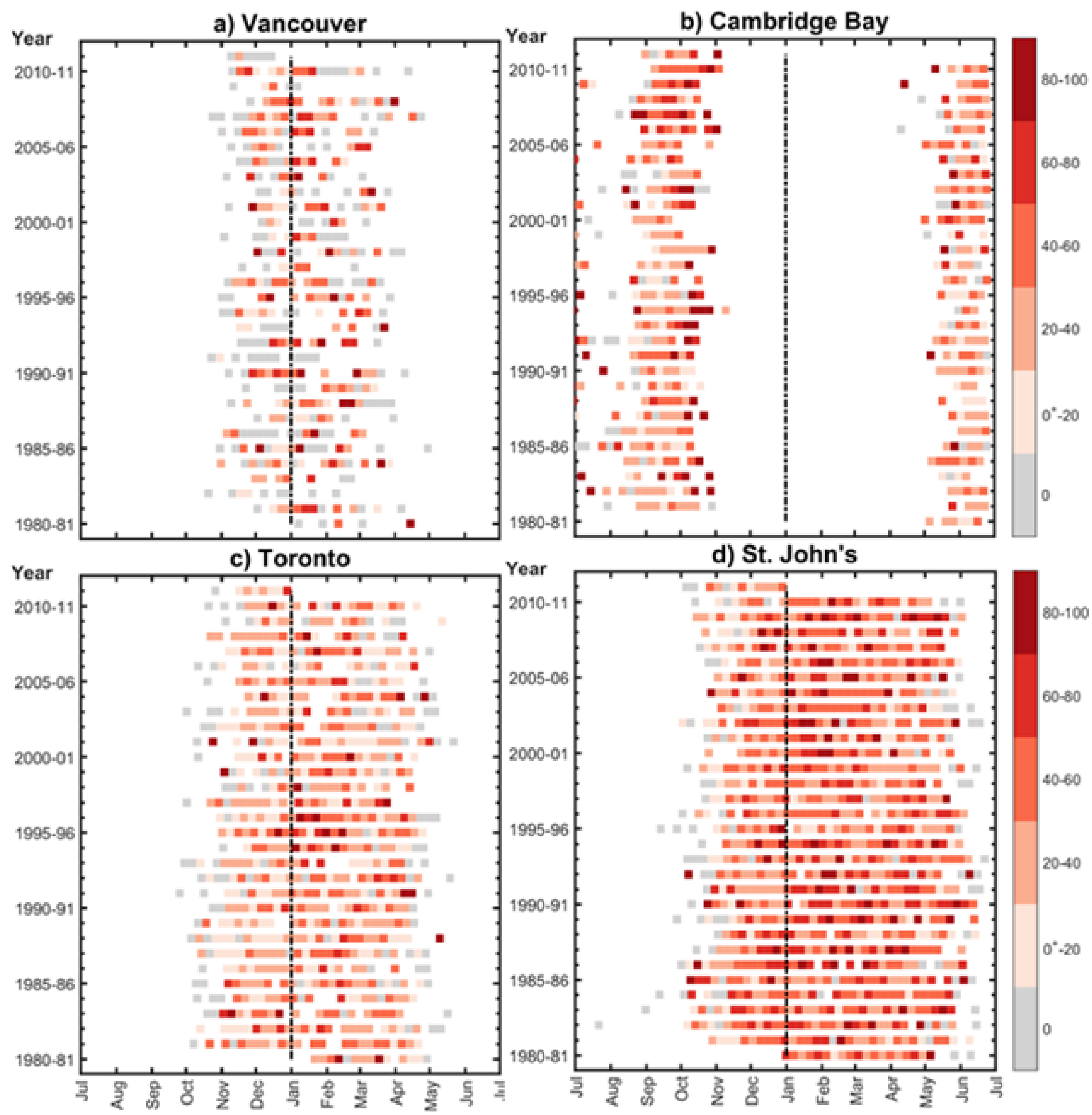
Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Elomaa, E., Gunther, T., Bates, R., Pangburn, T., Hanson, C., Emerson, D., Copaciu, V. and Milkovic, J.: Accuracy of Tretyakov precipitation gauge: Result of WMO intercomparison. Hydrological Processes, 9(8), 877-895. doi:10.1002/hyp.3360090805, 1995.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Bates, R., Pangburn, T. and Hanson, C. L.: Accuracy of NWS 8" standard nonrecording precipitation gauge: Results and application of WMO Intercomparison. Journal of Atmospheric and Oceanic Technology, 15(1), 54-68. doi:10.1175/1520-0426(1998)0152.0.co;2, 1998.

Comment 2: The last figure of the manuscript is a mess. Please, remove it or replace with something else that will better communicate your message.

Response: This figure has been redone. It shows the same information in a condensed weekly timestep. In this new format the weekly fraction (%) of near 0°C hours with (or without) precipitation is shown through shading rather than as a separate line.

New/Revised Text: The new figure and its revised caption are shown below.



Revised Figure 9 caption: "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."

Reviewer 2

Overview: The authors document the frequency and duration of near 0°C conditions (defined as -2.0°C ≤ Ta ≤ 2.0°C) along with the frequency of various precipitation types at a selection of research sites in Canada. They also evaluate whether statistically significant trends were observed for various air temperature and precipitation metrics over the 1981–2011 time period. Overall, they found spatial variability in the occurrence of near 0°C conditions and few significant trends in the various indicators they explored.

Although it is well-written and appropriate data and methods are used, the current paper reads too much like a case study of near-freezing precipitation in Canada, making it not suited to the high scientific standards of HESS. The authors even note themselves that: "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." In order to move towards acceptance the science will have to be expanded upon significantly and the international scope broadened. I offer some suggestions below, but the authors will need to take it upon themselves to determine what primary scientific questions are driving this research. I therefore suggest significant major revisions be undertaken or rejection if the authors do not increase the scientific merit of the paper.

Response: The authors appreciate the reviewer's comments on the manuscript being well written and the appropriateness of the data and methods. We also appreciate the comments regarding broadening of the international scope and expansion of the science. These comments are addressed in detail below.

Major issues:

Major issues #1. Lack of scientific content:

a. The authors present a possible scientific research question in Sect. 5.3 and the last paragraph of Sect. 6. Relating the sigmoidal curve of annual temperature variation (particularly where it reaches its minimum and how long it is near 0°C) to trends in near 0°C conditions would be interesting. For example, do sites with winter air temperatures near freezing express trends more frequently than those with winter air temperatures well below freezing. This could also be tied into trends in precipitation type (e.g., shifts from snow to rain or occurrences of freezing rain/drizzle/ice pellets). Additionally, such a quantitative approach could be connected to international work (major issue 3 below) by noting areas with similar hydroclimatic characteristics. I feel this could be relatively easily done by the authors through making their qualitative discussion section into a quantitative analysis.

Response: Thank you for the suggestions. There has never been a quantification of surface near 0°C conditions across Canada using hourly data and this study has begun to address this gap. It has revealed numerous spatial patterns in the temperature and associated precipitation type fields. We recognize that the time period being considered is relatively short and so it is not surprising that trends are not always apparent. We are limited by the availability of quality data. Nonetheless, we had originally carried out an analysis of trends in comparison with temperatures for our 9 selected stations and this has been improved and shown in other responses. We certainly agree that this work is relevant to many other areas of the world and, as suggested, this is now better articulated.

The quantification and interpretation of near 0°C patterns was always the key motivation for the article. We had done this originally and now, with updates arising from reviewer comments, it is even more so. To make this clearer, we have modified our objective as well as our title.

Objective:

Original: "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."

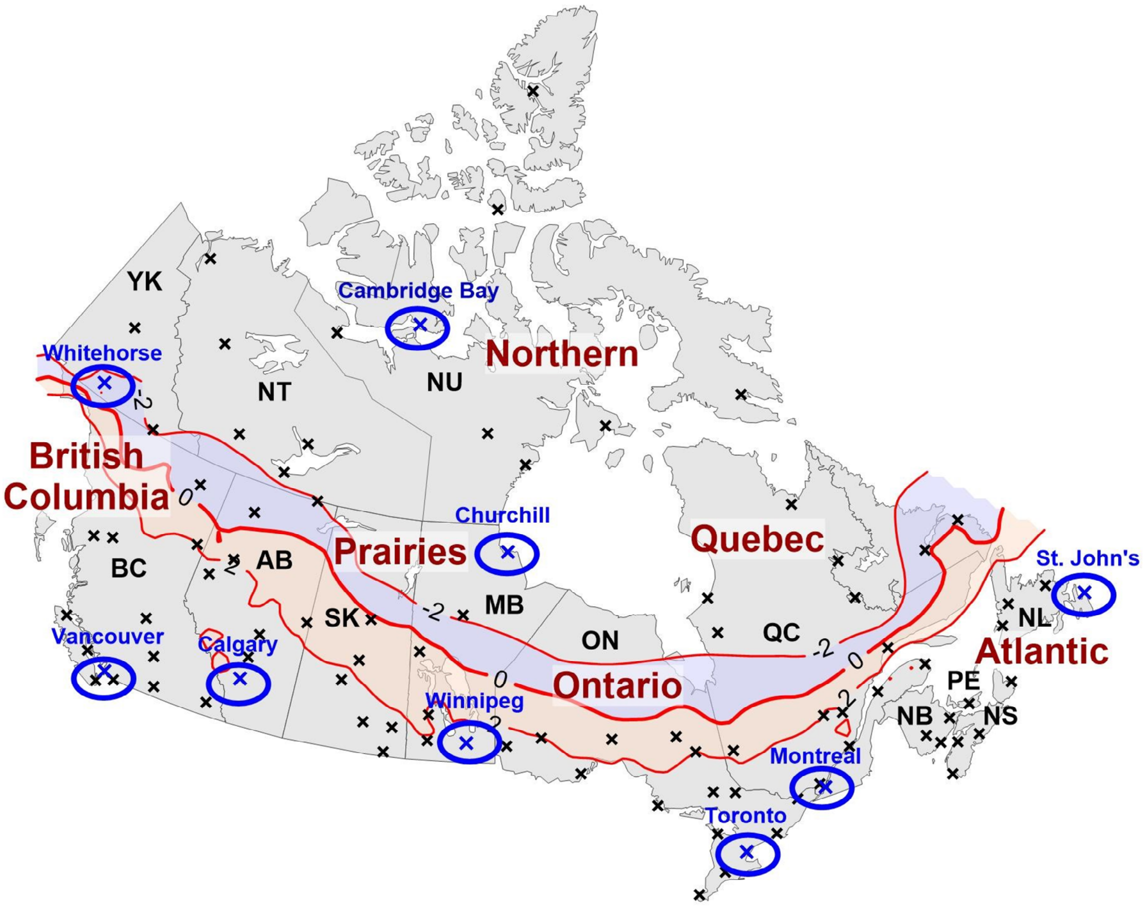
Updated: "The objective of this study is therefore to quantify and improve understanding of near 0°C temperature and precipitation type patterns across Canada."

Title:

Original: "Assessment of near 0°C temperature and precipitation characteristics across Canada"

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

To improve the context and to readily address the variations of spatial patterns, we also added the average annual 0°C, -2°C and 2°C surface temperature lines, computed from 1981-2010 normals (ECCC, 2019c), to Fig. 2.



New Fig. 2 caption: "The 92 stations used in the analysis (see text for details). Blue ellipses and blue crosses show the 9 selected 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."

Response: The authors believe that the original paper contained strong scientific content and, to address Reviewer 2's concern, we have both carried out additional analyses to our original work, and added new analyses. We note that these additions also address other reviewers' comments as outlined in many of our responses below. A few key examples include:

- The paper now clearly shows that near 0°C surface temperatures often occurred with higher than expected frequency relative to other temperature bands and inferences to the responsible driving factors are provided.
- We have quantified and interpreted spatial patterns in the occurrence of near 0°C conditions across Canada.
- We now show the fractional occurrence of the four pathways into and out of near 0°C conditions and their relation to precipitation type occurrence.
- We have improved trend analysis used to identify changes (or the lack thereof) in many of the near 0°C parameters within our period of interest.
- We have provided suggestions as to how near 0°C features may change in a future, warmer climate
- We have pointed out that similar near 0°C features and processes should be occurring elsewhere in the world.

New/Revised Text: The text has been updated in many places, and in every Section of the article as shown in our responses to other specific comments by Reviewer 2 and the other reviewers. We chose not to show all of these here since it would be a very long response. The following summarizes a few key examples including where these can be found:

- Improved our discussion of the common prominence of near 0°C temperatures relative to other temperature bands (response to Reviewer 4, major improvement 1).
- Improved the perspective on our analysis within Canada as a consequence of adding temperature contours to the maps in Figs. 2 through 5 (Fig. 2 is shown above and Figs. 3-5 are shown in our response to your comment regarding figure colours which is just a couple of comments below), your comment regarding Lines 120–173, and a comment by Reviewer 4 (major improvement 1).
- Improved our discussion of Fig. 8 (response to your comments on this figure) to better interpret near 0°C occurrences relative to average monthly temperatures.
- Carried out a new analysis to illustrate the importance of pathways into and out of near 0°C conditions on actual features (responses to your current comment here plus Reviewer 4, Major Improvement 2). This analysis had been suggested in our original Concluding Remarks (Sect. 6), as you pointed out, but now we have done it.
- Added a number of references from the international literature to better place this present study into context (response to your Major Point 3).

New Reference:

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 24, 2019), 2019c.

b. How sensitive are the trends and evaluated quantities to the selection of the admittedly non-physical -2°C to 2°C air temperature range? For example, precipitation is almost always snow at and below 0°C (e.g., Auer Jr, 1974; Dai, 2008; Kienzle, 2008). In the representative stations results (Sect. 4), snow is presented as the dominant precipitation type at all stations but St. John's. This is likely due to the selected air temperature range. Examining a different range (e.g, -1°C to 3°C) might yield different results.

Response: We appreciate that other temperature ranges could or would lead to different results. We based our analysis on a simple symmetric range relative to 0°C; such temperatures represent a critical zone with ice-dominated processes below and liquid dominated processes above. Analyzing the range of "mixed precipitation" associated with the $-2°C \leq T \leq 2°C$ temperature range has been done before with a good example being the recent WMO-SPICE final report (Nitu et al., 2018). In our next response (shown below), we include specific information addressing this issue.

To highlight this temperature range, we have also revised Fig. 2 (as shown in our response to your previous comment). Importantly, we show the location of the -2°C ≤ T ≤ 2°C temperature range over Canada.

New/Revised Text: We have not changed most of our text directly in response to this comment but, through responses to many other comments by yourself and the other reviewers, we have better justified our choice of temperature range including our next response (just below).

New Reference:

Nitu, R., Roulet, Y.A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, G.W., Lejeune, Y., Leppänen, L., Mekis, E.,Panel, J.M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Nishimura, K. and Senese, A.: WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012-2015), World Meteorological Organization Instruments and Observing Methods Report No. 131, Geneva, 2018.

c. The authors argue how important near 0°C conditions are but do not make quantitative comparisons to other temperature ranges except in Figure 1. It would be particularly useful to compare the near 0°C range to the ranges above and below. Is precipitation of any type more common near freezing than other temperature bands? Is there spatial variability in this result?

Response: We do understand that a different study could examine other temperature ranges but we have provided many reasons why temperatures near 0°C are so important and justify a singular focus here. We agree that precipitation in other temperature bands can be also important but our focus on near 0°C conditions in this article.

Through responses to your and other reviewer comments, we have better justified our choice of temperature range. In particular, we have included an improved justification for addressing the .. temperature range. Reviewers 1 and 4 had commented on this as well and the same response is given in each case.

New/Revised Text: "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 ≤ 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 temperature symmetric window straddling 0°C with embedded large fractions of overall occurrences of varying precipitation types, we defined near 0°C conditions as -2°C ≤ T ≤ 2°C throughout the paper."

New References:

Matsuo, T., Sasyo, Y. and Sato, Y.: Relationship between types of precipitation on the ground and surface meteorological elements, Journal of the Meteorological Society of Japan. Ser. II, 59(4), 462–476, doi:10.2151/jmsj1965.59.4_462, 1981.

Nitu, R., Roulet, Y.A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, G.W., Lejeune, Y., Leppänen, L., Mekis, E.,Panel, J.M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Nishimura, K. and Senese, A.: WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012-2015), World Meteorological Organization Instruments and Observing Methods Report No. 131, Geneva, 2018.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Elomaa, E., Gunther, T., Bates, R., Pangburn, T., Hanson, C., Emerson, D., Copaciu, V. and Milkovic, J.: Accuracy of Tretyakov precipitation gauge: Result of WMO intercomparison. Hydrological Processes, 9(8), 877-895. doi:10.1002/hyp.3360090805, 1995.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Bates, R., Pangburn, T. and Hanson, C. L.: Accuracy of NWS 8" standard nonrecording precipitation gauge: Results and application of WMO Intercomparison. Journal of Atmospheric and Oceanic Technology, 15(1), 54-68. doi:10.1175/1520-0426(1998)0152.0.co;2, 1998.

Major Issues # 2. Figure colors

I probably mention this in too many reviews, but please tell your colleagues: Stop using the jet/spectral/rainbow color ramp (http://www.fabiocrameri.ch/endrainbow.php, https://betterfigures.org/2015/06/23/picking-a-colour-scale-for-scientific-graphics/, etc.). The figures were adequate in general, but could use significant touching up. The color ramps are the most significant issue, especially considering many figures would be difficult to parse out for colorblind individuals. I would also use point size to denote magnitudes in figures 3 and 4 as was done in 5. To me, red does not suggest more near 0°C days than blue. Size, color, and shape should tell a cohesive, intuitive story when making figures.

Response: Thank you for the suggestion. All existing and redrafted colour figures have been re-plotted using a colorblind safe scale. These include Figs. 1, 3, 4, 6, 7, 8, and 9.

Regarding the suggestion for using point sizes to denote magnitudes in Figs. 3 and 4, the authors note, that the various magnitudes are depicted by the different colours and feel that this is an effective way to convey this information. Using scaled size format would hide stations in some regions and important information, which is not desirable. As commented above, these colours have been re-plotted using a colorblind safe scale. It was also preferred to keep the colour scheme in Figs. 3 and 4 the same (i.e., red denoting more days and blue fewer days) to be consistent with the revised trend maps in Figure 5.

Examples of updated figures are shown below. The average annual 0°C surface temperature line, computed from 1981-2010 climate normals of 1619 locations (ECCC, 2019c), is also shown in each figure.

New/Revised Text: At the end of Sect. 2.2 (methods): “The average annual surface temperature contour lines were computed from the 1981-2010 climate normal period (ECCC, 2019c). Kriging with a linear Variogram model on a grid spacing of 50 km was applied to create the interpolated surface temperature map from the 1619 stations for Canada.”

Figure 3 with new colour scale:

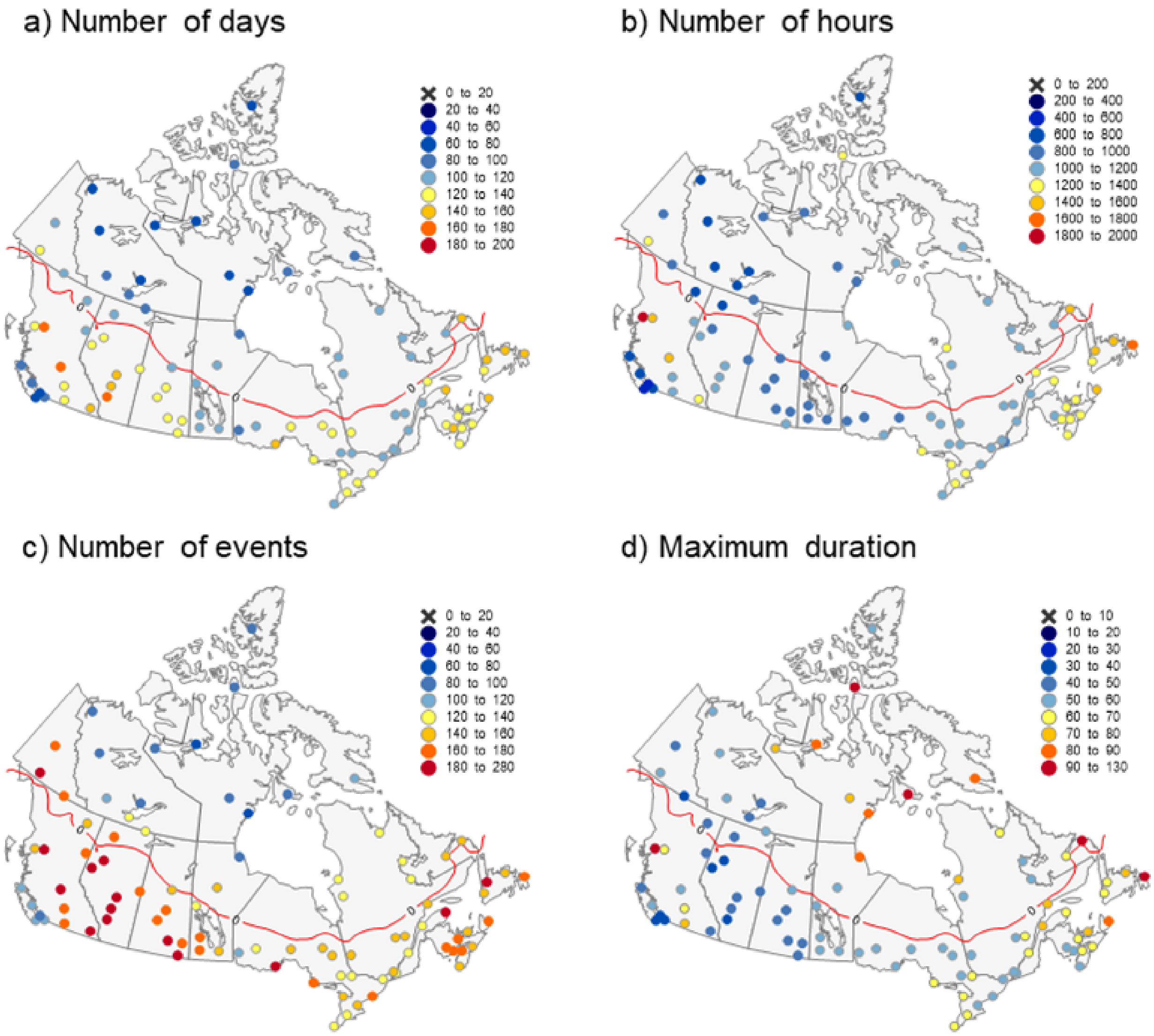


Figure 4 with new colour scale:

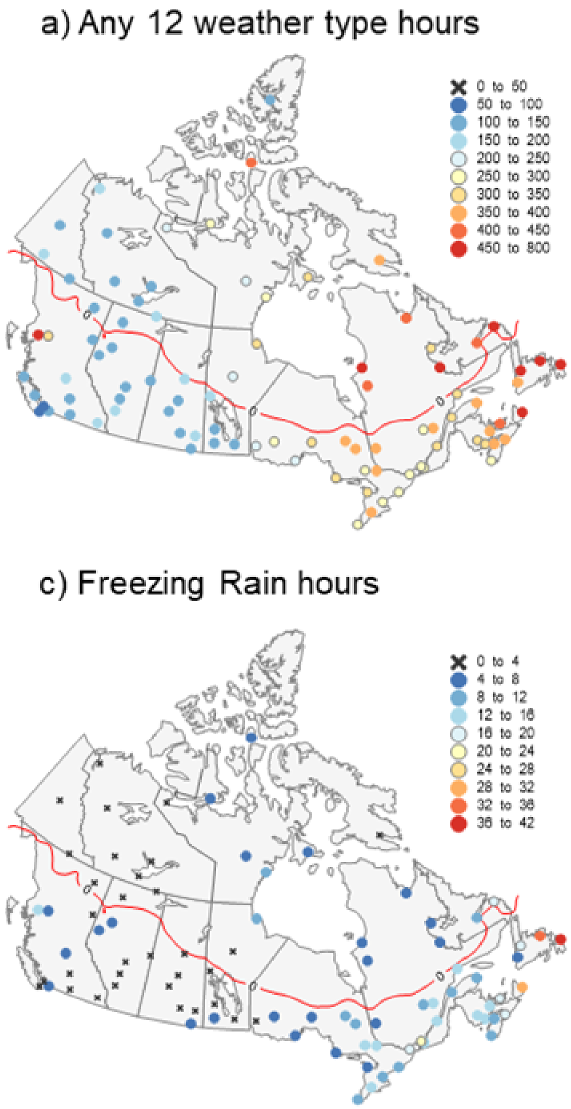
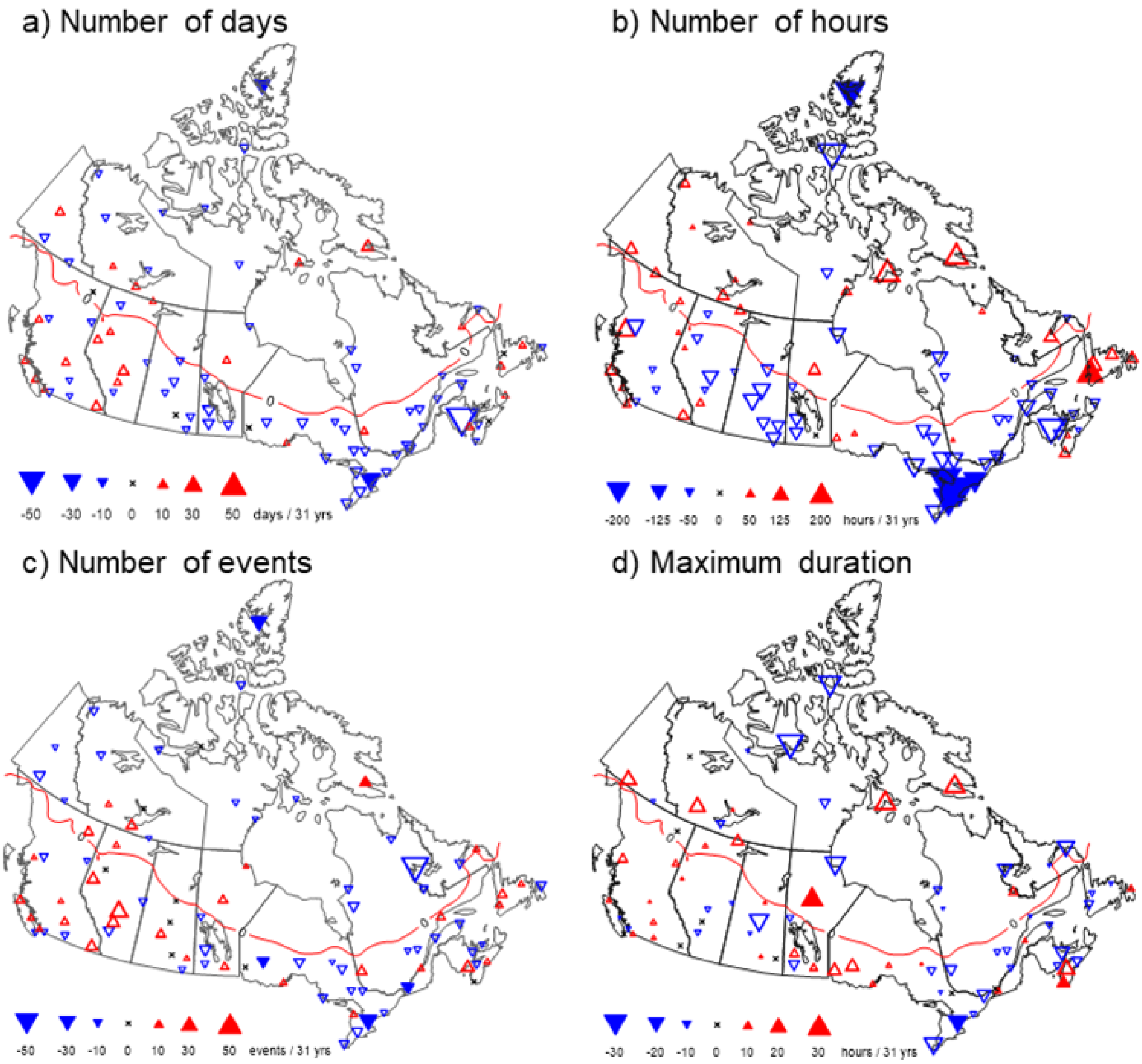


Figure 5 has been updated as follows. Green has been replaced by blue to accommodate the colorblind requirement and blue denotes decreasing trends and red associated with increasing trends as suggested (reversed from the original figures). The revised figure is shown below.



New Reference:

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 24, 2019), 2019c.

Major Issue #3: HESS has a larger international audience, but few connections to previous international work were made. The authors need to significantly bolster the amount of non-Canada research they cite in order to make this study suitable to HESS and its readers.

Response: We have added several new, non-Canadian references as suggested and have improved our text to provide a wider perspective.

Revised paragraphs in INTRODUCTION: "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 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), 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; 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 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).

Revised last two paragraphs in CONCLUDING REMARKS: "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 $-2°C \leq T \leq 2°C$ so called "mixed" precipitation range examined here. And, Dai (2008) and Jennings et al. (2018) illustrated rain/snow issues over 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."

New References:

Ahrens, C. D., Jackson, P. L. and Jackson, C. E. J.: Meteorology Today: An introduction to weather, climate, and the environment: Second Canadian edition, Nelson Education, 2016.

Auer Jr, A. H.: The rain versus snow threshold temperatures, Weatherwise, 27(2), 67–67, 1974.

Dai, A.: Temperature and pressure dependence of the rain-snow phase transition over land and ocean, Geophysical Research Letters, 35(12) [online] Available from: http://onlinelibrary.wiley.com/doi/10.1029/2008GL033295/full, 2008.

Intergovernmental Panel on Climate Change: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.

M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp., doi:10.1017/CBO9781107415324, 2013.

Jennings, K. S., Winchell, T. S., Livneh, B. and Molotch, N. P.: Spatial variation of the rain–snow temperature threshold across the Northern Hemisphere, Nature Communications, 9(1), doi:10.1038/s41467-018-03629-7, 2018.

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Matsuo, T. and Sasyo, Y.: Empirical formula for the melting rate of snowflakes, Journal of the Meteorological Society of Japan. Ser. II, 59(1), 1–9, doi:10.2151/jmsj1965.59.1_1, 1981a.

Matsuo, T. and Sasyo, Y.: Melting of snowflakes below freezing level in the atmosphere, Journal of the Meteorological Society of Japan. Ser. II, 59(1), 10–25, doi:10.2151/jmsj1965.59.1_10, 1981b.

Matsuo, T., Sasyo, Y. and Sato, Y.: Relationship between types of precipitation on the ground and surface meteorological elements, Journal of the Meteorological Society of Japan. Ser. II, 59(4), 462–476, doi:10.2151/jmsj1965.59.4_462, 1981.

Nitu, R., Roulet, Y.A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, G.W., Lejeune, Y., Leppänen, L., Mekis, E.,Panel, J.M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Nishimura, K. and Senese, A.: WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012-2015), World Meteorological Organization Instruments and Observing Methods Report No. 131, Geneva, 2018.

Sims, E. M. and Liu, G.: A parameterization of the probability of snow–rain transition, Journal of Hydrometeorology, 16(4), 1466–1477, doi:10.1175/jhm-d-14-0211.1, 2015.

Stewart, R. E., Szeto, K. K., Bonsal, B. R., Hanesiak, J. M., Kochtubajda, B., Li, Y., Thériault, J. M., Debeer, C. M., Tam, B. Y., Li, Z., Liu, Z., Bruneau, J. A., Duplessis, P., Marinier, S. and Matte, D.: Summary and synthesis of Changing Cold Regions Network (CCRN) research in the interior of western Canada – Part 1: Projected climate and meteorology, Hydrology and Earth System Sciences, 23(8), 3437–3455, doi:10.5194/hess-23-3437-2019, 2019.

Takeuchi, Y., Kodama, Y. and Ishikawa, N.: The thermal effect of melting snow/ice surface on lower atmospheric temperature, Arctic, Antarctic, and Alpine Research, 34(1), 20, doi:10.2307/1552504, 2002.

U.S. Army Corps of Engineers: Snow hydrology: Summary report of the snow investigations, North Pacific Division, Portland, Ore. 437 pp., 1956.

Wexler, R., Reed, R. J. and Honig, J.: Atmospheric cooling by melting snow, Bulletin of the American Meteorological Society, 35(2), 48–51, doi:10.1175/1520-0477-35.2.48, 1954.

Line-by-line comments:

Line 14: I assume near-surface air temperature is meant here. Please correct all instances throughout the paper.

Response: For the hourly temperature observations, the surface dry bulb temperature available in the Canadian National Archive was used throughout the paper. We have clarified this in Table 1 caption and in the data section in the manuscript. For other references to temperature, we use the term "surface temperature" when referring to direct observations and "temperature" when referring to temperature in general. These have been revised in both the original text and the revised text in all of our responses.

New/Revised Text: Examples of changes are:

Updated Table 1 caption:

"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)."

Methods section of the manuscript:

"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."

New References:

American Meteorological Society: Glossary of Meteorology, available at: http://glossary.ametsoc.org/wiki/Main_Page (last access: October 3, 2019), 2018.

ECCC (Environment and Climate Change Canada): MANOBS (Manual of Surface Weather Observation Standards), 8th Edition, available at: https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manobs-surface-observations.html (last access: October 3, 2019), 2019b.

World Meteorological Organization - International Cloud Atlas Manual on the Observation of Clouds and Other Meteors. (WMO-No. 407), available at: https://cloudatlas.wmo.int/home.html (last access: October 3, 2019), 2017.

Lines 18–19: I'm not clear what this sentence means. Do the Atlantic Stations more commonly have precipitation with near 0°C conditions or they have higher fractions of the listed types in parentheses?

This is Lines 18-19: "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."

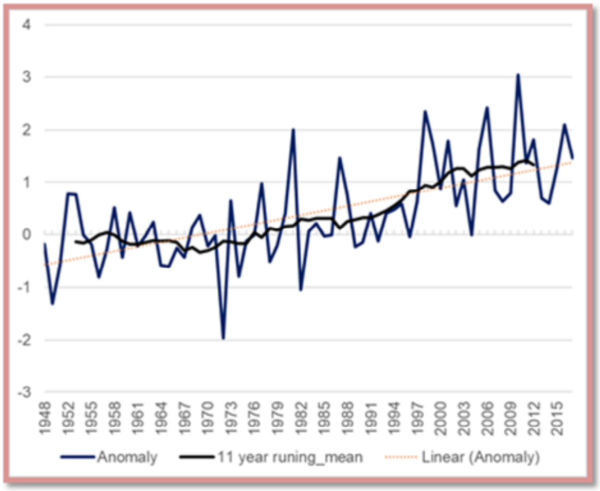
Response: Yes, they commonly have more reported precipitation type occurrence near 0°C and higher fractions of any type of precipitation.

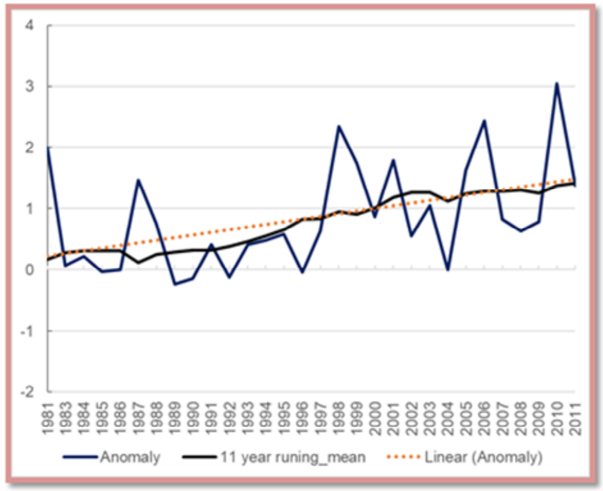
New/Revised Text: "Various types of precipitation (for example, rain, freezing rain, wet snow and ice pellets) sometimes occur with these temperatures. The near 0°C conditions and the reported precipitation type occurrences tends to be higher in Atlantic Canada, although high values also occur in other regions."

Line 20: Please remove this line unless systematic warming was shown for these stations over the 1981–2011 time period.

Original line 20 sentence is: "Trends of most *temperature-based and precipitation-based indicators show little or no change despite a systematic warming in annual temperatures."*

Response: The time-series in Canada's Changing Climate Report (Bush and Lemmen, 2019) (Figure 4.3.b) shows clear increasing trend of surface temperature for the 1981-2011 period. We received the full time-series from the referenced report (left panel), then selected and plotted the 1981-2011 period (right panel). In each panel, the temperature scale refers to the temperature anomaly (departures from baseline average) in 0°C expressed relative to the average for the period 1961–1990. These plots will not be in our paper, only the reference. For the sentence itself we have added the words "across Canada" to the end.





New/Revised Text:

In the abstract (no reference can be added here): "Trends of most temperature-based and precipitation-based indicators show little or no change despite a systematic warming in annual surface temperatures over Canada."

In the Conclusion Line 350: "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."

New Reference:

Bush, E. and Lemmen, D.S. (Eds.): Canada's changing climate report, Government of Canada, Ottawa, Ontario, 444 pp., 2019.

Lines 22–24: Clarify this is only for some stations (a separate peak in the near 0°C bin is shown in Figs. 1 a, e, f, g, i).

This is Lines 22-24: "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."

Response: The phrase "for some stations" has been added.

New/Revised Text: "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."

Lines 30–32: A significant amount of research has been devoted to these items. Please cite the associated authors.

Lines 30-32 are "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)."

Response: Several references are now included.

New/Revised Text: "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)."

New References:

Beltaos, S., Prowse, T., Bonsal, B., Mackay, R., Romolo, L., Pietroniro, A. and Toth, B.: Climatic effects on ice-jam flooding of the Peace-Athabasca Delta, Hydrological Processes, 20(19), 4031–4050, doi:10.1002/hyp.6418, 2006.

Kraatz, S., Jacobs, J. M. and Miller, H. J.: Spatial and temporal freeze-thaw variations in Alaskan roads, Cold Regions Science and Technology, 157, 149–162, doi:10.1016/j.coldregions.2018.10.006, 2019.

Laute, K. and Beylich, A. A.: Potential effects of climate change on future snow avalanche activity in western Norway deduced from meteorological data, Geografiska Annaler: Series A, Physical Geography, 100(2), 163–184, doi:10.1080/04353676.2018.1425622, 2018.

Lindenschmidt, K.-E., Das, A., Rokaya, P. and Chu, T.: Ice-jam flood risk assessment and mapping, Hydrological Processes, 30(21), 3754–3769, doi:10.1002/hyp.10853, 2016.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Papadopol, P., Campbell, K. and Hutchinson, M. F.: Change and evolution in the plant hardiness zones of Canada, BioScience, 64(4), 341–350, doi:10.1093/biosci/biu016, 2014.

Moen, J. and Fredman, P.: Effects of climate change on alpine skiing in Sweden, Journal of Sustainable Tourism, 15(4), 418–437, doi:10.2167/jost624.0, 2007.

Line 77: Note explicitly that these are visual reports of precipitation phase if so.

Lines 77 being considered: ... 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).

Response: ECCC's National Climate Archive includes many observations. For the present study the hourly surface air temperature and the manual precipitation type observations were selected. These elements are further described in the following two paragraphs. The word "visibility" is added to the description in the data section now.

New/Revised Text: "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 (ECCC, 2019b)."

New Reference:

ECCC (Environment and Climate Change Canada): MANOBS (Manual of Surface Weather Observation Standards), 8th Edition, available at: https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manobs-surface-observations.html (last access: October 3, 2019), 2019b.

Line 95: Adverbs ending in -ly are not followed by hyphens.

Response: Thank you for pointing this out.

New/Revised Text: "...physically based…"

Lines 98–99: For the first metric, please clarify if the daily average temperature is used.

Lines 98-99 being considered: "Four temperature-based indices were calculated from this information (Table 1)."

Response: The sentence is a general statement, but the input for temperature - namely the hourly surface dry bulb temperature is added to the sentence. Following the suggestion of Rev 4 as well, the sentence is extended further.

New/Revised Text: "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."

Line 103: What does "without the assurance" mean in this context?

Line 103 in question: "The first set of indicators are associated with the near 0°C condition without the assurance of any precipitation occurrence."

Response: The first set of indicators associated with the near 0°C conditions is based on temperature observations; it is not linked to the precipitation types as of yet. The paragraph is reworded and simplified following the suggestion of Rev 4.

New/Revised Text: "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 $-2 \leq T \leq 2$°C range. Note that to be considered a single event, there could be no more than three continuous hours of missing data. 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."

Lines 106–108: Is the percentage calculated from all hours in a year or just hours near freezing?

Lines 106-108 in question: "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."

Response: The percentage is just for the number of hours near freezing. The previous sentence reads "To assess precipitation during near 0°C conditions, further indicators combining the temperature and precipitation type conditions were computed (Table 1)". We believe that this is clear enough so we have not revised the text.

New/Revised Text: There is no revision to the text.

Line 110: Please clarify that Sen is used to compute the magnitude and sign of the trend.

Lines 110 in question: "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). "

Response: The text was clarified as suggested.

New/Revised Text: 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 (Kendall, 1955).

Line 116: How was hourly sky cover computed?

Line 116-117 in question: 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.

Response: We have added information on the computation of sky conditions in Lines 116-117.

New/Revised Text: "In addition to the temperature and precipitation type occurrence information, hourly sky conditions were also extracted over the nine selected 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, then the octas of the layers are summed. This information was only examined for the longest duration near 0°C conditions at these stations."

New Reference:

ECCC (Environment and Climate Change Canada): MANOBS (Manual of Surface Weather Observation Standards), 8th Edition, available at: https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manobs-surface-observations.html (last access: October 3, 2019), 2019b.

Lines 120–173: It would be useful to include additional quantitative results (i.e., attach numbers to the comparisons made in this section).

Response: Good point. Additional quantitative information has been added. The revised text includes some changes to the text in response to your and other reviewer comments. This includes additional information in relation to updated Figs. 3-5.

New/Revised Text:

"Figure 3a shows the average 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 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 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.

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 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. 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 Columbia; and northern British Columbia, Alberta 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 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 persistence of such events, is shown in Fig. 3d. Maximum 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.

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 (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 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 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 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 - 1.2%) does occur near Vancouver however."

Lines 123–125: These are discussion points and not part of the results. Given there is a dedicated discussion section (Sect. 5), these lines and all subsequent ones not dealing with results explicitly covered in this project (e.g., lines 154–155) should be moved.

Lines 123-125 in question: "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."

Lines 154-155 in question: "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)".

Response: This is a good point in regards to Lines 123-125 and Lines 154-155. They have been removed.

New/Revised Text: Lines 123-125 and Lines 154-155 have been deleted.

Line 128: Replace less with fewer.

Line 128 in question: "This area is colder than the previously mentioned regions with less incursions of warm air during the cold season. Lowest (40 to 80) values are in the North due to even fewer warm air incursions."

Response: Thank you for noticing this. The sentence has been revised

New/Revised Text: "This area is colder than the previously mentioned regions with <u>fewer</u> incursions of warm air during the cold season. Lowest (40 to 80) values are in the North due to even fewer warm air incursions."

Lines 160–162: Please rewrite to be more objective (i.e., remove "huge" and "enormous").

Lines 160-162 in question: "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."

Response: We have followed this suggestion.

New/Revised Text: "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)."

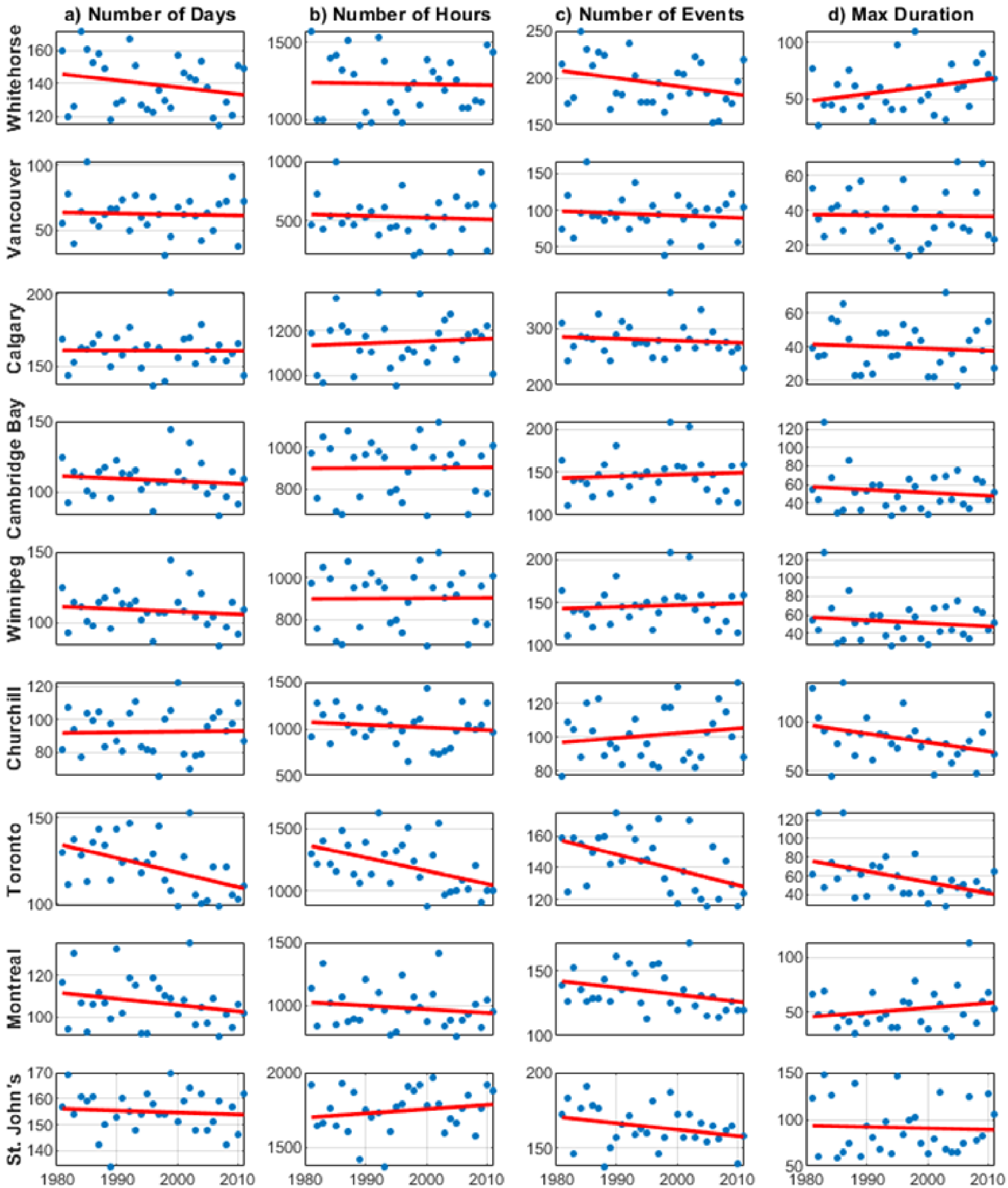
Lines 175–194: I would change the way the trends are discussed. It appears the values given are the differences between the beginning of the study period and the end, not the slope of the trend (e.g., days per decade, hour per year). This is inconsistent with the way trends are typically presented (change per time period) and should be changed. It would also be useful to include time series figures for the trends, perhaps in Sect. 4 where the representative stations are presented. I note below that figures 8 and 9 can be deleted, so there is room for more plots.

Response: We may not understand this question. The trend values are actually the change over the 1981-2011 period everywhere in the manuscript, which is the change over the 31 years, as requested. This approach is consistent with Vincent et al. (2018) used recently.

We agree that adding time-series for the selected set of nine stations enhances the understanding of the indicators and the associated changes. The new Figure X is attached. The Figure X trend values correspond to the trend values listed in Table 2.

New/Revised Text: "As discussed previously, many stations exhibited some changes but few were statistically significant (Fig. X and Table 2). This characteristic is also prevalent for the nine selected stations with only two experiencing significant change. In particular, Toronto showed significant decreases in all four temperature-related indicators while Montreal had a decrease in the number of events per year."

New Figure X caption: 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.



Line 201: Change least to fewest.

Line 201 in question: "In parallel, Calgary experienced the largest number of events; Cambridge Bay the least."

Response: Thank you for noting this. The change has been made.

New/Revised Text: "In parallel, Calgary experienced the largest number of events; Cambridge Bay the fewest."

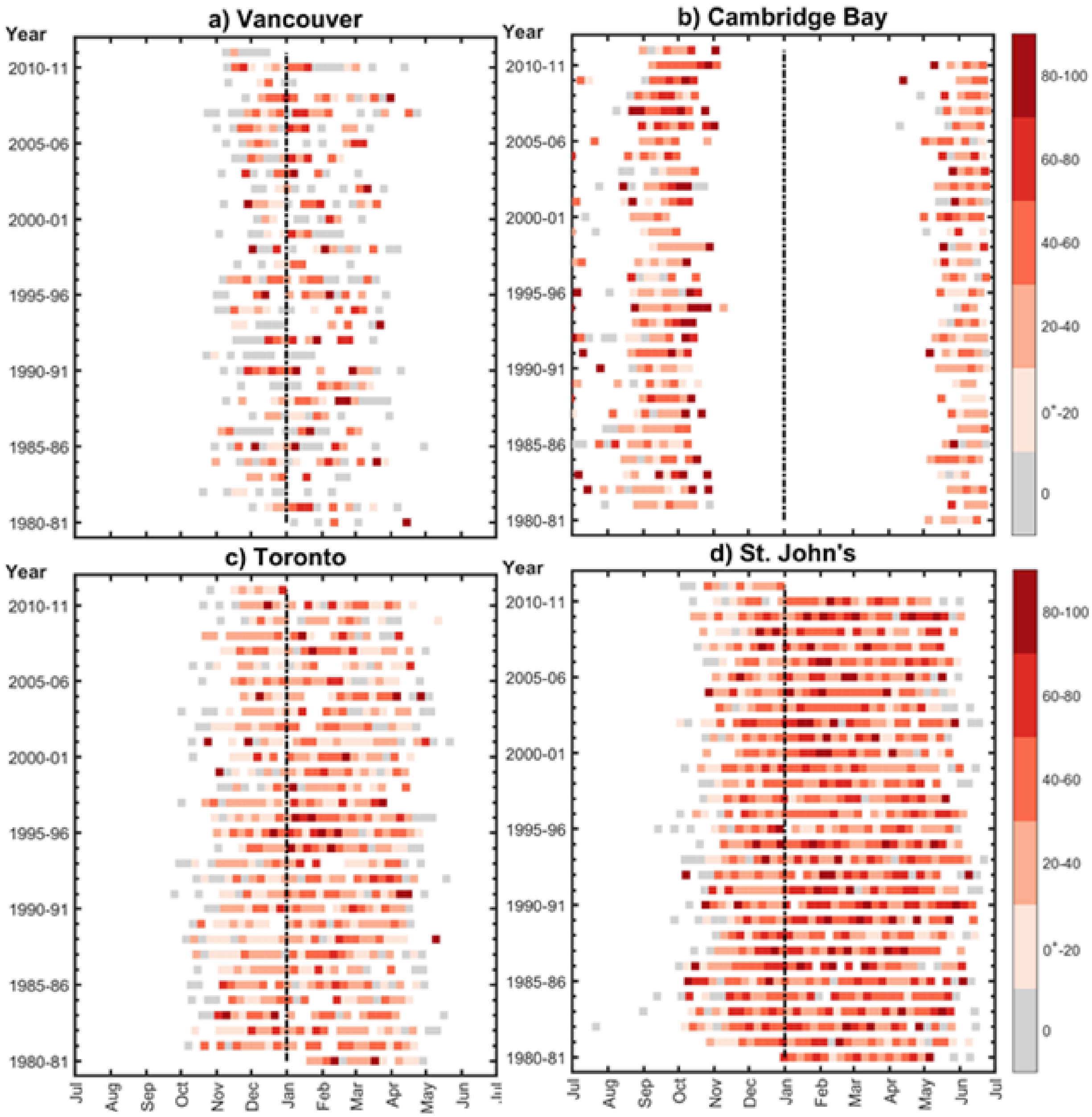
Lines 221–227: Remove.

Lines 221-227 in question: "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."

Response: The authors feel that Fig. 9 (with revisions based on all the reviewers' comments) provides critical insight into shorter sub-annual scales and thus the identified text has not been removed. We did update the text and figure to improve clarity.

Revised text: "Further insight can be gained by examining shorter time scales. For example, Fig. 9 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 (Fig. 9a,c,d) but they can occur in any other month. In contrast, these conditions only occur in summer at Cambridge Bay (Fig. 9b). The most frequent occurrence can be seen at St. John's (Fig. 9d)."

Revised Figure 9:



Revised Figure 9 caption: "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.

Lines 228–234: Interannual variability is not quantified in this study. Relying on Figure 9 for this information is iffy at best. I note below this figure should be deleted anyway.

Lines 228-234 in question: "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."

Response: We have now clarified that the only reference is to Fig. 9 and we have removed the text regarding inter-annual variability. In addition, a new table is provided to improve clarity. We label this as Table X with its numbering to be added later.

New/Revised Text: "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 X and Fig. 9c, both of these trends are significant at only one location, Toronto. Whitehorse shows significant earlier spring cessation (Table X) and St. John's shows significant later autumn onset (Fig. 9d and Table X). Cambridge Bay experiences near 0°C conditions in every 'warm season' month (Fig. 9b and Table X) 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 X)."

Table X: 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 Surface 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

New References:

Bush, E. and Lemmen, D.S. (Eds.): Canada's changing climate report, Government of Canada, Ottawa, Ontario, 444 pp., 2019.

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Lines 235–320: The discussion is generally well written and offers valuable information that complements the results. My main suggestions for this section are:

1) Reduce the amount of redundant results that are provided (for example, lines 279–283 are merely repeating results from the already-presented Figure 1).

Lines 279-283 in question: "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."

Response: Figure 1 was used to introduce the whole distribution of temperature at several stations across Canada and to point out that, naturally, temperatures near 0°C occur at each one regardless of the average annual temperature. In lines 279-283, the focus is on the factors associated with the common 'prominence' of these temperatures relative to others.

New/Revised Text: There is no change in the text.

2) Make greater connections to international work. What other regions are similar to these Canadian study sites? What connections can be made between the work here and other areas?

Response: Thank you. We addressed this in an earlier comment, Major Point 3. We could copy that response and place it here but there is a considerable amount of text.

New/Revised Text: The revised text is shown under Reviewer 2, Major Point 3 (starts page 11 in this document).

3) More rigorous citation of the proposed processes at work. Many of the hypothetical mechanisms are either lightly cited (e.g. lines 284–288) or not cited at all (e.g., lines 272–277). Please be sure to credit the authors whose work you are using to make this discussion section.

Lines 272-277 in question: "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 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."

Lines 284-288 in question: "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."

Response: As suggested, we have included more references to previous work.

New/Revised Text:

Lines 272-277: "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. (1995). These vigorous storms almost always are 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)."

Lines 284-288: "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 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 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."

New References:

Matsuo, T., Sasyo, Y. and Sato, Y.: Relationship between types of precipitation on the ground and surface meteorological elements, Journal of the Meteorological Society of Japan. Ser. II, 59(4), 462–476, doi:10.2151/jmsj1965.59.4_462, 1981.

Stewart, R.E.: Precipitation types in winter storms. Pure and Applied Geophysics, 123, 597-609, 1985.

Stewart, R. E., Isaac, G. A. and Shaw, R. W.: Canadian Atlantic Storms Program: The meteorological field project, Bulletin of the American Meteorological Society, 68(4), 338–345, doi:10.1175/1520-0477(1987)068<0338:casptm>2.0.co;2, 1987.

Stewart, R. and Patenaude, L.: Rain-snow boundaries and freezing precipitation in Canadian East Coast winter storms, Atmosphere-Ocean, 26(3), 377–398, doi:10.1080/07055900.1988.9649309, 1988.

Stewart, R. E., Yui, D. T., Chung, K. K., Hudak, D. R., Lozowski, E. P., Oleskiw, M., Sheppard, B. E. and Szeto, K. K.: Weather conditions associated with the passage of precipitation type transition regions over Eastern Newfoundland. Atmosphere-Ocean, 33, 25-53, 1995.

Takeuchi, Y., Kodama, Y. and Ishikawa, N.: The thermal effect of melting snow/ice surface on lower atmospheric temperature, Arctic, Antarctic, and Alpine Research, 34(1), 20, doi:10.2307/1552504, 2002.

Wexler, R., Reed, R. J. and Honig, J.: Atmospheric cooling by melting snow, Bulletin of the American Meteorological Society, 35(2), 48–51, doi:10.1175/1520-0477-35.2.48, 1954.

Lines 338–339 and 343–346: These are not conclusions based on results from this paper. Please rewrite or remove.

Lines 338-339 in question: "This is likely a 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."

Lines 343-346: *"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."*

Response: We have clarified this information. Regarding Lines 338-339, we have added a new sentence to follow Lines 268-269 in the Discussion section (5.1) of the Submitted article. The new lines are shown below. We have deleted Lines 338-339 from the Conclusions.

Regarding Lines 343-346, we feel that we have illustrated the importance of such factors. This stems not just from the original version of the article but also through changes made in connection with other reviewer comments. We certainly agree that this is an important issue. Even though the content has not changed, we have modified these sentences to improve clarity.

New/Revised Text:

Lines 338-339 have been moved and updated to follow Lines 268-269: "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)."

Lines 343-346: "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."

New Reference:

Hare, K.: Canada's climate: An overall perspective. In "The Surface Climates of Canada". McGill-Queen's University Press, 3-20, 1997.

Larouche, P. and Galbraith, P. S.: Canadian coastal seas and Great Lakes Sea Surface Temperature climatology and recent trends, Canadian Journal of Remote Sensing, 42(3), 243–258, doi:10.1080/07038992.2016.1166041, 2016.

Line 350: Air temperatures were not presented for the 1981–2011 time period. Please rewrite or remove.

The line in question: "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."

Response: A new reference has been added to the sentence.

New/Revised Text: "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."

New Reference:

Bush, E. and Lemmen, D.S. (Eds.): Canada's changing climate report, Government of Canada, Ottawa, Ontario, 444 pp., 2019.

Table 1: Please be consistent in use of T, Tdrybulb, surface temperature, etc. in this table and throughout the paper.

Response: Thank you for the suggestion. Table 1 is updated. The Tdrybulb index is removed and added to the title only. Throughout the paper the word "surface" is added before the occurrence of the word "temperature" in multiple spots in the text.

New/Revised Text: "Temperature" replaced with "surface temperature" in multiple spots.

Table 1: Table of indicators in the $-2 \leq T \leq 2$°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 $-2^{\circ}C \le T \le +2^{\circ}C$	days
Annual number of hours with $-2^{\circ}C \le T \le +2^{\circ}C$	hours
Annual number of independent events (continuous hours) with $-2^{\circ}C \le T \le +2^{\circ}C$	events
Annual Maximum Lengths with $2^{\circ}C \le T \le +2^{\circ}C$	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
... **any of the above 12** precipitation types	hours
Combination of surface temperature and precipitation type	
Annual number of hours with freezing rain and $-2^{\circ}C \le T \le +2^{\circ}C$	hours
Annual number of hours with any of the 12 precipitation types and $-2^{\circ}C \le T \le +2^{\circ}C$	hours
The percentage of time when Freezing Rain occurs during $[-2^{\circ}C \le T \le +2^{\circ}C]$ conditions	%
The percentage of time when any of the 12 types occurs during $[-2^{\circ}C \le T \le +2^{\circ}C]$ conditions	%

New References:

American Meteorological Society: Glossary of Meteorology, available at: http://glossary.ametsoc.org/wiki/Main_Page (last access: October 3, 2019), 2018.

ECCC (Environment and Climate Change Canada): MANOBS (Manual of Surface Weather Observation Standards), 8th Edition, available at: https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manobs-surface-observations.html (last access: October 3, 2019), 2019b.

World Meteorological Organization - International Cloud Atlas Manual on the Observation of Clouds and Other Meteors. (WMO-No. 407), available at: https://cloudatlas.wmo.int/home.html (last access: October 3, 2019), 2017.

Table 2: Av. or avg. are commonly used abbreviations for average, not aver. Also change the abbreviation for significance from sign to sig. Sign is confusing because it could be construed as referring to the sign of

the trend (i.e., positive or negative). Also, a unit for the trend must be given (is it hours per year, per decade, etc.?). These comments apply to subsequent tables and figures, as well.

Response: The whole table is updated. Since Table 2 shows trend values for the 31 year period (1981-2011), significance level and units have been added. Bold is used for significance indicator, columns with arrows and n/a have been removed.

New/Revised Text: The new Table 2 and its title are shown.

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 trends with 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

Figure 1: Please note these are 4°C temperature bins.

Response: We have added this to the caption of Fig. 1.

Revised caption: “Figure 1: The average annual surface temperature distribution (4°C bins) from 1981 to 2011 for 9 selected stations across Canada as shown in Fig. 2. The vertical black line indicates the average annual surface temperature using information from ECCC (2019c). The red bar identifies near 0°C surface temperatures defined as $-2 \leq T \leq 2$°C. Stations are arranged from west to east. Details on the temperature data are presented in Sect. 2.”

New Reference:

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Figures 3-4: Please see my major issues comment on figures.

Response: As discussed under Reviewer 2, Major Issue #2, we have updated our figures.

New/Revised Text: Updated figures are shown in the responses to other comments.

Figure 5: Fortunately there is a second coding in the plot points to differentiate between positive and negative trends, but the coloring should be changed (it is difficult for many color blind people to tell green and red apart).

Response: The figure is updated with the colorblind safe red/blue colors.

New/Revised Text: The revised figure is shown below.

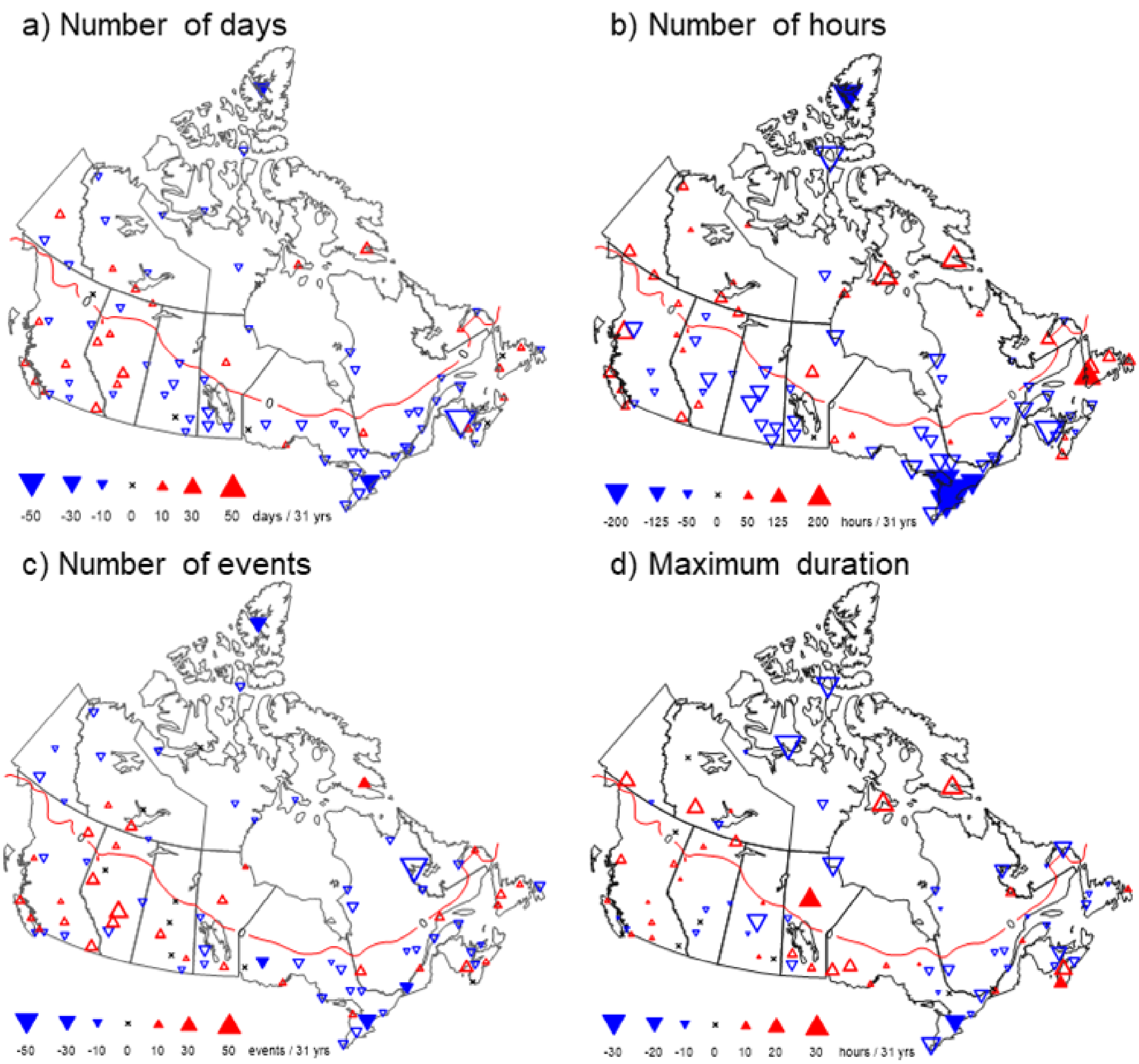


Figure 6: It is very difficult to tell the lines apart. Consider labeling the lines directly and change color ramp to one that is colorblind friendly.

Response: The figure has been improved by changing the colour palette, adding dashes in some cases, and updating the legend.

New/Revised Text: There is no change in the text.

The new figure is:

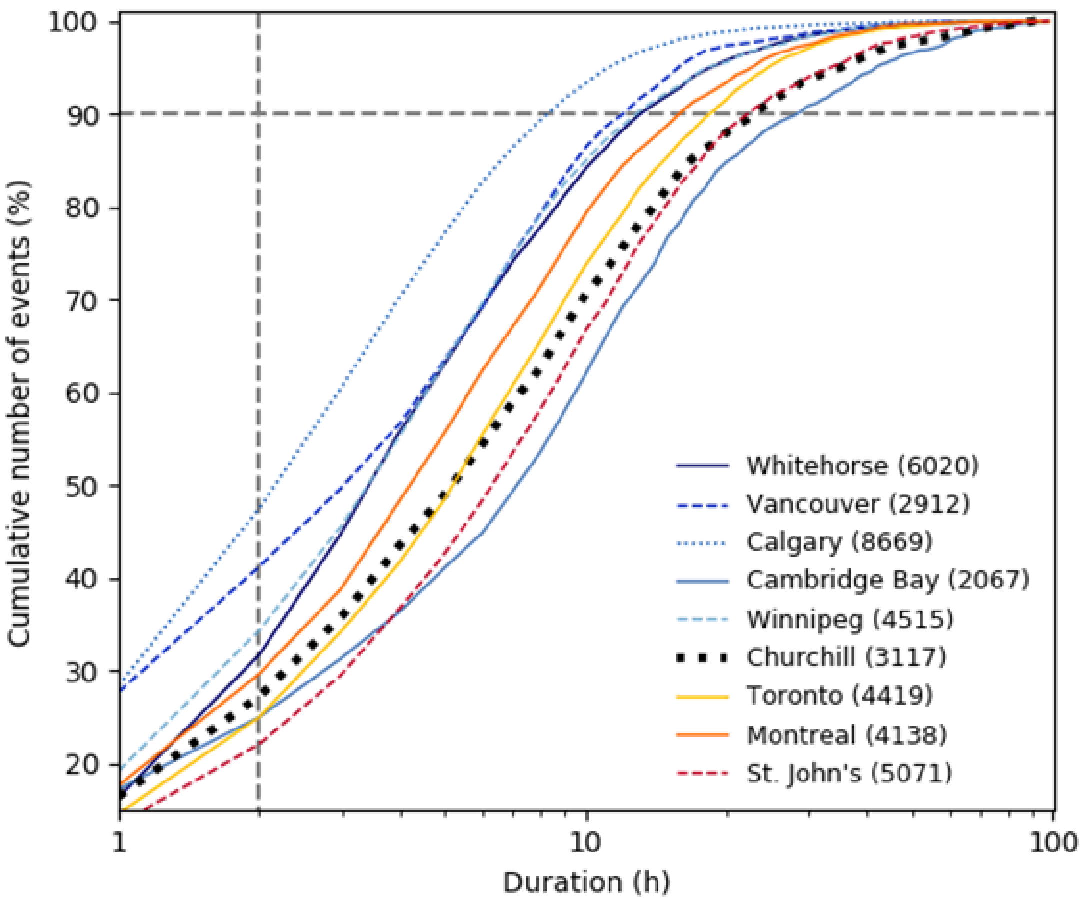


Figure 6 revised caption: Cumulative distribution of events (%) as a function of duration (h) of near 0°C (-2 ≤ T ≤ 2°C) events at the 9 selected stations across Canada over the 1981-2011 period arranged from west to east. The total number of events is shown in brackets and duration is plotted on a logarithmic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

Figure 7: Some precipitation types use different shadings of the same color (snow, rain) while others do not (ice, freezing). Ice pellet showers and rain showers are difficult to tell apart and the color ramp is not colorblind friendly.

Response: Figure 7 has been updated and it is shown below.

New/Revised Figure:

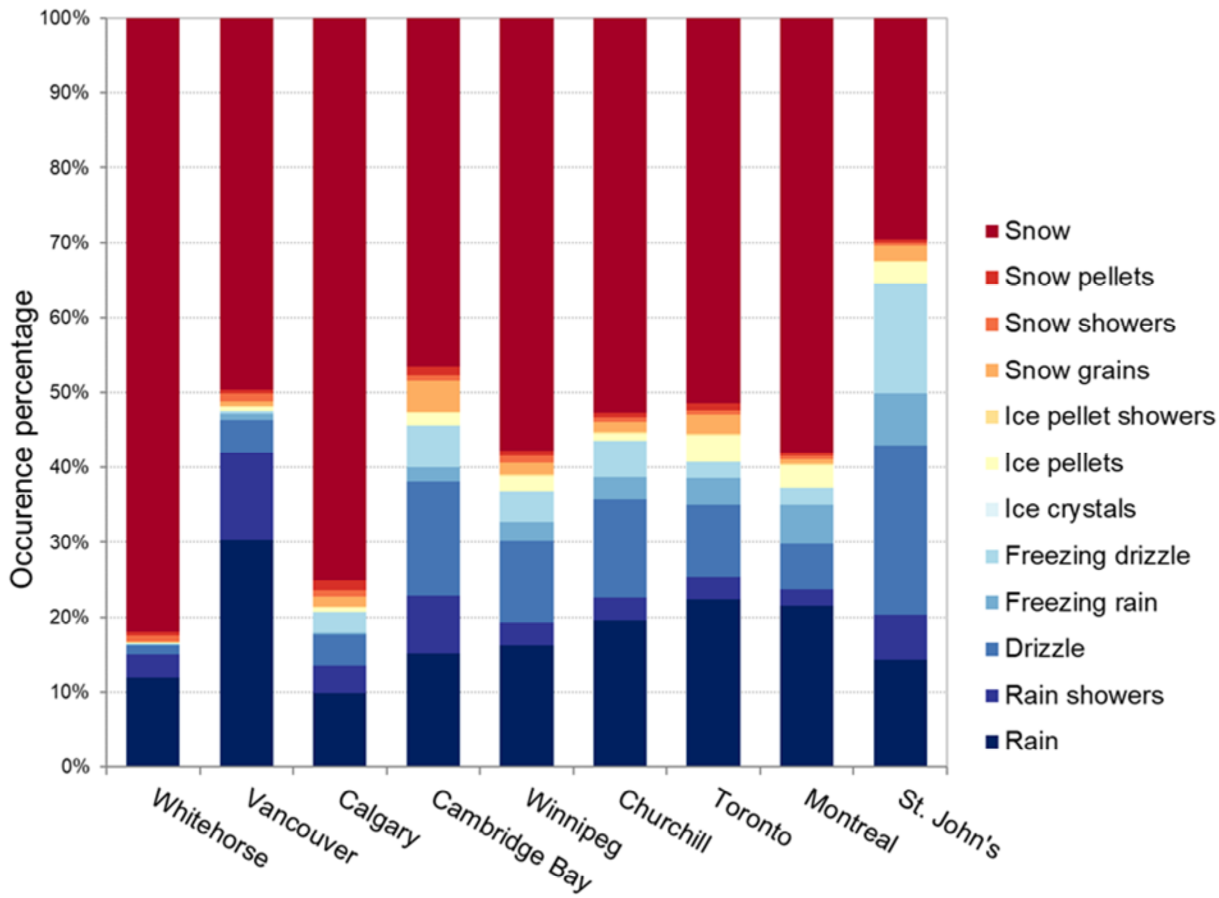


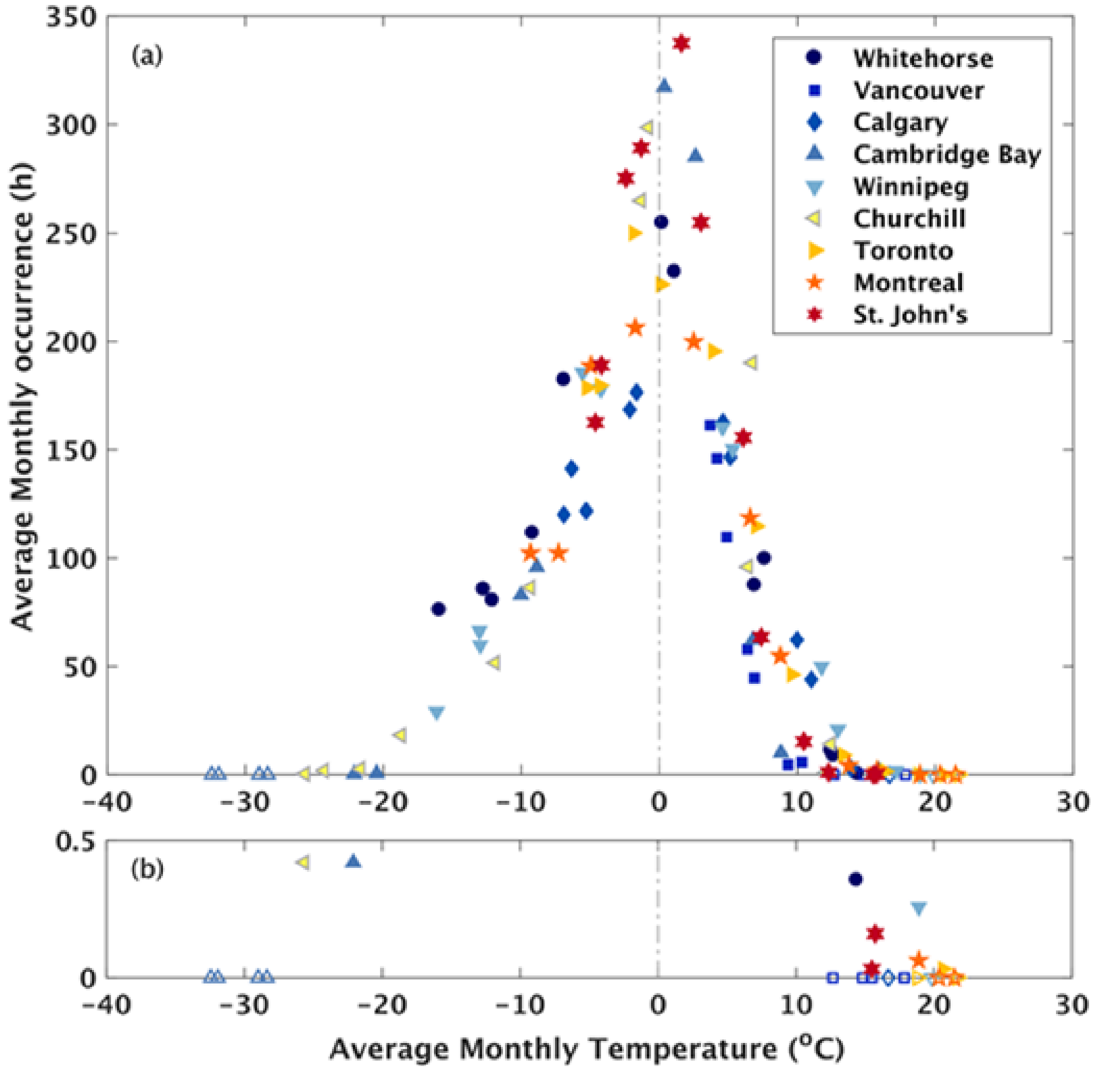
Figure 8: This figure shows monthly occurrences of near 0°C conditions are more common when monthly average air temperature is near 0°C. This is quite obvious and does not require a figure. The stations are also impossible to tell apart due to the color ramp.

Response: We agree that it is not an unexpected general pattern as we indicated in the original text. But additionally, this figure shows that the distribution is not symmetric around 0°C, it shows the actual quantitative distribution, and it indicates which stations have experienced near 0°C conditions when average conditions are far from this temperature. To improve clarity, we have improved the figure as well as the colours. We also produced a secondary panel that focuses on low occurrence values.

New/Revised Text: The text has been updated to include both panels in the updated diagram.

New/Revised Text: "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. 8a, 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 15-35% 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 more than 20°C away from 0°C (Fig. 8b). The five coldest differences occurred at Churchill and Cambridge Bay, and the five warmest ones occurred at Toronto, Winnipeg and Montreal."

The new figure and revised caption are shown below:

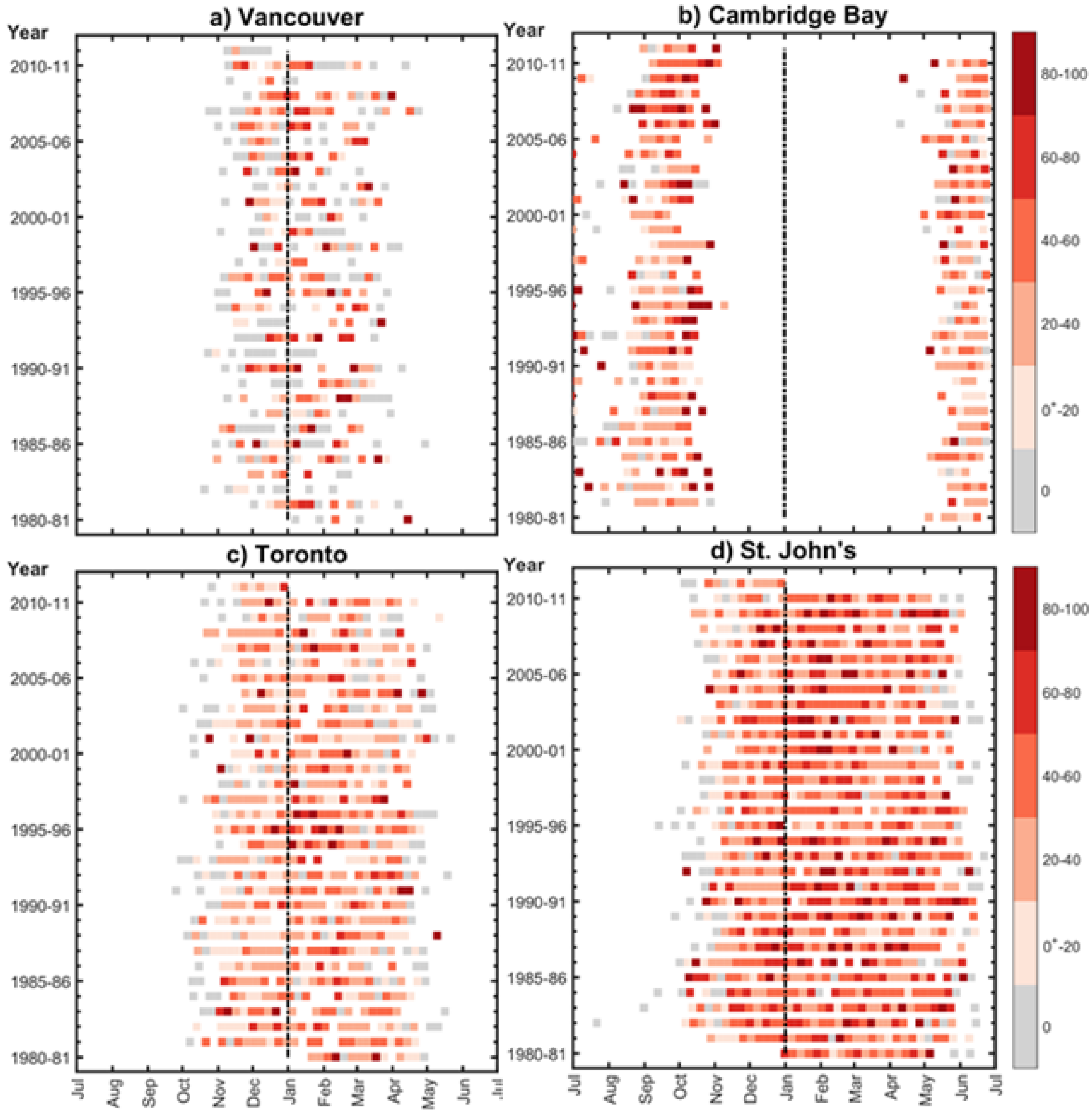


Revised caption: "Figure 8: (a) Average monthly occurrence (hours) of near 0°C conditions as a function of average monthly surface temperature for the nine selected stations over the 1981-2011 period. Filled symbols indicate occurrence and open or unfilled symbols indicate no occurrence. (b) An expanded view to better illustrate low values of average monthly occurrence."

Figure 9: This figure can also be deleted.

Response: We feel that this is an important figure but we have updated it to improve clarity. It shows the same information in a condensed weekly timestep. Additionally the fraction (%) of near 0°C hours each week with (or without) precipitation is shown through shading rather than as a separate line.

Revised Figure 9:



Revised Figure 9 caption: "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.

Reviewer 3

This paper presents climatology and trends in near 0°C temperature and precipitation conditions at 92 sites across Canada for 1981-2011. This is important because climate events such as freezing rain can have significant impacts on infrastructure and environment; however, the period 1981-2011 (31 years) is relatively short to detect any trends that are statistically significant. Wang (2006) has presented the trends in freezing rain over Canada for a longer period (1953-2004) and the results of this 2006-paper should be at least mentioned here.

Response: We had to select the shorter 1981-2011 period due to the more limited availability of precipitation type data; this was the common period for the hourly surface temperature and precipitation type.

Thank you for that suggestion. The suggested reference has been added to the introduction and conclusion.

New/Revised Text: In the introduction: "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)."

In the conclusion: "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."

New Reference:

Wang, X. L.: Climatology and trends in some adverse and fair weather conditions in Canada, 1953–2004, Journal of Geophysical Research, 111(D9), doi:10.1029/2005jd006155, 2006.

1. Table 1. 12 weather types were retrieved from the climate archives and the list is provided in Table 1. It would be informative if a short description of each type were provided in bracket. For example, what is the difference between rain and rain showers? Snow and snow showers? Are all observations made by human? What is "all weather types above" (any of the 12 weather types above)? "The fraction of $-2 \leq T \leq 2$ conditions associated with freezing rain, with any of the 12 types" is not clear. Maybe instead "the percentage of time when freezing rain occurs, when any of the 12 types occurs during $-2 \leq T \leq 2$ conditions" would be clear.

Response: Thanks for the suggestions.

- Observational procedures are described in ECCC (2019b) and the definitions are added to Table 1 using three sources that are now referenced.
- The variable intensity and the speed of change are factors distinguishing rain/snow showers from rainfall/snowfall.
- The hourly precipitation type measurements are manual observations, typically done at the airports. Further clarification is added.
- All weather type is indeed any of the 12 precipitation types above. It is corrected in the table.
- The word "fraction" is replaced with the suggested terms "percentage of time" in the table: "the percentage of time when Freezing Rain occurs during [$-2^oC \leq T \leq +2^oC$] conditions" and "the percentage of time when any of the 12 types occurs during [$-2^oC \leq T \leq +2^oC$] conditions."

New/Revised Table Text, Table and Title:

"For the 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 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)."

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
... **any of the above 12** precipitation types	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 percentage of time when Freezing Rain occurs during [-2°C ≤ T ≤ +2°C] conditions	%
The percentage of time when any of the 12 types occurs during [-2°C ≤ T ≤ +2°C] conditions	%

New References:

American Meteorological Society: Glossary of Meteorology, available at: http://glossary.ametsoc.org/wiki/Main_Page (last access: October 3, 2019), 2018.

ECCC (Environment and Climate Change Canada): MANOBS (Manual of Surface Weather Observation Standards), 8th Edition, available at: https://www.canada.ca/en/environment-climate-change/services/weather-manuals-documentation/manobs-surface-observations.html (last access: October 3, 2019), 2019b.

World Meteorological Organization - International Cloud Atlas Manual on the Observation of Clouds and Other Meteors. (WMO-No. 407), available at: https://cloudatlas.wmo.int/home.html (last access: October 3, 2019), 2017.

2. Methods, lines 98-99. The indices represent "the number of days per year" and not "the average number of days per year"… if not, please clarify.

Response: The reviewer is correct in that. Although the average is plotted, the index itself is "the number of days per year".

New/Revised Text: The word "average" has been removed from the sentence in all of the 3 occurrences.

3. Trends, line 175. It might be informative to mention at the beginning of the section that the period 1981-2011 is short to detect any statistical significant trends, there is considerable variability (or not) from one year to another, and the significance of the trend was assessed at the 5% level (this should also be mentioned in the caption). In addition, we expect trend significant at a few stations (5% of the stations) but this does not mean significant change in climate. Why is there no figure showing the trends in the precipitation types (same precipitation types as in fig. 4)?

Response: Following the suggestions and Reviewer 4 comments, the trend computation was modified, now it is described in the methods section. The period of trend computation is clearly stated along with the minimum 90% requirement (29 years out of the full 31 year period) for the surface temperature related indicators.

Trends were computed for individual stations, and the statistical significance of the trends were assessed at the 5% level. The "at 5% level" has also been added to the Fig. 5 caption and Line 175 as suggested.

The station selection was based on the hourly surface temperature quality / availability, not the precipitation type observations. For precipitation type, the only condition was the existence of the observation program. As a result of this, the precipitation type observations has many uncertainties due to variable observing practices and other data issues. It is the reason why the Canada wide figure could not be created. Even the 9 best quality station precipitation type trends have many missing values, as seen in Table 3.

This is described in the data section of the paper. Additional sentence has been added to clarify the limitations of precipitation type observations.

New/Revised Text: "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, the only condition was the existence of the observation during the study period.

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."

….

"The assessment of the trend can be challenging for time series with low occurrences and repetitive (tied) values (Frei and Schar, 2001; 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 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 (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).

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). In 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. "

New References:

Frei, C. and Schär, C.: Detection probability of trends in rare events: Theory and application to heavy precipitation in the alpine region, Journal of Climate, 14, 1568-584, 2001.

Keim, B. D. and Cruise, J. F.: A technique to measure trends in the frequency of discrete random events, Journal of Climate, 11, 848-55, 1998.

McCullagh, P. and Nelder, J. A.: Generalized linear models. 2nd ed. Monogr. on Statistics and Appl. Probability, No. 37, Chapman and Hall, London, UK, 1989.

4. Figure 6. It is difficult to see the distinction between the lines associated to Winnipeg, Cambridge Bay, Calgary and Vancouver because they are all blue. Maybe using fewer colors but full and dotted lines can be helpful. Why does Calgary experience the largest number of events while Cambridge has the least?

Response: The figure has been updated with a different colour palette,using dashes, and simplifying the legend. Information regarding the number of events was also shown in Figure 3 across the country. Section 5.1 discusses factors affecting the number of events. In that section, we point out that cold regions (such as Cambridge Bay) tend to have low numbers since these temperatures are not often reached and Calgary is subject to many short-term events due in part to chinooks.

New/Revised Text: There is no change in the text.

New figure:

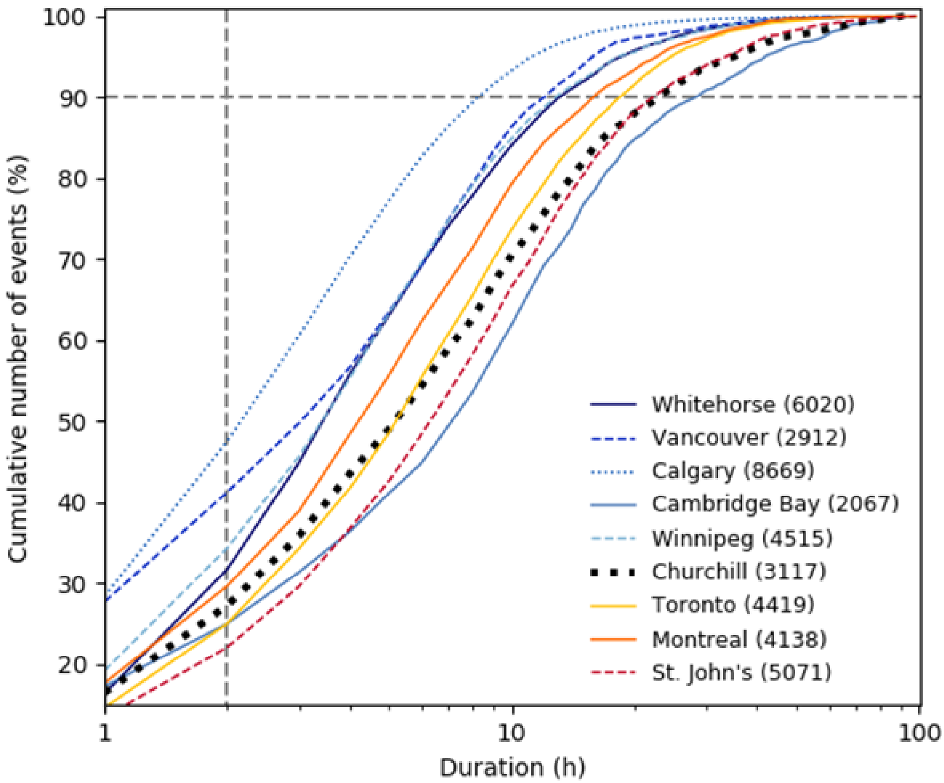


Figure 6 revised caption: Cumulative distribution of events (%) as a function of duration (h) of near 0°C ($-2 \leq T \leq 2$°C) events at the 9 representative stations across Canada over the 1981-2011 period arranged from west to east. The total number of events is shown in brackets and duration is plotted on a logarithmic scale.

5. Table 2. What are "average trend values"? Are they averages or trends over 1981-2011? It seems that Table 2 presents the trends for 1981-2011 (if not, please explain). Trends significant at the 5% level?

Response: Table 2 is updated. It includes both the average annual climatologies for the selected indicators and the trend values for the 1981-2011 period. To address the comment, Table 2 and its title have been revised including the addition of a significance level and units. Bold is now used for significance indicator and original columns with arrows and n/a have been removed.

New/Revised Text: The additional text (goes to the beginning of Sect. 4) and revised Table 2 and its title are shown below.

"Annual average frequencies for the four surface temperature and 13 precipitation type related indicators are shown in Tables 2 and 3 at each selected stations. 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 events occurred at Calgary (280 events) while the maximum duration are the coastal stations of St. John's, Cambridge Bay and Churchill (91, 89 and 84 hours, respectively). This is consistent with regional patterns shown in Figure 3 and 4."

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

6. Table 3. It seems that table 3 also presents the trends (not the average trends values). What is "n/a": this condition does not occur at the station or there is no sufficient data to compute a trend?

Response: Similarly to Table 2, Table 3 also updated. It includes both the average annual climatologies for the selected indicators and the trend values for the 1981-2011 period. Since the precipitation type indicators are proven not to be normally distributed, only the direction and significance of change is noted. Significance level and units were added. Original columns with arrows have been removed.

New/Revised Text: "To characterize these variables, the 1981-2011 average annual frequency was determined for each 92 stations 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; 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 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 (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).

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."

Additional text, the revised Table 3, its reference and title are shown below:

"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."

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

New References:

Frei, C. and Schär, C.: Detection probability of trends in rare events: Theory and application to heavy precipitation in the alpine region, Journal of Climate, 14, 1568-584, 2001.

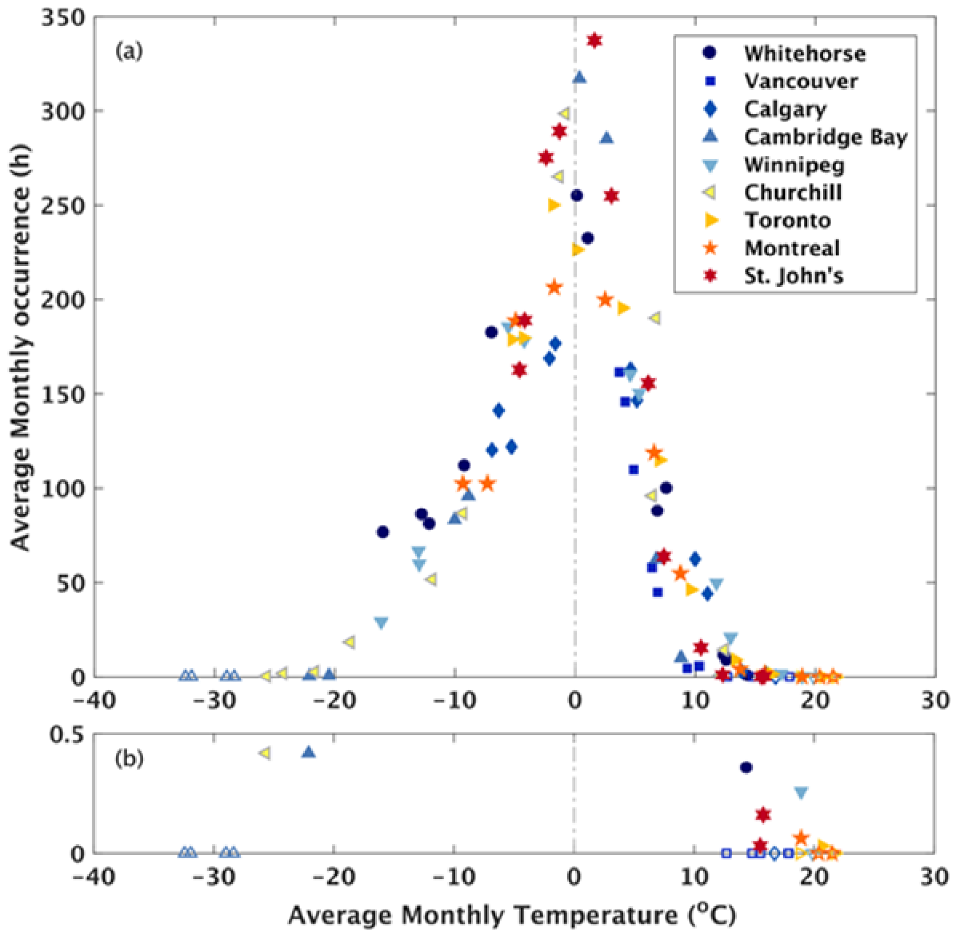
Keim, B. D. and Cruise, J. F.: A technique to measure trends in the frequency of discrete random events, Journal of Climate, 11, 848-55, 1998.

McCullagh, P. and Nelder, J. A.: Generalized linear models. 2nd ed. Monogr. on Statistics and Appl. Probability, No. 37, Chapman and Hall, London, UK, 1989.

7. Figure 8. What are the “Average monthly occurrences”? Are these calculated for the 12 months separately? For the winter months only? Maybe a sentence can be added to explain this.

Response: ‘Average monthly occurrences’ are calculated for each month separately. The initial sentences in this paragraph have been updated to improve clarity. The figure itself has also been improved and this has led to changes in the caption as well.

New/Revised Text: “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. 8a, 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 15-35% 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 more than 20°C away from 0°C (Fig. 8b). The five coldest differences occurred at Churchill and Cambridge Bay, and the five warmest ones occurred at Toronto, Winnipeg and Montreal.”

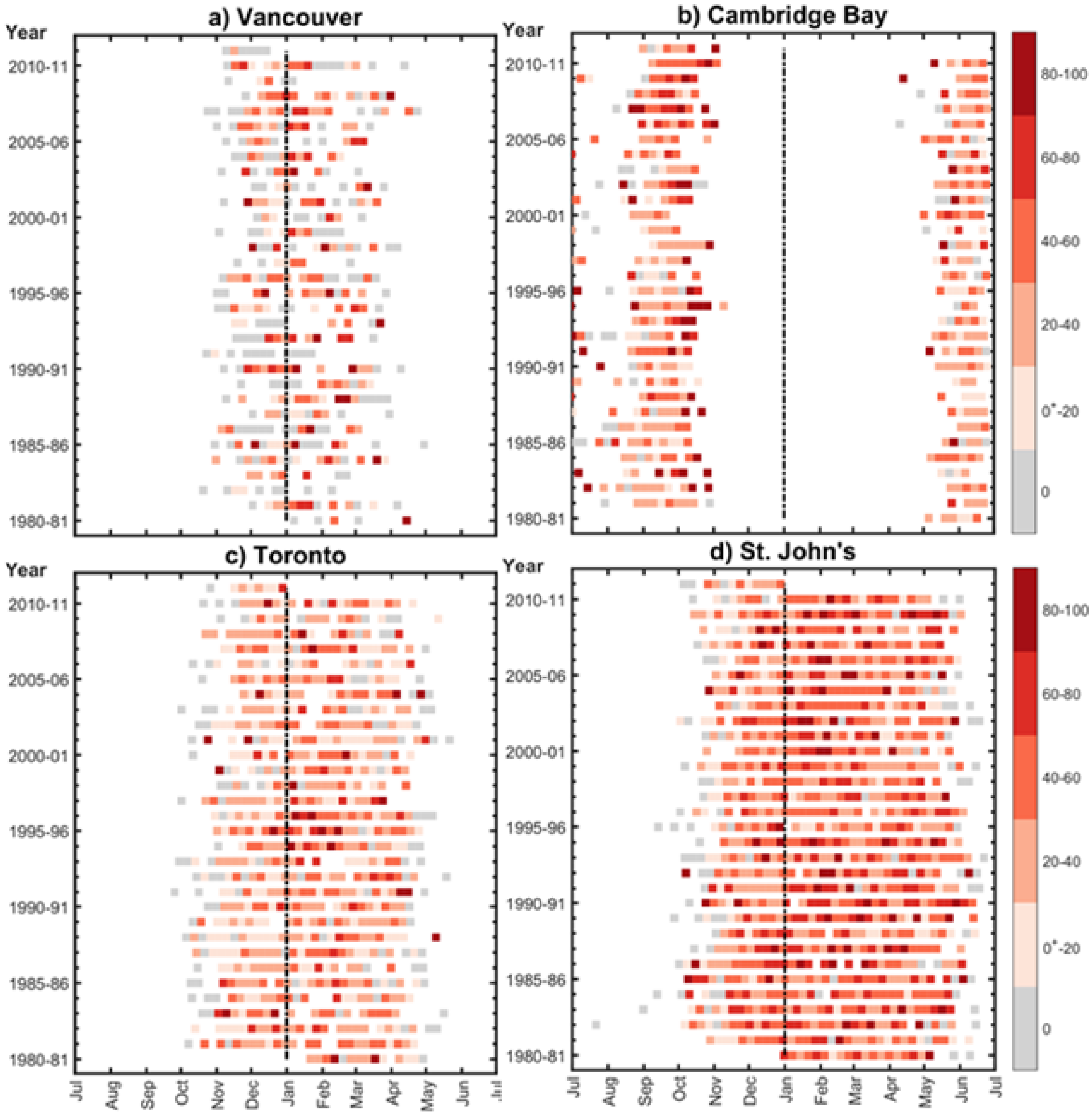


Revised caption: "Figure 8: (a) Average monthly occurrence (hours) of near 0°C conditions as a function of average monthly surface temperature for the nine selected stations over the 1981-2011 period. Filled symbols indicate occurrence and open or unfilled symbols indicate no occurrence. (b) An expanded view to better illustrate low values of average monthly occurrence."

8. Figure 9. This figure is too small and it is difficult to get the information. The units on y-axis should be "1980-81" instead of "80-81". The vertical dashed line is not visible.

Response: This figure has been redone. It shows the same information in a condensed weekly timestep. Following the suggestions the appearance of units and vertical line is improved. Additionally the fraction (%) of near 0°C hours each week with (or without) precipitation is shown through shading rather than as a separate line.

Revised Figure 9:



Revised Figure 9 caption: "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.

9. Concluding remarks. This is a very important section of the paper.

(i) Key findings should be about what has been found (shown/demonstrated) in the paper. For example:

a) There are 3 general regions of high occurrences of near 0°C temperature conditions: BC extended to Saskatchewan, southern Ontario and Atlantic region…

b) Maximum values of the precipitation types are concentrated in the eastern half of the country…

c) Trends were found in …

Response: We feel that our original text covers all these points and in the general order from average conditions, to processes, to trends. We have updated some of the conclusions based on responses to reviewers.

New/Revised Text: We only show concluding remarks which have been changed.

Lines 343-346: "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."

Line 347: "The longest duration events at the 9 selected stations are associated with persistent cloud conditions which act to reduce diurnally-driven temperature swings."

(ii) Key findings should not be about potential explanation. For example:

- "The longest duration events are associated with prolonged cloud cover" – this might be true but there is no results showing this in the paper.

Response: There is an analysis of sky conditions in the article that is the basis for this sentence. We have improved the wording in Section 5 (original Lines 261-267) to clarify the analysis. We have also added two additional columns to Table 4 to show the number of hours of associated precipitation and the percentage of time that the overall event was associated with precipitation.

We have also improved the wording of associated Line 347 in Section 6.

New/Revised Text: Revised Lines 261-267 in Section 5: "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 4). 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 4). 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."

New Reference:

Ahrens, C. D., Jackson, P. L. and Jackson, C. E. J.: Meteorology Today: An introduction to weather, climate, and the environment: Second Canadian edition, Nelson Education, 2016.

Revised Table 4 title: "The longest duration events at the 9 selected stations. Columns indicate maximum duration, start time, 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

Revised Line 347 in Section 6: "The longest duration events at the 9 selected stations are associated with persistent cloud conditions which act to reduce diurnally-driven temperature swings."

(iii) A sentence should be added in the key findings related to change in the frequency of freezing rain and in the frequency of any of the 12 weather types (because this is important to the reader). Something such as "This study shows that there is no change over 1981-2011 at most stations; however, the period is short to detect any statistically significant change, and it is important to continue to monitor these precipitation types. A previous study has shown that there are some areas in Canada with increasing trends in freezing rain events over 1953-2004… (Wang 2006)."

Response: This is a good suggestion.

New/Revised Text: "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. "

New Reference: Wang, X. L.: Climatology and trends in some adverse and fair weather conditions in Canada, 1953–2004, Journal of Geophysical Research, 111(D9), doi:10.1029/2005jd006155, 2006.

Reviewer 4

Paul Whitfield (Referee)

Paul Whitfield Senior Research Fellow, Centre for Hydrology University of Saskatchewan, Canmore Alberta

This paper develops a climatology of near 0˚C conditions across Canada. This is an interesting and timely contribution and with some improvements will merit publication. There are three specific concerns that will need attention if the paper is to be published better context setting, a more clear presentation about the sample window, and the use of appropriate statistical methods for trends in count/proportion data. I have also made some specific suggestions for changes in the text.

Major improvements

1. One of the issues in dealing with the occurrence of zero temperatures in a country as diverse as Canada is making the context of the data clear. This is important as the audience of this journal is international. Across Canada, zero can be a high, medium, or low temperature. This is inferred in Figure 1 but I am of the opinion that the 'con-text setting' would be better if the mean annual temperature was added to Figure 1, and contours of mean annual temperature added to Figure 2. Mapping of permafrost distribution might be an alternative to mean annual temperature. As well, this addi-tional context might better support the apparently arbitrary spatial divisions made in the manuscript. There are several specific places in the text where the reader could be reminded of this context.

Response: Following this good suggestion, we added the average annual surface temperatures to Fig. 1. We also added the -2°C, 0°C and +2°C isotherms to Fig. 2. In addition, we added the 0°C isotherm to Figs. 3-5, which led to new texts.

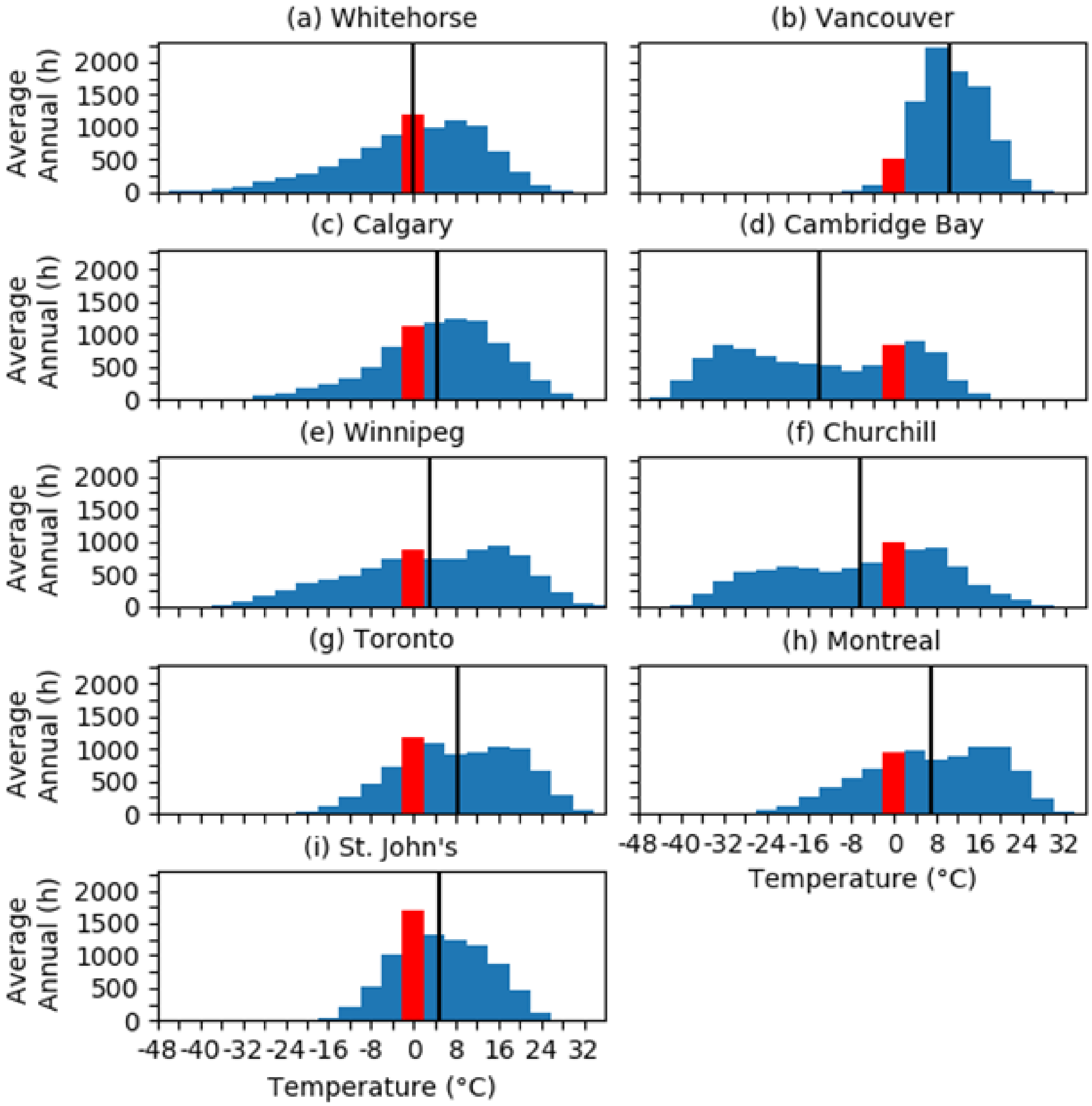
The spatial divisions shown in Fig. 2 is not arbitrary but follow the example used in a previous article addressing temperature and precipitation changes across Canada (Vincent et al., 2018).

New/Revised Text: The new Figs. 1 and 2 and their revised captions are shown below along with additional text for the regional distribution and Fig. 1:

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).

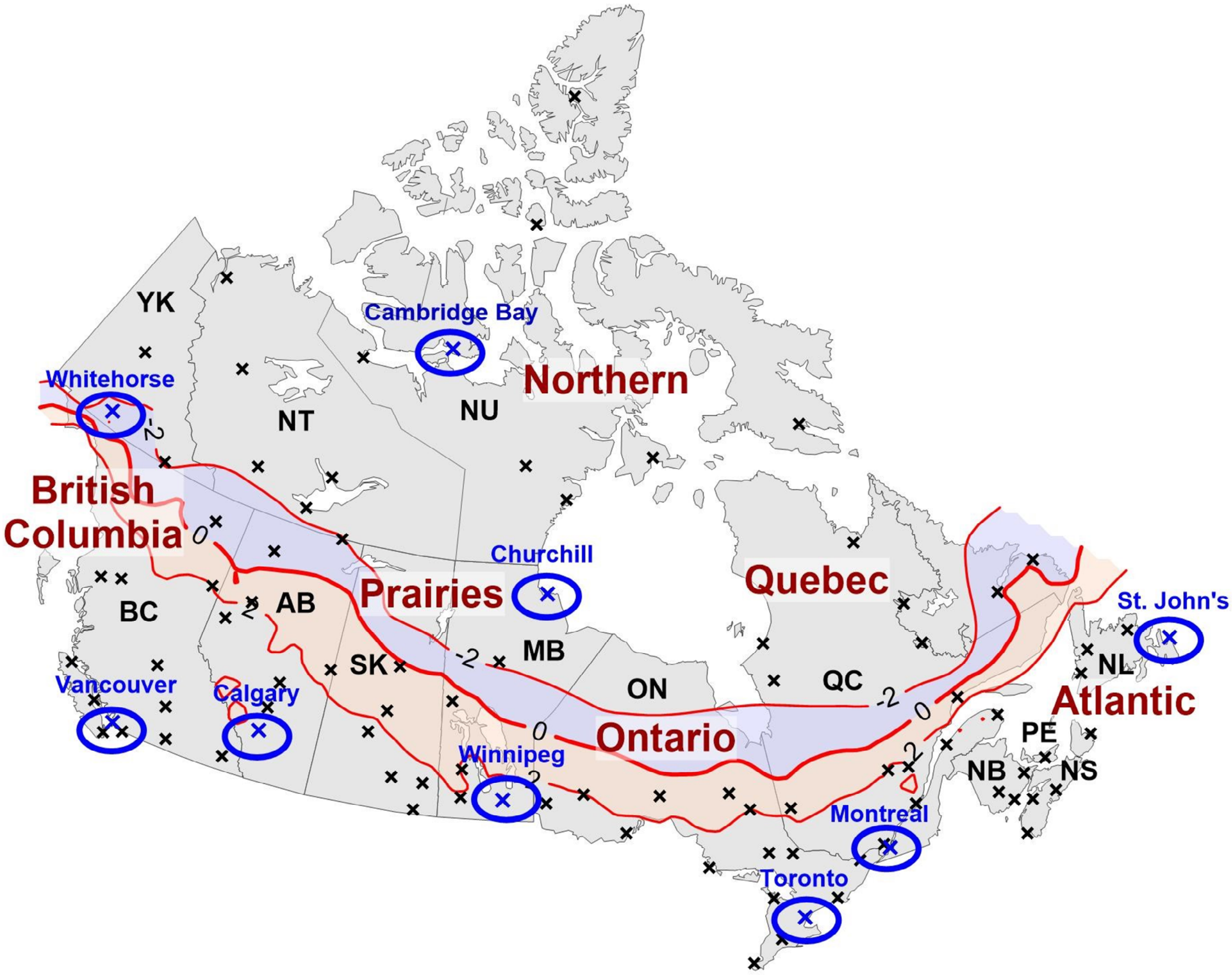
Starting at original Line 61: "Although studies have assessed various aspects of the 0°C conditions, there has been no Canada-wide assessment describing characteristics and trends in their historical occurrence. A preliminary assessment of near 0°C surface temperatures across Canada (Fig. 1) shows that 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."

At the end of Sect. 2.2 (methods): "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."



Revised caption: "Figure 1: The average annual surface temperature distribution (4°C bins) from 1981 to 2011 for 9 selected stations across Canada 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 $-2 \leq T \leq 2$°C. Stations are arranged from west to east. Details on the temperature data are presented in Sect. 2."

New Figure 2:



Revised caption: "Figure 2: The 92 stations used in the analysis (see text for details). Blue ellipses and blue crosses show the 9 selected 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 normals (ECCC, 2019c), are also shown."

As a direct consequence of the updated Figs. 2-5 with average annual surface temperature lines, we have added the following material in relation to Figs. 3-5. Updated Figs. 3-5 are shown below.

Figure 3: Four sentences will be inserted into the write up of this figure (Sect. 3.1) as follows:

- 3a: 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.
- 3b: 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.
- 3c: Similar to Fig. 3a, almost all high values occur at stations with average annual surface temperatures near or above 0°C.

- 3d: Maximum duration of events tend to show little dependence on the average annual 0°C surface temperature line across the entire country.

Figure 4: Four sentences will be inserted into the write up of this figure (Sect. 3.1) as follows:

- 4a: 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.
- 4b: As in Fig. 4a, there is little dependence on average annual surface temperature
- 4c: In contrast to Figs. 4a-b, highest values of freezing rain primarily occur at stations with average annual surface temperature above 0°C.
- 4d: 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.

Figure 5: Four sentences will be inserted into the write up of this figure (Sect. 3.2) as follows:

- 5a: There is no apparent relationship in these trends to the average annual 0°C surface temperature line.
- 5b: 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.
- 5c: No apparent pattern in relation to the 0°C surface temperature line was found.
- 5d: As in Figs. 5a-c, there is no simple relation to average annual surface temperature.

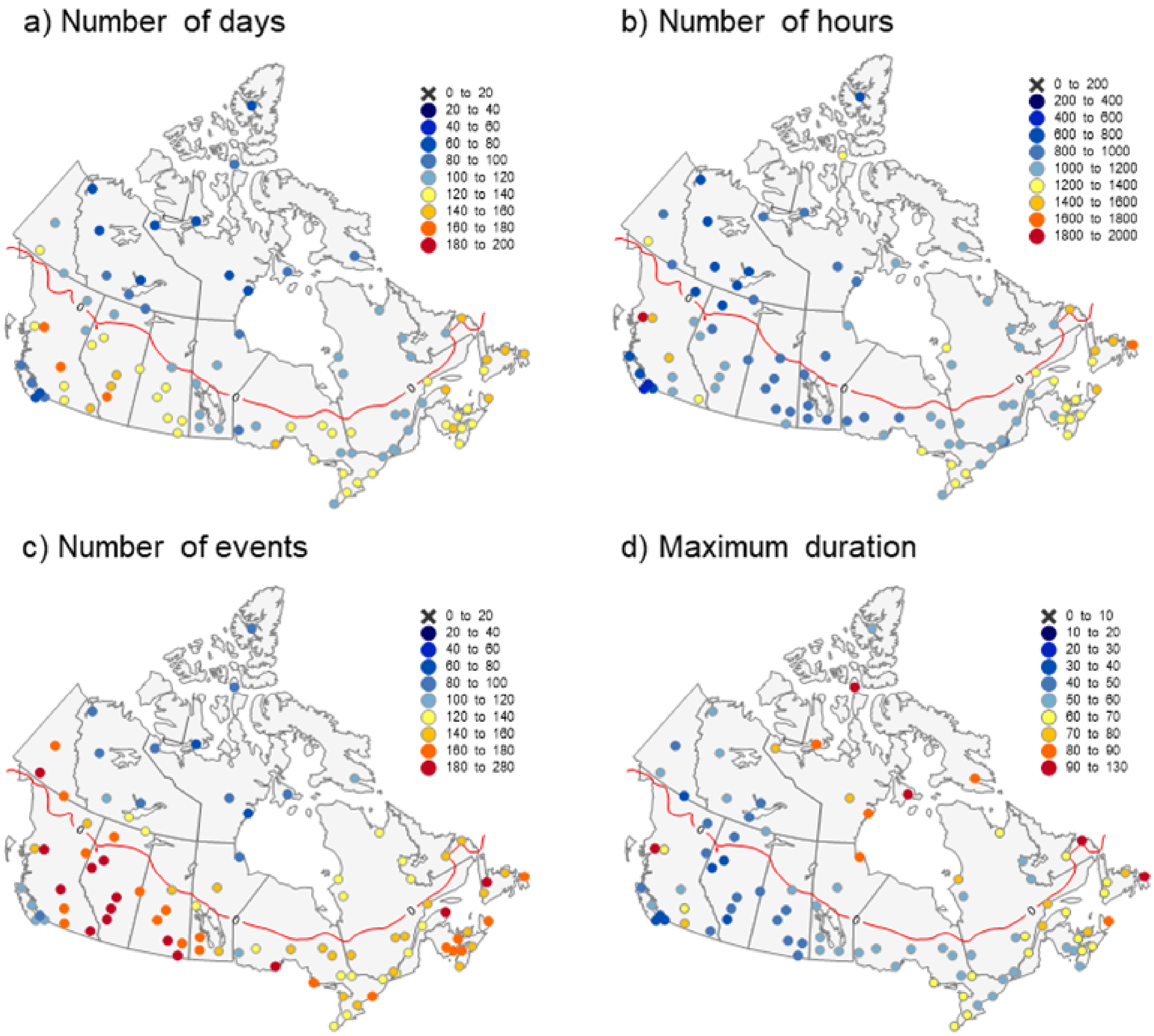
Based on this analysis, additional sentences will be added to Sect. 5.1 as follows:

Following Line 243: "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."

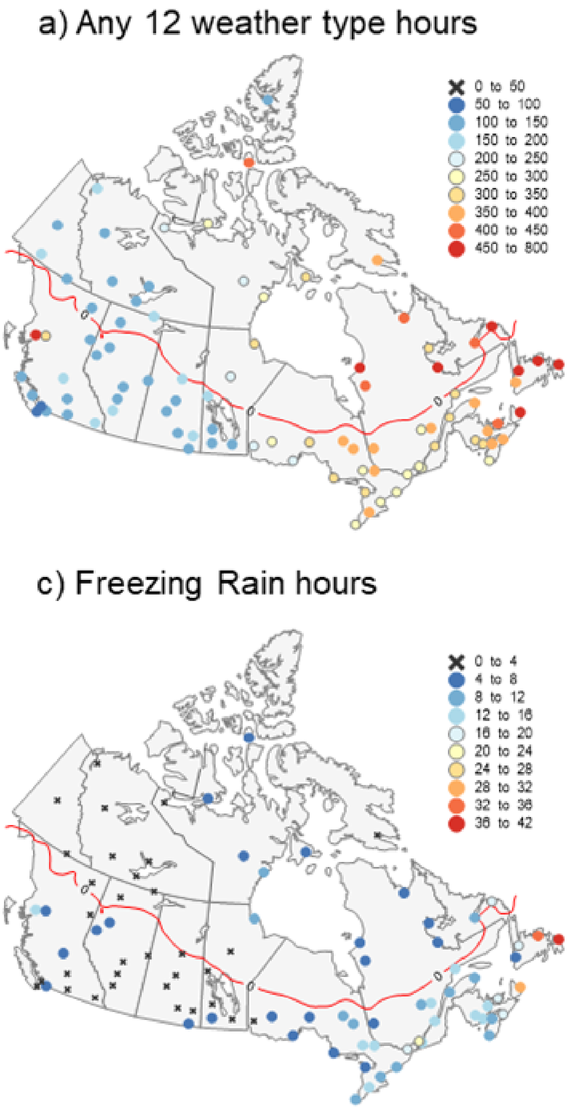
Following Line 271: "The regional patterns related to the occurrence of any precipitation type are not directly reflected in dependence on the average annual 0°C surface temperature line. This is not the case for freezing rain where high values generally occur at stations with above 0°C conditions."

Revised Figs. 3-5 titles: The titles have not changed except an additional line is added to each: "The red line indicates the annual average 0°C surface temperature computed from 1981-2010 climate normals (ECCC, 2019c)."

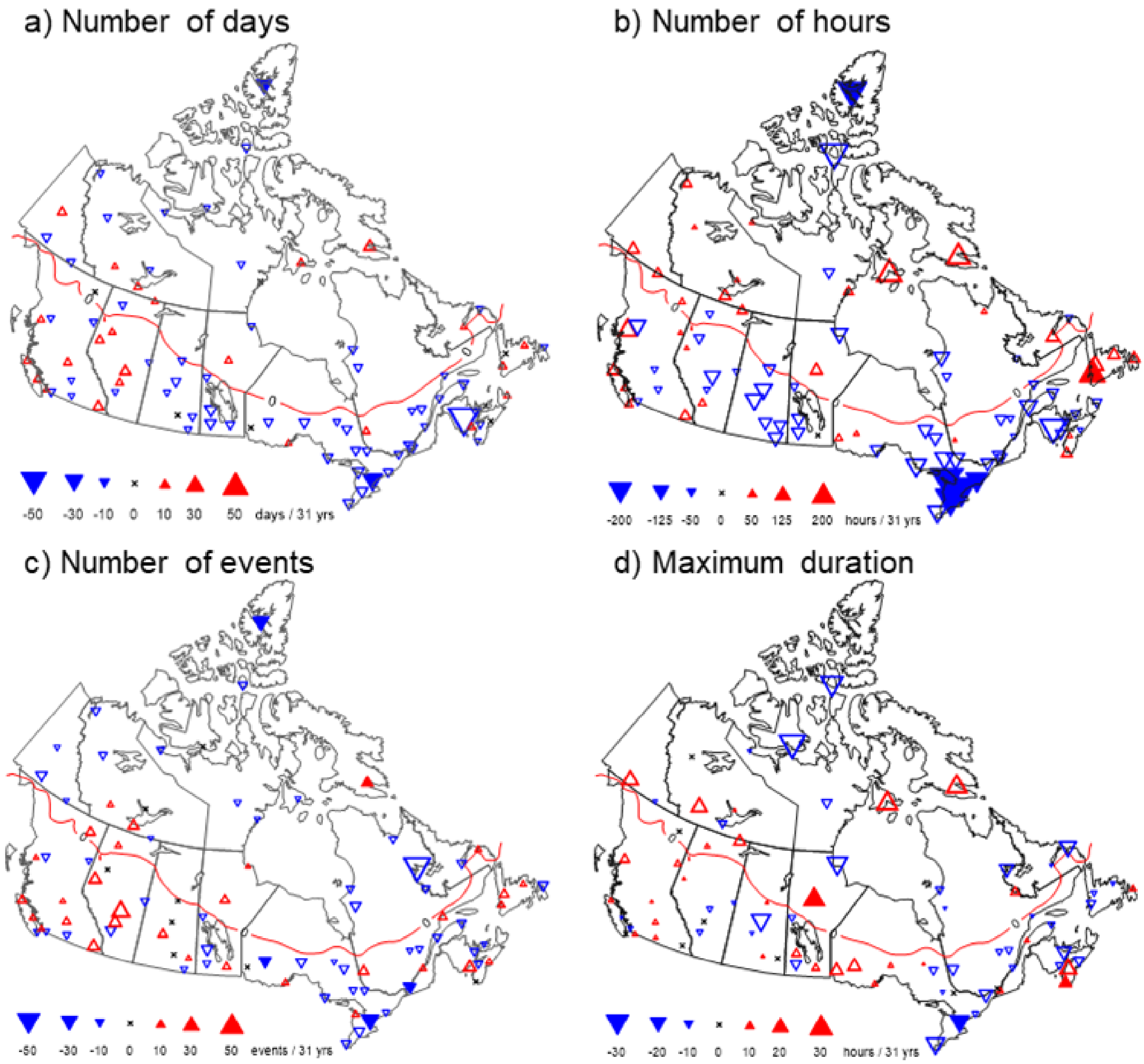
Revised Figure 3:



Revised Figure 4:



Revised Figure 5:



New References:

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Vincent, L. A., Zhang, X., Mekis, E., Wan, H. and Bush, E. J.: Changes in Canada's climate: Trends in indices based on daily temperature and precipitation data, Atmosphere-Ocean, 56(5), 332–349, doi:10.1080/07055900.2018.154579, 2018.

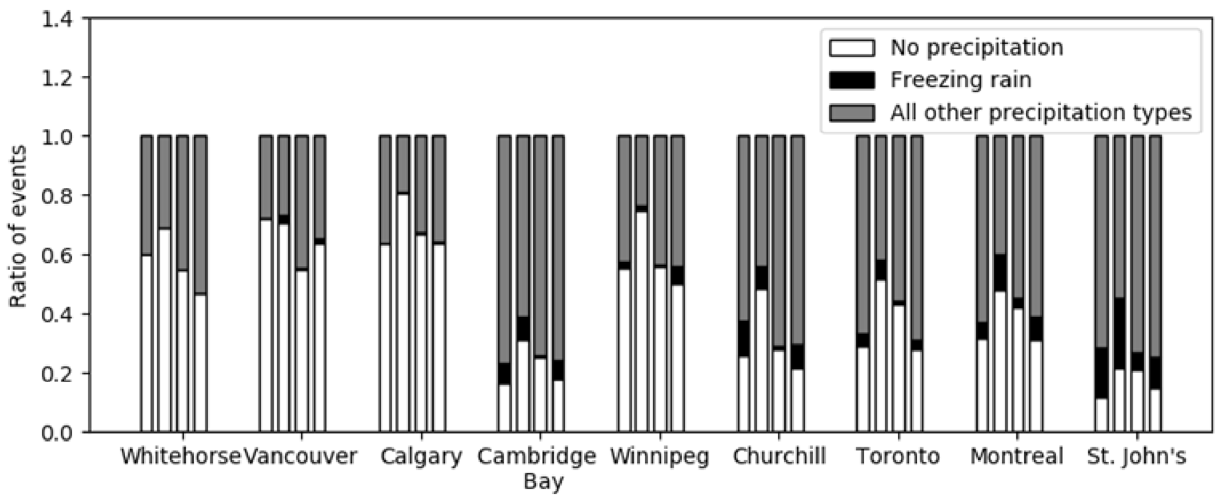
2. A key assumption is that a window from -2 to 2°C is an appropriate criteria for ‘near zero conditions’. While I would agree that the window needs to be wider that only exactly zero, I do think this deserves a more thorough and robust presentation. Is there literature available that supports or suggests how the width of the window should be set? With precipitation, surface air temperature is not necessarily the determinant of frozen forms. I am not asking that another window be considered, rather I would like to see more about the thinking that went into the selection of such a window. I would like to see some justification/discussion for the window being symmetrical about zero; an event that drops into the window but never reaches zero might produce the same count as an event that warms into the window without ever exceeding zero, but have quite different precipitation characteristics.

Response: The many issues associated with near 0°C conditions are so important that we felt that it was critical to focus on it. Having a very narrow window would end up basically just examining 0°C itself but making it too wide would mean that conditions substantially away from 0°C would be considered. We chose an intermediate value. We fully recognize that choosing such a window, any window, has drawbacks. We pointed out some of these issues in the Discussion section for example.

This same comment was made earlier in regards to Reviewer 1 and Reviewer 2 (Lines 95-98) and the same response is used here. We agree that there is no precise, physically based criterion that can be used to characterize conditions near 0°C. We did want to focus on conditions within which many changes in precipitation types are embedded. We have now included several references that point out that substantial fractions of some precipitation types occur within our chosen temperature window and we also indicate that we wanted a simple symmetric temperature window straddling 0°C.

Although we had mentioned in our original article that there are different pathways for entering and leaving near 0°C conditions, we had not addressed this issue further. We have now done so. We have produced a new figure to show this information, Fig. Y. Updated numbering will be added later.

This following plot was used to compare the relative fraction of precipitation types and freezing rain at each station and it will not be in our paper. It is only for reference. It shows the relative number of near 0°C events at the nine selected stations organized by surface temperature pathway. The four pathways are shown schematically in Fig. Y, and 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.



New/Revised Text:

In regards to temperature window:

"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 ≤ 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 as -2 ≤ T ≤ 2°C throughout the paper."

In regards to pathways:

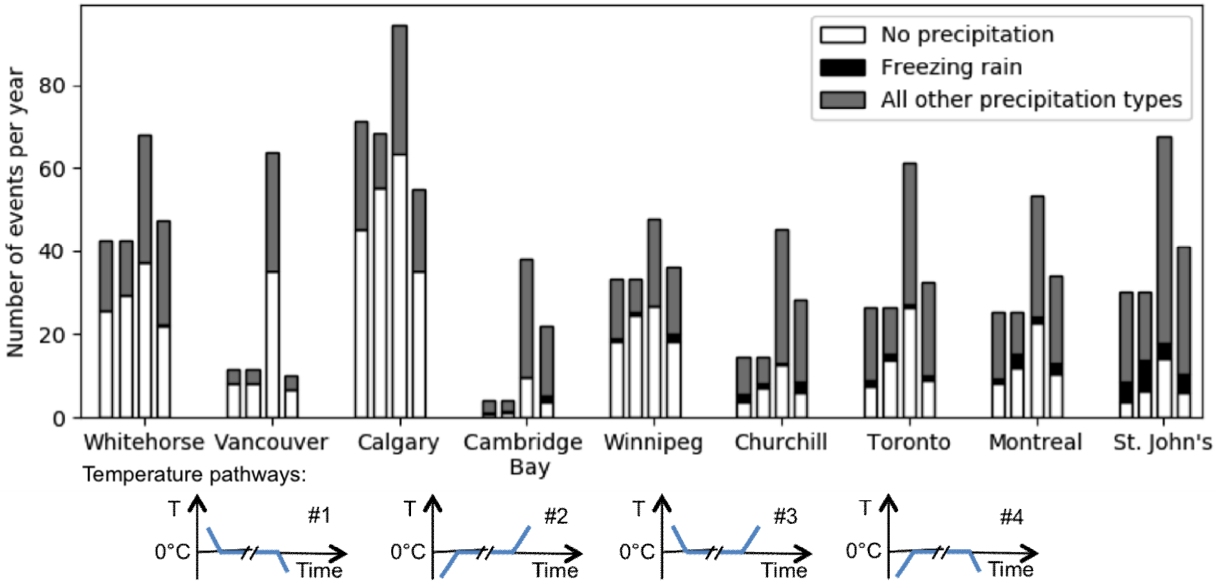
New paragraph at end of Sect. 4 (Selected Stations): "It is recognized that there are four pathways through which surface temperatures enter and leave near 0°C conditions (Fig. Y). These pathways are events (1) from above to below, (2) from below to above, (3) from above back to above, and (4) from below back to below. As shown in Fig. Y, 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.

New paragraph in Discussion: "An examination of the four pathways through which surface temperatures enter and leave near 0°C conditions revealed additional patterns (Fig. Y). 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., 1995)."

New sentence in Concluding remarks: "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."

New Figure Y:



New Fig. Y caption: "Average annual number of near 0°C events at the nine selected stations organized by surface temperature pathway. The four pathways are shown schematically in the insert below the diagram, and 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."

New References:

Matsuo, T., Sasyo, Y. and Sato, Y.: Relationship between types of precipitation on the ground and surface meteorological elements, Journal of the Meteorological Society of Japan. Ser. II, 59(4), 462–476, doi:10.2151/jmsj1965.59.4_462, 1981.

Nitu, R., Roulet, Y.A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, G.W., Lejeune, Y., Leppänen, L., Mekis, E.,Panel, J.M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Nishimura, K. and Senese, A.: WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012-2015), World Meteorological Organization Instruments and Observing Methods Report No. 131, Geneva, 2018.

Stewart, R. E., Yui, D. T., Chung, K. K., Hudak, D. R., Lozowski, E. P., Oleskiw, M., Sheppard, B. E. and Szeto, K. K.: Weather conditions associated with the passage of precipitation type transition regions over Eastern Newfoundland. Atmosphere-Ocean, 33, 25-53, 1995.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Elomaa, E., Gunther, T., Bates, R., Pangburn, T., Hanson, C., Emerson, D., Copaciu, V. and Milkovic, J.: Accuracy of tretyakov precipitation gauge: Result of wmo intercomparison. Hydrological Processes, 9(8), 877-895. doi:10.1002/hyp.3360090805, 1995.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Bates, R., Pangburn, T. and Hanson, C. L.: Accuracy of NWS 8" Standard Nonrecording Precipitation Gauge: Results and Application of WMO Intercomparison. Journal of Atmospheric and Oceanic Technology, 15(1), 54-68. doi:10.1175/1520-0426(1998)0152.0.co;2, 1998.

3. Statistical methods. While Mann-Kendall and Sen Slopes are widely used for con-tinuous variables they are not appropriate for count and proportion data. These data types are normally dealt with using logistic regression. Frei, C. (2013), trend R pack-age, version 1.5.1. http://www.iac.ethz.ch/edu/courses/master/electives/acwd. Jung, R. C., M. Kukuk, and R. Liesenfeld

(2006), Time series of count data: modeling, esti-mation and diagnostics, Computational Statistics & Data Analysis, 51(4), 2350-2364. Schmidli, J., and C. Frei (2005), Trends in heavy precipitation and wet dry spells in Switzerland during the 20th Century, International Journal of Climatology, 25, 753-771. Weller, E. A., and L. M. Ryan (1998), Testing for trend with count data, Biometrics, 54, 762-773.

Response: Although the original data are indeed based on the count of certain conditions, if the resulting annual time-series is normally distributed, the Mann-Kendall and Sen slopes can still be applied. Similar approach was used in Vincent and Mekis (2006) and Vincent et al. (2018). The problem can be the rarity of the events and the number of tied values (same values) in the time series (Frei and Schar, 2001; Keim and Cruise, 1998). If normality is not met, it is necessary to transform the count of data (frequency of rare events) so that conventional regression models can be used to estimate the trends. Acknowledging this fact, the approach was modified depending on the type of distribution.

The tables now includes both the average annual climatologies and the 31 year trend values with significance for the nine locations.

New/Revised Text: “The assessment of the trend can be challenging for time series with low occurrences and repetitive (tied) values (Frei and Schar, 2001; 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 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 (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).

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.”

Updated tables:

Table 2: Average annual frequencies of the selected near 0°C indicators along in bracket 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 Hours	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)	hours
Number of Days	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)	days
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

New References:

Frei, C. and Schär, C.: Detection probability of trends in rare events: Theory and application to heavy precipitation in the alpine region, Journal of Climate, 14, 1568-584, 2001.

Keim, B. D. and Cruise, J. F.: A technique to measure trends in the frequency of discrete random events, Journal of Climate, 11, 848-55, 1998.

McCullagh, P. and Nelder, J. A.: Generalized linear models. 2nd ed. Monogr. on Statistics and Appl. Probability, No. 37, Chapman and Hall, London, UK, 1989.

Detailed comments

Comment 1: Line 12-13 consider adding 'snowmelt' and permafrost here.

Lines 12-13 in question: "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."

Response: This is a good suggestion and has been followed.

New/Revised Text: "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 with a particular focus on the occurrence of its associated precipitation."

Comment 2: Lines 14-15. Consider stating positively. "The study develops a Canada-wide perspec-tive on near 0°C conditions using hourly temperature and precipitation type observa-tions from 92 climate stations for the period 1981 to 2011."

These are the lines being referred to: "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."

Response: This is a good suggestion and the change has been made.

New/Revised Text: "The 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."

Comment 3: Line 26 "In cold regions, such as Canada, both environmental..."

Line in question: "In cold regions such as Canada, numerous environmental processes and socio-economic activities are significantly impacted by temperatures near 0°C."

Response: As advised the word "numerous" is replaced with "both".

New/Revised Text: "In cold regions such as Canada, both environmental processes and socio-economic activities…"

Comment 4: Line 28. This seems to be not parallel, delete 'that affects open water evaporation'.

Line 28 in question: "… hydrologic processes (spring freshet, freshwater ice duration that affects open-water evaporation, flooding)..."

Response: The phrase "that affects open water evaporation" has been deleted.

New/Revised Text: "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)."

Comment 5: Lines 30-34. Could be clearer and maybe more simple. The real issue is that changes in episodes of near freezing increase the frequency of river ice-jams and ice-jam flood-ing, increase the depth and duration of ground ice that affects winter feeding of caribou and other species, increases the frequency of ice layers in snowpacks that increases the frequency of avalanches and poses a risk to skiing …

Lines 30-34 in question: "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."

Response: We appreciate that changes in near freezing conditions could lead to many subsequent changes. But, this is not just a study of future conditions. We are attempting to first of all characterize those conditions and then one can begin to quantify possible future changes. We tried to more clearly convey this. Following reviewer 2 request, several references are also added to this segment.

Revised Text: "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 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."

New References:

Beltaos, S., Prowse, T., Bonsal, B., Mackay, R., Romolo, L., Pietroniro, A. and Toth, B.: Climatic effects on ice-jam flooding of the Peace-Athabasca Delta, Hydrological Processes, 20(19), 4031–4050, doi:10.1002/hyp.6418, 2006.

Kraatz, S., Jacobs, J. M. and Miller, H. J.: Spatial and temporal freeze-thaw variations in Alaskan roads, Cold Regions Science and Technology, 157, 149–162, doi:10.1016/j.coldregions.2018.10.006, 2019.

Laute, K. and Beylich, A. A.: Potential effects of climate change on future snow avalanche activity in western Norway deduced from meteorological data, Geografiska Annaler: Series A, Physical Geography, 100(2), 163–184, doi:10.1080/04353676.2018.1425622, 2018.

Lindenschmidt, K.-E., Das, A., Rokaya, P. and Chu, T.: Ice-jam flood risk assessment and mapping, Hydrological Processes, 30(21), 3754–3769, doi:10.1002/hyp.10853, 2016.

McKenney, D. W., Pedlar, J. H., Lawrence, K., Papadopol, P., Campbell, K. and Hutchinson, M. F.: Change and evolution in the plant hardiness zones of Canada, BioScience, 64(4), 341–350, doi:10.1093/biosci/biu016, 2014.

Moen, J. and Fredman, P.: Effects of climate change on alpine skiing in Sweden, Journal of Sustainable Tourism, 15(4), 418–437, doi:10.2167/jost624.0, 2007.

Comment 6: Line 35 "Many regions of Canada have experienced. . .". My view is that it is better to be specific about which country in an international journal.

Lines 35 in question: "Many regions of the country have experienced major impacts from near 0°C events."

Response: That is a good point.

New/Revised Text: "Many regions of Canada have experienced..."

Comment 7: Line 49 insert "for Canada" after 'freezing precipitation'.

Line in question: "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)."

Response: Thank you. We have done this.

New/Revised Text: "...freezing precipitation for Canada..."

Comment 8: Line 51 "Two recent articles,"

Line in question: "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."

Response: As suggested, the starting phrase "As well," is removed.

New/Revised Text: "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."

Comment 9: Line 56 replace 'its' with 'freezing precipitation'

Line in question: "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."

Response: Replaced, thank you.

New/Revised Text: "...variations in freezing precipitation occurrence..."

Comment 10: Line 57-58 "A recent study identified the impacts of extreme weather on critical infrastructure in Europe..."

Line in question: "A recent study in Europe also identified the impacts of extreme weather on critical infrastructure (Groenemeijer et al., 2017)."

Response: Changed as suggested.

New/Revised Text: "A recent study identified the impacts of extreme weather on critical infrastructure in Europe (Groenemeijer et al., 2017)."

Comment 11: Line 62-63. This is a place where the 'context setting' could be improved. Here, a mention of mean annual temperature in relation to zero bears mention.

These are the lines in question: "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."

Response: We had added a comment regarding the average annual temperatures.

New/Revised Text: "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."

Comment 12: Lines 73 to 78. I don't think that this text is totally accurate. The access to the archive that is available publically does not allow downloading the complete daily or hourly data for a station. Rather, one must follow the line to Get More Data and then use alternative code to get the data through wget, Cygwin, or homebrew.

Lines in question: "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."

Response: This is a general statement. The data can be reached through the portal or writing a request to climate services identified on the contact page of the quoted climate data portal. The method would change based on the operating system, etc. The description of data access is out of the scope of the paper. The particular sentence in question has been updated to include the name of the data portal and the word "manual" before the precipitation type observation.

New/Revised Text: "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."

New Reference:

ECCC (Environment and Climate Change Canada): Historical Climate Data portal, available at: http://www.climate.weatheroffice.ec.gc.ca, last access: October 3, 2019a.

Comment 13: Line 79 Remove 'is fraught with' as the dangers are being specified.

Line in question: "Selecting appropriate stations is fraught with several complicating issues including missing values and changes to the observing program."

Response: It is removed as suggested.

New/Revised Text: "Selecting appropriate stations for further analysis was determined by data availability and the observing program."

Comment 14: Line 93. Missing from the text is a link describing the 'regions' in Figure 2 as being based upon provincial boundaries and not climatology. A bit of text is needed to support the selected nine representative stations. I would be of the opinion that Vancouver is not representative of British Columbia, so using 'nine stations selected from the Environment and Climate Change Canada regions shown in Figure 2.

Response: Thank you. An additional sentence is added to explain Fig. 2 further and to support our choice. The same approach had previously been used in the recent Vincent et al. (2018) paper. It should be noted that there is no objective way to define homogeneous rainfall regions in Canada, and different methods tend to lead to different groupings. Due to this fact we did not attempt to compute regional or national trends, the region definition was used for easier identification of areas in the discussion.

The selection of Vancouver was based on data availability and importance due to being an urban centre. As suggested the word "representative" has been removed here and it will be everywhere in the actual article.

New/Revised Text: "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)."

New References:

Gullett, D., Skinner, W. and Vincent, L.: Development of an historical Canadian climate database for temperature and other climatic elements. Climatological Bulletin, 26(2), 125–131, 1992.

Zhang, X., Hogg, W. D. and Mekis, É.: Spatial and temporal characteristics of heavy precipitation events over Canada. Journal of Climate, 14(9), 1923–1936, doi:10.1175/1520-0442(2001)0142.0.co;2, 2001.

Vincent, L., Zhang, X., Mekis, É, Wan, H. and Bush, E.: Changes in Canada's climate: Trends in indices based on daily temperature and precipitation data. Atmosphere-Ocean, 56(5), 332-349. doi:10.1080/07055900.2018.1514579, 2018.

Comment 15: Line 95-98. This is a key point in the paper and I think a bit more detail is needed to support using a window from -2 to 2°C.

This is Line 95-98: "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 ≤ T ≤ 2°C throughout the paper."

Response: This same comment was made earlier in regards to Reviewer 1 and Reviewer 4 (Major Point #2) and the same response is used here. We agree that there is no precise, physically based criterion that can be used to characterize conditions near 0°C. We did want to focus on conditions in which change in precipitation types is also common. We have now included several references that point out some precipitation type variation and we also pointed out that we wanted a simple symmetric temperature window straddling 0°C. We also deleted the dash between the words "physically" and "based" following a comment by another reviewer.

New/Revised Text: "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 ≤ 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 as -2 ≤ T ≤ 2°C throughout the paper."

New References:

Matsuo, T., Sasyo, Y. and Sato, Y.: Relationship between types of precipitation on the ground and surface meteorological elements, Journal of the Meteorological Society of Japan. Ser. II, 59(4), 462–476, doi:10.2151/jmsj1965.59.4_462, 1981.

Nitu, R., Roulet, Y.A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, G.W., Lejeune, Y., Leppänen, L., Mekis, E.,Panel, J.M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Nishimura, K. and Senese, A.: WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012-2015), World Meteorological Organization Instruments and Observing Methods Report No. 131, Geneva, 2018.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Elomaa, E., Gunther, T., Bates, R., Pangburn, T., Hanson, C., Emerson, D., Copaciu, V. and Milkovic, J.: Accuracy of Tretyakov precipitation gauge: Result of WMO intercomparison. Hydrological Processes, 9(8), 877-895. doi:10.1002/hyp.3360090805, 1995.

Yang, D., Goodison, B. E., Metcalfe, J. R., Golubev, V. S., Bates, R., Pangburn, T. and Hanson, C. L.: Accuracy of NWS 8" standard nonrecording precipitation gauge: Results and application of WMO Intercomparison. Journal of Atmospheric and Oceanic Technology, 15(1), 54-68. doi:10.1175/1520-0426(1998)0152.0.co;2, 1998.

Comment 16: Line 103-105 I found this text to be difficult to follow, perhaps this revision is clearer: A total of 21 indicators were considered. The first four indicators are associated with the near 0°C temperature condition without any consideration of precipitation. To assess precipitation during near 0°C conditions, a further thirteen precipitation type indicators were computed (Table 1). In addition, the combination of temperature and precipitation type provides an additional four indicators. These include the annual average hours with any or all of these 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 than other frozen precipitation, since freezing rain often results in major impacts.

Response: Thank you; we modified the text following the suggestions.

New/Revised Text: "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 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 than other frozen precipitation, since its occurrence often results in major impacts."

Comment 17: Line 114-115. This seems to be an opinion. Could it be supported using the work of others?

This is Line 114-115: "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."

Response: This decision can be supported with multiple examples. The most recent article is Vincent et al. (2018): "the trends were computed for stations with less than 10% missing years in the respective periods".

New/Revised Text: "Given the aforementioned aspect 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."

New References:

Mekis, É, Vincent, L. A., Shephard, M. W., and Zhang, X.: Observed trends in severe weather conditions based on humidex, wind chill, and heavy rainfall events in Canada for 1953–2012. Atmosphere-Ocean, 53(4), 383-397. doi:10.1080/07055900.2015.108697, 2015.

Vincent, L., Zhang, X., Mekis, É, Wan, H. and Bush, E.: Changes in Canada's climate: Trends in indices based on daily temperature and precipitation data. Atmosphere-Ocean, 56(5), 332-349. doi:10.1080/07055900.2018.1514579, 2018.

Comment 18: Lines 120 onwards. It seems that sometimes figures are "Figure x" and "Fig x" used interchangeably.

Response: We followed the journal's guidance and we quote from its Manuscript Preparation Guidelines for Authors: "The abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that..." As well, the journal uses 'Figs.' as the abbreviation of 'Figures'. We carefully went through our submitted article and yes, unfortunately, we had made 5 errors. Thank you for noticing.

New/Revised Text: We have revised the following lines in which the abbreviation or full word was incorrectly used:

Line 151: 'Figure' changed to 'Fig.'

Line 156: 'Figs' changed to 'Figs.'

Line 158: 'Fig' changed to 'Fig.'

Line 198: 'Figure' changed to 'Fig.'

Line 215: 'Figure' changed to 'Fig.'

Comment 19: Line 123 Cordillera

Line in question: "...western cordillera."

Response: Thank you for noticing this.

New/Revised Text: "... western Cordillera."

Comment 20: Lines 137 to 143. The presentation is awkward. It seems things have been left out. What variable and which figure is being considered? What is meant by: "In contrast, here are now three general areas of low values."

Lines 137-143 in question: "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, <u>there</u> are now three general areas of low values. The northern *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."*

Response: We have clarified the text to clearly indicate that this paragraph is referring to Fig. 3b. As part of this, we also revised the previous paragraph (Lines 133-136) and merged these paragraphs.

New/Revised Text: "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 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 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."

Comment 21: Lines 228-234. This text is unclear. For example in line 230. "Only Toronto (Fig. 5c) shows both of these trends to be statistically significant." It is not clear what the two trends are since only one figure is cited and it cannot be determined for the preceding sentences. It would be better to phrase this so that Toronto follows so the focus is on the trends. "Both of these trends (Figure 9c and Figure 5c) are significant at only one location, Toronto."

Lines 228-234 in question: 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.

Response: We have clarified the text following the suggestion.

New/Revised Text: "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 X and Fig. 9c, both of these trends are significant at only one location, Toronto. Whitehorse shows significant earlier spring cessation (Table X) and St. John's shows significant later autumn onset (Fig. 9d and Table X). Cambridge Bay experiences near 0°C conditions in every 'warm season' month (Fig. 9b and Table X) 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 X)."

Table X: 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 Surface 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

New References:

Bush, E. and Lemmen, D.S. (Eds.): Canada's changing climate report, Government of Canada, Ottawa, Ontario, 444 pp., 2019.

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Comment 22: Section 5: In section 5 the text contains insufficient links to Figures and in many places literature citations are required.

Response: There were several comments regarding this issue by reviewers. We have addressed these individually but, to be sure, we have added additional links to figures and tables.

New/Revised Text: The entire Sect. 5 from the submitted article is now shown with its changes. It is so long that we have not placed it here; we put it at the very end of this document.

Comment 23: "It the ongoing reference is to Figure 9 then where does Whitehorse fit?

Response: To save space, we did not show all 9 stations in Fig. 9. We chose four stations to illustrate a range of variations in the annual cycle of near 0°C conditions. Further material has been added and this includes a new table of trends at the 9 selected stations including Whitehorse. Somewhat similar comments were made by Reviewers 2 and 4 in regards to Figure 9 and we show the complete revised text below that also addresses this current comment.

New/Revised Text: "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 X and Fig. 9c, both of these trends are significant at only one location, Toronto. Whitehorse shows significant earlier spring cessation (Table X) and St. John's shows significant later autumn onset (Fig. 9d and Table X). Cambridge Bay experiences near 0°C conditions in every 'warm season' month (Fig. 9b and Table X) 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 X)."

Table X: 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 Surface 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

New References:

Bush, E. and Lemmen, D.S. (Eds.): Canada's changing climate report, Government of Canada, Ottawa, Ontario, 444 pp., 2019.

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Comment 24: Whitehorse shows significant earlier spring cessation and St. John's shows significant later autumn onset (Fig. 9d).

Response: This is addressed in Comments #21 and #23 above.

Comment 25: Cambridge Bay (Figure 9b) experiences near 0C conditions in every 'warm season' month (Fig. 9b) so the onset of near 0C in the spring and its cessation in the autumn were considered; neither showed statistically significant trends.

Response: This is addressed in Comments #21 and #23 above.

Comment 26: Lines 237 -243. Please indicate which figures are being referred to

Response: We have clarified the figure number in the revised text.

New/Revised Text: "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."

Comment 27: Lines 246-248. This text warrants literature support. Once a lake is frozen it no longer serves as a heat sink.

Lines 246-248 text: "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."

Response: The text has been modified and references have been added to address the reviewer's comment.

New/Revised Text: "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)."

New References:

Larouche, P. and Galbraith, P. S.: Canadian coastal seas and Great Lakes Sea Surface Temperature climatology and recent trends, Canadian Journal of Remote Sensing, 42(3), 243–258, doi:10.1080/07038992.2016.1166041, 2016.

Takeuchi, Y., Kodama, Y. and Ishikawa, N.: The thermal effect of melting snow/ice surface on lower atmospheric temperature, Arctic, Antarctic, and Alpine Research, 34(1), 20, doi:10.2307/1552504, 2002.

Comment 28: Line 255 sentence starting "Temperature changes with chinooks..." would be better as "Temperature changes during Chinooks. . ." and warrants literature support.

Line 255 in question: "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."

Response: The word 'during' is much better and we are making this change. We have also referenced and clarified the original statement and we have added an additional reference.

New/Revised Text: "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)."

New References:

Gough, W. A.: Theoretical considerations of day-to-day temperature variability applied to Toronto and Calgary, Canada data, Theoretical and Applied Climatology, 94(1-2), 97–105, doi:10.1007/s00704-007-0346-9, 2008.

Nkemdirim, L. C.: On the frequency and sequencing of chinook events, Physical Geography, 18(2), 101–113, doi:10.1080/02723646.1997.10642610, 1997.

Comment 29: Lines 256-257. Is this from the literature?

Lines 256-257 in question: "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."

Response: It is from the literature and we have now more clearly added the reference to Brinkman and Ashwell (1968).

New/Revised Text: "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."

New References:

Brinkmann, W. and Ashwell, I.: The structure and movement of the chinook in Alberta, Atmosphere, 6(2), 1–10, doi:10.1080/00046973.1968.9676548, 1968.

Comment 30: Lines 263-267. Literature support?

Lines 263-267 in question: "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."

Response: There is an analysis of sky conditions in the article that is the basis for this sentence. We have improved the wording in Section 5 (original Lines 261-267) to clarify the analysis. We have also added two additional columns to Table 4 to show the number of hours with any type of associated precipitation and the percentage of time that the overall event was associated with precipitation.

New/Revised Text: Revised Lines 261-267 in Section 5: "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 4). 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 4). Such sky conditions would contribute to reducing temperature swings associated with daytime heating and nighttime cooling (see, for example, Ahrens et al., 2016). 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."

New Reference:

Ahrens, C. D., Jackson, P. L. and Jackson, C. E. J.: Meteorology Today: An introduction to weather, climate, and the environment: Second Canadian edition, Nelson Education, 2016.

Revised Table 4 title: "The longest duration events at the 9 selected stations. Columns indicate maximum duration, start time, 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

Comment 31: Line 275 "... the Atlantic region is often buffeted by large storms..."

Response: There are certainly articles that discuss this point. Two good examples are a summary of winter storms across Canada (Stewart et al., 1995) and information on these storms in relation to a major field experiment examining them (Stewart et al., 1987). These are now cited and we have changed the word ‘buffeted’ as well.

New/Revised Text: “... the Atlantic region is often subjected to large storms coming from the south as discussed by, for example, Stewart et al. (1987) and Stewart et al. (1995).”

New Reference:

Stewart, R. E., Isaac, G. A. and Shaw, R. W.: Canadian Atlantic Storms Program: The meteorological field project, Bulletin of the American Meteorological Society, 68(4), 338–345, doi:10.1175/1520-0477(1987)068<0338:casptm>2.0.co;2, 1987.

Stewart, R., Bachand, D., Dunkley, R., Giles, A., Lawson, B., Legal, L., Miller, S., Murphy, B., Parker, M., Paruk, B. and Yau, M.: Winter storms over Canada, Atmosphere-Ocean, 33(2), 223–247, doi:10.1080/07055900.1995.9649533, 1995.

Comment 32: Line 332 Use “Canada” instead of “the entire country”

Line in question: “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.”

Response: Thank you for the suggestion. It is replaced in the text.

New/Revised Text: “Canada is characterized by highly variable near 0°C occurrences, events, durations, and associated precipitation types that have been quantified for the first time.”

Comment 33: Line 345 delete “In addition, ocean temperatures near Canada tend to often be near 0◦C during the cold season especially”. My view is that this doesn’t add to the conclusion nor was it thoroughly covered in the manuscript.

Response: We should have included this before but we have now added a reference providing quantitative information on sea surface temperatures around Canada. This article (Larouche and Galbraith, 2016) shows that, on average, SSTs tend to be close to 0°C in the cold season near some of the coastlines. 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.

New/Revised Text: “In addition, sea surface temperatures (SSTs) 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.”

New Reference:

Larouche, P. and Galbraith, P. S.: Canadian coastal seas and Great Lakes Sea Surface Temperature climatology and recent trends, Canadian Journal of Remote Sensing, 42(3), 243–258, doi:10.1080/07038992.2016.1166041, 2016.

Comment 34: Line 347 Is this conclusion supported earlier in the manuscript?

Line 347 in question: “The longest duration events are associated with prolonged cloud cover.”

Response: There is an analysis of sky conditions in the article that is the basis for this sentence. We have revised Line 347 to provide additional information.

New/Revised Text: "The longest duration events at the 9 selected stations are associated with persistent cloud conditions which act to reduce diurnally-driven temperature swings."

Comment 35: Line 369 It seems odd to state "It is not associated with a conference."

Response: Our understanding is that such a statement is required by the journal. Two other articles have been published in this journal in 2019 by co-authors of this current one; both those articles included this statement. Some of the early findings in this current article were presented at a conference but these were just accompanied by a short abstract.

New/Revised Text: There is no change in the text.

Comment 36: Table 1 In line 7 "12e" is listed, but there is no explanation of what "12e" refers to?

Response: Thank you. It was referring to all of the 12 precipitation types above. We decided to remove it from the title since it is not used further.

New/Revised Text: The "12e"text is now removed from the summary title and only included in the definitions in Table 1.

Comment 37: In line 20 this is a 13th pptn indicator?

Response: It refers to all of the 12 precipitation types above.

New/Revised Text: Following also a Reviewer 3 suggestion, the "all 12 weather-types above" phrase is replaced with "all 12 precipitation types above"

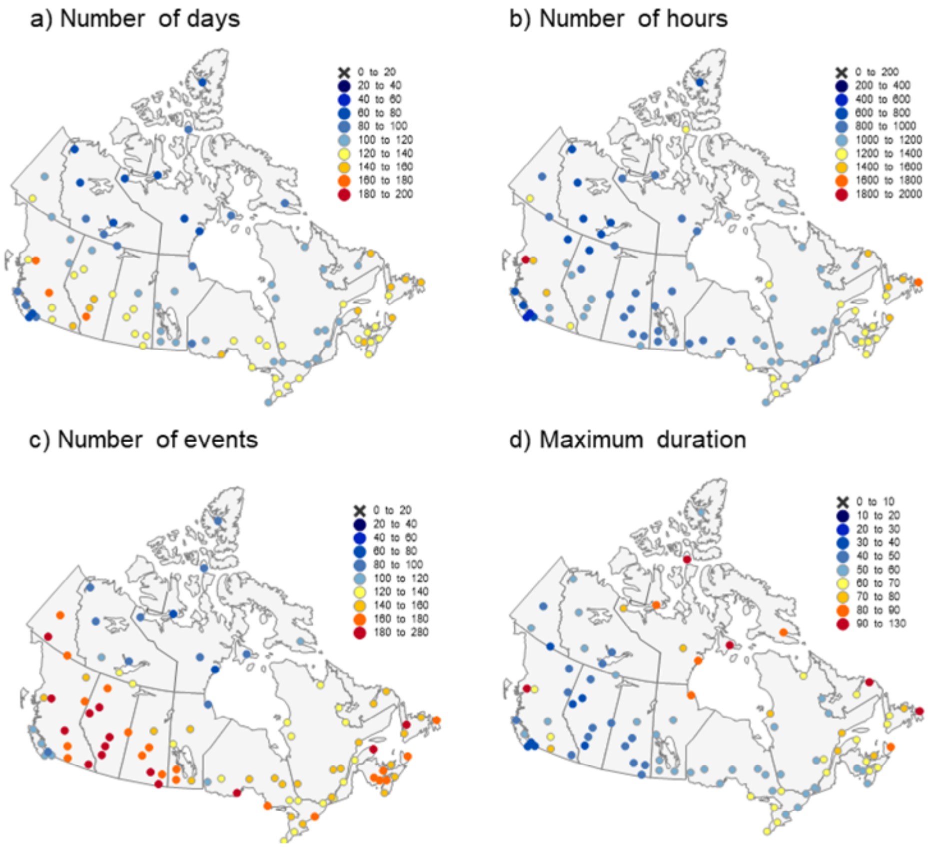
Revised Table 1 title: Table of indicators in the $-2 \leq T \leq 2$°C range. The "T" refers to hourly surface dry bulb temperature. Definitions were obtained from American Meteorological Society (2018), ECCC (2019b) and WMO (2017).

DEFINITIONS	UNIT
Surface temperature related	
Annual number of days with $-2^{o}C \leq T \leq +2^{o}C$	days
Annual number of hours with $-2^{o}C \leq T \leq +2^{o}C$	hours
Annual number of independent events (continuous hours) with $-2^{o}C \leq T \leq +2^{o}C$	events
Annual Maximum Lengths with $2^{o}C \leq T \leq +2^{o}C$	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 $-2^{o}C \leq T \leq +2^{o}C$	hours
Annual number of hours with any of the 12 precipitation types and $-2^{o}C \leq T \leq +2^{o}C$	hours
The fraction of [$-2^{o}C \leq T \leq +2^{o}C$] conditions associated with Freezing Rain	%
The fraction of [$-2^{o}C \leq T \leq +2^{o}C$] conditions with any of the 12 precipitation types	%

Comment 38: A general comment on the Figures; I find this colour palette difficult. The yellow dis-appears and the shades of blue cannot be distinguished. Consider using a different colour palette.

Response: Following also Reviewer 2 suggestion, the colour palette has been updated in all the figures using a colorblind safe scale.

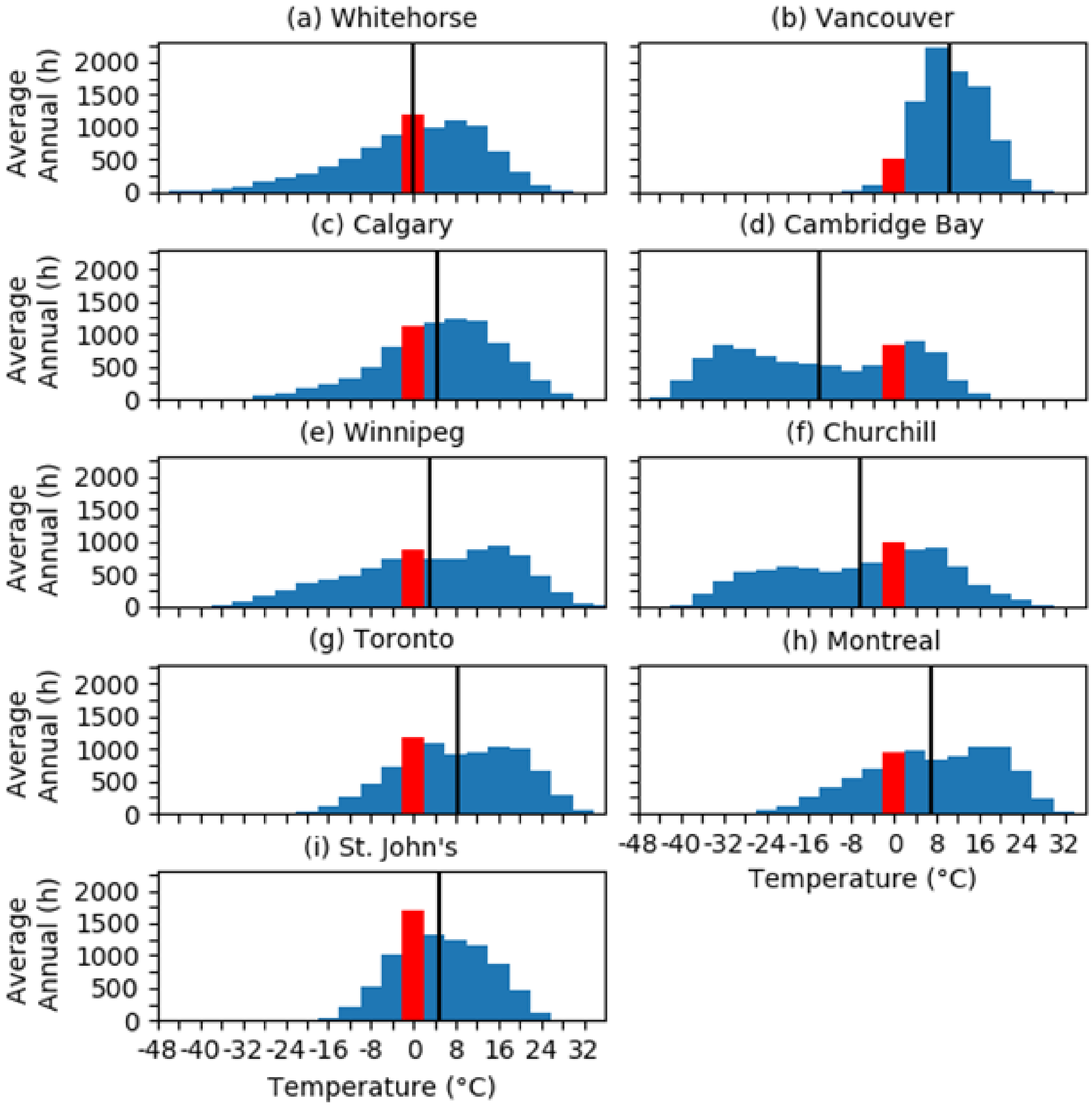
New/Revised Text: Here is an example of the new colour palette (Figure 3).



Comment 39: Figure 1. Consider adding a vertical line indicating mean annual temperature.

Response: This change has been made. This follows the earlier comments and responses for Reviewer 4, Major Improvements point number 1. The caption was also changed including a reference for the average temperatures.

New/Revised Text: The revised figure and caption as well as a new reference are shown below.



Revised caption: "Figure 1: The average annual surface temperature distribution (4°C bins) from 1981 to 2011 for 9 selected stations across Canada 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 presented in Sect. 2."

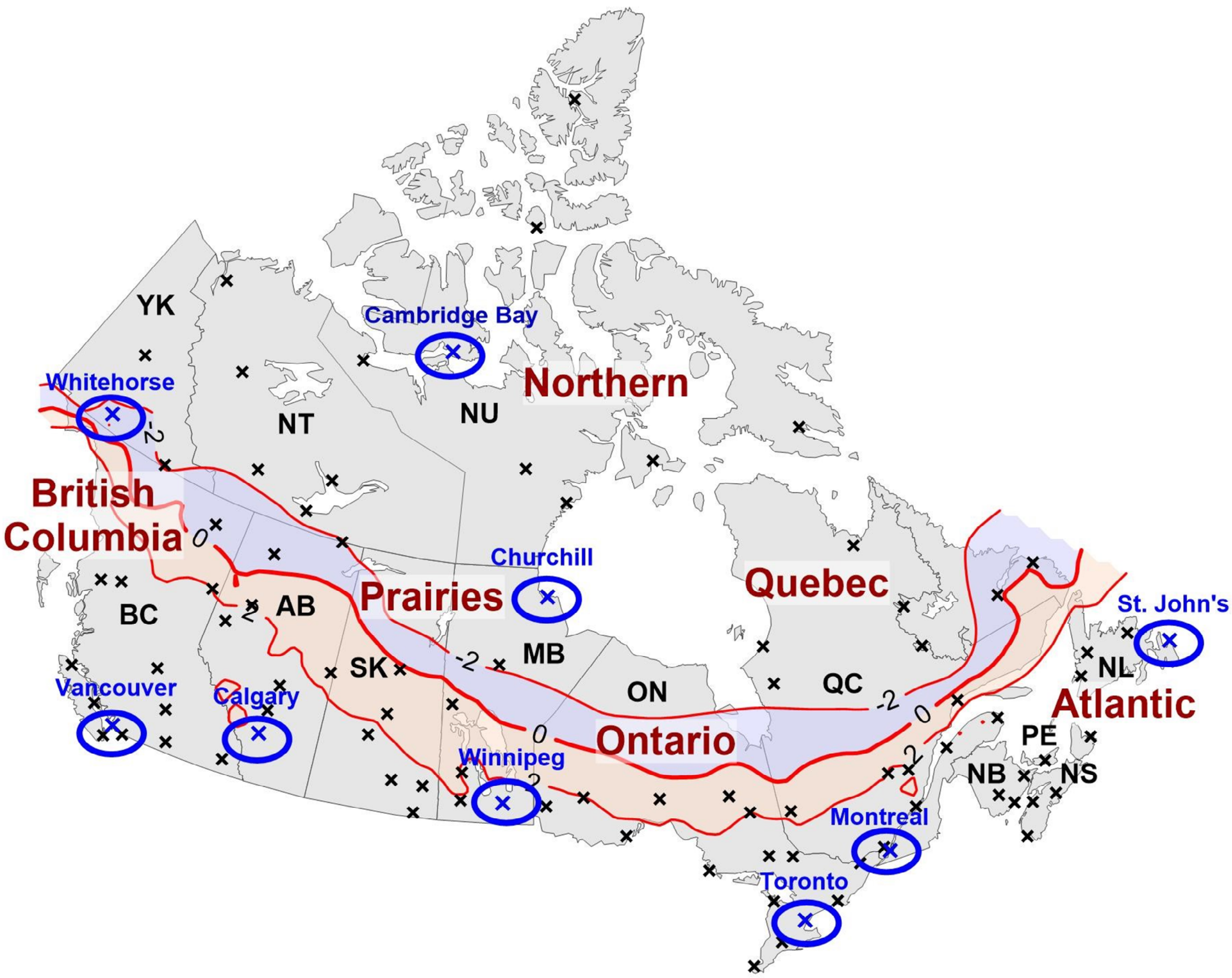
New Reference:

ECCC (Environment and Climate Change Canada): Historical Climate Data portal, available at: http://www.climate.weatheroffice.ec.gc.ca, last access: October 3, 2019a.

Comment 40: Figure 2. Add contours of mean annual temperature or permafrost.

Response: It is completed. This has also been addressed in response to other comments. The revised figure and caption are shown again below.

New/Revised Figure and Caption:



Revised caption: "Figure 2: The 92 stations used in the analysis (see text for details). Blue ellipses and blue crosses show the nine selected 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 normals (ECCC, 2019c), are also shown."

At the end of Sect. 2.2 (methods): "The average annual surface temperature contour lines were computed from the 1981-2010 climate normal period (ECCC, 2019c). Kriging with a linear Variogram model on a grid spacing of 50 km was applied to create the interpolated surface temperature map from the 1619 stations for Canada."

New Reference:

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Comment 41: Figure 6. Consider removing "Total =" from each case in the legend as this is clear from the caption. Consider changing lines types as well as colours.

Response: Thanks for the suggestions. The word "total" is removed, it has been updated with a different colour palette, use of dashes, and simplified legend (as suggested).

New/Revised Text: There is no change in the text.

Revised figure:

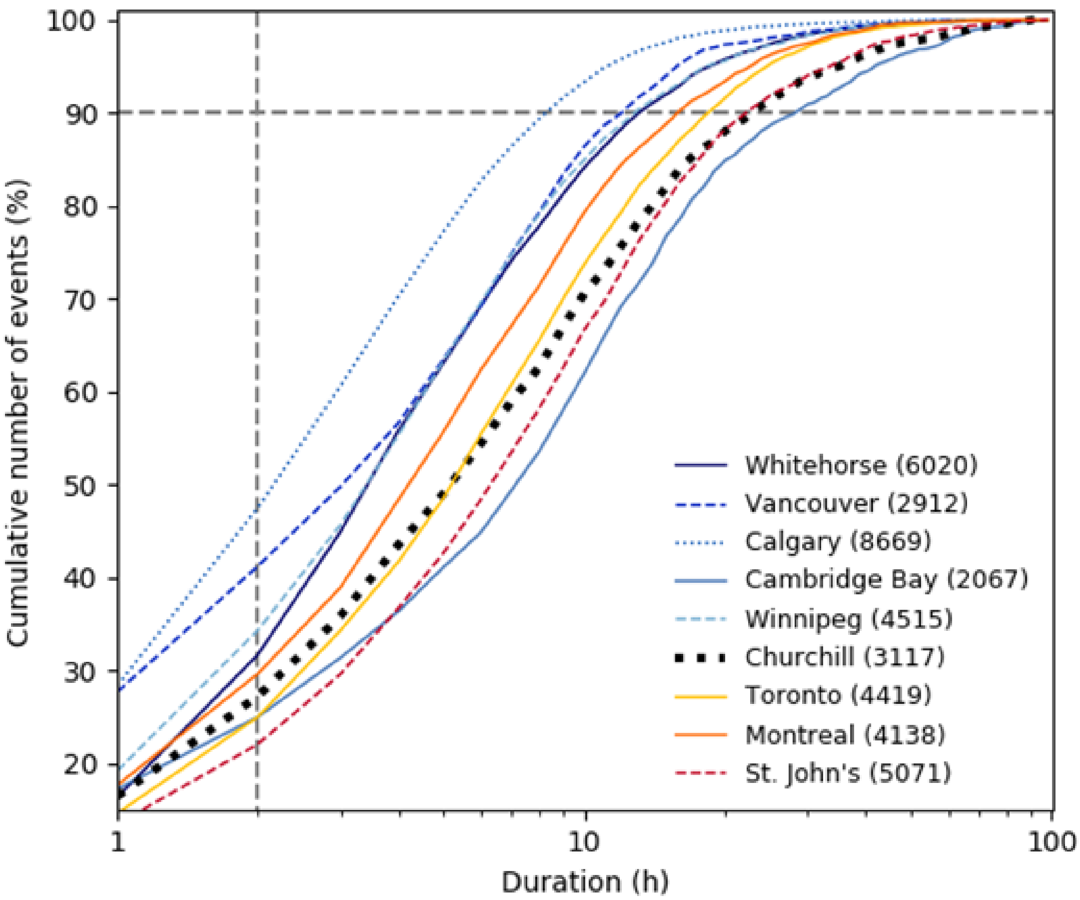


Figure 6 revised caption: Cumulative distribution of events (%) as a function of duration (h) of near 0°C ($-2 \leq T \leq 2$°C) events at the 9 selected stations across Canada over the 1981-2011 period arranged from west to east. The total number of events is shown in brackets and duration is plotted on a logarithmic scale.

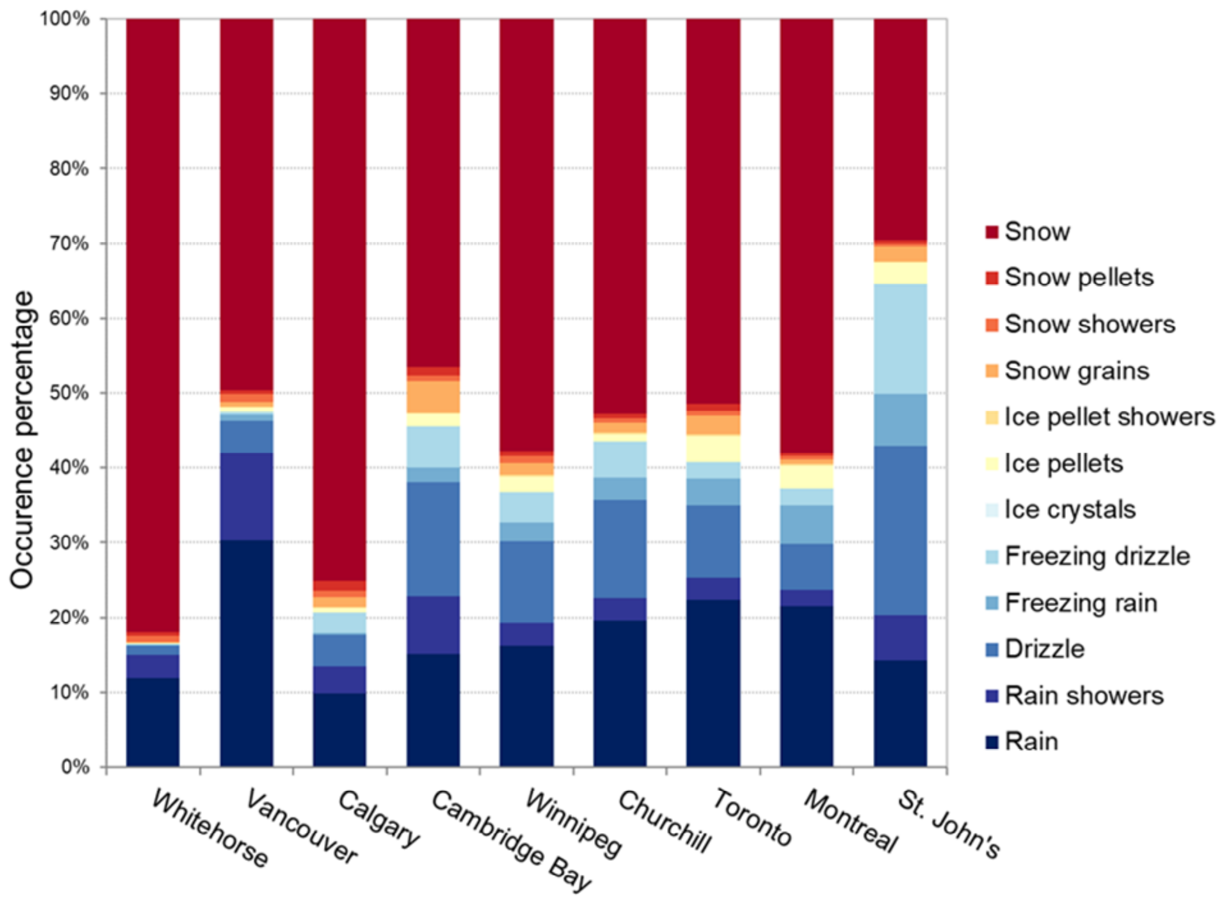
Comment 42: Figure 7. My opinion would be that this would be better presented as a table. The reader cannot make even simple comparisons between places and precipitation types.

Response: We have changed the colour palette in the diagram and modified it somewhat to improve clarity. We feel that the diagram better conveys information on variations of precipitation types at each station as well as between stations compared to the table format. We have included a table that shows the actual values but we will not include this in the article.

New/Revised Text: There is no change to the text or caption.

Revised figure is shown here.

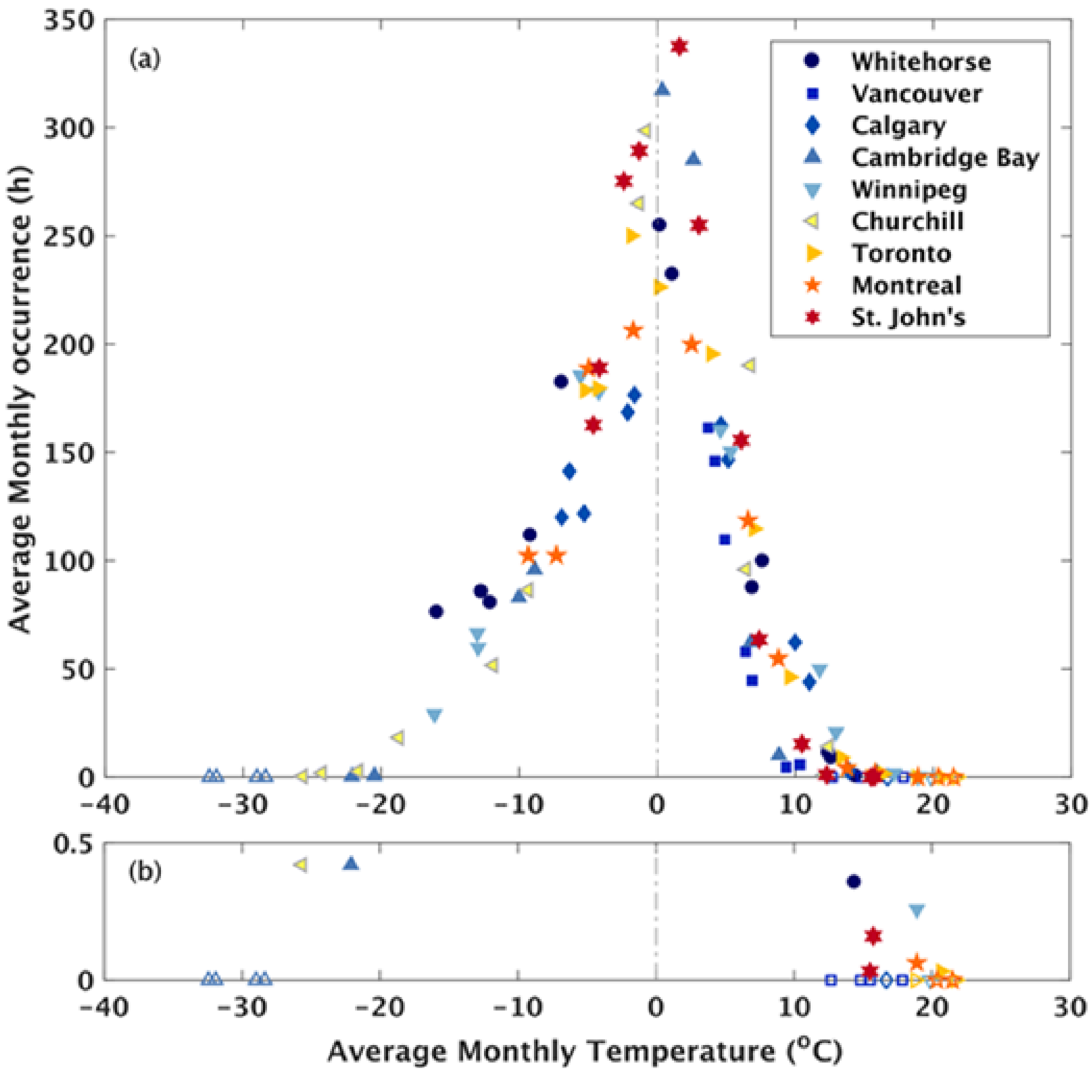
	Whitehorse	Vancouver	Calgary	Cambridge Bay	Winnipeg	Churchill	Toronto	Montreal	St. John's
Snow	82.0	49.7	75.2	46.5	57.8	52.8	51.5	58.1	29.6
Snow pellets	0.5	0.4	1.3	1.2	0.6	0.6	0.9	0.3	0.5
Snow showers	0.8	1.2	0.9	0.6	0.9	0.6	0.7	0.6	0.3
Ice pellet showers	0.05	0.2	0.2	0.1	0.2	0.3	0.2	0.2	0.1
Ice pellets	0.05	0.6	0.6	1.7	2.0	0.9	3.4	3.0	2.9
Ice crystals	0.00	0.00	0.00	0.02	0.00	0.02	0.01	0.00	0.00
Snow grains	0.1	0.5	1.2	4.2	1.6	1.4	2.5	0.6	2.1
Freezing drizzle	0.2	0.3	2.8	5.5	4.1	4.8	2.3	2.3	14.7
Freezing rain	0.1	0.9	0.2	1.9	2.5	3.0	3.6	5.1	7.0
Drizzle	1.1	4.3	4.2	15.3	11.0	13.1	9.6	6.2	22.6
Rain showers	3.1	11.6	3.6	7.7	3.0	3.0	3.0	2.2	5.9
Rain	12.0	30.3	9.9	15.2	16.3	19.6	22.3	21.5	14.3



Comment 43: Figure 8. Consider changing the symbol type between cases in addition to colour.

Response: As suggested, we have changed the symbols as well as the colours. We also produced a secondary panel that focuses on low occurrence values.

New/Revised Text: The new figure and caption are shown below:

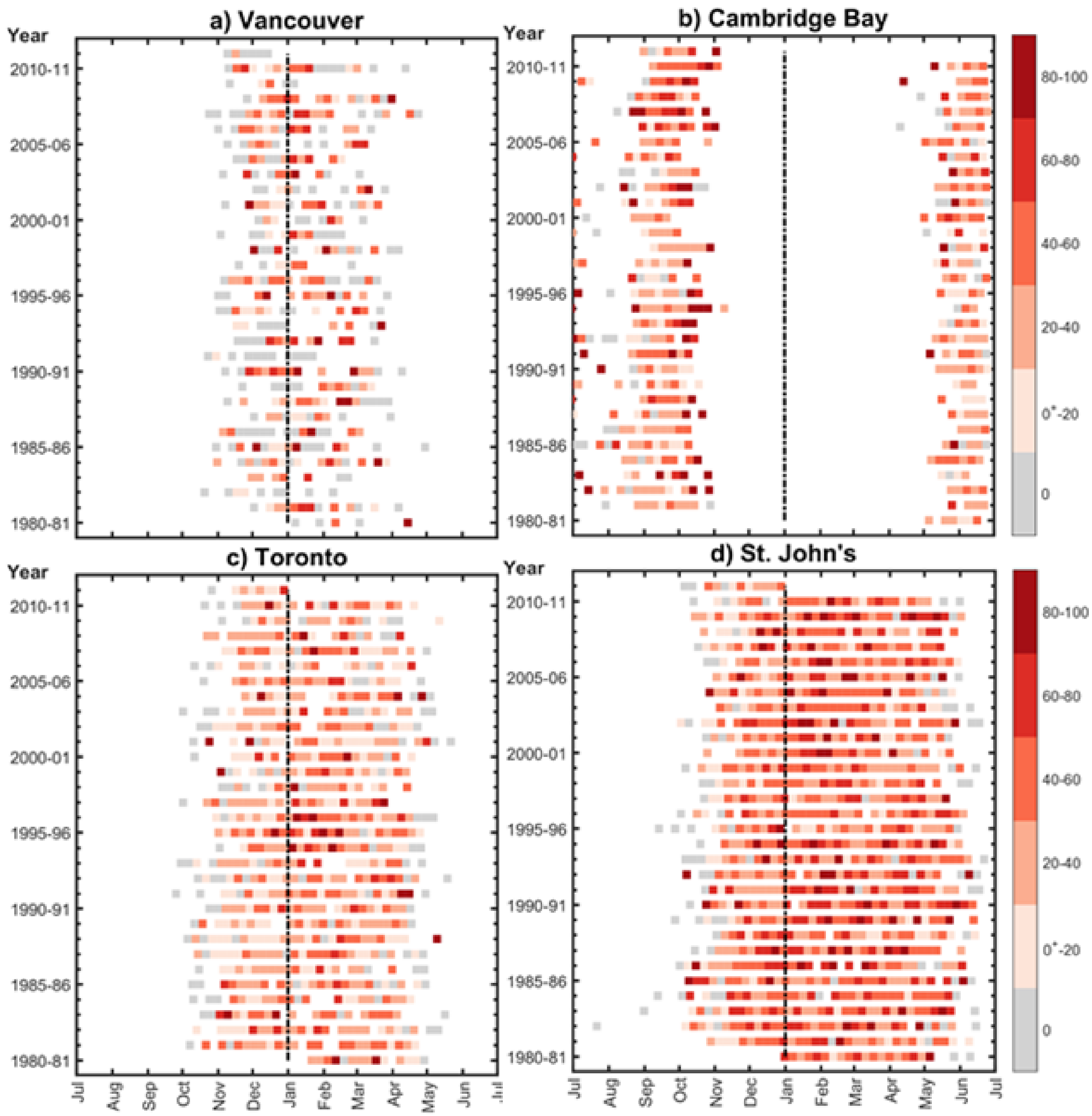


Revised caption: "Figure 8: (a) Average monthly occurrence (hours) of near 0°C conditions as a function of average monthly surface temperature for the nine selected stations over the 1981-2011 period. Filled symbols indicate occurrence and open or unfilled symbols indicate no occurrence. (b) An expanded view to better illustrate low values of average monthly occurrence."

Comment 44: Figure 9. This might be clearer if the blue points were labelled "temperature near zero" and the red points as "precipitation at temperatures near zero". I wonder if it would be better to make the blue points larger and overlay the red points directly without an offset. This to make the conditional "precipitation if temp is near zero" directly obvious.

Response: This figure has been redone. It shows the same information in a condensed weekly timestep. Additionally the fraction (%) of near 0°C hours each week with (or without) precipitation is shown through shading rather than as a separate line.

Revised Figure 9 is shown below.



Revised Figure 9 caption: "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."

Response to Reviewer 4 Comment 22 is shown below:

Comment 22: Section 5: In section 5 the text contains insufficient links to Figures and in many places literature citations are required.

Response: There were several comments regarding this issue by reviewers. We have addressed these individually but, to be sure, we have added additional links to figures and tables.

New/Revised Text: Below is the entire revised Sect. 5.

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 occurring 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). For some stations in the North and Atlantic regions, the development and melting of sea ice also must act 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 4). 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 4). Such sky conditions would contribute to reducing temperature swings associated with daytime heating and nighttime cooling (see, for example, Ahrens et al., 2016). 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.

Table 4: The longest duration events at the 9 selected stations. Columns indicate maximum duration, start time, 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

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. (1995). These vigorous storms almost always are 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).

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 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 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, significantly delayed onset of near 0°C conditions in the autumn, and significantly earlier spring cessation of these conditions (Table 2 and Table X). Montreal only showed significant declines in the number of near 0°C events (Table 2); Whitehorse showed significantly earlier spring cessation (Table X); St. John's showed significantly later autumn onset (Table X). 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 X), 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 X). With the observed overall warming, these stations experience a shift in the 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 been 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 Toronto (Table X) 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 X). 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."

Table X: 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 Surface 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

New References:

Ahrens, C. D., Jackson, P. L. and Jackson, C. E. J.: Meteorology Today: An introduction to weather, climate, and the environment: Second Canadian edition, Nelson Education, 2016.

Bush, E. and Lemmen, D.S. (Eds.): Canada's changing climate report, Government of Canada, Ottawa, Ontario, 444 pp., 2019

ECCC (Environment and Climate Change Canada): Canadian Climate normals, available at: http://climate.weather.gc.ca/climate_normals/index_e.html (last access: October 16, 2019), 2019c.

Gough, W. A.: Theoretical considerations of day-to-day temperature variability applied to Toronto and Calgary, Canada data, Theoretical and Applied Climatology, 94(1-2), 97–105, doi:10.1007/s00704-007-0346-9, 2008.

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~~Assessment of~~ Near 0°C surface ~~T~~temperature and ~~P~~precipitation type ~~Characteristics~~ patterns 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 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~~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~~ types of precipitation (~~including~~ 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. ~~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 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, ~~numerous~~ 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~~ 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 (e.g., Beltaos et al., 2006; Lindenschmidt et al., 2016), ~~animal starvation,~~

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 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 ~~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.

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 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), 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; 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 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. 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). ~~As well, t~~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~~ freezing precipitation 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 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 ~~P~~preliminary assessment ~~in the frequency~~ of near 0°C surface temperatures across Canada (Fig. 1) shows that they occur at stations at which average annual surface~~, with the exception of Vancouver, there is a relatively high frequency of these~~ temperatures range between below, near, and substantially above 0°C~~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~~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 ~~develop a Canada-wide perspective on~~of near 0°C conditions ~~with a particular focus on its associated~~ temperature and precipitation ~~types~~type patterns across Canada. Data and methods are described first, followed by an assessment of climatology and trends in key identified variables. Next, ~~representative~~ 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 ~~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 hourly 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 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 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~~s~~ 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 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).

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 ~~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~~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 ≤ 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 ~~(dry bulb)~~ temperature ~~(defined as T)~~ window straddling 0°C with embedded large fractions of overall occurrences of varying precipitation types, we defined near 0°C~~, these~~ conditions ~~were defined~~ 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 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 ≤ T ≤ 2°C range. Note that to be considered a 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. 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 ≤ T ≤ 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, these rather 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 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). 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). 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 of missing data and similar to earlier works (Mekis et al., 2015; Vincent et al., 2018), it was decided that, for trend computation, a minimum of 90% of the values (29 out of 31 years) was required. , 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, 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.

3 Climatology and Trends

3.1 The 31-Year Climatology for 1981-2011

Figure 3a shows the ~~average~~ number of days per year when surface temperatures were ~~was~~ 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 found in interior British Columbia and southern Alberta extending into southern Saskatchewan with maximum values within or on the leeward side of the western ~~c~~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~~ 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.

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 ~~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 east of the Canadian Rockies so they show up in the number of days but not ~~in~~ as an extended number of hours.

High values are even more pronounced in Fig. 3b than in Fig. 3a at one ~~near~~ northern coastal British Columbia station (Terrace) where maximum values of 1800-2000 hours represent approximately 80 days per year~~are also evident~~. This northern British Columbia station ~~next to~~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~~, here~~

are now three ~~general~~ 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 Columbia; and~~. The northern 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~~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.~~ 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. 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 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 (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 ~~the annual~~ events~~ lengths in hours~~, characterizing the occasional persistence of such events, is shown in Fig.~~ure~~ 3d. Maximum 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.~~ 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).~~

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 (except northern coastal British Columbia) with the lowest value (40 - 80 hours) 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 (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 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 ~~to~~ - 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 by far are in the Atlantic region (36 - 42 hours) and there is a regional maximum near Montreal (20 - 24 hours). Low~~. Small~~ 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 ~~ever~~ 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 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 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. ~~As in Fig. 5a, m~~Most stations 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 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 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 ~~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~~ 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 0ºC 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.~~ure~~ 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~~fewest.

While Table 3 contains the average number of hours~~Figure 7 shows the distribution in the occurrence~~ of the 12 precipitation types, Fig. 7 shows the distribution in the occurrence ~~included in this study~~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 ~~statistically~~ 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 ~~5~~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.~~ure~~ 9~~8~~a, 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 ~~the even~~ shorter time scales. For example, ~~Figure~~Fig. 10~~9~~ shows annual cycles of near 0°C conditions and associated precipitation type occurrences at four ~~of the nine representative~~ 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 is evident that there is large inter-annual variability and this can mask expected systematic trends. For example, i~~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. ~~Although not~~As shown in Table 3 and ~~, these patterns were generally not statistically significant. Only Toronto (~~Fig. 10~~5~~c,~~)~~ ~~shows~~ both of these trends ~~to be statistically~~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. 10~~9~~d and Table 4). Cambridge Bay experiences near 0°C conditions in every 'warm season' month (Fig. 10~~9~~b 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 ~~Country~~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 vari~~es~~y 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 ~~the~~ 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 ~~must~~ 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).~~ 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~~ 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).~~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, 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.~~. 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 based on surface temperature were further examined by identifying the longest ~~duration events~~periods at the ~~9 representative~~ selected stations (Table ~~4~~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~~Using the hourly observations at these stations, it is evident that all the events~~ were dominated by cloudy conditions~~, which~~ that were ~~often~~ sometimes accompanied with persistent precipitation (Table 5). Such sky ~~cover~~ 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. ~~The country~~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 ~~buffeted by~~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 ~~mean~~ associated with surface temperatures passing from below to above 0°C with near saturated conditions (Stewart and Patenaude, 1988); they also ~~have~~ 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 ~~representative~~ 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). ~~This is likely occurring in Canada b~~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 ~~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 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.~~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 thedelayed onset and cessation 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 showsed significantly earlier spring cessation ;and St. John's showsed significantly 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) 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 (Table 4), .e Even with the recent 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 (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 should 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). Snowcover and sea ice formed and melted; ground frozen and thawed. One exception may again be in southern Ontario where the ground may has not have frozen as much or be covered by as much snow (Vincent et al., 2015; Bush and Lemmen, 2019); 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 occurrences may be countered by warmer mid-winters, although at locations such as in Toronto (Table 4), mid-winter 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 (Table 4). 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 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:

- ~~The entire country~~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. ~~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 daily, radiatively-driven temperature variation ~~the solar heating~~ and the annual temperature cycle. As well, precipitation, snowcover, ~~precipitation, ground conditions~~ and sea/lake ice can be important; all of these ~~simultaneously~~ can melt and freeze with effects always being to tip temperatures towards 0°C. In addition, ~~ocean~~ sea surface temperatures ~~near~~ around Canada tend to ~~often~~ 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~~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.
- 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
- 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 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.

Although our $-2 \leq T \leq 2$°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 $-1 \leq T \leq 1$°C window or a $-3 \leq T \leq 3$°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 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).

~~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.~~ 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 $\leq T \leq 2$°C so called “mixed” precipitation range examined here. And, Dai (2008) and Jennings et al. (2018) illustrated rain/snow issues over 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.

~~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.

Special issue statement. This article is part of the special issue "Understanding and predicting Earth system and hydrological change in cold regions". It is not associated with a conference.

Acknowledgements. The authors would like to thank David Hudak from Environment and Climate Change Canada, and XX anonymous reviewers for their useful comments and suggestions that have helped to improve the manuscript. The research was supported by the Changing Cold Regions Network supported by the Natural Sciences and Engineering Research Council (NSERC); the Global Water Futures study supported by Canada First Research Excellence Fund; the NSERC Discovery grants of RES and JMT.

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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).

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

DEFINITIONS	UNIT
Temperature related	
Annual number of days with $-2^oC \le T_{drybulb} \le +2^oC$	days
Annual number of hours with $-2^oC \le T_{drybulb} \le +2^oC$	hours
Annual number of independent events (continuous hours) with $-2^oC \le T_{drybulb} \le +2^oC$	events
Annual Maximum Lengths with $2^oC \le T_{drybulb} \le +2^oC$	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 $-2^oC \le T_{drybulb} \le +2^oC$	hours
Annual number of hours with any of the 12 precip types and $-2^oC \le T_{drybulb} \le +2^oC$	hours
The fraction of [$-2^oC \le T_{drybulb} \le +2^oC$] conditions associated with Freezing Rain	%
The fraction of [$-2^oC \le T_{drybulb} \le +2^oC$] conditions with any of the 12 precip types	%

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.~~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

	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.~~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.~~

	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

	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: 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.

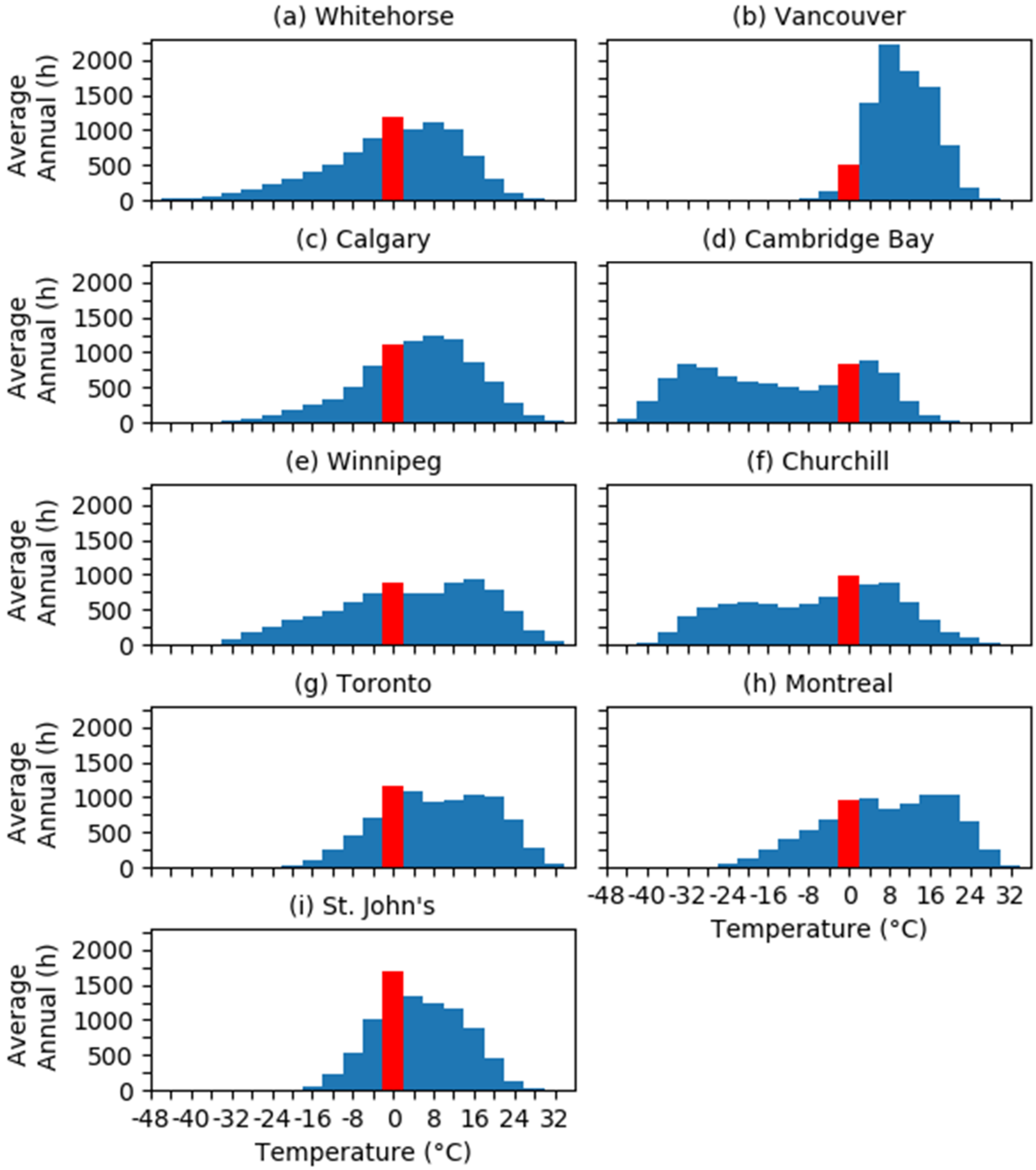
Station	Average Monthly Temperature (°C)			Autumn Onset Trend (days/31 years)	Spring Cessation Trend (days/31 years)
	December	January	February		
Whitehorse	-12.5	-15.2	-12.7	6.4	**-11.8**
Vancouver	3.6	4.1	4.9	8.3	-4.1
Calgary	-6.8	-7.1	-5.4	5.4	1.1
Cambridge Bay*	2.7	8.9	6.8	23.8	0.2
Winnipeg	-13.2	-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

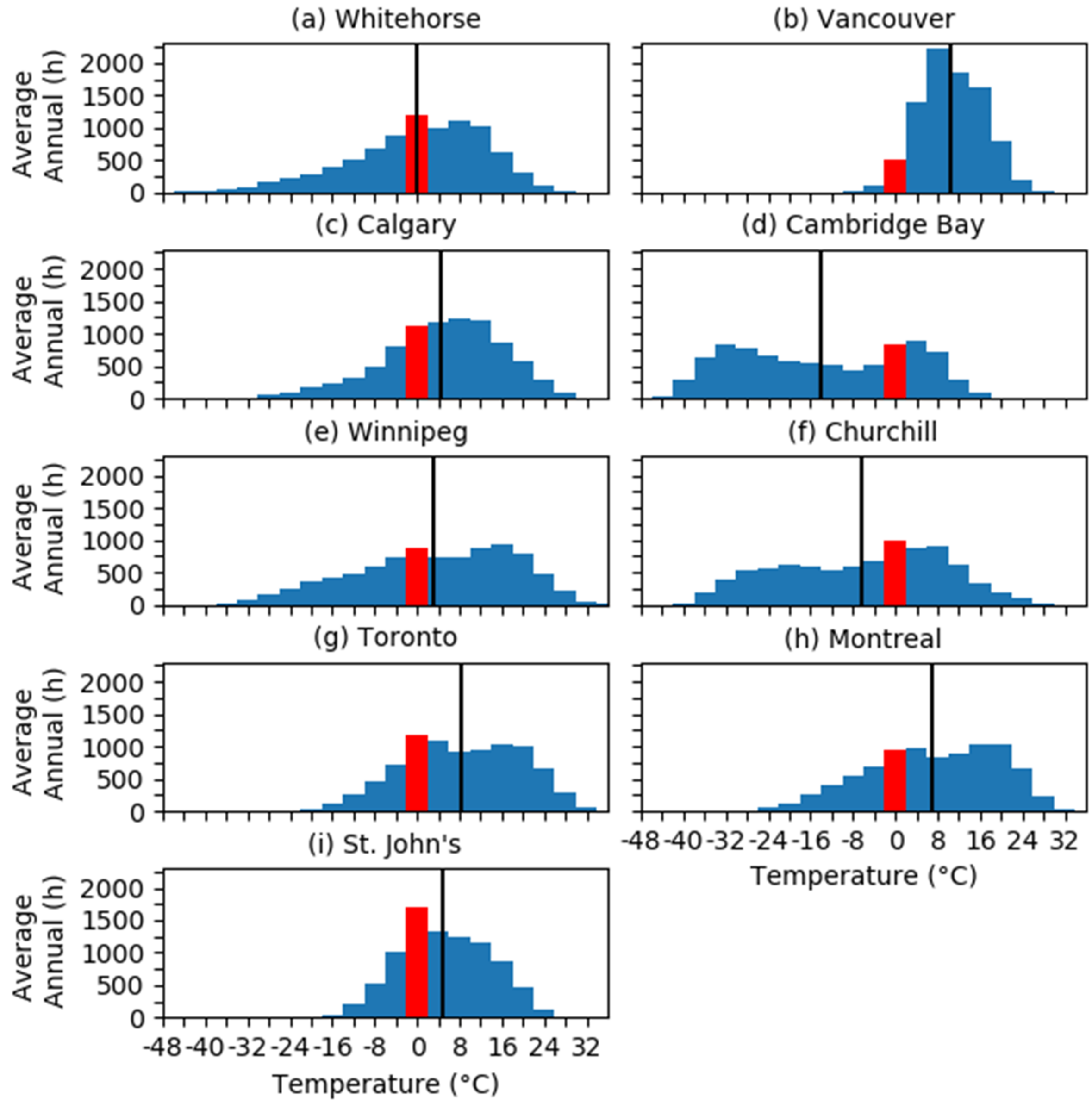
Table 45: The longest duration events at the 9 ~~representative~~ selected stations. Columns indicate maximum duration, start time, and hours (and fraction of duration) with mainly or completely clear ~~skies. Times are UTC.~~sky conditions, hours with any of the 12 reported precipitation types (and 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

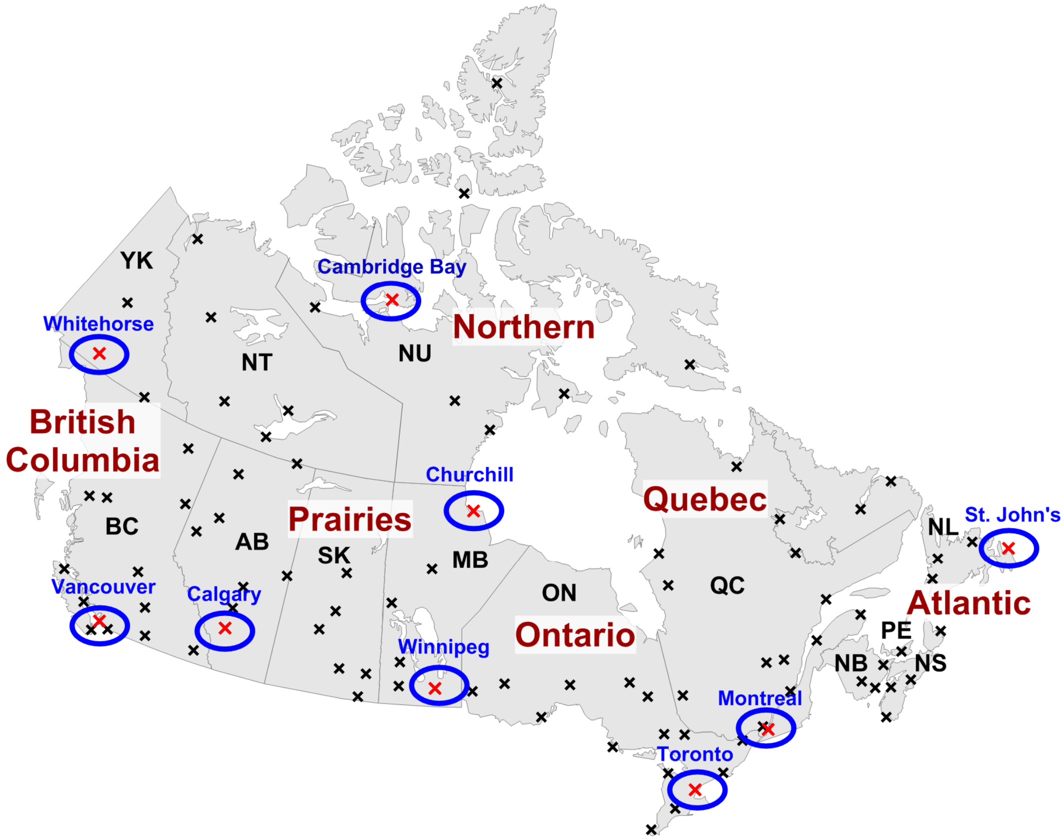
Station	Duration	Start Time	Mainly/Completely Clear	
	(h)	(YYYY-MM-DD-HH)	(h)	(%)
Whitehorse	110	1998-10-06-21	3.0	2.7
Vancouver	68	2005-01-06-04	1.0	1.5
Calgary	73	2003-05-05-10	0.0	0.0
Cambridge Bay	197	1987-06-11-08	3.0	1.5
Winnipeg	128	1983-03-01-15	0.0	0.0
Churchill	141	1986-10-18-12	1.0	0.1
Toronto	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

770 **Figures**


(a) Whitehorse
(b) Vancouver
(c) Calgary
(d) Cambridge Bay
(e) Winnipeg
(f) Churchill
(g) Toronto
(h) Montreal
(i) St. John's
Average Annual (h)
0
500
1000
1500
2000
-48 -40 -32 -24 -16 -8 0 8 16 24 32
Temperature (°C)



775 **Figure 1: The average annual surface temperature distribution (4°C bins) from 1981 to 2011 for 9 representative stations across Canada 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.**


YK
Cambridge Bay
Whitehorse
Northern
NT
NU
British Columbia
Churchill
Quebec
Prairies
St. John's
NL
BC
AB
SK
MB
ON
QC
Vancouver
Calgary
Atlantic
Winnipeg
Ontario
PE
NB
NS
Montreal
Toronto

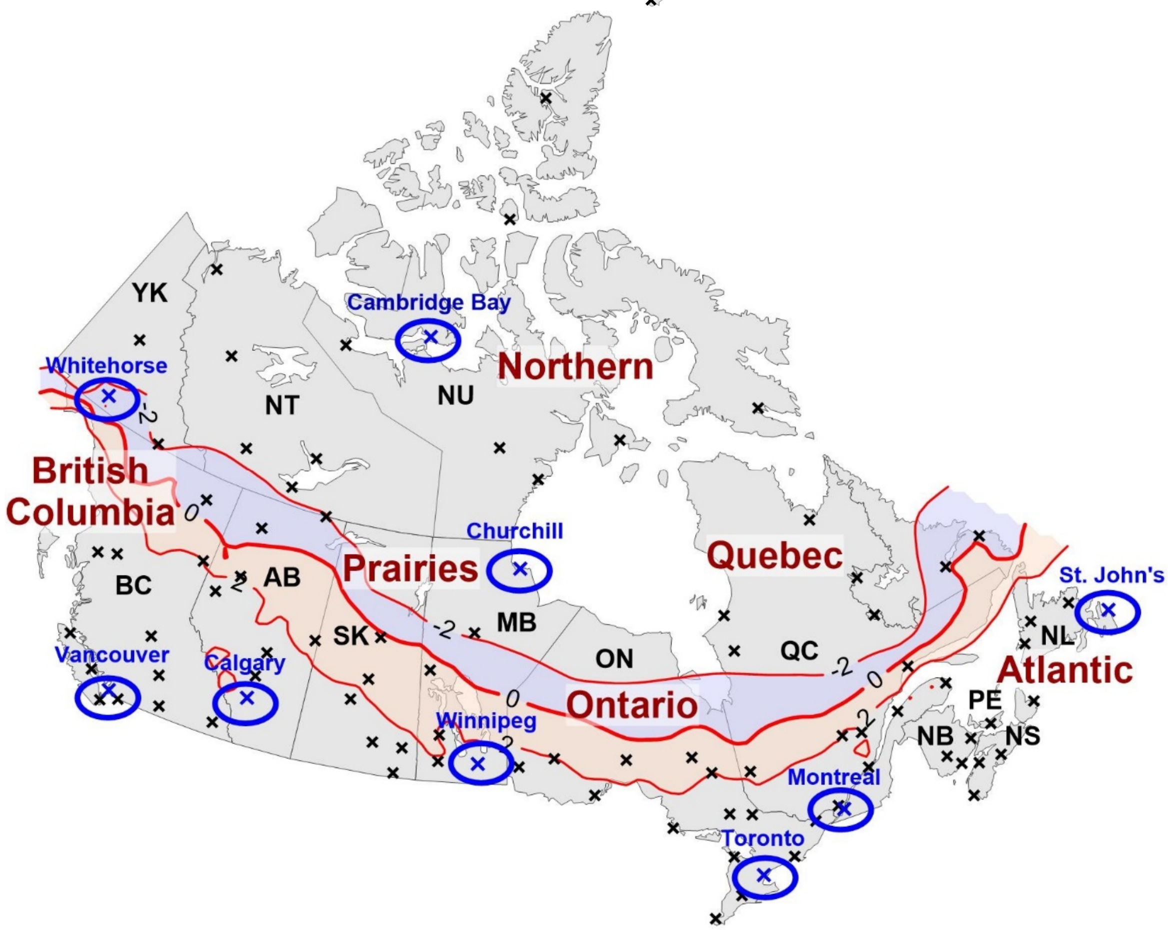
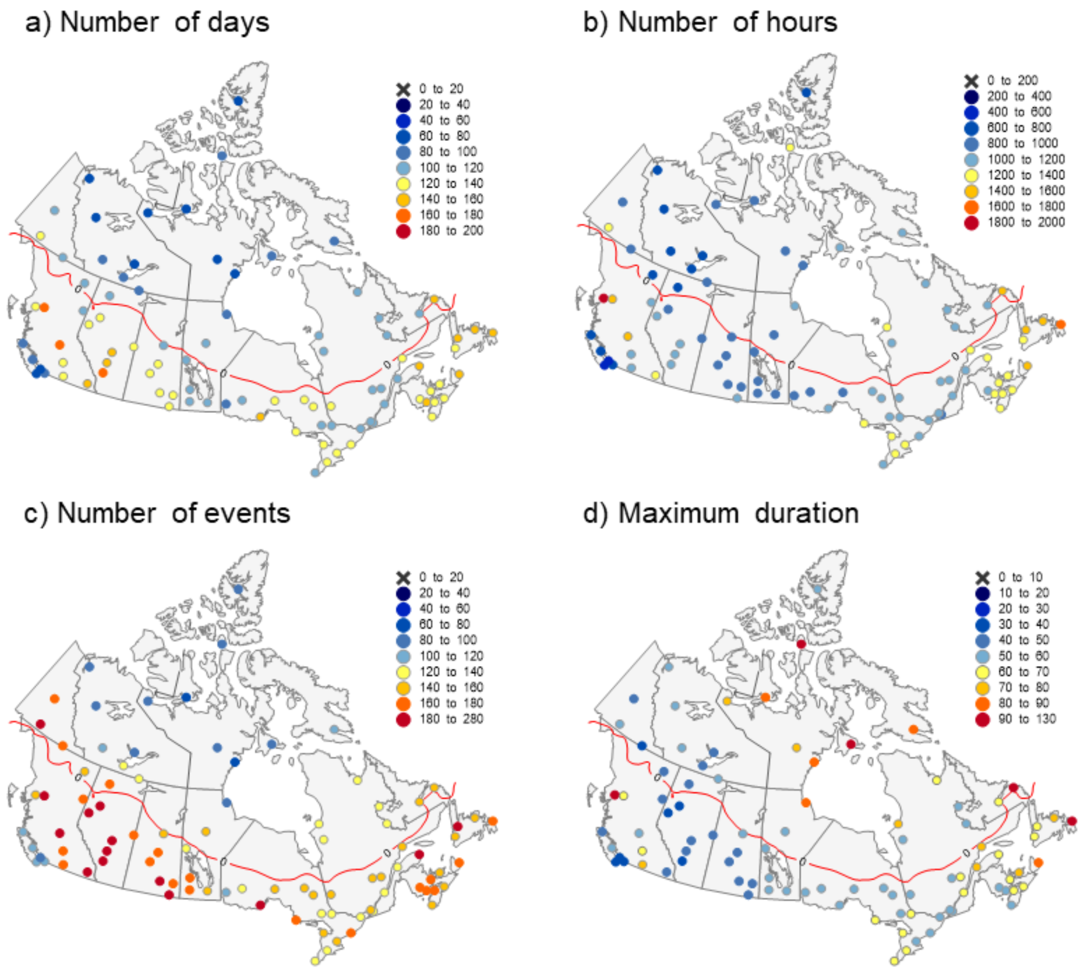

YK
Cambridge Bay
Northern
Whitehorse
NT
NU
British Columbia
Churchill
Quebec
Prairies
St. John's
BC
AB
SK
MB
NL
ON
QC
Vancouver
Calgary
Atlantic
Ontario
PE
Winnipeg
NB
NS
Montreal
Toronto
-2
0

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.


a) Number of days
0 to 20
20 to 40
40 to 60
60 to 80
80 to 100
100 to 120
120 to 140
140 to 160
160 to 180
180 to 200
b) Number of hours
0 to 200
200 to 400
400 to 600
600 to 800
800 to 1000
1000 to 1200
1200 to 1400
1400 to 1600
1600 to 1800
1800 to 2000
c) Number of events
0 to 20
20 to 40
40 to 60
60 to 80
80 to 100
100 to 120
120 to 140
140 to 160
160 to 180
180 to 280
d) Maximum duration
0 to 10
10 to 20
20 to 30
30 to 40
40 to 50
50 to 60
60 to 70
70 to 80
80 to 90
90 to 130

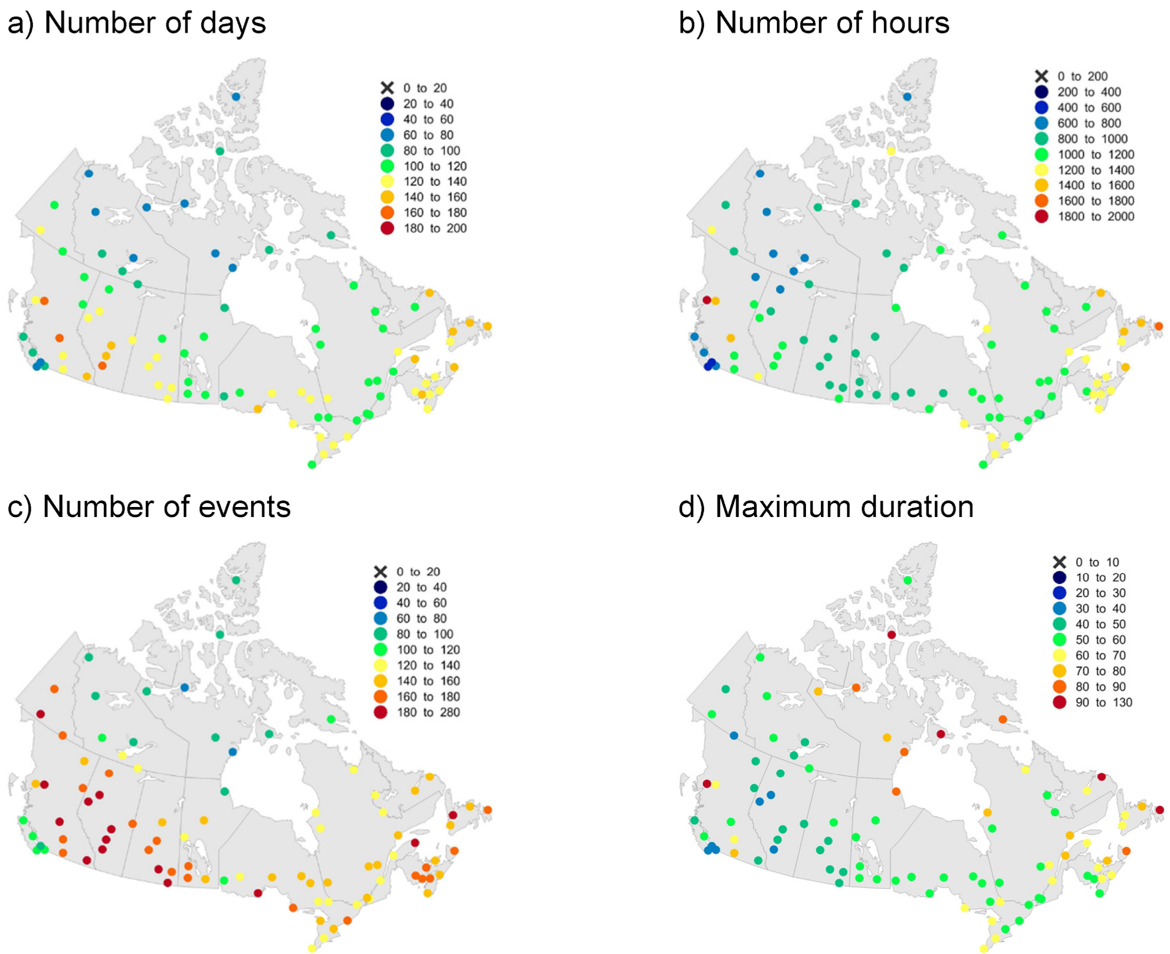
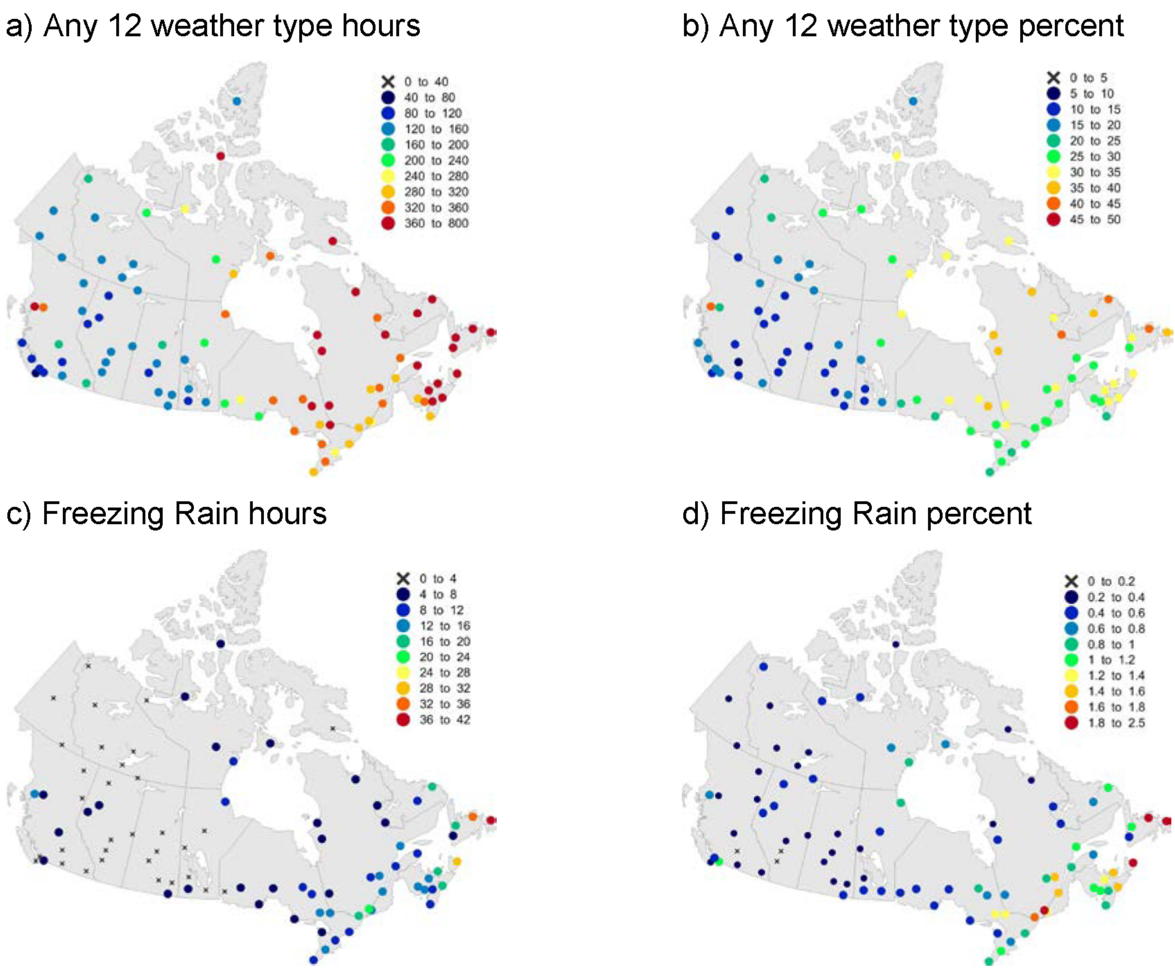


Figure 3: Average near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period for (a) number of days per year, (b) number of hours per year, (c) number of events per year, and the (d) annual maximum (max) duration of events. The red line indicates the annual average 0°C surface temperature computed from 1981-2010 climate normals (ECCC, 2019c).


a) Any 12 weather type hours
0 to 40
40 to 80
80 to 120
120 to 160
160 to 200
200 to 240
240 to 280
280 to 320
320 to 360
360 to 800
b) Any 12 weather type percent
0 to 5
5 to 10
10 to 15
15 to 20
20 to 25
25 to 30
30 to 35
35 to 40
40 to 45
45 to 50
c) Freezing Rain hours
0 to 4
4 to 8
8 to 12
12 to 16
16 to 20
20 to 24
24 to 28
28 to 32
32 to 36
36 to 42
d) Freezing Rain percent
0 to 0.2
0.2 to 0.4
0.4 to 0.6
0.6 to 0.8
0.8 to 1
1 to 1.2
1.2 to 1.4
1.4 to 1.6
1.6 to 1.8
1.8 to 2.5

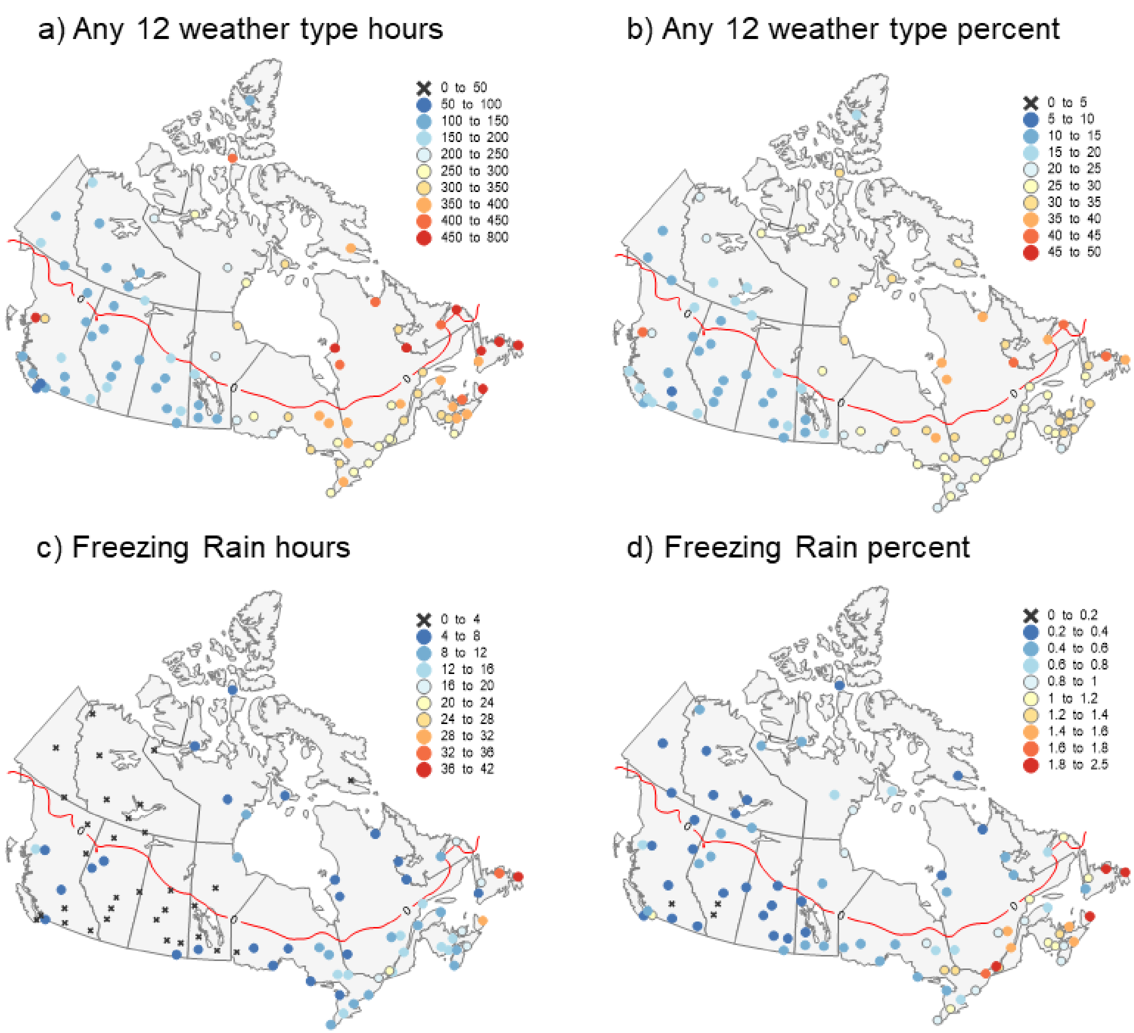
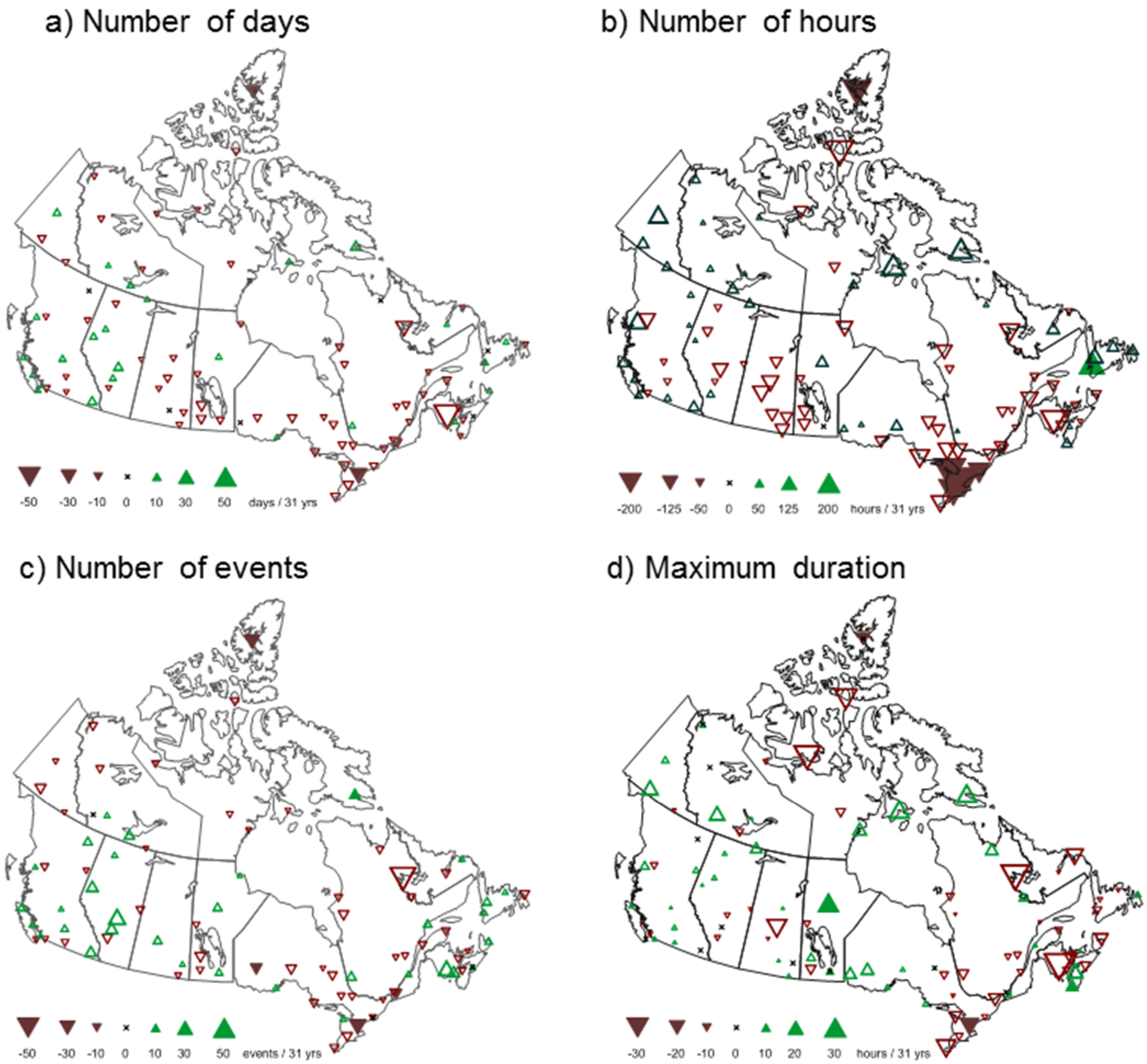


Figure 4: Precipitation type occurrences during near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period, where (a) average annual number of hours with reported precipitation types (any of the 12), (b) percentage of near 0°C conditions associated with reported precipitation types (any of the 12), (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 normals (ECCC, 2019c).


a) Number of days
-50 -30 -10 0 10 30 50 days / 31 yrs
b) Number of hours
-200 -125 -50 0 50 125 200 hours / 31 yrs
c) Number of events
-50 -30 -10 0 10 30 50 events / 31 yrs
d) Maximum duration
-30 -20 -10 0 10 20 30 hours / 31 yrs

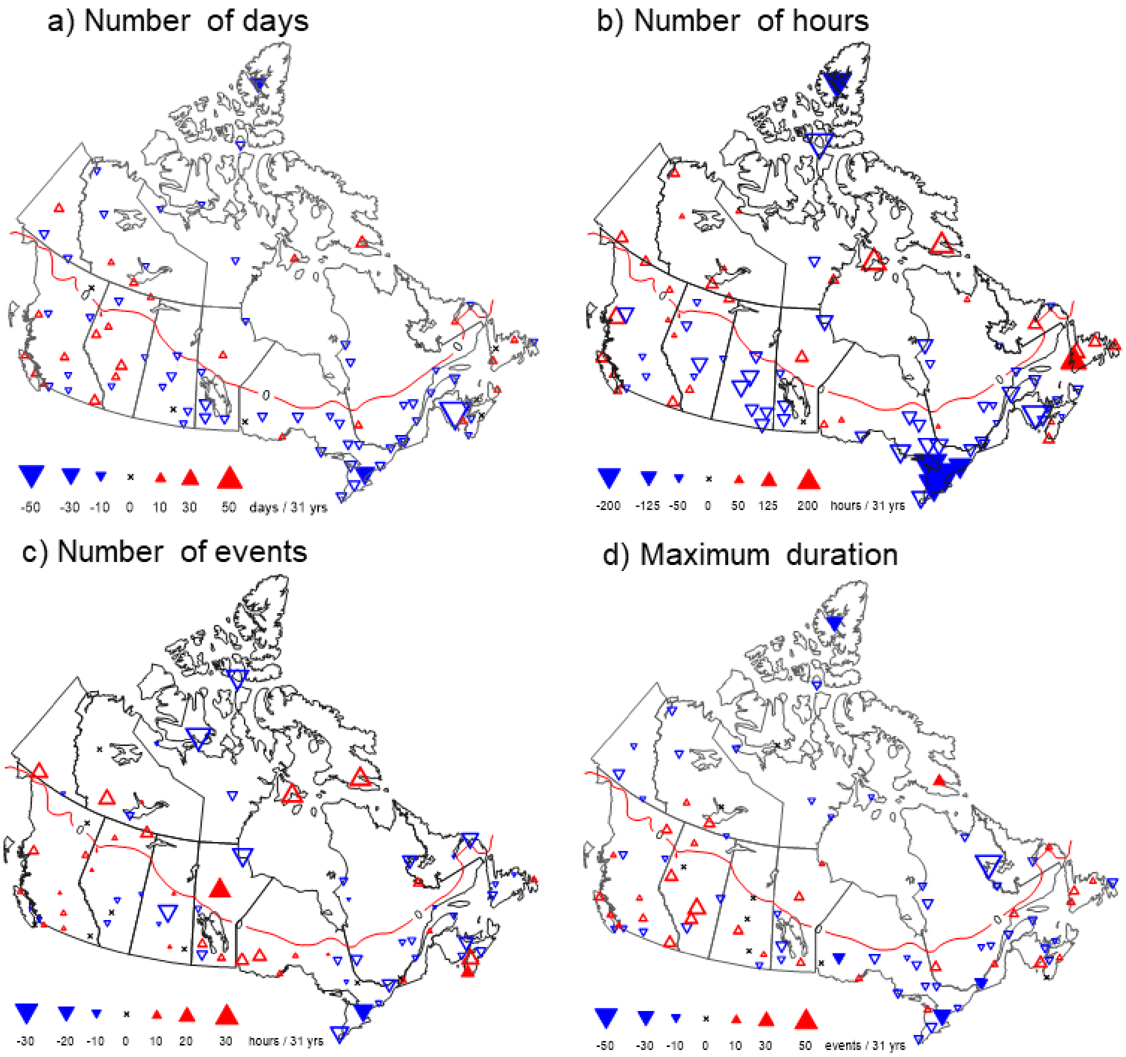
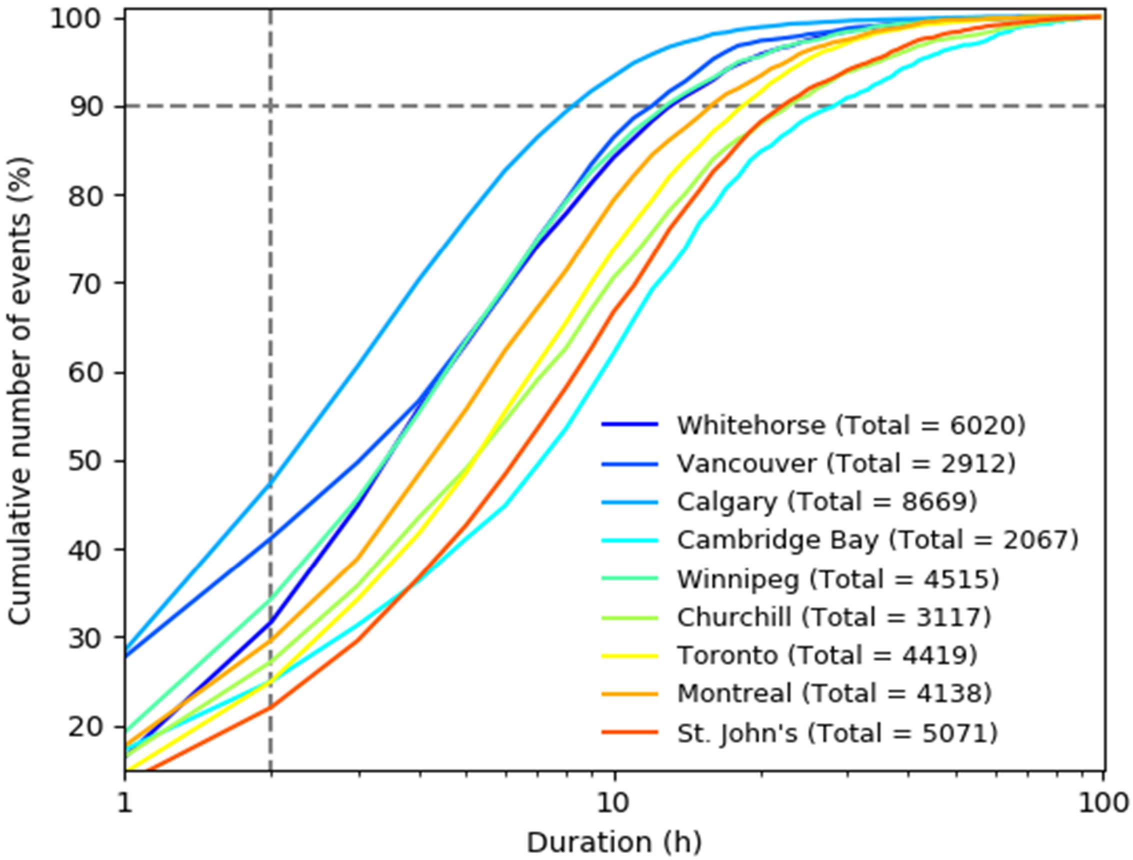


Figure 5: Trends in near 0°C (-2 ≤ T ≤ 2°C) conditions over the 1981-2011 period. (a) annual average number of days, (b) annual average hours, (c) annual number of events, and (d) annual maximum duration. A solid triangle indicates statistical significance at 5% level. The red line indicates the annual average 0°C surface temperature computed from 1981-2010 climate normals (ECCC, 2019c).


Cumulative number of events (%)
Duration (h)
Whitehorse (Total = 6020)
Vancouver (Total = 2912)
Calgary (Total = 8669)
Cambridge Bay (Total = 2067)
Winnipeg (Total = 4515)
Churchill (Total = 3117)
Toronto (Total = 4419)
Montreal (Total = 4138)
St. John's (Total = 5071)

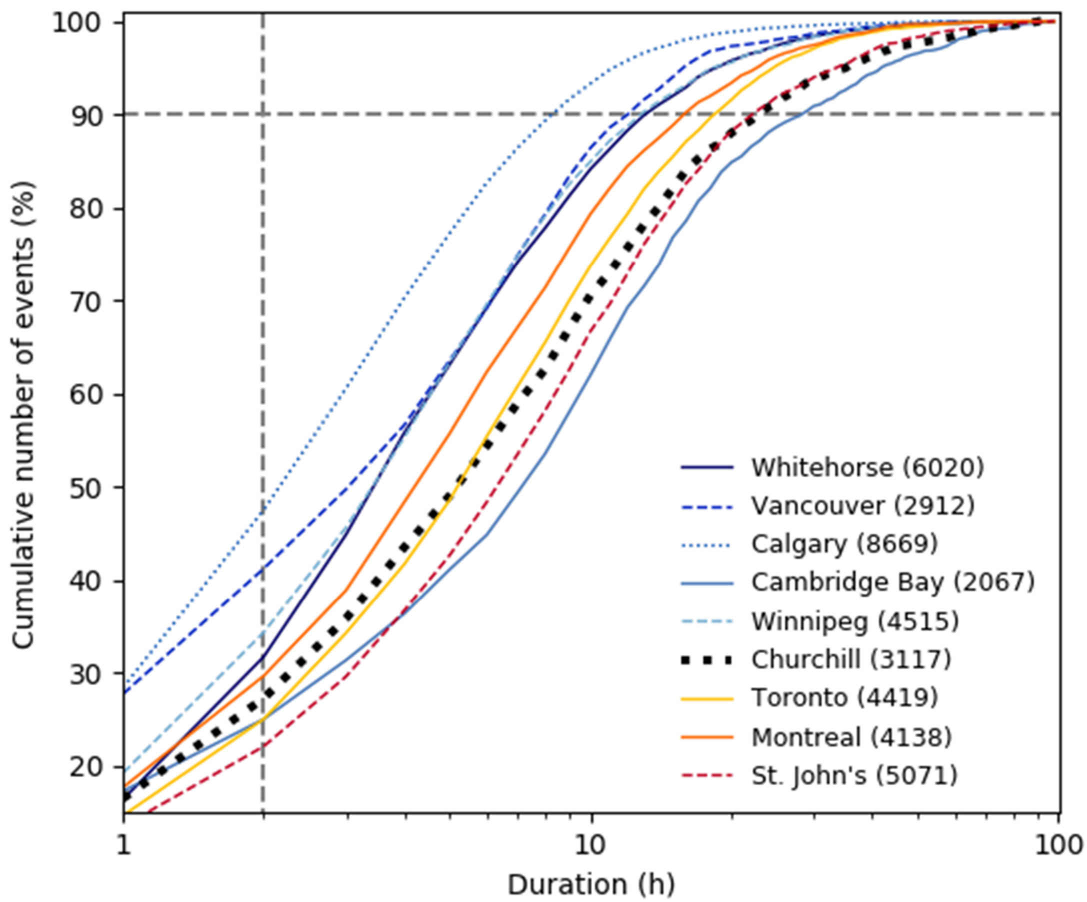
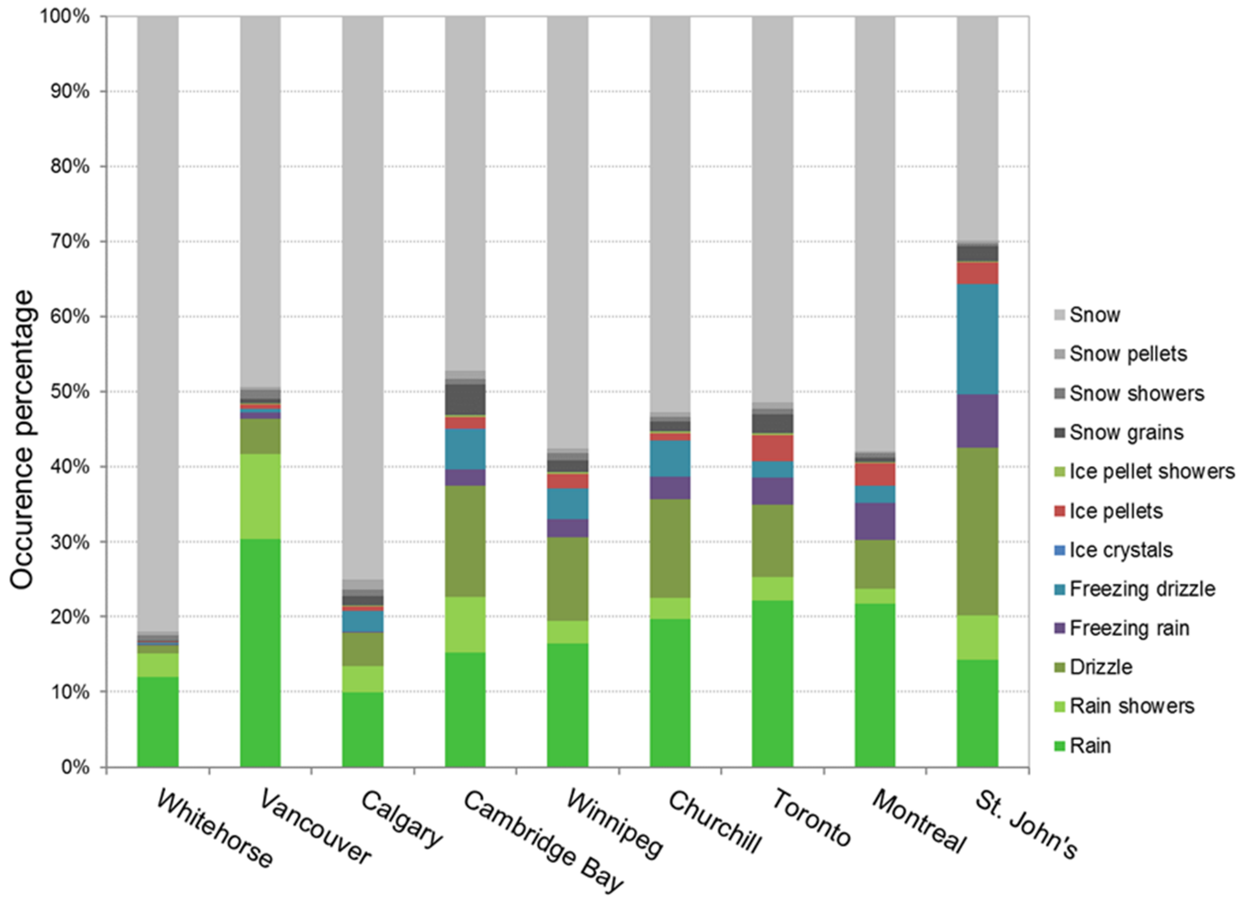


Figure 6: Cumulative distribution of events (%) as a function of duration (h) of near 0°C (-2 ≤ T ≤ 2°C) events at the 9 representative stations across Canada over the 1981-2011 period arranged from west to east. The total number of events is shown in brackets ~~also indicated~~ and duration is plotted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


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Occurence percentage
Whitehorse
Vancouver
Calgary
Cambridge Bay
Winnipeg
Churchill
Toronto
Montreal
St. John's
Snow
Snow pellets
Snow showers
Snow grains
Ice pellet showers
Ice pellets
Ice crystals
Freezing drizzle
Freezing rain
Drizzle
Rain showers
Rain

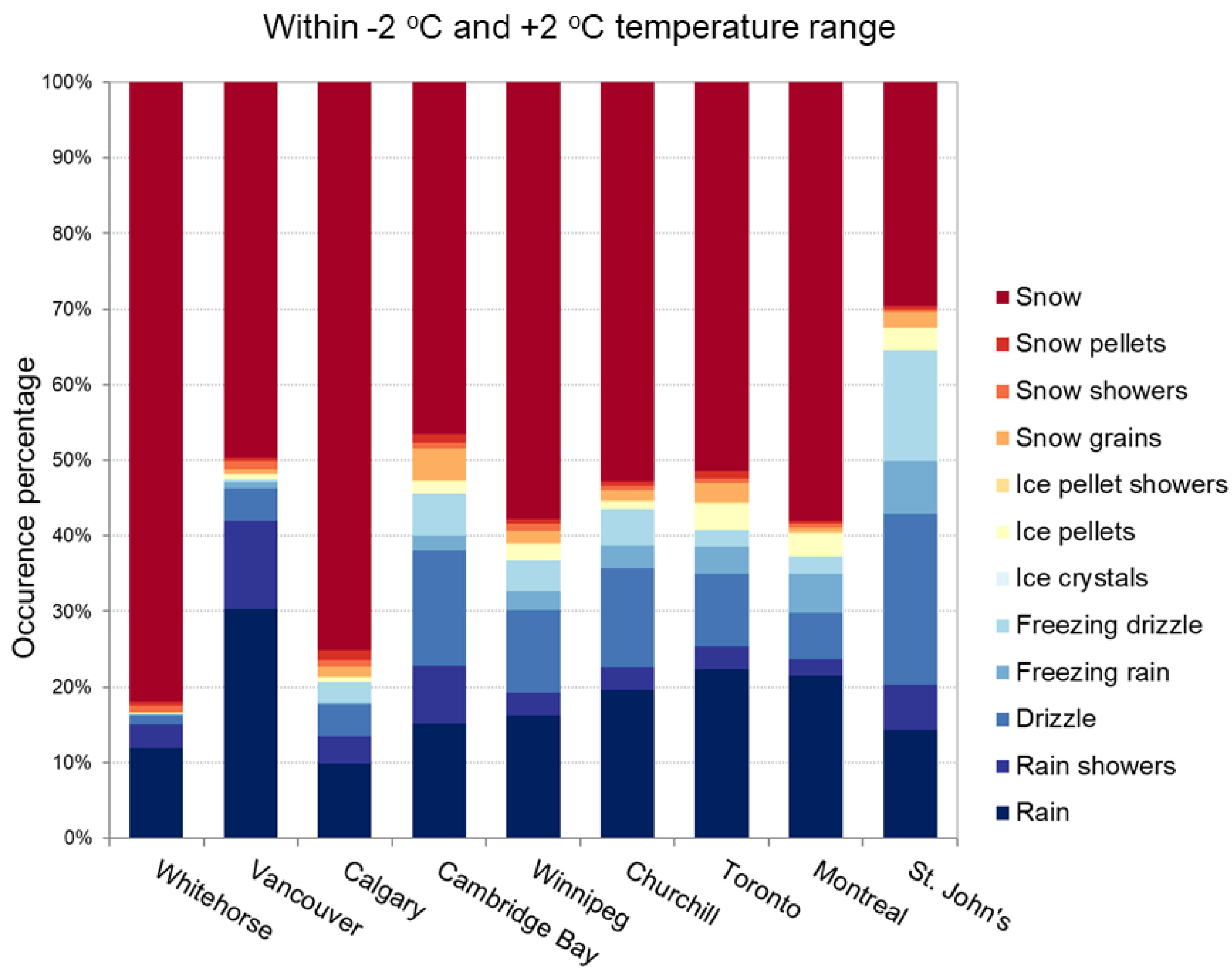


Figure 7: The distribution of precipitation type occurrence with near 0°C conditions at each of the 9 stations over the 1981-2011 period. Stations are arranged from west to east.

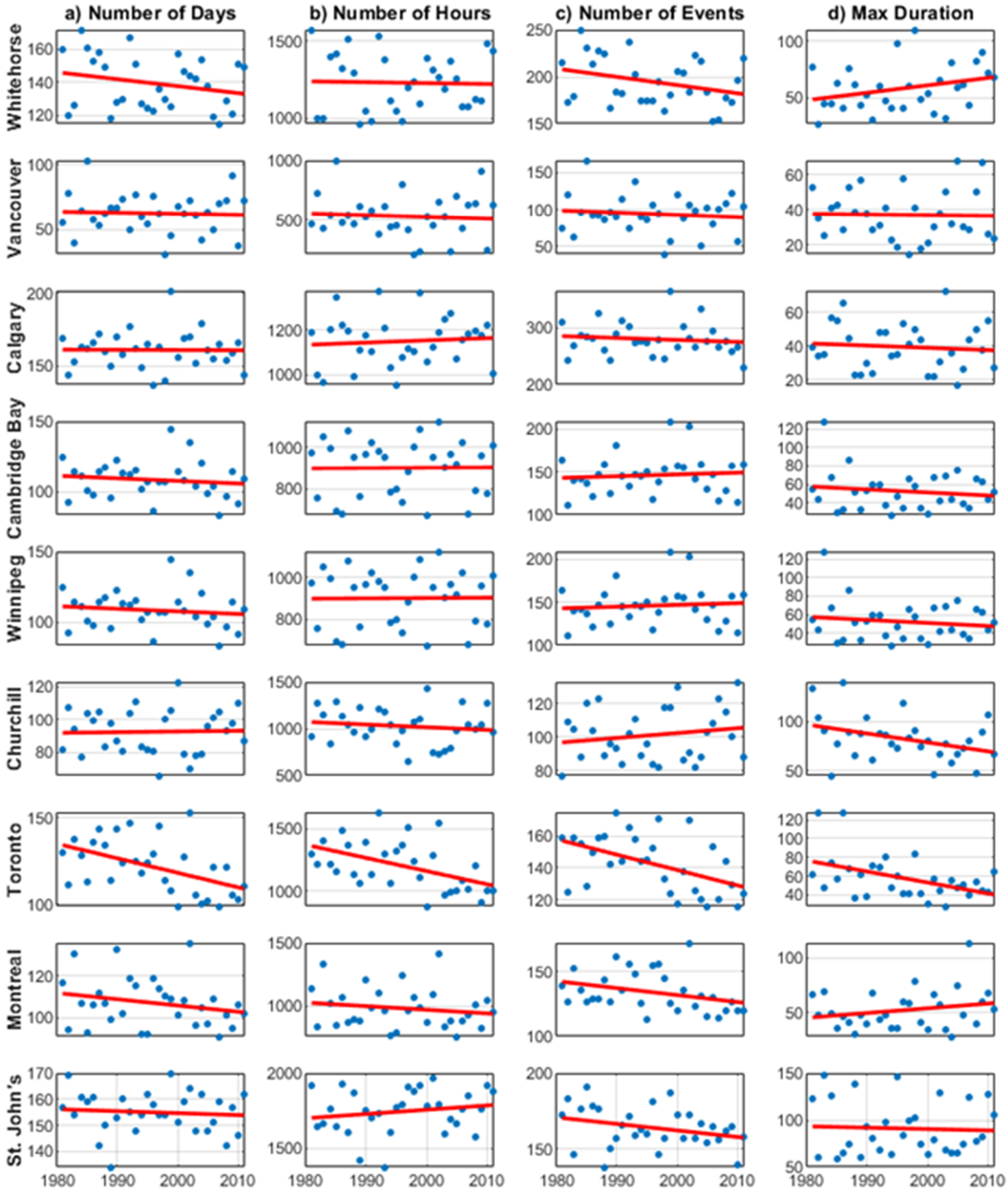
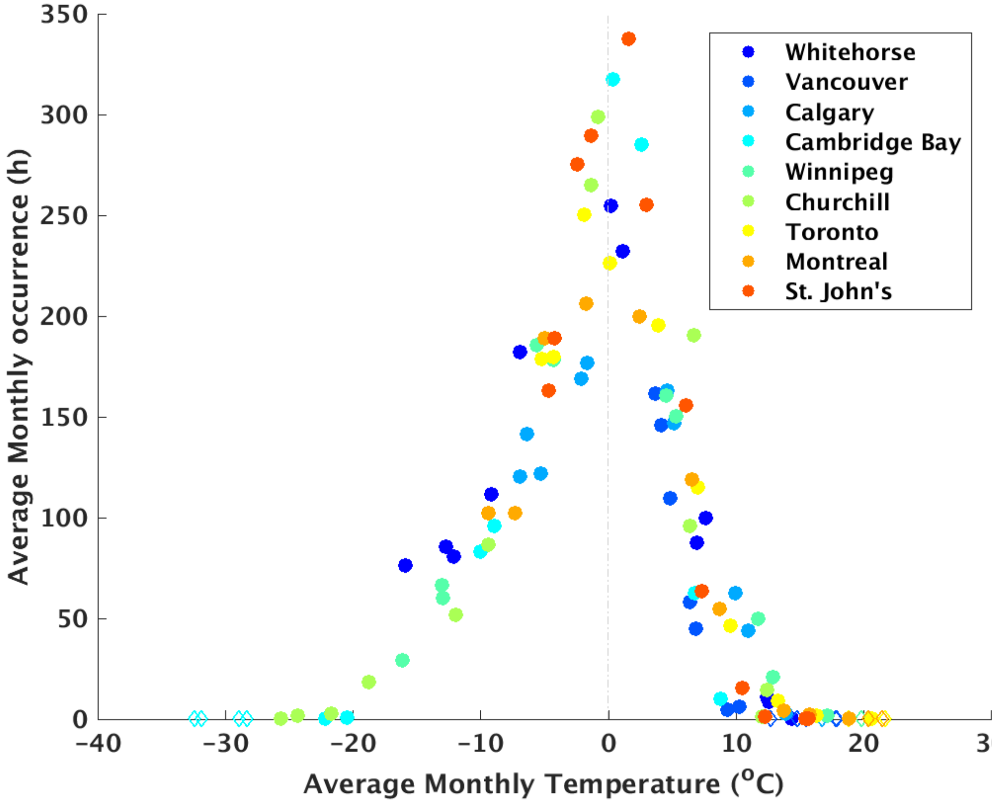


Figure 8: The 1981-2011 values of average (a) annual number of days, (b) annual number of hours, (c) annual number of events and (d) annual maximum duration (in hours) during near 0°C (-2 ≤ T ≤ 2°C) conditions for the nine selected locations in Canada. Linear trend lines are superimposed in red.



Average Monthly occurrence (h)
Average Monthly Temperature (°C)
Whitehorse
Vancouver
Calgary
Cambridge Bay
Winnipeg
Churchill
Toronto
Montreal
St. John's

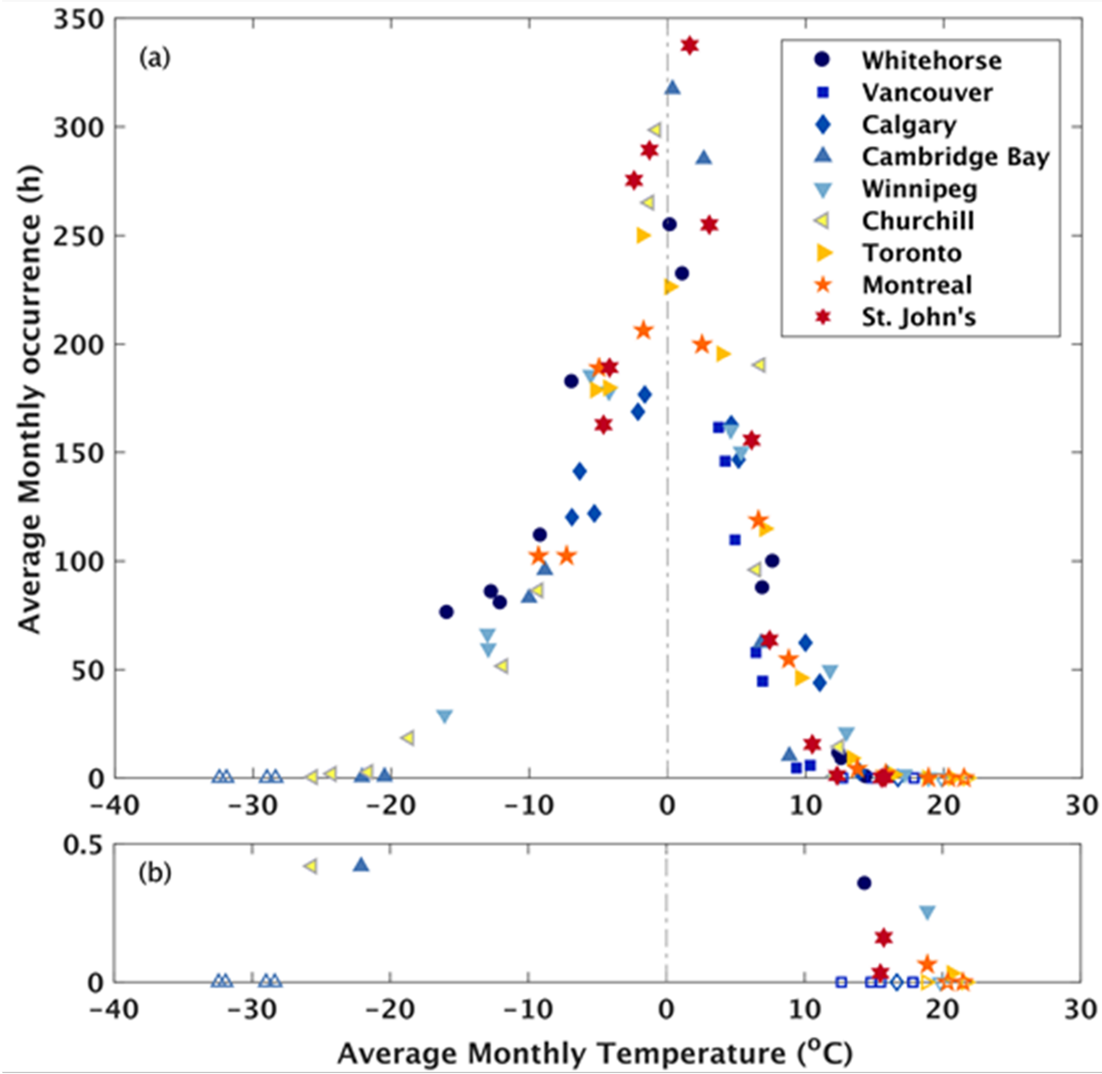
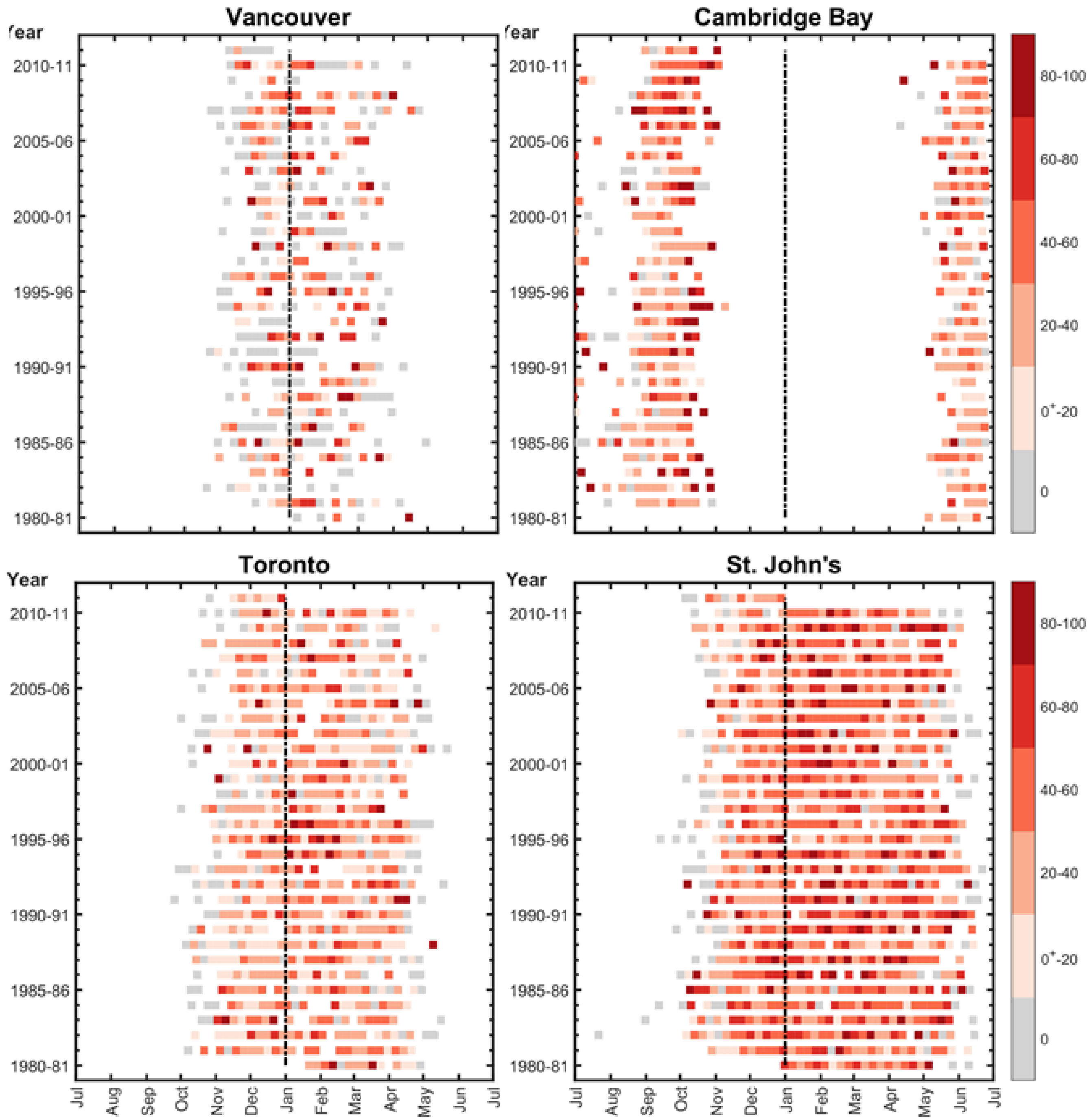


Figure 98: a) Average monthly occurrence (hours) of near 0°C conditions as a function of average monthly surface temperature for the nine ~~representative~~ selected stations over the 1981-2011 period. ~~The open diamond symbol indicates no occurrence.~~Filled symbols indicate occurrence and open or unfilled symbols indicate no occurrence. b) An expanded view to better illustrate low values of average monthly occurrence.


Vancouver
Cambridge Bay
Toronto
St. John's
Year
2010-11
2005-06
2000-01
1995-96
1990-91
1985-86
1980-81
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
80-100
60-80
40-60
20-40
0⁺-20
0

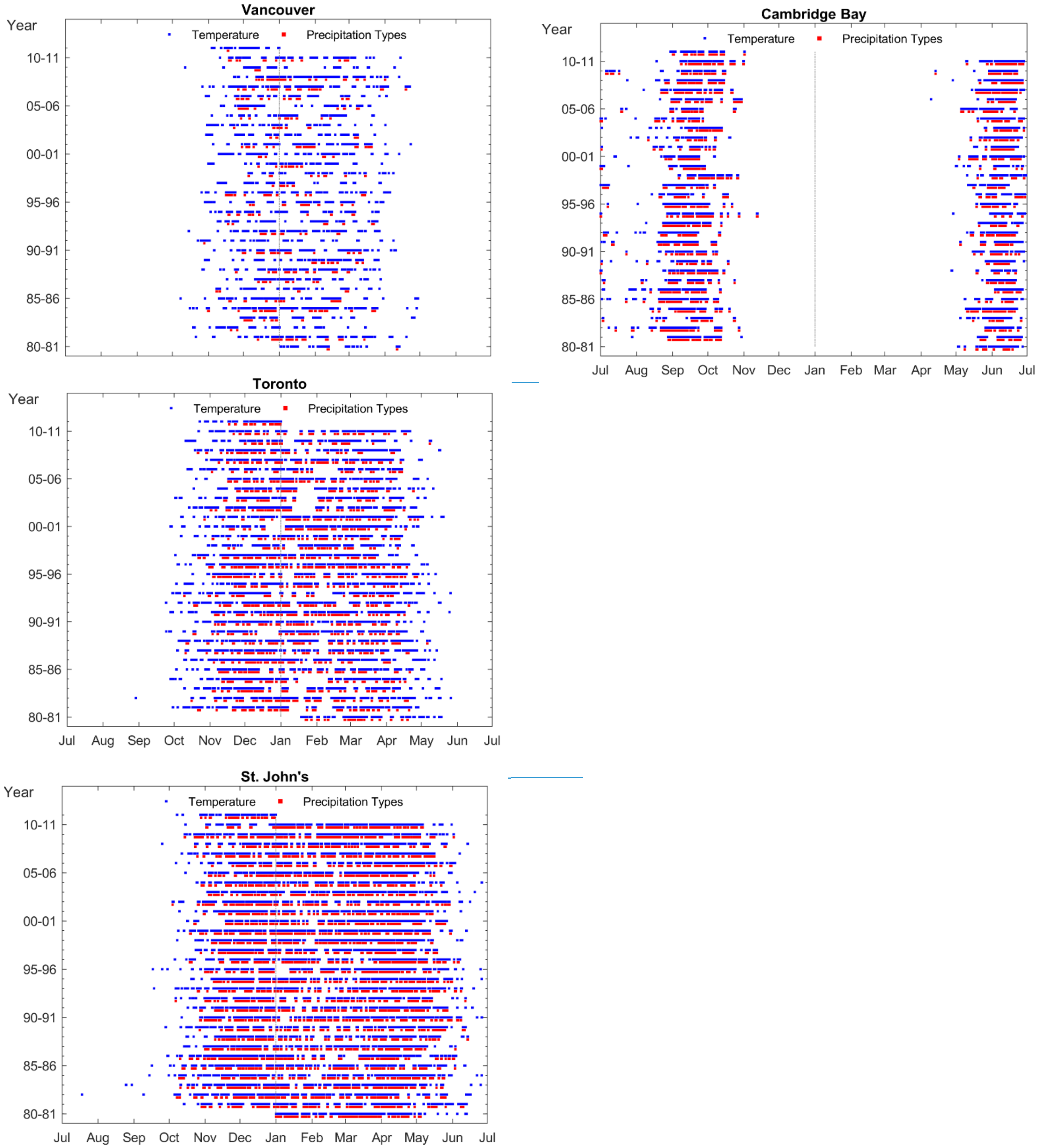


Figure 10~~9~~: The occurrence of near 0°C conditions and any (of the 12) associated precipitation types at (a) Vancouver, (b) Cambridge Bay (c) Toronto and (d) St. John's over the 1981-2011 period. Shading refers to the weekly fraction (%) of near 0°C hours with (or without) precipitation, the '0+ symbol' 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.~~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.~~

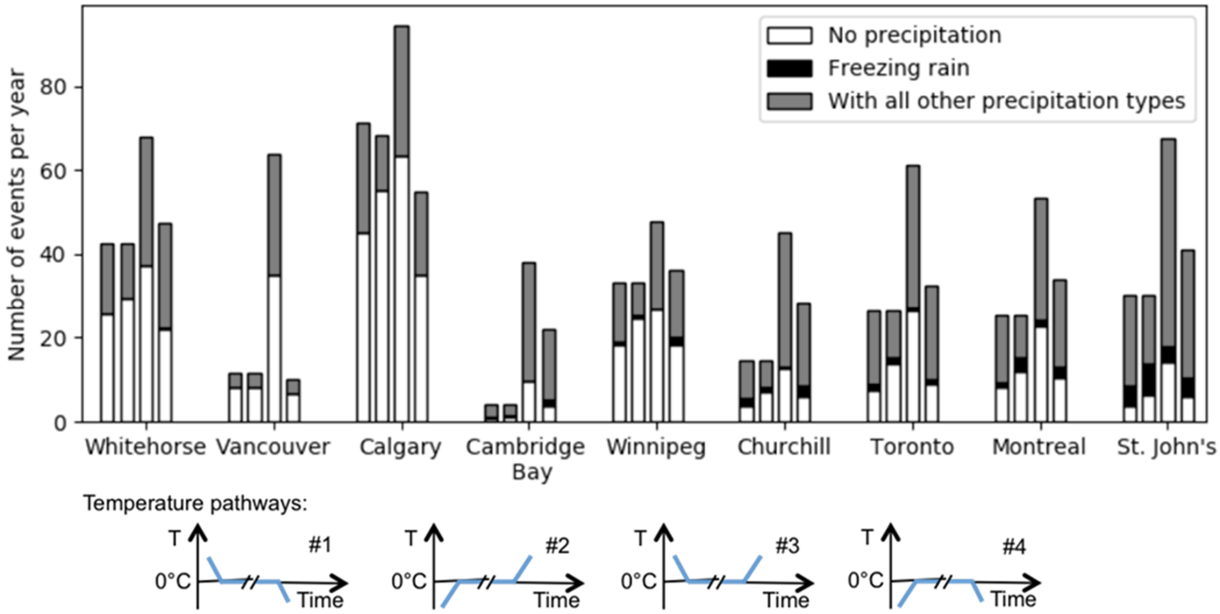


Figure 11: Average annual number of near 0°C events at the 9 selected stations organized by surface temperature pathways. The four pathways are shown schematically below the figure. They are represented by bars at each station from pathway 1 to 4 (left to right). No shading refers to the occurrence of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