Evaluating the Distribution of Water Resources in Western Canada using a Synoptic Climatological Approach

by

Brandi Wreatha Newton
B.Sc., University of Alberta, 2011

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Supervisory Committee

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Abstract

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The atmospheric drivers of winter and summer surface climate in western Canada are evaluated using a synoptic climatological approach. Winter snow accumulation provides the largest contribution to annual streamflow of the north-flowing Mackenzie and east-flowing Saskatchewan Rivers, while summer water availability is primarily a product of basin-wide precipitation and evapotranspiration. A catalogue of dominant synoptic types is produced for winter (Nov-Apr) and summer (May-Oct) using the method of Self-Organizing Maps. Water availability, quantified through high-resolution gridded temperature and precipitation data, associated with these synoptic types is then determined. The frequency of dominant types during positive/negative phases of the Southern Oscillation Index, Pacific Decadal Oscillation, and Arctic Oscillation reveal the atmospheric processes through which these teleconnections influence surface climate. Results from the winter analysis are more coherent than summer, with strong relationships found between synoptic types, teleconnections, and surface climate. Although not as strong, links between summer synoptic types and water availability also exist. Additionally, time-series analysis of synoptic type frequencies indicates a trend toward circulation patterns that produce warmer, drier winters as well as an earlier onset and extension of the summer season. This study increases our understanding of the atmospheric processes controlling the distribution of water resources in western Canada.

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Acknowledgements

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Chapter 1: Introduction

1.1 Introduction

The spatial and temporal distribution of water resources is strongly affected by patterns of air temperature and precipitation. In western Canada, the Mackenzie and Saskatchewan Rivers represent key sources of water, and the headwaters of these rivers are located on the eastern slopes of the Rocky Mountains. Winter snow accumulation and melt, particularly in alpine headwaters, provides the largest contribution to annual streamflow of these rivers. During summer months, when air temperatures are high, water availability is primarily a product of precipitation and evapotranspiration.

There have been a number of documented trends in climate and streamflow in western Canada, including seasonal and annual increases in temperature (Zhang et al. 2000; McBean et al. 2005; Linton et al. 2014) and a mixed signal of both increases and decreases in seasonal patterns of precipitation (Zhang et al. 2000; Yip et al. 2012; Linton et al. 2014) and streamflow (Whitfield and Cannon 2000; Zhang et al. 2001; Burn and Hag Elnur 2002; Burn et al. 2004a; Burn et al. 2004b; Rood et al. 2008; Yip et al. 2012; Bawden et al. 2014; Ahmed et al. 2013 *unpublished data*). Evidence indicates climate change has, and will continue to accelerate the hydrologic cycle (Huntingdon 2006; Déry et al. 2009). These changes have not been spatially or temporally uniform, and minor alterations to temperature and precipitation can result in substantial cumulative impacts for water availability within a large watershed and across watershed boundaries.

Surface climate, including air temperature and precipitation, is largely driven by synoptic-scale atmospheric circulation patterns. The strength and position of mid-tropospheric troughs and ridges direct the movement and persistence of air masses. As air temperature dictates the amount of moisture the atmosphere can hold, mid-latitude bodies of water, particularly the Pacific Ocean, supply the greatest volume of moisture influx to western Canada. Surface climate is also influenced by large-scale teleconnections, including El Niño-Southern Oscillation and the Pacific Decadal Oscillation. Although several studies have examined the influence teleconnections exert on surface climate, no previous study has focused on the statistical relationship between teleconnections and synoptic-scale circulation. This research forms part of a larger project addressing trends and variability in water resource availability in western Canada as described in the next section.

1.2 The CROCWR Project

The Climatic Redistribution of western Canadian Water Resources (CROCWR) project was designed to quantify past and current trends, and predict future changes to water distribution in Canada through the evaluation of a suite of hydroclimatic variables including atmospheric circulation patterns, air temperature, precipitation, and streamflow (Prowse et al. 2013). Although hydroclimatic changes have been documented for western Canada, research has primarily focused on either small regions or at broad, coarser scales. Given the heterogeneous changes to surface climate regimes in western Canada, it is necessary to evaluate hydroclimatic trends and variability within sub-basins of large watersheds to determine 'water rich' and 'water poor' regions as well as changes to drainage patterns affecting freshwater input to Hudson Bay and the Arctic Ocean. Water resources are essential for hydroelectricity generation, agricultural production, municipal and industrial use, and ecological integrity. Results from the CROCWR analysis will be invaluable to water resource managers and policy makers, as well as an integral component to evaluating the freshwater budget of the Arctic Ocean.

1.3 Goal and Objectives

The purpose of this research is to assess the characteristics of the dominant mid-tropospheric circulation patterns as they relate to the spatial and temporal distribution of water availability in western Canada, and determine how the identified patterns are associated with large-scale teleconnections. Of particular interest are winter snow accumulation and subsequent spring freshet, the major hydrologic event on snowmelt-driven rivers, and the precipitation-evaporation regime driving summer water availability. To address this goal, the following objectives are identified for both winter (Nov-Apr) and summer (May-Oct) seasons.

1. Classify daily 500 hPa geopotential heights for 1950-2011 into dominant synoptic types.

2. Describe characteristics of identified synoptic types, including frequency, persistence, and trajectory.
3. Identify significant temporal trends in seasonal synoptic type frequency.
4. Identify spatial air temperature and precipitation patterns associated with each synoptic type.
5. Using identified synoptic types and associated air temperature and precipitation patterns, identify variability in seasonal synoptic type frequency associated with spatial patterns of high and low seasonal water availability.
6. Evaluate the relationship between identified synoptic types and large-scale teleconnections that have been shown to influence the surface climate in the study region, including the Southern Oscillation Index, Pacific Decadal Oscillation, Pacific North American pattern, and Arctic Oscillation.

1.4 Thesis Format

This thesis is divided into five chapters including the introduction. A literature review, presented in Chapter 2, provides detailed background information regarding the implications of water resource redistribution in western Canada, the application of air temperature and precipitation in quantifying water availability, methods of synoptic classification, large-scale teleconnections, and recent trends and variability of hydroclimatic and streamflow variables. Chapters 3 and 4 are written as stand-alone journal-style articles focusing on winter and summer seasons, respectively. As objectives 1-6 apply to both winter and summer, they are addressed in each of Chapters 3 and 4. The thesis concludes with Chapter 5, including recommendations for future research. Due to the manuscript style format of this thesis, some components of the literature review are repeated in Chapters 3 and 4.

Chapters 3 and 4 have been submitted concurrently to a special issue of Hydrological Processes. Additionally, components of this research have been presented at several conferences and published in conference proceedings. A complete listing of presentations and conference proceedings appears below.

Presentations and Publications

The section below provides a comprehensive list of conference presentations and published proceedings that contain results from research, or components thereof, appearing in Chapters 3 and 4.

Newton, B.W. and Prowse, T.D. (2012), Methods in synoptic climatology: Principal Components Analysis and Self-Organizing Maps. Presented at the annual meeting of the Western Division of the Canadian Association of Geographers (WDCAG), Kelowna, BC, Canada.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2012), The role of synoptic climatology on rivers originating on the leeward slopes of the Rocky Mountains in Canada. Presented at annual meeting of the Canadian Geophysical Union and Canadian Water Resources Association, Banff, AB, Canada.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2012), Climatic Redistribution of western Canadian Water Resources (CROCWR): The role of synoptic-scale circulation on rivers originating on the leeward slopes of the Rocky Mountains. Presented at the annual meeting of the American Geophysical Union, San Francisco, CA, USA.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2012), Atmospheric circulation patterns affecting water availability of Rocky Mountain tributaries to the Mackenzie River. Presented at the ArcticNet annual scientific meeting, Vancouver, BC, Canada.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2013), The influence of teleconnections on synoptic-scale circulation patterns affecting western Canadian water resources. Climate Prediction S&T Digest Special Issue, proceedings of the 37th Annual NOAA Climate Diagnostics and Prediction Workshop, Fort Collins, Colorado, pp. 68-71.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2013), Synoptic-scale circulation characteristics Controlling Water Availability in Western Canada: A CROCWR Component. Presented at the annual meeting of the Canadian Geophysical Union, the Canadian Water Resources Association, and Canadian Meteorological and Oceanographic Society, Saskatoon, SK, Canada.

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2013), Synoptic Climatological Characteristics Associated with Water Availability in Western Canada: A CROCWR Component. Proceedings of the 19th Northern Research Basins Symposium, ed. Stuefer, S.L. and Bolton, W.R., Southcentral Alaska, pp. 167-177.

References

Ahmed, R., Prowse, T.D., Dibike, Y.B., and Bonsal, B.R. (2013) Spatial and temporal variation in the spring freshet of major circumpolar Arctic river systems. *Unpublished Master's thesis results*.

Bawden, A.J., Burn, D.H., and Prowse, T.D. (2014) Recent changes in patterns of western Canadian river flow and association with climatic drivers. *Submitted to Hydrological Processes*

Burn, D.H. and Hag Elnur, M.A. (2002), Detection of hydrologic trends and variability. Journal of Hydrology. 255, 107-122.

Burn, D.H., Cunderlik, J.M, and Pietroniro, A. (2004a), Hydrological trends and variability in the Liard River basin. Hydrological Sciences Journal. 49(1), 53-67.

Burn, D.H., Abdul Aziz, O.I. and Pietroniro, A. (2004b), A comparison of trends in hydrological variables for two watersheds in the Mackenzie River basin. Canadian Water Resources Journal. 29(4), 283-298

Déry, S.J., Hernández-Henríquez, M.A., Burford, J.E., and Wood, E.F. (2009), Observational evidence of an intensifying hydrological cycle in northern Canada. Geophysical Research Letters. 36, L13402

Huntington, T.G. (2006), Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology. 319, 83-95

Linton, H., Prowse, T., Dibike, Y., and Bonsal, B. (2014) Spatial and temporal analysis of hydroclimatic variables affecting streamflow in western Canada from 1950-2010. *Submitted to Hydrological Processes*

McBean, G., Alekseev, G., Chen, D., Førland, E., Fyfe, J., Groisman, P.Y., King, R., Melling, H., Vose, R., and Whitfield, P.H. (2005), Arctic climate: past and present. Arctic Climate Impacts Assessment (ACIA), C.Symon, L. Arris, and B. Heal (Eds)., Cambridge University Press, Cambridge, 21-60

Prowse, T.D., Bonsal, B.R., Burn, D.H., Dibike, Y.B., Edwards, T., Ahmed, R., Bawden, A.J., Linton, H.C., Newton, B.W., and Walker, G.S. (2013), Climatic redistribution of Canada's western water resources (CROCWR). In Stuefer, S.L. and Bolton, W.R. (Eds.) Proceedings from the 19th Northern Research Basins Symposium and Workshop (246). Fairbanks: University of Alaska Fairbanks

Rood, S.B., Pan, J., Gill, K.M., Franks, C.G., Samuelson, G.M., and Shepherd, A. (2008), Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probably impacts on floodplain forests. Journal of Hydrology. 349, 397-410

Whitfield, P.H. and Cannon, A.J. (2000), Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal. 25(1), 19-65

Yip, Q.K.Y., Burn, D.H., Seglenieks, F., Pietroniro, A., and Soulis, E.D. (2012), Climate impacts on hydrological variables in the Mackenzie River Basin. Canadian Water Resources Journal. 37(3), 209-230

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R. (2001), Trends in Canadian streamflow. Water Resources Research. 37(4), 987-998

Zhang, X., Vincent, L.A., Hogg, W.D., and Niitsoo, A. (2000), Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean. 38(3), 395-429

Chapter 2: Literature Review

The Rocky Mountains provide the headwater source for the primary tributaries to the Mackenzie River, Canada's largest freshwater contribution to the Arctic Ocean, and the Saskatchewan River, the primary water resource for the agricultural sector of the Prairie Provinces. Evaluating water availability within these large watersheds and assessing whether there has been a trend toward climatic redistribution of water resources across watershed boundaries requires knowledge of the processes related to precipitation, evapotranspiration, and snow accumulation and melt that are strongly influenced by atmospheric conditions at the synoptic scale. This chapter provides detailed background information about the Rocky Mountain tributaries to the Mackenzie River - the Liard, Peace, and Athabasca Rivers, and tributaries to the Saskatchewan River - the North Saskatchewan and South Saskatchewan Rivers. The hydroclimatic complexities of water resources in the study region are reviewed, including identifying source regions for moisture transport into and across watersheds, quantifying seasonal water availability, and documenting recent climatic and streamflow trends. Additionally, water resource supply and demand issues are addressed to provide contextual background information and highlight the importance of water availability studies in this region.

This research uses a synoptic climatological approach to evaluate atmosphere-surface climate links and determine the influence that large-scale teleconnections have on dominant atmospheric circulation patterns. Traditional synoptic typing methods are reviewed and a comprehensive description of self-organizing maps, the method used to classify synoptic circulation patterns, is provided. Teleconnection patterns known to influence surface climate in western Canada are also described, including El Nino-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Pacific North American (PNA) pattern, and the Arctic Oscillation (AO). Finally, synoptic climatological and teleconnection research conducted in western Canada, corresponding to the Saskatchewan and Mackenzie River Basins is reviewed. As this thesis is presented in manuscript format, it is necessary to repeat some components of this literature review in Chapters 3 and 4.

2.1 Study Region

2.1.1 Introduction

The north-flowing Mackenzie and east-flowing Saskatchewan Rivers (Fig. 2.1) are two large watersheds in western Canada that have been identified as vulnerable to changes in water resource distribution as a result of climate change. The snowmelt-dominated alpine tributaries to these rivers are located on the eastern slopes of the Rocky Mountains. These rivers flow from alpine headwaters to the Boreal Plains in the northern portion of the study area, and Prairie region in the south. The large mountain range acts as a physical barrier directing airflow and blocking a considerable amount of atmospheric moisture transported east from the Pacific Ocean. Consequently, the watersheds east of the Rocky Mountains are located in a rainshadow. The hydroclimatic effects of dry air descending these leeward slopes are explained in detail in Section 2.2.

As evident by the hypsometric profile given in Fig. 2.2, the proportion of alpine environment characterizing each basin is greater in the northern, compared with the southern, basins. During winter months, precipitation is higher over the alpine region than the Interior Plains, and this winter snowpack accumulation provides the largest contribution to annual flow of these rivers (Martz et al. 2007; Pentney and Orhn 2008). Precipitation is generally higher during summer than winter; however, as explained in Section 2.2, evapotranspiration plays an important role in summer water availability. Additionally, this availability is augmented by controlled release of stored water through hydroelectricity generation facilities and/or from glacial melt. The glacial contribution to streamflow is highest during mid-summer (Jul-Sep) and varies by sub-basin depending on percentage of basin area that is glacierized (Comeau et al. 2009).

2.1.2 Mackenzie River Basin

The largest source of freshwater to the Arctic Ocean is river discharge (Serreze et al. 2003; Arnell 2005), and the Mackenzie River provides the largest influx of freshwater to the Canadian region of the Arctic basin. The freshwater budget of the Arctic Ocean is important to numerous terrestrial and marine processes including feedbacks to the global climate (Lewis et al. 2000). For example, freshwater flux to the Arctic Ocean leads to density-based stratification and circulation, which impacts the formation of sea ice (Lammers et al. 2001; Arnell 2005). Volumetrically, most of the flow of the Mackenzie River originates outside the Arctic, primarily stemming from the Liard, Peace, and Athabasca Rivers (Fig.

2.1). Therefore, much of the freshwater flow into the Arctic Ocean is affected by hydroclimatic factors south of the Arctic. Recently, evidence has supported an intensification of the hydrologic cycle (Huntington 2006; Déry et al. 2009) and one of the greatest concerns over this intensification is the freshening of the Arctic Ocean (Morison et al. 2012; Arnell 2005). Of particular importance have been the changes to streamflow characteristics including earlier spring runoff and discharge volume (Zhang et al. 2001; Burn and Hag Elnur 2002; Abdul Aziz and Burn 2006). This raises concerns over changes to water resource distribution in these mid-latitude mountainous headwaters.

The Liard is unregulated and, as the largest tributary to the Mackenzie River, exerts the largest influence on streamflow. Snowfall amounts vary considerably throughout the Liard basin, with higher snowfall over the southwest corner of the basin due to the influence of moist air masses originating over the Pacific Ocean, and the remainder of the basin receiving a lower snowfall volume (Woo and Thorne 2006). The Liard River flows north from the Rocky Mountain headwaters and joins the Mackenzie River mainstem at Fort Simpson, Northwest Territories.

The Peace River flows across northern Alberta and drains into Lake Athabasca at the Peace-Athabasca Delta, a sensitive ecosystem with high biological productivity. A portion of the Peace-Athabasca Delta is located in Wood Buffalo National Park and is also listed as under the Ramsar Convention as a wetland of international importance (Peters et al. 2006; www.ramsar.org). The Peace River has been regulated by the W.A.C. Bennett dam since 1968, which has resulted in considerable increases in winter flow, decreases in peak spring flow, and a smoother hydrograph with lower annual variability (Peters and Prowse 2001). This hydrograph variability is an essential component of flood hydrology in the Peace-Athabasca Delta (Peters et al. 2006). The effects of regulation have also influenced aquatic hydroecology and river ice processes (Prowse et al. 2002). The Slave River connects Lake Athabasca to Great Slave Lake, connecting the Peace and Athabasca Rivers with the Mackenzie River.

The Athabasca River is characterized by low winter flow, high spring flow during freshet and sustained flow during summer months due to glacier melt (Woo and Thorne 2003). Glacial meltwater contributes to streamflow during late summer once snowpack has completely melted (Marshall et al. 2011). The Athabasca River is unregulated, and serves as a municipal water source for several small communities and a major industrial region in northeast Alberta. The Athabasca River streamflow has declined by 30% since 1970, including water withdrawals and natural changes (Schindler and Donahue 2006). In 2010, 74.5% of total Athabasca River surface water allocations were licensed for the oil and gas industry (Alberta Environment, http://environment.alberta.ca/ 01750.html).

2.1.3 Saskatchewan River Basin

The Saskatchewan River Basin (SRB; Fig. 2.1) is primarily located in a semiarid prairie ecozone, extending from Rocky Mountain headwaters at the continental divide to Lake Winnipeg in Manitoba. The Saskatchewan River is a major tributary to the Nelson River, which drains into the Hudson Bay. Winter snow cover across the prairies is generally sparse and annual evapotranspiration is greater than average annual precipitation (Schindler and Donahue 2006). Extended periods of drought and periods of extreme precipitation and/or flooding are frequently occurring components of prairie hydroclimatology, contributing to the high interannual variability of water resources (Shabbar et al. 2011). Natural hydroclimatic variability is one of the greatest risks to the region (Sauchyn and Kulshreshtha 2008), as there are economic and environmental consequences associated with droughts and periods of abundant rainfall. Maintaining adequate flow is challenging for water managers who must balance the water needs of all users within the basin, particularly during drought conditions and resultant low streamflow (Schindler and Donahue 2006).

The SRB faces several water management challenges including high seasonal demand, regulation, and numerous water-use licenses, particularly in Alberta. Water withdrawals, land-use changes, and other anthropogenic modifications have resulted in lower than natural flows on the rivers of the southern Prairie Provinces (Schindler and Donahue 2006). Surface water in the SRB is heavily allocated, the majority of which is licensed to the agricultural sector. In the South Saskatchewan River Basin, approximately 70% of surface water is withdrawn, 86.5% of which is for agricultural use and only 8.7% for municipal use, and irrigation-based water withdrawals are projected to increase (Martz et al. 2007). The 1969 Master Agreement of Apportionment between Alberta and Saskatchewan requires Alberta to pass approximately 50% of the natural flow on the South Saskatchewan River into Saskatchewan. Water demands are highest during summer months (May-Aug; Schindler and Donahue 2006), and the agreed-upon volume may exceed available resources during periods of drought due to allocated water withdrawals (Pentney and Ohrn 2008).

The Saskatchewan River is regulated by numerous dams and reservoirs, the largest of which is the Gardiner Dam and Coteau Creek hydroelectric facility south of Saskatoon. These dams are used for flood control, agriculture, and hydroelectricity generation (Pentney and Ohrn 2008). Dams have been shown to substantially alter the hydrologic regime of a river including timing and magnitude of high/low flows (Peters and Prowse 2001; Costigan and Daniels 2012). For example, naturally low winter flow is enhanced by the release of water from reservoirs to meet demand for electricity, creating hydrograph peaks during winter months (Martz et al. 2007; Lajoie et al. 2007). Byrne et al. (1999) found that the spring hydrograph on some dam regulated rivers frequently corresponds to magnitude of snowpack as reservoirs are managed to retain water during times of low snowpack or release stored water to increase capacity during times of high snowpack. Unlike other water uses, the generation of hydroelectric power is non-consumptive as water is returned to the river system, but it does require the availability of water corresponding to peak electricity demand. Therefore, dams and reservoirs are essential to maintaining water availability (Barnett et al. 2005) and may be used as a tool for water managers, retaining a portion of the spring freshet for summer water use, or attenuating flood events within the basin (Smith and Pérez-Arlucea 2008).

2.2 Water Resources in Western Canada

2.2.1 Quantifying Water Availability

As described above, the water resources of the Mackenzie and Saskatchewan Rivers are essential for municipal, industrial, and agricultural use, hydroelectricity generation, and ecosystem integrity. Therefore, understanding and forecasting water availability is fundamental for the management of resources and flood mitigation. Additionally, spatial and/or temporal changes to water availability are an indicator of climate change (Stewart et al. 2004). Variations in annual and seasonal streamflow are largely a function of climatic variables, mainly precipitation and air temperature, which are strongly influenced by synoptic-scale atmospheric circulation patterns.

Although there are several procedures that can be incorporated to quantify water availability at various spatial and temporal scales, the most conventional method over large regions and longer time scales is a water-balance approach, which quantifies measured variables of inputs from precipitation and groundwater and outputs to streamflow, evapotranspiration, and groundwater recharge (Thornthwaite and Mather 1955). The basic water-balance equation for streamflow is $P–E=R$, where P is precipitation, E is evapotranspiration, and R is runoff. Evapotranspiration is largely a function of air temperature, and dominates during summer when temperatures are high. During winter, air temperature primarily affects the length of the snow accumulation season through the onset of freeze up and snowmelt.

Precipitation and air temperature are measured continuously, alongside several other variables at a climate station, offering point source meteorological data. These climate stations are often located in populous areas or valleys that may not adequately capture the air temperature and precipitation regimes in surrounding areas or at higher elevations. Additionally, climate stations in southern Canada are numerous and have long data records, often as far back as 1911, but stations in northern Canada are sparse and records are shorter, often no more than 60 years. The accuracy of measured variables is affected by changes to meteorological instrumentation, the quantification of trace precipitation measurements, and evaporation effects (Mekis and Hogg 1999). In addition, climate station records often contain missing values.

Representing the spatial distribution of climate variables is best achieved through the use of gridded data sets, developed through the interpolation of climate station data. There have been a number of gridded air temperature and precipitation datasets developed for western Canada. Each is different in terms of their spatial scales, gridding procedures, and input climate stations. The majority of these datasets were produced at monthly time steps and have been used, for example, to evaluate the relationship between teleconnections and temperature (Shabbar and Khandekar 1996, Bonsal et al. 2001), assess temporal trends in precipitation and temperature (Zhang et al. 2000; Woodbury et al. 2009), and compare observed and simulated Global Climate Model (GCM; Bonsal and Prowse 2006). More recently, daily gridded temperature and precipitation datasets have been created for Canada, in 10-km resolution (1950-2010), using the ANUSPLIN method of thin-plate splines (Hutchinson 2004; McKenney et al. 2011). The ANUSPLIN interpolation method takes into account elevation in addition to latitude and longitude. Climate stations omitted from the gridding procedure were used to evaluate the quality of this dataset, and it was concluded that it is reliable and robust (Hutchinson et al. 2009).

2.2.2 Seasonal Water Availability

Seasonal water availability is the product of the cumulative effects of air temperature and precipitation over several months. A number of drought indices that are based solely on temperature and precipitation have been developed to quantify short- and long-term water availability. These include the Palmer Drought Severity Index (PDSI; Palmer 1965), the Standardized Precipitation Index (SPI; McKee et al. 1993), and the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010a). Although these indices have been primarily applied to drought research, they have also been used to evaluate periods of prolonged excessive moisture (e.g. Shabbar et al. 2011). The PDSI accounts for soil moisture conditions through precipitation and temperature measurements; however, the PDSI operates on a fixed time scale and was calibrated for a region in the mid-western United States (McKee et al. 1993). The SPI is based on precipitation alone and does not reflect the affect high air temperatures have on drought conditions (Vicente-Serrano et al. 2010a; Bonsal et al. 2012). The SPEI utilizes a water-balance equation proposed by Thornthwaite and Mather (1955), incorporating potential evapotranspiration as well as precipitation into the equation

(Vicente-Serrano et al. 2010a). Since the index is standardized, it can be applied to any region of interest. Comparisons between these indices consistently conclude the SPEI is superior in reflecting water availability, particularly at intermediate time periods (Vicente-Serrano et al. 2010b; McEvoy et al. 2012).

The magnitude of winter snowpack is the product of snow accumulation, and is an integral component of annual streamflow. The seasonal shift from liquid to solid precipitation, and the release of water from frozen storage is dictated by the evolution of air temperature above/below the freezing point. The cold season is subject to a number of processes that can reduce the snowpack, including sublimation (MacDonald et al. 2010) and Chinook winds (Goulding 1978). Chinook winds are dry, adiabatically warmed air descending the leeward slopes of the Rocky Mountains, and are more frequent in southern Alberta compared with the northern end of the Rocky Mountains (Longley 1967).

Summer water availability is highly variable, and periods of drought are common, particularly in the Prairie Provinces (Bonsal et al. 2012). Droughts are devastating and expensive natural disasters that have widespread agricultural and environmental implications (Wheaton et al. 2008; Stewart et al. 2011), and can affect hydroelectricity generation (Roberts et al. 2006). Periods of high-intensity precipitation and/or extended wet conditions can also have negative consequences and pose water management challenges. During summer, water availability is largely influenced by evapotranspiration as well as precipitation. Consequently, it is essential to evaluate seasonal moisture conditions using an index that reflects both of these variables.

2.2.3 Hydroclimatic Trends and Implications

Winter snowpack is the dominant hydroclimatic feature controlling water availability on western Canadian watersheds and changes to the snow accumulation season, spatial distribution of snowfall, and magnitude of snowpack alter the frozen storage reservoir and thus the hydrograph characteristics of mountainous tributaries (Barnett et al. 2005). Of particular importance to summer water availability are increases in air temperature, which enhance evapotranspiration and can result in net moisture decreases, even if precipitation increases occur (Tanzeeba and Gan 2012). Many trends have already been detected for the region encompassing the watersheds of the eastern slopes of the Rocky Mountains, and a number of hydrologic and cryospheric trends are described below.

Time-series trend analyses have been performed on many hydrological and climatological variables in western Canada at a range of spatial and temporal scales. Annual temperature increases were reported for the 1950-1998 period, with the greatest increases occurring in northwestern Canada (Zhang et al. 2000). The largest temperature increases were observed in winter (Dec-Feb) and spring (Mar-May), moderate increases for summer (Jun-Aug), and decreases for autumn (Sep-Nov). In a study focused on western Canada using the ANUSPLIN high-resolution daily gridded dataset (McKenney et al. 2011), Linton et al. (2014) detected annual temperature increases for western Canada over the 1950-2010 period, with the greatest increases occurring during the cold season (Nov-Apr), particularly in northern Canada.

In terms of precipitation, Zhang et al. (2000) found predominantly increasing trends for the 1950-1998 period, with the greatest increases over northern Canada during the winter (Dec-Feb), and decreases over southwestern Canada during winter and in the northwest corner of the Northwest Territories during summer (Jun-Aug). Using gridded data at 10-km resolution (McKenney et al. 2011), Linton et al. (2014) reported spatially varied precipitation increases and decreases throughout the year, with decreases largely occurring during the winter (Nov-Apr) and increases during summer (May-Oct). Additionally, summer precipitation increases were primarily focused in the southern Liard and northern Peace River Basins (Linton et al. 2014).

Increasing winter and spring air temperatures have resulted in an earlier average date that air temperatures shift from predominantly below to above 0°C, signaling the onset of snowmelt (Bonsal and Prowse 2003). Snowmelt in western Canada has increased for the 1950-2010 period during Mar-Apr, and decreased during May, indicating earlier snowmelt (Linton et al. 2014). Earlier snowmelt in alpine headwaters has resulted in a decreasing trend of river-ice conditions (Zhang et al. 2001), date of spring pulse onset, and peak spring discharge (Burn 1994; Whitfield and Cannon 2000; Zhang et al. 2001; Burn and Hag Elnur 2002; Burn et al. 2004a; Abdul Aziz and Burn 2006; Rood et al. 2008; Bawden et al. 2014).

Air temperature and precipitation trends and variability are linked to number of significant trends in streamflow in western Canada. However, much like the temperature and precipitation trends, the hydrologic responses have not been heterogeneous. Additionally, the evaluation of spatio-temporal hydrological changes is difficult given the generally shorter records at hydrometric stations. Although many studies have concluded that annual discharge of rivers in western Canada has been decreasing (Zhang et al. 2001; Burn and Hag Elnur 2002; Burn et al. 2004b; Rood et al. 2005), conflicting trend-analysis results exist as a result of different time periods analyzed, the number and selection of hydrometric stations, and methodology used to evaluate change. For example, a mix of increasing and decreasing annual or seasonal streamflow trends have been reported for various hydrometric gauging stations in the Mackenzie (Whitfield and Cannon 2000; Zhang et al. 2001; Burn and Hag Elnur 2002; Burn et al. 2004a,b; Rood et al. 2008; Yip et al. 2012, Bawden et al. 2014) and Saskatchewan River Basins (Westmacott and Burn 1997; Whitfield and Cannon 2000; Zhang et al. 2001; Burn and Hag Elnur 2002; Burn et al. 2008; Rood et al. 2008; Bawden et al. 2014). This emphasizes the need for additional research to identify hydroclimatic variables influencing hydrology of river basins in western Canada, including links to dominant atmospheric circulation patterns to explain such variation as next reviewed.

2.3 Synoptic Climatology

2.3.1 Introduction

Synoptic climatology is the science of understanding links between large-scale atmospheric circulation and surface climate variables, such as air temperature and precipitation (Yarnal, 1993). Air masses retain characteristics of their source region and are modified through surface energy interactions. Atmospheric pressure patterns dictate the direction and magnitude of the movements of these air masses. The mid-troposphere exhibits patterns of high, low, meridional, or zonal pressure gradients that vary spatially and temporally. The positions of troughs and ridges drive surface high- and low-pressure systems and indicate the location of surface frontal boundaries (Holton 1979). For example, located to the right of a ridge axis and the left of a trough axis is a region of convergence, resulting in descending air and surface divergence, suppressing cloud formation and precipitation. Conversely, to the left of a ridge axis and right of a trough axis is a region of divergence, resulting in surface convergence, rising air, which is conducive to cloud formation and precipitation (Holton 1979). Within the study area of this research, lee cyclogenesis is common as moist air rises over the Rocky Mountains, then dry air descends the leeward slopes, warming adiabatically and stretching the air column, causing instability (Martin 2006).

In synoptic climatological studies, a catalogue or archetype set of synoptic patterns is produced through objective or subjective analyses. Such a classification reduces a large dataset by grouping similar circulation types into a manageable set of patterns that can be used to facilitate analysis with surface climate. Traditional and new methods of synoptic classification are reviewed and compared below, and an in-depth summary of Self-Organizing Maps (SOM), the method used in this research, is provided. Additionally, a description of large-scale teleconnections that are known to influence climate in western Canada is given.

2.3.2 Synoptic Classification

Synoptic classification was initially performed using manual analysis (Yarnal et al. 2001); however, through the development of improved data collection and computerized statistical analysis techniques, classification methodologies have improved, including Kirchhofer sum-of-squares, K-means cluster analysis, and Principal Components Analysis (PCA; Yarnal 1987; Huth et al. 2008). A full description and literature review of a number of methods and applications of synoptic climatology can be found in Yarnal (1993), Yarnal et al. (2001), and Huth et al. (2008).

One of the challenges in synoptic classification is defining a suitable number of types, large enough for all relevant circulation patterns to be identified and small enough to avoid overgeneralization that leads to redundant patterns (Hewitson and Crane 2002; Cuell and Bonsal 2009). A staple for synoptic climatology over the past few decades has been PCA, a data-reduction method that isolates the variance in the dataset. PCA produces a set of eigenvectors, each representing a percentage of the total variance, with the first eigenvector (the principal component) explaining the largest variance, and each subsequent eigenvector a smaller percentage (Yarnal 1993). Hewitson (2008) suggests that PCA results are difficult to interpret due to the data reduction. PCA is frequently followed by cluster analysis, such as k-means, to produce a catalogue of discrete patterns. Yarnal (1993) recommends retaining only a few important eigenvectors, as they represent a large percentage of variance. However, retaining only a few components from PCA leads to a synoptic catalogue that may not be accurate, and the subjectivity involved in deciding how many eigenvectors to retain changes the resulting synoptic classification and retaining all eigenvectors defeats the data reduction purpose of performing PCA (Cuell and Bonsal 2009).

2.3.3 Self-Organizing Maps

SOM is a relatively new method being used to conduct synoptic classification. SOM allows large data sets to be organized and visualized to facilitate analysis, such as the previously noted relationship between synoptic-scale atmospheric circulation patterns and surface climate variables. SOM is an unsupervised, iterative training process that uses competitive and cooperative learning to cluster and project data onto an organized output array (Kohonen 2001). When applied to atmospheric circulation data, the vectors containing georeferenced, geopotential height (gph) data are organized such that the output array spans the continuum of atmospheric states. The learning process is similar to traditional cluster analysis as the input data are mapped to the best fit node; however, the goal of cluster analysis is classifying data into groups based on similarities, where SOM "attempts to find points in the physical space that are representative of nearby observations" (Huth et al. 2008, p. 113). Unlike cluster analysis, SOM produces a topologically ordered array through neighbourhood relationships between nodes (Kohonen 2001), thus representing a continuum of data space from the top-left to bottom-right corners.

The strength of SOM data projection is that nodes are connected through topological relationships. During training, when a 'winning' node is identified, the values of the node are updated to be closer to the data vector. Neighbouring nodes are also updated, but to a lesser extent. This updating procedure reduces the Euclidean distance between the neighbouring nodes. The number of neighbouring nodes to be updated during training is defined as the radius, which is initially a large number and reduces to 1 at the end of training process. There is no set consensus for defining radius in the literature. For example, Michaelides et al. (2007) recommends an initial neighbourhood radius of 90% of the smallest side of the output array. Others defined the initial radius as equivalent to the smallest side of the array (Hewitson and Crane 2002; Johnson et al. 2008). The initial radius may be defined as a small value, updating only the closest neighbouring nodes (Liu and Weisberg 2007; Schuenemann et al. 2009). If a radius of 0 was defined, SOM behaves like a cluster analysis tool without data projection, because neighbouring nodes are not updated during map training (Jiang et al. 2012). In most cases, the final SOM array used for analysis is the product of a large number of SOM training runs using varying parameters and selecting the best map, as recommended by Kohonen (2001).

Kohonen (2001) outlined a number of recommendations for creating stable, high-quality SOM arrays. As the library of literature using SOM methodology in synoptic climatology research has grown, new benchmarks have been established for choosing the optimal SOM output size and shape, and assessing quality of SOM results. Due to the geographic space depicted by synoptic atmospheric windows, researchers almost exclusively select the `rectangular' over `hexagonal' sheet for SOM array size and organization, although Kohonen (2001) suggests the `hexagonal' array to be visually superior. Kohonen (2001) also recommends choosing rectangular (e.g. 4x3) rather than square (e.g. 3x3) arrays for mathematical stability. The best-matching unit is the node to which an individual data vector is closest. The distance between the best- and the second-best matching units is also a measure of topological ordering. Ideally, the second-best matching unit is a direct neighbour of the best-matching unit, and the percentage of instances where this is not the case is referred to as topographic error (Vesanto et al. 2000). Quantization error is calculated as the average Euclidean distance between each data vector and corresponding best matching unit, and thus is a measure of within-group variance and how well SOM represents the data (Vesanto et al. 2000). Both topographic and quantization error are queries built into the SOM program. Root mean-square differences have also been used to quantify within-group variance (Hewitson and Crane 2002; Reusch 2010). These methods, along with additional quality assessments, allow the researcher a degree of confidence in the data representation of the SOM. However, some have declared the subjective choice of SOM array size to be as valid as using the measure of quantization and topographic error (Hewitson and Crane 2002; Cassano et al. 2006). Ultimately, as with any synoptic classification method, the SOM array chosen should serve the intended purpose (Huth et al. 2008). Therefore, the choices made with regards to SOM output array for synoptic climatology should account for some relationship with surface climate variables in addition to the quality assessment measures presented by Kohonen (2001) and others.

The first step in SOM is map initialization, which can be conducted either using random or linear initialization methods. Linear initialization uses the first two eigenvectors to determine variance that spans the array, and is the default setting in SOM. Random initialization was created to prove that data vectors become organized during the initialization process (Kohonen 2001). Random initialization demonstrates the ability of SOM to organize data, as data are presented in an arbitrary fashion rather than through eigenvectors. The initialized array contains an ordered set of nodes of representative data vectors, the number of which is defined by the user. For example, defining a 3x4 array results in a SOM with 12 nodes arranged in three rows and four columns.

Initialization is followed by training, using either sequential or batch algorithms. In sequential training, data vectors are presented one at a time, where batch training presents the entire set of data vectors at once. The aim of training is for each data vector to be matched to the 'winning' node, based on Euclidean distance (Kohonen 2001). Batch training was determined to be faster and less subjective than the sequential algorithm as the sequential algorithm requires definition of additional parameters (Kohonen 1993; Kohonen 1999; Liu and Weisberg 2005; Jiang et al. 2012).

A full description of the SOM algorithm and training process is available at Kohonen (2001), and application of SOM to geographic applications at Agarwal and Skupin (2008). Additionally, Reusch (2010) provides a comprehensive description of SOM implementation and explanation of the SOM output array in general terms and applied to a climatological problem. Sheridan and Lee (2011) review the use of SOM methodology in synoptic climatology research. Public domain software is available from the developers of SOM, including a SOM Toolbox for Matlab (Vesanto et al. 2000; http://www.cis.hut.fi/research/som-research/).

2.3.4 PCA-SOM Comparison

SOM presents many advantages over traditional synoptic classification methods (Hewitson and Crane 2002; Reusch et al. 2005; Cassano et al. 2006; Hewitson 2008; Reusch 2010). One of the primary advantages is the 'real world' visualization that SOM provides, as it treats the data as a continuum rather than discrete variables, unlike traditional typing methods, including PCA (Hewitson and Crane 2002). Reusch et al. (2005) determined that SOM is able to effectively handle discontinuous data by interpolating during the training phase, then failing to assign input data to the interpolated node, giving it a frequency of 0. SOM does not exclude outliers or cluster outliers with inappropriate groups, which is shown to be important when examining extreme events (Cassano et al. 2006).

As PCA has been a popular method of synoptic classification, a number of studies have compared the relative performance of SOM versus PCA (e.g. Astel et al. 2007; Liu and Weisberg 2006; Iseri et al. 2009; Jiang et al. 2012). Reusch et al. (2005) compared SOM with PCA using a synthetic dataset consisting of eight simple circulation patterns repeated randomly to create 1000 data vectors. Varying degrees of noise were added to the dataset for some of the comparison tests, and both rotated and unrotated PCA were tested. Results concluded that PCA failed to extract known patterns, blended patterns, and identified patterns not present in the original dataset. Conversely, the SOM array accurately represented original patterns and pattern frequency, and it was determined that SOM was less subjective of the two methods (Reusch et al. 2005). Cannon et al. (2002) suggest that a direct comparison of synoptic classification may be of limited use, as each method arrives at a synoptic catalogue through different goals. Reusch et al. (2005) also acknowledge the challenge of comparing these classification tools, but nevertheless conclude that SOM outperforms PCA.

2.3.5 Teleconnections

A teleconnection is a recurrent large-scale atmospheric pressure or sea-surface temperature (SST) pattern that has climatic implications ranging from local to global. Due to the recurrent nature of teleconnections, indexing is commonly performed, providing a consistent set of values readily available for statistical analysis with climatic data (Yarnal et al. 2001). Several teleconnections, including El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Pacific North American (PNA) pattern, and the Arctic Oscillation (AO) have been shown to influence climate in western Canada. Ocean-based teleconnections have long-term persistence, such as positive and negative ENSO phases lasting 6 months to several years, and positive and negative PDO phases persisting for several decades. By contrast, atmospheric teleconnections, such as the PNA pattern or AO, are based on atmospheric pressure heights at specific locations, can change on a daily basis, and can vary considerably through the course of a month or season, although long-term index averages may indicate predominantly positive or negative phases.

The Southern Oscillation Index (SOI) is one of many indices representing ENSO and is calculated as the difference in sea level pressure (SLP) anomalies between Tahiti, French Polynesia, and Darwin, Australia (http://www.cgd.ucar.edu/cas/catalog/climind/soi.html). Negative (positive) values of the SOI represent below (above) average SLP in Tahiti and above (below) average SLP in Darwin, and are also associated with above (below) average SST in the eastern edge of the tropical Pacific basin. Strong, persistent negative (positive) phases of SOI are referred to as El Niño (La Niña), while values in between are considered neutral. ENSO has been linked to global atmospheric phenomena including intensity of the Aleutian Low (Horel and Wallace 1981).

The PDO represents SST anomalies in the North Pacific Ocean calculated using empirical orthogonal function (EOF) analysis (Mantua et al. 1997). During the warm, or positive (cool, or negative) phase of the PDO, SST in central North Pacific is cooler (warmer) and the eastern edge of the North Pacific basin is warmer (cooler; Mantua and Hare 2002). The PDO oscillates between a cold and warm phase on a multi-decadal scale, with a well-documented cold- to warm- phase shift in the mid-1970s (e.g. Mantua et al. 1997; Hare and Mantua 2000). There has been some speculation that the PDO may have shifted from a predominantly positive to negative phase in 1998 (Peterson and Schwing 2003; Overland et al. 2008; Whitfield et al. 2010).

Monthly values of the PNA pattern are calculated using rotated principal components analysis (RPCA) of 500 hPa gph anomalies between 20° and 90°N, relative to 1950-2000 mean (Barnston and Livezey 1987). Daily values are then determined through Least Squares regression. The PNA pattern indicates mid-tropospheric circulation by identifying four centres of action located over the North Pacific, Hawaii, western Canada, and southeastern United States (Wallace and Gutzler 1981; Barnston and Livezey 1987). The PNA is an indicator of the intensity of the Aleutian Low, a frequent, persistent centre of low-pressure located over the Aleutian Islands off the coast of Alaska in the North Pacific (Wallace and Gutzler 1981) that has been linked to surface climate in western Canada, as described in Section 2.4. Positive phases of the PNA pattern are associated with lower than normal pressure over the North Pacific and higher than average pressure over western North America, and negative phases of the PNA pattern are associated with anomalously high pressure over the North Pacific and anomalously low pressure over western Canada.

The AO is calculated as the first eigenvector of sea-level pressure (SLP) anomalies poleward of 20°N referenced to the 1979-2000 mean value (Thompson and Wallace 1998). During the positive AO phase, anomalously low pressure exists over the Arctic and above average pressure exists over the mid-latitude region. The opposite relationship exists during negative phases. Because pressure gradients dictate air movement from regions of high to low pressure, high pressure above the Arctic leads to troughs of cold arctic air extending into the mid-latitudes and corresponding ridges of warmer air extending poleward. Conversely, low pressure above the Arctic suppresses these outbreaks of Arctic air masses. The AO shifts between predominantly negative or positive phases that persist for several years (Overland and Wang 2005). Loss of sea ice has been linked to atmospheric circulation patterns associated with recent trends in the AO (Rigor et al. 2002). This loss of sea ice increases ocean surface area and, thus, the capacity for heat storage and exchange (Rigor et al. 2002; Serreze et al. 2009), and is projected to further alter atmospheric circulation patterns (Overland and Wang 2010).

2.4 Previous Synoptic Climatological and Teleconnection Studies

2.4.1 Synoptic-Scale Circulation

Several general synoptic-scale circulation patterns have been identified as important to the hydroclimatology of the southern Prairie Provinces, the region containing the Saskatchewan River Basin, and in some cases also contain portions of the Athabasca and Peace River Basins. Due to the high summertime water demand and hydroclimatic variability, most of the studies conducted have focused on summer precipitation. For example, mid-tropospheric zonal flow across the prairies was found to be associated with high precipitation, whereas a ridge centred over the prairies and associated meridional flow was associated with low precipitation (Knox and Lawford 1990; Saunders and Byrne 1996; Bonsal et al. 1999; Shabbar et al. 2011). Knox and Lawford (1990), Bonsal et al. (1999), and Shabbar et al. (2011) used a ground-to-circulation method to create composite circulation patterns associated with dry and wet surface conditions. Conversely, using a circulation-to-ground approach, Saunders and Byrne (1996) created a catalogue of 20 synoptic types using the Kirchhofer method, and compared observed with GCM-simulated patterns as well as evaluating monthly precipitation efficiency. In general, persistent high-pressure ridging over the Prairie Provinces is most commonly associated with drought conditions as it blocks the advection of moisture from the Pacific Ocean or Gulf of Mexico (Bonsal and Wheaton 2005). In a study addressing Rocky Mountain winter snowpack in a region just south of the Canadian prairies, Chagnon et al. (1993) manually classified 500 hPa gph over Colorado, Idaho, Montana, Utah, and Wyoming, and found higher precipitation associated with a trough and meridional flow over the region and low precipitation associated with the opposite conditions.

For the case of the Mackenzie River Basin (MRB), lee cyclogenesis at the surface was found to be the largest producer of precipitation events (Lackmann and Gyakum 1996; Smirnov and Moore 1999; Spence and Rausch 2005; Finnis et al. 2009). Lee cyclones typically develop following a surface Aleutian Low or cyclone over the Gulf of Mexico, and these low-pressure systems occur primarily during winter months (Finnis et al. 2009; Cassano and Cassano 2010). Smirnov and Moore (2001) determined that the Pacific Ocean was the primary moisture source for the Mackenzie River Basin during winter. However, during summer months, storm tracks directed by a ridge of high pressure over the western continent resulted in the advection of moist air from the Arctic Ocean to the Mackenzie River Basin (Smirnov and Moore 1999; Smirnov and Moore 2001; Finnis et al. 2009; Cassano and Cassano 2010). Additionally, high precipitation events were shown to result from the intersection of lee cyclones and moist air masses originating over the Gulf of Mexico that easily pass over the relatively topographically flat prairie region (Brimelow and Reuter 2005).

2.4.2 Teleconnections

Teleconnection indices, including the SOI, PDO, PNA, and AO, have commonly been used to evaluate variability in surface climate and streamflow in western Canada. El Niño (negative SOI) has been linked to significantly below average winter precipitation and La Niña (positive SOI) with significantly above average winter precipitation in the southern Prairie Provinces; however, a portion of the Mackenzie River Basin experiences significantly above average precipitation during El Niño (Shabber et al. 1997). El Niño (La Niña) was also associated with above (below) average winter temperatures in western Canada (Shabbar and Khandekar 1996; Bonsal et al. 2001) and a higher frequency of extreme warm (cold) events during winter (Shabbar and Bonsal 2004). It should be noted that the link between ENSO and temperature is stronger and more consistent than that of precipitation. Additionally, many studies evaluating ENSO and surface climate conditions have focused on winter months as the ENSO signal is strongest during this time (Shabbar and Khandekar 1996). However, long-term or severe drought and extended dry periods during summer months (Jun-Aug) occur more frequently during El Niño compared with La Niña or neutral ENSO events (Bonsal and Lawford 1999; Bonsal and Wheaton 2005).

The SOI and PDO have been linked to characteristics of atmospheric circulation. Composite mid-tropospheric circulation maps reveal that the dominant circulation during El Niño conditions was a low-pressure centre over the North Pacific and high-pressure over central Canada (Shabbar and Khandekar 1996; Shabbar et al. 1997). Conversely, dominant circulation during La Niña was a ridge of high-pressure over the North Pacific (Shabbar and Khandekar 1996; Shabbar et al. 1997). Positive phases of the PDO have been linked to an increased frequency of a mid-tropospheric trough over the North Pacific Ocean, while a ridge over the same region is prevalent during negative phases (Bond and Harrison 2000).

Atmospheric circulation anomalies that occur during El Niño (La Niña) were found to be similar to patterns that occurred during positive (negative) phases of the PNA (Horel and Wallace 1981). Positive PNA was associated with increased advection of moderate Pacific air masses and negative PNA was associated with increased advection of dry polar air masses over North America, particularly during winter months (Sheridan 2003). Romolo et al. (2006a,b), employing PCA and k-means cluster analysis, examined links between El Niño and positive PNA with warm dry synoptic types and high-pressure ridges over western Canada. La Niña and negative PNA phases were linked to zonal flow or troughing that were associated with cool, wet synoptic types.

Although the influence of the AO extends to the mid-latitudes, this influence is not spatially uniform. For example, weak correlations exist between the AO and temporal characteristics of winter cold/warm spells (Shabbar and Bonsal 2004) and the timing of spring and autumn 0°C-isotherm dates (Bonsal and Prowse 2003) in western Canada. These findings are consistent with Deser (2000), who determined that AO exerts a greater influence in the mid-latitude region of the Atlantic than the Pacific.

Examining the potential synergies among multiple teleconnections is a key to understanding the climatology of a region, as there can be numerous interacting factors influencing surface climate. For example, Shabbar and Khandekar (1996) discovered instances where above (below) average temperatures occurred during La Niña (El Niño) events, the opposite of what is expected during ENSO phases. In another study, SST anomalies consistent with positive PDO (warm water adjacent to the west coast of North America and cool water in the central North Pacific) conditions were linked to increased frequency of El Niño and opposite SST conditions (consistent with negative PDO) associated with increased frequency of La Niña (Bonsal and Lawford 1999). Furthermore, Gershunov and Barnett (1998) and Bonsal et al. (2001) determined that PDO has a modulating effect on ENSO, where El Niño coupled with positive PDO or La Niña coupled with negative PDO resulted in a stronger influence on surface climate and mid-tropospheric circulation patterns, and opposite couplings (El Niño and negative PDO, La Niña and positive PDO) had a destructive relationship lacking the strong influence on climate and circulation anomalies. In general, failing to account for confounding variables and the destructive properties of out of phase teleconnections can lead to poor correlations when investigating the hydroclimatic response of a single teleconnection (Gobena and Gan 2006).

Teleconnections have been also shown to influence streamflow in western Canada. For example, Déry and Wood (2005) found that discharge to the Arctic Ocean to be significantly correlated with ENSO, PDO, and PNA, and discharge to the western Hudson Bay significantly correlated with ENSO, PDO, and AO. In the Prairie Provinces, negative streamflow anomalies occurred during the spring and summer following onset of El Niño, and positive anomalies occurred during the spring/summer following the onset of La Niña, although it was determined that the effects of ENSO were modulated by the PDO (Gobena and Gan 2006). Whitfield et al. (2010) review surface hydroclimatic effects of the PDO in western Canada, including temperature, precipitation, and streamflow. Additionally, Fleming and Moore (2008) summarized select hydrologic responses to ENSO, PDO, and AO in western Canada, and emphasized that individual watersheds may be affected differently than neighbouring watersheds due to complex factors influencing watersheds.

Few studies have examined the relationships between teleconnections and atmospheric circulation from a synoptic climatological perspective. For example, Cassano and Cassano (2010) linked positive (negative) AO and negative (positive) PDO to a decreased (increased) frequency of a winter (Dec-Feb) surface Aleutian Low. Furthermore, Stahl et al. (2006) reported significantly a higher (lower) frequency of synoptic types exhibiting low SLP over the North Pacific Ocean and lower (higher) frequency of synoptic types with high SLP over the Pacific Ocean during negative (positive) SOI, positive (negative) PDO, and positive (negative) PNA, statistically evaluated using the Chi-square test.

2.5 Conclusions

This chapter has provided a comprehensive examination of literature relating to the atmospheric drivers of water availability in western Canada. The Mackenzie and Saskatchewan Rivers are important for numerous terrestrial and marine processes, and are located in a region of high hydroclimatic variability. Air temperature and precipitation are fundamental components of water availability, and representing the spatial distribution of these variables over a large area requires the use of gridded data. Procedures used to create gridded datasets have progressed such that reliable high-resolution temperature and precipitation data are available in daily time steps. Additionally, these datasets can be used as inputs to calculate drought indices, including the SPEI, to determine water availability over a seasonal time period.

There are numerous methods available for classifying atmospheric circulation patterns, and over time these have improved as new methods, such as SOM, have been shown to be more superior. Few attempts have been made to link synoptic classifications and large-scale teleconnections. These linkages are necessary to fully understand the spatial and temporal dimensions of teleconnection patterns. As atmospheric circulation and teleconnections are fundamental features driving the hydro-climate of western Canada, knowledge of these synergies is vital to the understanding of factors that control water availability. The preceding information is applied to meet the objectives outlined in Section 1.3, specifically to create a catalogue of dominant synoptic types and relate those types to surface climate and teleconnections. This is carried out on both a winter (Chapter 3) and summer (Chapter 4) basis.

References

Abdul Aziz, O.I. and Burn, D.H. (2006), Trends and variability in the hydrological regime of the Mackenzie River Basin. Journal of Hydrology. 319. 282-294. DOI: 10.1016/j.jhydrol.2005.06.039

Agarwal, P. And Skupin, A. (Eds) (2008). *Self-Organising Maps: Applications in Geographic Information Science.* Chichester, UK: John Wiley & Sons, Ltd.

Arnell, N.W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean. Journal of Geophysical Research. 110, D07105. DOI: 10.1029/2004JD005348

Astel, A., Tsakovski, S., Barbieri, P., and Simeonov, V. (2007), Comparison of self-organizing maps classification approach with cluster and principal components analysis for large environmental data sets. Water Research, 41: 4566-4578

Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. (2005), Potential impacts of a warming climate on water availability in snow-dominated regions. Nature. 438, 303-309. Doi: 10.1038/nature04141

Barnston, A.G. and Livezey, R.E. (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly Weather Review. 115, 1083-1126

Bawden, A.J., Burn, D.H., and Prowse, T.D. (2014), Recent changes in patterns of western Canadian river flow and association with climatic drivers. *Submitted to Hydrological Processes*

Bond, N.A. and Harrison, D.E. (2000), The Pacific Decadal Oscillation, air-sea interaction and central north Pacific winter atmospheric regimes. Geophysical Research Letters, 27(5), 731-734

Bonsal, B.R. and Lawford, R.G. (1999), Teleconnections between El Nino and La Nina events and summer extended dry spells on the Canadian Prairies. International Journal of Climatology. 19, 1445-1458

Bonsal, B.R., Zhang, X., and Hogg, W.D. (1999), Canadian Prairie growing season precipitation variability and associated atmospheric circulation. Climate Research, 11, 191-208

Bonsal, B.R., Shabbar, A., and Higuchi, K. (2001), Impacts of low frequency variability modes on Canadian winter temperature. International Journal of Climatology. 21, 95-108.

Bonsal, B.R. and Prowse, T.D. (2003), Trends and variability in spring and autumn 0°C-isotherm dates over Canada. Climatic Change. 57, 341-358

Bonsal, B.R. and Wheaton, E.E. (2005), Atmospheric circulation comparisons between the 2001 and 2002 and the 1961 and 1988 Canadian prairie droughts. Atmosphere-Ocean, 43(2) 163-172

Bonsal, B.R. and Prowse, T.D. (2006), Regional assessment of GCM-simulated current climate over northern Canada. Arctic. 59(2), 115-128.

Bonsal, B.R., Aider, R., Gachon, P., and Lapp, S. (2012), An assessment of Canadian prairie drought: past, present, and future. Climate Dynamics. DOI: 10.1007/s00382-012-1422-0

Brimelow, J.C. and Reuter, G.W. (2005), Transport of atmospheric moisture during three extreme rainfall events over the Mackenzie River Basin. Journal of Hydrometeorology. 6, 423-440

Burn, D.H. (1994), Hydrologic effects of climatic change in west-central Canada. Journal of Hydrology. 160, 53-70.

Burn, D.H. and Hag Elnur, M.A. (2002), Detection of hydrologic trends and variability. Journal of Hydrology. 255, 107-122.

Burn, D.H., Cunderlik, J.M, and Pietroniro, A. (2004a), Hydrological trends and variability in the Liard River basin. Hydrological Sciences Journal. 49(1), 53-67.

Burn, D.H., Abdul Aziz, O.I. and Pietroniro, A. (2004b), A comparison of trends in hydrological variables for two watersheds in the Mackenzie River basin. Canadian Water Resources Journal. 29(4), 283-298

Burn, D.H., Fan, L., and Bell, G. (2008), Identification and quantification of streamflow trends on the Canadian Prairies. Hydrological Sciences Journal, 53(3), 538-549

Byrne, J.M., Berg, A., and Townshend, I. (1999), Linking observed and general circulation model upper air circulation patterns to current and future snow runoff for the Rocky Mountains. Water Resources Research. 35(12), 3793-3802

Cannon, A.J., Whitfield, P.H., and Lord, E.R. (2002), Synoptic map-pattern classification using recursive partitioning and principal component analysis. Monthly Weather Review, 130: 1187-1206, doi: http://dx.doi.org/10.1175/1520-0493(2002)130<1187:SMPCUR>2.0.CO;2

Cassano, E.N., Lynch, A.H., Cassano, J.J., and Koslow, M.R. (2006), Classification of synoptic patterns in the western Arctic associated with extreme events at Barrow, Alaska, USA. Climate Research, 30: 83-97

Cassano, E.N. and Cassano, J.J. (2010), Synoptic forcing of precipitation in the Mackenzie and Yukon River basins. International Journal of Climatology. 30, 658-674. DOI: 10.1002/joc.1926

Chagnon, D., McKee, T.B., Doeksen, N.J. (1993), Annual snowpack patterns across the Rockies: Long-term trends and associated 500-mb synoptic patterns. Monthly Weather Review, 121, 633-647

Comeau, L.E.L, Pietroniro, A., and Demuth, M.N. (2009), Glacier contribution to the North and South Saskatchewan Rivers. Hydrological Processes. 23, 2640-2653. DOI: 10.1002/hyp.7409

Costigan, K.H. and Daniels, M.D. (2012), Damming the prairie: Human alteration of Great Plains river regimes. Journal of Hydrology. 444-445, 90-99

Cuell, C. and Bonsal, B. (2009), An assessment of climatological synoptic typing by principal component analysis and kmeans clustering. Theoretical and Applied Climatology, 98, 361-373

Déry, S.J. and Wood, E.F. (2005), Decreasing river discharge in northern Canada. Geophysical Research Letters. 32, L10401. Doi: 10.1029/2005GL022845

Déry, S.J., Hernández-Henríquez, M.A., Burford, J.E., and Wood, E.F. (2009), Observational evidence of an intensifying hydrological cycle in northern Canada. Geophysical Research Letters. 36, L13402, doi: 10.1029/2009GL038852

Deser, C. (2000), On the Teleconnectivity of the "Arctic Oscillation." Geophysical Research Letters. 27, 6. 779-782.

Finnis, J., Cassano, J., Holland, M., Serreze, M., and Uotila, P. (2009), Synoptically forced hydroclimatology of major Arctic watersheds in general circulation models; Part 1: the Mackenzie River Basin. International Journal of Climatology, 29, 1226-1243. Doi: 10.1002/joc.1753

Fleming, S.W. and Moore, R.D. (2008), Local-scale controls on hydrologic responses to climatic variability. CMOS Bulletin, 36(1) 15-19.

Gershunov, A. and Barnett, T.P. (1998), Interdecadal modulation of ENSO teleconnections. Bulletin of the American Meteorological Society. 79(12), 2715-2725

Gobena, A.K. and Gan, T.Y. (2006), Low-frequency variability in southwestern Canadian stream flow: Links with large-scale climate anomalies. International Journal of Climatology. 26, 1843-1869. DOI: 10.1002/joc.1336

Goulding, D.L. (1978) Calculated snowpack evaporation during Chinooks along the eastern slopes of the Rocky Mountains in Alberta. Journal of Applied Meteorology, 17, 1647-1651

Hare, S.R. and Mantua, N.J. (2000), Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47, 103-145

Hewitson, B.C. and Crane, R.G. (2002), Self-organizing maps: applications to synoptic climatology. Climate Research. 22, 13-26

Hewitson, B. C. (2008), Climate Analysis, Modelling, and Regional Downscaling Using Self-Organizing Maps. In P. Agarwal and A. Skupin (Eds), *Self-Organising Maps: Applications in Geographic Information Science* (137-153). Chichester, UK: John Wiley & Sons, Ltd. doi: 10.1002/9780470021699.ch8

Holton, J.R. (1979), An Introduction to Dynamic Meteorology. Second edition. Academic Press, Inc. New York, New York

Horel, J.D. and Wallace, J.M. (1981), Planetary-scale atmospheric phenomena associated with the southern oscillation. Monthly Weather Review. 109, 813-829

Huntington, T.G. (2006), Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology. 319, 83-95

Hutchinson MF. 2004. ANUSPLIN Version 4.3. Canberra: Fenner School of Environment & Society, Australian National University. (26 February 2013; *http://fennerschool.anu.edu.au/research/software-datasets/anusplin)*

Hutchinson, M.F., McKenney, D.W., Lawrence, K., Pedlar, J.H., Hopkinson, R.F., Milewska, E., and Papadopol, P. (2009), Development and testing of Canada-wide interpolated spatial models of daily minimum-maximum temperature and precipitation for 1961-2003. Journal of Applied Meteorology and Climatology. 48. 725-741

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., Kyselý, J., and Tveito, O.E. (2008), Classifications of atmospheric circulation patterns: Recent advances and applications. Trends and Directions in Climate Research: Ann. N.Y. Acad. Sci. 1146: 105-152. doi: 10.1196/annals.1446.019

Iseri, Y., Matsuura, T., Iizuka, S., Nishiyama, K., and Jinno, K. (2009), Comparison of pattern extraction capability between Self-Organizing Map and principal components analysis. Memoirs of the Faculty of Engineering, 69(2) 37-47

Jiang, N., Cheung, K., Luo, K., Beggs, P.J., and Zhou, W. (2012), On two different objective procedures for classifying synoptic weather types over east Australia. International Journal of Climatology. 32, 1475-1494.

Johnson, N.C., Feldstein, S.B., and Tremblay, B. (2008), The continuum of northern hemisphere teleconnection patterns and a description of the NAO shift with the use of self-organizing maps. Journal of Climate. 21, 6354-6371

Knox, J.L. and Lawford, R.G. (1990), The relationship between Canadian Prairie dry and wet months and circulation anomalies in the mid-troposphere. Atmosphere-Ocean, 28(2) 189-215.

Kohonen, T. (1993), Things you haven't heard about the self-organizing map. Neural Networks, IEEE International Conference, 3: 1147-1156

Kohonen, T. (1999), Fast evolutionary learning with batch-type self-organizing maps. Neural Processing Letters, 9: 153-162

Kohonen, T. (2001), Self-Organizing Maps. Springer, New York

Lackmann, G.M. and Gyakum, J.R. (1996), The synoptic- and planetary- scale signatures of precipitating systems over the Mackenzie River Basin. Atmosphere-Ocean, 34(4), 647-674.

Lajoie, F., Assani, A.A., Roy, A.G., and Mesfioui, M. (2007), Impacts of dams on monthly flow characteristics. The influence of watershed size and seasons. Journal of Hydrology, 334: 423-439

Lammers, R.B., Shiklomanov, A.I., Vörösmarty, C.J., Fekete, B.M., and Peterson, B.J. (2001) Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research. 106, D4: 3321-3334.

Lewis, E.L. (2000), The Freshwater Budget of the Arctic Ocean. Kluwer Academic Publishers, Dordrecht.

Linton, H., Prowse, T., Dibike, Y., and Bonsal, B. (2014), Spatial and temporal analysis of hydroclimatic variables affecting streamflow in western Canada from 1950-2010. *Submitted to Hydrological Processes*

Liu, Y. and Weisberg, R.H. (2005), Patterns of ocean current variability on the west Florida shelf using the self-organizing map. Journal of Geophysical Research. 110, C06003

Liu, Y. and Weisberg, R.H. (2006), Performance evaluation of the self-organizing map for feature extraction. Journal of Geophysical Research, 111: C0501, doi: 10.1029/2005JC003117

Liu, Y. and Weisberg, R.H. (2007), Ocean currents and sea surface heights estimated across the west Florida shelf. Journal of Physical Oceanography. 37, 1697-1713

Longley, R.W. (1967), The frequency of winter Chinooks in Alberta. Atmosphere, 5(4), 4-16

MacDonald, M.K., Pomeroy, J.W., and Pietroniro, A. (2010), On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains. Hydrology and Earth System Sciences, 14, 1401-1415

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. (1997), A pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society. 78, 1069-1079.

Mantua, N.J. and Hare, S.R. (2002), The pacific decadal oscillation. Journal of Oceanography, 58, 35-44.

Marshall, S.J., White, E.C., Demuth, M.N., Bolch, T., Wheate, R., Menounos, B., Beedle, M.J., and Shea, J.M. (2011), Glacier water resources on the eastern slopes of the Canadian Rocky Mountains. Canadian Water Resources Journal. 36(2), 109-134

Martin, J.E. (2006) Mid-Latitude Atmospheric Dynamics: A First Course. John Wiley & Sons, Ltd. , Chichester, West Sussex, England

Martz, L., J. Bruneau and J.T. Rolfe (Eds.). (2007), Climate Change and Water, SSRB Final Technical Report. University of Saskatchewan. Saskatoon, Saskatchewan

McEvoy, D.J., Huntington, J.L., Abatzoglou, J.T., and Edwards, L.M. (2012), An Evaluation of Multiscalar Drought Indices in Nevada and Eastern California. Earth Interactions. 12. Paper 18. 1-18

McKee, T.B., Doesken, N.J., and Kleist, J. (1993), The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, 17-22 January 1993. American Meteorological Society, Boston MA, 179-184

McKenney, D.W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R.F., Price, D., and Owen, T. (2011), Customized spatial climate models for North America. Bulletin of the American Meteorological Society. 92(12) 1611-1622

Mekis, E. and Hogg, W.D. (1999), Rehabilitation and analysis of Canadian daily precipitation time series. Atmosphere-Ocean. 37(1), 53-85.

Michaelides, S.C., Liassidou, F., and Schizas, C.N. (2007), Synoptic classification and establishment of analogues with artificial neural networks. Pure and Applied Geophysics. 164, 1347-1364.

Monk, W.A., Peters, D.L., and Baird, D.J. (2012), Assessment of ecologically relevant hydrological variables influencing a cold-region river and its delta: the Athabasca River and the Peace-Athabasca Delta, northwestern Canada. Hydrological Processes. 26, 1827-1839. DOI: 10.1002/hyp.9307

Morison, J., Kwok, R., Peralta-Ferriz, C., Alkire, M., Rigor, I., Andersen, R., and Steele, M. (2012), Changing Arctic Ocean freshwater pathways. Nature. 481, 66-70. DOI: 10.1038/nature10705

Overland, J.E. and Wang, M. (2005), The Arctic climate paradox: The recent decrease of the Arctic Oscillation. Geophysical Research Letters, 32, L06701, doi:10.1029/2004GL021752

Overland, J., Rodionov, S., Minobe, S., and Bond, N. (2008), North Pacific regime shifts: Definitions, issues and recent transitions. Progress in Oceanography. 77, 92-102

Overland, J.E. and Wang, M. (2010), Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. Tellus, 62A, 1-9

Palmer, W.C. (1965), Meteorological drought. U.S. Department of Commerce Weather Bureau Research Paper No. 45.

Pentney, A. and Ohrn, D. (2008), Navigating from history into the future: the water management plan for the South Saskatchewan River Basin in Alberta. Canadian Water Resources Journal, 33(4) 381-396

Peters, D.L. and Prowse, T.D. (2001), Regulation effects on the lower Peace River, Canada. Hydrological Processes. 15, 3181-3194.

Peters, D.L., Prowse, T.D., Pietroniro, A., and Leconte, R. (2006), Flood hydrology of the Peace-Athabasca Delta, northern Canada. Hydrological Processes. 20, 4073-4096.

Peters, D.L., Atkinson, D., Monk, W.A., Tenenbaum, D.E., and Baird, D.J. (2012), a multi-scale hydroclimatic analysis of runoff generation in the Athabasca River, western Canada. Hydrological Processes, DOI: 10.1002/hyp.9699

Peterson, W.T. and Schwing, F.B. (2003), A new climate regime in northeast pacific ecosystems. Geophysical Research Letters, 30(17) 1896. DOI:10.1029/2003GL017528

Prowse, T.D., Conly, F.M., Church, M., and English, M.C. (2002), A review of hydroecological results of the Northern River Basins Study, Canada. Part 1. Peace and Slave Rivers. River Research and Applications. 18, 429-446.

Reusch, D.B., Alley, R.B., and Hewitson, B.C. (2005), Relative performance of self-organizing maps and principal component analysis in pattern extraction from synthetic climatological data. Polar Geography, 29(3), 188-212, http://dx.doi.org/10.1080/789610199

Reusch, D.B. (2010), Nonlinear climatology and paleoclimatology: Capturing patterns of variability and change with Self-Organizing Maps. Physics and Chemistry of the Earth, 35, 329-340

Rigor, I.G., Wallace, J.M., and Colony, R.L. (2002), Response of sea ice to the Artic Oscillation. Journal of Climate, 15, 2648-2663

Roberts, E., Stewart, R.E., and Lin, C.A. (2006), A study of drought characteristics over the Canadian prairies. Atmosphere-Ocean. 44(4), 331-345

Romolo, L., Prowse, T. D., Blair, D., Bonsal, B. R. and Martz, L. W. (2006a), The synoptic climate controls on hydrology in the upper reaches of the Peace River Basin. Part I: snow accumulation. Hydrological Processes, 20, 4097–4111. doi: 10.1002/hyp.6421

Romolo, L., Prowse, T. D., Blair, D., Bonsal, B. R., Marsh, P. and Martz, L. W. (2006b), The synoptic climate controls on hydrology in the upper reaches of the Peace River Basin. Part II: snow ablation. Hydrological Processes, 20, 4113–4129. doi: 10.1002/hyp.6422

Rood, S.B., Samuelson, G.M., Weber, J.K., and Wywrot, K.A. (2005), Twentieth-century decline in streamflows from the hydrographic apex of North America. Journal of Hydrology. 306, 215-233.

Rood, S.B., Pan, J., Gill, K.M., Franks, C.G., Samuelson, G.M., and Shepherd, A. (2008), Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probably impacts on floodplain forests. Journal of Hydrology. 349, 397-410

St. Jacques, J-M., Sauchyn, D.J., and Zhao, Y. (2010), Northern Rocky Mountain streamflow records: Global warming trends, human impacts or natural variability? Geophysical Research Letters. 37, L06407, DOI: 10.1029/2009GL042045

Sauchyn DJ, Kulshreshtha S (2008) Prairies. In: Lemmen DS, Warren FJ, Lacroix J, Bush E (eds) From impacts to adaptation: Canada in a changing climate 2007. Government of Canada, Ottawa, ON, pp 275–328

Saunders, I.R. and Byrne, J.M. (1996), Generating regional precipitation from observed and GCM synoptic-scale pressure fields, southern Alberta, Canada. Climate Research. 6, 237-249

Schindler D.W. and Donahue W.F. (2006), An impending water crisis in Canada's western prairie provinces. PNAS 103(19) 7210-7216

Schuenemann, K.C., Cassano, J.J, and Finnis, J. (2009), Synoptic forcing of precipitation over Greenland: Climatology for 1961-99. Journal of Hydrometeorology. 10, 60-78

Serreze, M.C., Bromwich, D.H., Clark, M.P., Etringer, A.J., Zhang, T., and Lammers, R. (2003), Large-scale hydro-climatology of the terrestrial Arctic drainage system. Journal of Geophysical Research, 108, D2, 8160.

Serreze, M.C., Barrett, A.P., Stroeve, J.C., Kindig, D.N., and Holland, M.M., (2009), The emergence of surface-based Arctic amplification. The Cryosphere. 3, 11-19.

Shabbar, A. and Khandekar, M. (1996), The impact of El Niño-Southern Oscillation on the temperature field over Canada: Research note. Atmosphere-Ocean, 34(2), 401-416.

Shabbar, A., Bonsal, B., and Khandekar, M. (1997), Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate. 10, 3016-3027.

Shabbar, A. and Bonsal, B. (2004), Associations between low frequency variability modes and winter temperature extremes in Canada. Atmosphere-Ocean, 42(2), 127-140.

Shabbar, A., Bonsal, B.R., and Szeto, K. (2011), Atmospheric and oceanic variability associated with growing season droughts and pluvials on the Canadian Prairies. Atmosphere-Ocean, 1, 1-17. doi: 10.1080/07055900.2011.564908

Sheridan, S.C. (2003), North American weather-type frequency and teleconnection indices. International Journal of Climatology. 23, 27-45. DOI: 10.1002/joc.863

Sheridan, S.C. and Lee, C.C. (2011), The self-organizing map in synoptic climatological research. Progress in Physical Geography. 35(1): 109-119. Doi: 10.1177/0309133310397582

Smirnov, V.V. and Moore, G.W.K. (1999), Spatial and temporal structure of atmospheric water vapor transport in the Mackenzie River Basin. Journal of Climate. 12, 681-696

Smirnov, V.V. and Moore, G.W.K. (2001), Short-term and seasonal variability of the atmospheric water vapor transport through the Mackenzie river basin. Journal of Hydrometeorology. 2, 441-452

Smith, N.D. and Pérez-Arlucea, M. (2008), Natural levee deposition during the 2005 flood of the Saskatchewan River. Geomorphology, 101, 583-594

Spence, C. and Rausch, J. (2005), Autumn synoptic conditions and rainfall in the subarctic Canadian shield of the Northwest Territories, Canada. International Journal of Climatology. 25, 1493-1506

Stahl, K., Moore, R.D., and McKendry, I.G. (2006), The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology. 26, 541-560, DOI:10.1002/joc.1268

Stewart, I.T., Cayan, D.R., Dettinger, M.D. (2004), Changes toward earlier streamflow timing across Western North America. Journal of Climate, 18, 1136-1155

Stewart, R., Pomeroy, J., and Lawford, R. (2011), The drought research initiative: A comprehensive examination of drought over the Canadian Prairies. Atmosphere-Ocean. 49(4), 298-302.

Stewart, R.E., Bonsal, B.R., Harder, P., Henson, W., and Kochtubajda, B. (2012), Cold and hot periods associated with dry conditions over the Canadian Prairies. Atmosphere-Ocean. 50(3), 364-372.

Tanzeeba, S. and Gan, T.Y. (2012), Potential impact of climate change on the water availability of South Saskatchewan River Basin. Climatic Change. 112. 355-386. DOI: 10.1007/s10584-011-0221-7

Thompson, D.W., Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophysical Research Letters. 25, 1297–1300.

Thornthwaite, C.W. and Mather, J.R. (1955), The water balance. Publications in Climatology, 8(1), 1-86.

Vesanto, J., Himberg, J., Alhoniemi, E., and Parhankangas, J. (2000), SOM toolbox for Matlab 5. Helsinki University of Technology. Rep. A57

Vicente-Serrano, S.M., Beguería, S., and López-Moreno, J.I. (2010a), A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate. 23, 1696-1718. DOI: 10.1175/2009JCLI2909.1

Vicente-Serrano, S.M. , Beguería, S., López-Moreno, J.I., Angulo, M., and El Kenawy, A. (2010b), A new global 0.5° gridded dataset (1901-2006) of a multiscalar drought index: Comparison with current drought index datasets based on the Palmer Drought Severity Index. Journal of Hydrometeorology. 11, 1033-1043

Wallace, J.M. and Gutzler, D.S. (1981), Teleconnections in the geopotential height field during the Northern Hemisphere winter. Monthly Weather Review. 109, 784-812

Westmacott , J.R. and Burn, D.H. (1997), Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin. Journal of Hydrology. 263-279.

Wheaton, E., Kulshreshtha, S., Wittrock, V., and Koshida, G. (2008), Dry times: Hard lessons from the Canadian drought of 2001 and 2002. The Canadian Geographer. 52(2), 241-262.

Whitfield, P.H. and Cannon, A.J. (2000), Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal. 25(1), 19-65

Whitfield, P.H., Moore, R.D. (Dan), Fleming, S.W., and Zawadzki, A. (2010), Pacific decadal oscillation and the hydroclimatology of western Canada – review and prospects. Canadian Water Resources Journal. 35(1), 1-28.

Woo, M-K. and Thorne, R. (2003), Streamflow in the Mackenzie Basin, Canada. Arctic. 56(4), 328-340

Woo, M-K. and Thorne, R. (2006), Snowmelt contribution to discharge from a large mountainous catchment in subarctic Canada. Hydrological Processes. 20, 2129-2139. DOI: 10.1002/hyp.6205

Woodbury, A.D., Bhuihan, A.K.M.N., Hanesiak, J., and Akinremi, O.O. (2009), Observations of northern latitude ground-surface and surface-air temperatures. Geophysical Research Letters. 36, L07703, doi: 10.1029/2009GL037400

Yarnal, B., Crane, R. G., Carleton, A. M. and Kalkstein, L. S. (1987), A new challenge for climate studies in geography. The Professional Geographer, 39, 465–473. doi: 10.1111/j.0033-0124.1987.00465.x

Yarnal, B. (1993), Synoptic Climatology in Environmental Analysis. Bellhaven: London

Yarnal, B., Comrie, A. C., Frakes, B. and Brown, D. P. (2001), Developments and prospects in synoptic climatology. International Journal of Climatology, 21, 1923–1950. doi: 10.1002/joc.675

Yip, Q.K.Y., Burn, D.H., Seglenieks, F., Pietroniro, A., and Soulis, E.D. (2012), Climate impacts on hydrological variables in the Mackenzie River Basin. Canadian Water Resources Journal. 37(3), 209-230.

Zhang, X., Vincent, L.A., Hogg, W.D., and Niitsoo, A. (2000), Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean. 38(3), 395-429

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R. (2001), Trends in Canadian streamflow. Water Resources Research. 37(4), 987-998

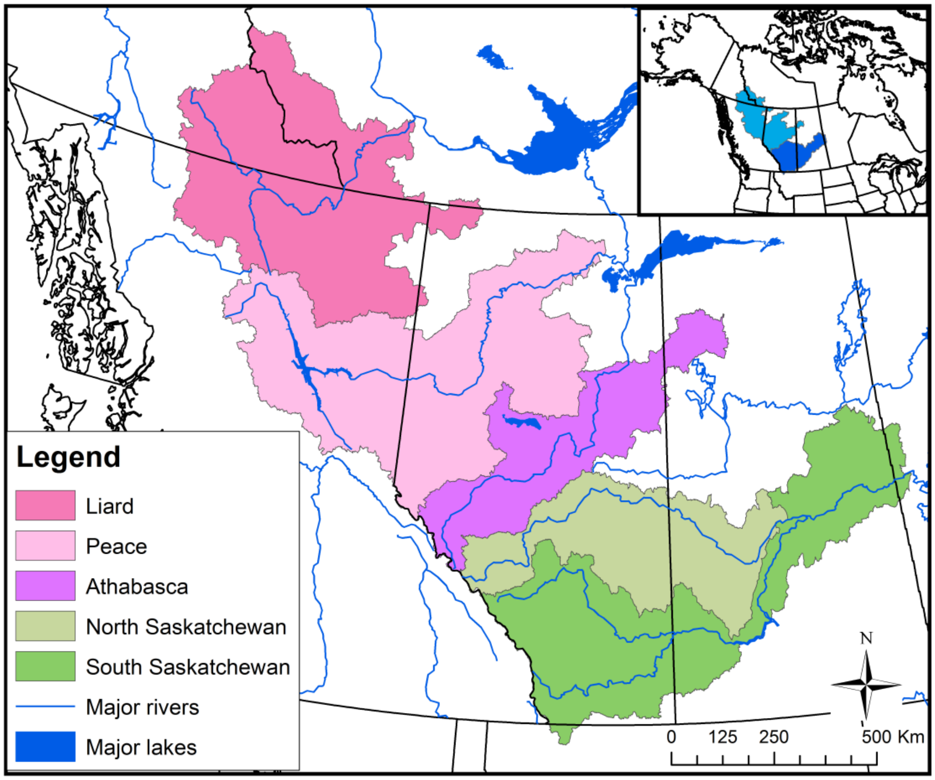

Figure 2.1: Rivers originating on the leeward slopes of the Rocky Mountains. The Liard, Peace, and Athabasca Rivers are tributaries to the north-flowing Mackenzie River, and the North and South Saskatchewan Rivers are tributaries to the east-flowing Saskatchewan River.

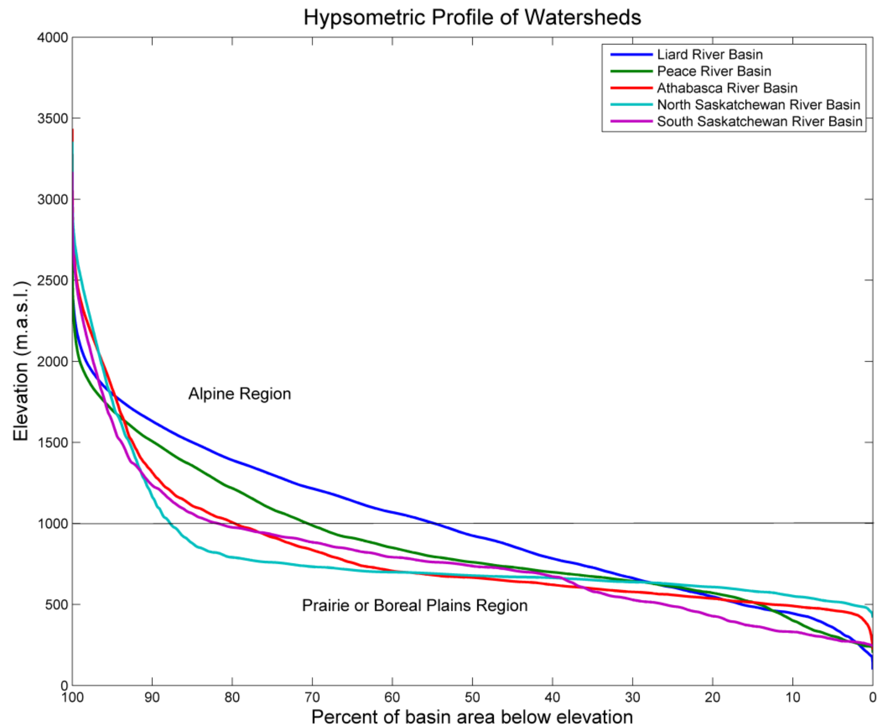

Figure 2.2: Hypsometric profile of the Liard, Peace, Athabasca, North Saskatchewan, and South Saskatchewan Rivers.

Chapter 3: Evaluating the distribution of water resources in western Canada using synoptic climatology and selected teleconnections. Part 1: Winter season

Abstract

The Climatic Redistribution of western Canadian Water Resources (CROCWR) project was designed to identify regions of increased/decreased water availability by evaluating a suite of atmospheric, hydroclimatic, and streamflow variables. This research component focuses on the atmospheric drivers of air temperature and precipitation in the watersheds originating on the leeward slopes of the Rocky Mountains. Dominant winter (Nov-Apr) synoptic-scale mid-tropospheric circulation patterns from 1950-2011 are classified using self-organizing maps (SOM), and frequency distributions for positive/negative phases of the Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), and Arctic Oscillation (AO) are compared. Corresponding high-resolution gridded air temperature and precipitation anomalies are calculated for each synoptic type and spatial patterns of above/below average air temperature and precipitation and north/south gradients are identified. Gridded six-month values of the Standardized Precipitation-Evapotranspiration Index (SPEI) are also used to categorize winters into regions of high/low snowpack. This study is unique in its focus on quantifying statistical relationships between synoptic-scale circulation patterns and teleconnections. Results indicate that the strength and position of a high-pressure ridge over the Pacific Ocean (western North America) is associated with anomalously cool (warm),

wet (dry) conditions in the study region. Statistically significant increases in high-pressure ridging over the Pacific Ocean (western continent) are associated with positive (negative) phases of the SOI, and negative (positive) phases of the PDO, while only weak associations with the AO are found. Through improved knowledge of the relationships between teleconnections, mid-tropospheric circulation, and surface climate, the spatial and temporal distribution of water resources in western Canada is better understood.

3.1 Introduction

The global impacts of climate change have varied spatially, and confounding these changes are an intensification of the hydrologic cycle (Huntingdon 2006; Déry et al. 2009) and increased atmospheric moisture transport (Zhang et al. 2013). Of particular concern are regional hydroclimatic responses to climate change in western Canada, an area of high hydroclimatic and physiographic variability. Climate and streamflow changes have been documented for discrete regions or river basins in western Canada, but previous studies have not evaluated climatic change from the perspective of water-resource redistribution across watershed boundaries. A major boundary dividing north-flowing and east- or west-flowing rivers of this region is located in the mid-latitudes. Therefore, even minor shifts in the spatial patterns of climate can have substantial consequences for the distribution of water resources in western Canada. Consequently, the Climatic Redistribution of western Canadian Water Resources (CROCWR) project was devised to address these broad-scale changes between mid- and high-latitude watersheds through the systematic evaluation of multiple hydroclimatic and streamflow parameters (Prowse et al. 2013; see also Bawden et al. 2014 and Linton et al. 2014).

A number of significant hydroclimatic trends, at a variety of scales, have been detected in western Canada. Winter temperatures have increased since 1950, particularly in northern Canada (Zhang et al. 2000; Linton et al. 2014). In addition, while autumn freeze-up dates have remained relatively unchanged, the timing of the spring 0°C-isotherm has become significantly earlier (Bonsal and Prowse 2003). Precipitation decreases since 1950 have been detected in western Canada (Zhang et al. 2000; Linton et al. 2014), although Zhang et al. (2000) reported increased precipitation in northern Canada. The magnitude of temperature and precipitation changes has not been heterogeneous (Linton et al. 2014). Likewise, the streamflow responses to these changes have been mixed. For example, both increasing and decreasing streamflow trends were reported for hydrometric stations in the Liard (Burn et al. 2004a, 2004b), Athabasca (Burn et al. 2004b), and Mackenzie River Basins (Yip et al. 2012). Additionally, Rood et al. (2008) reported streamflow increases on the Athabasca River, and mixed increases and decreases within the Saskatchewan River Basin. More recently, Bawden et al. (2014) detected generally decreased (increased) winter streamflow in southwestern (northwestern) Canada since 1976. One area of agreement among research has been the detection of trends toward an earlier spring pulse onset (Zhang et al. 2001; Burn et al. 2004a; Rood et al. 2008; Burn et al. 2008; Yip et al. 2012; Bawden et al. 2014).

The north-flowing Mackenzie and east-flowing Saskatchewan Rivers (Fig. 3.1) are key sources of water in western Canada, their headwaters being in the leeward slopes of the Rocky Mountains. The snowmelt-dominated alpine tributaries of this headwater region provide the largest contribution to annual streamflow of the Mackenzie and Saskatchewan Rivers, and are the focus of this study. Flow of these rivers is important for aquatic and terrestrial ecosystems, agricultural production, and hydroelectricity generation. Furthermore, the Mackenzie River is a major circumpolar contributor of flow to the Arctic Ocean – river discharge being the largest source of freshwater input to the Arctic Ocean (Serreze et al. 2003) where it is essential for density-based stratification, sea ice formation (Arnell 2005; Lammers et al. 2001), oceanic circulation patterns (Morison et al. 2012), and feedbacks to the global climate system (Lewis et al. 2000).

The Liard, Peace and Athabasca Rivers are the primary tributaries to the Mackenzie River. The boreal plains environment that characterizes much of the Liard River Basin extends southwards into portions of the Athabasca River Basin then rolls into a semi-arid prairie environment. The proportion of basins characterized by alpine environments is reduced toward the south end of the study region, such that only a small fraction of the Saskatchewan River Basin is mountainous (Fig. 3.2). The region east of the Rocky Mountains is prone to Chinook winds, caused by the adiabatic warming of air masses as they descend the leeward slopes. Chinook winds are more frequent in the southern portion of the Rockies than the north (Longley 1967), vary from year to year (Goulding 1978), and can increase loss of snowpack due to sublimation (MacDonald et al. 2010).

In general, the interannual variability of hydroclimatic conditions is largely controlled by large-scale atmospheric circulation. Specifically, mid-tropospheric circulation drives surface climate conditions through the forcing of vertical motion in the air column and the advection of warm and cold fronts at the surface (Holton 1979). For example, regions of mid-tropospheric convergence, located to the right of a ridge axis and left of a trough, are associated with surface divergence, consequently suppressing cloud formation and precipitation. By contrast, regions of mid-tropospheric divergence, located to the left of the ridge axis and right of the trough, are associated with surface convergence and rising in the air column, conditions conducive to cloud formation and precipitation (Holton 1979). For this study region, the area east of the Rocky Mountains is also prone to cyclogenesis related to the expansion of the air column as it descends the lee side of the mountain slopes (Martin 2006).

Specific synoptic-scale mid-tropospheric circulation patterns have been shown to influence winter surface climate in western Canada. For example, low precipitation has been linked to a ridge of high-pressure centred over western Canada (Saunders and Byrne 1996; Romolo et al. 2006a). Conversely, high precipitation has been linked to zonal flow (Romolo et al. 2006a) or a ridge of high pressure over the Pacific Ocean (Finnis et al. 2009; Cassano and Cassano 2010). The development of a lee cyclone at the surface, preceded by a mid-tropospheric low-pressure system over the Pacific Ocean (Aleutian Low) has been demonstrated to be the primary mechanism for producing precipitation (Lackmann et al. 1998). This low-pressure system results in a narrow band of moisture influx to the southwestern portion of the Mackenzie River Basin, and is the primary source of moisture to the region (Smirnov and Moore 2001). In a similar study, Liu and

Stewart (2003) identified both the Arctic and Pacific Oceans as winter moisture sources for the Saskatchewan River Basin.

A portion of the interannual variability in dominant atmospheric circulation and hydroclimatic variables for the study region results from large-scale teleconnections such as El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Pacific North American (PNA) pattern, and the Arctic Oscillation (AO). Teleconnection indices have commonly been used as tool for evaluating hydroclimatic variables. For example, negative (positive) phases of the Southern Oscillation Index (SOI), representing ENSO, have been associated with anomalously dry (wet) conditions (Shabbar et al. 1997; Romolo et al. 2006a) and above (below) average temperatures (Shabbar and Khandekar 1996; Bonsal et al. 2001) in western Canada. Additionally, ENSO was linked to the frequency, duration, and intensity of warm (El Niño) and cold (La Niña) events across Canada (Shabbar and Bonsal 2004). Positive (negative) phases of the PDO have also been associated with dry (wet), warm (cool) conditions (Bonsal et al. 2001). The AO was weakly correlated with winter climate in western Canada (Shabbar and Bonsal 2004). Both the ENSO and PDO signals were found to be stronger during winter months (Shabbar and Khandekar 1996; Fleming and Whitfield 2010).

Teleconnection indices have also been linked to streamflow. For example, negative phases of PDO were linked to earlier spring freshet on the Liard, Peace, and Athabasca Rivers (Burn 2008). Déry and Wood (2005) determined that discharge to the Arctic Ocean was positively correlated with ENSO, and negatively correlated with the PDO and PNA, while discharge to the western Hudson Bay was positively correlated with ENSO, and negatively correlated with the PDO and AO. In the prairies, negative (positive) phases of ENSO were linked to below (above) average streamflow (Gobena and Gan 2006).

The aim of this research is to identify the atmospheric drivers of winter water resource distribution in western Canada with a particular focus on changes in distribution across watershed boundaries. Note that this analysis is performed in conjunction with a companion paper evaluating summer water resource distribution (Newton et al. 2014). Specifically, high-resolution spatial patterns of air temperature and precipitation are identified in relation to dominant synoptic-scale circulation patterns. Changes in seasonal frequency of those synoptic patterns under the influence of positive and negative phases of the SOI, PDO, and AO are then statistically assessed. These winter and summer evaluations of water resource distribution are the first focused examinations among large-scale teleconnections, synoptic-scale circulation and surface hydroclimatic conditions.

3.2 Data and Methodology

3.2.1 Synoptic Classification

To create a catalogue of dominant synoptic types, daily winter (Nov-Apr) geopotential height (gph) data at 500-hPa for 1950-2011, obtained from NCEP/NCAR (Kalnay et al. 1996), are classified using the Self-Organizing Maps (SOM) Toolbox for MATLAB (Vesanto et al. 2000). SOM is a neural network process based on competitive and cooperative learning that clusters and projects data onto a topologically ordered array (Kohonen 2001), and has been found to offer several advantages over traditional classification methods including principal components analysis (Hewitson and Crane 2002; Reusch et al. 2005; Jiang et al. 2012). The SOM is linearly initialized using the first two eigenvectors of each dataset to establish maximum variance between opposing corners. Training is accomplished using the batch-training algorithm, which presents the entire dataset to the initialized SOM array. During this training process, the best matching unit (bmu) for each gph data vector is determined by Euclidean distance and that bmu vector is then updated to be closer to the value of the daily gph data vector (Kohonen 2001). Neighbouring units are also drawn toward the bmu, thus preserving topological relationships. The resulting array of representative synoptic types has a list of days corresponding to each type, which is used to compare with surface climate.

A number of metrics can be used to evaluate the quality of a SOM array, including the built-in Topographic and Quantization Error functions in the SOM Toolbox, which indicate the strength of neighbourhood relationships and the degree of within-group variance, respectively. An additional SOM array quality indicator is used - the correlation between daily synoptic type classification and daily Pacific North American (PNA) pattern index value. The PNA was chosen because it is representative of mid-tropospheric circulation, particularly capturing the intensity and position of the Aleutian Low (Wallace and Gutzler 1981), and, therefore, should be distinguishable in the synoptic classification.

3.2.2 Surface Climate

Analysis of surface climate is achieved through gridded air temperature and precipitation datasets at a 10-km resolution for 1950-2010, created using an ANUSPLIN thin-plate spline interpolation method and climate station data as described in McKenney et al. (2011). Hutchinson et al. (2009) compared the ANUSPLIN gridded dataset with data from 50 Canadian climate stations omitted from the original interpolation and concluded that the modelled and observed data were in good agreement. Therefore, the dataset was considered robust, and to be the best available daily dataset for this research application.

Daily air temperature anomalies at each grid are calculated as the deviation from the daily long-term (1950-2010) mean. These anomalies are then averaged for each synoptic type. Since unlike temperature, daily precipitation follows a long-tail distribution, the use of daily precipitation anomalies was not considered appropriate. Instead, precipitation associated with each synoptic type is calculated by determining the percentage of precipitation at each grid (for the synoptic type in question) relative to the mean (1950-2010) daily precipitation value at that grid. In each instance, the mean precipitation value is 0%.

Cumulative monthly temperature and precipitation values are calculated using the daily gridded datasets, and then the Standardized Precipitation-Evapotranspiration Index (SPEI) is calculated for the six-month winter period (Nov-Apr). The resolution of the dataset is recalculated to 50-km, using the mean value of each 5x5 grid section. The SPEI is a multi-scalar drought index based on a water-balance equation, using the difference between precipitation and potential evapotranspiration, which is largely a function of temperature (Vicente-Serrano et al. 2010). As precipitation dominates over evapotranspiration during winter months, gridded Nov-Apr SPEI values primarily represent the magnitude and spatial extent of winter snowpack.

3.2.3 Teleconnections

Teleconnection patterns that have been shown to influence surface climate in western Canada were selected for analysis. Monthly values of standardized SOI and daily values of PNA and AO were obtained from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/). Monthly values of the PDO were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (http://www.jisao.washington.edu/pdo/).

The SOI represents differences in sea level pressure (SLP) anomalies between Tahiti and Darwin, Australia. Negative values of SOI (El Niño) represent anomalously low pressure at Tahiti and anomalously high pressure at Darwin, and positive values of SOI (La Niña) signify opposite anomalies. El Niño (La Niña) also refers to above (below) average SST in the eastern Pacific, adjacent to the coast of South America. These SLP and SST anomalies affect global atmospheric circulation including the intensity of the Aleutian Low (Horel and Wallace 1981). Positive or negative phases of ENSO typically persist for 6-18 months and usually peak during the winter season.

The PDO represents SST anomalies in the North Pacific Ocean where positive (warm) phases are characterized by anomalously cool SST in the central North

Pacific and anomalously warm SST along the eastern edge of the North Pacific basin (Mantua et al. 1997). Opposite SST anomalies occur during negative (cool) phases. The PDO index is calculated as the first eigenvector of an Empirical Orthogonal Function (EOF) analysis of SST north of 20°N (Mantua et al. 1997). Ocean-atmosphere energy exchanges result in high SLP over regions of high SST and low SLP over regions of low SST; therefore, positive (negative) phases of the PDO correspond to low (high) pressure over Alaska and the North Pacific (Mantua and Hare 2002). Phases of the PDO persist for several decades, with the most recent shift, from predominantly cool to warm, occurring in the mid-1970s (Mantua et al. 1997), although there has been speculation that the PDO shifted back to the negative phase in the late 1990s (Overland et al. 2008; Whitfield et al. 2010).

The AO index is a measure of SLP over the Arctic, calculated as the leading principal component of EOF analysis of SLP anomalies north of 20°N, referenced to the 1979-2000 mean value (Thompson and Wallace 1998). Negative (positive) phases of the AO are characterized by anomalously high (low) pressure over the Arctic, enhancing (suppressing) outbreaks of cold Arctic air extending over the north- to mid- latitudes and anomalously low (high) pressure over the mid-latitudes. The AO oscillates between periods of predominantly negative or positive which can persist for several years (Overland and Wang 2005), and has been linked to loss of Arctic sea-ice extent (Rigor et al. 2002; Overland and Wang 2010).

The daily PNA index is calculated using Least Squares regression of monthly values, which are produced through a Rotated Principal Components Analysis (RPCA) of 500-hPa gph anomalies between 20°-90°N (Barnston and Livezey 1987).

The resultant four centres of action are structured such that when the PNA values are positive (negative), North Pacific gph anomalies are negative (positive), Hawaii and western Canada are positive (negative) and the southeastern United States is also negative (positive; Wallace and Gutzler 1981).

The most common method of describing dominant atmospheric circulation during positive/negative phases of teleconnections has been the creation of composite maps. For example, dominant circulation during negative (positive) SOI is a mid-tropospheric trough (ridge) over the Pacific Ocean and accompanying ridge (trough) over the western continent (Shabbar and Khandekar 1996; Shabbar et al. 1997). More recently, a synoptic climatological approach has emerged as a tool for evaluating teleconnections. For example, Cassano and Cassano (2010) identified a decreased (increased) frequency of a surface Aleutian low-pressure system during winters (Dec-Feb) dominated by positive (negative) AO or negative (positive) PDO; however, statistical analysis was not part of this research. In a study of synoptic SLP patterns influencing the climate of British Columbia, Stahl et al. (2006) reported several statistically significant differences between ENSO, PDO, and PNA and mean winter (Dec-Feb) synoptic type frequencies.

The atmospheric and climatic influence of each phase of the PDO extends several decades. Additionally, the PDO has modulating effect on ENSO, where out-of-phase relationships (i.e. negative SOI and positive PDO) have a constructive relationship and stronger influence on climatic conditions, and in-phase relationships (i.e. negative SOI and negative PDO) have a destructive relationship lacking strong influence on regional climate (Gershunov and Barnett 1998; Bonsal et al. 2001; Gobena and Gan 2006). Yu et al. (2007) linked the constructive relationship between ENSO and the North Pacific (NP) Index, a measure of SLP anomalies associated with PDO (Trenberth and Hurrell 1994), to variability in the PNA index. Similarly, Johnson and Feldstein (2010) linked ENSO phases to variability of frequency of PNA-like SLP patterns in the North Pacific. Consequently, a multiple-indices approach to teleconnection-based hydroclimatic analysis was recommended (Whitfield et al. 2010).

Monthly values of the SOI and PDO, and daily values of the AO were used to calculate three-month mean values for classifying winter (Dec-Feb) seasons into positive, negative, and neutral conditions, based on the top, bottom, and middle thirds of the 62 years included in the study period. PNA was not treated as a diagnostic tool, but rather an indicator of atmospheric conditions over the North Pacific.

3.3 Results and Discussion

3.3.1 Synoptic Classification

Daily 500-hPa gph were classified into 16 types on a 4 x 4 SOM array (Fig. 3.3). Although Kohonen (2001) recommended selecting a rectangular rather than square array for mathematical stability during the training process, the selection of a square (4x4) array best suits the dataset and withstands all quality measures including Topological and Quantization Errors, and correlation with the daily PNA index (r = 0.73, sig. 1%). Several SOM-classifications were tested using a variety of parameters, including larger and smaller arrays. The larger array resulted in redundant, or repeated, circulation patterns, and the smaller resulted in blending of patterns and loss of definition of important patterns.

The frequency of each type (in the same order as Fig. 3.3) during the winter season is shown in Fig. 3.4a. The trajectory map, a function of the topological ordering of the SOM, represents the temporal evolution of atmospheric states (Fig. 3.4b), while Fig. 3.4c shows the persistence of each pattern. The average daily PNA values for each synoptic type are given in Fig. 3.4d. The inherent topological ordering of the SOM array is evident by the arrangement of PNA values, where predominantly positive values occupy the right portion of the SOM array and negative values along the left portion. These patterns are also evident in Fig. 3.3.

Synoptic Types 1 and 2 are indicative of a strong ridge resulting in northerly meridional flow directing cold arctic air over the western provinces (Fig. 3.3). Types depicting more zonal flow (e.g. Types 4 and 7) lack the mid-tropospheric vorticity changes that result in vertical motion in the mid- to lower-atmosphere and associated high or low pressure systems (Holton 1979). Types on the right half of the SOM array indicate various strengths and positions of a high-pressure ridge over western North America. This ridge effectively blocks the intrusion of cold Arctic air into the region (Bonsal et al. 2001).

3.3.2 Surface Climate Analysis

The spatial distribution of precipitation anomalies (expressed as percentage of normal) associated with each synoptic type demonstrates clear patterns of high/low precipitation (Fig. 3.5). Results indicate that Type 1 produced a strong north-south gradient of precipitation between the Liard and Saskatchewan Basins. Types 2 and 5 also reveal below-average precipitation in the Liard Basin accompanied by above-average precipitation in the Saskatchewan Basin. This suggests the strength of the precipitation gradient is a function of the strength and position of a high-pressure ridge over the Pacific Ocean (Fig. 3.3). Opposite precipitation gradients were found in Types 10 and 11, which are characterized by a developing ridge of high-pressure over the western edge of the continent. A well-developed ridge (Types 13-16) effectively blocked moisture transport to the region, resulting in below-average precipitation, while zonal flow (Types 3 and 4) generates above-average precipitation to the study region.

Negative air temperature anomaly patterns associated with northerly meridional flow over the study region (Types 1-3 and 5-6) were the result of cold air advection from the Arctic (Fig. 3.6). Conversely, patterns of above-average air temperatures are generated by a ridge axis immediately above and to the west of the study region (Types 10-16). Several gradient patterns are also evident, such as Type 1, with a greater magnitude of below-average air temperature in the south compared with the north. Weak gradients of the opposite sign were found in Types 8 and 9, where Type 8 is characterized by zonal flow and a weak trough over the North Pacific Ocean and Type 9 is a strong ridge of high-pressure over the ocean-continent boundary.

Below average air temperatures accompanied by above-average precipitation have the potential to extend the snow accumulation season, particularly if the frequency of these types is high during the onset of the accumulation season (Nov) and spring freshet (Mar-Apr). Conversely, a high frequency of below-average precipitation and above-average temperatures can shorten the snow accumulation season by delaying the onset of snow accumulation, increasing the potential for mid-winter melt or rain on snow events, and/or initiating an early spring freshet. To aid in the corroboration of the cumulative effects of synoptic type frequency on long-term winter snowpack, seasonal water availability is determined using the SPEI. Although SPEI was developed as a drought index, in this context it is used to identify regions of high/low snowpack. SPEI data is classified into 9 types using SOM (Fig. 3.7) to identify dry, wet, average, and gradient types. The average synoptic type frequency for each winter season corresponding to the wet, dry, and gradient SPEI types are calculated, and departure from mean overall frequency determined (Fig. 3.8).

SPEI Types 1, 4 and 7 are characterized by uniform dry conditions across the study region (Fig. 3.7), and are associated with a higher frequency of a high-pressure ridge over the western continent (Synoptic Types 12-16; Fig. 3.3), and a lower frequency of a ridge over the Pacific Ocean or zonal flow (Synoptic Types 1-4). Conversely, SPEI Types 3 and 6 demonstrate wet conditions throughout the study region, and are associated with the opposite synoptic type frequencies. Of particular interest are those SPEI types depicting a north-south gradient. Dry north and wet south conditions are apparent in SPEI Type 2, resulting from an increased frequency of zonal flow (Synoptic Types 3 and 4) and decreased frequency of ridging over western North America (Synoptic Types 9, 10, and 12). The opposite gradient, wet north-dry south is found in Types 8 and 9. However, the synoptic regime associated with these suggests different mechanisms through which these conditions were created. In the case of SPEI Type 9, the boundary between wet north-dry south lies at the Athabasca-North Saskatchewan watershed boundary and is the product of relatively average synoptic type frequencies (Fig. 3.8), with slightly increased (decreased) strong Pacific Ocean (western continental) ridging, suggesting additional factors such as atmospheric moisture transport dynamics. In general, these results are consistent with above/below average temperature and precipitation patterns produced by each synoptic type and reveal that the predominance of certain synoptic types during individual winters have a significant impact on the snow pack available for spring freshet runoff in various regions of western Canada.

3.3.3 Synoptic Type Frequency Trends

Changes in synoptic type frequency from 1950 to 2011 were evaluated using the Mann-Kendall (M-K) non-parametric test for trend (Mann 1945; Kendall 1975). Types 2, 3, 4, and 8 have significantly decreased and Types 9, 13, and 14 have significantly increased over the study period (sig. 10%; Fig. 3.9). Consequently, there has been a decrease in both weak ridging over the Pacific Ocean and zonal flow, and an increase in strong ridging over the western continent. These trends suggest decreased precipitation, particularly for the Saskatchewan River Basin, and increased temperatures, especially for the Liard, Peace, and Athabasca River Basins. Furthermore, when compared with results from SPEI analysis, synoptic trends suggested an increased frequency of dry surface conditions, and thus a low snowpack, for the entire study region, with the greatest impacts in the southern basins.

3.3.4 Teleconnections

The SOI, PDO and AO three-month mean values were ranked from lowest to highest, and the top and bottom third for each index were then selected to represent positive and negative phases. The synoptic type frequency distributions for each positive-negative pair were then compared using the two sample non-parametric Kolmogorov-Smirnov (K-S) test, evaluated at the 10% significance level.

SOI analyses reveal a significantly higher (lower) frequency of Types 1-4 and lower (higher) frequency of Types 12, 15 and 16 during positive (negative) phases of SOI (Fig. 3.10a). Consequently, positive SOI is characterized by a ridge of high-pressure over the Pacific Ocean coupled with a low-pressure trough over western Canada (Types 1 and 2) or zonal flow across the study region (Types 3 and 4). Comparison with the PNA map (Fig. 3.4d) shows these types have generally high negative PNA values. Conversely, negative SOI is represented by a ridge over the western continent coupled with a low-pressure trough over Alaska and the North Pacific Ocean (Types 12, 15, and 16), and have generally high positive PNA values. Therefore, positive (negative) SOI is associated with synoptic types that produce cool (warm), wet (dry) conditions in the study region.

PDO results signified a relationship similar to that of SOI, but with positive and negative index positions interchanged (Fig. 3.10b). During positive PDO phases there is a significantly increased frequency of a high-pressure ridge over the western continent (Types 12 and 14-16), while negative PDO is associated with a higher frequency of a high-pressure ridge over the Pacific Ocean and low-pressure trough over the continent (Types 1 and 2) and zonal flow (Types 3 and 4). This suggests a relationship between positive (negative) PDO and positive (negative) PNA (Fig. 3.4d). There was a shift from predominantly negative to positive PDO in the mid-1970s (Mantua et al. 1997). As shown in Fig. 3.9, Types 2, 3, and 4 occurred with a greater frequency prior to this shift, and Type 14 occurred with a greater frequency after the shift. Therefore, an interactive effect between the PDO phase and several of the time-series trends is apparent. However, the PDO is correlated with Type 1 ($r = -0.45$, sig. 1%), Type 15 ($r = 0.54$, sig. 1%), and Type 16 ($r = 0.46$, sig. 1%), none of which were determined to have a significant temporal trend.

To further evaluate the constructive relationship between out-of-phase SOI and PDO, a subset of winters classified as both negative SOI and positive PDO (8 records), and winters classified as both positive SOI and negative PDO (13 records) were identified and frequency of synoptic types compared (Fig. 3.10c). The K-S analysis reveals that Types 1-4 and 7 occur with a significantly increased frequency during positive SOI-negative PDO, and Types 14-16 occur with a significantly increased frequency during negative SOI-positive PDO. The largest difference in frequency is found in Type 16, where the average frequency ranged from 5% to 16%, demonstrating a strong constructive relationship between SOI and PDO, particularly affecting the strength of the persistent low-pressure trough over Alaska and the North Pacific and high-pressure ridge over the western continent.

One of the most striking examples of synoptic type frequency anomalies during negative phases of SOI and positive PDO occurred during the two strongest El Niño event years, 1983 and 1998. During the winter of 1982-83 Type 16 has a frequency of 34%, including a long persistent stretch of 20 days, while during the winter of 1997-98 the frequency is 23%. In contrast, the winter of 2010-11 is classed as a La Niña event and the frequency of Type 16 is 3%, while the study period average frequency is 9%. This suggests that the frequency and persistence of a well-developed trough of low-pressure over the North Pacific is influenced by the strength ENSO. The correlation between Dec-Feb SOI values and corresponding Nov-Apr frequency of Type 16 is -0.59 (sig. 1%).

Results of K-S analyses between synoptic type frequency and the AO indicate an increased frequency of types with a lower (higher) gph at high latitudes during positive (negative) phases of AO (Fig. 3.10d). Of these frequency differences, only Types 4 and 14 are found to have statistically significant differences in distribution (sig. 10%). Type 4 occurred with an increased frequency and Type 14 with a decreased frequency during positive AO, with the opposite conditions during negative AO. Type 4 is characterized by zonal flow across the southern portion of the synoptic map, a developing trough of low-pressure over the Gulf of Alaska, and closely spaced gph contours in the mid-latitudes. Type 14 depicts a ridge of high pressure over the western continent, with the ridge axis following a line directly above provincial and territorial boundaries to the Beaufort Sea, and a low-pressure trough to the west of the ridge.

3.4 Conclusions

This study identifies the dominant mid-tropospheric winter (Nov-Apr) circulation patterns that control surface temperature and precipitation anomalies in the headwaters of two major river basins in western Canada, and evaluates the characteristics of those patterns including frequency, trajectory and persistence. Alpine snowpack in these headwaters provide the majority of annual streamflow on the Saskatchewan and Mackenzie Rivers. Analyses reveal that above-average precipitation and below-average temperature are linked to a ridge of high-pressure over the North Pacific Ocean and trough of low-pressure over the western continent, advecting cold Arctic air over the study region. Conversely, a ridge of high-pressure over the western continent effectively blocks the intrusion of cold Arctic outbreaks, and produces above-average temperatures and below-average precipitation. Additionally, the position of the ridge influences north-south precipitation and temperature gradients. These findings are consistent with mid-tropospheric synoptic climatological studies of snow accumulation and ablation in the Peace River Basin (Romolo et al. 2006a, 2006b).

Trend results show an increasing trend in ridging over the western continent, generating anomalously high air temperatures and low precipitation. Trend analysis also indicates a corresponding decrease in weak ridging over the Pacific Ocean and zonal flow across the continent and, consequently, below-average air temperatures and above-average precipitation. Consequently, there is a tendency toward reduced snowpack and a shorter snow accumulation season affecting all river basins in the study region, particularly in the Saskatchewan River

Basin. Similar winter spatial and temporal air temperature, precipitation, snow-accumulation, and snowmelt trends were found by Linton et al. (2014).

Statistically significant synoptic type frequency differences exist for the SOI, PDO, and AO, with the strongest responses found with the combined out-of-phase SOI and PDO indices. Negative SOI and positive PDO are associated with a trough of low-pressure over Alaska and the North Pacific along with a weak ridge over the western continent, while positive SOI and negative PDO are related to a ridge of high-pressure over the Pacific Ocean and trough of low-pressure over the continent. Atmospheric responses to SOI and PDO can also be interpreted as changes in dominant PNA-type patterns, similar to findings by Yu et al. (2007) and Johnson and Feldstein (2010). These results are consistent with circulation composites of El Niño and La Niña episodes by Shabbar and Khandekar (1996) and Shabbar et al. (1997), the out-of-phase SOI and PDO composites created by Bonsal et al. (2001), and composites of positive PDO by Mantua et al. (1997) and Mantua and Hare (2002).

The AO analyses reveal only two synoptic types with a significantly different distribution, suggesting limited influence over the study region. This is consistent with Deser (2000) who demonstrated that AO exerts a greater influence over the mid-latitude region of the Atlantic and a weaker influence over the mid-latitude region of the Pacific. Positive AO is associated with low gph over the high-latitudes, and negative AO with high gph over same region, results that are comparable to Cassano et al. (2006) and Cassano and Cassano (2010); however, neither of those studies statistically verified relationships between synoptic circulation and the AO.

The application of statistical analysis increases confidence in the understanding of atmospheric circulation and surface climate conditions produced by these teleconnections.

This research examines winter surface climate and controlling atmospheric circulation patterns as part of a broader project evaluating water resource distribution in two major watersheds in western Canada. Additionally, statistically based analyses combine synoptic climatology with frequency mapping of negative and positive phases of SOI, PDO, and AO to determine the influence of teleconnections on dominant circulation patterns. Research findings provide fundamental knowledge of the atmospheric drivers of water availability and contribute to our understanding of the spatial and temporal variation in water resource distribution in western Canada. Future research should include a synoptic-based approach to examine extreme events, including severe and multi-year droughts, and high precipitation and/or high-intensity snowmelt-induced flooding.

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References

Arnell, N.W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean. Journal of Geophysical Research. 110, D07105, DOI:10.1029/2004JD005348

Barnston, A.G. and Livezey, R.E. (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly Weather Review. 115, 1083-1126

Bawden, A.J., Burn, D.H., and Prowse, T.D. (2014), Recent changes in patterns of western Canadian river flow and association with climatic drivers. *Submitted to Hydrological Processes*

Bonsal, B.R., Shabbar, A., and Higuchi, K. (2001), Impacts of low frequency variability modes on Canadian winter temperature. International Journal of Climatology. 21, 95-108, DOI:10.1002/joc.590

Bonsal, B.R. and Prowse, T.D. (2003), Trends and variability in spring and autumn 0°C-isotherm dates over Canada. Climatic Change. 57, 341-358, DOI:10.1023/A:1022810531237

Burn, D.H., Cunderlik, J.M, and Pietroniro, A. (2004a), Hydrological trends and variability in the Liard River basin. Hydrological Sciences Journal. 49(1), 53-67, DOI:10.1623/hysj.49.1.53.53994

Burn, D.H., Abdul Aziz, O.I., and Pietroniro, A. (2004b), A comparison of trends in hydrological variables for two watersheds in the Mackenzie River Basin. Canadian Water Resources Journal. 29(4), 283-298, DOI:10.4296/cwrj283

Burn, D.H. (2008), Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. Journal of Hydrology. 352, 225-238

Burn, D.H., Fan, L., and Bell, G. (2008), Identification and quantification of streamflow trends on the Canadian Prairies. Hydrological Sciences Journal. 53:3, 538-549, DOI:10.1623/hysj.53.3.538

Cassano, J.J., Uotila, P., and Lynch, A. (2006), Changes in synoptic weather patterns in the polar regions in the twentieth and twenty-first centuries, part 1: Arctic. International Journal of Climatology. 26, 1027-1049, DOI:10.1002/joc.1306

Cassano, E.N. and Cassano, J.J. (2010), Synoptic forcing of precipitation in the Mackenzie and Yukon River basins. International Journal of Climatology. 30, 658-674, DOI:10.1002/joc.1926

Déry, S.J. and Wood, E.F. (2005), Decreasing river discharge in northern Canada. Geophysical Research Letters. 32, L10401. DOI:10.1029/2005GL022845

Déry, S.J., Hernández-Henríquez, M.A., Burford, J.E., and Wood, E.F. (2009), Observational evidence of an intensifying hydrological cycle in northern Canada. Geophysical Research Letters. 36, L13402, DOI:10.1029/2009GL038852

Deser, C. (2000), On the Teleconnectivity of the "Arctic Oscillation." Geophysical Research Letters. 27, 6. 779-782, DOI:10.1029/1999GL010945

Finnis, J., Cassano, J., Holland, M., Serreze, M., and Uotila, P. (2009), Synoptically forced hydroclimatology of major Arctic watersheds in general circulation models; Part 1: the Mackenzie River Basin. International Journal of Climatology, 29, 1226-1243. DOI:10.1002/joc.1753

Fleming, S.W. and Whitfield, P.H. (2010), Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and southeast Alaska. Atmosphere-Ocean, 48(2), 122-131. DOI:10.3137/AO1107.2010

Gershunov, A. and Barnett, T.P. (1998), Interdecadal modulation of ENSO teleconnections. Bulletin of the American Meteorological Society. 79(12), 2715-2725

Gobena, A.K. and Gan, T.Y. (2006), Low-frequency variability in southwestern Canadian stream flow: Links with large-scale climate anomalies. International Journal of Climatology. 26, 1843-1869. DOI:10.1002/joc.1336

Goulding, D.L. (1978) Calculated snowpack evaporation during Chinooks along the eastern slopes of the Rocky Mountains in Alberta. Journal of Applied Meteorology, 17, 1647-1651

Hewitson, B.C. and Crane, R.G. (2002), Self-organizing maps: applications to synoptic climatology. Climate Research. 22, 13-26, DOI:10.3354/cr022013

Holton, J.R. (1979), An Introduction to Dynamic Meteorology. Second edition. Academic Press, Inc. New York, New York.

Horel, J.D. and Wallace, J.M. (1981), Planetary-scale atmospheric phenomena associated with the southern oscillation. Monthly Weather Review. 109, 813-829

Huntington, T.G. (2006), Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology. 319, 83-95

Hutchinson, M.F., McKenney, D.W., Lawrence, K., Pedlar, J.H., Hopkinson, R.F., Milewska, E., and Papadopol, P. (2009), Development and testing of Canada-wide interpolated spatial models of daily minimum-maximum temperature and precipitation for 1961-2003. Journal of Applied Meteorology and Climatology. 48. 725-741

Jiang, N., Cheung, K., Luo, K., Beggs, P.J., and Zhou, W. (2012), On two different objective procedures for classifying synoptic weather types over east Australia. International Journal of Climatology. 32, 1475-1494, DOI:10.1002/joc.2373

Johnson, N.C., Feldstein, S.B. (2010), The continuum of North Pacific sea level pressure patterns: Intraseasonal, Interannual, and Interdecadal Variability. Journal of Climate. 23, 851-867. DOI:10.1175/2009JCLI3099.1

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., … Joseph, D. (1996), The NCEP/NCAR 40-year reanalysis project, Bulletin of the American Meteorological Society. 77, 437-471

Kendall, M.G. 1975. Rank Correlation Measures. Charles Griffin, London.

Kohonen, T. (2001), Self-Organizing Maps. Springer, New York

Lackmann, G.M. and Gyakum, J.R. (1998), Moisture Transport Diagnosis of a Wintertime Preciptitation Event in the Mackenzie River Basin. Monthly Weather Review. 126, 668-691

Lammers, R.B., Shiklomanov, A.I., Vörösmarty, C.J., Fekete, B.M., and Peterson, B.J. (2001) Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research. 106, D4:3321-3334, DOI:10.1029/2000JD900444

Lewis, E.L. (2000), The Freshwater Budget of the Arctic Ocean. Kluwer Academic Publishers, Dordrecht

Linton, H., Prowse, T., Dibike, Y., and Bonsal, B. (2014), Spatial and temporal analysis of hydroclimatic variables affecting streamflow in western Canada from 1950-2010. *Submitted to Hydrological Processes*

Liu, J. and Stewart, R.E. (2003), Water vapor fluxes over the Saskatchewan River Basin. Journal of Hydrometeorology. 4, 944-959

Longley, R.W. (1967), The frequency of winter Chinooks in Alberta. Atmosphere, 5(4), 4-16

MacDonald, M.K., Pomeroy, J.W., and Pietroniro, A. (2010), On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains. Hydrology and Earth System Sciences, 14, 1401-1415, doi:10.5194/hess-14-1401-2010

Mann, H.B. 1945. 'Non-parametric tests against trend', Econometrica. 13, 245-259

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. (1997), A pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society. 78, 1069-1079

Mantua, N.J. and Hare, S.R. (2002), The pacific decadal oscillation. Journal of Oceanography, 58, 35-44

Martin, J.E. (2006) Mid-Latitude Atmospheric Dynamics: A First Course. John Wiley & Sons, Ltd. , Chichester, West Sussex, England

McKenney, D.W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., … Owen, T. (2011), Customized spatial climate models for North America. Bulletin of the American Meteorological Society. 92(12) 1611-1622

Morison, J., Kwok, R., Peralta-Ferriz, C., Alkire, M., Rigor, I., Andersen, R., and Steele, M. (2012), Changing Arctic Ocean freshwater pathways. Nature. 481, 66-70. DOI: 10.1038/nature10705, DOI:10.1038/nature10705

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2014), Evaluating the distribution of water resources in western Canada using synoptic climatology and selected teleconnections. Part 2: Summer season. *Submitted to Hydrological Processes*

Overland, J.E. and Wang, M. (2005), The Arctic climate paradox: The recent decrease of the Arctic Oscillation. Geophysical Research Letters, 32, L06701, doi:10.1029/2004GL021752

Overland, J., Rodionov, S., Minobe, S., and Bond, N. (2008), North Pacific regime shifts: Definitions, issues and recent transitions. Progress in Oceanography. 77, 92-102

Overland, J.E. and Wang, M. (2010), Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. Tellus, 62A, 1-9, DOI:10.1111/j.1600-0870.2009.00421.x

Prowse, T.D., Bonsal, B.R., Burn, D.H., Dibike, Y.B., Edwards, T., Ahmed, R., Bawden, A.J., Linton, H.C., Newton, B.W., and Walker, G.S. (2013), Climatic redistribution of Canada's western water resources (CROCWR). In Stuefer, S.L. and Bolton, W.R. (Eds.) Proceedings from the 19th Northern Research

Basins Symposium and Workshop (246). Fairbanks: University of Alaska Fairbanks

Reusch, D.B., Alley, R.B., and Hewitson, B.C. (2005), Relative performance of self-organizing maps and principal component analysis in pattern extraction from synthetic climatological data. Polar Geography, 29(3), 188-212, DOI:10.1080/789610199

Reusch, D.B. (2010), Nonlinear climatology and paleoclimatology: Capturing patterns of variability and change with Self-Organizing Maps. Physics and Chemistry of the Earth, 35, 329-340

Rigor, I.G., Wallace, J.M., and Colony, R.L. (2002), Response of sea ice to the Artic Oscillation. Journal of Climate, 15, 2648-2663

Romolo, L., Prowse, T. D., Blair, D., Bonsal, B. R. and Martz, L. W. (2006a), The synoptic climate controls on hydrology in the upper reaches of the Peace River Basin. Part I: snow accumulation. Hydrological Processes, 20, 4097–4111. DOI:10.1002/hyp.6421

Romolo, L., Prowse, T. D., Blair, D., Bonsal, B. R., Marsh, P. and Martz, L. W. (2006b), The synoptic climate controls on hydrology in the upper reaches of the Peace River Basin. Part II: snow ablation. Hydrological Processes, 20, 4113–4129. DOI:10.1002/hyp.6422

Rood, S.B., Pan, J., Gill, K.M., Franks, C.G., Samuelson, G.M., and Shepherd, A. (2008), Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probably impacts on floodplain forests. Journal of Hydrology. 349, 397-410

Saunders, I.R. and Byrne, J.M. (1996), Generating regional precipitation from observed and GCM synoptic-scale pressure fields, southern Alberta, Canada. Climate Research. 6, 237-249

Serreze, M.C., Bromwich, D.H., Clark, M.P., Etringer, A.J., Zhang, T., and Lammers, R. (2003), Large-scale hydro-climatology of the terrestrial Arctic drainage system. Journal of Geophysical Research, 108, D2, 8160, DOI:10.1029/2001JD000919

Shabbar, A. and Khandekar, M. (1996), The impact of El Niño-Southern Oscillation on the temperature field over Canada: Research note. Atmosphere-Ocean, 34(2), 401-416, DOI: 1080/07055900.1996.9649570

Shabbar, A., Bonsal, B., and Khandekar, M. (1997), Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate. 10, 3016-3027

Shabbar, A. and Bonsal, B. (2004), Associations between low frequency variability modes and winter temperature extremes in Canada. Atmosphere-Ocean, 42(2), 127-140, DOI:10.3137/ao.420204

Smirnov, V.V. and Moore, G.W.K. (2001), Short-term and seasonal variability of the atmospheric water vapor transport through the Mackenzie river basin. Journal of Hydrometeorology. 2, 441-452

Stahl, K., Moore, R.D., and McKendry, I.G. (2006), The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. International Journal of Climatology. 26, 541-560, DOI:10.1002/joc.1268

Thompson, D.W., Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophysical Research Letters. 25, 1297–1300, DOI:10.1029/98GL00950

Trenberth, K.E. and Hurrell, J.W. (1994), Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics, 9, 303-319

Vesanto, J., Himberg, J., Alhoniemi, E., and Parhankangas, J. (2000), SOM toolbox for Matlab 5. Helsinki University of Technology. Rep. A57

Vicente-Serrano, S.M., Beguería, S., and López-Moreno, J.I. (2010), A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate. 23, 1696-1718. DOI:10.1175/2009JCLI2909.1

Wallace, J.M. and Gutzler, D.S. (1981), Teleconnections in the geopotential height field during the Northern Hemisphere winter. Monthly Weather Review. 109, 784-812

Whitfield, P.H., Moore, R.D. (Dan), Fleming, S.W., and Zawadzki, A. (2010), Pacific decadal oscillation and the hydroclimatology of western Canada – review and prospects. Canadian Water Resources Journal. 35(1), 1-28, DOI:10.4296/cwrj3501001

Yip, Q.K.Y., Burn, D.H., Seglenieks, F., Pietroniro, A., and Soulis, E.D. (2012), Climate impacts on hydrological variables in the Mackenzie River Basin. Canadian Water Resources Journal. 37(3), 209-230, DOI:10.4296/cwrj2011-899

Yu, B., Shabbar, A., and Zwiers, F.W. (2007), The enhanced PNA-like climate response to pacific interannual and decadal variability. Journal of Climate. 20, 5285-5300

Zhang, X., Vincent, L.A., Hogg, W.D., and Niitsoo, A. (2000), Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean. 38(3), 395-429, DOI:10.1080/07055900.2000.9649654

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R. (2001), Trends in Canadian streamflow. Water Resources Research. 37(4), 987-998, DOI:10.1029/2000WR900357

Zhang, X., He, J., Zhang, J., Polyakov, I., Gerdex, R., Inoue, J., and We, P. (2013), Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. Nature Climate Change. 3, 47-51, DOI:10.1038/nclimate1631

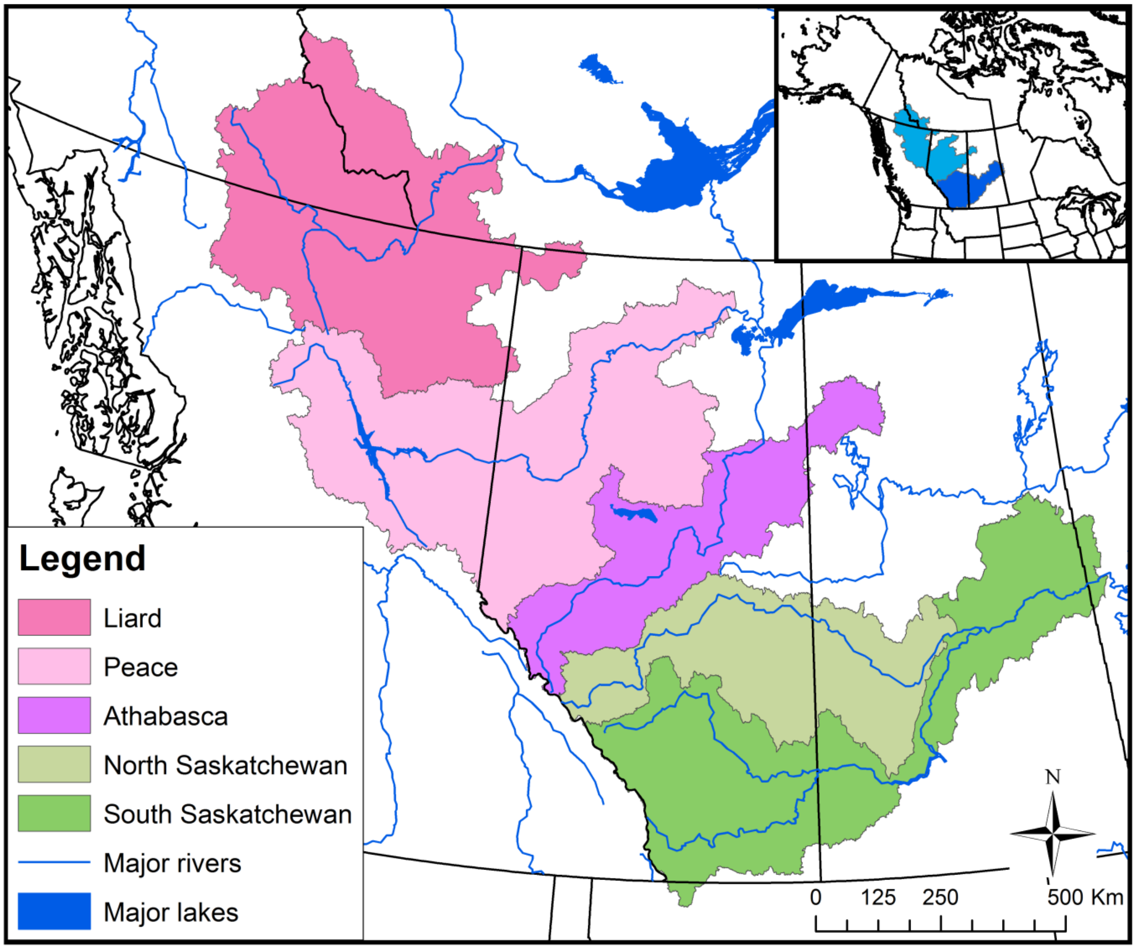


Figure 3.1: Rivers originating on the leeward slopes of the Rocky Mountains. The Liard, Peace, and Athabasca Rivers are tributaries to the north-flowing Mackenzie River, and the North and South Saskatchewan Rivers are tributaries to the east-flowing Saskatchewan River.

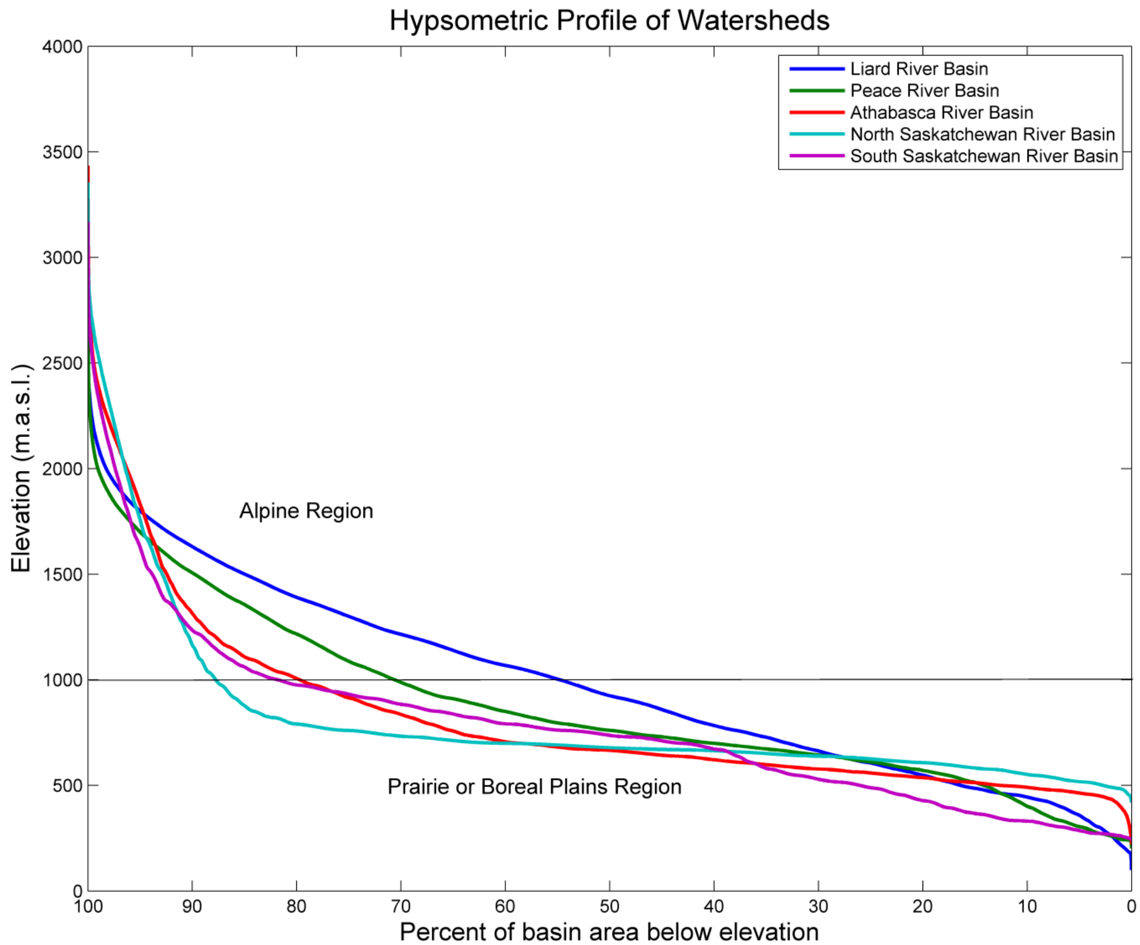


Figure 3.2: Hypsometric profile of the Liard, Peace, Athabasca, North Saskatchewan, and South Saskatchewan Rivers.

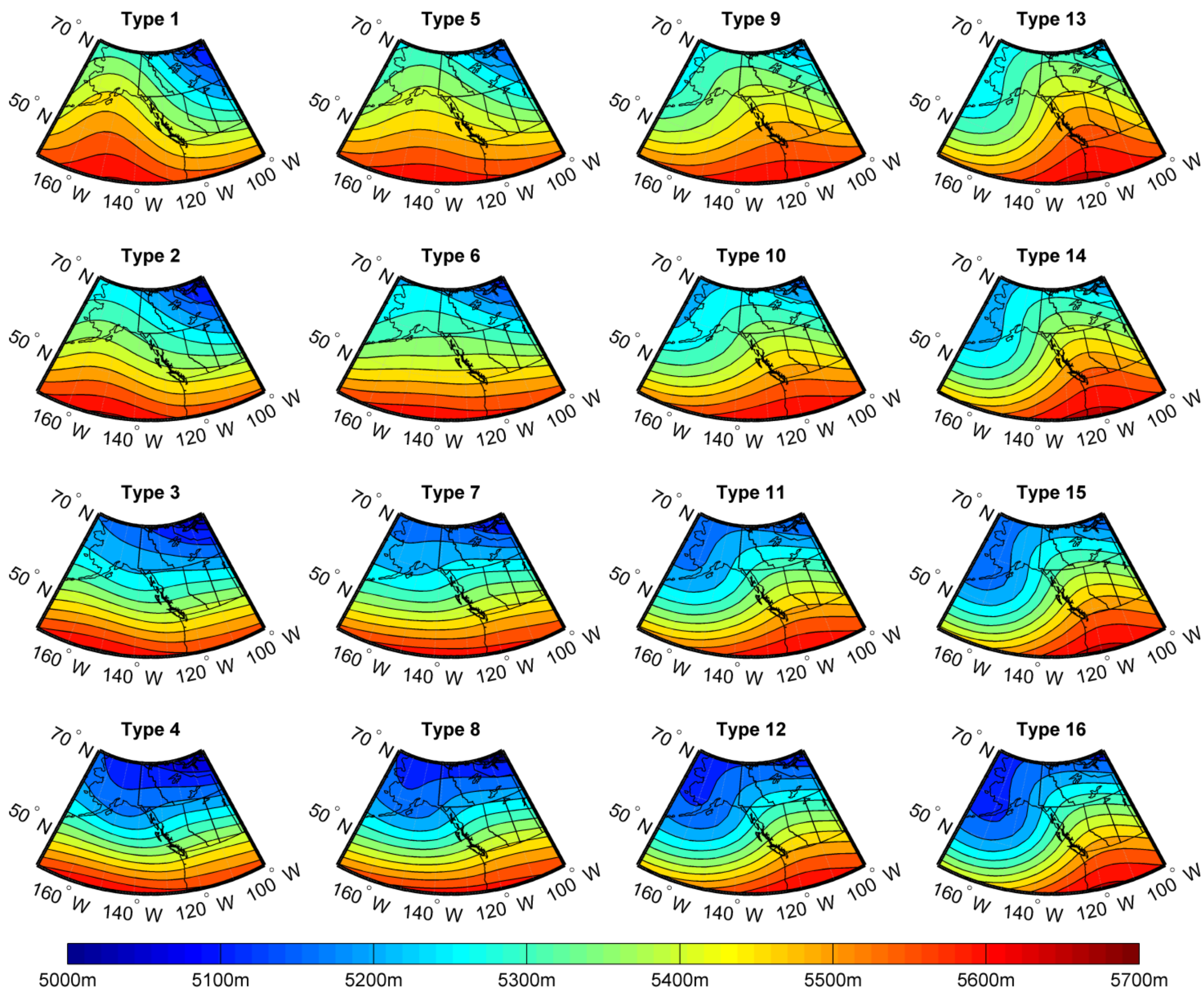
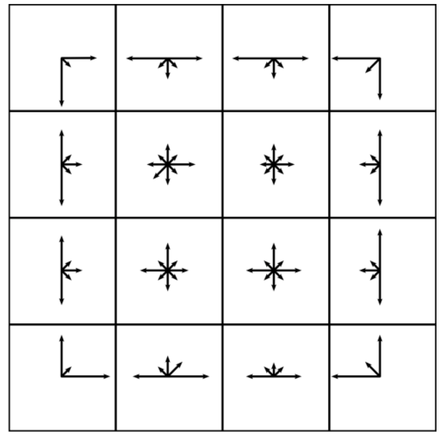


Figure 3.3: Daily winter (Nov-Apr) geopotential heights at 500hPa for 1950-2011 classified using Self-Organizing Maps (SOM).

a)

8.8	5.5	5.8	7.8
5.9	4.0	4.9	6.4
6.1	4.4	4.7	6.4
7.2	6.6	6.5	9.1

b)



c)

71	45	48	67
41	28	32	46
39	26	28	41
62	42	39	68

d)

-0.78	-0.28	0.15	0.62
-0.82	-0.14	0.20	0.73
-0.69	-0.04	0.34	0.77
-0.58	0.05	0.40	0.77

Figure 3.4: Synoptic type a) frequency (%) calculated as the percentage of total occurrences of each synoptic type over the study period, b) trajectory, where the length of each arrow is proportional to the percentage of shifts to neighbouring types, c) persistence (%), calculated as the percentage of occurrences were the pattern remains the same on the following day, and d) average PNA value during the study period (1950-2011).

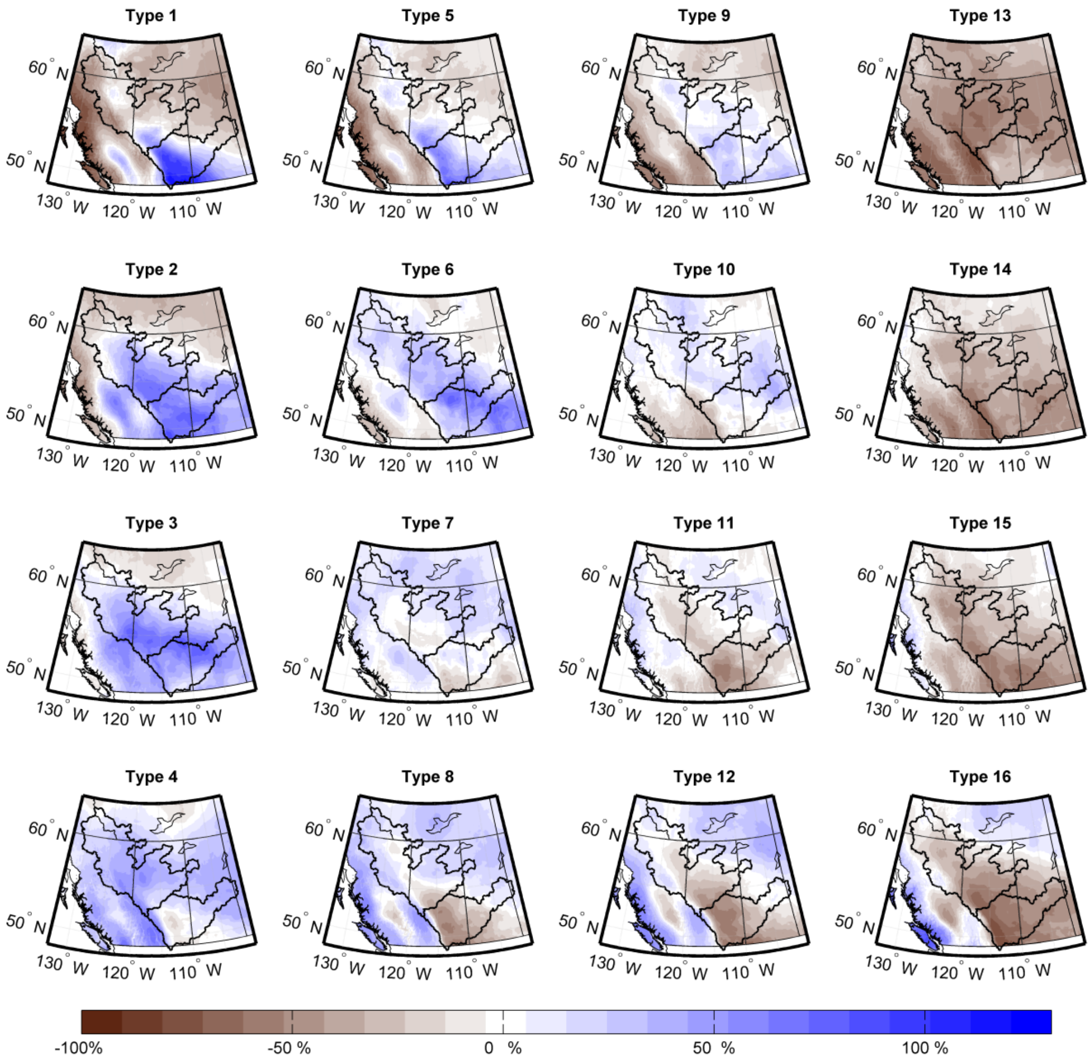


Figure 3.5: Precipitation associated with each synoptic type, calculated as the percentage of precipitation delivered to each grid point relative to the 1950-2010 mean values at each grid.

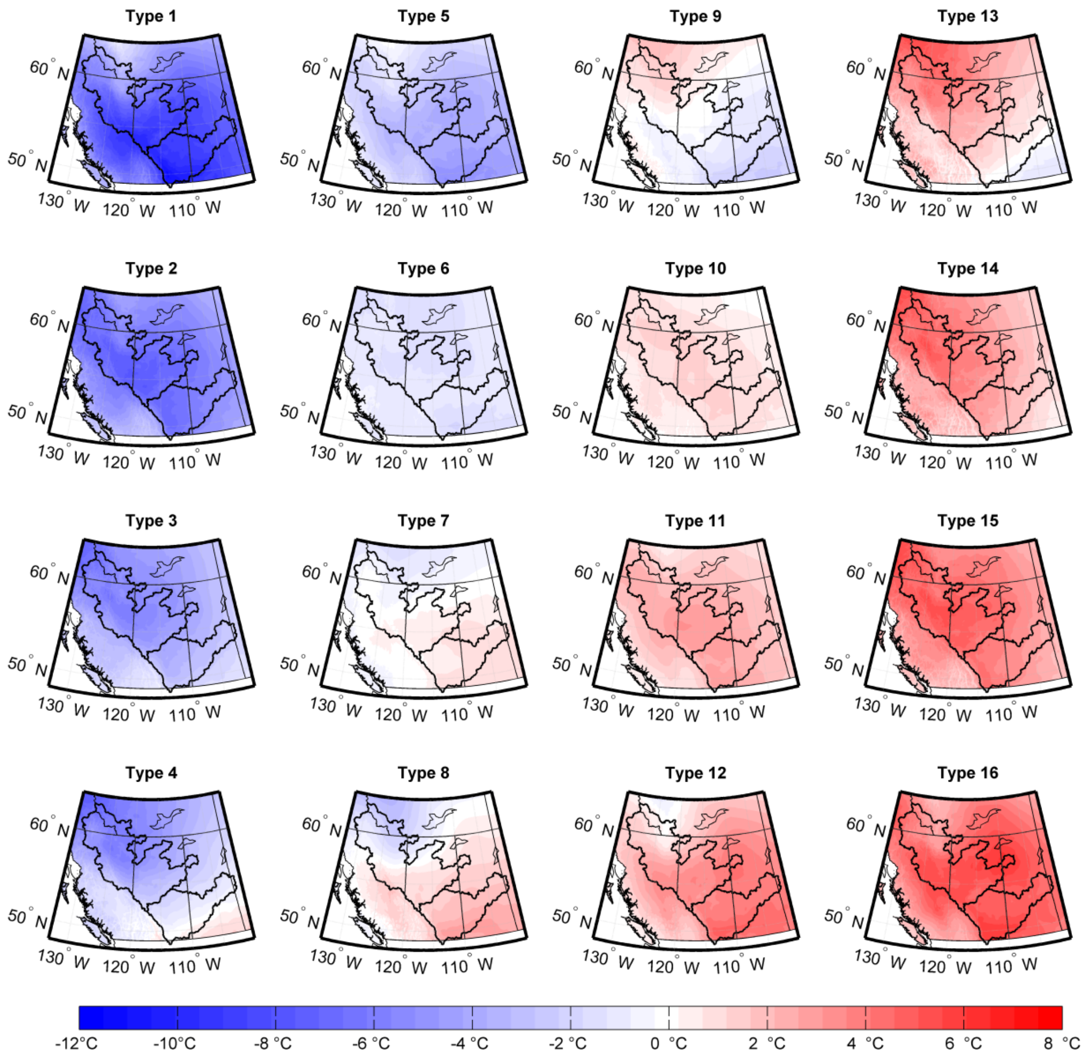


Figure 3.6: Temperature anomalies associated with each synoptic type, relative to the 1950-2010 mean values at each grid.

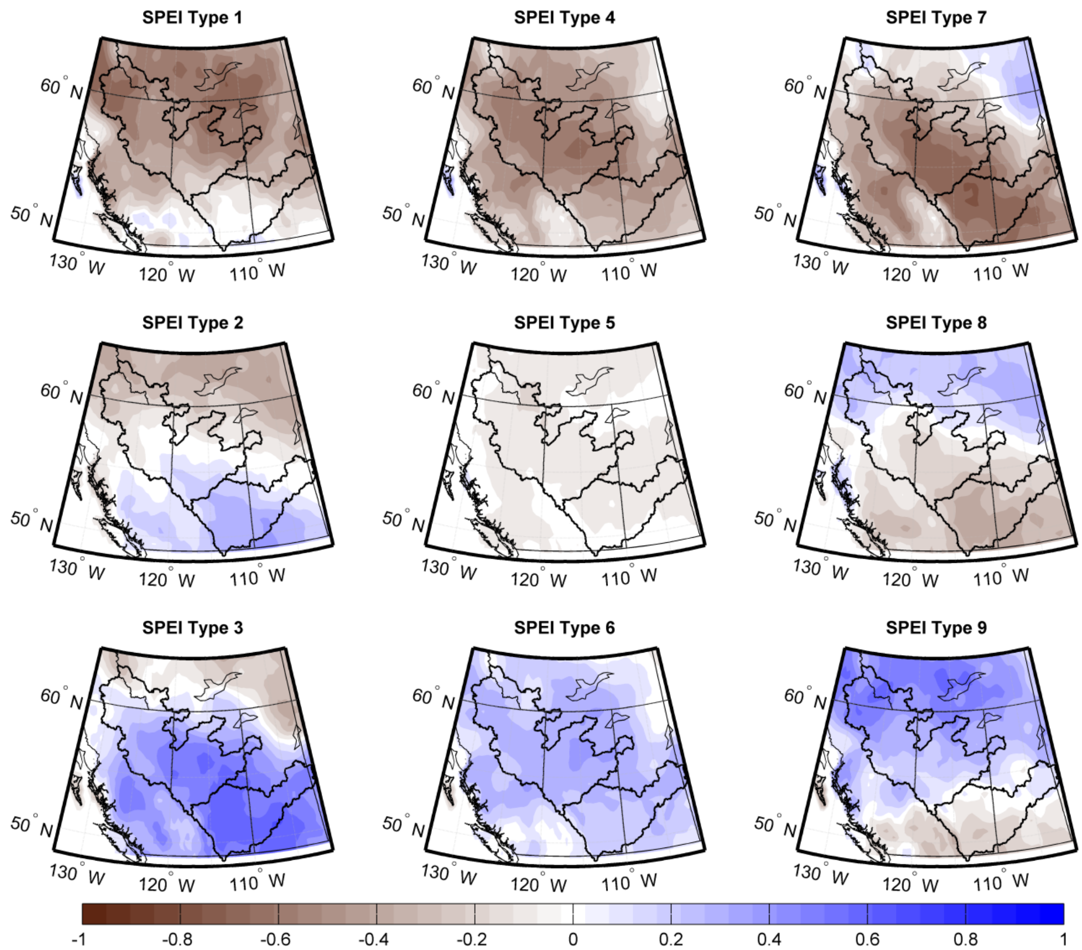


Figure 3.7: Winter Standardized Precipitation-Evapotranspiration Index (SPEI), classified into dominant patterns using SOM.

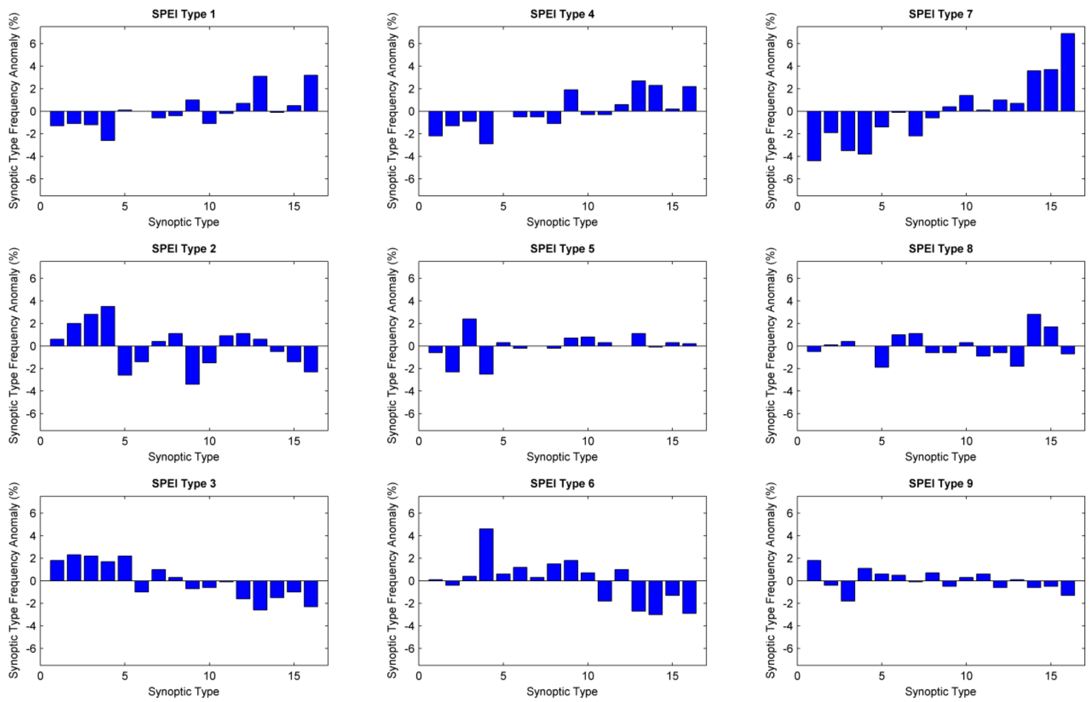


Figure 3.8: Synoptic type frequency anomalies associated with each SPEI pattern identified in Fig. 3.7.

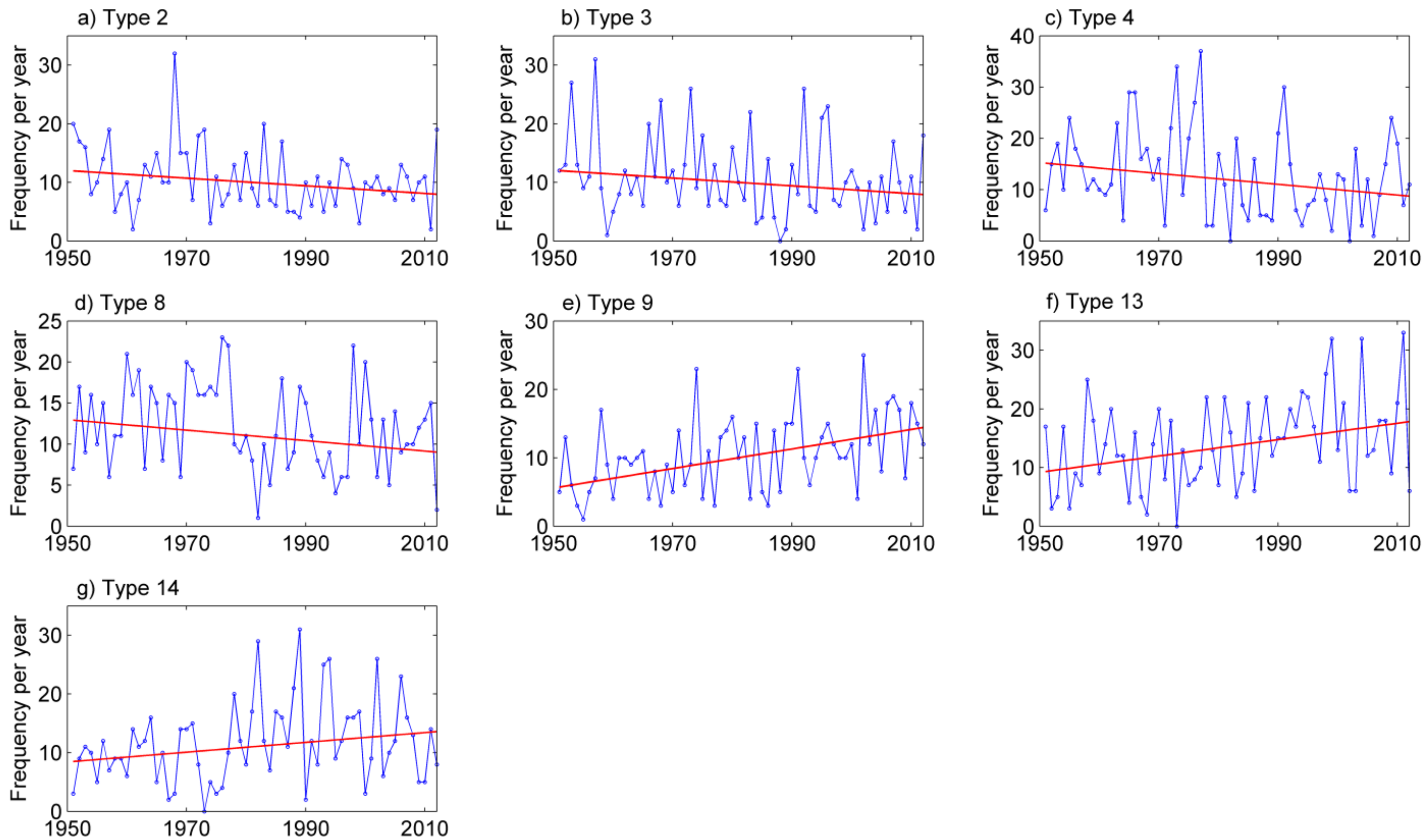


Figure 3.9: Synoptic type trends, evaluated using the non-parametric Mann-Kendall test. Only trends significant at 10% are shown, with percent increase/decrease over the study period (1950-2011), including decreasing trends a) Type 2 (-33%), b) Type 3 (-33%), c) Type 4 (-42%), d) Type 8 (-30%), and increasing trends e) Type 9 (150%), f) Type 13 (90%), and g) Type 14 (59%).

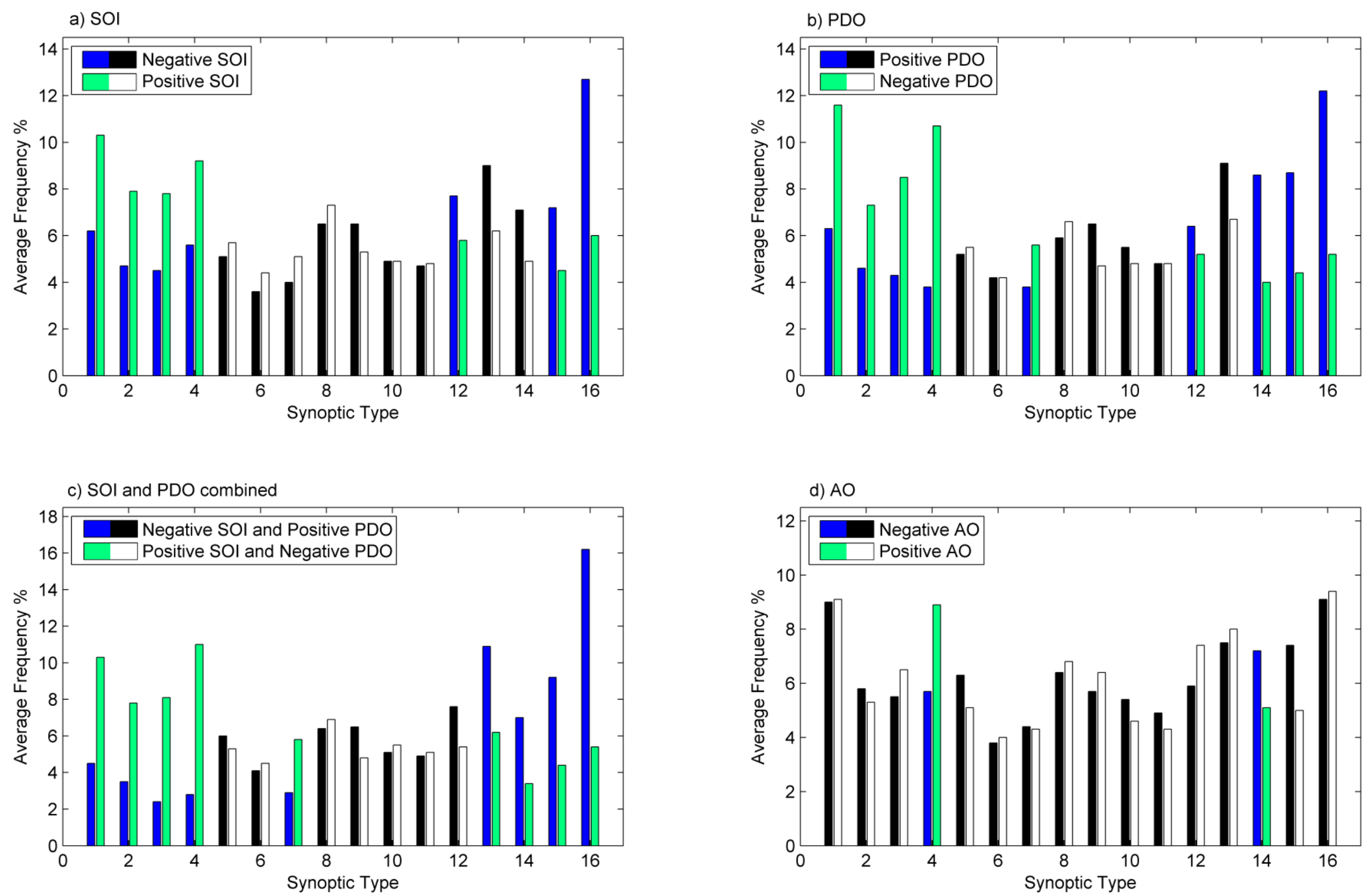


Figure 3.10: Synoptic type frequency distribution differences for a) positive and negative SOI, b) positive and negative PDO, c) negative SOI and positive PDO, and positive SOI and negative PDO, and d) positive and negative AO

Chapter 4: Evaluating the distribution of water resources in western Canada using synoptic climatology and selected teleconnections. Part 2: Summer season

Abstract

Minor changes to seasonal air temperature and precipitation can have a substantial impact on the availability of water resources within large watersheds. Two such watersheds, the north-flowing Mackenzie and east-flowing Saskatchewan Basins have been identified as highly vulnerable to such changes, and, therefore, selected for study as part of the Climatic Redistribution of western Canadian Water Resources (CROCWR) project. CROCWR aims to evaluate spatial and temporal changes to water resource distribution through the analysis of a suite of hydroclimatic and streamflow variables. As part of this analysis, dominant summer (May-Oct) circulation patterns at 500-hPa for 1950-2011 are identified using the method of self-organizing maps (SOM). Surface climate variables associated with these patterns are then identified, including both daily air temperature and precipitation, and seasonal Standardized Precipitation-Evapotranspiration Index (SPEI) values. Relationships between dominant circulation patterns and the Southern Oscillation Index (SOI) and Pacific Decadal Oscillation (PDO) are then statistically evaluated. Results indicate that mid-summer (Jul-Aug) is dominated by a split-flow blocking pattern, resulting in cool (warm), wet (dry) conditions in the southern (northern) portion of the study area. By contrast, the shoulder season (May and Oct) is dominated by a trough of low-pressure over the North Pacific

Ocean. The frequency of weak split-flow blocking is higher during positive SOI and negative PDO, while ridging over the western continent is more frequent during negative SOI and positive PDO. Results from this analysis increase our knowledge of processes controlling the distribution of summer water resources in western Canada.

4.1 Introduction

Changes to the global climate have been widespread and heterogeneous, including an amplification of warming over the high-latitudes compared with mid- and lower-latitudes (Zhang et al. 2000; Serreze et al. 2009; Serreze and Barry 2011). Two profound consequences of climate change have been an enhanced hydrologic cycle (Huntingdon 2006; Déry et al. 2009) and increased atmospheric moisture transport (Zhang et al. 2013), which may impact the frequency and magnitude of extreme weather phenomena, such as drought and high-intensity precipitation. Of particular concern are the regional hydroclimatic impacts that result in large-scale changes across the boundaries of large watersheds, leading to a redistribution of water resources.

The highly varied geography of western Canada gives rise to a number of hydroclimatic regions, and the rivers within these regions discharge to the Pacific Ocean, Arctic Ocean, and Hudson Bay. Concern over terrestrial water availability and changing flow regimes has created the need for a broad-scale analysis of a suite of hydroclimatic and streamflow variables in western Canada to evaluate the Climatic Redistribution of western Canadian Water Resources (CROCWR; Prowse et al. 2013). The CROCWR project aims to synthesize multi-variable analyses to determine locations of water resource redistribution and the climatic drivers behind these trends (see also Bawden et al. 2014 and Linton et al. 2014).

The headwaters of two major river systems in western Canada, the Mackenzie and Saskatchewan Rivers (Fig. 4.1), are located on the leeward slopes of the Rocky Mountains. The primary tributaries to the Mackenzie River – the Liard, Peace, and Athabasca Rivers, contribute the majority of annual streamflow of the Mackenzie River, and form a mid-latitude pathway to the Arctic Ocean. The tributaries to the Saskatchewan River, the North and South Saskatchewan Rivers, converge north of Saskatoon and ultimately drain into the Hudson Bay. Northern rivers flow through boreal and taiga plains before converging with the Mackenzie River, and the southern rivers flow through a semi-arid and relatively flat prairie region (Fig. 4.2).

Water resources during the summer season are essential for natural and human processes including aquatic and terrestrial ecosystems (Schindler and Donahue 2006; Stewart et al. 2011), agricultural production (Martz et al. 2007), and hydroelectricity generation (Pentney and Ohrn 2008). Furthermore, a number of marine processes are dependent on density-based stratification resulting from freshwater inputs from the Mackenzie River to the Arctic Ocean, including circulation pathways (Arnell 2005), sea ice formation (Lammers et al. 2001), and feedbacks to the global climate (Lewis et al. 2000).

Summer water resource availability is a function of basin-wide precipitation, evapotranspiration, and in some cases contributions from glacier melt and/or controlled release of water from reservoirs at hydroelectricity generation facilities. The region east of the Rocky Mountains, especially the southern prairies, is prone to considerable interannual hydroclimatic variability, including periods of excessively dry or wet conditions (Shabbar et al. 2011). Of particular concern are increases in evapotranspiration, a function of temperature, which can exacerbate drought conditions (Bonsal et al. 2011) and affect precipitation recycling (Raddatz 2005).

Droughts have agricultural and economic consequences (Stewart et al. 2011) as well as affecting terrestrial and aquatic health (Schindler and Donahue 2006) – the effects of severe or multi-year droughts being particularly devastating (Chipanshi et al. 2006; Wheaton et al. 2008). The frequency of droughts in the southern prairies is greater than other regions in Canada (Bonsal et al. 2012), and typically coincides with peak water demand. Summer months are often the lowest flow on the natural hydrograph, but the presence of hydroelectric dams and reservoirs have altered natural flow regimes, particularly on the Peace and South Saskatchewan Rivers (Peters and Prowse 2001; Pentney and Ohrn 2008). During times of drought, water resources may be insufficient to meet hydroelectricity production (Roberts et al. 2006) and agricultural irrigation demands (Wheaton et al. 2008). Therefore, there is a need to better understand atmospheric and hydroclimatic conditions that lead to droughts.

Several studies have evaluated temporal trends in summer climate and streamflow in western Canada. These studies have primarily focused on broad coarse-resolution changes or, in the case of streamflow, discrete regional changes. For example, Zhang et al. (2000) detected temperature increases during summer

(Jun-Aug), but found decreases for autumn (Sep-Nov), from 1950-1998. They also identified summer precipitation decreases in the southern prairies and northwestern Northwest Territories, but increases elsewhere in western Canada, while increased precipitation trends were observed across western Canada during autumn. In a similar study, but using data at a much finer scale, Linton et al. (2014) found statistically significant summer (May-Oct) increases (1950-2010) in minimum daily temperature across western Canada, where increases in maximum daily temperature were found primarily in northern Canada. Additionally, they found decreasing summer precipitation in the Lower Athabasca River basin, and increasing precipitation in the Liard River basin and portions of the Peace River basin. One advantage of fine-resolution scale analysis is the ability to evaluate climatic changes within and across watershed boundaries.

Summer river discharge has generally decreased in western Canada (Zhang et al. 2001). However, hydrologic responses to climate change have not been homogeneous. For example, both decreasing and increasing streamflow trends have been detected for various hydrometric gauging stations within the Mackenzie (Yip et al. 2012, Bawden et al. 2014), Liard (Burn et al. 2004a), Athabasca (Burn et al. 2004a, 2004b; Rood et al. 2008), and Saskatchewan (Westmacott and Burn 1997; Rood et al. 2008; Bawden et al. 2014) basins. Many of the trends during late spring and early summer can be partially attributed to a trend toward an earlier spring freshet (Zhang et al. 2001; Burn et al. 2004a; Rood et al. 2008; Burn 2008; Yip et al. 2012; Bawden et al. 2014).

Mid-tropospheric circulation and atmospheric moisture transport pathways largely control surface climate, including precipitation and air temperature. Specifically, mid-tropospheric ridges and troughs dictate the location and movement of cold and warm fronts (Holton 1979). The interaction between airflow and the Rocky Mountains results in orographic precipitation on the windward slopes and the descent of warm dry air down the leeward slopes. Lee cyclogenesis is common in the region east of the Rocky Mountains (Martin 2006), a feature important for the efficient generation of precipitation (Lackmann and Gyakum 1996; Spence and Rausch 2005).

During summer months, the Mackenzie and Saskatchewan River Basins receive moisture from the Pacific and Arctic Oceans, as well as the Gulf of Mexico and Gulf of California. The primary source of summer moisture over the Mackenzie River Basin is the Arctic Ocean, produced by a dominant split-flow blocking high (Smirnov and Moore 2001). However, high-intensity precipitation events in the Mackenzie and Saskatchewan River Basins have been traced to the Gulf of Mexico and Gulf of California (Liu and Stewart 2003; Liu et al. 2004; Brimelow and Reuter 2005). An additional source of moisture available for precipitation results from local evapotranspiration and convection, which can be precipitated locally or transported outside of the basin. For example, the Saskatchewan River Basin acts as a source region for summer convective precipitation in the Mackenzie River Basin (Liu and Stewart 2003). The Mackenzie River Basin has a generally high proportion of precipitation recycling (Szeto 2002) compared with the southern prairie region

(Raddatz 2000), and the relatively low soil moisture during drought conditions adversely affects the frequency of convective precipitation (Raddatz 2005).

Previous studies of synoptic-scale mid-tropospheric circulation and summer surface climate have determined that above-average precipitation over the Prairie Provinces was linked to zonal flow and below-average precipitation was linked to a high-pressure ridge centred over the region (Knox and Lawford 1990; Bonsal et al. 1999; Shabbar et al. 2011). The frequency of high-pressure ridging over the prairies has also been positively related to the frequency of drought conditions, due to the blocking of moisture transport from the Gulf of Mexico (Shabbar et al. 2011). Furthermore, the efficiency of precipitation over the Mackenzie River Basin is the product of high sea level pressure (SLP) over the North Pacific Ocean and the movement of a low-pressure system from the Gulf of Alaska over the Mackenzie River Basin (Spence and Rausch 2005; Finnis et al. 2009; Cassano and Cassano 2010).

A significant portion of the interannual variability of surface climate in western Canada results from positive and negative phases of large-scale teleconnections. Negative (positive) phases of El Niño-Southern Oscillation (ENSO) and positive (negative) phases of the Pacific Decadal Oscillation (PDO) were associated with anomalously dry (wet) conditions (Shabbar et al. 1997; Bonsal and Lawford 1999; Bonsal and Wheaton 2005; Shabbar 2006), and above (below) average temperatures (Shabbar and Khandekar 1996; Shabbar 2006) in western Canada. Sea surface temperature (SST) anomalies similar to those associated with a positive PDO have been linked to summer dry spells in southern Alberta, Saskatchewan, and Manitoba (Bonsal et al. 1993). However, the ENSO and PDO signals are stronger during winter months (Shabbar and Khandekar 1996; Fleming and Whitfield 2010). In the case of streamflow, positive (negative) phases of ENSO have resulted in lower (higher) than average flow (Gobena and Gan 2006). Additionally, both ENSO and PDO have been significantly correlated with streamflow discharge to the Arctic Ocean and western Hudson Bay (Déry and Wood 2005).

The objective of this research is to evaluate water resource distribution using a synoptic climatological approach to identify dominant mid-tropospheric circulation patterns controlling surface climate variables. The spatial distribution of above/below average air temperature and precipitation associated with dominant circulation patterns are identified using a high-resolution daily gridded dataset. Additionally, the synoptic type frequency differences associated with positive and negative teleconnection phases are statistically evaluated. This research is performed in conjunction with a winter synoptic climatological analysis (Newton et al. 2014) focusing on snowpack and snowmelt, and together they represent the first focused evaluation of the atmospheric drivers of climate change across large watershed boundaries in western Canada.

4.2 Data and Methodology

4.2.1 Synoptic Classification

Synoptic climatology seeks to determine links between atmospheric circulation and surface climate through classification of circulation patterns into dominant types. Self-Organizing Maps (SOM) is used to classify summer (May-Oct) synoptic circulation patterns using daily geopotential height (gph) data for 1950-2011 obtained from NCEP/NCAR (Kalnay et al. 1996). SOM is an iterative training process that clusters and projects data onto a topologically ordered array (Kohonen 2001). The batch SOM process presents data vectors to an initialized array, and topological ordering is achieved through competitive and cooperative learning as the best matching unit for each data vector is updated, along with neighbouring units based on a Euclidean distance function (Kohonen 2001). The procedure used to classify synoptic patterns using SOM follows the same methods described in Newton et al. (2014).

4.2.2 Surface Climate

To evaluate the relationship between synoptic types and surface climate, gridded air temperature and precipitation datasets for 1950-2010, at 10-km resolution are applied. These datasets were created using an ANUSPLIN thin-plate spline interpolation method compiled from measured climate station data (McKenney et al. 2011). The calculation of air temperature and precipitation data associated with each synoptic type follows methods outlined in Newton et al. (2014). Daily temperature anomalies for each grid are calculated as the departure from the daily mean 1950-2010 value at that grid. Precipitation data for each synoptic type are calculated as the percentage of precipitation that occurred relative to the mean (1950-2010) value for each grid point, where the mean value is set to 0%.

Quantifying seasonal water availability, including drought conditions, presents a challenge as a number of physical processes contribute to moisture conditions. For example, the Palmer Drought Severity Index (PDSI) is calculated using soil moisture, precipitation, and air temperature data over a fixed time period (Palmer 1965), whereas the Standardized Precipitation Index (SPI) is based solely on precipitation deficits (McKee et al. 1993) and fails to account for the effects of high temperatures on drought conditions by increasing potential evapotranspiration (Vicente-Serrano et al. 2010a; Bonsal et al. 2012). Recently, Vicente-Serrano et al. (2010a) developed the Standardized Precipitation-Evapotranspiration Index (SPEI) that is based on a water-balance equation and thereby accounts for evapotranspiration (Thornthwaite and Mather 1955). In a comparison of the PDSI and SPEI, Vicente-Serrano et al. (2010b) determined that the PDSI poorly represented droughts of a short or long time period, but reliably represented intermediate drought. As short- and long-term droughts can have severe ecological and hydrological impacts (Vicente-Serrano et al. 2010b), it is important to adequately represent drought at these scales. Additionally, future projections of drought conditions may be underreported if increases in temperature are not taken into account (Bonsal et al. 2011).

4.2.3 Teleconnections

Teleconnection indices, including the Southern Oscillation Index (SOI), the PDO, and the Pacific North American (PNA) pattern, have been selected for this study, as all have been shown to influence surface climate in western Canada.

Monthly values of the SOI and PDO, obtained from the Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/) and Joint Institute for the Study of the Atmosphere and Ocean (http://www.jisao. washington.edu/pdo/) respectively, were used to calculate a three-month mean (Jul-Sep) values for dividing each summer teleconnection distribution into thirds corresponding to positive, negative, and neutral conditions. Daily values of the PNA were obtained from the Climate Prediction Centre and are then matched to the corresponding daily synoptic type.

The SOI is used to quantify ENSO; negative phases of SOI (El Niño) represent low sea level pressure (SLP) over Tahiti and high SLP over Darwin, Australia, where positive phases of SOI (La Niña) represent the opposite SLP conditions. These SLP anomalies have been shown to affect characteristics of the Aleutian Low (Horel and Wallace 1981). The intensity of the Aleutian Low is also captured through the PNA index (Wallace and Gutzler 1981), which represents above (below) average gph at 500-hPa over western North America and below (above) average gph over southern Alaska during positive (negative) phases (Barnston and Livezey 1987). Positive (negative) phases of the PDO represent warmer (cooler) than average SST in the eastern North Pacific Ocean and cooler (warmer) than average SST in the central Pacific Basin, resulting in anomalously high (low) SLP over regions of high (low) SST (Mantua et al. 1997).

4.3 Results and Discussion

4.3.1 Synoptic Classification

Daily summer (May-Oct) gph were classified into 12 types on a 4x3 array (Fig. 4.3) using the SOM Toolbox for Matlab (http://www.cis.hut.fi/research/som-research/; Vesanto et al. 2000). Several SOM array sizes were created and the final SOM size was subjectively chosen based on an evaluation of redundancy versus the loss of important circulation features. Additionally, the quality of the SOM was evaluated by assessment of Topological and Quantization Errors, which are measures of the strength of topological relationships between neighbouring patterns and average distance between vectors and the best matching unit (Vesanto et al. 2000; Kohonen 2001). The correlation between summer SOM classification and the corresponding daily PNA index ($r = 0.32$, sig. 1%) indicates that mid-tropospheric circulation is fairly well represented by the SOM classification.

Characteristics of the SOM array, including frequency (Fig. 4.4a) and persistence (Fig. 4.4b), were calculated for the entire summer season. However, synoptic type frequency is not consistent from May to October, as demonstrated by the monthly frequency of dominant types (Fig. 4.5). Type 4, a highly persistent split-flow blocking pattern, is dominant during mid-summer months (Jul-Aug). Conversely, shoulder season months (May and Oct) are dominated by persistent troughs of low-pressure over the North Pacific Ocean (Type 9). A ridge of high-pressure over the study region (Types 11 and 12) is common during early summer, and zonal flow (Types 1 and 2) primarily occurs during late summer and early autumn. As the PNA pattern is far more prominent during winter months than summer (Barnston and Livezey 1987), most of the summer PNA values are relatively low. Nevertheless, negative PNA values occupy the left side of the SOM array, while positive values correspond to the right side (Fig. 4.6).

4.3.2 Surface Climate Analysis

Gridded precipitation departures from normal for each synoptic type are shown in Fig. 4.7. Results reveal that of the dominant mid-summer (Jul-Aug) synoptic types, Types 3 and 4 deliver above-average precipitation to most of the study area, while Types 8 and 12 result in below-average precipitation. Type 9, the dominant shoulder season (May and Oct) synoptic type, is associated with close to average precipitation in the Liard and Peace Basins and below-average precipitation in the Athabasca and Saskatchewan Basins. Zonal flow during the shoulder season (Type 1) produces above-average precipitation throughout the basins, while a ridge of high-pressure over the study basins (Types 10 and 11) is associated with below-average precipitation.

Above-average air temperatures across the study region (Fig. 4.8) are generally associated with a trough of low-pressure over Alaska and the North Pacific accompanied by a ridge of high-pressure over the continent (Types 9-12). The strength and position of the high-pressure ridge appears to be related to the magnitude and location of the air temperature anomalies in each basin. For example, Type 12 is characterized by a ridge axis extending from the southern prairies to northern Alaska with high gph over the entire region (Fig. 4.3). Corresponding above-average air temperatures closely follow the ridge, and shift to below-average to the right of the ridge axis in the Saskatchewan River Basin. Types

6 and 7 demonstrate weak air temperature gradient anomalies; however, these are low-frequency types, occurring on average 6-8 days during each summer season.

The snowmelt season in alpine headwaters extends into late spring and early summer (May-Jun), especially in northern basins. Shoulder season types producing below (above) average air temperatures can delay (enhance) snowmelt. The moisture conditions during late summer and early autumn (Sep-Oct) influence the spring freshet runoff ratio (Spence and Rouse 2002). Therefore, synoptic types associated with both above (below) average precipitation and below (above) average air temperatures generate abundant (insufficient) antecedent moisture conditions, thus increasing (decreasing) spring freshet runoff volume. For example, a high frequency of Type 1 (Type 10) during Sep-Oct is expected to produce wet (dry) conditions during freeze-up.

Negative precipitation anomalies are indicative of low water availability during times of high demand, and high temperatures exacerbate water availability deficits through increased evapotranspiration (Bonsal et al. 2011). Therefore, a high frequency of high temperature anomaly types (Types 9-12) can intensify drought conditions. To determine seasonal water availability and corroborate the cumulative effects of climatic conditions produced for each synoptic type, gridded six-month (May-Oct) values of the SPEI were calculated using six-month average of air temperatures and cumulative precipitation. The resolution of the dataset was then recalculated from 10- to 50-km grids to reduce the size of the dataset. The 61-year SPEI was classified into 9 types using SOM, resulting in specific dry, wet and gradient patterns (Fig. 4.9). Synoptic type frequency distributions were averaged for each SPEI type, and synoptic type frequency anomalies calculated (Fig. 4.10).

Dry conditions are most common in the Saskatchewan River Basin (SPEI Types 1-4, 7; Fig. 4.9), although the synoptic mechanisms that produced drought conditions are not consistent for each SPEI type. This supports the findings of Bonsal and Wheaton (2005). Dry conditions across the study region (SPEI Types 4 and 7) are associated with an anomalously low frequency of Synoptic Type 9, characterized by a trough of low pressure over the North Pacific Ocean that occurs primarily during May and Oct. Dry (wet) conditions in the southern (northern) portion of the study region (SPEI Types 1-3) are the product of a higher than average occurrence of Synoptic Type 9 and lower than average frequency of Synoptic Type 4, the dominant mid-summer split-flow blocking pattern. Conversely, wet (dry) conditions in the northern (southern) basins in the study region (SPEI Types 8 and 9) are associated with a higher frequency of zonal flow (Synoptic Type 2) and strong ridging over western North America (Synoptic Types 11 and 12) and a slightly lower frequency of Synoptic Types 5-10. It should be noted that SPEI Type 8 is the least frequent type, occurring only three times during the study period (1950-2010).

4.3.3 Synoptic Type Frequency Trends

The Mann-Kendall (M-K) non-parametric test for trend (Mann 1945; Kendall 1975) evaluates temporal changes in synoptic type frequency over the study period (1950-2011). Results indicate that Type 4 has significantly increased and Types 9 and 10 have significantly decreased over the study period (sig. 5%; Fig. 4.11). This suggests an increase in the split-flow high-pressure blocking pattern over the western continent (Type 4), and a possible extension of mid-summer conditions. Consequently, a tendency toward increased (decreased) precipitation and decreased (increased) air temperature occurs in the southern (northern) portion of the study region. Results applicable to the shoulder season indicate a decreased frequency of low-pressure troughing over the North Pacific Ocean (Types 9-10), and associated decreases in low-precipitation/high-temperature climatic conditions, with a greater impact in the Saskatchewan basin compared with the Mackenzie headwater basins. These trends may be linked to increased spring temperatures (Linton et al. 2014) and earlier spring pulse onset (Bawden et al. 2014).

4.3.4 Teleconnections

Seasonal (Jul-Sep) three-month mean values of the SOI and PDO were ranked and categorized into thirds corresponding to positive, negative, and neutral conditions. The synoptic type frequencies within these groups were calculated, then the distributions between each positive-negative pair were statistically analyzed using the two sample non-parametric Kolmogorov-Smirnov (K-S) test (sig. 10%).

Results indicate a generally poor separation between positive-negative pair frequencies. However, a number of statistically significant distributions are found. For example, positive phases of the SOI are associated with a higher frequency of Type 3 compared with negative SOI (Fig. 4.12a), which suggest cooler, wetter conditions during positive phases of the SOI. Negative phases of the PDO are also associated with a higher frequency of Types 3 and 9 (Fig. 4.12b). The frequency distribution of Type 9 during positive and negative phases of the PDO may be partially explained by the decreasing trend detected for this type. The PDO shifted from a predominantly negative to positive phase during the late 1970s (Mantua et al. 1997); therefore, Type 9 occurred with a greater frequency during the predominantly negative PDO phase, and a lower frequency during the predominantly positive PDO phase.

A subset of seasons corresponding to both positive SOI and negative PDO (12 records) and those corresponding to negative SOI and positive PDO (9 records) were identified to compare effects of combined relationships. Significantly different synoptic type frequency distributions between each coupled SOI and PDO subset were detected for Types 3, 8, and 9 (Fig. 4.12c). In the case of Types 3 and 9, the distribution differences are enhanced compared with individual teleconnection analyses (Figs. 4.12a-b). Type 8 occurs with a significantly higher frequency during summers classed as negative SOI and positive PDO, signifying increased warm, dry conditions during these summers. Furthermore, an increased frequency of Type 8 is associated with drought conditions (Figs. 4.9), particularly in the Saskatchewan River Basin.

4.4 Conclusions

This research classifies daily summer (May-Oct) gph data into 12 types using SOM, and identifies surface climate conditions associated with those types to increase knowledge of atmospheric conditions influencing summer water availability. Summer water availability is a function of precipitation and evapotranspiration; therefore, the multi-scalar SPEI drought index is appropriate for defining the spatial distribution of wet/dry conditions.

Results indicate that dominant synoptic circulation patterns have a well-defined temporal occurrence between shoulder season and mid-summer. Shoulder season zonal flow results in above-average precipitation, while troughing over the North Pacific results in below-average precipitation. The prevailing mid-summer circulation pattern, a split-flow blocking high-pressure pattern over the western continent, is associated with slightly below (above) average precipitation and above (below) average temperatures in the northern (southern) portion of the study region. Mid-summer synoptic types exhibiting a ridge of high-pressure over the western continent are associated with below-average precipitation and anomalously high temperatures in the study region. These findings are consistent with composite mid-tropospheric circulation analyses corresponding to summer wet and dry surface conditions performed by Knox and Lawford (1990), Bonsal et al. (1999), and Shabbar et al. (2011). Additionally, analyses of seasonal SPEI and corresponding synoptic type frequency anomalies corroborate the temperature and precipitation results.

Synoptic frequency trend analyses reveal an increasing tendency for the dominant mid-summer split-flow blocking pattern, and decreasing trend in the shoulder season trough of low-pressure over the North Pacific Ocean. These results imply an earlier shift, and extension of, mid-summer climatic conditions, and a shortening of the spring season. However, in-depth trend analysis of monthly synoptic circulation pattern frequencies may provide further insight into temporal changes to dominant shoulder and mid-summer season synoptic types.

The evaluation of summer teleconnection indices reveals few significant relationships between the SOI or PDO and patterns of mid-tropospheric circulation. This is likely due to a combination of factors, primarily the greater strength of the teleconnection signals in winter compared with summer (Barnston and Livezey 1987; Shabbar and Khandekar 1996). Additionally, Jul-Sep was selected to calculate a three-month mean value used to classify positive, negative, and neutral summers, while several synoptic types occur primarily during May-Jun and Oct and minimally or not at all during mid-summer months. Due to the seasonal progression of synoptic types, classifying teleconnection phases using any three-month period would result in similar circumstances. Furthermore, ENSO commonly enters a positive or negative phase during the autumn, and this phase often persists through the following spring. Nevertheless, positive (negative) SOI and negative (positive) PDO were found to significantly increase (decrease) a weak split-flow blocking type. Coupled PDO-SOI analyses reveal that negative (positive) SOI and positive (negative) PDO were associated with a significantly increased (decreased) frequency of ridging over the western continent. These links suggests that positive (negative) SOI and negative (positive) PDO are associated with above (below) average precipitation and below (above) average temperature in the study region.

In addition to synoptic-scale circulation driving moisture transport into the research basins, summer precipitation is generated by meso-scale convective processes (Raddatz and Hanesiak 2008) that are subject to spatial and interannual variability (Szeto et al. 2002; Raddatz 2000; Raddatz 2005). Convective precipitation redistributes water resources, either within or across watersheds (Liu and Stewart 2003). Synoptic-scale mid-tropospheric circulation dynamics generate the conditions conducive to convective processes; however, as these precipitation events are localized and widespread, a degree of precipitation blending is inherent in the calculation of precipitation anomalies associated with each synoptic type. Additionally, as many high-intensity precipitation events are the product of the relatively rare convergence of atmospheric moisture transport originating over the Gulf of Mexico or Gulf of California and lee cyclones, these events are not captured by the synoptic climatology created for this analysis. This research is intended to provide analysis of average climatic conditions produced by synoptic-scale circulation rather than diagnose extreme weather phenomena. Therefore, future research should focus on the synoptic-scale circulation characteristics that are associated with extreme weather, including an in-depth analysis of enhanced atmospheric wave amplitude, which has been hypothesized as a driving force behind increased frequency and magnitude of extreme events (Francis and Varvus 2012).

Results from this research, and the companion study evaluating winter atmospheric drivers of climatic conditions (Newton et al. 2014), increase our understanding of the processes related to the spatial and temporal patterns of water resource availability. The statistical approach utilized in evaluating the influence of teleconnections on synoptic-scale mid-tropospheric circulation in this and the companion study enhanced confidence in describing these relationships. Results from this analysis are consistent with results from other CROCWR analyses (Bawden et al. 2014; Linton et al. 2014) and, when combined, provide a multi-dimensional analysis of water distribution and redistribution patterns in western Canada.

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References

Arnell, N.W. (2005), Implications of climate change for freshwater inflows to the Arctic Ocean. Journal of Geophysical Research. 110, D07105, DOI:10.1029/2004JD005348

Barnston, A.G. and Livezey, R.E. (1987), Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Monthly Weather Review. 115, 1083-1126

Bawden, A.J., Burn, D.H., and Prowse, T.D. (2014), Recent changes in patterns of western Canadian river flow and association with climatic drivers. *Submitted to Hydrological Processes*

Bonsal, B.R., Chakravarti, A.K., and Lawford, R.G. (1993), Teleconnections between North Pacific SST anomalies and growing season extended dry spells on the Canadian Prairies. International Journal of Climatology. 13, 865-878DOI:10.1002/joc.3370130805

Bonsal, B.R. and Lawford, R.G. (1999), Teleconnections between El Niño and La Niña events and summer extended dry spells on the Canadian Prairies. International Journal of Climatology. 19, 1445-1458, DOI:10.1002/(SICI)1097-0088(19991115)19:13<1445::AID-JOC431>3.0.CO;2-7

Bonsal, B.R., Zhang, X., and Hogg, W.D. (1999), Canadian Prairie growing season precipitation variability and associated atmospheric circulation. Climate Research, 11, 191-208, DOI:10.3354/cr011191

Bonsal, B.R. and Wheaton, E.E. (2005), Atmospheric circulation comparisons between the 2001 and 2002 and the 1961 and 1988 Canadian prairie droughts. Atmosphere-Ocean, 43(2) 163-172

Bonsal, B.R., Wheaton, E.E., Chipanshi, A.C., Lin, C., Sauchyn, D.J., and Wen, L. (2011), Drought research in Canada: A review. Atmosphere-Ocean. 49(1), 303-319. DOI:10.1080/070559900.2011.555103

Bonsal, B.R., Aider, R., Gachon, P., and Lapp, S. (2012), An assessment of Canadian prairie drought: past, present, and future. Climate Dynamics. DOI:10.1007/s00382-012-1422-0

Brimelow, J.C. and Reuter, G.W. (2005), Transport of atmospheric moisture during three extreme rainfall events over the Mackenzie River Basin. Journal of Hydrometeorology. 6, 423-440

Burn, D.H., Cunderlik, J.M, and Pietroniro, A. (2004a), Hydrological trends and variability in the Liard River basin. Hydrological Sciences Journal. 49(1), 53-67, DOI:10.1623/hysj.49.1.53.53994

Burn, D.H., Abdul Aziz, O.I. and Pietroniro, A. (2004b), A comparison of trends in hydrological variables for two watersheds in the Mackenzie River basin. Canadian Water Resources Journal. 29(4), 283-298

Burn, D.H. (2008), Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. Journal of Hydrology. 352, 225-238, DOI:10.4296/cwrj283

Cassano, E.N. and Cassano, J.J. (2010), Synoptic forcing of precipitation in the Mackenzie and Yukon River basins. International Journal of Climatology. 30, 658-674, DOI:10.1002/joc.1926

Chipanshi, A.C., Findlater, K.M., Hadwen, T., and O'Brien, E.G. (2006), Analysis of consecutive droughts on the Canadian Prairies. Climate Research, 30: 175-187, DOI:10.3354/cr030175

Comeau, L.E.L, Pietroniro, A., and Demuth, M.N. (2009), Glacier contribution to the North and South Saskatchewan Rivers. Hydrological Processes. 23, 2640-2653. DOI:10.1002/hyp.7409

Déry, S.J. and Wood, E.F. (2005), Decreasing river discharge in northern Canada. Geophysical Research Letters. 32, L10401. DOI:10.1029/2005GL022845

Déry, S.J., Hernández-Henríquez, M.A., Burford, J.E., and Wood, E.F. (2009), Observational evidence of an intensifying hydrological cycle in northern Canada. Geophysical Research Letters. 36, L13402, DOI:10.1029/2009GL038852

Finnis, J., Cassano, J., Holland, M., Serreze, M., and Uotila, P. (2009), Synoptically forced hydroclimatology of major Arctic watersheds in general circulation models; Part 1: the Mackenzie River Basin. International Journal of Climatology, 29, 1226-1243. DOI:10.1002/joc.1753

Fleming, S.W. and Whitfield, P.H. (2010), Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and southeast Alaska. Atmosphere-Ocean, 48(2), 122-131. DOI:10.3137/AO1107.2010

Francis, J.A. and Varvus, S.J. (2012) Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophysical Research Letters, 39, L0680, DOI:10.1029/2012GL051000

Gobena, A.K. and Gan, T.Y. (2006), Low-frequency variability in southwestern Canadian stream flow: Links with large-scale climate anomalies. International Journal of Climatology. 26, 1843-1869, DOI:10.1002/joc.1336

Holton, J.R. (1979), An Introduction to Dynamic Meteorology. Second edition. Academic Press, Inc. New York, New York.

Horel, J.D. and Wallace, J.M. (1981), Planetary-scale atmospheric phenomena associated with the southern oscillation. Monthly Weather Review. 109, 813-829

Huntington, T.G. (2006), Evidence for intensification of the global water cycle: Review and synthesis. Journal of Hydrology. 319, 83-95

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., … Joseph, D. (1996), The NCEP/NCAR 40-year reanalysis project, Bulletin of the American Meteorological Society. 77, 437-471

Kendall, M.G. 1975. Rank Correlation Measures. Charles Griffin, London.

Kohonen, T. (2001), Self-Organizing Maps. Springer, New York

Lackmann, G.M. and Gyakum, J.R. (1996), The synoptic- and planetary-scale signatures of precipitating systems over the Mackenzie River Basin. Atmosphere-Ocean, 34(4), 647-674

Lammers, R.B., Shiklomanov, A.I., Vörösmarty, C.J., Fekete, B.M., and Peterson, B.J. (2001) Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research. 106, D4: 3321-3334, DOI:10.1029/2000JD900444

Lewis, E.L. (2000), The Freshwater Budget of the Arctic Ocean. Kluwer Academic Publishers, Dordrecht

Linton, H., Prowse, T., Dibike, Y., and Bonsal, B. (2014), Spatial and temporal analysis of hydroclimatic variables affecting streamflow in western Canada from 1950-2010. *Submitted to Hydrological Processes*

Liu, J. and Stewart, R.E. (2003), Water vapor fluxes over the Saskatchewan River Basin. Journal of Hydrometeorology. 4, 944-959

Liu, J., Stewart, R.E., and Szeto, K.K. (2004), Moisture transport and other hydrometeorological features associated with the severe 2000/01 drought over the western and central Canadian Prairies. Journal of Climate. 17, 305-319

Mann, H.B. 1945. 'Non-parametric tests against trend', Econometrica. 13, 245-259

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and Francis, R.C. (1997), A pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society. 78, 1069-1079

Martin, J.E. (2006) Mid-Latitude Atmospheric Dynamics: A First Course. John Wiley & Sons, Ltd. , Chichester, West Sussex, England

Martz, L., J. Bruneau and J.T. Rolfe (Eds.). (2007), Climate Change and Water, SSRB Final Technical Report. University of Saskatchewan. Saskatoon, Saskatchewan

McKee, T.B., Doesken, N.J., and Kleist, J. (1993), The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, 17-22 January 1993. American Meteorological Society, Boston MA, 179-184

McKenney, D.W., Hutchinson, M.F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R.F., Price, D., and Owen, T. (2011), Customized spatial climate models for North America. Bulletin of the American Meteorological Society. 92(12) 1611-1622

Newton, B.W., Prowse, T.D., and Bonsal, B.R. (2014), Evaluating the distribution of water resources in western Canada using synoptic climatology and selected teleconnections. Part 1: Winter season.

Palmer, W.C. (1965), Meteorological drought. U.S. Department of Commerce Weather Bureau Research Paper No. 45.

Pentney, A. and Ohrn, D. (2008), Navigating from history into the future: the water management plan for the South Saskatchewan River Basin in Alberta. Canadian Water Resources Journal, 33(4) 381-396, DOI:10.4296/cwrj3304381

Peters, D.L. and Prowse, T.D. (2001), Regulation effects on the lower Peace River, Canada. Hydrological Processes. 15, 3181-3194, DOI:10.1002/hyp.321

Prowse, T.D., Bonsal, B.R., Burn, D.H., Dibike, Y.B., Edwards, T., Ahmed, R., Bawden, A.J., Linton, H.C., Newton, B.W., and Walker, G.S. (2013), Climatic redistribution of Canada's western water resources (CROCWR). In Stuefer, S.L. and Bolton, W.R. (Eds.) Proceedings from the 19th Northern Research Basins Symposium and Workshop (246). Fairbanks: University of Alaska Fairbanks

Raddatz, R.L. (2000), Summer rainfall recycling for an agricultural region of the Canadian prairies. Canadian Journal of Soil Science. 80, 367-373, DOI: 10.4141/S99-016

Raddatz, R.L. (2005), Moisture recycling on the Canadian Prairies for summer droughts and pluvials from 1997 to 2003. Agricultural and Forest Meteorology. 131, 13-26

Raddatz, R.L. and Hanesiak, J.M. (2008), Significant summer rainfall in the Canadian Prairie Provinces: Modes and mechanisms 2000-2004. International Journal of Climatology. 28, 1607-1613. DOI:10.1002/joc.1670

Roberts, E., Stewart, R.E., and Lin, C.A. (2006), A study of drought characteristics over the Canadian prairies. Atmosphere-Ocean. 44(4), 331-345, DOI:10.3137/ao.440402

Rood, S.B., Pan, J., Gill, K.M., Franks, C.G., Samuelson, G.M., and Shepherd, A. (2008), Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probably impacts on floodplain forests. Journal of Hydrology. 349, 397-410, DOI:10.1016/j.jydrol.2007.11.012

Schindler D.W. and Donahue W.F. (2006), An impending water crisis in Canada's western prairie provinces. PNAS 103(19) 7210-7216, doi:10.1073/pnas.0602793103

Serreze, M.C., Barrett, A.P., Stroeve, J.C., Kindig, D.N., and Holland, M.M., (2009), The emergence of surface-based Arctic amplification. The Cryosphere. 3, 11-19, DOI:10.5194/tc-3-11-2009

Serreze, M.C. and Barry, R.G. (2011), Processes and impacts of Arctic amplification: A research synthesis. Global and Planetary Change. 77, 85-96, DOI:10.1016/j.gloplacha.2011.03.004

Shabbar, A. and Khandekar, M. (1996), The impact of El Niño-Southern Oscillation on the temperature field over Canada: Research note. Atmosphere-Ocean, 34(2), 401-416, DOI: 1080/07055900.1996.9649570

Shabbar, A., Bonsal, B., and Khandekar, M. (1997), Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate. 10, 3016-3027.

Shabbar, A. (2006), The impact of El Niño-Southern Oscillation on the Canadian Climate. Advances in Geosciences. 6, 149-153

Shabbar, A., Bonsal, B.R., and Szeto, K. (2011), Atmospheric and oceanic variability associated with growing season droughts and pluvials on the Canadian Prairies. Atmosphere-Ocean, 1, 1-17. DOI:10.1080/07055900.2011.564908

Sheridan, S.C. and Lee, C.C. (2011), The self-organizing map in synoptic climatological research. Progress in Physical Geography. 35(1): 109-119. DOI:10.1177/0309133310397582

Smirnov, V.V. and Moore, G.W.K. (2001), Short-term and seasonal variability of the atmospheric water vapor transport through the Mackenzie river basin. Journal of Hydrometeorology. 2, 441-452

Spence, C., and Rouse, W. (2002), The energy budget of Canadian Shield subarctic terrain and its impact on hillslope hydrological processes. Journal of Hydrometeorology. 3, 208-218.

Spence, C. and Rausch, J. (2005), Autumn synoptic conditions and rainfall in the subarctic Canadian shield of the Northwest Territories, Canada. International Journal of Climatology. 25, 1493-1506, DOI:10.1002/joc.1185

Stewart, R., Pomeroy, J., and Lawford, R. (2011), The drought research initiative: A comprehensive examination of drought over the Canadian Prairies. Atmosphere-Ocean. 49(4), 298-302, DOI:10.1080/07055900.2011.622574

Szeto, K.K. (2002), Moisture recycling over the Mackenzie basin. Atmosphere-Ocean. 40(2), 181-197, DOI:10.3137/ao.400207

Thornthwaite, C.W. and Mather, J.R. (1955), The water balance. Publications in Climatology, 8(1), 1-86.

Vesanto, J., Himberg, J., Alhoniemi, E., and Parhankangas, J. (2000), SOM toolbox for Matlab 5. Helsinki University of Technology. Rep. A57

Vicente-Serrano, S.M., Beguería, S., and López-Moreno, J.I. (2010a), A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate. 23, 1696-1718. DOI:10.1175/2009JCLI2909.1

Vicente-Serrano, S.M. , Beguería, S., López-Moreno, J.I., Angulo, M., and El Kenawy, A. (2010b), A new global 0.5° gridded dataset (1901-2006) of a multiscalar drought index: Comparison with current drought index datasets based on the Palmer Drought Severity Index. Journal of Hydrometeorology. 11, 1033-1043

Wallace, J.M. and Gutzler, D.S. (1981), Teleconnections in the geopotential height field during the Northern Hemisphere winter. Monthly Weather Review. 109, 784-812

Westmacott , J.R. and Burn, D.H. (1997), Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin. Journal of Hydrology. 263-279, DOI:10.1016/S0022-1694(97)00073-5

Wheaton, E., Kulshreshtha, S., Wittrock, V., and Koshida, G. (2008), Dry times: Hard lessons from the Canadian drought of 2001 and 2002. The Canadian Geographer. 52(2), 241-262, DOI:10.1111/j.1541-0064.2008.00211.x

Yip, Q.K.Y., Burn, D.H., Seglenieks, F., Pietroniro, A., and Soulis, E.D. (2012), Climate impacts on hydrological variables in the Mackenzie River Basin. Canadian Water Resources Journal. 37(3), 209-230, DOI:10.4296/cwrj2011-899

Zhang, X., Vincent, L.A., Hogg, W.D., and Niitsoo, A. (2000), Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean. 38(3), 395-429, DOI:10.1080/07055900.2000.9649654

Zhang, X., Harvey, K.D., Hogg, W.D., and Yuzyk, T.R. (2001), Trends in Canadian streamflow. Water Resources Research. 37(4), 987-998, DOI:10.1029/2000WR900357

Zhang, X., He, J., Zhang, J., Polyakov, I., Gerdex, R., Inoue, J., and We, P. (2013), Enhanced poleward moisture transport and amplified northern high-latitude wetting trend. Nature Climate Change. 3, 47-51, DOI:10.1038/nclimate1631

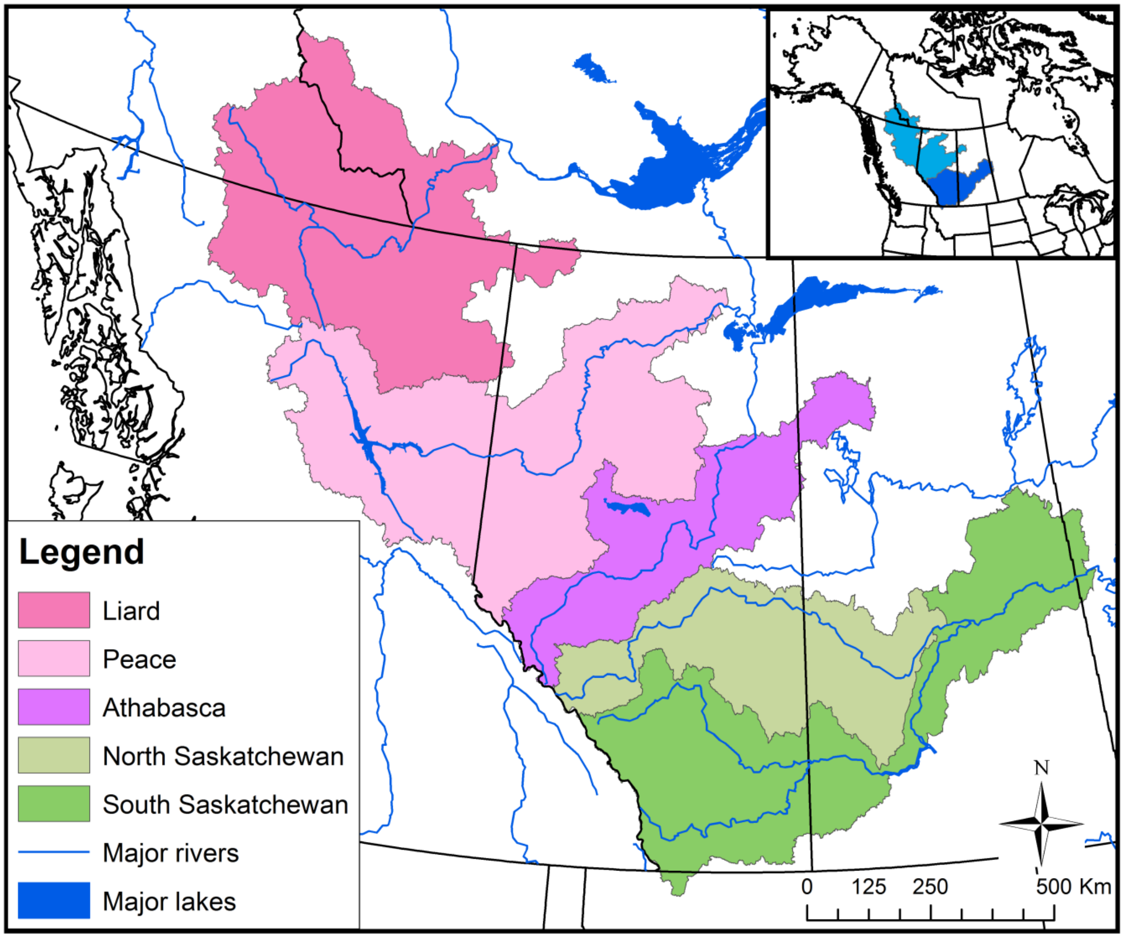

Figure 4.1: Rivers originating on the leeward slopes of the Rocky Mountains. The Liard, Peace, and Athabasca Rivers are tributaries to the north-flowing Mackenzie River, and the North and South Saskatchewan Rivers are tributaries to the east-flowing Saskatchewan River.

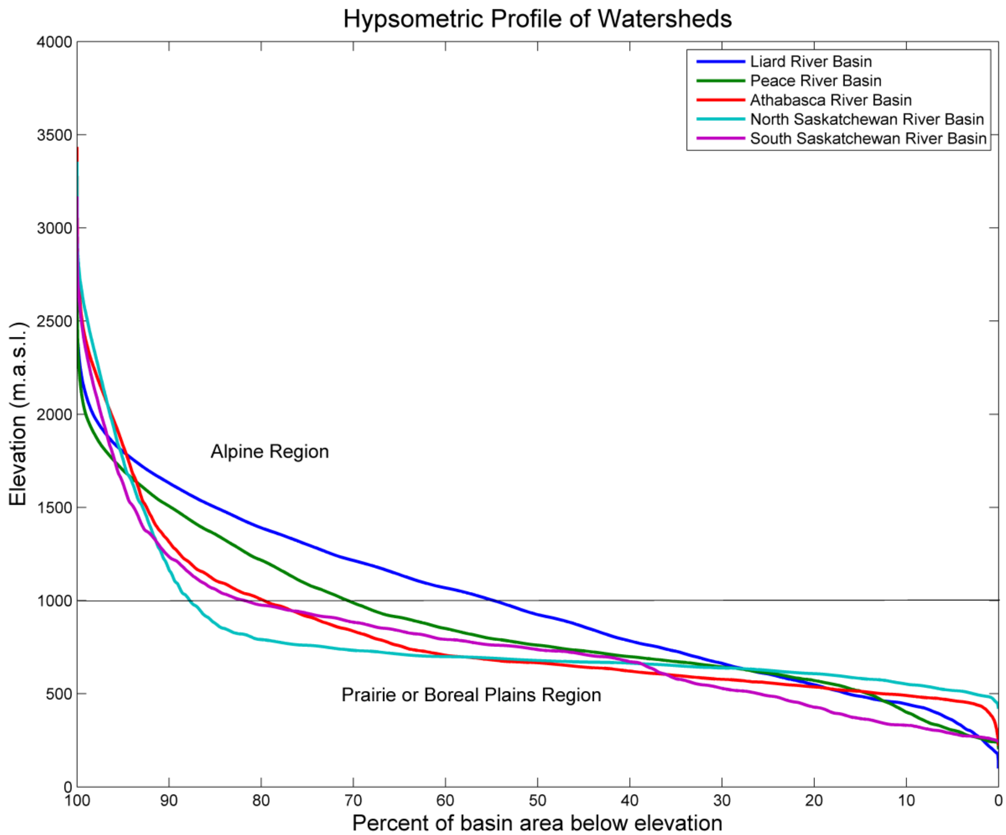

Figure 4.2: Hypsometric profile of the Liard, Peace, Athabasca, North Saskatchewan, and South Saskatchewan Rivers.

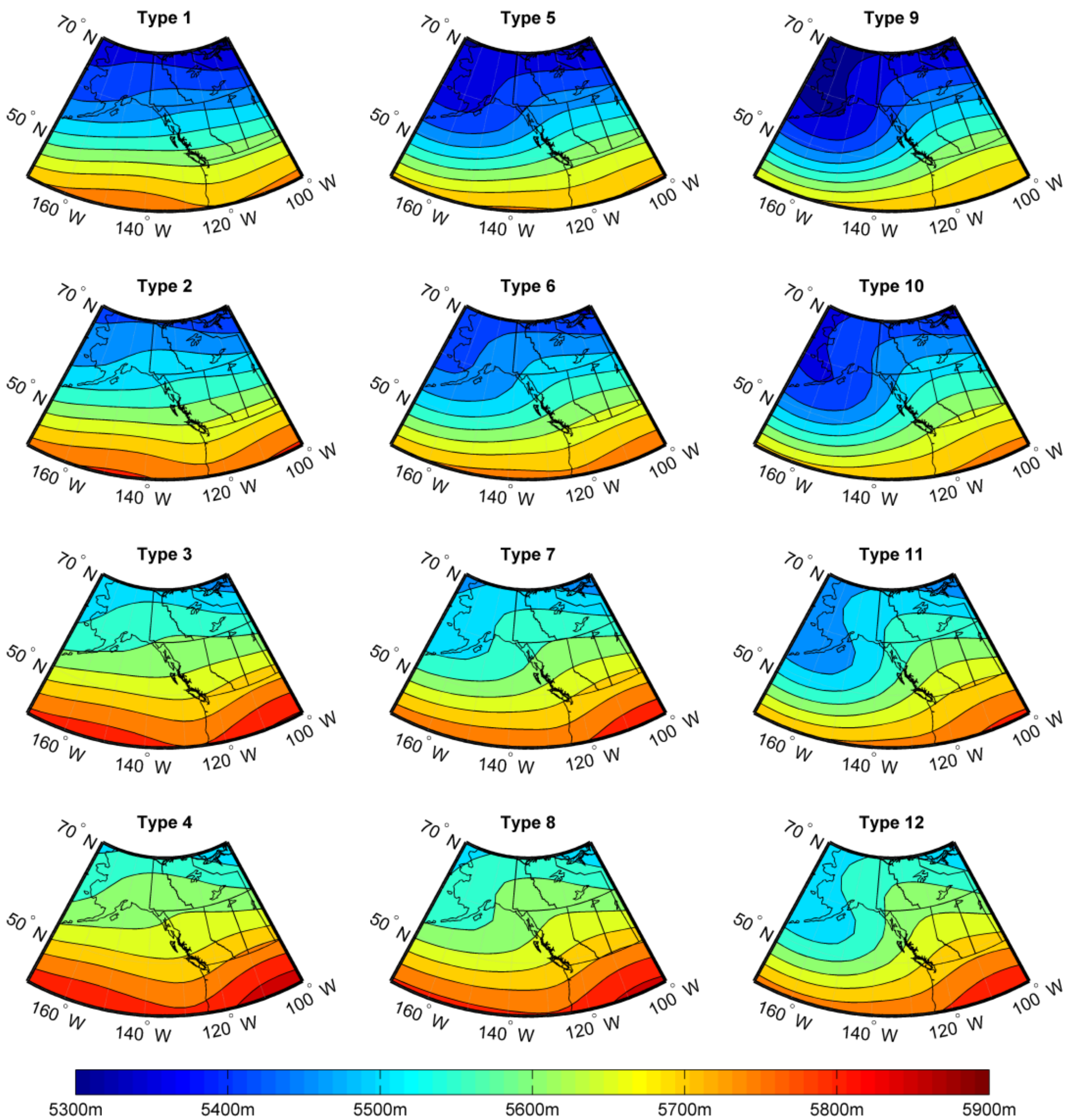

Figure 4.3: Daily summer (May-Oct) geopotential heights at 500hPa for 1950-2011 classified using Self-Organizing Maps (SOM).

a)

7	5	15
6	3	8
9	4	9
20	7	7

b)

68	43	83
59	34	62
61	47	70
85	50	62

Figure 4.4: Synoptic type a) frequency (%) calculated as the percentage of total occurrences of each synoptic type over the study period and b) persistence (%), calculated as the percentage of occurrences were the pattern remains the same on the following day.

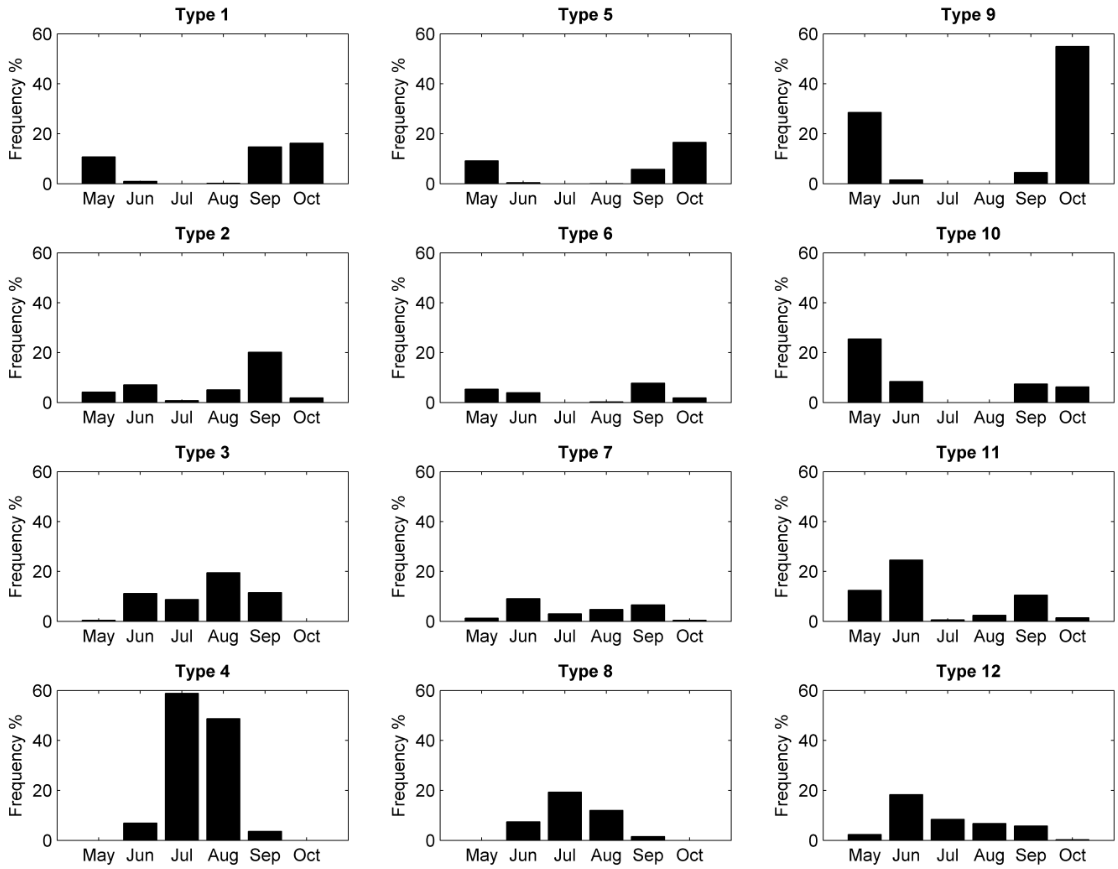

Figure 4.5: Monthly synoptic type frequency, indicating the seasonal evolution of dominant synoptic types.

-0.67	-0.39	0.23
-0.18	-0.10	0.33
-0.20	0.07	0.31
-0.14	0.28	0.47

Figure 4.6: Average PNA value for each synoptic type during the study period (1950-2011).

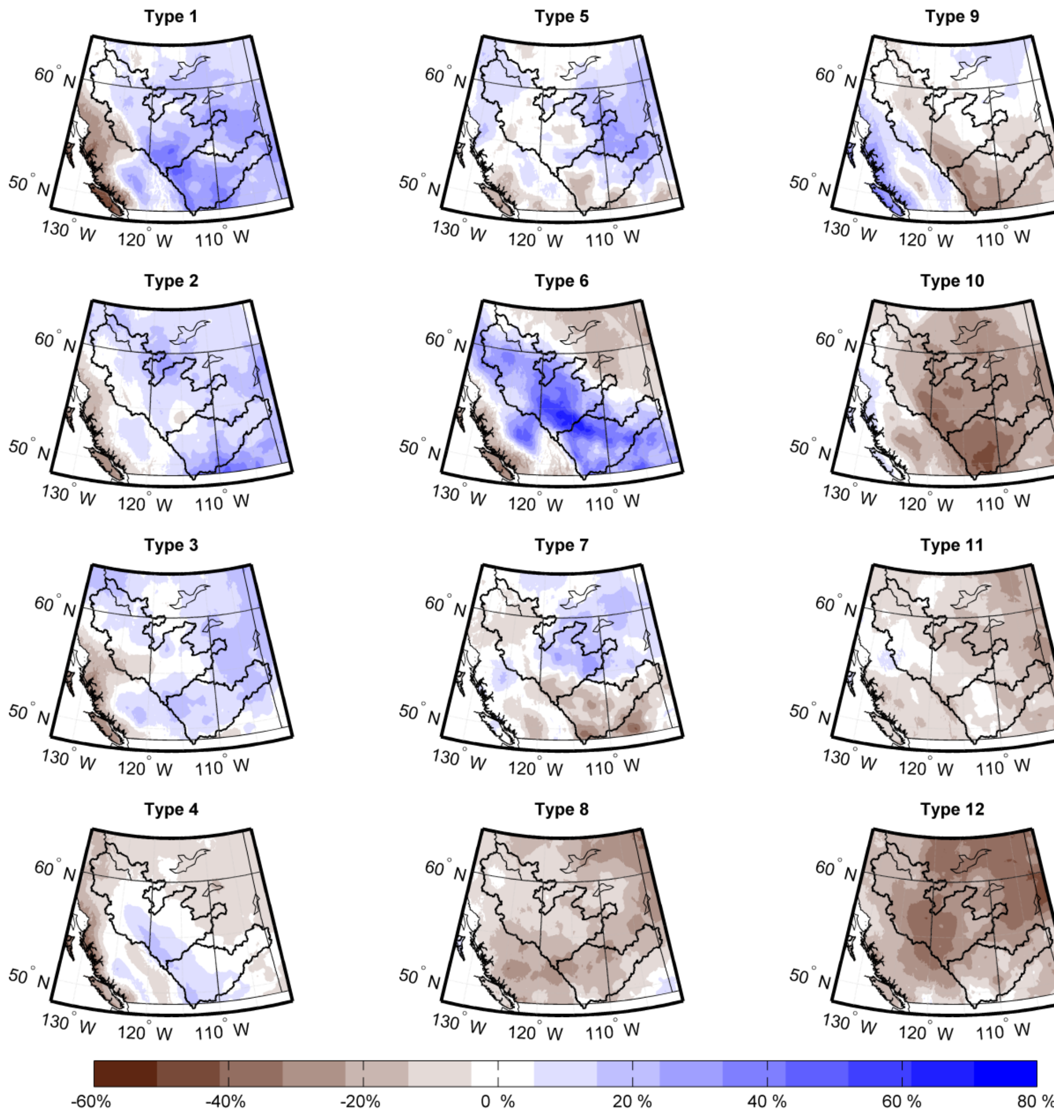

Figure 4.7: Precipitation associated with each synoptic type, calculated as the percentage of precipitation delivered to each grid point relative to the 1950-2010 mean values at each grid.

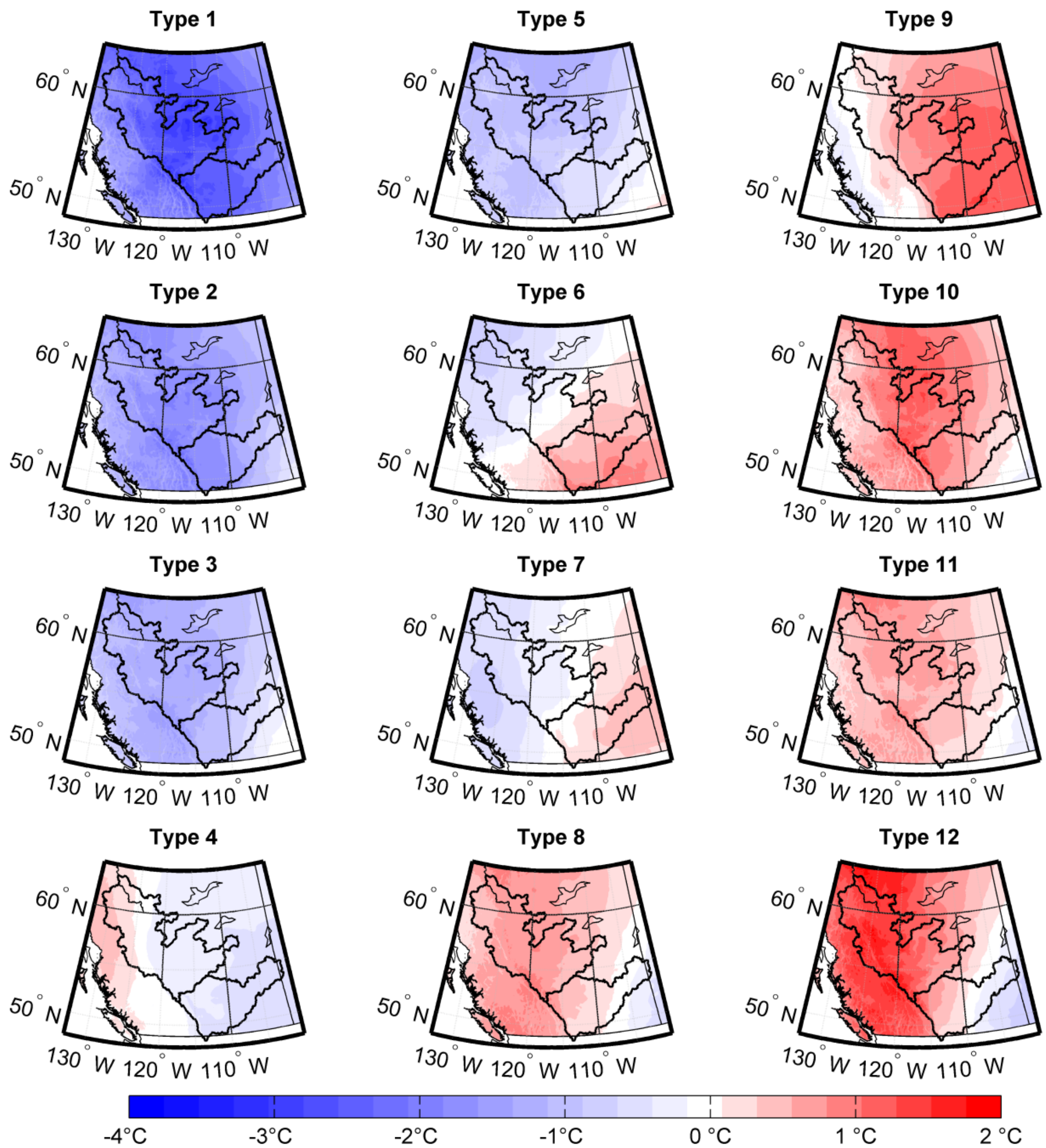

Figure 4.8: Temperature anomalies associated with each synoptic type, relative to the 1950-2010 mean values at each grid.

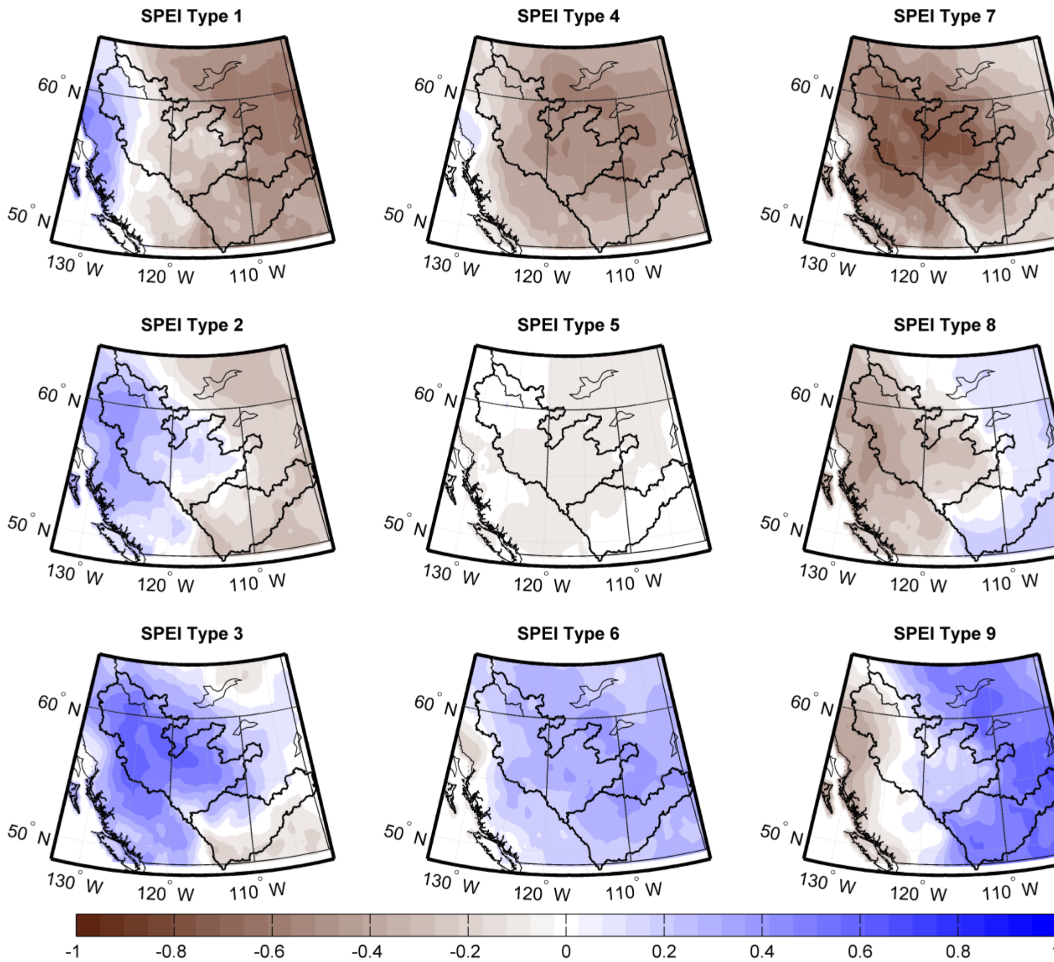

Figure 4.9: Summer Standardized Precipitation-Evapotranspiration Index (SPEI), classified into dominant patterns using SOM.

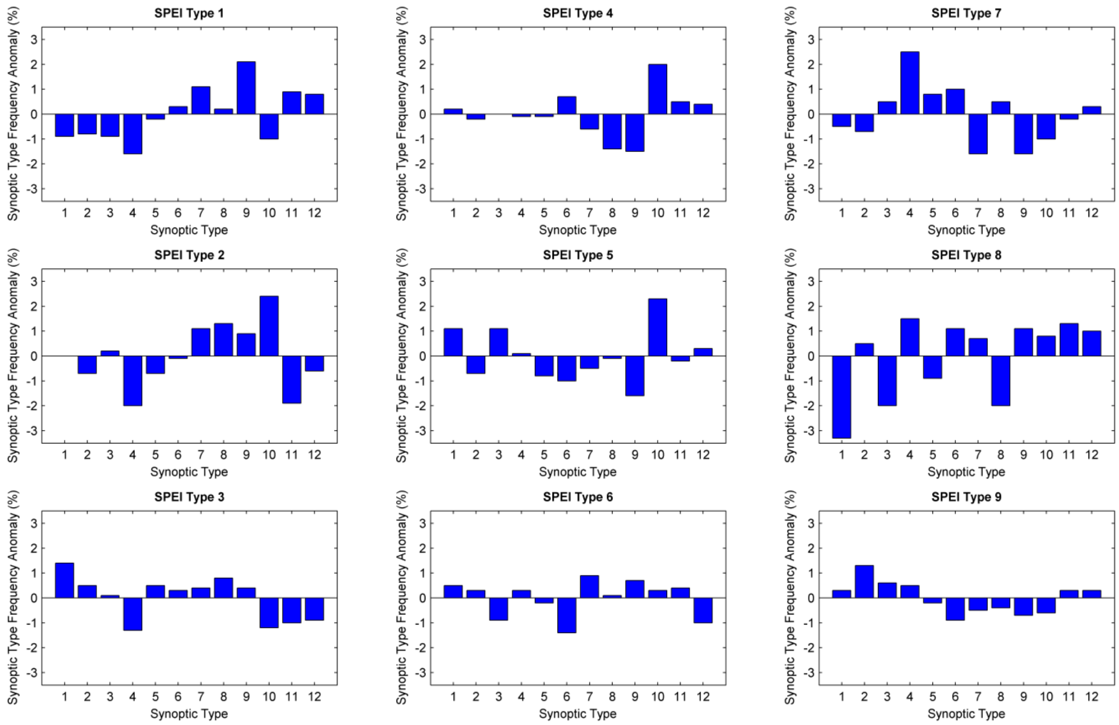

Figure 4.10: Synoptic type frequency anomalies associated with each SPEI pattern identified in Fig. 4.9.

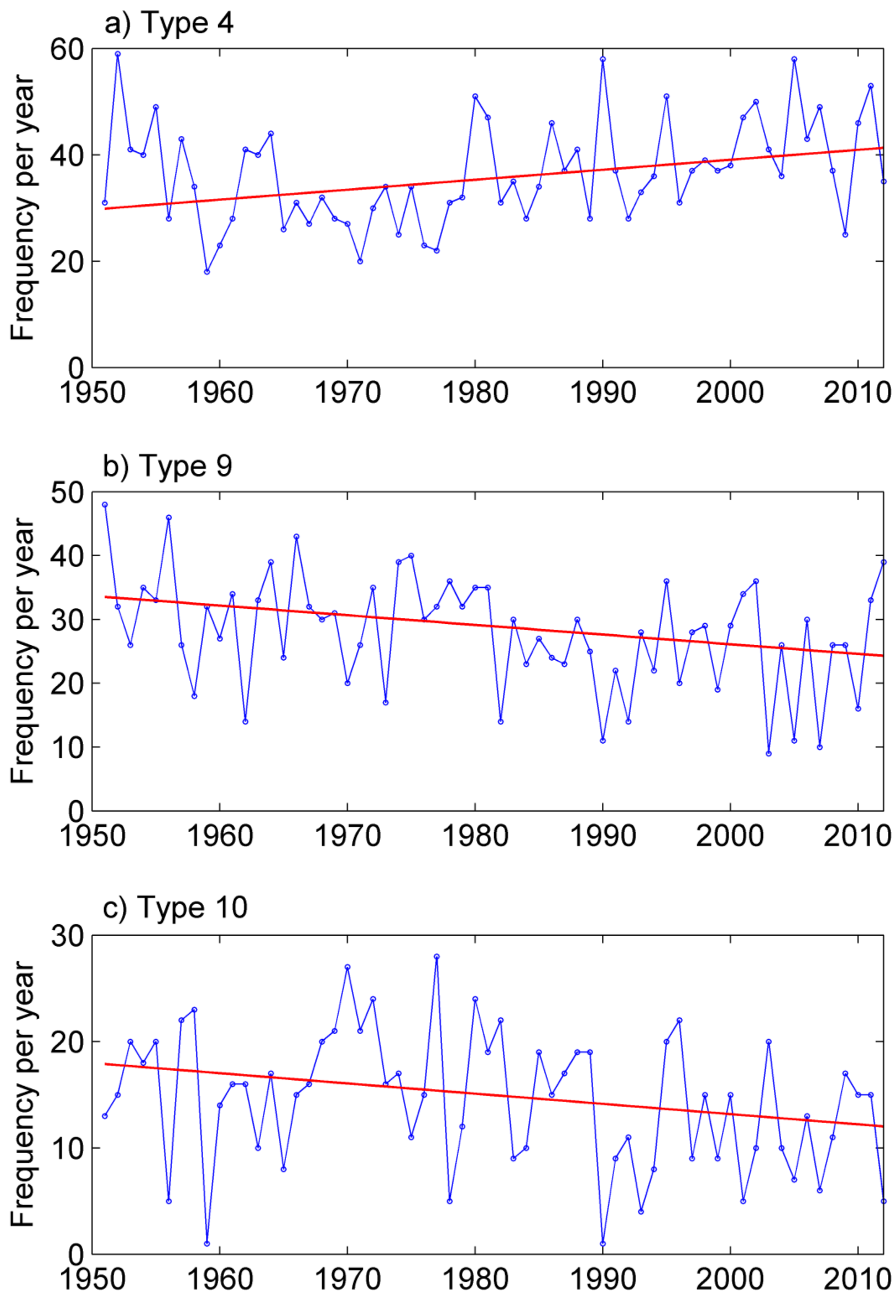

Figure 4.11: Synoptic type trends, evaluated using the non-parametric Mann-Kendall test. Only trends significant at 10% are shown, with percent increase/decrease over the study period (1950-2011), including a) Type 4 (38%) and decreasing trends b) Type 9 (-27%) and c) Type 10 (-32%).

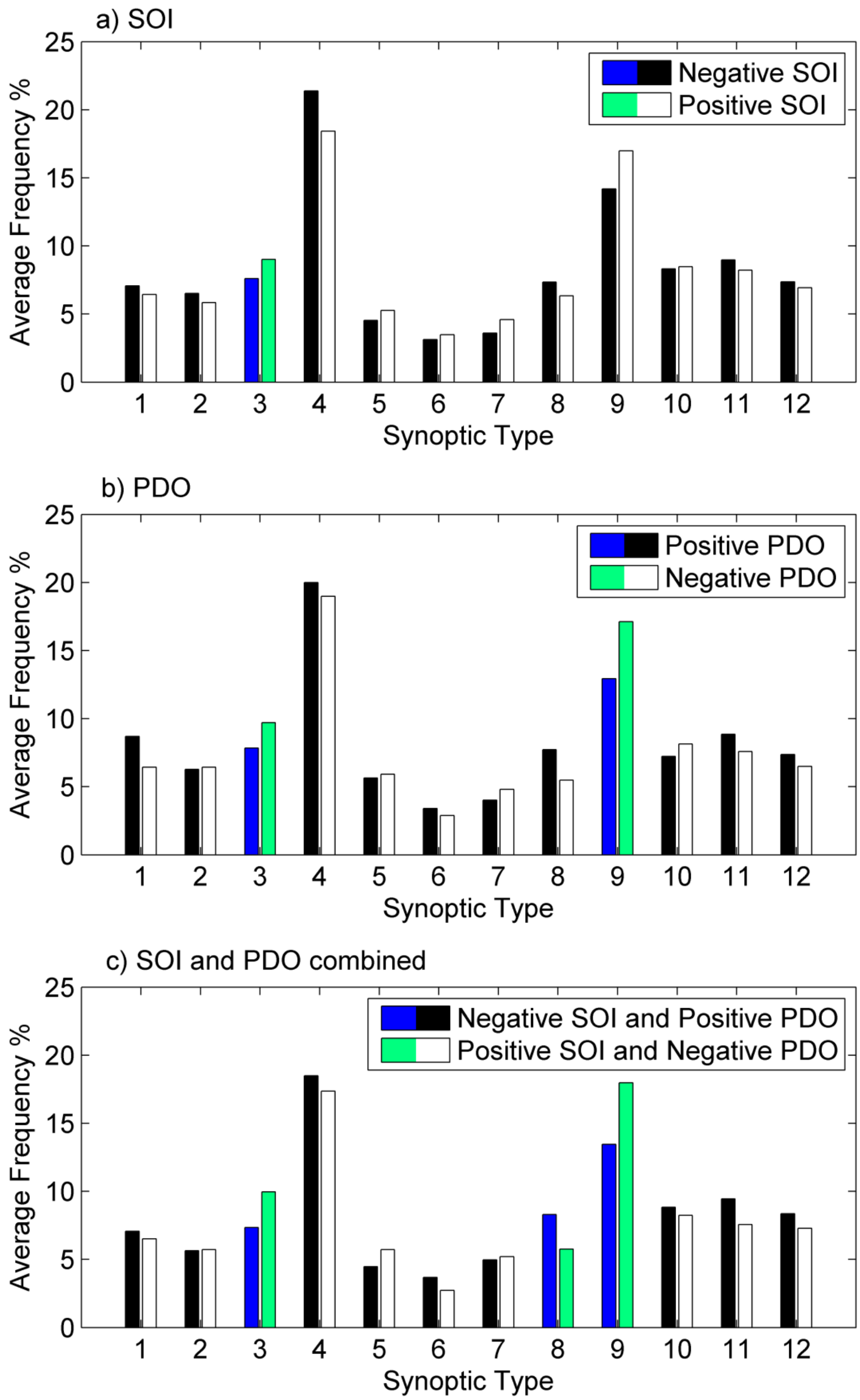

Figure 4.12: Synoptic type frequency distribution differences for a) positive and negative SOI, b) positive and negative PDO, and c) negative SOI and positive PDO, and positive SOI and negative PDO.

Chapter 5: Conclusions

This research provides a comprehensive evaluation of the atmospheric drivers of water resource distribution in western Canada, and is one component of the multi-dimensional CROCWR project. A series of objectives were identified to meet the goals of this research including classifying and describing the dominant mid-tropospheric circulation patterns and relating those patterns to the spatial and temporal distribution of temperature and precipitation during both the winter (Nov-Apr) and summer (May-Oct) seasons. Additionally, this is the first study to focus on determining the statistical relationships between synoptic classifications and large-scale teleconnections.

The literature review (Chapter 2) outlined background information regarding the processes related to seasonal water availability in the headwater basins of the Mackenzie and Saskatchewan Rivers, and the best available methods for addressing the goals of this research. The objectives of this study were met for the winter (Nov-Apr) season in Chapter 3 and summer (May-Oct) season in Chapter 4, presented as two journal-style manuscripts. In each case, synoptic classifications used the method of Self-Organizing Maps (SOM), as it was determined to be superior to traditional classification methods. Surface climate associated with seasonal synoptic types were evaluated using a high-resolution daily gridded dataset.

Results from winter synoptic climatological analysis (Chapter 3), showed that the strength of the relationships between mid-tropospheric circulation, large-scale teleconnections, temperature, and precipitation are apparent in the inherent topological ordering of the SOM array. Specifically, the right and left sides of the SOM array display nearly opposite synoptic types, teleconnection phases, and climate anomalies, while the centre columns represent transitions between these two extremes. Furthermore, the links between synoptic types and surface climate were strongly substantiated by seasonal water availability analysis. Several synoptic types were found to have a statistically significant increasing or decreasing trend over the study period (1950-2011), the cumulative result of which suggests a trend toward warmer, drier winters, resulting in reduced snowpack and shorter snow accumulation seasons.

The SOI and PDO significantly affected the frequency of certain synoptic types, with an increased frequency of a ridge (trough) over the Pacific Ocean coupled with a trough (ridge) over western North America during positive (negative) SOI and negative (positive) PDO. Given the links between these synoptic types and surface climate, the relationship between positive (negative) SOI and negative (positive) PDO and anomalously cool (warm), wet (dry) winter climate in the study region can be inferred. Previous studies have primarily focused on relating teleconnections directly to surface climate. Results from this research provide the atmospheric links through which the SOI and PDO affect surface climate and enhance our understanding of these processes.

Chapter 4 presents research findings from the summer synoptic analysis. The synoptic classification had a strong seasonal progression, with clear shoulder (May, Sep-Oct) and mid-summer (Jun-Aug) types emerging. Shoulder season types were similar to several of those in the winter synoptic classification, while a split-flow blocking pattern emerges during mid-summer. This split-flow blocking type has significantly increased in frequency over the study period (1950-2011), while shoulder-season troughing over the North Pacific has significantly decreased. This suggests a trend toward circulation patterns conducive to an earlier shift from spring to summer atmospheric conditions, and lengthening of the dominant mid-summer climate, which can have implications for seasonal water availability.

The relationships between synoptic types and surface climate are not as strong as during the winter season, likely due to the additional processes affecting water availability, including high evapotranspiration, rainfall recycling, and moisture transport from water bodies south of the study region, well outside the synoptic window selected for this study. The weak associations were also observed for the SPEI analysis and associated seasonal synoptic type frequency anomalies. Poor relationships were also found between summer synoptic types and the SOI and PDO.

Although this study has answered several important research questions regarding the atmospheric drivers of water resource distribution in western Canada, it has also identified additional areas that require further analysis. Three main future research recommendations are as follows.

1. Although strong relationships were found between winter synoptic types and the Pacific-related teleconnections (SOI and PDO), associations with the circumpolar Arctic Oscillation (AO) were almost non-existent. Since characteristics of circumpolar circulation, including outbreaks of Arctic air masses, have the potential to strongly

influence mid-latitude weather systems and associated surface climate, it is recommended that additional metrics, such as Rossby wave or jet stream characteristics be explored in more detail.

2. This analysis focused on a longer summer period (May-Oct), and for the most part produced less coherent results when evaluating summer synoptic types, teleconnections, and seasonal water availability compared with winter analysis. Therefore, it is recommended that further research, focusing on different methods for classifying positive and negative teleconnection phases, and examining water availability using monthly or three-month values of the SPEI, may provide additional insight into these relationships.
3. Since past climate trends have influenced the distribution of water resources in western Canada, it raises the question of how projected climate change will impact synoptic type frequency, strength, and persistence, and associated consequences for water availability in western Canada. Additionally, what impacts will projected climate change have on the frequency and magnitude of large-scale teleconnections, and, in turn, what effects will this have on mid-tropospheric circulation patterns?

In summary, this research provides a comprehensive synoptic climatology of western Canada that can be used in conjunction with CROCWR project analyses of climate and streamflow trends and variability to effectively evaluate the spatial and temporal distribution of water resources in this region. The procedures outlined in the suite of studies performed under the CROCWR project, including this research, can be used to evaluate water resources in other regions, including eastern and northern Canada.