Climate Change in Dawson City, YT: Summary of Past Trends and Future Projections

31 December 2009

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PACIFIC CLIMATE IMPACTS CONSORTIUM

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Some of the data presented in the report were provided in-kind by national modelling centers. The Canadian Regional Climate Model (CRCM4) outputs are one example of this important data, which were used to produce the mapped projections in this report. These were provided by the Ouranos Consortium in collaboration with the Canadian Centre for Climate Modelling and Analysis of Environment Canada.

Katrina Bennett, Anne Berland and David Bronaugh are gratefully acknowledged for their assistance with evaluating the influence of climate variability on the DCR. Andrew Weaver, Professor in the School of Earth and Ocean Sciences (SEOS) at UVic, Canada Research Chair in Climate Modelling and Analysis and PCIC's Senior Scientist, provided a useful review.

About PCIC

The mission of the Pacific Climate Impacts Consortium is to quantify the impacts of climate change and variability on the physical environment in Pacific North America. The Pacific Climate Impacts Consortium is financially supported by BC Ministry of Environment, BC Hydro, BC Ministry of Forests and Range and several regional and community stakeholders. For more information see www.PacificClimate.org.

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Disclaimer

Executive Summary

The Arctic regions of the world are some of the most likely to experience rapid and amplified climate change that might result in large impacts on resources and ecosystems. Dawson City has taken proactive measures to reduce its vulnerability by assessing the impact of climate change. This work is a precursor to long range planning activities, such as developing an adaptation plan. The following report summarizes historical trends and projected future changes in the hydro-climatology for Dawson City and the greater Dawson City Region (DCR).

Dawson City, YT is located in an area that is responsive to climate variability and has experienced trends. The effects of climate variability, such as the El Niño / Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), on monthly climate are presented. During the ENSO warm phase (El Niño) minimum, maximum and mean temperatures are 3.5°C to 3.9°C warmer on average than during its cool phase (La Niña), in December through February. Precipitation is not highly responsive to ENSO. The warm phase of PDO influences not only the winter months but also the spring, increasing temperatures from 0.5°C (June) to 3.7°C (January). Statistically significant differences were found in May for precipitation, where precipitation was 20% greater on average during the warm PDO phase versus the cool PDO phase. The Arctic Oscillation (AO) was found to be related to increased temperatures from May through August in the area and to increased streamflow during April and decreased streamflow during August in snow-melt dominated basins (Fleming et al., 2006).

Warming trends in the DCR exceed those found across British Columbia and other more southern regions of Canada. Trends in mean temperature were 6.2°C per century for Dawson A and 5.8°C per century for Mayo A for the 1955-2004 period. Minimum temperatures (night-time lows) increased faster than maximum temperatures (day-time highs) with increases of 7.2°C per century and 4.8°C per century, respectively, at the Dawson A station. At Mayo A, temperature increases were only slightly greater for night-time lows than day-time highs with increases of 6.0°C per century and 5.4°C per century. Dawson A is slightly farther north than Mayo A. Trends in precipitation are much more spatially variable than temperature. Dawson A indicated a 29% per century decline in precipitation, 26% per century decline in rainfall and a 31% per century decline in snowfall over a 50 year interval (1955-2004), although none of these trends were significant. Mayo A showed significant, increasing trends for precipitation (27% per century), rainfall (13% per century) and snowfall (30% per century) during this 50-year time period. Pelly Ranch also showed a significant, positive trend in precipitation of 30% per century (1955-2004).

Future winter temperatures are projected to increase 2.1°C to 3.5°C for the 2050s (2041-2070) compared with the 1961-1990 baseline based on the mid-range (25^{th} to 75^{th} percentiles) of an ensemble of 30 Global Climate Model projections. Precipitation is projected to increase slightly more in winter (+6% to +18%) than in summer (+3% to +16%). Higher resolution projections from the Canadian Regional Climate Model (CRCM) demonstrate a spatial pattern of warming in the winter and summer seasons that is relatively uniform across the DCR, but precipitation increases will be more intense in the western regions during winter and around the perimeter of the DCR in summer. The CRCM was driven by the Canadian GCM at the boundaries and is above the 75^{th} percentile in temperature and precipitation when compared to the 30 GCM/emissions scenarios ensemble. Future streamflow projections were not available.

Preface

This report is one in a series of regional assessments conducted by the Pacific Climate Impacts Consortium (PCIC) on past and future climate and hydrology. It is a product of the Regional Climate Impacts Theme, one of the four major Themes of the PCIC program. To support the creation of the City of Dawson Community Adaptation plan, the Northern Climate ExChange (NCE) of Yukon College engaged PCIC to provide climate information for the Dawson City Region (DCR). The mission of the NCE is to "provide a credible independent source of information, develop shared understanding and promote action on climate change in northern Canada." PCIC worked with Ryan Hennessey of the NCE to summarize information and provide graphics and images that were used at adaptation workshops and in summary documents leading up to the finalized Plan. These materials have also been used by the Community Adaptation and Vulnerability in Arctic Regions (CAVIAR) project led by Dr. Frank Duerden.

This collaboration has resulted in a technical resource for information on historical and future climate and hydrology as it applies to the Dawson City Region, where temperature has been increasing more rapidly than most parts of North America, and where future projections indicate that the region will be expected to continue to experience more rapid climate change than most areas.

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15 December 2009

1. Introduction

The following provides a summary of the past trends and future projections for Dawson City, Yukon. The baseline climatology and trends from an observational station at Dawson City are provided in addition to the baseline climatology over the region, as depicted by the PRISM dataset. Projections for the 2041-2070 (2050s) period are shown for temperature and precipitation from the Canadian Regional Climate Model. Lastly, Global Climate Model projections from 15 models, following two emissions scenarios (A2 & B1) over the region are summarized via boxplots.

2. Baseline Climatology

Planning is often carried out on the basis of means and extremes of climatological values such as temperature and precipitation over a given period for example, 30 years. These averages are called climatology, or climate normals. In climate science, future projections of climate change are frequently given as a difference from these average recent conditions. See section II for future climate projections in the Dawson City Region (DCR).

This section provides two types of climate information for the 1961-1990 climate normal period. Annual mean temperature and precipitation climatologies are shown with maps where station data has been interpolated to 4 km resolution by the Precipitation-elevation Regressions on Independent Slopes Model (PRISM). These maps provide an overview of the variation in temperature and precipitation over this area. Data are also presented in a tabular format from the Adjusted Historical Canadian Climate Dataset (AHCCD)[i]. Monthly, seasonal and annual values of mean, minimum and maximum temperature, precipitation, rain and snow are summarized.

2.1. West-central Yukon

PRISM is an interpolation of station-based measurements of monthly and annual temperature and precipitation to regularly spaced grid cells (Daly et al., 1994). The resulting high resolution (4 km) surface reflects spatial variations in climate caused by elevation, aspect, effectiveness of terrain as a barrier to flow, proximity to the coast, moisture availability and inversions[ii]. Station data provided by Environment Canada and the global historic climatology network (GHCN) were used to create PRISM in BC and the Yukon (Simpson et al., 2005).

The 1961-1990 average of annual mean baseline temperature from the PRISM dataset ranged from -7.2°C to -1.2°C for the majority of the DCR. Temperatures north of Dawson City were lower, in the range of -11.2°C to -5.2°C. Average 1961-1990 annual precipitation ranged from 200 mm to 500 mm in the DCR. The area north-east of Dawson City had higher precipitation, from 400 mm to 800 mm per year during the same interval.

[i] http://www.cccma.bc.ec.gc.ca/hccd/data/access_data.shtml
[ii] http://www.prism.oregonstate.edu/

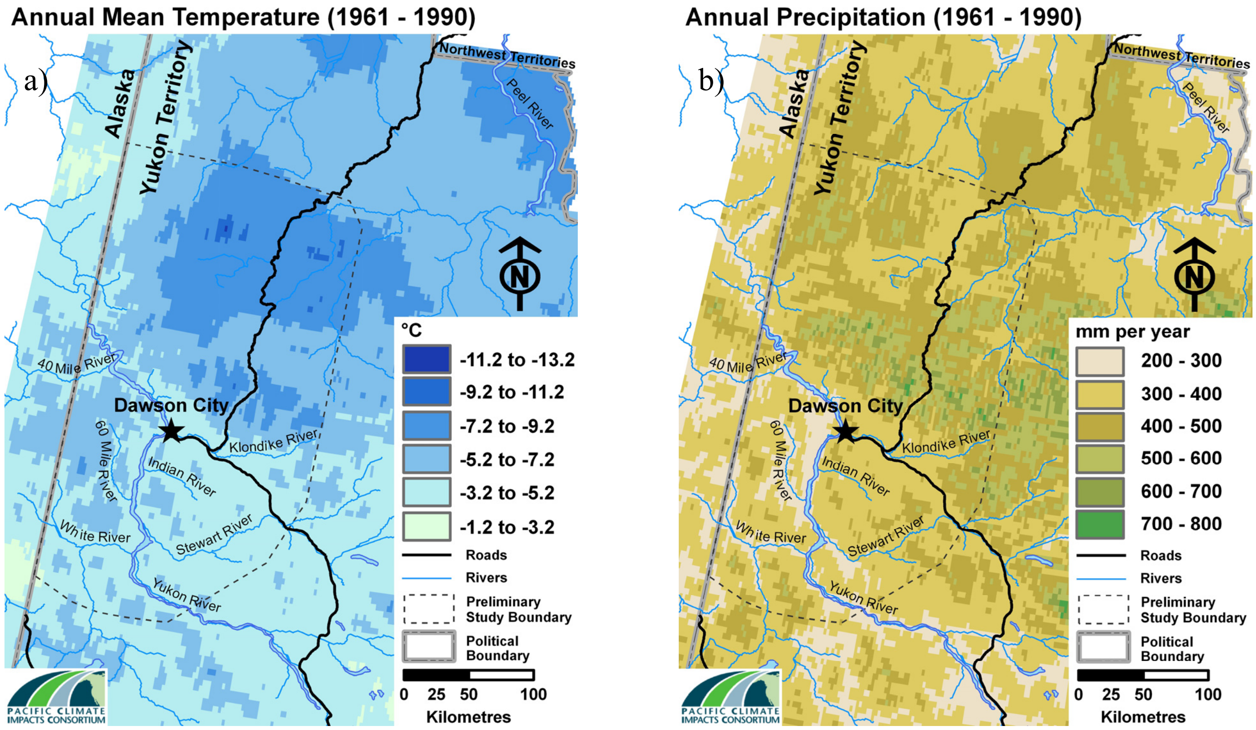

Figure 2-1 - Baseline climate maps over the west-central region of the Yukon (a) annual mean temperature and (b) precipitation for 1961-1990 climatology. Source: PRISM (Daly et al., 2004).

2.2. Dawson City

Climatology was also established from the three nearest AHCCD stations: Dawson A; Mayo A and Pelly Ranch. Dawson A has the longest record, stretching back to 1897. It also is at the lowest elevation and is farthest north-west. The second longest record is Mayo A, located at the highest elevation and farthest east of the three. Pelly Ranch has precipitation data only, is farthest south, has the shortest record and is at a slightly lower elevation than Mayo A (Table 2-1). Annual mean temperature for 1961-1990 was -5.3°C at Dawson A and -3.6°C at Mayo A (Table 2-2). Dawson A, the station farthest north, is coolest annually. These values fall within the temperatures found with PRISM's baseline climatology. Winter (summer) minimum (maximum) temperatures were lowest (highest) at Dawson A, at -31.2°C (21.0°C).

Precipitation data was available for all three stations. Mean annual precipitation over 1961-1990 was recorded as 412 mm, 372 mm and 316 mm for Dawson A, Mayo A and Pelly Ranch, respectively. These values fall within those found with the PRISM interpolated baseline and are arid (Table 2-3). Snowfall was greatest at Dawson A, at 191 cm a year on average for 1961-1990.

Table 2-1 - Metadata for AHCCD climate stations near Dawson City.

Number	Name	Latitude	Longitude	Time Period	Elevation (m)
2100402	Dawson A	64.043	-139.128	1897-2005	370
2100700	Mayo A	63.617	-135.867	1924-2007	504
2100880	Pelly Ranch	62.817	-137.367	1955-2007	454

Table 2-2 - Baseline (1961-1990) temperature data from AHCCD in the Yukon.

		Annual			Winter			Summer		
		Min Temp (°C)	Mean Temp (°C)	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Max Temp (°C)
Dawson A 2100402	MEAN	-11.8	-5.3	1.1	-31.2	-26.3	-21.4	5.7	13.4	21.0
	STDEV	1.5	1.4	1.4	4.3	4.2	4.1	0.7	0.7	1.0
	COEFF of VAR	-0.1	-0.3	1.2	-0.1	-0.2	-0.2	0.1	0.1	0.0
Mayo A 2100700	MEAN	-9.5	-3.6	2.4	-28.8	-23.2	-17.6	7.2	14.0	20.8
	STDEV	1.7	1.6	1.5	4.7	4.8	4.9	0.8	0.8	1.0
	COEFF of VAR	-0.2	-0.4	0.6	-0.2	-0.2	-0.3	0.1	0.1	0.0

Table 2-3 - Baseline (1961-1990) precipitation data from AHCCD in the Yukon.

		Annual			
		Precipitation (mm)	Snowfall (cm)	Snow Depth March 31st (cm)	Snow Depth December 31st (cm)
Dawson A 2100402	MEAN	412	191	NA	NA
	STDEV	85	55	NA	NA
	COEFF of VAR	0.2	0.3	NA	NA
Mayo A 2100700	MEAN	372	145	36	31
	STDEV	58	36	19	13
	COEFF of VAR	0.2	0.3	0.5	0.4
Pelly Ranch 2100880	MEAN	316	110	28	25
	STDEV	44	19	15	10
	COEFF of VAR	0.1	0.2	0.5	0.4

3. Climate Variability

Climate has a natural cycle of variability that brings different temperatures and precipitation amounts from those found on average (section 2). There are multiple modes of variability including those with shorter periods such as the El Niño/Southern Oscillation and those that persist for extended (decadal) time periods like the Pacific Decadal Oscillation. These oscillations are statistically significant, recurring and persistent circulation patterns between two or more geographic areas (Hatzaki et al, 2006).

The **El Niño/Southern Oscillation (ENSO)** is an irregular tropical Pacific ocean-atmosphere phenomenon associated with anomalously warm, or cool, sea water in the equatorial Pacific that influences climate around the world. The warm phase of ENSO is commonly referred to as El Niño, while the cool phase is called La Niña. ENSO tends to shift between the two extremes and a neutral state irregularly within a two to seven year period. Usually it does not remain in either the warm or cool phase for any longer than a year or two (although longer instances have occurred). Its effects are different from one episode to the next, depending on the strength and structure of the particular event.

The **Pacific Decadal Oscillation (PDO)** is a large-scale climate oscillation characterized by spatial variations in the sea surface temperature (SST) and atmospheric pressure anomalies in the northern Pacific Ocean (Mantua et al., 1997; Zhang et al., 2000). The positive PDO phase is observed when the SSTs in areas of the North Pacific Ocean are below average and the SSTs along the west coast of North America are above average. The negative PDO phase is observed when the situation is reversed.

The positive and negative phases of the PDO described above can also be referred to as warm and cool phases. One feature that distinguishes PDO from ENSO is its long lasting phases, which usually persist for 20 to 30 years, while typical ENSO events persist for 6 to 18 months (Mantua et al., 1997). The PDO amplifies or dampens the effects of ENSO (Mantua et al., 1997). For example, during the warm phase of the PDO, El Niño years tend to be even warmer (and similarly La Niña years even cooler during the PDO cool phase). PDO was in a cool phase from about 1890-1924 and from 1947-1976 and was in a warm phase from 1925-1946 and from 1977 until at least the mid-1990s (Hare and Mantua, 2000). A change from warm to cool may have occurred since the mid to late-1990s, but it is difficult to positively identify the change between phases until sufficient records have been accumulated, many years after a shift occurs. The PDO pattern as identified during the 20th century may also be significantly altered by climate change.

The ENSO and the PDO were investigated for their influence on temperature, and precipitation in the DCR. Monthly response in minimum, maximum and mean temperatures and precipitation to ENSO and PDO is shown below. Results are presented via barplots and created by subtracting El Niño years from La Niña years (ENSO) and warm PDO years from cool PDO years for each month using composites of CANGRID data over the DCR from 1950-2007 (ENSO) and 1950-1998 (PDO). CANGRID is available over Canada at a resolution of 50 km and was created by interpolating AHCCD using the Gandin optimal interpolation technique[iii].

[iii] Source Climate Research Branch of Environment Canada

Mean temperatures were from 3.5°C warmer during El Niño than during La Niña in December and 3.7°C warmer during El Niño than during La Niña in January and February (Figure 3-1a). The months of December through February were significantly different at the 95% confidence level (Figure 3-1a). Differences for minimum temperatures were similar, from 3.2°C warmer during El Niño than during La Niña in December to 3.9°C warmer during El Niño than during La Niña in February (Figure 3-2a). Maximum temperatures were also significantly different in December through February by 3.5°C to 3.8°C (Figure 3-3a). Precipitation differences were not significant in any of the months (Figure 3-4a).

PDO responses were similar to those from ENSO with the exception of having significant differences in the spring, in addition to winter. The warm PDO phase yielded significantly warmer mean temperatures in January, February, May and June (Figure 3-1b). Mean temperatures were as much as 3.6°C warmer during the warm PDO phase in January and as little as 0.5°C warmer in June. Minimum temperatures were significantly different between the warm and cool PDO phases in January, February and May. January was warmer during the warm PDO phase by as much as 3.7°C (Figure 3-2b). Response in maximum temperature was similar to that for mean temperatures. Temperature differences from 0.7°C to 3.5°C were significant in January, February, May and June (Figure 3-3b). These findings support those found by N. Cormer in the DCR recently (pers. comm., September 2008). Precipitation differences were significant for the PDO phases in May only, where precipitation was 20% greater on average during the warm PDO phase versus the cool PDO phase (Figure 3-4b).

A third large-scale circulation system, the Arctic Oscillation (AO), also influences the DCR. An evaluation of the AO for 1951-2007 in the DCR with composites of CANGRID suggests that response is strongest in fall during the positive AO phase when precipitation can be 15% to 20% greater than the mean. During the winter and spring, mean temperature can be 0.5°C to 1.0°C greater for positive AO phases versus the mean over the analysis period. Most of this response is due to maximum temperatures increases of as much as 1.5°C. Decreases of 0.5°C were found in the fall. The consequences of the positive AO on snow-melt dominated basins just south of the DCR were increased streamflow during April and decreased streamflow in August (Fleming et al., 2006). The spring freshet may take place earlier during positive AO, which results in lower summer flows. Increased temperatures from May through August may increase evapotranspiration leading to water loss in these months (Fleming et al., 2006).

The historic influences of these teleconnections can be used as analogues for the response local climate might have to climate warming in the future, especially in years when the warm phases of the oscillations reinforce each other (i.e. El Niño with warm PDO). However, future climates will still have climate variability superimposed on changes to the average climate and may modify the strength and temporal variability of these oscillations. Awareness of their effects can provide valuable information for planning purposes by helping managers to understand the historical variability of the climate[iv].

[iv] The ENSO signal is used to make relatively short term (compared to climate change projections in section 6) seasonal outlook predictions up to a year in advance by Environment Canada http://www.weatheroffice.gc.ca/saisons/index_e.html

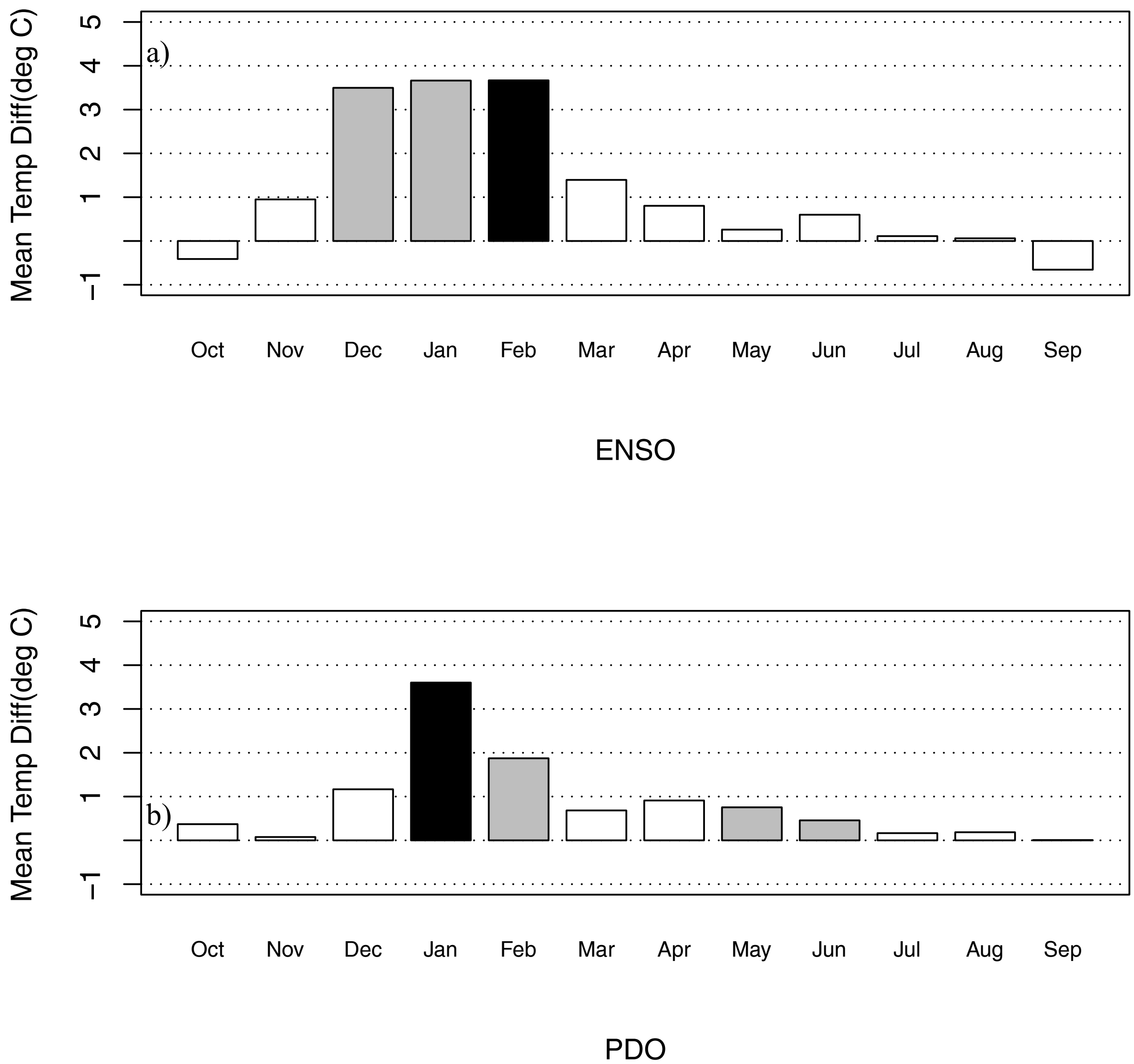

Figure 3-1 - Monthly difference in mean temperature (°C) in the Dawson City Region for (a) El Niño versus La Niña and (b) warm PDO versus cool PDO. Statistical significance is indicated by gray (90%) or black (95%) shading. Source: CANGRID (50 km), CIG 2006.

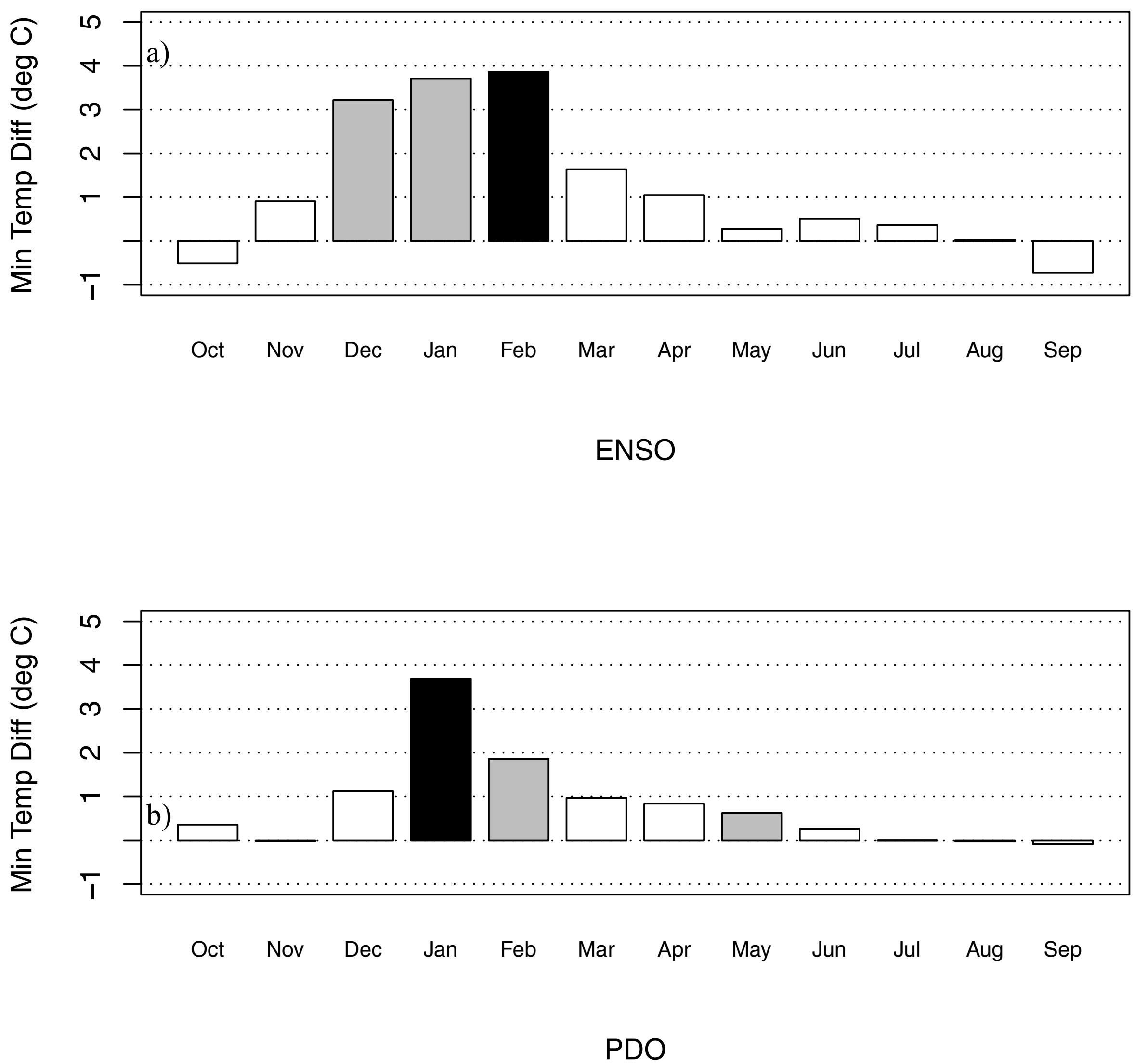

Figure 3-2 - Monthly difference in minimum temperature (°C) in the Dawson City Region for (a) El Niño versus La Niña and (b) warm PDO versus cool PDO. Statistical significance is indicated by gray (90%) or black (95%) shading. Source: CANGRID (50 km), CIG 2006.

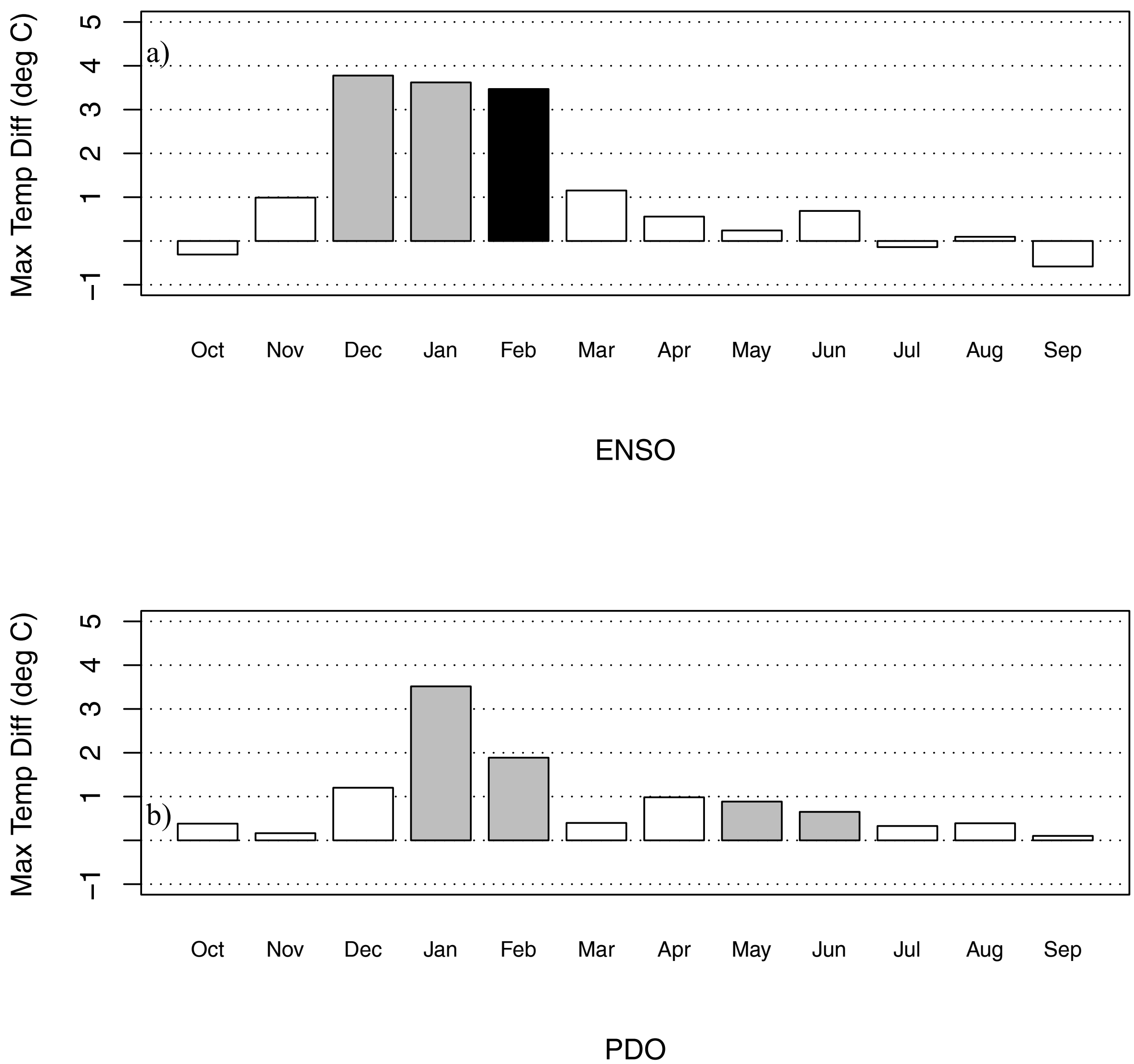

Figure 3-3 - Monthly difference in maximum temperature (°C) in the Dawson City Region for (a) El Niño versus La Niña and (b) warm PDO versus cool PDO. Statistical significance is indicated by gray (90%) or black (95%) shading. Source: CANGRID (50 km), CIG 2006.

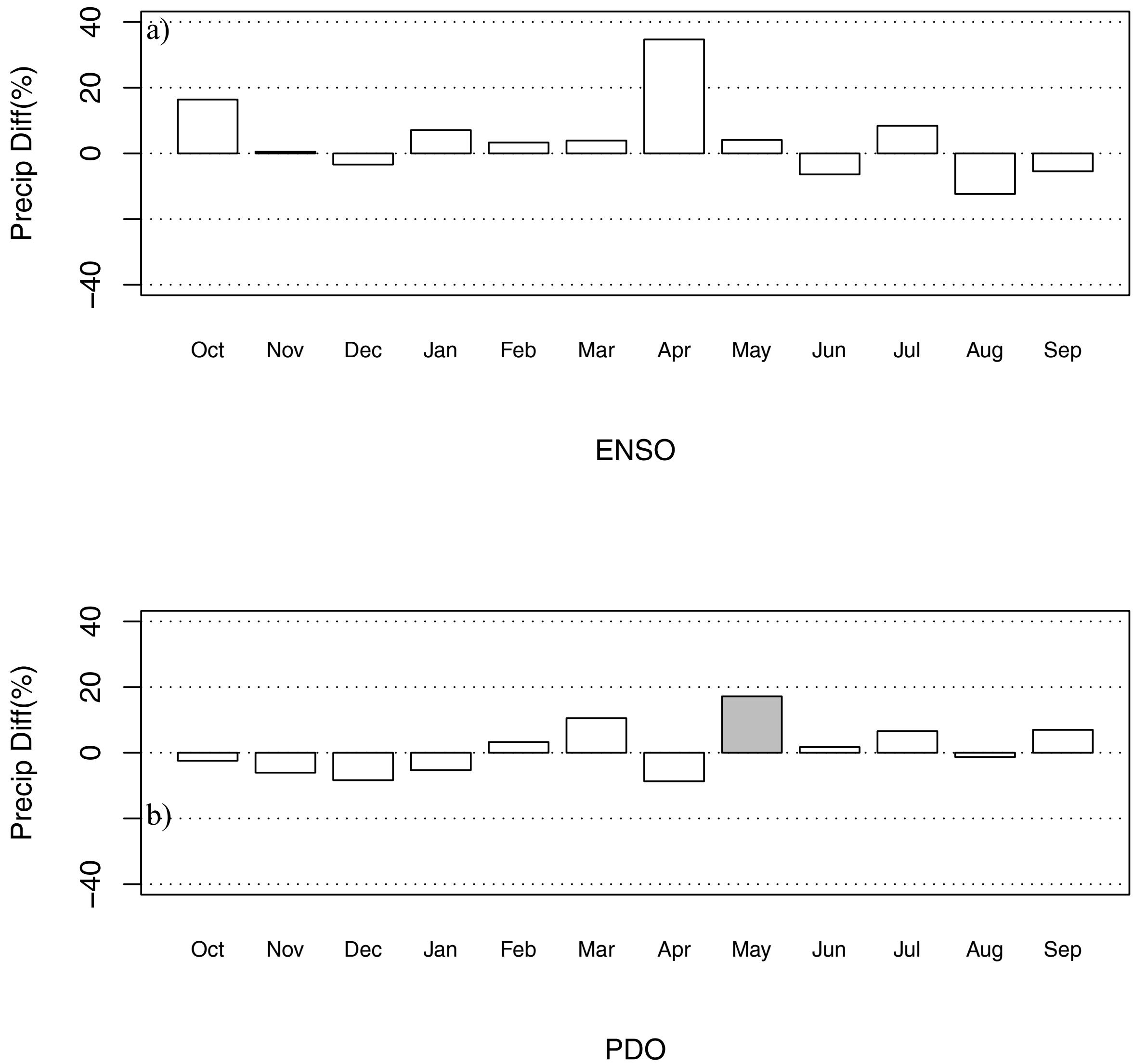

Figure 3-4 - Monthly difference in precipitation (%) in the Dawson City Region for (a) El Niño versus La Niña and (b) warm PDO versus cool PDO. Statistical significance is indicated by gray (90%) or black (95%) shading. Source: CANGRID (50km), CIG 2006.

4. Climate Trends

Eleven of the twelve years between 1995 and 2006 rank among the twelve warmest in the instrumental global surface air record since 1950 (Solomon et al., 2007). The global rate of warming over the last 50 years (0.13°C $\pm$ 0.03°C per decade) (1956-2005) is almost twice that for the last 100 years (0.074°C $\pm$ 0.018°C per decade) (1906-2005) (Solomon et al., 2007). Warming has been shown to be greatest in the northern latitudes and the majority of this warming has taken place in winter and spring (Solomon et al., 2007).

Analyzing trends in temperature, precipitation and streamflow for Dawson City and its surrounding area gives some indication of how these variables are being affected locally. Although current trends may not be extrapolated into the future, trend analysis illustrates the changes that have taken place in this region and provides context for comparison of trends in this area relative to others. It is also important to note that the trends are influenced by modes of decadal variability, such as the PDO (section 3).

Trends in annual temperature and precipitation for several periods in the historical record are presented below. The three AHCCD stations described in section 2 Baseline Climatology, Dawson A, Mayo A and Pelly Ranch, were analysed for trends. This was completed using an iterative approach to pre-whitening and testing for trend (Zhang et al., 2000). The magnitude of the trend was computed with the Theil-Sen method and significance was assessed with the Mann-Kendall test. Streamflow trends are discussed in section 5.2, where trends of five-day means of streamflow and associated trends in temperature and precipitation are provided.

Trend analysis revealed an increase in mean temperature of 6.2°C per century for Dawson A and 5.8°C per century for Mayo A for the 50-year interval from 1955-2004 (Table 4-1, Figure 4-1 and Figure 4-2). For Dawson A, minimum temperatures (night-time lows) increased faster than maximum temperatures (day-time highs) with an increase of 7.2°C per century and 4.8°C per century, respectively. At Mayo A temperature increases were only slightly greater for night-time lows than day-time highs with 6.0°C per century and 5.4°C per century increases. This could be because Dawson A is slightly farther north than Mayo A.

Local trends in precipitation varied considerably between stations. Dawson A indicated a 29% per century decline in precipitation over a 50 year interval (1955-2004). Rainfall declined at 26% per century, while snowfall declined at 31% per century. Mayo A showed an increasing trend for precipitation of 27% per century from 1955-2005, rainfall increased by 13% per century and snowfall also increased by 30% per century during this 50-year time period. Pelly Ranch also showed a positive trend for 1955-2004 with an increase in precipitation of 30% per century. However, rainfall increased (32% per century) more than snowfall (7% per century) for that period. The Pelly Ranch and Mayo A stations are east and slightly south of Dawson A and are also roughly 100 m higher than the Dawson A station. Trends in precipitation are much more spatially variable than temperature. For example, precipitation is influenced by storm track positions, topography and inversions.

A careful review of precipitation trends for Dawson A by PCIC confirmed that these are opposite to those for Pelly and Mayo A for 1955 to 2004, but for 1976 to 2004 the trends correspond, although the magnitude of the Dawson A trend from 1976 to 2004 is not as large. Additionally, Dawson A is missing data for 2002, 2003 and 2004 and metadata for the Dawson A station is limited. None of the trends were statistically significant. The Dawson A station trends for the 1902-2005 period showed a 1.7% decrease in annual precipitation that was not significant. The trends for other time periods were also negative and non-significant for this station. However, trends at other precipitation stations relatively nearby were positive for all time periods and significant. Perhaps precipitation at Dawson A is more variable than at other stations, which would account for the lack of significance in the trends at this station. Precipitation is highly sensitive to the influence of modes of climate variability and is spatially variable. Using trends at one station to infer how precipitation may change in the future is not advisable.

Table 4-1- Trends in minimum, maximum and mean temperature and precipitation for three AHCCD stations (a) Dawson A, (b) Mayo A and (c) Pelly Ranch. *Bold values significant at the 95% confidence level.

(a) Dawson A 2100402	**Time Period**		1902-2005	1955-2004
	Number of years		*104*	*50*
	Trend per time period*	Min Temp (°C)	**2.6**	**3.6**
		Mean Temp (°C)	**1.9**	**3.1**
		Max Temp (°C)	**1.5**	**2.4**
		Precipitation (%)	-1.7	-14.5
		Rainfall (%)	**4.2**	-13.0
		Snowfall (%)	-9.8	-15.3
	Trend per decade*	Min Temp (°C)		0.7
		Mean Temp (°C)		0.6
		Max Temp (°C)		0.5
		Precipitation (%)	-0.2	-2.9
		Rainfall (%)	0.4	-2.6
		Snowfall (%)	-0.9	-3.1
	Trend per century*	Min Temp (°C)	2.5	**7.2**
		Mean Temp (°C)	1.8	**6.2**
		Max Temp (°C)	1.4	**4.8**
		Precipitation (%)	-1.7	-29.0
		Rainfall (%)	4.0	-26.1
		Snowfall (%)	-9.4	-30.6
(b) Mayo A 2100700	**Time Period**		1927-2005	1955-2004
	Number of years		*79*	*50*
	Trend per time period*	Min Temp (°C)	**1.9**	**3.0**
		Mean Temp (°C)	**1.8**	**2.9**
		Max Temp (°C)	**1.7**	**2.7**
		Precipitation (%)	**33.1**	**13.6**
		Rainfall (%)	**19.1**	**6.4**
		Snowfall (%)	**46.2**	**15.5**
	Trend per decade*	Min Temp (°C)		0.6
		Mean Temp (°C)		0.6
		Max Temp (°C)		0.5
		Precipitation (%)	**4.2**	**2.7**
		Rainfall (%)	**2.4**	**1.3**
		Snowfall (%)	**5.8**	**3.0**
	Trend per century*	Min Temp (°C)	2.4	**6.0**
		Mean Temp (°C)	2.2	**5.8**
		Max Temp (°C)	2.1	**5.4**
		Precipitation (%)	**42.0**	**26.8**
		Rainfall (%)	**24.1**	**12.6**
		Snowfall (%)	**58.4**	**30.3**
(c) Pelly Ranch 2100880	**Time Period**			1955-2004
	Number of years			*50*
	Trend per time period*	Precipitation (%)		**15.2**
		Rainfall (%)		**16.0**
		Snowfall (%)		**3.3**
	Trend per decade*	Precipitation (%)		**3.0**
		Rainfall (%)		**3.2**
		Snowfall (%)		**0.7**
	Trend per century*	Precipitation (%)		**30.2**
		Rainfall (%)		**31.9**
		Snowfall (%)		**6.7**

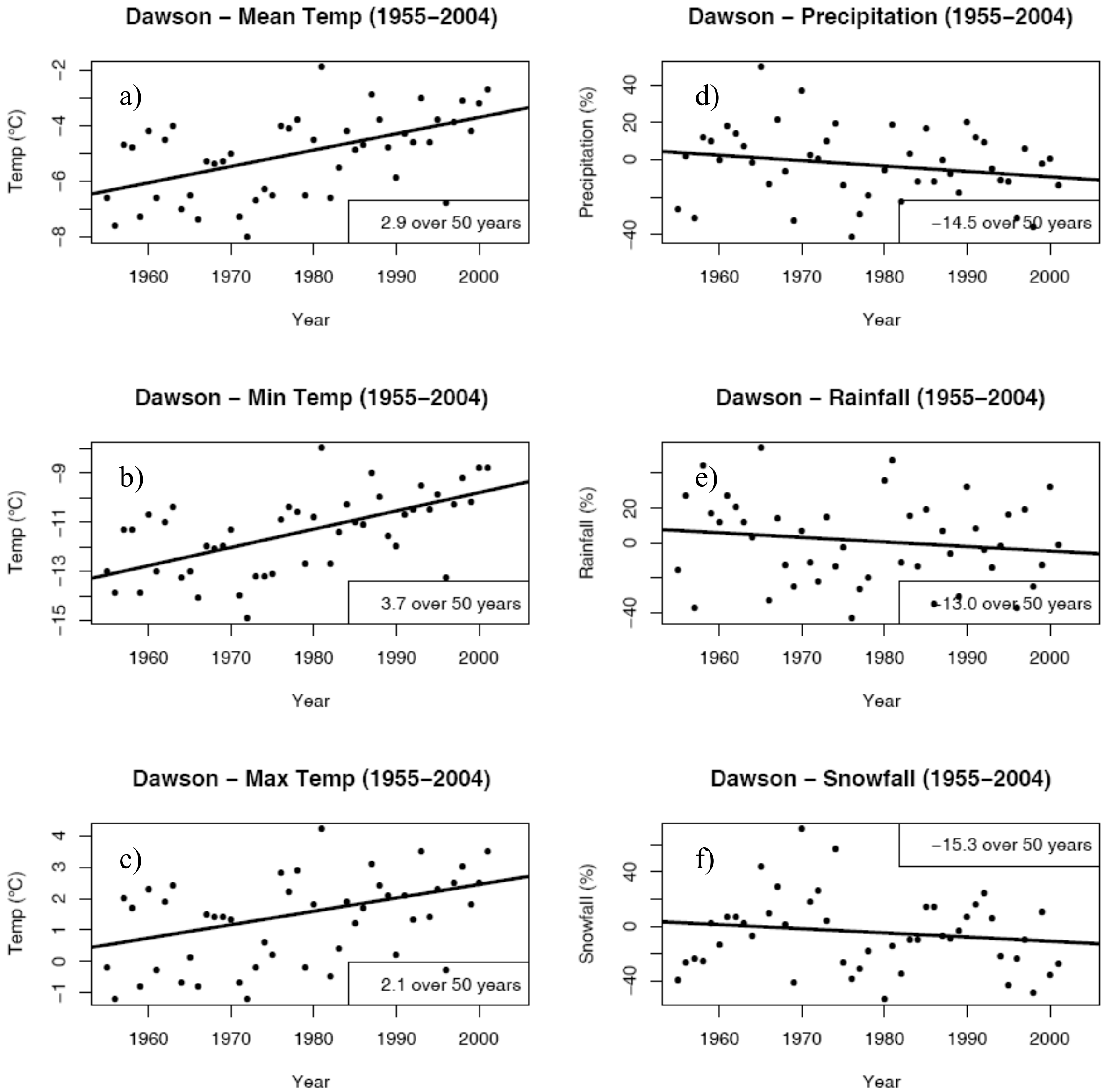

Figure 4-1 - Trends for the Dawson A climate station (2100402 AHCCD) for 1955-2004 (a) mean temperature, (b) minimum temperature, (c) maximum temperature, (d) precipitation, (e) rainfall and (f) snowfall. Temperature trends are shown as absolute value (°C) and precipitation, rain and snowfall trends are shown as percentage difference (%) from their 1961-1990 mean.

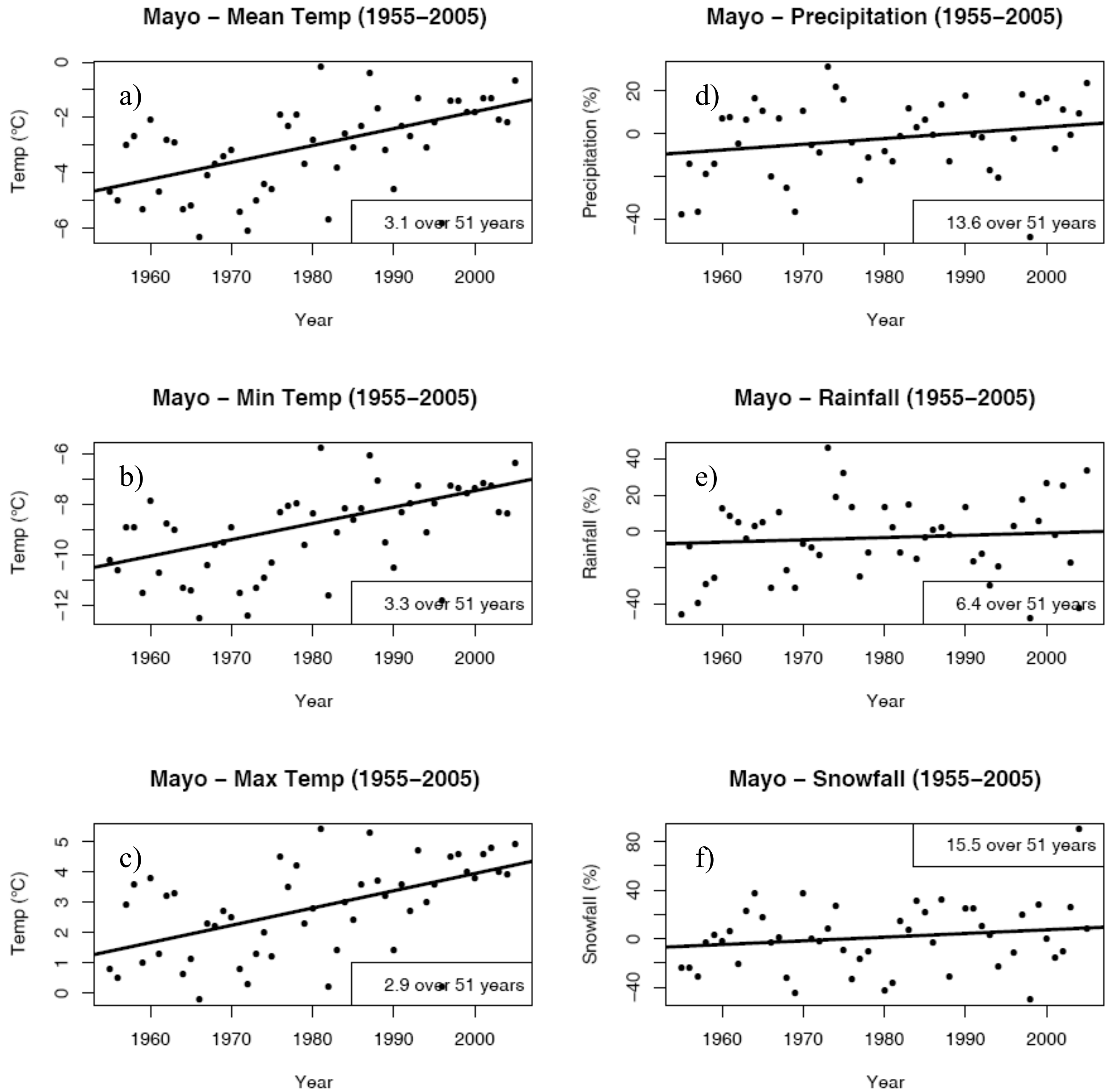

Figure 4-2 - Trends for the Mayo A climate station (2100700 AHCCD) for 1955-2004 (a) mean temperature, (b) minimum temperature, (c) maximum temperature, (d) precipitation, (e) rainfall and (f) snowfall. Temperature trends are shown as absolute value (°C) and precipitation, rain and snowfall trends are shown as percentage difference (%) from their 1961-1990 mean.

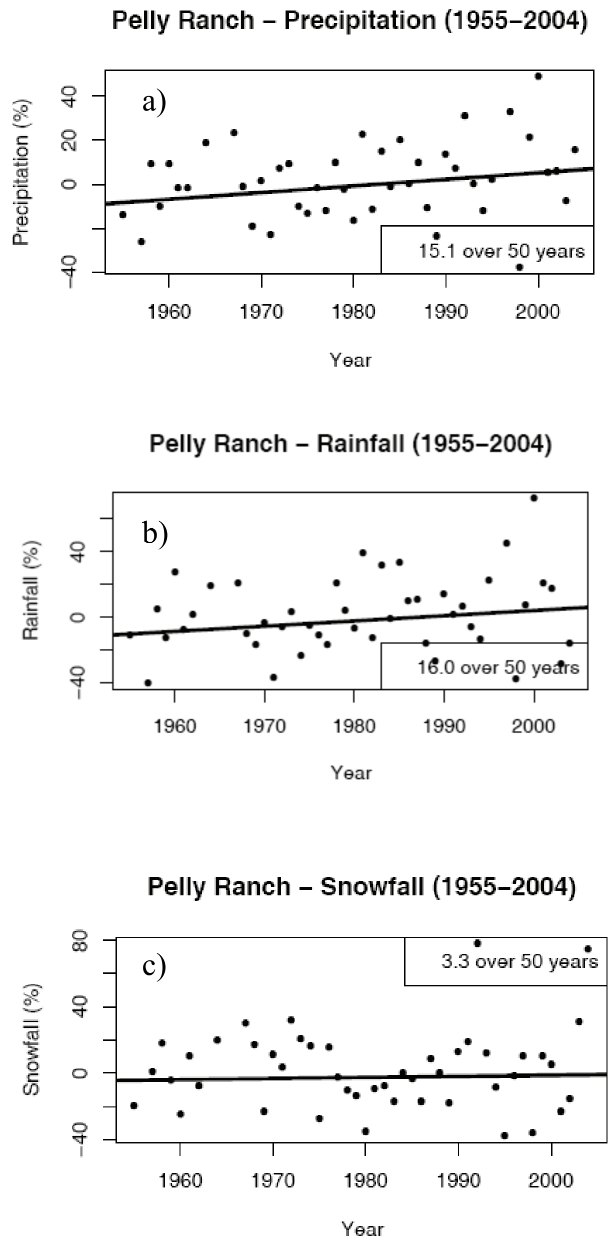

Figure 4-3 - Trends for the Pelly Ranch climate station (2100880 AHCCD) for 1955-2004 (a) mean temperature, (b) minimum temperature, (c) maximum temperature, (d) precipitation, (e) rainfall and (f) snowfall. Temperature trends are shown as absolute value (°C) and precipitation, rain and snowfall trends are shown as percentage difference (%) from their 1961-1990 mean.

5. Hydro-climatology

Streamflow regimes can be classified into one of four categories: rainfall dominated (pluvial), a mixture of rainfall and snow-melt dominated (hybrid), snow-melt dominated (nival) and snow-melt and glacier-melt dominated (nival/glacial). Each category has defining characteristics that can be used to better understand streamflow response under a changing climate. Streamflow in rivers fed by glacier melt tend to peak in June or July, while those fed by snow melt peak in May. Summer precipitation may also contribute to flow from July through September in these systems, but both generally have low-flows from November to April. All other things being equal, catchments with glacier cover have larger and longer freshets that peak later than snow-melt dominated catchments, as well as higher base flow conditions (Fleming, 2005). The amount of glacier cover in a catchment is important in determining the magnitude of annual streamflow from a catchment.

Stations used in the analysis are identified in Table 5.1. All are near Dawson City and include both Reference Hydrometric Basin Network (RHBN) stations and non-RHBN stations[v]. Stations classified as RHBN should not be affected by human influences such as land-use change or water extraction, which makes them more suitable for climate studies. However, some RHBN stations have been impacted by activities such as logging or by natural disturbances such as the spruce bark beetle. Caution should be taken when interpreting the non-RHBN results especially. Trends in streamflow at these stations cannot be directly attributed to climate trends or variability.

Table 5-1 - Hydrometric station metadata.

Station Number	Station Name	Basin Area (km^2)	Lat	Long	Years of Record	RHBN
09BC001	Pelly River at Pelly Crossing	49000	62.830	-138.581	1951-present	Yes
09CD001	Yukon River above White River	150000	63.084	-139.494	1956-present	No
09DD003	Stewart River at the mouth	51000	63.282	-139.249	1951-present	No
09DD004	Mcquesten River near the mouth	4870	63.611	-137.269	1979-present	No
09EA003	Klondike River above Bonanza Creek	7800	64.043	-139.408	1965-present	No
09EA004	North Klondike River near the mouth	1100	64.021	-138.583	1974-present	No
09EB003	Indian River above the mouth	2220	63.771	-139.629	1981-present	No

All of the stations listed in Table 5.1, except for Pelly River at Pelly Crossing, were not classified as RHBN stations. Pelly River is relatively far from Dawson City, but was included for comparison to the non-RHBN station in the region. Trend analysis was carried out on non-RHBN stations for the Dawson City area due to the lack of RHBN stations. Hence, caution should be taken when interpreting these interim results. Also note, although each basin was investigated for glacier cover, no glacier information was available. This does not indicate that there were no glaciers.

[v] http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=main_e.cfm

Average streamflow for each pentad (5-day period) is shown for five stations for the 1961-1990 and 1976-2005 periods to demonstrate the average annual characteristics of each system (Figure 5.1). These five stations had adequate data over these two periods (Table 5.1). The hydrograph plots start in October (typically the onset of the wet season) and end in September, displaying the 12-month period known as the hydrologic year. All stations tend to have the lowest flows over the winter season (December through March). Streamflow starts to increase in April and peaks in late-May or June. There is a slow drawn-out recession of flow into the early fall suggesting contributions by glacier-melt. Unfortunately, this glacier cover information was not available for any of the stations investigated in this study. The volume of water in the summer and fall period varies across the watersheds. Overall, most of these basins could be classified as snow/glacier-melt dominated.

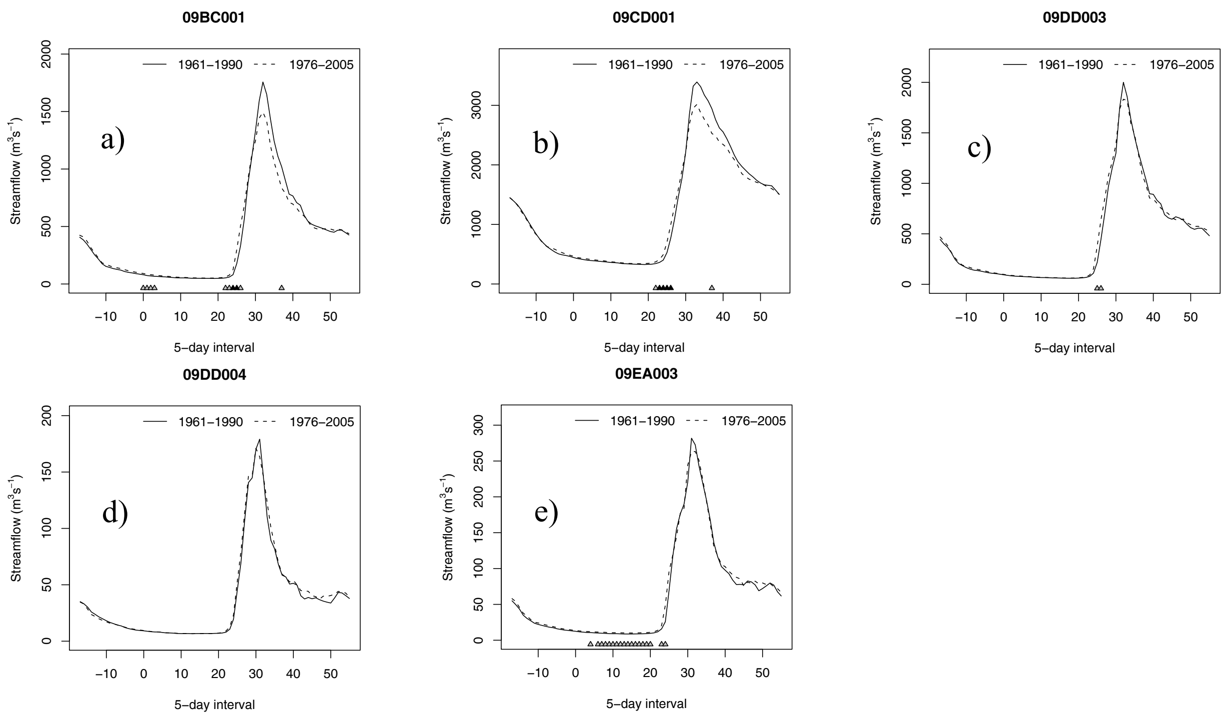

Figure 5-1 - Pentad (5-day interval) climatology hydrographs for 1961-1990 baseline and 1975-2006 time periods (a) 09BC001, (b) 09CD001, (c) 09DD003, (d) 09DD004 and (e) 09EA003. See Table 5.1 for station names and meta data. Average streamflow for each pentad (5-day period) is provided in m3/s. The grey and black triangles indicate significant differences at the 95% and 99% confidence levels respectively. Source: RHBN data.

Between the two thirty year periods (1961-1990) and (1976-2005), four of the five stations had significant changes in their streamflow. Flow was greater in early winter and spring and decreased in summer at Pelly River at Pelly Crossing (09BC001) (Figure 5-1a). Streamflow was greater in May for Yukon River above White River (09CD001) and Stewart River at the mouth (09DD003) suggesting melt started earlier in the later period (Figure 5-1b and Figure 5-1c). Winter low-flows increased over many months at Klondike River above Bonanza Creek (09EA003) in the 1975-2006 period (Figure 5-1e). No notable changes were found for Mcquesten River near the mouth (09DD004) between the two periods (Figure 5-1d).

5.1. Streamflow, Temperature and Precipitation Trends

Trends in average streamflow for each pentad (5-day period) are useful for analyzing change in the timing of streamflow and to evaluate the rate at which changes have taken place (Dery, 2009). The following approach is modeled after Dery et al.'s (2009) methodology. Averages were calculated for each of the seventy-three 5-day periods that occur over a year for each station. Then to ease comparison between stations, data for each pentad period were normalized by subtracting their mean and dividing by their standard deviation over the analysis period. The normalized data was then evaluated for trend for the 1965-2006 and 1985-2006 periods and provided as the total change in standardized flow over the period of analysis. For example, for those stations analyzed for 1965-2006, the trend (increase or decrease in standardized flow) over 42 years of record is shown. Data is presented to best represent streamflow. Since peak flows generally occur between winter and spring it was best to start the plot on October 1st and end September 30th. Months are given as a reference at the top of the plots. Closed circles on the plots represent values that are significant at the 95% confidence level; open circles are not. Due to the relatively short period of record for the majority of the sites and limitations to interpreting statistical significance of streamflow trends (Dery, 2009), the following discussion will focus on the magnitude and direction of the trend.

For both periods (1965-2006 and 1985-2006) increasing trends occurred during the winter low-flow period. Changes are most pronounced for Pelly River at Pelly Crossing (09BC001) and Klondike River above Bonanza Creek (09EA003) where streamflow increases from November to February, and into March for the Klondike over 1965-2006. Stewart River at the mouth (09DD003) and the Yukon River above White River (09CD001) had increases, but they were not as persistent.

Temperature and precipitation were also analyzed for trend by pentad. Results are presented in units of ^{o}C change per year for temperature and mm change per year for precipitation for each 5-day period over the time of investigation. Data were not normalized in this case because values from the various stations were not largely different from each other and could be compared without standardization. These trends in temperature and precipitation can provide insight on drivers of changes for streamflow.

Minimum temperature increased in almost every pentad for both stations over 1965-2006. The magnitude of temperature increase was largest in December, January and February with a greater than 0.6 ^{o}C year^{-1} increase in temperature over the 42 year period. Maximum temperatures also increased at almost all pentads most notably over the winter. These increased temperatures could have caused precipitation to fall as rain instead of snow increasing streamflow over this period. The amount of precipitation contributing to snow pack would have been reduced and likely melted faster and sooner, thus increasing spring runoff and advancing the hydrograph. As a result less moisture would have been available in spring and summer, which would reduce runoff. Temperature trends were variable over 1985-2006 and not significant. The majority of the warm years over the last 100 years occurred near the end of the 20th century. Thus, temperature over the 1985-2006 period was warmer over most of the record, but for the 1965-2006 started relatively cool and got warmer later in the record. Trends in 5-day mean precipitation were highly variable in both periods and difficult to interpret.

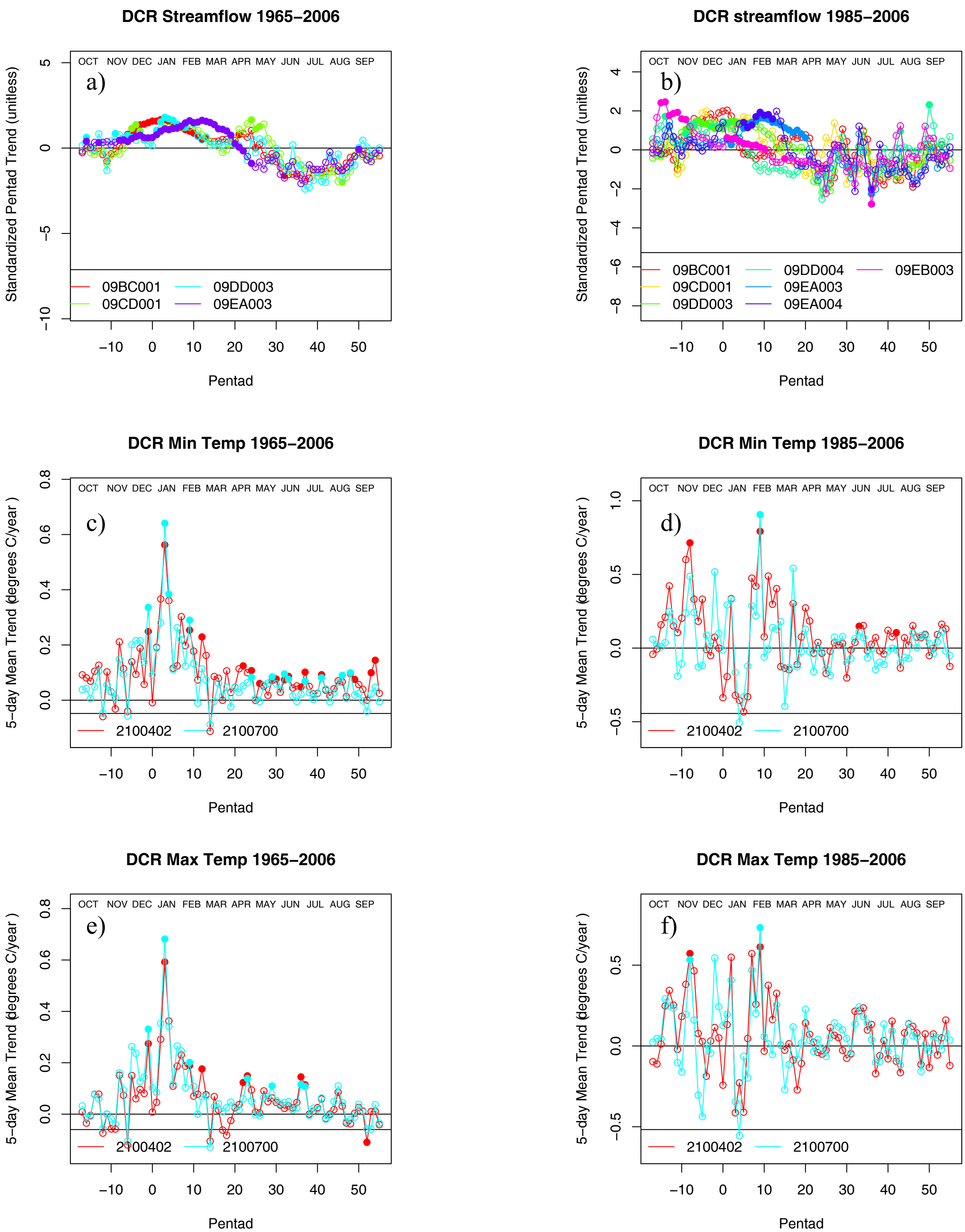

Figure 5-2 - Trends in (a) streamflow expressed in standardized units for (a)1956-2006 and (b) 1985-2006, minimum temperature expressed in °C year^{-1} for (c) 1956-2006 and (d) 1985-2006, and maximum temperature expressed in °C year^{-1} for (e) 1956-2006 and (f) 1985-2006 for 5-day means (pentads). Filled circles denote statistically-significant trends at the 95% confidence level. Source: AHCCD, HYDAT and RHBN data.

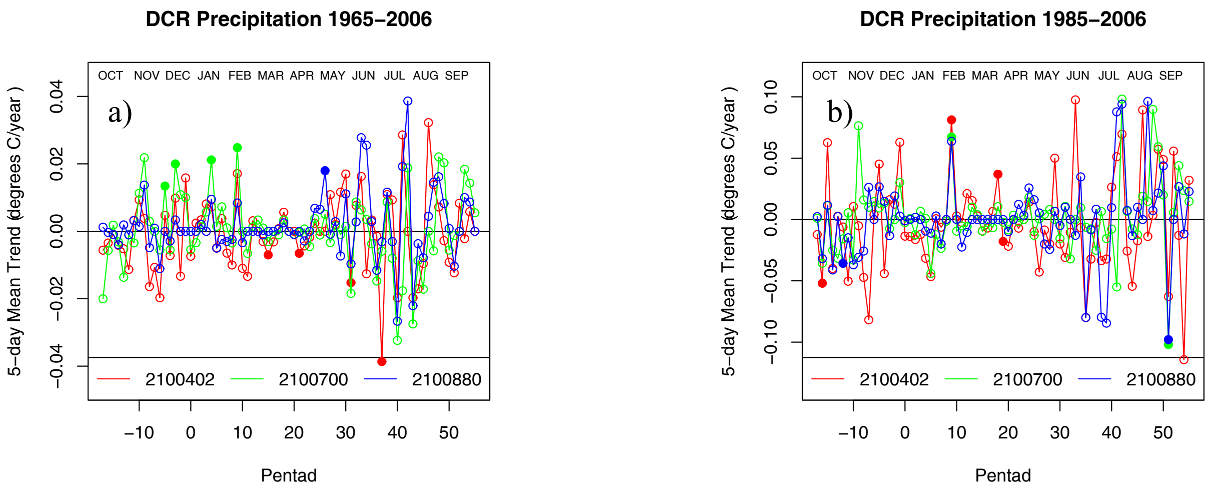

Figure 5-3 - Trends in precipitation for 5-day means (pentads) all expressed in mm year^{-1} for (a) 1956-2006 and (b) 1985-2006. Filled circles denote statistically-significant trends at the 95% confidence level. Source: AHCCD data.

Streamflow in the Dawson City Region will also be influenced by climate change in other areas of the Yukon. For example, the Yukon River has been shown to be strongly influenced by trends in temperature and precipitation at higher altitudes and increasing streamflow contributions have been shown upstream of Whitehorse (Werner and Murdock, 2008). The increased contribution of water to the river has also been attributed to increased snowpack on the Atlin River and a related increased contribution from thickening glaciers in the North Coast Mountains (Schiefer et al, 2007).

6. Future Projections of Climate Change and Uncertainty

Projections of future climate are provided in two forms, box plots and maps. Box plots were generated to summarize the projections of 15 Global Climate Models (GCMs) following two emissions scenarios, A2 and B1. GCMs are numerical representations of the climate system based on the physical, chemical and biological properties of its components, their interactions and their feedback processes. The IPCC A2 emissions scenario is considered to be 'business as usual' in which society continues to burn fossil fuels for most of its energy. The other emissions scenario commonly used is B1 which assumes much less greenhouse gas use globally. Differences between projected climate change impacts across emissions scenarios are not large in the 2050s time frame, but become considerable later in the 21st century (Rodenhuis et al., 2007). For the 2050s, more uncertainty is contributed by the various models than by different emissions scenarios (Rodenhuis et al., 2007). The box captures the 25th and 75th percentiles or 50% of the GCM projections, the horizontal bar within the box indicates the median value of the model projections. Data for the boxplots was produced by the Regional Analysis Tool on the PCIC website using a custom region developed for the Dawson City region[vi]. Boxplots are valuable for showing both the climate change projected by the majority of model runs as well as the level of uncertainty among models.

Regional Climate Models (RCMs) build on the results of Global Climate Models (GCMs) by incorporating elevation, topography, and other physical and dynamic processes at an increased resolution of 45 km. The Canadian RCM output was mapped to show variability in temperature and precipitation projected by climate change within the DCR at a higher spatial resolution than GCMs. The projections shown are from the latest version of the CRCM (version 4), which is forced (through boundary conditions at the edges of its domain – North America) by the ~350km resolution projection from the Canadian Global Climate Model (CGCM3) following the A2 emissions scenario (run 4). However, fewer runs from RCMs are available. For the benefit of exploring the spatial variation in climate change, run 4 from the CRCM4 as forced by the Canadian GCM with the A2, "business as usual" emissions scenario was provided. Results are presented as a difference from the 1961-1990 baseline for the 2050s (2041-2070). The projected shifts in temperature and precipitation in the DCR are summarized below.

6.1. Temperature

Based on the mid-range (25th to 75th percentiles) of the ensemble of 30 GCM projections, annual temperature is projected to become 1.8°C to 2.5°C warmer by the 2050s (2041-2070), compared to the 1961-1990 baseline. Temperature is projected to increase twice as much in winter than summer. For more details see Figures 6-1, 6-2 and Table 6-1. Night-time low (Minimum Daily Temperatures) and day-time high (Maximum Daily Temperatures) temperatures projections indicate similar increases of 2.0°C to 3.5°C (PCIC website Regional Analysis Tool, accessed August 2008).

For the Dawson region and the west-central Yukon, there is a relatively uniform increase in annual temperature projected for the 2050s by the CRCM of 2.5°C to 3.5°C compared with the 1961-1990 baseline. The greatest warming is projected for the winter and is between 4°C to 6°C,

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[vi] http://www.pacificclimate.org/tools/select

with greater temperature increases projected in the region just south of Dawson. These are some of the largest projected increases in temperature for Western North America and are above the average 2.6°C increase projected for BC by the CRCM (Rodenhuis et al., 2007). Summer warming is projected to be between 1.5°C and 2.5°C. For the most part, the CRCM projections fall on the warmer side of those provided for the area by the 15 GCMS following two emissions scenarios A2 and B1 (Figures 6-1 and 6-2).

For the Yukon region, the CGCM3 following the A2 emissions scenario projected changes to temperature and precipitation that were warmer and wetter than the 75th percentile of 30 GCM projections. Thus, it is probable that the CRCM4 results, because they are forced by the CGCM3 following the A2 emissions scenario, are on the warmer and wetter end of a spectrum of results. Further information on RCMs will soon be available from the North American Regional Climate Change Assessment Program (NARCCAP), which has set out to systematically investigate the uncertainties in future climate change projections at a regional level. This will be done by running multiple RCMs with multiple GCMs over North America[vii].

Table 6-1 - Temperature projections for the 2020s, 2050s and 2080s based on 30 GCM projections averaged over the Dawson City region.

Winter Mean Temperature	**2020s (°C)**	**2050s (°C)**	**2080s (°C)**	**Summer Mean Temperature**	**2020s (°C)**	**2050s (°C)**	**2080s (°C)**
Maximum	3.8	5.3	9.0	Maximum	2.2	3.4	5.7
75th percentile	2.4	3.5	5.1	75th percentile	1.1	1.9	3.3
Median	1.3	2.9	4.4	Median	0.9	1.3	2.0
25th percentile	0.7	2.1	3.5	25th percentile	0.6	1.0	1.5
Minimum	-0.7	0.6	2.1	Minimum	0.4	1.0	2.0

[vii] http://www.narccap.ucar.edu/index.html

Table 6-2 - Delta change for the climate stations using the RCM data.

Station	**Dawson A 2100402**	**Mayo A 2100700**	**Pelly Ranch 2100880**
Annual Precipitation 2050s (mm)	502	453	384
Annual Mean Temperature 2050s (°C)	-2.1	-0.4	NA

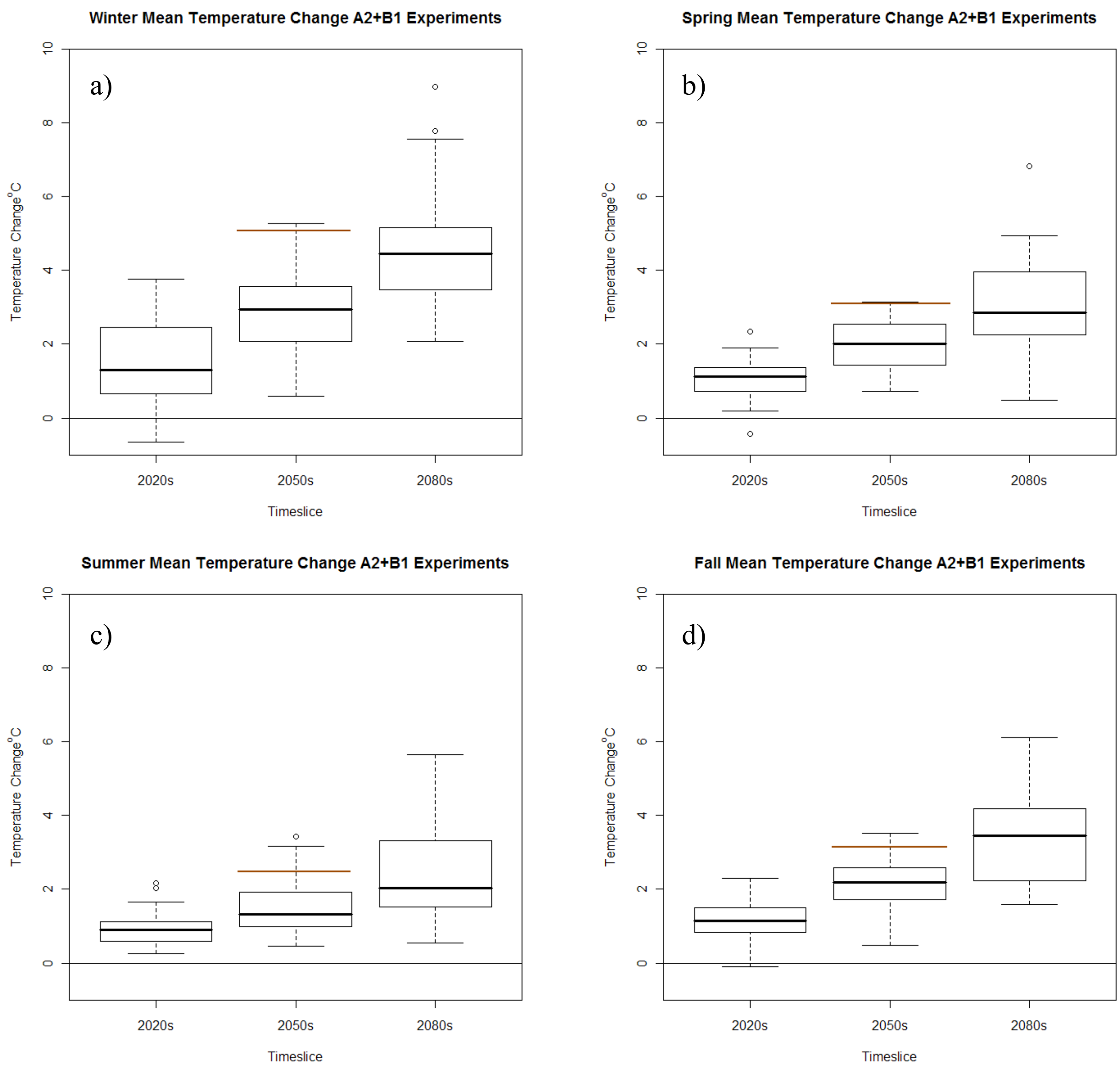

Figure 6-1 - Box plots of GCM projected change in (a) winter (b) spring (c) summer and (d) winter mean temperature for the Dawson City region as compared to the 1961-1990 baseline based on 30 GCM projections that include 15 GCMs, run under the A2 and B1 emissions scenarios. The red line indicates results from run 4 of CGCM3 forced with the A2 emissions scenario over the Dawson City region.

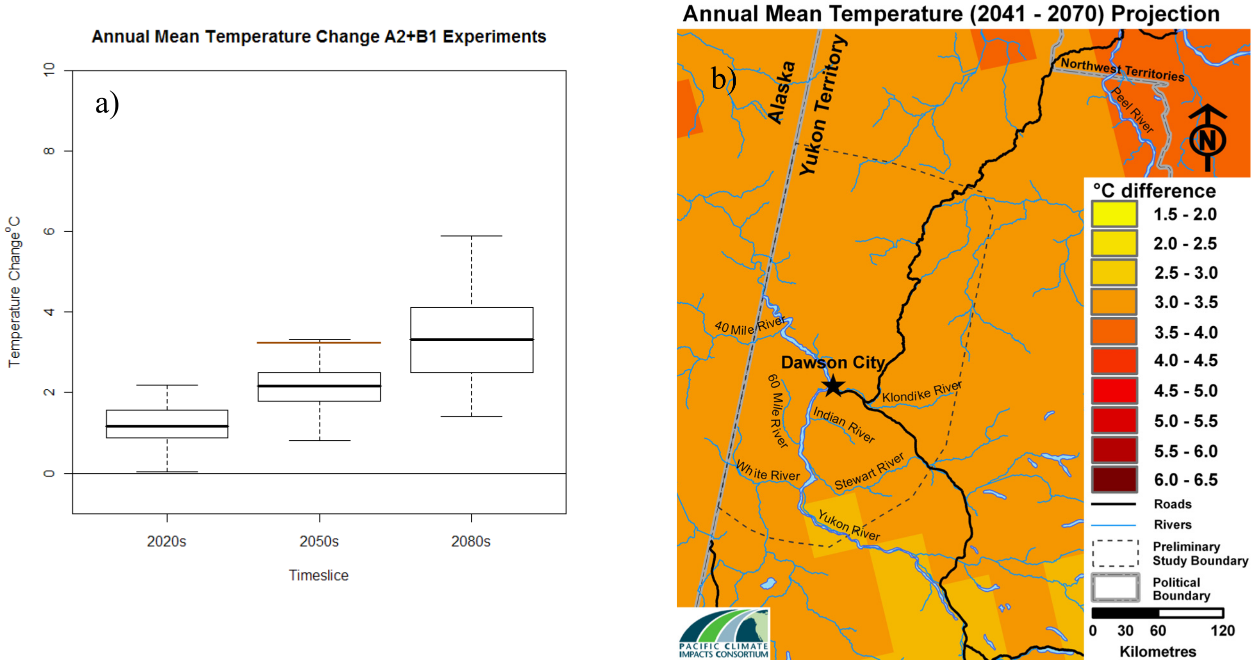

Figure 6-2 - a) Box plot of GCM projected change in annual mean temperature for the Dawson City region as compared to the 1961-1990 baseline based on roughly 30 GCM projections that include 15 GCMs, run under the A2 and B1 emissions scenarios. The red line indicates results from run 4 of CGCM3 forced with the A2 emissions scenario over the Dawson City region. b) Dawson City region 2050s (2041-2070) projected annual mean precipitation anomaly from the 1961-1990 baseline. Source: Ouranos Consortium (CRCM4 forced with CGCM3 following the A2 emissions scenario).

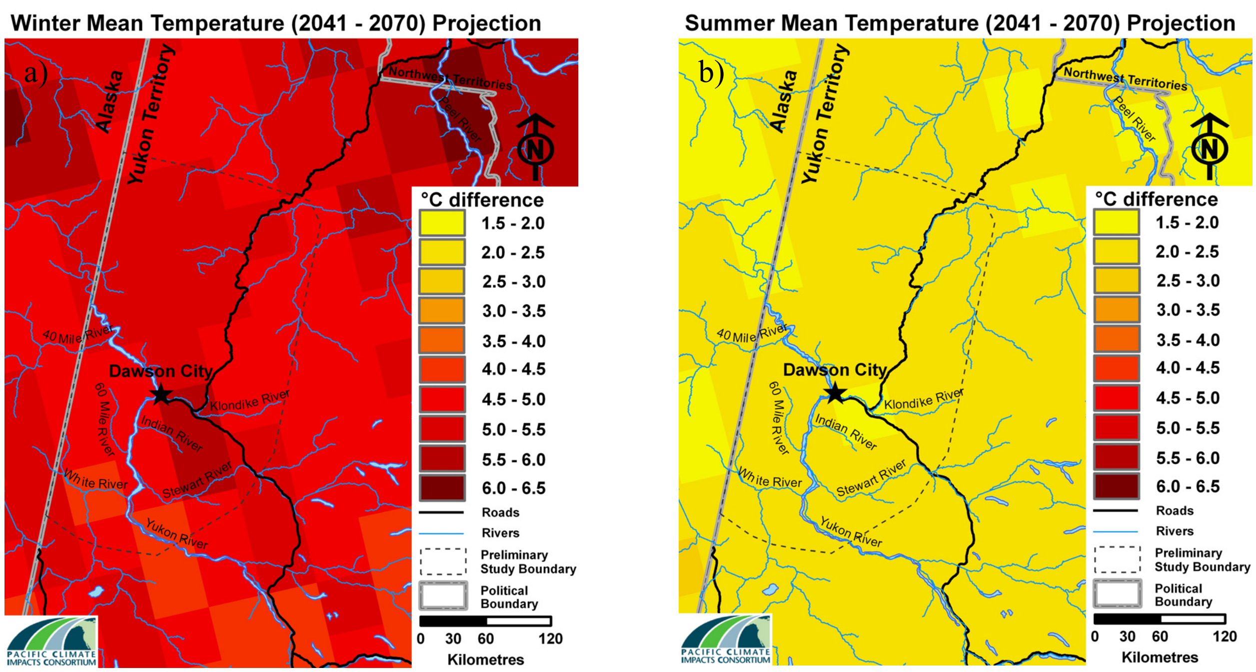

Figure 6-3 - Dawson City region 2050s (2041-2070) projected (a) winter and (b) summer mean temperature anomaly from the 1961-1990 baseline. Source: Ouranos Consortium (CRCM4 forced with CGCM3 following the A2 emissions scenario).

6.2. Precipitation

Based on the mid-range (25th to 75th percentiles) of the ensemble of 30 GCM projections, annual precipitation is projected to increase by 5% to 14% for the 2050s (2041-2070) compared with the 1961-1990 baseline (Table 6-3 and Figure 6-5a). Precipitation is projected by the GCMs to increase slightly more in winter (+6% to +18%) than in summer (+3% to +16%) (Table 6-3, Figure 6-4a and Figure 6-4c).

In the CRCM, annual precipitation is projected to increase by 10% to 40% for the DCR, with the lower end of the range to the north and east of Dawson City. Increases are projected to take place more so in winter than in summer. A 30% to 50% increase in winter precipitation is projected with the higher values falling north-west and south-west of Dawson. Summer projections range from 10% to 30% with slightly higher increase projected for the area south of Dawson City. These changes are more dramatic than those projected to occur south of the Yukon in mid-latitude locations, such as BC (see section 4.2 RCM Projections of Rodenhuis et al. (2007)). Projected rates of warming in the high-latitudes are some of the fastest on the globe (IPCC, 2007).

There is a great deal more uncertainty with precipitation projections than with temperature projections due to the large variability in precipitation over space and in time. Furthermore, the CRCM model used to produce these maps is driven by the CGCM3, which tends to have warmer, wetter conditions when compared to other GCMs. While drought conditions are not currently projected, drought cannot be ruled out as a possibility. Projected changes in the number and magnitude of dry spells should be investigated.

Table 6-3 - Precipitation projections for the 2020s, 2050s and 2080s based on 30 GCM projections averaged over the Dawson City region.

Winter Precipitation	**2020s (%)**	**2050s (%)**	**2080s (%)**	**Summer Precipitation**	**2020s (%)**	**2050s (%)**	**2080s (%)**
Maximum*	26	33	62	Maximum*	15	24	37
75th percentile	13	18	28	75th percentile	9	16	22
Median	8	14	23	Median	5	11	15
25th percentile	3	6	12	25th percentile	2	3	8
Minimum	-6	-4	-4	Minimum	-3	-1	2

*The highest value of winter precipitation for 2080 and 2020, and the second highest value for 2050 were all projected from the GCM gfdl_cm21 A2-run1. The highest value of summer precipitation for 2050 and 2020, and the second highest value for 2080 were all projected from the GCM inmcm30 A2-run1.

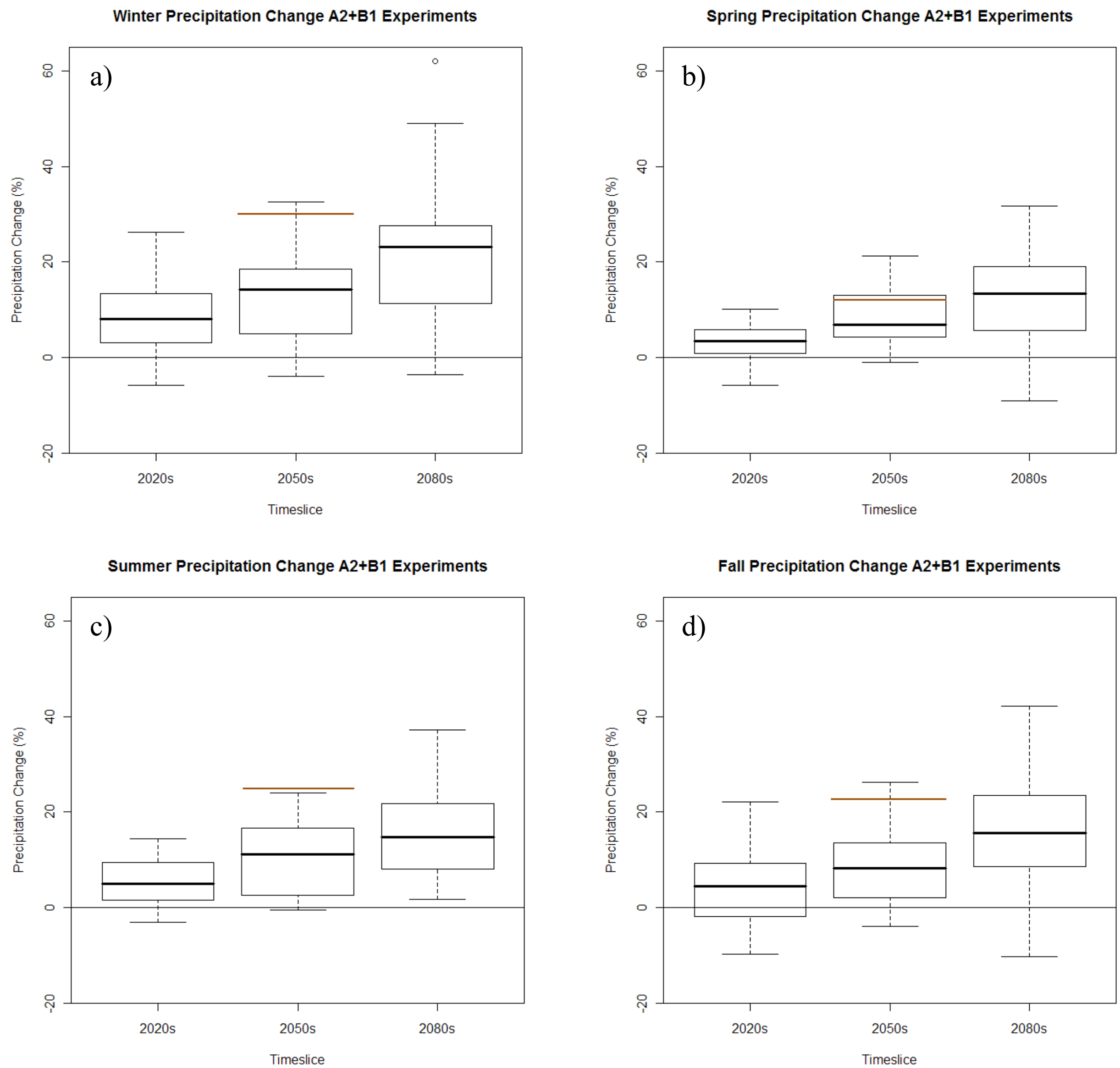

Figure 6-4 - Box plots of GCM projected change in (a) winter, (b) spring, (c) summer and (d) fall mean precipitation for the Dawson City region as compared to the 1961-1990 baseline based on 30 GCM projections that include 15 GCMs, run under the A2 and B1 emissions scenarios. The red line indicates results from run 4 of CGCM3 forced with the A2 emissions scenario over the Dawson City region.

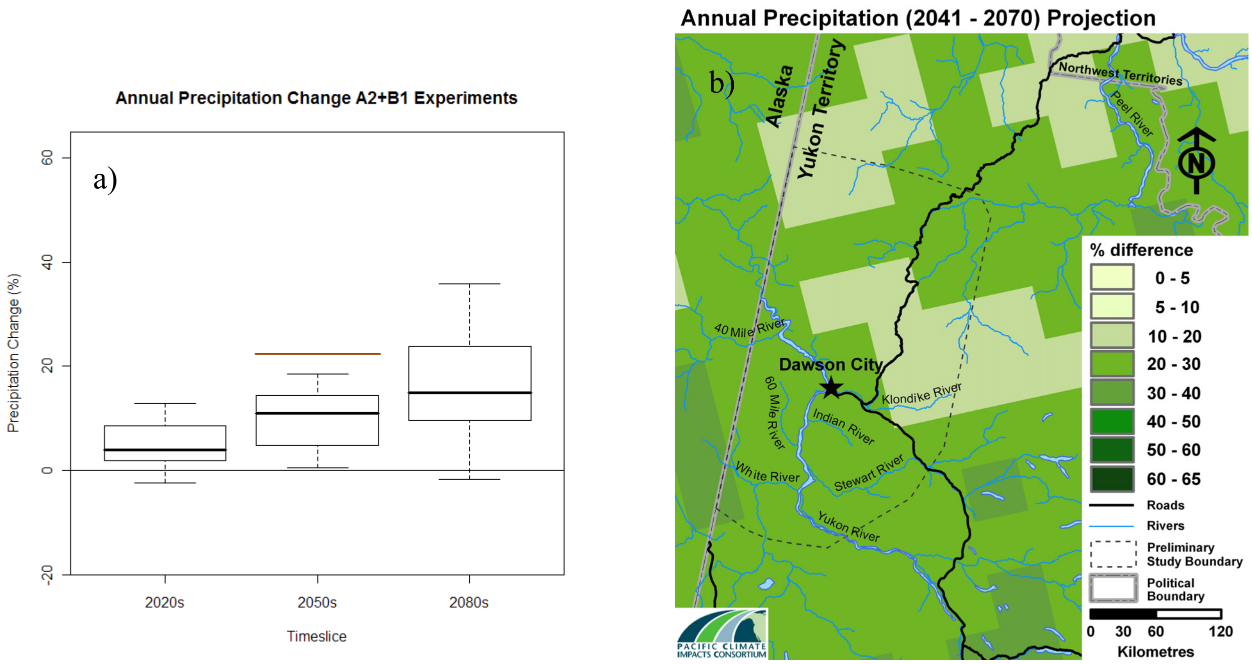

Figure 6-5 - a) Box plot of GCM projected change in annual mean precipitation for the Dawson City region as compared to the 1961-1990 baseline based on 30 GCM projections that include 15 GCMs, run under the A2 and B1 emissions scenarios. The red line indicates results from run 4 of CGCM3 forced with the A2 emissions scenario over the Dawson City region. b) Dawson City region 2050s (2041-2070) projected annual mean precipitation anomaly from the 1961-1990 baseline. Source: Ouranos Consortium (CRCM4 forced with CGCM3 following the A2 emissions scenario).

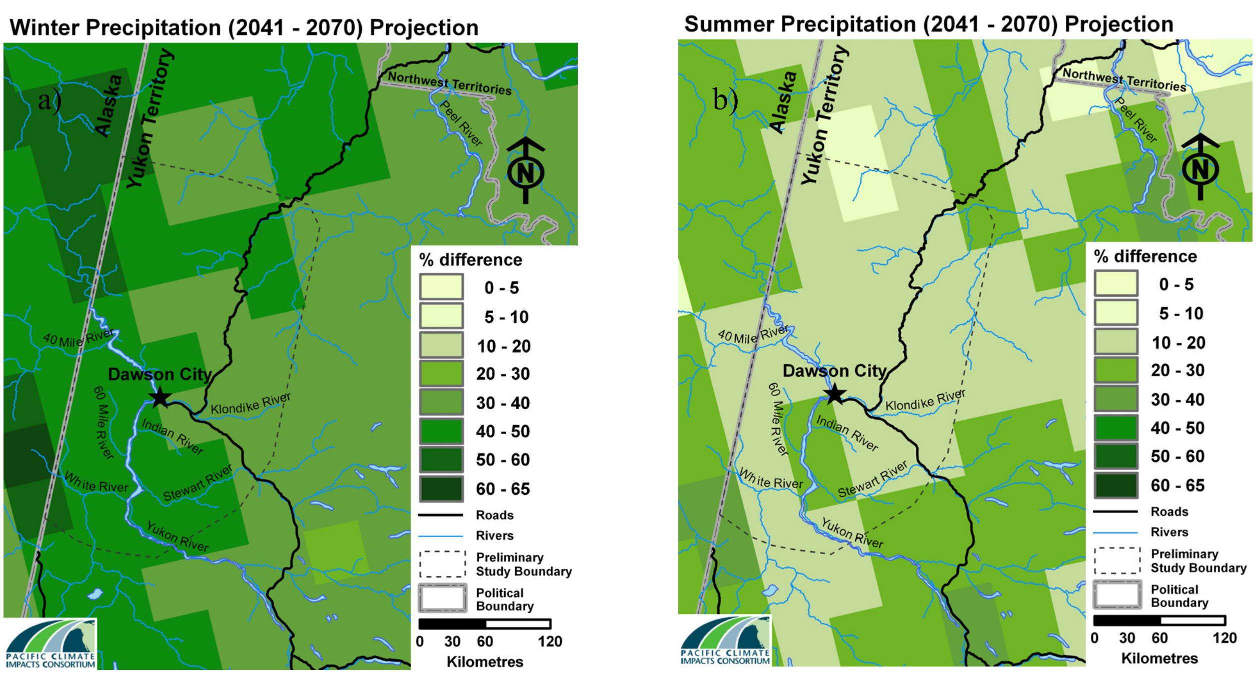

Figure 6-6 - Dawson City region 2050s (2041-2070) projected (a) winter and (b) summer mean precipitation anomaly from the 1961-1990 baseline. Source: Ouranos Consortium (CRCM4 forced with CGCM3 following the A2 emissions scenario).

7. Limitations and Uncertainties

Evaluation of past trends is limited by the data available for investigation. In the DCR, there is paucity of data, and of the stations that are available, there is some disagreement in results that could be related to station movements over the period of record. Trends are influenced by modes of climate variability, of which only two were investigated here. Several other modes exist such as the North Atlantic Oscillation which has been shown to influence climate in the Arctic regions by several other studies. Although the impact of climate variability on trends was noted in the discussion of the trend results, efforts have not been made to decipher which parts of the trend are due to climate change and which are due to climate variability directly. Impacts of climate change on streamflow are difficult to establish given the limited metadata available on the watersheds monitored by the assessed gauges. More information on land use changes and glacier area would be invaluable to better understanding the given results.

Future projections were presented for several coarse-scale GCMs and with one higher resolution RCM for the region. Spatial variability in climate change over the DCR was explored with the RCM, but the boxplots of the GCMs helped to assess the uncertainty for projections. Multiple GCMs are more readily available than multiple RCMs and since the RCM is driven by the GCM at the boundary many of the characteristics of a given GCM, such as being warmer and wetter may be carried through to the RCM. It is important to evaluate the range from several projections to reflect uncertainty in GCMs and emissions scenarios. By the 2050s, the emissions scenarios do not have largely differing GHG concentrations, thus most of the uncertainty in projections originates from the GCMs. By the 2080s, concentrations of GHGs vary widely by emissions scenario and more of the range in projections is due to discrepancies between GHG concentrations.

8. Conclusions

In spite of these limitations, the results point to several conclusions. Over the past, climate change in the DCR has taken place at rates greater than more southern regions of Canada. In many cases, there is anecdotal evidence to support that trends have taken place at these accelerated rates. Trends in the past support that increases in GHG have resulted in increased temperatures in this region of the world. Projections for the future increase in temperature are greater than those for regions farther south. Changes in winter temperatures are greater than in any other season in the past and in the future. Minimum temperature has increased more than maximum in the past, but projections are for mean temperature only. Streamflow increased over the winter and spring period and decreased over the summer and early fall for many rivers.

Further work should be carried out to assess the natural climatic variability of the region and to establish the signal of change as compared to the background “noise”. Increased monitoring would assist with establishing the climate of the region and assessing its changes.

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