Summary and Synthesis of Changing Cold Regions Network (CCRN) Research in the Interior of Western Canada: Part I – Projected Climate and Meteorology

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Abstract. The Interior of Western Canada, up to and including the Arctic, has experienced rapid change in its climate, hydrology, cryosphere and ecosystems and this is expected to continue. Although there is general consensus that warming will occur in the future, many critical issues remain. In this first of two articles, attention is placed on atmospheric-related issues that range from large scales down to individual precipitation events. Each of these is considered in terms of expected change organized by season and utilizing mainly "business as usual" climate scenario information. Large scale atmospheric circulations affecting this region are projected to shift differently in each season with conditions that are conducive to the development of hydroclimate extremes in the domain becoming substantially more intense and frequent after mid-century. When coupled with warming temperatures, changes in the large scale atmospheric drivers lead to enhancements of numerous water-related and temperature-related extremes. These include winter snowstorms, freezing rain, drought, forest fires as well as atmospheric forcing of spring floods although not necessarily summer convection. Collective insights of these atmospheric findings are summarized in a consistent, connected physical framework.

1 Motivation and objective

Climate and its changes are having huge impacts everywhere. A particular 'hotspot' in Canada in terms of recent temperature changes and projections of continuation is the central part of western Canada and its extension to the Arctic Ocean (DeBeer et al., 2016). Although there is widespread consensus that warming will continue, there is considerable uncertainty in its magnitude and distribution in time and space. There is even greater uncertainty in terms of precipitation although it is very likely that there will be less snow and more rain, and the north will become wetter (Bush and Lemmen, 2019).

All of these changes will likely have a huge impact on water resources, cryosphere and ecosystems. In terms of hydrology, this includes the amount of water as well as the timing of its peak flow; in terms of the cryosphere, this includes the fate of numerous glaciers, regions of permafrost and the duration and amount of snow; in terms of ecosystems, this includes movement of grasslands, tundra, shrubs and boreal forests (Bush and Lemmen, 2019).

These critical issues have been the motivation for substantial climate-related research within the central part of western Canada. Much of this was organized within collaborative multi-year projects. The first was the Mackenzie GEWEX Study (MAGS), under the auspices of the Global Energy and Water Exchanges (GEWEX) project of the World Climate Research Programme, that brought together atmospheric and hydrological researchers to examine the cycling of water within the Mackenzie River basin (Stewart et al., 1998; Woo et al., 2008). This was followed by, for example, the Drought Research Initiative (DRI) that examined atmospheric, hydrologic and land surface processes associated with a devastating 1999-2005 drought across the Canadian Prairies (Stewart et al., 2011; Hanesiak et al., 2011). In parallel, the Western Canadian Cryospheric Network (WC2N; http://wc2n.unbc.ca) and the Improved Processes and Parameterization for Prediction in Cold Regions Hydrology Network (IP3; www.usask.ca/ip3) examined hydrologic and cryospheric issues affecting the western Canadian Cordillera. Major scientific progress was made within these projects, as largely summarized in DeBeer et al. (2016), but their main focus was examining the past and present climate and improving the understanding and modelling of key processes with relatively little focus on future conditions.

The importance of these issues and the collaborative foundation established by previous projects set the stage for the Changing Cold Regions Network (CCRN). This 5-year (2013-18) research program aimed to understand, diagnose and predict interactions amongst the cryospheric, ecological, hydrological and climatic components of the changing Earth system at multiple scales with a geographical focus on Western Canada's rapidly changing cold interior (DeBeer et al., 2015). Its area of concern is shown in Fig. 1, and this includes the Saskatchewan and Mackenzie River systems; all geographic locations and terms referred to in this article are also indicated. CCRN represents a regional hydroclimate project that was formed under the auspices of the Global Energy and Water Exchanges (GEWEX) project of the World Climate Research Programme.

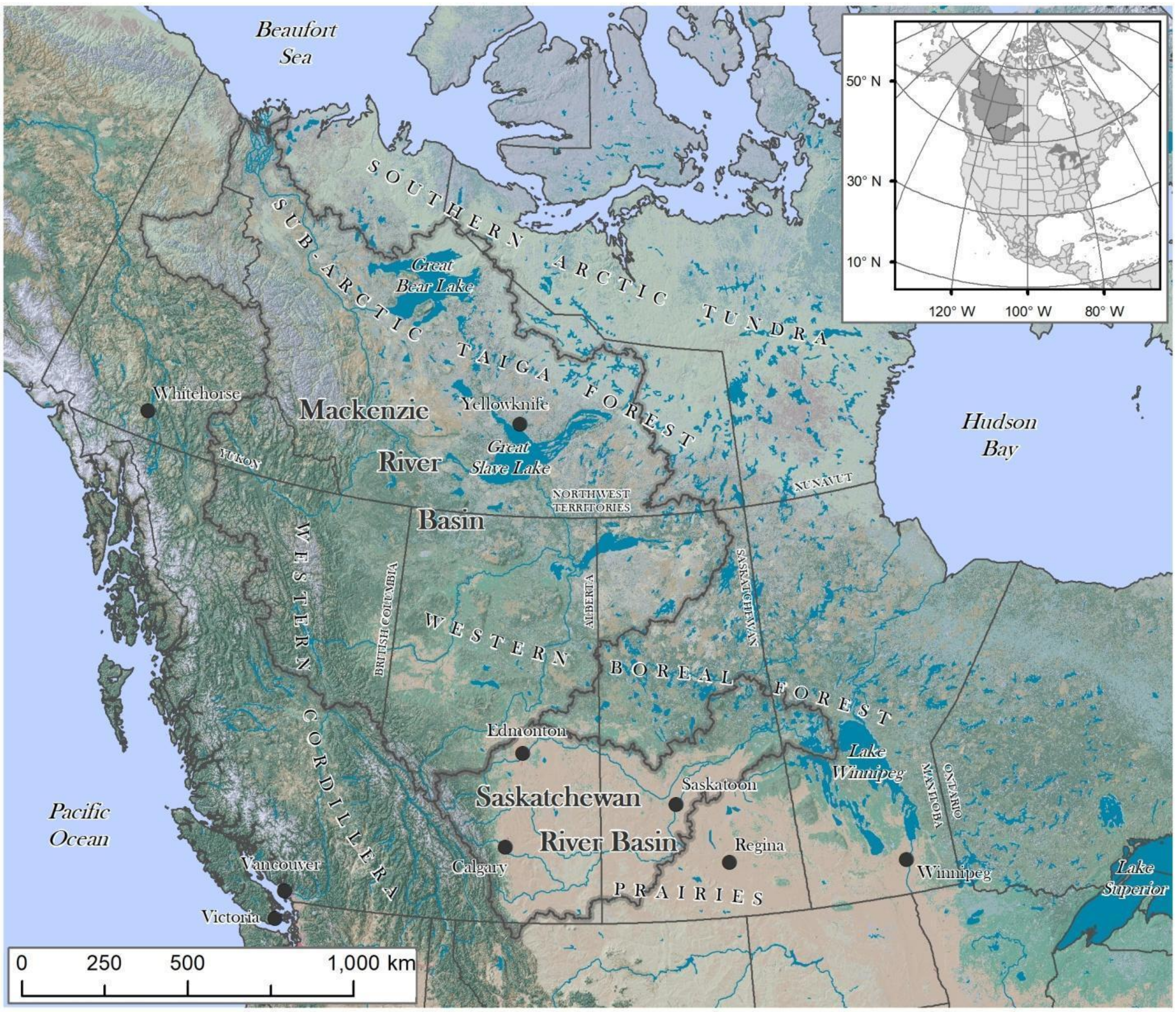


Figure 1: The region of concern for this article with the main focus being in the central region from Alberta to Manitoba and northwards to the Arctic Ocean. The names of Canadian provinces and territories, several cities, large water bodies and several land cover-related areas are also shown.

The insert highlights the Mackenzie and Saskatchewan River basins.

Initially, CCRN collated many studies documenting a wide variety of variables to best characterize recent change over this region (DeBeer et al., 2016). Widespread change was documented in air temperature, precipitation, seasonal snow cover, mountain glaciers, permafrost, freshwater ice cover, and river discharge. Increases in air temperature were the most notable, with annual values rising on average 2°C throughout the western interior since 1950. These temperature increases, believed to be mainly due to increased greenhouse and associated atmospheric factors (Bush and Lemmen, 2019), have been associated with changes to precipitation regimes and unambiguous declines in snow cover depth, persistence, and spatial extent and it has caused mountain glaciers to recede at all latitudes, permafrost to thaw at its southern limit, and active layers over permafrost to thicken. Some of these many changes might have accelerated temperature increases largely through ice albedo feedbacks. Despite these changes, integrated effects on annual streamflow amounts are complex and often offsetting, but the timing of the spring freshet has, in general, advanced to earlier in the year as a result of rising air temperatures and earlier snowmelt.

As indicated above, one of the key goals of CCRN is linked with future conditions. Many articles have utilized climate model projections using, for example, Coupled Model Intercomparison Project Phase 5 (CMIP5) information (Taylor et al., 2012) and Intergovernmental Panel on Climate Change (IPCC) reports (such as IPCC, 2013). A summary of such studies has recently been developed by Environment and Climate Change Canada (Bush and Lemmen, 2019); the CCRN region of interest is projected to continue being subjected to increasing temperatures and associated changes in many surface variables although there is considerable uncertainty.

But, more insight is required into the processes and drivers of this change over the CCRN region including, for example, physically-based examination of features in the future and conceptual models of change. Such insight provides guidance as to the reliability of models and to research focal points for improving future projections. We follow this avenue by examining projected changes in several, often related, phenomena in a physically-consistent manner through a cascade of scales and through physical understanding.

With this background, our objective is to summarize and synthesize our collective assessments of future conditions across the CCRN domain. The breadth of CCRN is so large that this overall issue cannot be addressed within one article. It is broken into parts as follows:
Part 1: climate and meteorology
Part 2: terrestrial ecosystems, cryosphere, and hydrology

The specific objective**s** of this first article is to illustrate how changing large scale conditions will affect regional and storm scales with a general, although not exclusive, focus on precipitation-related phenomena. This approach facilitates increasing our insights into regional hydroclimate response to projected large-scale circulation changes. Overall warming will be associated with changes in large scale atmospheric circulations and moisture, but it is critical to quantify these changes and to examine consequences on smaller scale features. The article is comprised of key outcomes from completed studies, new analyses as well as an overall synthesis.

The article is organized as follows. Section 2 provides a summary of model datasets and analysis, Sect. 3 examines issues at seasonal scales, Sect. 4 addresses phenomena in more detail within the cold season, spring and early summer, as well as summer periods. Section 5 presents a synthesis and Sect. 6 contains the concluding remarks and sets the stage for the second article focused on surface-related issues.

2 Model datasets and analysis

Given that the main objective of this article is to attain a deeper and more coherent understanding of different regional aspects of climate change in western Canada, we adopt the notion that climate change alters large-scale circulations that govern much of the climate variability and extremes at regional and smaller scales. This premise provides a perspective for analyzing the CMIP5 data and it also provides a dynamically-based conceptual framework to synthesize the diverse regional climate change results. Monthly projections using the RCP8.5 scenario from 39 CMIP5 models were analyzed to gain insight into the cascading processes that link regional responses to changes in the large-scale circulations. In particular, this information was used to generate ensemble mean, median as well as the top and bottom 25^{th} percentile values. The evolution of several standard and derived variables over the 21^{st} century was examined and there was a particular focus on differences between mean 2081-2099 and mean 1981-2000 values (Table 1). Similar 20 year long periods were used within the recent Canada's Changing Climate Report (Bush and Lemmen, 2019).

Table 1: Model products used in this study as well as time periods used for mean historical and future conditions. Acronyms are defined in the text.

Model	Scenario	Time Periods	
CMIP 5	RCP8.5	1981-2000	2081-2099
CRCM5	RCP8.5	1981-2000	2081-2100
NARCCAP	SRES A2	1971-2000	2041-2070
NCEP/NCAR	-	1976-2005	-

This approach does not capture the impacts arising from a full range of emission scenarios. It nonetheless allows for a physically-based analysis and interpretation of a business-as usual scenario although it is recognized that there is considerable uncertainty within this one scenario. The results can be used as a basis for follow-on studies that explore a wider range of possible futures.

Given the distinct seasonal differences in the study region's present and projected climate, results are organized largely by seasonal change. It is well-known that the climate of the region is strongly influenced by teleconnection patterns that occur on a wide range of spatiotemporal scales (Bonsal et al., 2001; Bonsal and Shabbar, 2008; Szeto, 2008). In accord with the objectives of CCRN, we will focus on intra-annual time scales where the large-scale circulation variability exerts the most direct influences on hydroclimate extremes within the domain. In particular, emphases are placed on the analysis of future changes of the Pacific North American (PNA) pattern (Wallace and

Gutzler, 1981) which strongly affects the cold-season climate of the region (see for example, Table 2 of Szeto, 2008), and quasi-stationary upper air circulation features over the northwestern U.S.A. that exert strong influences on the hydroclimate of southwestern Canada during the warm seasons (Shabbar et al., 2011; Brimelow et al. 2015, Szeto et al., 2015, 2016).

The projected changes of these cold- and warm-season circulation features are examined by calculating the "4-point" PNA index as formulated in Wallace and Gutzler (1981) and the H-index introduced in Szeto et al. (2016) using the CMIP5 500 hPa geopotential height data, respectively. The "4-point" PNA index quantifies the amplitude of the PNA wave train by comparing the 500 hPa height at four different fixed locations and the H-index quantifies the magnitude of an upper-level circulation feature by comparing the height field at the center and enclosing areas of the feature. In addition to focusing on the most prominent large-scale circulations that affect the region, this approach also simplifies the interpretation of the influences of these features on regional warming distribution and future high impact climate extreme events in western Canada. As appropriate, this insight is supplemented by those from previous, related studies as well as analyses conducted with CMIP5 daily data.

Global climate model (GCM) information is essential but additional datasets are needed because the analysis considers regional and storm scales. New analyses were conducted by using regional data to fill in critical research gaps that had not been addressed in previous regional studies (Table 1). Those include dynamically downscaled regional and storm scale datasets such as CRCM5 (Canadian Regional Climate Model version 5, Martynov et al., 2013 and Šeparović et al., 2013), NARCCAP (North American Regional Climate Change Assessment Program, Mearns et al., 2013), NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) re-analysis (Kalnay et al., 1996), and Environment and Climate Change Canada (ECCC) weather station information.

As appropriate, the historical period is generally considered to be 1981-2000 although some Fourth Assessment Report (AR4) analyses have used 30 year averages with 1971-2000 as the base period. Temporal changes are examined over various domains although one focus is the southern Prairies bounded here by the latitude-longitude box (95-115°W, 47.5-55°N).

3 Large and regional scale patterns

As we are focusing the discussion on projected changes of the PNA pattern and quasi-stationary upper air circulation features over the northwestern U.S., it is appropriate to briefly summarize how these large-scale drivers affect the current hydroclimate climate over western Canada during the cold- and warm seasons, respectively.

The autumn and winter positive (negative) PNA pattern is characterized by large-scale upper-level negative (positive) and positive (negative) height anomalies centered above the Aleutian Islands and the western Canadian Prairies, respectively. At the surface, a broad anomalous low (high) centered just south of the Aleutians and extending into the Mackenzie basin is typically found during the positive (negative) phase. The warm (cold) temperature advections associated with the low-level southwesterly (northwesterly) anomalous flow typically induces warm (cold) temperature anomalies over northwest Canada during positive (negative) PNA. In addition, dry (wet) conditions over the western Prairies are associated with the positive (negative) pattern.

As shown in Shabbar et al. (2011), Brimelow et al. (2015) and Szeto et al. (2015, 2016), the tracking and development of synoptic systems that affect significantly the warm-season hydroclimate of southwestern Canada are strongly affected by the large-scale upper-level pressure anomaly over the northwestern U.S. In particular, anomalously wet (dry) conditions are typically found to be associated with upper low (high) pressure anomalies over the region.

Results in Szeto (2008) and Szeto et al. (2015, 2016) show that significant correlations are exhibited between hydroclimate variables in the domain and the intensities of these seasonal circulation features. In addition, cold- and warm-season extreme conditions are often associated with intense respective circulation anomalies as reflected in extremity of the corresponding PNA and H-indices that measure the intensity of these circulation anomalies. Since there are physical bases for such associations between regional climate variability and extremes in the domain and these large-scale circulation anomalies, it is not unreasonable to assume that such relationships will also hold for future changes in these large-scale drivers and the regional climate responses. We further assume that any significant future changes in the mean circulation pattern will, at least partially, be manifested in changes of the intensity and/or the frequency of similar anomalous circulation patterns with respect to current conditions. This assumption will be verified with model data in the following and the validity of this assumption will lend support to the idea that changes in the mean circulation could be linked to extreme climate responses in the area.

3.1 Autumn

Projected mid-tropospheric (500 hPa) circulation changes resemble a westward shifted negative PNA pattern (Fig. 2a). An anomalous trough is projected to occur above British Columbia/Yukon and extending into the Pacific off the west coast of the U.S. while an anomalous high is projected to occur over the southwest vicinity of the Aleutian Islands. These circulation anomalies, as well as those to be discussed below for other seasons, are deep structures that extend to the top of the troposphere. Similar circulation patterns are typically found during negative PNA conditions with an anomalous low centered above the southern Prairies, and a high above the Aleutians. Corresponding changes in anomalous mean sea-level pressure (MSLP) include a projected high centered just east of the upper high and a trough that extends from the Arctic Ocean into central north Canada. Circulation changes at higher levels effectively reduce the waviness of the upper flow and jet stream by weakening both the climatological Aleutian low and the upper ridge over western Canada.

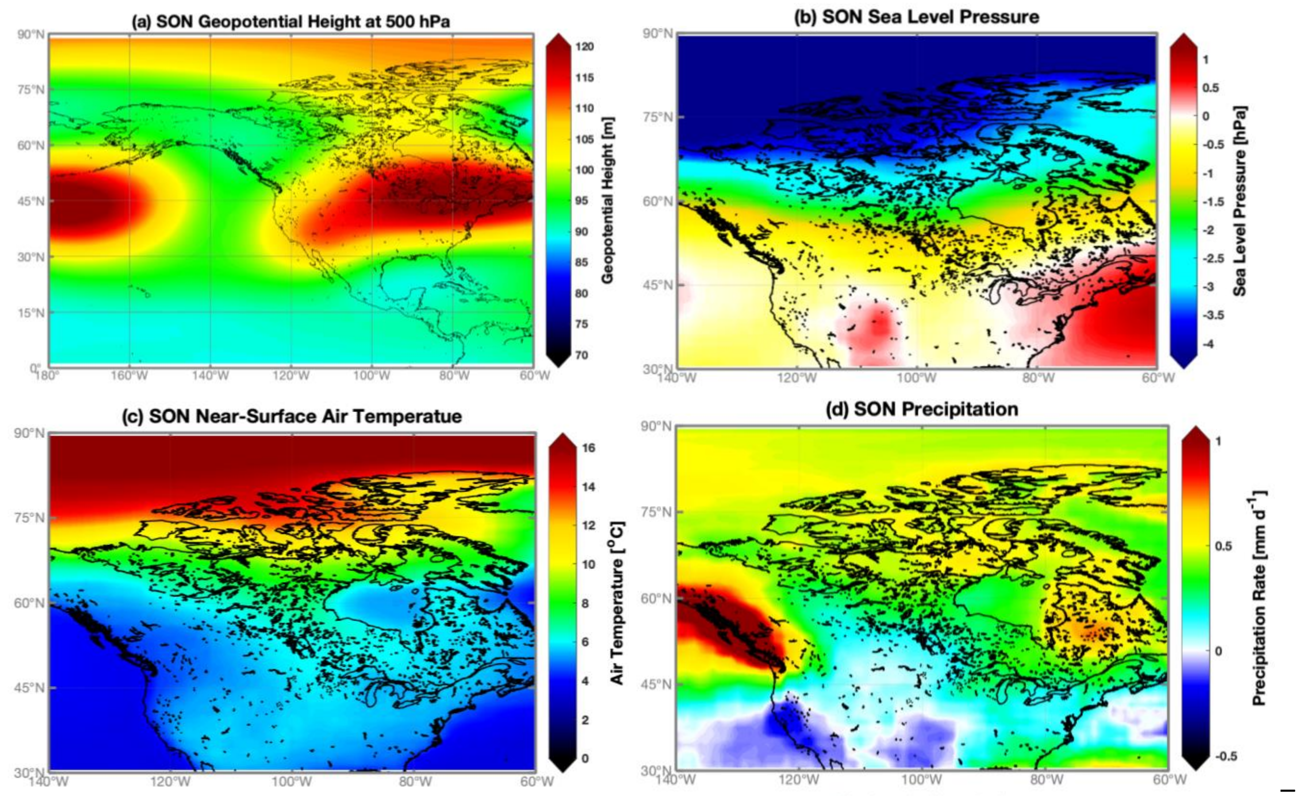


Figure 2: CMIP5 RCP8.5 projected changes of 39-model ensemble mean between the period (2081-2099) and (1981-2000) for autumn (SON). For each 3-month period, the four panels show differences in (a) 500 hPa height (m), (b) sea level pressure (hPa), (c) near-surface (2 m) air temperature (°C) and (d) precipitation rate (mm d^{-1}).

The time series of SON PNA index (Fig. 3a) suggests that the afore-mentioned circulation change is projected to commence around mid-century. Although inter-model spread as measured by the interquartile range is large, a statistically significant (at 5% level) decreasing trend of the ensemble-median is projected to occur during the second half of the century. The mean near-neutral PNA condition that characterizes the first half of the century is replaced by mean negative (-0.26) conditions and 9 out of the 10 strongest negative PNA autumns are found after 2060; this latter result provides support to the assumption that changes in the mean circulation pattern is partly manifested in changes in the frequency and/or intensity of the extreme similar anomaly patterns.

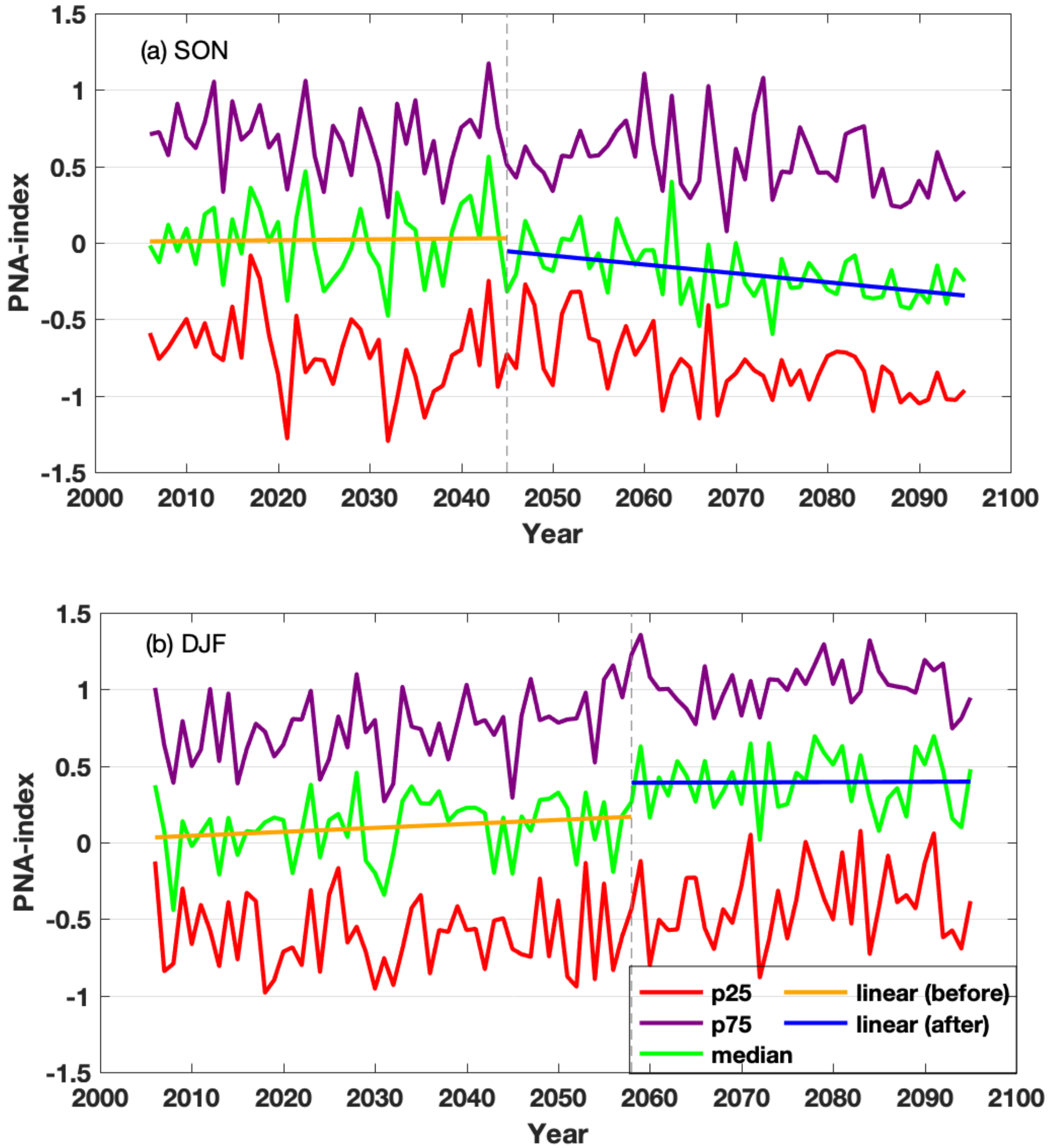


Figure 3: The (a) autumn (SON) and (b) winter (DJF) PNA index over the 21st century computed by applying CMIP5 ensemble model information to the formula given in Wallace and Gutzler (1981). The lines indicate the median, 25th percentile and 75th percentile. Also shown are piecewise linear regression lines separated at the 'break' year indicated by the dashed line. Assessments using the Mann-Kendall method (Kendall, 1995) show that the after (before) break trend for SON (DJF) is significant at 5% (10%) while the other trends are not significant. The before and after break trends are significantly different at 5% (10%) for SON (DJF).

Projected regional climate responses to the circulation changes are consistent with those found during negative PNA, but shifted in association with the projected circulation features. In particular, the cold air advection into northwestern Canada by the anomalous anti-cyclonic flow associated with the surface North Pacific high found in typical negative PNA conditions is much reduced due to the westward-shifted location of the high. Instead, the surface high enhances low-level flows towards the Pacific coast of Canada, which when combined with the upper low over British Columbia, would substantially enhance precipitation over the coastal regions (Fig. 2d). The enhanced cross-barrier flow and associated precipitation induce subsidence and adiabatic warming over the Prairies (Szeto et al., 2007; Szeto, 2008). The warming over the south effectively reduces the S-N gradient of net anthropogenic warming (Fig. 2c) and partly offsets its detrimental effects on the low-level background baroclinicity and synoptic storms that affect southwestern Canada.

Quasi-geostrophic theory (e.g., Holton, 1979) predicts that cyclone activities would be enhanced in the downstream vicinity of the upper anomalous trough, i.e., over southwestern Canada. Despite the potential increases in autumn cyclones and atmospheric moisture in the warming environment, Prairie precipitation is projected to increase by only ~10%. This is likely related to the significant depletion of Pacific moisture over the coastal mountains and enhanced lee-side subsidence that are associated with the enhanced cross-barrier flow discussed earlier. As a result, although the precipitation increase is statistically significant (i.e., the increase is larger than the natural variability of historical modelled precipitation for the region), it is substantially lower than the relative increases projected for the winter and spring. These results indicate that the complex topography of the region, as well as changes in the synoptic scale forcing, could play an important role in affecting the autumn precipitation over the Prairies under this warming scenario.

3.2 Winter

The winter anomaly pattern is projected to be characterized by a pronounced upper low centered in the eastern Pacific and enhanced ridging over central northern Canada (Fig. 4a). In contrast to projected SON changes, the circulation change resembles an eastward-shifted positive PNA pattern. An increasing trend, albeit merely significant at the 10% level, in the ensemble-median DJF PNA index is found only during the first half of the century (Fig. 3b). An abrupt 'jump' is projected to occur at the end of the increasing trend during the late 2050s where the piecewise linear regression lines over the two periods is separated by a statistically significant gap that is larger than the variability of the index. The significance of the mid-century change is reflected in the marked increase of mean PNA index from 0.10 in the first half of the century to 0.37 in the second half as well as in the fact that all of the 10 projected strongest PNA winters occur after 2060. This latter result also provides support to the assumption we made on the relationship between changes in the mean and extreme patterns.

These results might be related to those of Zhou et al. (2014) who showed that the eastward shift of tropical convective anomalies under climate warming would cause the ENSO-forced winter PNA pattern to move eastward and intensify. These projected changes effectively enhance the waviness of the upper flow and jet over the North Pacific by strengthening and broadening the North Pacific upper trough towards the west coast of the U.S. while broadening the climatological upper ridge and making the flow more zonal over northwestern Canada. Some changes at the lower levels (Fig. 4b) are similar to those found in positive PNA conditions with an anomalous trough extending from the Aleutians into areas off the west coast of North America. But, a strong anomalous surface ridge that is typically located over the western U.S. under positive PNA conditions is projected to be centered over southwestern Canada.

Similar to positive PNA conditions, the low-level high-low couplet allows the warm Pacific air to be advected into the Yukon and the Mackenzie basin. On the other hand, the reduced onshore flow could decrease the precipitation along the British Columbia coast and the associated weakening of adiabatic warming and lee-cyclogenesis over the southern Prairies. These combined effects enhance the S-N anthropogenic warming gradients (Fig. 4c), weaken the background surface frontal zone, and contribute to the development of the anomalous surface ridging in the region. For example, the mean DJF N-S near-surface temperature gradient over the southern Prairies is projected to decline by ~25% towards the end of the century. In addition, the weakened mean upper northwesterly flow over northwestern Canada reduces the number of North Pacific systems that enter Alaska to migrate down to the southern Mackenzie basin. Collectively, these changes in circulation and dynamic features are expected to reduce the frequency and intensity of weak cyclones that typically affect the region in winter.

Despite these considerations, winter precipitation at the end of the century is projected to increase by approximately 19% over the Prairies and by larger amounts at higher latitudes. This 19% increase is significantly higher than that predicted for SON. This result can be explained by considering the anomalous upper and low-level troughs projected to occur off the U.S. west coast which allow more moisture-laden Pacific systems to develop and affect the western U.S., as reflected in the enhanced troughing and precipitation projected over this region (Figs. 4b and d). With the weakened mean upper northwesterly flow over western Canada, some of these moisture-laden southern systems could be able to track into the Prairies and produce more frequent extreme winter precipitation events.

Preliminary analysis of projected daily Prairie precipitation provides strong support for the above inference. It is a preliminary analysis because we only have access to daily data for 21 out of the 39 models for this analysis. The results show that, although the ensemble mean frequency of precipitation days (daily precipitation $P > 0.5$ mm d^{-1}) only increases marginally from 743 days during 2006-2020 to 778 days during the last 15 years of this century, the corresponding frequency of extreme precipitation days (daily $P > Pc$, the 99^{th} percentile of daily P during DJF 2006-2020) increases from 10 to 29. In addition, although the mean frequency of extended (longer than 1 day) precipitation events hardly changes between the two periods (157 versus 158), the frequency of extended extreme precipitation events (multi-day events with daily $P > Pc$) increases 5-fold from 0.6 to 3.3 between these 2 periods.

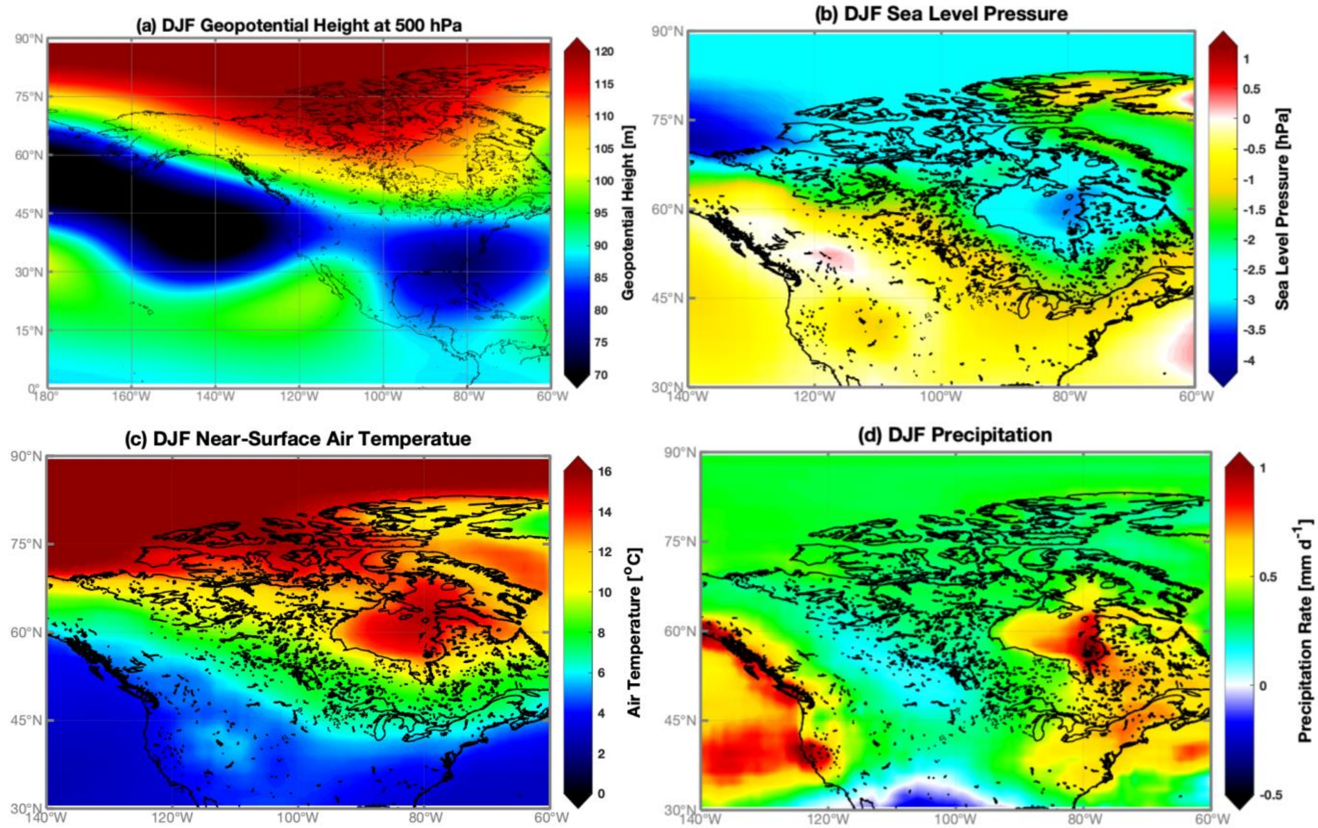


Figure 4: As in Fig. 2 but for winter (DJF).

3.3 Spring

The most prominent circulation anomaly feature is the quasi-stationary upper low centered over the northwest U.S. (Fig. 5a). This large-scale setting favours the development of cyclones that bring warm-season precipitation to southwestern Canadian regions (Szeto et al., 2011, 2015, 2016). The intensity of the low can be quantified by the H-index as detailed earlier and the development of this feature is shown in Fig. 6. The low is a robust feature projected by most models (Fig. 6a). The mean magnitude of the low (i.e., negative H-index) is projected to intensify mainly during mid-century (Fig. 6a). In fact, the 20-y mean H (not shown) decreases by 15 m (from -10 m to -25 m) during 2045-2065, suggesting that some radical changes in the MAM large-scale circulations are projected to occur mid-century. It is noteworthy that this mid-century decrease in 20-y mean H is even larger than the standard deviation of H over the century (13.9 m). In addition, 8 of the 10 lowest H-index springs, i.e., springs that are likely to be associated with extreme wet conditions over the Prairies, occur after 2040. At the lower levels, the S-N warming gradient is relatively weak (Fig. 5c), and thus has little effect on the mean frontal zone across the southern Canadian regions. As a result, cyclone activity that affects the region is expected to increase, as reflected in the anomalous N-S surface trough that extends from Hudson Bay into the eastern Prairies and central U.S. (Fig. 5b).

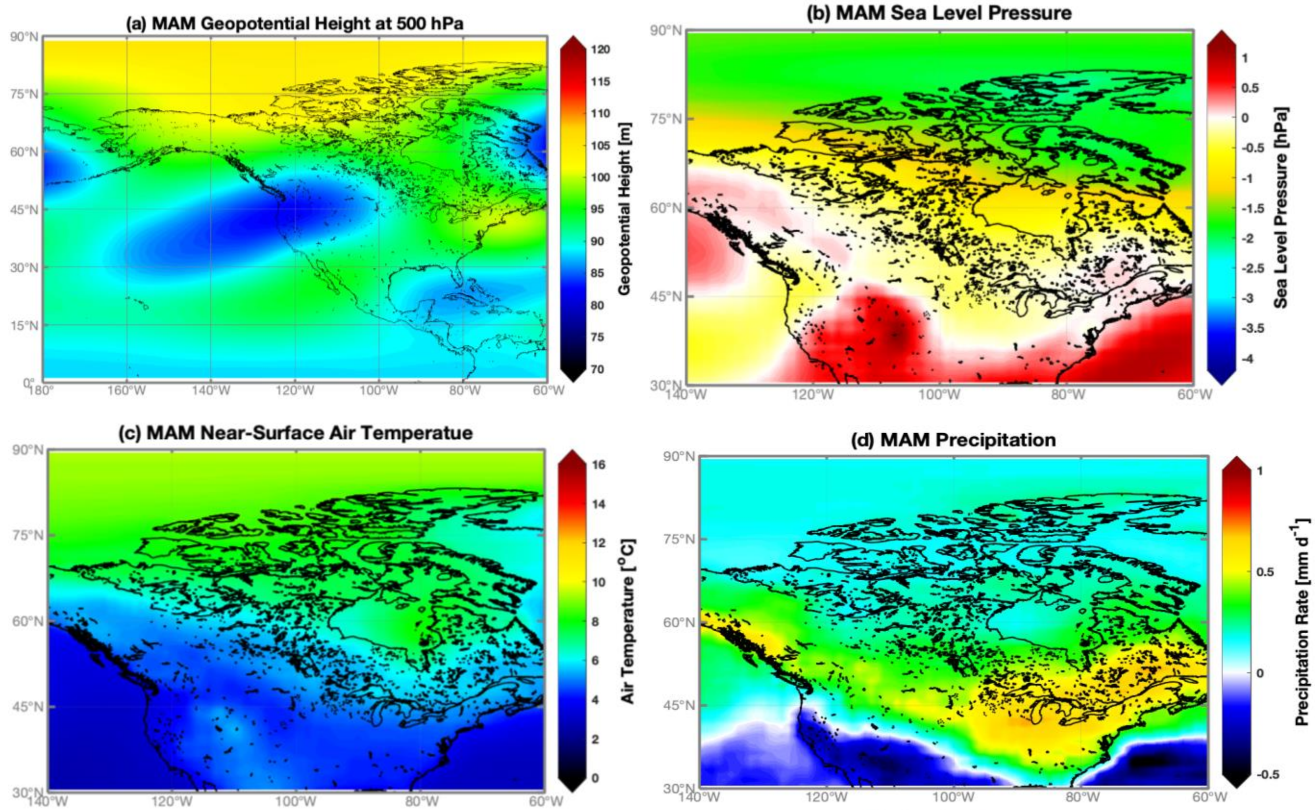
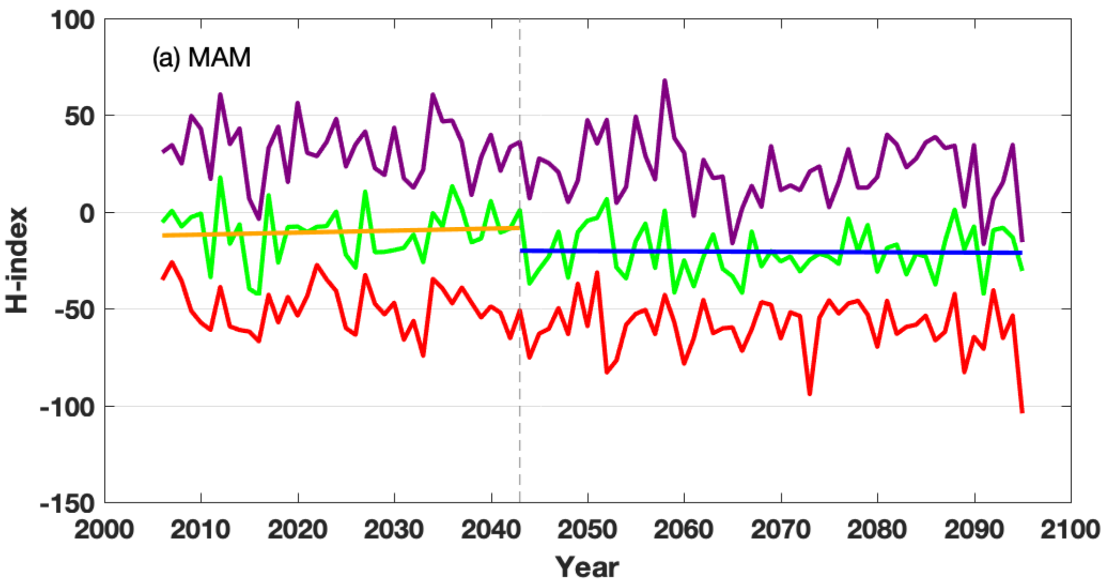


Figure 5: As in Fig. 2 but for spring (MAM).



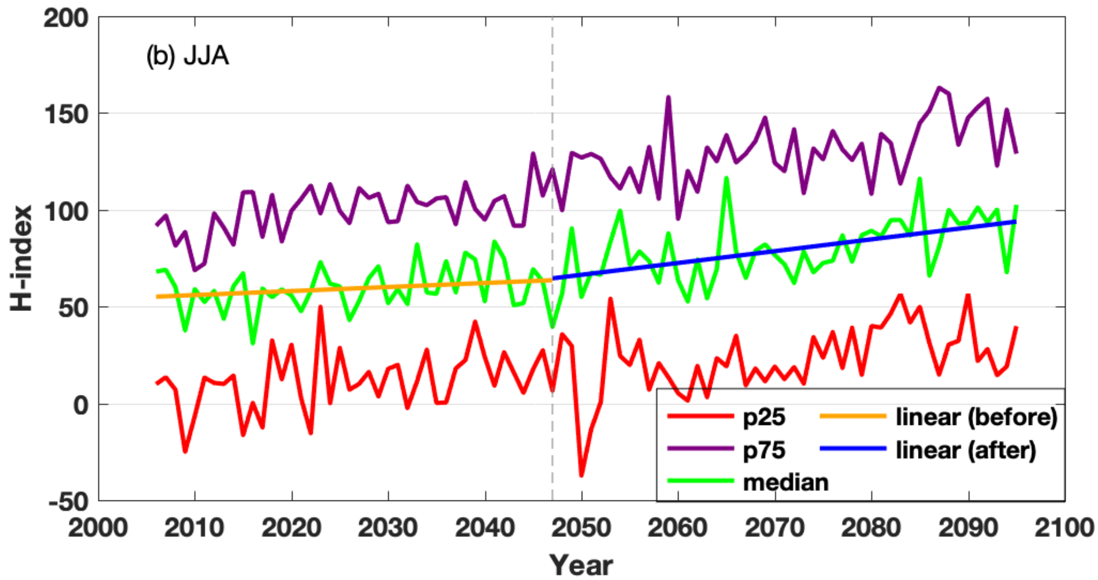


Figure 6: H-index for (a) the spring (MAM) anomalous low and (b) summer (JJA) anomalous high centered over northwest USA during the 21st century projected from CMIP5 ensemble model information. The lines indicate the median, 25th percentile and 75th percentile. Also shown are piecewise linear regression lines separated at the 'break' year indicated by the dashed line. Assessments using the Mann-Kendall method (Kendall, 1995) show that only the after break trend for JJA is significant at 5% level. The before and after break trends are significantly different at 5% for JJA only.

Consequently, spring precipitation is projected to increase significantly over southern Canada in general (Fig. 5c). For example, Prairie MAM precipitation increases by 26%, the largest among the seasons. This Prairie spring precipitation is projected to increase starting from the 1990s and continue until around 2060 (not shown) following the stabilization of the anomalous upper low. It is noteworthy that the predicted intensification of the upper low and associated increasing trends of mean and extreme precipitation over the eastern Prairies during the turn of the century are also evident in observations (Szeto et al., 2015).

Results from the analysis of daily Prairie precipitation provide further insight into the regional precipitation response to the circulation change. In particular, the frequency of extreme precipitation days (daily P > Pc, where Pc is the 99th percentile of daily P during MAM 2006-2020) doubles from 10.5 days during the early-century period to 20.4 days towards the end of the century (2086-2100). In addition, although the mean frequency of extended precipitation events hardly changes between the two periods (153 versus 156), the frequency of extended extreme precipitation events increases 3-fold from 1.2 to 3.7 between these 2 periods. Although both the DJF and MAM results suggest substantial future increases in extreme precipitation events, it is noteworthy that, although the relative seasonal precipitation increase for MAM is higher, the increase of extreme precipitation event frequency is somewhat higher for DJF. The apparent discrepancy is likely related to the difference in the model ensembles (21 vs 39 members for daily and monthly analysis, respectively) that were used in the assessments.

The long-term mean large-scale upper low pressure anomaly would allow more upper low systems to enter the continent through the northwest U.S. Analysis of historical extreme Prairie precipitation events (not shown) suggest that the location of heavy precipitation is sensitive to the location of the upper low due to the topography that characterizes the region. In particular, strong upslope rainstorms over southern Alberta, similar to the one that caused the 2013 Calgary flood (Pomeroy et al., 2015; Liu et al., 2016; Kochtubajda et al., 2016; Li et al., 2017), could result from upper lows that are located over the northwest U.S., whereas flood producing extreme rain events over the eastern Prairies (see for example, Brimelow et al., 2014; Szeto et al., 2015) could result from upper lows that were centered only slightly to the east. Furthermore, some systems that track slowly across the region could bring extreme precipitation to both the eastern and western regions (e.g., Szeto et al., 2011). When combined with the increased winter precipitation and earlier snowmelt and freshet in a warmed climate, the expected increase in extreme spring precipitation could substantially increase the risk of extreme Prairie spring floods over both the western and eastern Prairies.

3.4 Summer

In contrast to the projected spring conditions, the most prominent circulation anomaly feature is the quasi-stationary upper high centered over the northwest U.S. and southern British Columbia (Fig. 7a). This blocks cyclones that bring warm-season precipitation to southwestern Canadian regions. The decreased summer cyclone activity is also reflected in the anomalous N-S surface ridge over the western continent (Fig. 7b). Schubert et al. (2016) had previously pointed out that SST values over the Pacific also affect precipitation deficits over the continent, and Li et al. (2018) indicated that expected higher SST values in the central Pacific by the end of the century will affect the Madden-Julian Oscillation in a manner conducive to reduced summer precipitation over the Canadian Prairies. It is not clear though whether the anomalous upper high is related to such pattern changes over the central Pacific.

The development of the anomalous upper high is evident in the time series of the JJA H-index (Fig. 6b). Unlike the spring upper low that is projected to be located at the same general location, the intensification of the high is expected to accelerate after the mid-2040s when a significant (at 5%) increasing trend commences. The mean index increases by 19.1 after the "break" which is larger than the standard deviation of the index during the century (17.2). It is also notable that all of the top 10 highest H-index summers, i.e., summers that extreme warmth and dryness likely occurring in the Prairies, occur after 2050.

Under the influence of the upper high, downward solar radiation is projected to increase up to ~5 W m^{-2} over southern Prairies by 2100. JJA near-surface air temperature is expected to increase by ~2^{o}C over the next 30 years (by 2050) and by an additional 4^{o}C over the following 50 years (by 2100) along with even stronger warming over its southern vicinity. As a result, a “hot spot” with maximum summer warming that extends into southwestern Canada is projected to be induced under the upper high (Fig. 7c). The projected large-scale changes induce a significant decrease in precipitation over the Great Plains (Fig. 7d). In accordance with the temporal development of the upper high, the Prairie JJA precipitation is projected to remain rather constant until approximately 2070 and then decrease by 5% towards the end of the century. Although this is not a significant decrease, summer is the only season with projected reduction in precipitation over the study region.

In contrast, evapotranspiration (not shown) is projected to increase slowly until 2060 (~6 % of historical values) and then decrease very slowly again towards the end of the century.

The reduction in summer precipitation, along with the enhanced evapotranspiration induced by the strong surface warming could increase the potential for summer drought and wildfires over western Canada. Increases in surface sensible and latent heat fluxes that would accompany the projected strong warming could also enhance convective activity. On the other hand, the projected upper high is expected to suppress convection when fully-developed. As a result, it is not clear how summer convection might change during the mid-to-late century; it may be enhanced or suppressed.

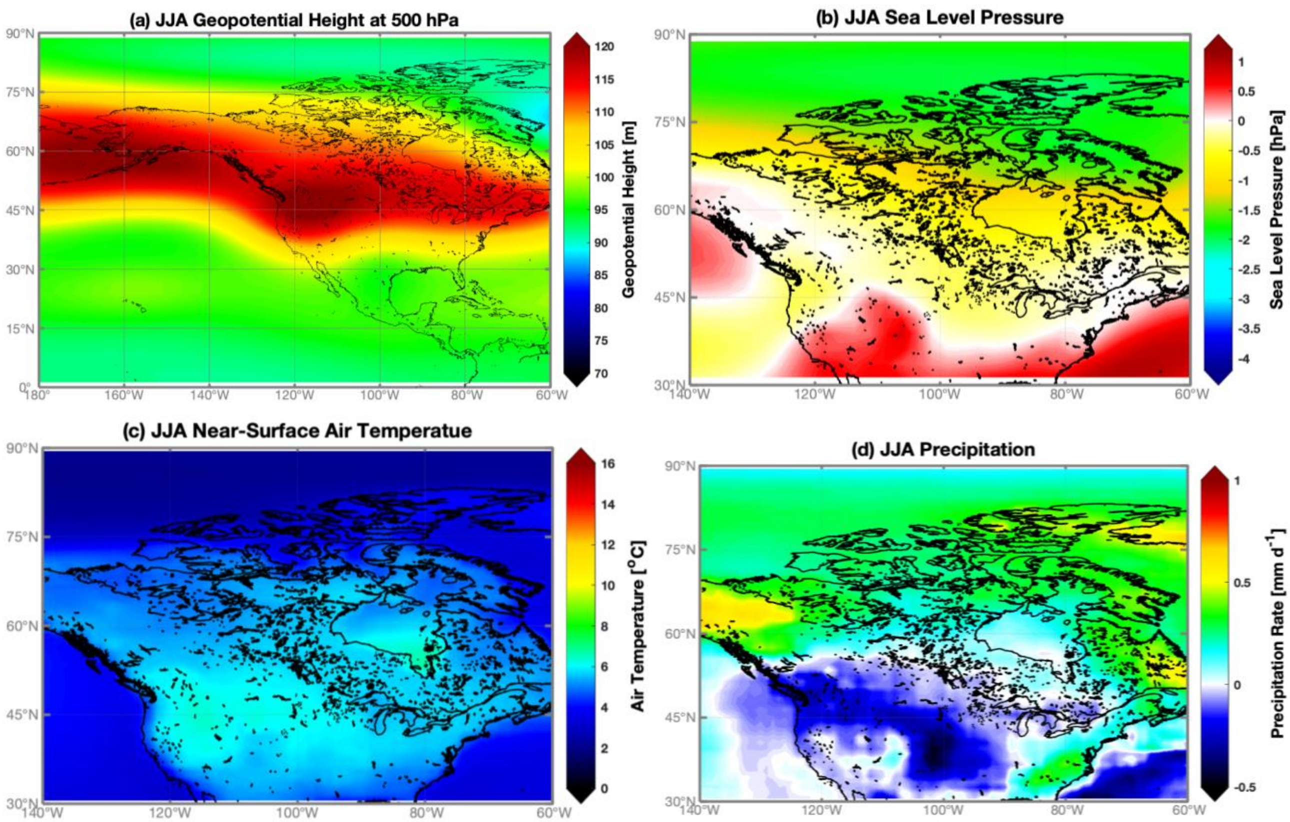


Figure 7: As in Fig. 2 but for summer (JJA).

4 Examination of critical phenomena

Although Sect. 3 addressed numerous phenomena, three overarching categories were investigated in more detail. They are organized under cold season, spring and early summer, as well as summer issues.

4.1 Cold season and near 0°C conditions

The location of the 0°C isotherm is a critical aspect of this region's climate. It is closely linked with the melting of snow at the surface which in turn affects albedo, land-atmospheric energy exchange and precipitation runoff (Jennings et al., 2018). Precipitation near this temperature furthermore varies greatly in occurrence and type and can be linked with major hazards (e.g. freezing precipitation). Changes in these features are examined here.

4.1.1 0°C isotherm movement and pattern

In association with overall warming, the near 0°C region will move northward. To quantify this, monthly average locations of the 0°C isotherm were calculated from different model datasets. The NCEP/NCAR re-analysis was used to compute locations for 1976-2005. The future time periods were computed by adding the CMIP5 39-model ensemble median of the RCP8.5 10-y mean air temperature delta (future period – 1976-2005 historical) projected for 3 different periods (2046-2055, 2066-2075, 2086-2095) to the NCEP/NCAR climatology. Locations of the isotherm for each ensemble member were estimated by interpolating air temperatures onto a 1 degree by 1 degree latitude-longitude grid.

Results of these calculations are shown for two months (March and November) that illustrate some of the greatest movements (Fig. 8). In central regions of the country, the movement of the 0°C isotherm is of order 50-100 km per decade (especially in November) although it is much less in some areas of high terrain in the Western Cordillera. The high terrain means that the near 0°C region would move vertically but little horizontally.

Note that there is considerable variation between models in the actual locations of this isotherm. Some of the narrowest spreads occur in the interior of the country, far from oceans and mountains. In the western Cordillera, the spread is large in part due to different regions having high terrain which strongly influences the locations of this isotherm. Oceanic regions also exhibit large spreads with the East Coast and Hudson Bay being impacted by variable sea ice cover.

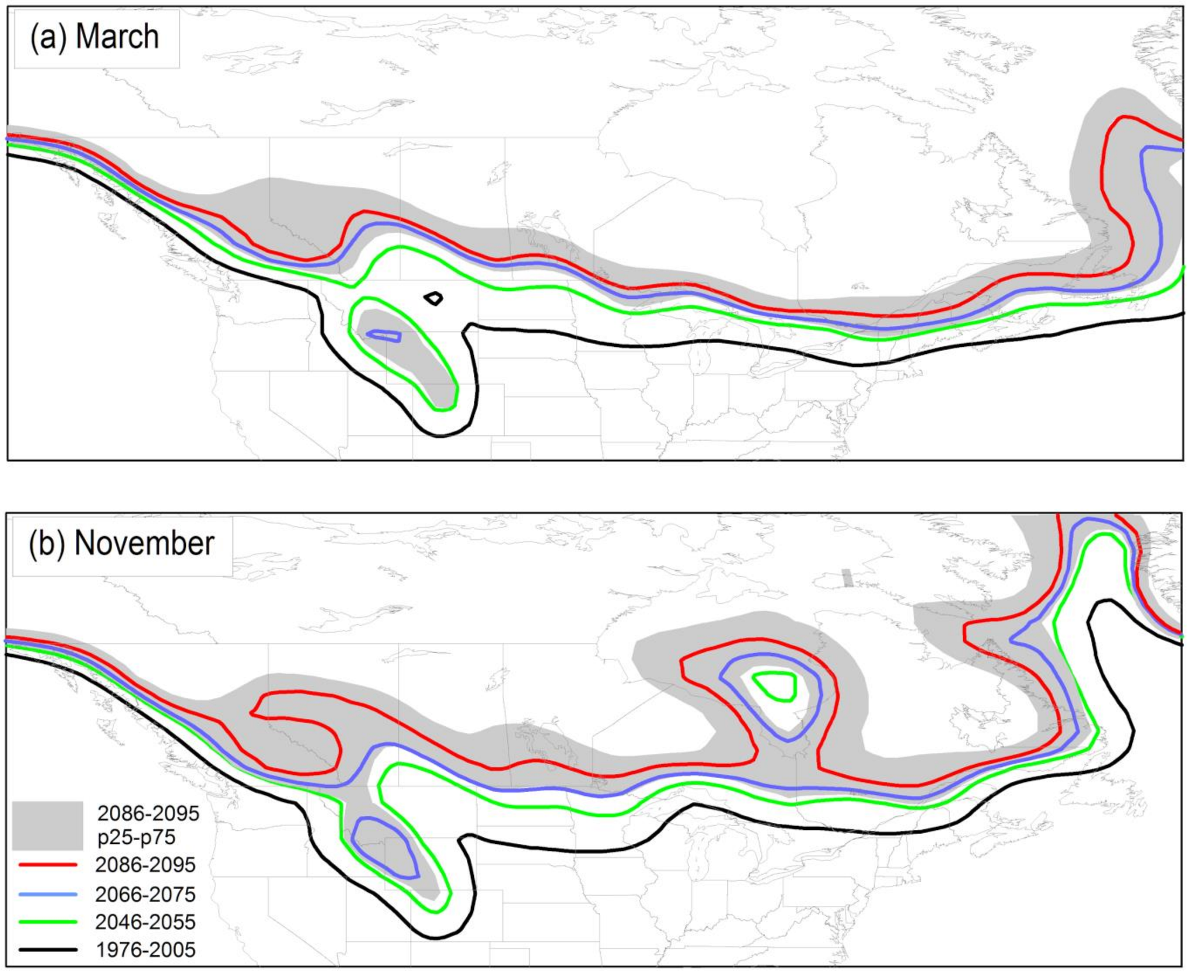


Figure 8: Locations of the 0°C isotherm during (a) March and (b) November over four different time periods. The NCEP/NCAR re-analysis was used to compute locations for 1976-2005. The future time periods were computed by adding the CMIP5 39-model ensemble median of the RCP8.5 10-y mean air temperature delta (future period – 1976-2005 historical) projected for 3 different periods to the NCEP/NCAR climatology. The grey area shows the region bounded by the 0°C isotherms in the 25th and 75th ensemble percentiles of the 2086-2095 mean air temperatures.

This large spread in projected western Cordillera patterns is accentuated when considering whether rain or snow will fall. For example, in the spring of 2015 in the Kananaskis area of the Alberta foothills, a mixture of rain and snow has been observed at temperatures as high as 9°C in some events, whereas it only occurred below 2-3°C in other events (Thériault et al., 2018).

Critical factors behind such varying observations include the near-surface vertical profiles of temperature and atmospheric moisture as well as the density of the falling solid precipitation. For example, low (high) values of particle density lead to rapid (slow) melting and a low (high) upper temperature threshold. This dependence of surface precipitation phase on particle density has been quantified using a 1-D column cloud model coupled to a microphysical scheme (Sankaré and Thériault, 2016). Snow pellets (high density of 400 g/m^3) would fall approximately 200 m more before melting than would snowflakes (low density of 100 g/m^3) under the same vertical temperature and moisture profile (Duplessis et al, 2016). This can lead to solid, instead of liquid, precipitation at the surface. Such factors make the determination of the rain-snow transition a challenging issue even in the present climate, let alone the future one.

4.1.2 Freezing rain

The movement of near 0°C conditions must be linked with changes in freezing rain occurrence. This type of precipitation, not even considering its accumulation, is difficult to simulate and project into the future. Atmospheric factors driving its formation over the CCRN region typically include extra-tropical cyclones with warm fronts although chinook-associated patterns are also important (Kochtubajda et al., 2017a); surface factors include the degree of sea ice over Hudson Bay that, when present, acts to maintain the necessary cold near-surface temperatures. The generally low occurrence of freezing precipitation, in comparison with other regions, is partially attributable to particle sublimation or evaporation below cloud (Kochtubajda et al., 2017a).

To assess future changes in the occurrence of freezing rain, the fifth generation of the Canadian Regional Climate (CRCM5) model with a 0.44° grid mesh was used (Fig. 9). CRCM5 was driven by the GCM from the Max-Planck Institute for Meteorology Earth System Model (MPI-ESM-MR) for the 1981-2000 and 2081-2100 periods using the RCP8.5 scenario (Moss et al., 2010). Freezing rain was diagnosed using the technique developed by Bourgouin (2000); this approach is used operationally at ECCC. Results shown in Fig. 9a indicate that the model driven by MPI-ESM-MR reproduced the general pattern of the mean annual number of hours of freezing rain over the domain and basically shows the same features as a hindcast simulation driven by reanalysis data (not shown) but somewhat weaker. The main differences are a strong negative bias west of the Hudson Bay as well as in an area stretching from northern Alberta to southern Manitoba. This latter area is likely due to the cold bias for that region as suggested by Šeparović et al. (2013); it is produced by the cold sea surface temperature bias in Northern Pacific in the driving data.

Projections suggest little change in the southern portion of the region but increases in excess of 20 h yr^{-1} in the Northwest Territories. Such increases are comparable to current annual values. This pronounced increase in the north is due, at least in part, to the northward movement of near 0°C temperatures (Sect. 4.2.1).

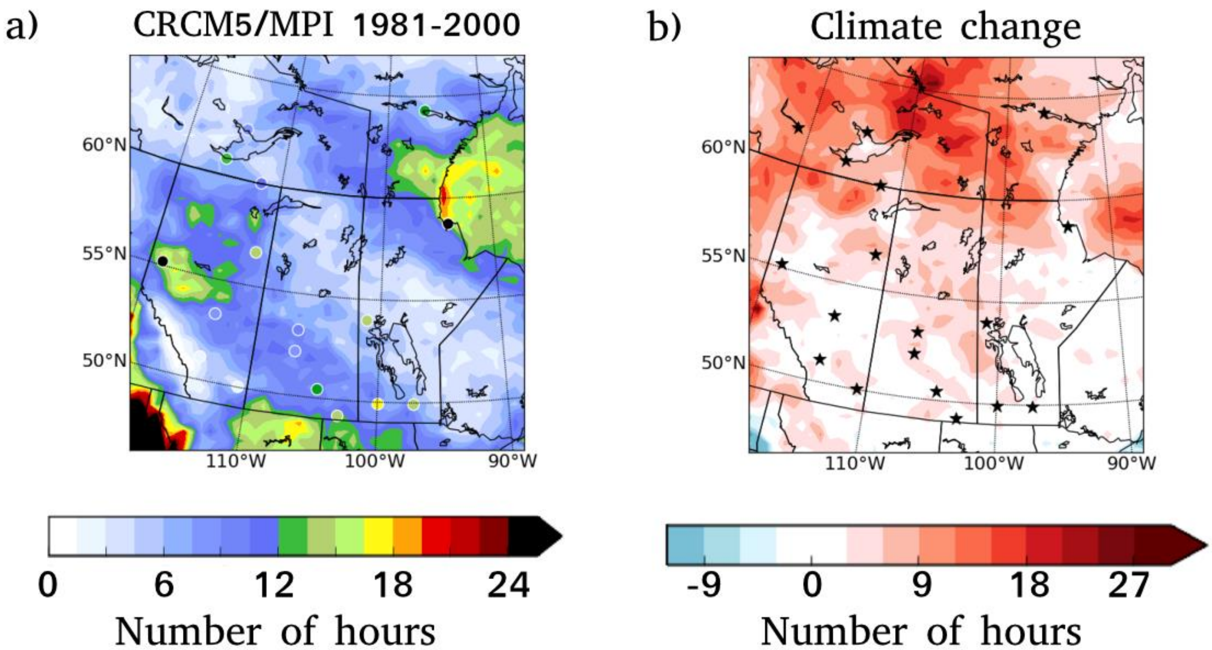


Figure 9: The mean annual number of hours of freezing rain (a) observed and simulated by the CRCM5 driven by MPI-ESM-MR for the 1981-2000 period, (b) the change in the number of hours based on the difference between 2081-2100 and 1981-2000 assuming the RCP8.5 scenario. Observational locations are indicated by circles in (a) and stars in (b).

4.2 Spring and early summer flooding

Flooding often occurs across this region in the spring and early summer. One such area is the eastern Prairies and it has experienced devastating events recently. Future aspects of these floods are examined here from an atmospheric perspective.

Large to synoptic scale atmospheric forcing is critical to the likelihood of spring and early summer flooding over the eastern Prairies. In particular, persistent atmospheric patterns often bring extended periods of precipitation extremes, either wet or dry, depending on location across the region relative to the circulation pattern (Brimelow et al., 2014; Brimelow et al., 2015; Szeto et al., 2015). Such persistent patterns were linked with spring or early summer rainfall that contributed to flooding on the Assiniboine River in 2011 and 2014; this precipitation also coincided with snow melt.

A few studies have examined how such persistent patterns are expected to change across different regions of the Prairies. Szeto et al. (2015) found that persistent patterns conducive to eastern Prairie spring and early summer enhanced precipitation and flooding may become more pronounced. Using 500 hPa output from several RCM/GCM combinations, Bonsal et al. (2017) and Bonsal and Cuell (2017) identified future (2041-2070) changes to the frequency of key summer (JJA) circulation patterns associated with extreme dry and wet conditions over the south-western Canadian Prairies and the Athabasca River Basin (ARB), respectively. Most of the models simulated general features of observed circulation patterns, and these also occur in the future but with some changes to their average frequency. However, there was considerable inter-model variability.

Flooding events in Canada are often associated with numerous factors (including extreme precipitation) that occur in combination. For example, one critical aspect of the 2014 Assiniboine flood was a cool spring followed by rapid snowmelt combined with above normal precipitation (Szeto et al., 2015). MAM temperatures were approximately 2.5^{o}C below the 1995-2014 normal and AMJ precipitation was approximately equal to the 90th percentile of AMJ precipitation that occurred during 1950-2005.

CMIP5 information was examined to determine whether the likelihood of this combination would change in the future. Comparisons of historical and projected future surface temperatures over the eastern Prairies (not shown) suggest that spring melt would commence in February and be completed in March towards the end of the century. As such, the frequency of wet MAM and cool FM during 2081-2100 is compared to historical (1986-2005) wet AMJ combined with cool MA, using the anomalous conditions for the 2014 flood as criteria for each model. The focus area is the eastern Prairies (47.5-55^{o}N latitude by 255-262.5^{o}E longitude).

Results indicate that the ensemble mean frequency of wet MAM (i.e., MAM with P> 90th percentile of MAM precipitation during 1950-2005) is projected to be 4.6 seasons/decade, which is substantially higher than the corresponding mean frequency of 1.2 seasons/decade for wet AMJ during 1986-2005. In addition, the mean frequency of combined wet MAM and cool FM (i.e., FM temperature 2.5^{o}C cooler than the 2081-2100 mean) was projected to be 0.8 seasons/decade, which is 8 times larger than the frequency of 0.1 seasons/decade estimated for the co-occurrence of wet AMJ and cool MA during 1986-2005. The results suggest that the projected large-scale atmospheric conditions that are favorable for the development of wet MAM could substantially increase the risk for eastern Prairie floods that are associated with cool and wet springs.

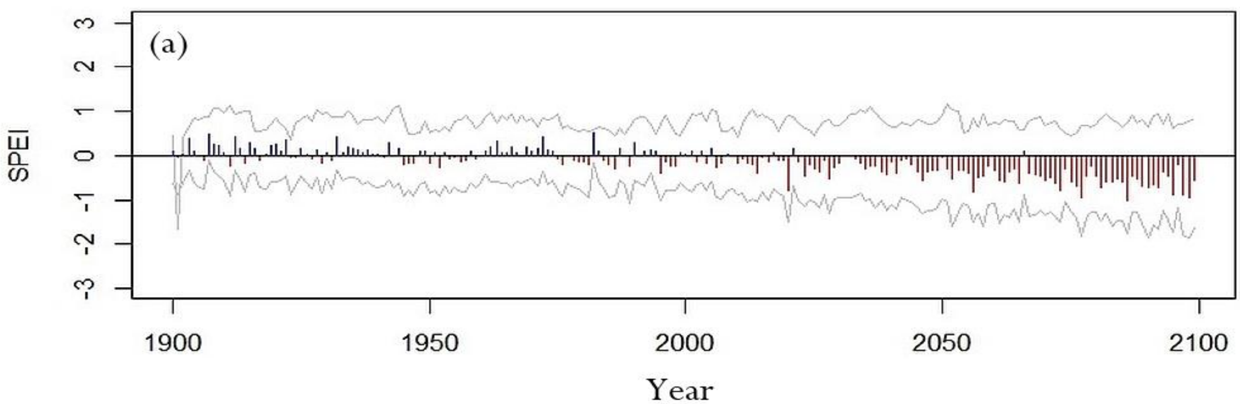
4.3 Summer severe conditions

Summer across the region can be associated with severe conditions ranging from widespread drought to severe thunderstorms. Their combination can furthermore be key factors linked with forest fires. Expected changes in these phenomena are examined here.

4.3.1 Drought

The projected large-scale summer changes (Fig. 7) are expected to impact future drought conditions. Given that past droughts over western Canada have been associated with a persistent mid-tropospheric (500 hPa) large-amplitude ridge centered over the area (e.g., Bonsal et al., 1999), it is anticipated that the quasi-stationary anomalous upper high centered over the northwest U.S. and southern British Columbia (Fig. 7a) will result in more drought-like conditions in this region. Some evidence for these changes was found by Bonsal et al. (2017) and Bonsal and Cuell (2017) who examined future (2041-2070) changes to summer (JJA) Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010) values over two southern Canadian Prairie watersheds and the Athabasca River Basin (ARB), respectively. For the southern basins, results indicated an uncertain future ranging from a substantial increase in drought, with a higher degree of inter-annual variability, to relatively no change from current conditions. Farther north in the ARB, projections revealed an average change toward more drought-like summer conditions, but there was a substantial range among the climate models. Over a larger study area that included all western Canadian river basins, Dibike et al. (2018) incorporated six CMIP5 GCMs to assess future SPEI changes on annual and summer scales for the periods 2041-2070 and 2071-2100 (relative to 1971-2000) using RCP4.5 and RCP8.5 emission scenarios. They found that southern watersheds showed a gradual increase in annual water deficit throughout the 21st century whereas the opposite was true for northern basins. In contrast, for summer, all river basins with the exception of the extreme northern ones were expected to experience decreasing water availability.

A comprehensive Canada wide drought study assessed changes in the SPEI using outputs from 29 CMIP5 models (Tam et al., 2018). In agreement with Fig. 7, results showed strong relative summer drying during the 21st century over much of western Canada including interior southern British Columbia, as well as west-central portions of the country from the Prairies to the Arctic. In addition, the frequency of extended relatively dry periods (e.g., consecutive years that are characterized by strongly negative summer SPEI) is projected to increase markedly during the second half of this century. Compared to other locations in Canada, the southern Prairies exhibit the largest likelihood of extended severe drought during the latter part of this century under the RCP8.5 scenario (Fig. 10a). The intensification, following approximately 2050, is consistent with the accelerated intensification of the upper ridge during the second half of the century (Figs. 6b and 7a).



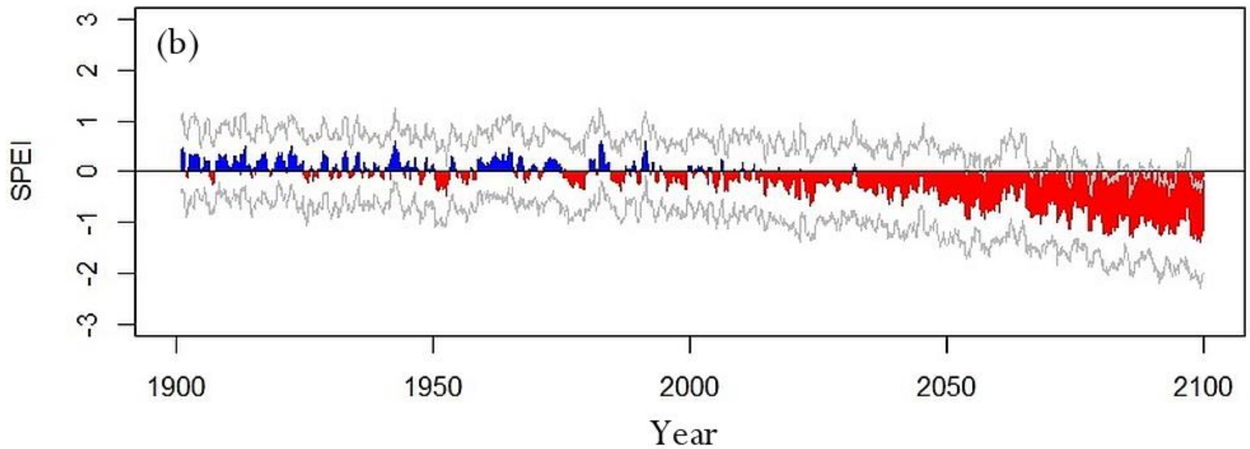


Figure 10: CMIP5 29-models ensemble medians of projected (a) summer (JJA) and (b) annual SPEI for RCP8.5 from 1900 to 2100 over the southern Prairies (defined in Sect. 2). Negative (red) values indicate surface water deficit relative to 1950-2005 conditions. Grey lines denote the 25th and 75th percentiles.

On annual scales, a dry-south–wet-north pattern characterizes projected drought changes over the CCRN domain (see Fig. 10b for drying over the south) (Tam et al., 2018). This pattern is largely accounted for by the combined results of projected dry conditions during the summer and autumn over southern regions, and the projected wet conditions during winter and spring over the northern and coastal regions of Canada. The projected surface water deficit during summer and autumn would thus play a dominant role in affecting the future annual water budget over the southern domain.

An important issue concerning drought is its future intra-seasonal character. Many droughts tend to be hot with almost no precipitation. In contrast, others are not associated with especially elevated temperatures and can even have cool periods (Stewart et al., 2012), can have rain showers (Evans et al., 2011), and/or experience occasional large precipitation events (Szeto at al., 2011) that may or may not increase in a warmer world (as discussed in Sect. 4.2.2). Such differences in character can substantially affect their impact but the CMIP5 information does not have sufficient resolution to resolve this issue.

4.3.2 Convection and hail

Analysis of future convection related precipitation requires higher spatial resolution than available from global climate models. Suitable datasets are available with dynamically downscaled RCMs, such as NARCCAP (Mearns et al., 2012), previously mentioned in Section 2. However, future scenarios are only available to mid-century when, as discussed in Sect. 3.4, dry conditions are not expected to be so dominant over the southern Prairies (Fig. 10).

NARCCAP historic (1971 to 2000) and mid-century future (2041 to 2070) model output was used to assess future changes in convective precipitation and hail over the Canadian Prairies, southern Northwest Territories and U.S. northern plains. Convective precipitation is defined to occur when the model convective scheme is triggered to release latent energy and convective instability through simulated vertical motion. Brimelow et al. (2017) suggested that the three most consistent NARCCAP model pairings to assess convective precipitation and hail for the regions of interest herein, included MM5-HadCM3, MM5-CCSM and HRM3-HadCM3, based on their ability to reproduce the precipitation climatology. No other NARCCAP studies focused on hail or warm season convection-only precipitation, although Mearns et al., (2013) and Mailhot et al., (2011) looked at ensemble summer total precipitation and annual maximum precipitation, respectively, while other studies focused on other seasons (e.g. Gutowski et al., 2010; Kawazoe and Gutowski, 2013).

Changes in future summer (JJA) convective precipitation are shown in Fig. 11 for three NARCCAP model pairs under the SRES A2 scenario. All three model pairs show increases over much of the Prairies but with varying amounts (near zero to 50 mm). MM5-CCSM and HRM3-HadCM3 are consistent with CMIP5 RCP8.5 results for the same future period (not shown) and the spatial patterns in other studies (that is, increases in Canada but decreases in central/southern U.S. Plains) (e.g. Mearns et al., 2013; Mailhot et al., 2011). These results are also consistent with general increases in CAPE and surface dew points in a warming climate over much of the Prairies (e.g. Brimelow et al., 2017).

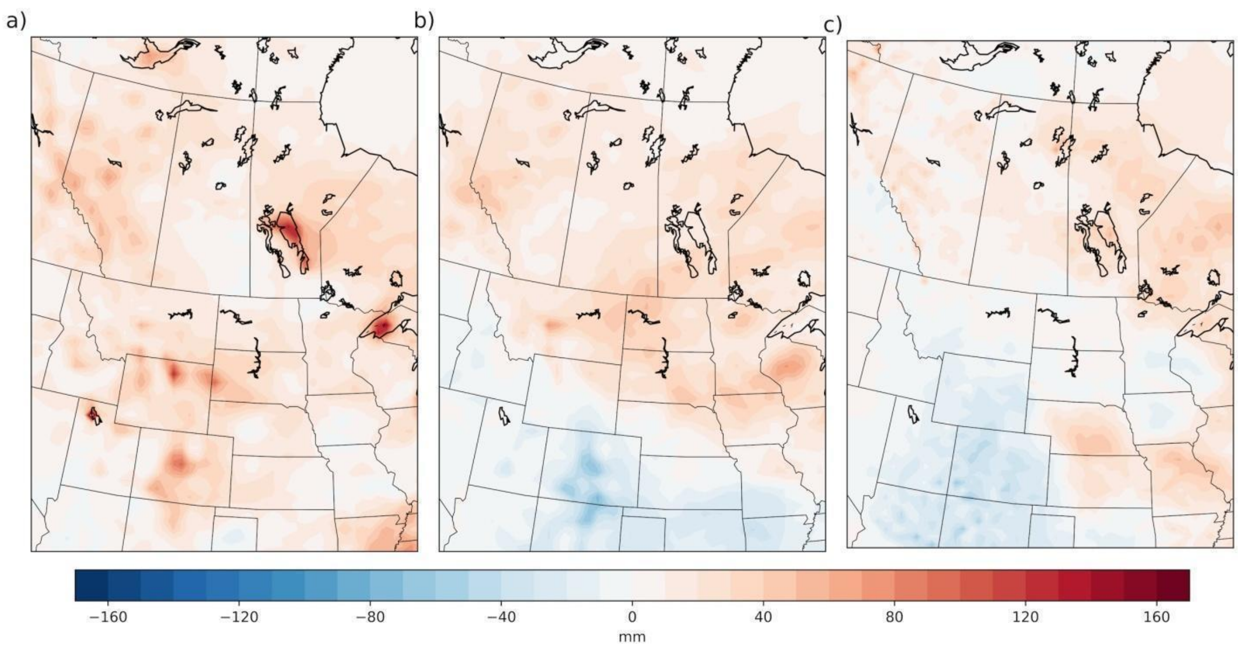


Figure 11: Changes in future warm season (JJA) convective precipitation (mm) for three NARCCAP model pairs of (a) MM5-HadCM3, (b) MM5-CCSM and (c) HRM3-HadCM3. Positive values imply greater future precipitation (i.e. 2041-2070 minus 1971-2000).

The future occurrence of hail is also important. A recent study by Brimelow et al. (2017) highlighted future changes (2041–2070 minus 1971–2000) in hail character over North America based on simulations from a one-dimensional cloud-hail model (HAILCAST; Brimelow et al., 2002) forced with the same three NARCCAP model pairs discussed above. Over the CCRN domain, results show that the number of hail days generally decline in Manitoba and Saskatchewan in summer (JJA), while increases occur in the western half of Alberta and extreme southwest Northwest Territories (see Brimelow et al., 2017 Fig 1). Over much of Alberta and southwest

Northwest Territories, there are general increases in accumulated kinetic energy (AKE) and maximum hail size, even in some regions where the number of hail days does not change in the future. That is, when it does hail, it will potentially be larger and more destructive (larger AKE). Parts of Saskatchewan and central to northern Manitoba may also see increases in AKE and hail size even though the number of hail days decreases. This is thought to be primarily due to more moisture and energy available to summer storms when they do occur (Brimelow et al., 2017).

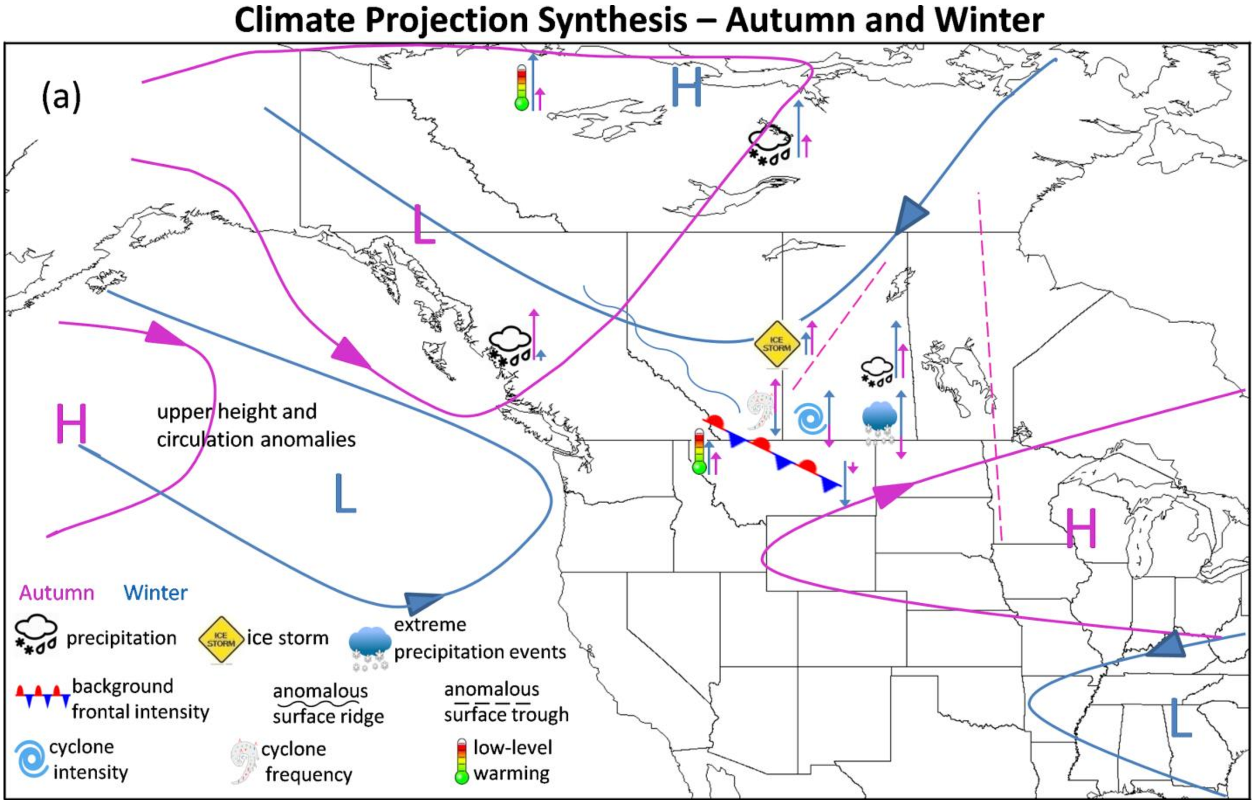
4.3.3 Lightning and Wildfires

As indicated in Sect. 3.4, convection may be enhanced or suppressed by the latter part of the century. A related issue is lightning. Since long term observations by satellite-based or ground-based lightning location systems of lightning do not exist, studies assessing past trends around the world have used thunderstorm day records (Changnon and Changnon, 2001; Pinto et al., 2013; Huryn et al., 2016) although none of these was carried out over the CCRN region. In terms of future occurrence, climate model simulations using parameterizations or proxy data for global lightning have been carried out (Price and Rind, 1994a; Romps et al., 2014; Finney et al., 2018). Although these model simulations have not been evaluated over the CCRN region, Finney et al. (2018) and Price and Rind (1994b) both projected an increase at latitudes above approximately 60°N, whereas Finney et al. (2018) projected a decrease (not statistically significant) and Price and Rind (1994b) projected an increase over parts of the Prairies. Overall, uncertainty in convection certainly translates into substantial uncertainty in lightning occurrence.

Wildfires are a major issue over the CCRN region. Their occurrence is influenced by three factors; fuels, ignition sources including lightning, and weather conditions (Flannigan and Wotton, 2001). The number of wildfires and areas burned over the CCRN region have varied dramatically from year-to-year. For example, the Northwest Territories averages 279 fires annually and these consume nearly 5,700 km^2 but, during 2014, mostly lightning-caused wildfires consumed a record 33,900 km^2 (Kochtubajda et al., 2019). This year was also characterized by a higher than normal frequency of atmospheric ridging and subsequent ridge breakdown patterns. As well, Canada's costliest natural disaster and Alberta's third largest fire event occurred in May 2016 around Fort McMurray and this included the ignition of four fires from a pyrocumulonimbus cloud (Kochtubajda et al., 2017b). Future conditions described in previous sections of this article, higher temperatures and drier summer conditions with more ridging, are consistent with a possible increase in wildfires as previously described by Flannigan et al. (2015), Flannigan et al. (2009) and Mann et al. (2017). Although not discussed in this article, fuel amount, type, and moisture content are important elements for fire occurrence and spread and are dependent on climate conditions Consequently, the projected summer conditions may also result in drier fuels which would also increase wildfire activity (Flannigan et al., 2015).

5 Synthesis of future conditions

The preceding information has examined large scale expected seasonal change as well as its impact on smaller-scale events with a focus on physical processes and inter-connections. The basis for this insight rested on new research findings as well as published articles. This insight is pulled together into conceptual frameworks largely applicable to the end of the century (Fig. 12).



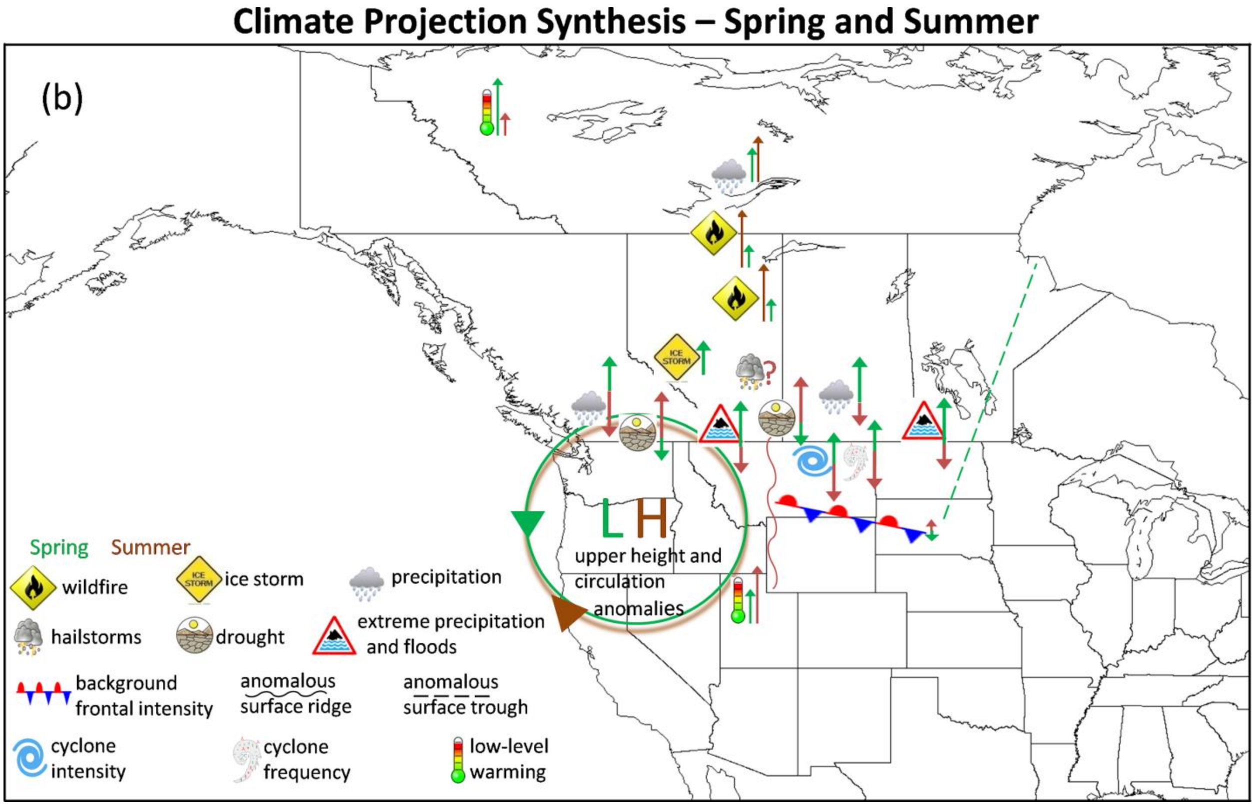


Figure 12: Conceptual depiction of upper atmospheric, surface and phenomena changes projected under the RCP8.5 emissions scenario by the end of the century during (a) autumn (purple) and winter (blue) and (b) spring (green) and summer (brown). Upwards (downwards) pointed arrows indicate an expected increase (decrease). No arrow indicates no change and a question mark indicates uncertainty.

Based on this insight, the future climate is expected to include substantial change. This includes strong and distinct seasonal dependence of large-scale dynamic drivers and a general increase in 'intensity' of these drivers. Upper level and surface patterns sometimes conspire, for example, to increase cyclonic activity but reduce it in other seasons. This overall setting is expected to have major impacts on regional and local scales. These include patterns in hydroclimatic responses that vary with season. In particular, the expectation is for greater excesses and deficits of precipitation as well as its intensity and character. There will also be distinct shifts in events directly related with temperature including those near 0°C.

These expected changes can be summarized seasonally. Figure 12a shows that, in autumn, the projected upper air circulation change resembles a westward-shift negative PNA pattern that leads to more frequent but generally weaker frontal cyclones, and associated increases in precipitation and freezing rain, over the southern CCRN region. In contrast, upper circulation change that resembles an eastward-shifted positive PNA pattern is projected for winter. The frequency of weak winter cyclones would be reduced but more intense, major snow storms over the southern CCRN region is expected. Figure 12b shows that, in spring, a pronounced upper low anomaly just southwest of the CCRN region will be conducive to more cyclonic systems and precipitation and more likelihood of spring flooding. In summer, a pronounced upper level high pressure anomaly to the southwest of the CCRN region will be linked with a greater likelihood of somewhat decreased precipitation as well as drought and forest fires.

Information on the timing of change is critical for the development of effective mitigation and adaptation measures. Analyses of the time evolution of regional hydroclimate responses show that the development of many hydroclimate variables and extremes (e.g., extreme Prairie drought) is projected to be accelerated near mid-century. The results suggest that this regional acceleration is associated with the corresponding temporal behavior of the upper air large-scale drivers.

Additional and more comprehensive investigations on the origin and evolution of changes are certainly required. For example, as shown in Sect. 4.3.2, convective precipitation may increase by mid-century before large scale circulation changes become more prominent. It is unclear how summer convection will change, particularly by the end of the century; competing factors will be acting to enhance and suppress it.

6 Concluding remarks

This article has addressed changes in atmospheric-related phenomena. The atmosphere and associated features have changed and will continue to do so due to natural and anthropogenic factors. This certainly applies to the rapidly changing interior of western and northern Canada, the focus of the Changing Cold Regions Network (CCRN).

This study has examined conditions mainly applicable towards the end of the century over the CCRN domain, largely using one business-as-usual emissions scenario (RCP8.5), and placed these within a strong physical basis. Although not as extensive, some attention was paid to the evolution of these conditions. These analyses led to the development of a physically-based conceptual framework relating large scale atmospheric change to smaller scale associated features. Because of projected seasonal shifts in circulations and temperature, four conceptual depictions were developed to account for changes in associated phenomena.

Although these syntheses are based on solid physical interpretation, they have limitations. First, the inter-scenario and inter-model variability of both the large-scale drivers and regional responses need to be better assessed. The article furthermore was largely based on the interpretation of available information on the intra-annual time scale and Pacific North-America domain. The analysis of this information mainly focused on their multi-year smoothed characteristics and some rudimentary analyses of the evolving pattern of large scale upper atmospheric and surface drivers. The further characterization and determination of origins of large-scale circulation changes and the assessment of whether the associations between these large-scale drivers and smaller scale phenomena that were established using historical data would change in the future need to be investigated to a greater extent. Preliminary results revealed many ‘surprises’ which include radically different seasonal regional responses to flips in circulation patterns with season. In addition, statistically significant differences identified in the trends and other statistics of upper circulation patterns before and after mid-century suggest possible regime shifts of the seasonal large-scale drivers during this timeframe. Further research to elucidate the nature of such abrupt changes and to examine how such nonlinear large-scale responses to climate change are simulated in different models is critical for future improvements of climate change projections.

In addition, the analyses mainly relied on coarse resolution model outputs and future studies need to address critical issues in more detail. In particular, CMIP5 models may not properly account for all critical processes in the atmosphere, surface and boundary layer; their projections may lead to different hydroclimatic conditions than those from finer-resolution regional models. Higher resolution model projections are of particular importance for the region because many of the hydroclimate extremes in the area are related to frontal and organized convective systems that develop over the complex terrains which characterize the region. Moreover, numerous feedbacks from the evolving land surface, including vegetation changes, snowcover and freeze-thaw processes, need to be better accounted for; these affect atmospheric circulations, storms and precipitation distributions. Other surface-related feedbacks involve shifting oceanic circulations and sea ice evolution. The analyses furthermore did not directly consider the critical role of clouds in governing the atmospheric and surface water and energy budgets of the region; this certainly needs to be addressed. A related issue is ensuring that vertical atmospheric profiles are well handled over this evolving cold climate region; this is critical for atmospheric stability considerations which influence many atmospheric phenomena including precipitation distributions. Progress made here is therefore an important accomplishment that future studies can build on.

In summary, an assessment of future weather and climate conditions over the interior of western and northern Canada has been carried out largely based on CCRN-related research. Expectations are for a future with distinct seasonal changes in large scale atmospheric forcing, as well as temperature, and these are associated at least in part with changes in a host of associated smaller scale atmospheric-related phenomena.

Part two of this review and synthesis explores the associated changes at the surface and the responses and feedbacks to future climate of terrestrial ecosystems, the cryosphere, and regional hydrology.

Data availability.

CMIP5 data can be obtained from its data portals at https://cmip.llnl.gov/cmip5/data_getting_started.html (registration required).

The NARCCAP dataset is available at: http://www.narccap.ucar.edu/data/index.html.

The SPEI data can be obtained from CCDS (Canadian Climate Data and Scenarios) at http://climate-scenarios.canada.ca

The NCEP/NCAR re-analysis dataset is available at:
https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html

The CRCM5 dataset is available upon request to Julie Thériault (theriault.julie@uqam.ca) and Katja Winger (winger.katja@uqam.ca).

Author Contribution. RES was the lead author and carried out some of the analyses. KKS carried out several analyses and wrote sections of the manuscript. BRB, JMH, BK, YL, JMT and CMD carried out analyses and contributed to the manuscript. JAB, SM and DM, PYT, ZLi and ZLiu carried out computations and contributed to the manuscript. All authors contributed scientifically by providing comments and suggestions.

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