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Hydroclimatological Trends in the Kananaskis Valley

Geog 490: Topics in Physical Geography

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Abstract

The Kananaskis Valley was examined on a monthly and annual scale for evidence of changes in climate that would have hydrological implications. Two stations, Kananaskis Field Station (KFS) (1939-2007) and Pocaterra (1976-2007) provided direct observations while stations in the Marmot Creek area (circa 1966-1987) were extended by linear regression with KFS. Trend analysis was calculated using the non-parametric Mann-Kendall test. Air temperature increased significantly with the greatest increases observed quantitatively in the minimum daily temperature and temporally during the winters. Precipitation showed few trends with time and were hard to correlate between stations. A technique to separate rainfall and snowfall was used to differentiate precipitation in Marmot Creek based on mean daily air temperature but was unsuccessful due to the large temporal scale of the extended data and coarse nature of calculated statistic. Stream flow data for Middle Creek (1963-1986) was extended up to 2007 based on linear regression to Marmot Creek. Trend analysis showed that June, July, peak spring flow and May to October mean flow all decreased significantly with time while October stream flow increased. Flow in other months as well as the timing of the spring peak were not observed to change with time. Using Kendall's tau$_b$, the PDO was found correlated to temperature but not precipitation. The correlation was weaker after 1975. Other work has shown that these observed trends are consistent with anthropogenic climate change though some of the inter-annual variation can be attributed to the Pacific Decadal Oscillation (PDO). The temporal trends of the Kananaskis Valley are consistent with anthropogenic climate change. Hydrologically the greatest observed impacts are resulting from increasing temperatures and decreasing stream flow.

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Introduction

Climate change is a very current and prevalent topic. Manny climate change studies have been undertaken but few in the context of looking at the alpine hydroclimatological changes in the Alberta Rockies. This is partly due to the lack of instrumental records at high elevations with necessary recording duration. This study addresses this gap by using data from the Kananaskis Valley and extending the intermittent dataset from the Marmot Creek research basin. The study provides information that would be a direct benefit to government agencies relating to parks, forestry, water management, energy and environment as well as affecting private sector industries such as tourism, ranching and farming.

Objectives

There are three primary objectives that this study is meant to address:

1. To examine the long term climate records from the Kananaskis Valley to determine if there are temporal trends.
2. To reconstruct the climate and hydrometric data set of Marmot Creek Research Basin to determine if there are temporal trends due to changing climate.
3. To analyze and discuss the hydrological significance of the observed trends.

Literature Review:

In light of recent climate change research a detailed analysis of our past climate is crucial to our understanding of current and future processes. Canada is especially vulnerable due to its high latitude region where the climate change signal is predicted to be relatively stronger than the global signal (Zhang et al., 2000). Globally the IPCC (2007) has reported that the average temperature increase has been 0.74°C ± 0.18°C over the last century. Attribution of this increase has been the focus of much intensive study and has been tied to a rise in anthropogenically produced greenhouse gases such as CO_2 (IPCC, 2007). Non-anthropogenic influences also affect climate records as has been shown with the Pacific Decadal Oscillation (PDO) (Stewart et al., 2004). Among other aspects, rising temperatures are thought to impart an influence upon precipitation patterns as well as evapotranspiration. Thus in terms of hydroclimatological changes these impacts are expected to manifest themselves as changes in temperature, evapotranspiration , precipitation patterns and the integrated response of these changes over a basin as stream flow (Yue et al., 2003).

Most climate studies use the instrumental record to do analyses; unfortunately a lack of high altitude stations exist in the Rockies. The data sets that do exist were only initiated at time of western expansion into the Rockies in the early 1900's and include Banff, Lake Louise, Valemount, Golden and Jasper (Luckman, 1997). The elevations of these stations relative to local relief do not provide high altitude alpine representation as they all occur in valley bottoms (Luckman, 1997). An example is Lake Louise (1530m) which is located on the valley bottom with local relief reaching elevations nearing 3600m (Luckman, 1997). None of these long term records exist above the tree line (Luckman, 1997). Thus long term records representative of alpine regions are few and far between. Proxy studies have been conducted but their main drawback has been that calibration data does not exist at high elevations. The lack of high altitude stations is a concern due to the potential for prediction of climate impacts to become biased to lower elevations even though much of the hydrologic implications of climate change in the mountains occur above the tree line in the snowpack (Lapp et al., 2005).

Anthropogenic Forcings of Climate

The anthropogenic effect of greenhouse gas (GHG) emissions upon atmospheric composition has been implicated for recent climate change. The addition of greenhouse gases has led to a reduction of the earth's ability to reradiate energy back to space resulting in an enhanced greenhouse effect (Hardy, 2003). The primary GHG in terms of atmospheric composition, $CO_{2,}$ increased from a pre industrial level of 280ppm to 387ppm at the end of the 20th century (Hardy, 2003). This increase in radiative forcing, approximately 2.45 watts/m^2, has caused the thermodynamics of the global climate to change (Hardy, 2003). Large scale energy redistribution patterns have changed and are amplified to account for this change in energy. The high latitude locations are at a greater risk, as to reach thermodynamic equilibrium these regions must absorb more energy (Hardy, 2003). The polar amplification of energy redistribution results in large changes to components of climate such as the temperature and hydrologic cycle in places like Canada (IPCC, 2001).

Land use changes are often associated with changes in climatic indices. A common effect of land use change in terms of cities is the initiation of the urban heat island effect. Essentially, the physical disturbance of natural land cover and the construction of buildings which resist air movement and absorb more heat results in rising temperatures (Hardy, 2003). This signal has often been mistaken for global warming. As the Kananaskis Valley is not urbanized this effect does not need to be addressed in this study. In terms of actual land use changes that may affect trends in the Kananaskis, considerable logging was undertaken in Marmot Basin (Swanson et al., 1986). The reduction in tree cover reduces the interception of snow and its subsequent sublimation. As a result, the snowpack in clearings is much greater than in the forested regions and results in an increase in snowmelt contribution to stream flow (Swanson etal., 1986). This has changed stream flow for the affected portions of the basin. No other significant land use changes that could confuse the anthropogenic climate change signature have occurred in the valley.

Non-anthropogenic forcings of climate

Within the climate system, variations and trends exist separate of anthropogenic forcings. For the region of western North America one of the largest of the forcings is the Pacific Decadal Oscillation (PDO), during which the sea surface temperature goes though warm and cool phases. During a warm phase the western Pacific cools and the eastern portion warms, and in a cool phase the opposite occurs (Mantua, 2001). The oscillation affects atmospheric circulation and in warm phases results in above average temperature and below average precipitation in North America and vice versa in a cool phases (Mantua, 2001). These are effects are causally linked to the size of the spring snowpack, timing of melt and rain-snow ratios (Stewart et al., 2004; Knowles et al., 2006). The periodicity of this oscillation is on a decadal cycle of about 15-30 years with a switch to a cool phase observed in 1947 followed by a warm phase starting in 1976 (Mantua, 2001). The PDO trends are not independent of the climate warming trends and do not account for all of the observed climatic anomalies (Stewart et al., 2004; Knowles et al., 2006).

Temperature

The most direct and easily quantified variable in a changing climate is temperature and as such has been the subject of many statistical analyses. Observed data suggests that in the 20th century the average warming in Canada has been between 0.5-1.5 °C (Zhang et al., 2000). While mean temperature has been increasing the distribution of increases between minimum and maximum temperatures has not been uniform. (Bonsal et al., 2001; Vincent & Mekis, 2004; IPCC, 2007) On a daily basis the number of extreme minimum temperatures is decreasing significantly while the number of days that are experiencing extreme maximum temperatures has experienced a smaller increase or not at all. Essentially the climate was found to be becoming "less cold". In actual changes this is manifested by an increase in the number of frost-free days by 15-20 days (Vincent & Mekis, 2004). Alternatively (Zhang et al., 2000) found that while minimum temperature was observed to increase in the first half of the century, maximum temperature did not, and the second half of the century had magnitudes of increase between both variables being the same. Studies of Canada's climate consistently show a warming climate. A study of the data from Calgary and the Elbow Ranger station, in the foothills of the Alberta Rockies near the Kananaskis Field Station, observed an annual mean temperature increase of 0.056°C/year or 2°C in the last 40 years (Valeo et al., 2007).

The effect of minimum and maximum temperatures increasing at different amounts has been hypothesized to lead to a decrease in the daily temperature range (Zhang et al., 2000; Bonsal et al., 2001). Analyses by Zhang et al., (2000), Bonsal et al., (2001) and Vincent & Mekis (2004) have shown that statistically significant decreases in the temperature range in Canada have been observed. The decrease in temperature range is strongly correlated to an increase in cloud cover which has been estimated to have increased by 2% globally (IPCC, 2001) and over the United States by 10% over the last century (Pearce, 1994). The linkage is due to the effect that clouds have in tempering warming during the day by reflecting shortwave radiation and at night absorbing and reemitting long wave radiation back to the atmosphere and earth (Hardy, 2003). The effect of clouds directly decreases the daily temperature range though globally changes in it have not been observed since 1974; although trends are highly variable between regions (IPCC, 2007).

The greatest change in temperature has been found to occur in the winter months of the northern hemisphere (IPCC, 2001; Michaels et al., 2000). (Michaels et al., 2000) found that over 78% of the observed warming in the last century was observed during the winter months and spatially isolated on 26% of the global land surface in the northern hemisphere. This is due to the effect that increasing water vapour has on the longwave emissivity of cold dry air. A logarithmic relationship between atmospheric emissivity and water vapour exists (Michaels et al., 2000). A small addition of water vapour results in a greater emissivity increase at lower temperatures than higher at temperatures, leading to more energy being trapped, per unit of water vapour added. Thus a water vapour-radiative forcing positive feedback loop exists as greater temperatures lead to increased evaporation (greater water vapor) (Dingman, 2002). The effect is compounded by northern regions experiencing anticyclones which disconnect the air masses from atmospheric circulation for periods of time, resulting in cold air masses not mixing with the atmosphere and warming greater relative to other regions (Michaels et al., 2000). Alternatively, a study of warming in Canada showed the greatest changes in temperature are occurring in the southwestern portion of the country during the spring and summer (Zhang et al., 2000). The disagreement between these studies may be due to use of different data sets. (Zhang, et al., 2000) used observed climate station data while (Michaels et al., 2000) used gridded climate data. Michaels et al., (2000) does not explicitly define the nature of warming southwestern Canada and consequently southwestern Canada may represent an anomaly from the global trends. A study of Alberta foothills, near Kananaskis, supports the observation of Michaels et al., (2000) in that it showed that the greatest increases in temperature occurred in January, March, April, July and August (Valeo et al., 2007). As is exemplified here, a regionally specific analysis can identify trends that are independent of clearly defined larger scale trends.

Precipitation

The effect of a changing climate upon precipitation is less well understood than the effect on temperature, as it is indirectly a consequence of increased temperatures, although trends have been identified for precipitation (Zhang et al., 2000). An increase in temperature leads to an increase in evapotranspiration, resulting in more water vapor present in the atmosphere and subsequently an increase in precipitation (Dingman, 2002). As noted earlier, cloud cover is increasing, which is a direct result of increased evaporation and water vapor in the atmosphere (Dingman, 2002). In terms of precipitation, this acceleration of the hydrologic cycle is believed to be responsible for an increase in precipitation of about 0.5-1 % per decade globally (IPCC, 2007). The increase is expected to be greater in mid to high latitudes due to the polar amplification effect, whereby the global atmospheric circulation transports moisture and energy pole ward in greater amounts due to the altered thermodynamics resulting from the unequal distribution of incident solar energy (Hardy, 2003).

Over the last century Canadian precipitation south of the 60th parallel been estimated to have increased by one analysis between 5-35% (Zhang et al., 2000) and another by 13% (Groisman & Easterling, 1994). Problems exist in the quantification of this trend due to the highly variable nature of precipitation and the inability of statistical tests to deal with large variation. This is a consequence of an inverse relationship of the power of the chosen statistical test and the variation in the time series (Yue et al., 2002). Nonetheless southern Canada over the last century has been getting gradually wetter (Zhang et al., 2000). Analysis of several indices by Vincent and Mekis (2004) has shown that over the last half century the number of days with precipitation has increased by 20-40 days. This substantial increase in rainy days has been offset by a reduction in extreme rainfall events occurring. Essentially while more days of precipitation occurred, a proportional increase in total precipitation was not observed. In southern Alberta, at the Calgary and

Elbow Ranger Station, precipitation has not shown trends on an annual scale but rather on the monthly scale with increases observed in the winter, early spring and fall (Valeo, et al. 2007).

Rain to Snow Transition

A common hypothesis of hydroclimatological literature in regards to climate change is the effect that warming temperatures will have on the preferential separation of precipitation into rainfall rather than snowfall. Even if precipitation does not increase appreciably, the effect that the separation of precipitation that would normally fall as snowfall into rainfall will have major implications for snowmelt dominated hydrological systems (IPCC, 2007). These could include smaller snowpack's leading to earlier snowmelt and reduced stream flow. (Dingman, 2002; Lapp et al., 2005).

The segregation of precipitation into either snow or rain has been shown to be a function of both temperature and humidity (Auer, 1974), although when solely relating form of precipitation to temperature, snow never occurs above 6°C while rain never forms below 0°C (Auer, 1974). Work by (Auer, 1974) has shown that the critical temperature (Tcrit), where the probability of precipitation falling as rain or snow is equal, is 2.5°C. Auer's (1974) work was conducted across the contiguous United States and may or may not have some correlation geographically with the processes in the Kananaskis Valley. Work by Olafsson & Haroldsdottir (2003) in Iceland has shown that Tcrit is related the stability of the atmosphere with lower values associated with stable atmospheric conditions and high values associated with unstable atmospheric conditions. The use of humidity and temperature data to separate precipitation phase has been shown to be physically and operationally superior. Marks and Winstral (2007) found that a dew point temperature of 0°C in a small Idaho mountain basin provided a robust separation of precipitation phase. Dew point temperatures, during a precipitation event, below zero indicated snow while above zero indicated rain. More specifically the wet/ice bulb temperature has also been shown to provide an even better separation technique as this is the temperature that the precipitation "feels" (Fuchs, 2006).

The process of the rain-snow transition is due to the vertical temperature profile of the atmosphere and to humidity. This is best represented by the wet bulb temperature. As the necessary data for wet bulb temperature calculations are not always available observed surface temperatures can be used (Auer, 1974). Precipitation when formed in the atmosphere is predominantly snow, rain rarely forms directly, as temperatures at high altitude are quite low due to the cooling effect of the lapse rate. As it falls and nears the ground if it enters an air mass greater than 0°C it begins to melt (Dingman, 2002). If the air temperature is high enough or air parcel large enough it may melt completely into rain by the time it reaches the ground and if not will fall as either a combination of rain/snow or just snow (Dingman, 2002). The temperature near the ground does not provide insight into the depth of the warm air mass or humidity. The result is that snow and rain can occur at the same time and a transition temperature range as defined by (Auer, 1974) exists.

The effect of rising temperatures due to climate change suggests that more precipitation will fall as rain. (Zhang et al., 2000) examined this concept by analyzing the ratio of snow to total precipitation over the last century and found that over southern Canada the ratio had a gradual positive trend. This increase was attributed to the increasing precipitation during winter which falls as snow when the temperature is not near the Tcrit. During the spring season, though, the ratio of snowfall decreased (Zhang et al., 2000). In the transition between winter and summer, temperatures are closer to Tcrit and thus sensitive to changes in temperature in regards to segregation of snow. Another analysis of the ratio of snow to total precipitation by Vincent & Mekis (2004) shows that the ratio is decreasing over much of Canada on an annual basis over the last century. When analyzed in light of observations of areal extent of snow cover in the northern hemisphere, there is agreement as extent has decreased about 10% with the decreases having statistically significant correlations with land surface temperatures (IPCC, 2001). The city of Calgary has seen a significant change in precipitation segregation as rain has increased while snow has decreased (Valeo et al., 2007). The effect of a warming climate is evident upon the rain snow transition as less precipitation is falling as snow though regional variations do exist.

Stream flow

The variability of a basin's stream flow is a result of the integrated response of a basin to changes in climate, namely temperature and precipitation. (Zhang et al., 2000) While the stream flow is an integrated response it is not a simple response. Wigley & Jones (1985) found that stream flow changes are: more sensitive to changes in precipitation than evapotranspiration; the relative change in runoff is greater than a relative change in precipitation; and runoff is more sensitive to climatic changes in arid regions than humid regions. As well, (Dingman, 2002) states that snowmelt contributes more effectively to stream flow than rainfall. The hypothesized increased precipitation may increase the amount of stream flow, negating the effect of increased evapotranspiration and leading to increased flows. The relative changes of stream flow as a result of a 1-2 °C increase in temperature is not expected to have much effect while the same change in precipitation (1-2%) will result in up to a six fold change in relative stream flow (Dingman, 2002). These broad generalizations have merit but observed regional changes are more complex.

Conclusive studies by Burn & Elnur (2002) have shown that in Canada, hydrological variables such as stream flow are related to meteorological variables and mirror changes in them. However, as explored earlier, temperatures and precipitation are not changing uniformly. The current state of research points to decreasing flow volumes in the south of Canada on an annual basis (Zhang et al., 2000). In a study by Burn & Elnur (2002) these fluctuations were attributed to changes in temperature and precipitation as would be expected. The specific response of Canadian stream flow may be explained by the greater change in temperature, leading to increased evapotranspiration that is not matched by an increase in precipitation. Though inter-seasonal variations from this generalization do exist in spring flows in southern Canada, March and April have been seen to be increasing while the rest of the months in the year are decreasing (Zhang et al., 2000; Rango & Katwijk, 1990). This anomaly is because snow packs are beginning to melt earlier in the spring season, leading to stream flow in periods where there previously was not any melt (Rango & Katwijk, 1990). The earlier melts result in less water to maintain stream flow levels in later portions of the year (Rango & Katwijk, 1990).

Spring stream flow timing has also been extensively studied and has been shown to be sensitive primarily to temperature (Burn, 1994; Stewart et al., 2004). This is due to the positive feedback of the melt process with energy input; an increase in energy input produces a corresponding increase in snowmelt and stream flow production (Dingman, ,2002; Stewart et al., 2004; Lapp et al., 2005). As energy becomes available earlier the peak correspondingly occurs earlier. Even with an increase in precipitation, the rising temperature will reduce the proportion of snow falling, leading to smaller snowpacks as has been observed by (Stewart et al., 2004; Lapp et al., 2005). In a study of western Canada, over half of all sites studied showed an earlier peak in spring runoff timing (Burn, 1994). Southern B.C. has also experienced a significantly earlier snowmelt due to high spring temperatures (Zhang et al., 2000). Correspondingly, the peak flows have also been observed to decrease as a shorter accumulation period for an already reduced snowpack provides less snow available for snow melt and stream flow (Stewart et al., 2004).

The literature to date of the effects that a changing climate will have on have on Western Canada alpine environments, of which the Kananaskis Valley is considered representative, has detailed significant changes in terms of hydroclimatological indicators. Rising temperatures could lead to an enhanced hydrological cycle as evaporation increases. The increased atmospheric water vapor from evaporation could reduce the temperature range, increases precipitation. As well, precipitation has a greater probability of falling as rain as temperature increases, resulting in smaller snowpacks. These features, along with an earlier spring melt, can reduce the amount of stream flow on a monthly and annual basis. Attributions of the inter-annual trends can be partially attributed to the PDO as well as long term anthropogenic forcings. The Kananaskis Valley climate is expected to show some of these trends though not all general trends may be discerned in a regionally specific study.

Data and Methods

Study Area

The Kananaskis Valley, Figure 1, is located approximately 70 km west of Calgary in the Front Ranges of the Alberta Rockies. It is designated as a provincial recreation area and as such few large scale commercial and industrial operations are present. The valley is a destination for hiking, paddling, golfing and camping. Other than the Nakiska Ski Area, Kananaskis Village, hydro power stations and other park facilities there are no other activities which have significant effects upon the valley.

The vegetation is typical of a subalpine valley as it is predominantly montane forest. The forest species vary and include, but are not limited to, lodgepole pine, Engelmann spruce, subalpine fir and alpine larch (Swanson et al., 1986).

The surficial geology is dominated by well drained glacial tills. The depth of these unconsolidated materials varies from zero to 18 to 20m in the lower confluences of the valleys (Beckstead & Veldman, 1985). A consequence of the unconsolidated valley bottom is that 98% of stream flow contribution is from subsurface flow (Beckstead & Veldman, 1985)

The climate of the Kananaskis Valley using the Koppen classification falls under the humid continental category (Beckstead & Veldman, 1985). This means it has long cold winters and cool wet summers. Referencing available data from Environment Canada (http://climate.weatheroffice.ec.gc.ca/climate_normals) for the Kananaskis Field Station (KFS), the warmest month, July, on average is 14.1°C while the coldest month, January, has a mean temperature of -7.5 °C. The temperatures, though, are quite variable with extremes of 33.9°C and -45.6°C being recorded. The mean annual precipitation is 638mm. In this region Chinooks, are common during the winter months and can significantly affect the local climate and hydrology due to their warm and dry nature. Chinooks, also known as Föhn winds, are defined as air masses that cool at the wet adiabatic rate and precipitate completely on the windward side of mountain due to the orographic effect and subsequently warm at the dry adiabatic rate on the lee ward side (Strahler 2007). During the period of December to February, on average 29 days have a mean temperature above 4.5 degrees Celsius (Beckstead & Veldman, 1985).

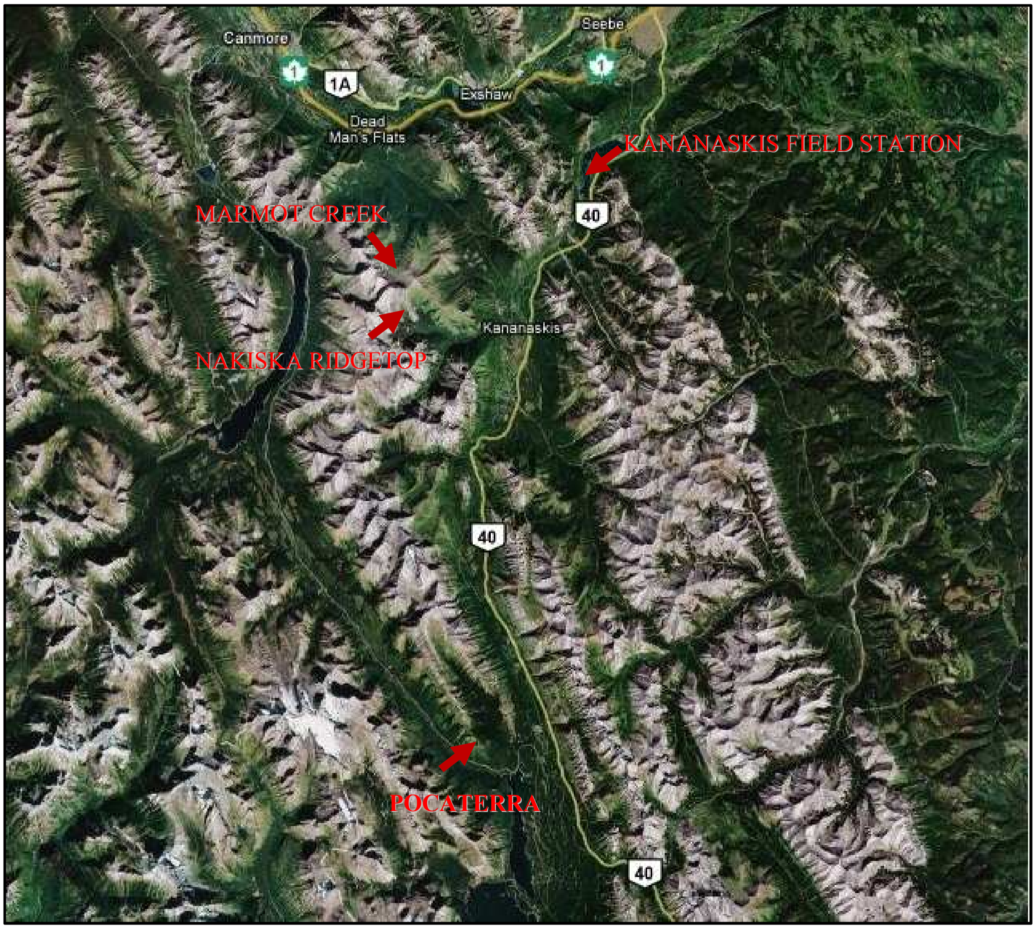

Figure 1: Kananaskis Valley Station Locations, courtesy 2008 Google-Imagery

Station Selection

Within the Kananaskis Valley over the last half century many climate and hydrometric stations have been installed and removed. In order to complete the required analysis the station selection was limited to the stations with the longest continuous records. In this regard none of the fire lookout records were used as they only operated in summer months. The following stations were selected:

Kananaskis (Environment Canada ID 3053600)
Located at the Kananaskis Field Station (KFS), it is operated under contract to Environment Canada. It is located in the foothills adjacent to the entrance of the valley and as such is not always affected by the same weather patterns as those in the valley.

Pocaterra (Environment Canada ID 3053604)

Pocaterra is located within the Kananaskis Valley near the outlet of the Lower Kananaskis Lake. It is operated by Environment Canada and is located in the valley bottom 44 km south of KFS.

Nakiska Ridgetop (Environment Canada ID305MGFF)

This station, operated by Environment Canada, is located on the alpine ridge above the Nakiska Ski Area. Relative to KFS, it is located 14 km to the south west. It is at a higher elevation than any other station considered and provides insights into the climate of the upper elevations.

Marmot Creek

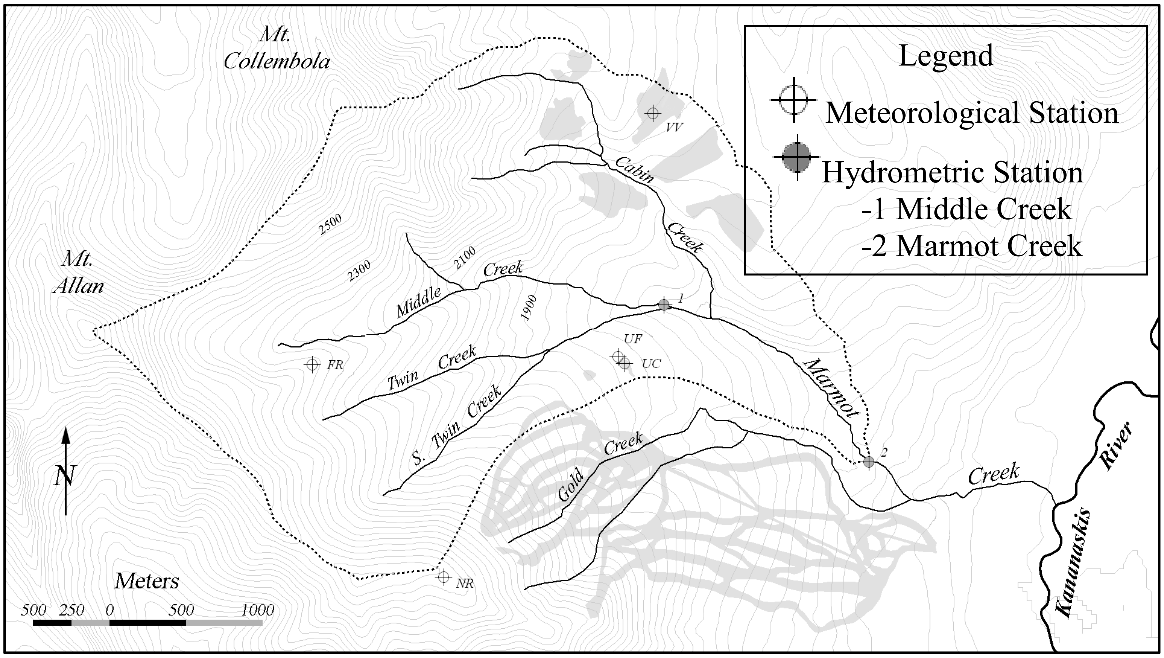

Figure 2: Marmot Creek Instrumentation courtesy Chris DeBeer

† Historical Station locations relatively correspond to recent station locations (TN1 and FR, CB5 and VV, CN5 and UC/UF)

Marmot Creek, see Figure 2, has the reputation of being the most heavily instrumented basin in the Canadian Rockies though with a gap in data collection from 1986 to

2005(Swanson et al., 1986). Relative to the position of Nakiska Ridgetop, it is in the basin immediately to the north. It covers an area of approximately 9.4 km^2 and ranges in elevation from about 1500m to 2800m (Beckstead & Veldman, 1985). The basin was the focus of an intensive research program between 1962 and 1986 with the objective, by use of forestry practices, to increase the water yield (Swanson et al., 1986). As such, two of the three sub basins, Cabin Creek and Twin Creek, had extensive logging. On Cabin Creek a traditional clear cut operation was undertaken in 1974 and on Twin Creek a honeycomb pattern (1 tree width clearings) cutting program was conducted between 1977-1979 (Beckstead & Veldman, 1985). The result of these investigations is a considerable data set of climate as well as hydrometric data from the period. Three climate stations were selected from within Marmot Creek.

- Confluence 5 (CN5) located at the confluence of Twin and Cabin Creek in the sub alpine forest.
- Cabin 5 (CB5) located within Cabin Creek sub basin.
- Twin 1 (TN1) located on Fiserra Ridge near the tree line

As well as climate stations, hydrometric stations were also considered. The Water Survey of Canada (ID 05BF016) installed a water gauge on Marmot Creek near the mouth of the basin in 1962 (Beckstead & Veldman, 1985). Its total drainage area is 9.1 km^2. The unaltered sub basin, Middle Creek, was used as a control for the harvesting program and was gauged above the confluence to Twin Creek draining an area of 1.76km^2 (Beckstead & Veldman, 1985)

Starting in 2005, another research program was initiated by the University of Saskatchewan's Centre for Hydrology in the basin as part of the work of the IP3 network. Of the stations installed in the basin only the Upper Clearing (UC), Upper Forest (UF), Vista View (VV) and Fiserra Ridge (FR) stations were selected due to their spatial proximity to the historic climate station locations of CN5, CB5 and TN1.

Data Sources and Quality

The data for the Kananaskis, Pocaterra and Nakiska Ridgetop stations were downloaded from the online Environment Canada Climate Data Archive http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html and as such conform to Environment Canada data quality standards. Summary of the site locations as well as data quality can be found in Appendix A, Table 1.

Kananaskis

The overall quality of this station was excellent and by far the most complete record, as well as the longest. Measurements were originally made beginning in 1939 and continuously until the present. The standards to collect this data conform to Environment Canada's standard and as such are considered reliable. Few significant data gaps exist.

Pocaterra

This station has a much shorter temporal scale than KFS. The period of October 1990 to August 1992 is missing, giving it a much larger percentage of missing data. Smaller gaps, one month or less, in the record are present throughout. From 2005 to 2007 the frequency of missing data increases to the point of unreliability. Data for temperature and precipitation follow the same pattern for missing observations, though precipitation generally has more observations.

Nakiska Ridgetop

While data collection began in March 1994, the data set does not achieve a continuous standard of quality until June 1999. Thereafter the data is continuous except for April and May 2002 where data is missing. Precipitation is not recorded at this location due to the incredibly high winds on the alpine ridge making gauging unreliable.

Marmot Creek

The data pertaining to Marmot Creek, except for the Water Survey of Canada data, all comes from the watershed management research program the Canadian Forestry Service

(CFS) conducted in Marmot Creek. The purpose was to analyze the effect of forest manipulation upon the hydrology of the basin and data was initially collected with mechanical drum chart technology. In 1982 the instrumentation was changed over to Campbell Scientific CR21 data loggers. The program was discontinued in 1987. In this study the variables of interest are limited to temperature, precipitation and stream flow. For the period of record the temperature data is of high quality. Except for significant gaps near the beginning and end of the data, no other gaps occur. The precipitation data, on the other hand, is of a lower quality. The periods of record are generally shorter than that of the temperature and have more gaps. Often associated with these gaps, the first observation following a gap is representative of the cumulative precipitation over the gap. Some of these gaps are spread over several months and calculation of monthly values as such is problematic.

The stream flow data recorded for Middle Creek sub basin is of exceptional quality. While three percent of the data is missing it is only missing during the winter months when flow is very small and of little interest to this study. The sub basin during the period of record and till present has not experienced any anthropogenic activities that would affect its stream flow and as such can be considered natural flow.

The data for Marmot Creek near the mouth of the basin was downloaded from the Water Survey of Canada online HYDAT database accessed at http://www.wsc.ec.gc.ca/hydat/H2O/. This data is also of exceptional quality with zero percent of the data missing from the recorded period. It should be noted that the measurement schedule was changed from continuous to seasonal (May to October) in 1987 as a result of the end of the CFS program. The stream flow has experienced anthropogenic effects due to the forest manipulations. Beginning in 1972, roads were built in the basin to access the treatment areas (Beckstead & Veldman, 1985). In 1974 Cabin Creek was subject of a simulated commercial harvest in which 21% of the basin was clear cut (Swanson et al., 1986). Between 1977 and 1979 the Twin Creek sub basin was the subject of a treatment in which the forest was cut into a honeycomb pattern of 2103 one tree width clearings (Beckstead & Veldman, 1985). The total area cleared represented about 40% of the total forest area in the sub basin (Beckstead & Veldman, 1985). The intent was to maximize snow accumulation on the ground and reduce sublimation. The result of both of these treatments and their effect on stream flow is open to interpretation. Some studies have shown no significant effects while others have shown significant changes of up to a 6% increase in stream flow (Beckstead & Veldman, 1985).

The recent station installations of UC, UF, VV and FR and their recorded data are of good quality. The major limitation of these data sets is their record length as can be seen in Appendix A, Table 10. The temperature data for the most part is of excellent quality except for FR where the sensor has recorded a number of error values. Another concern is the precipitation data from UC. UC has both a tipping bucket rain gauge as well as a Geonor precipitation gauge. There might have been a problem with the UC tipping bucket, as precipitation may be measured by the Geonor but not the tipping bucket, implying that snow is falling, yet the temperature was 20°C. To circumvent this issue, data from the tipping bucket located at UF was used in place of the UC tipping bucket. The correlation between the tipping bucket at UF and the Geonor at UC and temperature are much more logical.

Variables analyzed

For all variables the data was summarized at the monthly as well as annual temporal scales. This procedure was useful in reducing the effects of outliers as well as the amount of data and subsequently the complexity of the data analysis. In terms of summarizing the data into monthly and annual scales for temperature, the values are simply averages of the daily values. For precipitation the monthly and annual values are sums of the daily observed precipitation. As with most climate data, missing values do exist which for these stations is seen summarized in Appendix A, Table 10. The procedure used to deal with missing values was if a month was missing more than four days of data it was omitted and subsequently the annual value was also omitted.

The variables analyzed depended on the available data which varied between stations. For KFS and Pocaterra the data sets were identical and as such the variables considered were mean temperature (Tmean), maximum temperature (Tmax), minimum temperature (Tmin), snow, rain, total precipitation (Prcp), temperature range, and percent of precipitation as rain (%rain). Temperature and %rain were calculated as:

$$Temperature\ range = Tmax - Tmin$$

and

$$\%\,rain = Rain/Prcp$$

These calculations were initially completed on daily values and then averaged/summed to the monthly or annual scale. Standard Deviation (STDEV) values were also computed on a monthly and annual basis to quantify variability for Tmax, Tmin, Tmean and temperature range. Precipitation STDEV was not calculated as precipitation is conditional and often does not occur leading to erroneous values of variability. The variables analyzed for NR differed from these stations only in regards to it not having any precipitation data to consider. As NR's record was not used for direct long term trend analysis, variability (STDEV) was not calculated either.

Marmot Creek had fewer variables to choose from in comparison to the Environment Canada data. At all three stations, TN1, CN5 and CB5, temperature and precipitation were recorded. As such Tmean, Tmin, Tmax and Prcp were calculated. Temperature range was considered but as the regression relationships between KFS's temperature range and Marmot Creek's temperature range were weak. As a result the temperature range was not calculated nor extended for Marmot Creek.

For the recent stations in Marmot Creek the variables analyzed are identical to the variables in the historical data sets. This data has been collected at 15 minute intervals and as such the variables are first calculated at a daily interval. Tmean is simply the mean of all values, Tmin is the minimum value of that day and Tmax is the maximum value of that day. In order to get the data into the monthly and annual formats Tmean Tmin and Tmax were averaged over their respective scales.

The stream flow data is organized as a daily time series and as such calculations must be done to acquire the necessary variable. The variables of interest were timing of peak spring runoff flow, the peak spring runoff flow as well as average flow values for monthly as well as seasonal temporal scales. The data for Middle Creek and Marmot Creek are of the same format and as such subject to the same procedures. The only constraint is the seasonal May-October nature of the post-1987 data in the Marmot Creek data set and as such the analysis was limited to the May to October period for both Middle and Marmot creek over the entire record, 1963-2007. Timing of spring peak runoff and its stream flow was collected by analyzing the records on an annual basis. Predominantly, but not as a rule, the peak flow is the same as peak spring runoff. Large rainfall events do occur that sometimes exceed the spring peak flow and need to be taken into account (Burn, 1994). As such the annual hydrograph was visually analyzed and peak spring runoff flow was determined manually (Burn, 1994). The mean monthly and mean seasonal (May-October) flows were calculated by simply averaging the stream flow data over the respective time scale.

Pacific Decadal Oscillation Data

The PDO is commonly quantified by an index. The calculated index, found at http://www.jisao.washington.edu/pdo/, is based upon spatially averaged sea surface temperature of the northern part of the Pacific Ocean north of 20°N latitude (Mantua, 2001). The global sea surface temperature anomaly is subtracted from the average to remove any climate change effect (Mantua, 2001). The PDO data used was obtained from http://jisao.washington.edu/pdo/, which is updated regularly. This data has a monthly scale and for purpose of the analysis was averaged to represent the annual scale.

Statistical Methods

The statistics employed in this analysis are non-parametric. Non-parametric tests do not have a data distribution assumption and as such are preferred when analyzing environmental observations (Yue et al., 2002). Environmental data, while often assumed to be normally distributed, are often not. The relaxation of a distribution assumption is preferred as the computed statistics have greater power and significance both statistically and practically (Yue et al., 2003).

Mann-Kendall Test

The Mann-Kendall (MK) test is a non-parametric test that assesses if the data in a time series exhibits a monotonic trend or not (Yue et al., 2003). The test has been used extensively to analyze trends in hydrometeorological indicators such as temperature, precipitation and streamflow in a number of studies (Burn, 1994; Burn & Elnur, 2002; Vincent & Mekis, 2004; Yue et al., 2003; Zhang et al., 2000; Zhang et al., 2000; Bonsal et al., 2001; Valeo et al., 2007). While other nonparametric trend tests do exist such as the Spearman's rho the results have been shown to be the same as the MK test (Yue et al., 2002). In addition, the MK test statistic, relative to Spearman's rho, approaches normality more rapidly and provides an estimate of the population parameter, resulting in the MK test results to be considered to be more interpretable and thus preferred (Yue et al., 2003). The power of the MK test is also dependent upon several factors. The power of the test to identify trends increases with an increase in the data period, magnitude of the trend, and predetermined significance level of the tests (Yue et al., 2002). An inverse relationship exists between the power of the test and the variability in the time series (Yue et al., 2002).

As the test is nonparametric it avoids the assumption of normality, although assumptions of serial independence and randomness do exist. Many studies have assumed serial independence of data when computing the MK test when such assumptions may be false (Yue et al., 2003). A common approach to deal with the assumption of serial correlation in the data is to conduct a pre-whitening operation upon the data. When a serially correlated data series is identified, a pre-whitening procedure as outlined in Yue et al., (2003) can be applied. In this analysis the program used to compute the MK test, courtesy of Alain Pietroniro, applied the pre whitening approach of Yue et al. (2003) when serial correlation was identified in the data set. The assumption of randomness in hydrometeorological data is of concern as long-term memory in data sets have been shown to exist and is known as the Hurst phenomenon (Klemes, 1974). Hydroclimatological data sets cannot be assumed to be random or serially independent. The MK test is considered to be robust and powerful enough to identify trends in light of these issues.

The MK test as described in Yue et al. (2002) computes the test statistic S by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

Equation 1

Where n is the number of observations, x_j and x_i are sequential data values and sgn is:

$$sgn(\theta) = \begin{cases} 1 \ if\ \theta > 1 \\ 0 \ if\ \theta = 0 \\ -1 \ if\ \theta < 1 \end{cases}$$

Equation 2

Where θ is a simplification of the product of $(x_j - x_i)$. The S statistic when the n is ≥ 8 has a mean E(S) of 0 and variance V(S) that approaches 1 and can be calculated as follows:

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18}$$

Equation 3

Additionally

$$S' = S - sgn(S)$$

Equation 4

Whereupon

$$z = \frac{S'}{\sqrt{V(S)}}$$

Equation 5

The z statistic has a mean of zero and standard deviation of one and, using a normal distribution, the probability of the statistics due to chance alone can be assessed (Yue et al., 2002).

Null hypothesis (accept if p: <0.90):

the time series does not exhibit a statistically significant monotonic trend

Alternate Hypothesis (accept if p≥0.90):

the time series does a exhibit a statistically significant monotonic trend

The magnitude of trend is calculated as the median change in the variable of interest per year as:

$$trend = median\ (b_1, b_2, \ldots., b_{n-1}, b_n)$$

Equation 6

Where b is equivalent to :

$$b = \left(\frac{x_2 - x_1}{t_2 - t_1}\right)$$

Equation 7

Where x_2 and x_1 are sequential data values and where t_2 and t_1 are the corresponding times. Thus the calculated trends, while the variables being examined may have a physical connection, do not have a mathematical relation and must be considered independent of one another

An issue arises in the use of the MK test when a trend is identified yet the slope of the trend is, for all intensive purposes, of a negligible magnitude. This exemplifies the difference of statistical and practical significance. While a trend may be statistically significant, it may not have any practical meaning. Alternatively, the opposite can be the case where a trend may be practically significant yet not have statistical significance. Statistical significance often occurs in larger data sets when any slope, no matter the size, can be determined to be statistically significant (Yue et al., 2002). Judgment must be exercised in the interpretation of results to identify trends that are both statistically and practically significant.

Mann-Whitney U test

The Mann-Whitney U (MWU) test is a non-parametric test that assesses if two samples of data are from the same probability distribution. It is the non parametric equivalent of a t-test as it compares the medians of two groups. The test statistic U is calculated as follows for both samples (SPSS Inc., 2006):

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1$$

Equation 8

Where n_1 and n_2 are the number of samples in population 1 and 2. R is the sum of ranks of either sample 1 or 2. U values are calculated for both samples and the smaller U value of the two is used in the calculation of probability of significance as follows:

$$Z_u = \frac{\left|U_{obt} - \left({}^{n_1 n_2}/_{2}\right)\right|}{\sqrt{\frac{n_1 n_2}{(N(N-1)}\left(\frac{N^3 - N}{12} - \sum_i T_i\right)}}$$

Equation 9

Where n_1 and n_2 are number of samples in population 1 and 2 respectively and U_{obt} is the product of equation 7. N is the number of samples for both populations and $\sum_i T_i$ is the sum of ties between the two samples. Z_u follows a normal distribution and thus provides an estimate of the probability of the samples coming from the same population or not.

Null hypothesis (accept if $p>0.05$):

two populations are from the same distribution

Alternate hypothesis(accept if p: ≤ 0.05):

the populations are from different distributions

The MWU test in this study has been used primarily to assess the significance of regression relationships and to compare of similarities of predicted values.

Kendall's tau (b)

To test correlations between the PDO index and climate variables, the non parametric Kendall's tau (b) was used. It tests the degree to which paired observations are concordant (changes in a similar manner) or disconcordant (changes in a different manner) (SAS Institute Inc., 1999). The correlation coefficient varies from 1 to -1 where 1 is a perfect correlation and -1 is a perfect but inverse correlation (SAS Institute Inc., 1999). A value of 0 implies that the two data sets are independent of one another. The Kendall's tau (b) was calculated, rather than tau (a) or tau(c), as it makes a correction for data that have the same ranks, referred to as ties. The following equations are from (SAS Institute Inc., 1999)

$$\tau = \frac{S}{\sqrt{(T_0 - T_1)(T_0 - T_2)}}$$

Equation 10

Where S is calculated in the same manner as the S from Equation 1 and:

$$T_0 = n(n-1)/2$$

Equation 11

$$T_1 = \sum t_i(t_i - 1)/2$$

Equation 12

$$T_2 = \sum u_i(u_i - 1)/2$$

Equation 13

Where t_i is the number of tied x_i values in the i^{th} group of tied x_i values, and u_i is the number of tied x_j values in the j^{th} group of tied x_j values. SPSS 15.0 computed the correlation coefficients for the selected data and provided a value for the two-tailed significance of the correlations

Null hypothesis (accept if $p>0.05$):

two populations are not concordant thus not correlated

Alternate hypothesis (accept if $p\leq0.05$):

the populations are concordant thus correlated

Reconstruction Methods

KFS to Marmot Creek

Objective two of this study is to try to extend the data set from the historical Marmot Creek study to the present. Table 1 shows the difference in average temperatures between the historical data and current elevation adjusted data for Marmot Creek.

Table 1: Comparison of mean annual historic and recent Marmot Creek temperatures

	Period	Tmax	Tmean	Tmin
		°C	°C	°C
CN5	1968-1987	5.697732	-0.11284	-5.68449
UC	2005-2007	6.575832	1.309255	-3.48444

The differences suggest, though inconclusively due to inter-annual variations and the short averaging period for UC, that the climate may be changing. Thus it is worth extending the data set in order to conduct a more detailed and valid analysis. The basic approach is to establish regression relationships between the historical Marmot Creek data and other station records that overlap. The Kananaskis Field Station’s data overlaps the period of activity in the basin beginning in 1966 and ending in 1986. Pocaterra was considered in order to develop a multiple linear regression but was not used due to significant data gaps, shorter calibration period as well as being located a long distance from the basin. The regressions equations between Marmot Creek and KFS are summarized in Table 2 and an example is given in Figure 3.

Table 2: Summary of Regressions between KFS and Marmot Creek

Variable	Station	R^2	Standard Error	Regression Variables†	
				a	constant
Mean			°C		
	CB5	0.977	1.1944	0.934	-4.125
	CN5	0.983	1.08157	0.982	-2.982
	TN1	0.955	1.61854	0.884	-4.145
Min			°C		
	CB5	0.954	1.57293	0.93	-2.972
	CN5	0.966	1.4062	0.977	-2.474
	TN1	0.919	2.05521	0.898	-2.335
Max			°C		
	CB5	0.984	1.227	0.957	-4.921
	CN5	0.985	1.10352	0.989	-3.356
	TN1	0.967	1.47661	0.878	-5.611
Prcp			mm		
	CB5	0.611	22.08409	0.766	19.954
	CN5	0.646	18.96894	0.727	12.026
	TN1	0.544	28.98588	0.821	29.211

† Linear: y=ax+constant

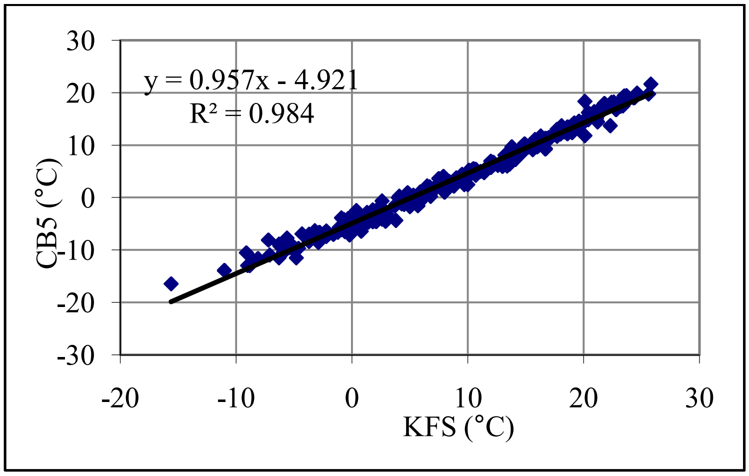

Figure 3: Example Regression, CB5 vs. KFS Tmax

The difference in temperature between KFS and Marmot Creek, based upon the linear regression calculated, is physically based as the differences can be attributed to the environmental lapse rate. In a linear regression with a slope nearing a value of 1, the intercept represents the average lapse rate between the two stations. As such, the Tmean regressions of the three stations were compared to the average environmental lapse often estimated at 6.5°C/1000m (Dingman, 2002). Table 3 summarizes the lapse rates observed and shows that the lapse rate is near the observed average environmental lapse rate of 6.5°C.

Table 3: Lapse Rates between KFS (1391.1m) and Marmot Creek

Station	Elevation	Difference From KFS	Actual Temp Difference	Actual Lapse Rate
	(m)	(m)	°C	°C/1000m
CB5	2170	778.9	4.11	5.27
CN5	1753	361.9	2.97	8.20
TN1	2286	894.9	4.12	4.60
Average			3.73	6.02

Nakiska Ridgetop to Marmot Creek

The location of the Nakiska Ridgetop Station is the nearest of stations considered to Marmot Creek and as such its regression relationships are considered to be more accurate. This is because its conditions resemble the conditions in Marmot Creek better than conditions at KFS. With the installation of the recent stations in the basin, in areas near the historical stations, several tasks were performed with these datasets. Initially the stations had, based on calculated lapse rates between Nakiska Ridgetop and recent stations, lapse rates applied to correct for elevation differences. The resulting regressions allow for a validation of the regressions based on the KFS data. The predicted values were infilled into the extended data set as the predicted data based on Nakiska Ridgetop data is assumed to more closely resemble the basin.

A lapse rate was applied to FR, VV and UC data to account for the change in elevation from the historical stations. Since the exact locations of CB5, TN1 and CN5 are not known the differences are assumed to be explained by elevation alone and thus by an environmental lapse rate. The relative change in elevation is explained by Table 4.

Table 4: Difference in elevation between historical and recent meteorological stations

Historical Stations	elevation	Recent Stations	elevation	elevation difference	Environmental Lapse Rate
	m		m	m	°C/1000m
CB5	2170	VV	1956	214	-5.25
CN5	1753	UC	1844.6	-91.6	-2.96
TN1	2286	FR	2325.6	-39.6	-3.87

The lapse rates applied to the elevation differences in Tabel4 were based on the median monthly observed temperature difference between Nakiska Ridgetop and the respective stations. Taking into account the elevation difference, an individual lapse rate for each station was calculated and applied to the elevation difference between the recent and historical climate stations. Thereafter the altered VV, UC and FR datasets were assumed to be equivalent to the historical stations CB5, CN5 and TN1.

A linear regression between the elevation adjusted VV, UC and FR data sets and NR was performed. The resulting regressions are summarized in Table 5 and an example given in Figure 4.

Table 5: Regression Relationships between NR and recent Marmot Creek Stations

Variable	Stations	R2	error	Regression Variables	
Tmean			°C	A	constant
	VV	0.994	0.671	1.035	2.022
	FR	0.996	0.551	1.024	0.615
	UC	0.988	0.867	1.054	3.066
Tmin			°C		
	VV	0.994	0.63	1.013	1.215
	FR	0.995	0.598	1.04	0.531
	UC	0.99	0.744	1.006	1.488
Tmax			°C		
	VV	0.992	0.824	1.025	3.435
	FR	0.996	0.565	1.026	0.883
	UC	0.984	1.108	1.112	4.63

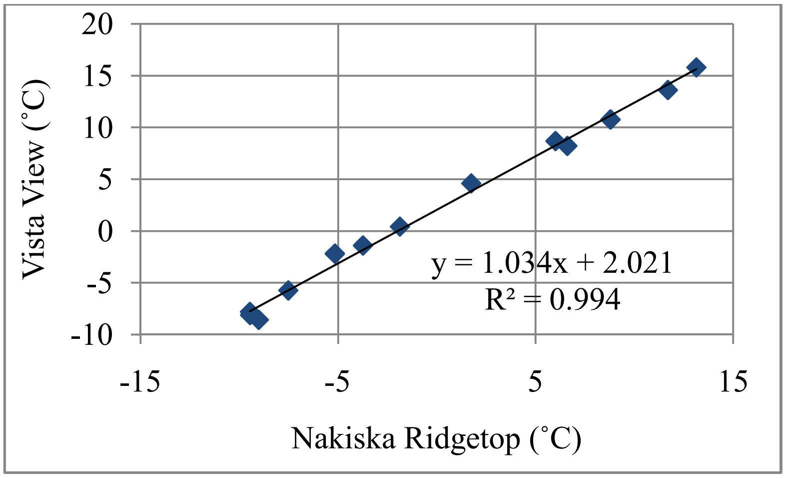

Figure 4: Vista View vs. Nakiska Ridgetop monthly Tmean regression

Significance of Regressions

The significance of the regressions was assessed with the use of the MWU test. The observed and predicted values of both regressions as well as the overlapping predicted regressions were compared. The datasets being compared are independent and as such the statistical significance of the regressions and their ability to predict Marmot Creek

Table 6: Summary of Mann- Whitney U test on regressions

Stations	Variable	observed/predicted KFS	observed/predicted NR	predicted NR and KFS
VV-CB5	Tmax	0.882	0.858	0.463
	Tmin	0.878	0.739	0.061
	Tmean	0.864	0.858	0.214
	Prcp	0.559		
UC-CN5	Tmax	0.964	0.705	0.939
	Tmin	0.984	0.940	0.085
	Tmean	0.936	0.880	0.438
	Prcp	0.411		
FR-TN1	Tmax	0.894	0.952	0.661
	Tmin	0.862	0.979	0.844
	Tmean	0.846	0.966	0.997
	Prcp	0.592		

conditions was assessed. In comparison of the predicted values from the NR and KFS regressions, the null hypothesis is that the two populations predict conditions in the same way and thus the author assumes that the regression relationships are valid. The alternate hypothesis is that the regressions do not explain the conditions in the basin and as such the relationships are invalid. The Mann-Whitney U test statistics are summarized in Table 6. The results show that the NR and KFS regressions can be considered to be significant as observed and predicted values are the same. The assessment of whether or not the predicted values of KFS and NR shows that the regressions predict the temperature is a similar manner further validating the regressions.

In order to test the constancy of the relationships the MK test was used. The MK test was performed by analyzing the residuals of the regressions to see if a statistically significant trend over time existed. The null hypothesis is that the relationships are constant over time. The alternate hypothesis is that the regression relationship is changing over time and not constant. Table 11 in Appendix B summarizes the result of the Mann-Kendall analysis of the residuals. Only the residuals of the regression with KFS were used as the Mann-Kendall test is only useful in data sets that have greater than 8 observations. The MK analysis of the KFS residuals, Appendix B Table 11, showed that only 4 variables out of a possible 52, or 7.6 %, on the monthly scale had significant trends. As a 90% significance level was used, the probability of these trends occurring solely by chance is possible, since 7.6% is less than 10%.

Middle Creek Stream flow Reconstruction and Analysis

A gauge was located on Middle Creek from 1963-1986 to operate as a control to the forestry experiments on Cabin and Twin Creeks. No activity since then has occurred in Middle Creek basin and flow is considered natural. Using data from the Marmot Creek gauge, having a record from 1962-2007, the Middle Creek data was extended up to 2007. See Appendix C for greater analysis of relative changes of monthly mean flow, spring timing and peak spring flow as a result of logging activity. A regression based on monthly streamflow was computed between Marmot and Middle Creek with Middle

Creek as the dependent variable. Spring runoff timing and peak were also extended by linear regression. The regressions used all the data available, 1963-1986, as on a monthly basis the relative contributions of Middle vs. Twin and Cabin creeks have not been affected by the logging activities, see Appendix C. In terms of spring peak timing as can be seen in Table 8 Middle Creek has a linear relationship with Marmot Creek timing. Though the peak spring streamflow has changed and as a result is regressed only over 1975-1986. This is to account for and negate the effects of the forestry manipulation experiments removing the climate change signal from Marmot Creek flow. Figure 5 and 6 provide examples of stream flow regressions and Table 7 summarizes the regressions. This analysis is statistically invalid as Middle Creek stream flow is not independent of Marmot Creek flow. However, as not other records exist, Middle and Marmot Creek must be related in order to extend the data set. If one references Appendix C though it is clear that on a monthly scale the relative contributions between the other creeks and Middle remain consistent over time. Thus while Middle creek is not independent of Marmot Creek its relative contribution has not changed and the regression relationship consequently is assumed to be representative of Middle Creek flow. The timing of peak

Table 7: Stream flow regression relationships between Middle and Marmot Creek

Month	r^2	Error	A	constant	Mann- Whitney U sig.
		m^3/s	m^3/s	m^3/s	
Monthly flow	0.984	0.009	0.353	0.003	0.809
Spring peak flow	0.953	0.028	0.399	-0.011	0.817
Spring peak timing	0.992	0.922	1.022	-3.3560	0.984

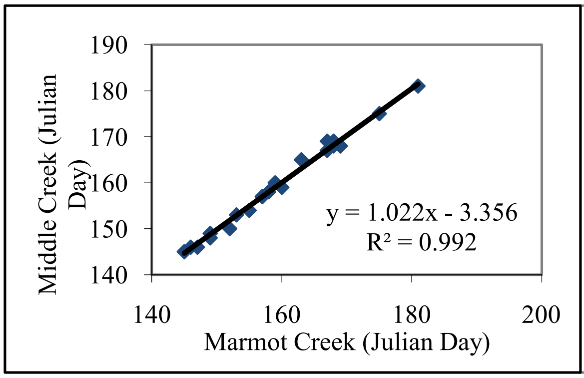

Figure 5: Middle vs. Marmot Creek Spring Peak Timing Regression

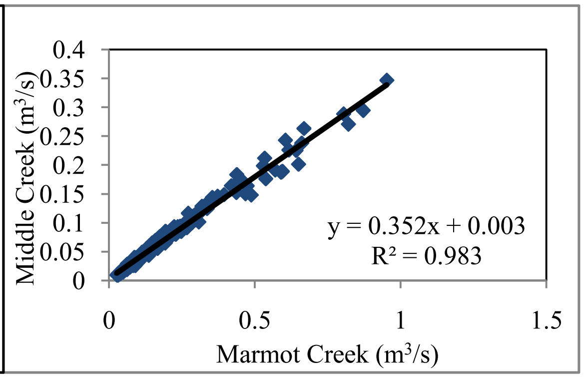

Figure 6: Middle vs. Marmot Creek Monthly Mean Stream flow Regression

spring runoff of Middle Creek can be considered as the same as Marmot Creeks. Figure 5 shows the strong correlation that exists over the entire record (pre- and post-treatment) and when the regression is forced through zero the slope of the line is 0.9996. Thus in this analysis of spring runoff timing, it is assumed that the timing of Marmot Creek is the same as that for Middle Creek.

Rain to Snow Transition

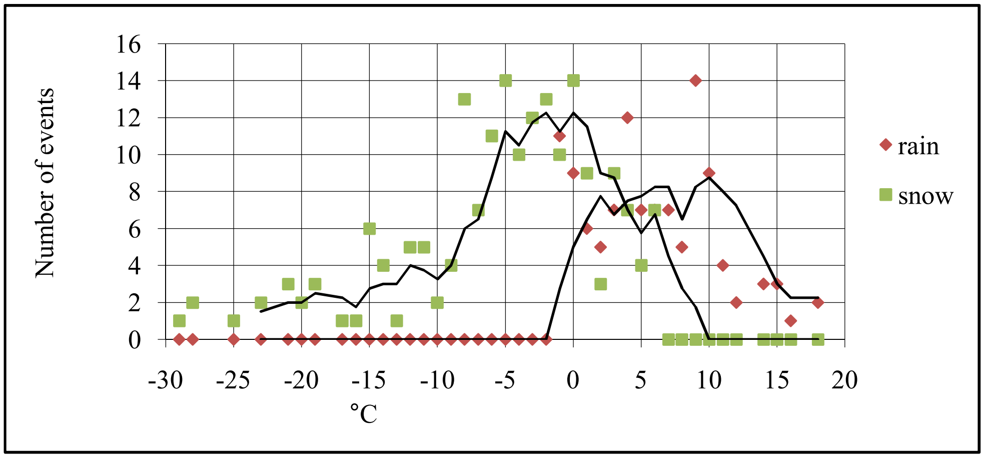

Figure 7: Upper Clearing/ Upper Forest Tcrit

While Pocaterra and KFS precipitation data is divided into rain or snow, the Marmot Creek data is not. A technique based on Tmean to attempt to differentiate precipitation into rain or snow was applied to the Marmot Creek data. The analysis determines the critical air temperature separating the probability of precipitation falling as rain or snow. This provides an estimate of the proportion of rain and snow that should occur during a precipitation event. The number of rain or snow events was totaled and plotted for every change in degree Celsius. Subsequently, moving averages of these events were plotted and the intersection point of the two moving average lines defined the critical temperature (Tcrit). The Environment Canada data identifies rain and snow events and a two point moving average for Pocaterra and KFS provided enough smoothing to define the Tcrit. Tcrit was computed for KFS and Pocaterra in order to see if the Tcrit computed for Marmot Creek was reasonable, as the data sets for KFS and Pocaterra was of higher quality and greater duration. In Marmot Creek the precipitation data is provided by a Geonor- Alter Shielded precipitation gauge and a Texas tipping bucket. At the UC site a

Geonor precipitation gauge records by weighing total precipitation falling into a bucket that contains antifreeze (which melts snow) and oil that prevents evaporation. The tipping bucket from the UF was used to determine the occurrence of precipitation falling as rain. A tipping bucket was located at UC but analysis of data concluded that it was of questionable quality and thus UF data was utilized. Data from the tipping bucket was summarized as a daily sum. Data from the Geonor was summarized as the daily change in water collected. This was done by looking at the change in precipitation at midnight of each day; reducing the chances of wind affecting the sensors. Rain events consequently were identified when the Geonor recorded precipitation as well as when the tipping bucket recorded precipitation. Snow events were identified when the Geonor recorded precipitation but not the tipping bucket. The number of snow and rain events was summed for each change of 1°C. To account for erroneous values produced by the Geonor all daily total precipitation less than 0.1mm was discounted. Additionally, all precipitation events occurring at mean temperatures greater than 8 °C were considered to be rain. This assumption is based on Dingman (2002) who states that snow never occurs at temperatures greater than 6 °C. The computed Tcrit, Figure 7, the air temperature where the probability of snowfall or rainfall is equal, is found to be 3.8°C at Upper Clearing/ Upper Forest. In terms of trend analysis of changing hydrologic parameters, the Tcrit is of little importance by itself. Thus the Tcrit was applied to the temperature time series of Marmot Creek to see if the number of months per year with Tmean greater than Tcrit is changing. This number is equivalent to the number of months per year with a greater probability of precipitation falling as rain versus snow. Subsequently the computed data was assessed by the MK test to determine if a significant trend occurred in the data.

Correlation of Kananaskis Valley Climate to the PDO

The PDO has been shown to have an influence upon North American Climate in terms of precipitation, temperature and stream flow patterns (Stewart et al., 2004). As these variables are of interest to this study, the relationships were tested using the correlation statistic Kendall’s tau (b). It is not meant to determine causality as other studies have

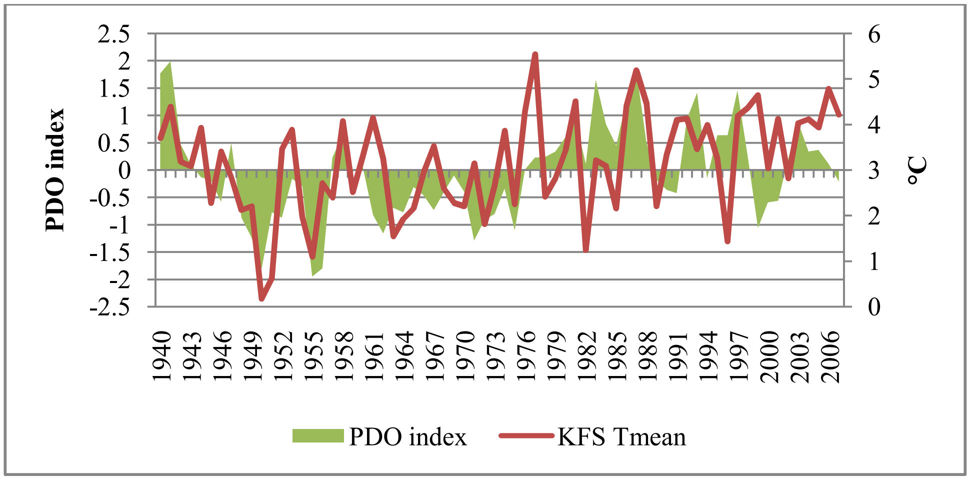

Figure 8: PDO vs. KFS Tmean

defined the casual relationship, but rather to determine if a relationship does exist, its degree of significance and direction. Annual values of climate variables and the PDO were used as the PDO signal has been shown to vary in strength over the course of the year (Mantua, 2001). The annual scale simplifies the analysis and the interpretation of results. Preliminary visual analysis shows a perceived decoupling of the inter-annual variations around 1975. Thus in addition to running the Kendall's tau (b) correlation just on the entire series 1940-2007 it was decomposed to a pre-1975 (1949-1975) period and a post-1975 (1976-2007) period.

Results

The results of the Mann-Kendall analysis of the outlined variables for Kananaskis Field Station, Pocaterra and Marmot Creek extended record are summarized in Appendix B, Tables 12, 13 and 14. In all bar charts statistical significance at the 90% significance level is denoted by magnitudes of trends outlined in black.

Temperature Trends

Kananaskis Field Station

The results of the MK test conducted on KFS are summarized in Figure 8. As can be

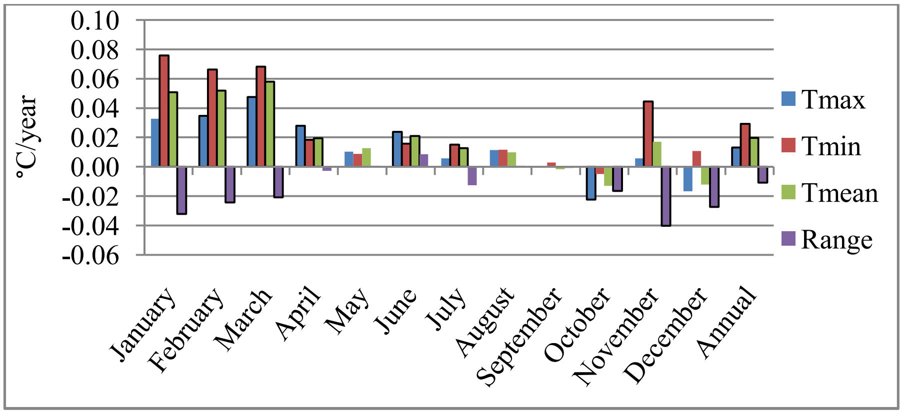

Figure 8: Magnitude of Significant Temperature Trends at KFS

seen on an annual basis, Tmean, Tmin, and Tmax all have statistically significant positive trends. The greatest increase occurred in Tmin, followed by Tmean and the least increase in Tmax. When broken down to the monthly scale, statistically significant trends for Tmean occur in the earlier part of the year: January, February, March, April, June and July. Tmin is observed to have trends in January, February, March, April, June, July and November. Tmax exhibits statistically significant positive trends in February, March, April and June and a negative trend in October. Of the statistically significant trends identified, the ones occurring in the winter months had greater magnitudes than those occurring in the summer and fall. Except for the months of April and June the magnitudes of the trends followed the same relative ordering with the greatest increases in Tmin followed by Tmean and Tmax.

The temperature range exhibited statistically significant decreasing trends on an annual scale as well as on the monthly scale for January, February, March, October, November, and December.

Pocaterra

Pocaterra, see Figure 9, exhibited the greatest variation in trends of all the stations analyzed which may be explained by its short record length. On an annual scale only Tmean and Tmax showed statistically significant positive trends with Tmean magnitude

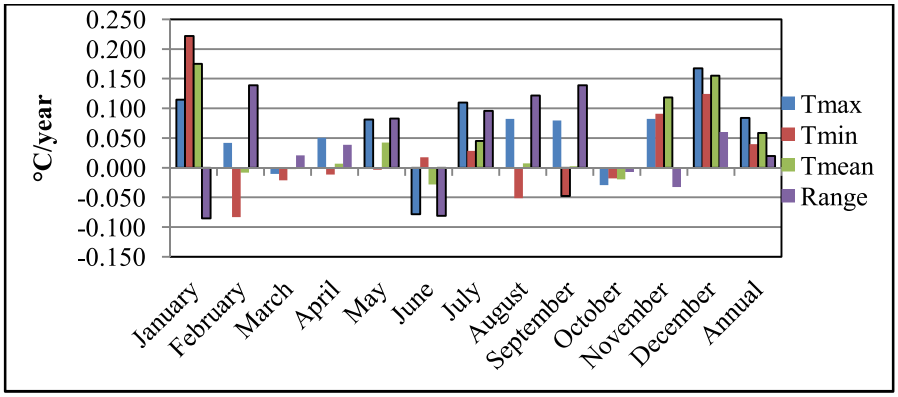

Figure 9: Magnitudes of Significant Temperature trends at Pocaterra

less than the Tmax magnitude. At the monthly scale significant tends were observed for Tmax in January, May, June, July and December. Tmin is increasing in January and decreasing in September. Tmean is increasing in January, July, November and December.

The most significant changes occurred in the temperature range of the data set. Temperature range showed an annual increase but had a small magnitude. On the monthly scale it was observed to increase in February, May, July, August, September and decrease in January and June. There is a weak tendency for the late spring and early summer trend magnitudes to be less than the fall and winter magnitude

Marmot Creek

The extended data set for Marmot Creek has the most significant as well as the most consistent trends relative to the other datasets, see Appendix B Table 14. On an annual scale the statistically significant trends for Marmot Creek were limited to Tmin and Tmean for all stations. For CB5 and CN5 Tmax was also observed to being increasing at a statistically significant level. The Tmin and Tmean magnitudes of these trends, in relation to one another, were consistent as the Tmin magnitude was always greater than Tmean. The magnitude of the trends were also related to elevation as the greatest increases occurred at CN5, the lowest elevation and the smallest increases occurred at TN1, the highest elevation. The monthly trends varied as follows:

CB5

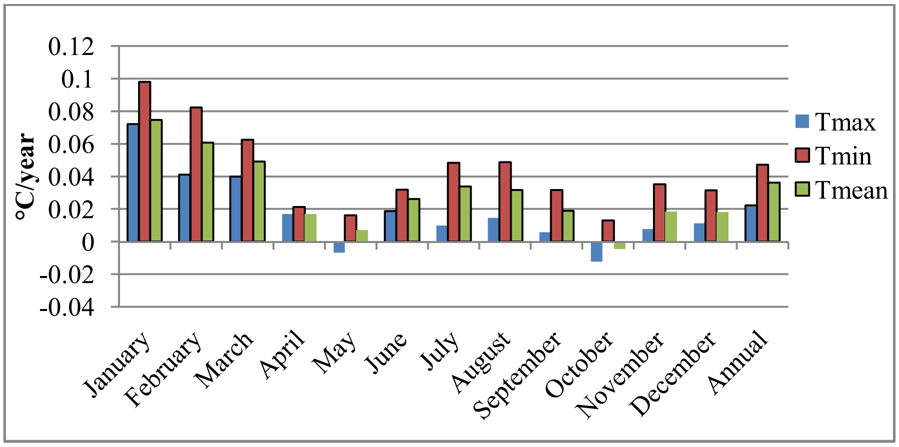

Figure 10: Magnitude of Significant Temperature trends at CB5

As shown in Figure 10 significant trends in Tmean occurred in January, February, March, June, July, August and September. Tmin had increasing significant trends in every month. Tmax had a statistically significant increasing trend in January, February, and March and June. The relationship of the magnitude of the median trends was with Tmin consistently showing a greater increase, followed by Tmean and Tmax. The magnitudes of the trends were greater in winter than in summer.

CN5

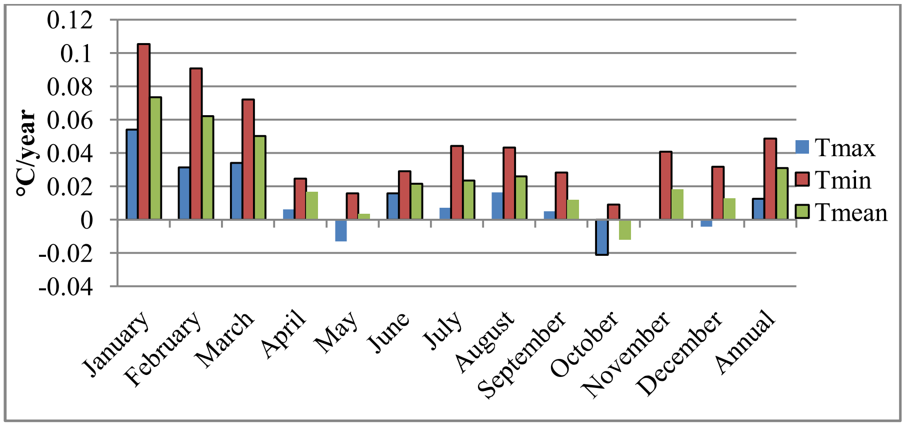

Figure 11: Magnitude of Significant Temperature trends at CN5

As seen in Figure 11significant trends occurred in Tmean in the months of January, February, March, June, July and August. Tmin showed significant trends in every month. Tmax increased in January, February, March and June and decreased in October. The relation of the magnitudes of trend between the variables showed that the greatest increases were in Tmin followed by Tmean and Tmax. The magnitudes of the trends were greater in winter than in spring and summer.

TN1

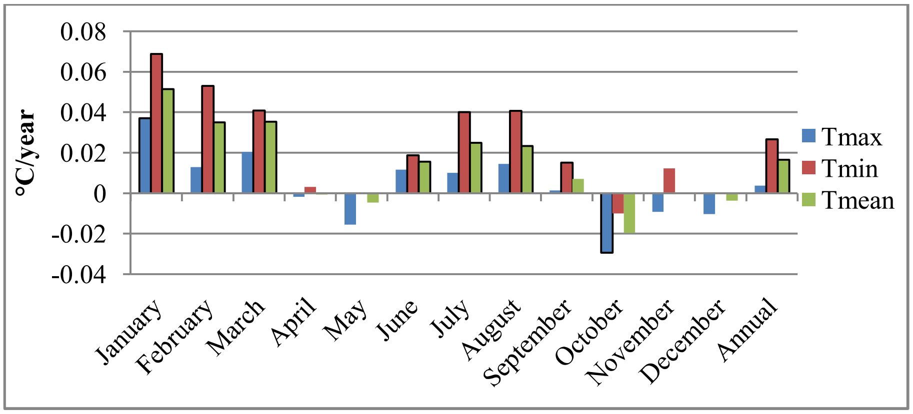

Figure 12: Magnitude of Significant Temperature trends at TN1

Following the pattern established by CB5 and CN5, TN1, as seen in Figure 12, showed significant increasing trends in Tmean in winter and summer, January, February, March, June, July and August. Tmin increased in January, February, March, June, July, August and September. Tmax showed an increasing trend for January while a decreasing trend in October. The magnitude of the trends showed that Tmin increased at a greater rate than Tmean and Tmax consistently. The magnitudes of the trends were greater in winter than in summer.

Precipitation Trends

Kananaskis Field Station

KFS Precipitation, as shown in Figure 13, exhibited some statistically significant trends. One should keep in mind the concept of practical versus statistical significance as shown by the statistically significant trends where the slope is near zero. With this in mind, practically and statistically significant trends for rain were observed only in the month of

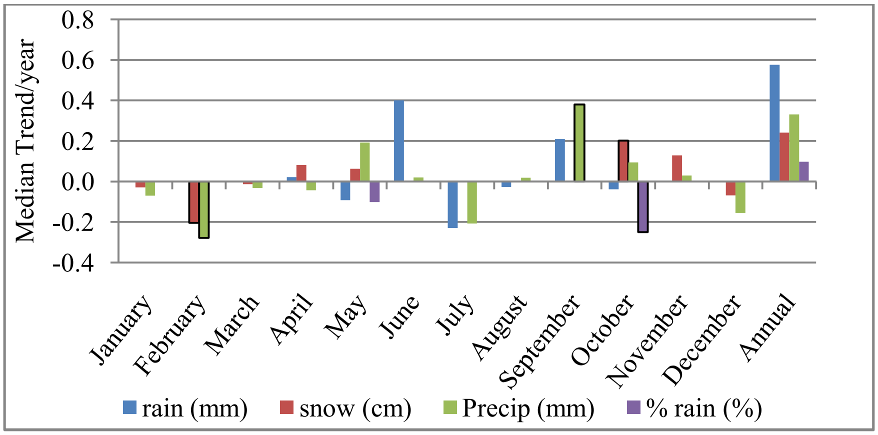

Figure 13: Magnitude of Significant Precipitation trends at KFS

April. Snow showed a decreasing trend in February and an increasing trend in October. Total precipitation showed a decrease in February that corresponded with the decrease in snow while an increase in September is noted. The percentage of precipitation falling as rain only showed a decrease in October that also corresponds to an increase in snow. These results must be interpreted with caution against one another as the trends observed are median trends and not regressed or even average changes. Each data set inherently has different amounts of variability and thus the power of the MK test for trend detection is variable. As precipitation data has the greatest variability, compared to temperature, one must be careful in making quantitative generalizations of trends when comparing different variables.

Pocaterra

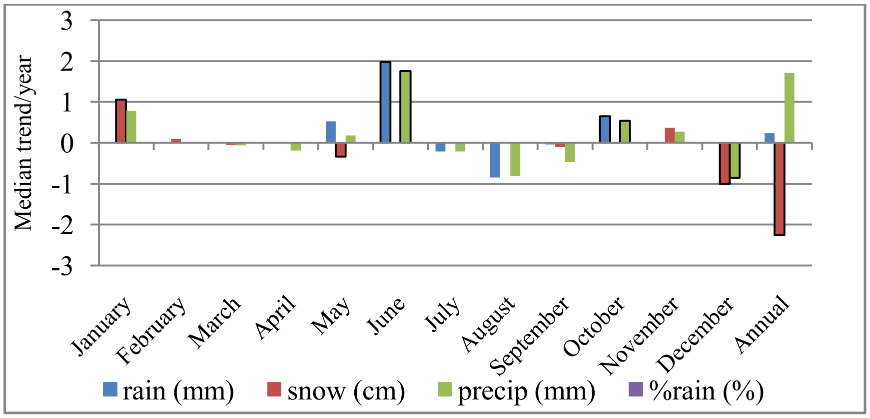

Figure 14: Magnitude of Significant Precipitation trends at Pocaterra

As shown in Figure 14, rainfall was observed to increase in June and October which corresponds to an increase in the total amounts of precipitation. On an annual scale snowfall was observed to decrease. On a monthly scale snowfall increased in January but decreased in May and December. There is disagreement in terms of annual trends with a large statistically significant decrease in snowfall not corresponding to a statistically insignificant increase in precipitation. One must keep in mind what the trends actually mean and resulting problems as describe previously. In this case though the increase in precipitation is not a statistically valid trend and thus the difference is not a significant concern. The decrease in December snowfall corresponds to an almost equal decrease in total precipitation. The percentage of total precipitation occurring as rain increased in May but at such a small amount the increase is negligible and practically insignificant.

Marmot Creek

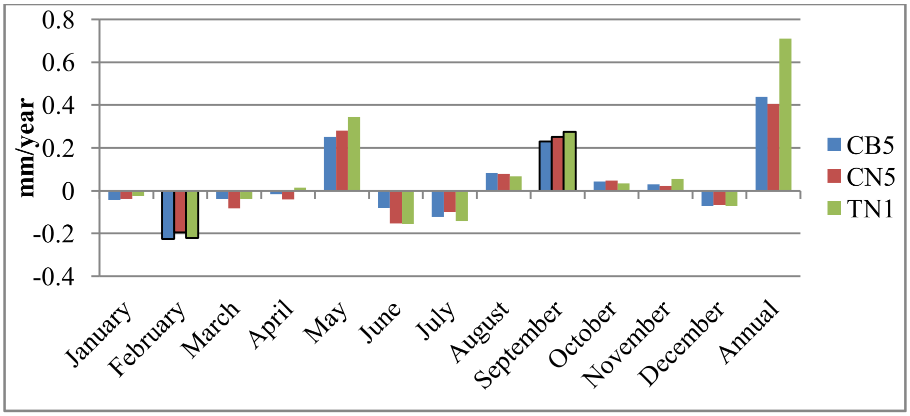

Figure 15: Magnitude of Significant Precipitation trends at Marmot Creek

Marmot Creek, see Figure 15 showed statistically significant trends of similar magnitude for all stations that were, for total precipitation, decreasing for February and increasing in September. No statistically significant annual trends were noted due to large variability in the data.

Variability Trends

Kananaskis Field Station

KFS temperature variability, see Figure 16, as determined by the standard deviation of

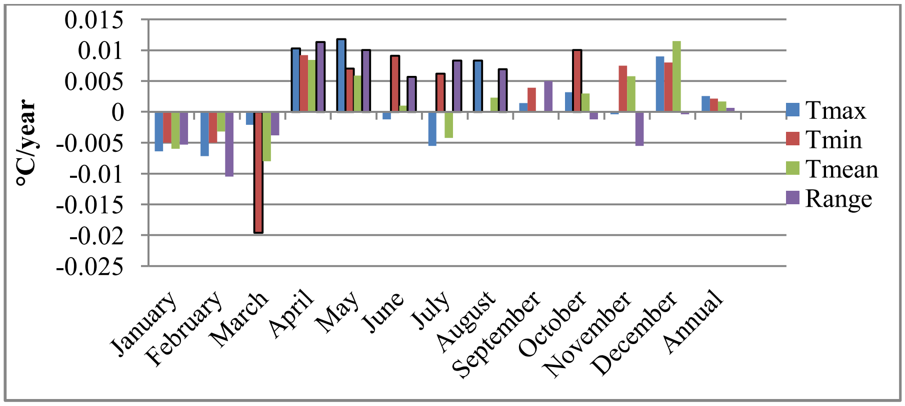

Figure 16: Magnitude of Significant Temperature Variability trends at KFS

Tmean, Tmin Tmax, and temperature range over monthly and annual scales. Showed statistically significant trends occurring primarily on a monthly scale in spring and summer and primarily in Tmin, Tmean and temperature range. No statically significant trends occurred in Tmax. Tmean showed an increase in variability in April, May and August. Tmin showed increasing trends in June, July, August and November while a decreasing trend was observed in April. Temperature range variability showed an increase in April, May, June, July and August. Overall temporal trends do not show consistent trends meaning that temperature variability cannot be authoritatively said to be changing or not changing.

Pocaterra

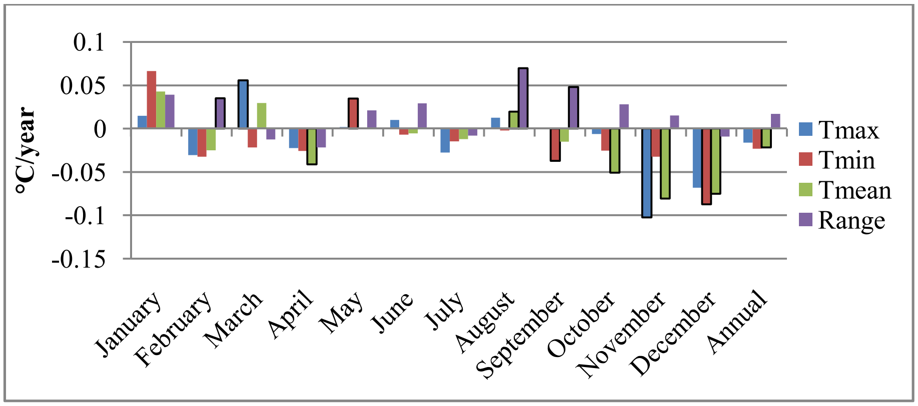

Figure 17: Magnitude of Significant Temperature Variability trends at Pocaterra

Pocaterra's variability trends, see Figure 17, were quite different than KFS and varied considerably over the year. In terms of Tmax variability it was observed to increase in

March and decrease in November. Tmin variability was observed to increase in May and decrease in September and December. On an annual scale, Tmean variability was observed to decrease as well as on the monthly scale of April, October, November and December while in August it was observed to increase. Temperature range variability increased in February, August and September. In terms of the seasonal distribution of variability, trends observed in spring and summer were generally increasing while the trends in fall and early winter were primarily decreasing. As with the variability of KFS the observed trends did not have consistent temporal patterns or magnitudes and thus generalizations cannot be made

PDO Correlation to Kananaskis Valley Climate

As shown in Figure 8, much of the inter-annual variation in KFS Tmean is related to the PDO, although the correlation seems to be stronger prior to 1975 when there was a switch from the cool phase to the warm phase. The correlations for the entire period of record as well as pre-1975 and post-1975 are calculated and summarized in Appendix D, Table 15. When correlating the entire dataset (1939-2007) the PDO was shown to be strongly correlated to temperature, %rain, and snow while not correlated to total precipitation, temperature range and rain at KFS. At Marmot Creek the temperature but not the precipitation was significantly correlated over the entire period. Of the significant correlations, only snow had an inverse relationship with the PDO while the rest exhibited positive correlations. While the correlation does exist over the whole record after 1975 it is not significant. A decoupling was perceived in the data as significant correlations that existed prior to 1975 do not occur after 1975. If the correlation coefficients between the 1940-2007 and 1940-1975 period are compared one can notice that generally the correlations over 1940-2007 are less than the correlations in the 1940-1975 period. This implies that even though a correlation exists over the whole period it ceased in 1975.

General Climate Trends for the Kananaskis Valley

In terms of general temporal trends in temperature, all of the stations had statistically significant increases occurring in winter and summer which in turn reflect significant

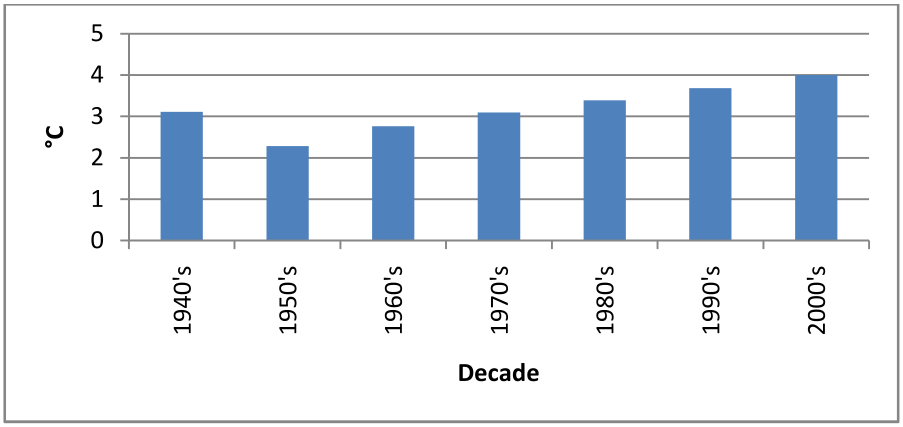

Figure 18: Decadal plot of mean air temperature at Kananaskis Field Station

trends in the annual scale, see Figure 18. Quantitatively, the statistically significant trends have greater magnitudes in the winter than in the summer. As well, Tmin and Tmean are observed to have a greater proportion of significant trends than Tmax and temperature range. When looking at the magnitude of these trends one can see that Tmin is increasing more than Tmean. Thus we can say that the region is getting less cold. The median increase of Tmean relative to Tmin and Tmax is a product of the unequal warming. As an average, the effect of a large rise in Tmin and a small rise in Tmax means that the change in Tmean will be between the Tmin and Tmax magnitudes of increase. The increases, in terms of Marmot Creek, can be related to elevation with the greatest increases occurring in lower elevations (CN5 and KFS) rather than the higher elevations (CB5 and TN1).

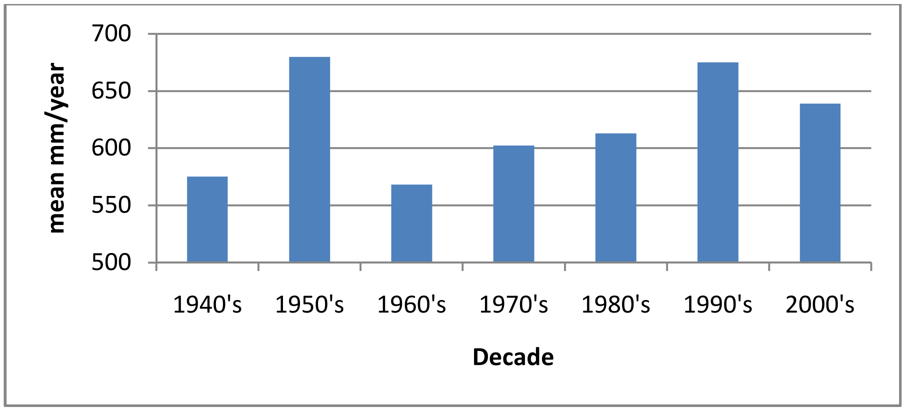

Figure 19: Decadal Plot of mean precipitation at Kananaskis Field Station

Overall the precipitation records for the region did not show general trends and example being at KFS, Figure 19. No statistically significant trends occurred in any of the records on an annual scale while the trends observed on a monthly scale did not show any consistency or correlation between stations or variables.

Stream flow

Analysis of the natural stream flow for the extended Middle Creek dataset showed several statistically significant trends as summarized by Table 8. The average ice-free season stream flow, as shown in the May-October mean, showed a statistically significant decrease. On the monthly scale, significant decreases in stream flow occurred in June and July. The combined effect of a decrease in the early summer melt months (June and July) and little change in the later summer results in a relative dampening of the extremes of the hydrograph. October does not follow this pattern as a small increase in monthly stream flow is noted to be statistically significant. In terms of spring peak runoff, the timing does not show a statistically significant trend or even a median trend, as it is observed to be zero. This finding is of note and can be seen plotted in Figure 21. The stream flow observed on the same day as the timing of peak spring runoff shows a statistically significant decreasing trend consistent with the decreasing flows observed in June, see Figure 20, the month in which the majority of spring peak flows occur.

Table 8: Mann-Kendall analysis of trend in Middle Creek Stream Flow

	May	June	July	August	September	October	May-October mean	Spring melt timing	Spring peak flow
	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	Julian days	m^3/s
Average	0.0827	0.1973	0.0946	0.0414	0.0331	0.0257	0.0786	158.6	0.3848
Median trend	-0.0004	**-0.0017**	**-0.0011**	-0.0001	0.0001	**0.0002**	**-0.0005**	0	**-0.0026**
Significance	0.81	**0.97**	**0.99**	0.64	0.74	**0.91**	**0.99**	0.63	**0.91**

†Significant trends are highlighted in red

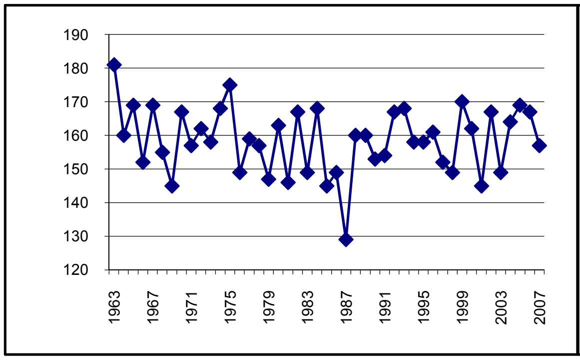

Figure 21: Middle Creek Spring Timing

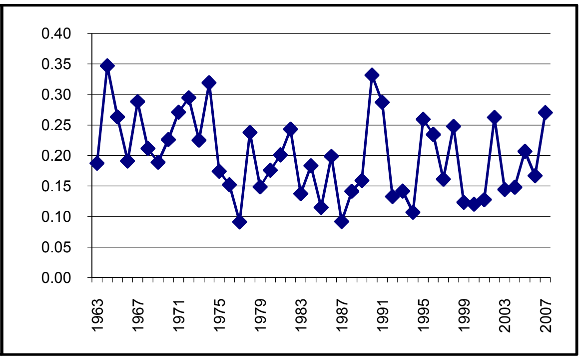

Figure 20: Middle Creek June Stream flow

While the median trend in the spring melt timing is zero there is considerable variation in the timing. Late season melts, see Figure 21, occurred in 1963, 1975, 1984, 1999 and 2005 and early melts occurred in 1969, 1976, 1987 and 2001. To further highlight the variation, June flows, as seen in Figure 20, exhibited the greatest variation of all months with large flows occurring in 1964, 1974, 1982, 1990 and 1995, 2002 and 2007 and relatively small flows in 1977, 1987, 1995 and 2000. This alternating high to low periodicity seems to occur on a decadal time scale. Within both data sets a step function seems to occur between 1975 and 1976. This timing and decadal periodicity coincides with the transition of the PDO, known to have a decadal frequency, into a warm phase from a cool phase. As the PDO elsewhere has been shown to affect the timing of the spring melt (Stewart et al., 2004) a correlation of stream flow data using the Kendall's tau (b) was conducted to see if the PDO was correlated to the stream flow timing data.

A relationship between timing of melt relative to the PDO index is observed in Figure 21. The relationships are inverse with cool phases of the PDO resulting in later spring melt and higher flows. The calculated Kendall's tau (b) correlation coefficients further validate this observation; see Table 9. While a correlation does exist it does not account for all of the variation in melt timing or June flow. No other components of Middle Creek stream flow were observed to be correlated at a statistically significant level, suggesting that the other components of the climate of the Kananaskis have a greater control on stream flow.

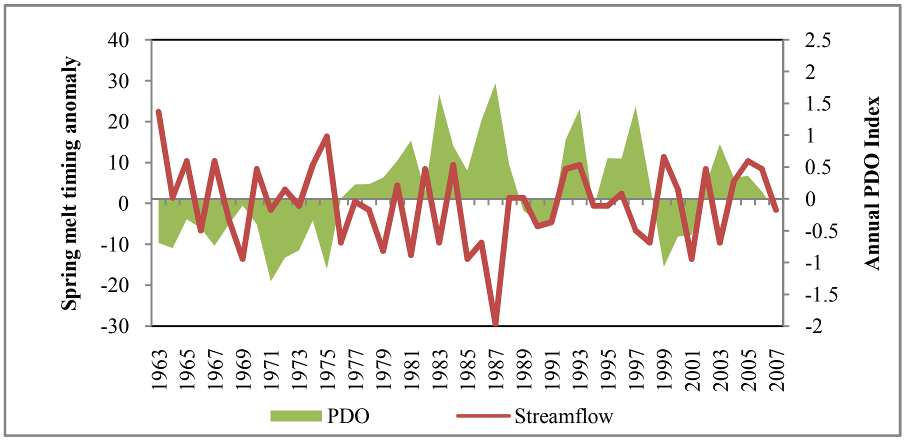

Figure 22: PDO and Spring Peak Timing Correlation

Table 9: PDO and Middle Creek Stream Flow Correlation

	timing	peak flow	May	June	July	August	September	October	Seasonal Mean
correlation coefficient	**-0.39**	-0.16	0.10	**-0.41**	-0.21	0.23	0.21	0.24	-0.21
significance	**0.01**	0.30	0.51	**0.01**	0.17	0.14	0.17	0.12	0.18

†Significant trends are highlighted in red

Rain to Snow transition

The Tcrit Marmot Creek at UC/UF (Figure 21) is about 3.8 °C while KFS and Pocaterra have Tcrit's of 3.8 °C and 3°C respectively, see Appendix E Figures 30 and 31. There is considerable scatter in the UC/UF plot due to the limited number of observations of precipitation events and consequently the relationship is not as well defined as at Pocaterra and KFS. Nonetheless an agreement between these three stations implies that the Tcrit at Marmot Creek, the most uncertain data set, is correct.

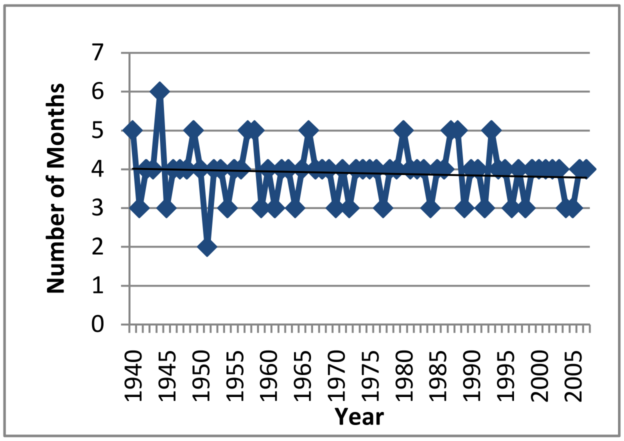

Figure 23: Number of Months at CB5 with Tmean ≥Tcrit

Error within these values undoubtedly exists though the analysis did not facilitate the calculation of error. Since Pocaterra and KFS have differentiated data already the application of the critical temperature is limited to Marmot Creek. The numbers of months per year computed to have a temperature greater than 3.8°C, most likely to experience rain rather than snow at CB5 is presented in Figure 23. The other stations can be seen in Appendix E, Figure 32 and 33. The MK test was unable to compute a statistic as too many ties existed in the data. Visual analysis implies a reduction in variability but no significant trends in the number of months with a Tmean greater than 3.8°C. The number of months showing a greater probability of rain is inversely related to altitude as CN5 has a greater number of months greater than 3.8°C than CB5 or TN1 which are at higher elevations.

Discussion

The trends observed in the Kananaskis Valley reflect similar trends observed in studies of similar regions. These changes reflect the common signature that has been attributed to anthropogenic climate change. Other factors such as the PDO also exert a significant control on the region, though at differing degrees of strength over time. The analysis of the extended Marmot Creek data in particular requires a certain level of caution due to assumptions made in the extension of the data. The trends observed, while significant, are a result of multiple causes, such as the PDO, increased radiative forcing and natural inter-annual variations, resulting in non-linear responses in observed climate.

Climate Reconstruction

The reconstruction of the Marmot Creek data merits discussion due to the assumptions involved. The most important assumption of the whole process is that the period of record used to develop a regression relationship is representative of the past and present climate and has not changed through time before or after the data collection period.

Several other problems exist. While NR was used for the climate reconstruction, a MK analysis of the residuals was not conducted, and constancy of the relationships was not calculated, due to the MK test having little power on short data sets. The NR regressed values were limited temporally thus any significant changes in the relationship would not have a large period to manifest themselves. The calibration period of the KFS regressions was also used as the validation period, and as such a bias is shown toward a stationary relationship (Type 1 error). The validation period used with the current stations was very short and a calculated environmental lapse rate was applied. While the lapse rate is calculated it cannot be assumed to be constant and may vary considerably over the year. These issues, though present, for the sake of this project were considered to be insignificant and thus the predicted values are considered to be satisfactory.

The regression relationships had an error which was inserted into the extended Marmot Creek data set. The average temperature error, see Table 2, was between 1-2°C. While the error was relatively small for the temperature data, it still made the resulting extended data set have a degree of uncertainty. In terms of the validity of the observed trends the error of the regression is greater than the observed median yearly changes. The trends observed are possibly due to variation in the error of the regressions alone. Although possible, this may not be the case as the observed trends for Marmot Creek show similar temporal and quantitative patterns as KFS and Pocaterra. When looking at the trend over the period of record the error is clearly less than the change.

The regression relationships in this study were taken to be linear, though there exists in some relationships a non linear tendency, such as in Figure 3, where at the lower range of temperature KFS shows lower temperatures than CB5. The regressions were taken to be linear as they were operationally simpler as well as had a physical basis. It was observed that the regressions at lower temperatures often showed greater variability and had lower values in the Marmot Creek stations relative to KFS. This is most likely due to the existence of temperature inversions in the winter occurring at Marmot but not at KFS. Thus the temperatures on the lower ranges of Tmean, Tmax and Tmin in winter at Marmot may be overestimated.

The regressed and extended precipitation data was of very poor quality, see Table 2, due to R^2 values in the 0.6 range and standard errors between 20 and 30mm/month. This error in some cases is greater than the observed precipitation. Though the precipitation data showed the relative trends it is not of high quality and not much confidence should be placed in it. Even though KFS and Marmot Creek are only 14 kilometers apart, there are considerable differences that have a great effect on precipitation. The first is elevation differences; more precipitation occurs at higher elevations (Dingman, 2002). Additionally, weather patterns are influence by the topography, resulting in orographic effects and wind flow disruption leading to precipitation events not occurring at both sites (Dingman, 2002). As well, this is compounded by the nature of convective rain storms, common in the region, as they are very localized and vary considerably in terms of precipitation rates over small spatial scales. The extended data set is essentially the elevation adjusted precipitation rate for Kananaskis and does not take into account local precipitation activity. The degree of confidence in this data is low.

The regression relationships used to establish the extended temperature data set for Marmot were of high quality as they were based on the monthly scale. The selection of a smaller time interval would lead to lower quality relationships and, subsequently, a data set with a larger uncertainty. Benefits for the use of smaller timescales include improved rain and snow separation over the time series. The increasing error of the relationships though would most likely nullify the benefits of an increase in temporal resolution.

Temperature

The trends observed in terms of temperature are consistent with other studies of western North America. The most significant and prevalent trend throughout all time series is that the Tmin is increasing at a rate greater than any other component of temperature and thus leading to the concept of the climate becoming “less cold”. This trend as observed by Bonsal et al. (2001),Vincent & Mekis (2004), and Zhang et al. (2000) has been shown to be occurring over all of southern Canada, especially the west. This increase in Tmin is due to the decrease in number of extreme minimum temperature events.

As is the case with uneven distribution of heating, greater increases in minimum temperature relative to maximum temperature results in a decrease in the temperature range. As can be seen in the data at KFS, the temperature range is consistently decreasing as well. This agrees with Bonsal et al. (2001) who also noticed that the temperature range is decreasing. Among other causes, such as decreasing extreme minimum temperature events, this may be due to increasing cloud cover which has been observed (IPCC, 2001). Shortwave radiation data does exist for the Kananaskis Valley though was not considered in this analysis and thus the primary reason for this decrease is not known, whether it be cloud cover or an increasing Tmin.

The greatest increase in temperature as observed to occur in winter concurs with other studies. Michaels et al. (2000), who found that up to 69% of observed warming occurs in the winter in the northern hemisphere, attributed the change to changing atmospheric emissivity and the positive water vapor-radiative feedback loop. As the Kananaskis Valley shows the greatest warming in the winter, is located in the northern hemisphere and experiences cold winter anticyclones, the water vapor-radiative feedback loop is the most likely cause of winter warming.

A possible reason that changes in temperature were not observed as frequently in the spring and fall relative to the winter and summer periods may be a type 2 error of the MK test. It has been noted that the power of the MK test has an inverse relation between power and variance (Yue et al., 2002). The spring and fall months are transition months between the extremes of winter and summer. Thus the variance of these months is much greater than other months. This increase in variance may be too much for the MK test. One cannot say that trends do not exist in these months due to possible type 2 errors.

The trends at KFS and Pocaterra are inconsistent with one another. Possible reasons for this may be a result of the record period, location and other climate controls. The primary difference may be due to the record lengths which are different. The MK test power has a positive relationship with record length thus the Pocaterra data set may not have the necessary length to allow the MK test to capture the trends, a type 2 error. This most likely is not the case, as the trends identified do not correspond between one another. The trends observed in the KFS dataset and not Pocaterra's may be because the datasets are representative of their respective periods which are different. Pocaterra provides an analysis of very recent climate changes while KFS and Marmot give a perspective of more long-term changes. The difference in location may also influence the trends; Pocaterra is located 50 kilometers south of KFS in the valley while KFS is in the foothills. Different factors may lead the climates to be a greater function of their local environment and not subject to large scale changes. These local effects most likely manifest themselves in the data and may produce noise in the record that negates the detection of a trend (Type 2 error) or alter trends so the trends detected are not representative of the climate change signal (Type 1 error). The two periods as well may be products of different climate controls. As explained by the results of the PDO correlation, the KFS dataset may represent a climate coupled over the entire record to the PDO while the Pocaterra data is representative of a decoupled climate. While the two datasets may be different, greater confidence is place upon the KFS dataset as it is longer, thus the MK test is more powerful (fewer Type 2 errors), and of higher quality (fewer type 1 errors).

The combined effects of the increasing minimum temperature, greater warming in winter and reduction in temperature range has large hydrologic implications. The greatest implications hydrologically relate to the snowpack, as it may experience changes in accumulation, redistribution and melt due to it receiving greater amounts of energy. The result of this has been shown to lead to smaller snowpacks (Burn, Hydrologic effects of climatic change in west-central Canada, 1994). The implications of this for stream flow will be discussed later.

Temperature Variability

The common trend of temperature variability for North America is that it is decreasing (IPCC, 2001). The two stations tested for variability, KFS and Pocaterra, showed opposite trends. Some possible reasons for the discrepancies between these sites have been discussed previously. KFS contradicts the common theme of the literature as its variability is increasing. Thus other local controls must be dominating the variability as it does not follow an observed climate change signature. The variability of Pocaterra is not uniformly increasing or decreasing. However, in the fall and winter a trend of decreasing variability is observed. This agrees with literature that states that cloud cover is increasing and extreme temperatures are decreasing, both of which lead to less variability (Hardy, 2003). The trends observed are not consistent and inadequate to discuss possible reasons or consequences.

Precipitation

There were few observed trends and ones observed were inconsistent. Possible reasons for this are that there are few trends to begin with; the temporal scale is too large; or there is large variability within the datasets. In terms of Marmot Creek, this may be due to the regression relationships used which are inaccurate to the point of being operationally useless.

The lack of trends observed in the data may be because there are no trends. Precipitation is a highly variable conditional process that is a result of many components of the climate system interacting. The relative importance of each system is relative and may have differing sensitivities to climate change. Other reasons may be that even with documented increase in water vapor in the atmosphere, the rain shadow effect, which dominates control of the Kananaskis Valley, may negate any changes.

The temporal scale may also inhibit the detection of trends (type 2 error). Zhang et al. (2000) found that what changed in terms of precipitation patterns was that total number of rainy days increased while extreme events and total precipitation increased at a lesser rate. The monthly scale of this analysis did not facilitate the consideration of this variable. Thus while the monthly scale did not observe a trend the daily scale might have (type 2 error).

Precipitation data, of all the variables considered, had the greatest variability and thus the power of the MK test was severely reduced. The variability is a result of precipitation being the sum of individual events that may or may not occur every month. This is most likely the greatest contributor to a lack of trends identified. As well the differences in the trends that were observed between KFS and Pocaterra are likely due to actual differences between the two data sets. Precipitation is a spatially variable process and it is not a surprise that the trends do not show a coupling.

Rain to Snow Transition

The procedure employed to differentiate the Marmot Creek precipitation into rain or snow and to determine any changes was unsatisfactory. The problem is that the number of months calculated to have a daily mean temperature greater than 3.8°C do not vary greatly and the Mann Kendall test cannot compute a statistic due to the large number of ties in the data; V(S) equation 4 cannot be computed. Thus the analysis must be done visually and subsequently the unquantified trend and significance is considered to be negligible and most likely not statistically significant. While the method, due to its coarse nature, cannot determine a trend one can note that the number of months > 3.8°C varies by station and is related to elevation. This is due to the environmental lapse rate as the lowest station CN5 has the largest number of months > 3.8°C while TN1, the highest station has the lowest number of months > 3.8°C. What really limits this analysis is that the Tmean of a month may have little correlation to the actual temperature during a precipitation event. The probability of predicting a conditional event with the mean temperature of the month is very low.

When considering trends in precipitation separation, the variable for %rain at KFS and Pocaterra is examined. The months of the year in which this variable is most dynamic is in April, May, September and October. Since precipitation separation varies greatly over April, May, September and October these months are the most sensitive to any changes in Tmean. Of these identified months, only Tmean has a significant trend in October for CB5 and TN1 and it is decreasing. This corresponds with the observed change in %rain at KFS. KFS showed a statistically significant decrease in %rain and an increase in snow fall. While not being able to quantify a change in the proportion of rain to snow, a change is most likely of all of the transition months to occur in October and to be in the direction of less rain and more snow. This procedure is unsatisfactory due to its lack of temporal detail and further study is recommended.

Further work is needed to properly address this important factor. The development of a snow to rain transition curve based on the probability of snow or rain at a certain temperature would provide a much better analytical tool with to assess possible changes in the rain snow transition due to temperature. Development of such a curve was attempted but was limited due to the short record length as well as unclear rain and snow events. With a longer data set and better rain and snow separation a transition curve most likely can be developed. With such a tool the percentage of precipitation falling as rain can be assessed, which has a much finer resolution than the Tcrit approach.

Stream flow

The stream flow at the outlet of a basin and any changes observed in it are the result of the integrated response of the basin to changes in climate. Marmot Creek has undergone significant land use changes and thus steps must be taken to remove these impacts from the analysis. Middle Creek, which has natural flow, was reconstructed with a regression based on the post disturbance Marmot Creek stream flow. The timing of the peak has been shown not to change while any changes in flow due to logging in Marmot Creek are accounted for as the regression is based on the post logging period. As such, the reconstructed Middle Creek can be considered to be representative of natural flow.

The observed trends of decreasing mean ice-free flow (May-October), June, July and peak flow are consistent with findings of Burn (1994), Burn & Elnur (2002), Stewart et al. (2004), Yue et al. (2003) and Zhang et al. (2000). The trends observed among these inter-annual variations can be related to climate variables. Temperature is observed to have an inverse relationship with snowpack size and average stream flow while a positive relationship with snowmelt timing exists. As Marmot Creek stream flow is snowmelt-dominated, the spring melt is of hydrologic importance and sensitive to changes in temperature. Thus with the observed changes in temperature, in the reduced snowpack, due to mid-winter melts and/or possibly the change of snowfall to rainfall, less snow is available to melt and thus smaller spring peak flows occur. Studies have shown that the peak flows across North America have also been occurring earlier. This is not the case in Marmot Creek.

The bulk of the change in stream flow is most likely due to a change in temperature rather than precipitation. Of the trends examined, little evidence is seen for any significant changes in precipitation, see Figures 13-15. Precipitation change would have a great effect, but as it is not, changing temperatures have the primary effect, see Figures 8-13. The increase in temperature, with its impact on spring melt and rain snow transition discussed, may cause the evapotranspiration duration to increase as well. In summer months when evapotranspiration rates are greatest, little change is observed in the stream flow. Thus the predicted changes due to increased evapotranspiration duration have not been observed. As the basin's hydrology is snow melt dominated, the observed trends of increasing temperatures and their effects on the snowpack are considered to have the greatest impact. With mid winter temperature increases the chance of mid winter melts increases as well as higher amounts rainfall versus snowfall. Both processes reduce the size of the snowpack that may be melted. Though mid winter melt water can be stored in basal or stream ice. Smaller snowpacks hydrologically will result in reduced spring stream flow and consequently a reduced recession limb.

PDO and Inter-Annual Variability

The temperature and precipitation of a region are linked to atmospheric circulation and reflect variations that may occur due to changes in the circulation (Stewart et al., 2004). Thus certain climate controls such as the PDO have an effect on the inter-annual variation of temperature and precipitation. Since stream flow is the integrated climate response of a basin, the PDO signature should be detectable in this record. In terms of Middle Creek, a statistically significant correlation exists between the PDO indices and spring timing and June flow. These two components are directly related, as June flow is related to the timing of spring melt. The PDO index has been shown elsewhere to be related positively to temperature (Mantua, 2001). Thus during warm phases, with corresponding warm temperatures, more energy is available to snowmelt and an earlier snowmelt and spring runoff is observed. The spring peak often occurs in late May to the end of June and so the earlier the melt the larger proportion of melt water production occurs in June resulting in a larger mean monthly streamflow. As these warm periods correspond to less snowfall, the snowpacks are smaller, resulting in less snow available to be melted and correspondingly having low flows. The PDO, while it does have effect on the stream flow, does not account for all of the variation. This can be seen in Table 15 as the correlation coefficients are only around 0.4, meaning the PDO can only explain 40% of the variation. As well, the weakening of the PDO and temperature relationship, as seen in Table 15, shows that the climate system is changing in some way which is making the PDO less of an explanation of inter-annual variation.

The PDO has been shown to have significant control over the temperature and precipitation of north western North America (Stewart et al., 2004; Mantua, 2001). In the Kananaskis Valley this correlation exists between the PDO and temperature, but not with precipitation, as can be seen in Table 15. This lack of correlation in precipitation may be due to the variability of the data set (Type 2 error) or may mean that the linkage is simply not very strong, although the correlation of the PDO changes over time as shown in Table 15. This decoupling of the correlation may be a result of a number of factors. One can always argue that the correlation used in this analysis does not define causality; thus the correlations are entirely due to chance. This assumption is deemed to be false as other studies have determined that a causal relationship does exist (Stewart et al., 2004).

Another cause for the perceived decoupling may be that the point for the comparison of correlation, 1975, is the same as the switch from the cool to warm phase in the PDO. The period was chosen because a distinct step function seemed to occur at this time in most of the data sets, such as spring peak timing and mean temperature. A possible reason this could be is that the cool phase has a much stronger relationship to the continental climate relative to the warm phase. This would explain the greater correlation in the pre 1975 period than the post 1975 period. This time period also coincides with the starting point of the beginning of the latest warming period (IPCC, 2001). Thus the warming from anthropogenic forcing may result in it overwhelming the PDO signal and resulting in the PDO having a smaller influence upon climate. The PDO, while still affecting inter-annual variability, does not exert a significant control relative to anthropogenic forcings.

In the calculation of the PDO index the global seas surface temperature anomaly is removed (Mantua, 2001). This may provide another explanation for the decoupling of the index from the observed climate data. While the sea surface temperatures may be rising in absolute terms, the removal of the anomaly from the index may misrepresent the linkage between the ocean and the atmosphere. With the increase in the observed rate of warming beginning in the 1970s, the corrected PDO index may not reflect accurately the current changes in the climate that it represented well in the past.

The PDO has been shown to account for some of the variability in climate but not all of it (Stewart et al., 2004). The relative strengths of the relationships between warm and cool phases and climate, to the authors knowledge, have not been mentioned in the literature and thus most likely not the case. With the well-documented anthropogenically induced warming trends, the overriding of the PDO signal is the most likely cause.

Nonetheless, the fact is that climate changes do not occur always in a linear manner (Hardy, 2003). The step function noticed in the1975 period, while coinciding with the switch in PDO phase, is also the point where anthropogenic warming is shown to have increased its rate of warming (IPCC, 2001). These processes may not be independent of one another. It may be an example of a tipping point in the ocean's thermal capacity to absorb heat due to anthropogenic forcing without exhibiting any changes previously. This study is not meant to be an attribution study, though a detailed analysis of a climate record cannot occur without preliminary explorations of potential causes.

Conclusion

Analysis of the Kananaskis Valley climate and hydrometric data sets reveals the existence of trends in the observed variables. Most of these trends agree with other observed trends from the regional to the continental scale. These trends include a climate that is "less cold" (Bonsal et al., 2001; IPCC, 2001; Vincent & Mekis, 2004; Zhang et al., 2000), greater proportion of warming in winter (IPCC, 2001;Michaels et al., 2000), reduction in temperature range (Bonsal et al., 2001; Hardy, 2003; IPCC, 2001; Zhang, et al., 2000), reduced spring peak stream flow (Burn, 1994; Burn & Elnur, 2002; Zhang et al., 2000; Rango & Katwijk, 1990) as well as decreased monthly spring as well as annual stream flows (Zhang et al., 2000; Rango & Katwijk, 1990; Burn & Elnur, 2002). Trends that are observed in other studies but not in the Kananaskis include reduced temperature variance (Bonsal et al., 2001; IPCC, 2001), increases in precipitation (Groisman & Easterling, 1994; Zhang et al., 2000), change in snow and rain proportion (Zhang et al., 2000; Lapp et al., 2005), as well as earlier stream flow timings (Burn, 1994; Rango & Katwijk, 1990; IPCC, 2001; Stewart et al., 2004; Zhang et al., 2000). The data sets examined show that the Kananaskis Valley is subject to the inter-annual variations related to the PDO which is a known control of climate (Mantua, 2001; Stewart et al., 2004). The relative strength of this linkage, however, may be changing.

The lack of confirmation of all trends may be due to the coarse temporal scale of the analysis that may not show fine scale trends. The implications for the Kananaskis Valley, if these trends were to continue, is for a greater frost-free season, fewer extreme cold spells, overall warmer temperatures, increased evapotranspiration and reduced stream flow (Bonsal et al., 2001; IPCC, 2001). The observed changes hydrologically will be closely tied to the change in temperature. As has been seen in the Kananaskis Valley temperature can be related to reduced spring peak stream flow as well. Primarily this is a result of smaller snowpacks. While precipitation has not been shown to be changing the greater occurrence of mid winter melts and greater proportion of precipitation as rain, not observed though hypothesized are the primary causes of this change. The assimilative capacity of the hydrologic system to these hydroclimatic changes will define if these impacts will result in great changes to the hydrology of the region.

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Appendix A: Data Summary

Table 10: Daily Data Summary for the Kananaskis Valley

Station Name	Location	Elevation (m)	Variables†	Period of Record	Years	Percentage Missing Data
Kananaskis	51° 1.800' N 115° 1.800' W	1391.1	Tmean	1939-2007	69	3
			Tmin	1939-2007	69	3
			Tmax	1939-2007	69	2
			rain	1939-2007	69	1
			Snow	1939-2007	69	1
			Prcp	1939-2008	69	2
Pocaterra	50° 42.600' N 115° 7.200' W	1610	Tmean	1976-2007	32	17
			Tmin	1976-2007	32	14
			Tmax	1976-2007	32	16
			rain	1976-2007	32	12
			Snow	1976-2007	32	12
			Prcp	1976-2007	32	12
Nakiska Ridgetop	50° 56.400' N 115° 11.400' W	2543	Tmean	1994-2007	14	25
			Tmin	1994-2007	14	24
			Tmax	1994-2007	14	25
Cabin 5	50° 58' N 115° 11' W	2170	Temp	1966-1987	22	6
			Prcp	1973-1986	14	14
Confluence 5	50° 58' N 115° 10' W	1753	Temp	1968-1987	20	2
			Prcp	1969-1986	18	13
Twin 1	50° 58' N 115° 11' W	2286	Temp	1966-1987	22	8
			Prcp	1969-1986	18	20
Vista View	50° 58' 15"N 115° 10' 19"W	1956	Temp	2006-2007	2	0
Upper Clearing	50° 57' 23"N 115° 10' 31" W	1844.6	Temp	2005-2007	3	1
			Prcp	2005-2007	3	1
Upper Forest	50° 57' 24"N 115° 10' 34" W	1890.7	Prcp	2005-2007	3	0
Fiserra Ridge	50° 57' 24" N 115° 12' 15"W	2325.3	Temp	2006-2007	2	9
Middle Creek	50° 57' 30" N 115° 11' 56" W		Flow	1963-1986	24	3
Marmot Creek ‡	50°57'1" N 115°9'8" W		Flow	1962-2007	46	0

† Abbreviations: Tmean=mean temperature, Tmin=minimum temperature, Tmax=maximum temperature, Prcp= precipitation, Temp=temperature, Flow= Stream flow

‡ Continuous recording from 1962-1986 and then switched to seasonal (May to October) from 1987-2007

Appendix B: Results of Mann-Kendall Analysis

Table 11: Mann-Kendall analysis of trend for KFS regression residuals

Station	Variable	January	February	March	April	May	June	July	August	September	October	November	December	Annual
CB5	Tmax	0.825	0.5	0.182	0.142	0.595	0.128	0.72	0.653	0.59	0.157	0.337	0.182	0.376
	Tmin	0.686	0.825	0.385	0.072	0.476	0.602	0.809	0.512	0.752	0.109	0.758	0.029	0.076
	Tmean	0.818	0.584	0.41	0.005	0.5	0.238	0.858	0.607	0.879	0.128	0.65	0.029	0.288
	Prcp	0.267	0.562	0.622	0.32	0.419	0.775	0.269	0.316	0.684	0.476	0.473	0.825	0.763
CN5	Tmax	0.825	0.5	0.182	0.142	0.595	0.128	0.72	0.653	0.59	0.157	0.337	0.182	0.376
	Tmin	0.686	0.825	0.385	0.072	0.476	0.602	0.809	0.512	0.752	0.109	0.758	0.029	0.076
	Tmean	0.818	0.584	0.41	0.005	0.5	0.238	0.858	0.607	0.879	0.128	0.65	0.029	0.288
	Prcp	0.267	0.562	0.622	0.32	0.419	0.775	0.269	0.316	0.684	0.476	0.473	0.825	0.763
TN1	Tmax	0.772	0.843	0.04	0.436	0.472	0.034	0.043	0.011	0.304	0.376	0.47	0.248	0.105
	Tmin	0.772	0.885	0.615	0.5	0.709	0.583	**0.914**	0.63	**0.942**	0.337	0.311	0.236	0.217
	Tmean	0.791	0.809	0.337	0.627	0.487	0.201	**0.919**	0.428	**0.955**	0.363	0.248	0.128	0.689
	Prcp	0.214	0.5	0.5	0.675	0.268	0.5	0.222	0.411	0.786	0.69	0.187	**0.901**	0.251

†Significant trends are highlighted in red

Table 12: Mann-Kendall analysis of trend for KFS 1939-2007

Variable		January	February	March	April	May	June	July	August	September	October	November	December	Annual
Tmean	median trend	**0.051**	**0.052**	**0.058**	**0.020**	0.013	**0.021**	**0.013**	0.010	-0.002	-0.013	0.017	-0.012	**0.020**
	Significance	**0.949**	**0.974**	**0.998**	**0.900**	0.879	**0.993**	**0.959**	0.834	0.544	0.877	0.752	0.719	**0.999**
Tmin	median trend	**0.076**	**0.066**	**0.068**	**0.019**	0.009	**0.016**	**0.015**	0.012	0.003	-0.005	**0.045**	0.011	**0.029**
	Significance	**0.986**	**0.988**	**0.999**	**0.969**	0.875	**0.994**	**0.994**	0.887	0.633	0.677	**0.979**	0.655	**1.000**
Tmax	median trend	0.033	**0.035**	**0.048**	**0.028**	0.010	**0.024**	0.006	0.011	0.000	**-0.022**	0.006	-0.017	**0.013**
	Significance	0.891	**0.948**	**0.997**	**0.913**	0.788	**0.988**	0.681	0.773	0.504	**0.919**	0.591	0.808	**0.974**
Temperature Range	median trend	**-0.032**	**-0.024**	**-0.021**	-0.003	0.001	0.009	-0.013	0.001	-0.001	**-0.016**	**-0.040**	**-0.027**	**-0.011**
	Significance	**0.998**	**0.975**	**0.972**	0.591	0.524	0.841	0.867	0.520	0.520	**0.928**	**1.000**	**0.999**	**0.987**
Rain	median trend	**0.000**	0.000	**0.000**	**0.021**	-0.092	0.400	-0.229	-0.027	0.210	-0.039	**0.000**	0.000	0.576
	Significance	**1.000**	0.610	**1.000**	**0.970**	0.641	0.834	0.875	0.520	0.879	0.745	**0.967**	0.560	0.770
Snow	median trend	-0.029	**-0.204**	-0.013	0.081	0.063	0.000	0.000	0.000	**0.000**	**0.201**	0.129	-0.069	0.241
	Significance	0.595	**0.947**	0.552	0.644	0.821	0.749		0.836	**0.989**	**0.979**	0.871	0.739	0.644
Precipitation	median trend	-0.070	**-0.279**	-0.033	-0.043	0.192	0.020	-0.208	0.018	**0.379**	0.095	0.029	-0.156	0.331
	Significance	0.758	**0.989**	0.614	0.595	0.749	0.532	0.858	0.516	**0.941**	0.794	0.599	0.894	0.663
Percent Rain	median trend	**0.000**	0.000	**0.000**	**0.000**	-0.102				**0.000**	**-0.250**	**0.000**	0.000	0.097
	Significance	**1.000**	0.603	**1.000**	**0.933**	0.834				**0.969**	**0.954**	**0.919**	0.773	0.879
Tmean STDEV	median trend	-0.006	-0.0032	-0.008	0.0084	0.0059	0.001	-0.0042	0.0023	0	0.003	0.0058	0.0115	0.001704
	Significance	0.606	0.599	0.755	0.867	0.836	0.622	0.851	0.758	0.508	0.663	0.677	0.770	0.647
Tmin STDEV	median trend	-0.005	-0.005	**-0.0196**	0.0092	**0.007**	**0.0091**	**0.0062**	0	0.0039	**0.01**	0.0075	0.008	0.002158
	Significance	0.614	0.691	**0.915**	0.846	**0.968**	**0.997**	**0.985**	0.520	0.794	**0.911**	0.739	0.722	0.708
Tmax STDEV	median trend	-0.0064	-0.0072	-0.0021	**0.0103**	**0.0118**	-0.0012	-0.0055	**0.0083**	0.0014	0.0032	-0.0004	0.009	0.002542
	Significance	0.595	0.719	0.567	**0.919**	**0.959**	0.556	0.839	**0.913**	0.587	0.626	0.512	0.767	0.758
Temperature Range STDEV	median trend	-0.0053	**-0.0105**	-0.0038	**0.0113**	**0.01**	**0.0057**	**0.0083**	**0.0069**	0.005	-0.0012	-0.0055	-0.0004	0.000649
	Significance	0.659	**0.900**	0.695	**0.986**	**0.980**	**0.903**	**0.957**	**0.946**	0.821	0.560	0.739	0.516	0.598

† Blank significance cells denote that the test due to an excessive number of ties in the data could not compute the Z

‡Significant trends are highlighted in red

Table 13: Mann-Kendall analysis of Trend for Pocaterra 1976-2007

Variable		January	February	March	April	May	June	July	August	September	October	November	December	Annual
Tmean	median trend	**0.175**	-0.008	-0.002	0.007	0.042	-0.028	**0.046**	0.008	0.002	-0.019	**0.119**	**0.155**	**0.059**
	significance	**0.936**	0.552	0.540	0.648	0.867	0.813	**0.901**	0.591	0.516	0.729	**0.969**	**0.946**	**0.962**
Tmin	median trend	**0.222**	-0.083	-0.021	-0.011	-0.004	0.018	0.028	-0.051	**-0.047**	-0.018	0.091	0.124	0.040
	significance	**0.954**	0.752	0.540	0.629	0.556	0.729	0.877	0.875	**0.961**	0.666	0.853	0.841	0.894
Tmax	median trend	**0.115**	0.042	-0.011	0.051	**0.081**	**-0.078**	**0.110**	0.083	0.079	-0.029	0.082	**0.168**	**0.084**
	significance	**0.907**	0.767	0.641	0.826	**0.916**	**0.961**	**0.984**	0.879	0.862	0.659	0.802	**0.962**	**0.995**
Temperature Range	median trend	**-0.085**	**0.139**	0.021	0.039	**0.083**	**-0.081**	**0.096**	**0.122**	**0.139**	-0.007	-0.033	0.060	**0.020**
	significance	**0.900**	**0.984**	0.716	0.811	**0.966**	**0.989**	**0.973**	**0.988**	**0.981**	0.571	0.702	0.871	**0.916**
Rain	median trend	**0.000**	**0.000**	0.000	0.000	0.525	**1.975**	-0.211	-0.845	-0.037	**0.656**	**0.000**	**0.000**	0.233
	significance	**0.965**	**0.964**	0.858	0.802	0.785	**0.994**	0.652	0.841	0.552	**0.957**	**0.907**	**0.944**	0.856
Snow	median trend	**1.063**	0.093	-0.055	0.000	**-0.335**	0.000	0.000	0.000	-0.105	-0.035	0.371	**-1.000**	**-2.250**
	significance	**0.936**	0.516	0.556	0.500	**0.942**	0.779	0.745	0.524	0.877	0.532	0.791	**0.963**	**0.928**
Precipitation	median trend	0.781	0.000	-0.061	-0.186	0.183	**1.755**	-0.211	-0.815	-0.470	**0.541**	0.278	**-0.852**	1.709
	significance	0.896	0.500	0.532	0.629	0.524	**0.975**	0.652	0.841	0.726	**0.900**	0.709	**0.925**	0.688
Percent Rain	median trend	**0.000**	**0.000**	0.000	0.000	**0.011**				0.000	0.008	**0.000**	**0.000**	0.004
	significance	**0.969**	**0.964**	0.858	0.702	**0.965**				0.755	0.813	**0.922**	**0.944**	0.871
Tmean STDEV	median trend	0.0429	-0.025	0.0297	**-0.0412**	0.001	-0.0053	-0.0122	**0.0196**	-0.0152	**-0.0508**	**-0.0806**	**-0.075**	**-0.0217**
	significance	0.785	0.726	0.824	**0.913**	0.500	0.670	0.688	**0.916**	0.705	**0.913**	**0.984**	**0.919**	**0.932**
Tmin STDEV	median trend	0.0663	-0.0322	-0.0217	-0.0259	**0.0347**	-0.0068	-0.0148	-0.0023	**-0.0373**	-0.0255	-0.0325	**-0.0871**	-0.0232
	significance	0.883	0.698	0.648	0.791	**0.991**	0.540	0.896	0.508	**0.982**	0.791	0.749	**0.995**	0.869
Tmax STDEV	median trend	0.0147	-0.0304	**0.0558**	-0.0225	0.0018	0.01	-0.0277	0.0127	0	-0.0063	**-0.1025**	-0.0683	-0.0163
	significance	0.595	0.655	**0.941**	0.883	0.548	0.695	0.889	0.655	0.500	0.610	**0.977**	0.871	0.782
Temperature Range STDEV	median trend	0.0392	0.035	-0.0125	-0.0215	0.0212	0.0291	-0.0081	**0.0695**	**0.0478**	0.0281	0.0151	-0.0092	0.0169
	significance	0.875	0.943	0.648	0.802	0.844	0.862	0.603	**0.996**	**0.946**	0.813	0.659	0.633	0.848

† Blank significance cells denote that the test due to an excessive number of ties in the data could not compute the Z

‡Significant trends are highlighted in red

Table 14: Mann-Kendall analysis of trend for extended Marmot Creek, 1939-2007

Variable		January	February	March	April	May	June	July	August	September	October	November	December	Annual
CB5														
Tmean	median trend	**0.0581**	**0.0436**	**0.0371**	0.0044	-0.0083	**0.0135**	**0.0163**	**0.0153**	0.0036	**-0.0206**	0.0028	0	**0.0162**
	significance	**0.989**	**0.987**	**0.987**	0.610	0.773	**0.908**	**0.971**	**0.933**	0.618	**0.974**	0.552	0.508	**0.998**
Tmin	median trend	**0.0791**	**0.0662**	**0.0476**	0.0096	0.0025	**0.0185**	**0.0358**	**0.035**	**0.0162**	-0.0056	0.0199	0.0136	**0.0305**
	significance	**0.998**	**0.998**	**0.997**	0.773	0.614	**0.995**	**1.000**	**1.000**	**0.963**	0.719	0.819	0.709	**1.000**
Tmax	median trend	**0.0515**	**0.0245**	**0.0254**	-0.0015	**-0.0236**	0.0013	-0.0055	-0.0025	-0.0102	**-0.0304**	-0.0057	-0.0048	0.0021
	significance	**0.979**	**0.916**	**0.925**	0.524	**0.957**	0.548	0.670	0.571	0.698	**0.985**	0.641	0.567	0.633
Precipitation	median trend	-0.0443	**-0.2242**	-0.0401	-0.0171	0.2502	-0.0819	-0.1224	0.0811	**0.2307**	0.0424	0.0291	-0.0722	0.4375
	significance	0.726	**0.988**	0.659	0.571	0.834	0.641	0.776	0.637	**0.905**	0.659	0.599	0.808	0.800
CN5														
Tmean	median trend	**0.071**	**0.0586**	**0.0477**	0.0149	0.001	**0.0189**	**0.021**	**0.0229**	0.0095	-0.014	0.0156	0.0096	**0.0277**
	significance	**0.996**	**0.997**	**0.998**	0.841	0.532	**0.962**	**0.997**	**0.987**	0.834	0.896	0.752	0.670	**1.000**
Tmin	median trend	**0.1022**	**0.0879**	**0.07**	**0.0217**	**0.013**	**0.0274**	**0.0426**	**0.041**	**0.0256**	0.0047	**0.0391**	0.0295	**0.0467**
	significance	**1.000**	**1.000**	**1.000**	**0.975**	**0.934**	**1.000**	**1.000**	**1.000**	**0.999**	0.663	**0.978**	0.894	**1.000**
Tmax	median trend	**0.0508**	**0.0284**	**0.0326**	0.0041	-0.0154	0.0133	0.0053	0.0133	0.0019	**-0.0248**	-0.0015	-0.0067	**0.0094**
	significance	**0.969**	**0.924**	**0.970**	0.622	0.873	0.873	0.698	0.826	0.567	**0.937**	0.548	0.633	**0.945**
Precipitation	median trend	-0.0372	**-0.1943**	-0.0822	-0.0411	0.2808	-0.1527	-0.0992	0.0789	**0.2505**	0.0467	0.0224	-0.0664	0.4045
	significance	0.736	**0.984**	0.802	0.587	0.855	0.695	0.764	0.674	**0.926**	0.698	0.606	0.797	0.742
TN1														
Tmean	median trend	**0.0494**	**0.0337**	**0.0339**	-0.0019	-0.0058	**0.0147**	**0.0234**	**0.0221**	0.0051	**-0.0213**	-0.0018	-0.005	**0.0145**
	significance	**0.984**	**0.946**	**0.974**	0.567	0.729	**0.915**	**0.998**	**0.974**	0.677	**0.969**	0.536	0.599	**0.999**
Tmin	median trend	**0.0678**	**0.0514**	**0.0393**	0.001	-0.001	**0.0175**	**0.0395**	**0.0389**	**0.0133**	-0.0118	0.0107	-0.0023	**0.0248**
	significance	**0.995**	**0.987**	**0.989**	0.567	0.548	**0.992**	**1.000**	**1.000**	**0.903**	0.853	0.691	0.548	**1.000**
Tmax	median trend	**0.0356**	0.011	0.0193	-0.0029	**-0.0174**	0.0102	0.0089	0.0125	0	**-0.03**	-0.0104	-0.013	0.0023
	significance	**0.945**	0.729	0.875	0.579	**0.901**	0.834	0.808	0.871	0.500	**0.977**	0.736	0.776	0.666
Precipitation	median trend	-0.0264	**-0.2205**	-0.0376	0.0143	0.3439	-0.1549	-0.1431	0.0666	**0.2752**	0.034	0.0547	-0.0706	0.7102
	significance	0.610	**0.986**	0.637	0.524	0.885	0.688	0.811	0.591	**0.918**	0.644	0.698	0.758	0.862

†Significant trends are highlighted in red

†Significant trends are highlighted in red

Appendix C: Relative Contributions of Twin and Cabin Creek to Middle Creek

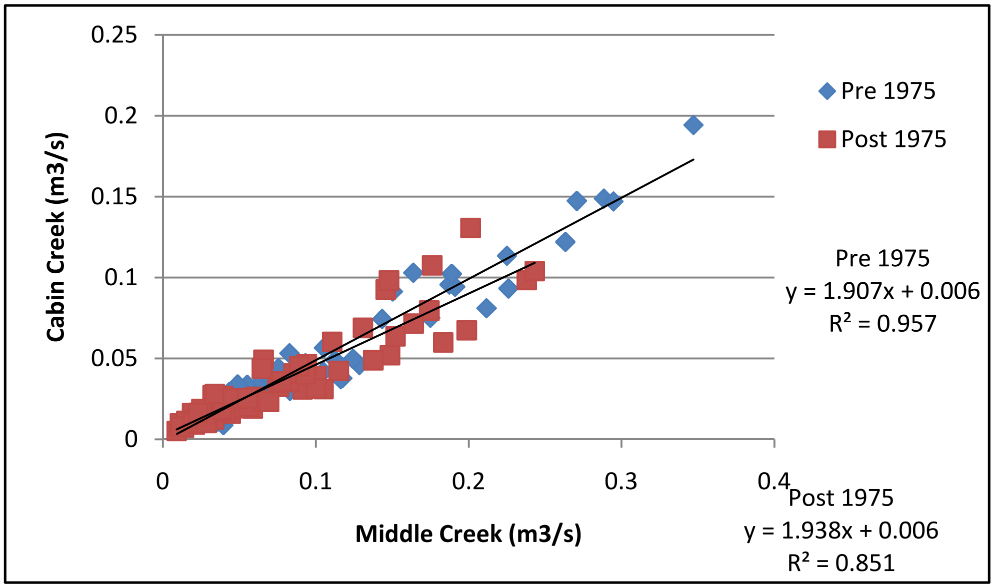

Figure 24: Middle vs. Cabin Creek Monthly Stream flow 1963-1986

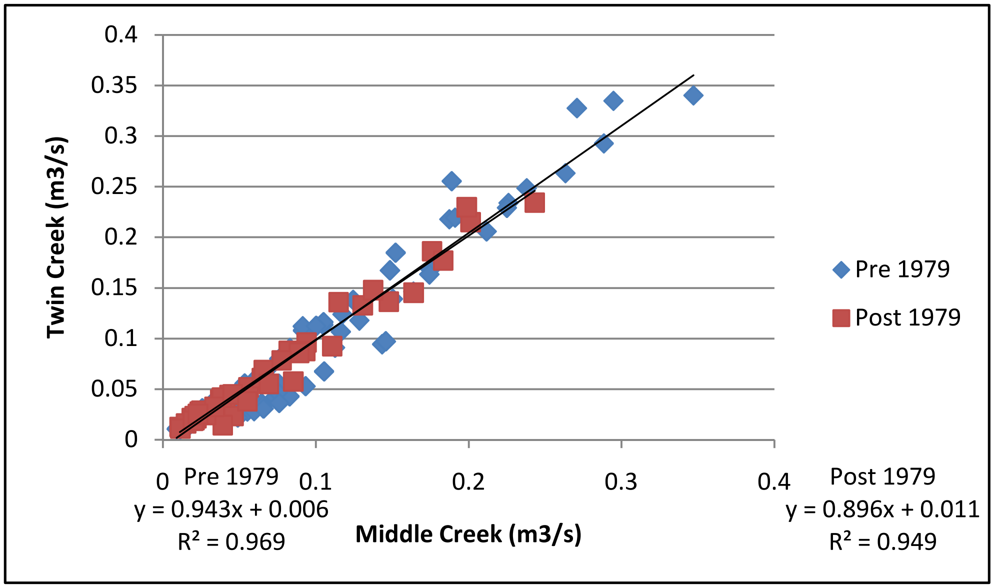

Figure 25: Middle vs. Twin Creek Monthly Stream flow 1963-1986

The agreement between the relative contributions of stream flow between basins for before and after logging activity suggest that the logging has not had an effect on monthly stream flow.

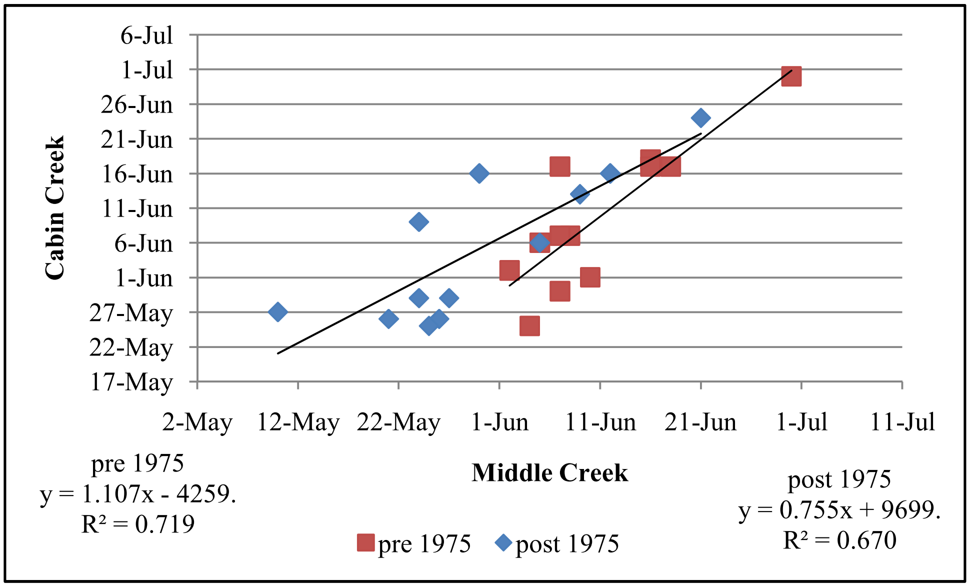

Figure 26: Cabin vs. Middle Creek Spring melt timing

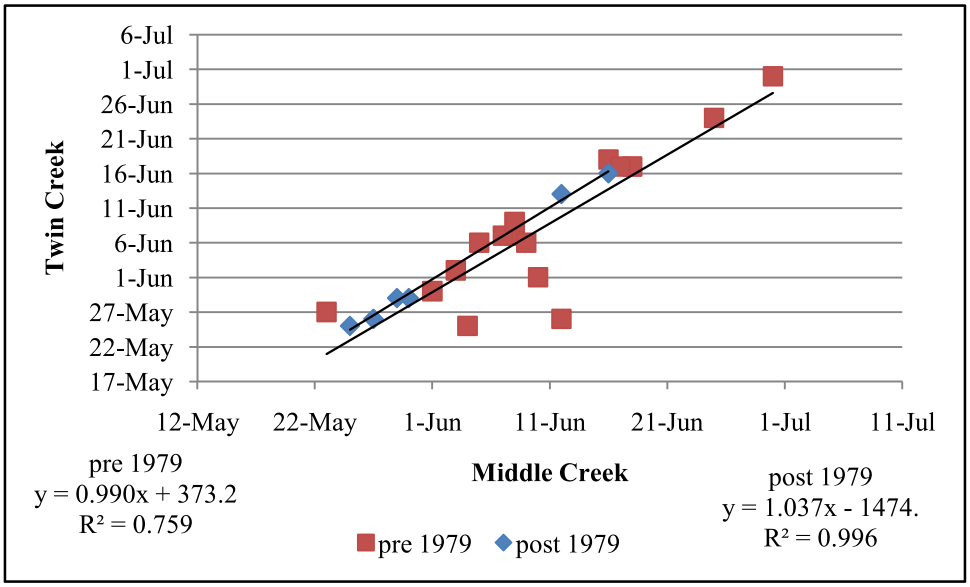

Figure 27: Twin vs. Middle Creek Spring melt timing

The effect of the logging activity shows an effect in the consideration of spring peak timing though the greatest changes occur in Cabin creek rather than Twin creek. Twin Creek and Middle Creek comprise the bulk of stream flow and as such the change in Cabin creek does not have a great effect. Regression of peak timing is computed over the whole period of record.

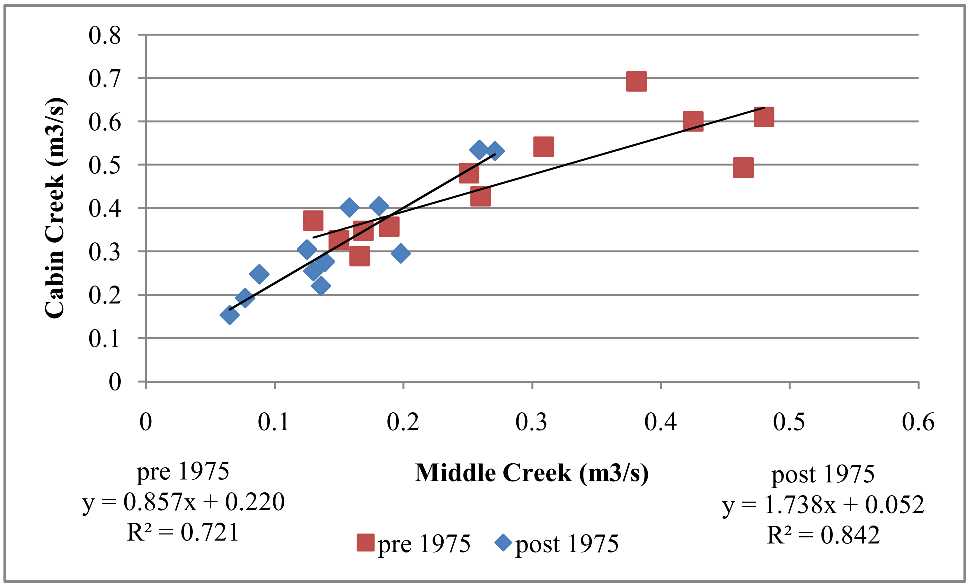

Figure 28: Cabin vs. Middle Creek peak spring stream flow

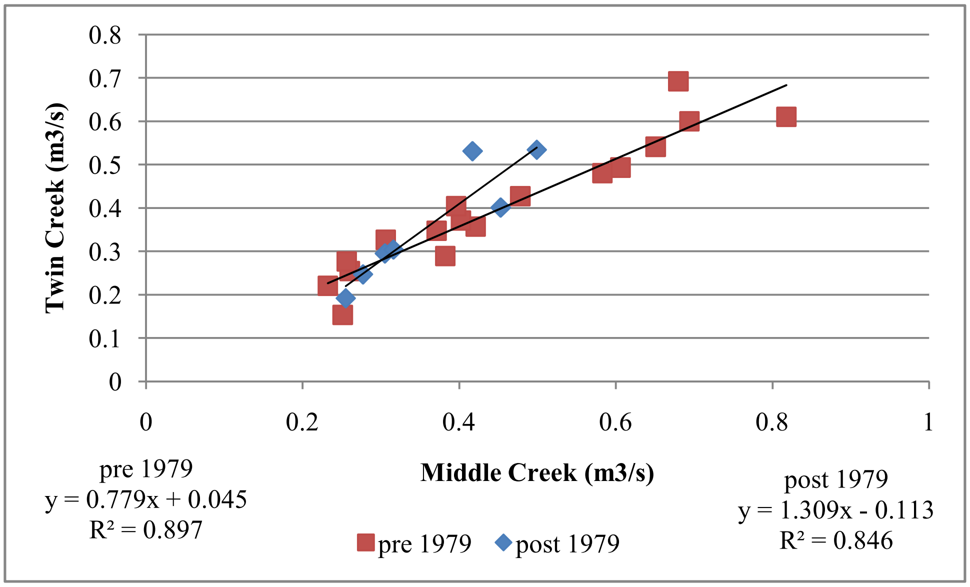

Figure 29: Twin vs. Middle Creek peak spring stream flow

The peak stream flow of both Twin and Cabin creek show significant changes relative to Middle Creek as a result of logging. The new relationships appear linear and regression for computing peak stream flow is based on the post logging period 1976-1986 when regressing peak stream flow.

Appendix D: Summary of Correlations of PDO to Kananaskis Climate

Table 15: Summary of PDO to Kananaskis Climate correlations

Station		Tmean	Tmin	Tmax	Prcp	%rain	TDR	Snow	Rain
1940-2007									
KFS	Correlation	**0.306**	**0.299**	**0.271**	-0.024	**0.282**	0.089	**-0.184**	0.128
	Significance	**0.000**	**0.000**	**0.001**	0.775	**0.001**	0.287	**0.027**	0.125
CB5	Correlation	**0.317**	**0.327**	**0.281**	-0.030				
	Significance	**0.000**	**0.000**	**0.001**	0.723				
CN5	Correlation	**0.293**	**0.310**	**0.284**	-0.045				
	Significance	**0.000**	**0.000**	**0.001**	0.588				
TN1	Correlation	**0.287**	**0.262**	**0.286**	0.000				
	Significance	**0.001**	**0.002**	**0.001**	1.000				
1940-1975									
KFS	Correlation	**0.317**	**0.252**	**0.314**	-0.043	**0.278**	**0.265**	-0.177	0.142
	Significance	**0.007**	**0.031**	**0.007**	0.713	**0.017**	**0.024**	0.130	0.225
CB5	Correlation	**0.343**	**0.357**	**0.322**	-0.091				
	Significance	**0.003**	**0.002**	**0.006**	0.443				
CN5	Correlation	**0.306**	**0.303**	**0.303**	-0.037				
	Significance	**0.009**	**0.010**	**0.010**	0.754				
TN1	Correlation	**0.308**	**0.299**	**0.287**	-0.097				
	Significance	**0.009**	**0.010**	**0.014**	0.406				
1976-2007									
KFS	Correlation	0.053	0.045	0.012	0.079	0.140	0.006	-0.083	0.113
	Significance	0.673	0.721	0.922	0.527	0.263	0.961	0.506	0.364
CB5	Correlation	0.071	-0.011	0.188	0.095				
	Significance	0.575	0.932	0.139	0.454				
CN5	Correlation	-0.032	-0.082	0.093	0.060				
	Significance	0.799	0.518	0.465	0.634				
TN1	Correlation	0.004	-0.013	0.147	0.099				
	Significance	0.973	0.919	0.247	0.434				
Pocaterra†	Correlation	0.120	0.134	0.108	0.212	0.139	-0.089	0.020	0.117
	Significance	0.381	0.327	0.428	0.114	0.303	0.518	0.884	0.393

† Pocaterra record is form 1976-2005

‡Significant correaltions are highlighted in red

Appendix E: Rain Snow Transition

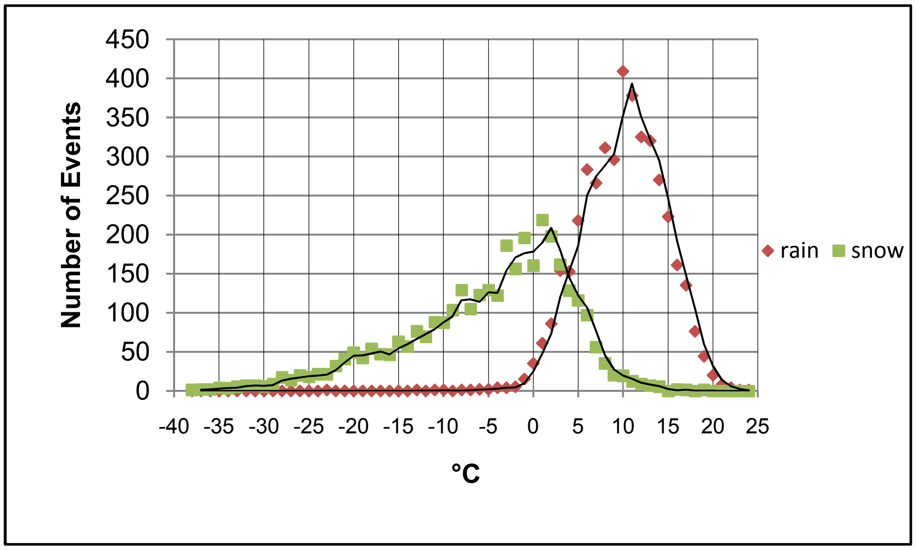

Figure 30: Rain-Snow events at Kananaskis Field Station

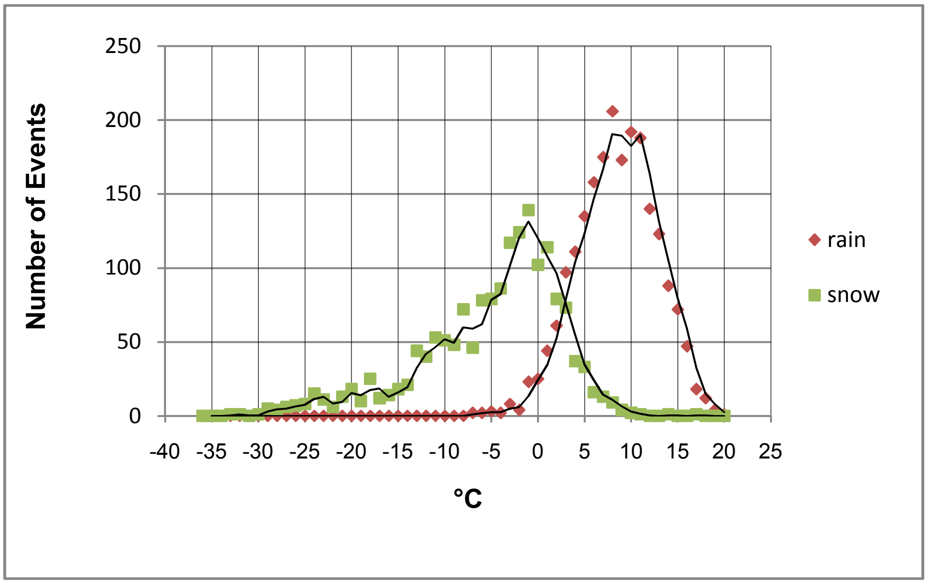

Figure 31: Rain-Snow Events at Pocaterra

The calculated critical temperature for the rain snow is 3.8°C at Kananaskis Field Station while at Pocaterra it is calculated as 3°C.

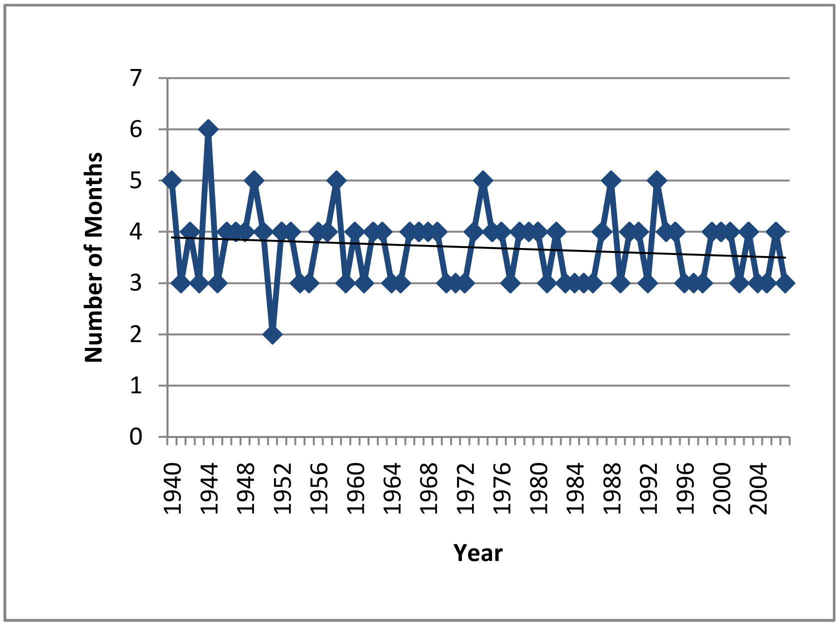

Figure 33: Months per year at TN1 with temperature greater than 3.8°C

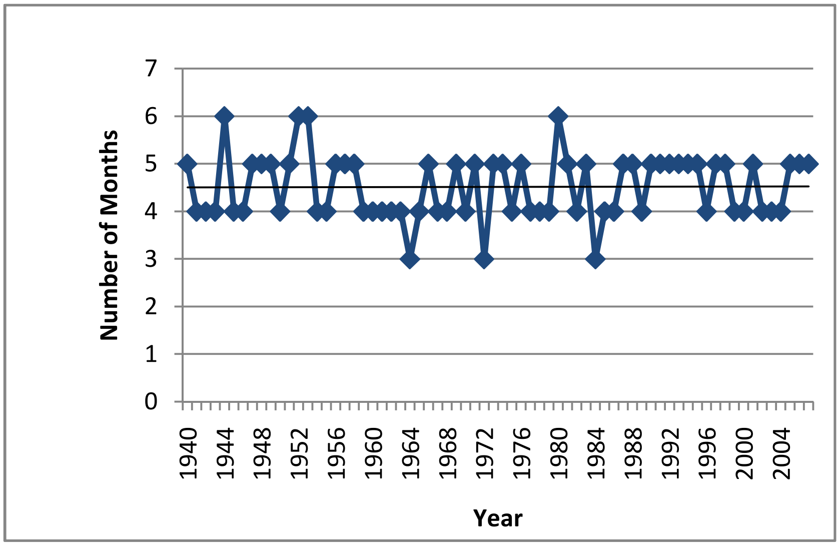

Figure 32: Months per year at CN5 with temperature greater than 3.8°C

Appendix F: Updated Rainfall snowfall separation technique and results

Air temperature is not the best indicator of precipitation phase as dew point (Marks & Adams, 2007) and wet bulb temperatures (Fuchs, 2006) have been shown to be much better. Thus using dew point and wet bulb temperatures probability curves were plotted.

Dew point (T_d) was calculated as:

$$T_d = \frac{\ln\left(0.611 * exp\left(\frac{17.3 * T}{T + 273.3}\right) * RH\right)}{0.0708 - 0.00421 * \ln\left(0.611 * exp\left(\frac{17.3 * T}{T + 273.3}\right) * RH\right)}$$

Where T is temperature and RH is relative humidity. This equation was derived from Dingman (2002).

Ice bulb temperature

The calculation for ice bulb temperature was based on a spreadsheet from John Pomeroy titled "icebulb2.xls". The equation used is a linear approximation of the ice bulb temperature which is:

$$T_{ice} = T - L_f\left(1 - \frac{RH}{100}\right)\left(\frac{q^*(t)}{C_p + L_f * \Delta}\right)$$

The units for the ice bulb equations are unclear. Where T is temperature, RH is relative humidity %, L_f is 2850000 and C_p is 1005. The values for $q^*(t)$ and Δ are results of other calculation and are found as:

$$\Delta = \varepsilon * L_f\left(\frac{q^*(t)}{R * T_k^2}\right)$$

Where ε is 0.622, R is 287 and T_k is temperature in Kelvin and $q^*(t)$ is:

$$q^*(t) = \left(\frac{\varepsilon}{P}\right) * 611.213 * exp\left(\frac{22.4422 * T}{272.186 + T}\right)$$

and P is pressure in Pa[3] which can be approximated based on the barometric formula (NOAA, 1976) as:

$$P = P_0\left(\frac{T_0}{T_0 + L(H - H_0)}\right)^{\frac{g*m}{R*L}}$$

Where P_0 is the pressure at elevation zero in this case sea level where pressure is 101325 Pa[3], L is the lapse rate taken to be -6.5°C/1000m, H is elevation of interest and H_0 is initial elevation in this case sea level or 0m, g is gravity 9.81m/s^2, m is the molar mass of the atmosphere 28.9644g/mol, R is the mixing constant 8.31432 Nm/molK and T_0 is the temperature in Kelvin at sea level which is taken as:

$$T_0 = T + L * (H - H_0)$$

Additionally at temperatures below 0°C a correction for relative humidity must be applied which is based on Buck (1981). A second order polynomial best fit line is applied to the variation in relative humidity based on temperature and can be expressed as:

$$RH_{ice} = 0.00005 * T^2 + 0.009 * T + 0.999$$

This correction was applied to the relative humidity for the calculation of the ice bulb temperature.

Rainfall and Snowfall event separation

At KFS the rainfall and snowfall events in the data are clearly defined. Data for relative humidity necessary for dew point and ice bulb calculations is only available for November 1999- present. Unfortunately the precipitation data is on a daily scale and as such mean daily values of the dew point and ice bulb temperatures may not reflect the temperature of precipitation phase change exactly. For the purposes of comparison the transition curves for upper clearing was also defined on the daily scale.

At Upper Clearing the data was collected every 15 min. To account for variation and to define and distinguish precipitation phase of precipitation events clearly a series of conditions were applied to the data. Precipitation data from the Texas Electronics tipping bucket and Alter Shielded precipitation gauge was represented as the change for every 15 minute interval. The criteria to identify precipitation phase had to be met in the following order.

For Rainfall:

1. Precipitation > 0mm recorded in the Geonor precipitation gauge

2. Precipitation >0mm recorded in the tipping bucket rain gauge

For Snowfall

1. Precipitation > 0mm recorded in the Geonor precipitation gauge
2. No precipitation recorded in the tipping bucket rain gauge
3. Not considered snowfall if in the previous and subsequent 15 minute time period no precipitation recorded by the precipitation Geonor precipitation gauge
4. Not considered snowfall if tipping bucket recorded precipitation >0mm in the previous or subsequent 15 minute time period

If the following conditions are met the events are classified into the respective precipitation phase. On a daily scale the number of 15 minute intervals meeting the outlined criteria is summed and the fraction of rainfall versus snowfall events is the product. When defining the transition curve for either dew point or ice bulb temperature the number of rainfall and snowfall events is summed for every degree change. The temperatures are given as a daily average. The fraction of events occurring as rain for each degree change are quantified as a percentage defined as:

$$Rainfall\ Fraction = \frac{Rainfall\ events}{Rainfall\ events + Snowfall\ events}$$

Transition Curves

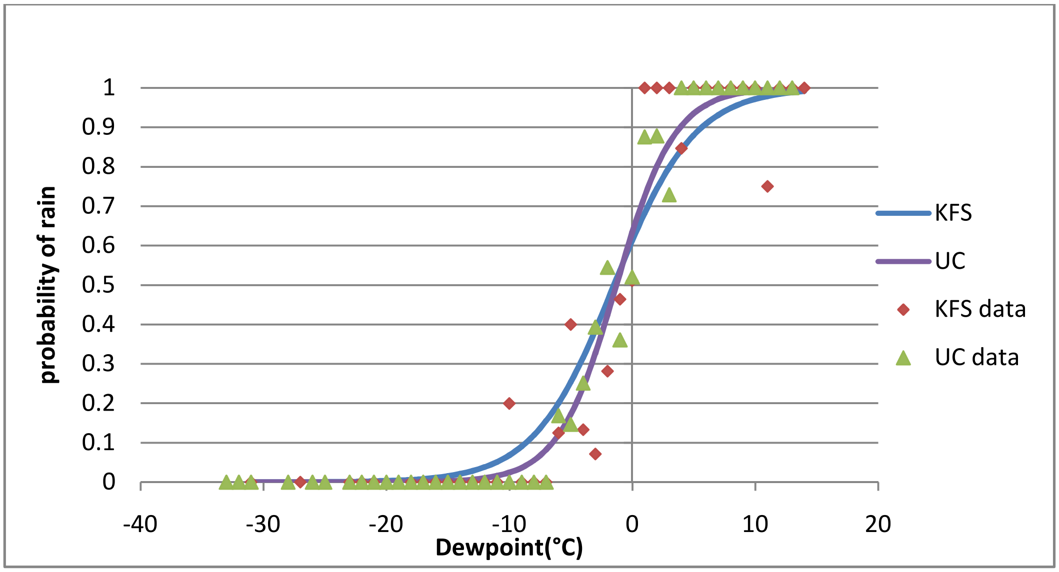

Figure 34: Precipitation phase transition as function of Dew point temperature

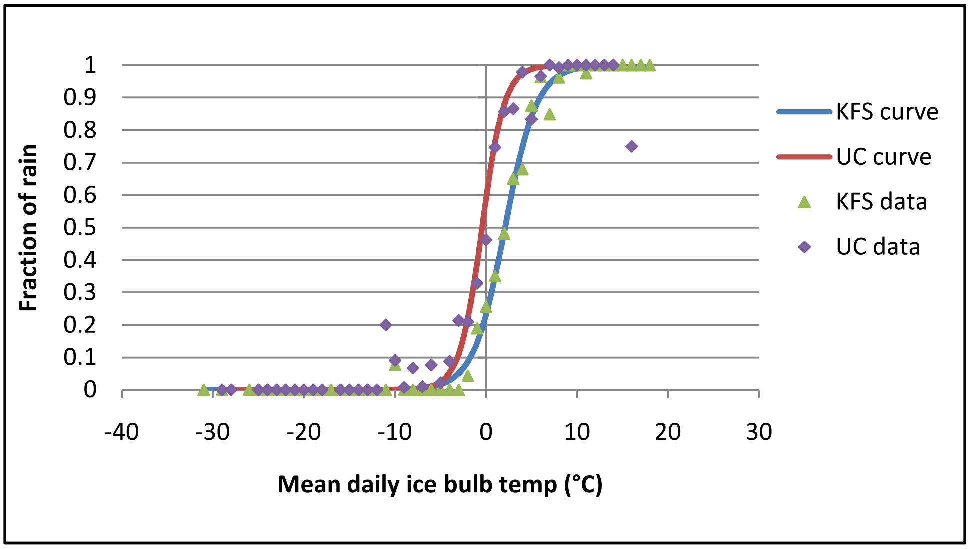

Figure 35: Probability of Rain as function of ice bulb temperature

Transition curves were computed with iPlot in IDL 4.4 and shown in Figures 34 and 35. The form of the best fit line is that of a logistic regression where:

$$y = \frac{1}{A + BC^x}$$

The coefficients for the regressions as follows in Table 16.

Table 16: Summary of precipitation phase curve coefficients

	A	B	C
KFS dew point	1	0.63373054	0.73579911
KFS ice bulb	1	3.3261619	0.56303587
UC dew point	1	0.57957763	0.6549986
UC ice bulb	1	0.69956017	0.44443302

Conclusions

These relationships while emphasizing a transition range that is similar to an air temperature relationship are better. This is the case as the transition curves for dew point and ice bulb temperature between UC and KFS are more similar. In the case of dew point the curves are very close to the same which shows that even though the two stations are in different places the transition process has the same relationship with phase change. Ice bulb temperature transition curves are not as well correlated as dew point though this may be due to problems in the ice bulb temperature calculation. The ice bulb temperature actually should be calculated as the wet bulb though the difference will not be large.

With this curve one would suggest that the zero degree Celsius dew point would be a good indicator of precipitation phase change. While variations do occur in the near zero region it would suffice as a robust indicator of precipitation phase from the historical Marmot Basin data. One approach would be to estimate rain snow separation by looking at dew point and observed precipitation. Differentiating precipitation into rain and snow provides data for running the Mann-Kendall analysis. Another approach is to observe the change in number of days per month above or below the specified dew point temperature used for differentiating precipitation phase.

References

Buck, A. L. (1981). New Equations for Computing Vapor Pressure and Enhancement Factor. Journal of Applied Meteorology. 20(12), 1527-1532.

US Standard Atmosphere. Publication NOAA-S/T76-1562. Washington, DC: US Government Printing Office, 1976.