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Exploratory Data Analysis of the Canadian River Ice Database Variables and their Correlations with Seasonal Temperature

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Environment and Climate Change Canada has recently published the Canadian River Ice Database (CRID), which incorporates a network of 196 National Hydrometric Program (NHP) stations throughout Canada that were in operation within the period 1894 to 2015. The CRID holds information on water levels, discharges and dates corresponding to the occurrence of freeze-up and winter-low events, midwinter break-up, ice thickness, spring breakup, and maximum open-water level. This paper presents an exploratory analysis, including homogeneity tests, basic statistics and trends in the magnitude and timing of the CRID variables at each hydrometric station. The study also carried out correlation analysis between seasonal temperature and selected river-ice variables. The homogeneity tests identified 45 stations with non-homogeneous water level time series that were removed from further analysis. Statistical analysis at the remaining 151 stations identified spatial and temporal variations in the magnitude and timing of CRID variables depending on the predominant climatic and geophysical characteristics of station locations. While some river-ice variables have similar trend direction at most of the stations, others show no trends or opposite trends at different part of the study domain. The most consistent result is the significant correlation between high seasonal temperature and delayed freeze-over, as well as earlier break-up and peak break-up water level timings. This broad scale exploratory data analysis is performed as a first step of more

comprehensive river-ice studies targeting specific variables and individual or groups of stations in the CRID that would include effects of more climatic drivers on the river ice regime across Canada.

1. Introduction

River ice is a common feature in the majority of Canadian rivers and streams during the cold season. Hamilton (2003) found that, despite bias in Water Survey of Canada's (WSC) hydrometric network towards open water conditions, ice-affected streamflow (identified by the 'B' flag) accounts for 18.7% of all the daily streamflow data in Canada until the year 2000 published by the WSC. The annual cycle of ice affected rivers includes the end of summer open-water season, followed by dropping seasonal temperature resulting in autumn freeze-up and ice cover formation that would continue under below freezing temperature. Subsequent increase in temperature above freezing and increased runoff would lead to mid-winter and/or spring break-up periods and back to the open water season. The prominent cold-season processes include the onset of ice conditions, development of a competent ice cover, potential for mid-winter break-up (MWB) events, under-ice winter minimum flow and water levels, and the initiation of spring break-up and ice jamming events (Hicks, 2008; Beltaos and Prowse, 2009). Advances in the study of river ice have largely been driven by observation and collection of field-based data at a specific site and season (e.g. Beltaos et al., 2006; Beltaos and Carter 2009). Following Allen's (1977) mapping of ice thickness on Canadian rivers, a national scale map showing the average start and end date of river ice conditions was published in the Hydrological Atlas of Canada (1978). Subsequently, Prowse and Onclin (1987) produced a Canadian map of river ice free timing and observed the orderly progression of breakup related to the warming effect of latitude and climate. However, most of the earlier analysis relied primarily on the timing of ice free conditions, with little information on other ice affected flow parameters. Subsequent studies (Beltaos et al., 2006; Bonsal et al., 2006; de Rham et al., 2008a&b; Goulding et al., 2009a&b; Lesack et al., 2013) have advanced river ice research by using archived records of water level time series to identify break-up chronology or peak break-up water levels at multiple locations covering wider regions in Canada. A Canada-wide analysis of trend in break-up water levels and their timing was also conducted using original water level records and digital data at 136 Water Survey of Canada hydrometric stations over 1969-2006 period (von de Wall et al., 2010). Chen and She (2020) examined temporal variations of breakup timing across Canada's terrestrial ecozones and within five major river basins for the period 1950 - 2016. Relationships with climatic drivers (including air temperature, snowfall, and rainfall) as well as elevation and anthropogenic activities were also examined. Brooks et al. (2013) has quantified freshwater ice thickness and volume at global scale indicating that national scale patterns of river ice timing and thickness are also observable at the global scale.

A more comprehensive analysis of river ice characteristics in Canada has generally been limited by a lack of readily available river ice data over a large spatial and temporal domain and covering the whole river ice season. This limitation has been partially lifted by the recently released Canadian River Ice Database (CRID) that has broadened earlier efforts and contains a wide range of river ice related information at a network of 196 National Hydrologic Program's (NHP) hydrometric stations across Canada (de Rham et al., 2020). The main objective of this study is to perform an exploratory statistical analysis on river ice related data in the CRID and examine the spatial and temporal variation in the different ice affected flow variables including water levels, discharges and their timings. Solvang (2013) noted that studies that report on trends in ice phenology often omit any discussion on the homogeneity of ice records. To address this important issue, we have conducted homogeneity tests on water level variables at each of the CRID stations and removed from further analysis those stations that were found to contain non-homogeneous time series. Based on the homogeneous time series, the study investigated trends in the magnitude and timing of the river ice variables over different time windows and assessed their spatial variations over the study domain. The study also examined linear correlations between the river ice variables and associated mean seasonal temperatures to identify any spatial and temporal patterns in their relationships.

2. Study Area and Data

While the NHP currently operates over 2,000 stations in Canada and a total of over 7,000 stations exist in its archive, the CRID only covers the subset of those stations that were in operation within the period 1894 to 2015 and met some specific selection criteria (de Rham et al., 2020b). The selected stations cover a wide range of basin areas and climate types as they are located in all jurisdictions in Canada except two Maritime Provinces and the Arctic Archipelago. Figure 1 shows the locations of the stations, station type and length of station operation. Around 60% of the stations operated for a period of more than 30 years, making the data suitable to examine baseline conditions and trends. Station types and operation status are distributed throughout the country with 150 stations on unregulated rivers and 46 stations on a regulated river system. Basin area for these stations ranges between 20.4 km^2 and 1.68M km^2. The CRID holds information on water level, discharge and timing of up to 15 ice affected variables covering 10,378 station years of active operation (see Figure 2 and Table 1). While most of the variables represent daily or instantaneous water levels, discharges, dates and time corresponding to major ice-related events/processes occurring between the First and Last B dates, CRID also contains variables corresponding to annual maximum open water level for comparison.

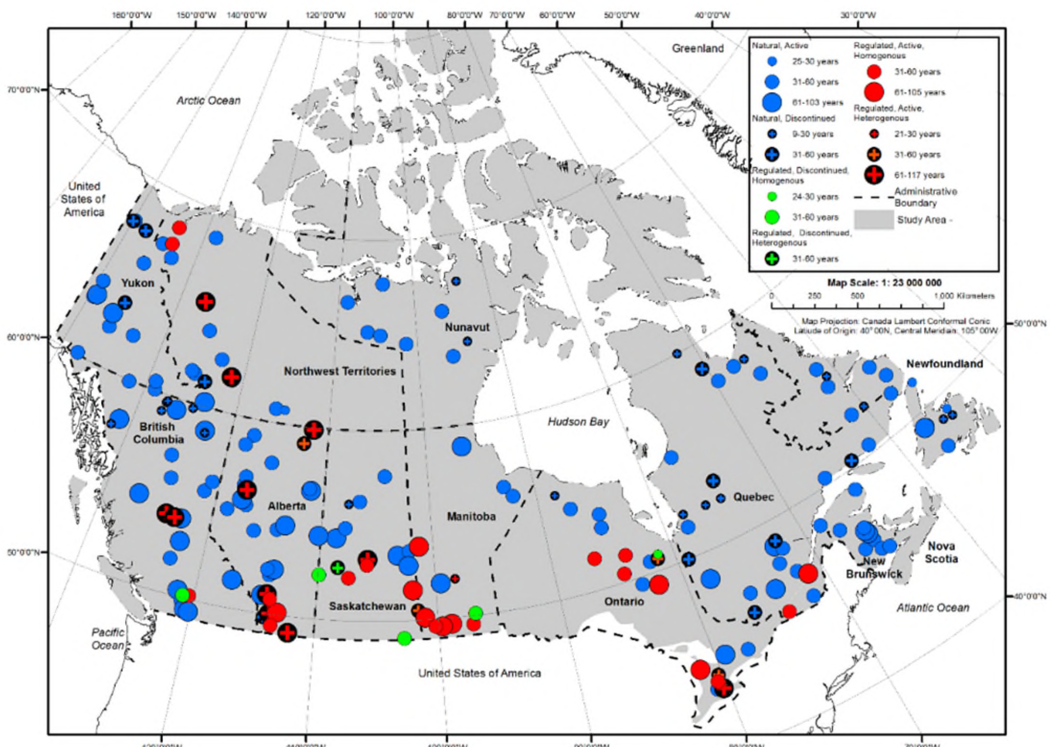


Figure 1: The 196 NHP gauging locations from the CRID used in this study. The stations are classified into six types based on flow regime (Natural or Regulated), operational status (Active or Discontinued) and period of regulation (Homogeneous or Heterogeneous). Symbols are scaled to length of available flow record by: up to 30 years, 31 to 60 years and over 60 years.

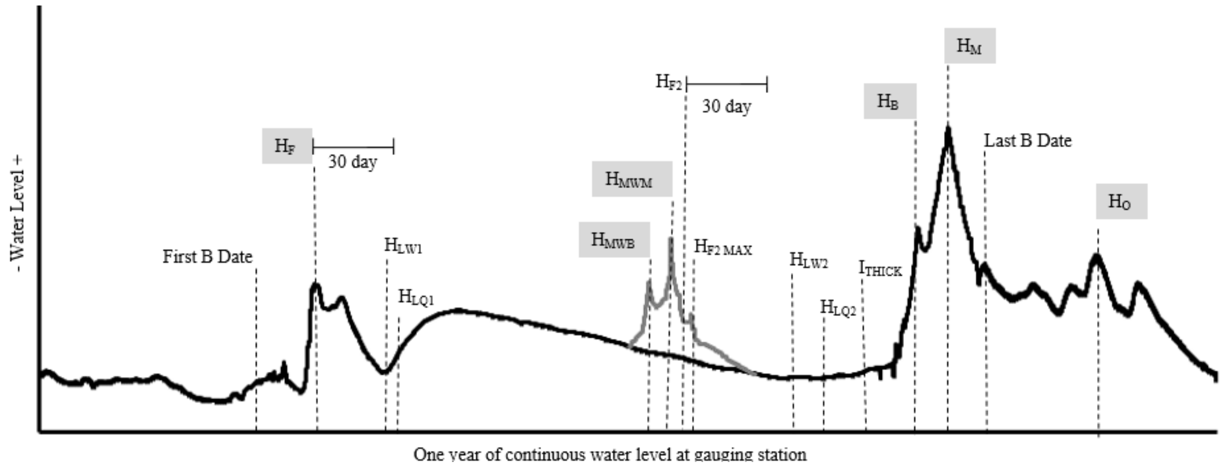


Figure 2. Conceptual schematic of continuous river water level hydrograph over a water year spanning September to August (black line). Period of ice affected flow is constrained by First and Last B Dates. Possible Mid-Winter Breakup (MWB) event shown as grey line. Symbols for the 15 ice related variables in the CRID are shown in the figure (see Table 1 for additional information; source de Rham et al., 2020).

Table 1. The river ice related variables in the CRID along with their symbols and description. The exploratory analysis in this study is performed on the water level, discharge and timing data associated with each of these variables (source de Rham et al., 2020).

Season	**Variable**	**Symbol**	**Description**
Freeze-up	First Day With Backwater Due To Ice	First B Date	First day that ice affects channel flow conditions
Freeze-up	First Freeze-Over Water Level	H_F	Channel wide ice cover; daily water level at H_F and following 29 days
Ice cover	First Minimum Winter Water Level	H_{LW1}	Minimum daily water level between H_F and H_B
Ice cover	First Minimum Winter Discharge	H_{LQ1}	Minimum daily discharge between H_F and H_B
Ice cover	Mid-Winter Break-Up Initiation	H_{MWB}	Initiation of mid-winter break-up event
Ice cover	Maximum Mid-Winter Break-Up Water Level	H_{MWM}	Maximum mid-winter break-up event water level
Ice cover	Maximum Winter Water Level	H_{F2}	Freeze-up after H_{MWM}. If no Mid-winter event, first day of 7 day average if exceeds H_F 7 day average
Ice cover	Maximum Winter Water Level 7 Day	$H_{F2\ MAX}$	Maximum daily water level within first 7 days following H_{F2}
Ice cover	Second MinumumWinter Water Level	H_{LW2}	Minimum daily water level between H_{F2} and H_B if H_{LW1} before H_{F2}
Ice cover	Second Minimum Winter Discharge	H_{LQ2}	Minimum daily discharge between H_{F2} and H_B if H_{LQ1} before H_{F2}
Ice cover	River Ice Thickness	I_{THICK}	Average channel ice thickness prior to spring break up
Break-up	Spring Break-Up Initiation	H_B	Beginining of spring break up event
Break-up	Maximum Spring Break -Up Water Level	H_M	Maximum spring break-up water level event
Break-up	Last Day With Backwater Due To Ice	Last B Date	Final day that ice affects channel flow conditions
Open-Water	Maximum Open-Water Level	H_O	Maximum water level occuring outside First B date to Last B date

3. Methodology

3.1 Testing homogeneity in river ice variables

The river ice variables in the CRID are derived from continuous, discrete or daily water level and discharge records at each of the hydrometric stations identified for the database. However, there are various circumstances during each station's operational history, such as change in station location, change in reference (geodetic) datum, change in stage-discharge relationship (morphological changes), change in measuring techniques (devices and technology), or the installation of regulating structures that can affect the homogeneity of the measured water level time series (de Rham et al., 2020a). Since river ice processes are highly site specific, it is important to identify such inconsistency or non-homogeneity present in the time series prior to performing any statistical analysis on river ice related variables. One approach, which is often referred to as a 'direct method' (Peterson et al. 1998), is to perform an exhaustive review of all available metadata information (in paper or digital archival documents) as presented by de Rham et al. (2021) in a companion paper in these conference proceedings. While reviewing metadata information to identify non-homogeneities in the time series may be more appropriate, it is also very time consuming and depends on the completeness of the archived metadata. The second option, and the one employed for this analysis, is to conduct statistical tests of homogeneity to identify any step change/s in the time series that may be attributable to one of the possible causes described above. These two approaches are also complementary and an iterative evaluation using both would enhance the identification process even further (Karl and Williams, 1987). Since river ice event dates and corresponding discharges may not be significantly affected by external intervention, such as station movement or datum change, the homogeneity tests were performed only on the water-level time series that are directly affected by such interventions.

Statistical techniques to reveal non-homogeneity have received attention for many years in the hydrological (e.g. Dahmen and Hall, 1990) and atmospheric (e.g. Vincent, 1998) literature. There are several techniques to perform homogeneity tests on a time series by checking if two (or more) datasets come from the same distribution by detecting the presence of one or more breakpoint/s. There are limited studies on the detection of homogeneity in river ice variables; nevertheless, methods used for other hydro-meteorological variables are likely applicable for river ice time series (Solvang, 2013). Since each method has its pros and cons, multiple tests are usually preferred for achieving robust result. Therefore, this study applied the following six commonly used statistical methods from the Python package *pyhomogeneity* (Shourov, 2020; Pohlert, T., 2020): Pettitt test (Pettitt, 1979), Standard Normal Homogeinity Test (SNHT) (Alexandersson, 1986), Buishand Q Test, Buishand's Range Test, Buishand's Likelihood Ration Test and Buishand U Test (Buishand, 1982). At every CRID station, each testing method was applied independently to each river ice variable related water level time series. Non-homogeneities of the time series were tested at $p = 0.05$ (5%) and $p = 0.1$ (10%) significance level. The final decision on whether the river ice data at a station is homogeneous was determined by calculating the percentage of significant test results across all test method/variable pairs and comparing it with a predefined threshold value for classification. Different thresholds of homogeneity test results (40%, 50% and 60%) were examined for classifying stations as homogeneous or non-homogeneous, and results are verified based on visual inspection of water level time series plots and known gauge history.

3.2 Basic Statistics and Trend Analysis

Basic statistics (min, max, mean, range, standard deviation) were calculated for each river ice variable, including event dates, water levels and discharges at each of the CRID stations that were identified to have homogeneous time series. Since data availability over the whole historical period varies with time, the statistics were calculated over 1985-2015 and 1965-2015 windows. While the short and most recent time window includes the largest number of stations and provides good spatial coverage, the longer window provides longer time series, albeit with relatively fewer stations and less spatial coverage. For each variable over each time window, basic statistics were calculated when at least 2/3 of the data in the selected window are available, and results are presented in summary tables and contour plots.

The non-parametric Mann–Kendall (MK) trend analysis was also applied to river ice variables at each station (Kendall, 1975, Hirsch and Slack, 1984). As a non-parametric test, MK bases the test statistics entirely on rank order of the data rather than actual data values, hence does not assume that data follow a normal distribution (Hamed, 2008). The trend test is performed for each time window only when the variable satisfies the 2/3 data availability criteria (Duguay et el., 2006). The Python package *pyMannKendall* (Shourov, 2020) is used for the analysis and a t- statistics is applied to determine trend significance at the 5% (p = 0.05) and at the 10% (p=0.1) levels.

3.3 Correlations with seasonal temperature

This analysis used seasonal temperature as a potential climatic driver affecting the magnitude and timing of river ice variables similar to previous studies (Prowse at al. 2007). The Natural Resources Canada (NRCan)'s gridded observational data set (NRCANmet; Hopkinson et al., 2011), which is at 10 km resolution, and ECCC's Adjusted and Homogenized Canadian Climate Data (AHCCD; Vincent et al, 2012), which is station based, were considered as a source of climate data. However, most of the CRID station were often at a great distance from any of the AHCCD stations with sufficient data in the required period for the analysis. Therefore, for each station, air temperature data were extracted from the closest NRCANmet grid point and mean seasonal temperatures for the different time windows were calculated as shown in Table 2.

Table 2. The different seasonal windows used for averaging air temperature in the correlation analysis.

Seasons	**Months in the Season**
Autumn	September-November
Winter	December-February
Spring	March-May
Summer	June-August
Autumn+Winter	September-February
Winter+Spring	December-May
Spring+Summer	March-August

Pearson correlation was conducted between each river ice variable and the corresponding mean seasonal temperature using the *Statsmodels* python package (Seabold and Perktold, 2010). Each river-ice variable was correlated with mean seasonal temperature occurring in the same or earlier seasons of the water year. Pearson correlation coefficient (Pearson's r) measures the linear correlation between the two and the results have values between −1 and 1. The significance of each correlation was also tested using t-statistics at p=0.05 (5%) and p=0.1 (10%) levels.

4. Results and Discussion

4.1 Homogeneity of the river ice data

Threshold values of 40%, 50% and 60% non-homogeneity resulted in 65, 50, and 45 stations, respectively, to be classified as non-homogeneous (out of the 196 stations). Visual inspection of water level time series plots at each of the CRID stations indicates that the 60% non-homogeneity threshold included almost all of the stations with identifiable step changes and/or discontinuities in their water level time series. Therefore, a 60% threshold value was adopted and the corresponding 45 stations were classified as non-homogeneous (Figure 3). There are possibilities to adjust or truncate and rectify the time series at a non-homogeneous station based on metadata information. However, for this preliminary analysis, it was decided to remove the 45 non-homogeneous stations (22% of the CRID stations) and only use the remaining 151 stations (24 regulated and 127 unregulated) that are reasonably distributed throughout the study region for trend and correlation analysis.

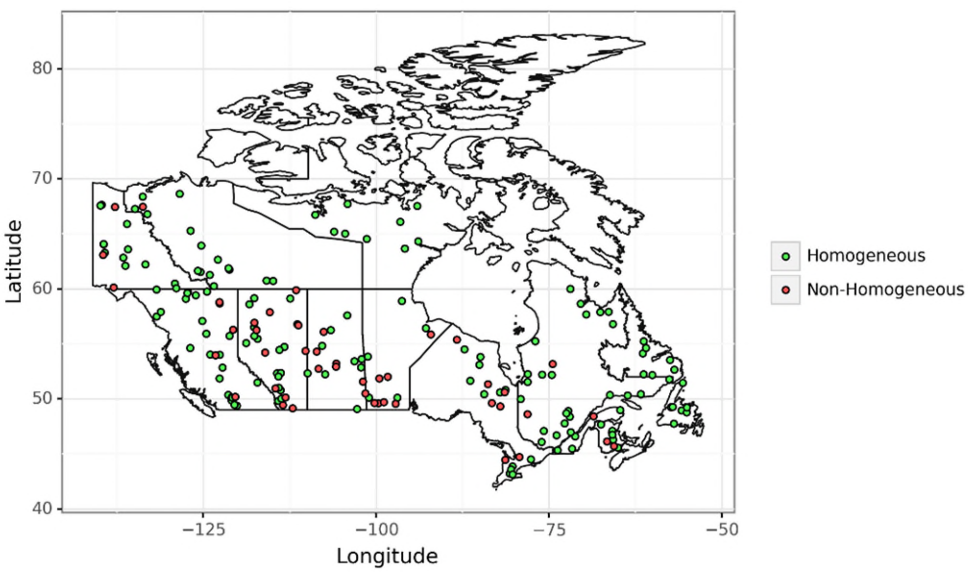


Figure 3. CRID station classification into homogeneous and non-homogeneous time series of ice related water levels based on the 60% non-homogeneity threshold.

4.2 Spatial variations in river ice variables

Figure 4 presents contour maps of the annual mean values for a select river ice variables showing their regional variations across Canada. The mean freeze-over date (H_F) varies from mid-October in the northwest to end of December in the southeast. On the other hand, the mean break-up date (H_B) varied from the end of February in the southwest to the end of May in the central north. This has resulted in the mean ice cover duration to vary between two and half months in the southeast to seven months in the northwestern part of Canada, although, at stations with frequent mid-winter breakups, these values may not necessarily reflect the number of days with continuous ice cover. The mean river ice thickness (I_{THICK}) prior to break-up also varied between 0.45 m in the south to

1.5 m in the northern part of Canada. However, these ice thickness values are based on end of ice cover season measurements and may not necessarily represent the annual maximum ice thickness since operational and safety consideration determine when measurements are taken at each site. Besides, prior to ~1995, measurements were generally limited to water surface elevation to bottom of ice cover and thus may underestimate the actual thickness of the ice cover as the specific gravity of river ice is commonly taken as 0.92. Since the timing and magnitude of river ice variables at individual stations depend on local geophysical characteristics, these contour plots only represent the broad spatial patterns, rather than actual measured values at specific location.

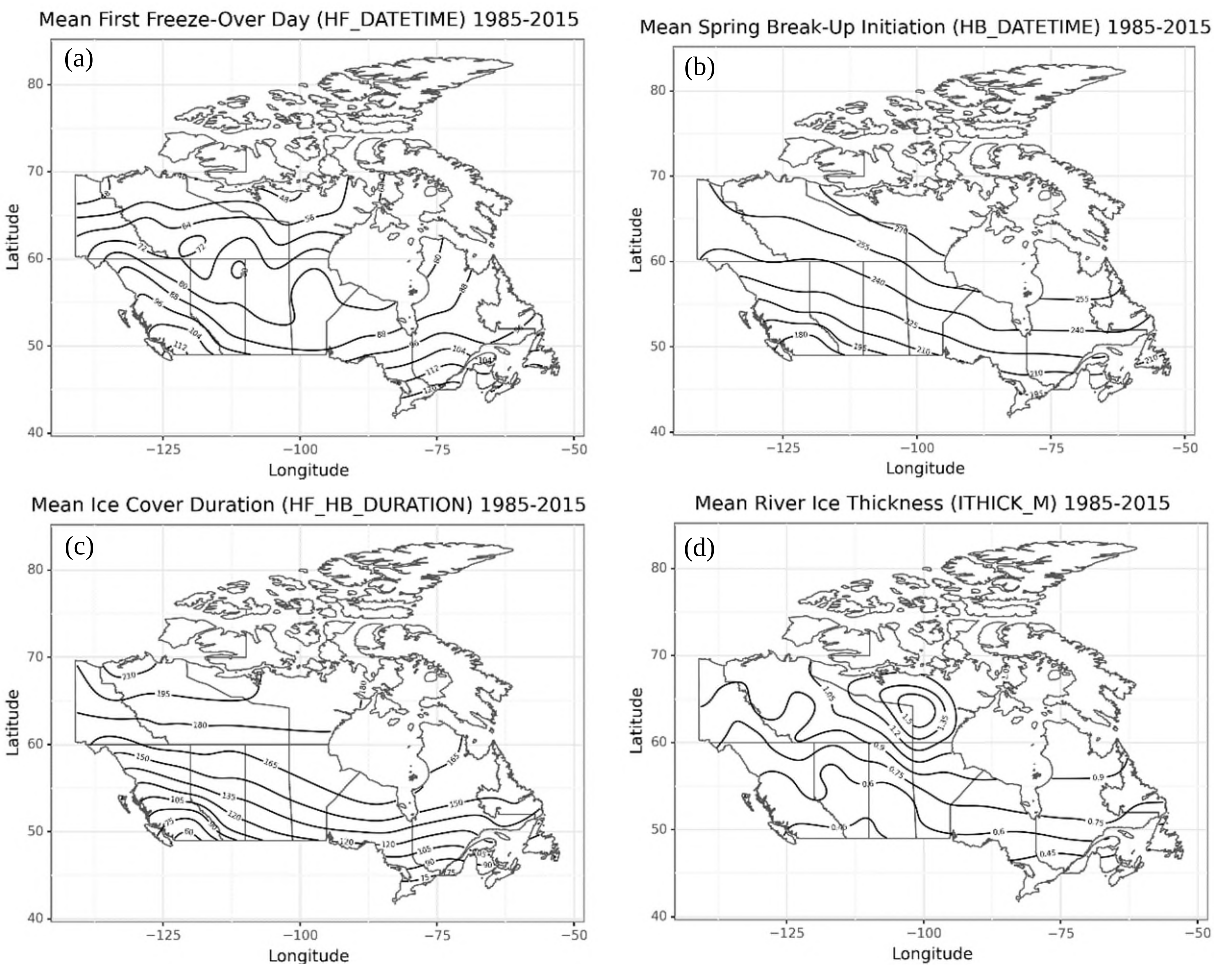
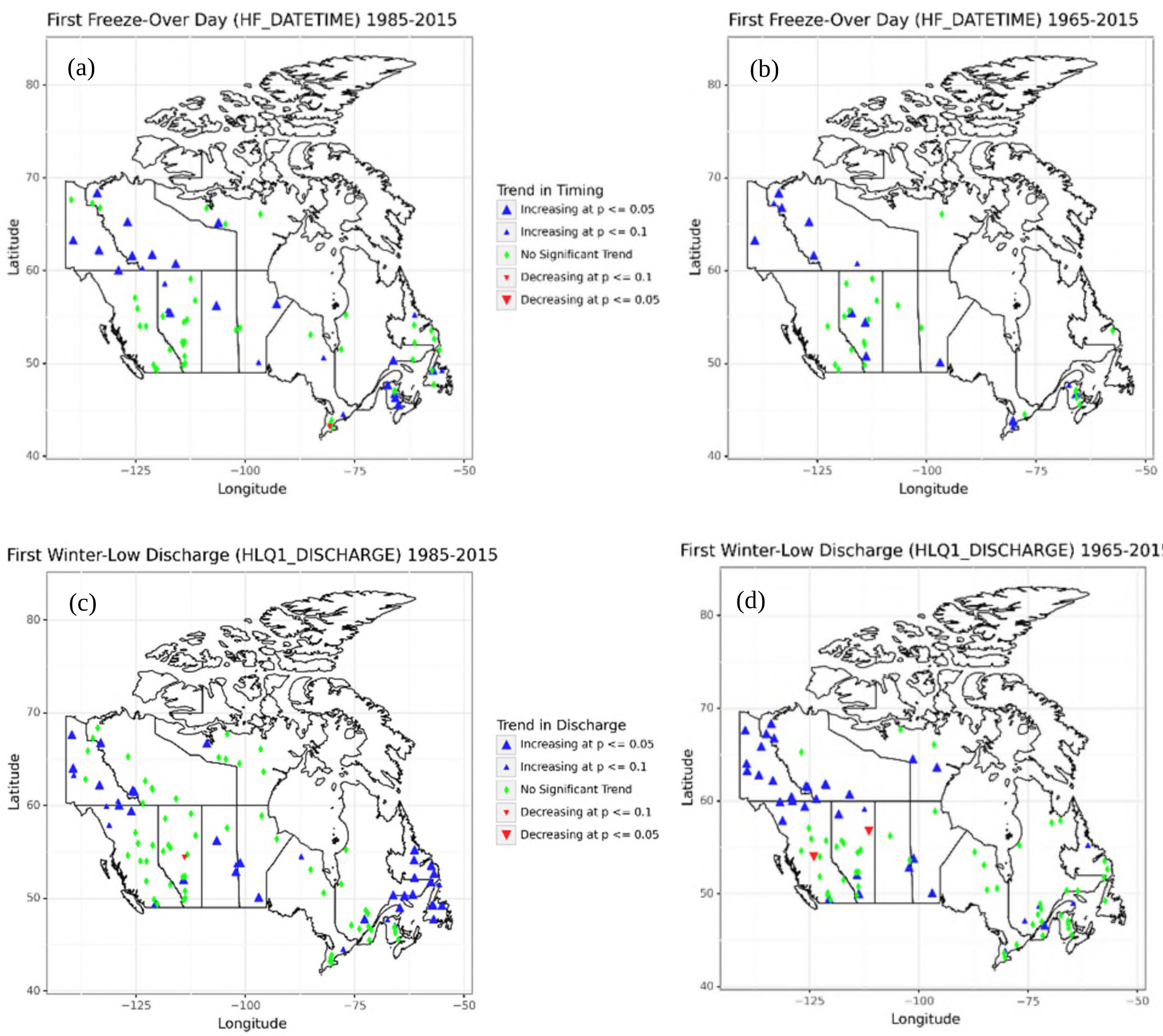


Figure 4. Isochrones of mean (a) date of freeze-over (b) date of spring break-up (c) ice-cover duration and (d) maximum river ice thickness, averaged over the 1985-2015 window, showing regional variations across Canada (date counting for (a) and (b) starting on September 1st).

4.3 Trends in river ice variables

The results of trend analyses for those variables where significant trends have been found at a large number of stations is presented in Figure 5 while the number of stations with significantly increasing or decreasing trends over the 1985-2015 and 1965-2015 time windows are summarized in Figure 6. Figures 5a & 5b indicate that the first freeze-over day is being delayed in several stations, especially in the northwestern region of Canada, including the Yukon and Northwest Territories, and the eastern maritime provinces. More stations (26) are showing this trend in the most recent (1985-2015) than the longer (1965-2015) time window (16). Similarly, the winter low flows (minimum discharge under stable ice cover) at several stations (Figures 5c & 5d) have also shown increasing trends over the most recent time window (40) while fewer stations located in the northwestern part of Canada show this trend over the longer time window (36). Figure 5f shows significant trends towards earlier spring breakup initiation at several stations (15) over the 1965-2015 time window. However, similar trends are identified at only two stations over the 1985-2015 time window (Figure 5e) and even some stations (6) show the opposite trend. The maximum spring breakup water levels (Figures 5g & 5h) show more significantly decreasing trends (11) than increasing ones (4) over the longer time window while over the shorter time window, results indicate both increasing (12) and decreasing (9) trends at few stations in different parts of the study region.



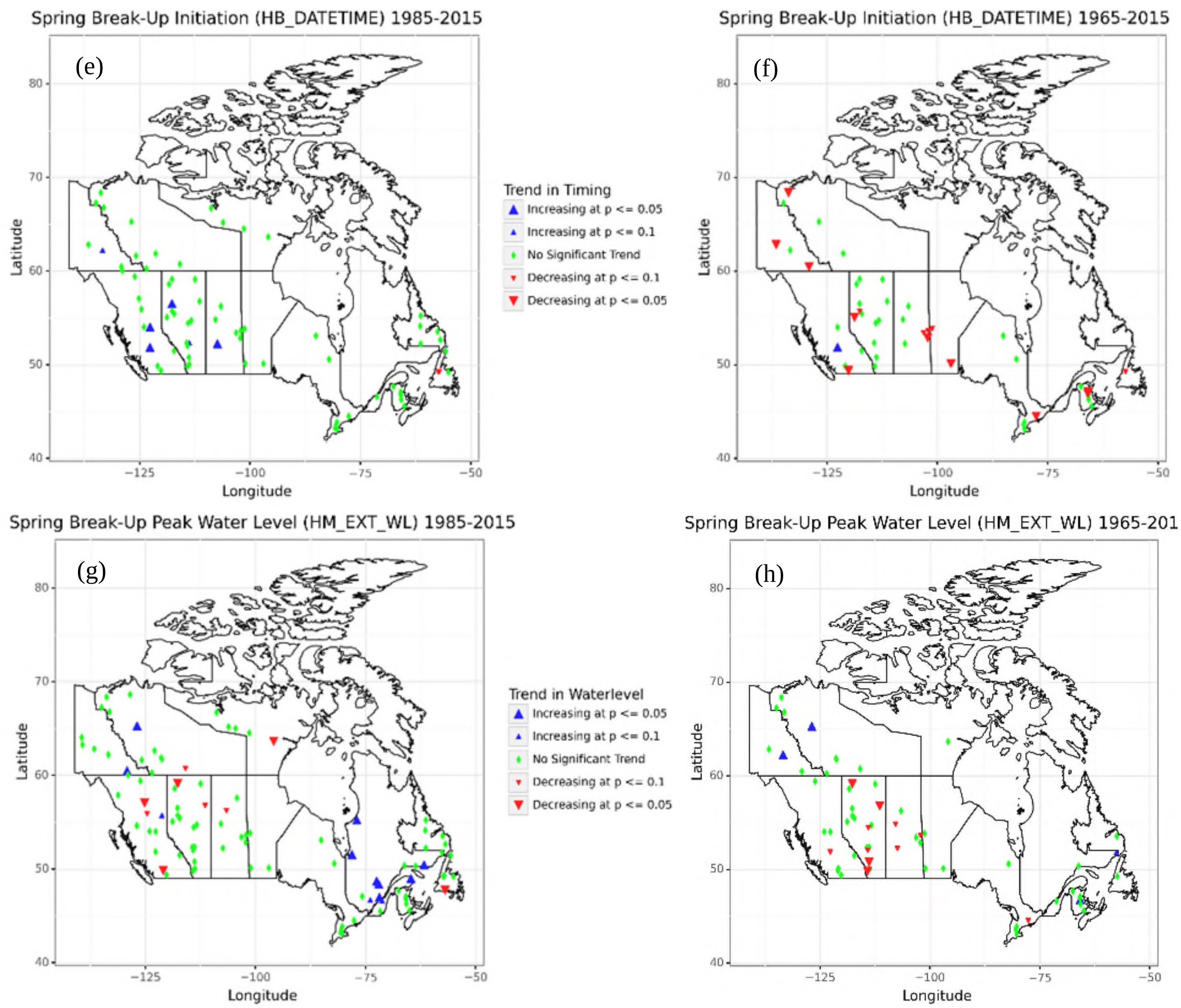


Figure 5. The Mann–Kendall trends across Canada for selected variables over the 1985-2015 (left column) and 1965-2015 (right column) time windows.

The summary presented in Figure 6a and 6b shows that, in addition to those presented in Figure 5, freeze-over water levels (H_F_wl) as well as discharges during maximum spring breakup (H_M_discharge) and open water levels (H_O_discharge) show more stations with significantly increasing than decreasing trends over the 1985-2015 window. However, for most variables, the number of stations with non-significant or no trends are much more that those with significant increasing or decreasing trends over both time windows. Figure 6 also reveals that for almost half of the river ice variables, only few (or no) stations have sufficient data within either time windows to perform trend analysis.

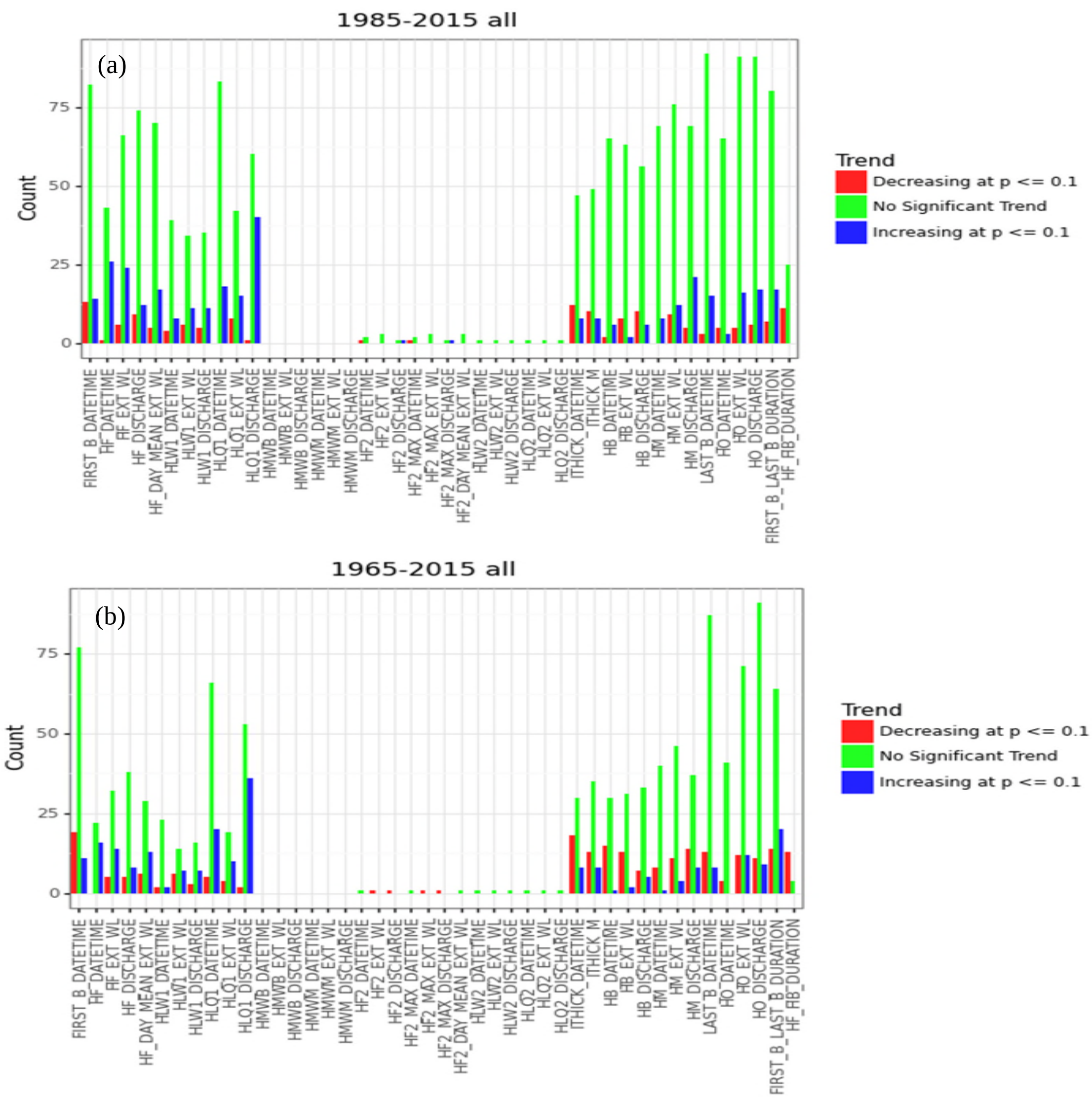


Figure 6. Summary plots for the number of stations with significantly increasing, decreasing or no trends at p<=0.1 for each CRID variable over (a) the 1985-2015 and (b) 1965-2015 time widows.

4.4 Correlations between mean seasonal temperature and river ice variables

The correlations between dates of selected river ice variables and mean seasonal temperatures over the 1985-2015 and 1965-2015 time windows are presented in Figure 7. The first freeze-over dates are significantly correlated with mean autumn temperature at 92/151 and 96/151 stations over the two time windows respectively (Figures 7a & 7b). The dates of break-up and peak break-up water levels are also significantly inversely correlated with the spring temperature at 116/151 and 120/151 stations over the 1985-2015 time windows and 124/151 and 126/151 stations over the 1965-2015 time windows, respectively (Figures 7c to 7f). These results indicate that delayed freeze-over dates and advanced break-up and peak break-up water level dates are highly correlated with the mean autumn and spring temperatures respectively at the majority of the stations. Temperature-phenology correlations are in general agreement with results reported by Chen and She (2020).

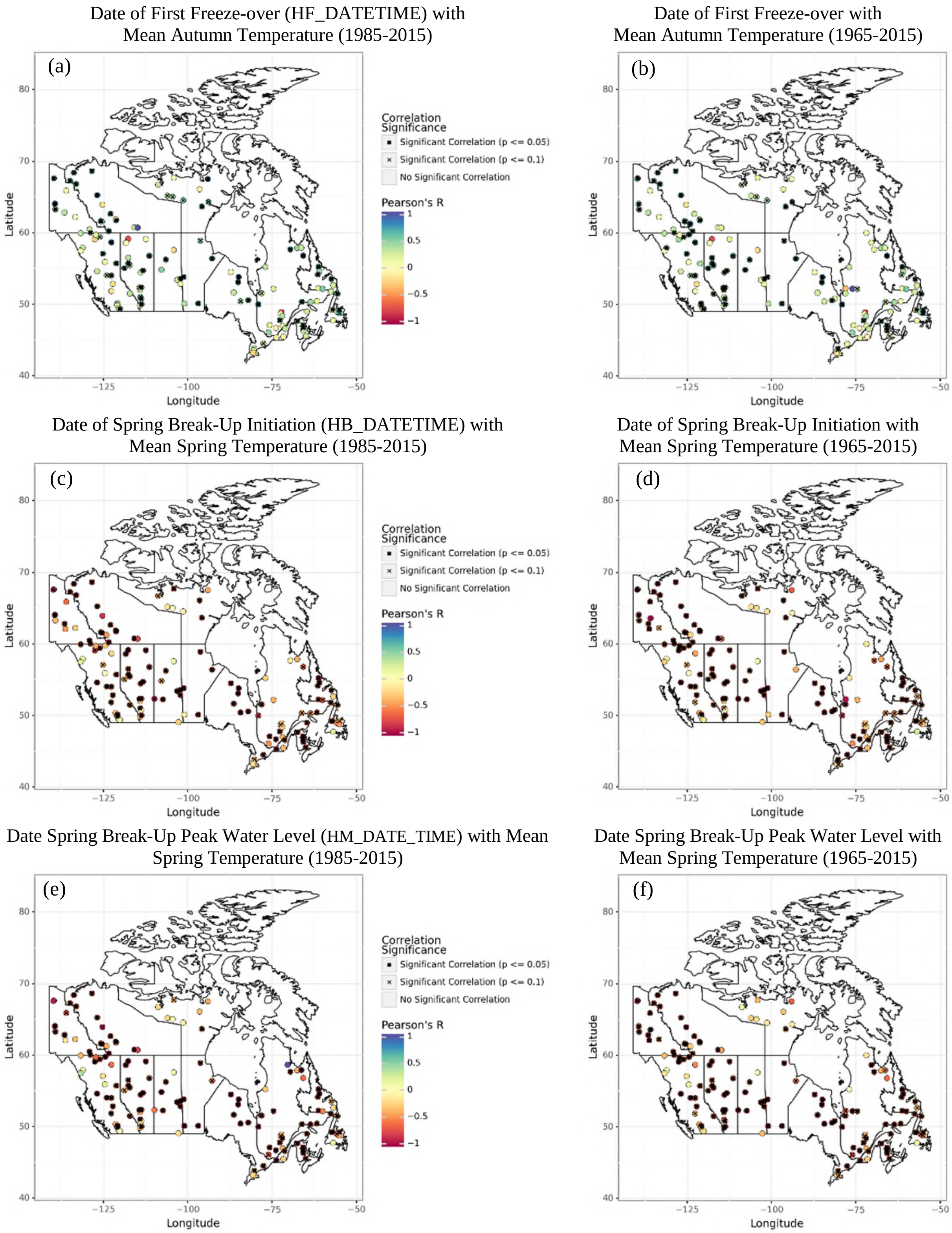


Figure 7. Correlations between selected river-ice event timing variables and mean seasonal temperatures at each of the CRID stations over the 1985-2015 (left column) and 1965-2015 (right column) time windows.

Figure 8 summarizes the proportion of significantly correlated stations, over the 1965-2015 period, corresponding to each mean seasonal temperature and CRID variable combination. The results indicate that seasonal temperature is significantly correlated with the dates (or timing) of river ice variables at a larger number of stations than the corresponding water levels or discharges. This may be because temperature is the main driver of phase change, hence event timings, while other hydroclimatic factors, including seasonal precipitation, affect water levels and discharges. Nevertheless, seasonal temperature is also significantly correlated with water level and discharge variables associated with spring break-up (H_B), spring break-up peak (H_M) and maximum open water levels (H_o) as well as river ice thickness at up to one third of the stations. However, only few stations with mid-winter breakup events are significantly correlated with seasonal temperature. This may be because MWB events are usually triggered by temperature spike above freezing and associated rain on snow events over a relatively shorter time periods (days/week(s)) that are likely not captured in seasonal mean values (Newton et al., 2017).

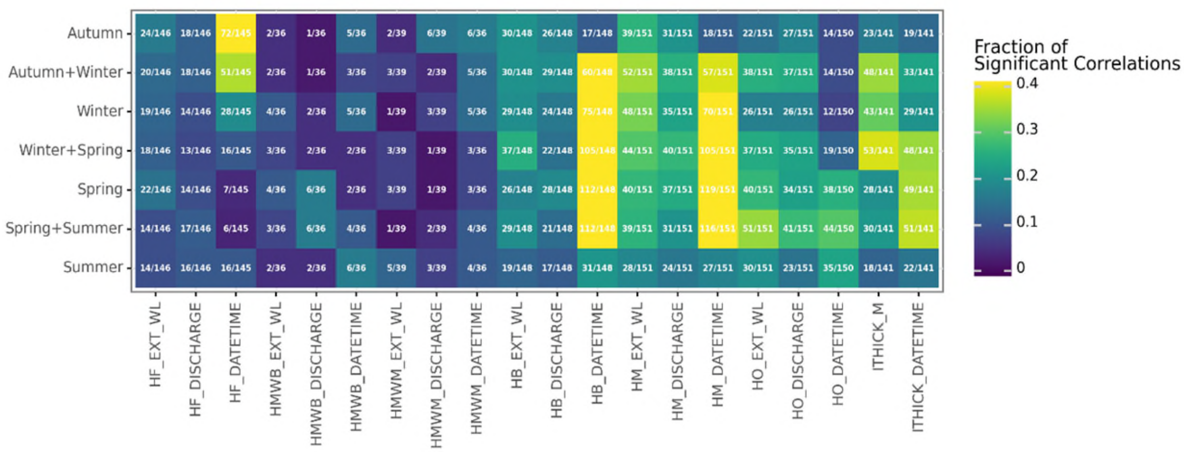


Figure 8. Summary of correlation analysis results over the 1965-2015 period showing the fraction of stations with significant correlation (at p=0.1) corresponding to each mean seasonal temperature and CRID variable pair.

5. Summary and Conclusions

The CRID includes time series data on water levels, discharges and dates corresponding to prominent cold season processes and associated events in selected Canadian rivers. This paper presented the results of an exploratory statistical analysis that examined the spatial and temporal variation in the different CRID variables and their correlations with mean seasonal temperature. Multiple statistical tests were conducted on the water level time series at each of the CRID stations to detect non-homogeneities likely resulting from such factors as changes in station location, reference datum, river morphology, etc. Applying the 60% significant threshold for non-homogeneity across all test methods/variable pairs, 45 out of 196 stations were classified as non-homogeneous. While adjusting and rectifying the time series at the non-homogeneous stations may be possible using metadata information, this task requires a good site-specific knowledge and process understanding in its implementation. Therefore, the exploratory analysis was conducted using the data from the 151 stations which, excluding the Arctic Archipelagos, have a good spatial coverage across Canada. The results indicated that the river ice season over the Canadian continental mainland spans the period between early October and end of May while the mean ice cover duration varies from two and a half months in the southeast to over seven months in the northwestern part of Canadian. The average river ice thickness, prior to break-up, also varies between 0.45 m in the south to 1.5 m in the northern part of Canada. Although the general spatial pattern across Canada corresponds with that reported by Allen (1977), the ice thickness values in the present study may not necessarily represent the annual maximum ice thickness due to limits in the timing of site visits for operational and safety considerations.

Delayed first freeze-over day, increasing winter low flows and earlier spring breakup initiation are some of the prominent trends identified in this study. The maximum spring breakup water levels also show more decreasing trends that increasing over the longer time window indicating the possibility of more thermal (rather than dynamic) breakups with a warming climate. This result corresponds with that of Smith (2000) who observed (in Russian Arctic Rivers) trend towards a longer period of pre-break-up melt that would tend to favor less severe, thermal break-ups. Freeze-over water levels (H_F_wl), maximum spring breakup discharge (H_M_discharge) and maximum open water levels (H_O_wl) have also shown more significantly increasing than decreasing stations over the 1985-2015 window, possibly a consequence of an overall increase in precipitation over the most recent period. However, the analysis also revealed that for most variables, the number of stations with non-significant trends is much greater than the number of those with significant increasing or decreasing trends over both time windows considered. This may be an indication that either those variables are not affected by the changing climate or the change signal to variability ratios for those variables are not big enough for the trends to be significant. The study also found the first freeze-over dates to be significantly correlated with mean autumn temperature at the majority of the stations while the dates of break-up and peak break-up water levels are inversely correlated with the spring temperature at most of the stations.

6. Future Research

This broad scale exploratory data analysis of the CRID was performed to examine the spatial and temporal variation in some of ice affected flow variables across Canada. The simple correlation analysis revealed potential relationships between mean seasonal temperature and some of the river ice variables. While the first step in this study was to identify the issue of non-homogeneity in the CRID using statistical tests, future studies will look into validating these results with the findings of metadata analysis (de Rham et al., 2021). Some of the river ice variables explored in this study (e.g. timing of First Freeze-Over (H_F), magnitude of First Minimum Winter Discharge (H_{LQ1}), mean Ice Cover Duration (H_B-H_F)) have never been assessed before at this pan-Canadian scale. However, to get a more complete picture of river ice regimes across Canada, additional analysis using other climatic drivers (such as seasonal precipitation) and temperature indices (such as autumn and spring zero-degree isotherm dates) will be conducted. Climatic controls of river ice variables will also be investigated further using Multiple Linear Regression (MLR) techniques with seasonal temperature, precipitation and other relevant climatic indices as potential predictors. This quality controlled river ice database can be used to calibrate/validate river-ice models that can project climate change impact on river ice characteristics across Canada. Future studies may also target specific variables and individual or groups of stations in the CRID for a more in-depth process understanding of the underlying mechanisms.

7. Acknowledgments

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